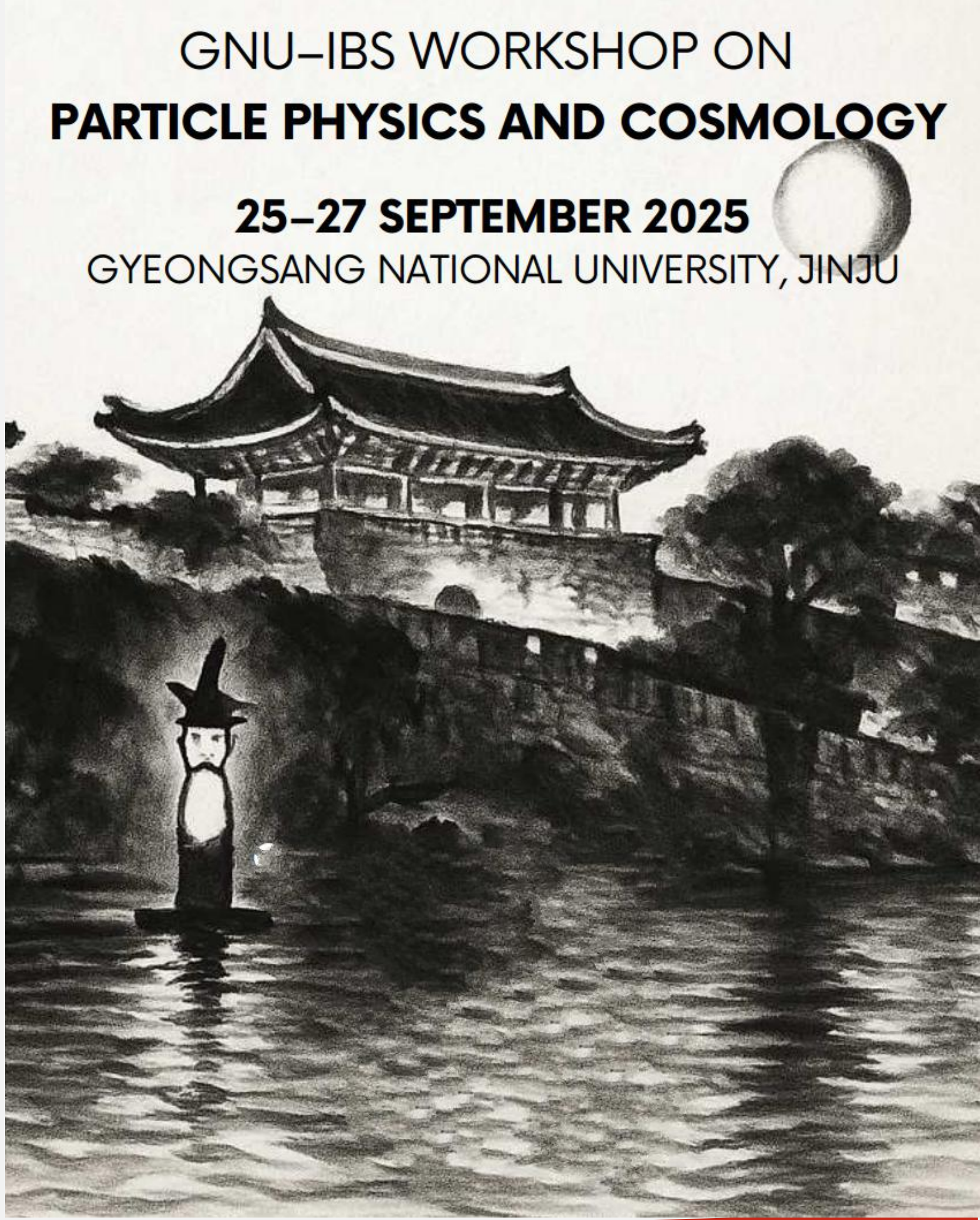
Testing Neutrino Mass Origins with Supernova Neutrinos



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arXiv:2404.17352 [hep-ph], PRL 133 (2024) 12, 121802

In collaboration with: Shao-Feng Ge & Alexei Y. Smirnov

Institute for Basic Science

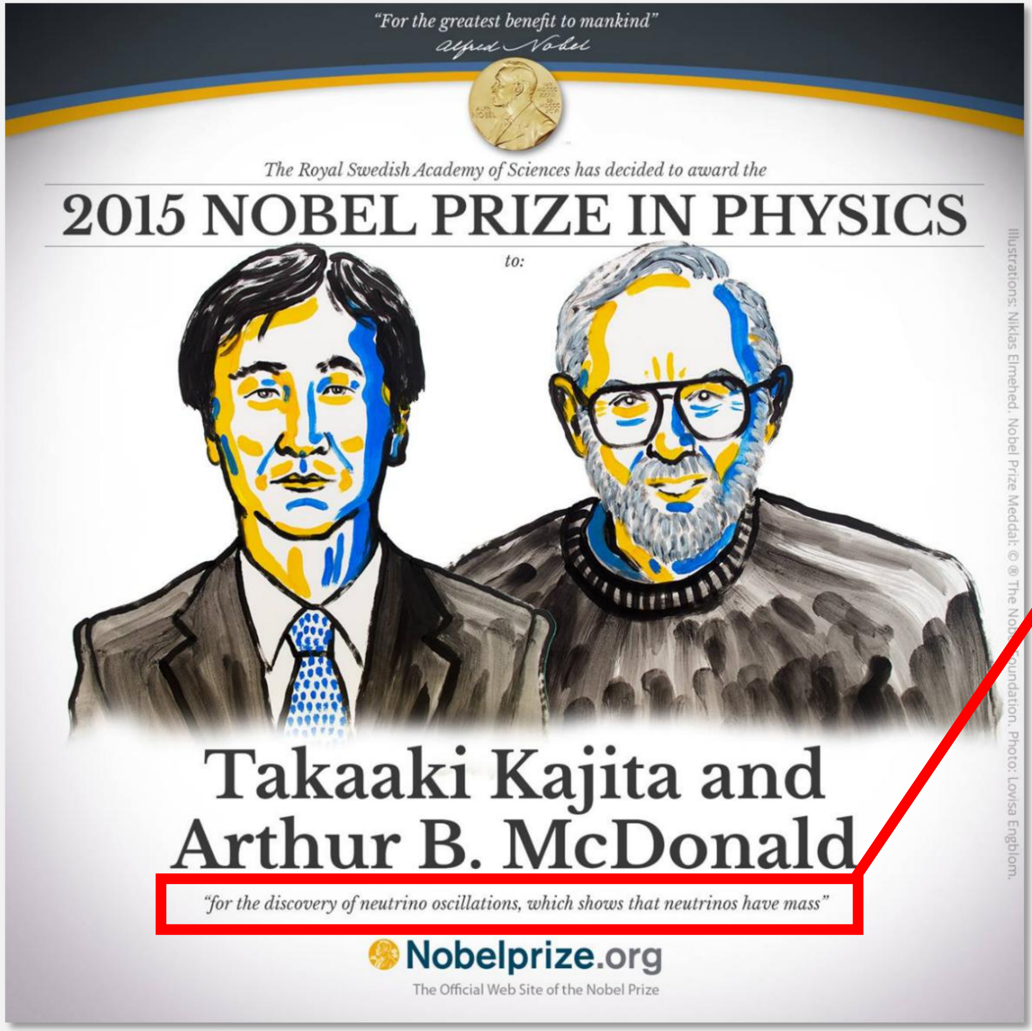
GNU-IBS Workshop @ Jinju

Sep. 26, 2025

- *Evidence of neutrino mass from oscillation*
- *Neutrino mass origins*
- *Experimental sensitivities*

Evidence of neutrino mass from oscillation

Evidence of Neutrino Mass



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Evidence of Neutrino Mass

Institute for Basic Science

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

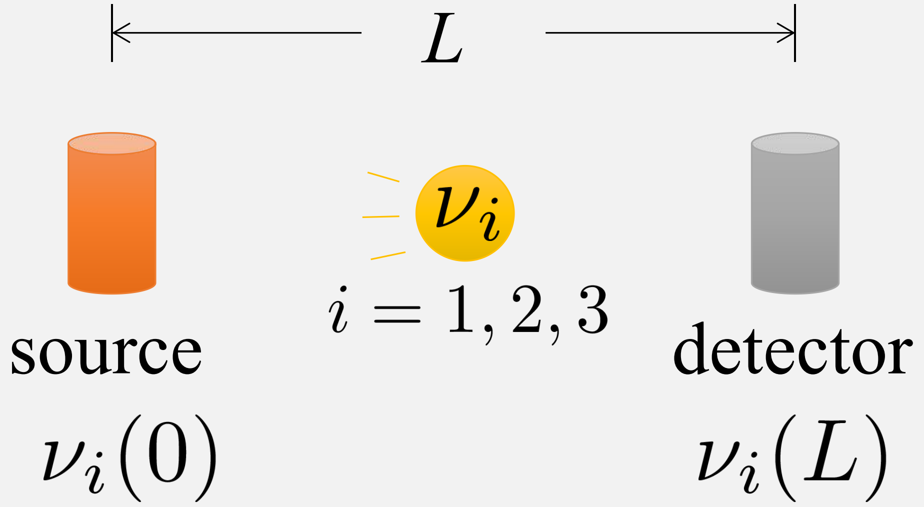
neutrino mass eigenstates:

ν_1 ν_2 ν_3

$$m_1 \neq m_2 \neq m_3$$

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass



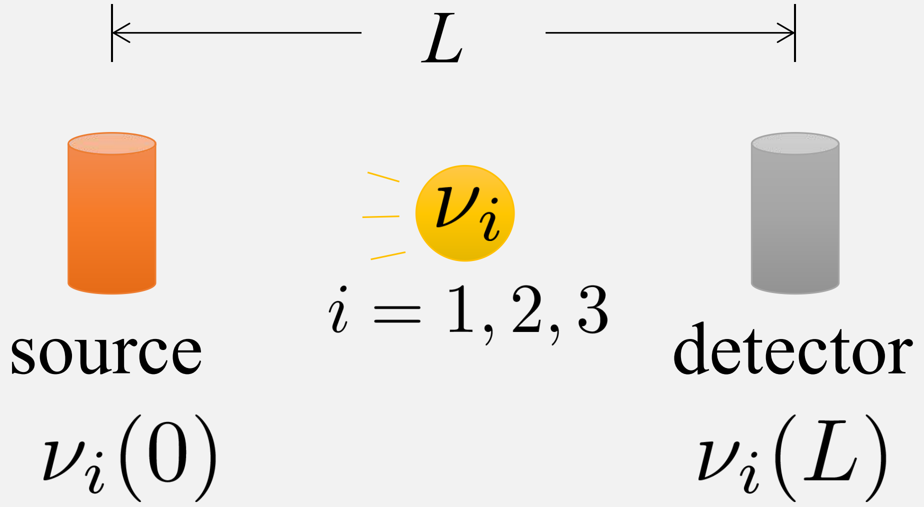
Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

Evolution in space:

$$\nu_i \propto e^{-ip_i x}$$

$$\nu_i(L) = e^{ip_i L}\nu_i(0)$$



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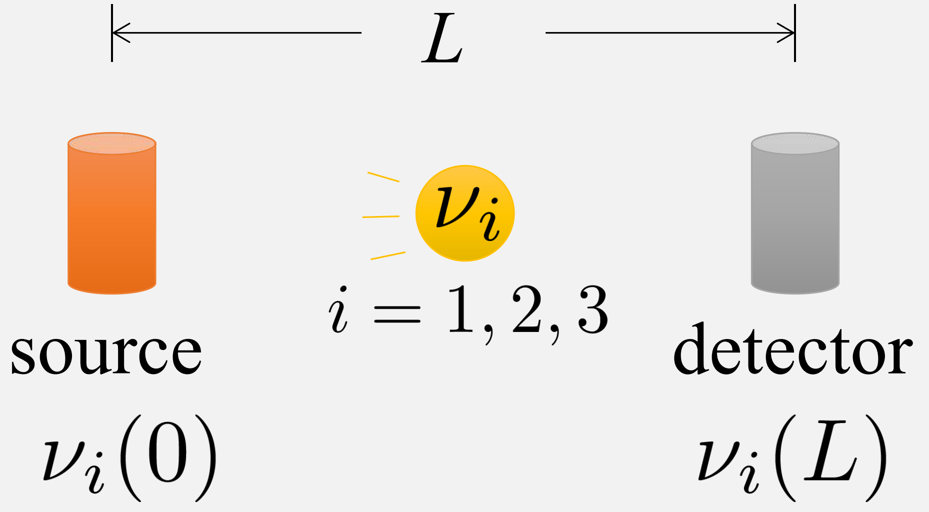
Ultra-relativistic: $p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$



$$\nu_i(L) = e^{iEL - i\frac{m_i^2}{2E}L}\nu_i(0)$$

Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

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$$\nu_i \propto e^{-ip_i x}$$

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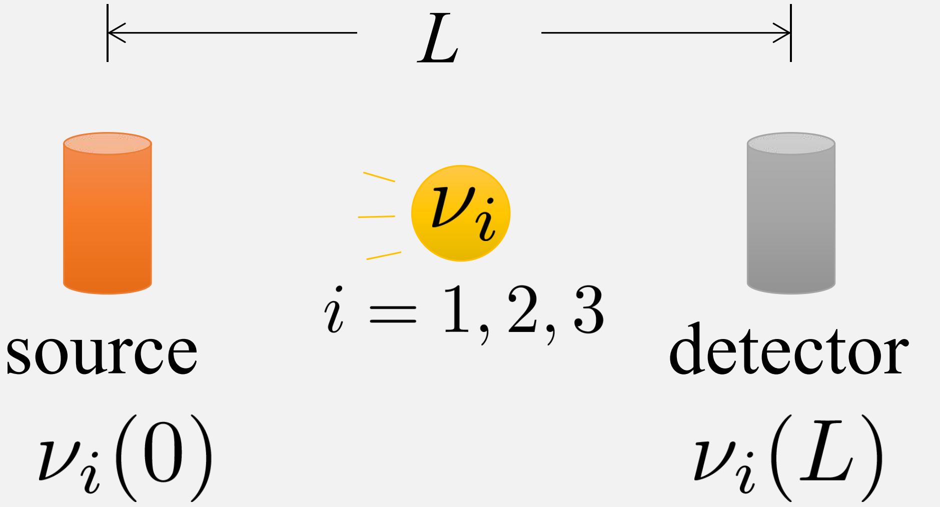


Ultra-relativistic: $p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$

$$\nu_i(L) = e^{i\cancel{E}L - i\frac{m_i^2}{2E}L}\nu_i(0)$$

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

ν_1 ν_2 ν_3

$$e^{-i\frac{m_1^2}{2E}L} \qquad e^{-i\frac{m_2^2}{2E}L} \qquad e^{-i\frac{m_3^2}{2E}L}$$

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

ν_1	ν_2	ν_3
$e^{-i\frac{m_1^2}{2E}L}$	$e^{-i\frac{m_2^2}{2E}L}$	$e^{-i\frac{m_3^2}{2E}L}$
↓	↓	↓
1	$e^{-i\frac{\Delta m_{21}^2}{2E}L}$	$e^{-i\frac{\Delta m_{31}^2}{2E}L}$

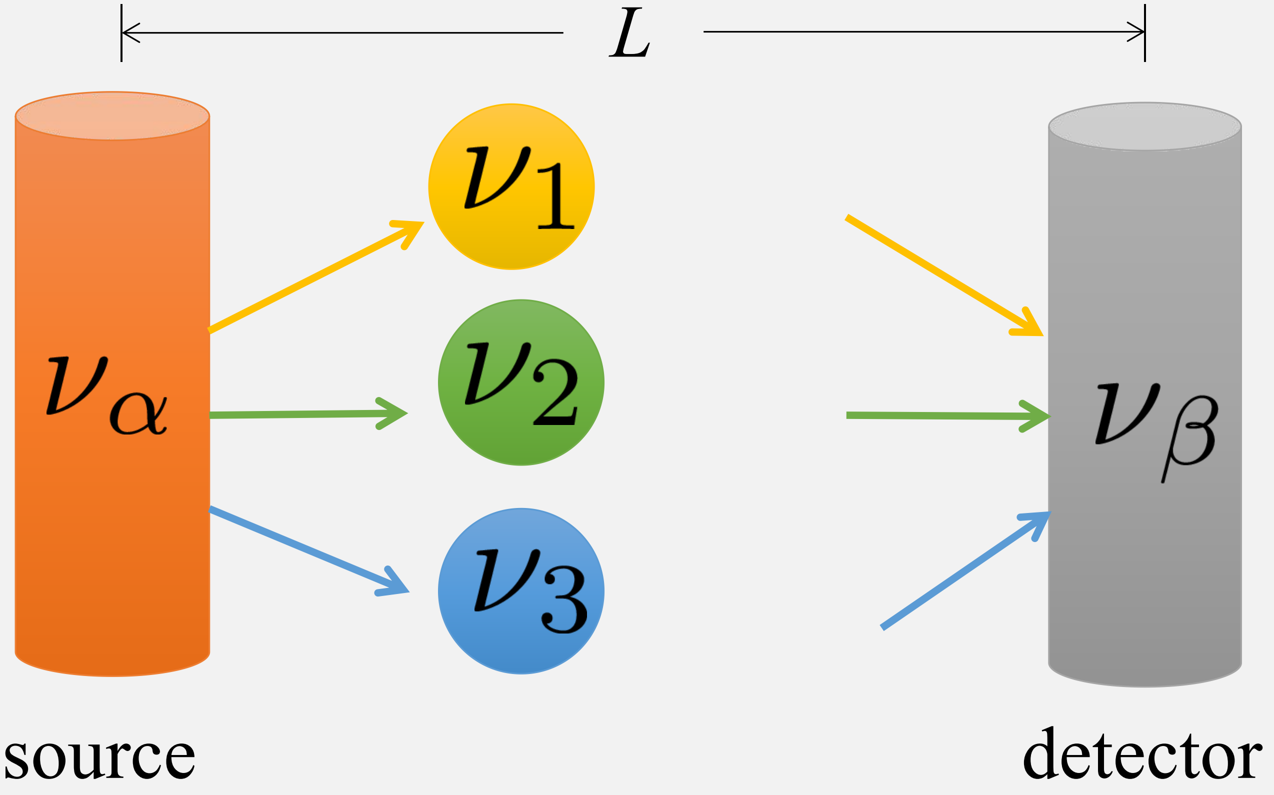
$$[\Delta m_{21}^2 \equiv m_2^2 - m_1^2, \quad \Delta m_{31}^2 \equiv m_3^2 - m_1^2]$$

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

Mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

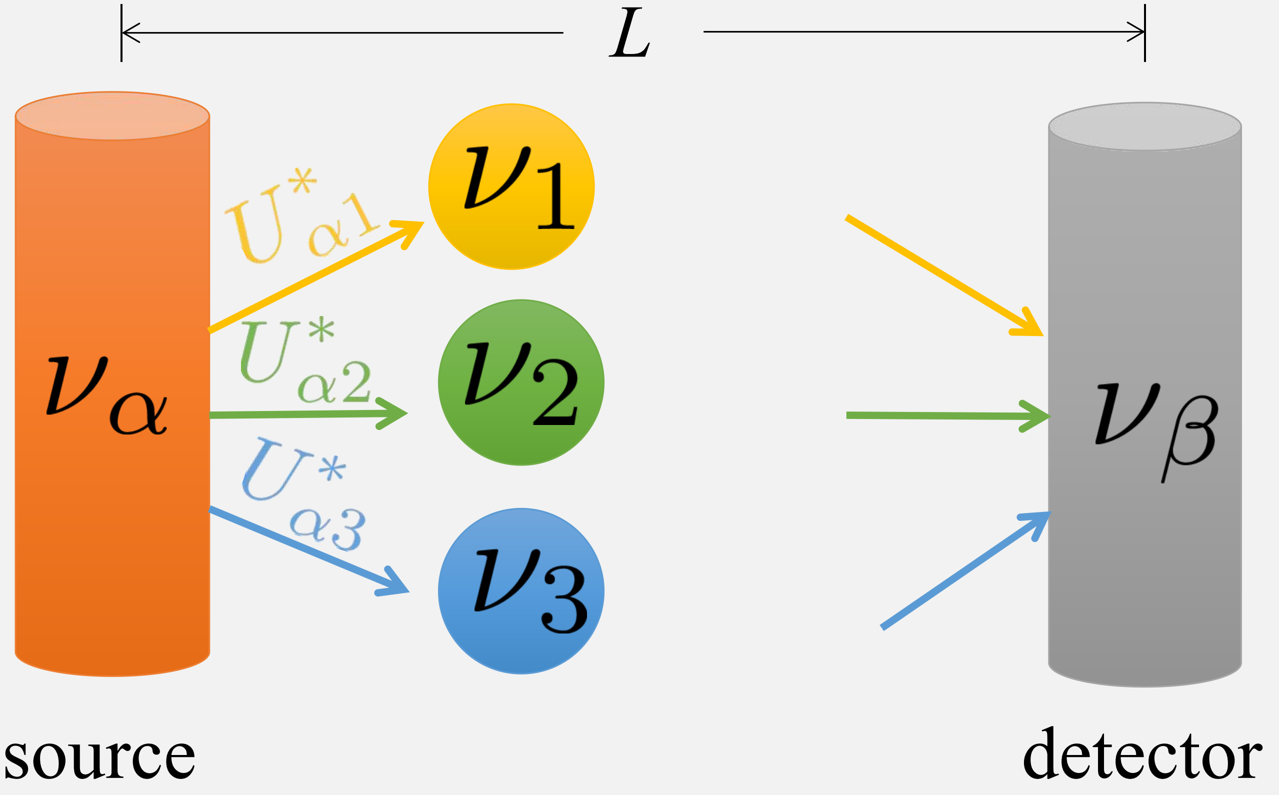


Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

production:

$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$



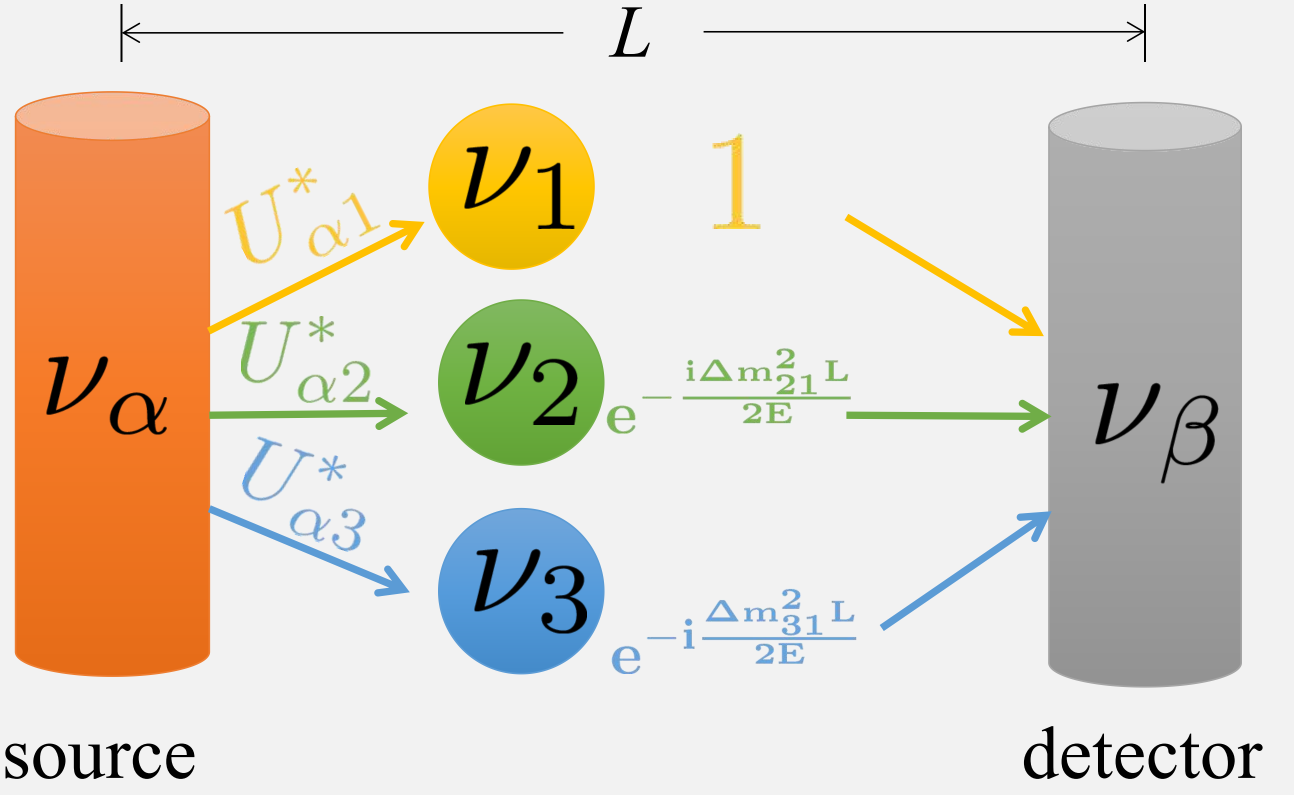
Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

production:

$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$

$$1 \qquad e^{-\frac{i\Delta m^2_{21}L}{2E}} \qquad e^{-i\frac{\Delta m^2_{31}L}{2E}}$$



Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

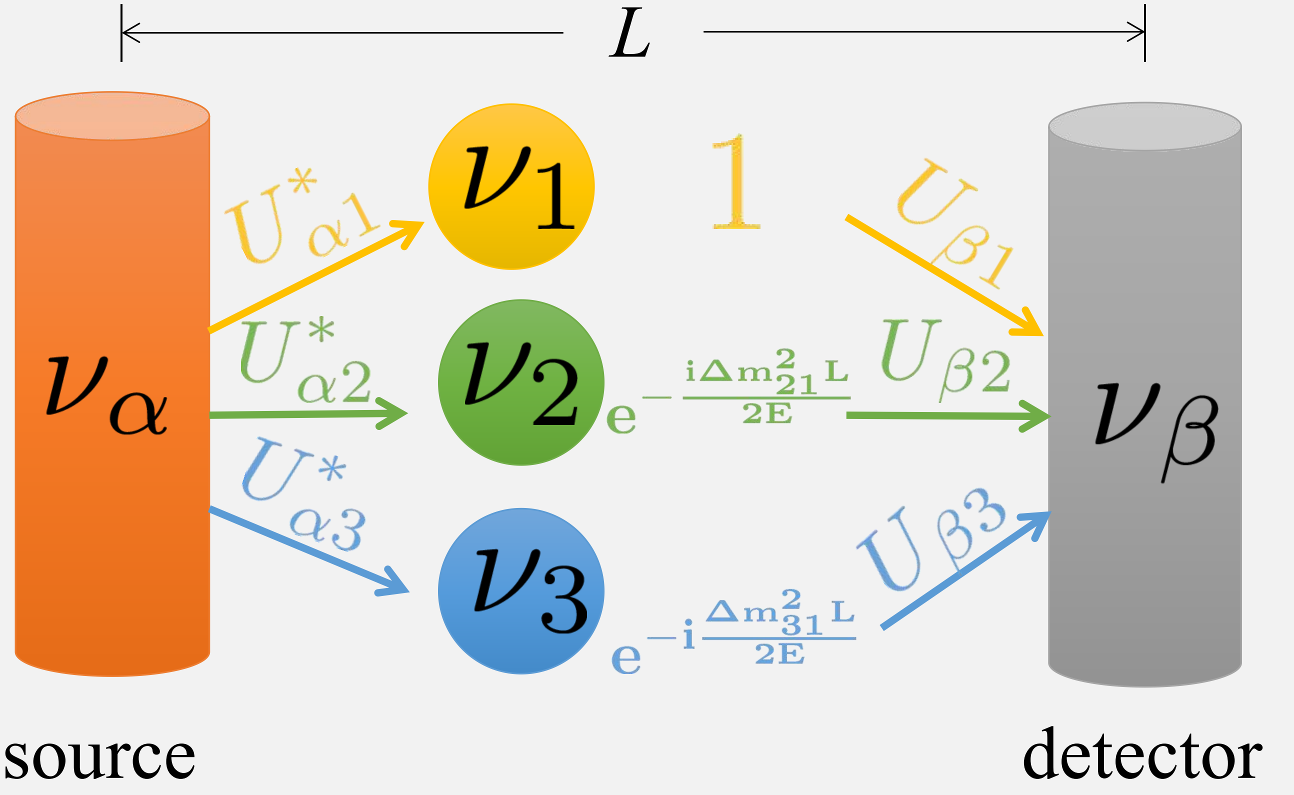
production:

$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$

1 $\qquad e^{-\frac{i\Delta m^2_{21} L}{2E}}$ $\qquad e^{-i\frac{\Delta m^2_{31} L}{2E}}$

detection:

$$\langle\nu_\beta| = U_{\beta 1}\langle\nu_1| + U_{\beta 2}\langle\nu_2| + U_{\beta 3}\langle\nu_3|$$

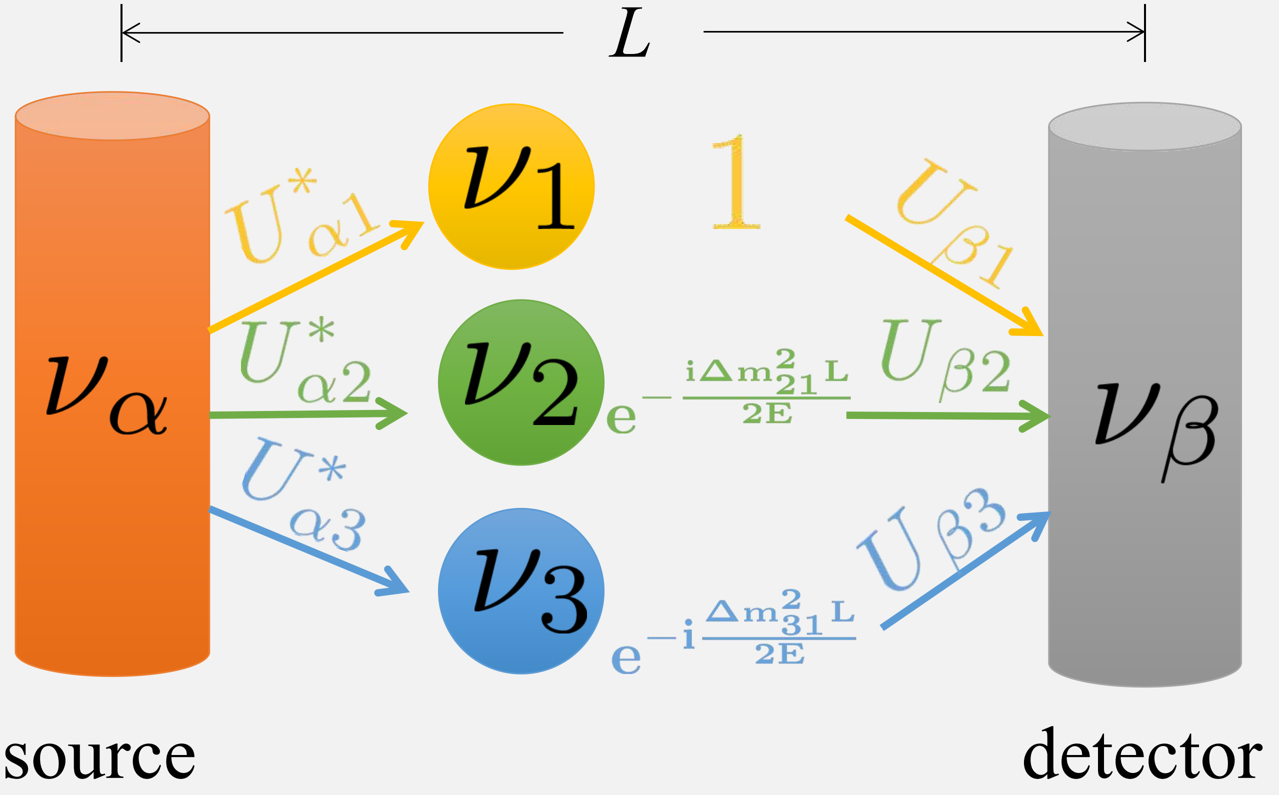


Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

Oscillation amplitude

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \mathbf{U}^*_{\alpha 1}\mathbf{U}_{\beta 1} + \mathbf{U}^*_{\alpha 2}\mathbf{e}^{-i\frac{\Delta m^2_{21}}{2E}L}\mathbf{U}_{\beta 2} + \mathbf{U}^*_{\alpha 3}\mathbf{e}^{-i\frac{\Delta m^2_{31}}{2E}L}\mathbf{U}_{\beta 3}$$

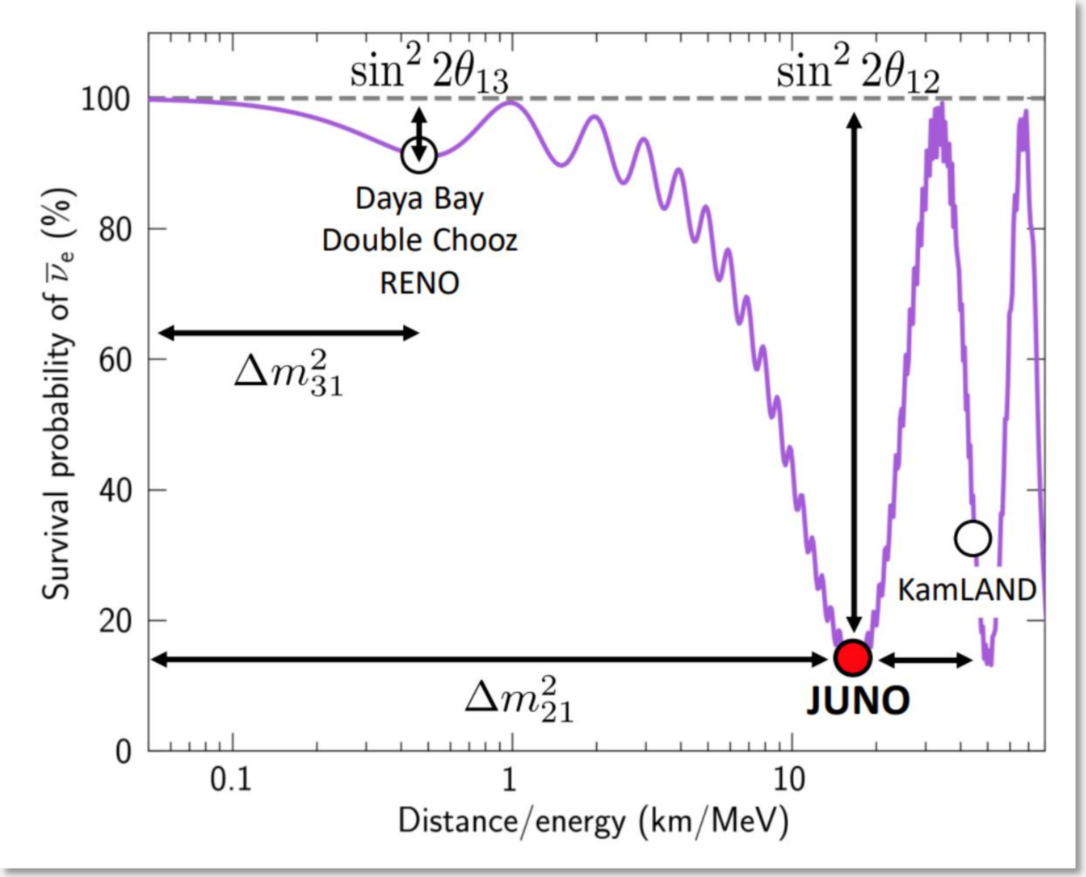


Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2$$

$$\text{oscillation phase} : \propto \frac{\Delta m_{ij}^2 L}{E_\nu}$$



credit: JUNO

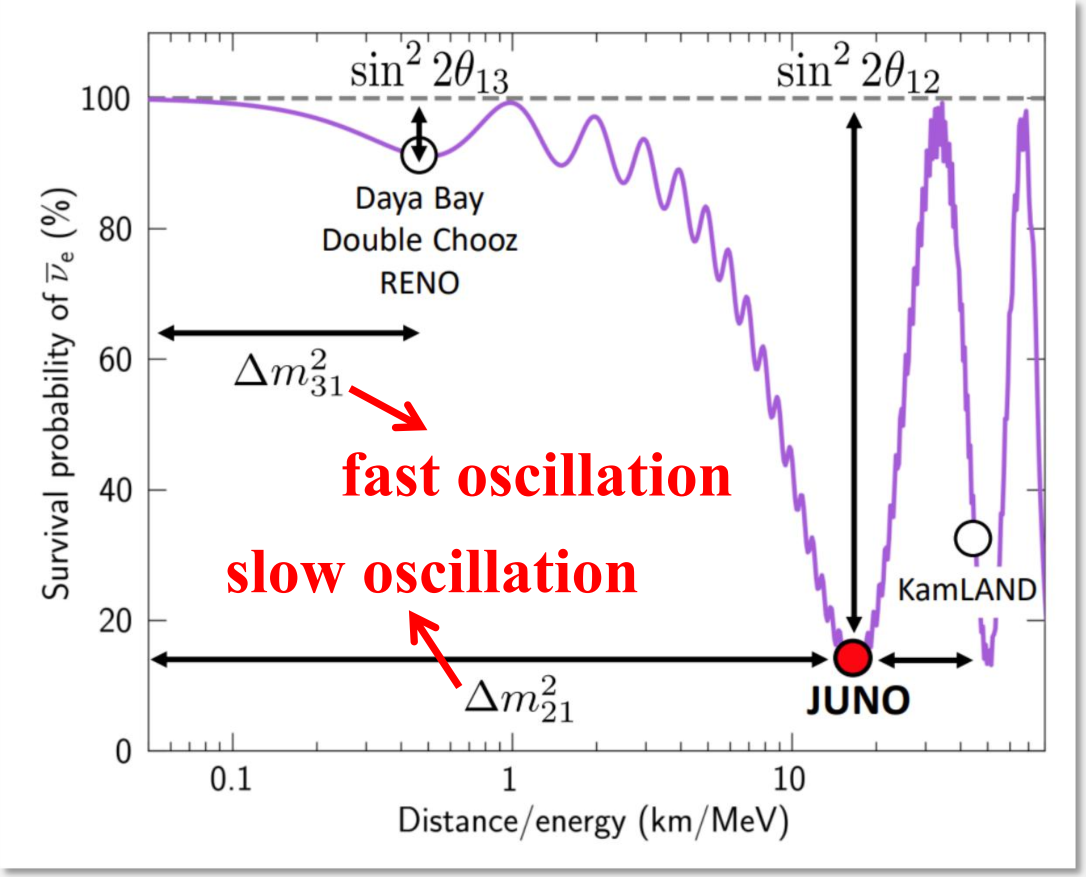
Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

$$P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2$$

$$\text{oscillation phase} : \propto \frac{\Delta m^2_{ij} L}{E_\nu}$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\mathrm{eV}^2, \Delta m^2_{31} \approx 2.5 \times 10^{-3}\mathrm{eV}^2$$



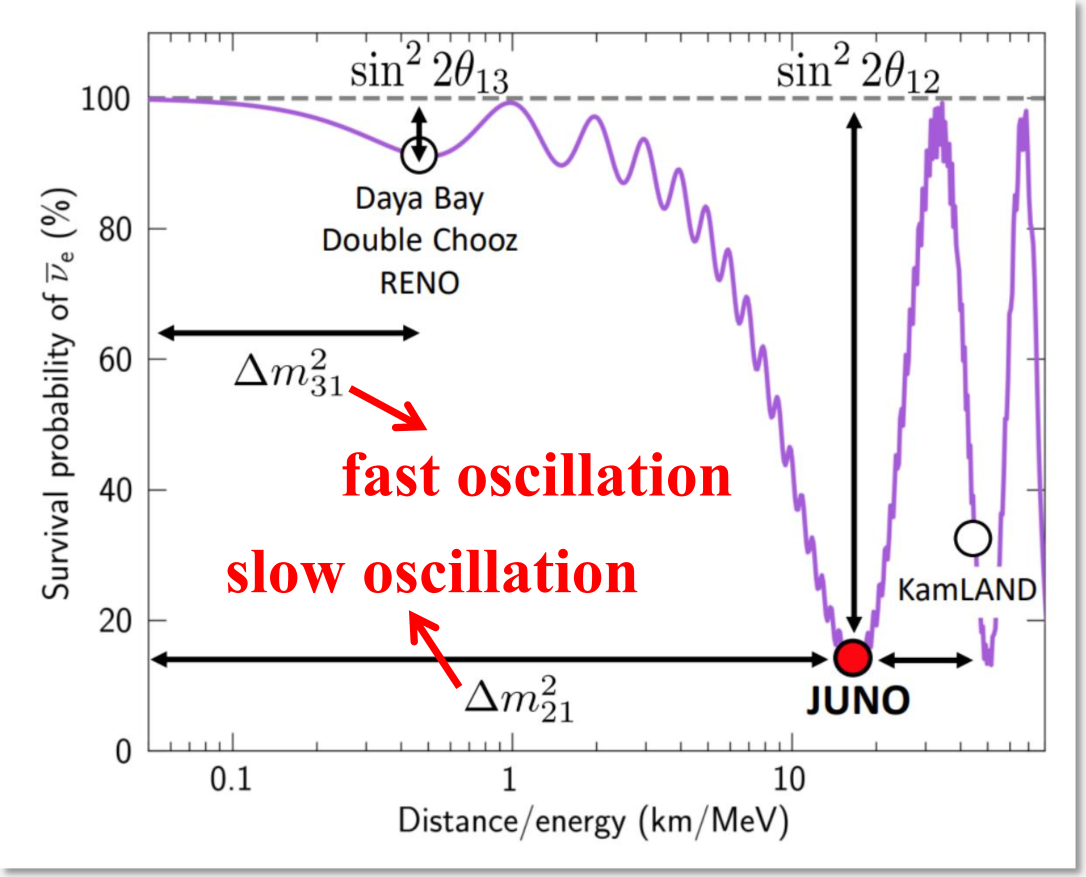
credit: JUNO

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

$$\text{oscillation phase} : \propto \frac{\Delta m_{ij}^2 L}{E_\nu}$$

Neutrino masses drive the oscillation behavior !



credit: JUNO

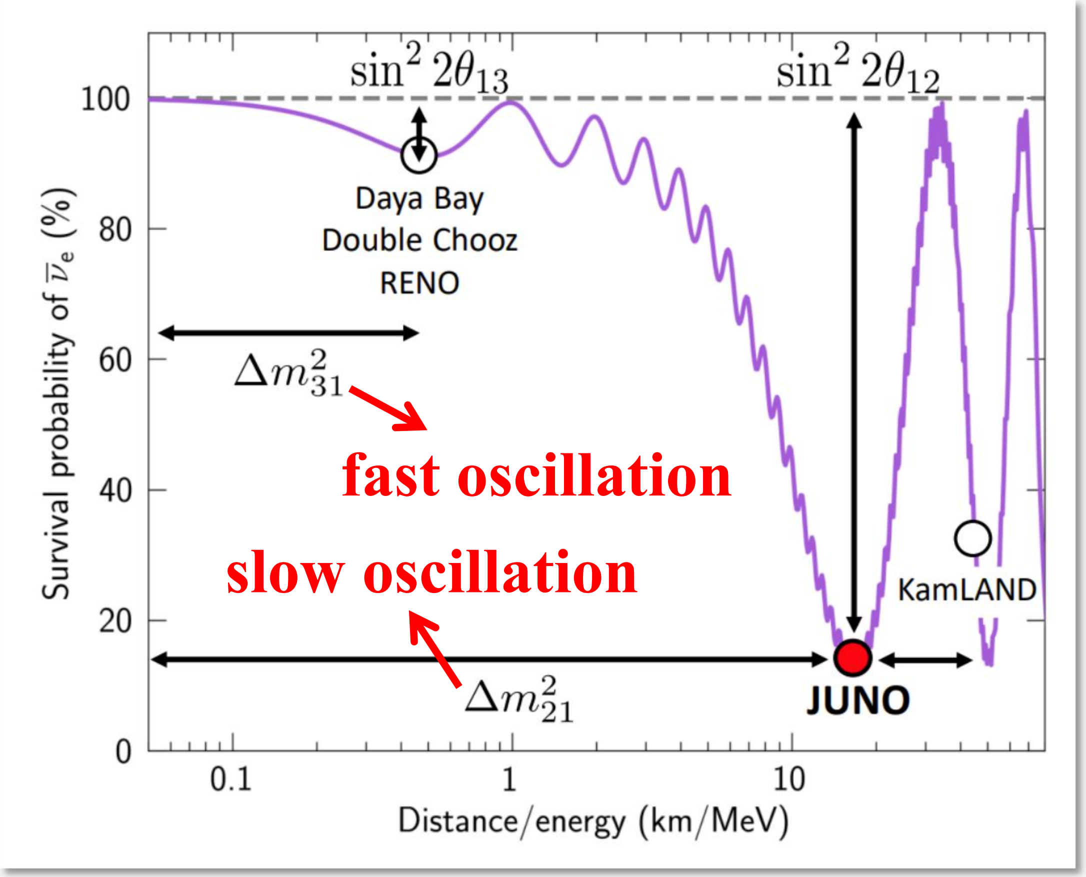
Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

$$\text{oscillation phase} : \propto \frac{\Delta m_{ij}^2 L}{E_\nu}$$

Neutrino masses drive the oscillation behavior !

What's the origin of neutrino mass?



credit: JUNO

Neutrino mass origins

Neutrino Mass Origin

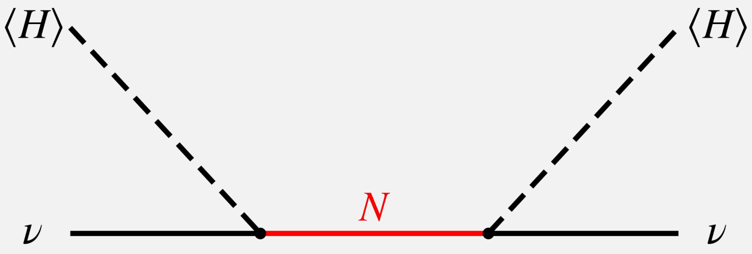
Neutrino mass origins

vacuum neutrino mass | dark neutrino mass

Neutrino Mass Origin I: vacuum mass

Vacuum Neutrino Mass

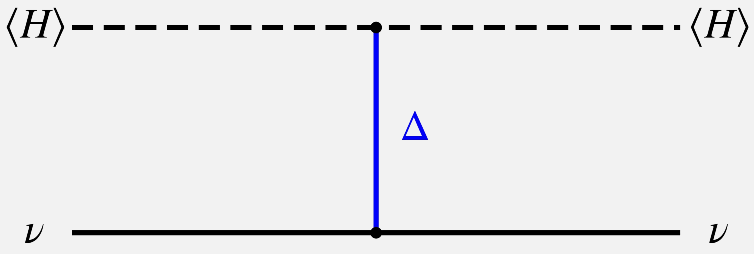
Type-I seesaw



$$M_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$

P. Minkowski
T. Yanagida
M. Gell-Mann
…

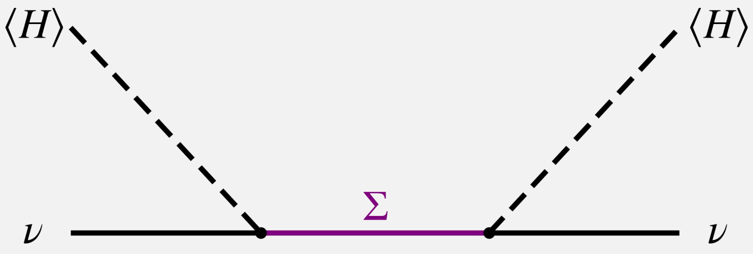
Type-II seesaw



$$M_\nu = \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

M. Magg & C. Wetterich
G. Lazarides, Q. Shafi, & C. Wetterich
R. Mohapatra & G. Senjanovic
…

Type-III seesaw



$$M_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

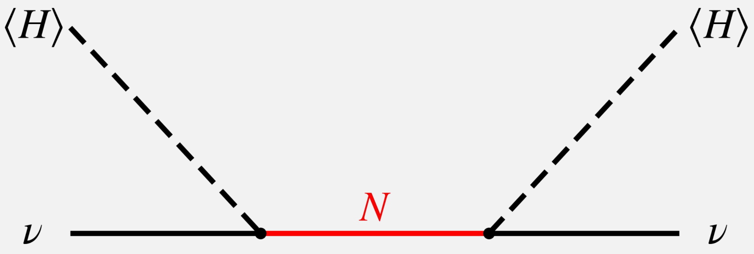
R. Foot, H. Lew, X.-G. He, & G.C. Joshi
E. Ma
…

•••

Neutrino Mass Origin I: vacuum mass

Vacuum Neutrino Mass

Type-I seesaw



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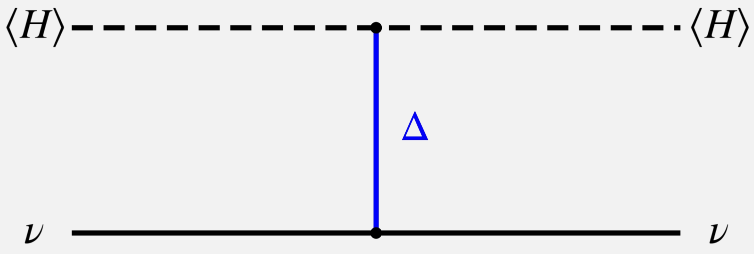
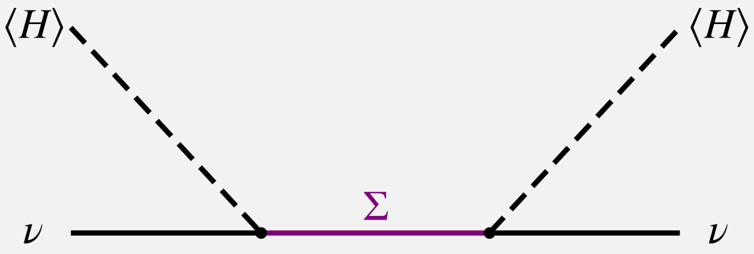


$$M_\nu = \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

Type-III seesaw



$$M_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

...

$$m_{\rm vac}^2 = \text{constant}$$

Neutrino Mass Origin II: dark mass

$$H \sim \sqrt{p^2 + |m|^2} \approx p + \boxed{\frac{|m|^2}{2E}}$$

drives neutrino oscillation

Neutrino Mass Origin II: dark mass

$$H \sim \sqrt{p^2 + |m|^2} \approx p + \frac{|m|^2}{2E}$$

What if $m = 0$, but neutrino matter potential

$$H \approx p + V, \quad \text{with } V = \frac{\cdots}{2E}$$

Neutrino Mass Origin II: dark mass

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What if $m = 0$, but neutrino matter potential

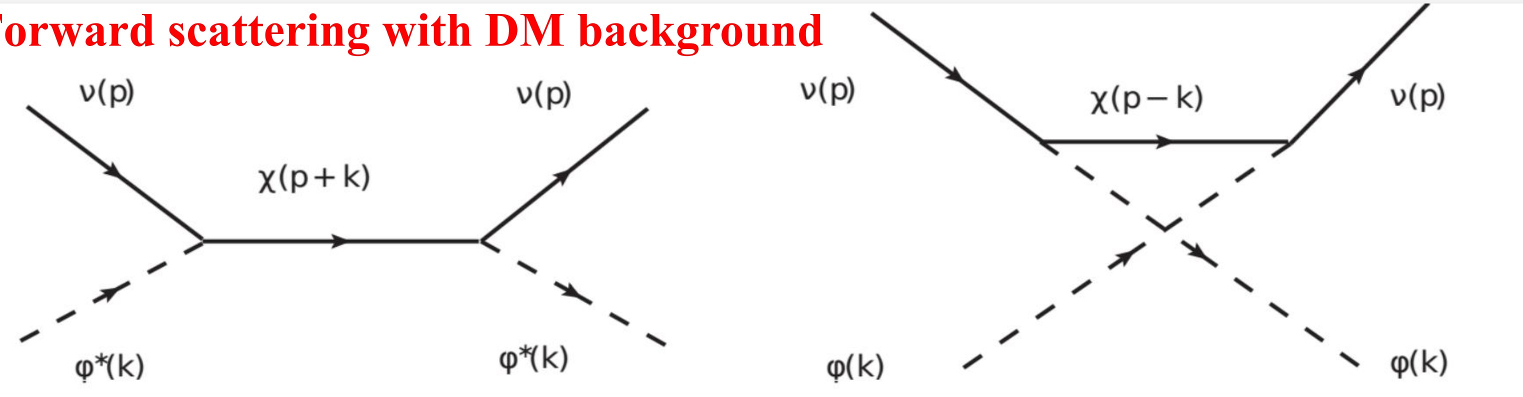
$$H \approx p + V, \quad \text{with } V = \frac{\boxed{\dots}}{2E}$$

effective mass
or
"dark" mass

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass

Forward scattering with DM background



Introduce the effective or refractive mass squared as

$V = m_{ref}^2/2E$

$m_{ref}^2 = 2EV$

$m_{ref}^2 = 2EV$

$$m_{ref}^2 = m_{as}^2 \frac{y(y - \varepsilon)}{y^2 - 1}$$

$$m_{as}^2 = \Sigma_k\, g_{\alpha k}\, g_{\beta k}^* \frac{\rho_\phi}{m_\phi^2}$$

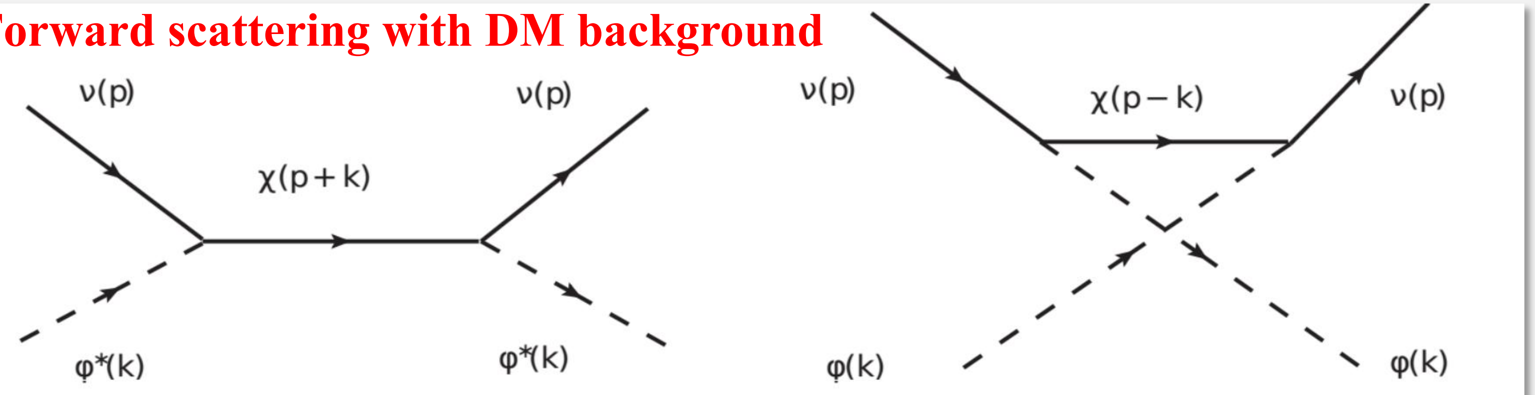
A. Y. Smirnov, talks@MAYORANA Workshop

[S.-F. Ge & H. Murayama, arXiv:1904.02518; K. Y. Choi, E. J. Chun & J. Kim, arXiv:1909.10478, 2012.09474; M. Sen and A. Y. Smirnov, arXiv:2306.15718]

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass

Forward scattering with DM background



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A. Y. Smirnov, talks@MAYORANA Workshop

$$m^2_{\rm dark}(x) \propto \rho_\phi$$

Neutrino Mass Origins Comparison

Institute for Basic Science

Vacuum Neutrino Mass: $m_{\rm vac}^2 = \text{constant}$

vs.

Dark Neutrino Mass: $m_{\rm dark}^2(x) \propto \rho_\phi$

Neutrino Mass Origins Comparison

Institute for Basic Science

Vacuum Neutrino Mass: $m_{\rm vac}^2 = \text{constant}$

vs.

Dark Neutrino Mass: $m_{\rm dark}^2(x) \propto \rho_\phi$

Can we distinguish these two origins ?

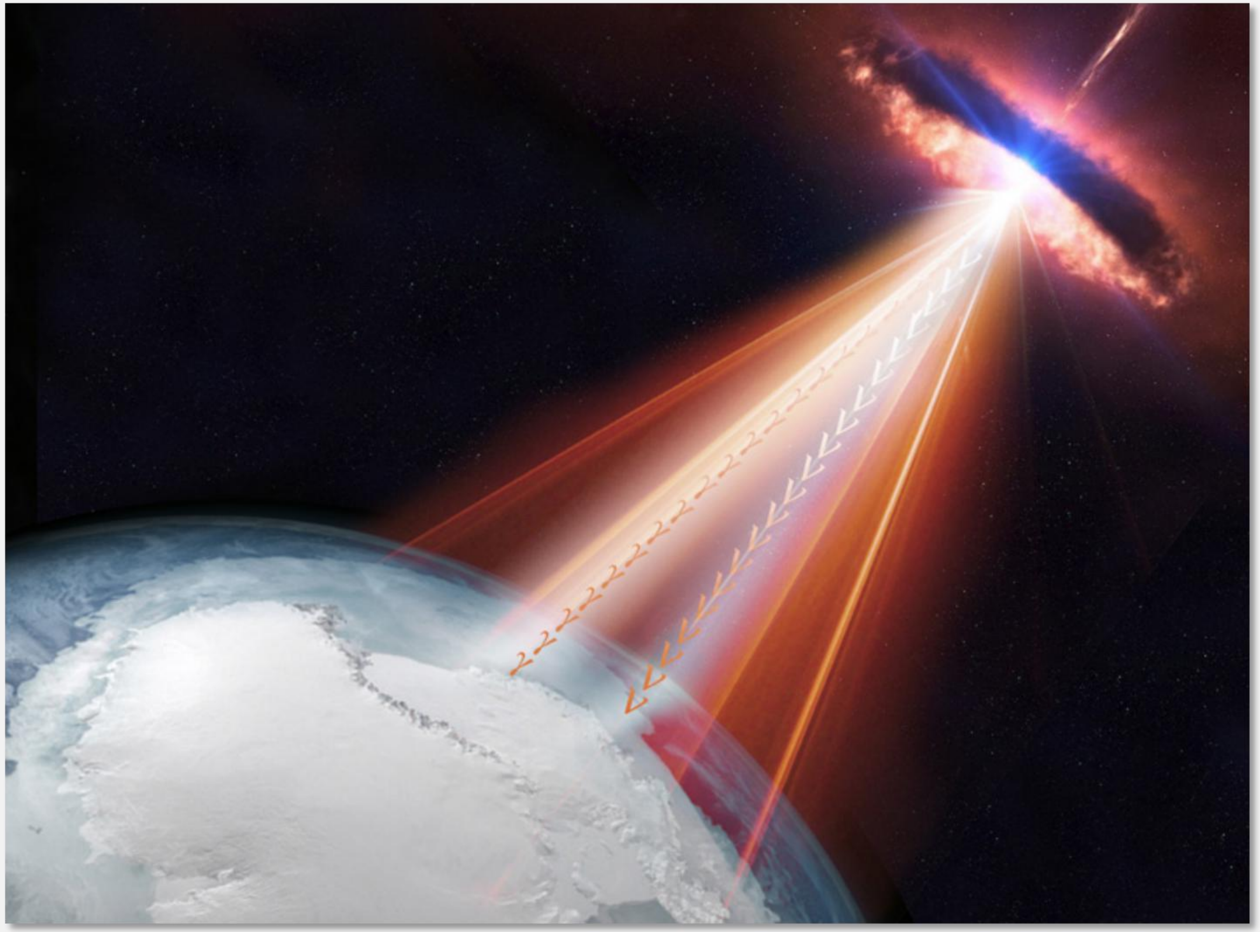
Large Scales

Yes! Look into larger scales!

$$m_{\text{vac}}^2 = \text{constant}$$

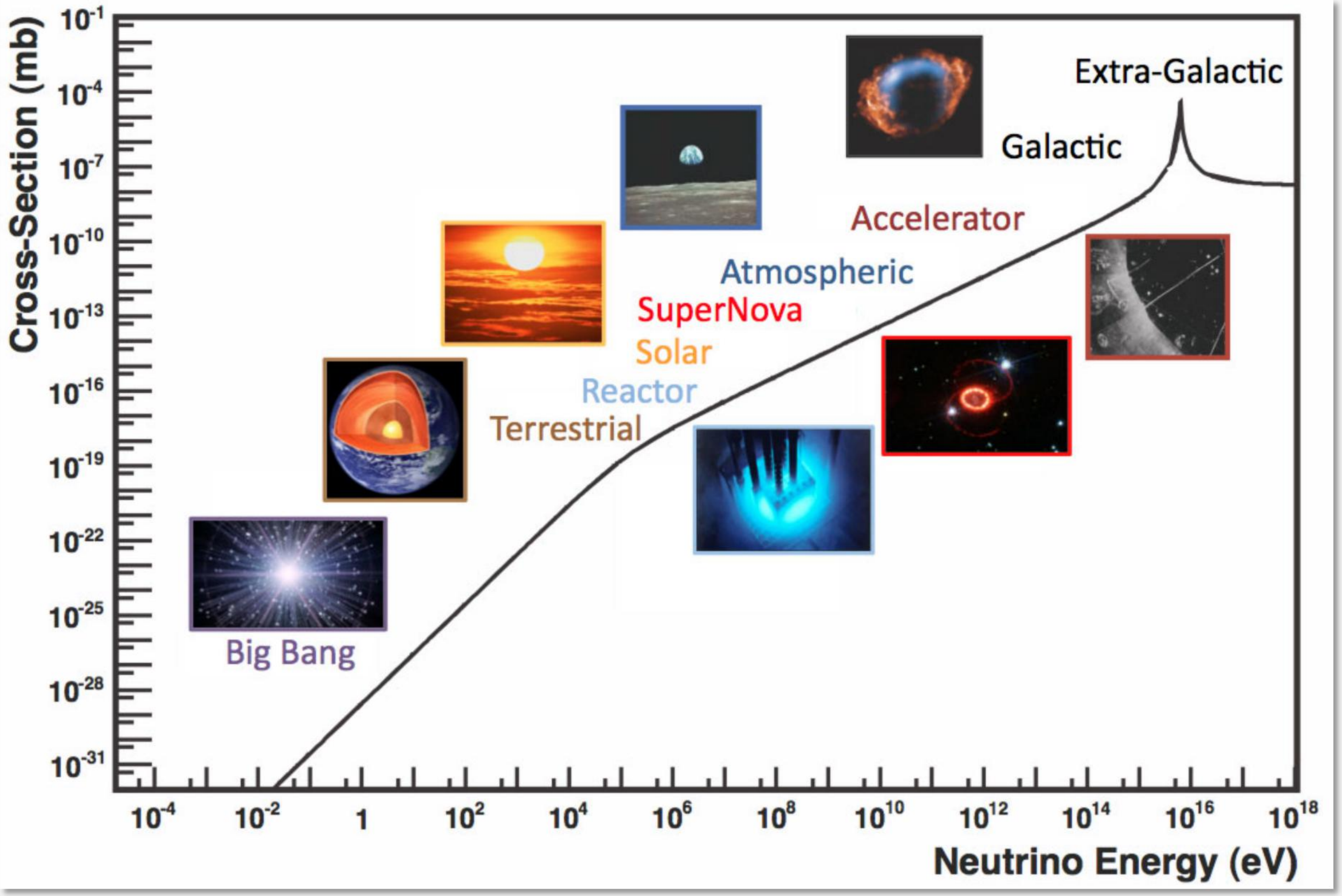
vs.

$$m_{\text{dark}}^2(x) \propto \rho_\phi$$



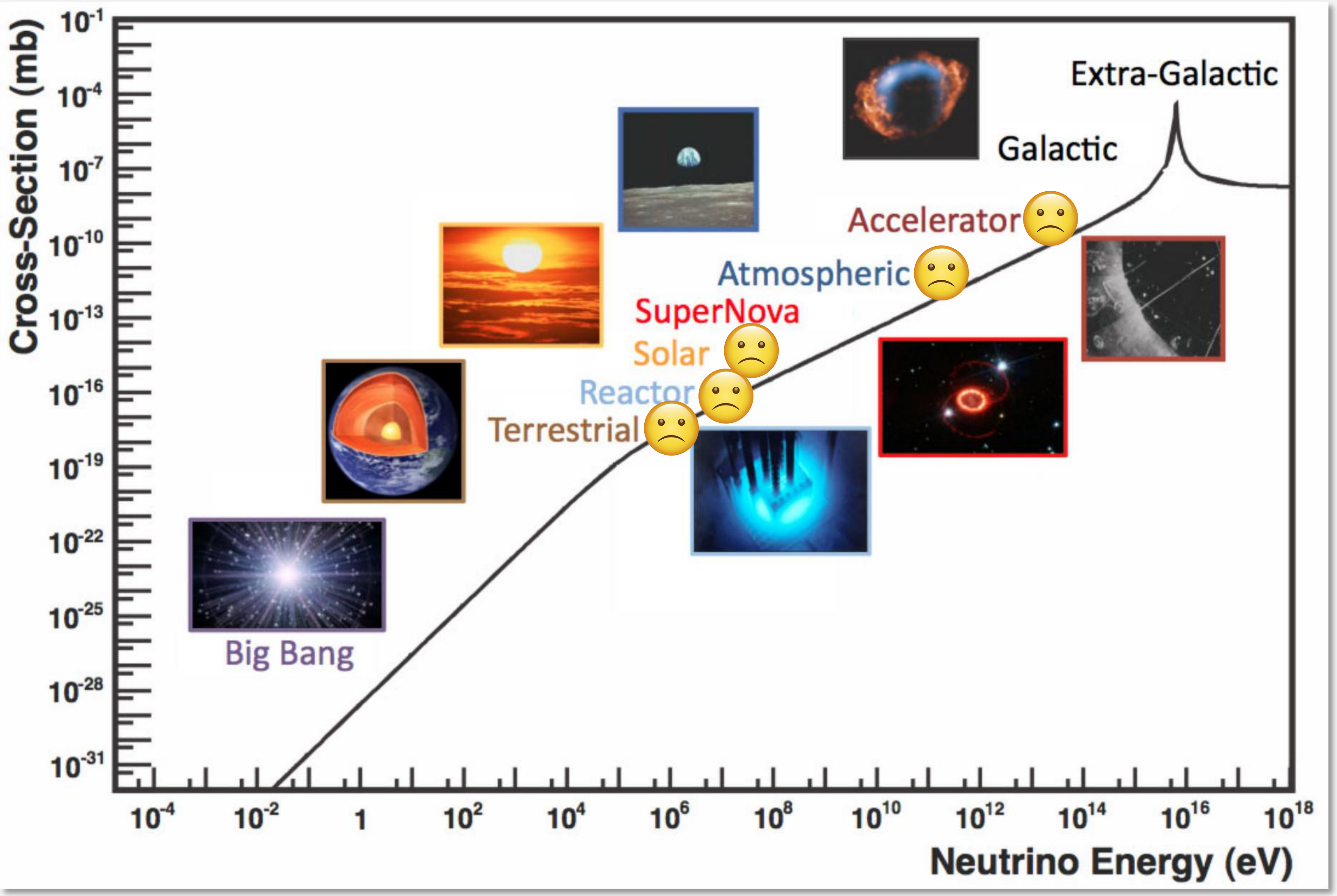
Credit: IceCube

Large Scales



Credit: J.A. Formaggio and G.P. Zeller

Large Scales



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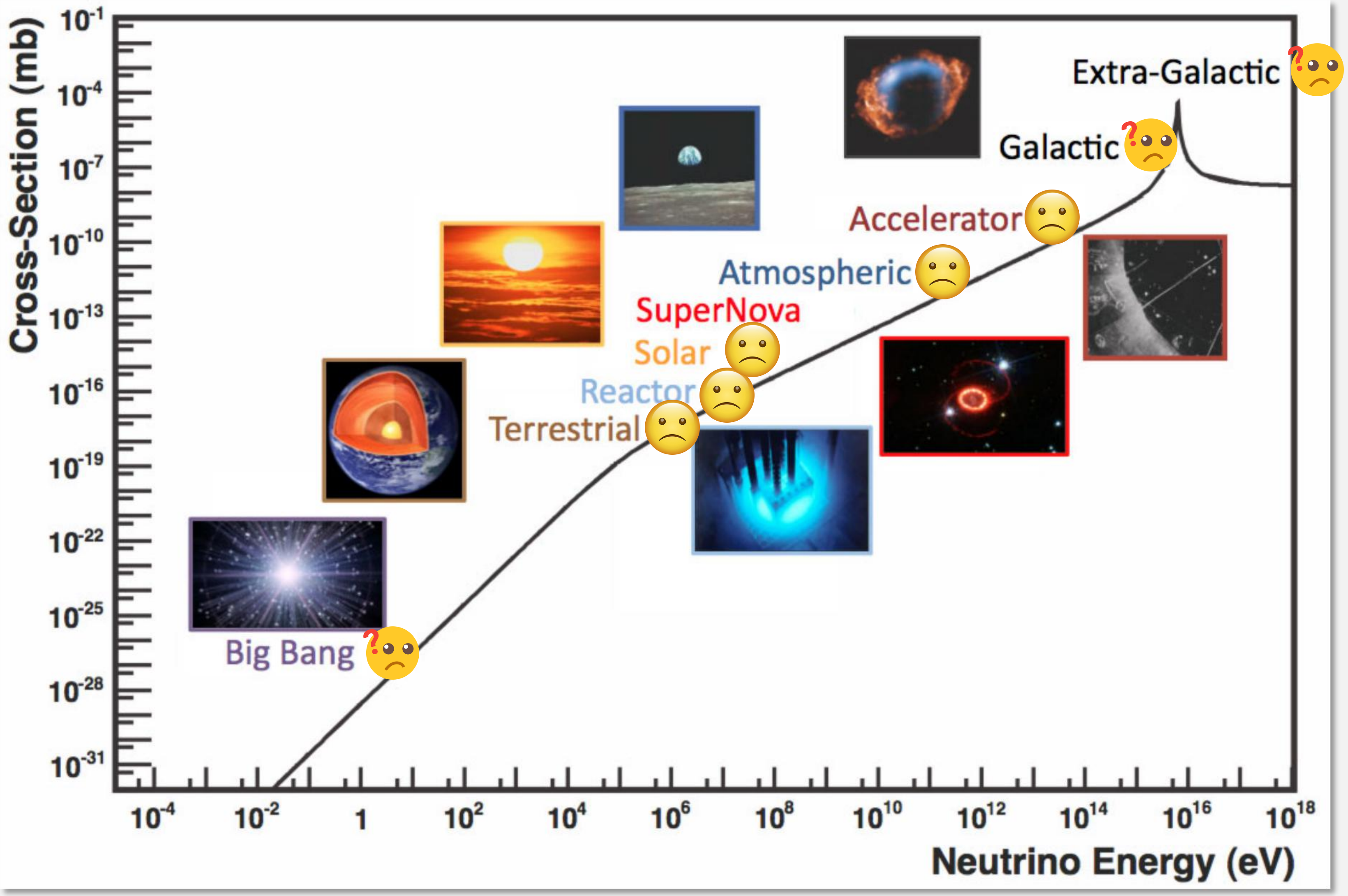

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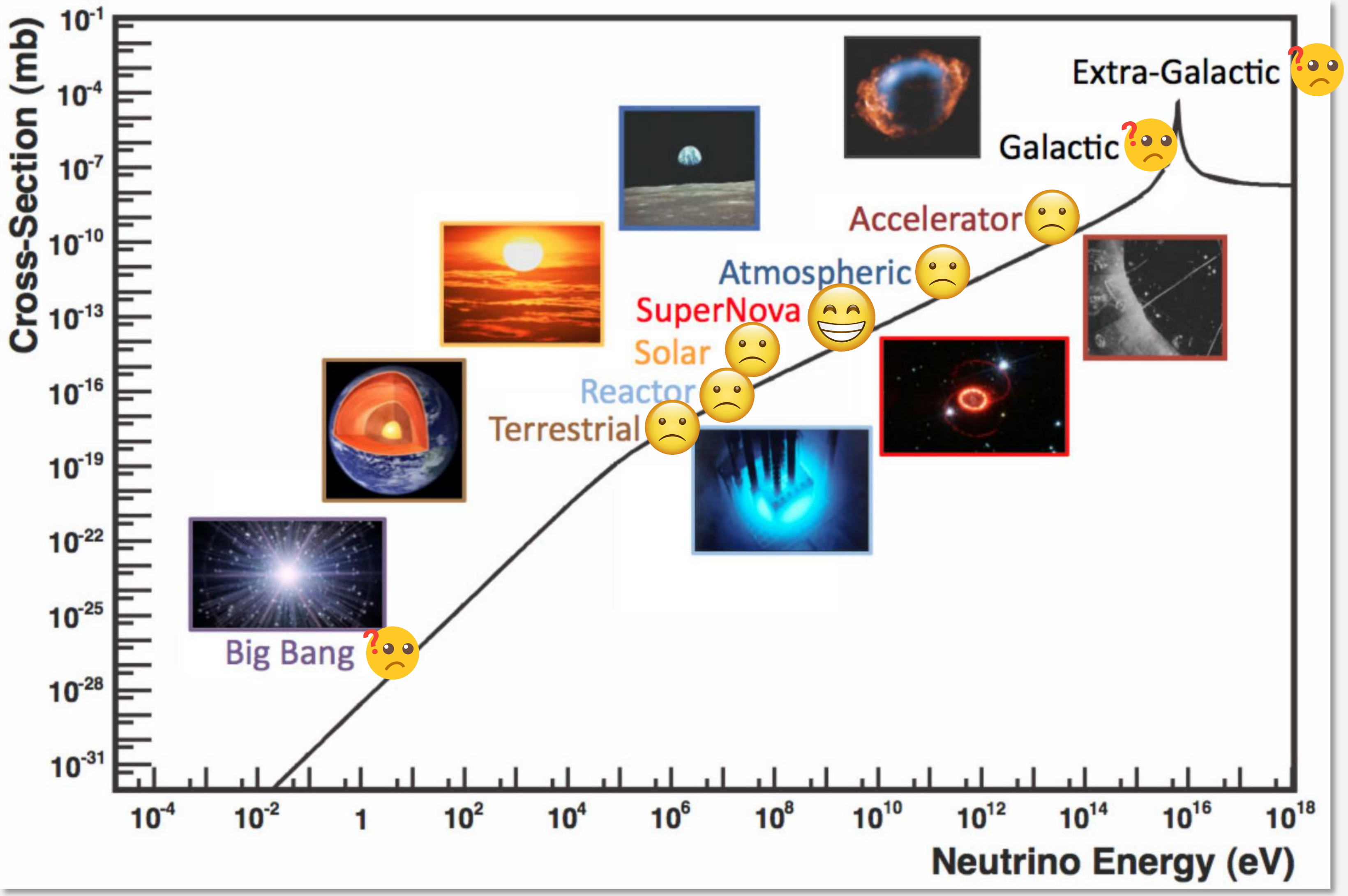
Large Scales



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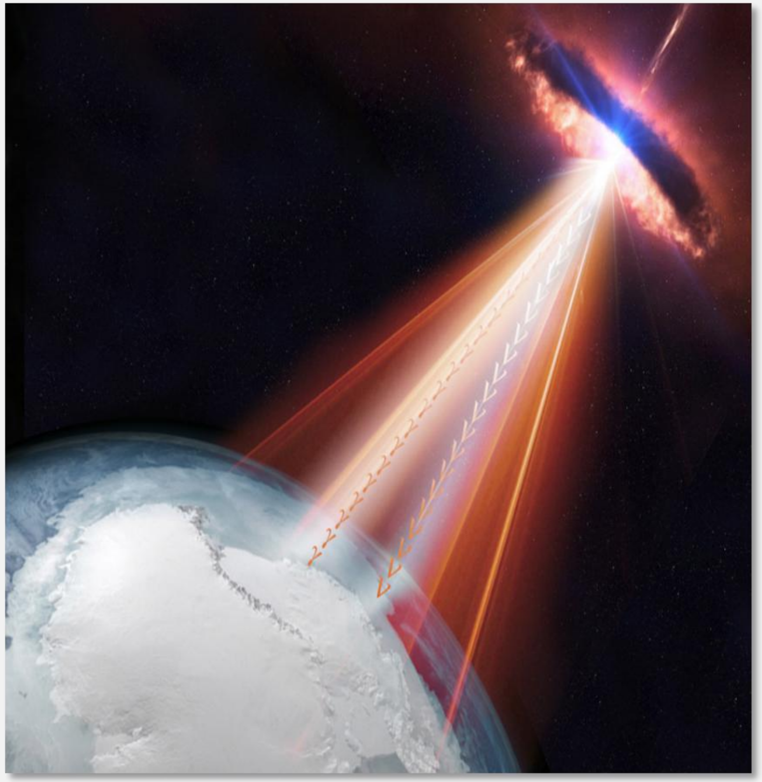
Supernova Neutrino Time Delay



Credit: IceCube

Galactic supernovae are ideal neutrino sources!

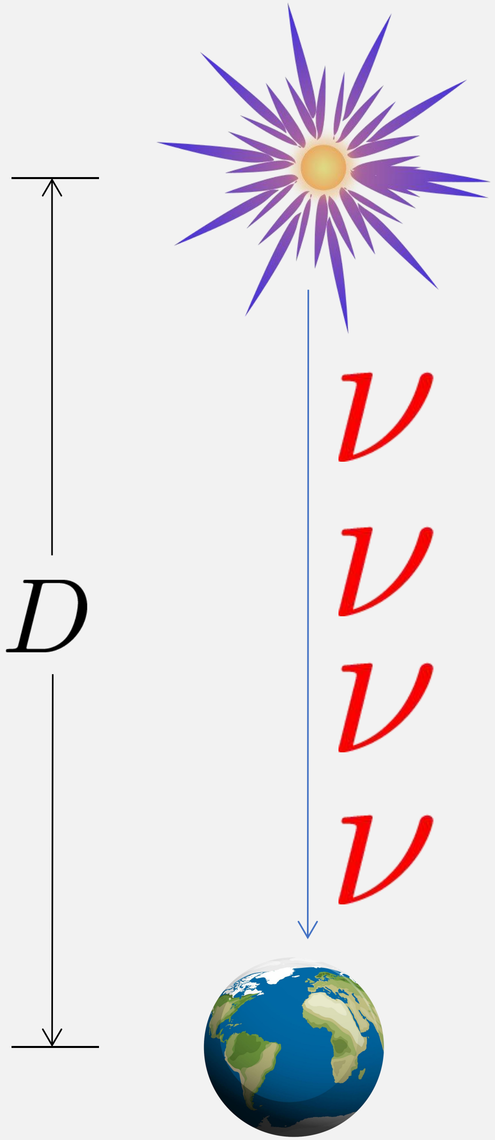
POSSIBILITY OF DETERMINING THE UPPER LIMIT OF THE NEUTRINO MASS FROM THE TIME OF FLIGHT

G. I. Zatsepin
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 20 July 1968
ZhETF Pis. Red. 8, No. 6, 333-334 (20 September 1968)

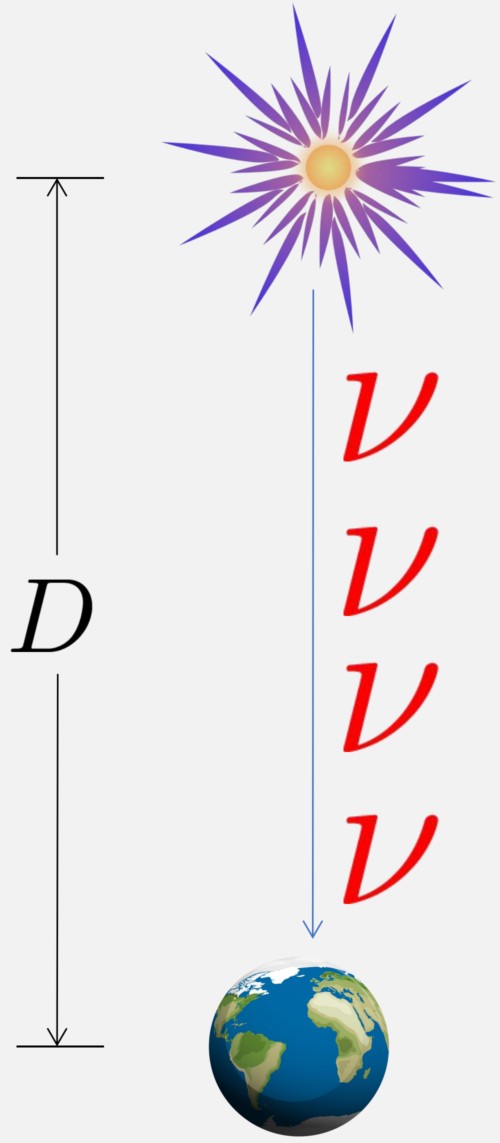
57 years ago!

[T. J. Loredo and D. Q. Lamb, astro-ph/0107260; E. Nardi and J. I. Zuluaga, astro-ph/0306384, hep-ph/0412104; G. Pagliaroli, F. Rossi-Torres and F. Vissani 1002.3349; J. S. Lu, J. Cao, Y. F. Li and S. Zhou, 1412.7418; R. S. L. Hansen, M. Lindner and O. Scholer, 1904.11461; F. Pompa, F. Capozzi, O. Mena and M. Sorel, 2203.00024; F. Pompa and O. Mena, 2310.05474; G. Parker and M. Wurm, 2311.10682 ...]

Supernova Neutrino Time Delay



I. Vacuum Neutrino Mass

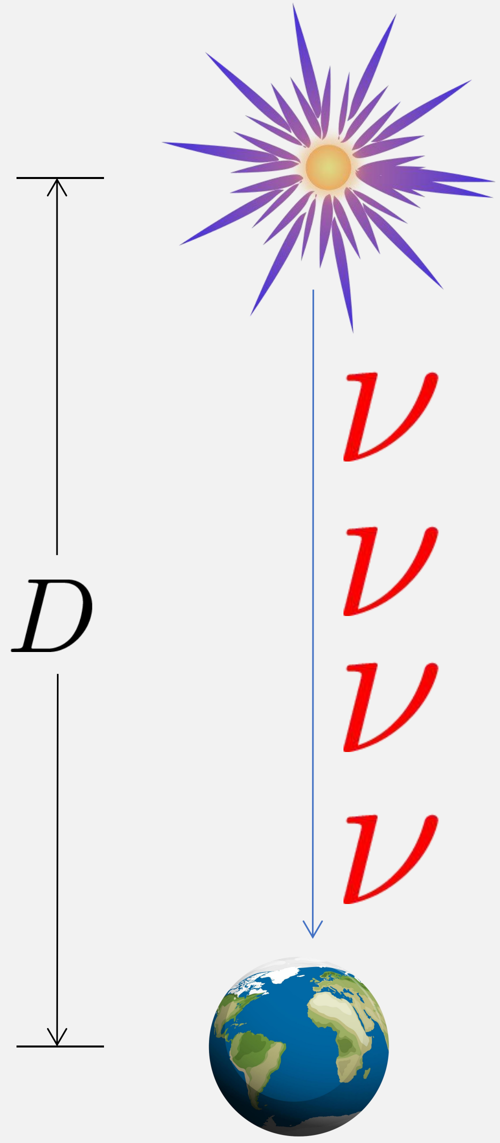


$$E_\nu = \sqrt{p_\nu^2 + m^2}, \quad v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

$$v = \frac{p}{E} = \sqrt{1 - \frac{m_{\rm vac}^2}{E^2}} \approx 1 - \frac{m_{\rm vac}^2}{2E^2}$$

I. Vacuum Neutrino Mass



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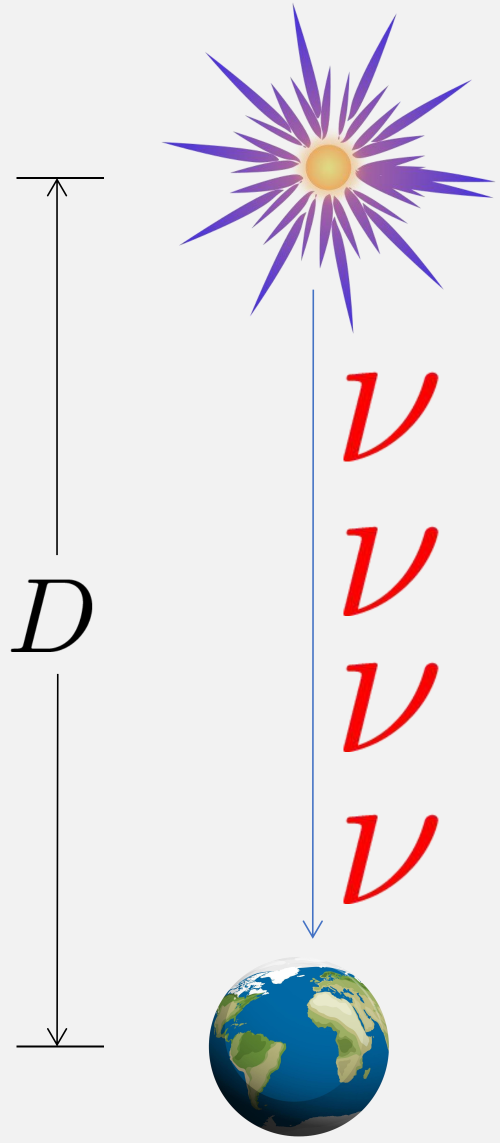
smaller than speed of light

&

space-time independent

I. Vacuum Neutrino Mass



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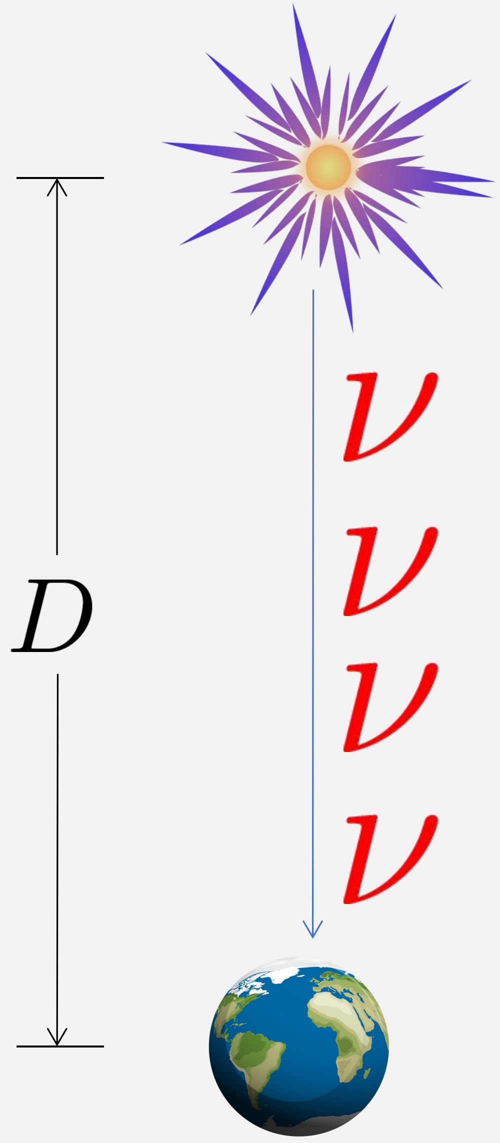
group velocity:

$$v = \frac{p}{E} = \sqrt{1 - \frac{m_{\rm vac}^2}{E^2}} \approx 1 - \frac{m_{\rm vac}^2}{2E^2}$$

time delay:

$$\Delta t_{\rm vac} \equiv \frac{D}{v} - \frac{D}{c(\equiv 1)} = \frac{m_{\rm vac}^2}{2E^2} D \approx 5.14\,{\rm ms} \left(\frac{m_{\rm vac}}{\rm eV}\right)^2 \left(\frac{10\,{\rm MeV}}{E}\right)^2 \frac{D}{10\,{\rm kpc}}$$

I. Vacuum Neutrino Mass



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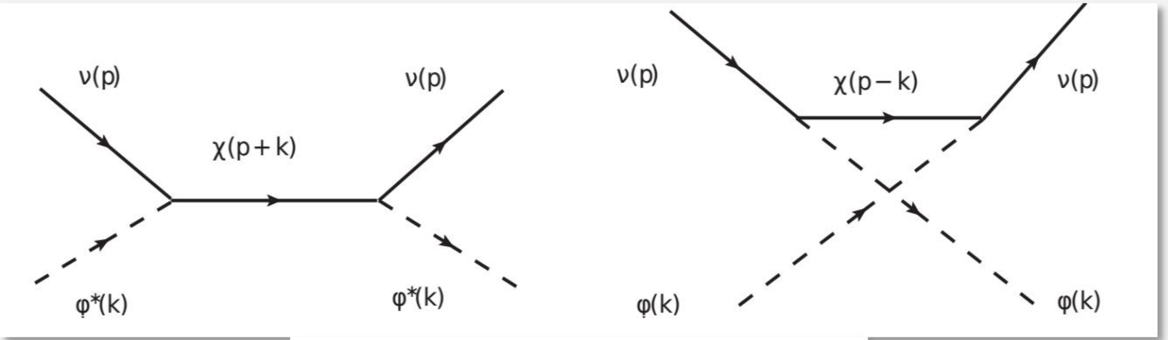
Institute for Basic Science

Recall



Introduce the effective or refractive mass squared as

$V = m_{ref}^2/2E$

$m_{ref}^2 = 2EV$

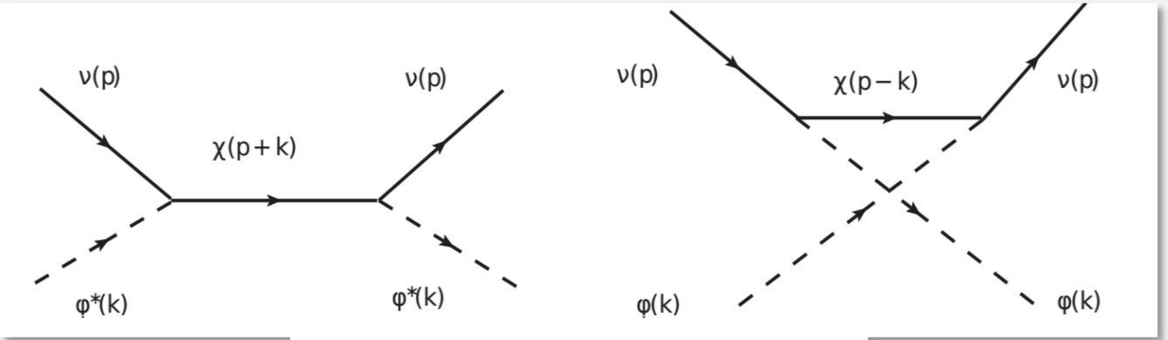
$$E_\nu = p_\nu + V, \quad v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

$$1 - v(\mathbf{x}) = \frac{m^2_{\text{dark}}(\mathbf{x}, p_\nu)}{2p_\nu^2} - \frac{1}{2p_\nu}\frac{dm^2_{\text{dark}}(\mathbf{x}, p_\nu)}{dp_\nu}$$

II. Dark Neutrino Mass

Recall



Introduce the effective or refractive mass squared as

$V = m_{ref}^2/2E$

$m_{ref}^2 = 2EV$

$$E_\nu = p_\nu + V, \quad v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

$$1 - v(\mathbf{x}) = \frac{m^2_{\text{dark}}(\mathbf{x}, p_\nu)}{2p_\nu^2} - \frac{1}{2p_\nu}\frac{dm^2_{\text{dark}}(\mathbf{x}, p_\nu)}{dp_\nu}$$

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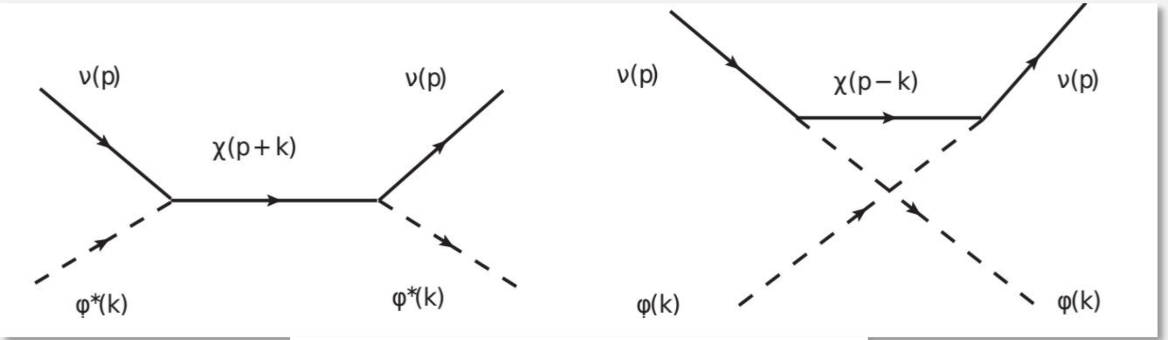

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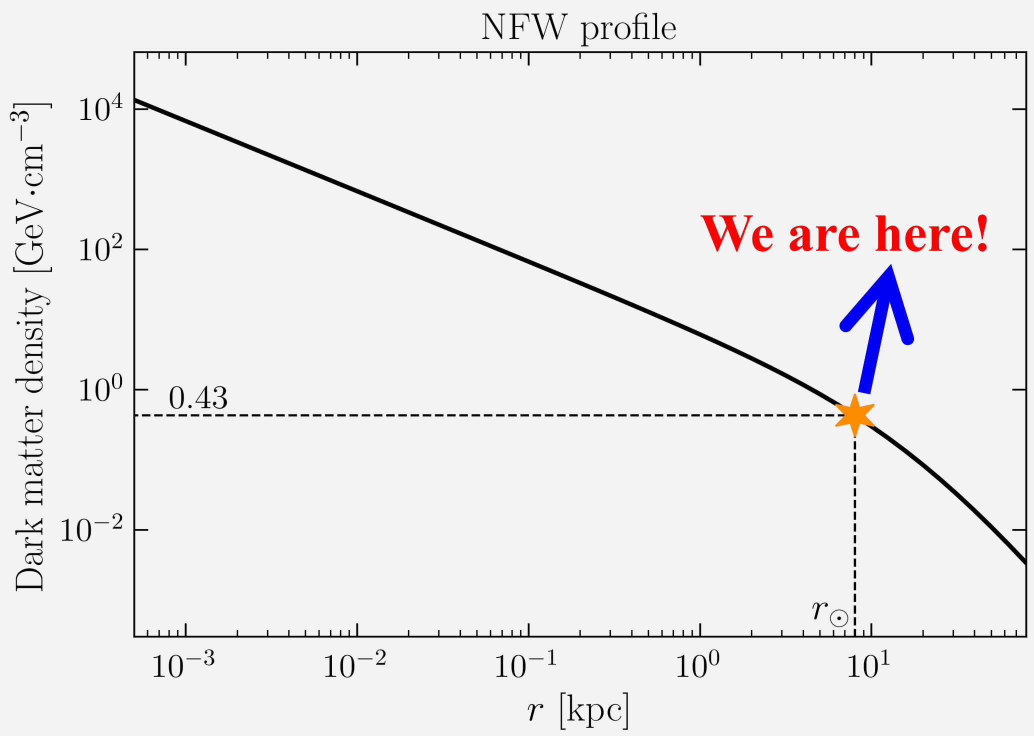
space-time dependent!

$[\mathbf{x}_\odot$: solar system position$]$

II. Dark Neutrino Mass



Navarro-Frenk-White profile

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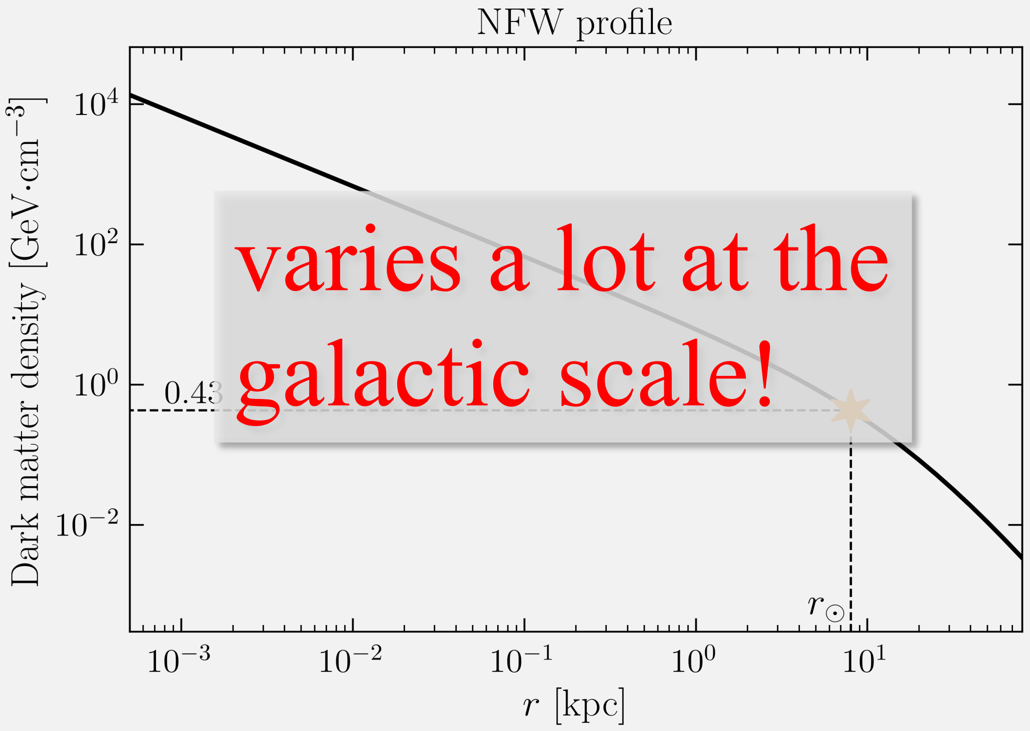

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$$1 - v(\mathbf{x}) = \frac{m^2_{\mathrm{dark}}(\mathbf{x}_\odot)}{2E^2} \frac{\rho_\phi(\mathbf{x})}{\rho_\phi(\mathbf{x}_\odot)}$$

$$\Delta t_{\mathrm{dark}} \equiv \int_{\mathbf{x}_\star}^{\mathbf{x}_\odot} \left(\frac{1}{v(\mathbf{x})} - 1 \right) |d\mathbf{x}| \approx \int_{\mathbf{x}_\star}^{\mathbf{x}_\odot} (\mathbf{1} - \mathbf{v}(\mathbf{x})) \, |\mathbf{dx}|$$

just an integration over neutrino trajectory

II. Dark Neutrino Mass

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$$\Delta t_{\rm dark} = \boxed{\frac{m^2_{\rm dark}(\mathbf{x}_\odot)D}{2E^2}}\boxed{\frac{\int_{\mathbf{x}_\star}^{\mathbf{x}_\odot}\rho_\phi(\mathbf{x})|d\mathbf{x}|}{D\rho_\phi(\mathbf{x}_\odot)}} \equiv \boxed{\Delta t_\odot}\boxed{\frac{\overline{\rho_\phi}(\mathbf{x})}{\rho_\phi(\mathbf{x}_\odot)}}$$

vacuum neutrino mass

differed by this factor!

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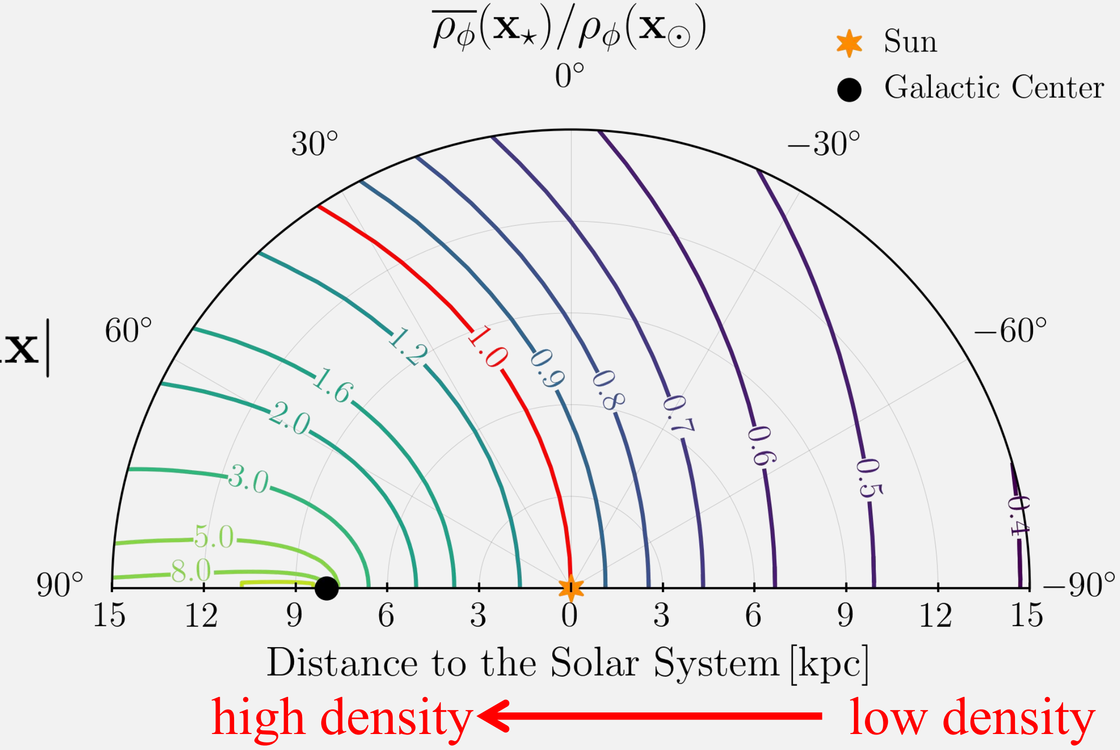


*Ge, **CFK**, Smirnov*
arXiv: 2404.17352

Experimental sensitivities

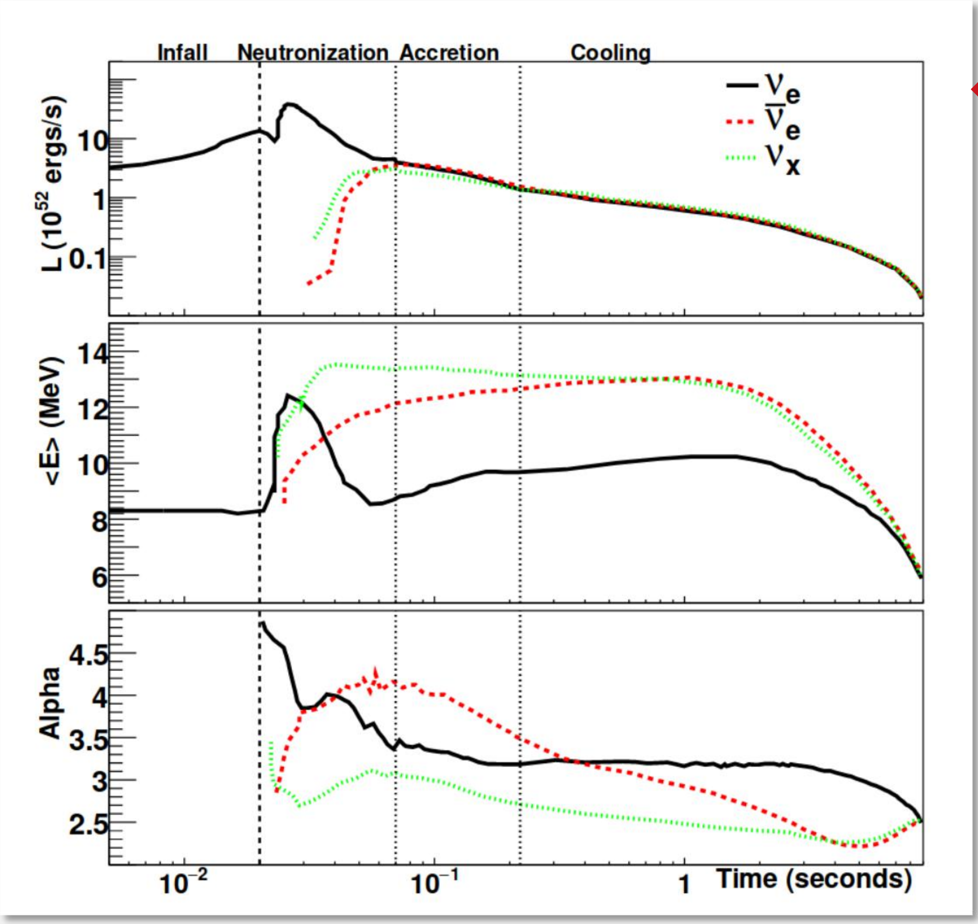
Supernova Neutrino Production

- ν_e SN burst production (Garching model):

$$\Phi^0_{\nu_\beta}(t_\mathrm{e}, E_\nu) = \frac{L_{\nu_\beta}(t_\mathrm{e})}{\langle E_{\nu_\beta}(t_\mathrm{e})\rangle} \varphi_{\nu_\beta}(t_\mathrm{e}, E_\nu)$$

$$\varphi_{\nu_\beta}(t_\mathrm{e}, E_\nu) \equiv \xi_\beta(t_\mathrm{e}) \left(\frac{E_\nu}{\langle E_{\nu_\beta}(t_\mathrm{e})\rangle} \right)^{\alpha_\beta(t_\mathrm{e})} e^{\frac{-\left(\alpha_\beta(t_\mathrm{e})+1\right)E_\nu}{\langle E_{\nu_\beta}(t_\mathrm{e})\rangle}}$$

Supernova Neutrino Production



DUNE Collaboration
arXiv: 2008.06647

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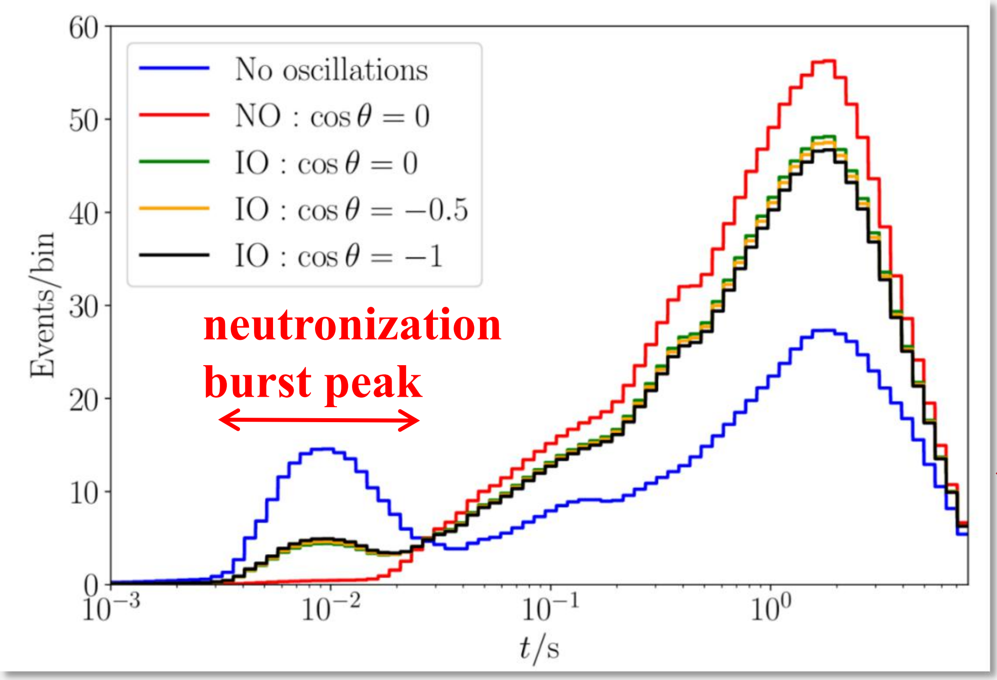
Supernova Neutrino Production

NO: normal ordering
IO: inverted ordering



F. Pompa, F. Capozzi, O. Mena, & M. Sorel
arXiv:2203.00024

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- MSW matter effect (from core to surface):

$$\Phi_{\nu_e} = p\Phi^0_{\nu_e} + (1-p)\Phi^0_{\nu_x}$$

$$p = |U_{e3}|^2 \approx \sin^2\theta_{13}, \text{NO}$$

$$p \approx |U_{e2}|^2 \approx \sin^2\theta_{12}, \text{IO}$$

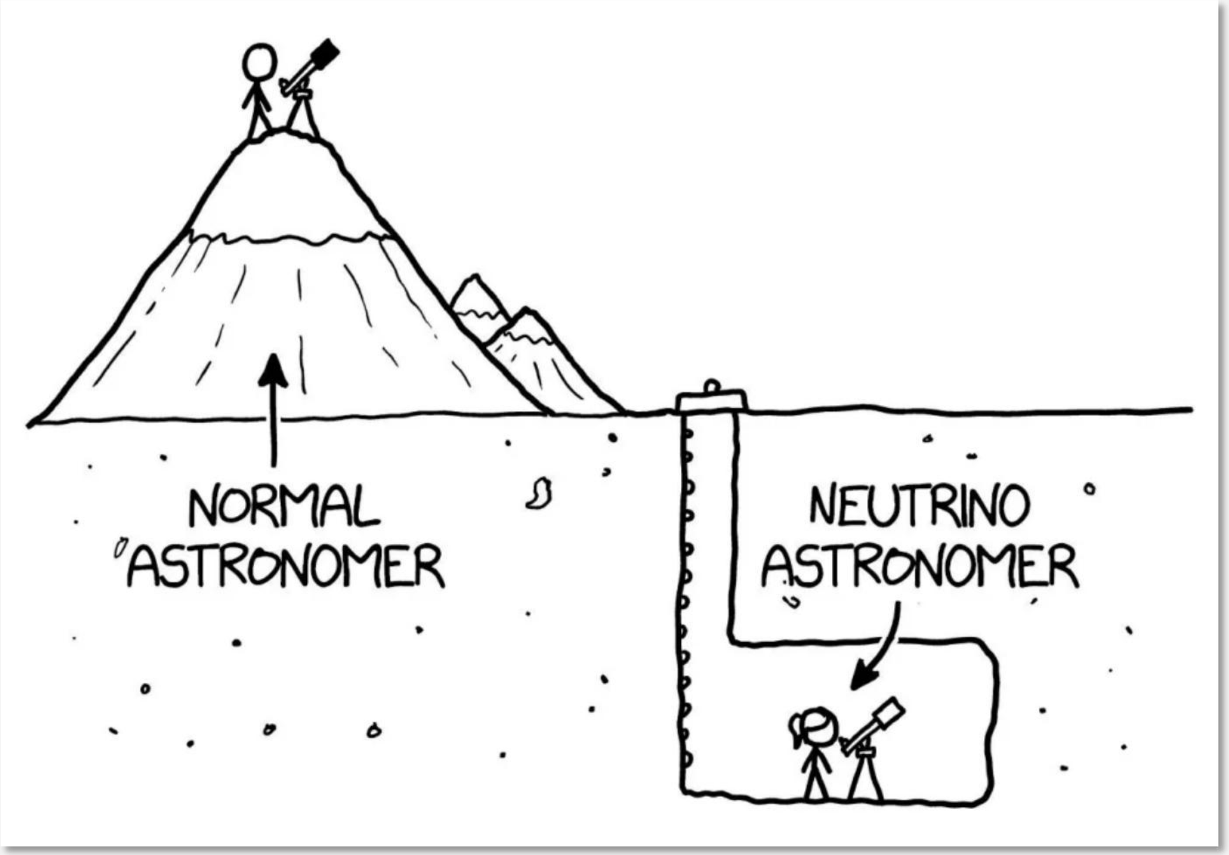
from global fit result: $[\sin^2\theta_{13} \approx 0.022,\ \sin^2\theta_{12} \approx 0.3]$

Supernova Neutrino Detection @ DUNE

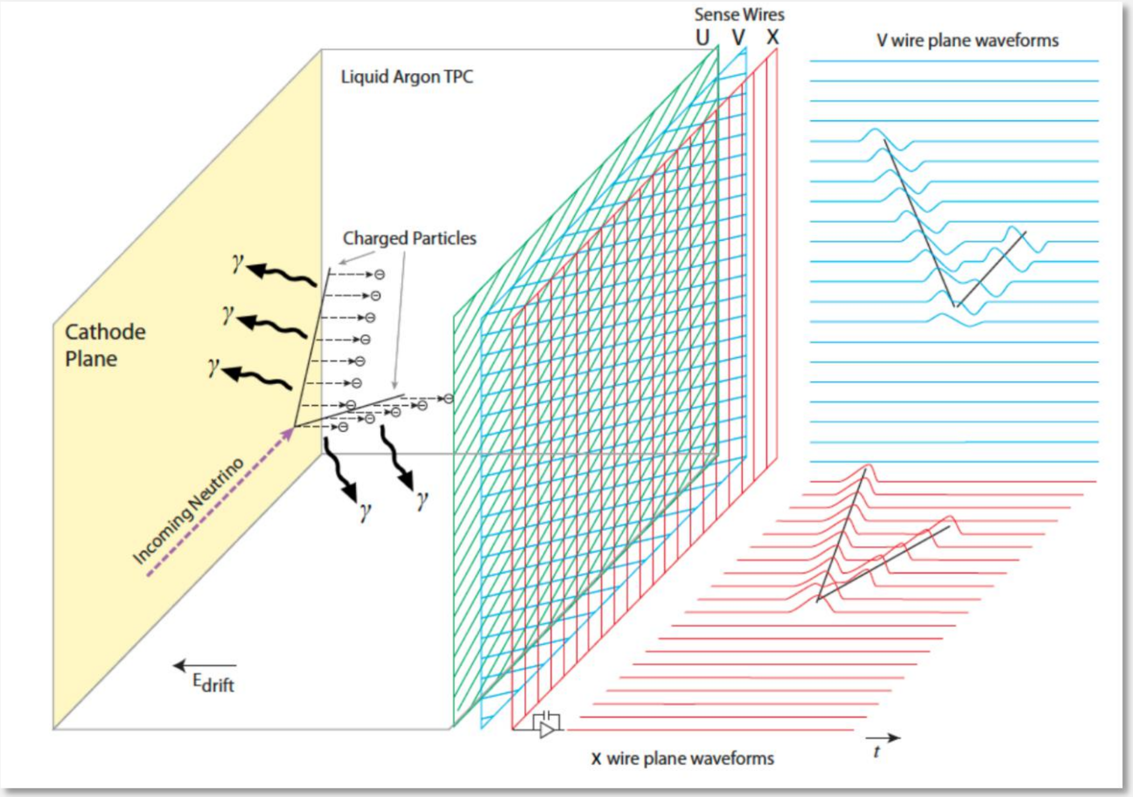
Institute for Basic Science

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Liquid Argon Time Projection Chamber (LArTPC)
40 kt fiducial mass (?)



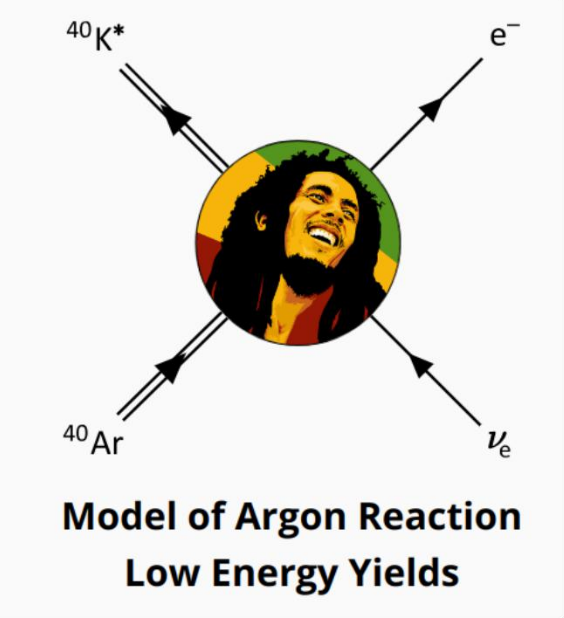
credit: PHYSICSGG



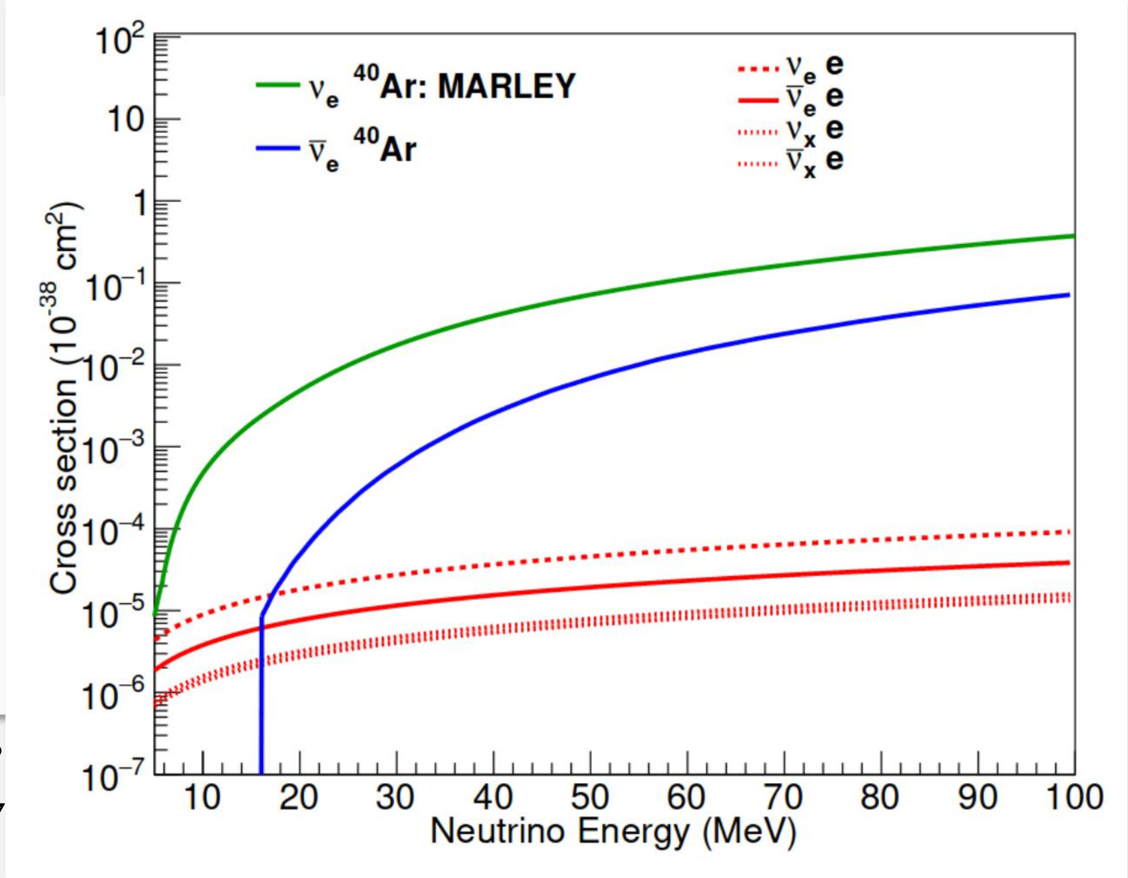
credit: DUNE

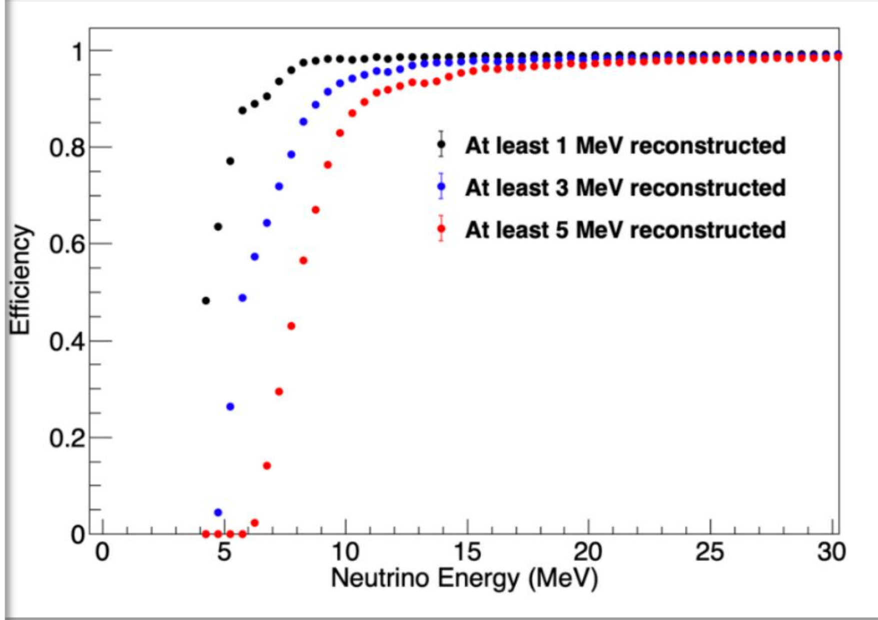
Supernova Neutrino Detection @ DUNE

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



S. Gardiner, 2010.02393 & 2101.11867





DUNE Collaboration arXiv: 2008.06647

Time Distribution

Event rate:

$$R(t, m, E) = \frac{\Phi_{\nu_e}}{4\pi D^2} * A * \sigma_{\nu_e} * \epsilon$$

[Φ_{ν_e} : ν_e flux

A : target nucleon number

σ_{ν_e} : cross section

ϵ : efficiency]

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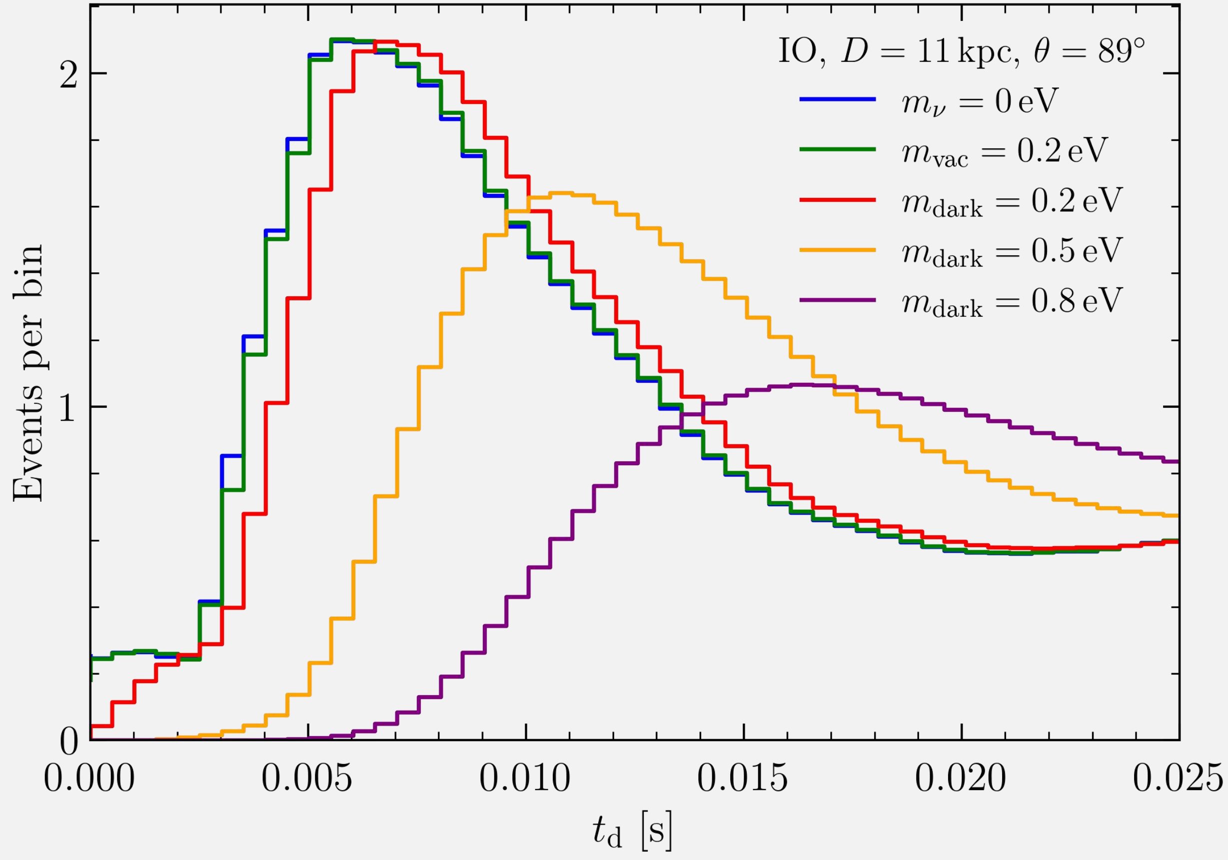
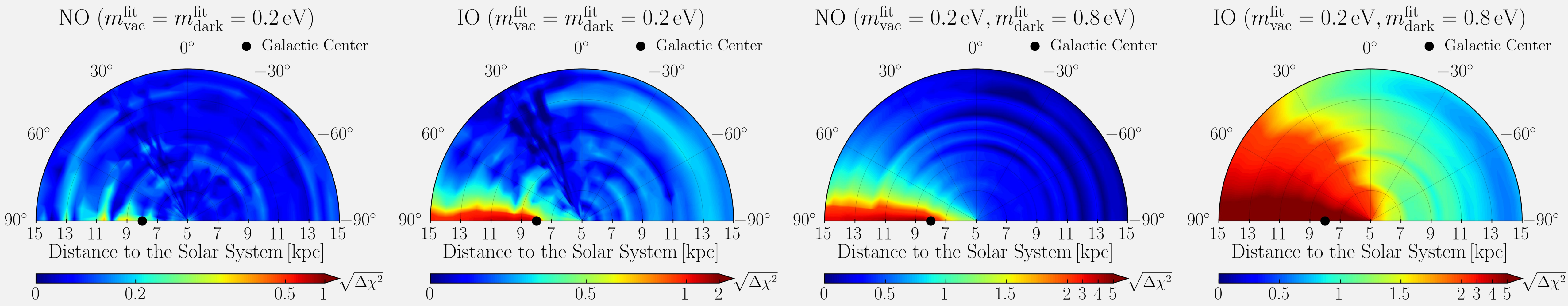
❖ The time distribution becomes wider as the neutrino mass increases

energy integrated out



*Ge, **CFK**, Smirnov*
arXiv: 2404.17352

Sensitivities



*Ge, **CFK**, Smirnov*
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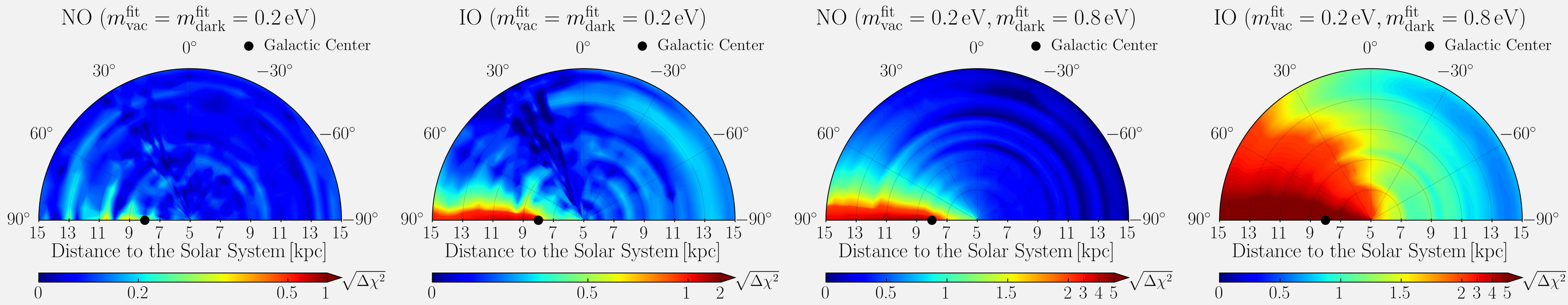

❖ The sensitivity is enlarged by measuring supernova neutrinos around the galaxy center

*Ge, **CFK**, Smirnov*
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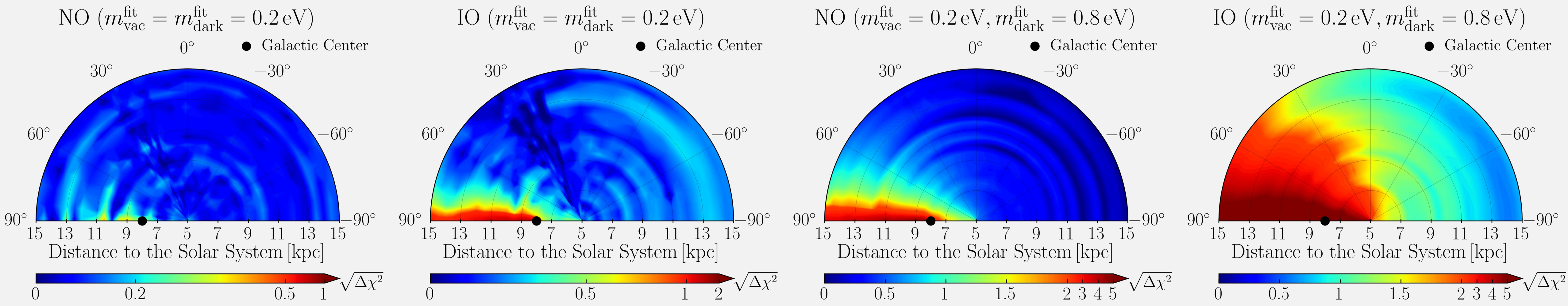
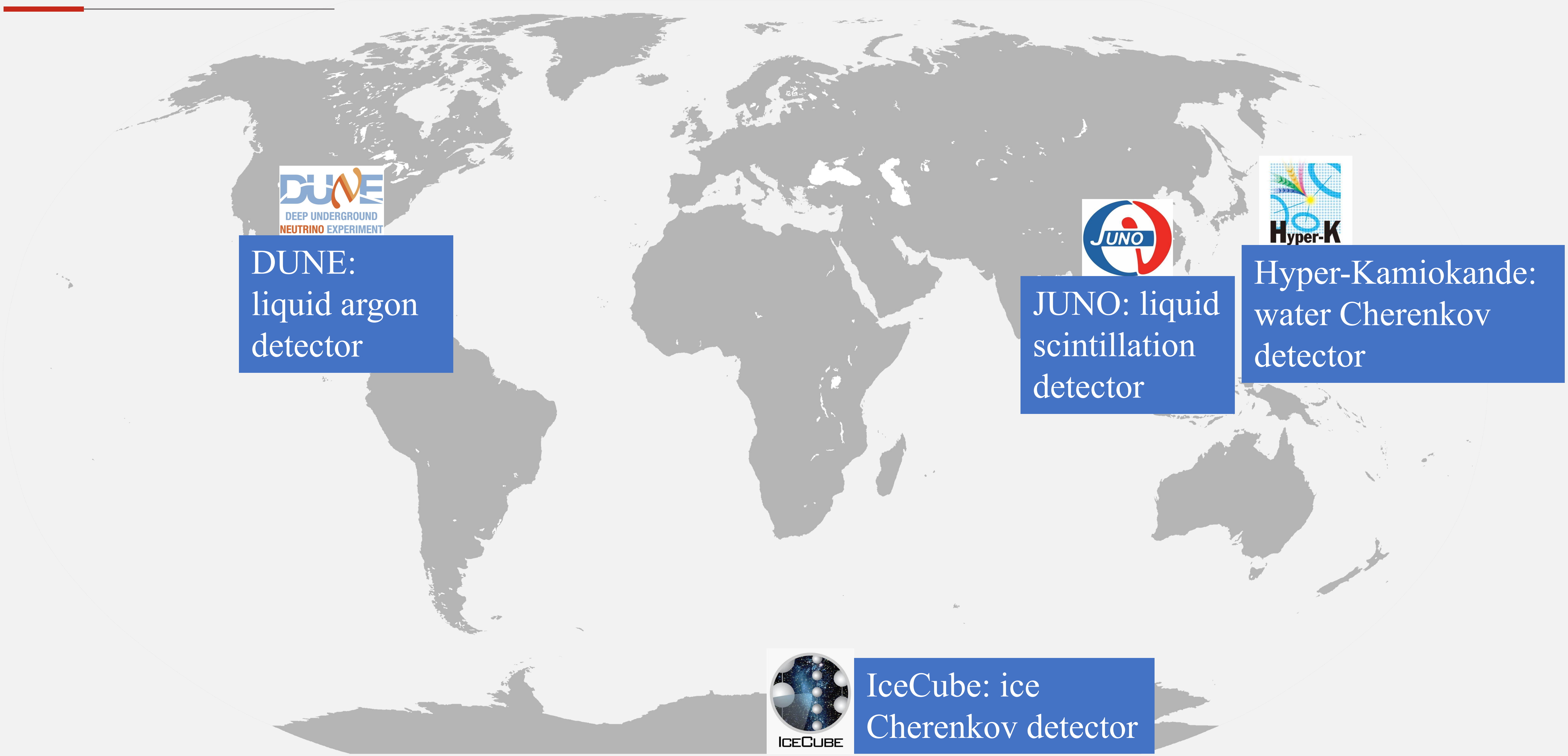


- The sensitivity is enlarged by measuring supernova neutrinos around the galaxy center
- Sensitivity for normal ordering (NO) is reduced by MSW matter effect

*Ge, **CFK**, Smirnov*
arXiv: 2404.17352

Supernova Neutrino Detectors



Supernova Neutrino Detectors

DUNE: liquid argon detector

Stay tuned!

UNO: liquid cintillation etector

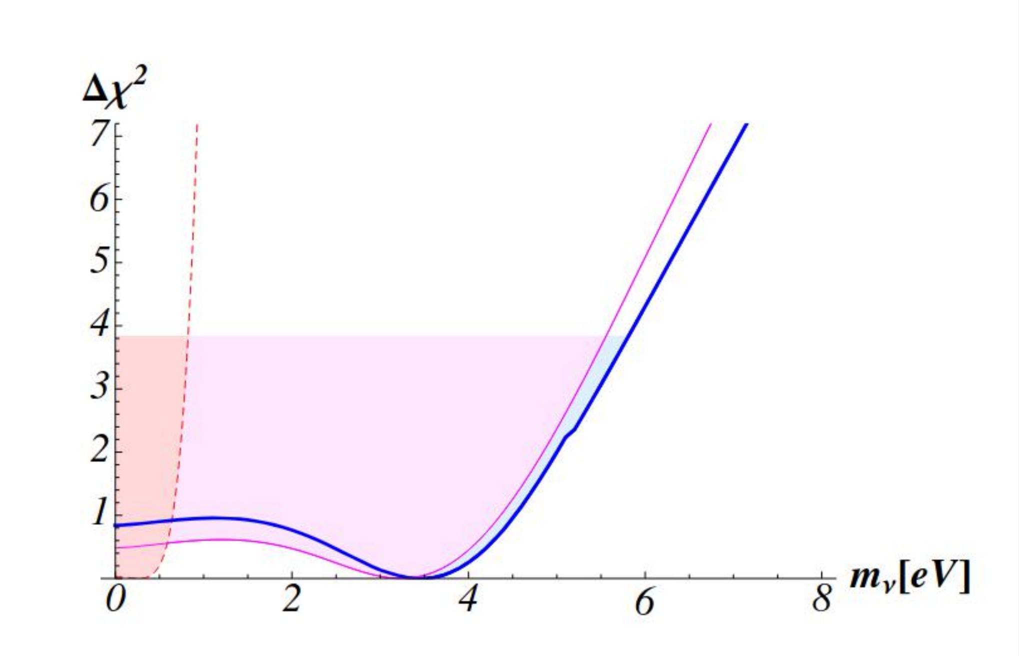
Hyper-Kamiokande: water Cherenkov detector

IceCube: ice Cherenkov detector

Thank you for your attention!

Backup

SN1987A



G. Pagliaroli, F. Rossi-Torres, & F. Vissani
arXiv:1002.3349

The minimum is located at ~ 3.5 eV, although not statistically significant

Backup

parameter space

(i) $m_\phi \sim 10^{-10}$ eV, $g \sim 10^{-10}$, $m_\chi \sim 10^{-4}$ eV, and (ii) $m_\phi \sim 10^{-22}$ eV, $g \sim 10^{-21}$, $m_\chi \sim 10^{-10}$ eV.

M. Sen and A. Y. Smirnov, arXiv:2306.15718, 2407.02462

Backup

matter potential

$$V_{\alpha\beta} = \sum_k g_{\alpha k} g^*_{\beta k} \left[\frac{\bar{n}_\phi (2Em_\phi - m^2_{\chi k})}{(2Em_\phi - m^2_{\chi k})^2 + (m_\chi \Gamma_{\chi k})^2} + \frac{n_\phi}{2Em_\phi + m^2_{\chi k}} \right],$$

M. Sen and A. Y. Smirnov, arXiv:2306.15718