Flavor composition of supernova neutrinos

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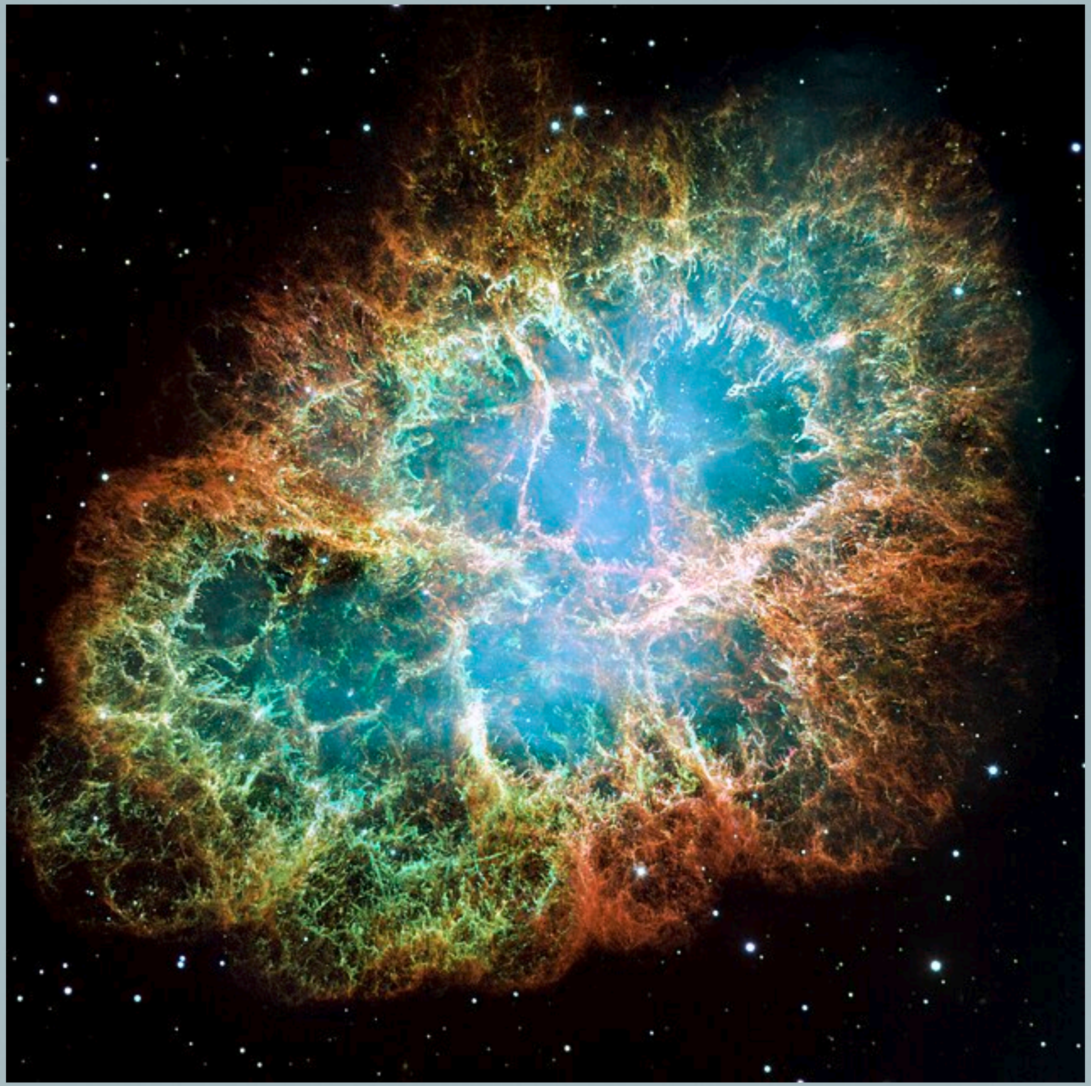


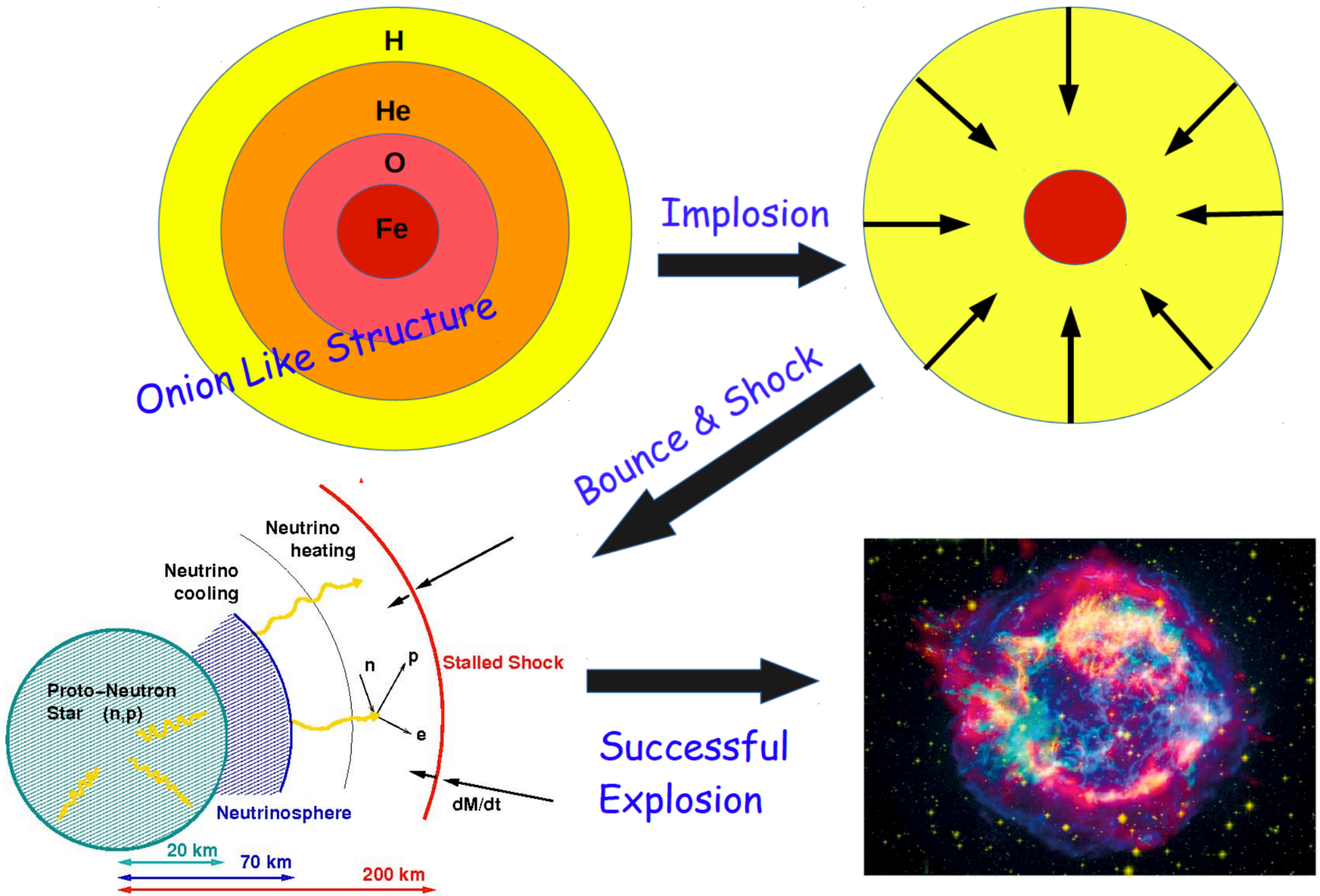
Crab Nebula (Messier 1/ M 1/NGC 1952)

Lomonosov Conference (08/25/2025)

Outline

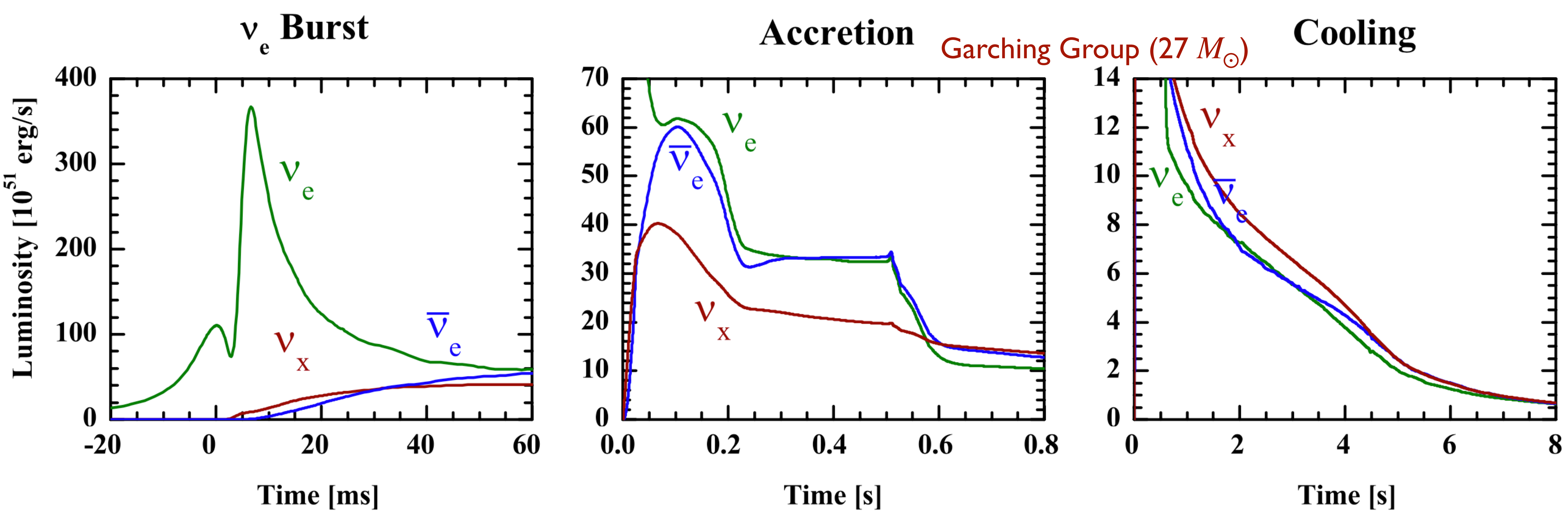
- **Supernova mechanism & neutrino emission:** core collapse, bounce, and neutrinos as the main energy channel.
- **Flavor evolution across emission phases:** burst, accretion, and cooling.
- **Collective effects ($\nu - \nu$ interactions):** Fast and slow conversions introduce uncertainties in SN dynamics and flavor outcome.
- **Standard matter effects & trajectory averaging** constrain the observable flavor mix at Earth.

Supernovae and neutrinos



- 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).

Supernovae and neutrinos



- Robust signal (independent of SN mass/EoS).
- Clean probe of new physics (e.g. scalar NSI)

arXiv: 2508.16558

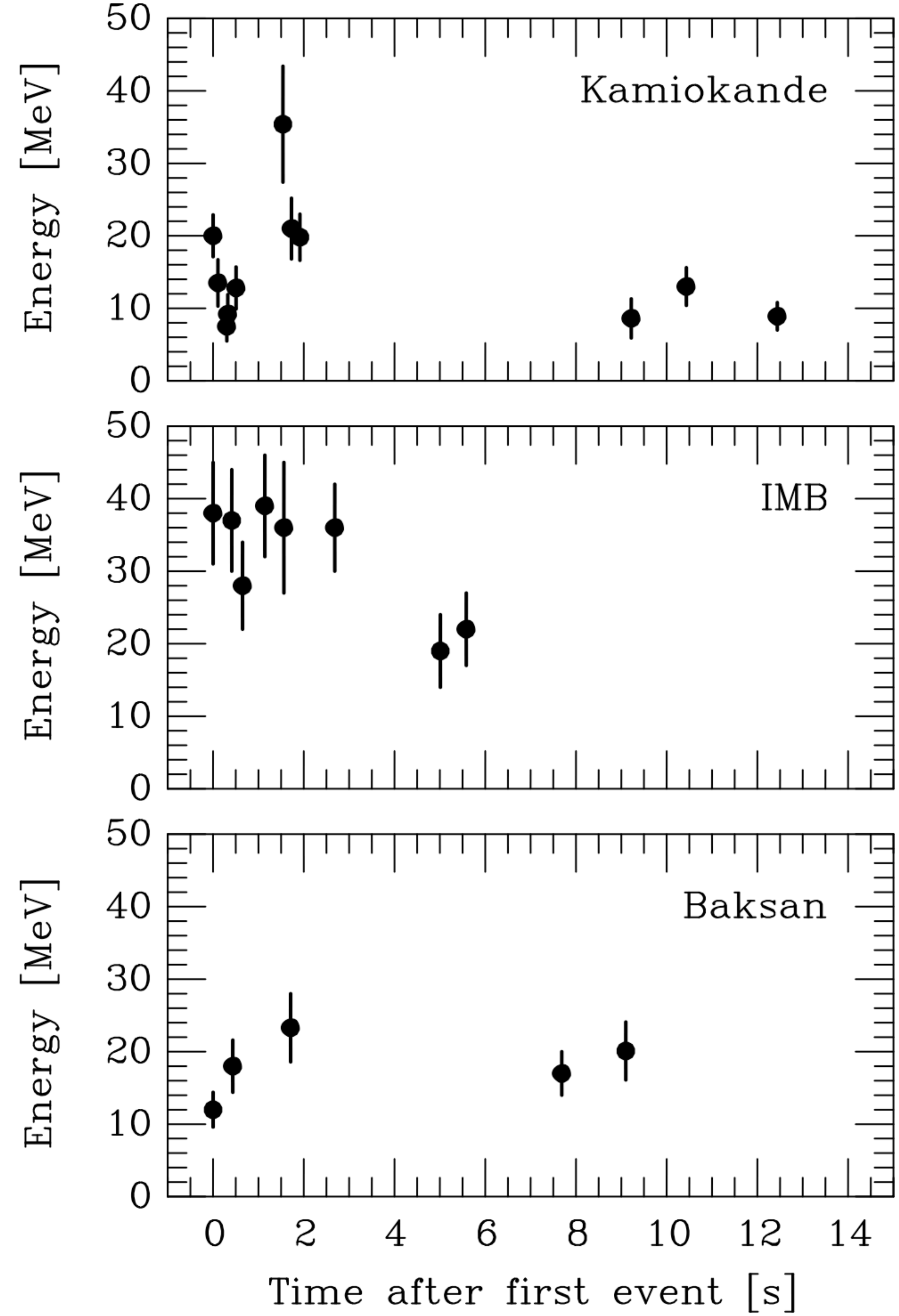
Observation of the ν_e burst can enhance sensitivity to scalar NSI (see also Peter Denton's talk).

- Strong dependence on mass, EoS, and dynamics.
- Possible onset of **collective effects**.
- **Flavor composition** uncertain.

- Sensitive to EoS and SN mass → significant model dependence.
- **Collective effects** expected to develop and impact SN dynamics.
- **Flavor composition** uncertain.

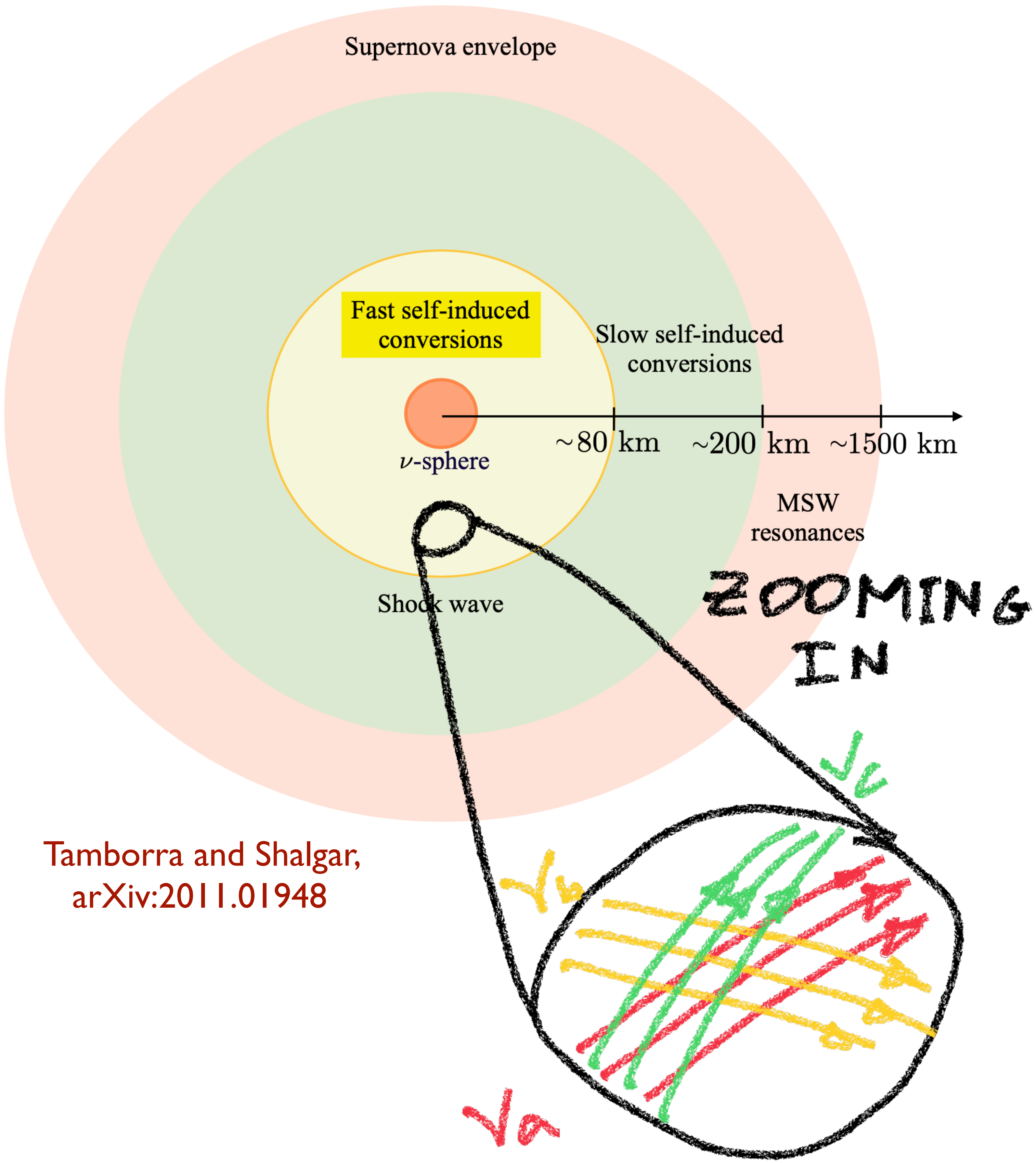
SN1987A: the first SN seen in neutrinos

- Galactic supernovae (~10 kpc) are rare: about 1–2 per century.
- SN1987A: first naked-eye SN since Kepler (1604).
- Progenitor: Sanduleak 69202 in the Large Magellanic Cloud, 51 kpc away.
- Detected via neutrinos by Kamiokande-II, IMB, and Baksan.
- Total: ~24 detected events out of ~10^{58} emitted.
- **Consistent with the basic SN neutrino paradigm (energy, timescale, luminosity).**



Janka, Handbook of Supernovae (2017)

Where flavor conversion happens in a SN

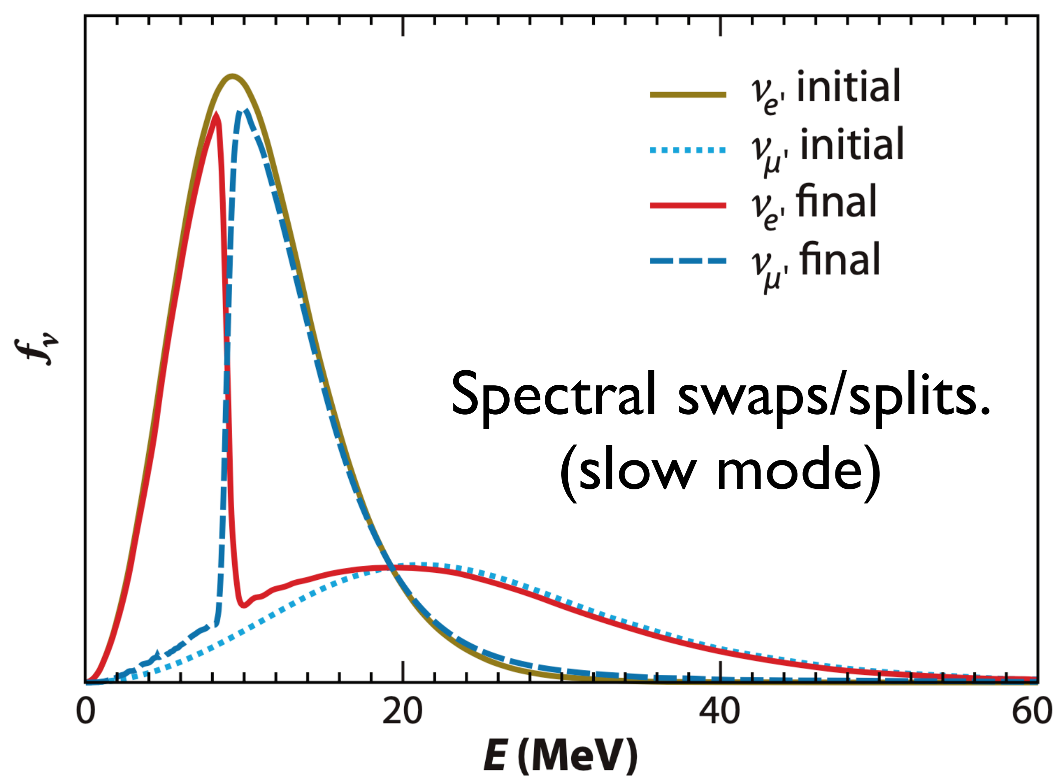


Tamborra and Shalgar, arXiv:2011.01948

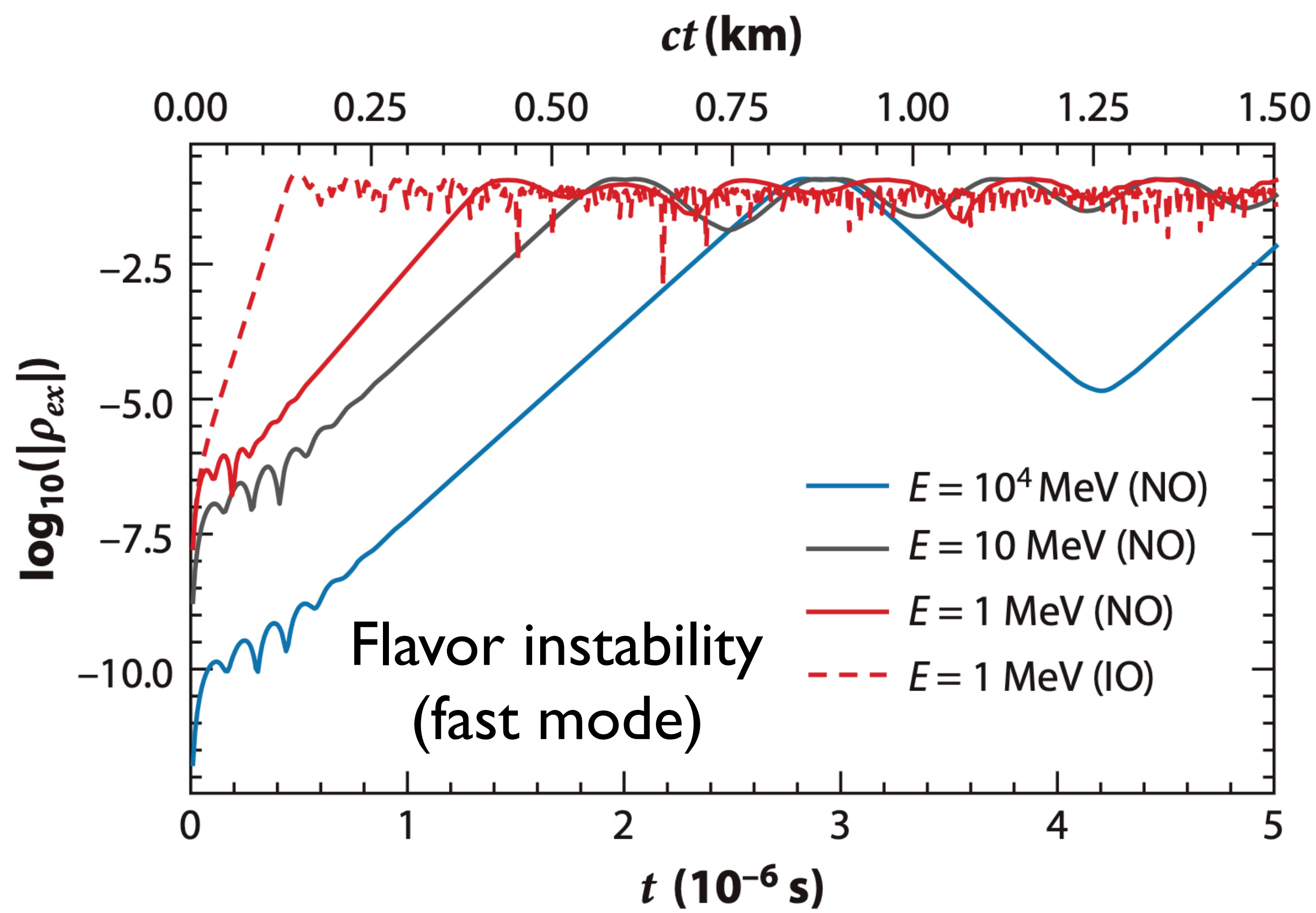
- Current picture: local neutrino–neutrino interactions dominate.
- Outcome depends on details we may never access directly.
- Potentially crucial for SN physics (heating, Y_e, nucleosynthesis).
- Theory still debated: mean-field vs. many-body, role of entanglement.

Collective neutrino oscillations

- **Slow conversion:** Collective oscillations driven by $\nu - \nu$ refraction and vacuum frequency ($\Delta m^2/2E$). Produce spectral swaps/splits. Occurs ~100–1000 km above the ν-sphere.
- **Fast conversion:** Flavor instabilities triggered by electron lepton number (ELN) angular crossings; evolve on ns/meter scales, independent of $\Delta m^2/2E$. Occurs very close to the ν-sphere, $\lesssim$10–100 km.

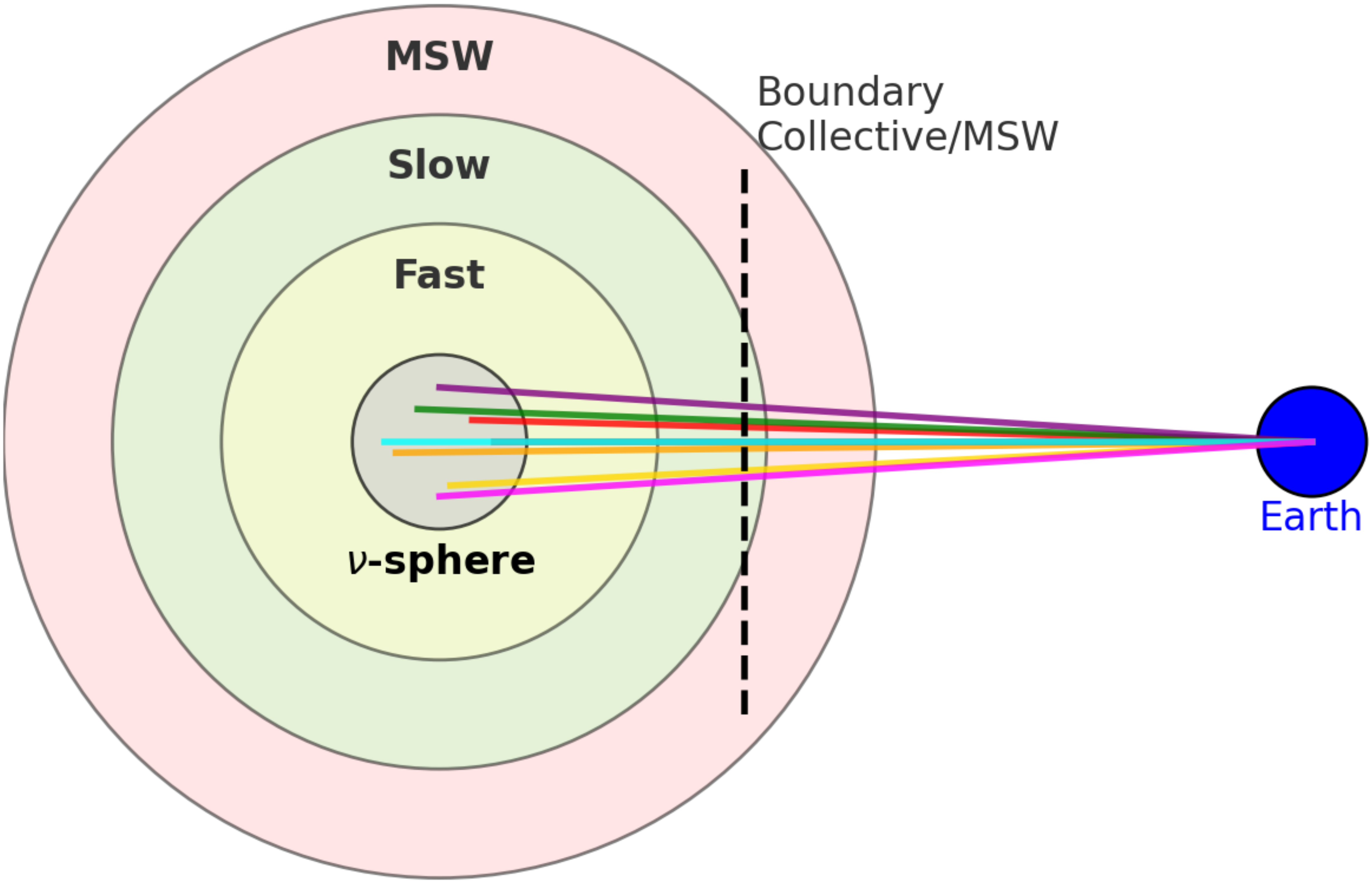


Duan, Fuller and Qian,
arXiv:1001.2799



Tamborra and Shalgar,
arXiv:2011.01948

Our approach: tracing flavor evolution to Earth



Our approach

- In the **boundary** between collective and standard matter effects, each neutrino ν_i has its state (in the flavor basis) described by:

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

- In a millisecond, 10^{12} ν_i's reach the Earth. If we imagine the (average) ensemble of these ν_i's in the boundary, we have:

$$\rho_{\nu} = \frac{1}{10^{12}} \sum_{i=1}^{10^{12}} \begin{pmatrix} |\alpha_i|^2 & 0 & 0 \\ 0 & |\beta_i|^2 & \beta_i \gamma_i^* e^{i\phi_i} \\ 0 & \beta_i^* \gamma_i e_i^{-i\phi_i} & |\gamma_i|^2 \end{pmatrix}$$

- The off-diagonal terms, encoding phase coherence, most likely damp out → effectively leaving a diagonal ensemble.

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:

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

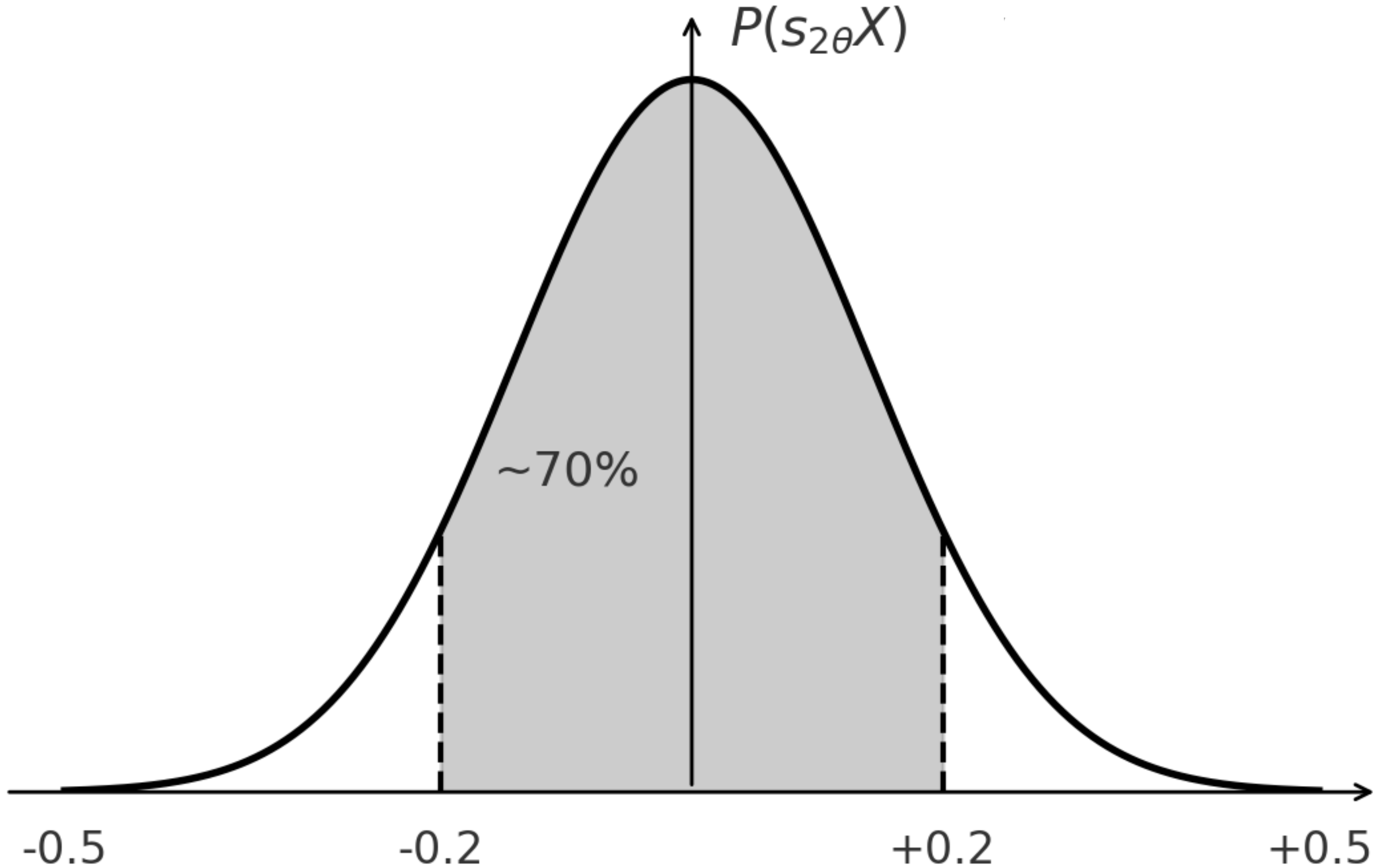
- In this case, after rotating to the flavor basis, we obtain

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

- $s_{2\theta}$ parametrizes the μ'–τ' mixing rotation, and $X \equiv \frac{1}{N}\sum_{k=1}^{N}\left(\beta_k'^2 - \gamma_k'^2\right)$ 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 $a = \frac{\sum_i \alpha_i}{10^{12}}$, $b = \frac{\sum_i \beta_i}{10^{12}}$ and $c = \frac{\sum_i \gamma_i}{10^{12}}$.

- 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)

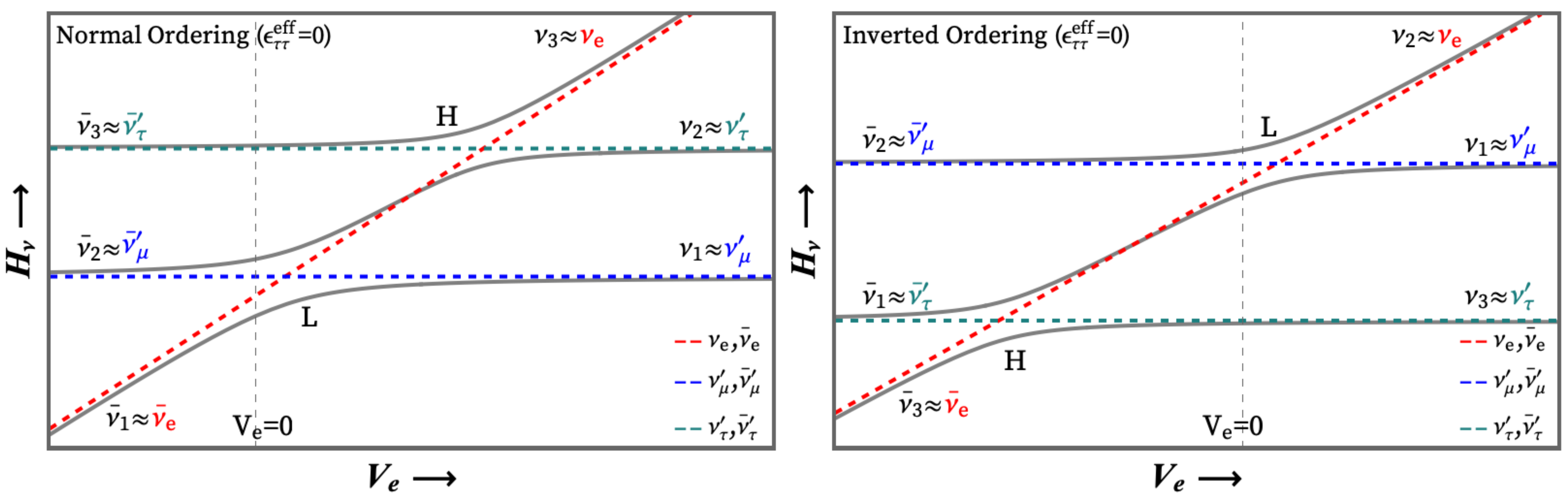
- For IO, it is analogous to the NO case, but with $U_{e3} \leftrightarrow U_{e2}$

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

- 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

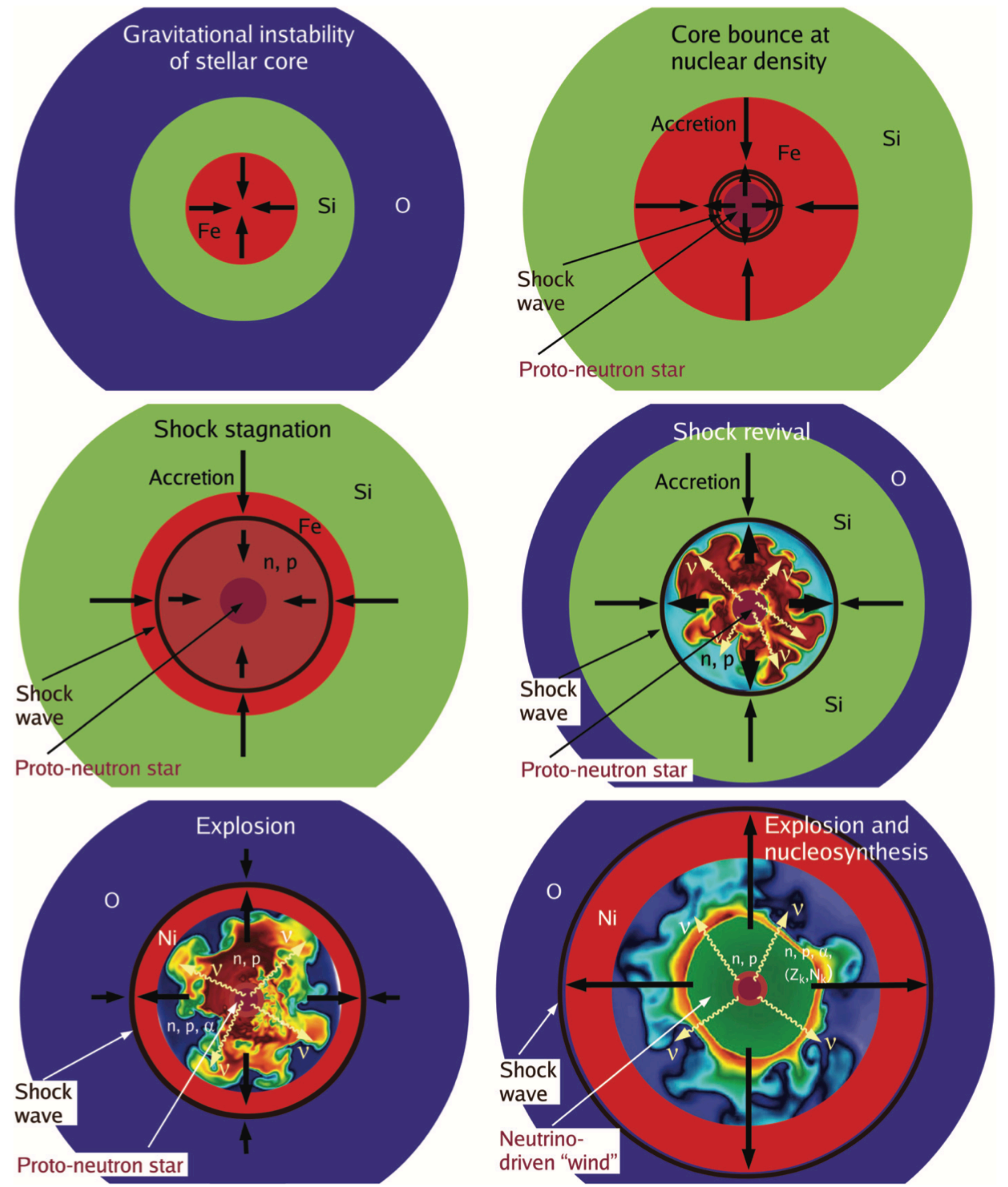
- Shock waves can disrupt the SN envelope and affect adiabaticity of the H resonance early on ($U_{e3} \leftrightarrow U_{e2}$).

- For NO: adiabaticity is broken,

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

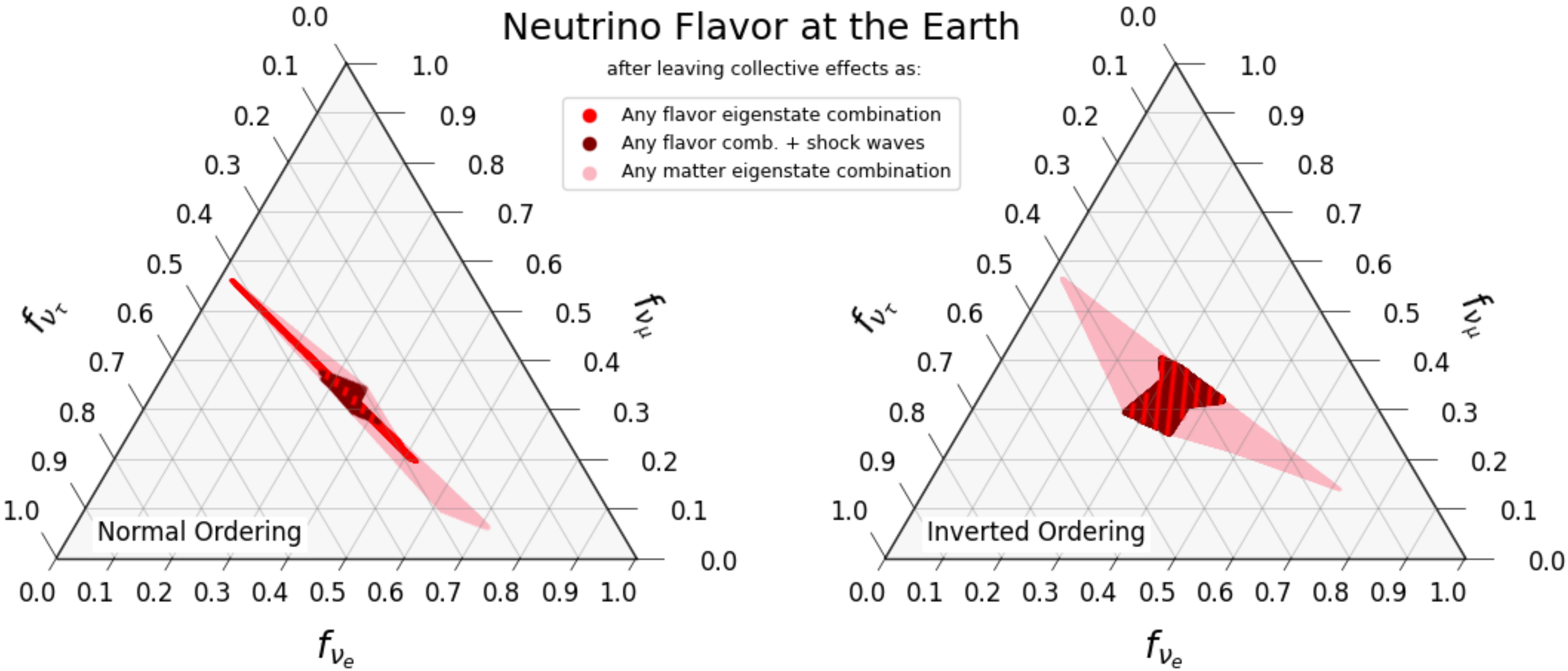
- For IO: unaffected, remains

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



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.

Conclusion

- We constrain the SN neutrino flavor content with only basic, robust assumptions.
- Our results are robust: independent of time evolution, emission direction, or uncertain SN details.
- A nearby supernova will let us test these predictions directly.

Thank you!