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

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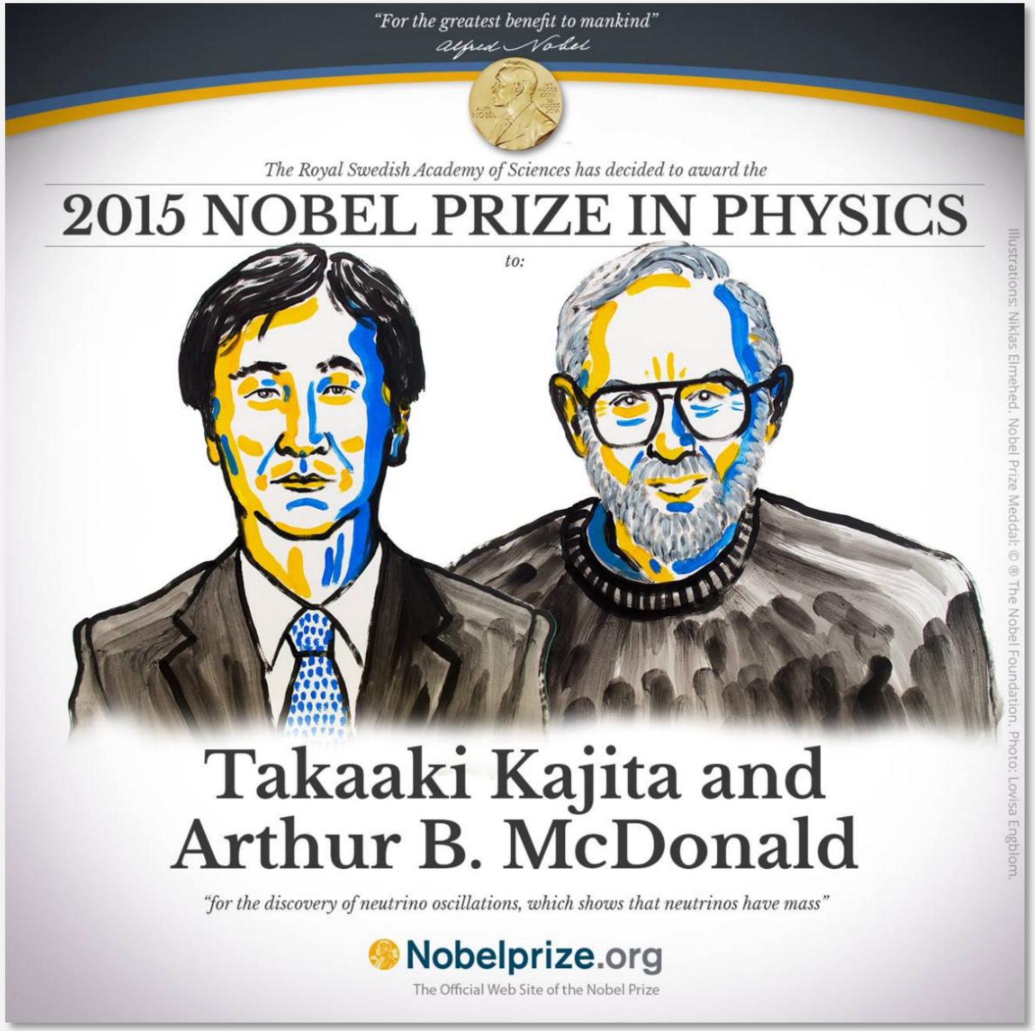
BL 2024

KIT
Karlsruher Institut für Technologie

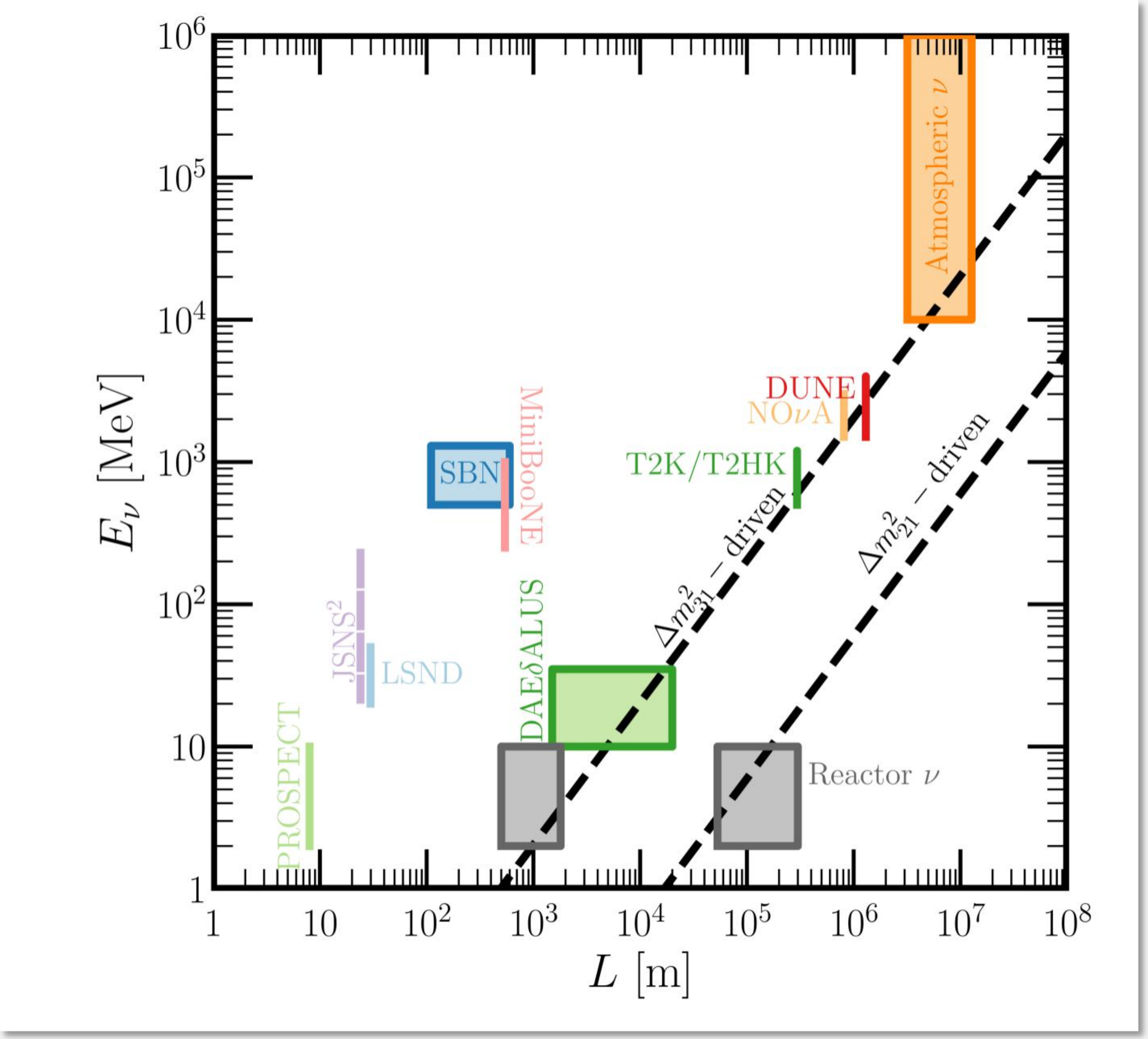
BLV @ KIT, Oct 8-11 2024

Evidence of Neutrino Mass



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

Evidence of Neutrino Mass



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

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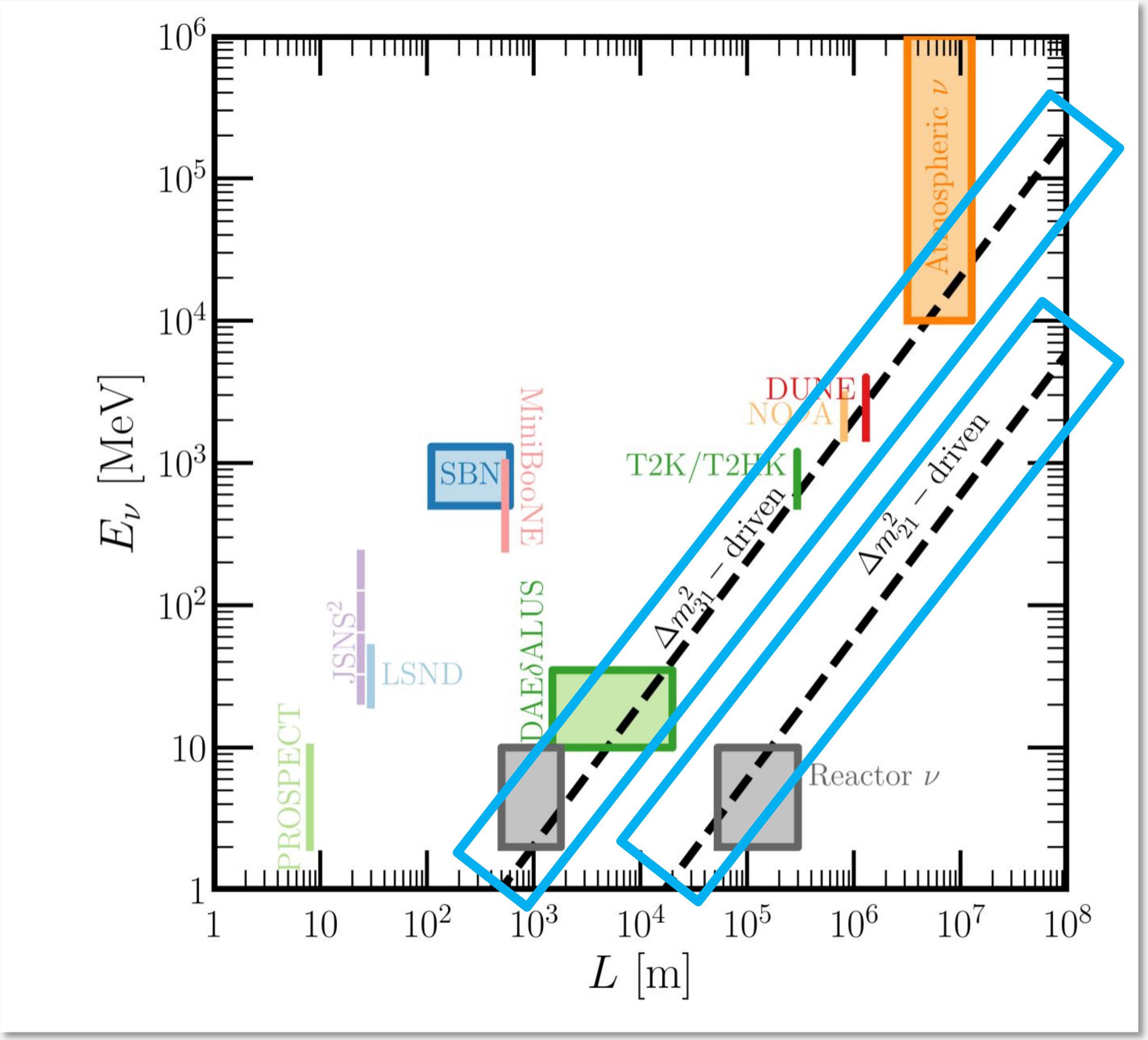

[see talks by Michele Maltoni, Renata Zukanovich Funchal, Daniel Naredo]

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

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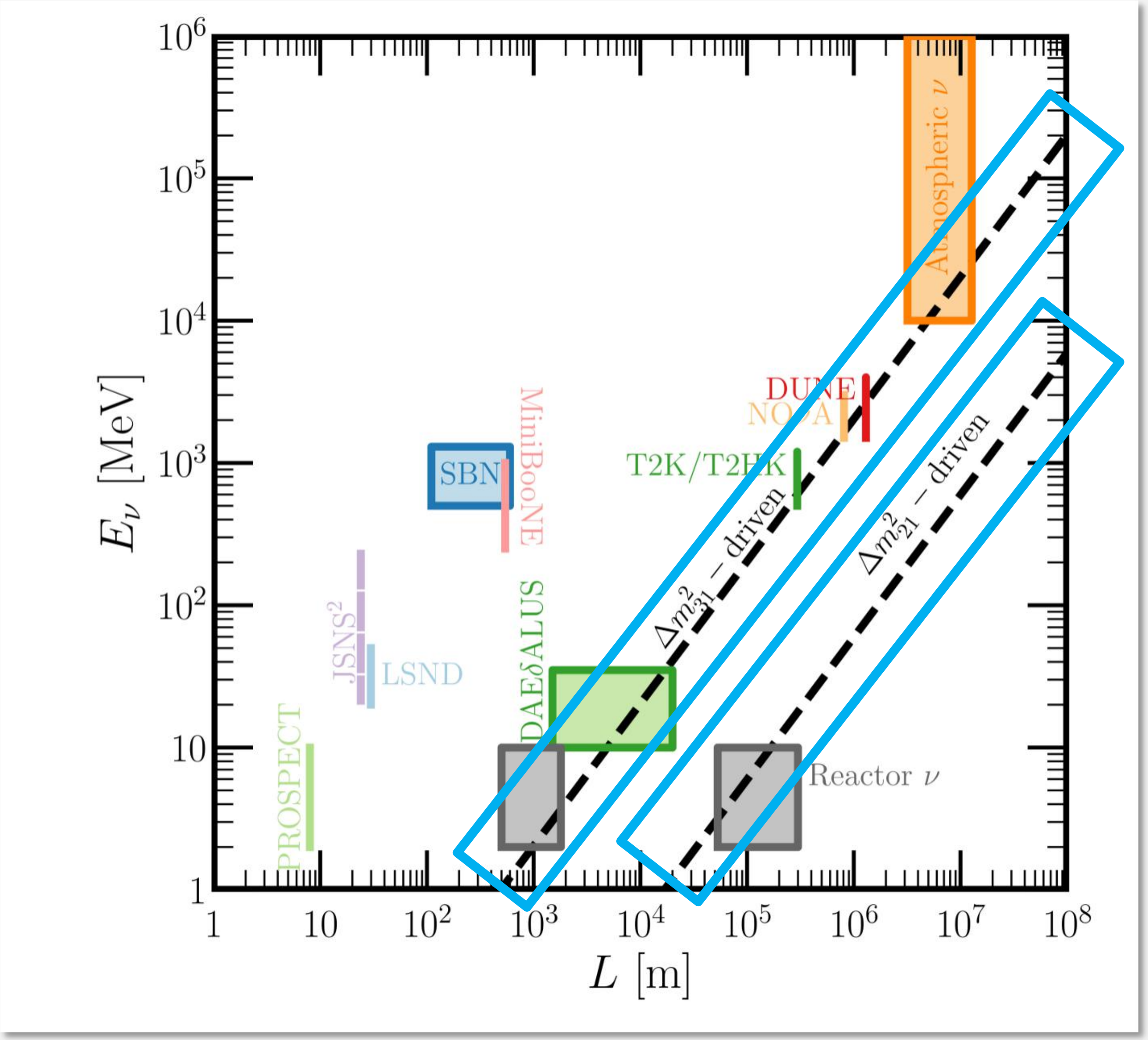

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↓

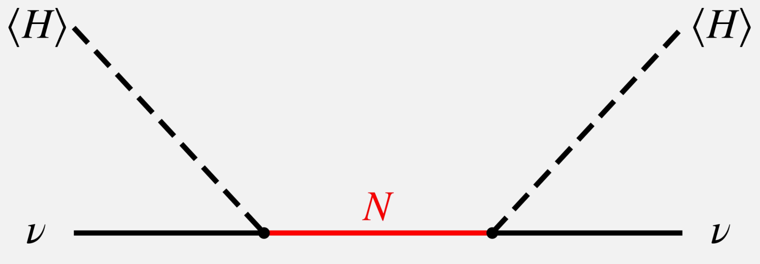
Q: What's the origin of neutrino mass?

Neutrino Mass Origin I: vacuum mass

[see talks by Ana M. Teixeira, Kevin Alberto Urquía-Calderón, Stefan Antusch, Richard Ruiz, Jonathan Kriewald]

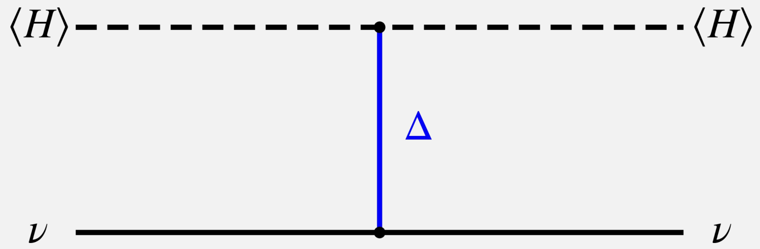
Vacuum Neutrino Mass

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



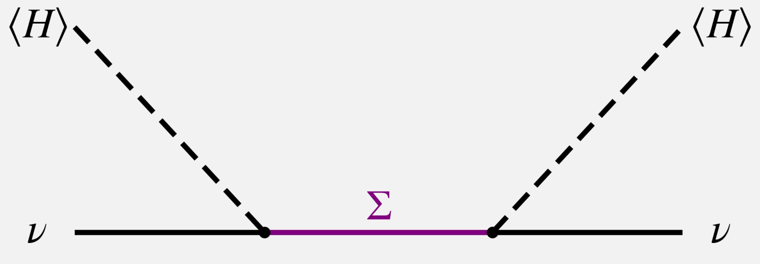
$$M_\nu = -\frac{1}{2} Y_\nu \frac{v^2}{M_R} Y_\nu^T$$

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...



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

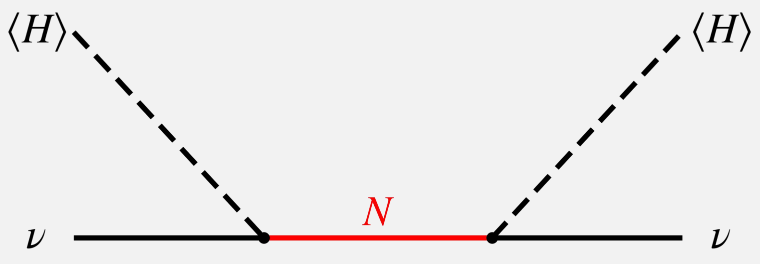
R. Foot, H. Lew, X.-G. He, & G.C. Joshi
E. Ma...

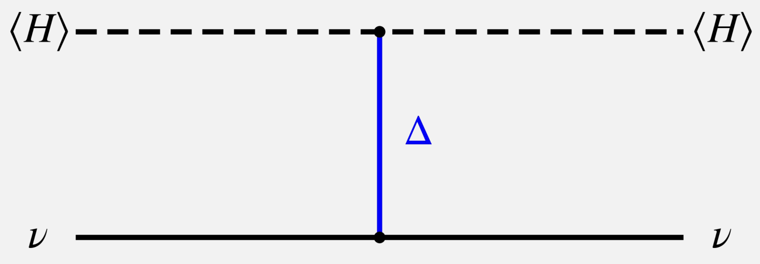
Neutrino Mass Origin I: vacuum mass

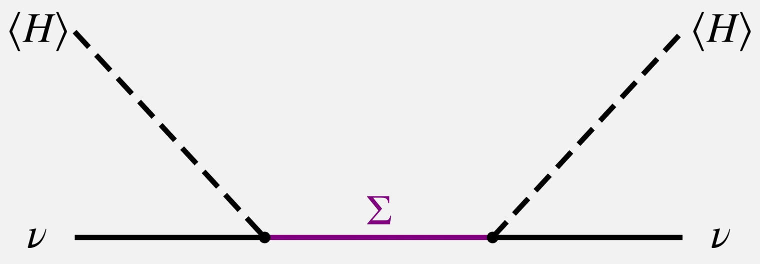
[see talks by Ana M. Teixeira, Kevin Alberto Urquía-Calderón, Stefan Antusch, Richard Ruiz, Jonathan Kriewald]

Vacuum Neutrino Mass

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







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

Neutrino Mass Origin II: dark mass

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

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

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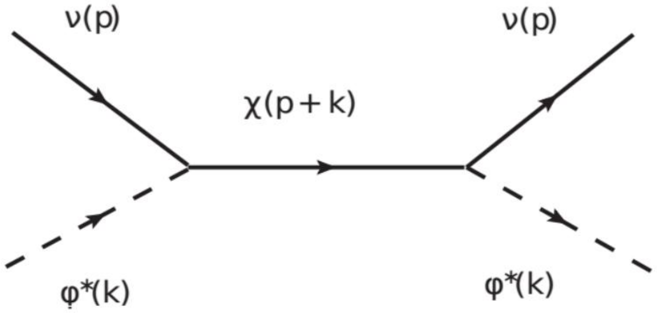
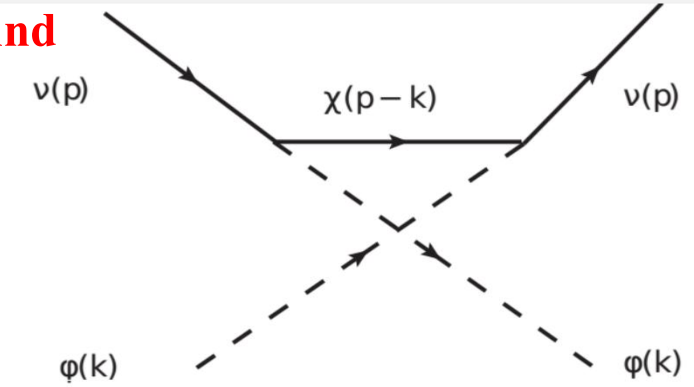
interpreted as effective mass or dark mass

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass

Forward scattering with DM background





Introduce the effective or refractive mass squared as

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

$$m_{ref}^2 = 2EV$$

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

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

A. Y. Smirnov, talks@MAYORANA Workshop

[H. Davoudiasl, G. Mohlabeng, & M. Sullivan, arXiv:1803.00012; 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

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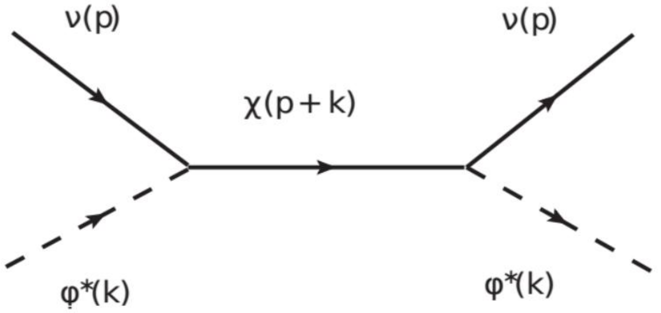

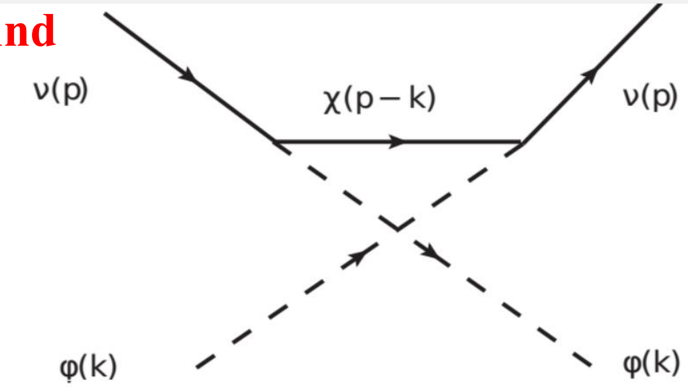

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A. Y. Smirnov, talks@MAYORANA Workshop

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

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

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

vs.

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

Can we distinguish these two origins ?

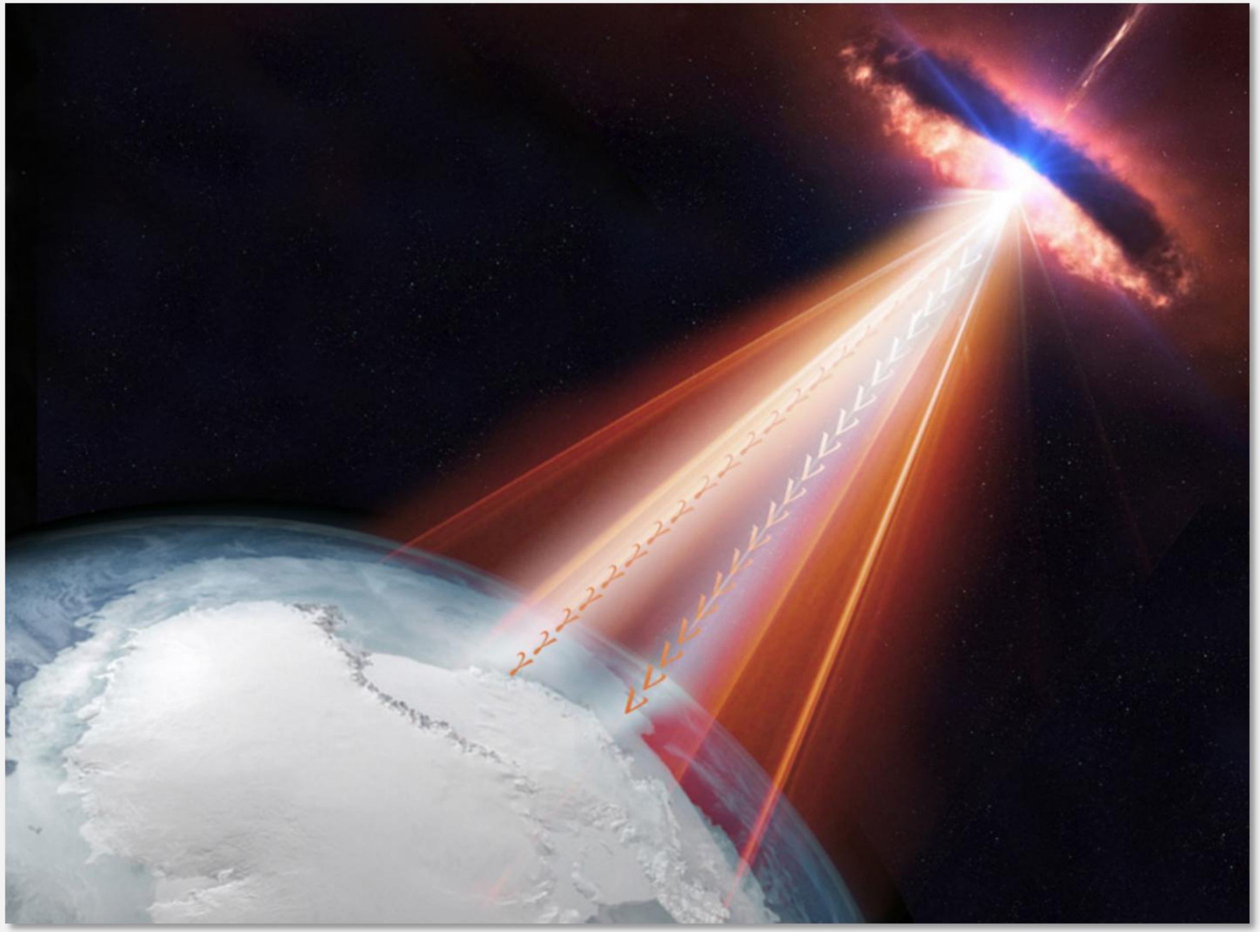
Large Scales

Yes! Look into larger scales!

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

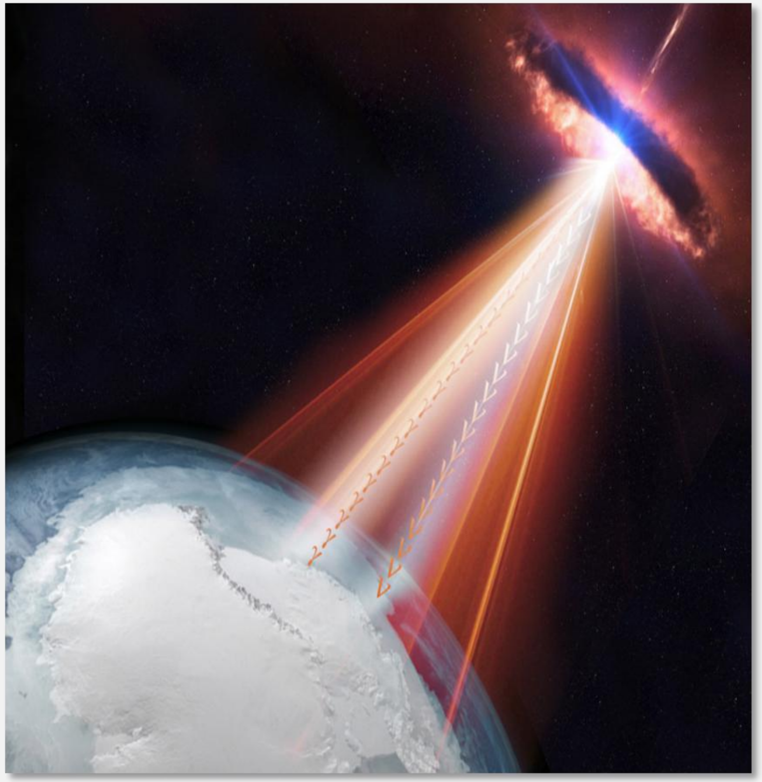
vs.

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



Credit: IceCube

Supernova Neutrino Time Delay



Galactic supernovae are ideal neutrino sources!

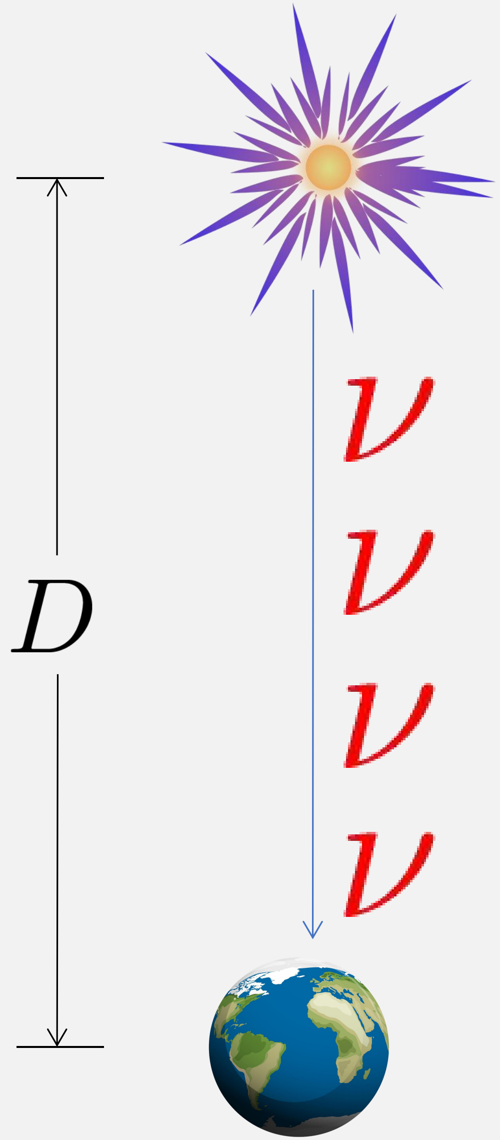
POSSIBILITY OF DETERMINING THE UPPER LIMIT OF THE NEUTRINO MASS FROM THE TIME OF FLIGHT

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)

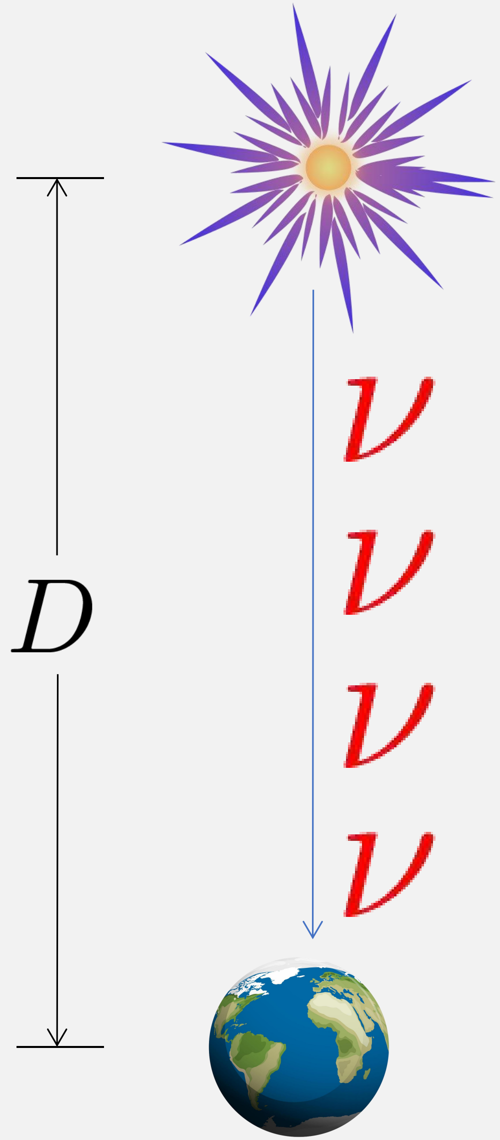
56 years ago!

[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



Supernova Neutrino Time Delay (vacuum neutrino mass)

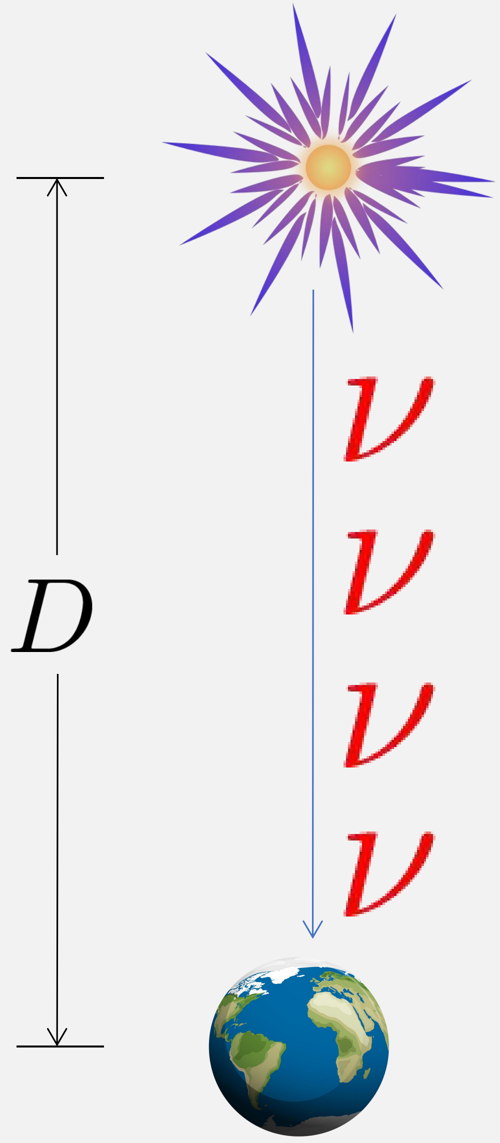


$$E_\nu = \sqrt{p_\nu^2 + m^2}, \quad v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

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

Supernova Neutrino Time Delay (vacuum neutrino mass)



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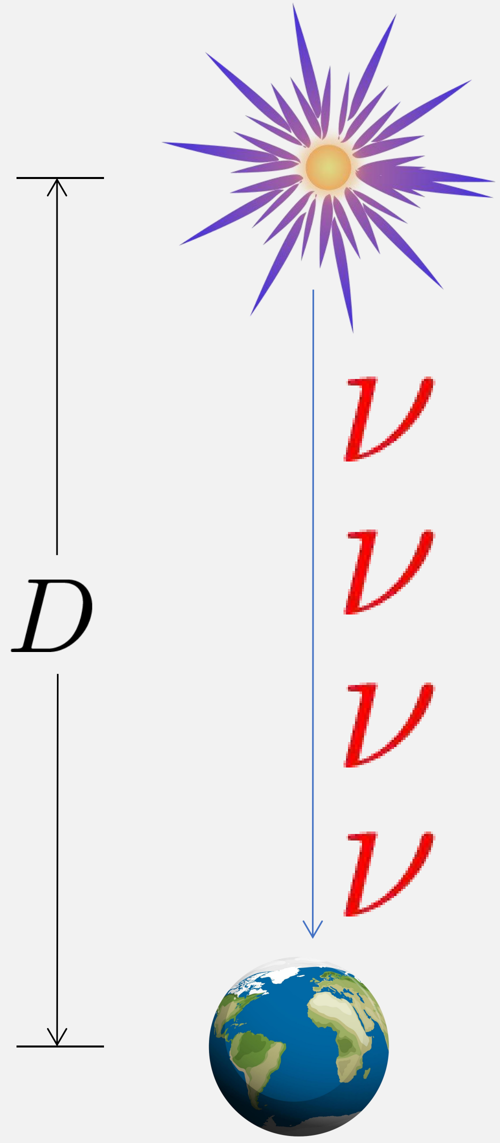
smaller than speed of light!

&

space-time independent

Supernova Neutrino Time Delay (vacuum neutrino mass)



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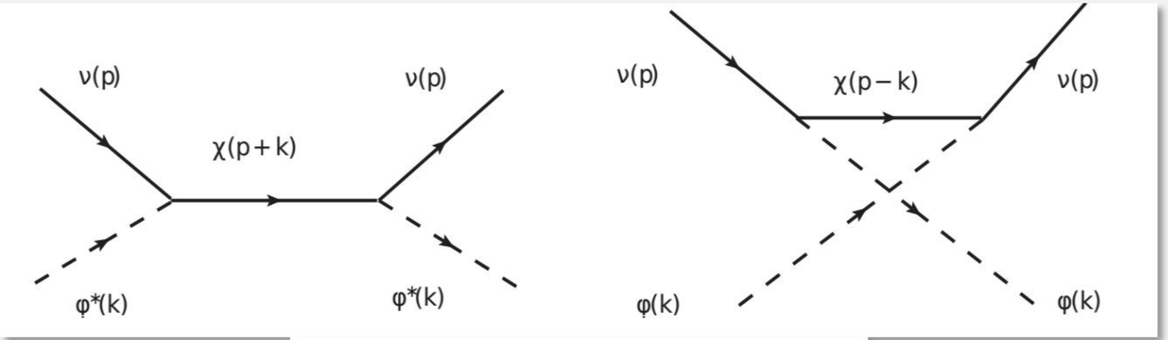
time delay:

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

Supernova Neutrino Time Delay (dark neutrino mass)

Recall



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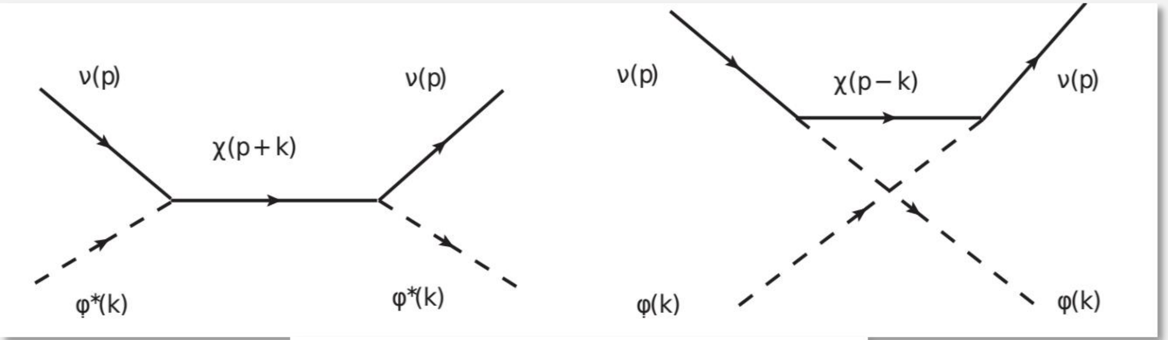

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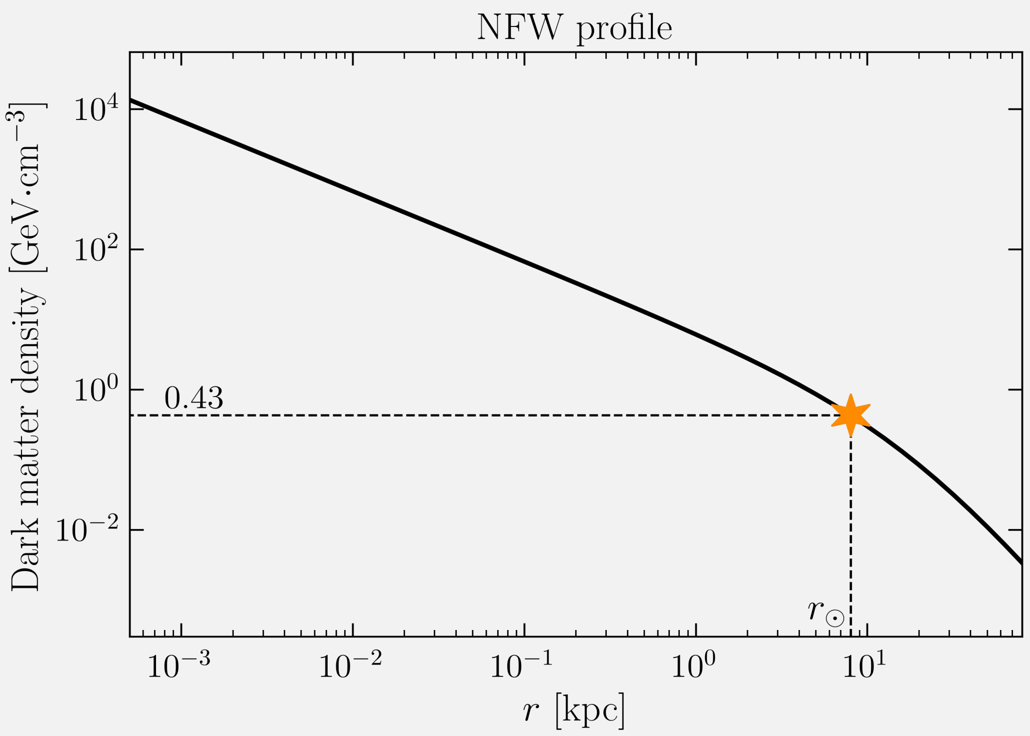
space-time dependent!

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

Supernova Neutrino Time Delay (dark neutrino mass)



Navarro-Frenk-White profile

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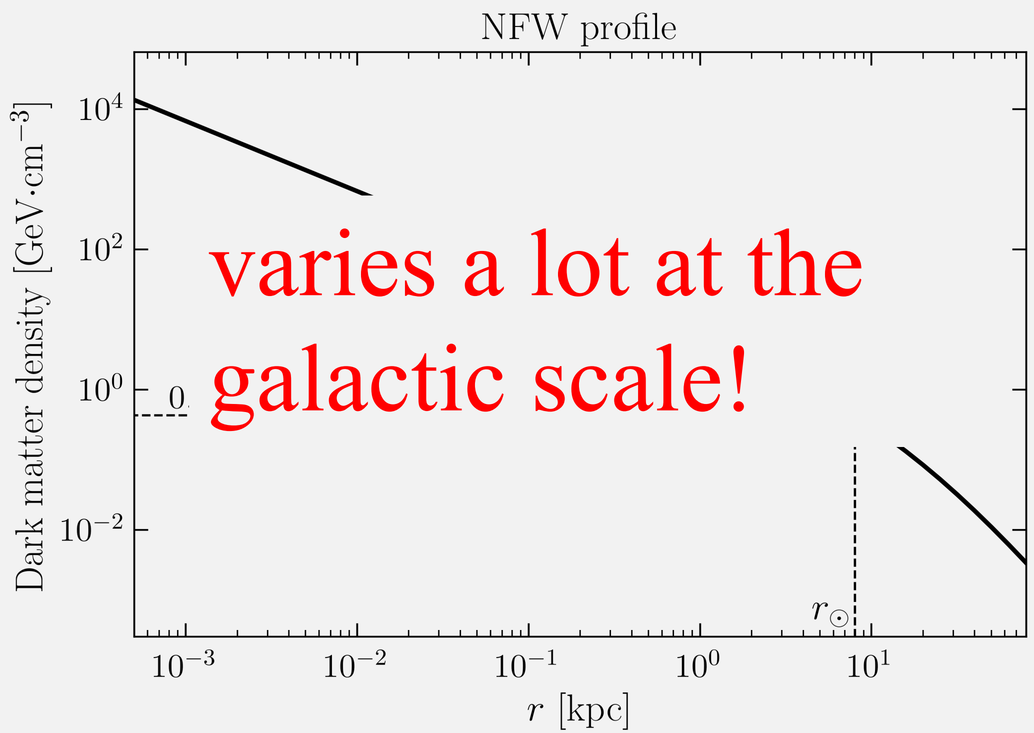

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Supernova Neutrino Time Delay (dark neutrino mass)

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

just an integration over neutrino trajectory

Supernova Neutrino Time Delay (dark neutrino mass)

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vacuum neutrino mass

differed by this factor!

Supernova Neutrino Time Delay (dark neutrino mass)

...

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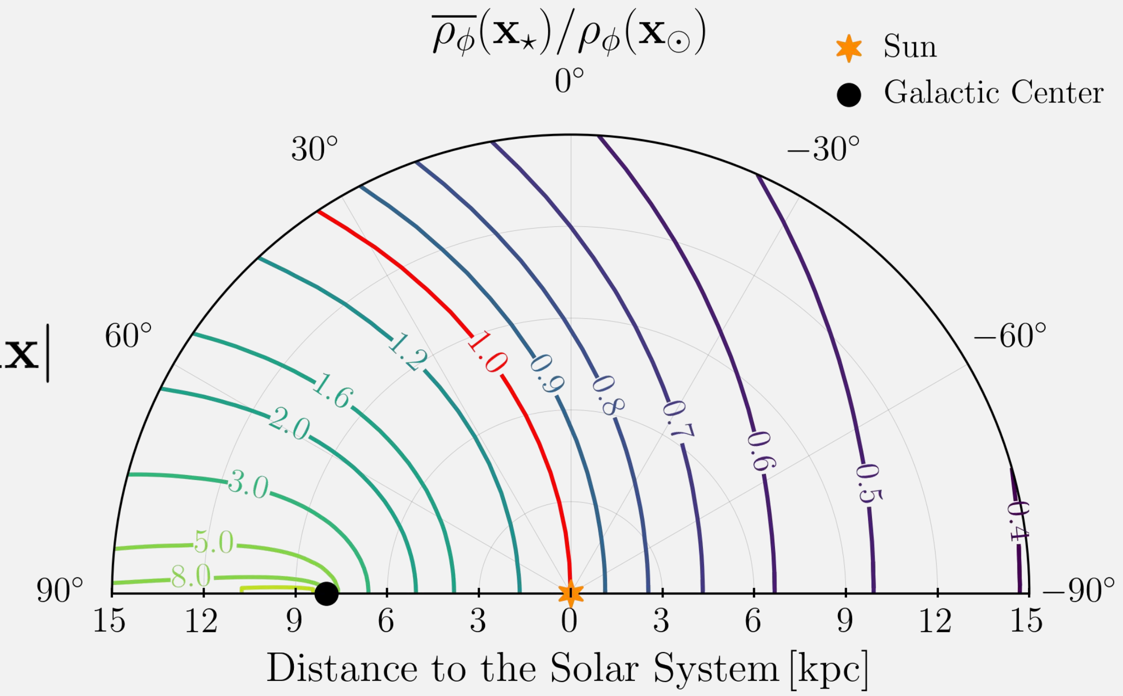


*Ge, **CFK**, Smirnov*
arXiv: 2404.17352

Simulation

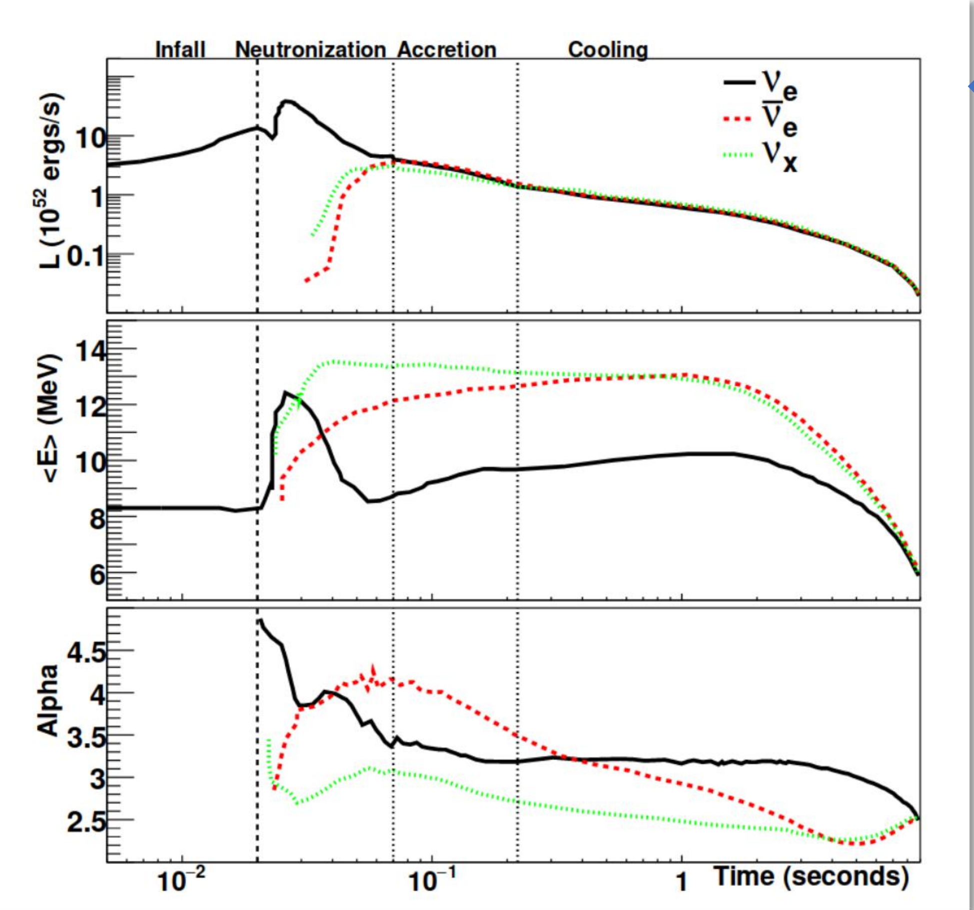
Supernova Neutrino Prdocution

- ν_e SN burst production (Garching model):

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

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

Supernova Neutrino Prdocution



DUNE Collaboration
arXiv: 2008.06647

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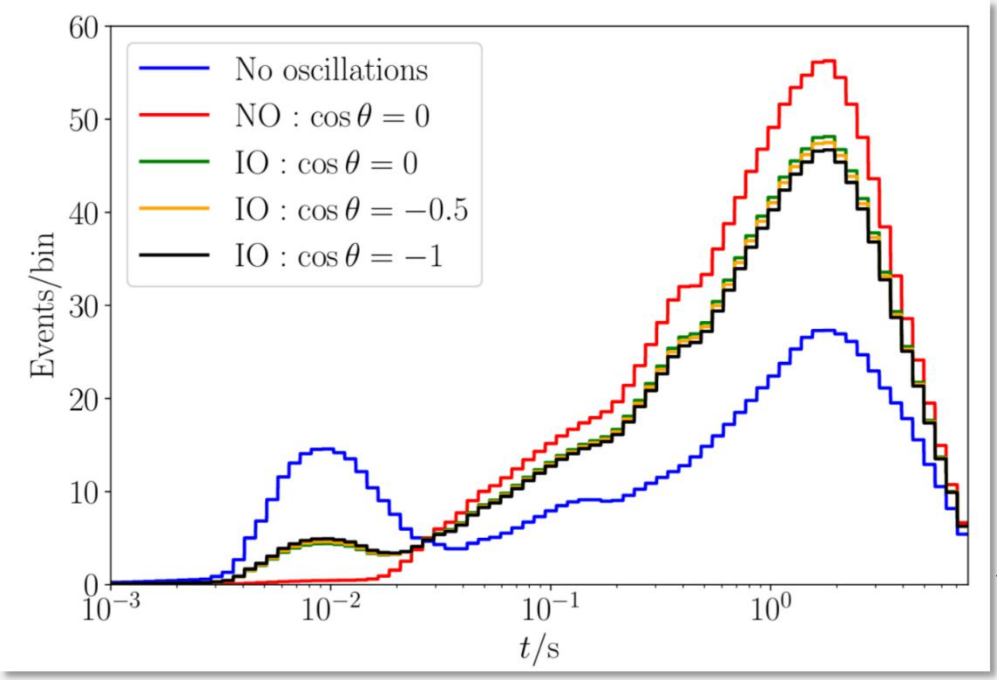
Supernova Neutrino Prdocution

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):

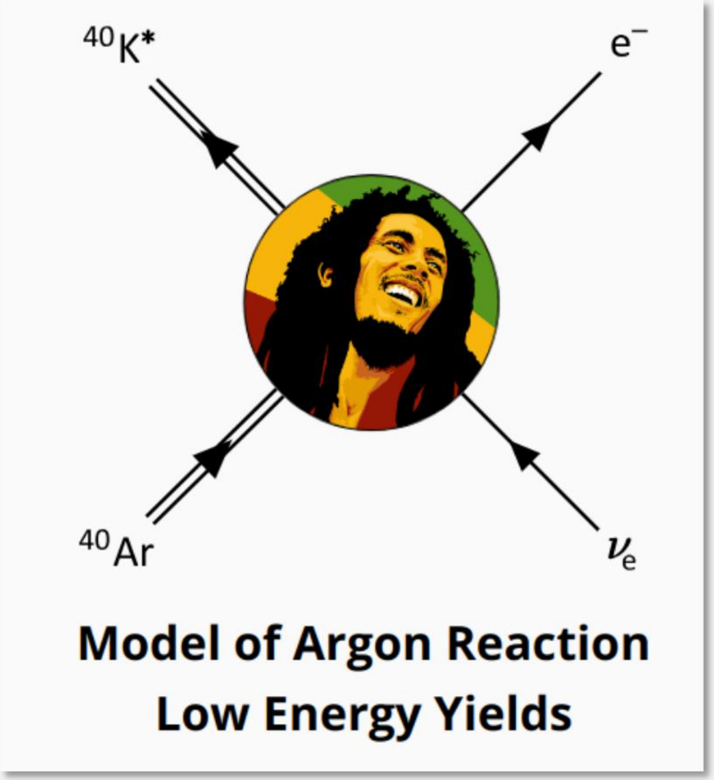
$$\Phi_{\nu_e} = p\Phi^0_{\nu_e} + (1-p)\Phi^0_{\nu_x}$$

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

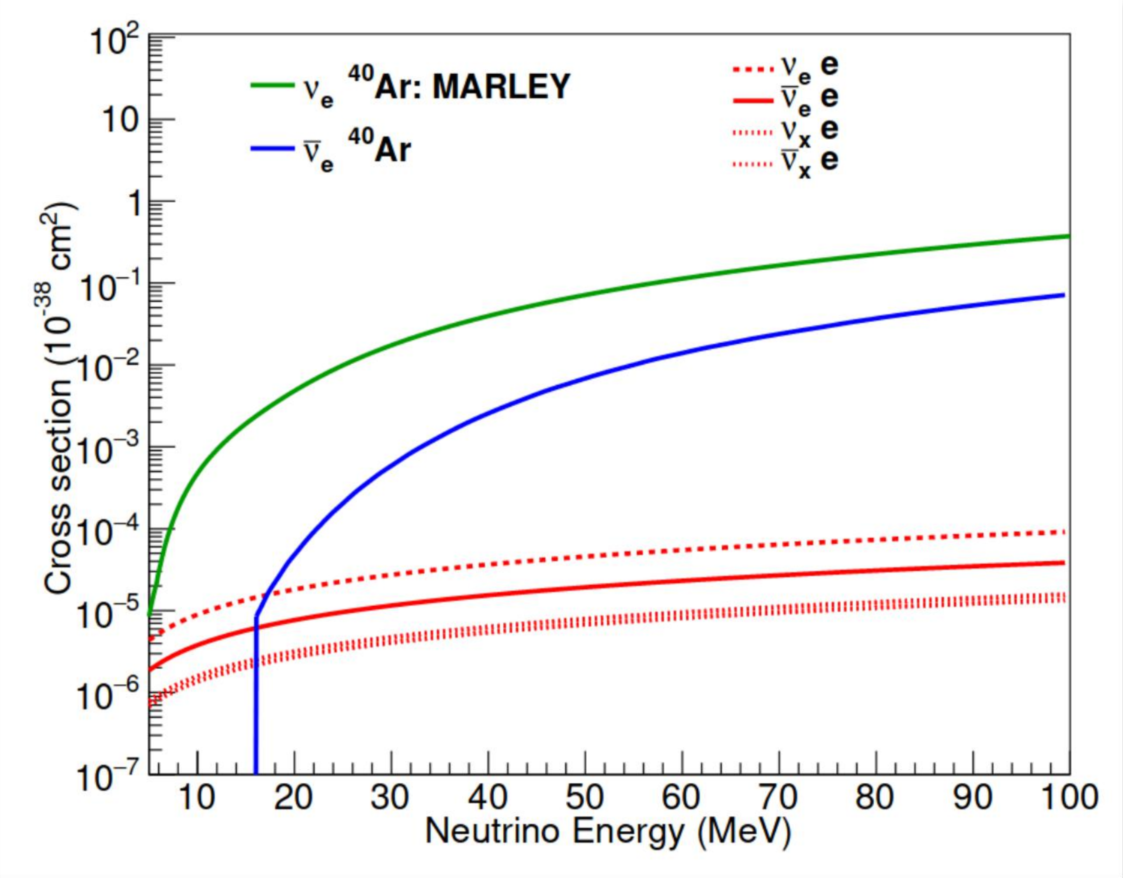
$$p \approx |U_{e2}|^2 \approx \sin^2\theta_{12}, \text{IO}$$

Supernova Neutrino Detection @ DUNE

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



S. Gardiner, 2010.02393
& 2101.11867



DUNE Collaboration
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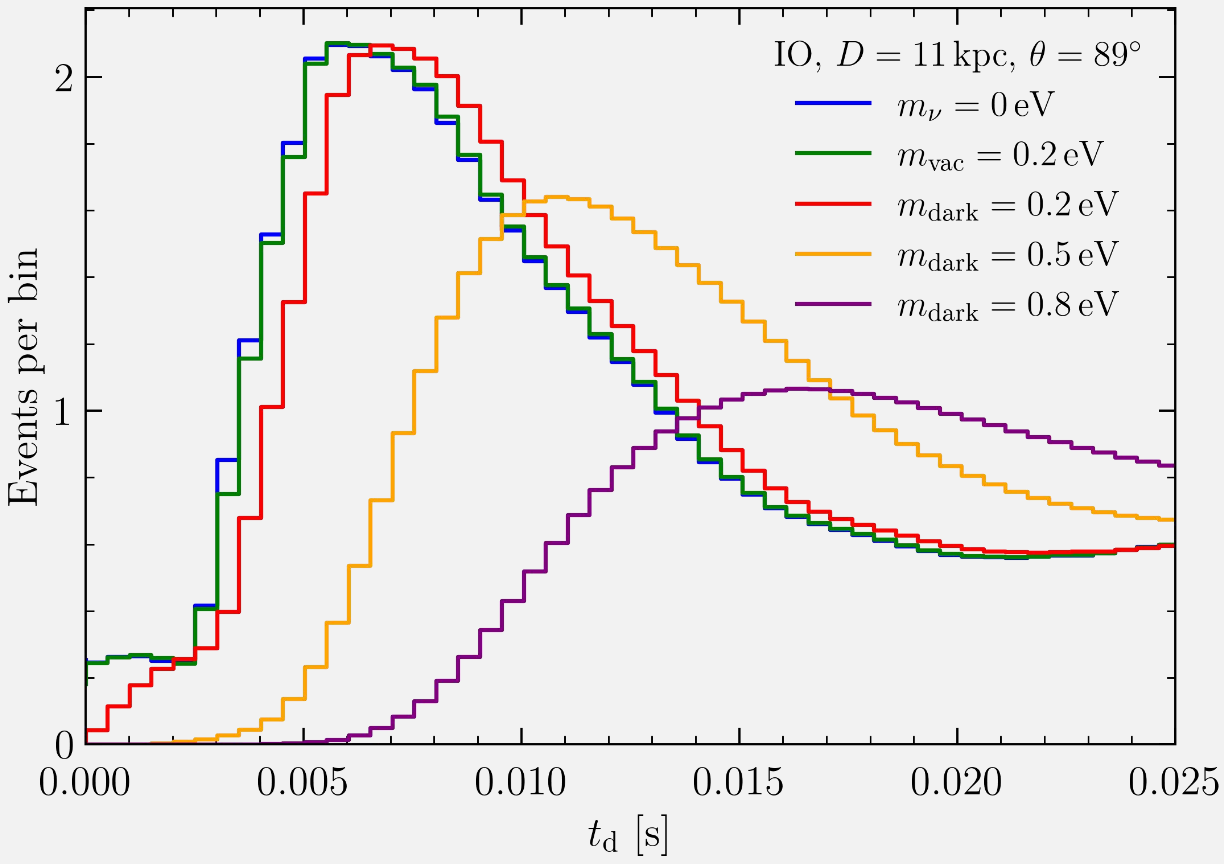
Time Distribution

The time distribution becomes wider as the neutrino mass increases



*Ge, **CFK**, Smirnov*
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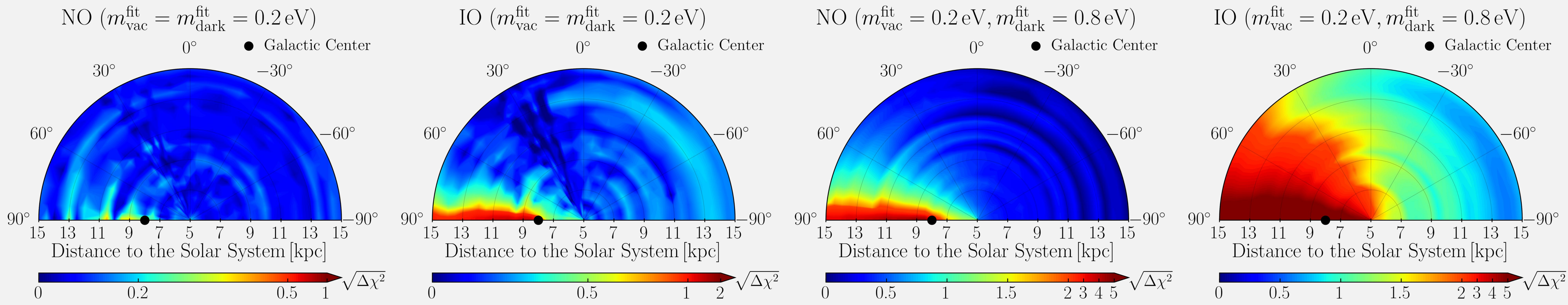
Sensitivities



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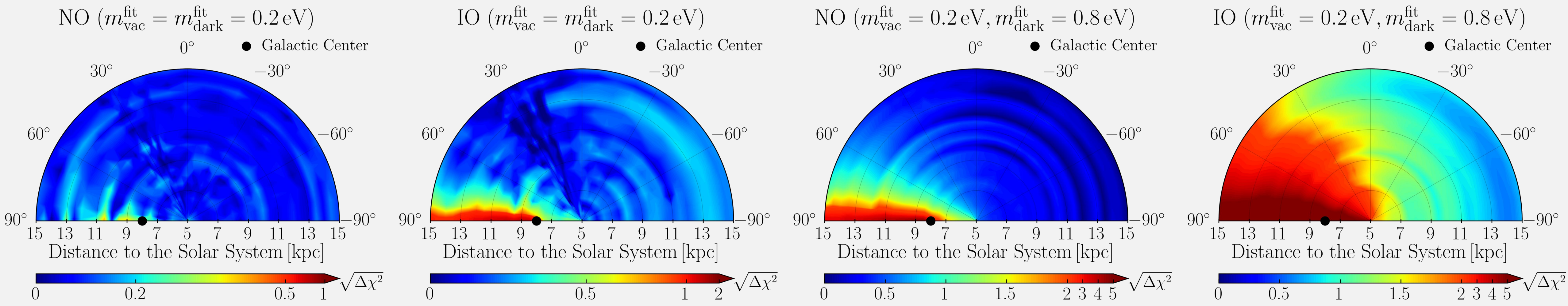
arXiv: 2404.17352

Sensitivities



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

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

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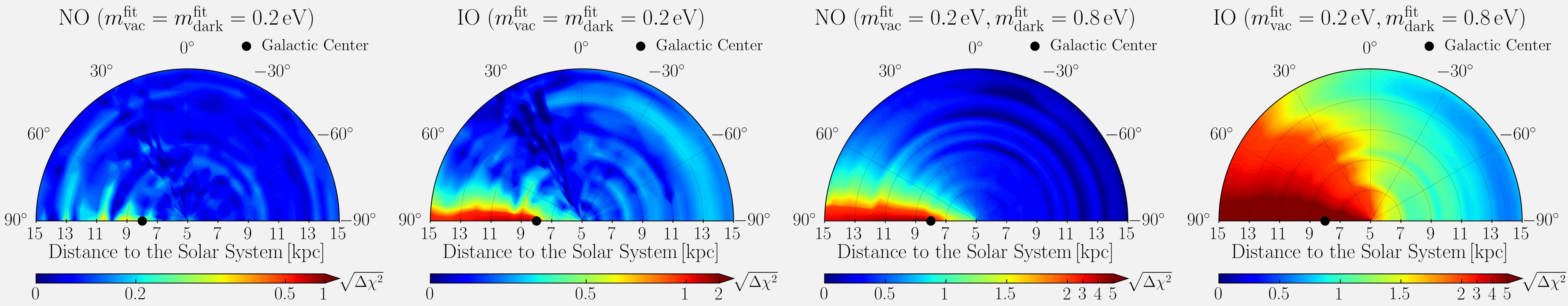

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- Sensitivity for normal ordering (NO) is reduced by MSW matter effect

*Ge, **CFK**, Smirnov*
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Summary

- The dark neutrino mass is space-time dependent due to the DM 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

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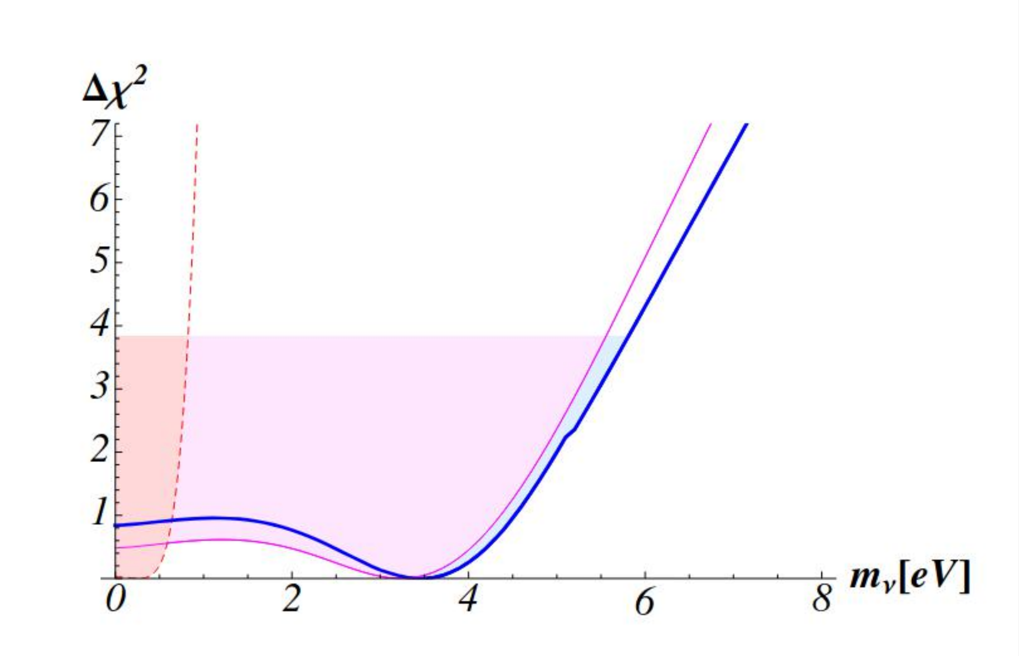
Thank you for your attention!

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