Testing Neutrino Mass Origins with Supernova Neutrinos

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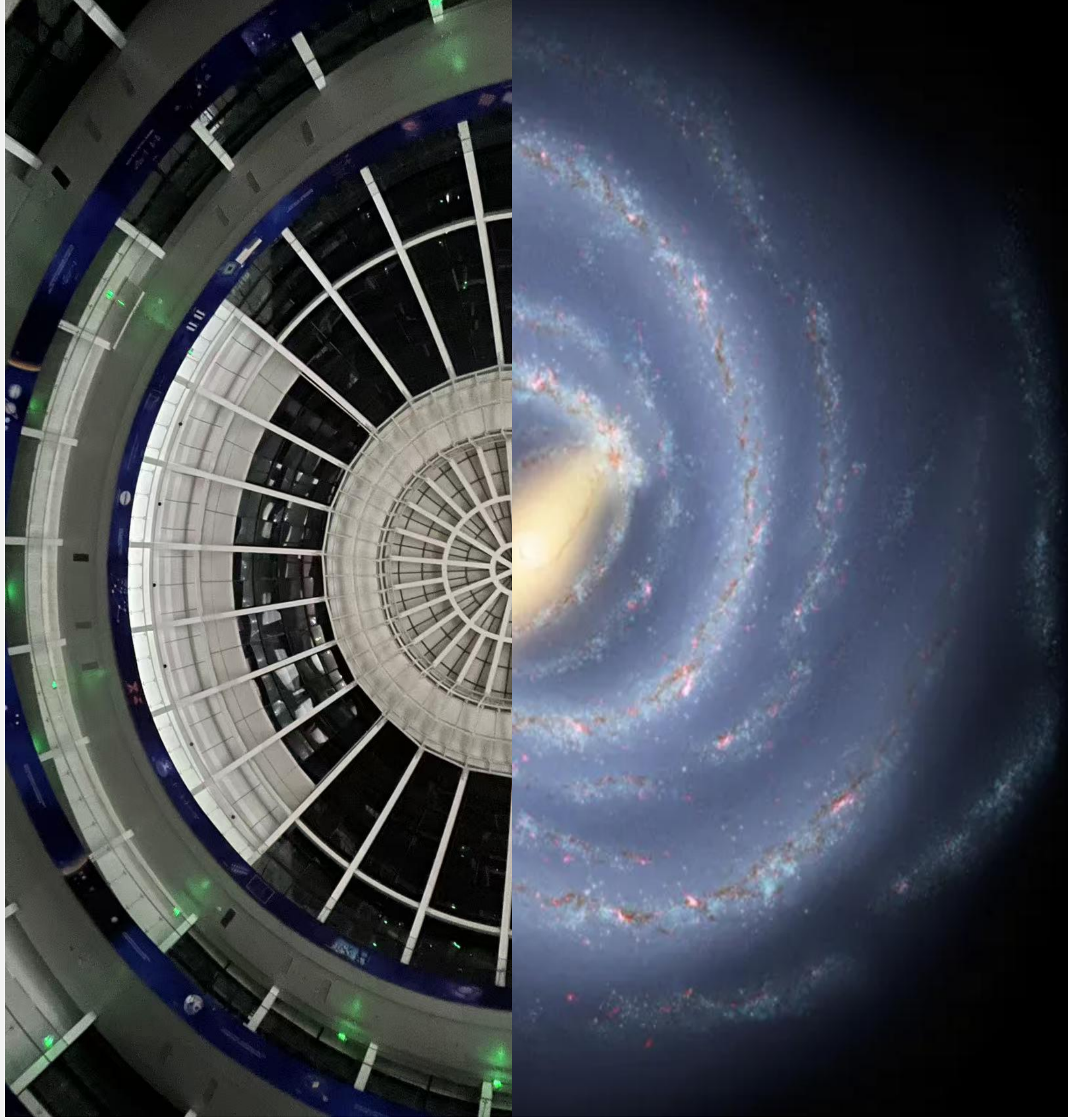


arXiv:2404.17352 [hep-ph], PRL 133 (2024) 12, 121802

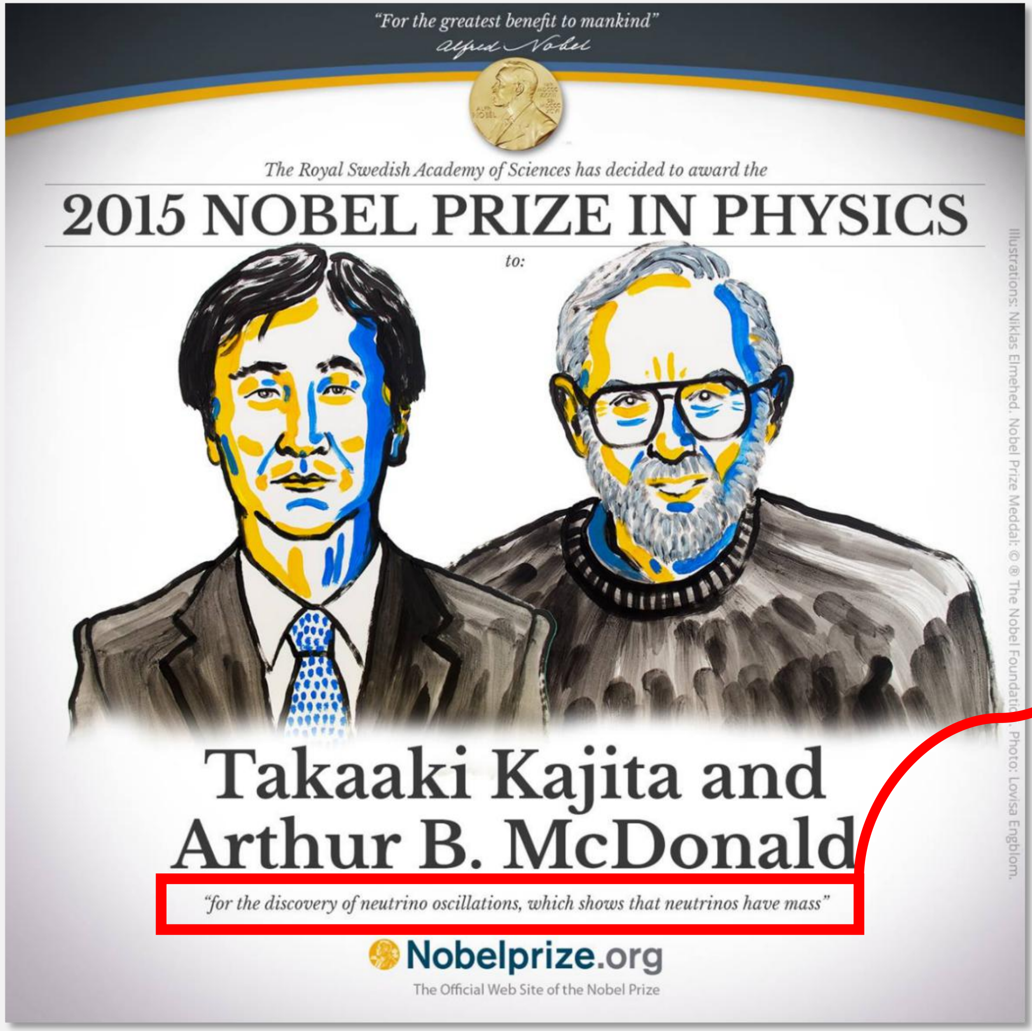
In collaboration with: Shao-Feng Ge & Alexei Y. Smirnov

李政道研究所
TSUNG-DAO LEE INSTITUTE

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

SPCS 2024 @ TDLI
Nov 13, 2024

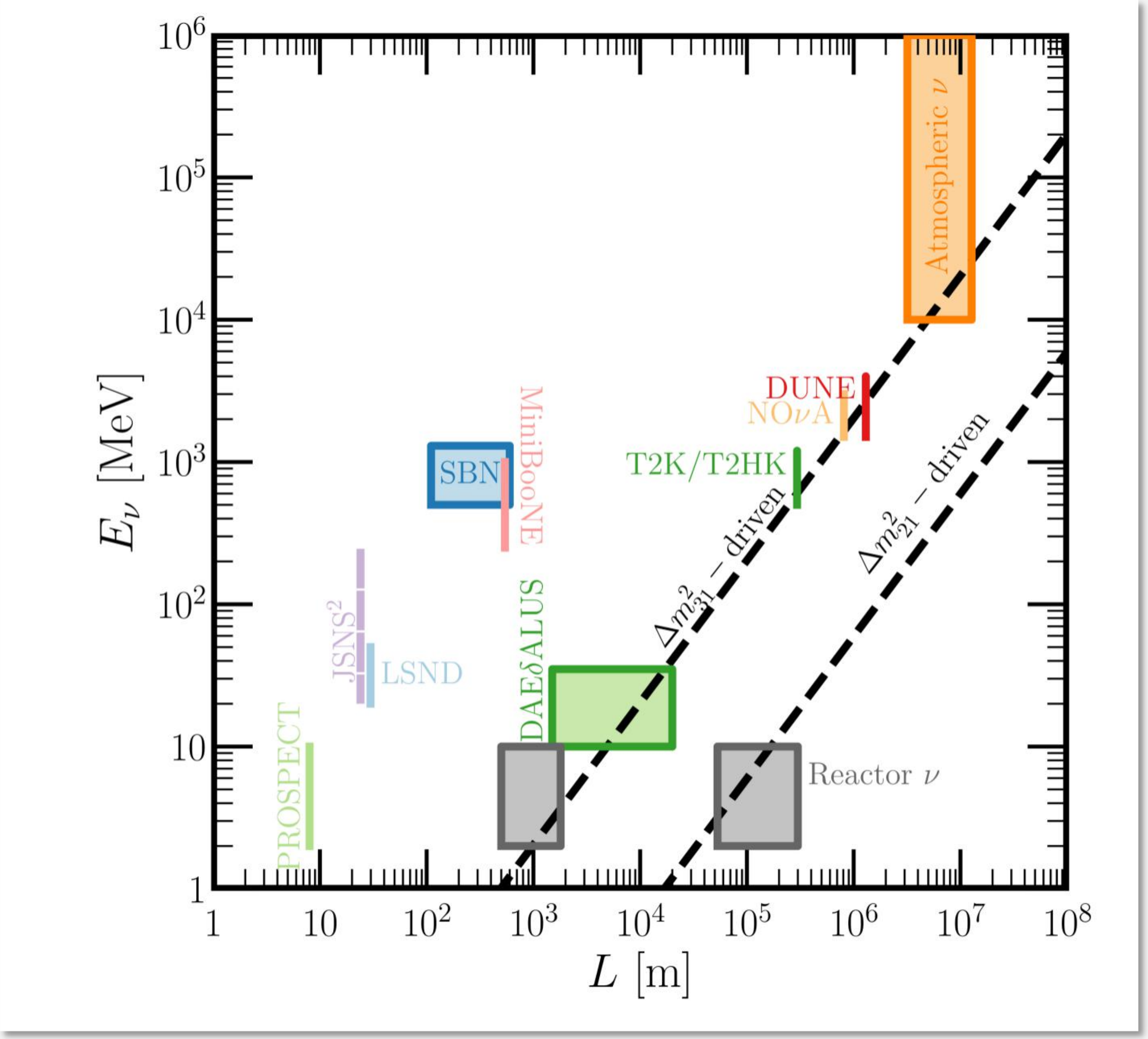
Evidence of Neutrino Mass



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

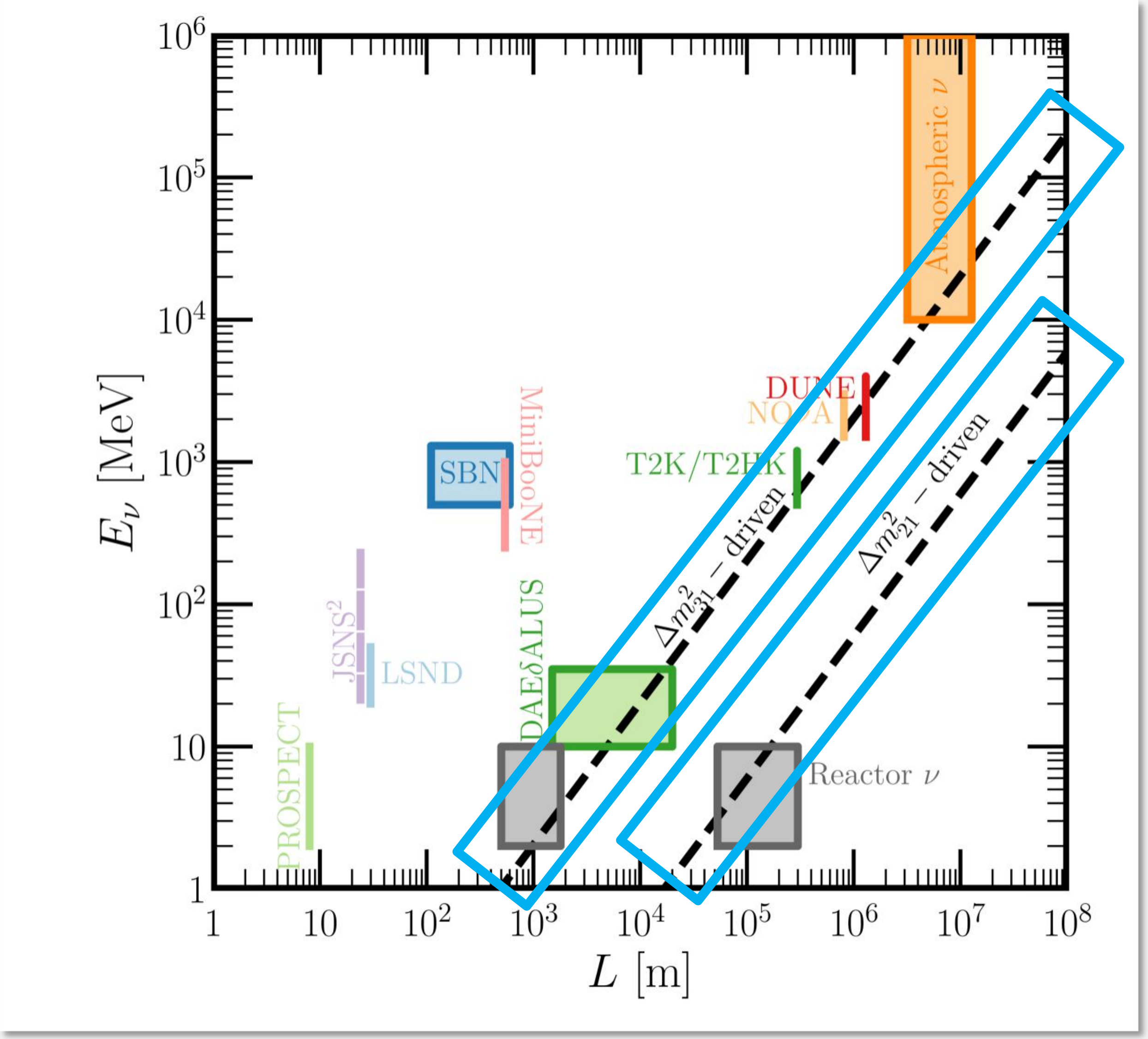
Evidence of Neutrino Mass

[see talks by Concha Gonzalez-Garcoa, Shun Zhou, Jun-Jie Jiang]



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

Evidence of Neutrino Mass

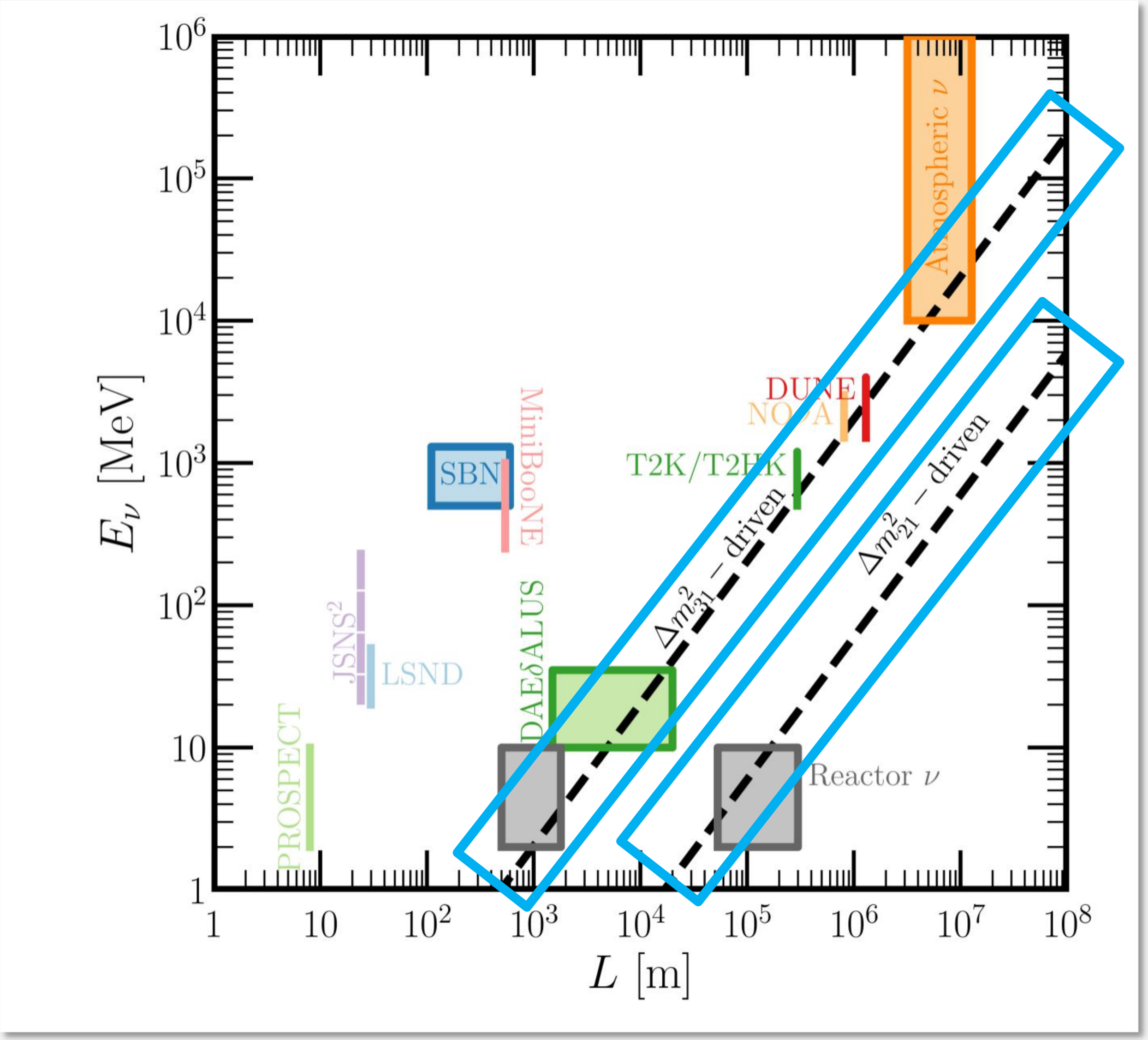


oscillation phase : $\propto \dfrac{\Delta m^2_{ij} L}{E_\nu}$

Neutrino masses drive the oscillation behavior !

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

Evidence of Neutrino Mass



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

Neutrino masses drive the oscillation behavior !

What's the origin of neutrino mass?

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

Neutrino Mass Origins

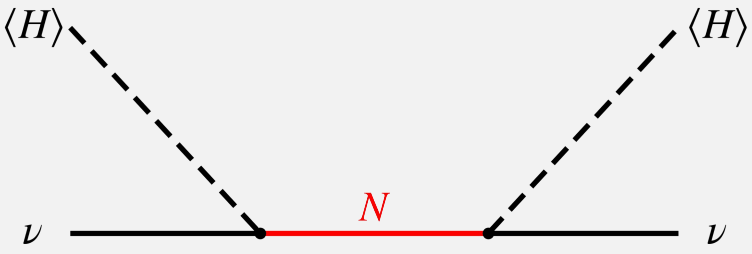
$$\underbrace{\text{vacuum neutrino mass} \qquad\qquad \text{dark neutrino mass}}_{\text{Neutrino mass origins}}$$

Neutrino Mass Origin I: vacuum mass

[see talk by Shun Zhou]

Vacuum Neutrino Mass

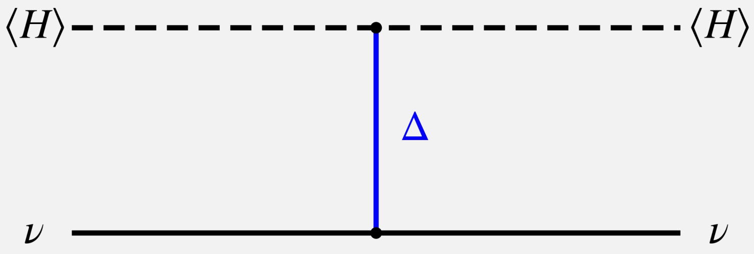
Type-I seesaw



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

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

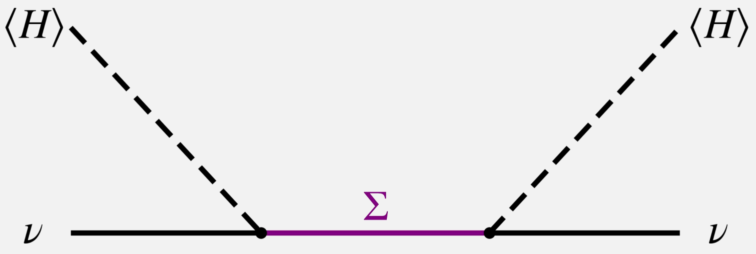
Type-II seesaw



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

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

Type-III seesaw



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

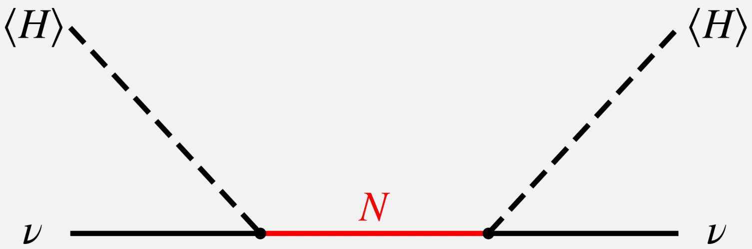
R. Foot, H. Lew, X.-G. He, & G.C. Joshi
E. Ma
...

•••

Neutrino Mass Origin I: vacuum mass

Vacuum Neutrino Mass

Type-I seesaw



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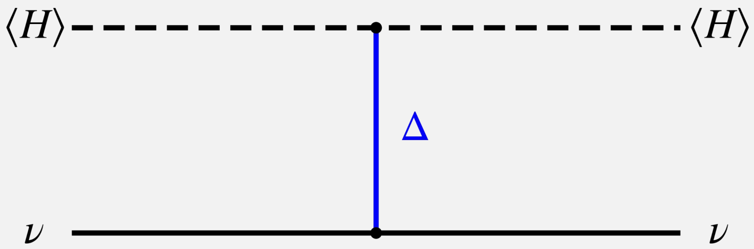

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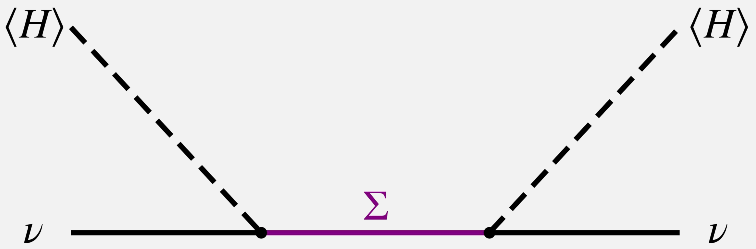

$$M_\nu = -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T$$

•••

$$m^2_{\text{vac}} = A$$

Neutrino Mass Origin II: dark mass

neutrino oscillation

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

Neutrino Mass Origin II: dark mass

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

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

Neutrino Mass Origin II: dark mass

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

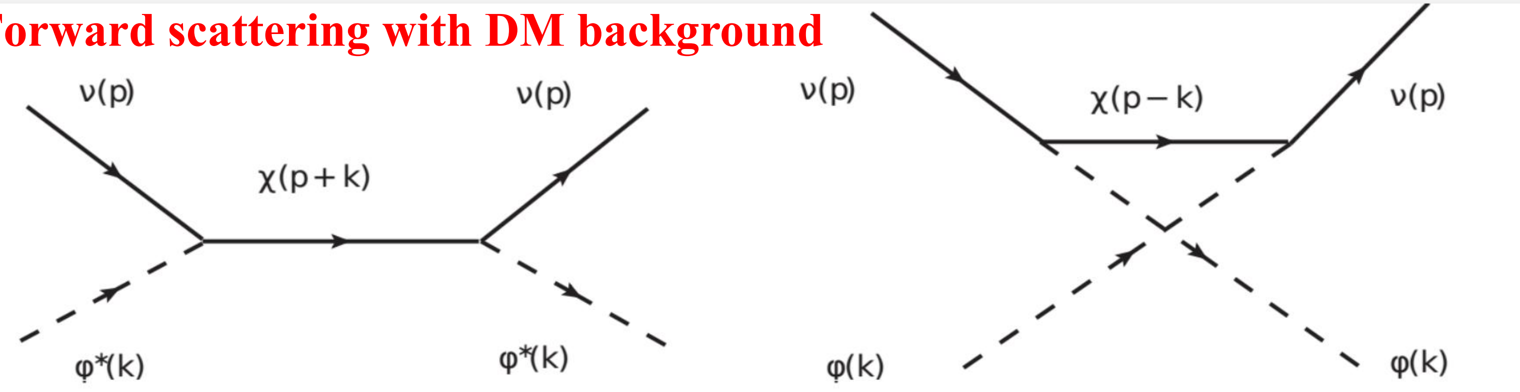
$$H \approx p + V, \quad \text{with } V = \frac{\boxed{\ldots}}{2E}$$

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

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

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

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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

[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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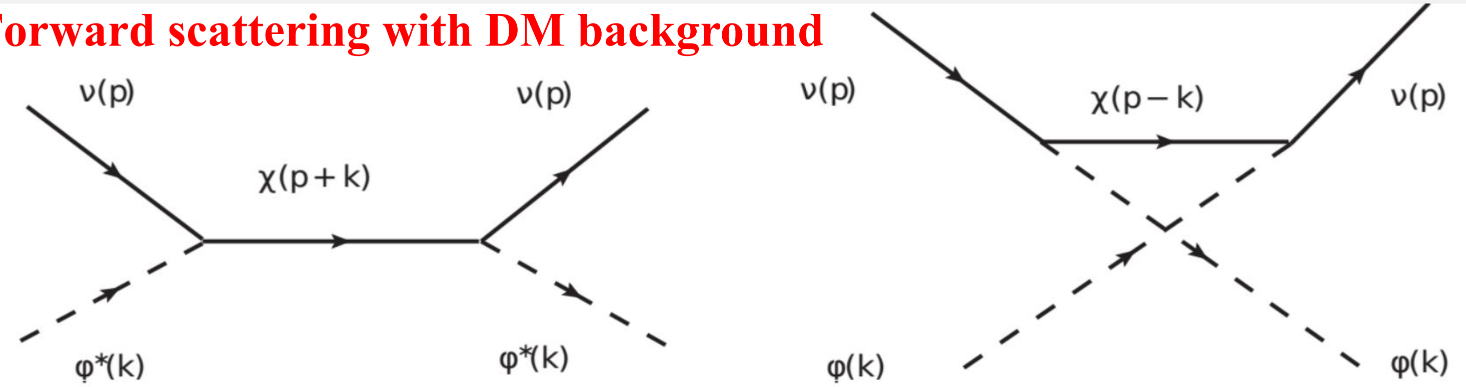

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A. Y. Smirnov, talks@MAYORANA Workshop

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

Neutrino Mass Origins Comparison

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

vs.

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

Neutrino Mass Origins Comparison

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

vs.

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

Can we distinguish these two origins ?

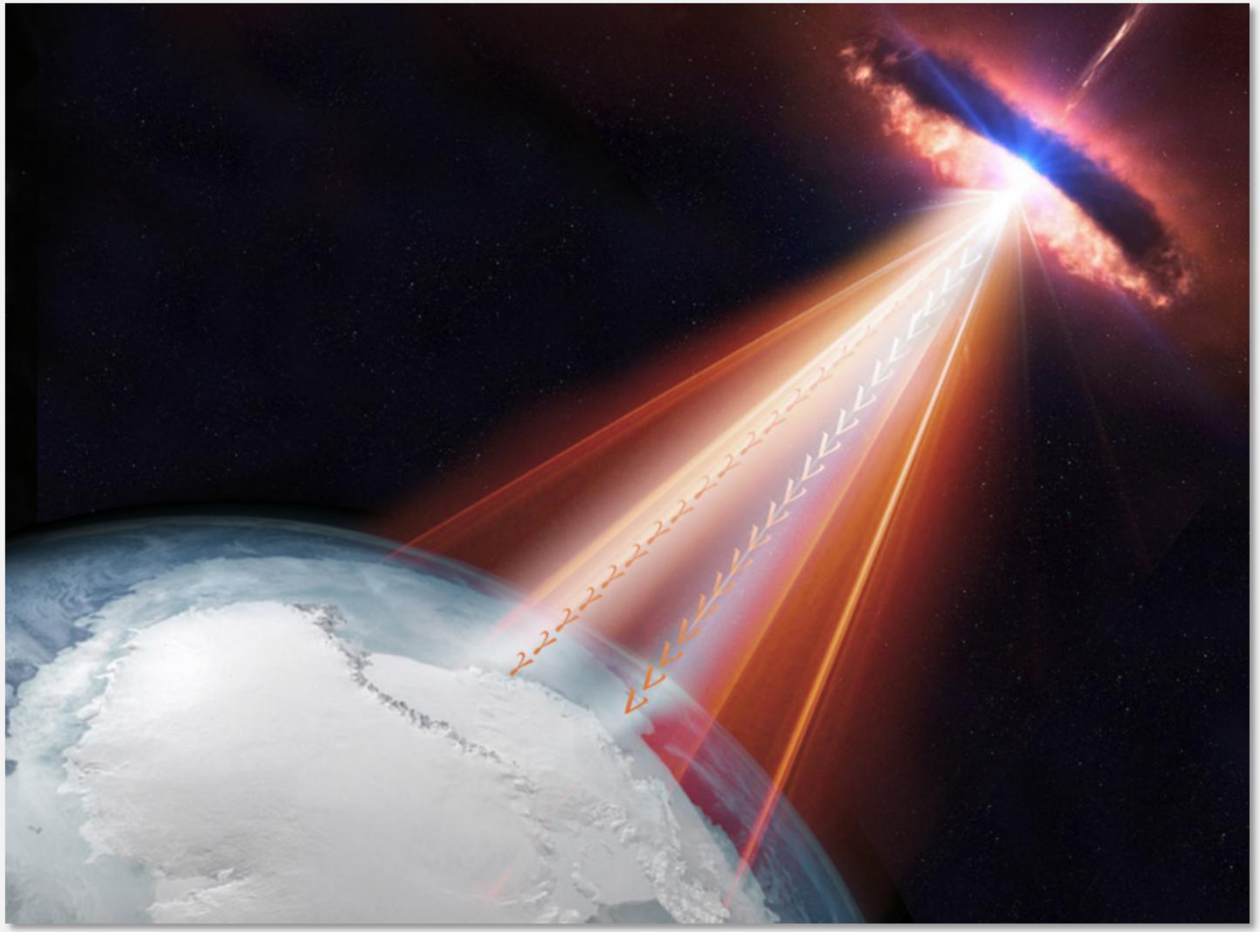
Large Scales

Yes! Look into larger scales!

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

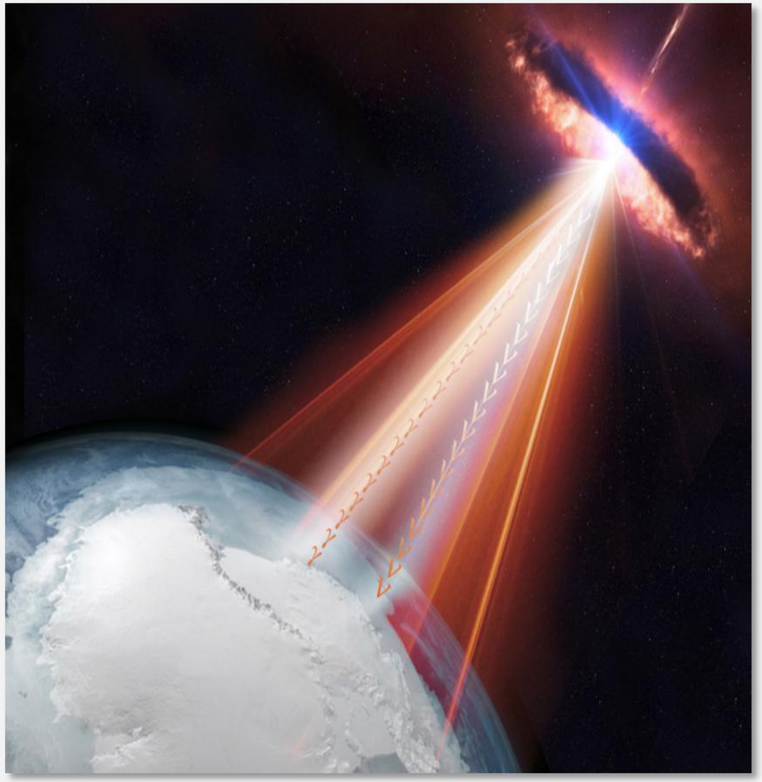
vs.

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



Credit: IceCube

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)

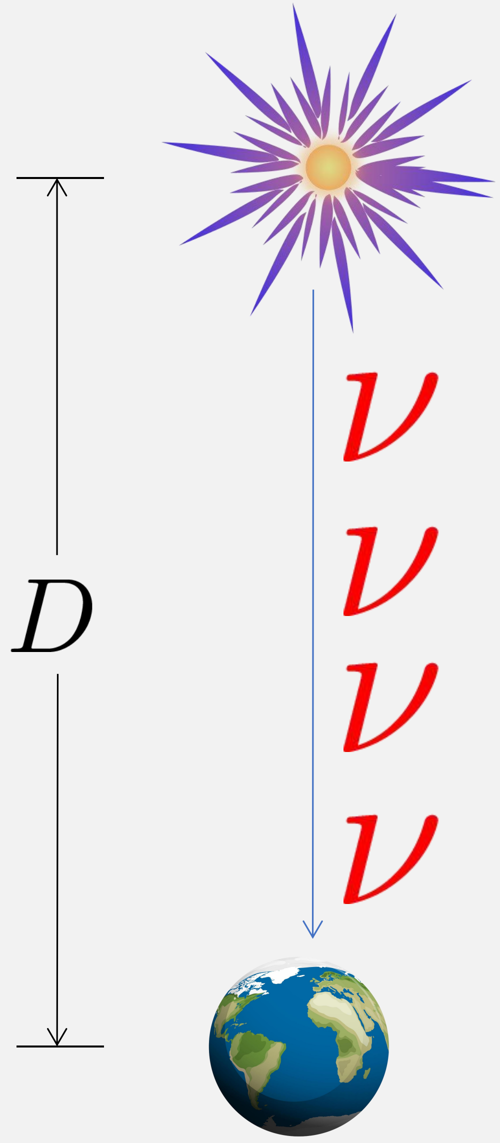
56 years ago!

[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

[see talk by Yu-Feng Li]

Supernova Neutrino Time Delay (vacuum neutrino mass)

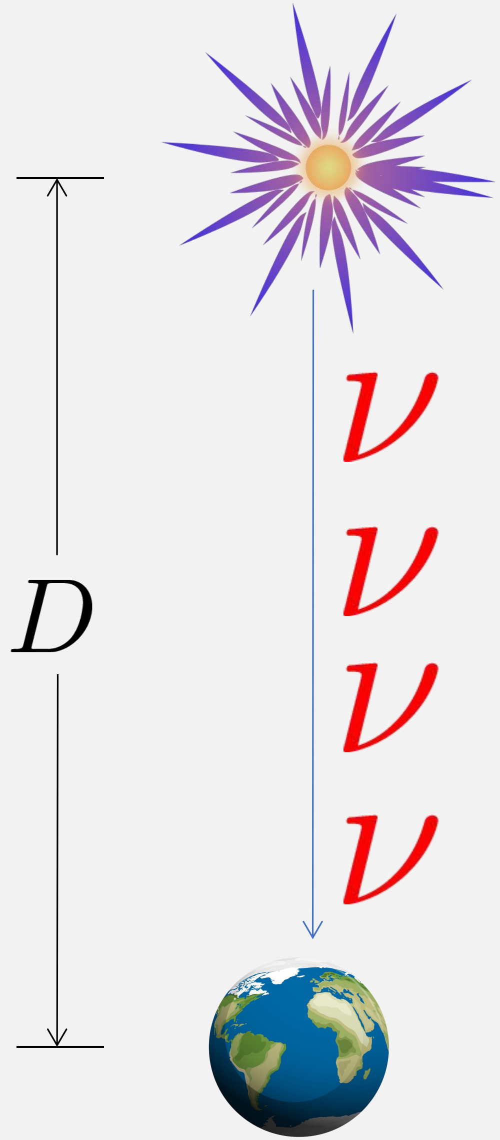


$$E_\nu = \sqrt{p_\nu^2 + m^2}, \quad v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

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

Supernova Neutrino Time Delay (vacuum neutrino mass)



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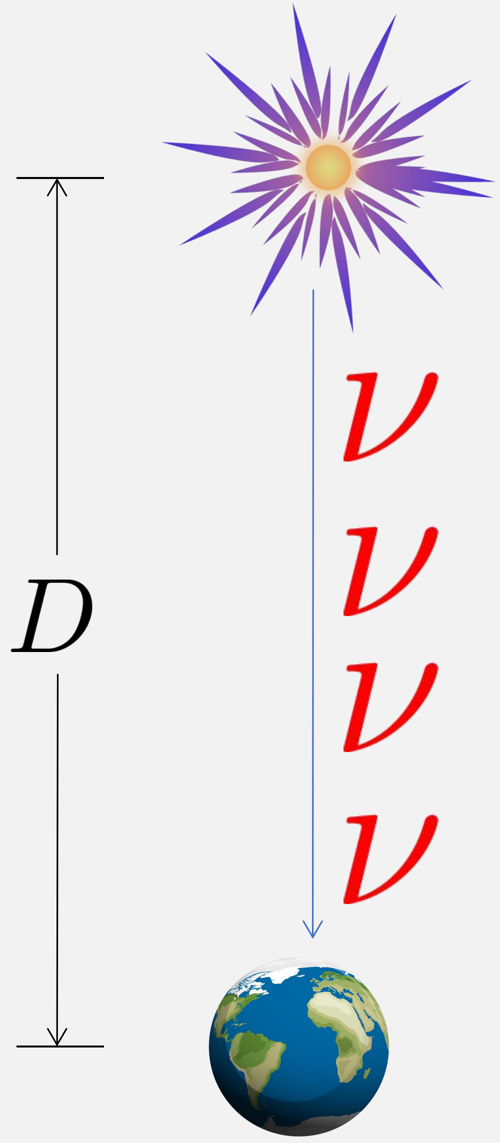
smaller than the speed of light

&

space-time independent

Supernova Neutrino Time Delay (vacuum neutrino mass)



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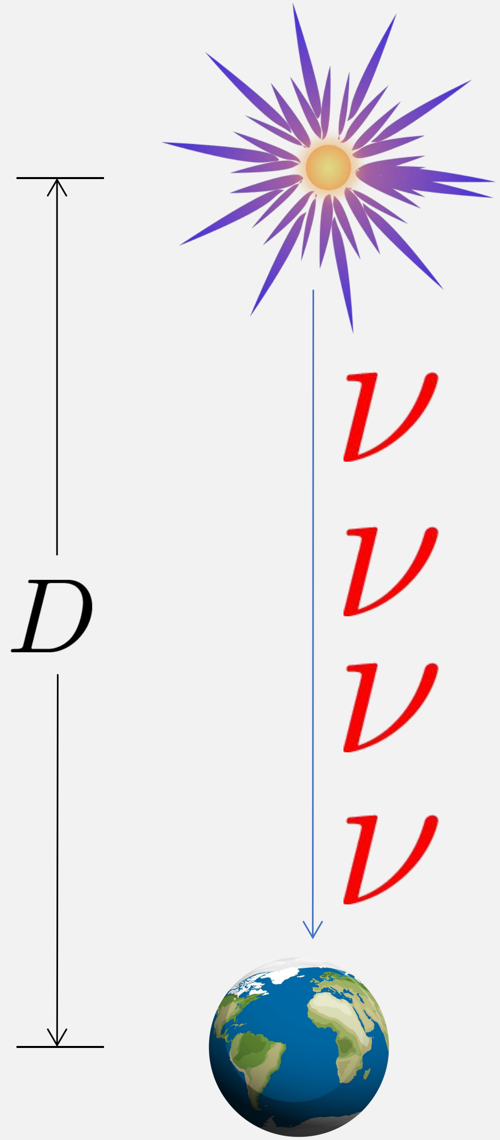
time delay:

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

Supernova Neutrino Time Delay (vacuum neutrino mass)



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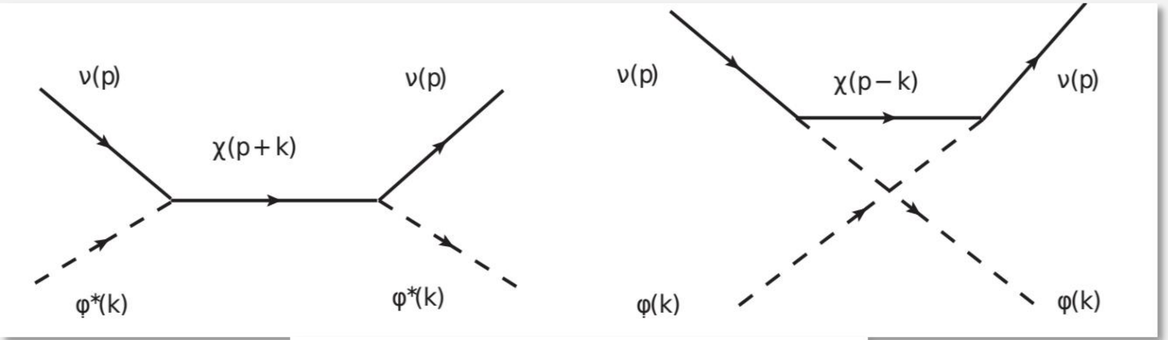
Supernova Neutrino Time Delay (dark neutrino mass)

Recall



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Supernova Neutrino Time Delay (dark neutrino mass)

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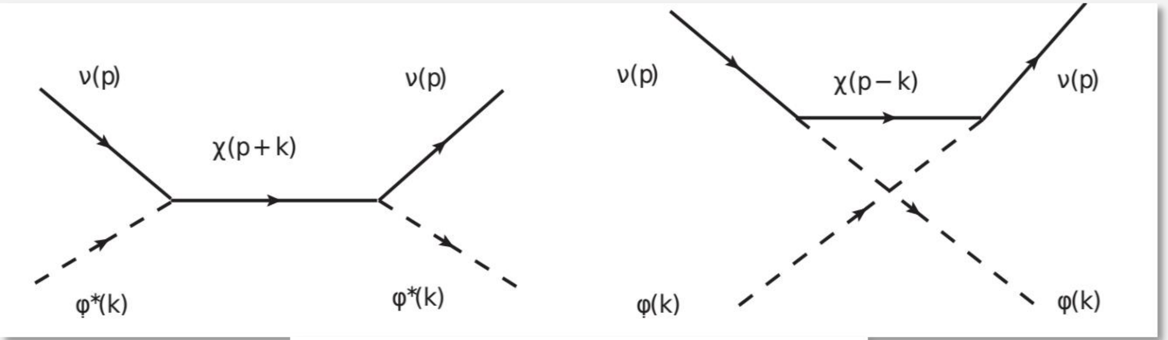

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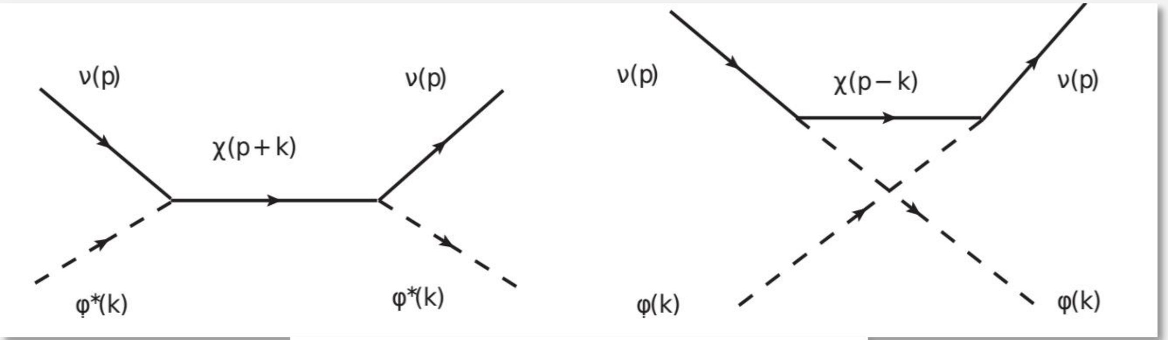

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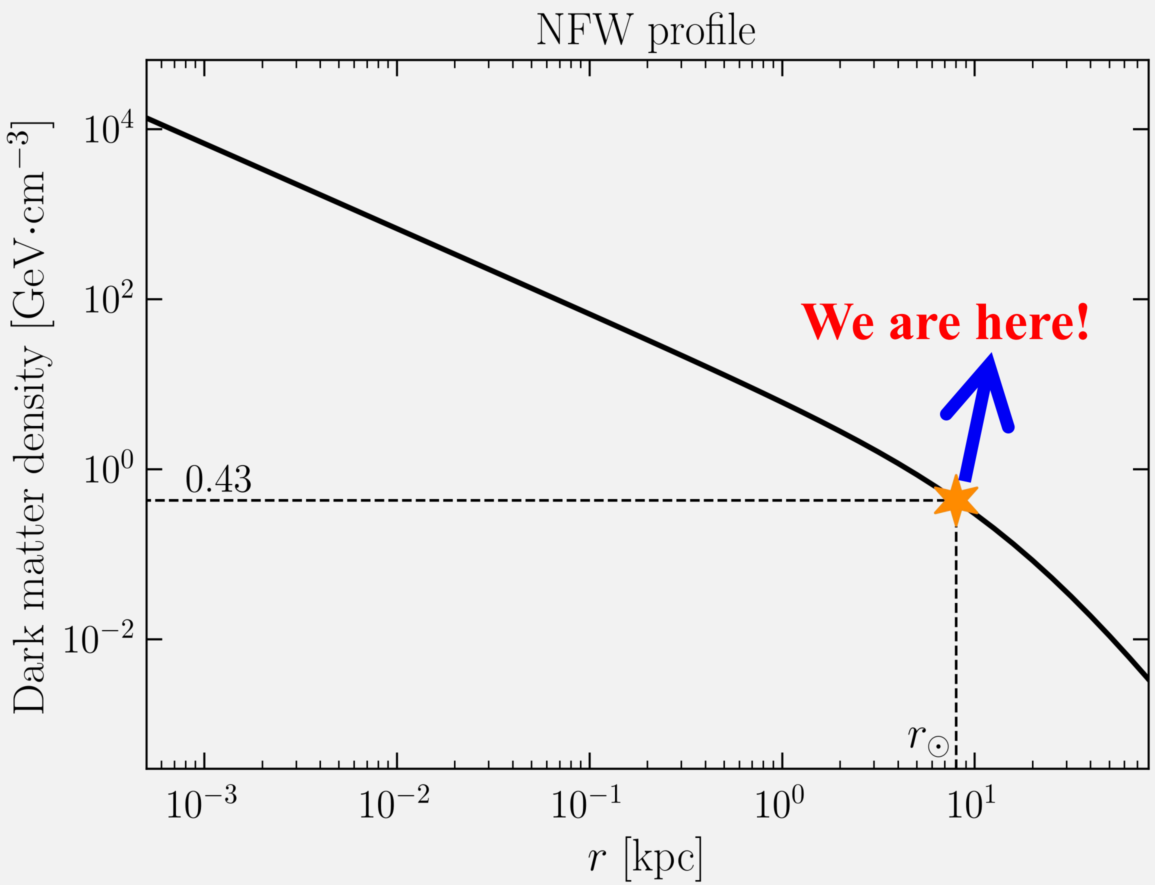
space-time dependent!

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

Supernova Neutrino Time Delay (dark neutrino mass)



Navarro-Frenk-White profile

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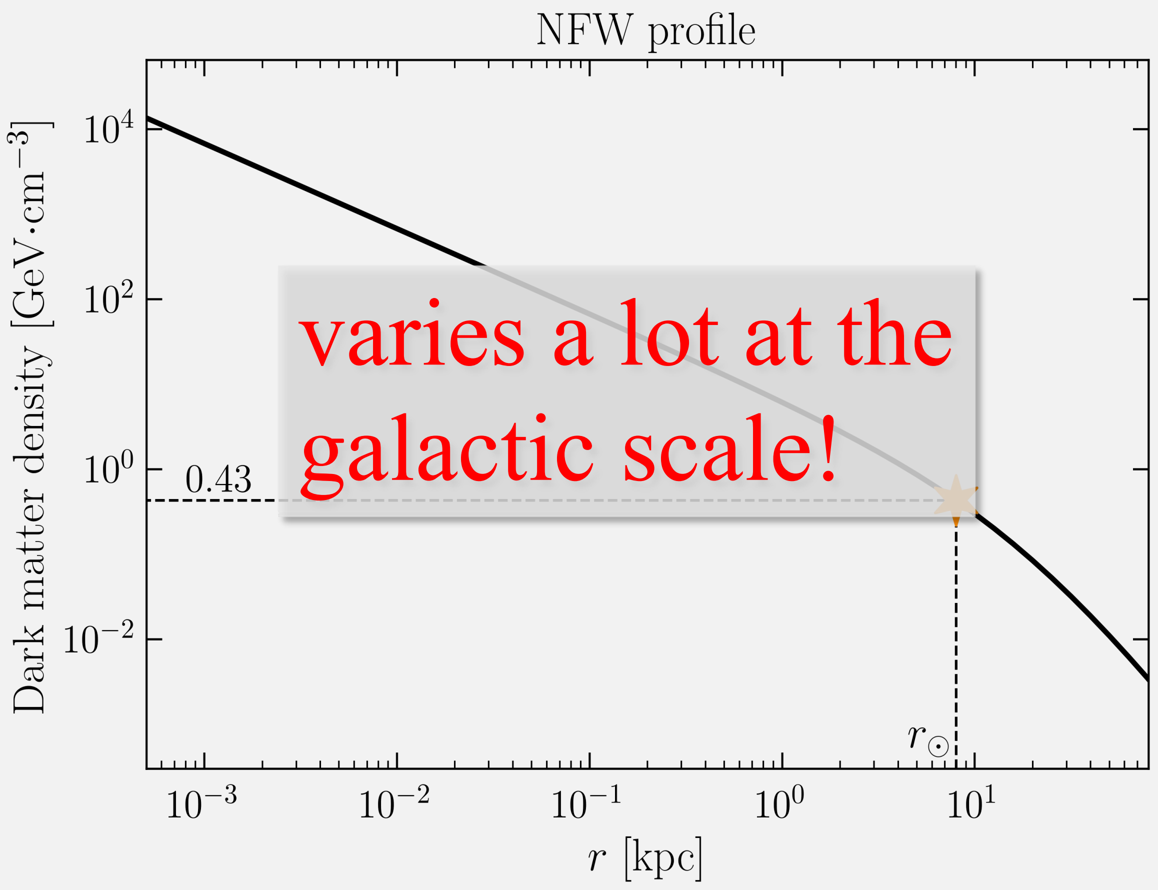
Supernova Neutrino Time Delay (dark neutrino mass)



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

Supernova Neutrino Time Delay (dark neutrino mass)

...

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

just an integration over neutrino trajectory

Supernova Neutrino Time Delay (dark neutrino mass)

…

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

vacuum neutrino mass   differed by this factor!

Supernova Neutrino Time Delay (dark neutrino mass)

...

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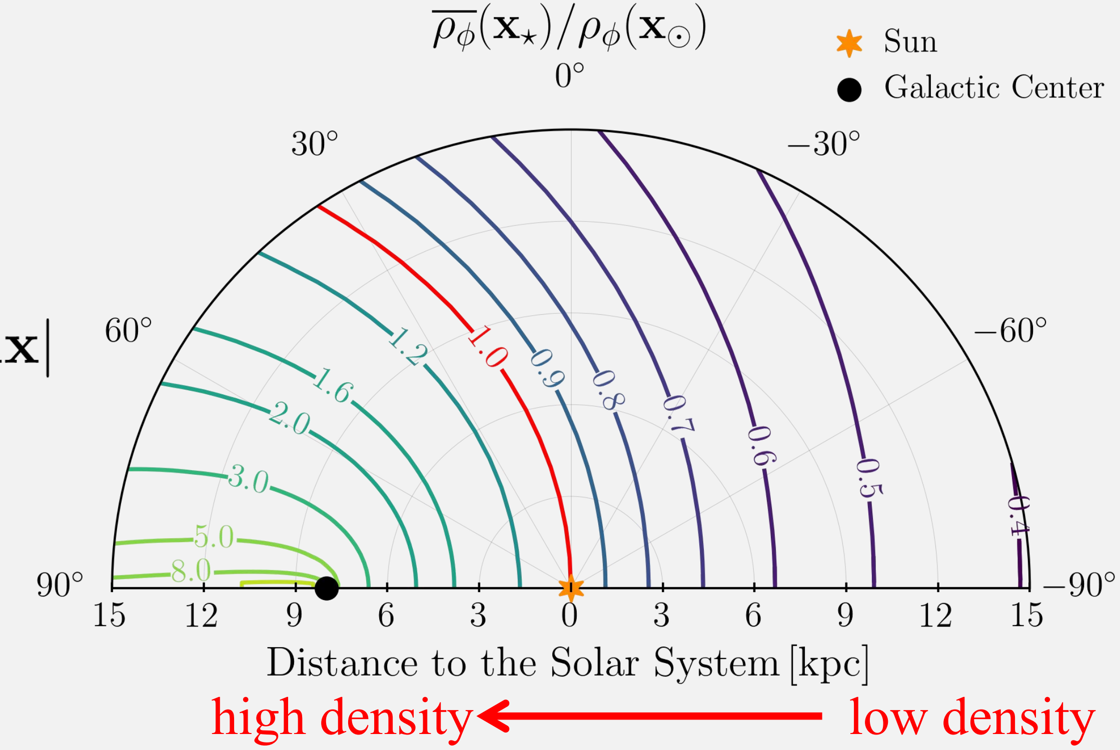
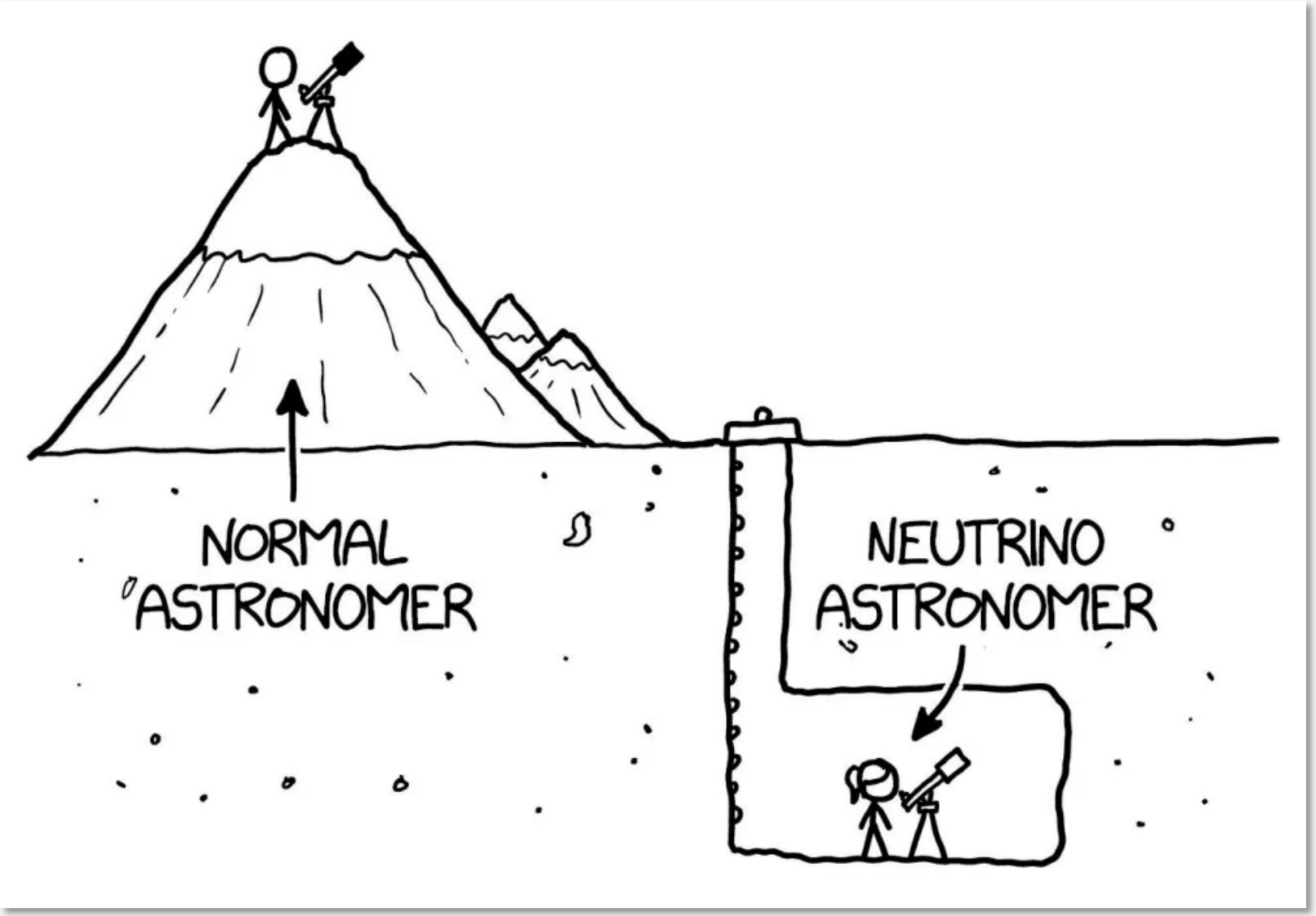


*Ge, **CFK**, Smirnov*
arXiv: 2404.17352

Experimental Sensitivity



credit: PHYSICSGG

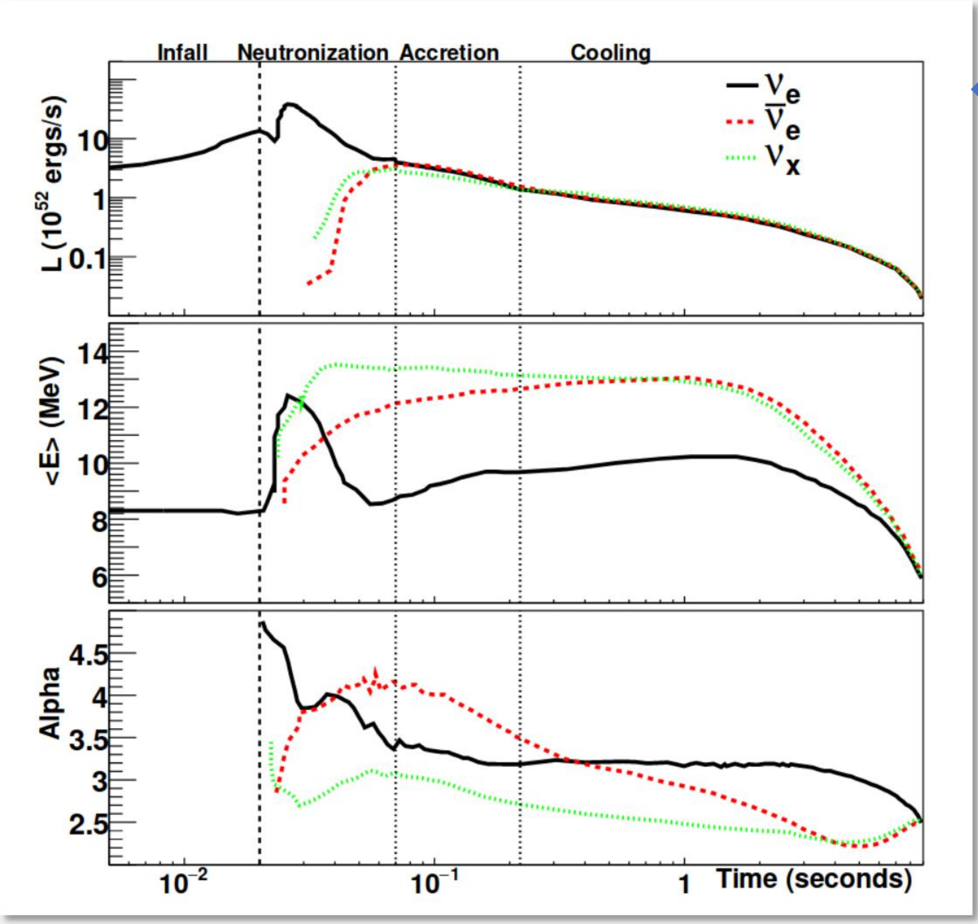
Supernova Neutrino Production

- 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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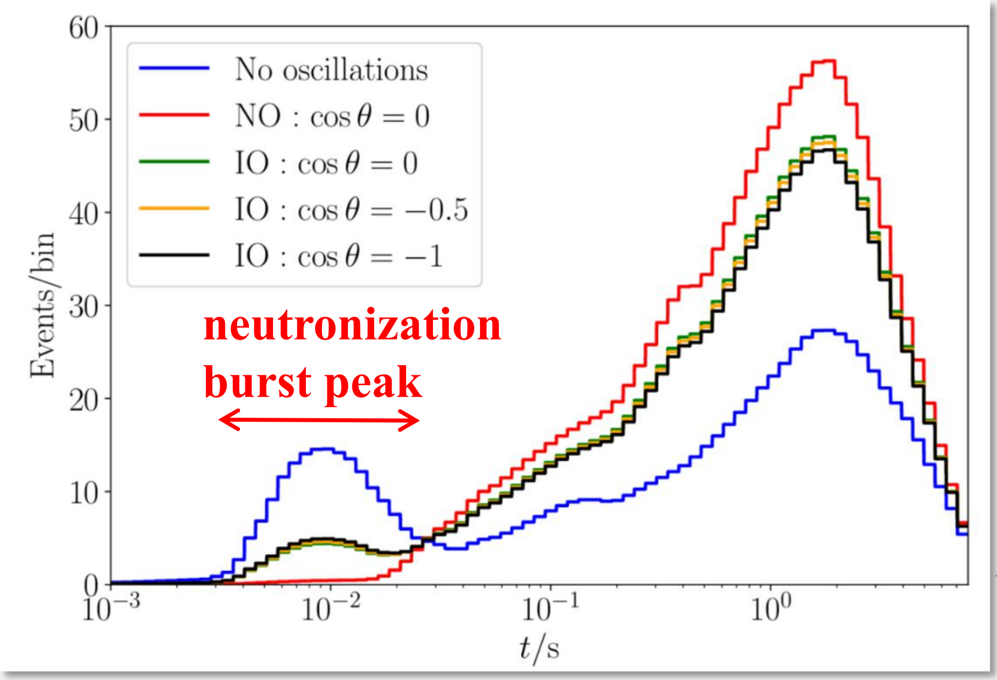
Supernova Neutrino Production

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):

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

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

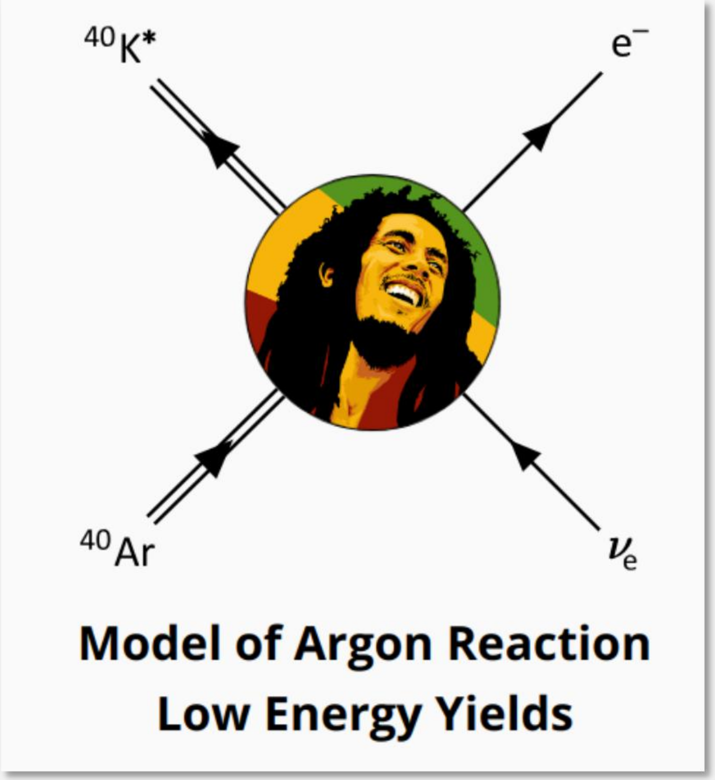
$$p \approx |U_{e2}|^2 \approx \sin^2\theta_{12}, \mathrm{IO}$$

$[\sin^2\theta_{13} \approx 0.022, \sin^2\theta_{12} \approx 0.3]$

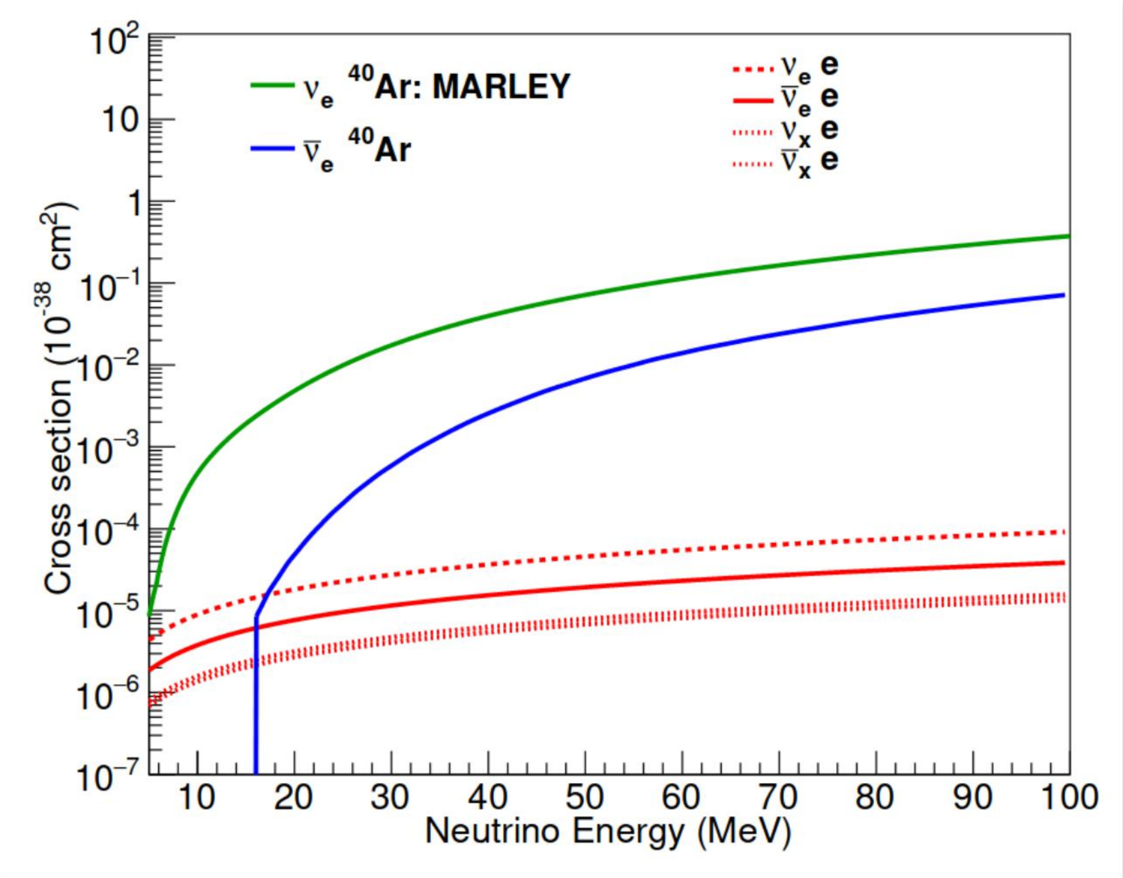
Supernova Neutrino Detection @ DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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



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

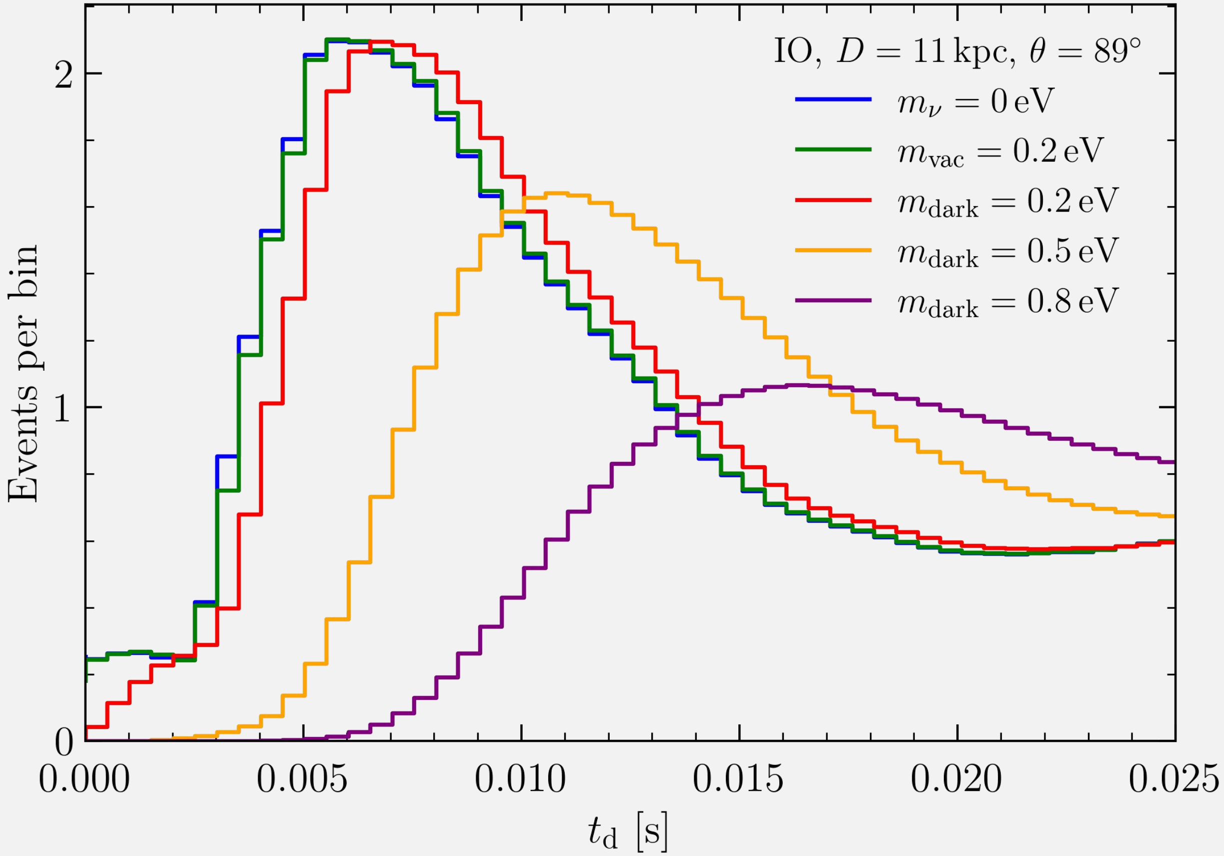
A : target nucleon number

σ_{ν_e} : cross section

ϵ : efficiency]

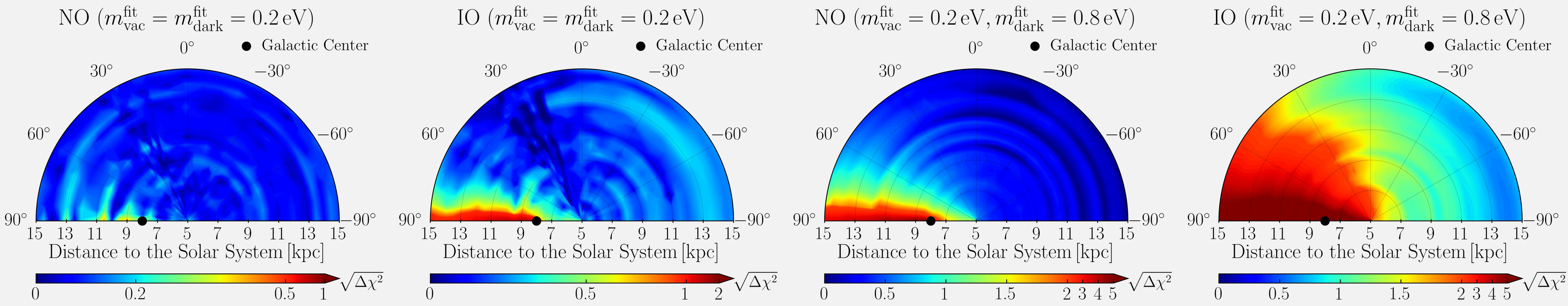
❖ The time distribution becomes wider as the neutrino mass increases

energy integrated out



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

Sensitivities



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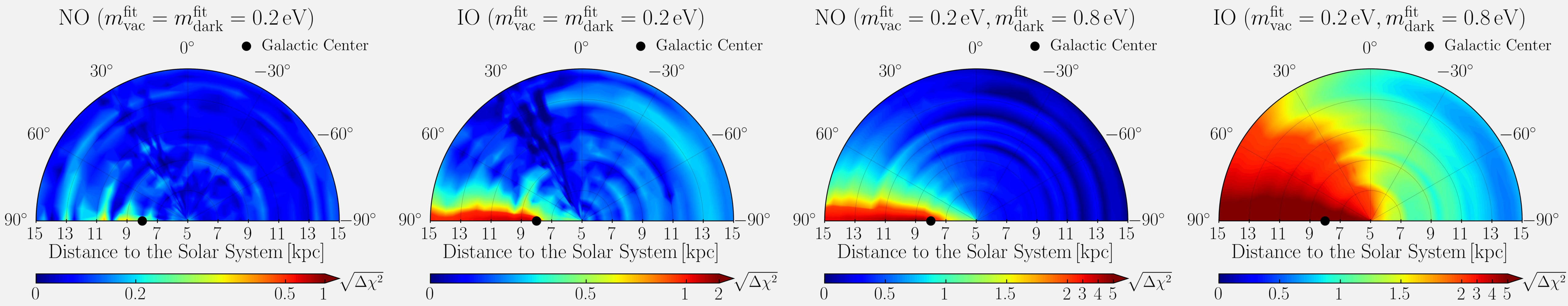

❖ The sensitivity is enlarged by measuring supernova neutrinos around the galaxy center

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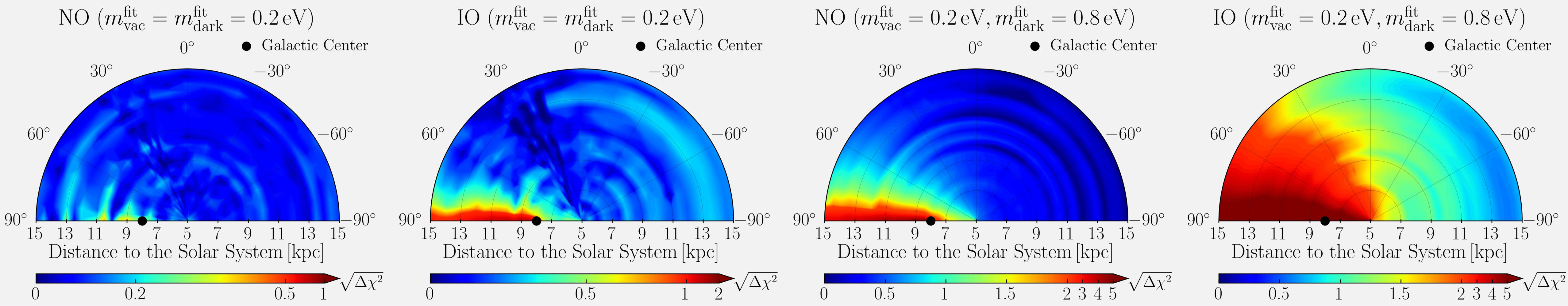
Sensitivities



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

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

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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

Summary

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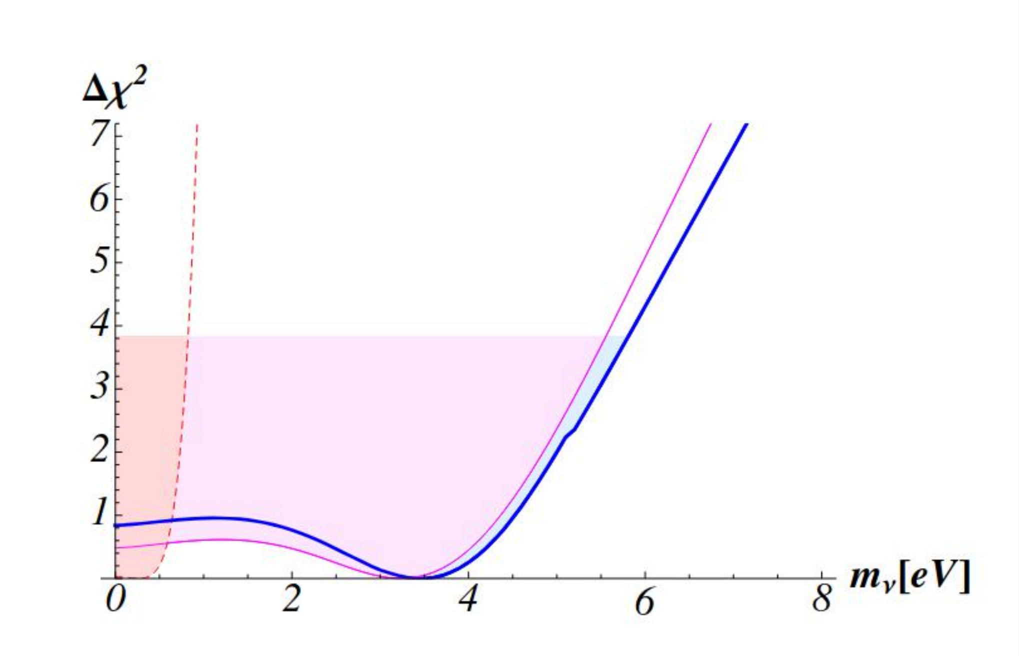
Thank you for your attention!

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