The Onset of Neutrino Oscillations in Supernovae

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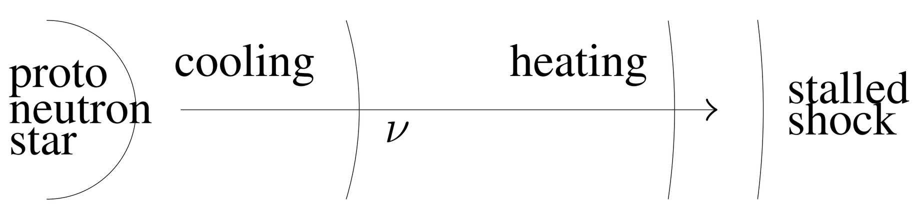
Neutrinos are emitted over several kilometers in a supernova. This strongly suppresses the effective mixing angle for neutrinos [1].

Supernovae and Neutrinos

Core-collapse supernovae emit 99% of their energy as neutrinos.

- The explosion shock wave stalls at $\mathcal{O}(100)$km due to infalling matter.
- Neutrinos can help revive the explosion.



Neutrino oscillations $\nu_{\mu/\tau} \leftrightarrow \nu_e$ can impact several aspects of the supernova. They can

- enhance neutrino heating since $E(\nu_{\mu/\tau}) > E(\nu_e)$.
- modify nucleosynthesis by changing the proton to neutron ratio.
- modify the neutrino signal observed from a galactic supernova.

Collective Oscillations

- Required: Many neutrinos in the background.
- Result: Interesting non-linear dynamics.

Naive Expectation

- For every energy, there is a frequency $\omega = \frac{\Delta m^2}{4E}$.
- Common amplitude, $\sin^2(2\theta)$, for mixing angle θ.

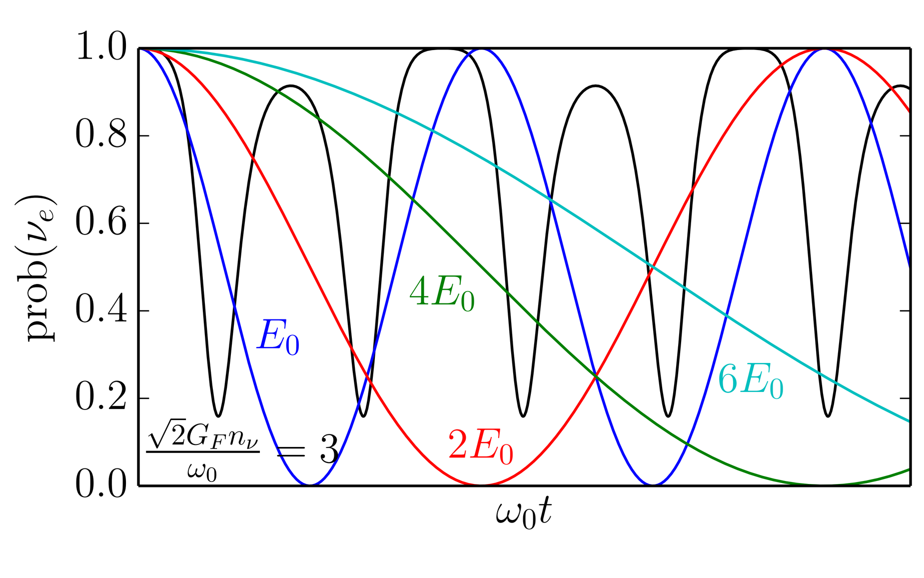


Figure 1: *Oscillations in vacuum or constant matter with mixing angle* $\sin^2(2\theta) = 1$ *(colour) and collective oscillations with mixing angle* $\sin^2(2\theta) = 0.09$ *(black). The frequency is* $\omega_0 = \frac{\Delta m^2}{4E_0}$.

Collective oscillations

- The conversion is independent of energy.
- A small mixing angle can lead to a large conversion.

Neutrino Sphere

Neutrinos decouple at $\mathcal{O}(10)$km. The probability for a neutrino to be emitted at radius r_e is:

$$p(r_e) = \Gamma(r_e)\exp(-E/T)\exp\left(-\int_{r_e}^{\infty}\Gamma(r')dr'\right).$$

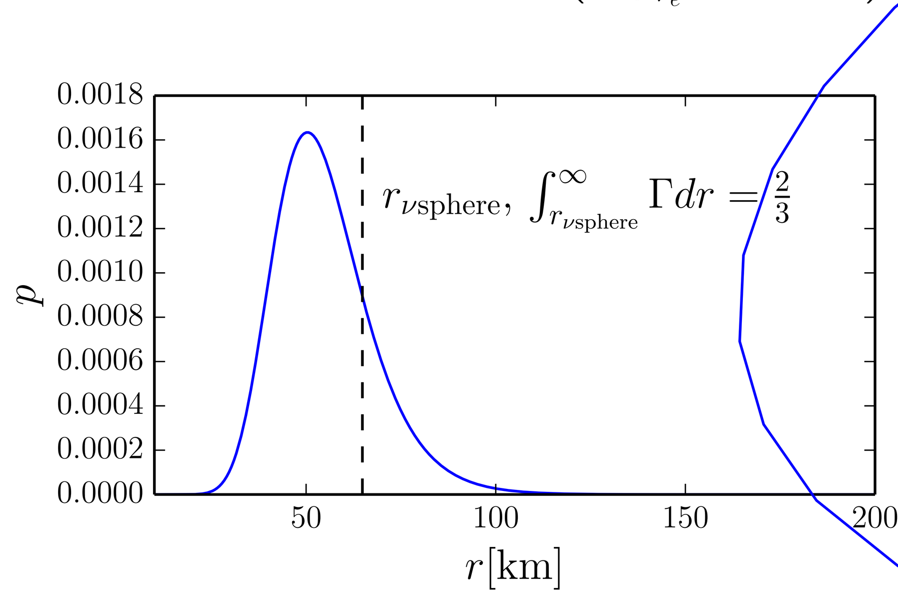


Figure 2: *Neutrino sphere for* $\rho = \rho_0 e^{-r/r_0}$, $\rho_0 = 10^{13}$*g/cm*^{3}, $r_0 =$*15km.*

Polarisation Vector

Neutrino oscillations with two flavours (ν_e and ν_x) can be described using polarisation vectors, $\vec{P}$.

P_x and P_y describe the phase, and

$$\text{prob}(\nu_e) = \frac{1}{2}(1 + P_z).$$

The equation of motion is

$$\dot{\vec{P}} = \vec{V} \times \vec{P}.$$

$\vec{V}$ is given by the Hamiltonian.

Averaging and Damping

The average angle $\tilde{\theta}$ between $\vec{P}$ and $\vec{V}$ is given by

$$\sin 2\tilde{\theta}(r) = \int_0^r p \sin 2\theta_m \exp\left(i\int_{r_e}^{\infty}\Gamma(r')dr'\right) dr_e.$$

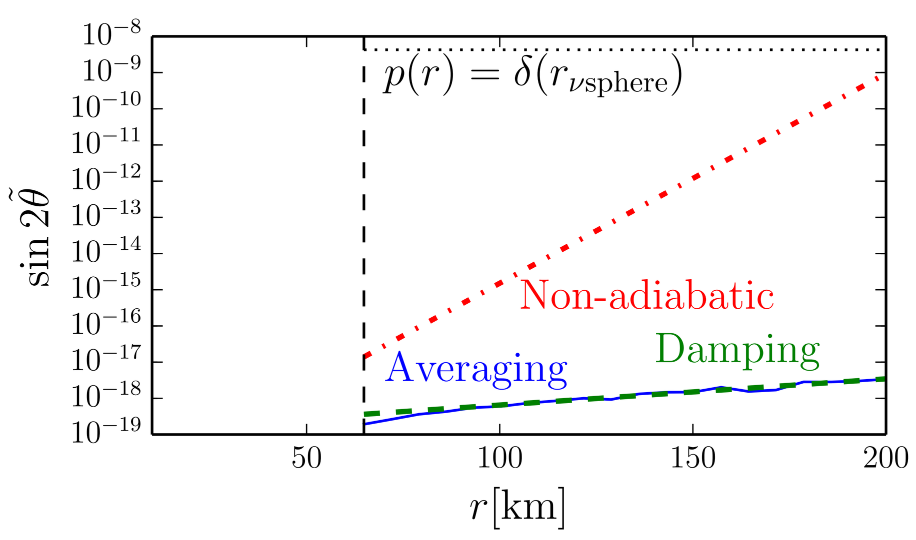


Figure 3: *Effective mixing angle,* $\tilde{\theta}$.

Averaging is equivalent to the effect of damping.

$$\dot{\vec{P}} = \vec{V} \times \vec{P} - D\vec{P}_T.$$

with the adiabatic [2] and non-adiabatic solutions

$$\sin 2\tilde{\theta} \approx \frac{V_x D}{V_z^2}, \qquad \sin 2\tilde{\theta} \approx \frac{V_x \dot{V}_z}{V_z^3}.$$

Non-linear averaging

Solving the non-linear equations numerically, it is seen that averaging delays conversion, but it does not remove it.

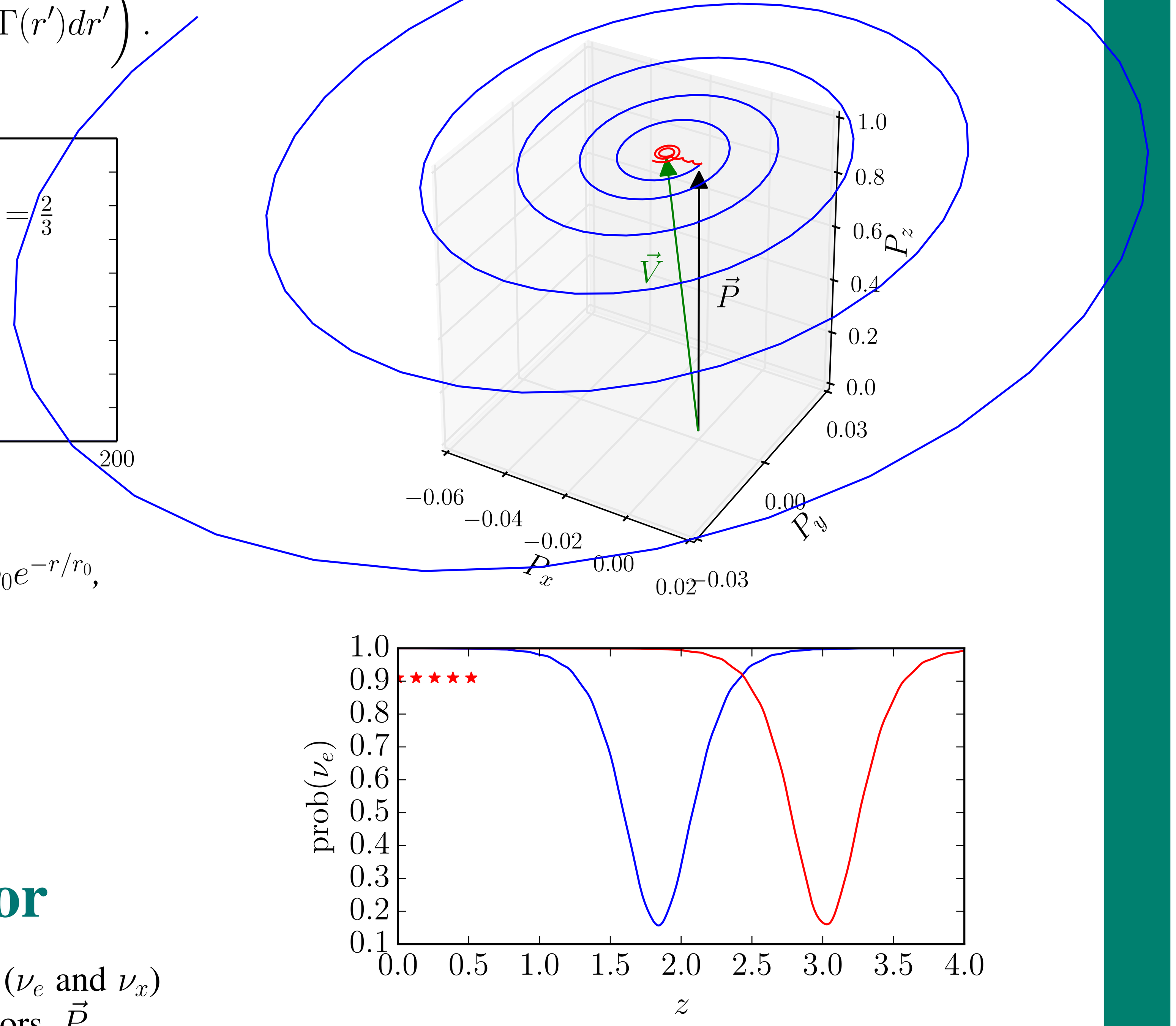


Figure 4: *Evolution of the polarization vector from* $z = 0$ *to* $z = 0.84$ *(upper) and the probability (lower) for no averaging and averaging over* 3.5 *periods (the region indicated by stars).*

Fast Growth Rates

- Different neutrino spheres for $\bar{\nu}_e$ and ν_e might trigger very fast conversions.
- The conversion scale can be meters. For non-fast conversion it is kilometers.
- The initial condition must be set according to Figure 3.

References

[1] R. S. L. Hansen and A. Y. Smirnov, JCAP **1804** (2018) 057 [arXiv:1801.09751].

[2] S. Hannestad, I. Tamborra and T. Tram, JCAP **1207** (2012) 025 [arXiv:1204.5861].

The suppressed mixing angle can be understood as averaging or as damping. Non-adiabaticity often dominates.

Collective oscillations are delayed, but not removed.

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