Supernovae as Laboratories for BSM

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Based on:

arXiv: 2404.17352 [Phys.Rev.Lett. 133 (2024) 12, 121802]

w/ Shao-Feng Ge (TDLI & SJTU), Alexei Y. Smirnov (MPIK)

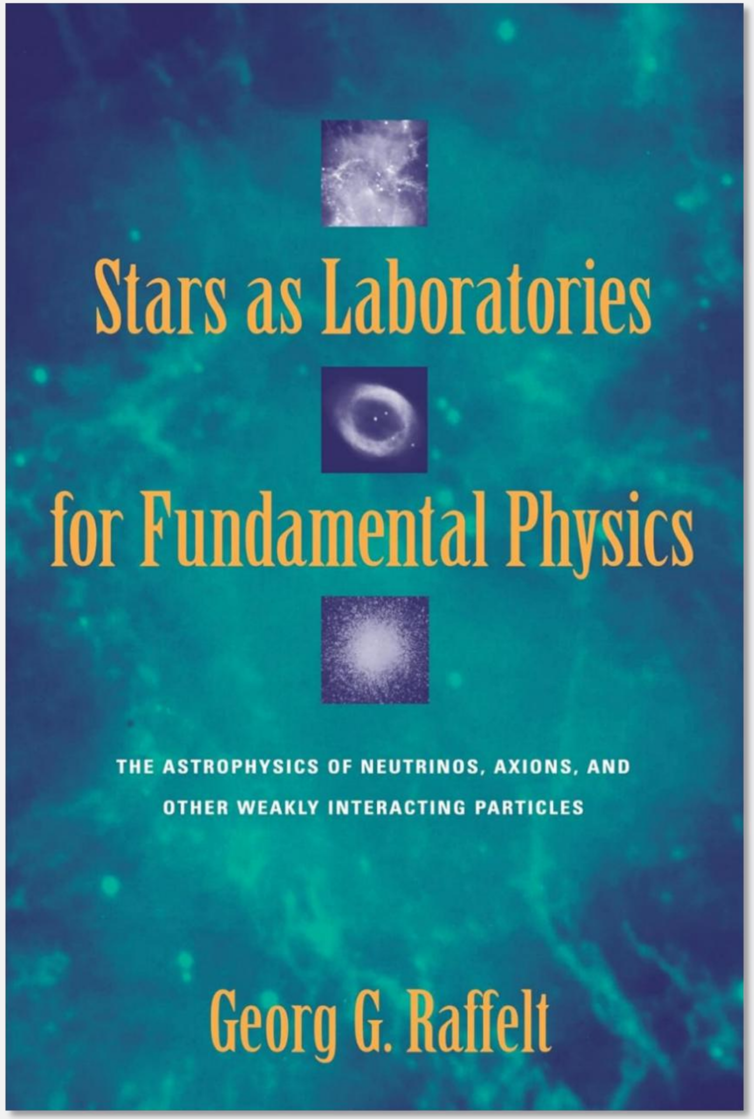
arXiv: 2603.09615 [Phys.Rev.Lett. 137 (2026) 11, 111005] + 2609.18247

w/ Yu Cheng (KAIST & U. Chicago), Yen-Hsun Lin (Academia Sinica), Meng-Ru Wu (Academia Sinica), Seokhoon Yun (KNU & IBS)

Institute for Basic Science

Brookhaven HET Seminar

Sep 17, 2026



Preface

400 years ago: fundamental laws of physics

Ever since Newton proposed that the moon on its orbit follows the same laws of motion as an apple falling from a tree, the heavens have been a favorite laboratory to test the fundamental laws of physics, notably classical mechanics and Newton's and Einstein's theories of gravity. This tradition carries on—the 1993 physics Nobel prize was awarded to R. A. Hulse and J. H. Taylor for their 1974 discovery of the binary pulsar PSR 1913+16 whose measured orbital decay they later used to identify gravitational wave emission. However, the scope of physical laws necessary to understand the phenomena observed in the super-lunar sphere has expanded far beyond these traditional fields. Today, astrophysics has become a vast playing ground for applications of the laws of *microscopic* physics, in particular the properties of elementary particles and their interactions.

Now: new physics

credit: G. Raffelt

Outline

I.

Testing neutrino mass orgins with supernova neutrinos

arXiv: 2404.17352 [Phys.Rev.Lett. 133 (2024) 12, 121802]

II.

Circumstellar medium of supernovae as new probes for FIPs

arXiv: 2603.09615 [Phys.Rev.Lett. 137 (2026) 11, 111005]

+

arXiv: 2609.18247

I.

Testing neutrino mass orgins with supernova neutrinos

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Evidence of neutrino mass from neutrino oscillation

Evidence of Neutrino Mass

Institute for Basic Science

oscillation $\longleftarrow$ interference $\longleftarrow$ phase difference $\longleftarrow$ different mass

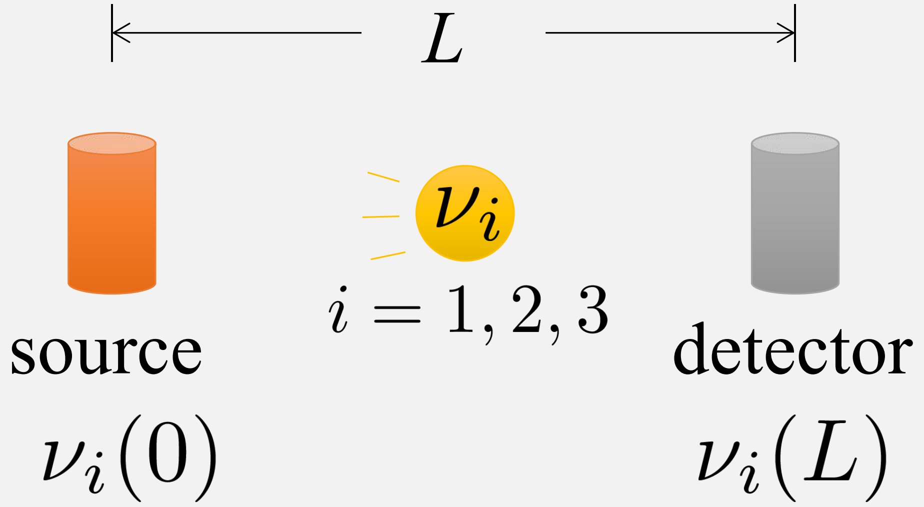
neutrino mass eigenstates:

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

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

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

$$\downarrow \quad \downarrow \quad \downarrow$$

$$1 \quad e^{-i\frac{\Delta m_{21}^2}{2E}L} \quad e^{-i\frac{\Delta m_{31}^2}{2E}L}$$

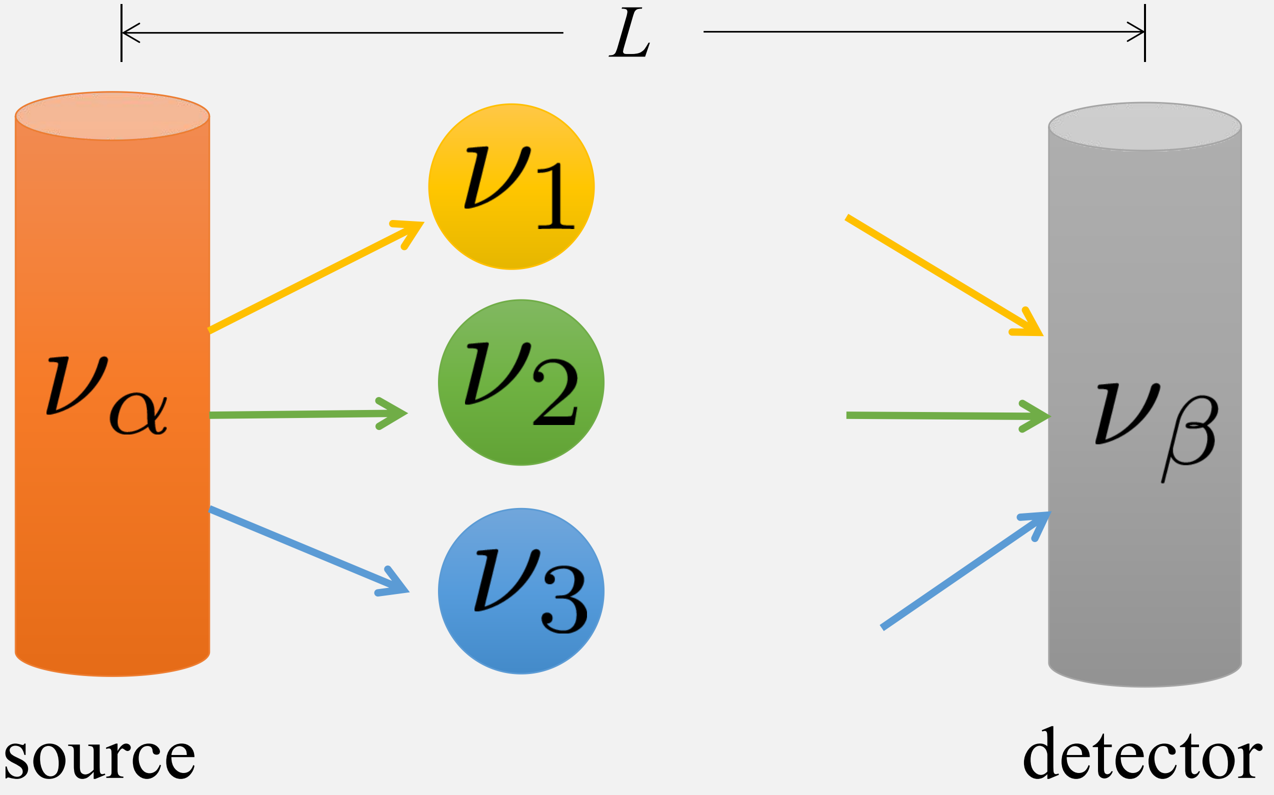
$[\Delta m_{21}^2 \equiv m_2^2 - m_1^2,$
$\Delta m_{31}^2 \equiv m_3^2 - m_1^2]$

Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

Mixing:

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

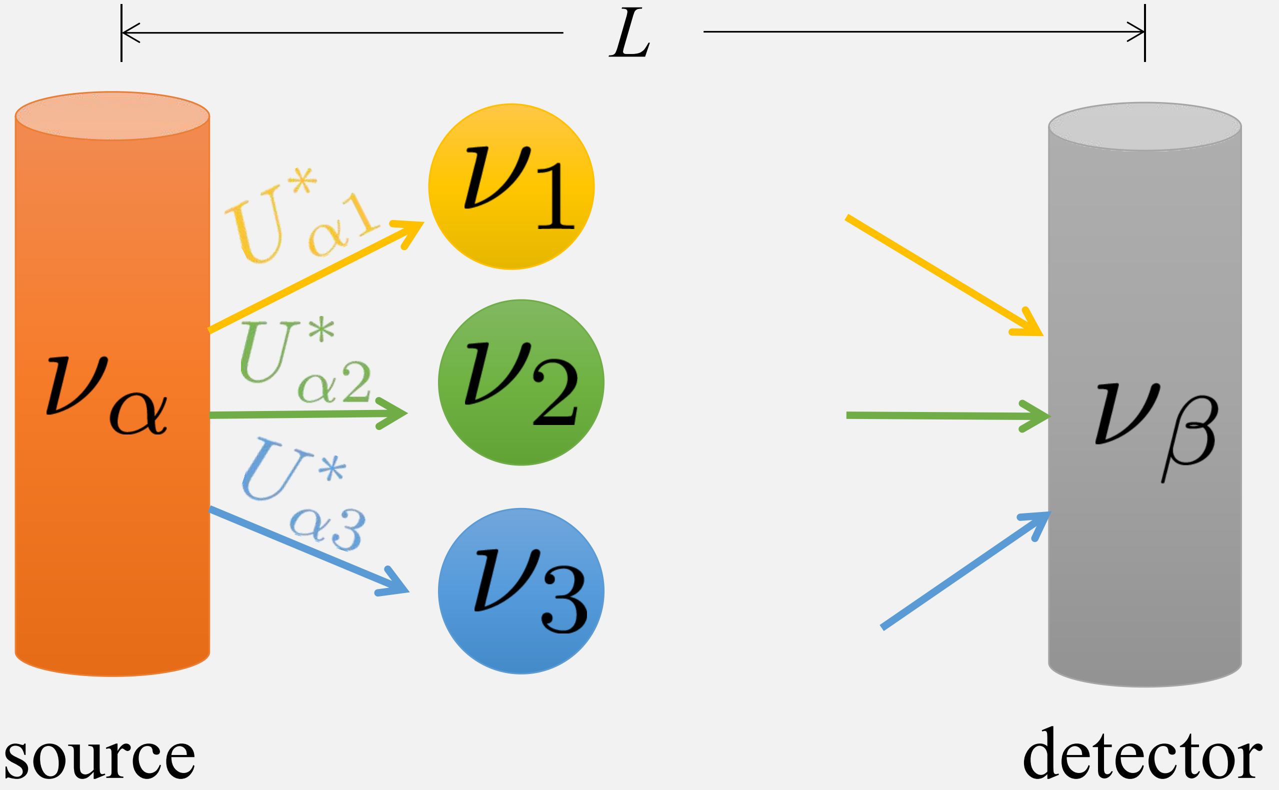


Evidence of Neutrino Mass

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

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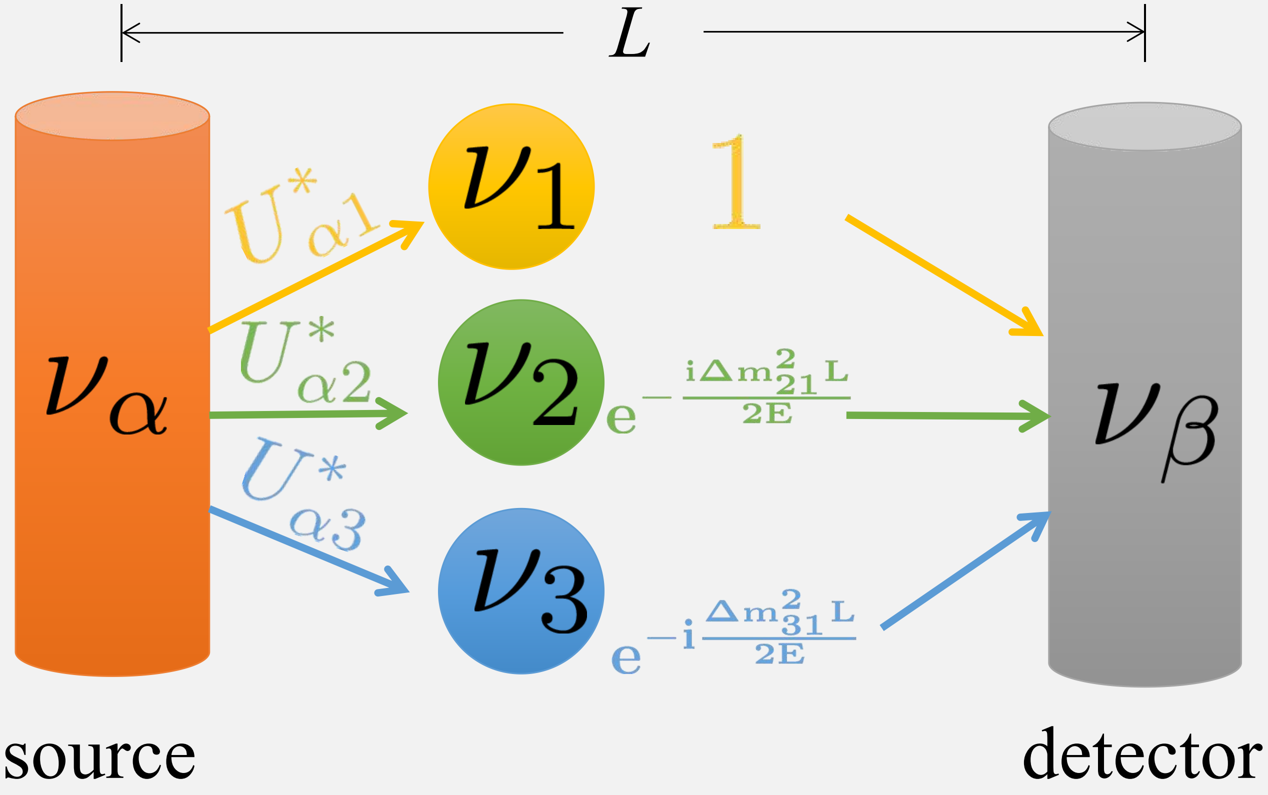
$$|\nu_\alpha\rangle = U^*_{\alpha 1}|\nu_1\rangle + U^*_{\alpha 2}|\nu_2\rangle + U^*_{\alpha 3}|\nu_3\rangle$$

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



Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

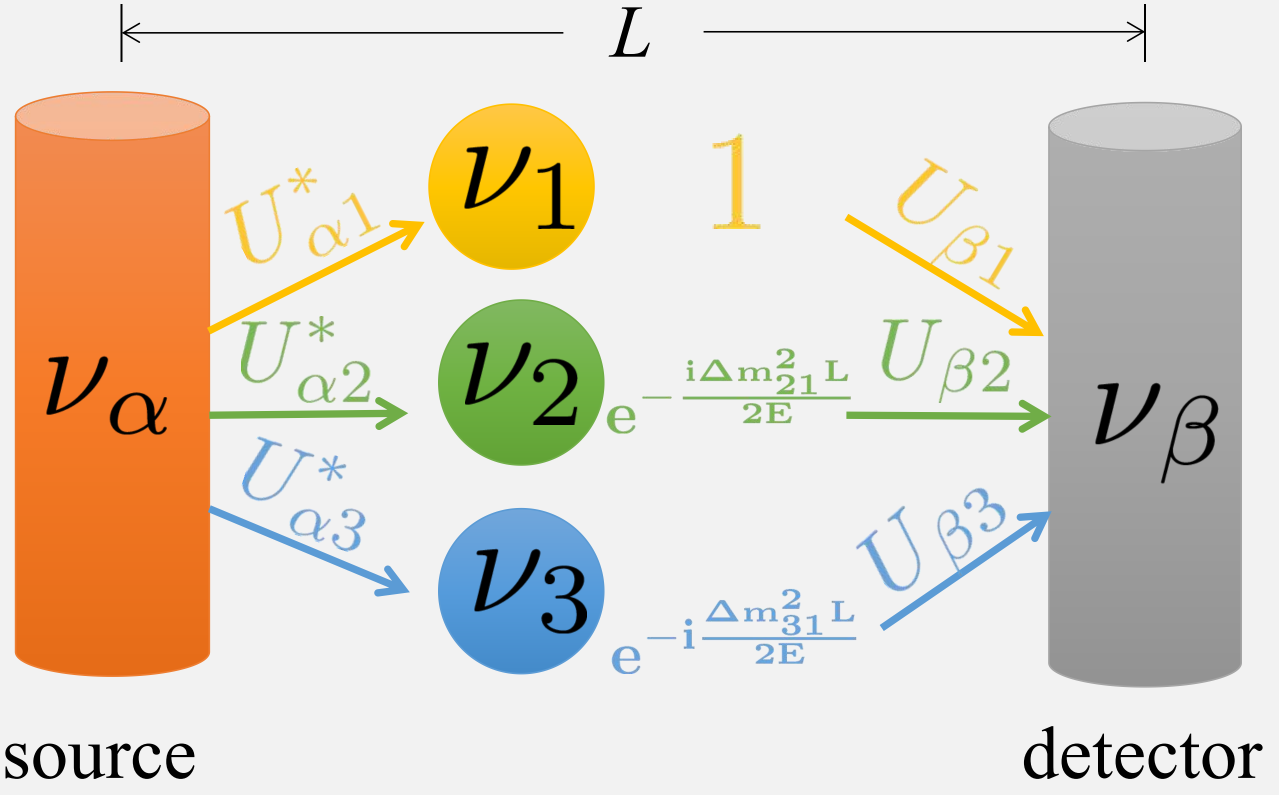
production:

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

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

detection:

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

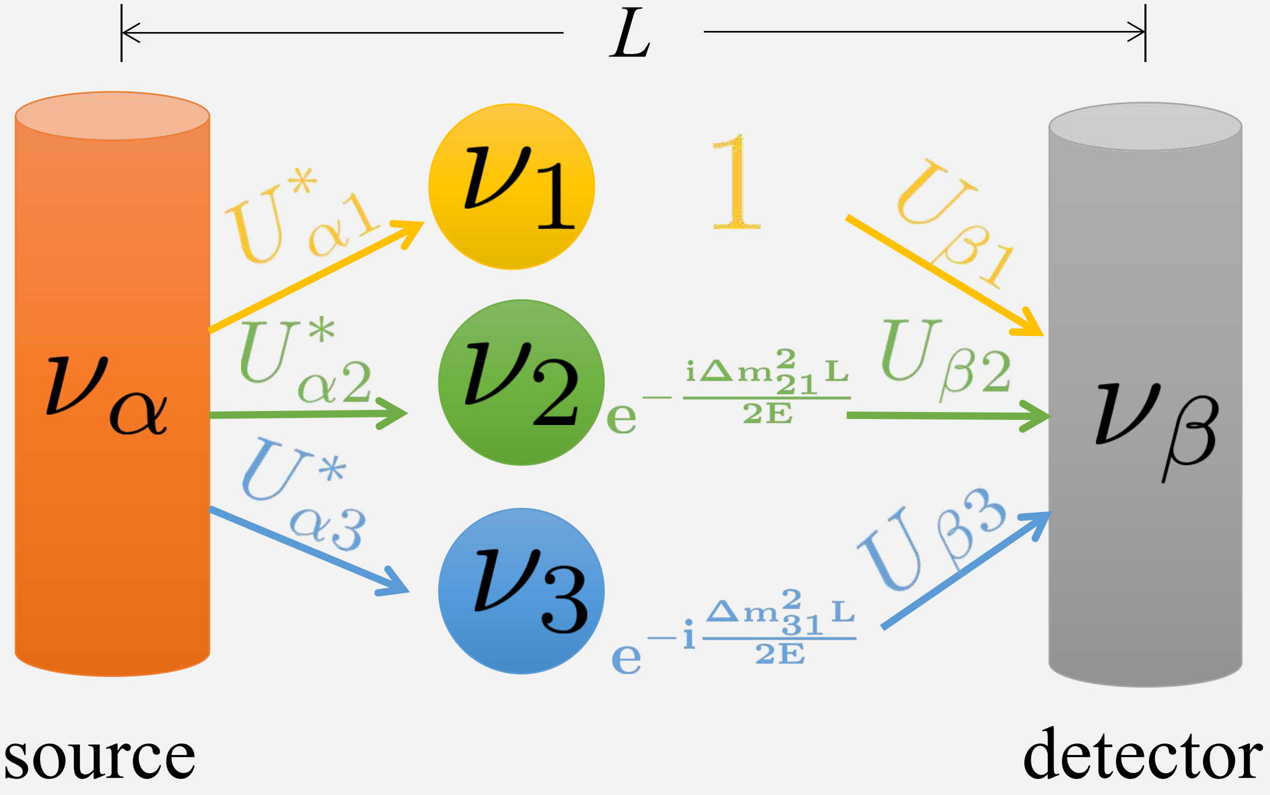


Evidence of Neutrino Mass

oscillation ← interference ← phase difference ← different mass

Oscillation amplitude

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

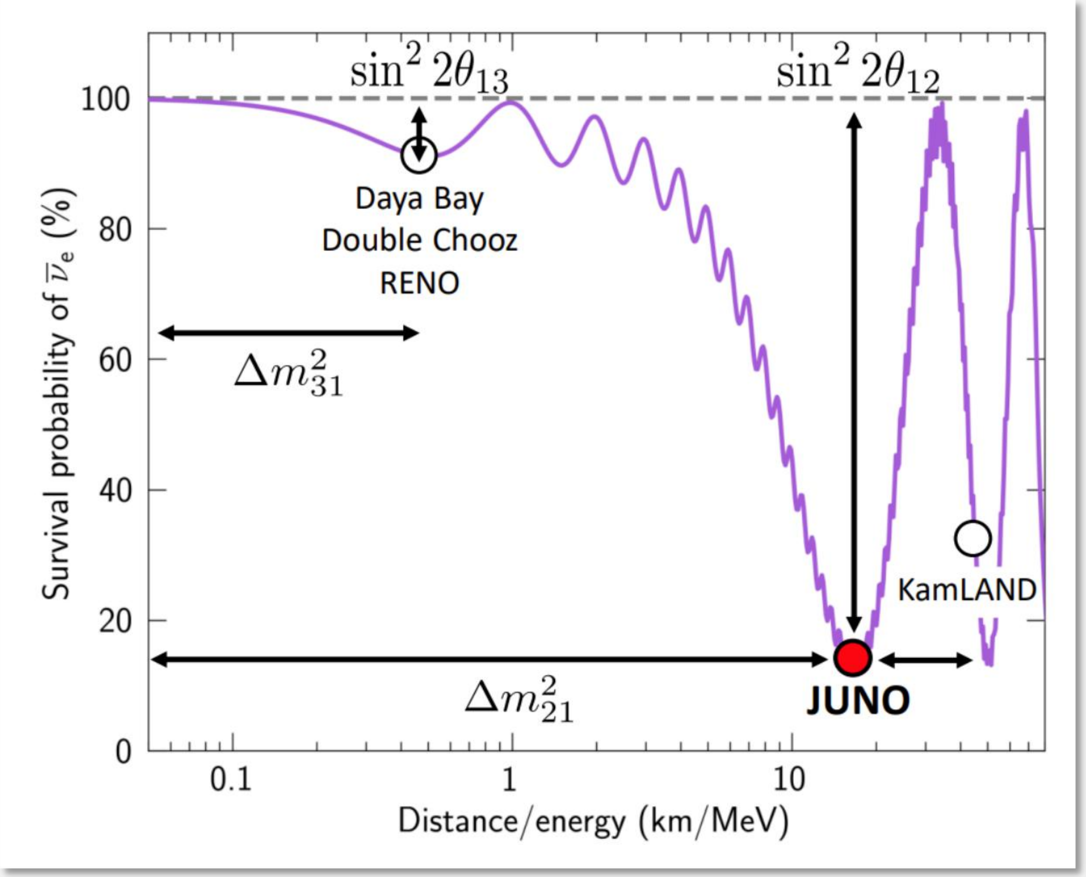


Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

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

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



credit: JUNO

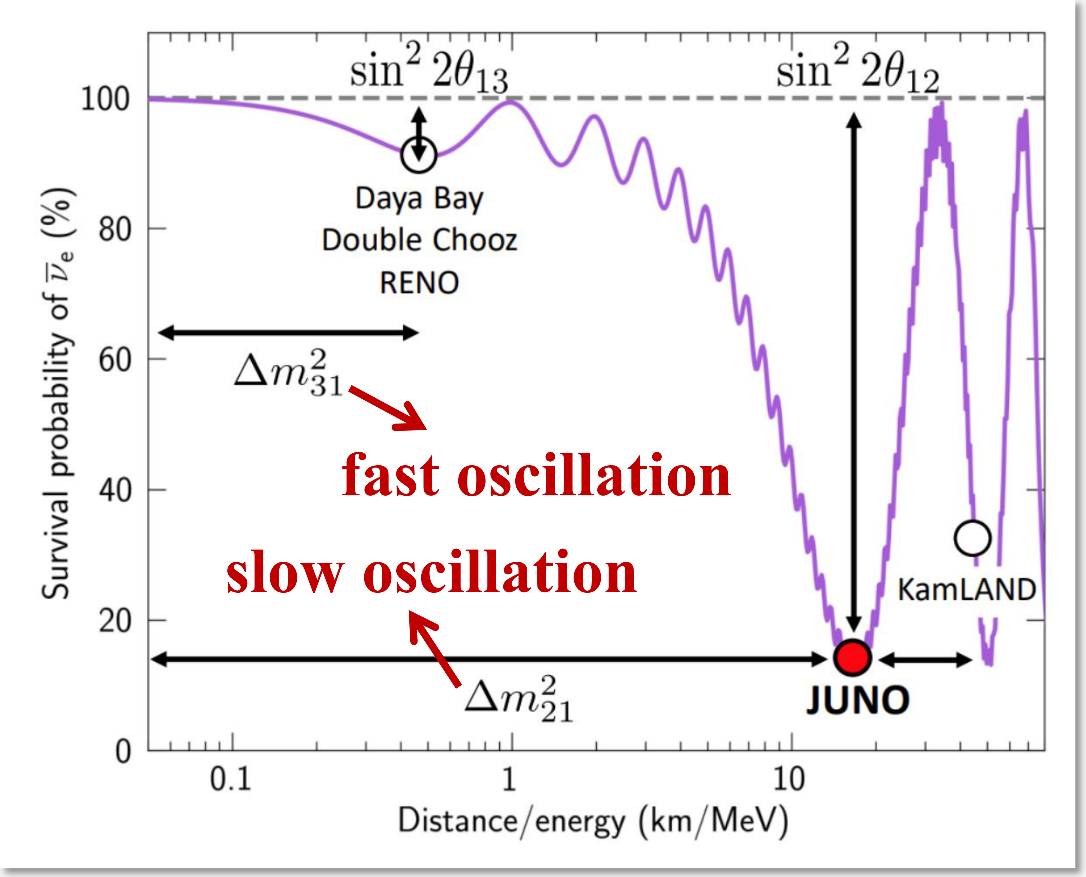
Evidence of Neutrino Mass

oscillation ⟵ interference ⟵ phase difference ⟵ different mass

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

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

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



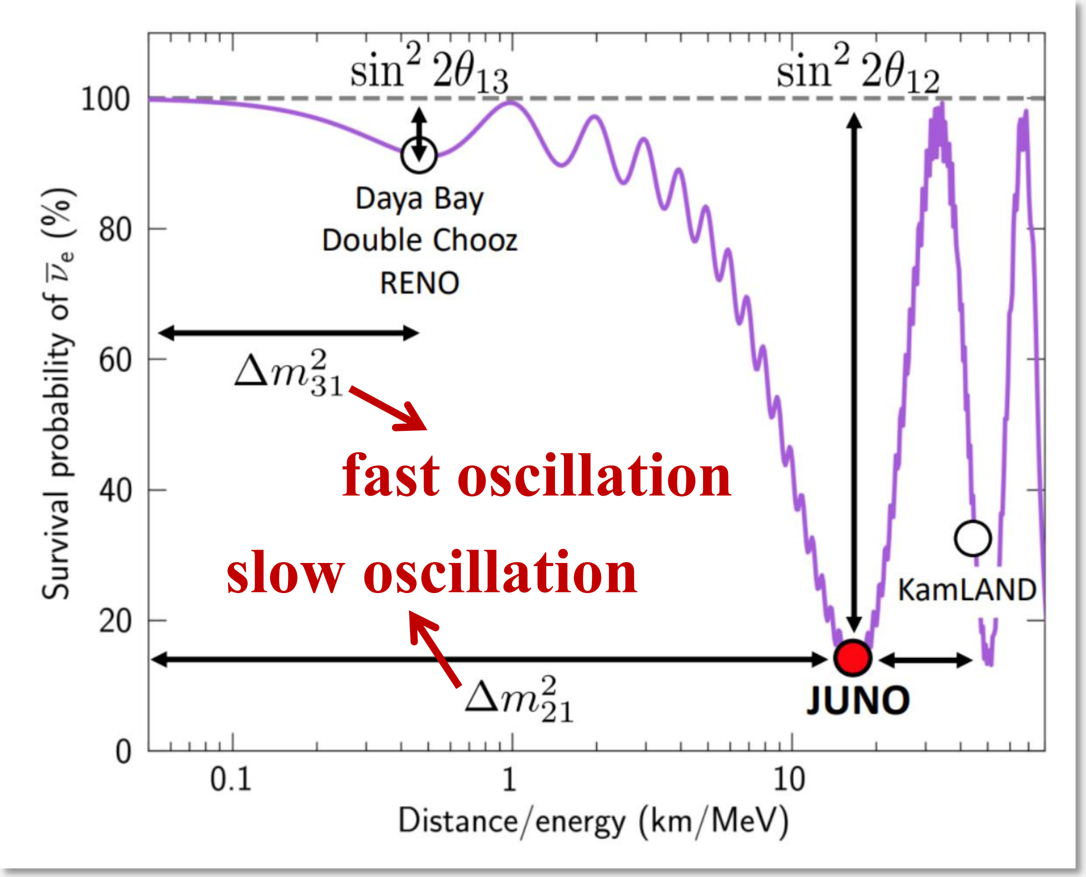
credit: JUNO

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

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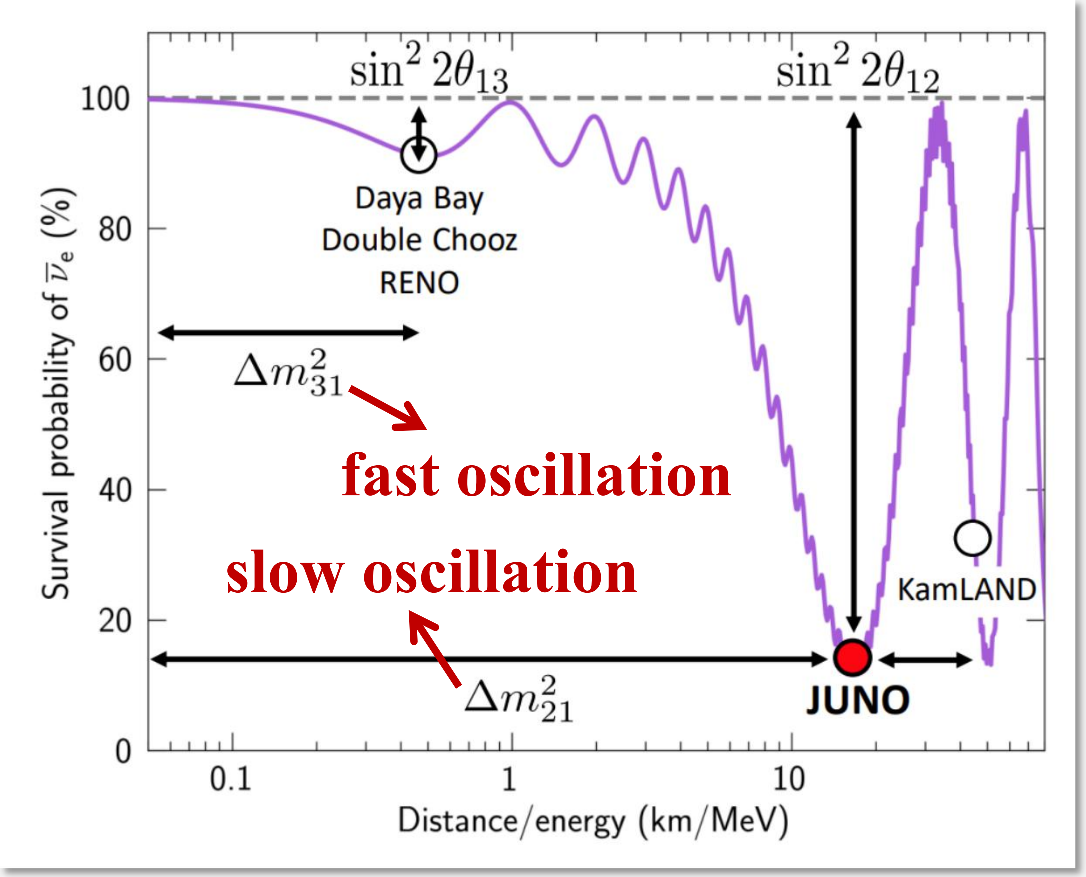
Neutrino masses drive the oscillation behavior !

What's the origin of neutrino mass?



credit: JUNO

Neutrino mass origins

Neutrino Mass Origin

$$\overbrace{\text{vacuum neutrino mass} \qquad\qquad\qquad \text{dark neutrino mass}}^{\text{Neutrino mass origins}}$$

Neutrino Mass Origin I: vacuum mass

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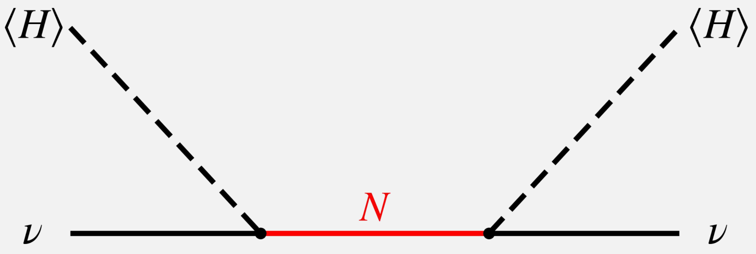
Vacuum Neutrino Mass

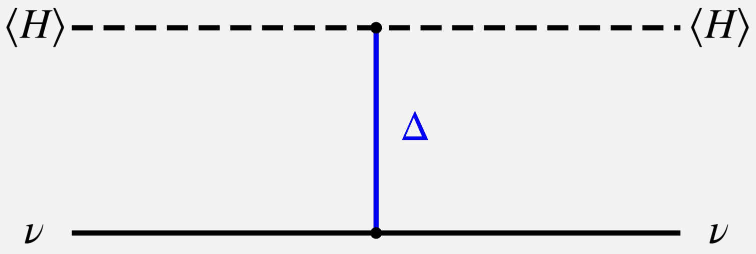
Type-I seesaw



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

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

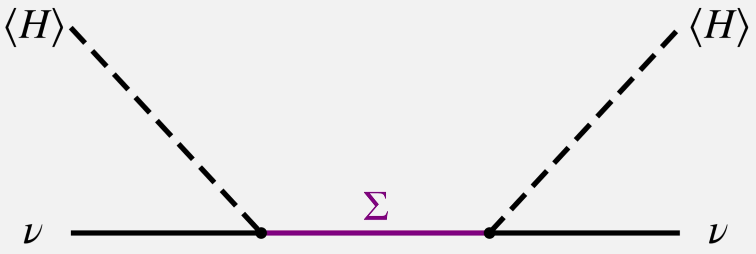
Type-II seesaw



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

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

Type-III seesaw



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

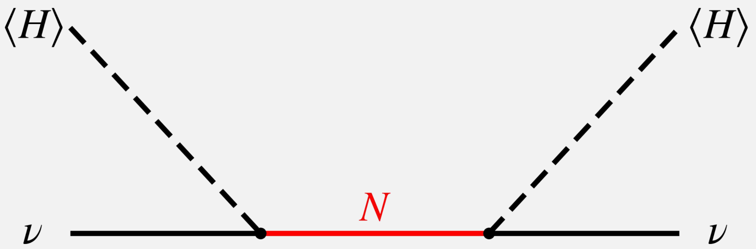
R. Foot, H. Lew, X.-G. He, & G.C. Joshi
E. Ma
…

•••

Neutrino Mass Origin I: vacuum mass

Vacuum Neutrino Mass

Type-I seesaw



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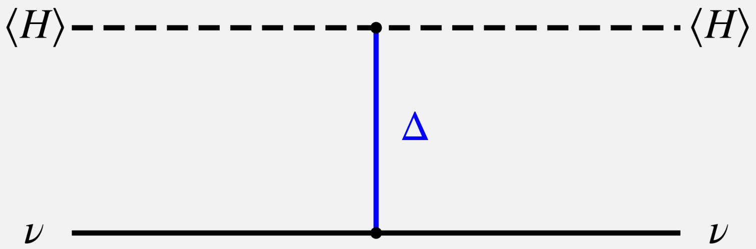
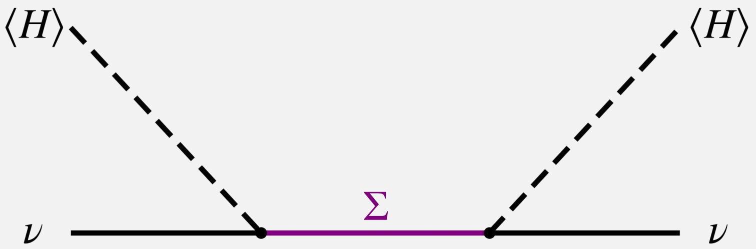
Type-II seesaw



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

Type-III seesaw



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

•••

$$m^2_{\mathrm{vac}} = \mathrm{constant}$$

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

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

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

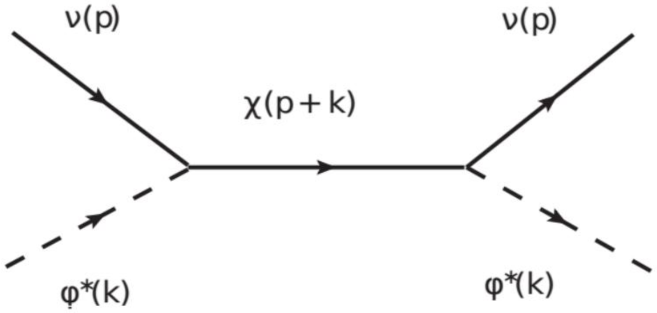
$$H \approx p + V, \quad \text{with } V = \frac{\boxed{\ldots}}{2E}$$

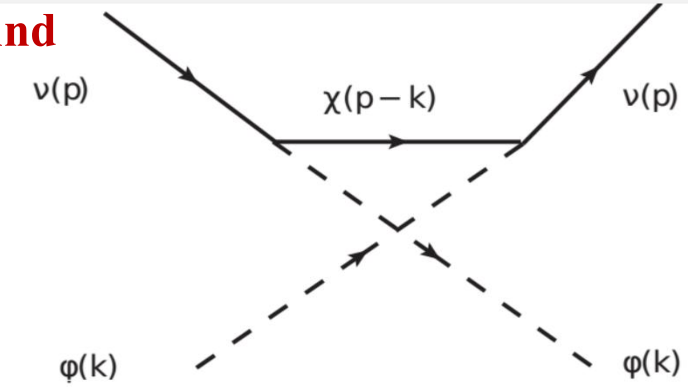
effective mass
or
"dark" mass

Neutrino Mass Origin II: dark mass

Dark Neutrino Mass

Forward scattering with DM background





Introduce the effective or refractive mass squared as

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

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

$m_{ref}^2 = 2EV$

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

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

A. Y. Smirnov, talks@MAYORANA Workshop

[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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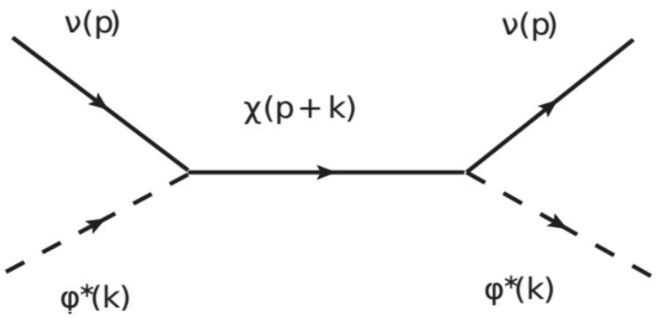
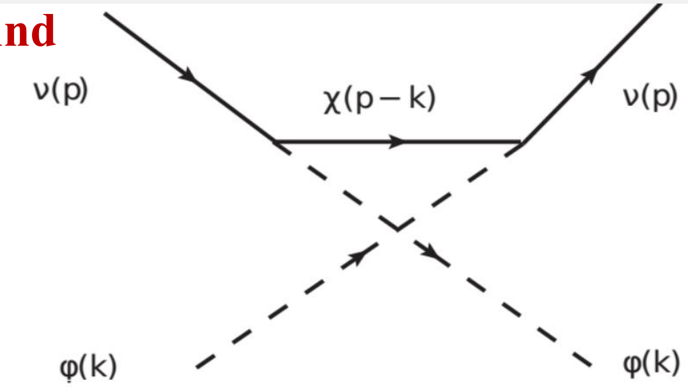
Dark Neutrino Mass

Forward scattering with DM background





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A. Y. Smirnov, talks@MAYORANA Workshop

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

Neutrino Mass Origins Comparison

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

vs.

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

Neutrino Mass Origins Comparison

Institute for Basic Science

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

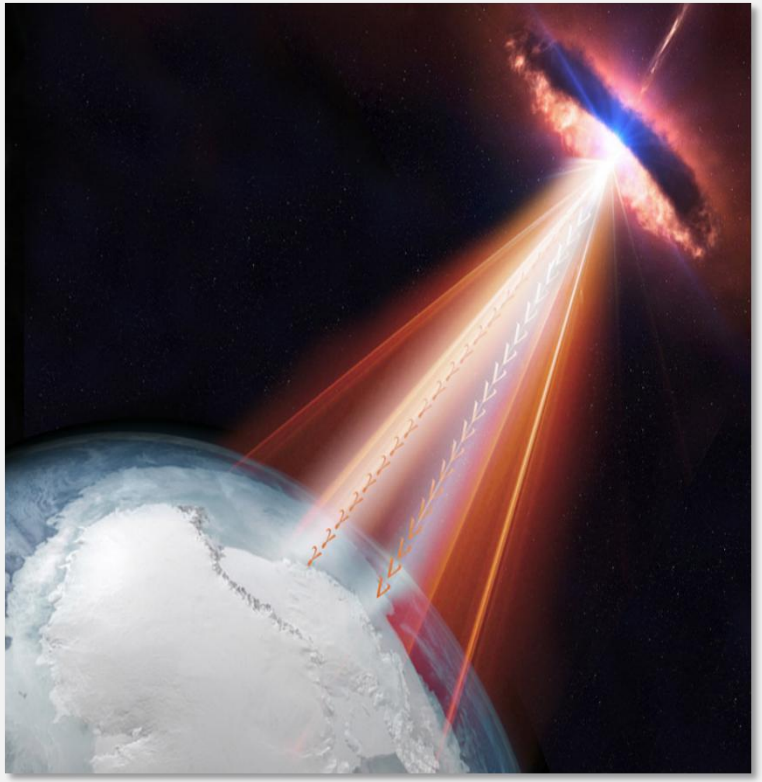
vs.

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

Can we distinguish these two origins ?

Supernova Neutrino Time Delay

Yes! Look into larger scales!



Credit: *IceCube*

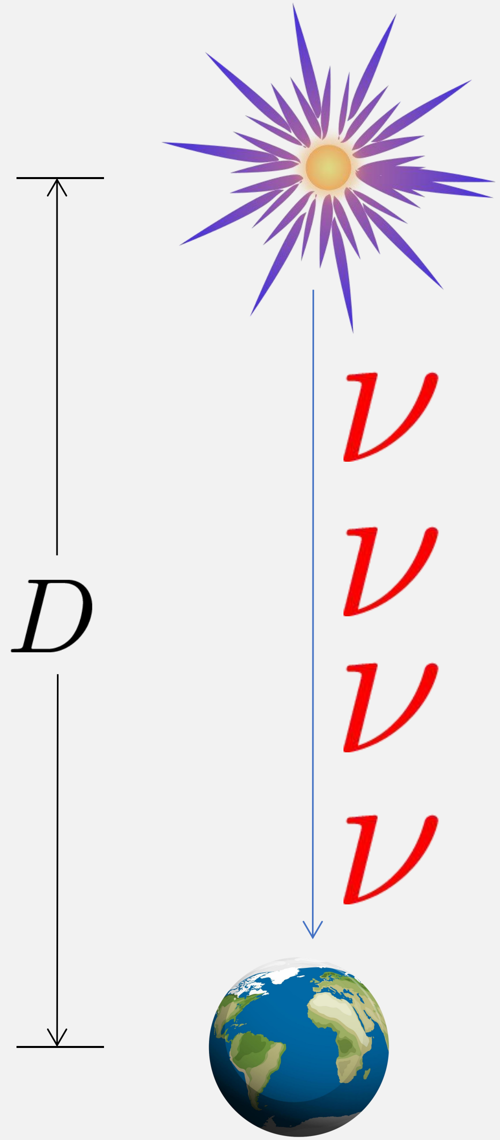
Galactic supernovae provide ideal neutrino sources

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

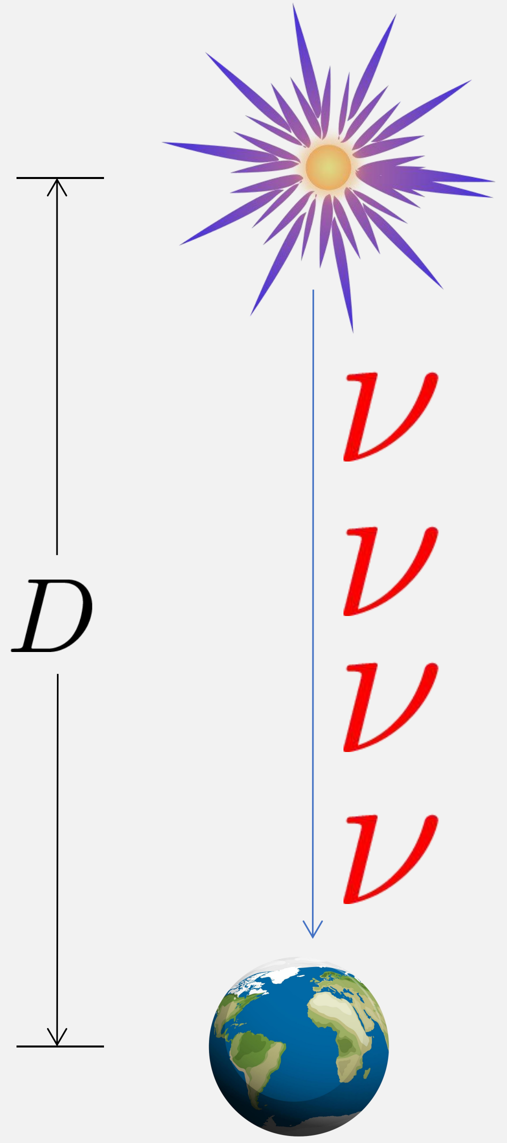
G. I. Zatsepin
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 20 July 1968
ZhETF Pis. Red. 8, No. 6, 333-334 (20 September 1968)

[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; P. Denton and Y. Kini, 2411.13634 ...]

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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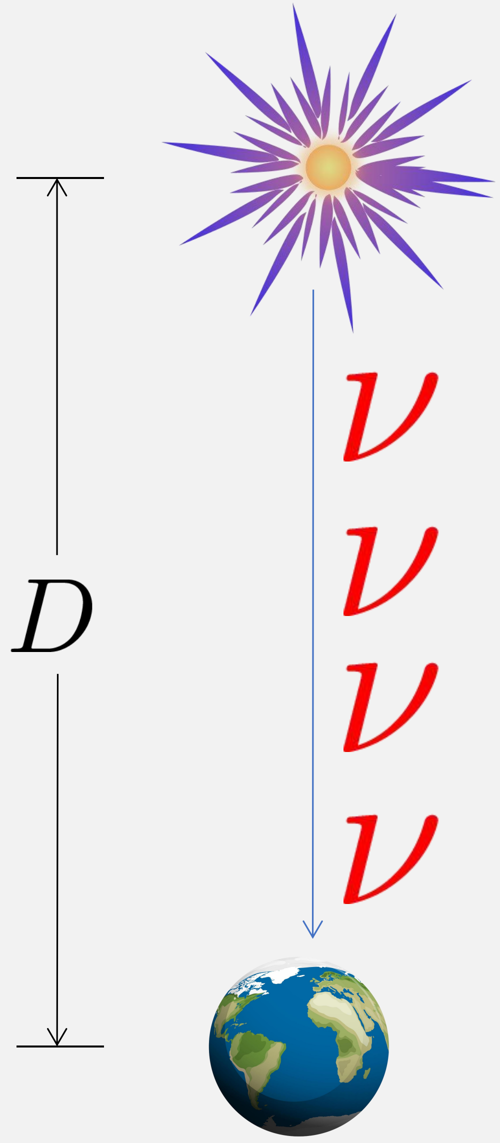

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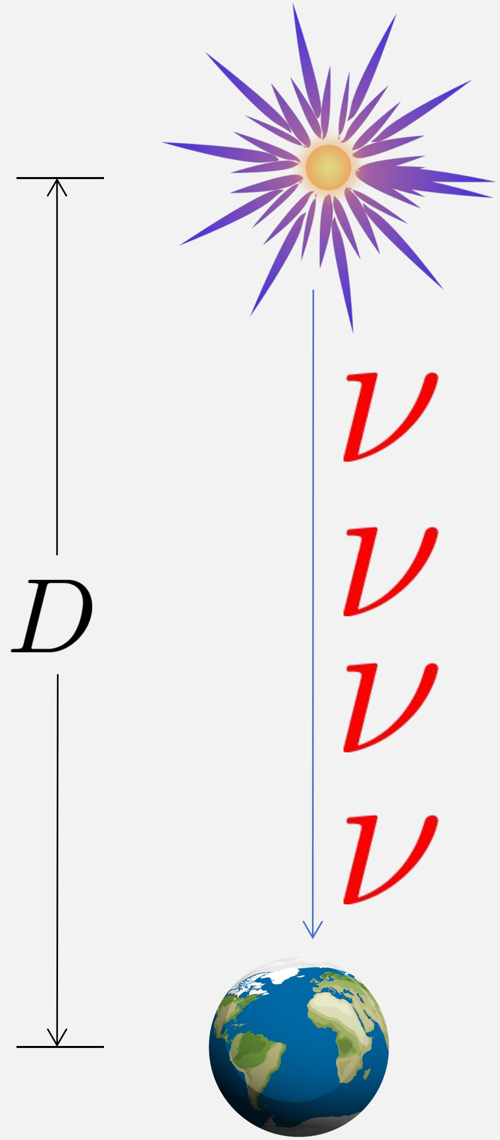
smaller than speed of light

&

space-time independent

I. Vacuum Neutrino Mass



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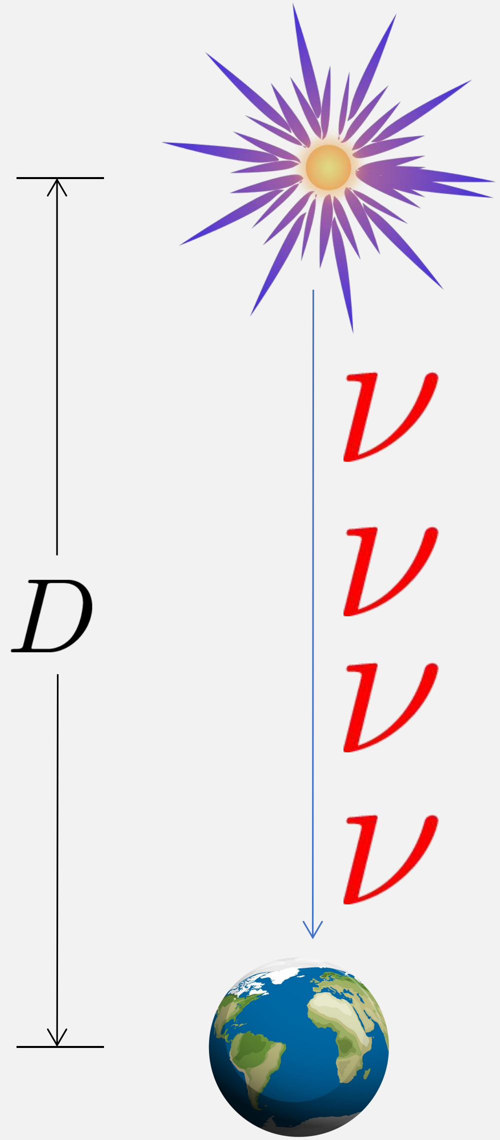
time delay:

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

I. Vacuum Neutrino Mass



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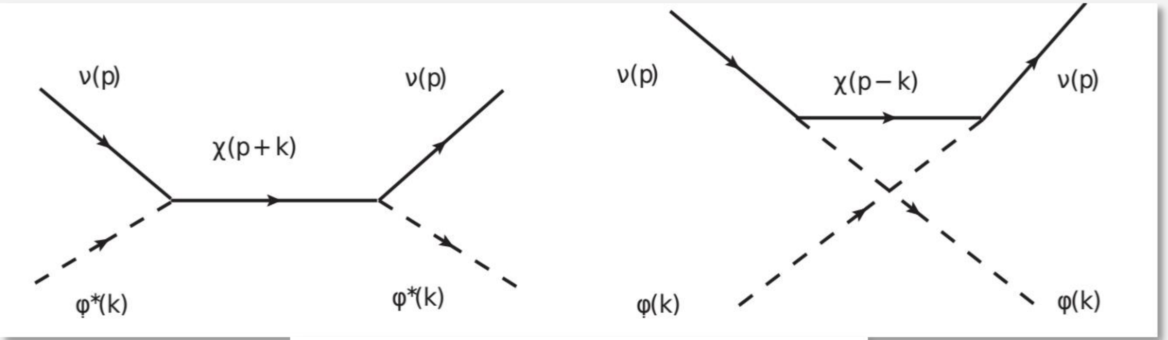
II. Dark Neutrino Mass

Recall



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$m_{ref}^2 = 2EV$

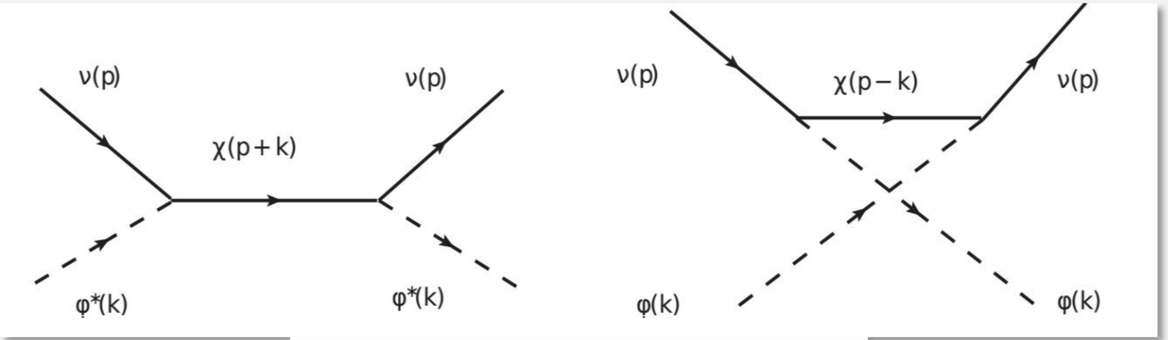
$$E_\nu = p_\nu + V, \;\; v = \frac{dE_\nu}{dp_\nu}$$

group velocity:

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

II. Dark Neutrino Mass

Recall



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II. Dark Neutrino Mass

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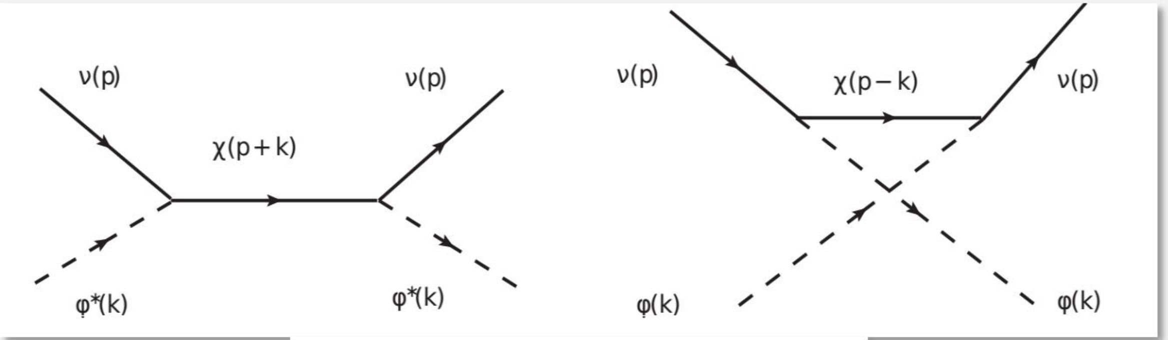

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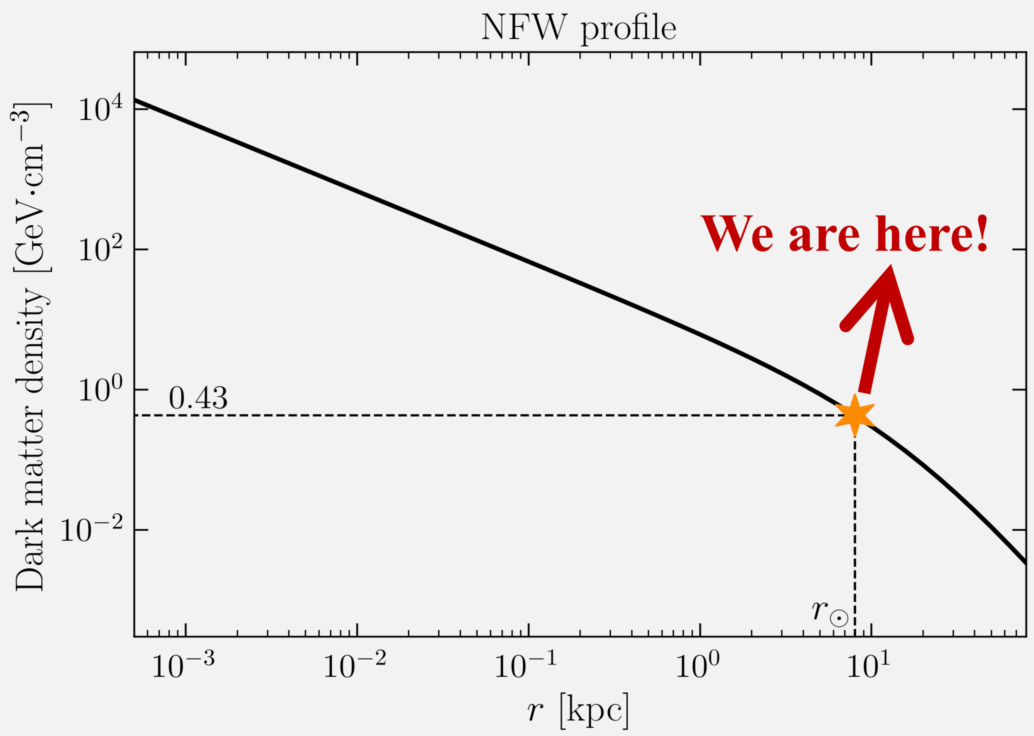
$$1 - v(\mathbf{x}) = \frac{m^2_{\rm dark}(\mathbf{x}_\odot)}{2E^2}\frac{\boxed{\rho_\phi(\mathbf{x})}}{\rho_\phi(\mathbf{x}_\odot)}$$

space-time dependent!

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

II. Dark Neutrino Mass



Navarro-Frenk-White profile

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

group velocity:

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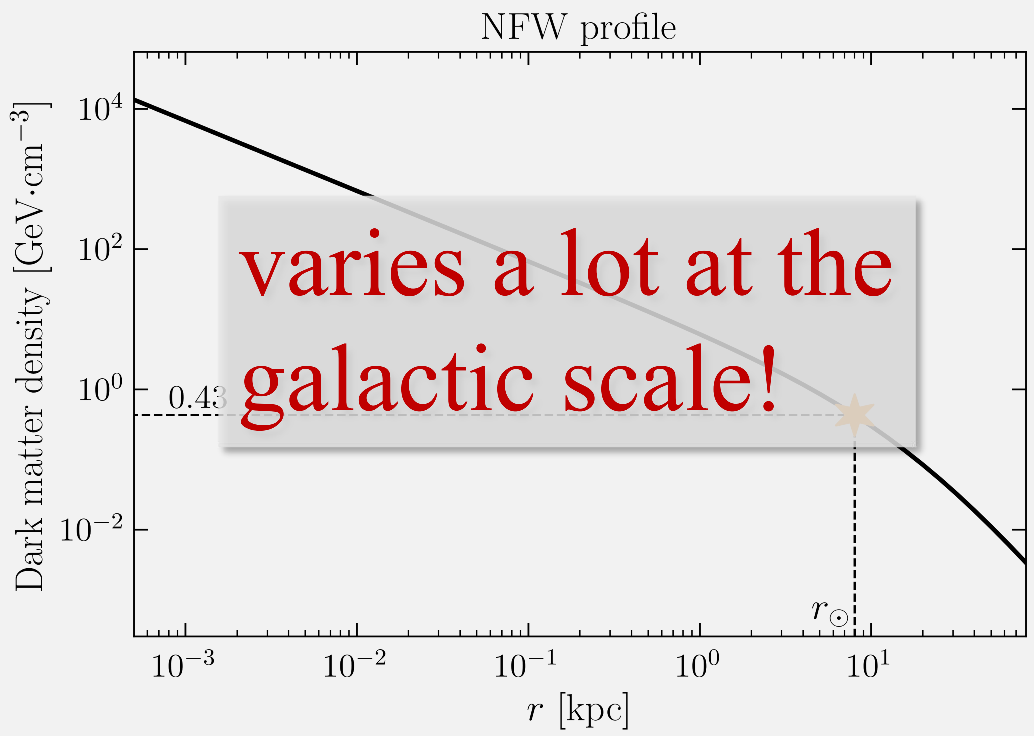
$$1 - v(\mathbf{x}) = \frac{m^2_{\text{dark}}(\mathbf{x}_\odot)}{2E^2}\frac{\boxed{\rho_\phi(\mathbf{x})}}{\rho_\phi(\mathbf{x}_\odot)}$$

space-time dependent!

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

Institute for Basic Science



Navarro-Frenk-White profile

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

group velocity:

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

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

space-time dependent!

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

II. Dark Neutrino Mass

…

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

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

just an integration over neutrino trajectory

II. Dark Neutrino Mass

...

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

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

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

vacuum neutrino mass

differed by this factor!

II. Dark Neutrino Mass

...

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

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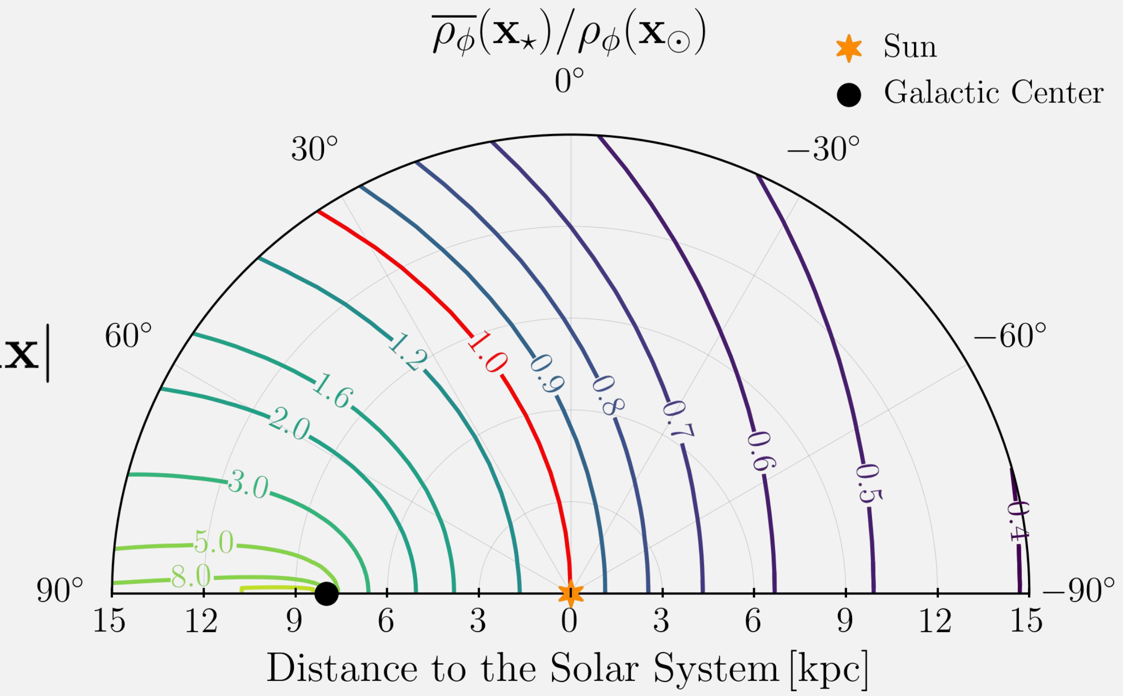


high density ← low density

*Ge, **CFK**, Smirnov, PRL 24*

Experimental sensitivities

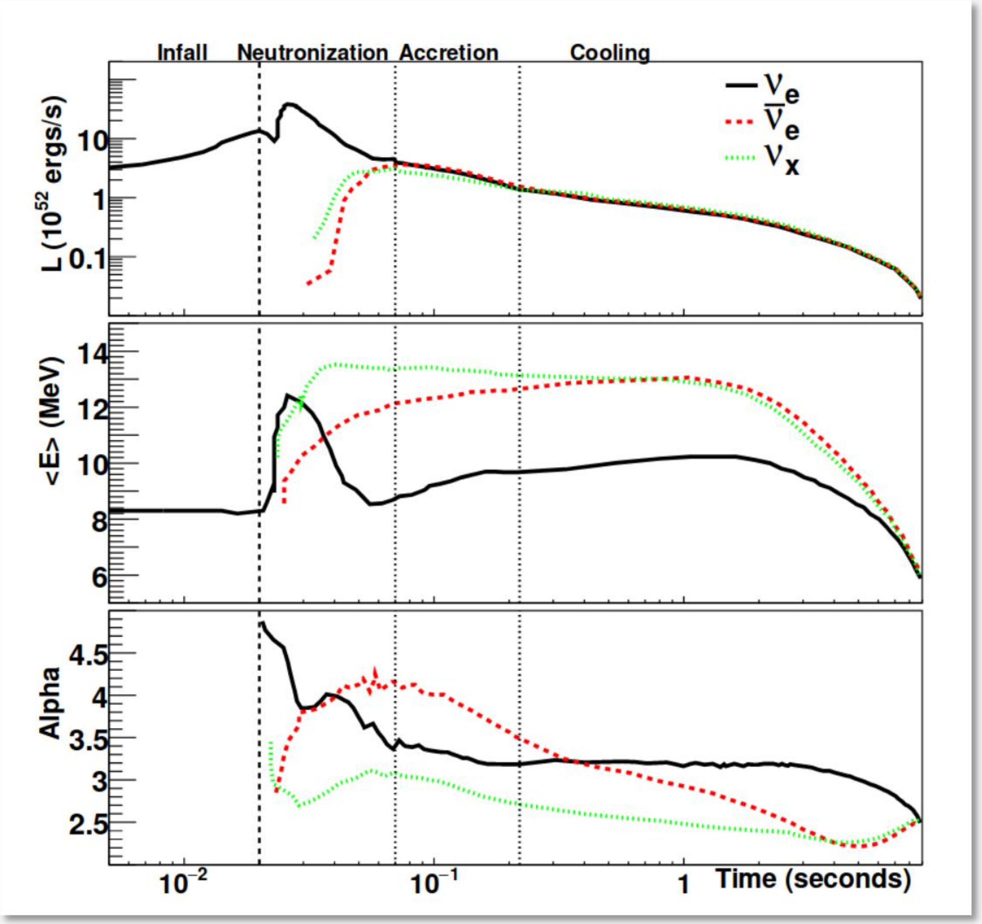
Supernova Neutrino Production

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

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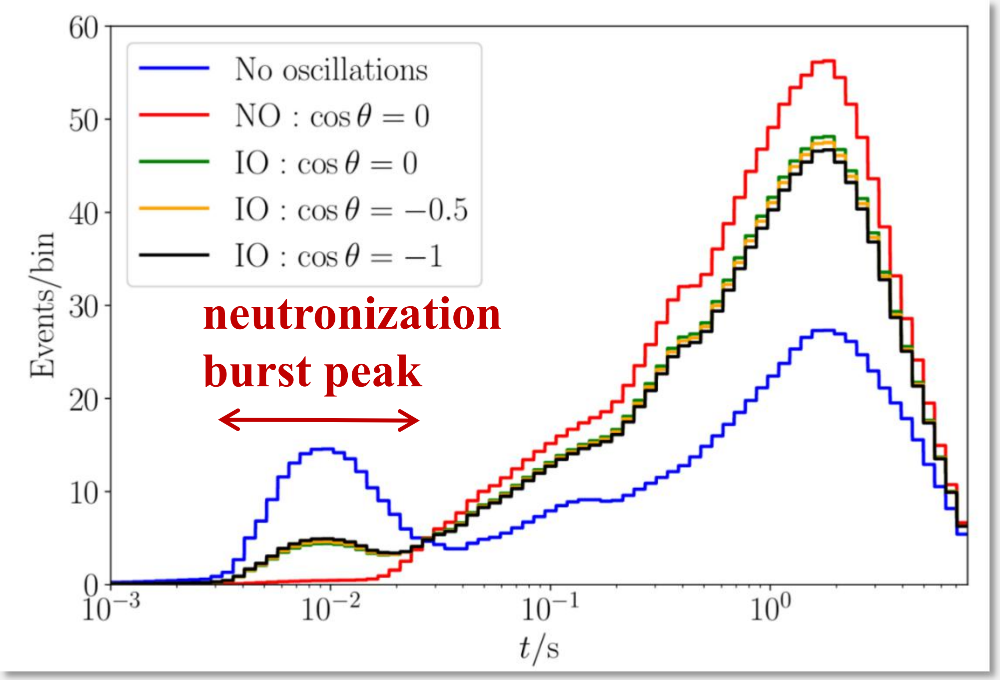
Supernova Neutrino Production

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):

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

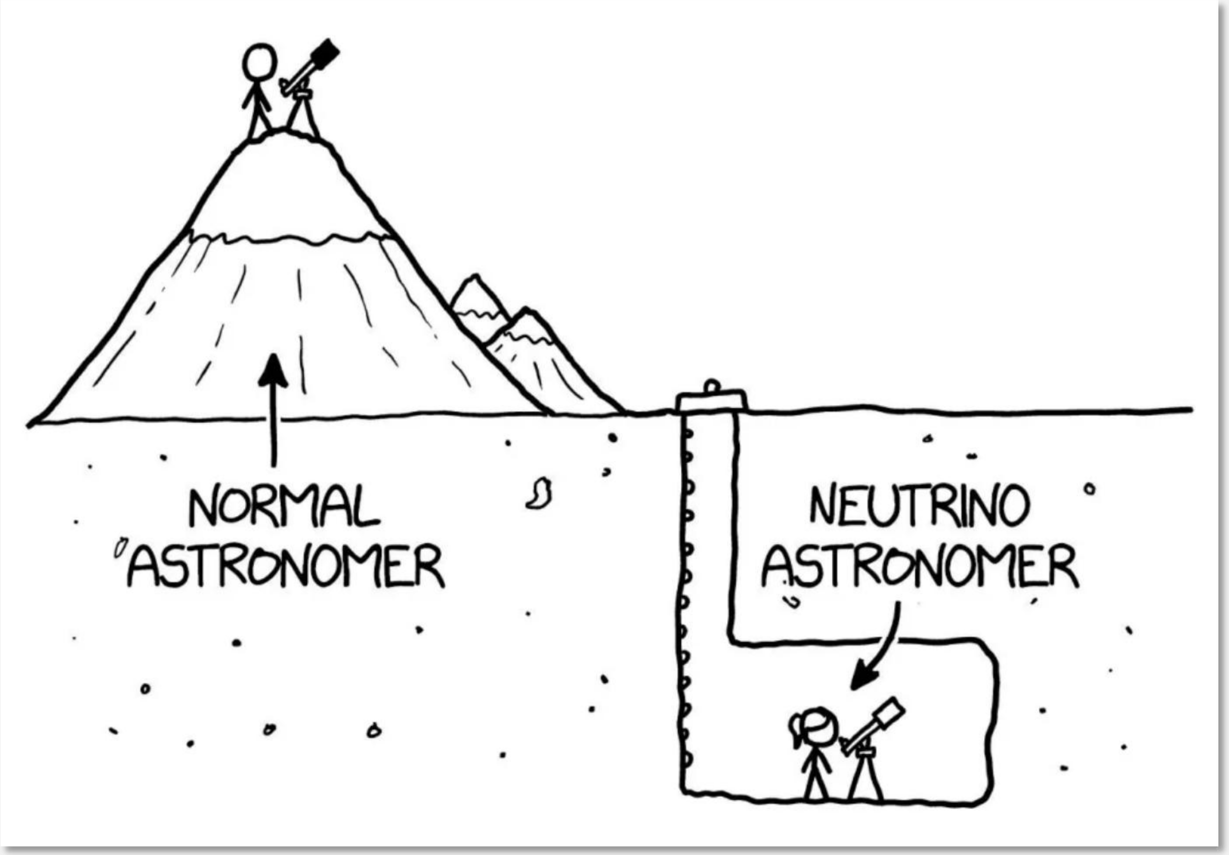
$$p = |U_{e3}|^2 \approx \sin^2\theta_{13}, \mathrm{NO}$$

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

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

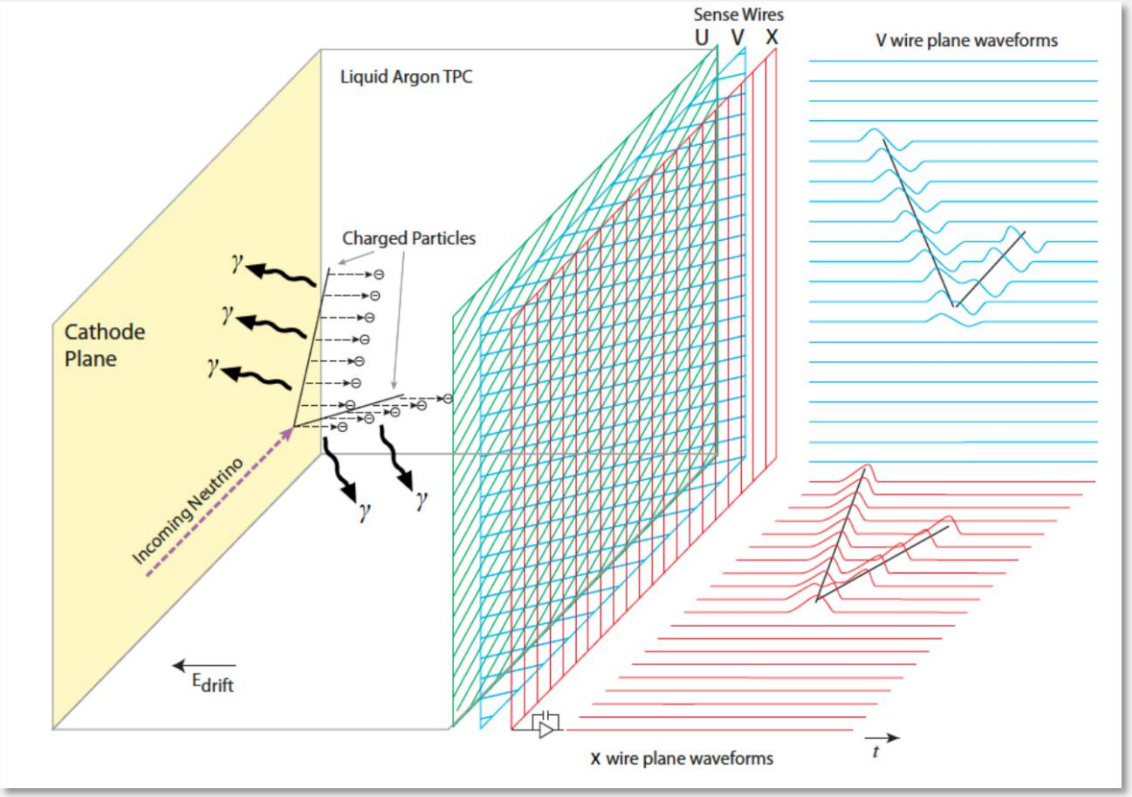
Supernova Neutrino Detection @ DUNE

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



credit: PHYSICSGG

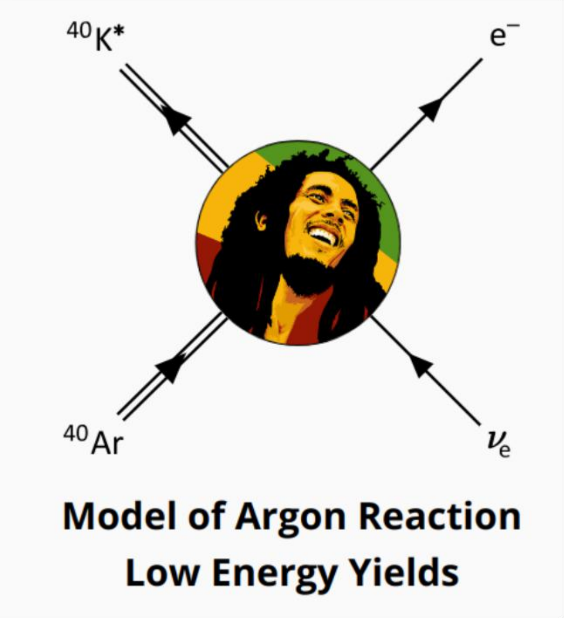
Liquid Argon Time Projection Chamber (LArTPC)
40 kt fiducial mass (?)



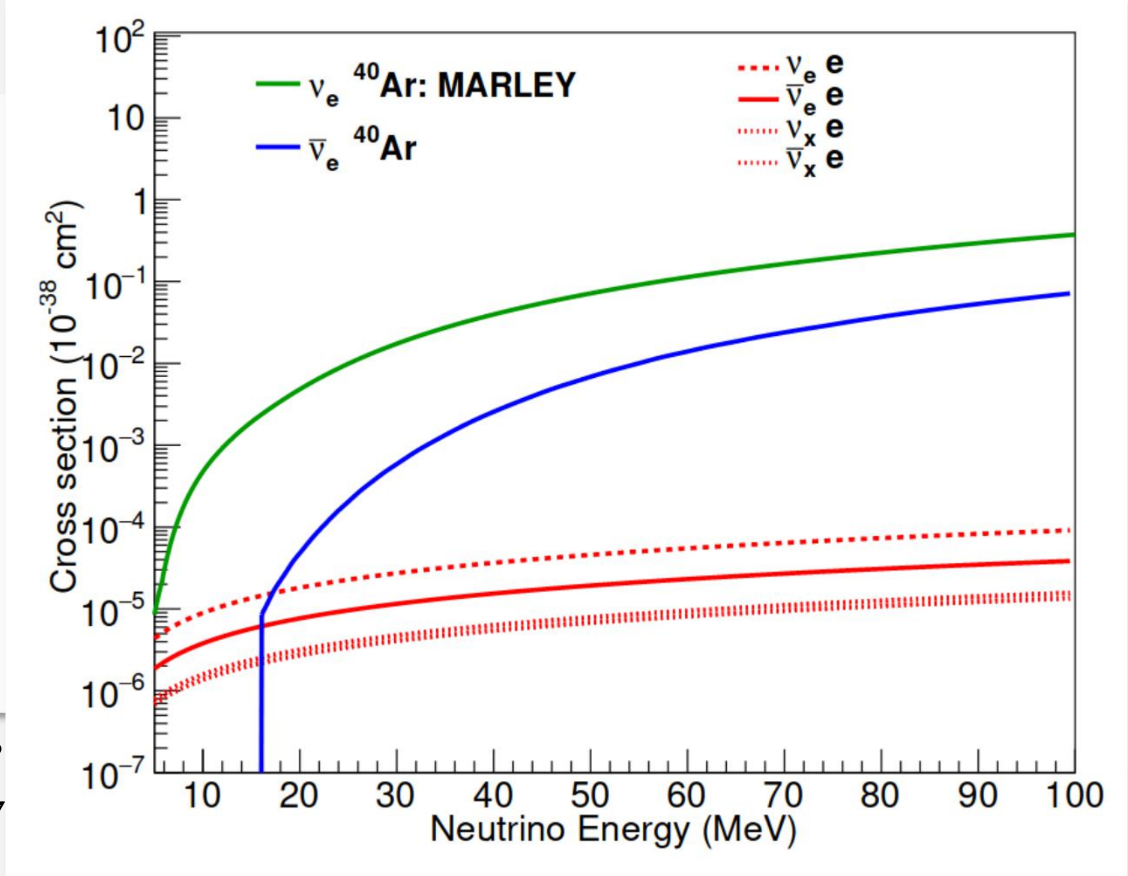
credit: DUNE

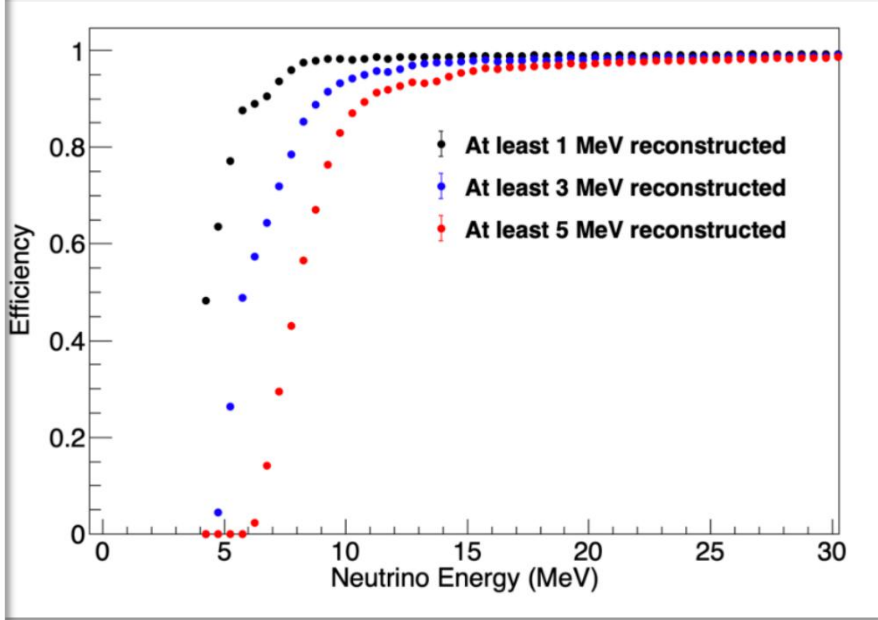
Supernova Neutrino Detection @ DUNE

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



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]

Time Distribution

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$[\Phi_{\nu_e}$: ν_e flux

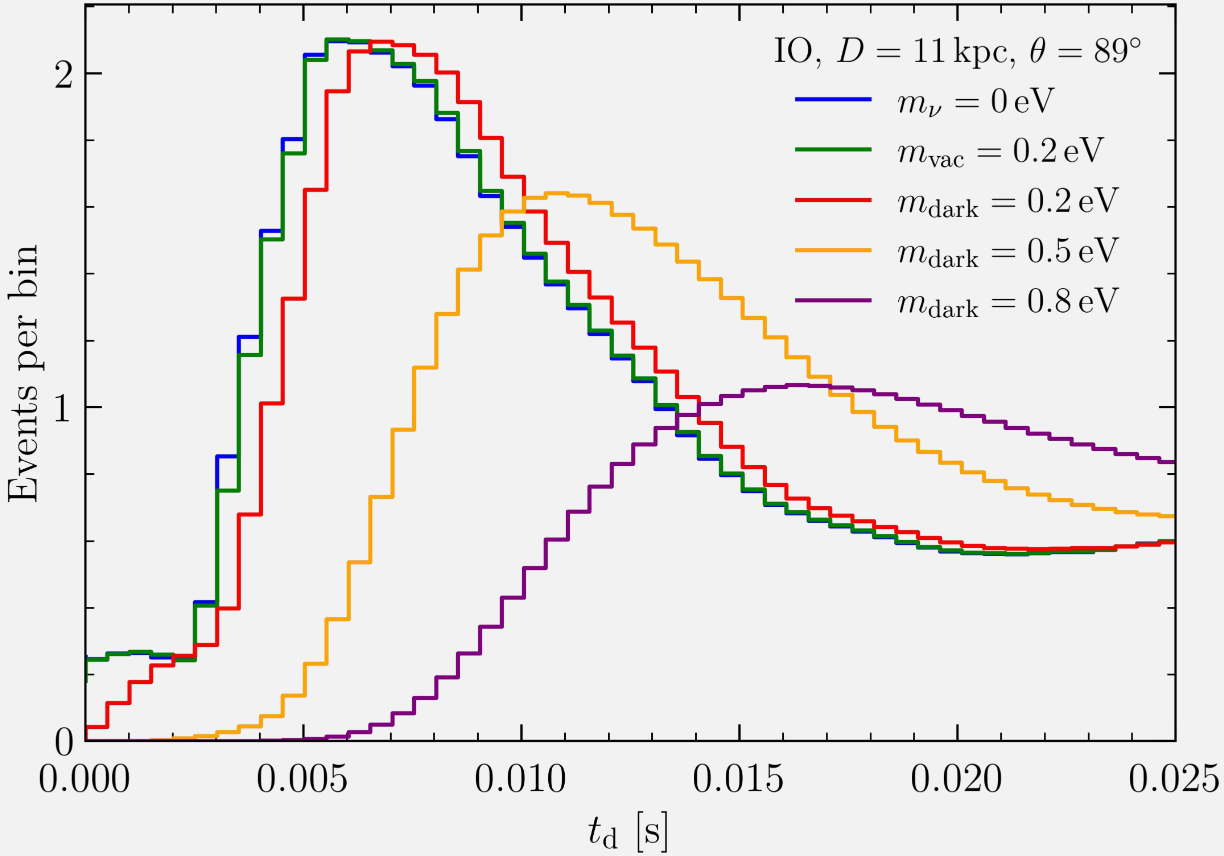
A : target nucleon number

σ_{ν_e} : cross section

ϵ : efficiency$]$

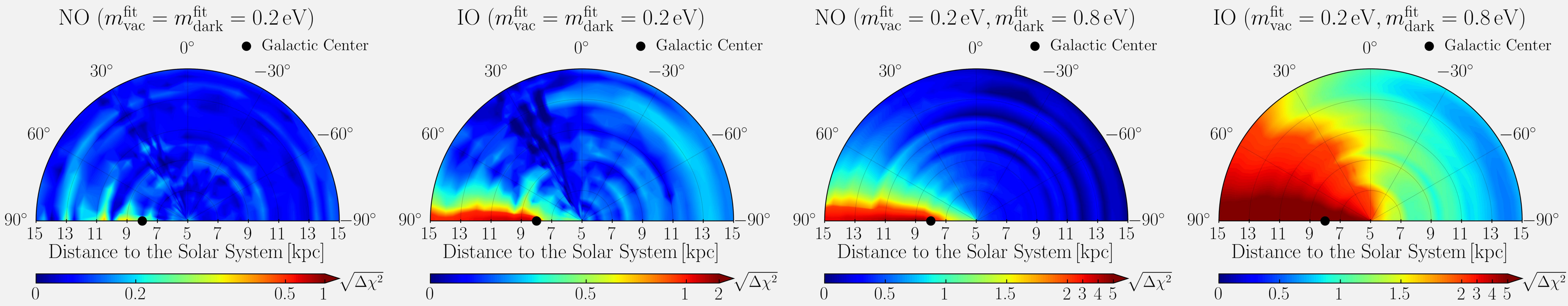
- The time distribution becomes wider as the neutrino mass increases

energy integrated out



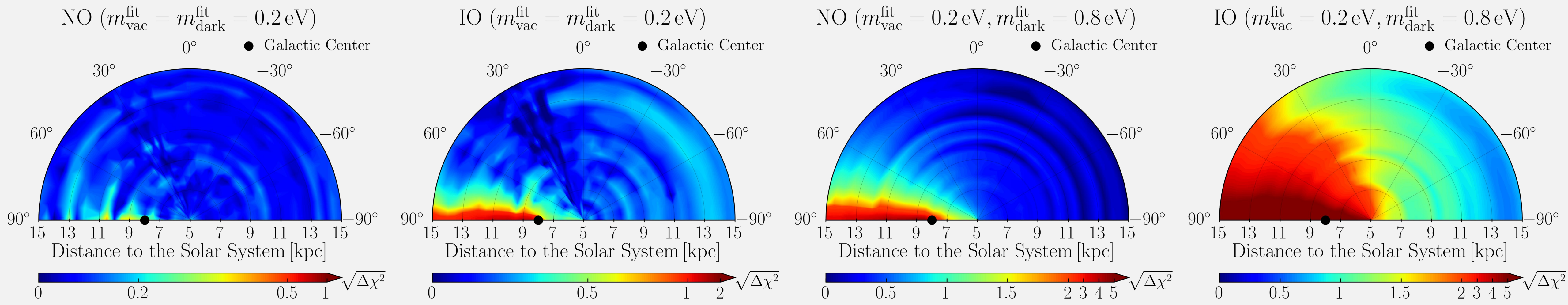
*Ge, **CFK**, Smirnov, PRL 24*

Sensitivities



*Ge, **CFK**, Smirnov, PRL 24*

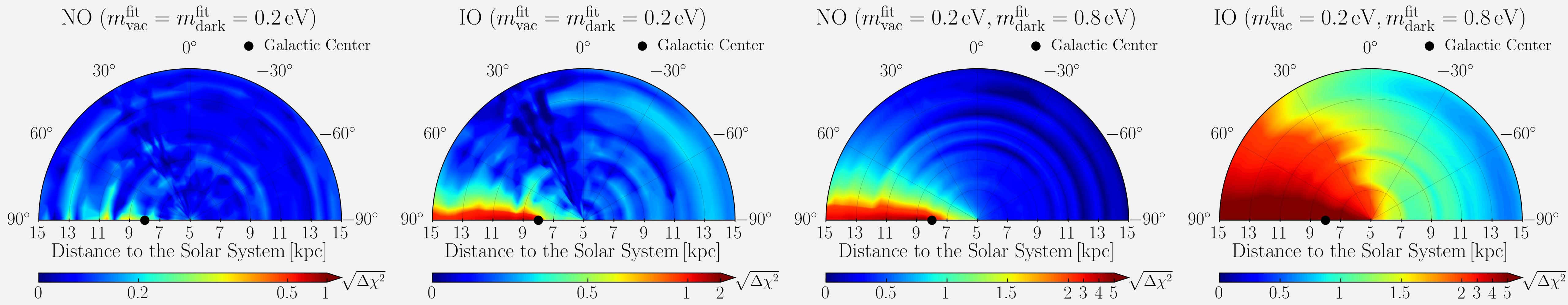
Sensitivities



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

*Ge, **CFK**, Smirnov, PRL 24*

Sensitivities



- 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, PRL 24*

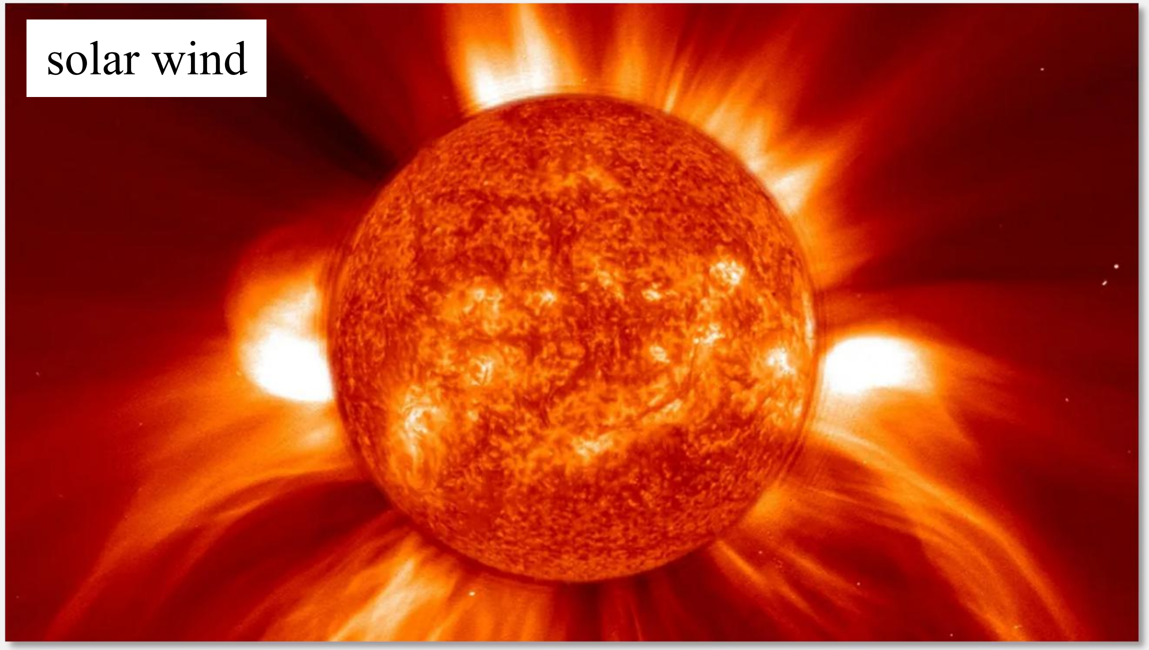
II.

Circumstellar Medium (CSM) of supernovae as new probes for FIPs

What is CSM

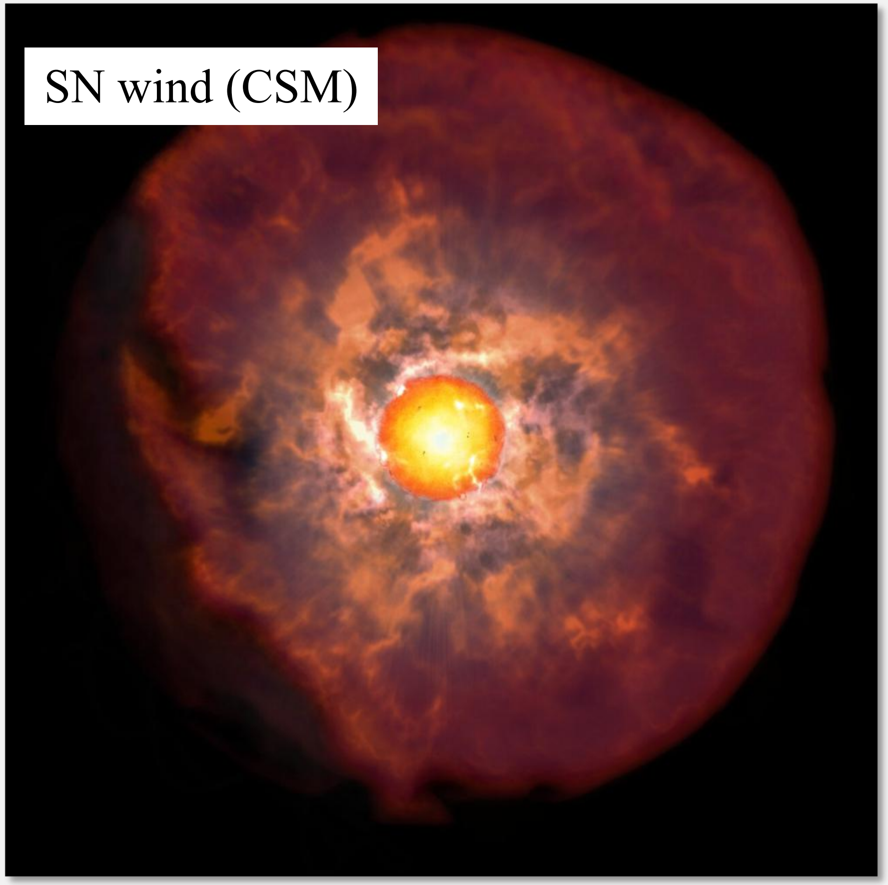
Production of CSM

Mass loss via the wind



credit: NASA

$$v \sim \mathcal{O}(100)\,\mathrm{km/s}$$

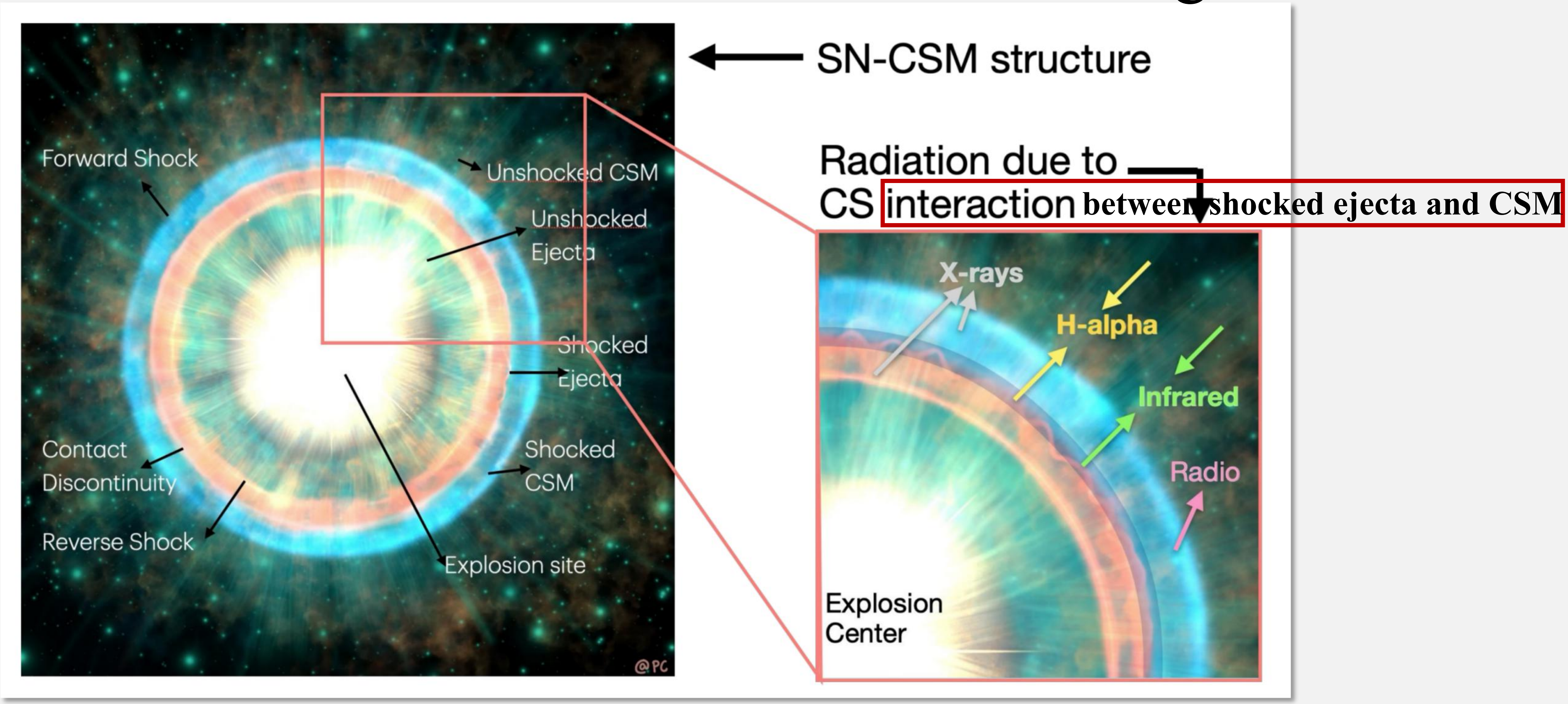


credit: NAOJ

$$v \sim \mathcal{O}(10)\,\mathrm{km/s}\ \text{for RSG}$$

Observational Evidence

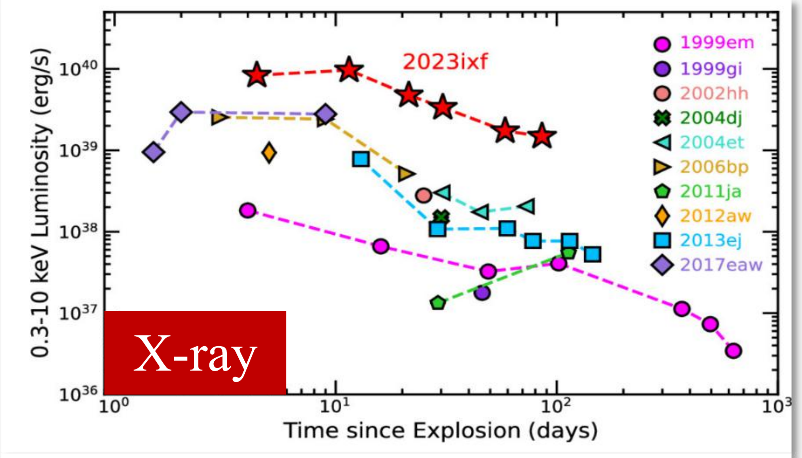
How do we know there is CSM surrounding SN?

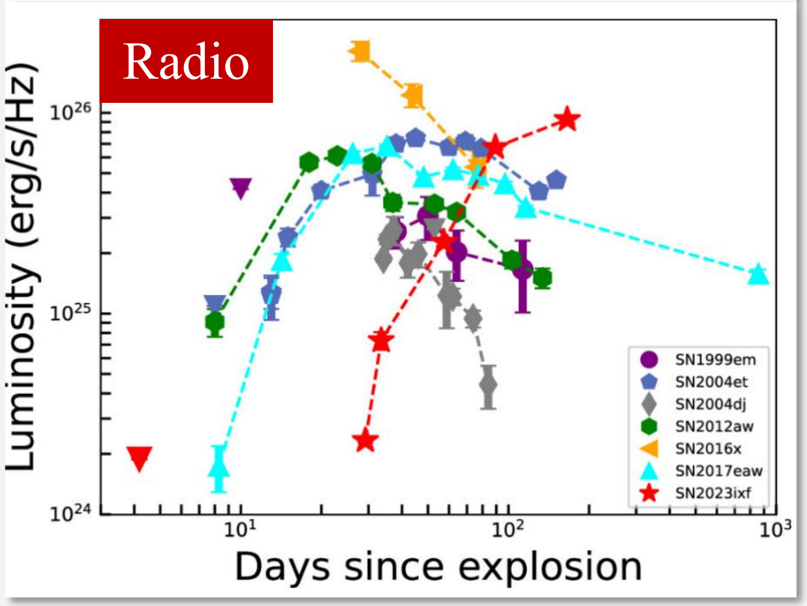


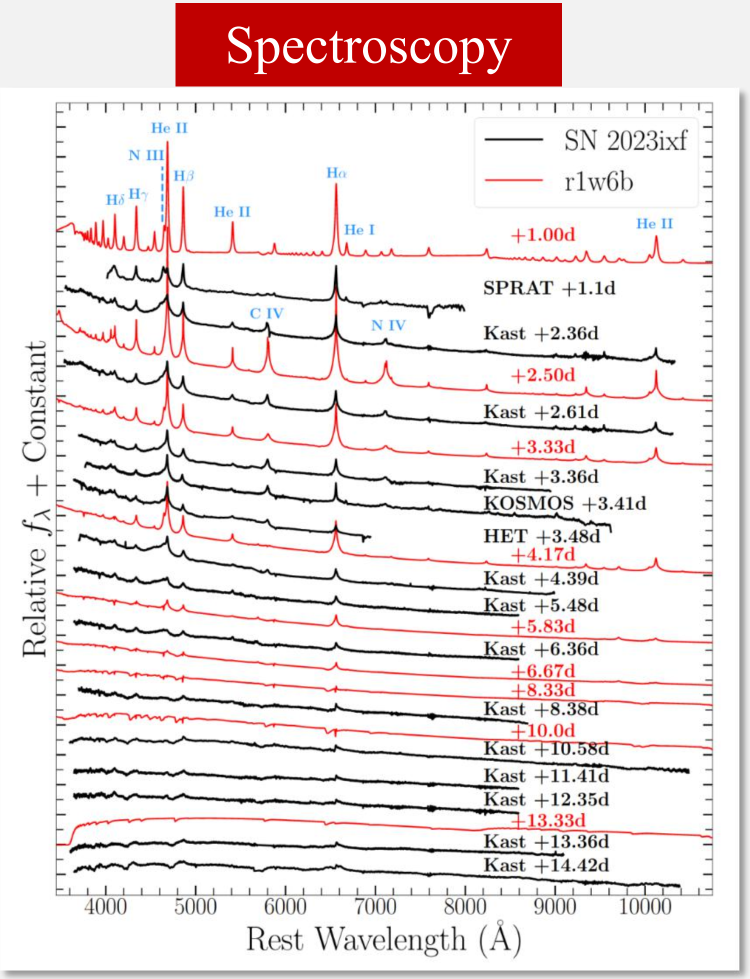
P. Chandra, arXiv:2510.20913

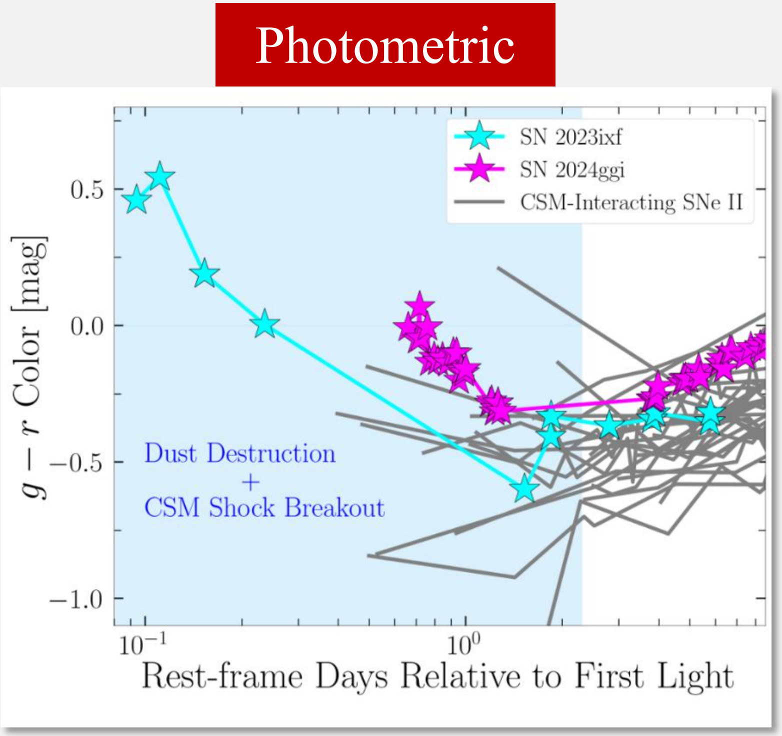
Observational Evidence

Plenty of measurements!







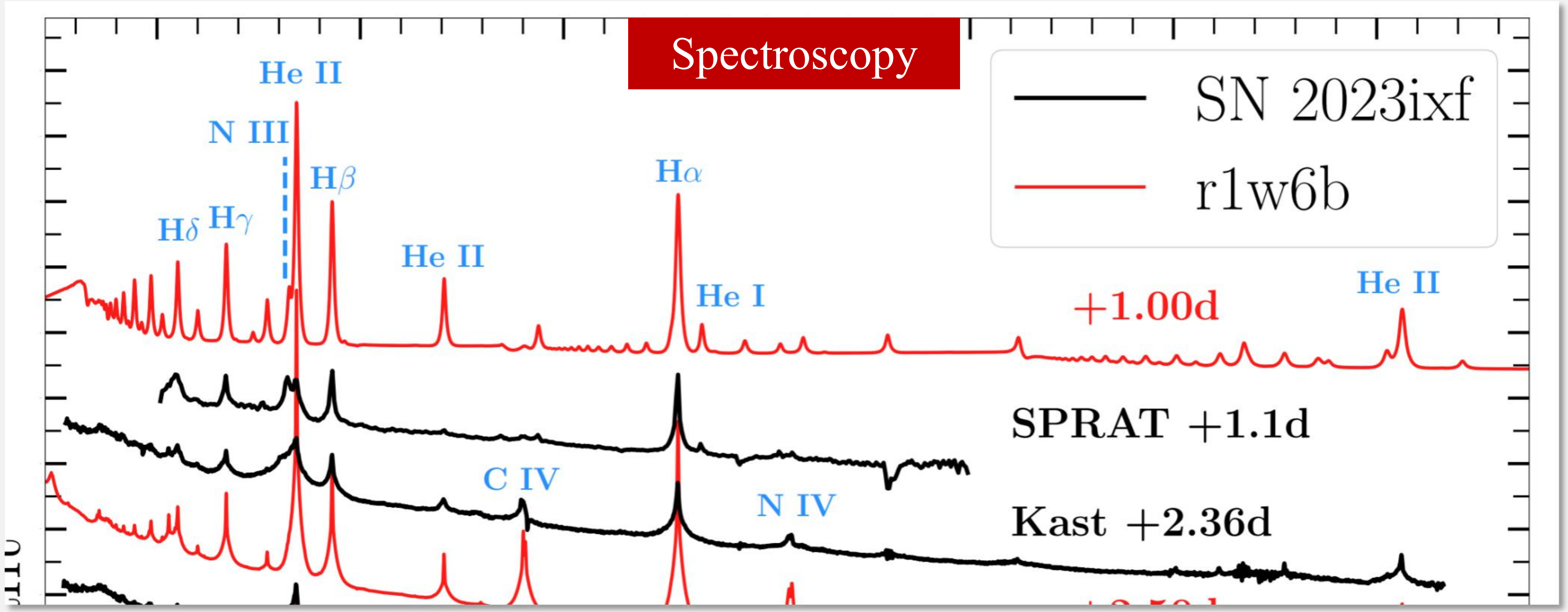


W.V. Jacobson-Galán, arXiv:2507.08078

Component of CSM

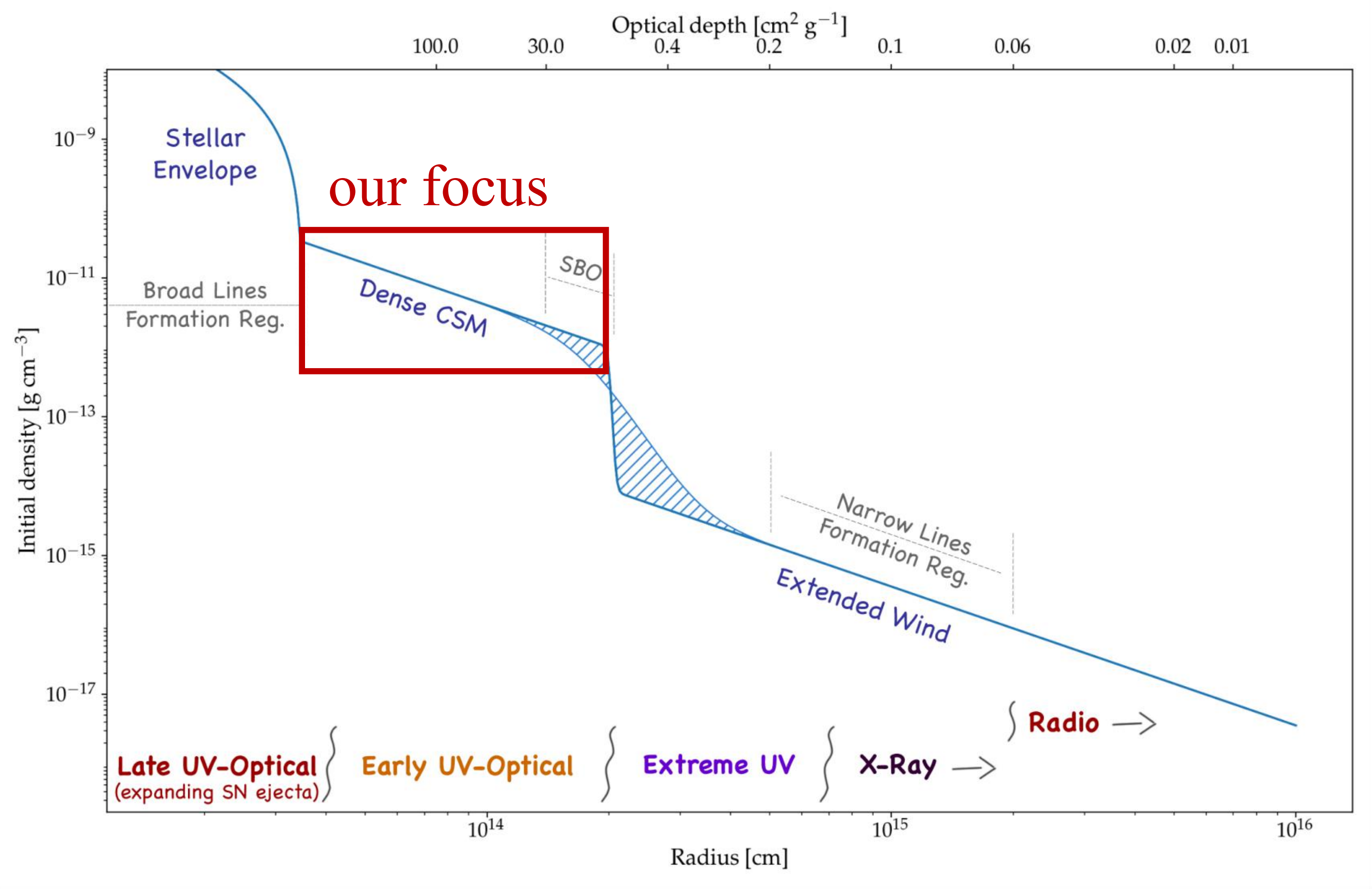
What makes of CSM

- Hydrogen
- Helium
- Carbon
- Nitrogen
- + Heavier elements



W.V. Jacobson-Galán, arXiv:2507.08078

CSM Density Profile



E.A. Zimmerman et al. Nature 627 (2024) 759

Why we consider CSM

Traditional Method

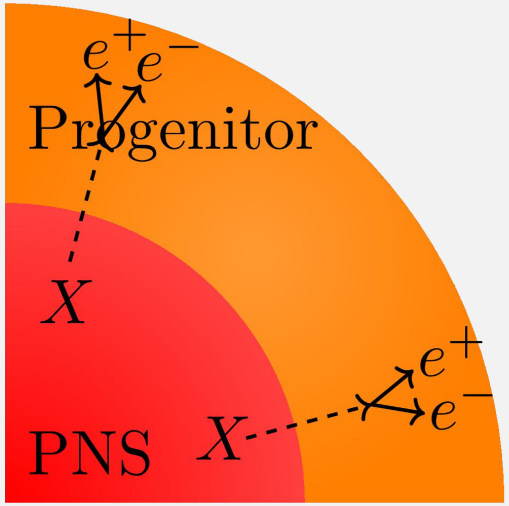
After FIPs (X) produced inside a proto-neutron star (PNS)

Traditional Method

After FIPs (X) produced inside a proto-neutron star (PNS)

$$\overbrace{\hspace{20em}}$$

Decay inside mantle → Energy trapped

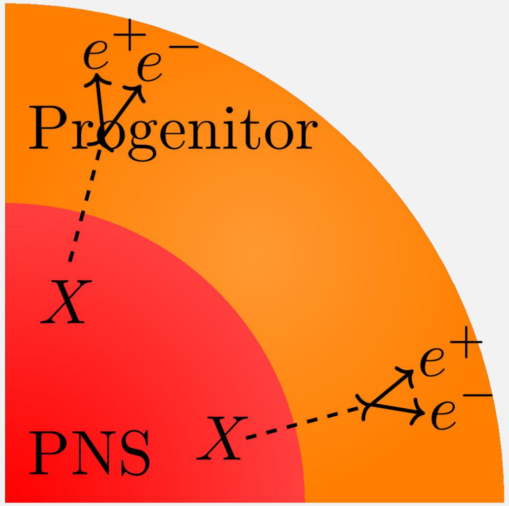


Traditional Method

After FIPs (X) produced inside a proto-neutron star (PNS)

Decay inside mantle → Energy trapped

Constraint from low-energy SN



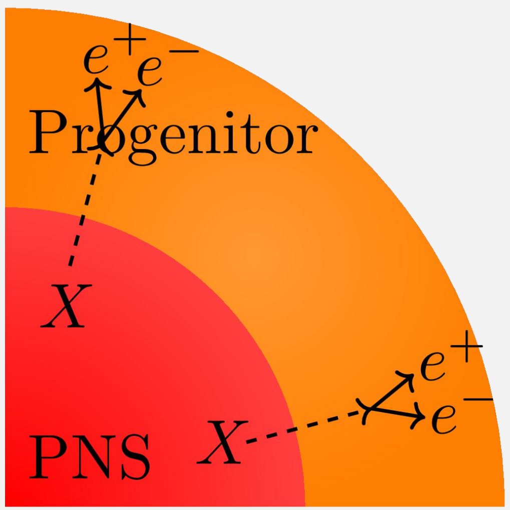
Traditional Method

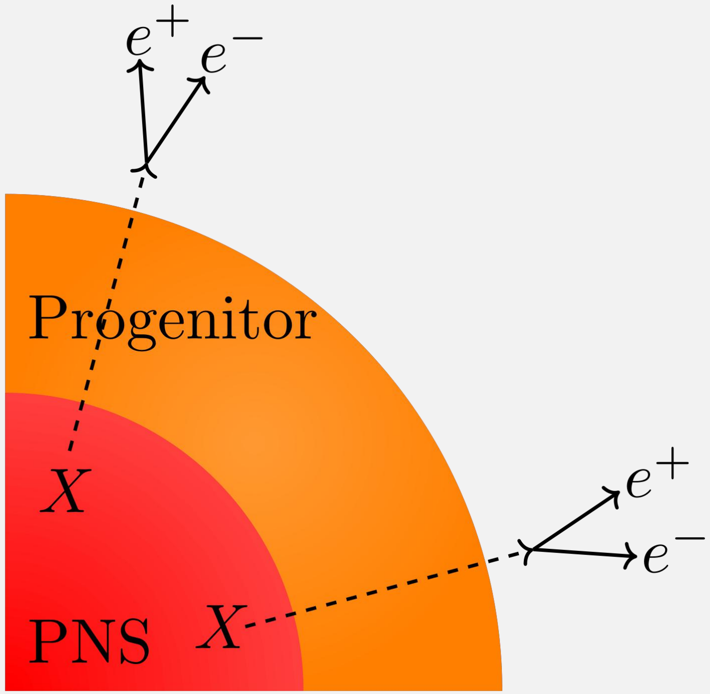
After FIPs (X) produced inside a proto-neutron star (PNS)

Decay inside mantle → Energy trapped

Decay outside mantle → Energy escaped

Constraint from low-energy SN





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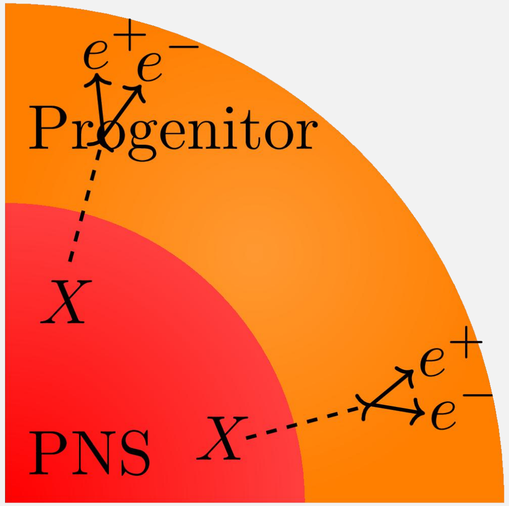
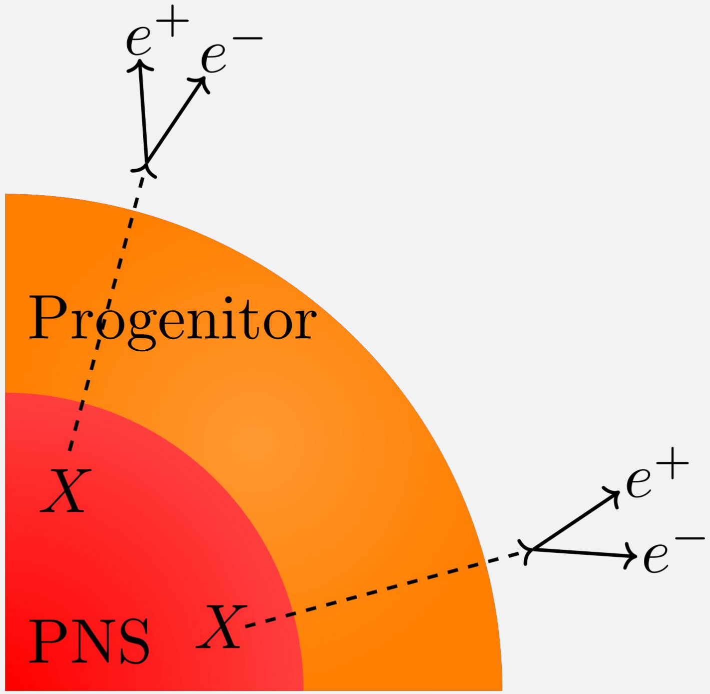


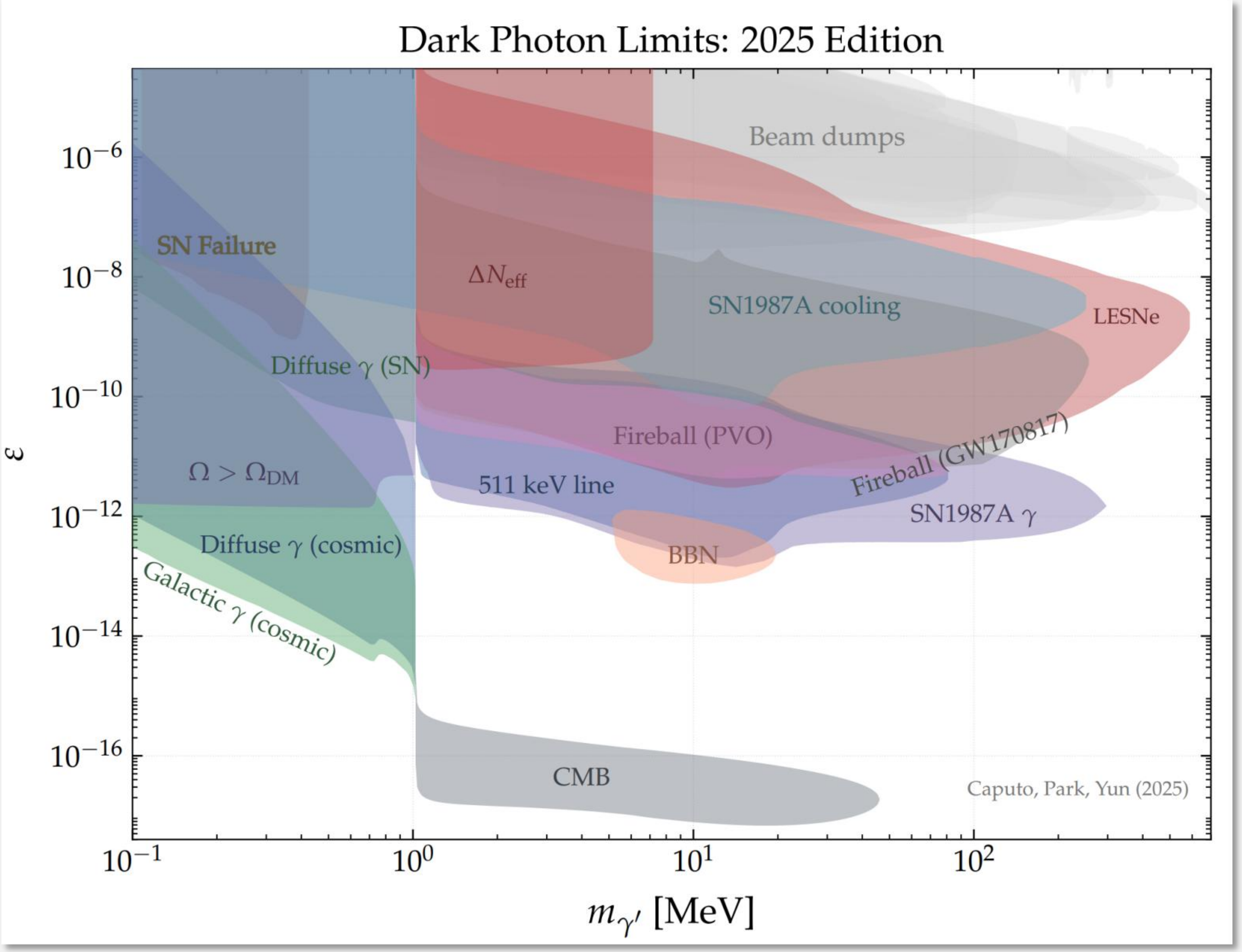
Decay outside mantle → Energy escaped

Constraint from cooling, fireball, galactic positron (511 keV), prompt gamma ray



Exsisting Constraints w/o CSM

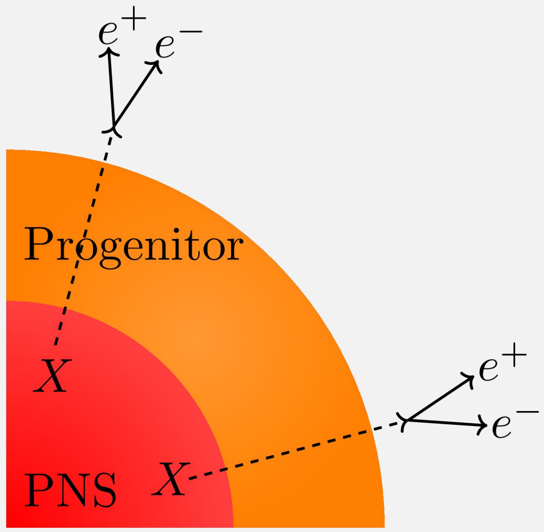
Institute for Basic Science



A. Caputo, J. Park, S. Yun
arXiv:2511.15785

CSM as A New Playground

However, CSM exists!



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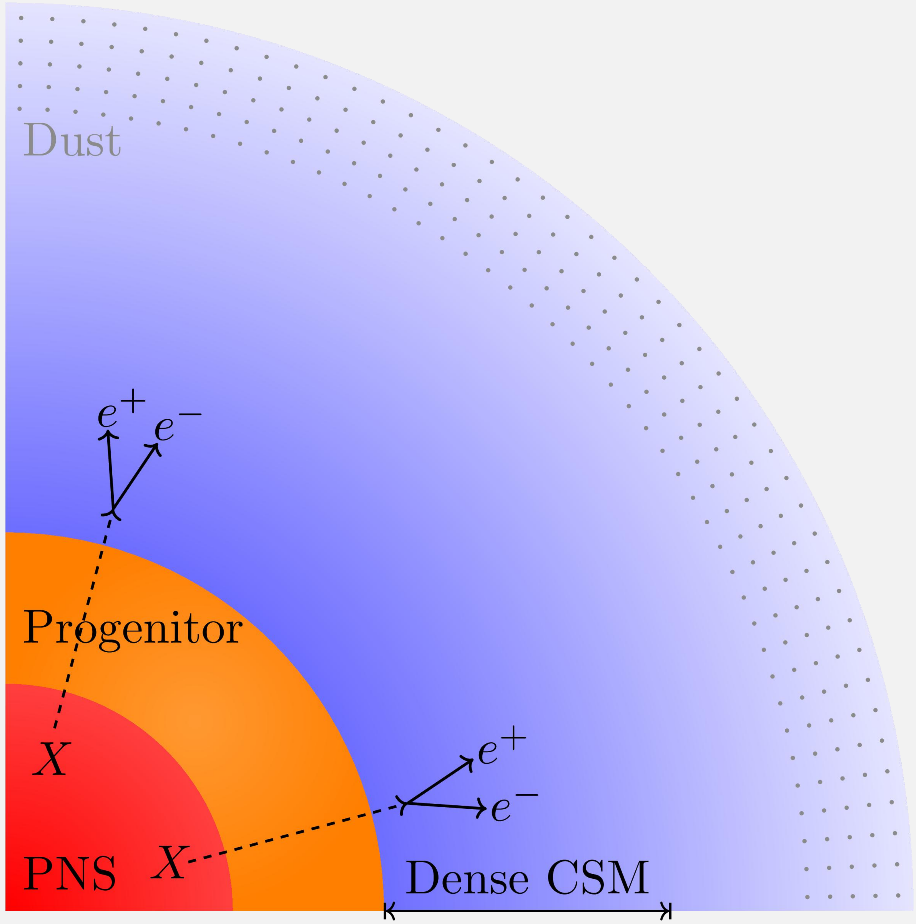

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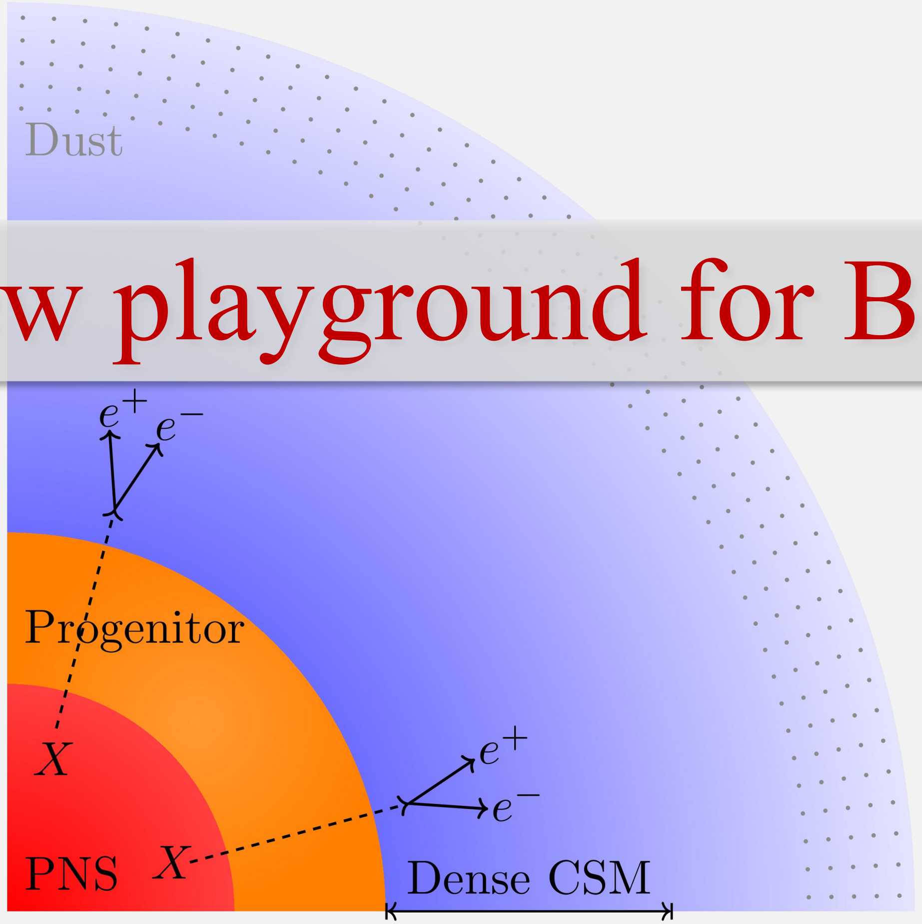
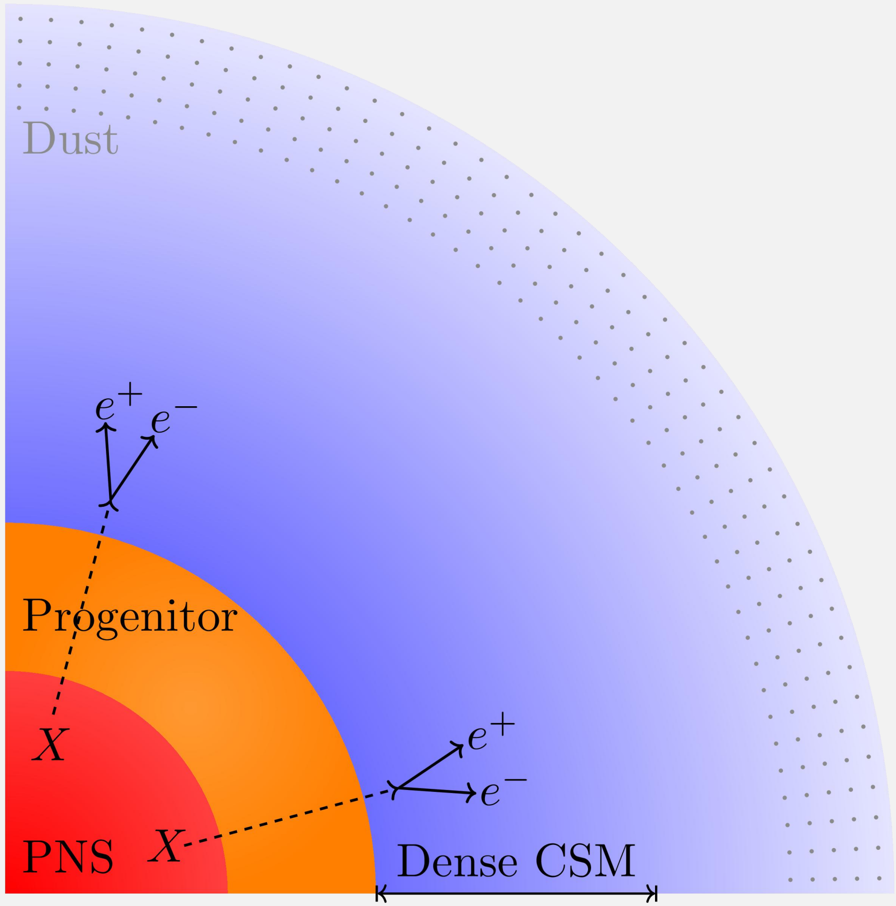


A new playground for BSM!

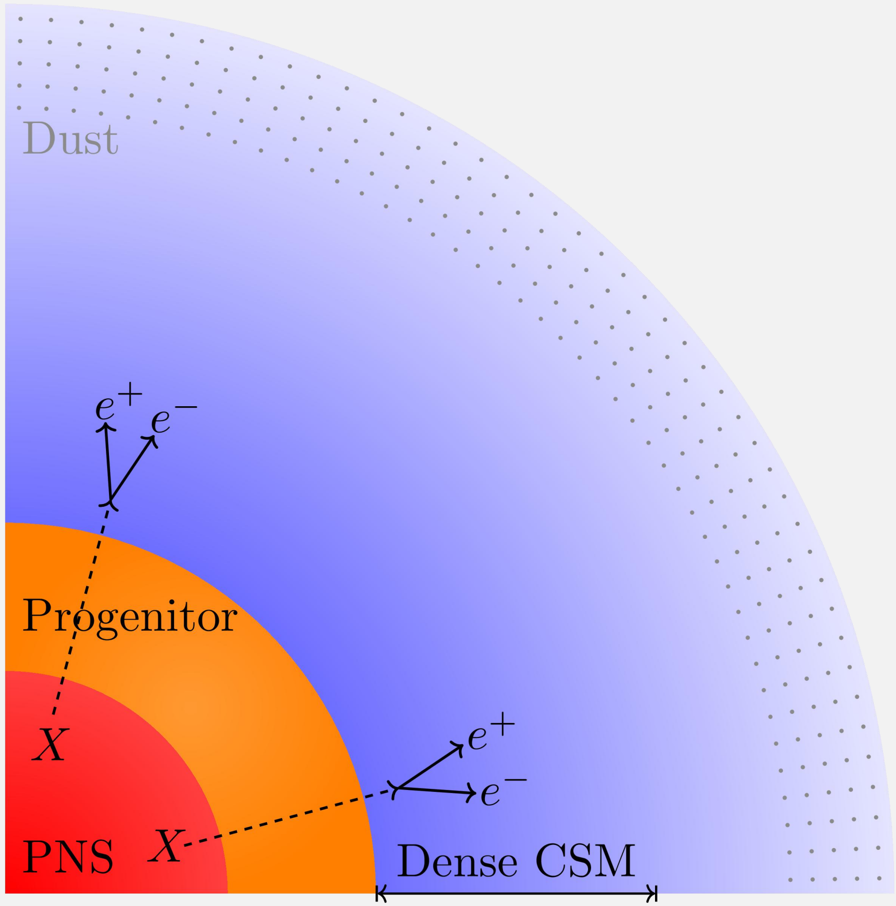
How CSM constrains on FIPs

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

$$\frac{dQ}{dr} = \underbrace{\int d\boxed{k} \frac{1}{\boxed{L_d}} \boxed{\frac{dN_{\gamma'}}{dk}} e^{-r/L_d}}_{\#\text{ of } e^\pm \text{ produced at } r} \underbrace{\sum_i \int dE_i \boxed{E_i} \boxed{\frac{dN_i}{dE_i}}}_{\text{integrated energy spectra}}$$

DP momentum

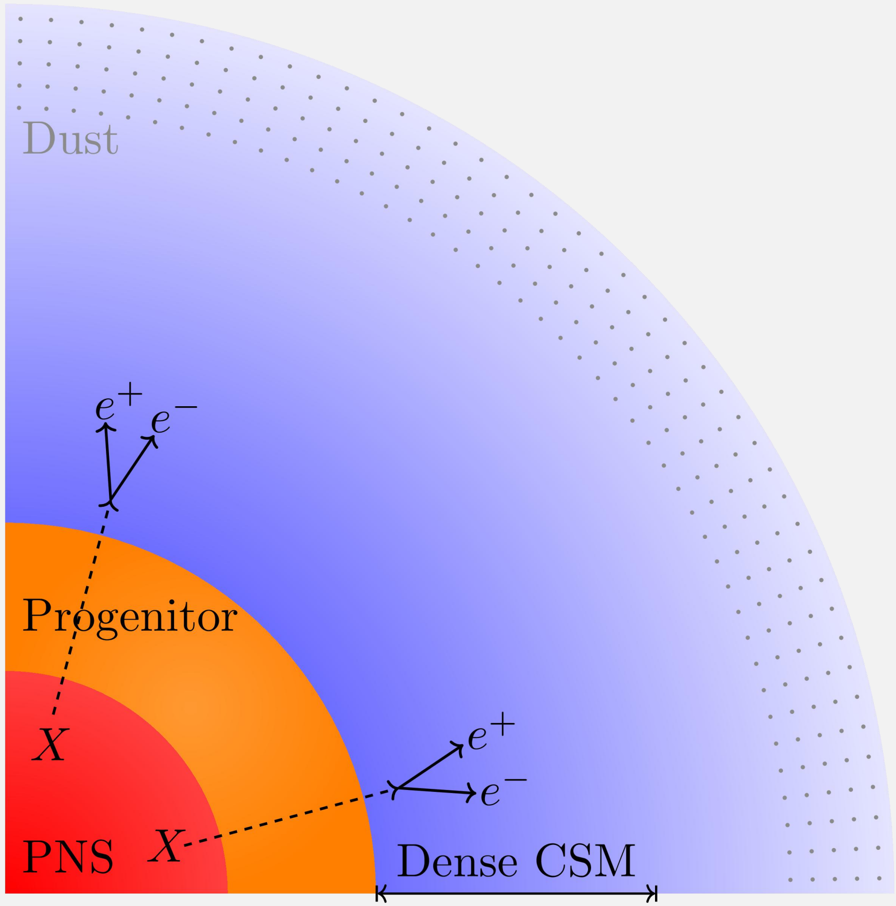
DP decay length

DP momentum distribution

electron/positron energy

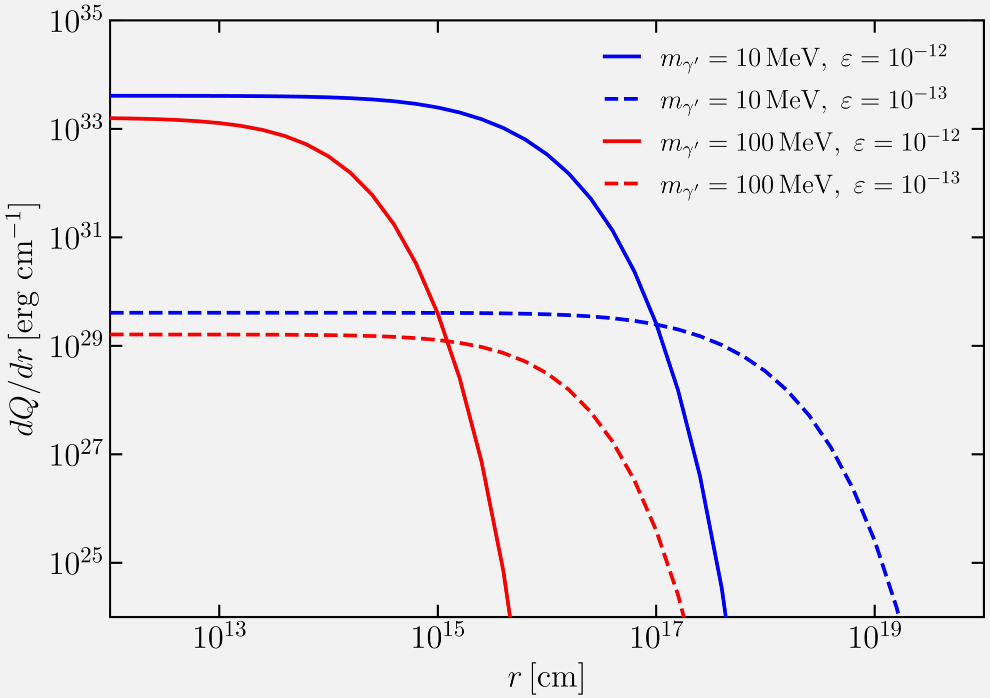
electron/positron energy distribution

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

$$\frac{dQ}{dr} = \int dk \frac{1}{L_d} \frac{d\mathcal{N}_{\gamma'}}{dk} e^{-r/L_d} \sum_i \int dE_i E_i \frac{dN_i}{dE_i}$$



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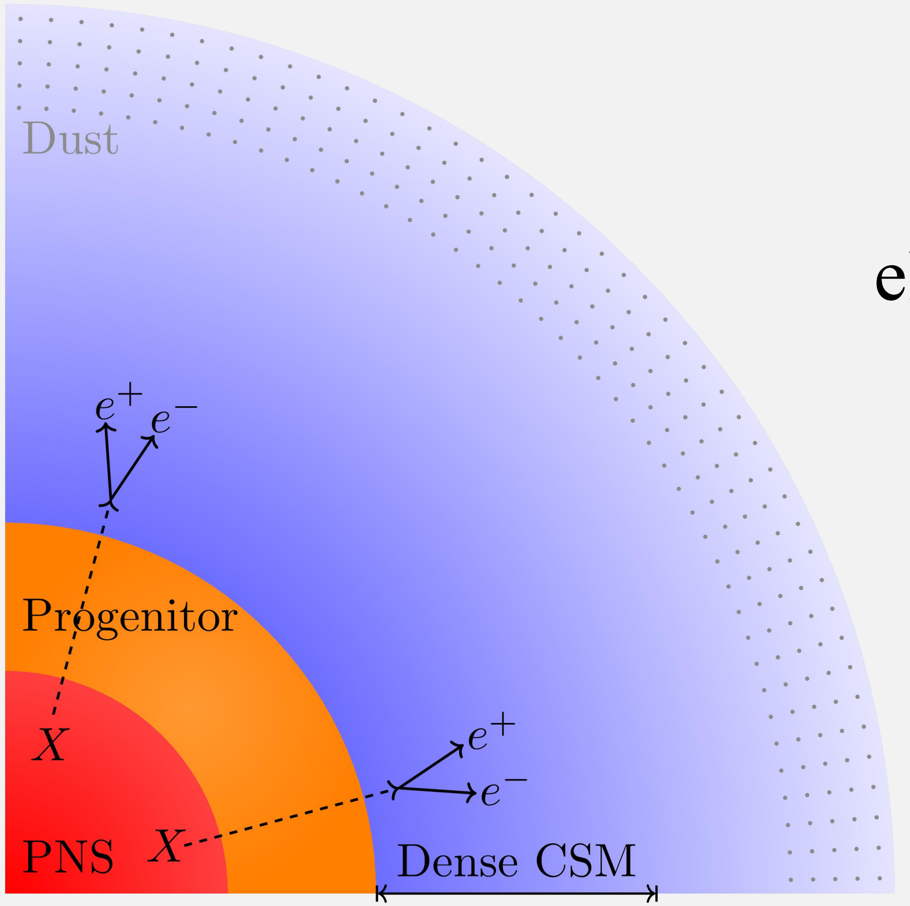
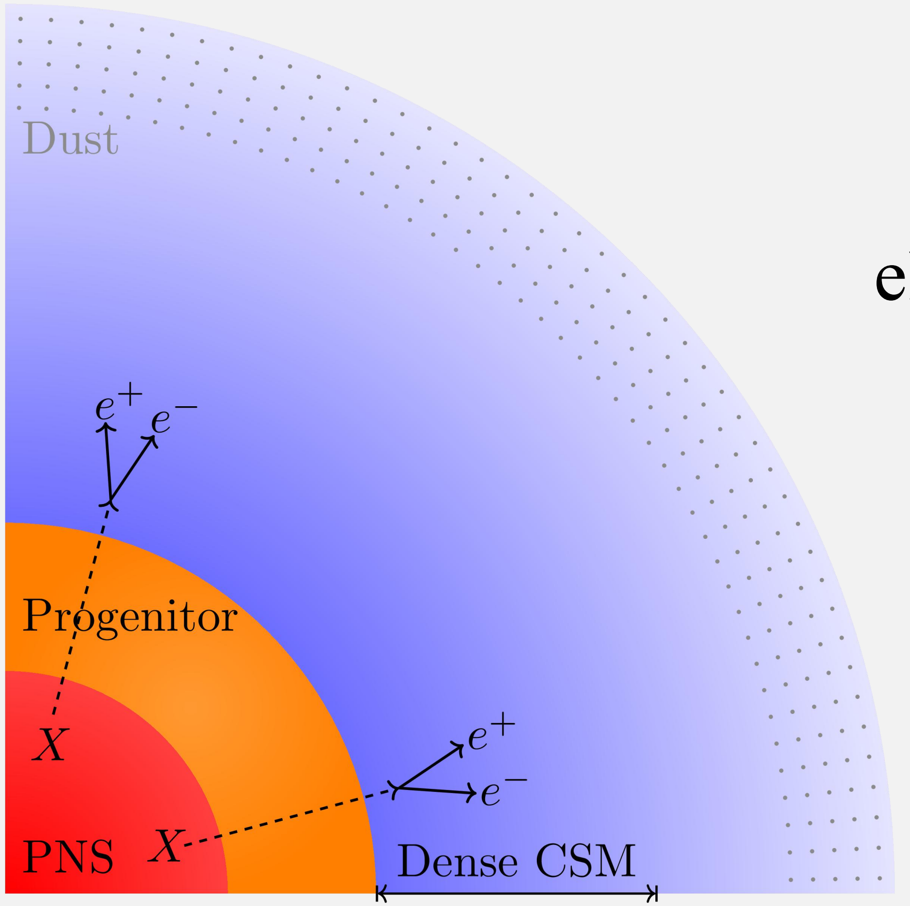


FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

Photosphere Induced by FIP Decay



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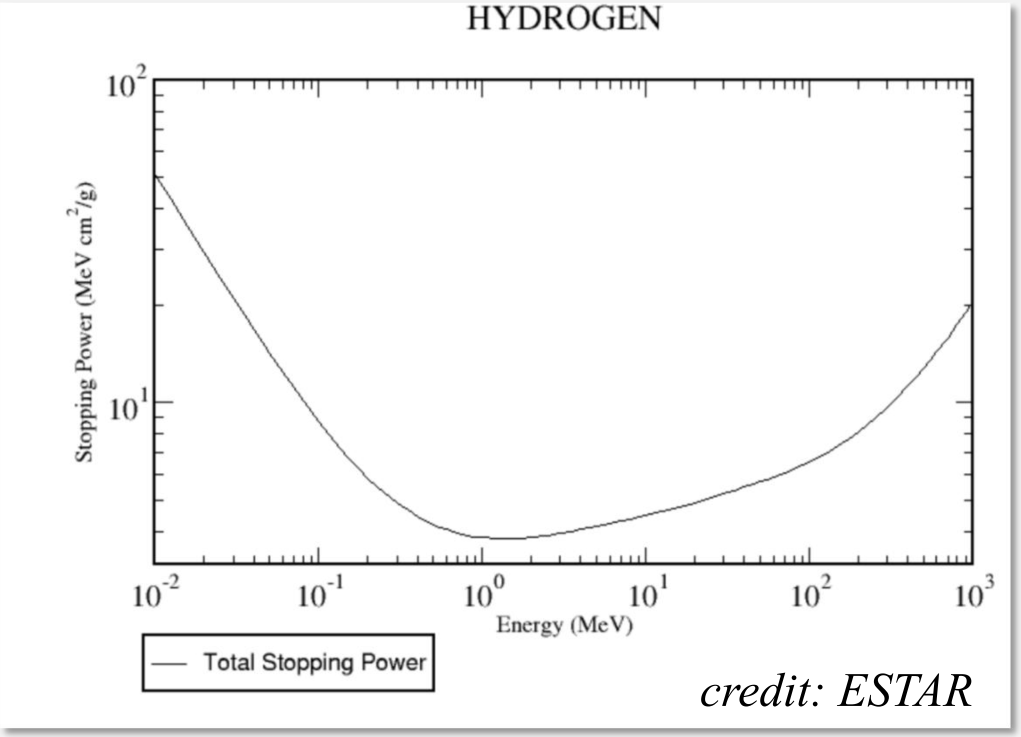
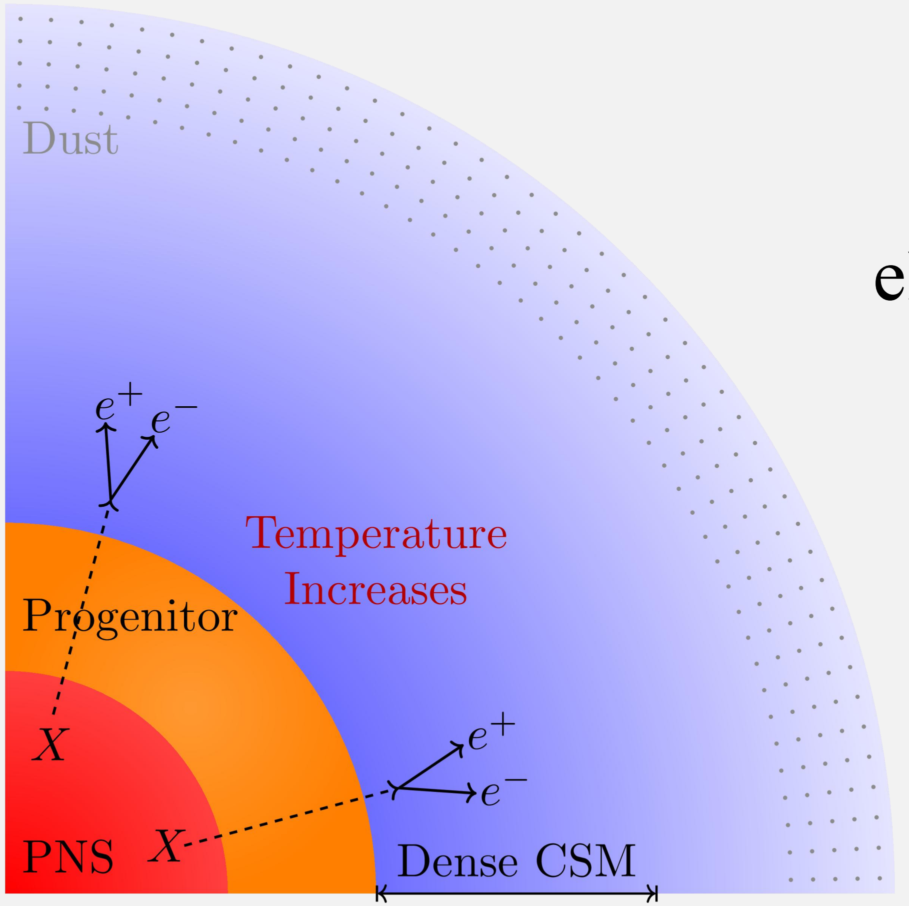


credit: ESTAR

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

CSM temparature increases

$$\frac{dQ}{dr}\frac{\boxed{\bar{\eta}}}{4\pi r^2} = \boxed{u_{\rm gas}} + \boxed{I_{\rm ion}} + \boxed{u_{\rm rad}}$$

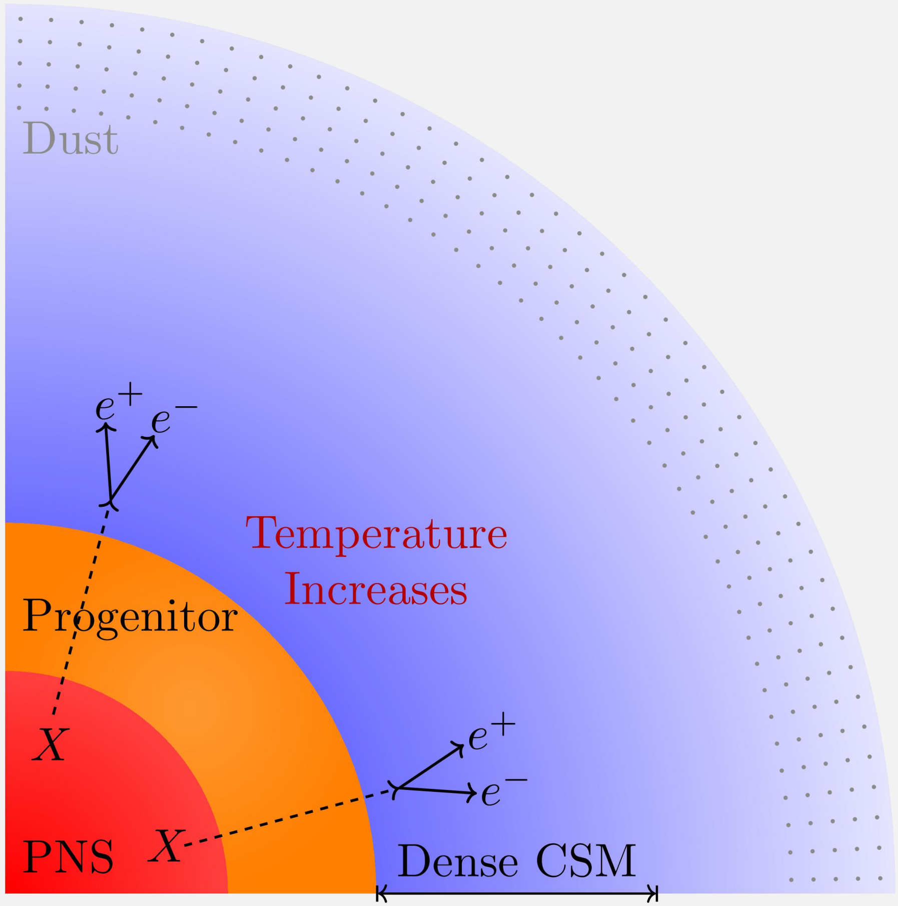
energy deposition efficiency

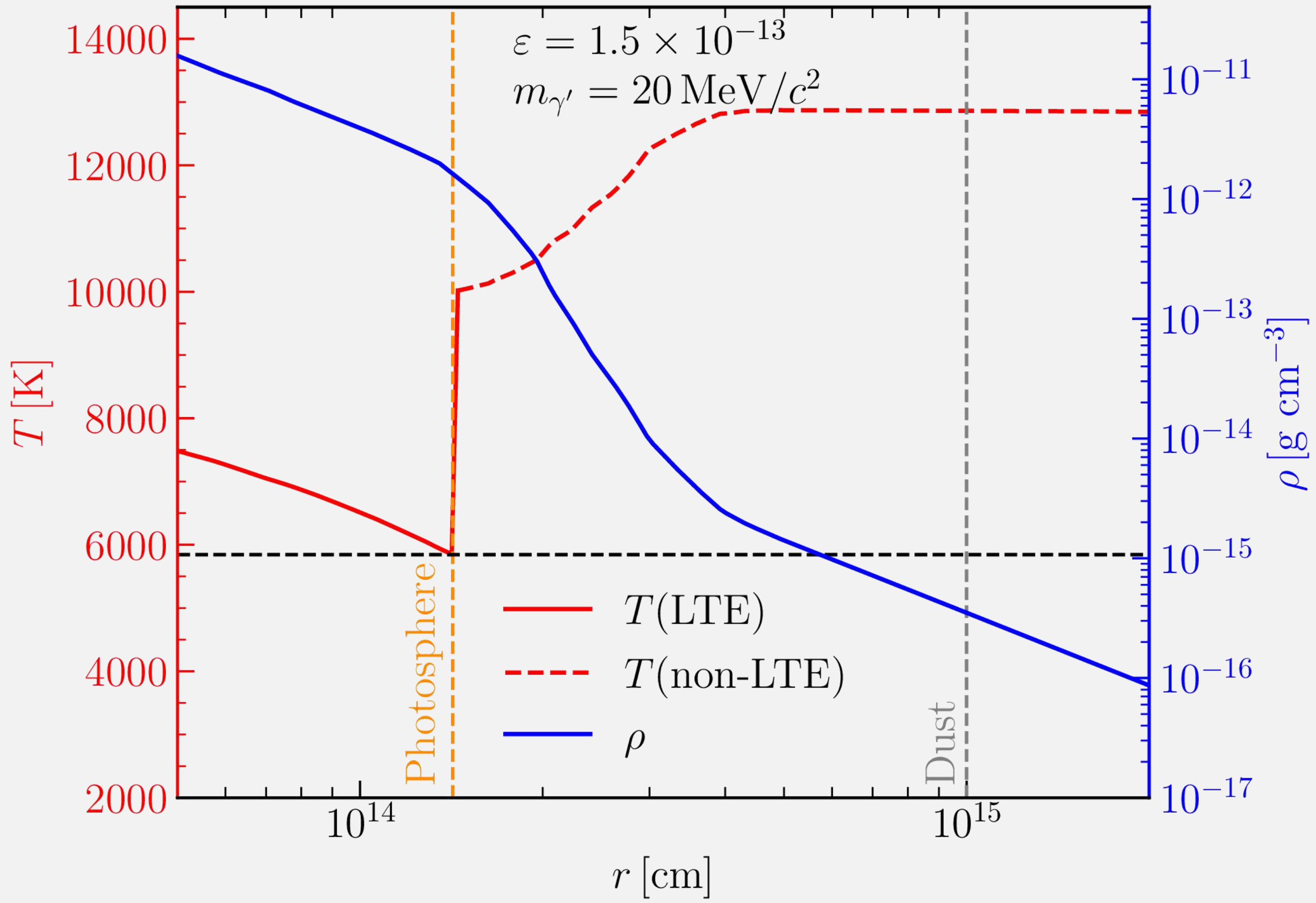
$u_{\rm gas} = (3/2)(n + n_e)k_B T$ internal energy density of ideal gas

ionization energy density

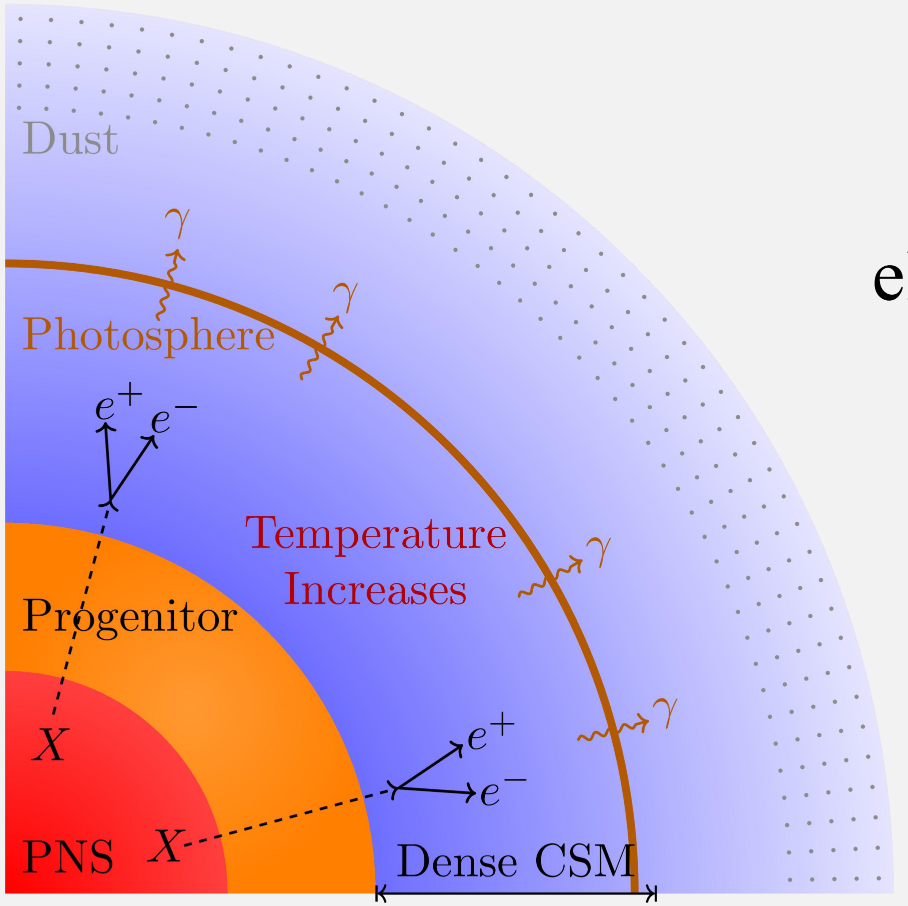
radiation energy density

Photosphere Induced by FIP Decay





Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

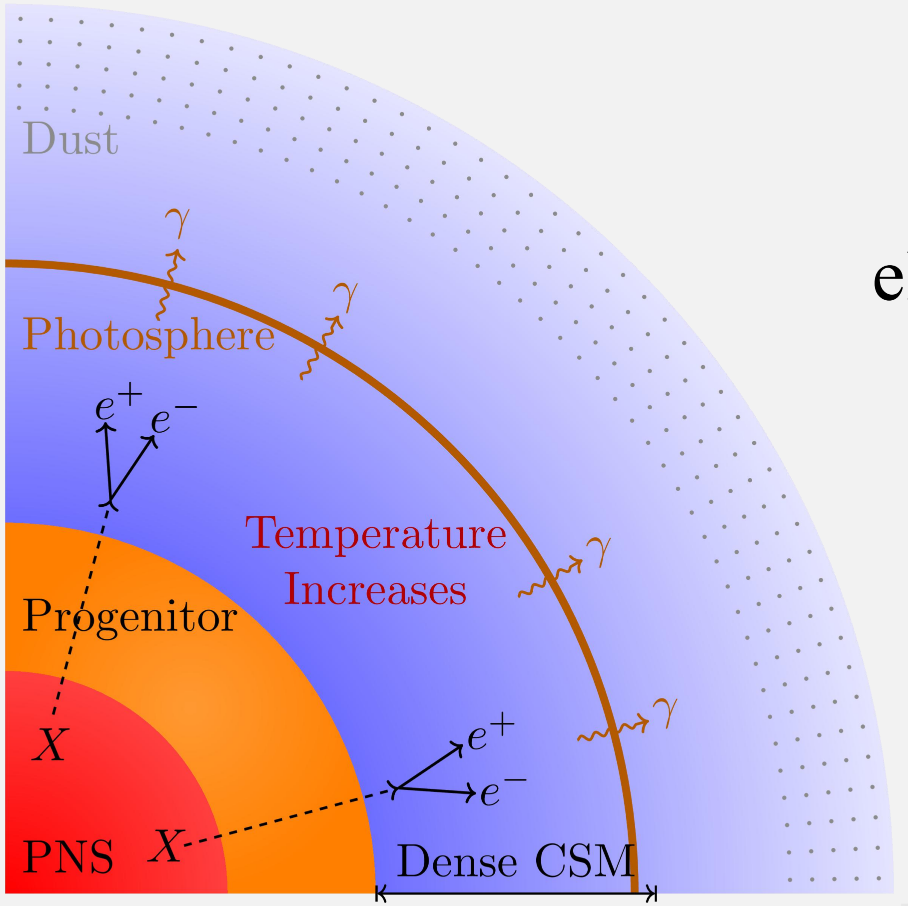
CSM temparature increases

↓

extra blackbody (BB) emission

$$L_{\rm BB} \simeq 4\pi r_{\rm ph}^2 \sigma_{\rm SB} T_{\rm ph}^4$$

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

↓

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↓

extra blackbody (BB) emission

$$L_{\rm BB} \simeq 4\pi r_{\rm ph}^2 \sigma_{\rm SB} T_{\rm ph}^4$$

constrained by observations!

SN 2023ixf as A Case Study

Inside the nearby galaxy Messier 101, with a distance ~ 6.85 Mpc

Review

SN 2023ixf: The Closest Supernova of the Decade

Wynn Jacobson-Galán[1,2]

nature

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Article | Published: 27 March 2024

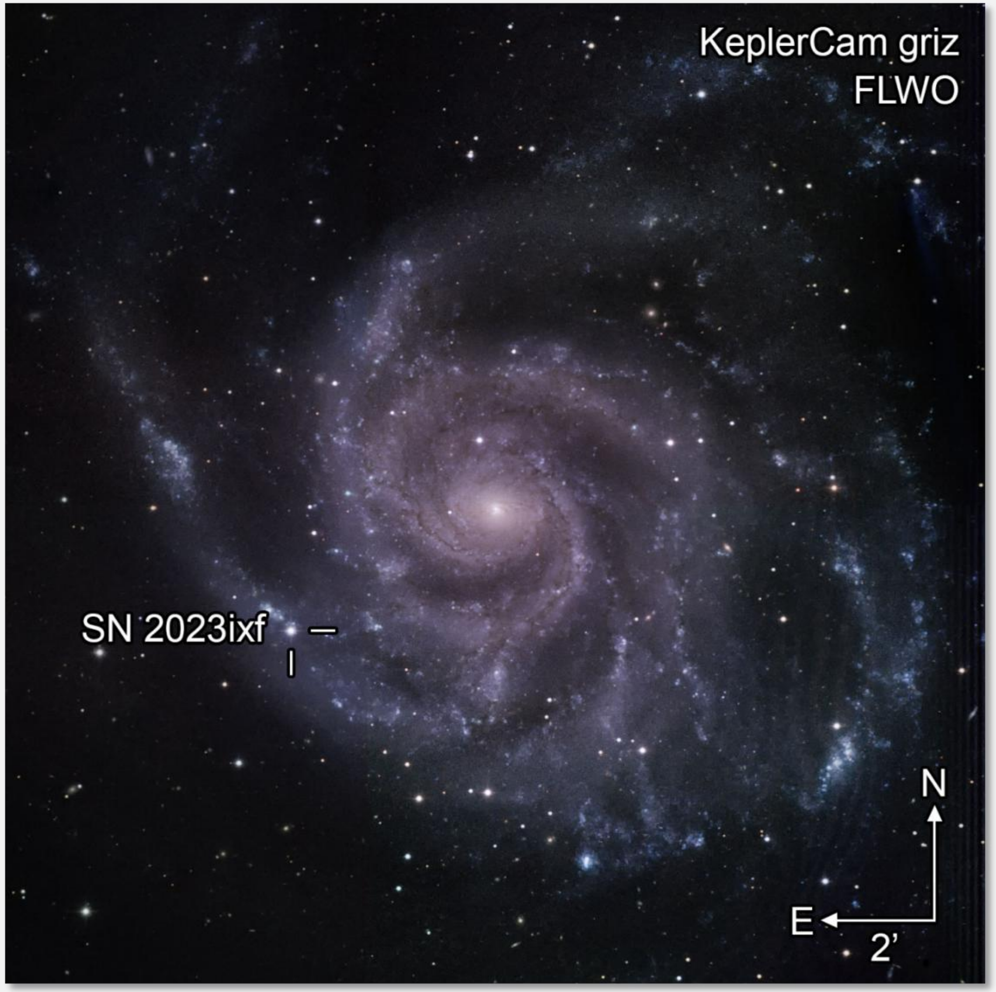
The complex circumstellar environment of supernova 2023ixf

E. A. Zimmerman, I. Irani, P. Chen, A. Gal-Yam, S. Schulze, D. A. Perley, J. Sollerman, A. V. Filippenko, T. Shenar, O. Yaron, S. Shahaf, R. J. Bruch, E. O. Ofek, A. De Cia, T. G. Brink, Y. Yang, S. S. Vasylyev, S. Ben Ami, M. Aubert, A. Badash, J. S. Bloom, P. J. Brown, K. De, G. Dimitriadis, ... K. Zhang + Show authors

Nature **627**, 759–762 (2024) | Cite this article

4259 Accesses | **121** Citations | **205** Altmetric | Metrics

E.A. Zimmerman et al. Nature 627 (2024) 759

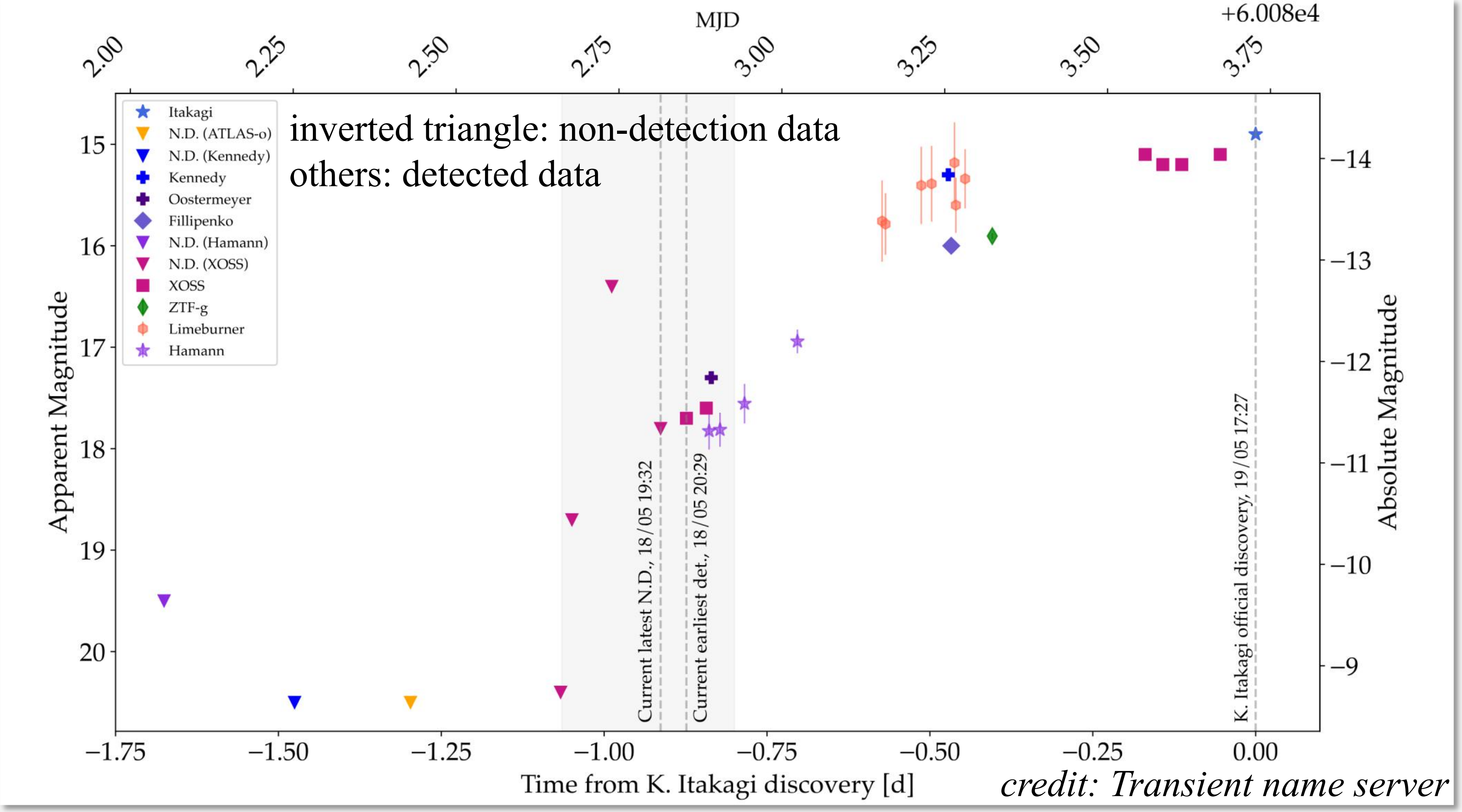


credit: S. Gomez/STScI

SN 2023ixf as A Case Study

Institute for Basic Science

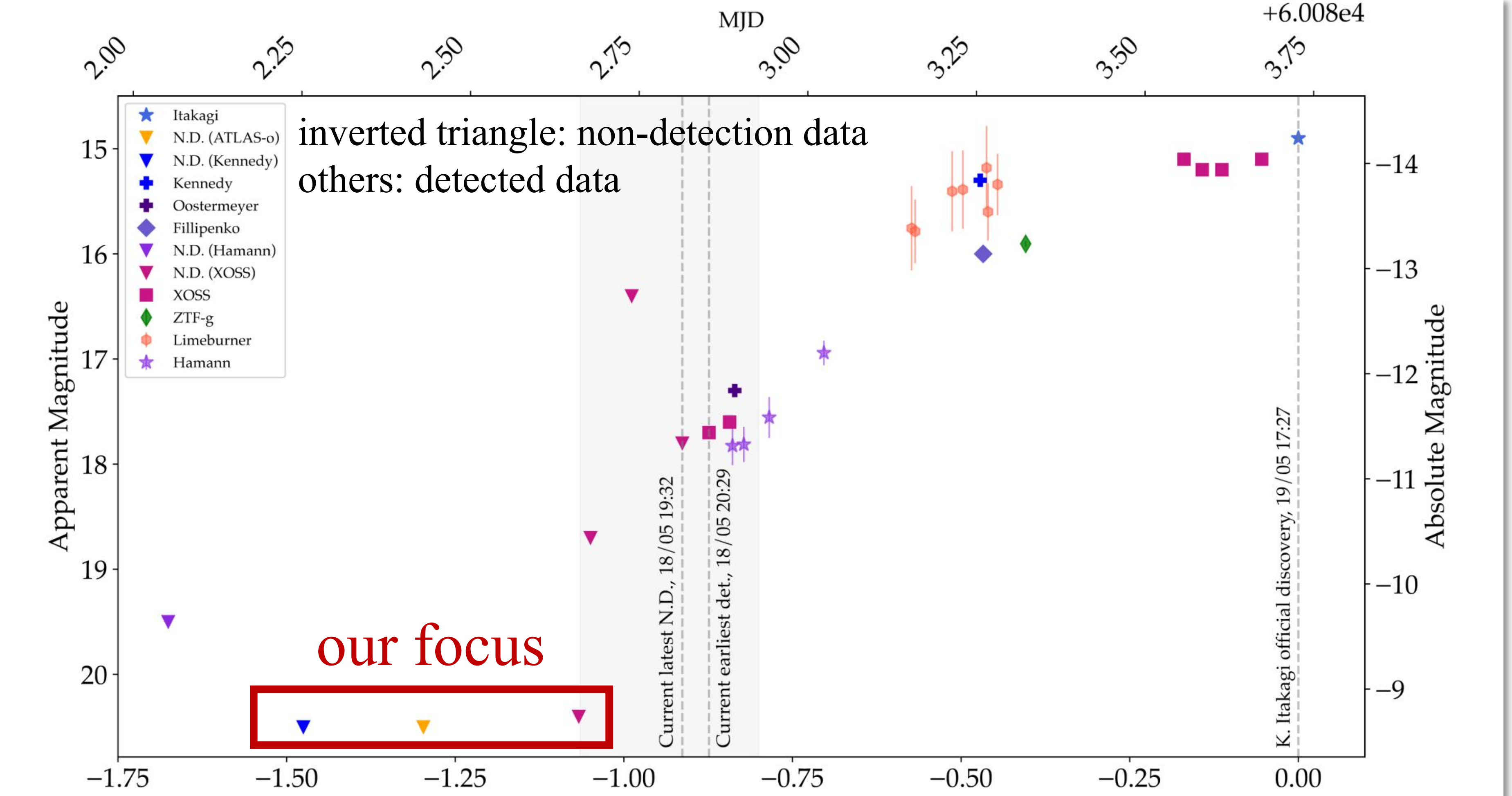
Early-time observations of SN 2023ixf



credit: Transient name server

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



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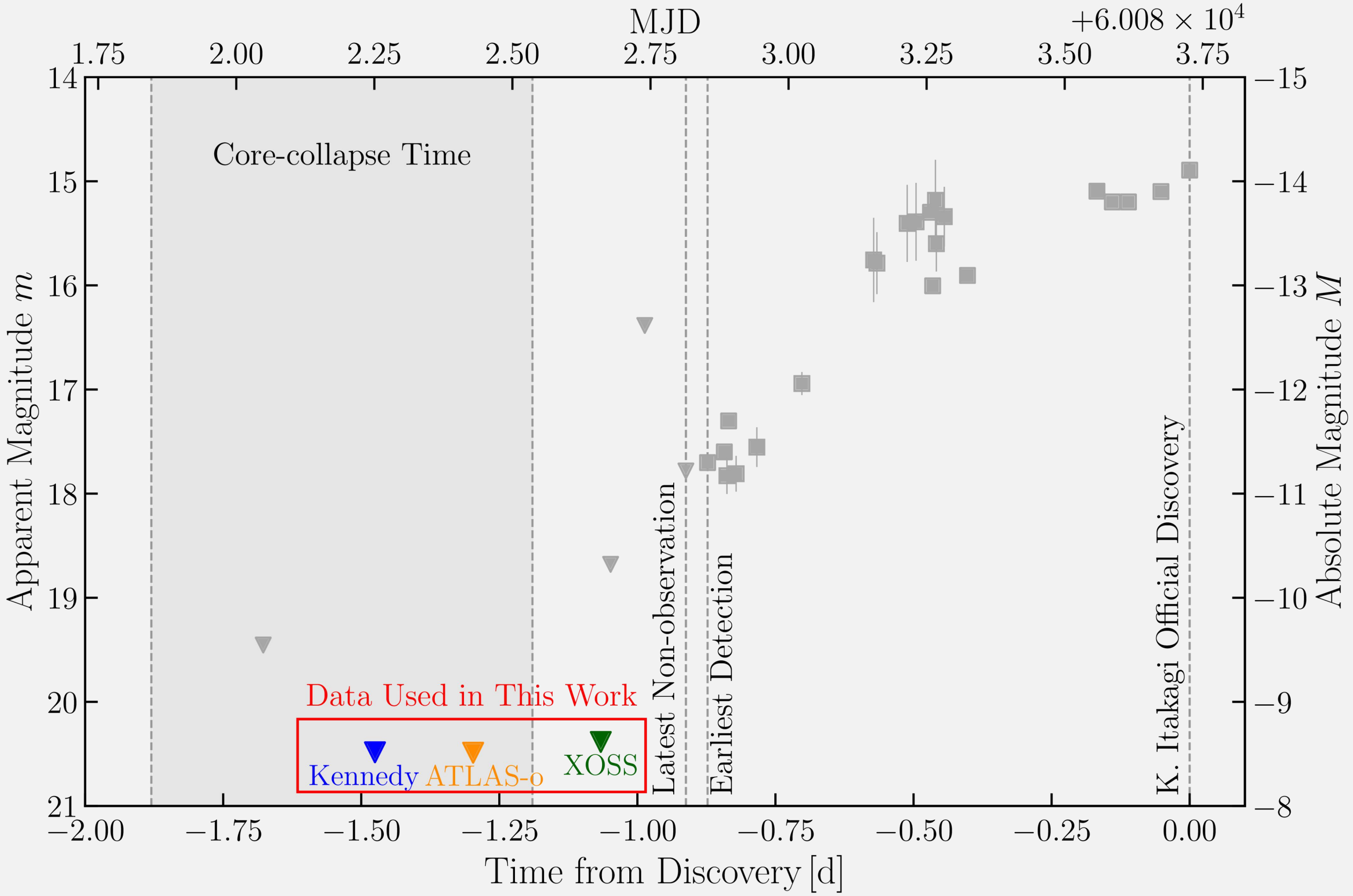
SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

$$\frac{L}{L'_\odot} = 10^{0.4(M'_\odot - M)}$$

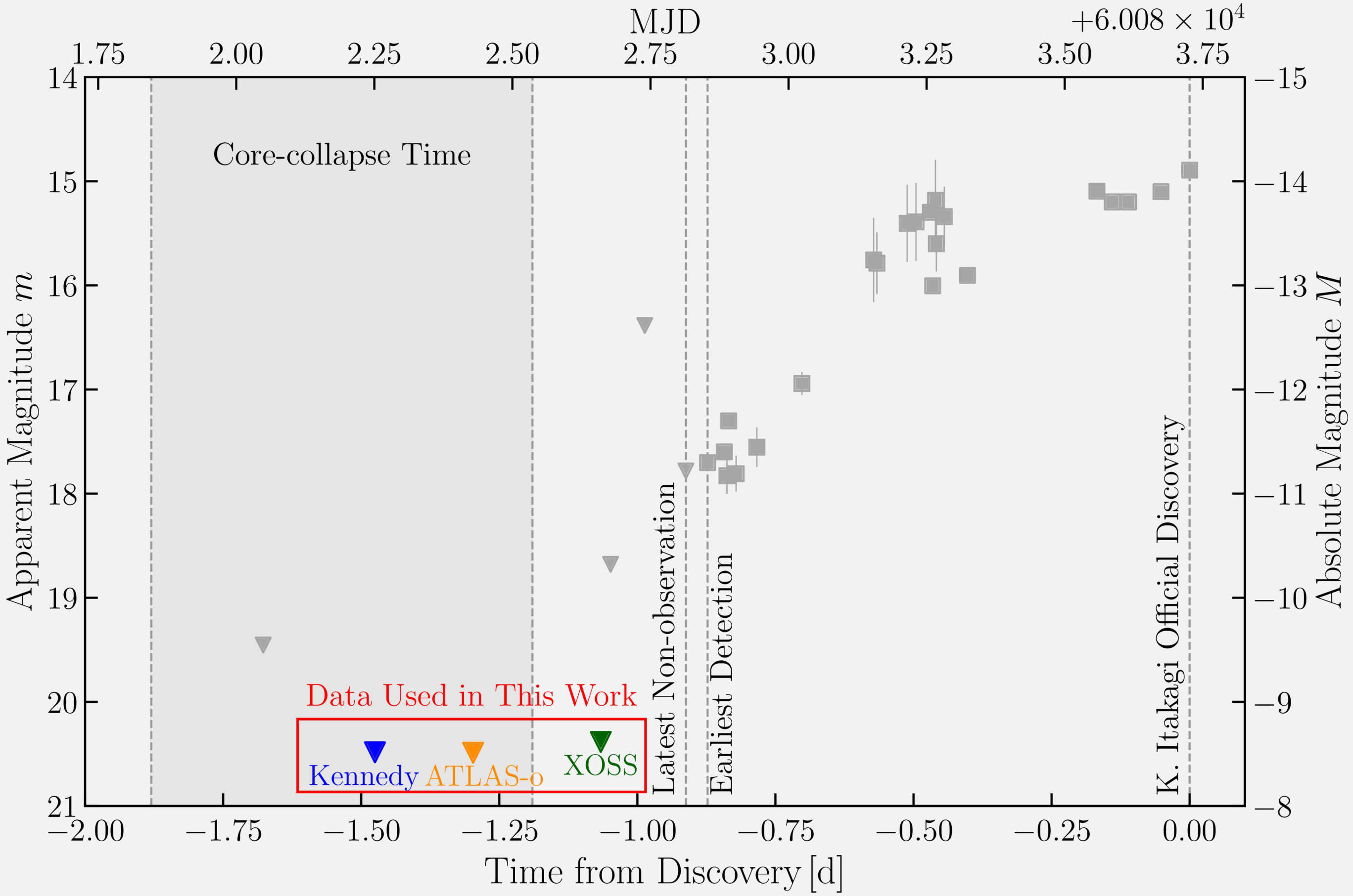
$L'_\odot$: solar luminosity in $400 - 900\,\mathrm{nm}$

$M'_\odot$: solar absolute magnitude in $400 - 900\,\mathrm{nm}$

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
PRL 26

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



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$$L \leq 8.16 \times 10^{38}\,\mathrm{erg\,s^{-1}}$$

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
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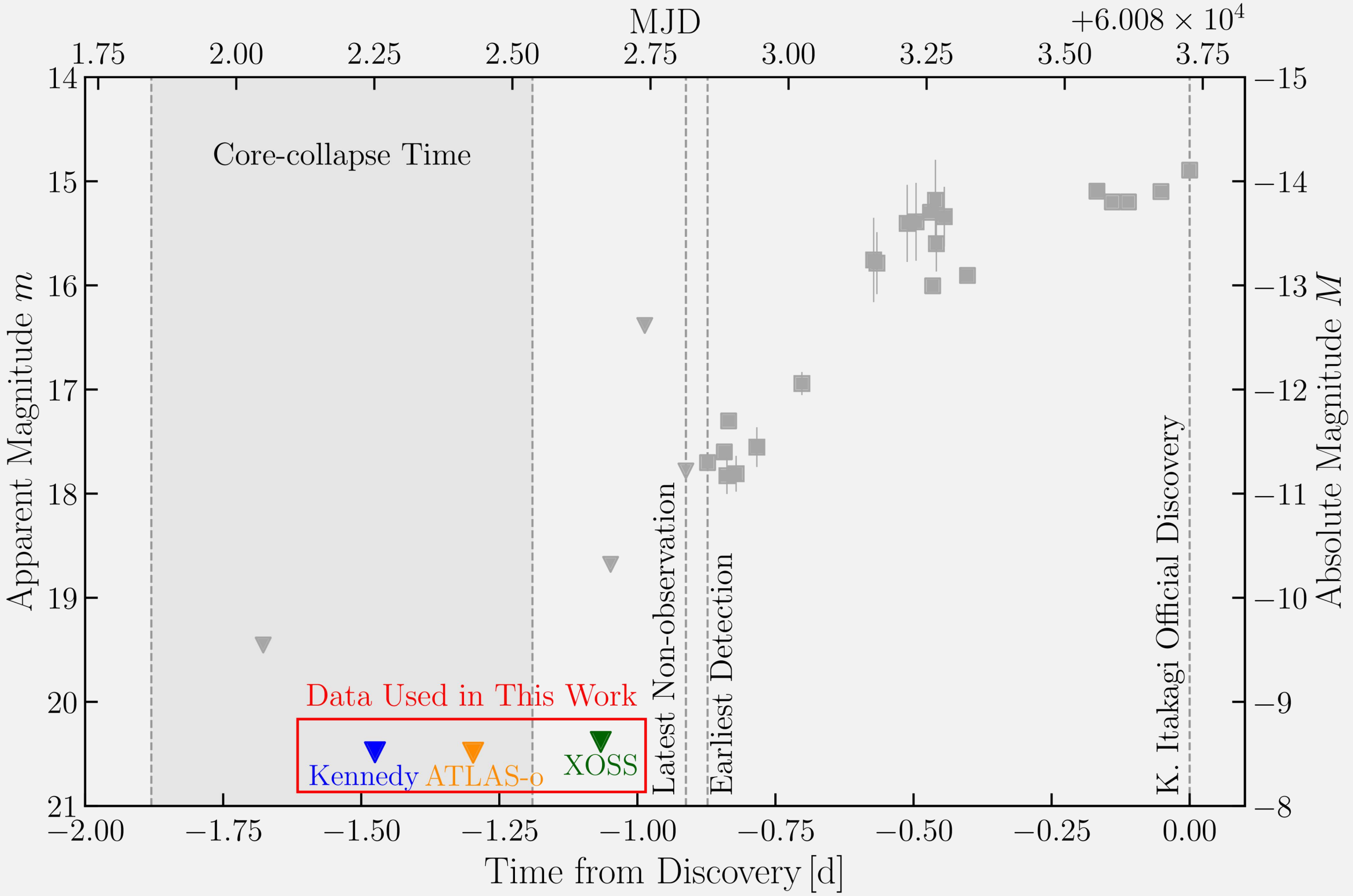

optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

$$L \leq 8.16 \times 10^{38}\,\mathrm{erg\,s^{-1}}$$

our **conservative** criteria:

$$\iota(T_{\rm ph}) L_{\rm BB}(\varepsilon, m_{\gamma'}) \leq 8 \times 10^{39}\,\mathrm{erg\,s^{-1}}$$

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
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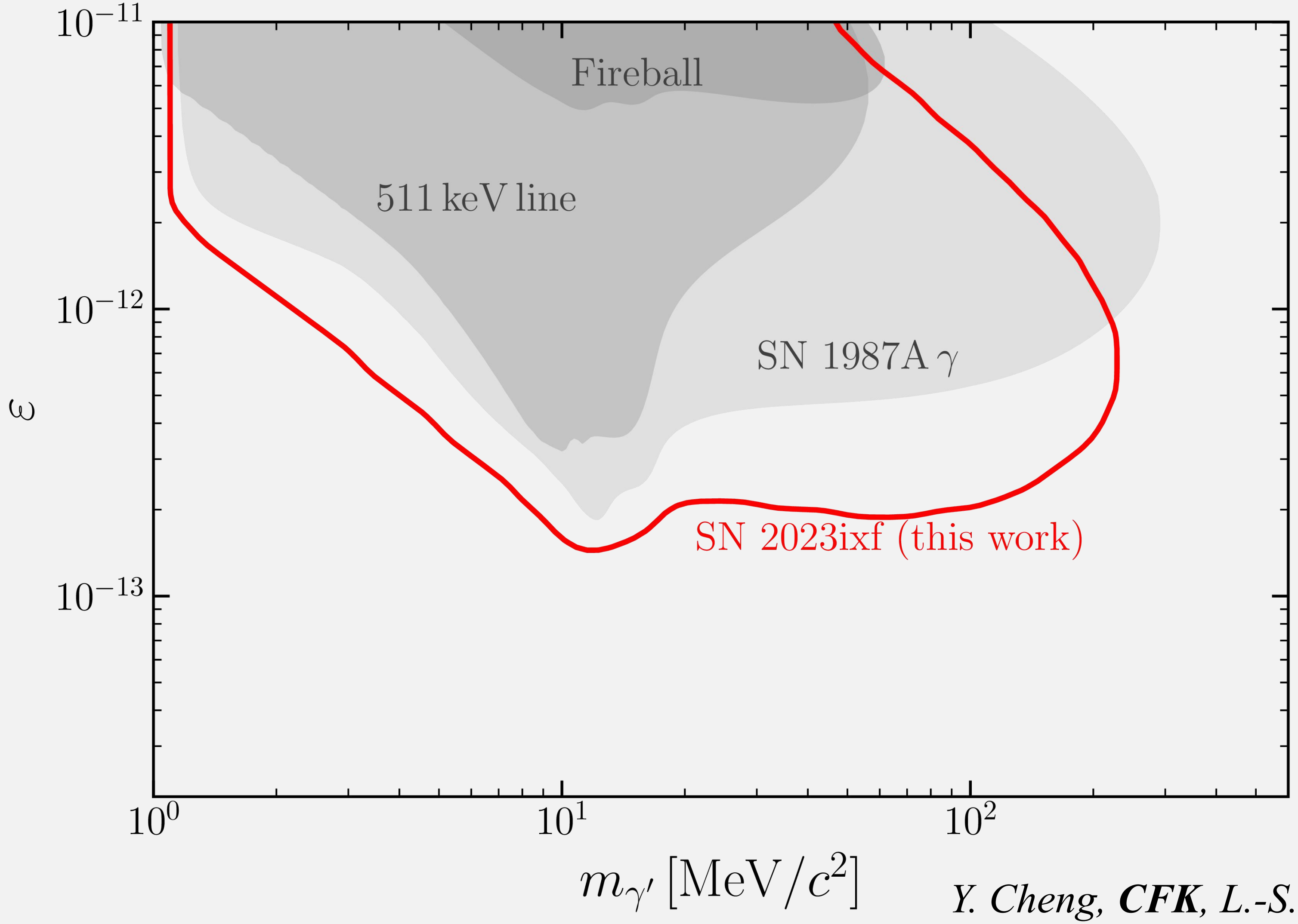
Constraint on DP (i)



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
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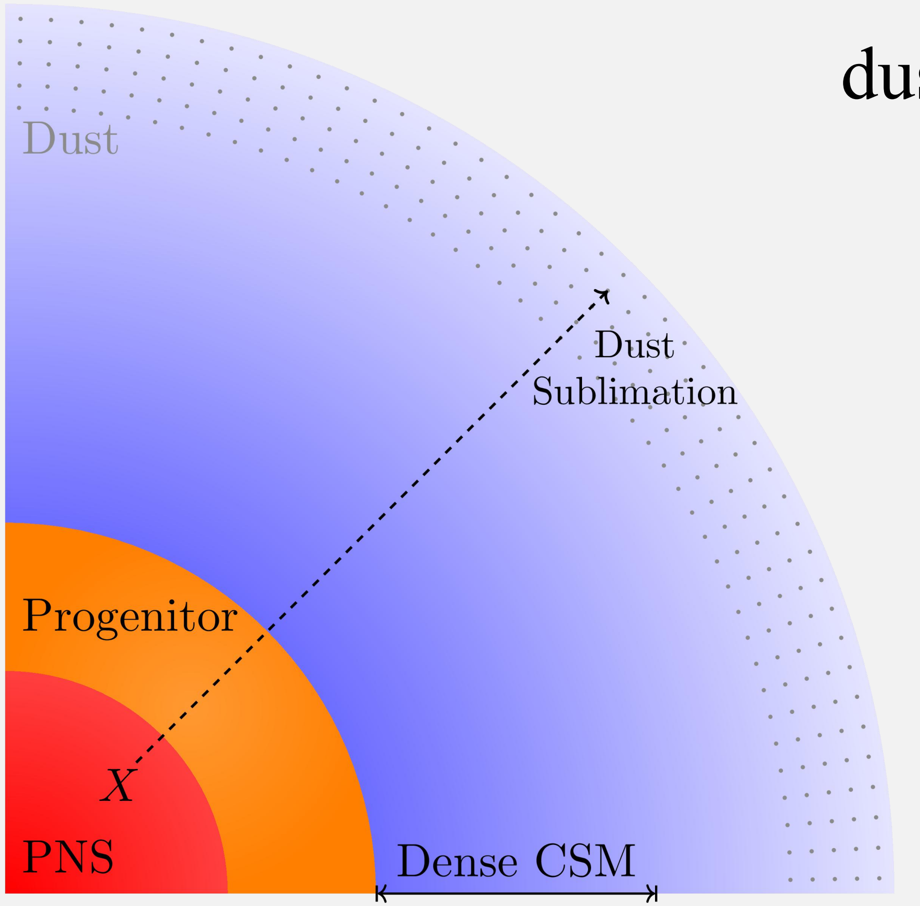
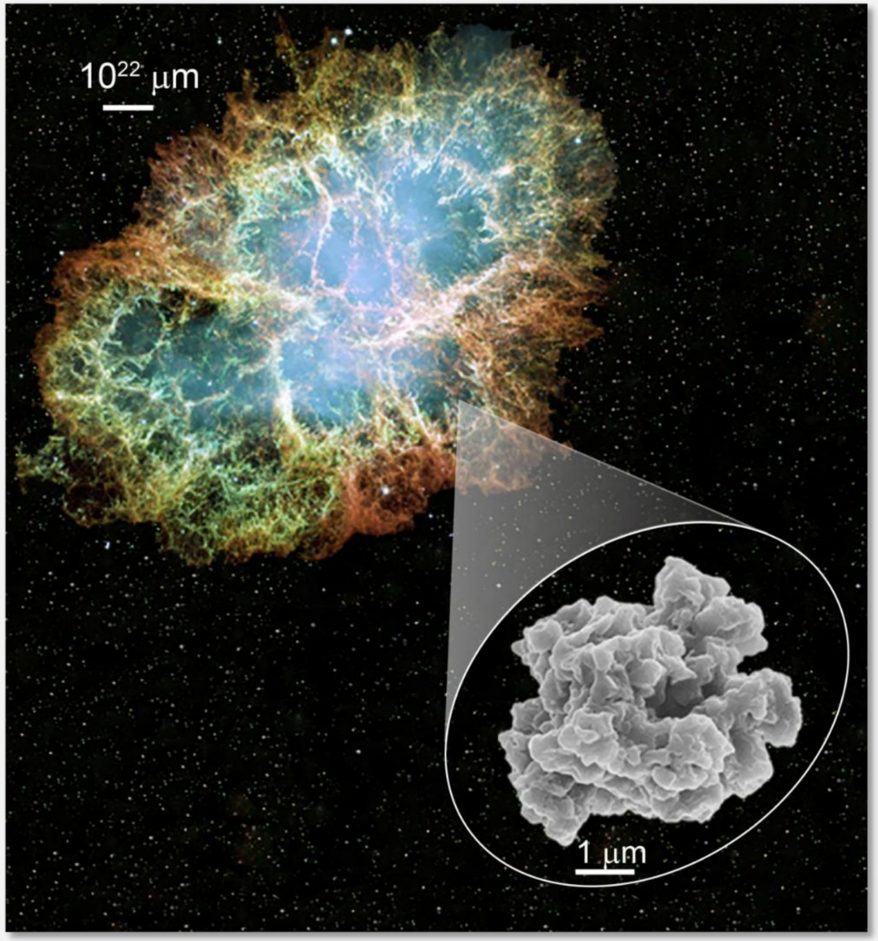
Dust Sublimation

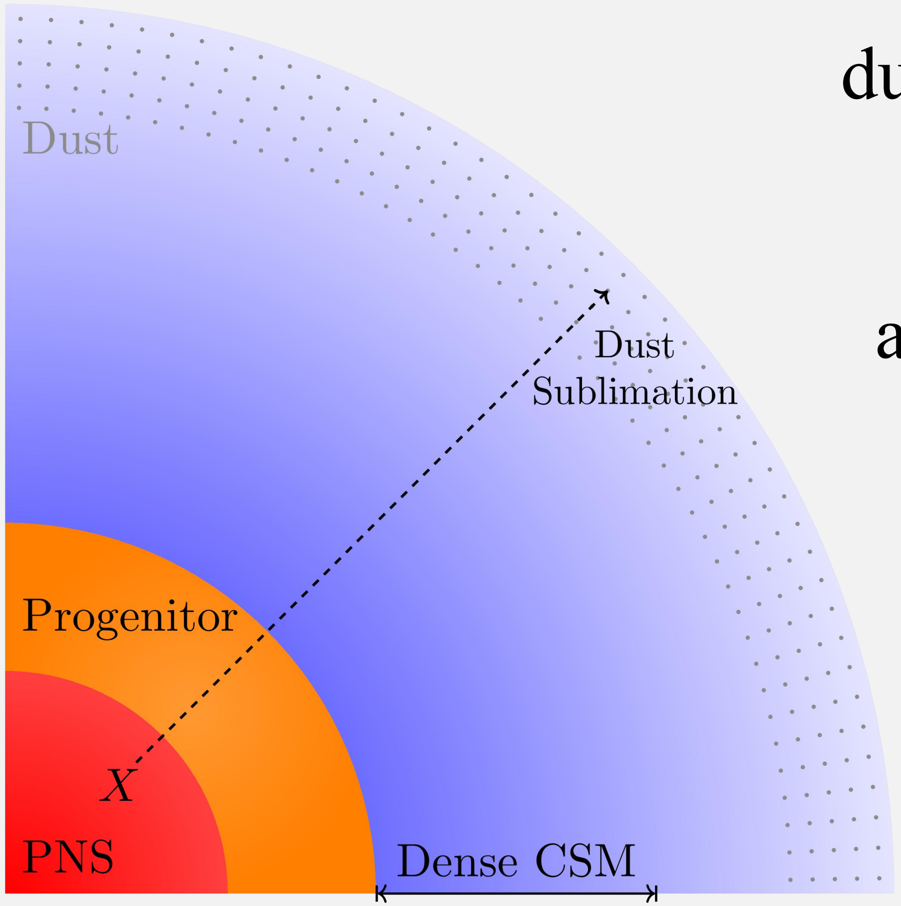


dust grains (molecules) exist in outer layer of CSM



credit: L. Nittler

Dust Sublimation

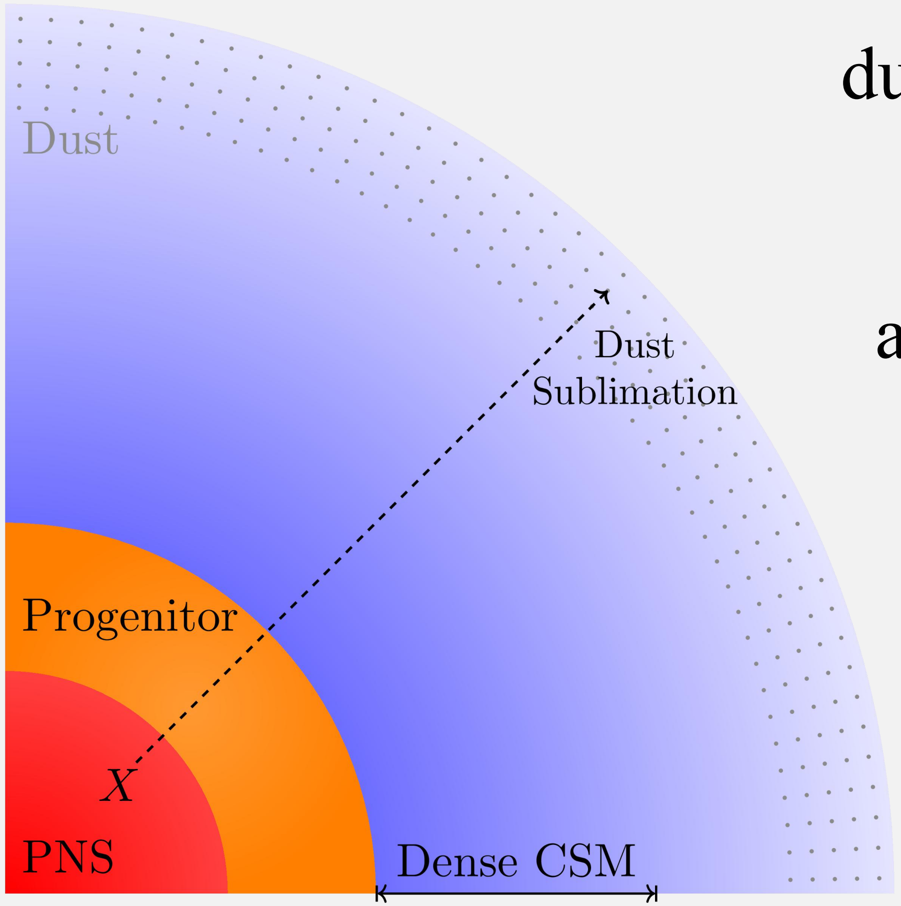


dust grains (molecules) exist in outer layer of CSM

↓

absorb optical photons and reprocess into infrared

Dust Sublimation



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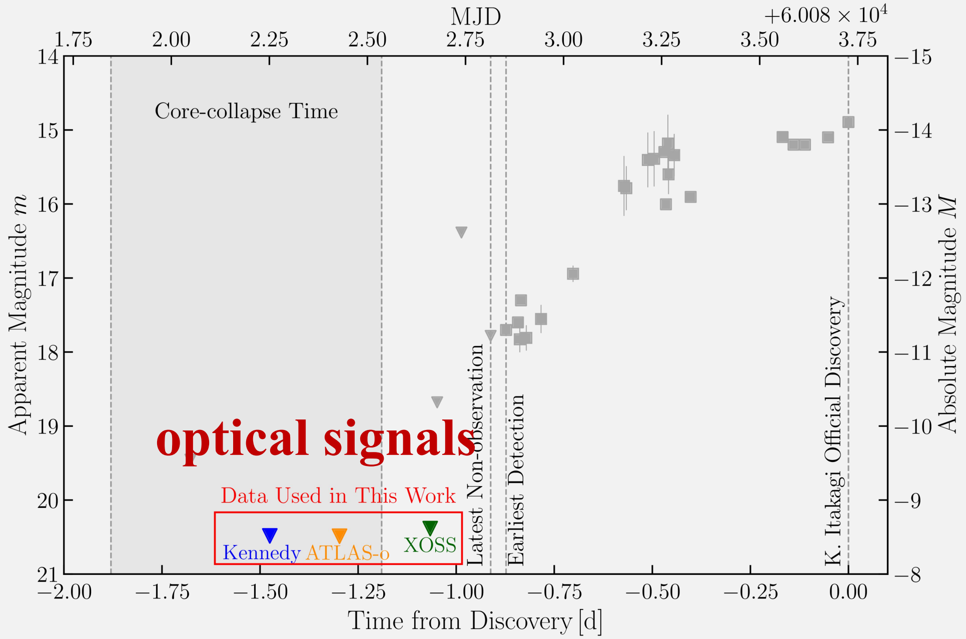
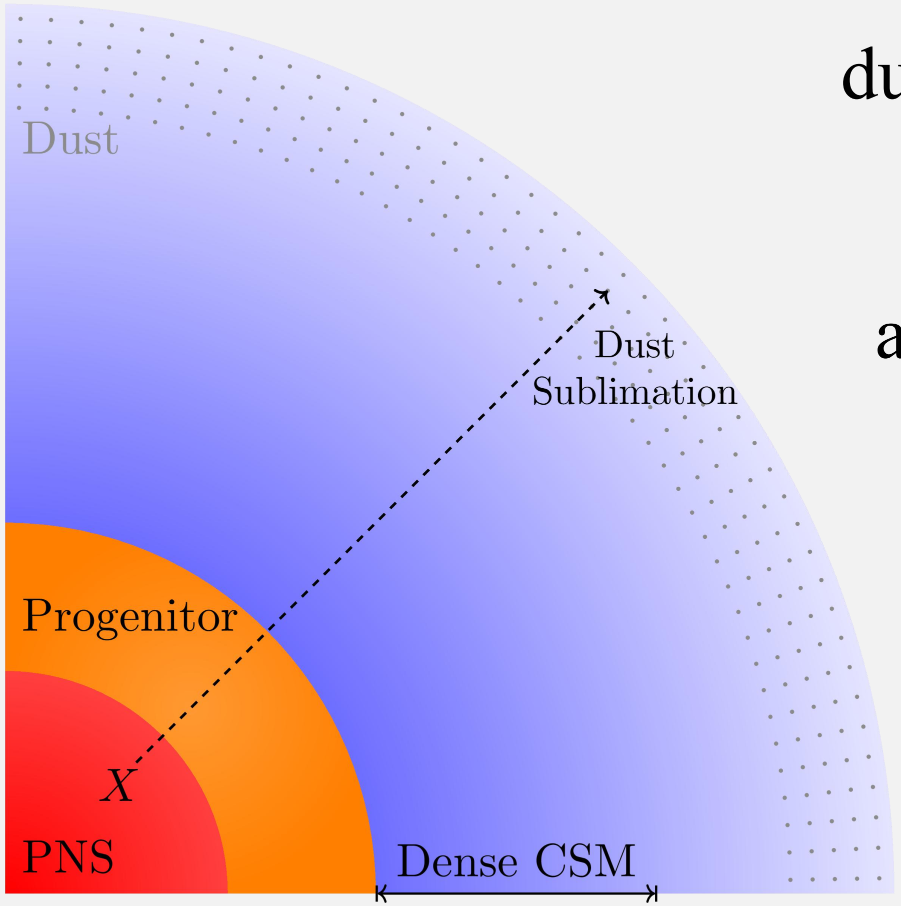


Dust Sublimation



dust grains (molecules) exist in outer layer of CSM

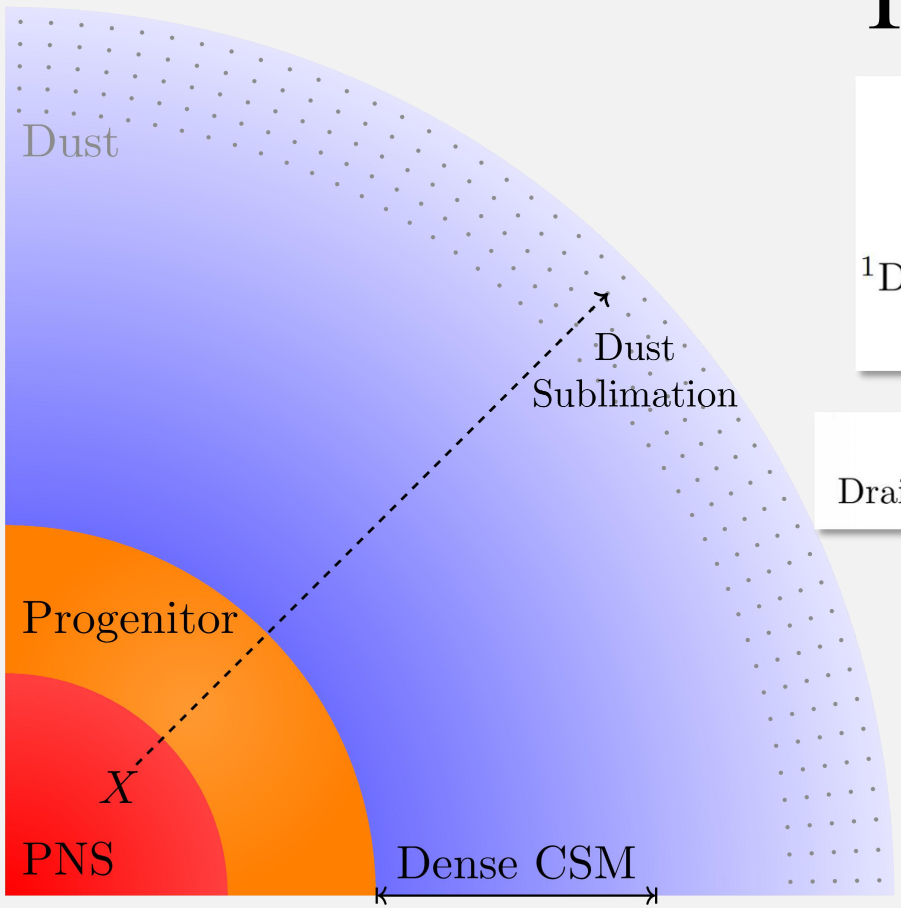
↓

absorb optical photons and reprocess into infrared

↓

an additional dust-destruction requirement

Dust Sublimation



How to destruct dust? Still heating!

Dust sublimation by GRBs and its implications

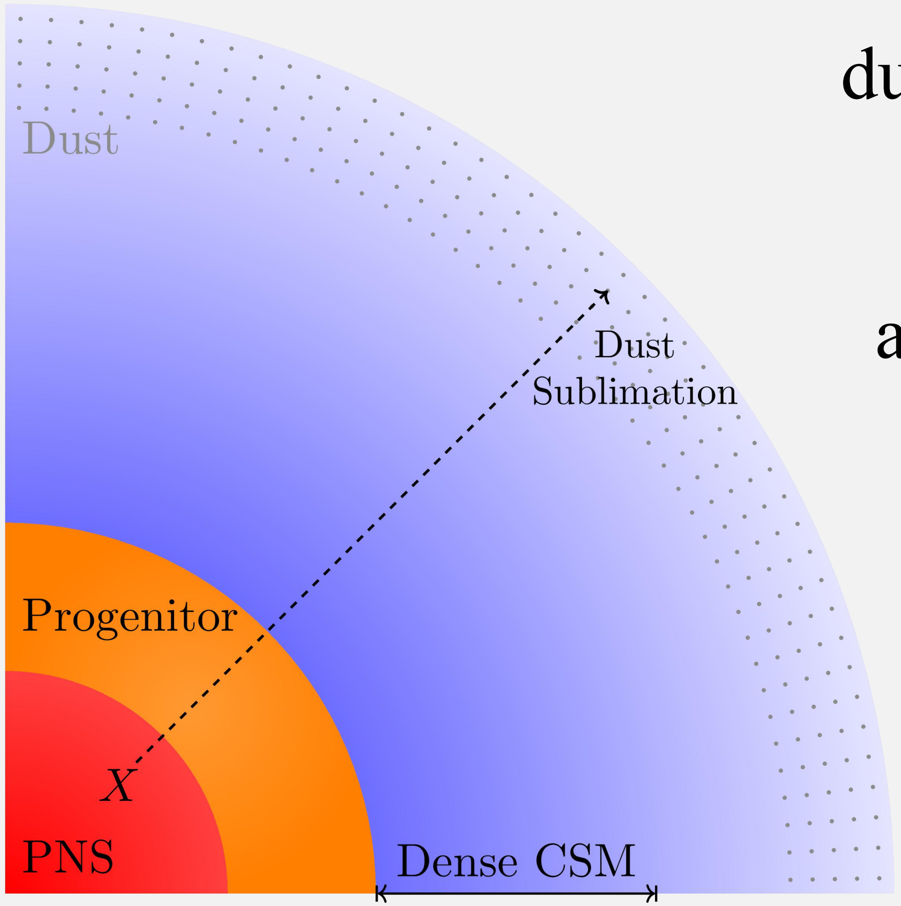
E. Waxman[1] and B. T. Draine[2]
[1]Department of Condensed-Matter Physics, Weizmann Institute, Rehovot 76100, Israel
[2]Princeton University Observatory, Peyton Hall, Princeton, NJ 08544

The infrared emissivity is quite different for graphite and silicate materials (Draine & Lee 1984; Draine 1999a). For the temperature range of interest for dust sublimation, $2000\,\mathrm{K} \lesssim T \lesssim 3000\,\mathrm{K}$,

same scale as Van der Waals force

E. Waxman, B. Draine
arXiv:astro-ph/9909020

Dust Sublimation



dust grains (molecules) exist in outer layer of CSM

↓

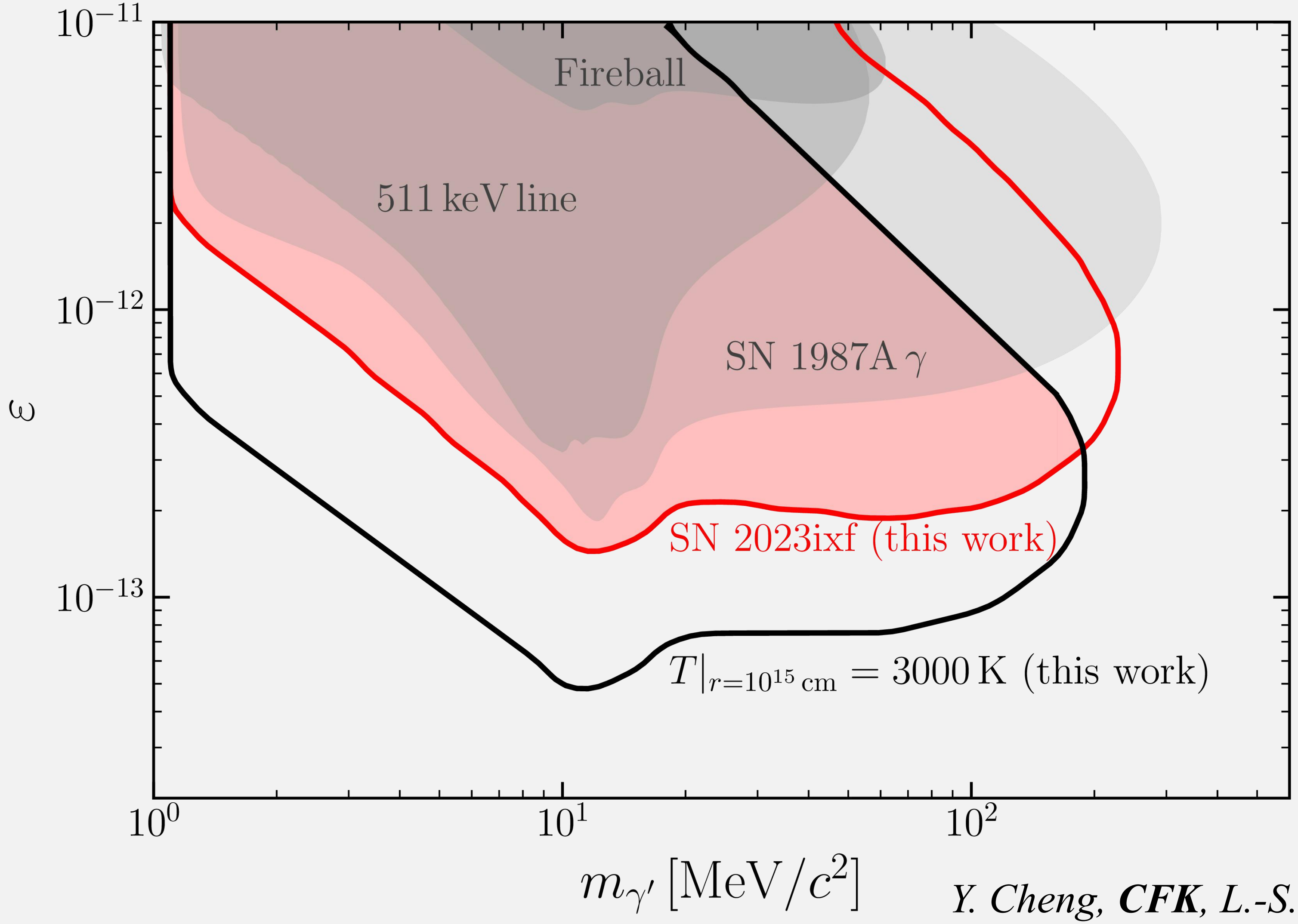
absorb optical photons and reprocess into infrared

↓

an additional dust-destruction requirement

$$T\big|_{r=10^{15}\,\mathrm{cm}} > 3000\,\mathrm{K}$$

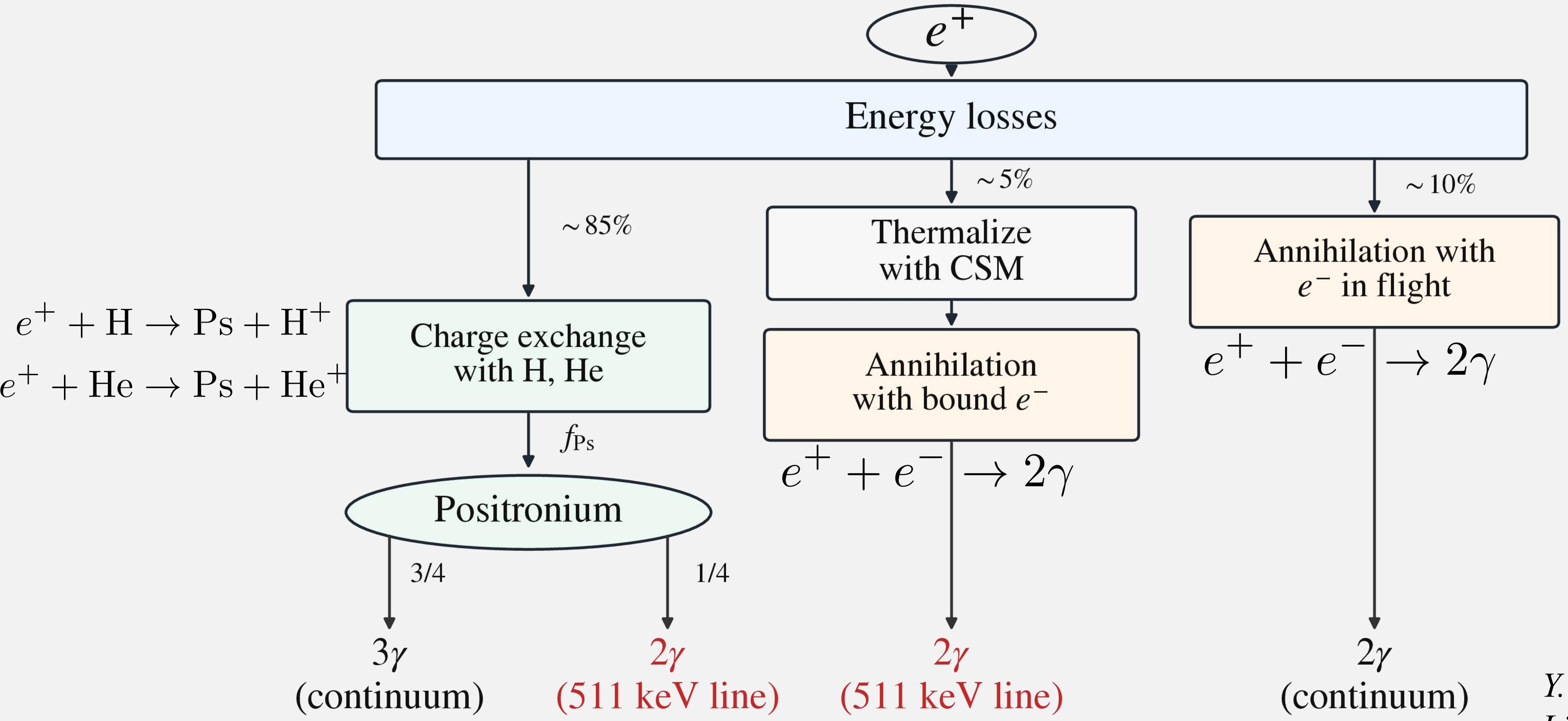
Constraint on DP (ii)



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
PRL 26

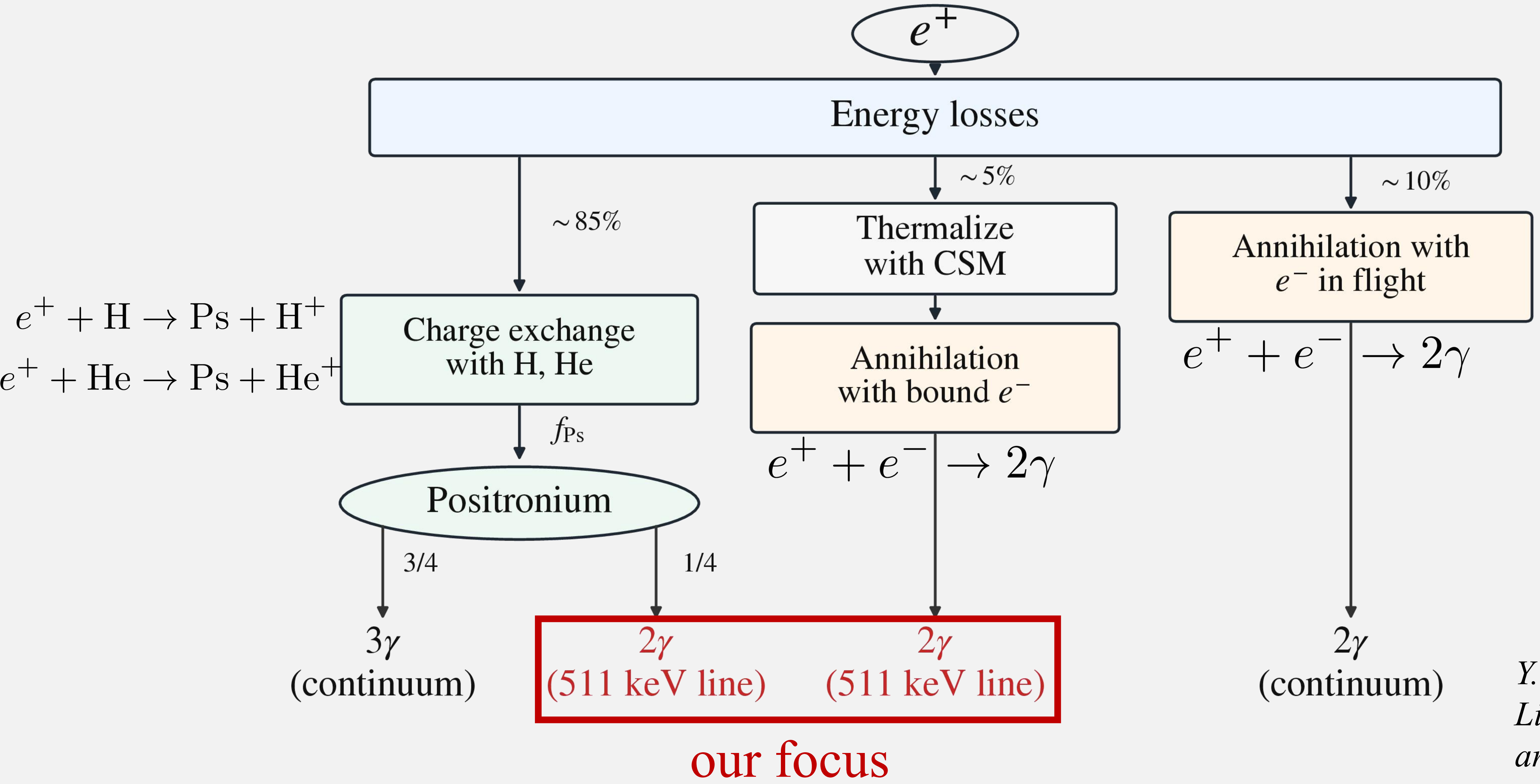
Besides extra BB radiation, what’s more?

511 keV Photon Production



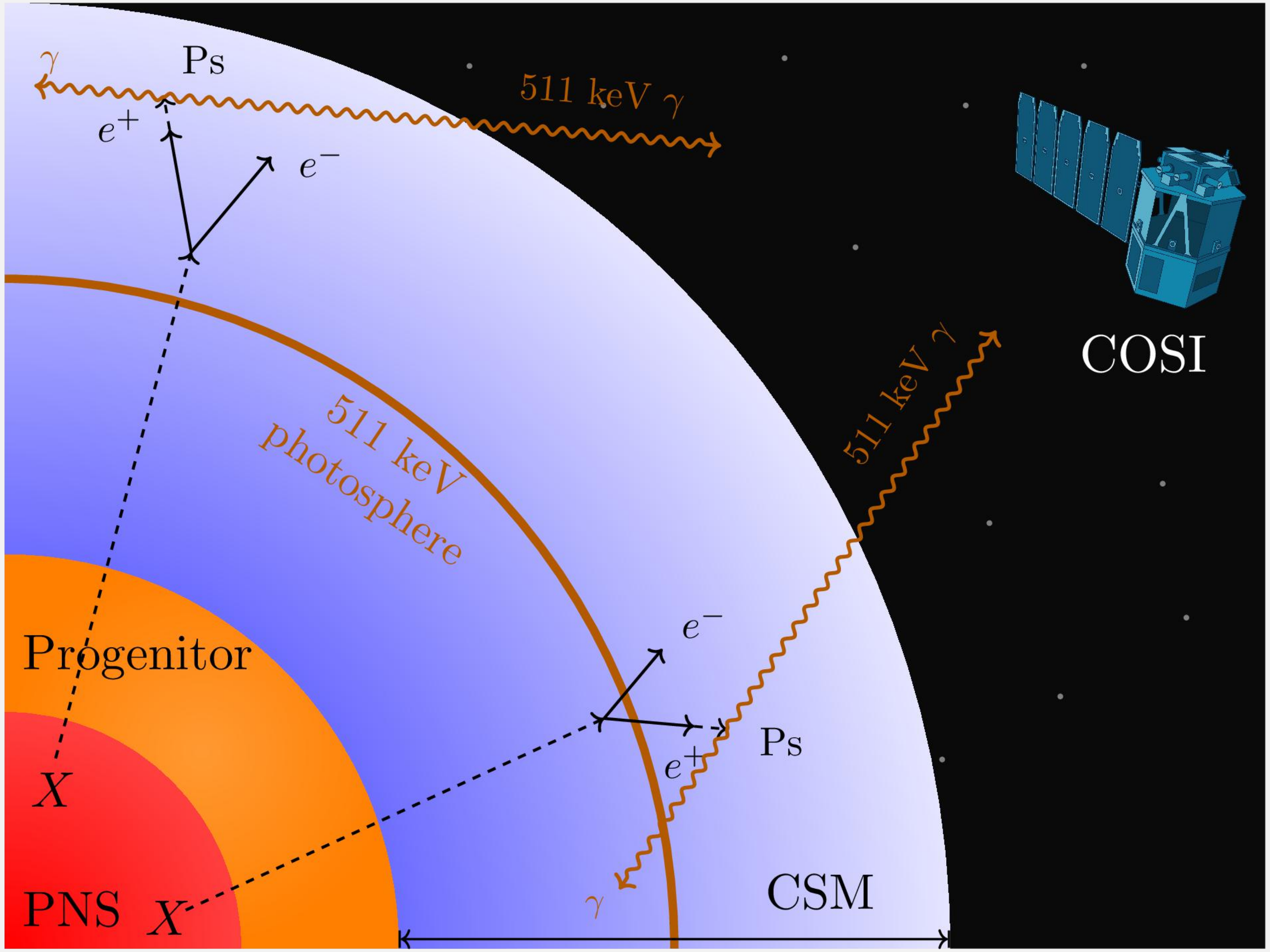
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.18247*

511 keV Photon Production



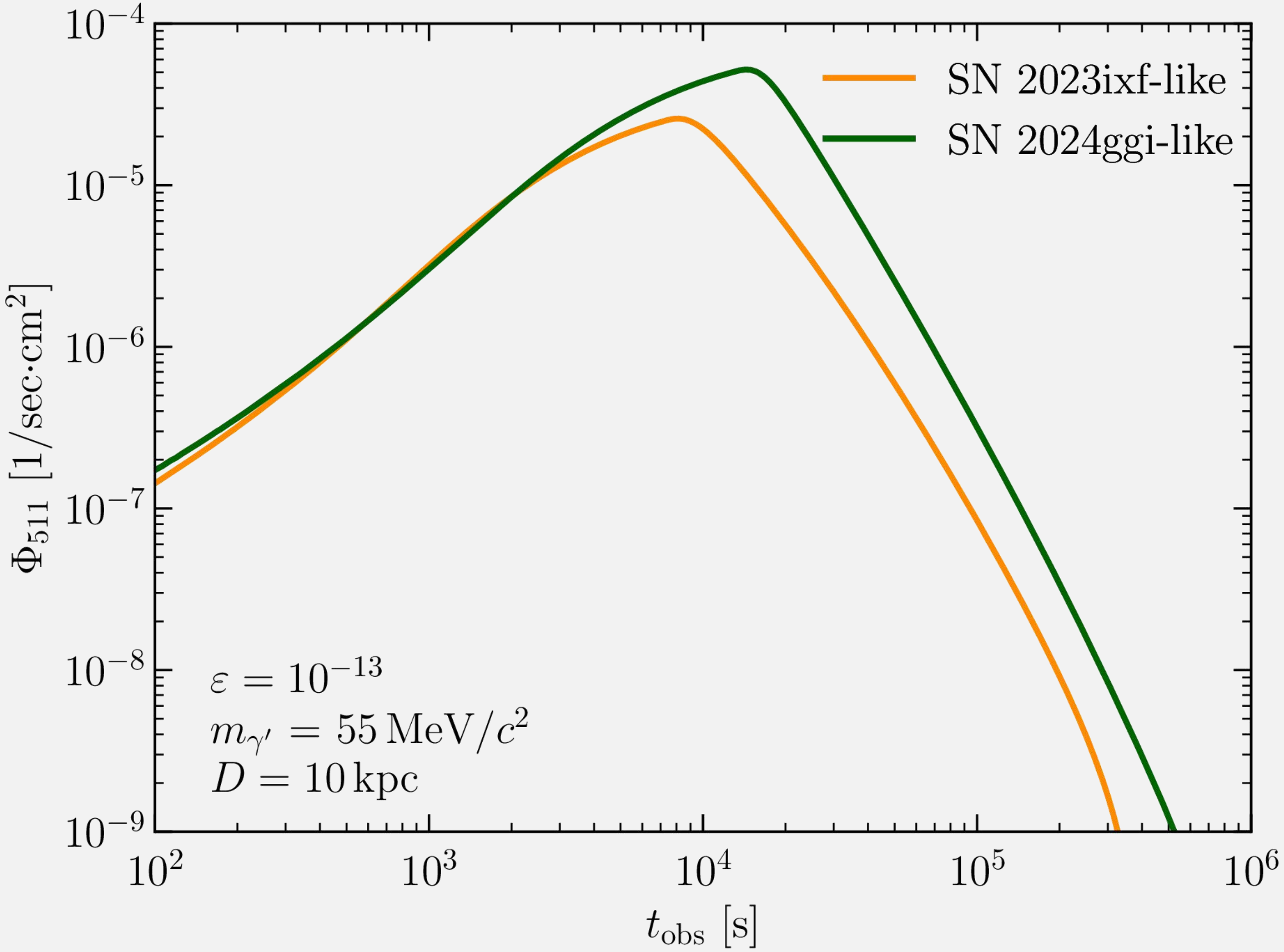
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.18247*

511 keV Photon Production



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.18247*

511 keV Photon Production

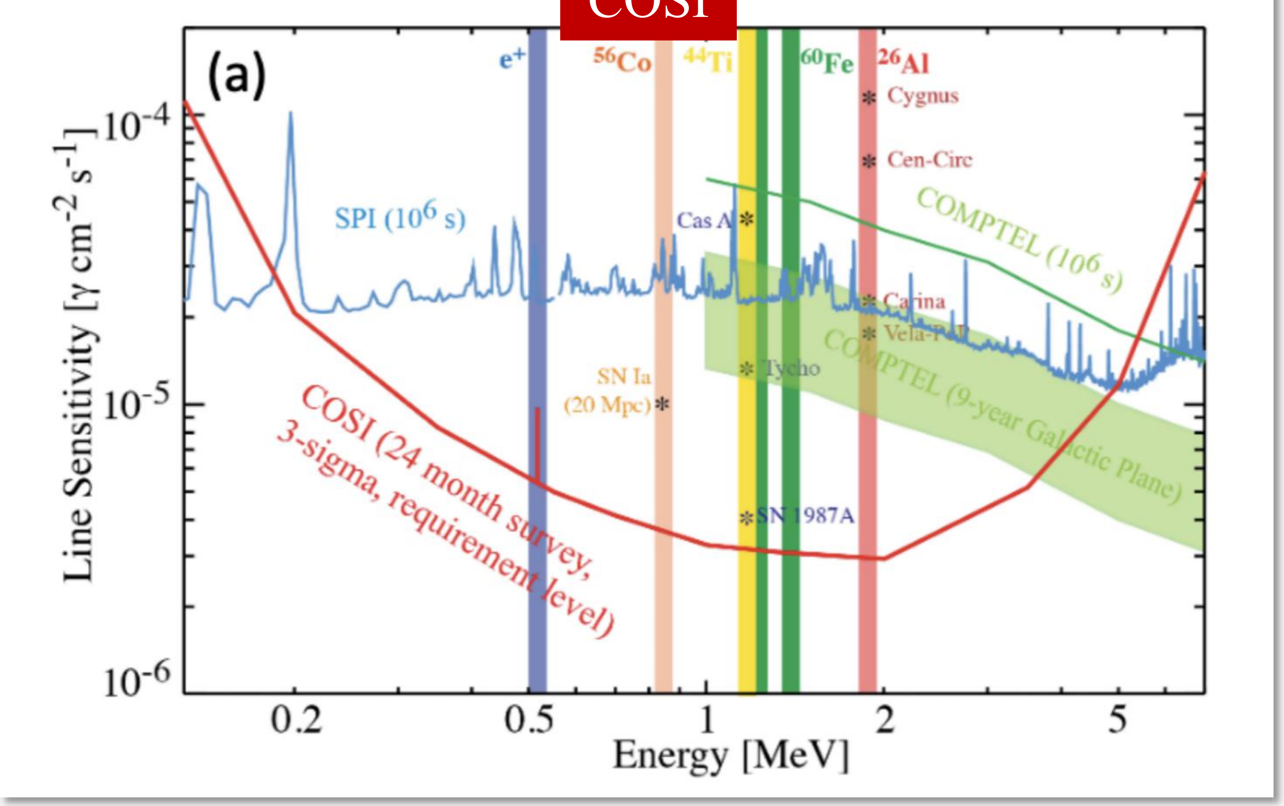


*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.18247*

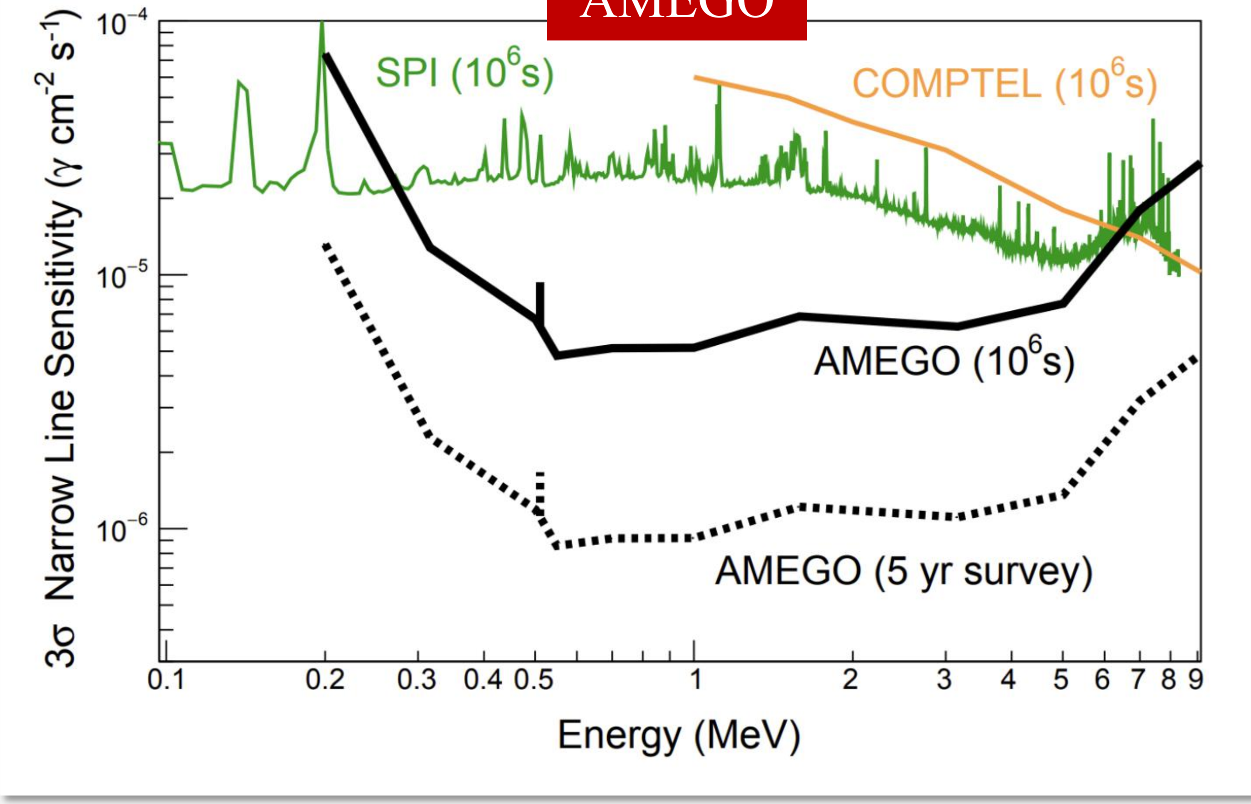
Experimental Sensitivities

launch planned in 2027

COSI



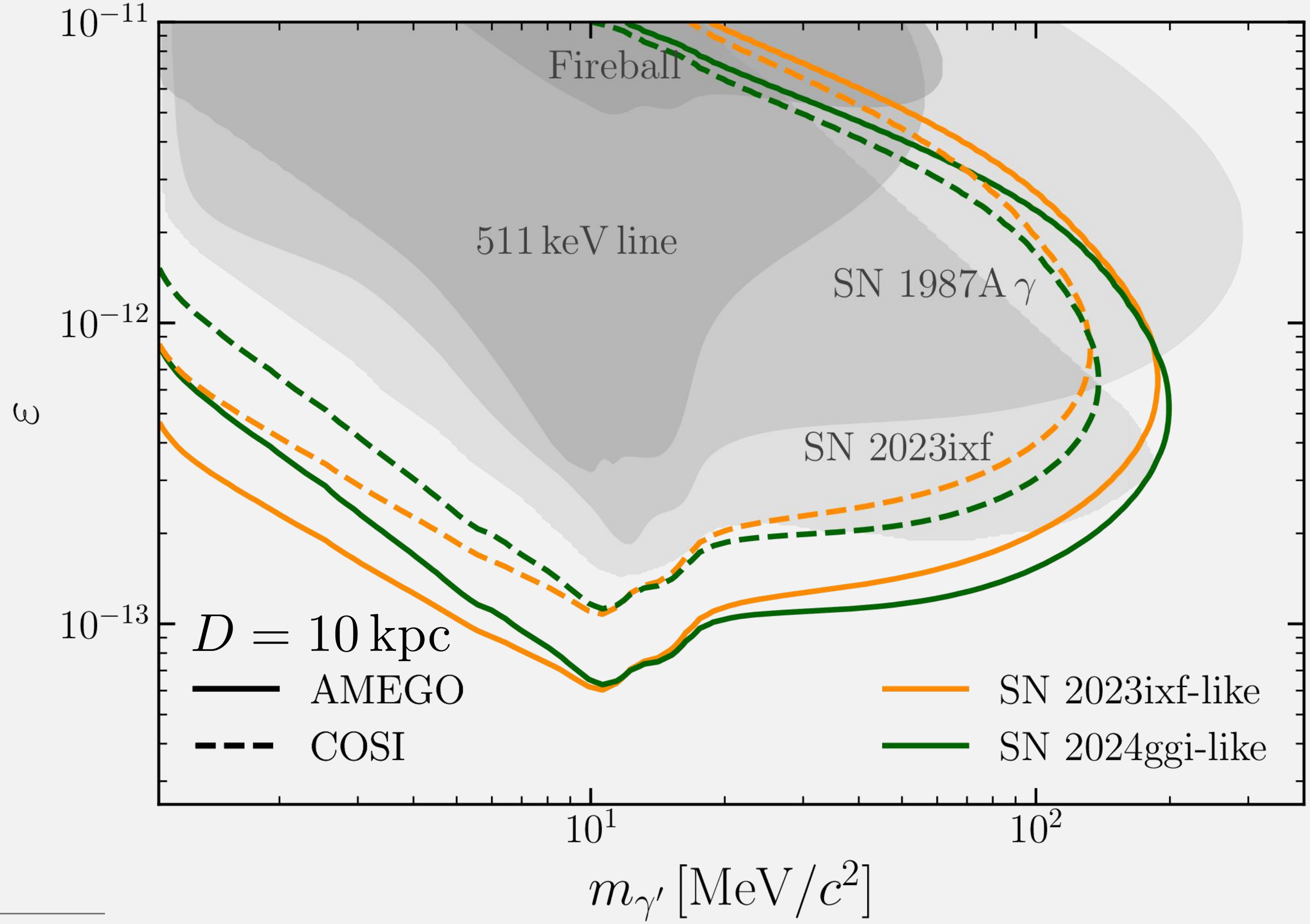
AMEGO



COSI Collaboration arXiv:2308.12362

AMEGO Collaboration arXiv:1907.07558

Projected Constraints from 511 keV Line



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.18247*

Summary

- Supernova neutrino time delay can be a powerful tool to test neutrino mass origins, which could be either *vacuum neutrino mass* or *dark neutrino mass*
- Circumstellar medium (CSM), which exists in the outsphere of SN, can be heated up by extra energy depoisition and emits light via blackbody radiation
- Early-time observation of SN 2023ixf luminosity provides a strong constraint on such extra energy depoisition
- 511 keV line search can also put a strong projected contraint

Summary

Institute for Basic Science

- Supernova neutrino time delay can be a powerful tool to test neutrino mass origins, which could be either *vacuum neutrino mass* or *dark neutrino mass*
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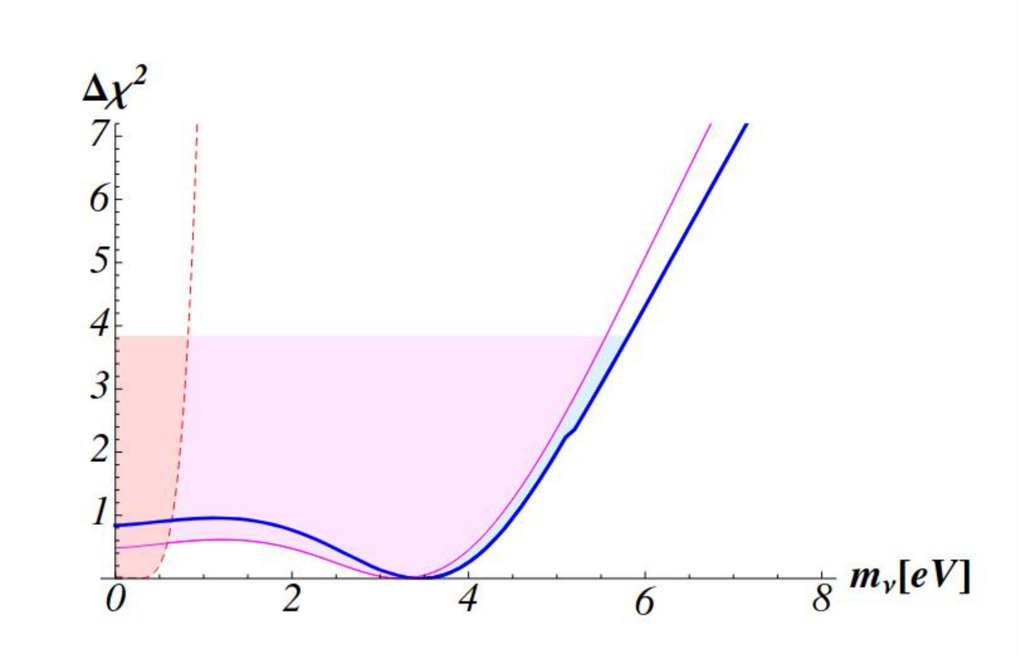
Thank you for your attention!

Back up

Back up

SN1987A



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

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

Back up

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

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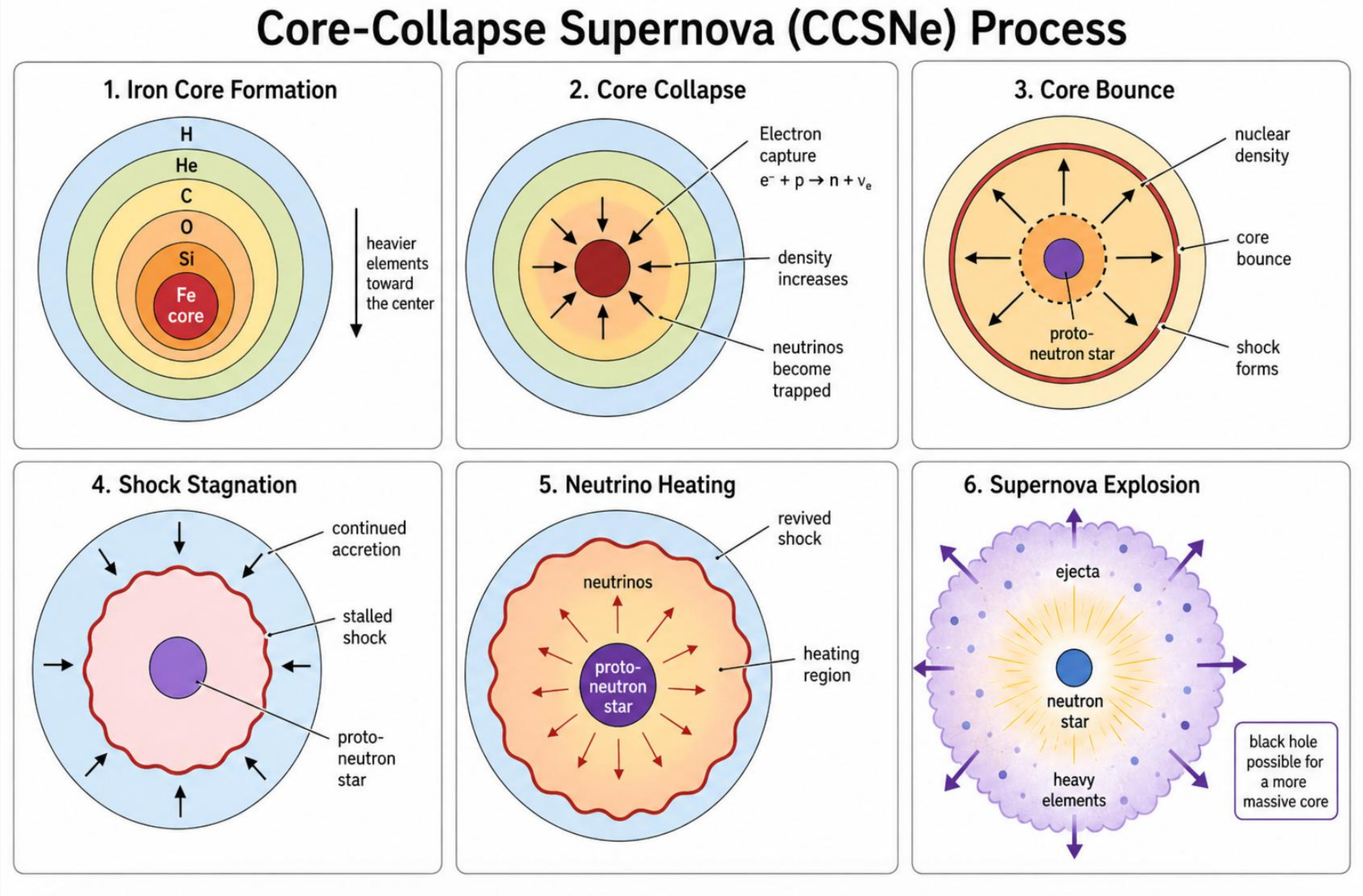
matter potential

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

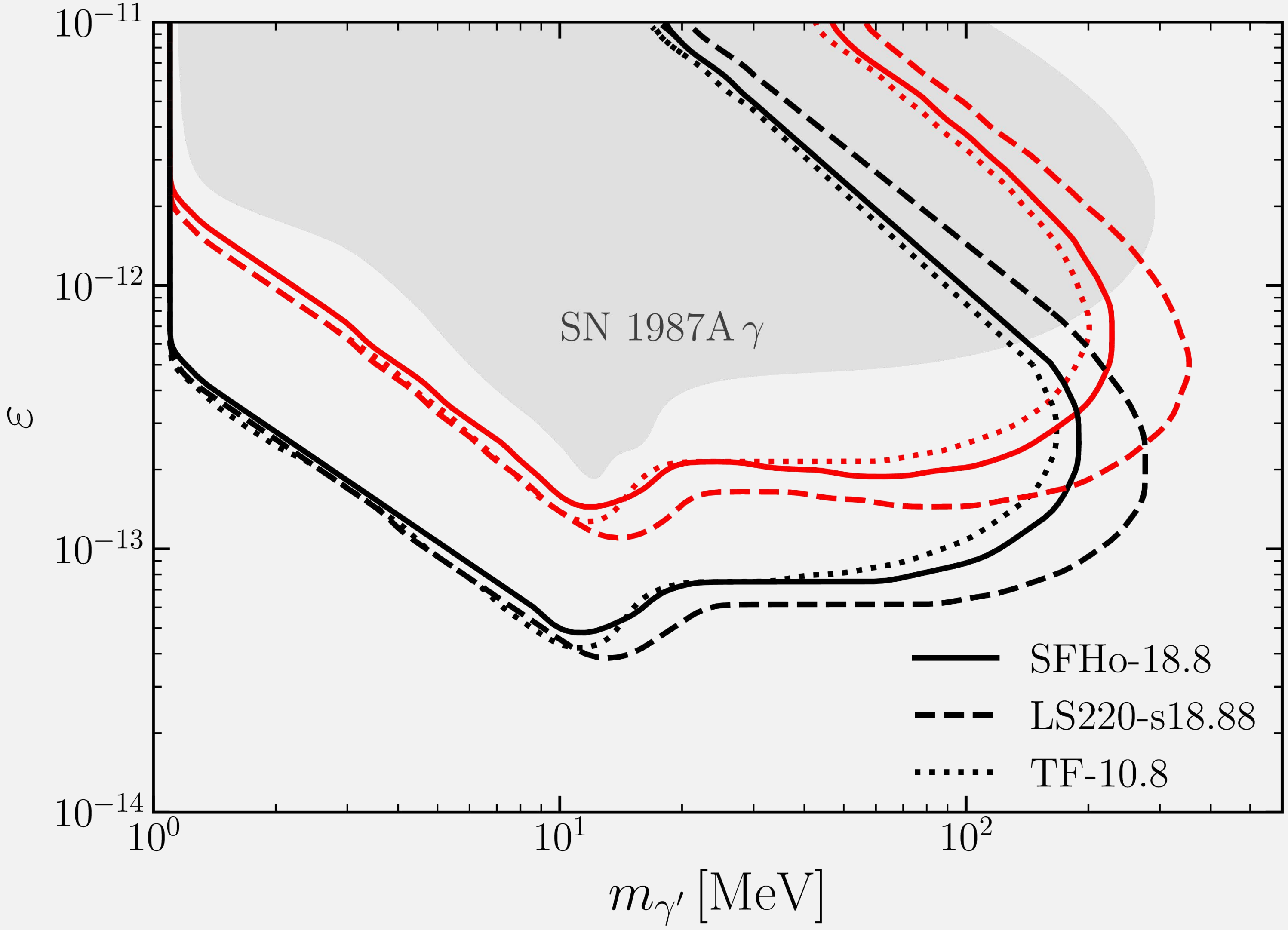
M. Sen and A. Y. Smirnov, arXiv:2306.15718

SN



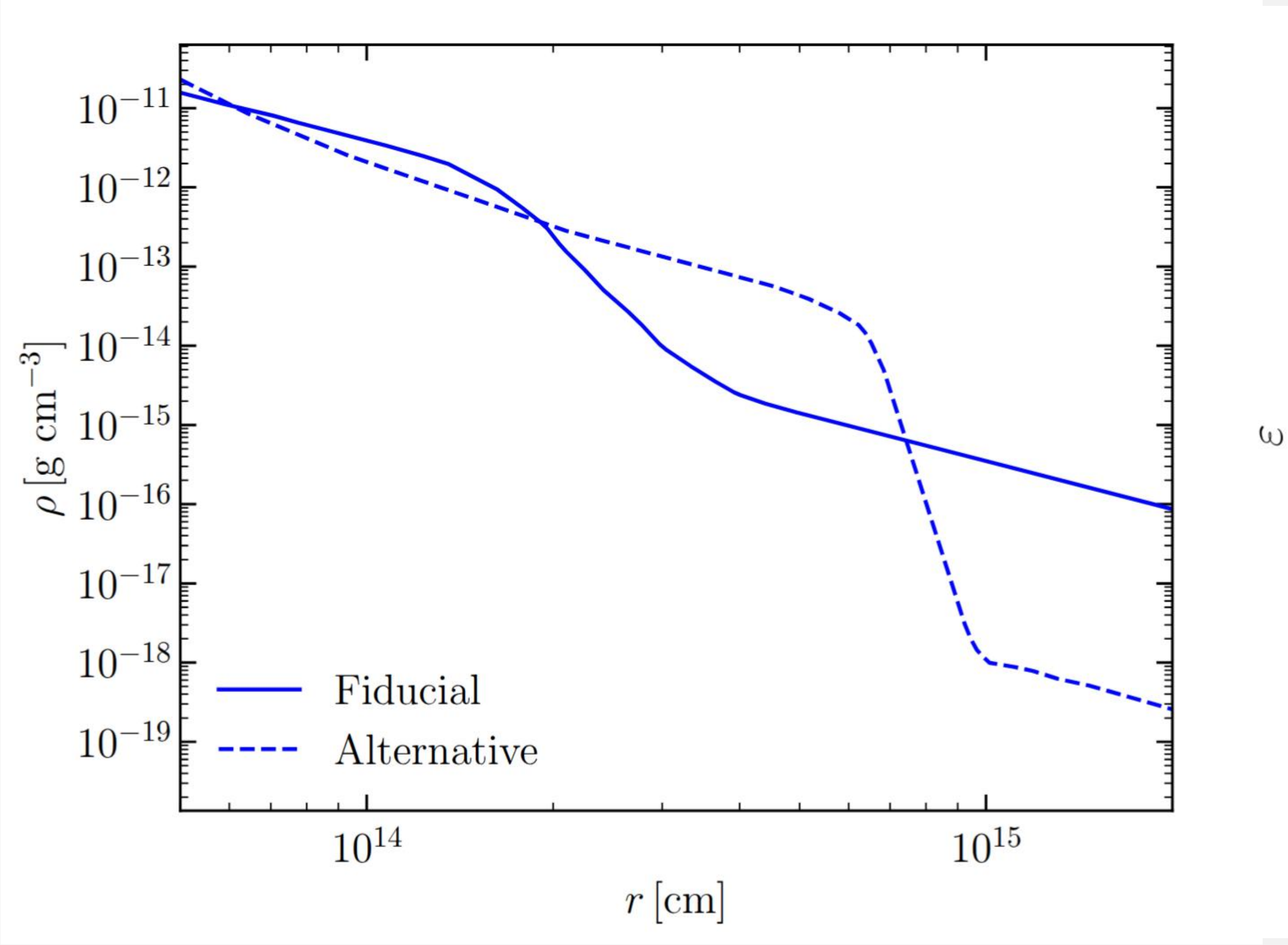
Core-Collapse Supernova (CCSNe) Process
1. Iron Core Formation
H
He
C
O
Si
Fe core
heavier elements toward the center
2. Core Collapse
Electron capture
$e^- + p \rightarrow n + \nu_e$
density increases
neutrinos become trapped
3. Core Bounce
nuclear density
core bounce
shock forms
proto-neutron star
4. Shock Stagnation
continued accretion
stalled shock
proto-neutron star
5. Neutrino Heating
revived shock
neutrinos
heating region
proto-neutron star
6. Supernova Explosion
ejecta
neutron star
heavy elements
black hole possible for a more massive core

Back up

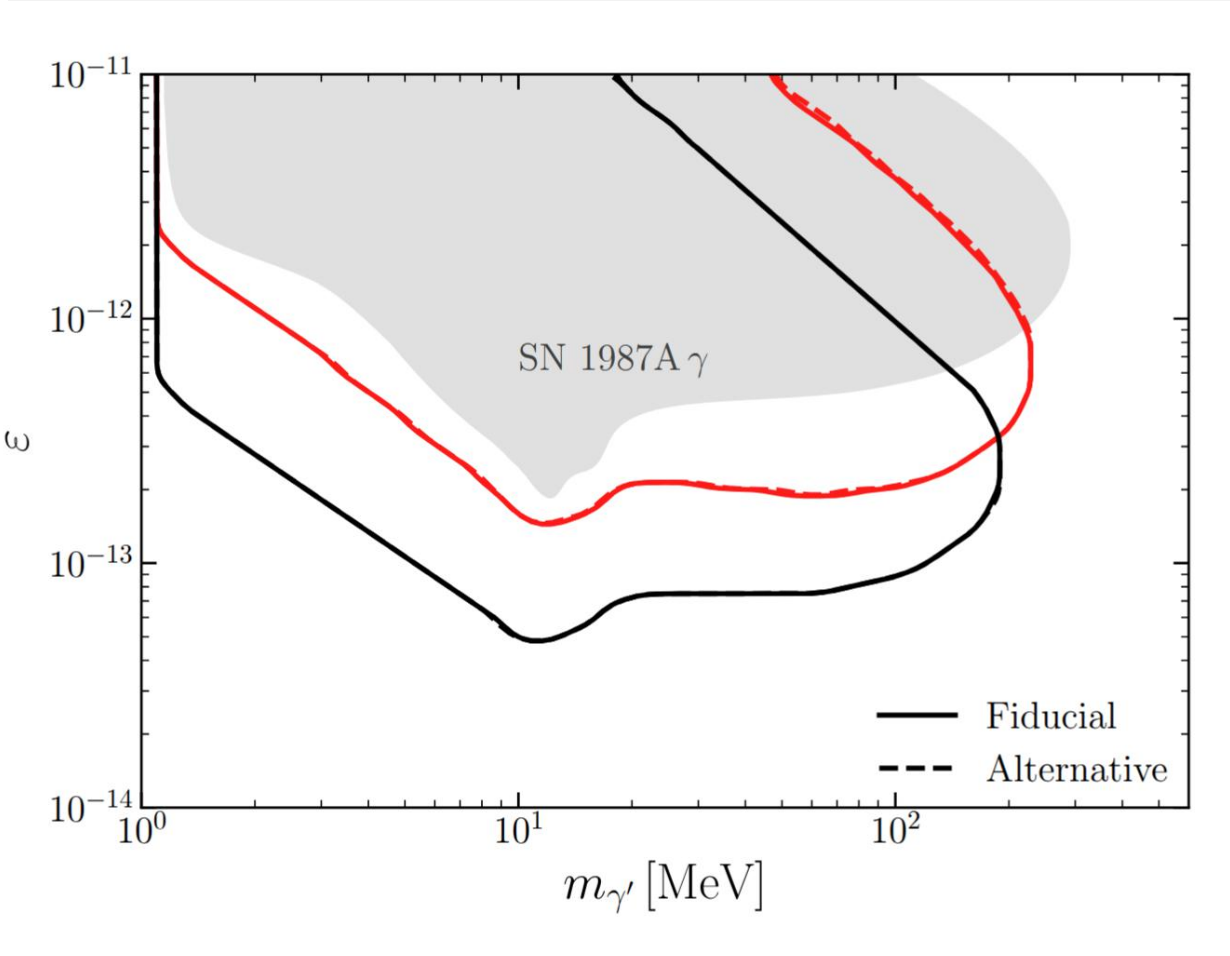


10^{-11}
10^{-12}
10^{-13}
10^{-14}
ε
SN 1987A γ
SFHo-18.8
LS220-s18.88
TF-10.8
10^{0}
10^{1}
10^{2}
$m_{\gamma'}$ [MeV]

Back up



$\rho\,[\mathrm{g\ cm^{-3}}]$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{14}
10^{15}
r [cm]
Fiducial
Alternative



ε
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{0}
10^{1}
10^{2}
$m_{\gamma'}$ [MeV]
SN 1987A γ
Fiducial
Alternative

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$$\mathcal{L}_{\mathrm{DP}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + eA_\mu J^\mu_{\mathrm{EM}}$$

Back up

Explosion energy = Ejecta kinetic energy

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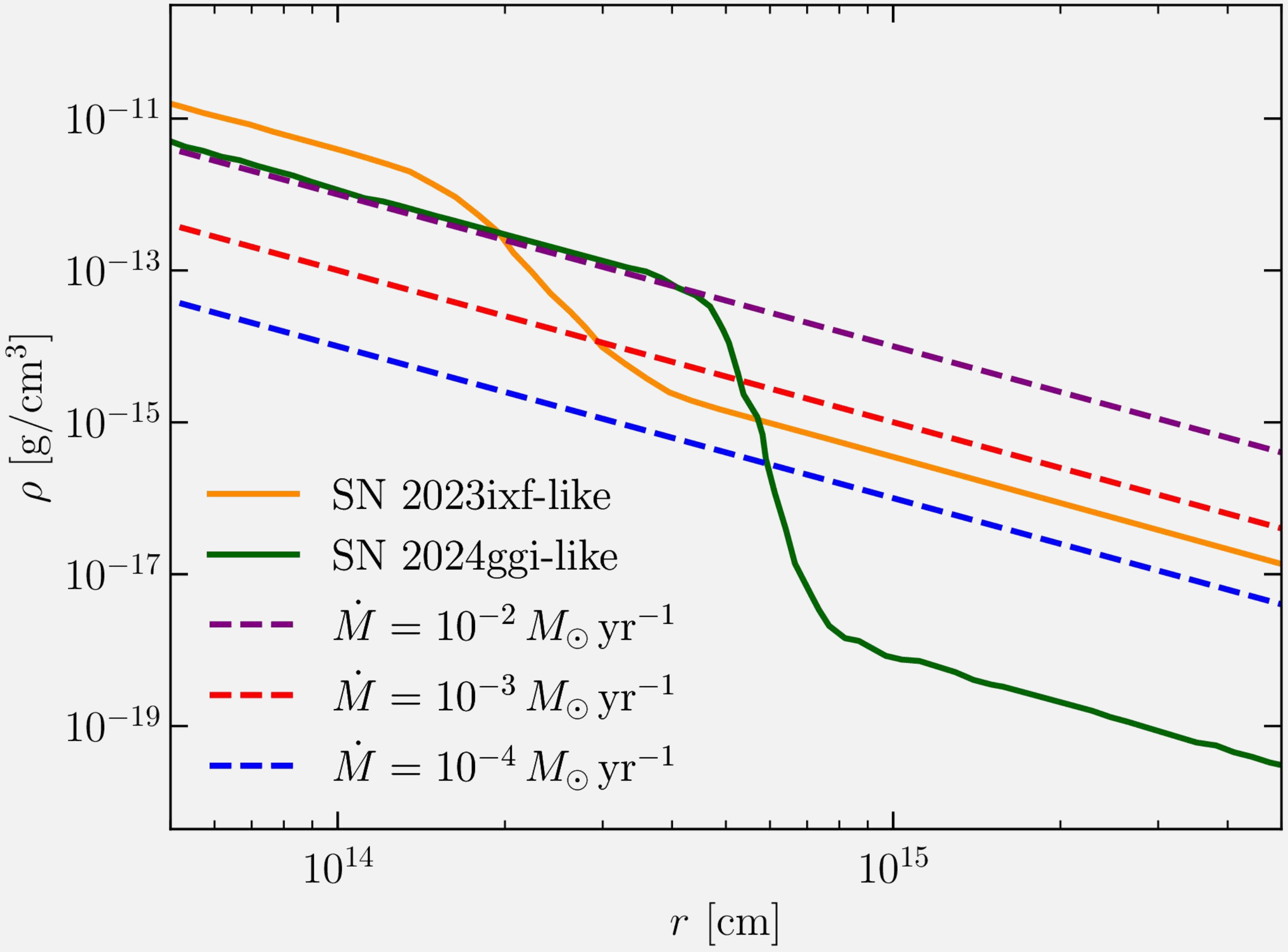
$$S(T_{\text{win}}) = S_{\text{ref}} \left(\frac{T_{\text{ref}}}{T_{\text{win}}} \right)^{1/2}$$

Back up



10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
ρ [g/cm^3]
10^{14}
10^{15}
r [cm]
SN 2023ixf-like
SN 2024ggi-like
$\dot{M} = 10^{-2}\, M_\odot\, \mathrm{yr}^{-1}$
$\dot{M} = 10^{-3}\, M_\odot\, \mathrm{yr}^{-1}$
$\dot{M} = 10^{-4}\, M_\odot\, \mathrm{yr}^{-1}$