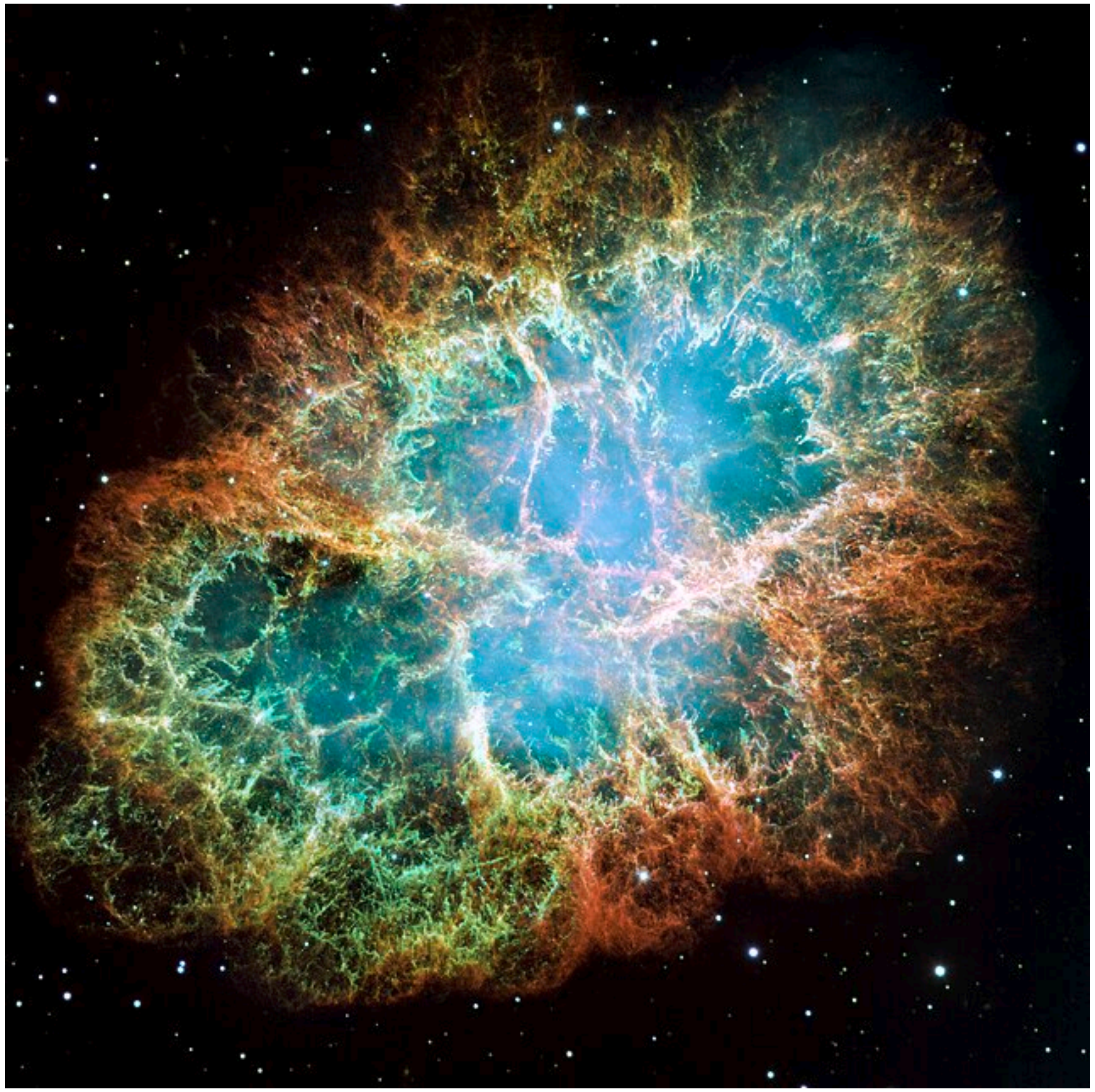
How to interpret supernova neutrino data without knowing the source in detail



Crab Nebula, SN 1054 remnant

SFB 1258 Neutrinos Dark Matter Messengers

Yago Porto (Technical University of Munich)

CETUP* 2026 (07/07/2026)

TUM

Motivation

- **SN neutrinos are often presented as a uniquely informative signal.**

  A nearby event could reveal the explosion physics, flavor evolution, and neutrino properties.

- **But high statistics do not automatically imply high information.**

  The bottleneck is often interpretation, not detection.

- **Source uncertainties can dominate the inference.**

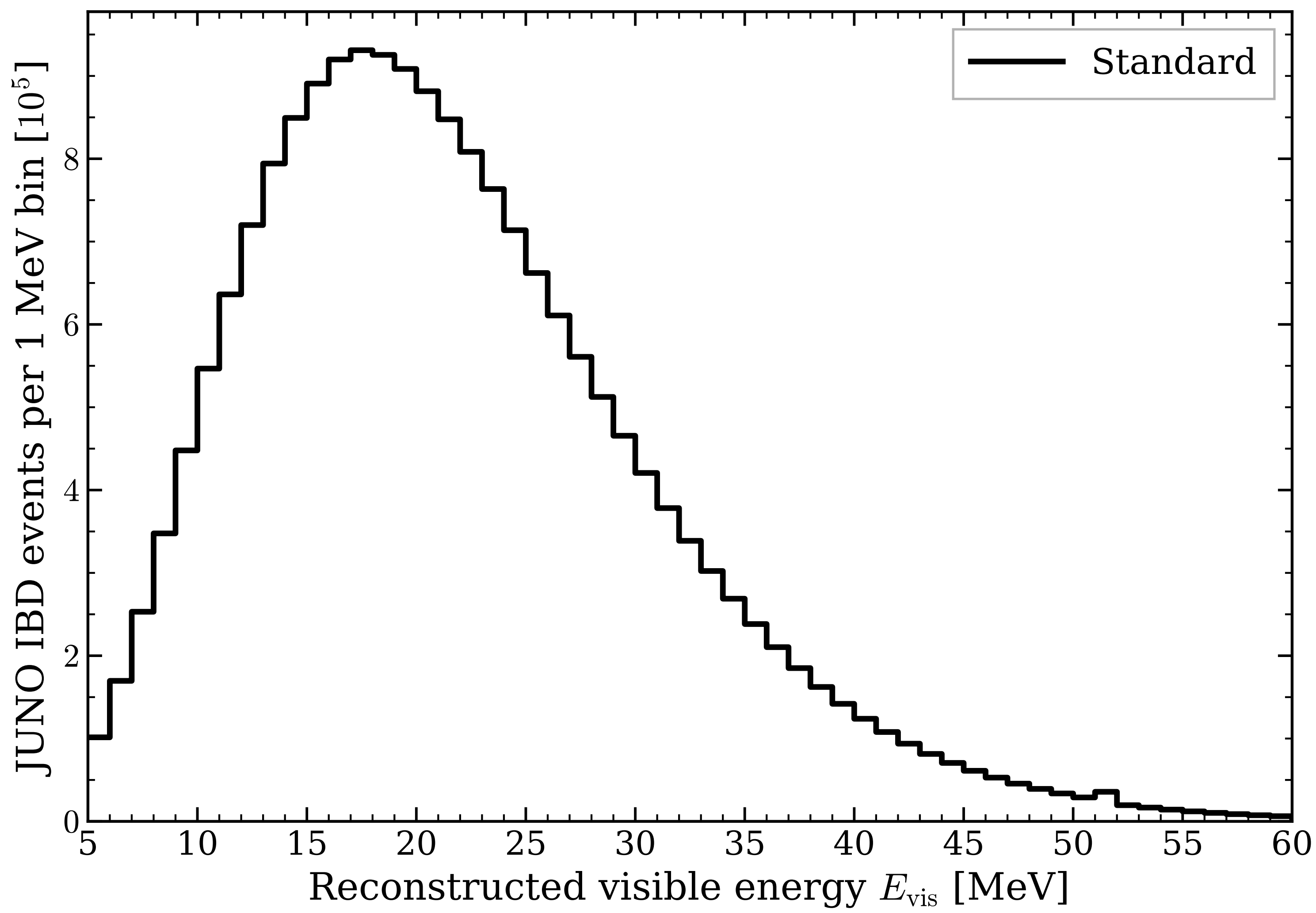
  Emission spectra, luminosities, and time evolution are model dependent.

- **This leads to both overclaims and excessive skepticism.**

  The goal is to find observables that remain meaningful under minimal source assumptions.

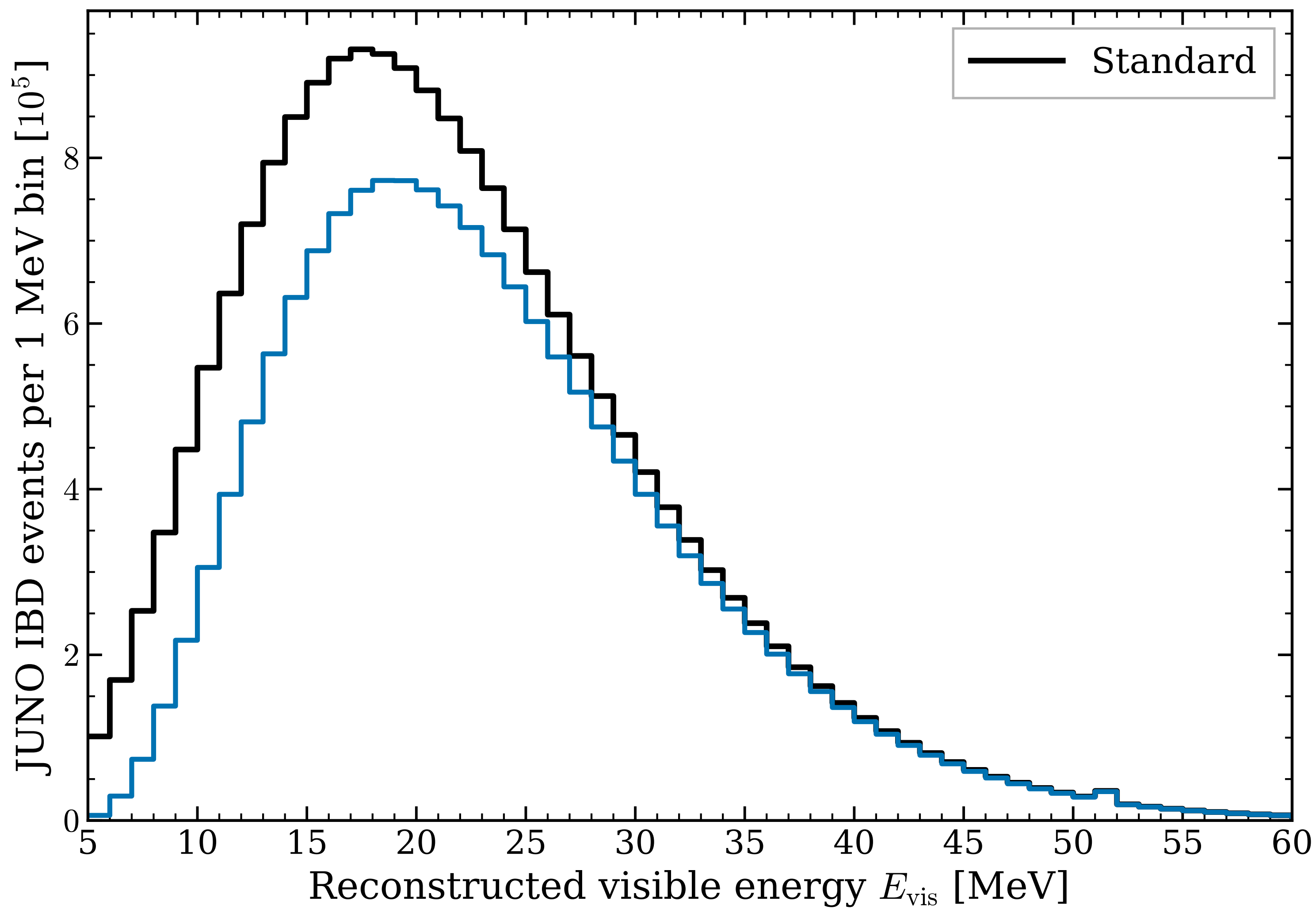
Imagine Betelgeuse goes supernova

- For a Betelgeuse-like source at $D \simeq 0.2\,\mathrm{kpc}$, we use a Garching $20\,M_\odot$ flux model.
- JUNO would collect an enormous IBD sample.



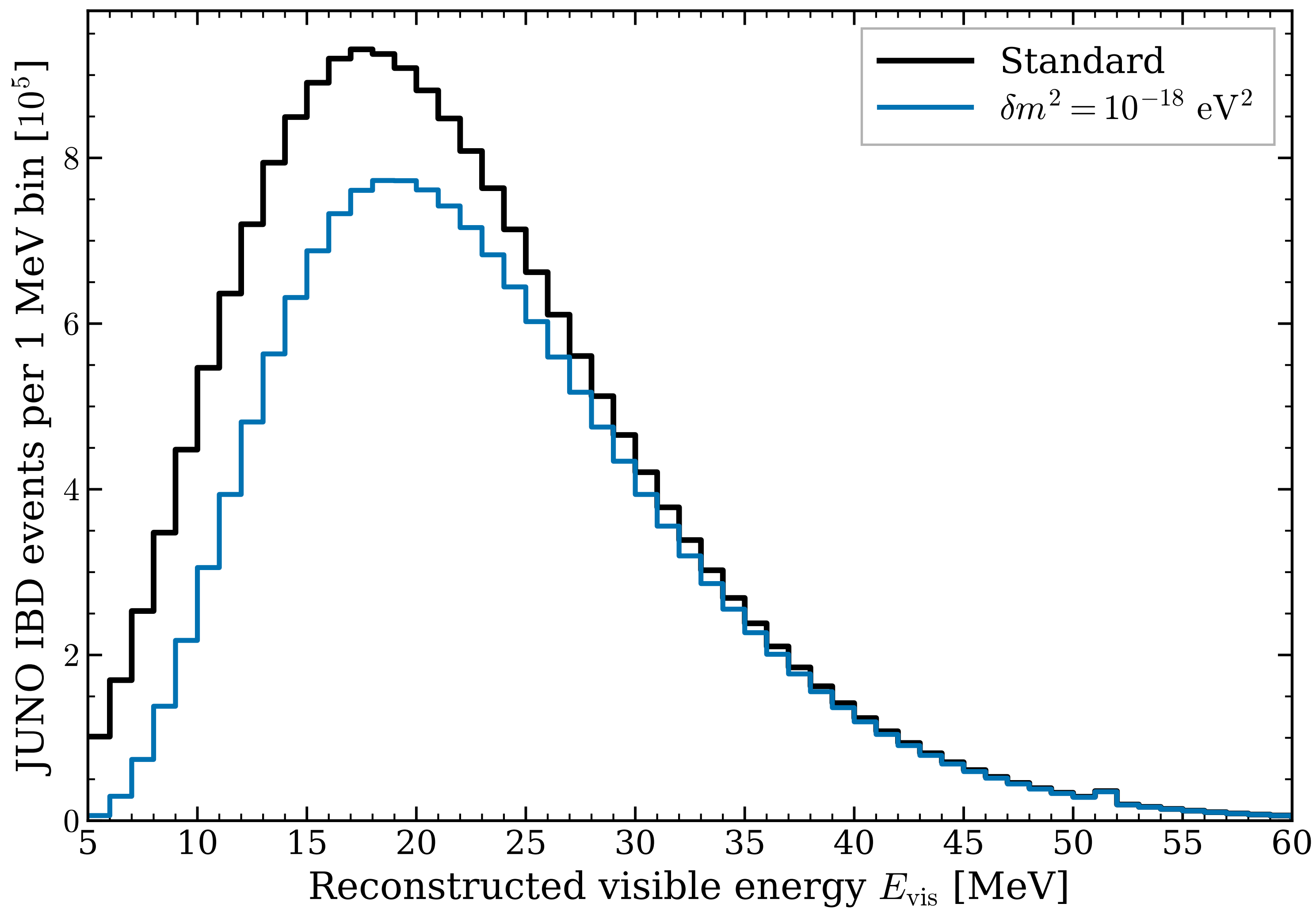
Imagine Betelgeuse goes supernova

- Suppose the blue curve is the observed JUNO spectrum.
- The black curve is only one reference source model.
- Without detailed source knowledge, this mismatch may not look especially suspicious.



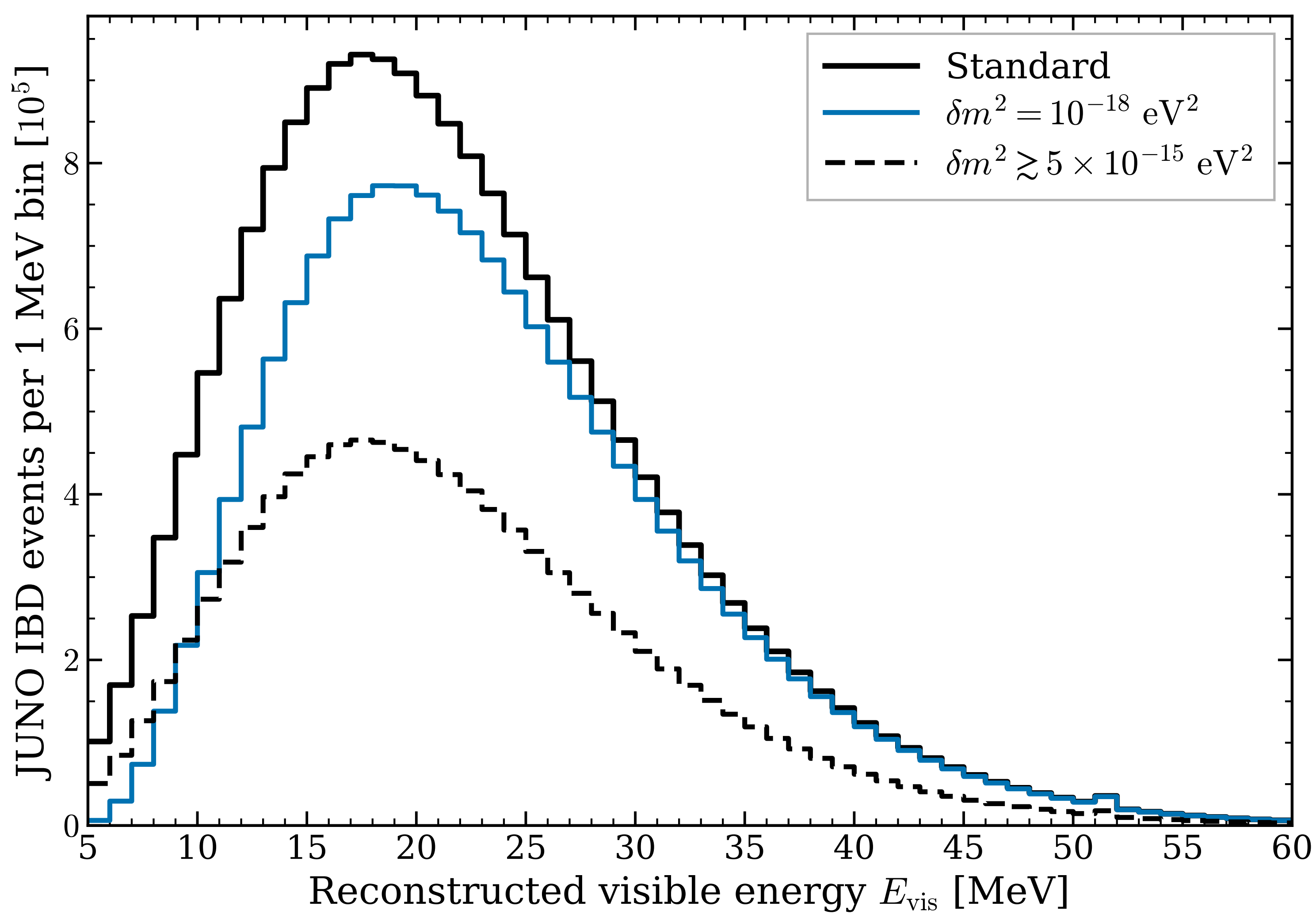
But the mismatch was not source physics

- The blue curve is the standard signal after pseudo-Dirac oscillations during propagation.
- The effect does not appear as a dramatic spectral feature.
- A flexible source fit would hide the most important piece of information.



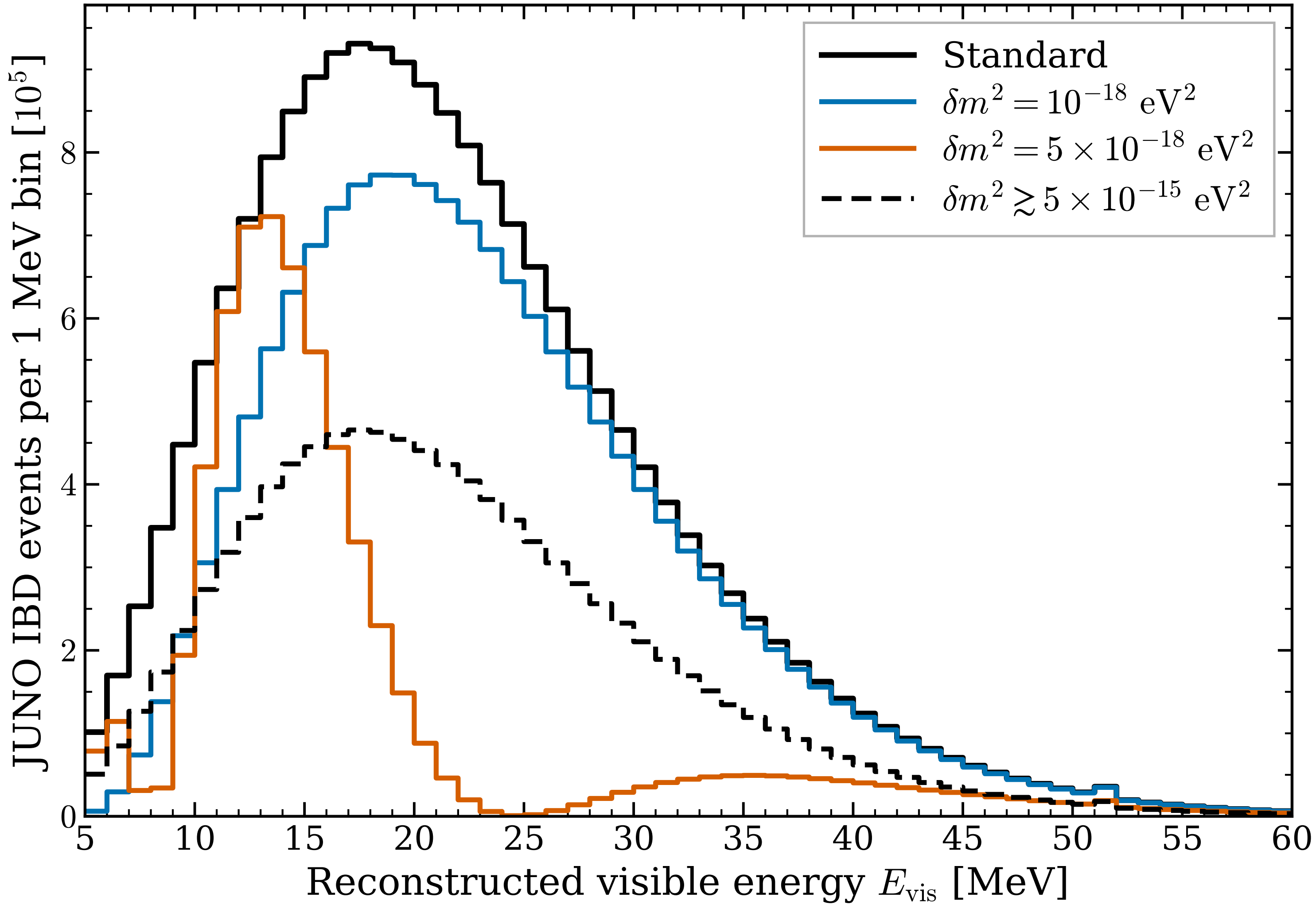
It can get worse

- If the oscillations are fast enough, the detector cannot resolve the wiggles.
- The spectrum keeps almost the same shape, but with roughly half the normalization.
- Then even the spectral clue disappears.



The favorable case

- The orange curve is the favorable case: the oscillation minimum falls in the high-statistics region.
- Then the spectral distortion is large enough that it would be hard to miss.
- But this is not generic; many propagation effects look like modest source changes or smooth normalization shifts.



Outline

- **Supernova basics:**

  Core collapse and the main phases of neutrino emission.

- **Neutronization burst**

  A clean early ν_e-dominated phase with weak dependence on later source evolution.

- **Flavor composition at Earth**

  How to extract flavor information without detailed source modeling.

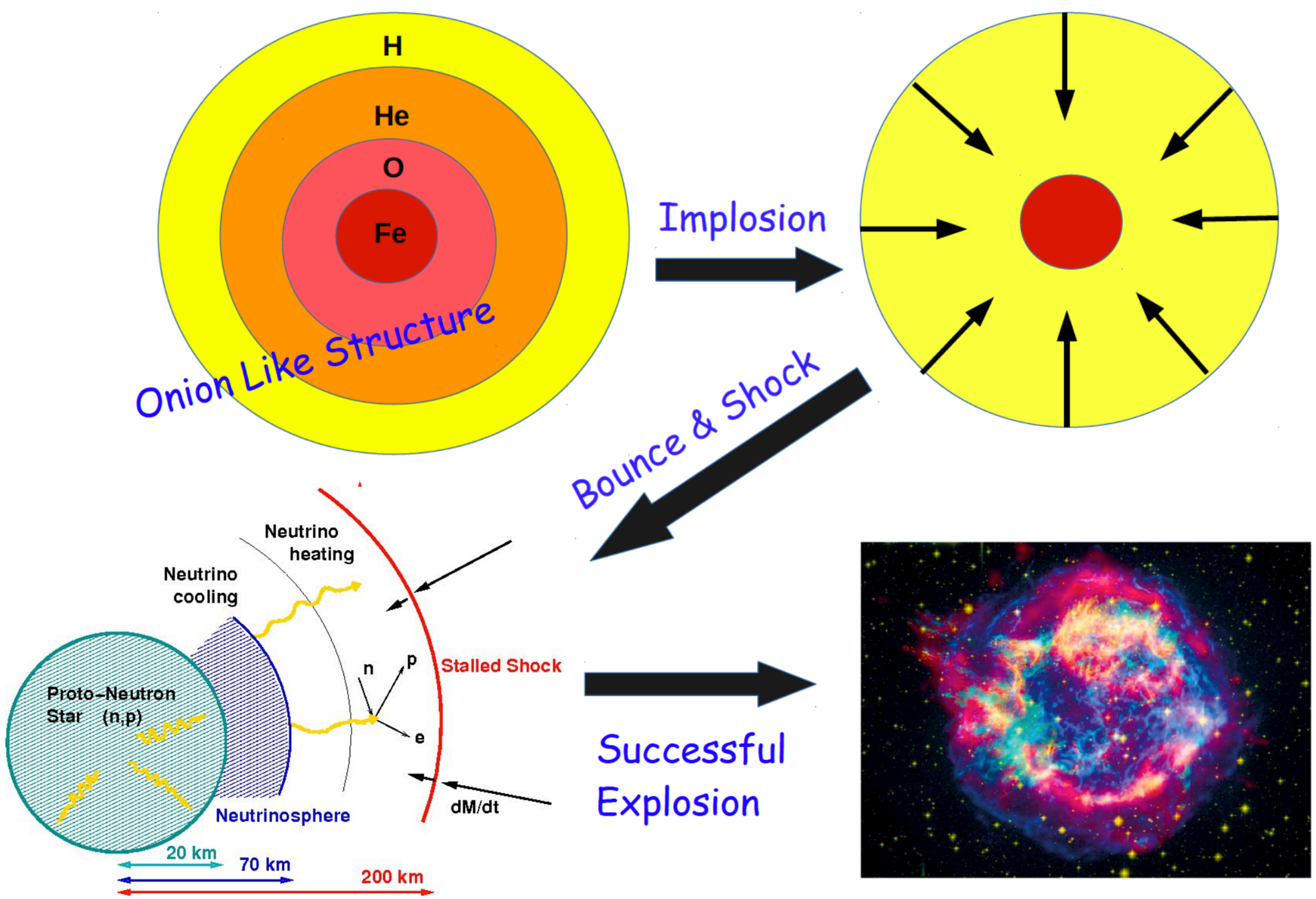
- **Gamma-ray echo**

  An astrophysical near detector for Galactic neutrino propagation.

- **What makes an observable robust?**

  Predictions set by simple physics, not by detailed source modeling.

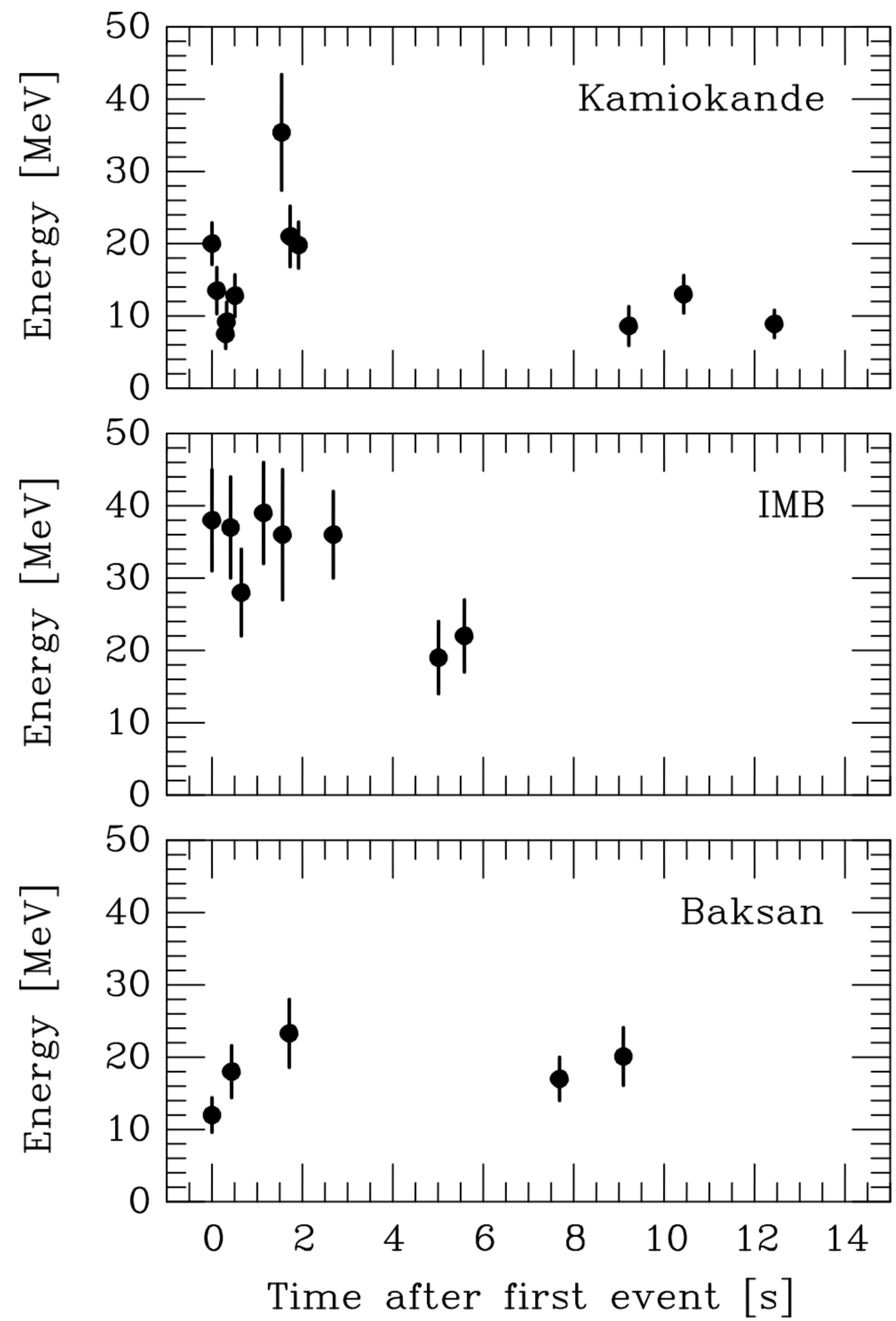
Core collapse supernovae



- 99% of the gravitational binding energy is emitted as neutrinos ($\sim 10^{53}$ erg).
- ~1% goes into the kinetic energy of the ejecta.
- ~0.01% is released in photons (the visible supernova).

SN 1987A: the first supernova seen in neutrinos

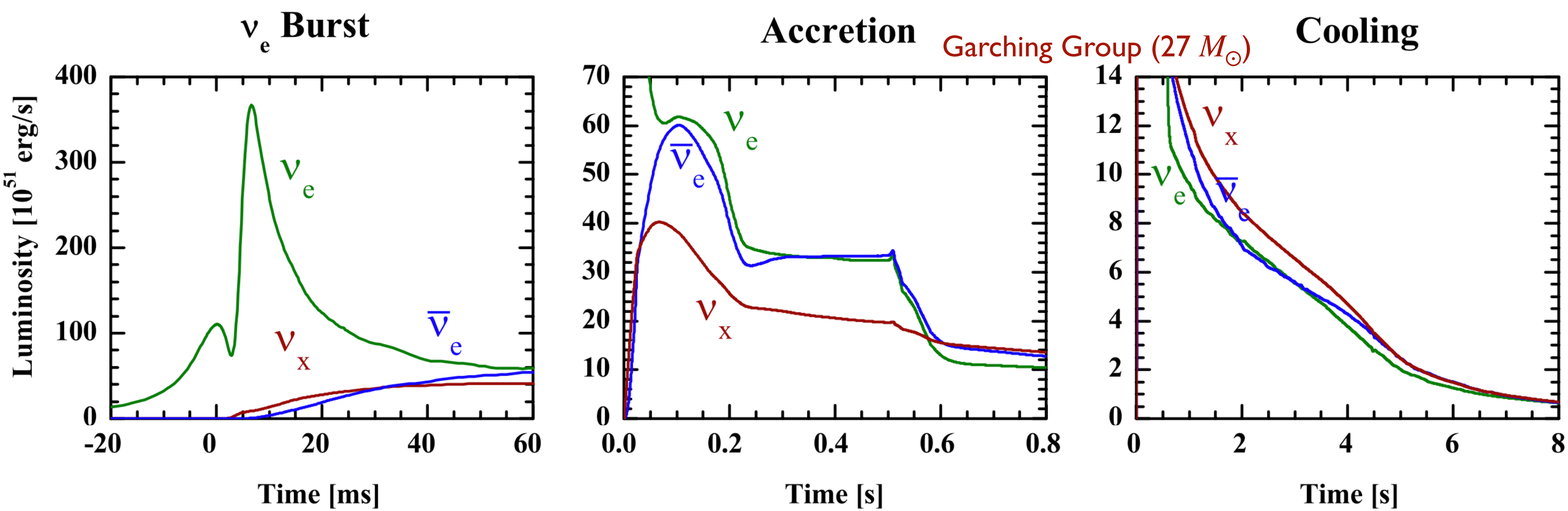
- First naked-eye supernova since Kepler's SN in 1604.
- Located in the Large Magellanic Cloud, ~ 51 kpc away.
- Detected by Kamiokande-II, IMB, and Baksan.
- Only ~ 24 neutrino events observed.
- Confirmed the basic SN-neutrino paradigm: energy scale, duration, and luminosity.



Janka, Handbook of Supernovae (2017)

The neutronization burst

Phases of supernova neutrino emission



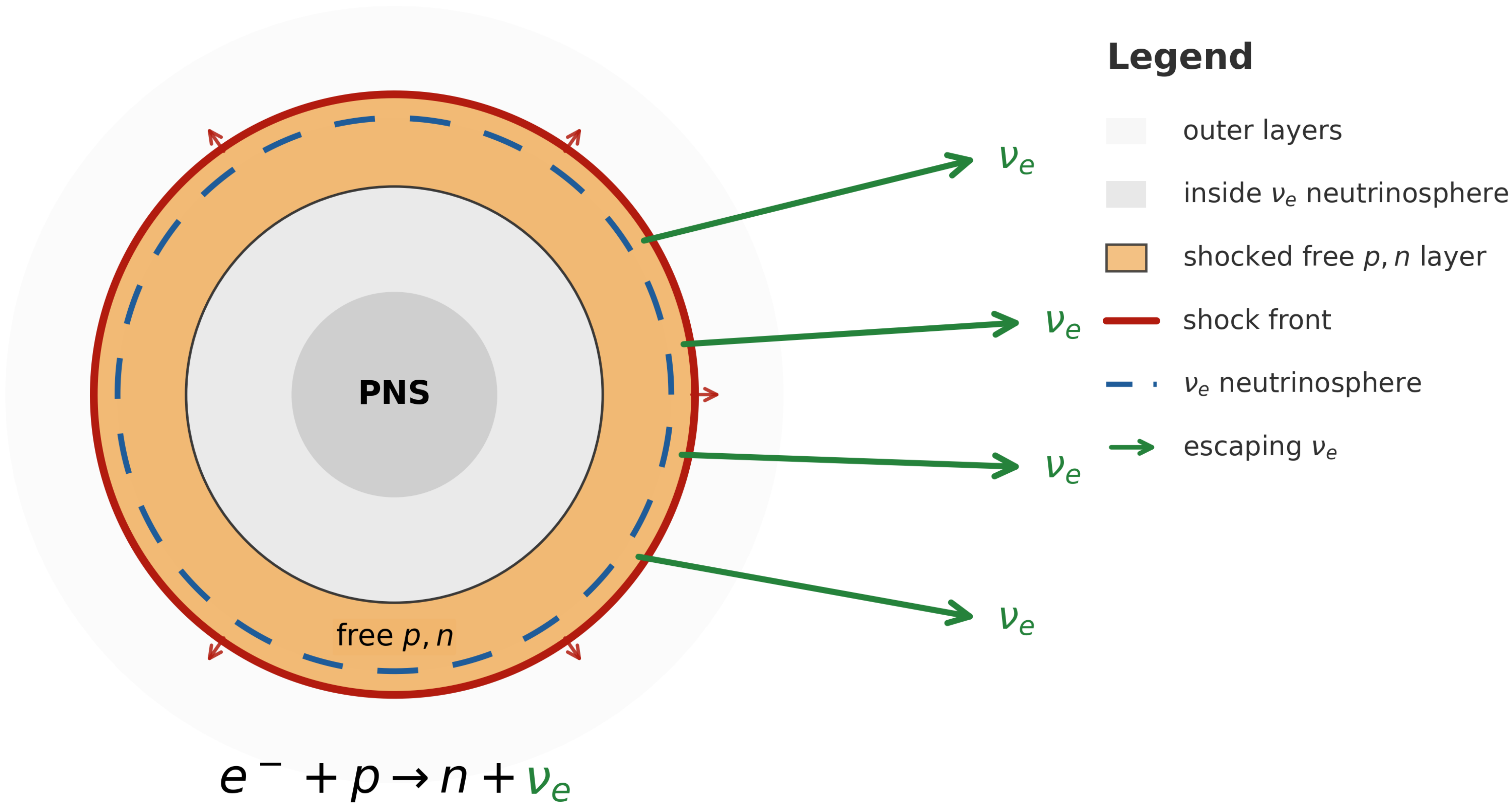
- Early ν_e flash from rapid deleptonization.
- Less sensitive to progenitor structure and EoS.

- Shock stalls; accretion powers large neutrino luminosities.
- Neutrino heating can revive the shock and drive the explosion.

- Proto-neutron star cools by neutrino emission over seconds.
- Neutrino-driven winds may contribute to nucleosynthesis.

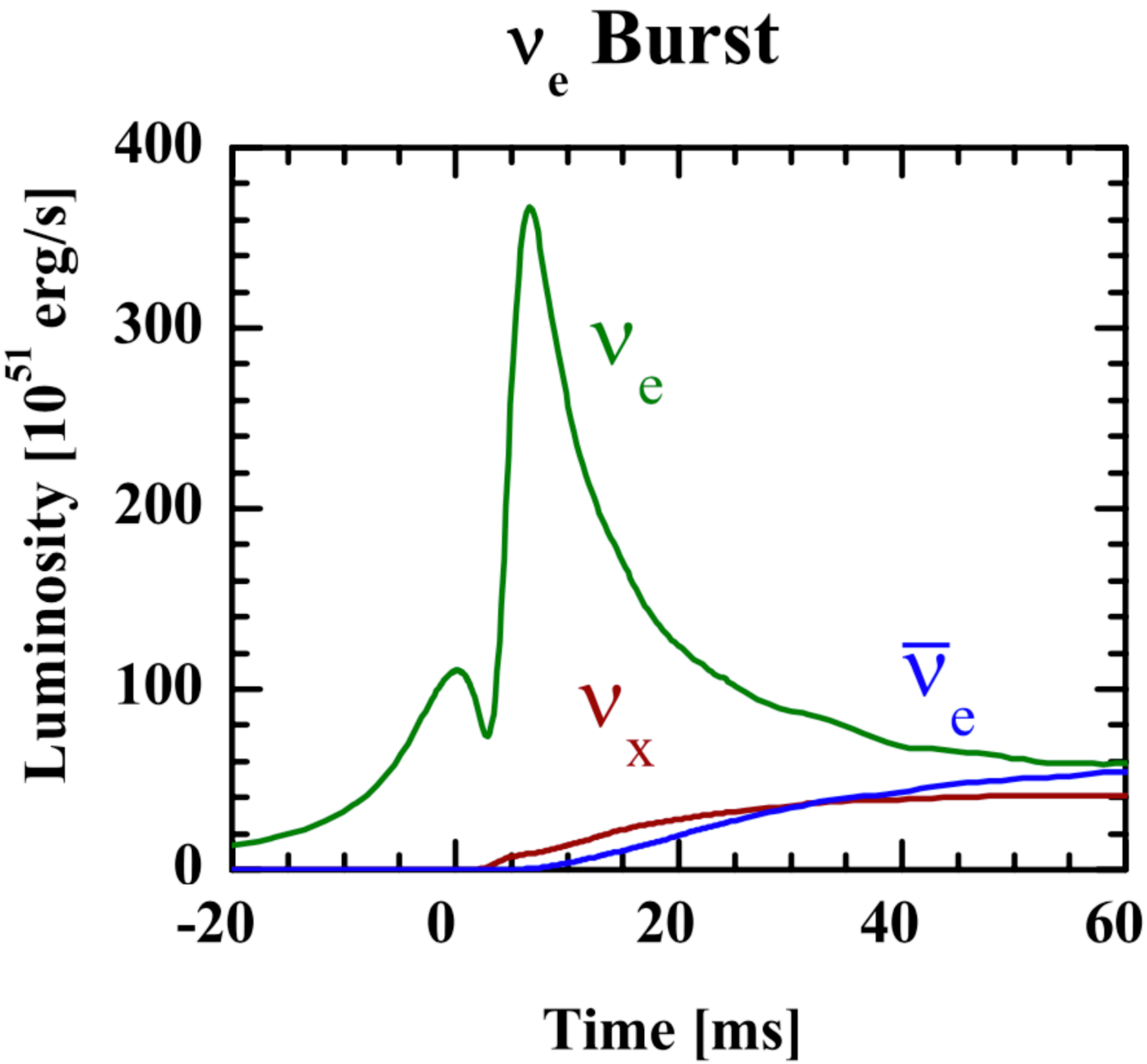
What is the neutronization burst?

- Core bounce launches an outward-moving shock wave that heats the matter and dissociates heavy nuclei into free nucleons.
- As the shock crosses the ν_e neutrinosphere, electron capture — especially on newly freed protons — produces ν_e that can escape.



The sharp ν_e peak

- The burst lasts only ~ 10 ms.



Why is the neutronization burst robust?

- **It happens before the explosion becomes complicated.**

  The shock has just formed, and the outer stellar layers are still essentially intact.

- **Its origin is a basic weak process.**

  The shock dissociates nuclei into free nucleons, enabling rapid electron capture on free protons and producing a short ν_e flash.

- **Its timing is set by shock breakout through the ν_e neutrinosphere.**

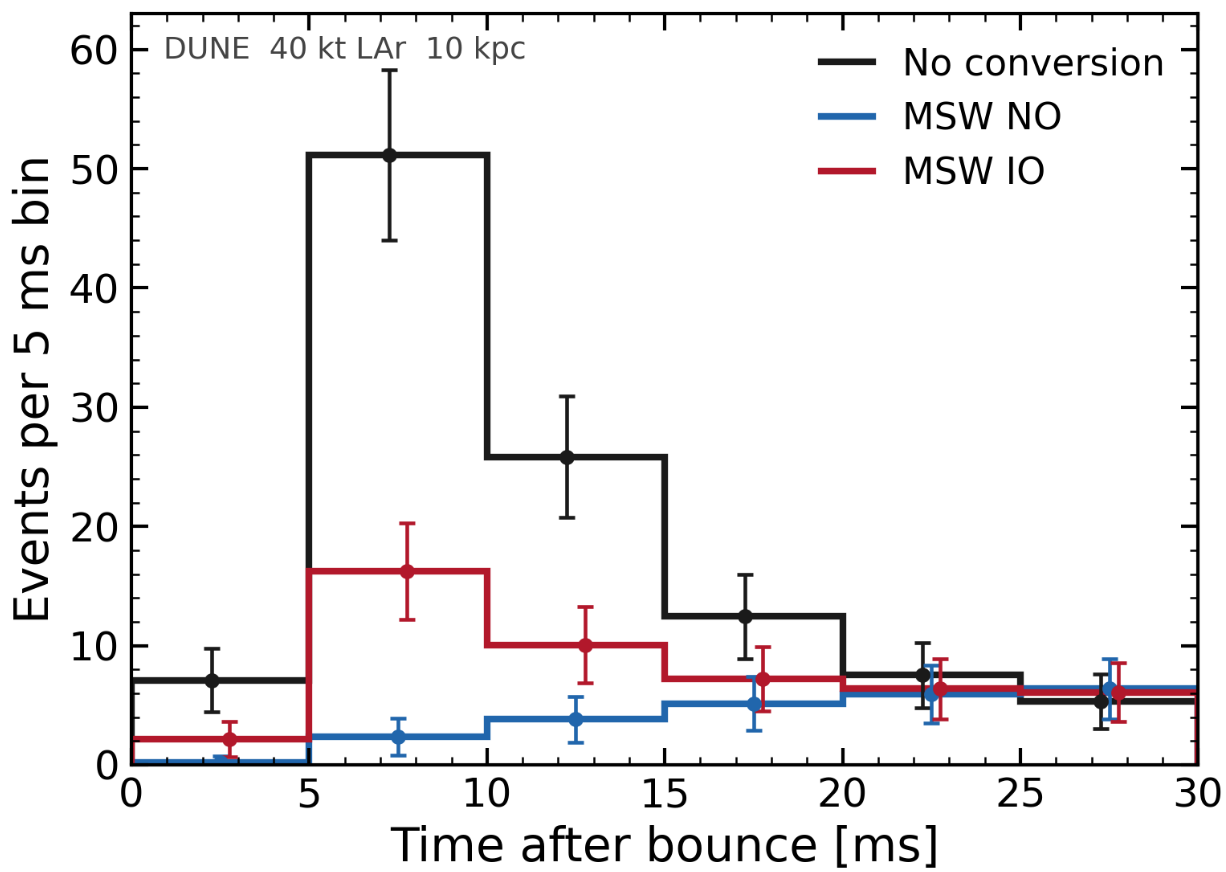
  This short crossing produces a ~ 10 ms ν_e flash.

- **It is less sensitive to detailed source modeling.**

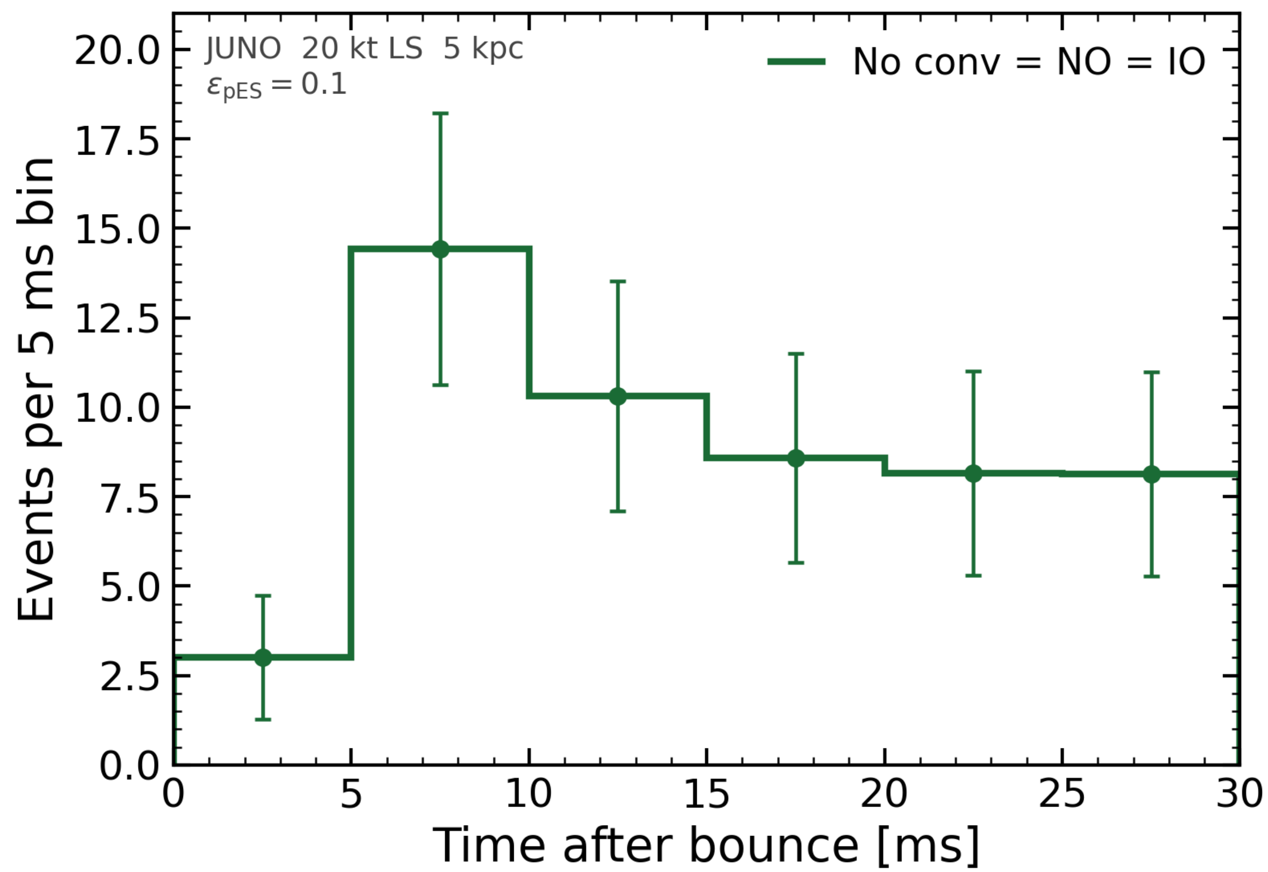
  Compared with accretion and cooling, it depends weakly on progenitor structure, turbulence, and shock revival.

Experimental signature

DUNE, 40 kt LAr, 10 kpc



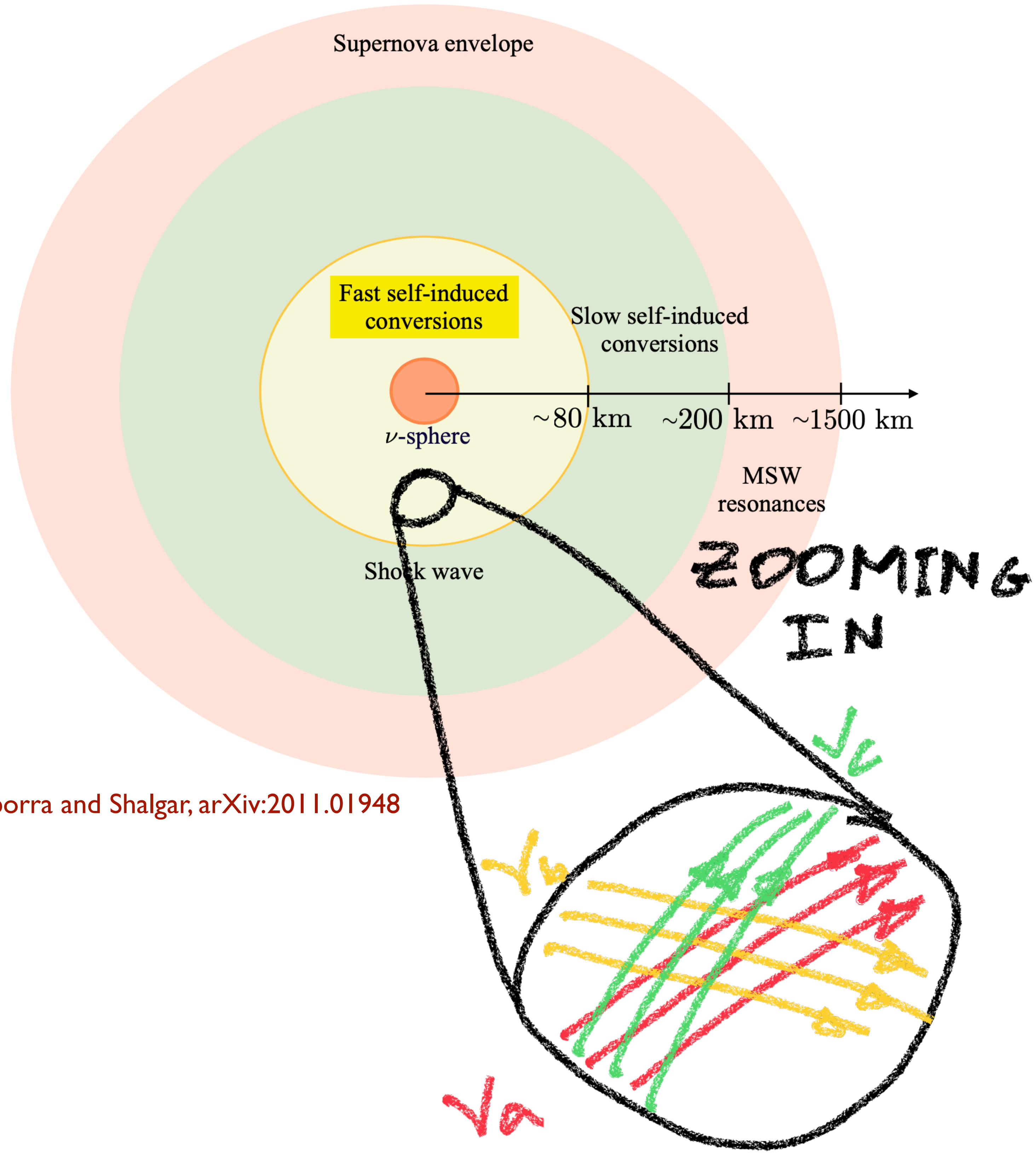
JUNO pES, 20 kt LS, 5 kpc



- In DUNE, flavor conversion can hide the ν_e peak; JUNO NC is ordering-independent.

Flavor composition

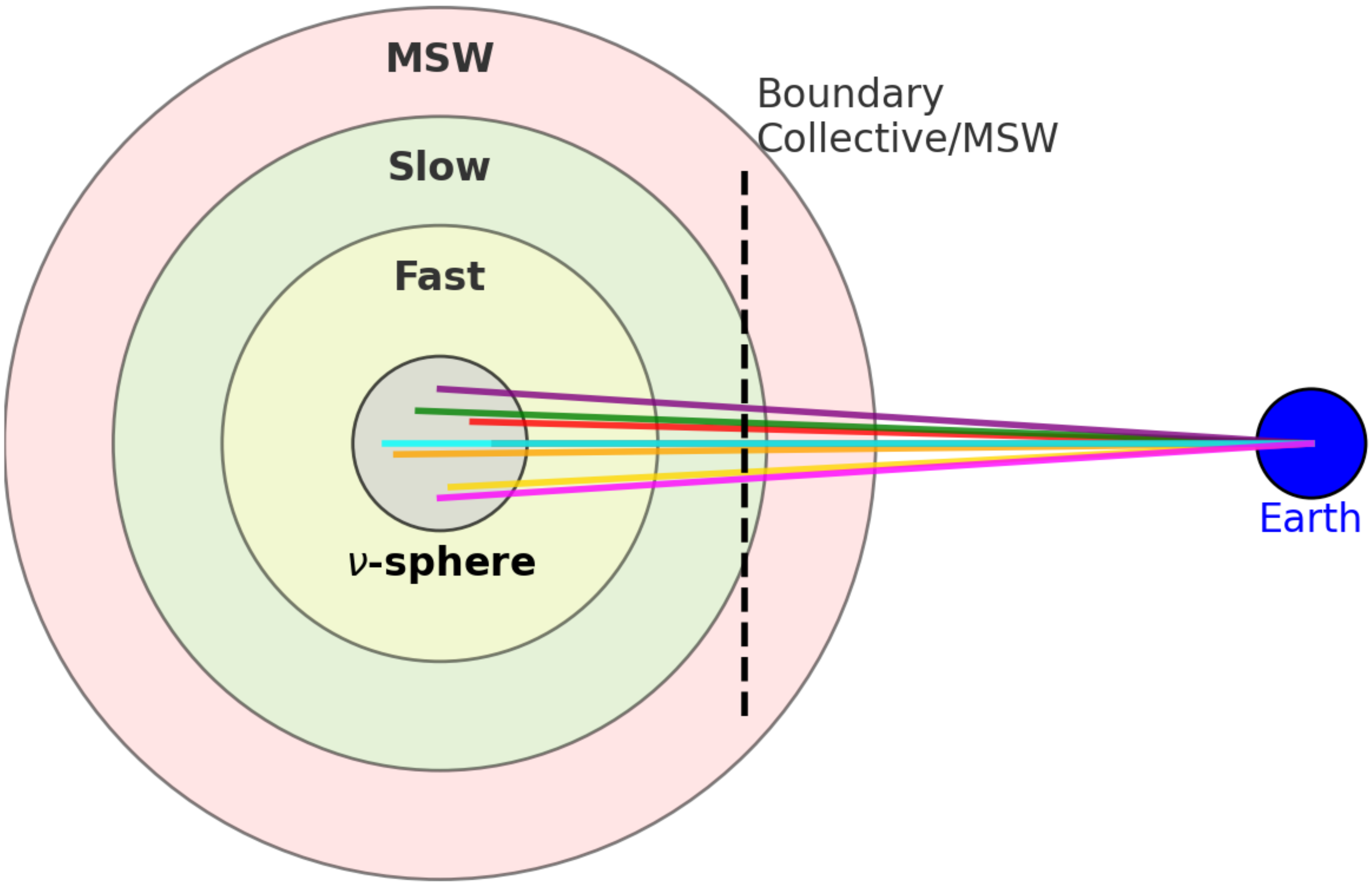
Where flavor conversion happens



Tamborra and Shalgar, arXiv:2011.01948

- Close to the ν-sphere, neutrino–neutrino interactions can dominate.
- The outcome depends on local SN conditions that are difficult to reconstruct.
- Flavor conversion there can affect heating, Y_e, and nucleosynthesis.
- The theoretical picture is still unsettled.

Flavor composition as an averaged outcome



Flavor composition as an averaged outcome

- At the input to the MSW region, the matter potential singles out the ν_e direction, while the $\mu - \tau$ sector remains effectively symmetric:

$$\rho_{\nu_i} = \begin{pmatrix} |\alpha_i|^2 & 0 & 0 \\ 0 & |\beta_i|^2 & \beta_i \gamma_i^* e^{i\phi_i} \\ 0 & \beta_i^* \gamma_i e^{-i\phi_i} & |\gamma_i|^2 \end{pmatrix}$$

- Phase and trajectory averaging suppress coherence:

$$\rho \to \begin{pmatrix} f_{\nu_e} & 0 & 0 \\ 0 & f_{\nu_\mu} & 0 \\ 0 & 0 & f_{\nu_\tau} \end{pmatrix}$$

- Because $\theta_{23} \simeq 45^\circ$, ν_μ and ν_τ project almost equally onto the same two matter eigenstates:

$$\nu_\mu \sim \frac{\nu_a + \nu_b}{\sqrt{2}}, \qquad \nu_\tau \sim \frac{\nu_a - \nu_b}{\sqrt{2}}$$

- After averaging, the two matter eigenstates in the $\mu - \tau$ sector are populated similarly, which constrains the flavor composition at Earth:

$$f_{\nu_e}^{\mathrm{NO}} \lesssim 0.5, \qquad f_{\nu_e}^{\mathrm{IO}} \simeq \frac{1}{3}.$$

Capanema, YP, Saez, arXiv:2403.14762 (2024)

Measuring flavor composition requires many detectors

- No single detector measures all flavors.
- Different channels project the fluence with different flavor weights:

$N_{\text{Ar}} \sim \Phi_{\nu_e}$	DUNE
$N_{\text{IBD}} \sim \Phi_{\bar{\nu}_e}$	water/scintillator
$N_{\text{NC}} \sim \Phi_{\nu_e} + \Phi_{\bar{\nu}_e} + \Phi_{\nu_x} + \Phi_{\bar{\nu}_x}$	NC-like
$N_{\text{ES}} \sim \Phi_{\nu_e} + 0.42\Phi_{\bar{\nu}_e} + 0.18\Phi_{\nu_x} + 0.15\Phi_{\bar{\nu}_x}$	ES

- The measurement becomes possible because the flavor weights are different.

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- The measurement becomes possible because the flavor weights are different.
- Where we have used $\Phi_{\nu_x} = A\Phi_{\nu_e}$ and $\Phi_{\bar{\nu}_x} = B\Phi_{\bar{\nu}_e}$.
- The parameters A and B encode the flavor composition:

$$f_{\nu_e} = \frac{1}{1+A}, \qquad f_{\bar{\nu}_e} = \frac{1}{1+B}\,.$$

- In the expected regions:

$$f_{\nu_e}^{\mathrm{NO}} \lesssim 0.5 \Leftrightarrow A \gtrsim 1, \qquad f_{\nu_e}^{\mathrm{IO}} \simeq \frac{1}{3} \Leftrightarrow A \simeq 2.$$

But detectors do not measure bare A and B

- The clean A, B system is only meaningful inside a broad time/energy bin:

$$\Delta \equiv \Delta E \times \Delta t, \qquad \Phi_{\nu_x}(E,t) \simeq A_\Delta \Phi_{\nu_e}(E,t), \qquad \Phi_{\bar{\nu}_x}(E,t) \simeq B_\Delta \Phi_{\bar{\nu}_e}(E,t)\,.$$

- Real event rates are predicted by folding these fluences through each detector response:

$$N_j^{\rm pred}(A_\Delta, B_\Delta) = \sum_\alpha \int_\Delta dE_\nu\, dt\, dE_{\rm vis}\, K_{j\alpha}(E_{\rm vis}, E_\nu, t)\, \Phi_\alpha(E_\nu, t)\,.$$

- DUNE and IBD anchor Φ_{ν_e} and $\Phi_{\bar{\nu}_e}$; ES and NC-like channels then constrain A_Δ and B_Δ.

How SNO solved the solar neutrino problem

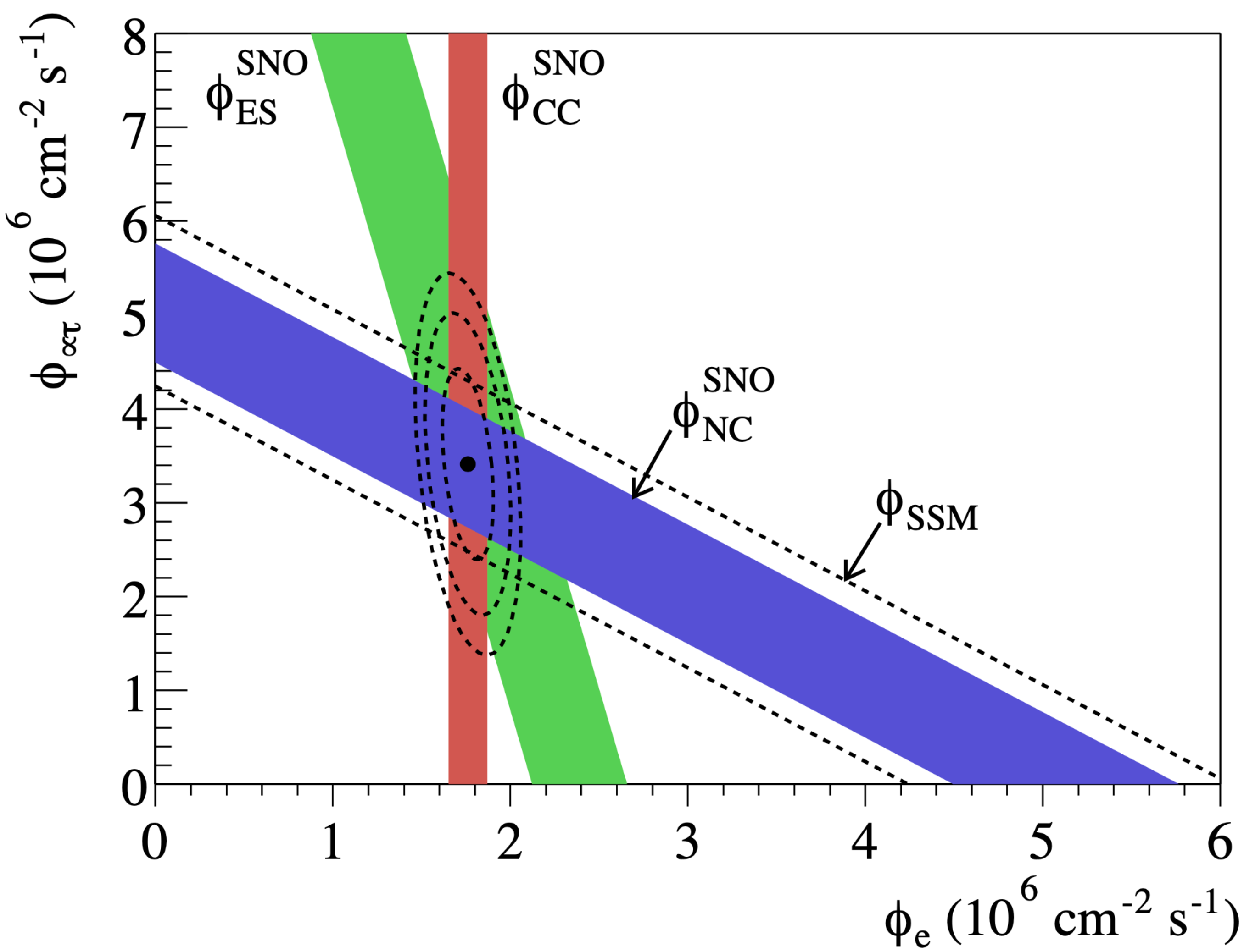
- SNO combined channels with different flavor sensitivities: CC measured Φ_{ν_e}, while NC fixed the total active flux.

$$N_{\rm CC} \sim \Phi_{\nu_e} \qquad \nu_e + d \to p + p + e^-$$

$$N_{\rm NC} \sim \Phi_{\nu_e} + \Phi_{\nu_{\mu,\tau}} \qquad \nu_\alpha + d \to p + n + \nu_\alpha$$

$$N_{\rm ES} \sim \Phi_{\nu_e} + 0.15\Phi_{\nu_{\mu,\tau}} \qquad \nu_\alpha + e^- \to \nu_\alpha + e^-$$

- The combined CC, NC, and ES result showed that the missing solar ν_e flux reappeared as non-electron active flavors.



SNO Collaboration,
arXiv:nucl-ex/0204008

Gamma ray echo

Gamma-ray echo: a delayed 511 keV signal

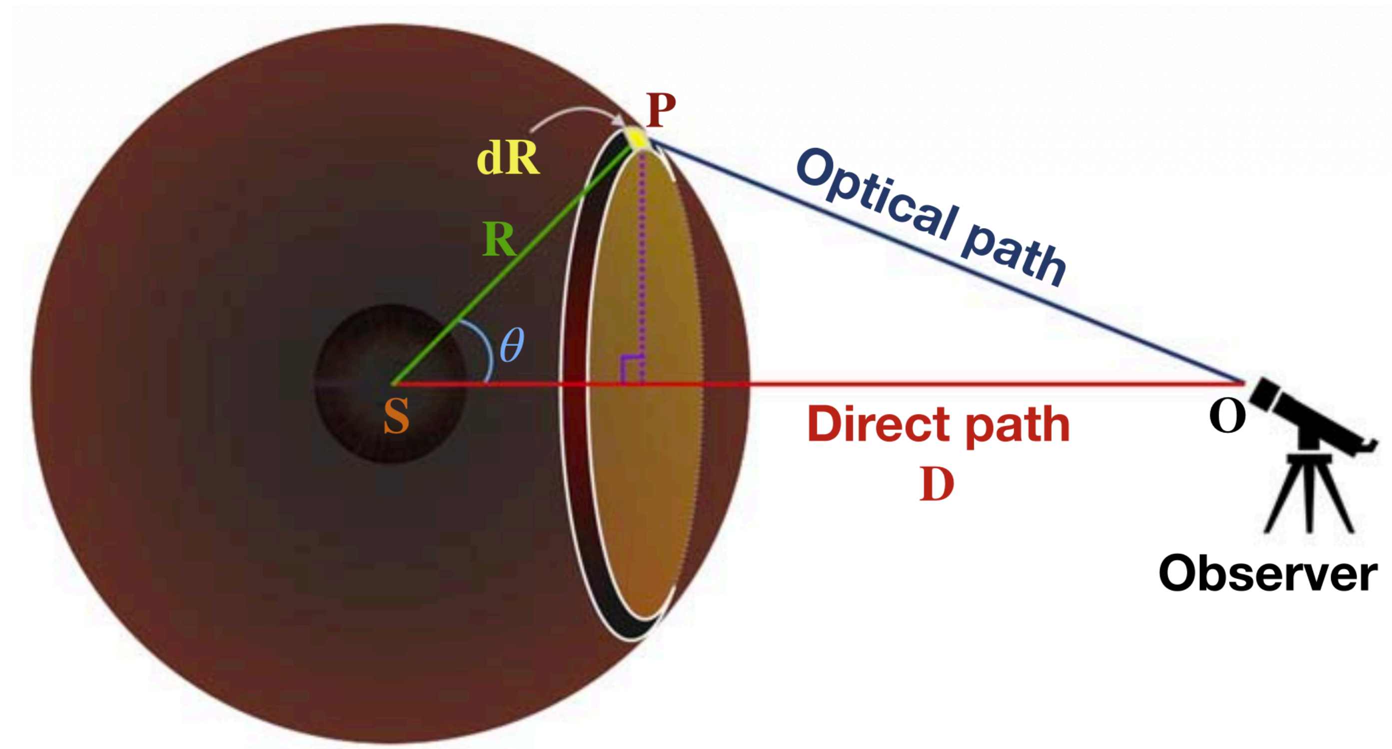
- The SN $\bar{\nu}_e$ burst crosses the hydrogen-rich outer envelope.

- A small fraction undergoes IBD near the stellar surface, producing positrons:

$$\bar{\nu}_e + p \rightarrow n + e^+ .$$

- Positron annihilation generates a delayed 511 keV echo:

$$e^+e^- \rightarrow 2\gamma\,(511\,\mathrm{keV}) .$$



- The delayed 511 keV emission appears from different regions of the visible stellar disk at successive times.

Lunardini et al., arXiv:2312.13197

The echo measures the surface $\bar{\nu}_e$ fluence

- The echo is produced after flavor conversion inside the supernova.
- But it is produced before neutrino propagation from the star to Earth.
- Therefore it probes the post-conversion $\bar{\nu}_e$ fluence at the stellar surface:

$$N_\gamma^\oplus = \frac{A_{\rm eff}}{4\pi D^2} C_\gamma \int dE_\nu dt\, \sigma_{\rm IBD}(E_\nu) \Phi_{\bar{\nu}_e}^{\rm surf}(E_\nu, t)\,.$$

- C_γ encodes the envelope composition, photon escape, and positron-annihilation physics.

$$C_\gamma = \frac{\eta_\gamma}{2} \frac{n_p}{n_e} \frac{1}{\sigma_C}$$

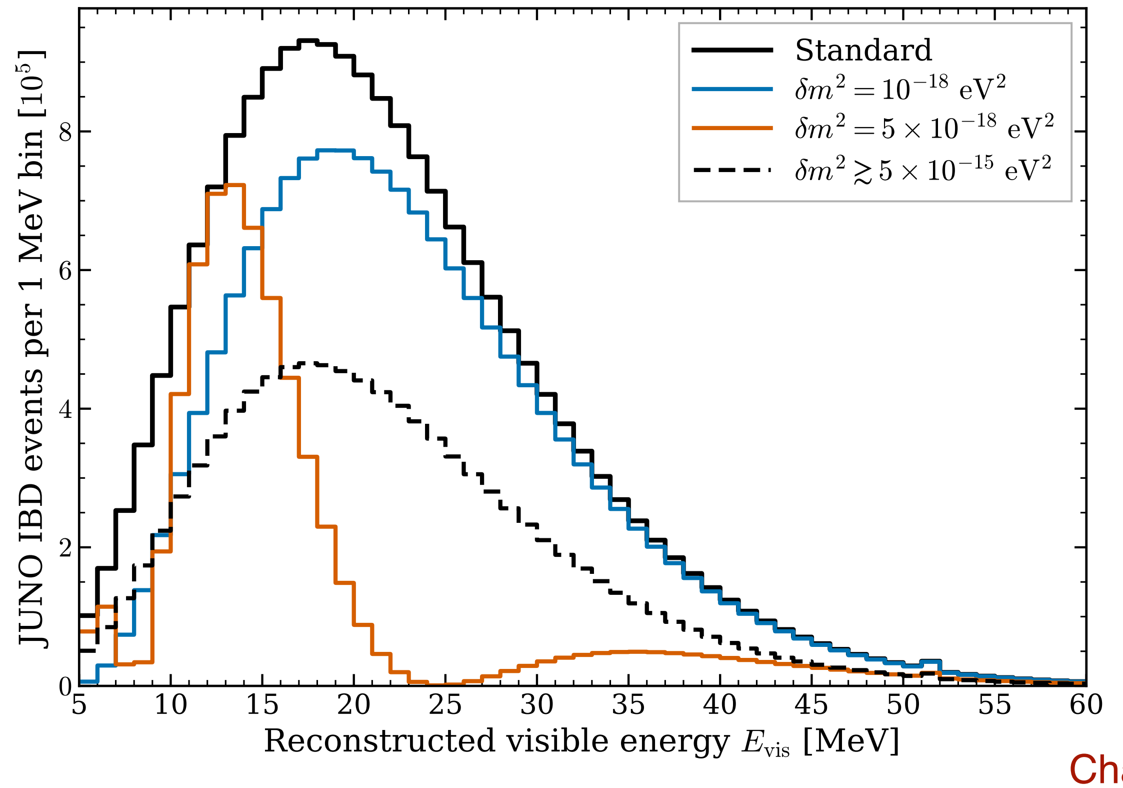
- This makes the gamma-ray echo **an astrophysical near detector** for $\Phi_{\bar{\nu}_e}^{\rm surf}$.

The far detector measures the propagated burst

- Terrestrial IBD detectors measure the $\bar{\nu}_e$ flux after propagation from the stellar surface to Earth:

$$N_{\rm IBD}^{\oplus} = \frac{N_p \epsilon_{\rm IBD}}{4\pi D^2} \int dE_\nu dt\, \sigma_{\rm IBD}(E_\nu) S(E_\nu) \Phi_{\bar{\nu}_e}^{\rm surf}(E_\nu, t)\,.$$

- Here $S(E_\nu)$ describes any propagation effect between the star and Earth.
- If the propagation effect leaves a resolved spectral distortion, it may be seen directly in the IBD spectrum.
- If it averages out, it becomes an energy-smooth depletion — degenerate with the unknown emitted fluence.

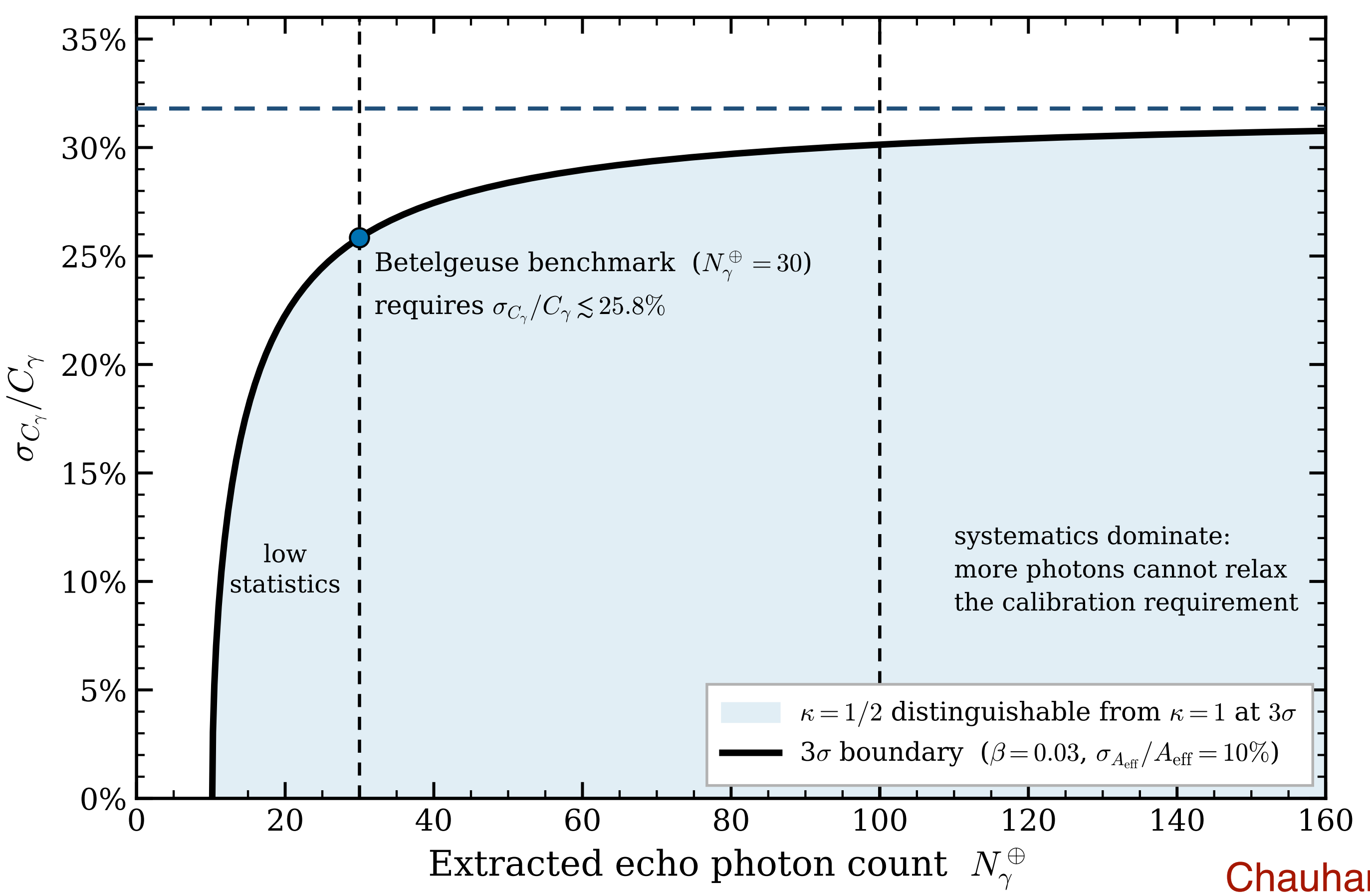


Chauhan and YP, in preparation

Comparing the near and far $\bar{\nu}_e$ fluence

$$\kappa \equiv \frac{N^{\oplus}_{\rm IBD}}{N^{\oplus}_{\gamma}} \frac{A_{\rm eff} C_\gamma}{N_p \epsilon_{\rm IBD}} .$$

- Standard propagation gives $\kappa \simeq 1$.
- A fully averaged pseudo-Dirac depletion gives $\kappa \simeq 1/2$.
- The figure shows when $\kappa = 1/2$ can be distinguished from $\kappa = 1$ at 3σ.
- For $N^{\oplus}_{\gamma} \simeq 30$, resolving $\kappa = 1/2$ requires echo calibration at the $\sim 25\,\%$ level.
- This makes the test experimentally feasible for very nearby SNe, roughly within $\sim 1\,\mathrm{kpc}$ for planned MeV telescopes.



Chauhan and YP, in preparation

Discussion/Conclusion

Discussion/Conclusion

- The observables discussed here are designed as consistency checks with minimal dependence on detailed supernova modeling.
- If these robust checks fail, the next Galactic supernova could provide evidence for unexpected neutrino physics even with limited knowledge of the source.

Thank you!

Backup slides

Our approach: exploiting μ–τ symmetry

- Since μ and τ leptons are absent in the SN environment, the μ–τ sector is symmetric, and the choice of basis is arbitrary.

$$\rho_\nu^B = \frac{1}{N}\sum_{k=1}^{N}\begin{pmatrix} \alpha_k^2 & 0 & 0 \\ 0 & \beta_k'^2 & \beta_k'\gamma_k' e^{-i\phi_k'} \\ 0 & \beta_k'\gamma_k' e^{i\phi_k'} & \gamma_k'^2 \end{pmatrix}$$

- Assume that the off-diagonal terms vanish in an arbitrary basis:

$$\frac{1}{N}\sum_{k=1}^{N}\beta_k'\gamma_k' e^{i\phi_k'} \approx 0.$$

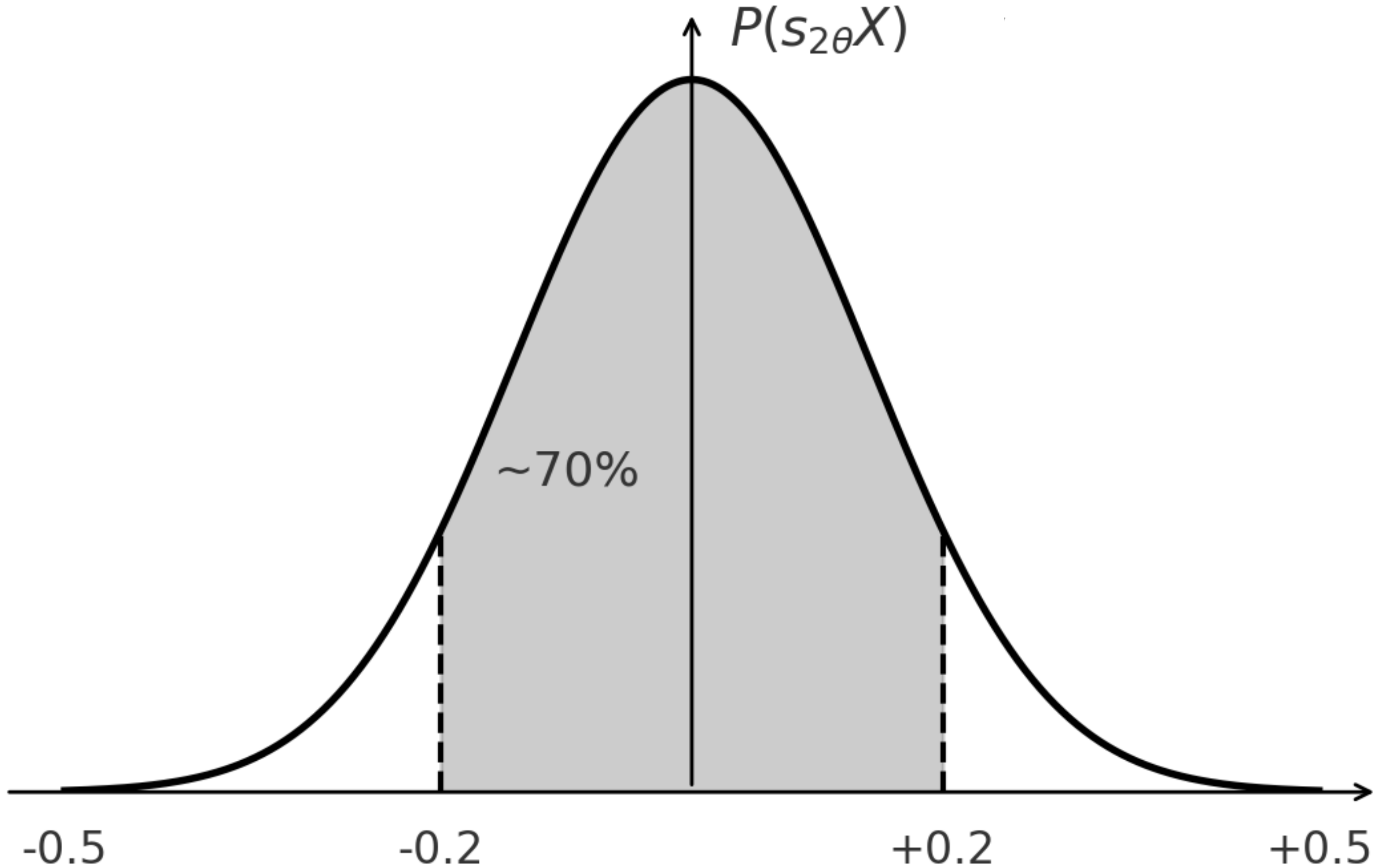
- In this case, after rotating to the flavor basis, we obtain

$$\rho_\nu^F = \frac{1}{N}\sum_{k=1}^{N}\begin{pmatrix} \alpha_k^2 & 0 & 0 \\ 0 & c_\theta^2\beta_k'^2 + s_\theta^2\gamma_k'^2 & \frac{1}{2}s_{2\theta}(\beta_k'^2 - \gamma_k'^2) \\ 0 & \frac{1}{2}s_{2\theta}(\beta_k'^2 - \gamma_k'^2) & s_\theta^2\beta_k'^2 + c_\theta^2\gamma_k'^2 \end{pmatrix}$$

- $s_{2\theta}$ parametrizes the μ'–τ' mixing rotation, and $X \equiv \dfrac{1}{N}\sum_{k=1}^{N}\left(\beta_k'^2 - \gamma_k'^2\right)$ encodes the μ'–τ' population asymmetry.

Our approach: exploiting μ–τ symmetry

- Assume $s_{2\theta} \in [-1,1]$ and $X \equiv \frac{1}{N}\sum_{k=1}^{N}\left(\beta_k'^2 - \gamma_k'^2\right) \in [-1,1]$ are uniformly distributed. Then the product $s_{2\theta}X$ is most likely close to zero.



- Thus, even if decoherence occurs in a rotated basis, coherence in the flavor basis is most likely suppressed.

Our approach: ensemble → flavor ratios

- Assuming off-diagonal terms to vanish, we can write the state of the ensemble at the boundary as:

$$\rho_\nu = \begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}$$

- Where $a = \dfrac{\sum_i \alpha_i}{10^{12}}$, $b = \dfrac{\sum_i \beta_i}{10^{12}}$ and $c = \dfrac{\sum_i \gamma_i}{10^{12}}$.

- Thus, the ensemble can be summarized by the flavor ratios (a, b, c).

Normal Ordering (NO)

- Assuming NO and adiabatic propagation, we have $\nu_e \to \nu_3$:

$$(1,0,0)_{SN} \to \left(|U_{e3}|^2, |U_{\mu 3}|^2, |U_{\tau 3}|^2\right)_{\oplus} \quad .$$

- Conversely, for the non-electron flavors,

$$(0,1,0)_{SN} \quad \text{or} \quad (0,0,1)_{SN} \to$$
$$\frac{1}{2}\left(|U_{e1}|^2 + |U_{e2}|^2, |U_{\mu 1}|^2 + |U_{\mu 2}|^2, |U_{\tau 1}|^2 + |U_{\tau 2}|^2\right)_{\oplus} \quad .$$

- For any initial combination $(a, b, c)_{SN}$, we obtain on Earth the ν_e fraction:

$$f_{\nu_e}^{NO} = a\,|U_{e3}|^2 + b\frac{|U_{e1}|^2 + |U_{e2}|^2}{2} + c\frac{|U_{e1}|^2 + |U_{e2}|^2}{2} \quad .$$

- From the unitarity of the PMNS matrix and $a + b + c = 1$, it simplifies to

$$f_{\nu_e}^{NO} = \frac{1}{2}\left(1 - |U_{e3}|^2\right) + \frac{a}{2}\left(3\,|U_{e3}|^2 - 1\right) \quad ,$$

- Adopting $|\,U_{e3}\,|^2 \approx 0.02 \ll 1$, we obtain

$$f_{\nu_e}^{NO} \approx \frac{1-a}{2} \lesssim 0.5^{+0.06}_{-0.08}$$

Inverted Ordering (IO)

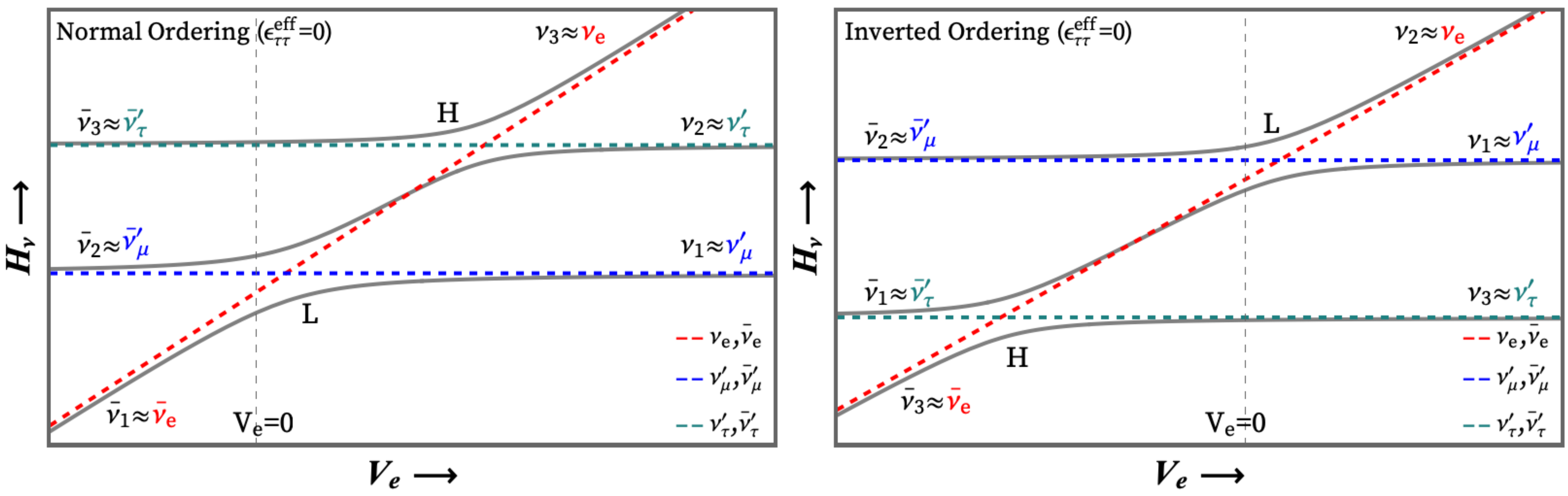
- For IO, it is analogous to the NO case, but with $U_{e3} \leftrightarrow U_{e2}$

$$f_{\nu_e}^{IO} = \frac{1}{2}\left(1 - |U_{e2}|^2\right) + \frac{a}{2}\left(3\,|U_{e2}|^2 - 1\right) \ .$$

- Assuming $|U_{e2}|^2 \approx 1/3$, we have

$$f_{\nu_e}^{IO} \approx 1/3^{+0.1}_{-0.1} \, .$$

- Consistent with flavor equipartition.



Shock waves

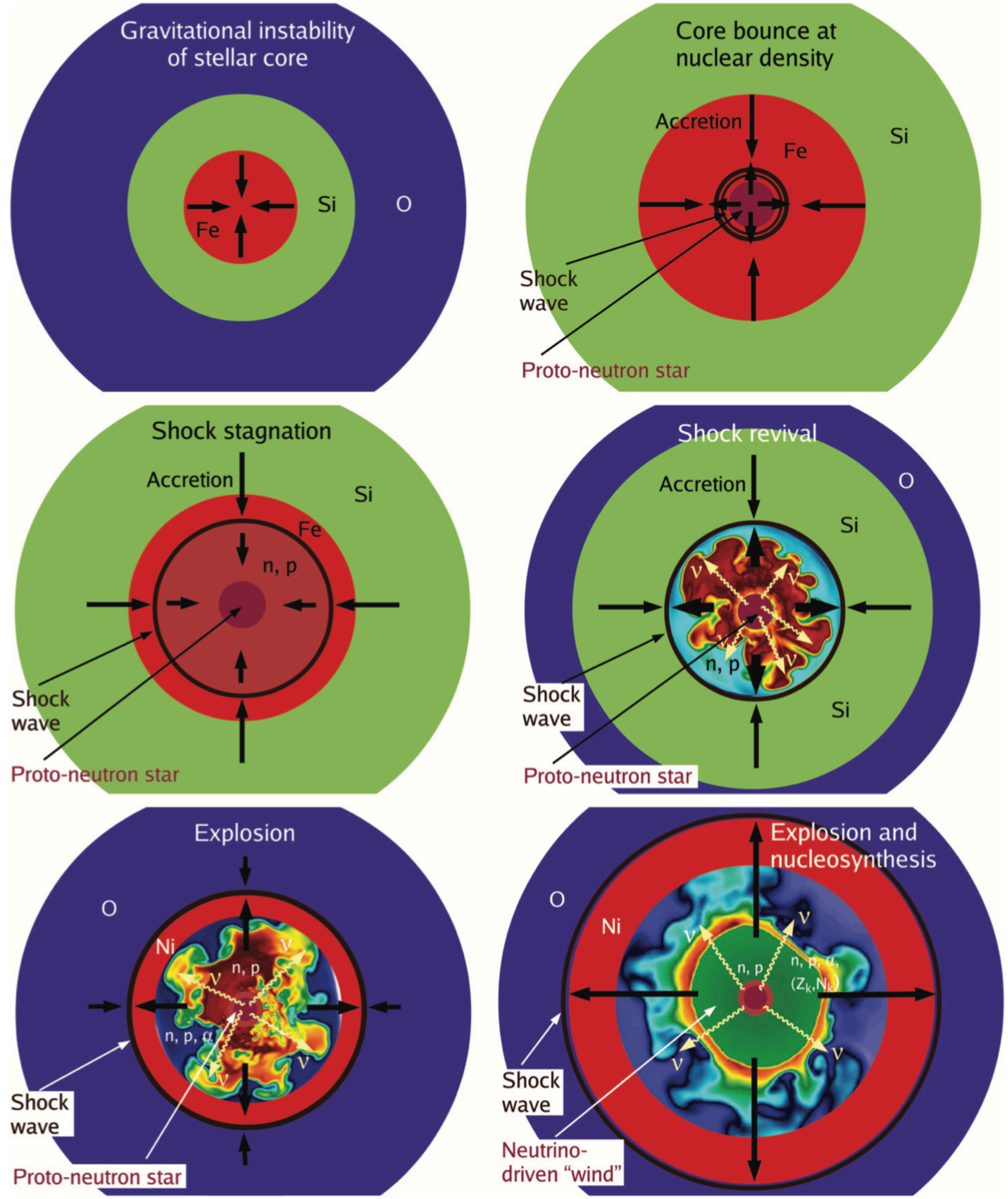
- Shock waves can disrupt the SN envelope and affect adiabaticity of the H resonance early on ($U_{e3} \leftrightarrow U_{e2}$).

- For NO: adiabaticity is broken,

$$f_{\nu_e}^{NO}(\text{non-ad } H) \approx \frac{1}{3} \ .$$

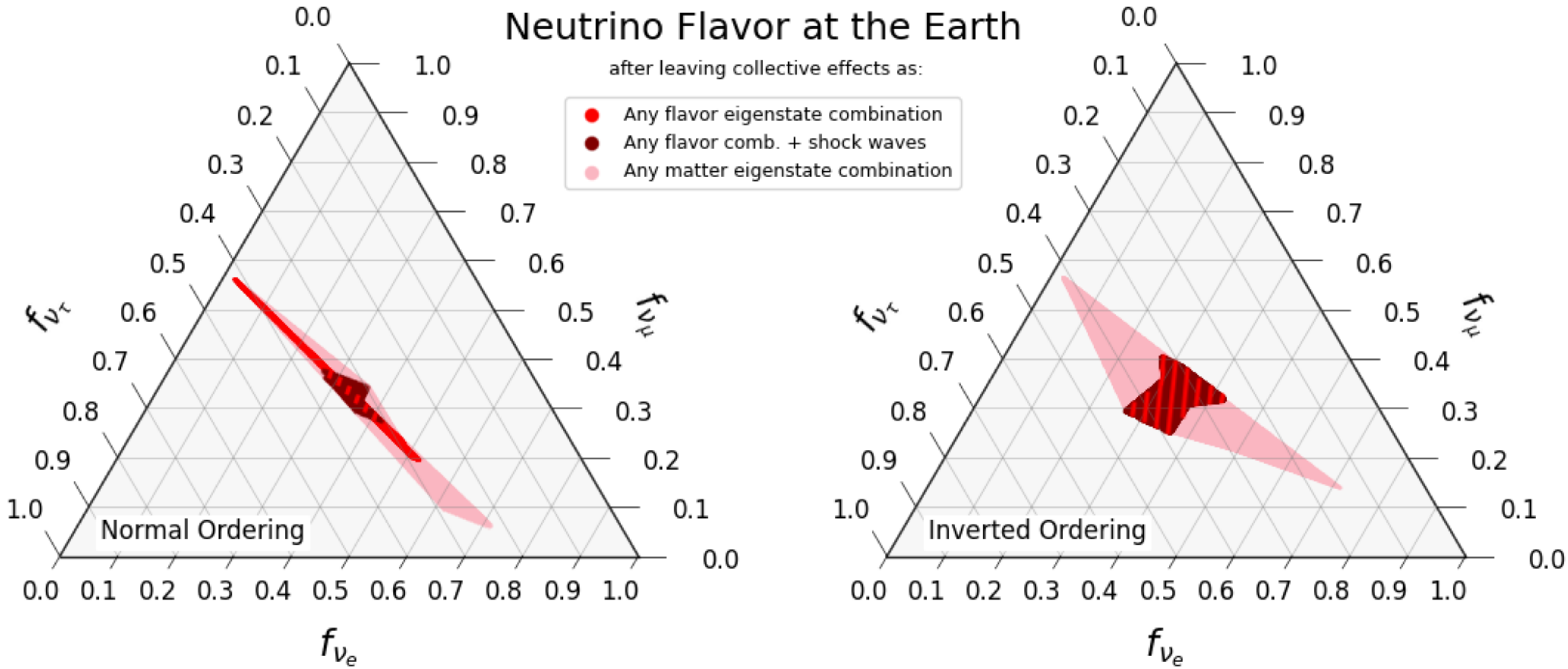
- For IO: unaffected, remains

$$f_{\nu_e}^{IO}(\text{non-ad } H) \approx \frac{1}{3} \ .$$



Shock wave propagation and revival (Janka et al. 2012)

Results



- **Red regions:** Flavor composition under adiabatic evolution.
- **Maroon regions:** Flavor composition under non-adiabatic transitions (H-resonance + shock wave).
- **Pink regions:** Flavor composition if if the $\mu - \tau$ symmetry is broken.