Testing the Origins of Neutrino Mass with Supernova Neutrino Time Delay

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Based on arXiv: 2404.17352 [hep-ph] (Phys.Rev.Lett. 133 (2024) 12, 121802)

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

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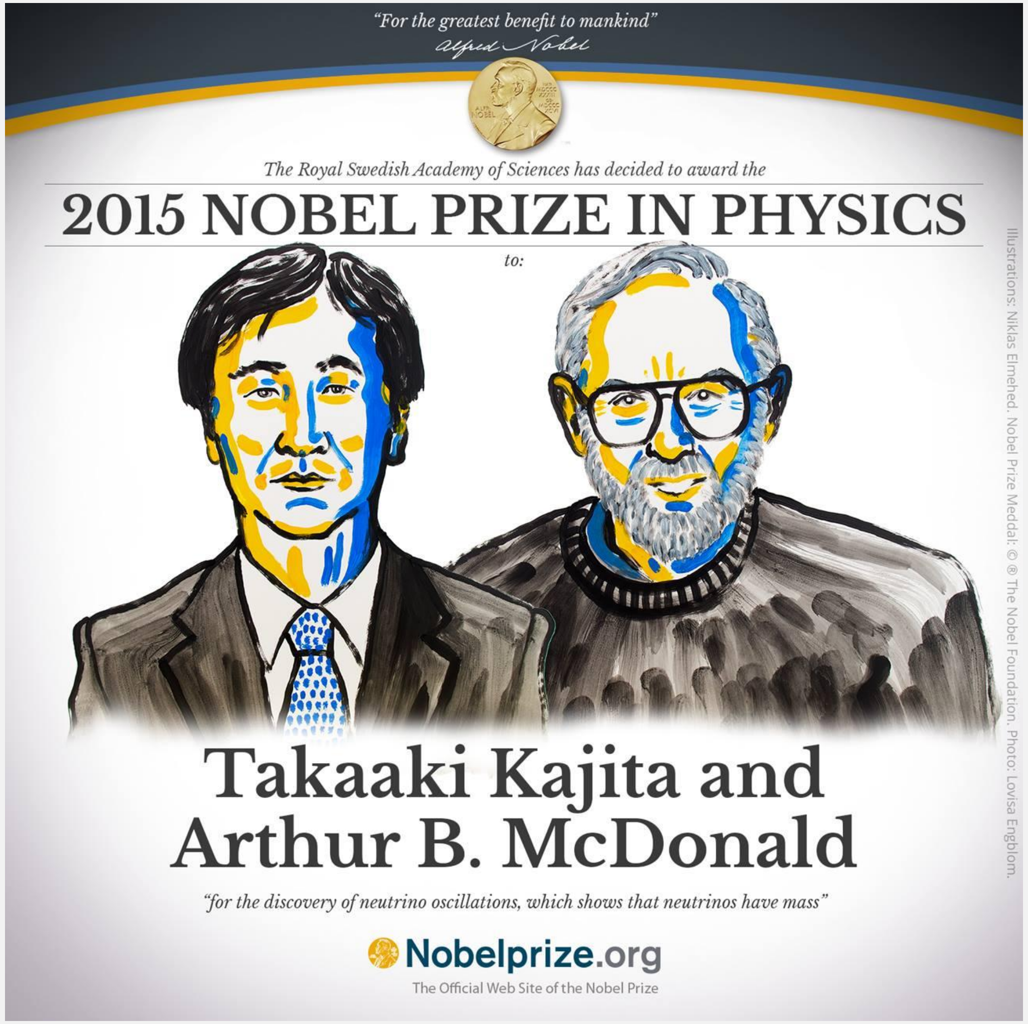
EuCAPT
Astroneutrino Theory Workshop 2024
Prague, Czech Republic

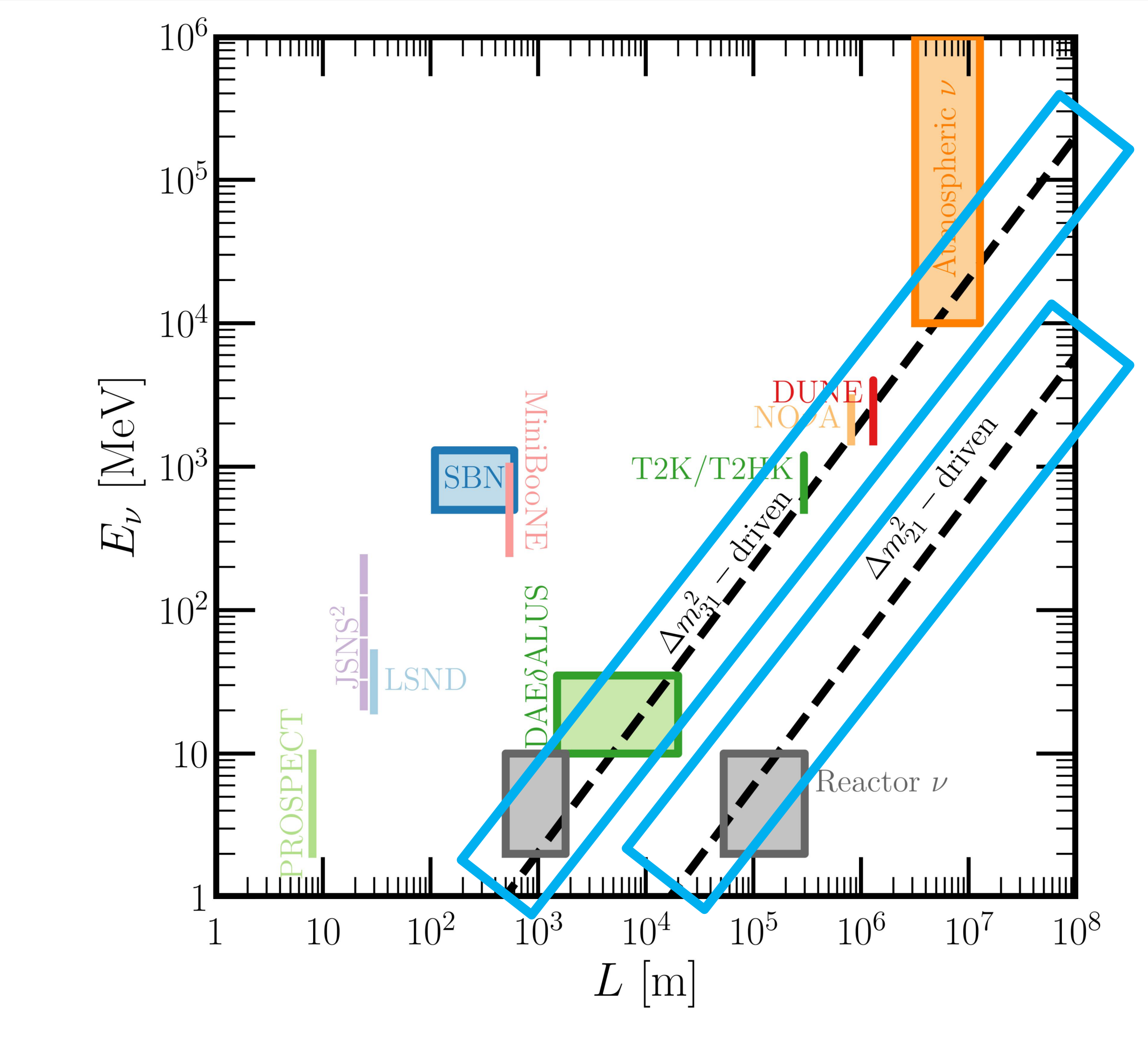
EuCAPT @ Prague, 2024 Sep. 24

Evidence of Neutrino Mass



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

Evidence of Neutrino Mass



[see Prof. Smirnov & Prof. Schwetz's lectures]

Neutrino oscillations have $\Delta m^2_{ij}/2E_\nu$ dependence

R. Harnik, K. Kelly, P. Machado arXiv: 1911.05088

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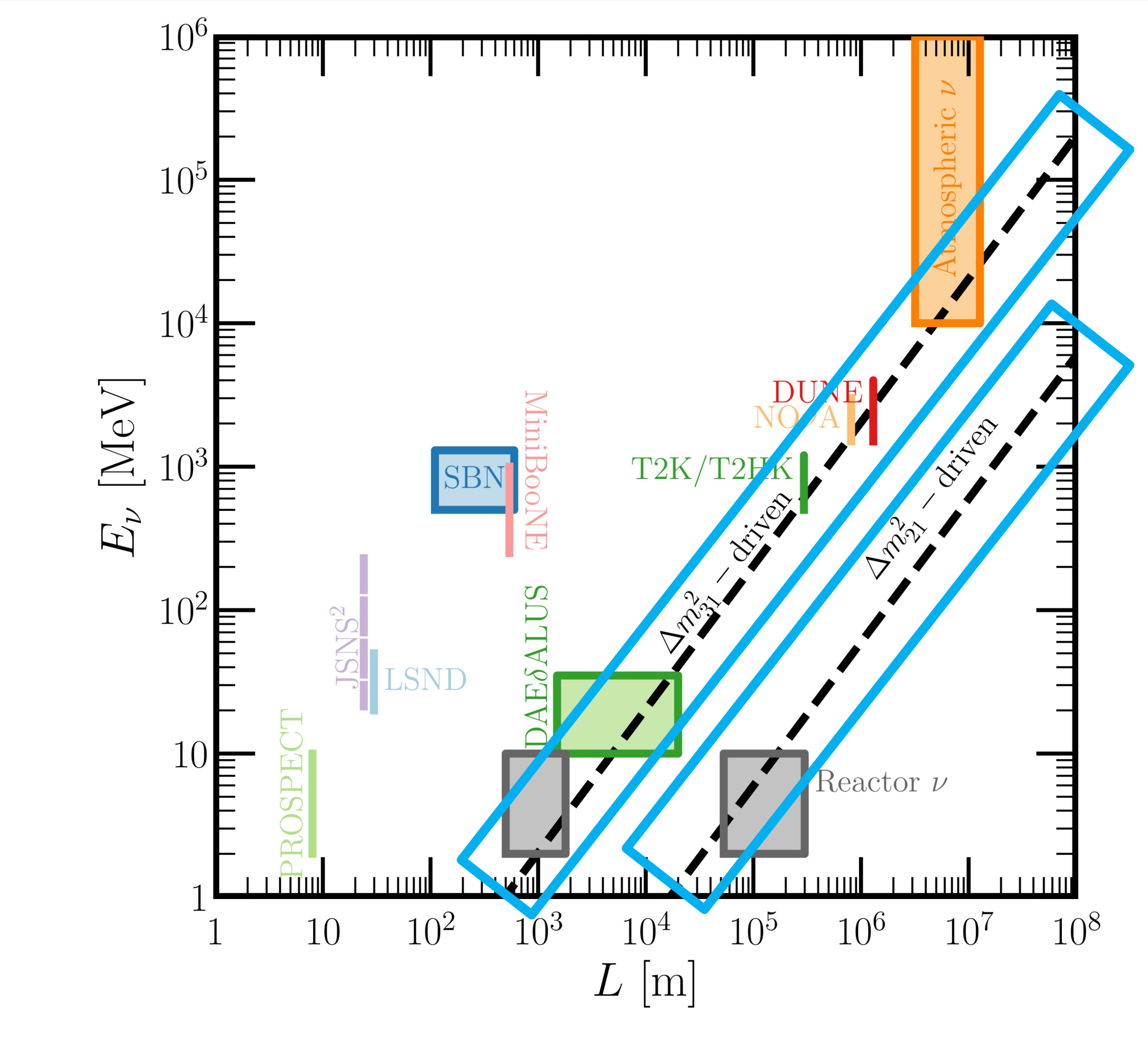


[see Prof. Smirnov & Prof. Schwetz's lectures]

Neutrino oscillations have $\Delta m^2_{ij}/2E_\nu$ dependence

↓

Q:What's the origin of Δm^2_{ij} ?

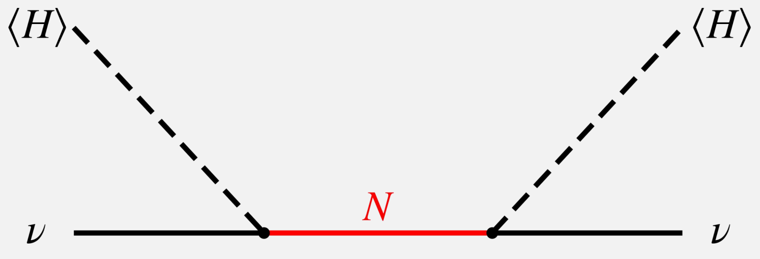
R. Harnik, K. Kelly, P. Machado arXiv: 1911.05088

Neutrino Mass Origin I: vacuum mass

Vacuum Neutrino Mass

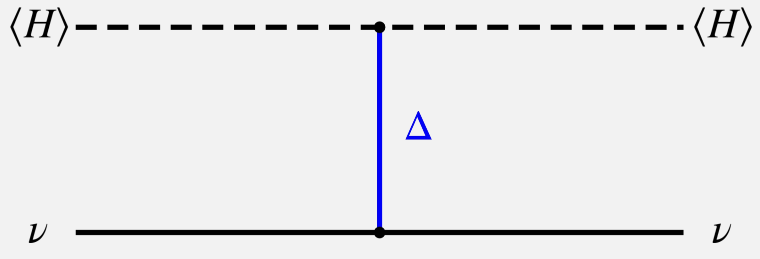
[see Prof. Malinský & Prof. Deppisch's lectures]

Type-I seesaw | Type-II seesaw | Type-III seesaw | •••



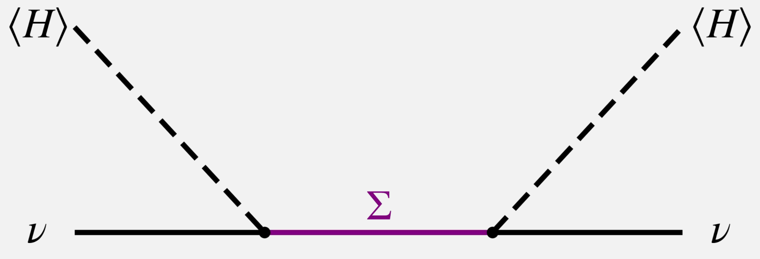
$$M_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$

P. Minkowski
T. Yanagida
M. Gell-Mann



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

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



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

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

Neutrino Mass Origin I: vacuum mass

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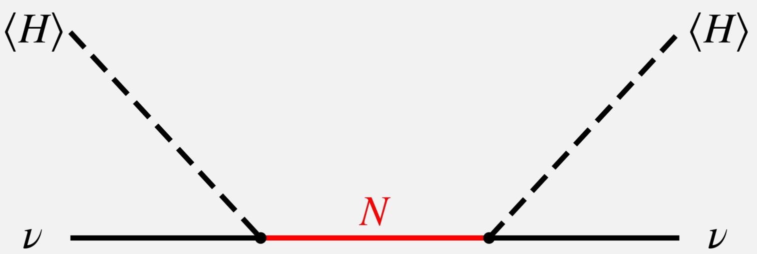
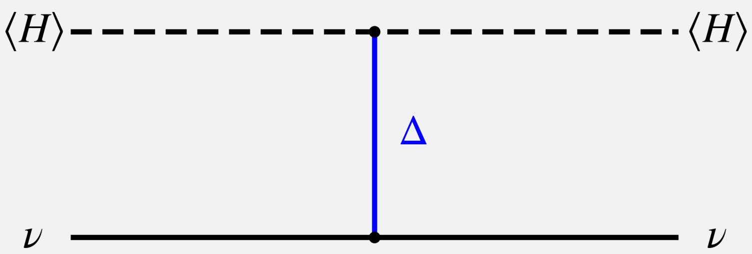
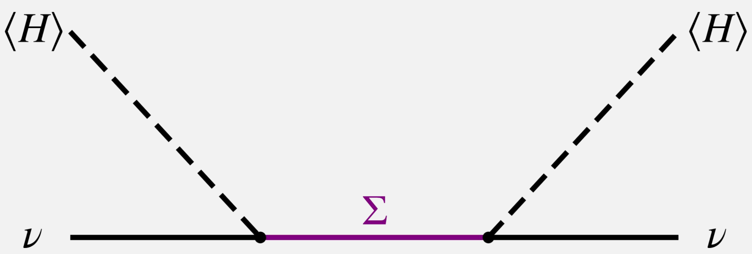


$$M_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$



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



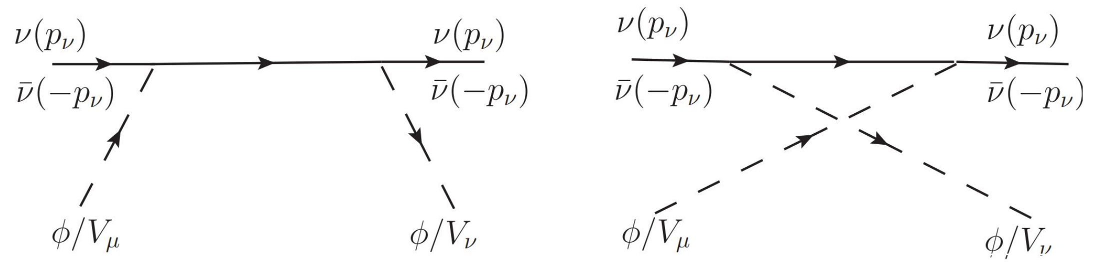
$$M_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

$$m_{\rm vac}^2 = A$$

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass

- The **forward scattering** with the **DM background**

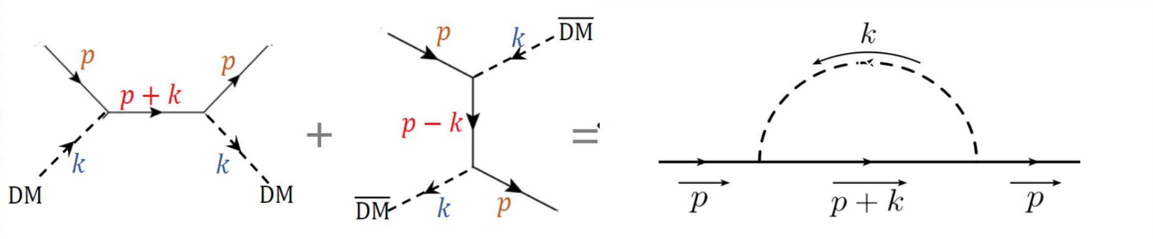


- Due to $1/E_\nu$ **dependence**, the **dark potential** is promoted to mass correction

$$H = \frac{M^2}{2E_\nu} - \frac{1}{\mathbf{E}_\nu}\sum_j y_{\alpha j} y^*_{j\beta}\frac{\rho_\chi}{m_\phi^2} \equiv \frac{M^2 + \delta \mathbf{M}^2}{2\mathbf{E}_\nu}$$

S.-F. Ge & H. Murayama, arXiv:1904.02518
S.-F. Ge, PoS NuFact 2019, 108 (2020)
S.-F. Ge, J. Phys. Conf. Ser. 1468, no.1,012125 (2020)

- Coherent forward scattering=medium one-loop correction



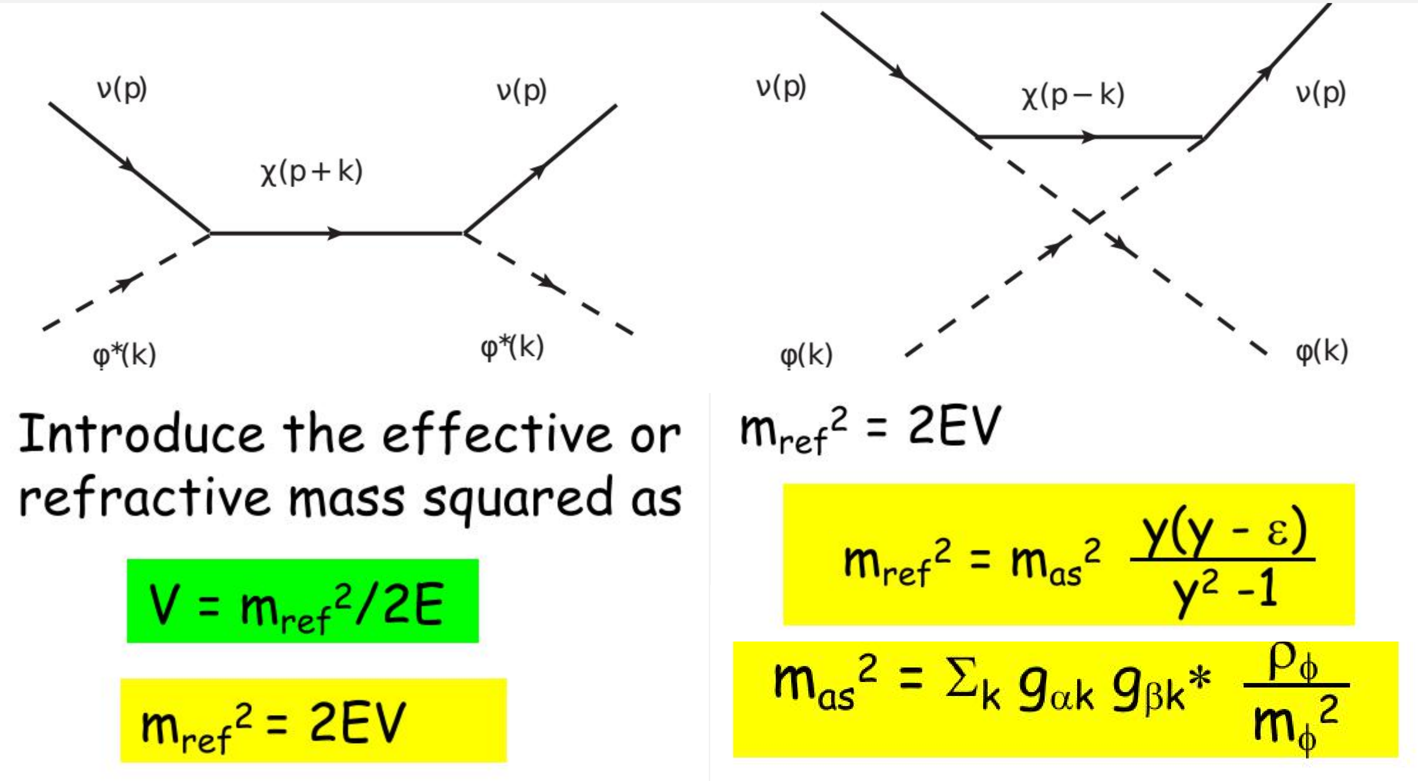
- Massless neutrinos get the dispersion $E = \sqrt{p^2 + \delta m^2}$, that is, $E \approx p + \frac{\delta m^2}{2p}$ for $p^2 \gg \delta m^2$.
- Neutrino oscillation from flavor-dependent couplings:

$$\mathcal{L}' = g_{\alpha\beta}\phi\overline{\nu_\alpha}\nu_\beta + h.c. \Rightarrow (\delta m^2)_{\alpha\beta} = (gg^\dagger)_{\alpha\beta}\frac{\rho_\phi}{m_\phi^2}$$

K. Y. Choi, E. J. Chun & J. Kim, arXiv:1909.10478
K. Y. Choi, E. J. Chun & J. Kim, arXiv:2012.09474
E. J. Chun, talks@TDLI

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass



Mass depends on the DM density

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

M. Sen and A. Y. Smirnov, arXiv:2306.15718
A. Y. Smirnov, talks@MAYORANA Workshop

Neutrino Mass Origins Comparison

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

vs.

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

Neutrino Mass Origins Comparison

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

vs.

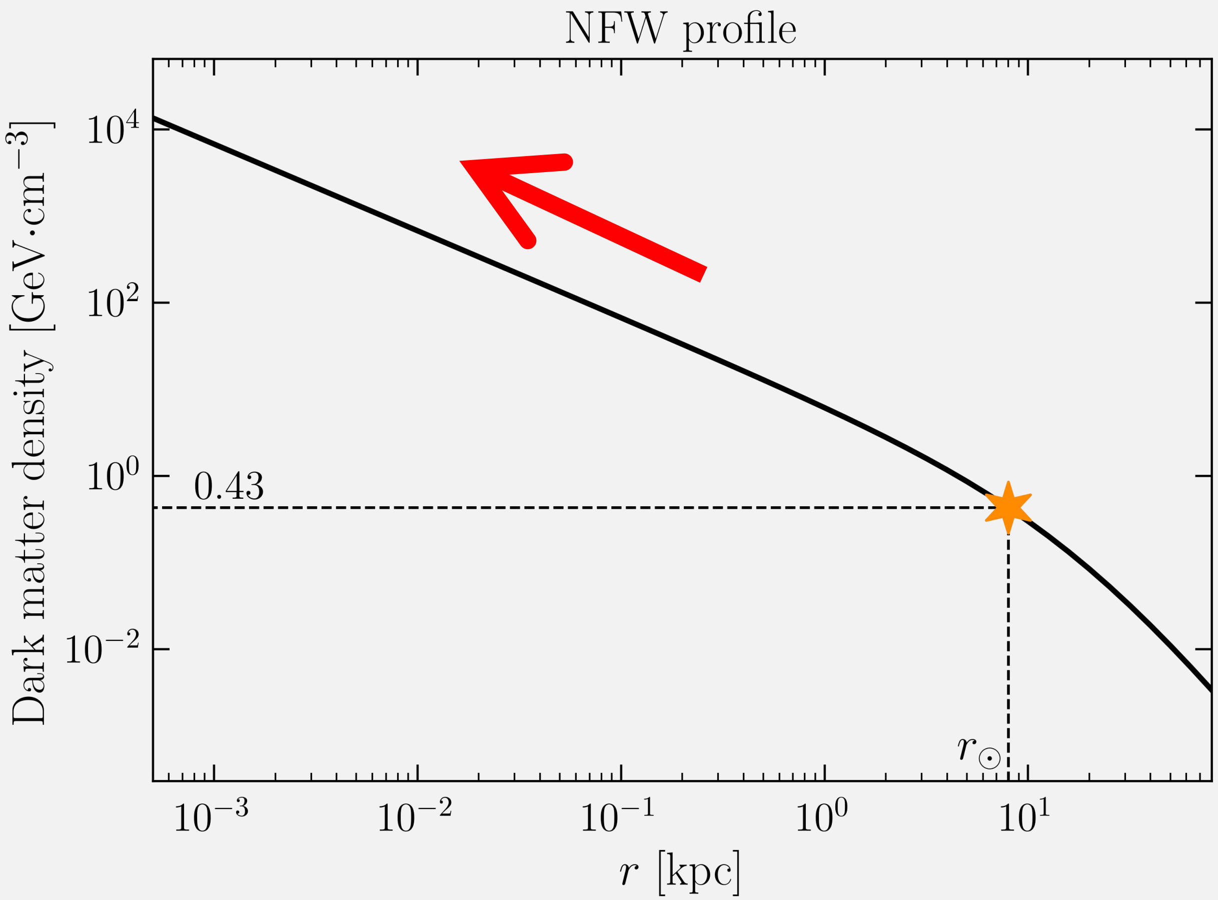
Dark Neutrino Mass: $m_{\rm dark}^2(x) \propto \rho_\phi$

Can we distinguish these two origins ?

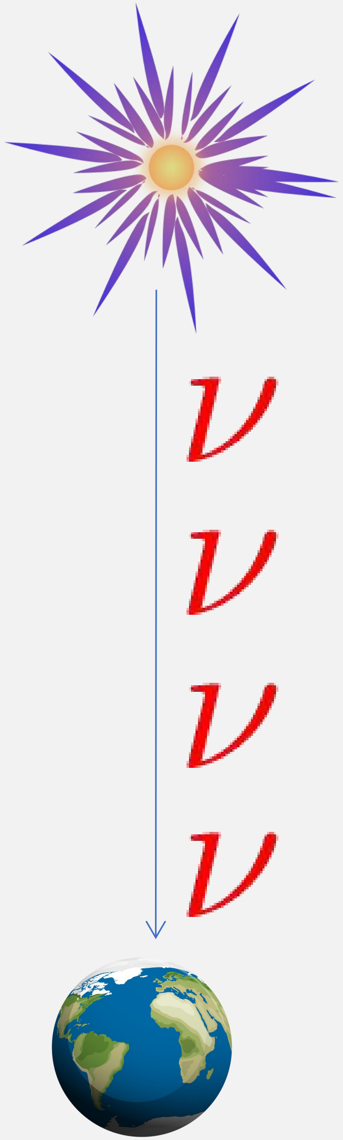
Yes! Look into larger scales

[see Prof. Dev's lecture]

Credit: IceCube/NASA



Supernova Neutrino Time Delay



Neutrinos are massive

group velocity:

$$v = \frac{p}{E} = \sqrt{1 - \frac{m^2}{E^2}} \approx 1 - \frac{m^2}{2E^2}$$

time delay (vacuum mass):

$$\Delta t \equiv \frac{D}{v} - D = \frac{m^2}{2E^2} D = 5.14\,\mathrm{ms} \left(\frac{m}{\mathrm{eV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{E}\right)^2 \frac{D}{10\,\mathrm{kpc}}$$

Supernova Neutrino Time Delay

How about the dark mass?

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

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

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

Supernova Neutrino Time Delay

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How about the dark mass?

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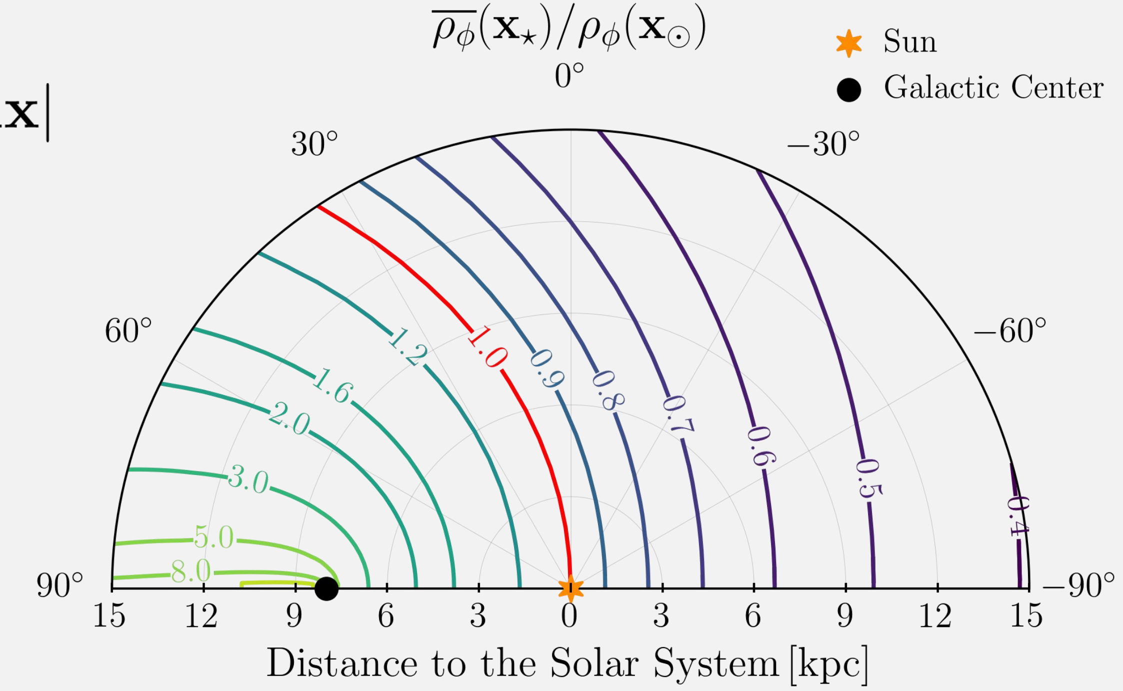
differed by this factor



Ge, CFK, Smirnov
arXiv: 2404.17352

Supernova Neutrino Prdocution & Detection

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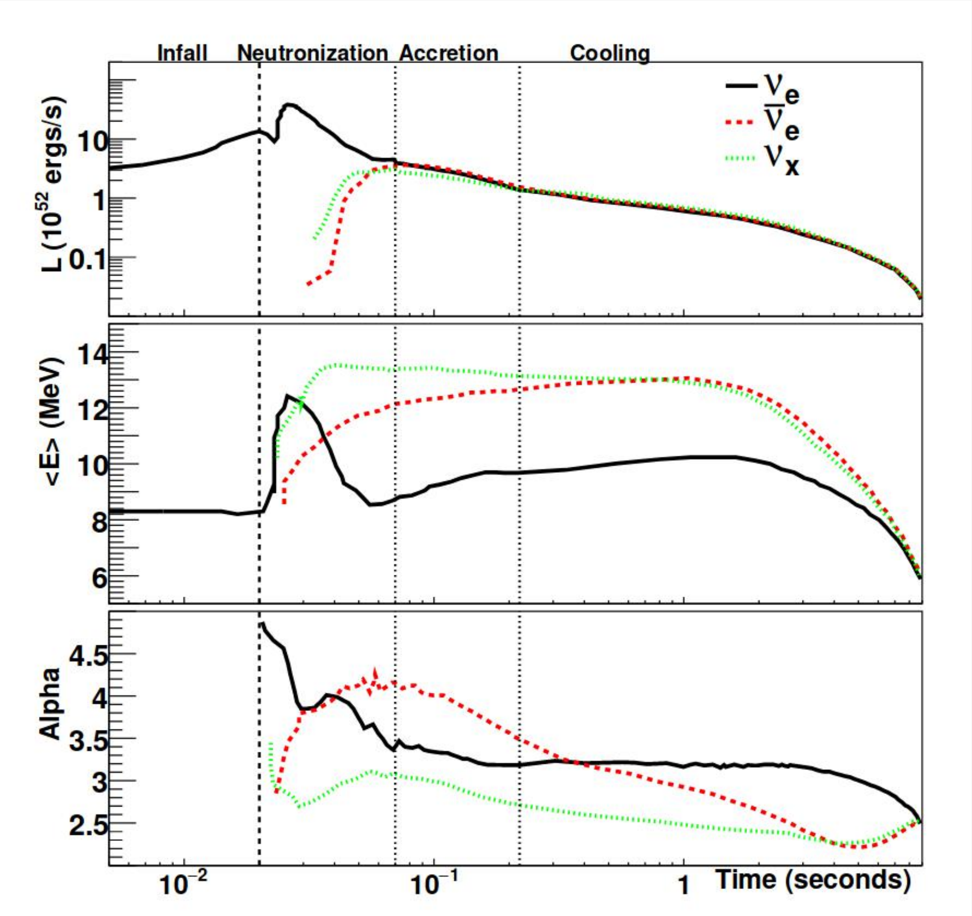


DUNE Collaboration
arXiv: 2008.06647

- ν_e SN burst production (Garching model):

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

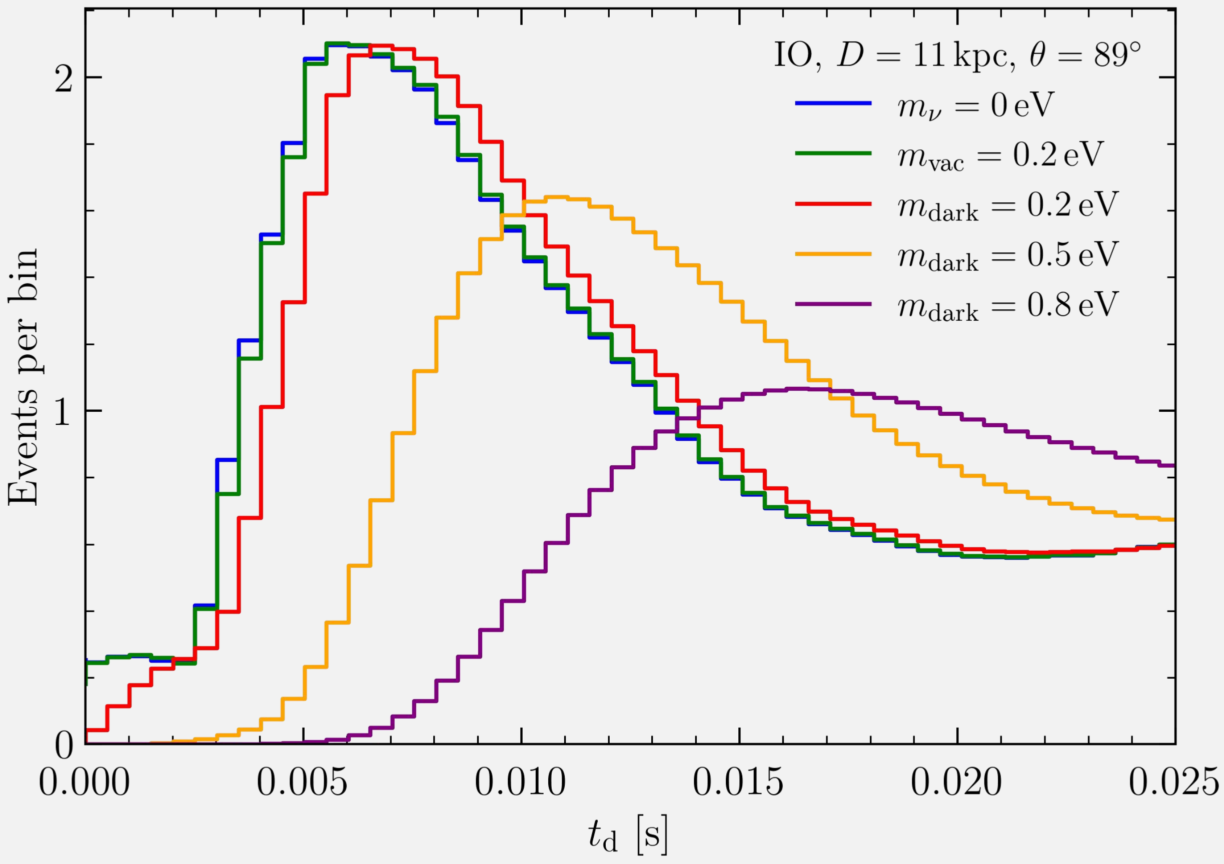
$$\varphi_{\nu_\beta}(t_{\rm e}, E_\nu) \equiv \xi_\beta(t_{\rm e})\left(\frac{E_\nu}{\langle E_{\nu_\beta}(t_{\rm e})\rangle}\right)^{\alpha_\beta(t_{\rm e})} e^{\frac{-\left(\alpha_\beta(t_{\rm e})+1\right)E_\nu}{\langle E_{\nu_\beta}(t_{\rm e})\rangle}}$$

- ν_e SN burst detection at DUNE:

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

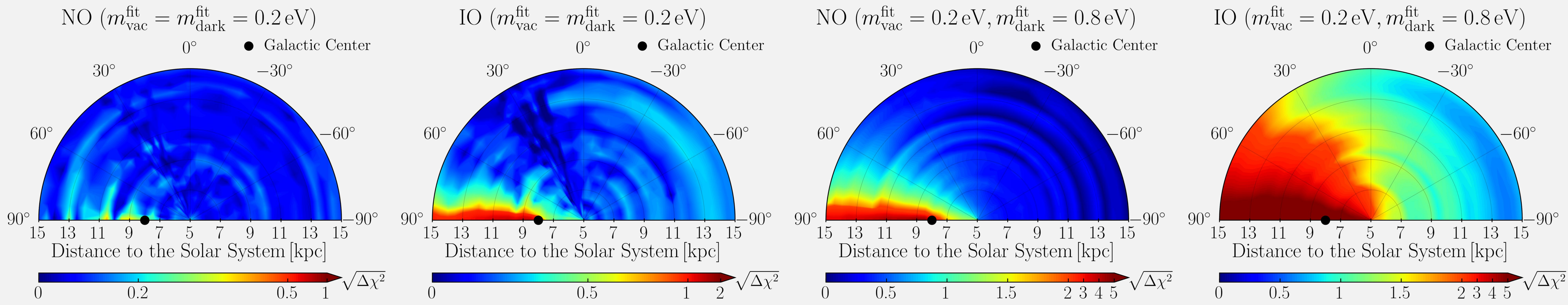
Time Distribution

The time distribution becomes wider as the neutrino mass increases



Ge, CFK, Smirnov
arXiv: 2404.17352

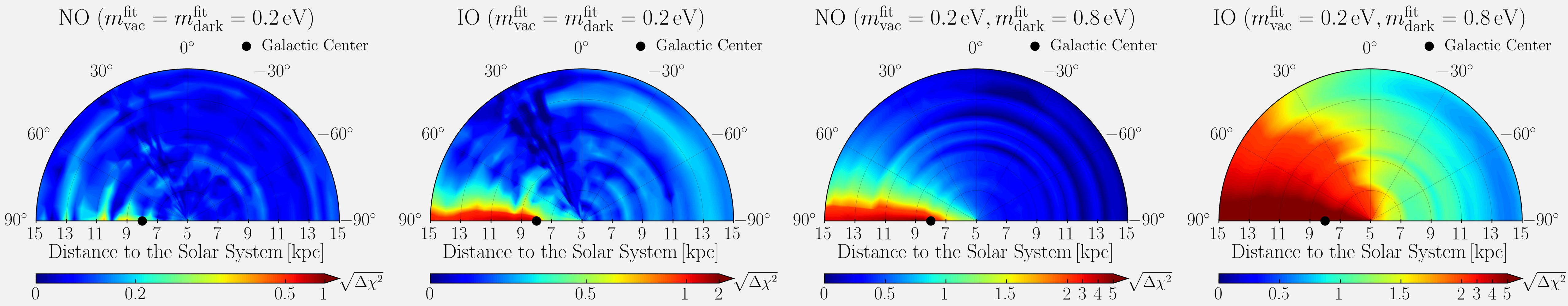
Sensitivities



❖ **Location dependence:** the sensitivity is enlarged by measuring neutrinos around the galaxy center

Ge, CFK, Smirnov
arXiv: 2404.17352

Sensitivities



❖ **Location dependence:** the sensitivity is enlarged by measuring neutrinos around the galaxy center

❖ **Neutrino mass ordering dependence:** sensitivity for normal ordering (NO) is reduced by MSW effect

Ge, CFK, Smirnov
arXiv: 2404.17352

Summary

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- The dark neutrino mass is space-time dependent due to the dark matter distribution
- The supernova neutrino time delay can be much enhanced around galaxy center
- The neutrino mass origins (vacuum or dark mass) can be tested by measuring supernova neutrinos
- Better test can be done by measuring neutrinos from supernovae at different locations

Summary

- The dark neutrino mass is space-time dependent due to the dark matter distribution
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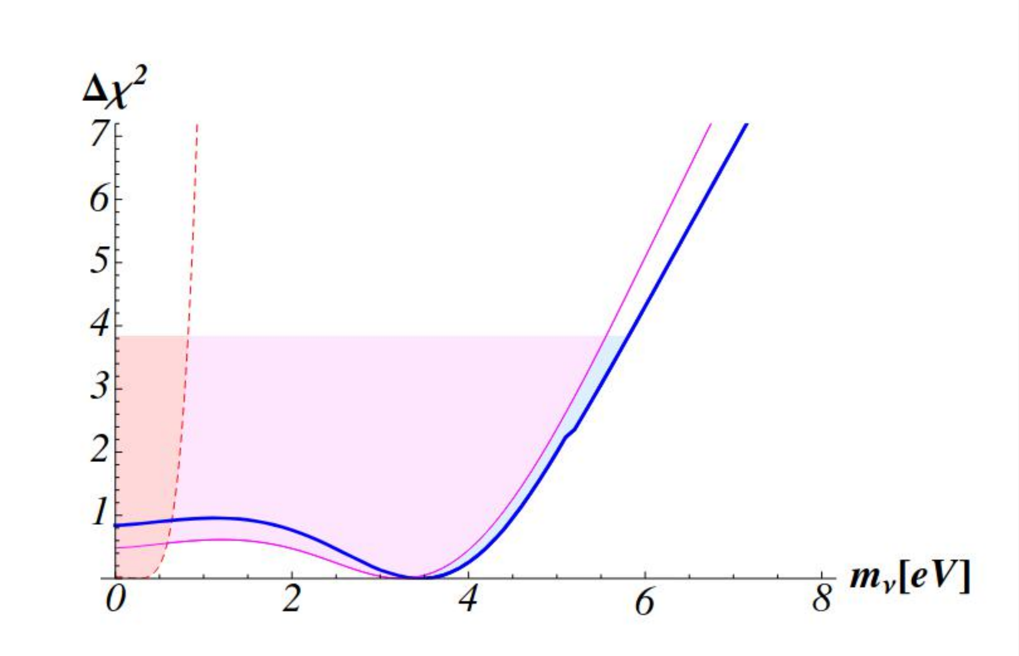
- Better test can be done by measuring neutrinos from supernovae at different locations

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

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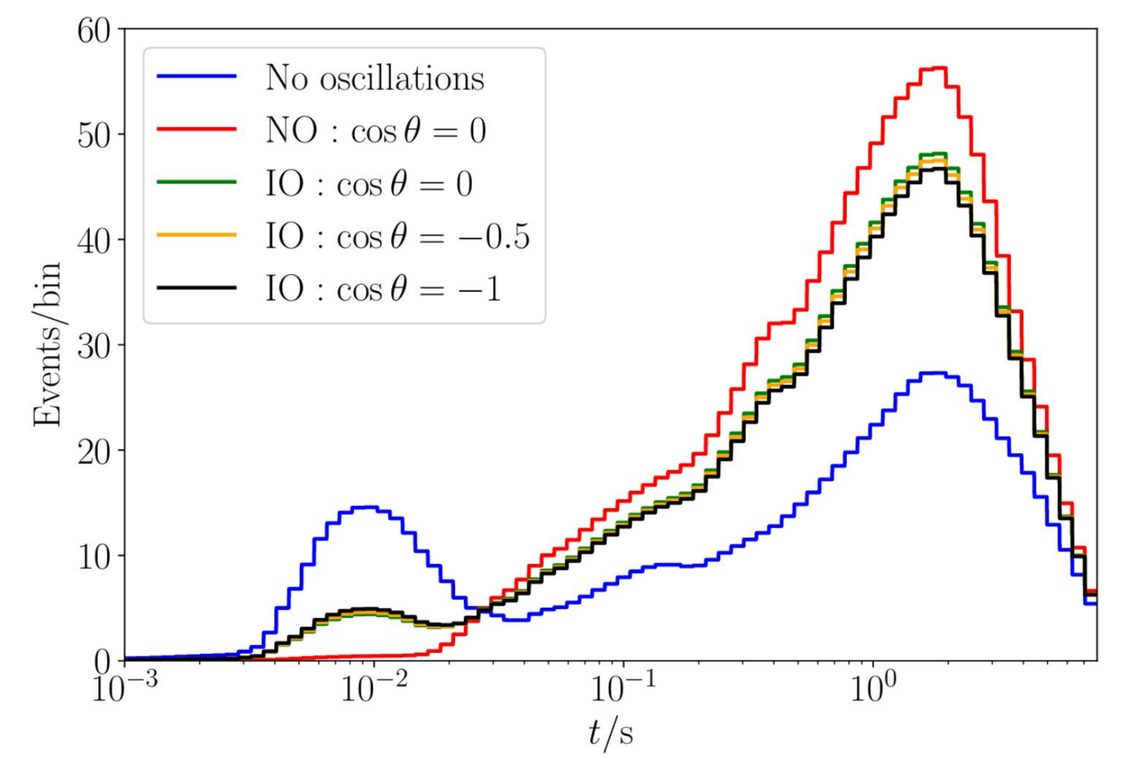
MSW effect

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

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

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



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

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neutrino group velocity

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

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