Time-Dependent Collective Neutrino Oscillations in Supernovae

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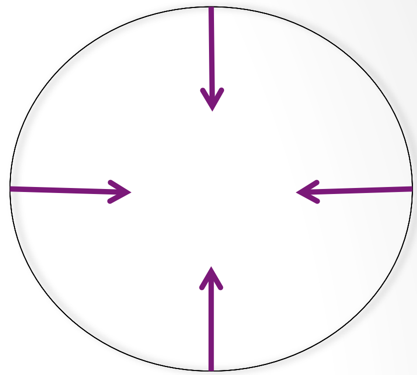
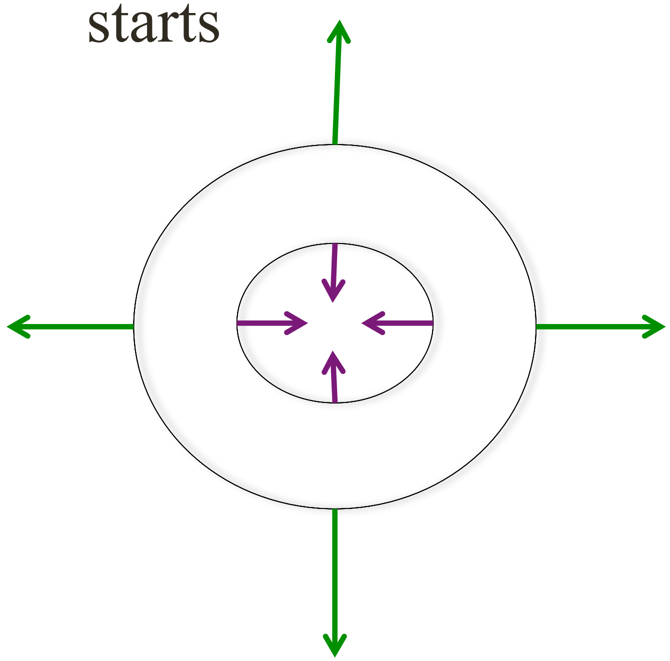
Supernova Explosion

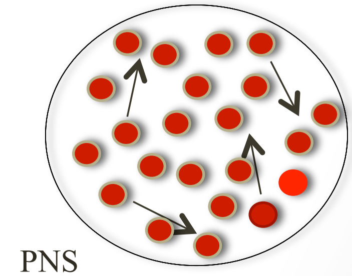
- When the mass of the core exceeds the Chandrasekhar limit, the collapse starts





- Collapse is halted when the equation of state stiffens and explosion happens

- Neutrinos are trapped inside the neutrino sphere because their mean free path is very small



Supernova Neutrinos

- Neutrinos interact with matter and background neutrinos above proto-neutron star

- We need to study neutrino evolution above proto-neutron star

    - they modify n/p ratio

$$\bar{\nu}_e + p \leftrightarrow n + e^+$$
$$\nu_e + n \leftrightarrow p + e^-$$

    - we can detect SN neutrinos

Supernova Neutrinos

- Equation of motion

$$i(\partial_t + \mathbf{v} \cdot \nabla)\rho = [H, \rho]$$

- Hamiltonian

$$H = H_V + H_m + H_{\nu\nu}$$

$$H_V = \frac{\Delta m^2}{4E} \begin{bmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{bmatrix}$$

$$H_m = \begin{bmatrix} \sqrt{2} G_F n_e & 0 \\ 0 & 0 \end{bmatrix}$$

$$H_{\nu\nu} = \sqrt{2} G_F \int \mathrm{d}^3 q \, (1 - \mathbf{v}_p \cdot \mathbf{v}_q)(\rho_q - \bar{\rho}_q)$$

Neutrino Bulb Model

- We have a 7-D problem!

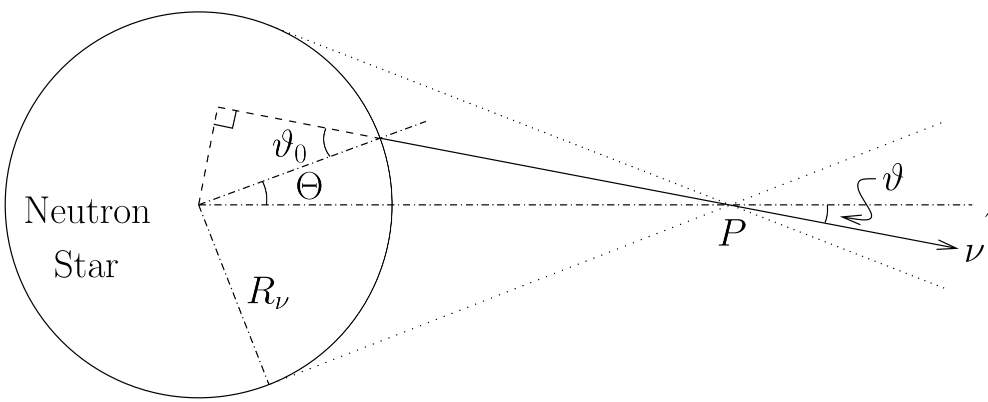
$$\rho(t;\ \underbrace{r, \Theta, \Phi}_{\text{space}};\ \underbrace{E, \theta, \phi}_{\text{momentum}})$$

time translation symmetry

$$\rho(\not{t};\ r, \Theta, \Phi;\ E, \theta, \phi)$$

spherical symmetry & axial symmetry around radial direction

$$\rho(\not{t};\ r, \not{\Theta}, \not{\Phi};\ E, \theta, \not{\phi})$$



Duan et al., Phys.Rev. D74 (2006) 105014

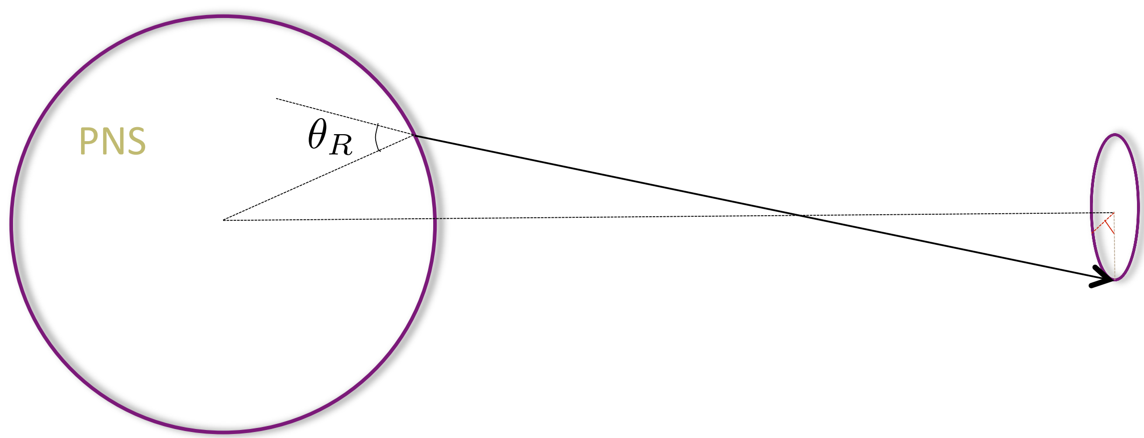
Azimuth-angle Flavor Instability

- Axial symmetry is broken in NH

[Raffelt et al., Phys.Rev.Lett. 111 (2013) 9, 091101]

$$\rho(\not{t};\ r, \not{\Theta}, \not{\Phi};\ E, \theta, \not{\phi})$$

?

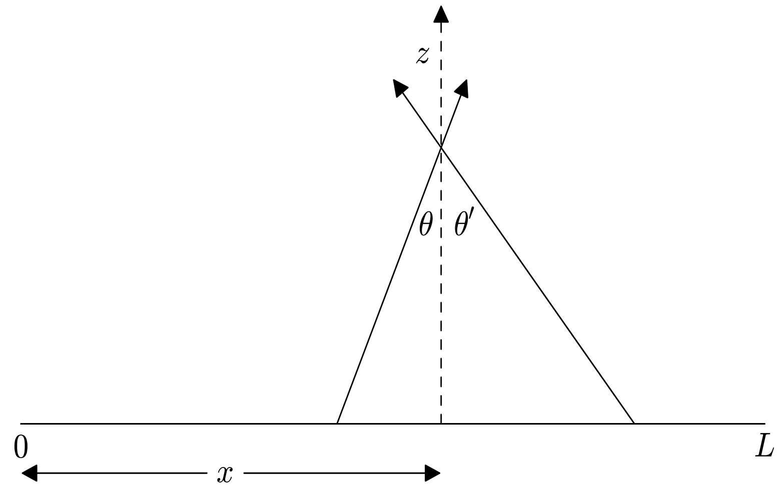


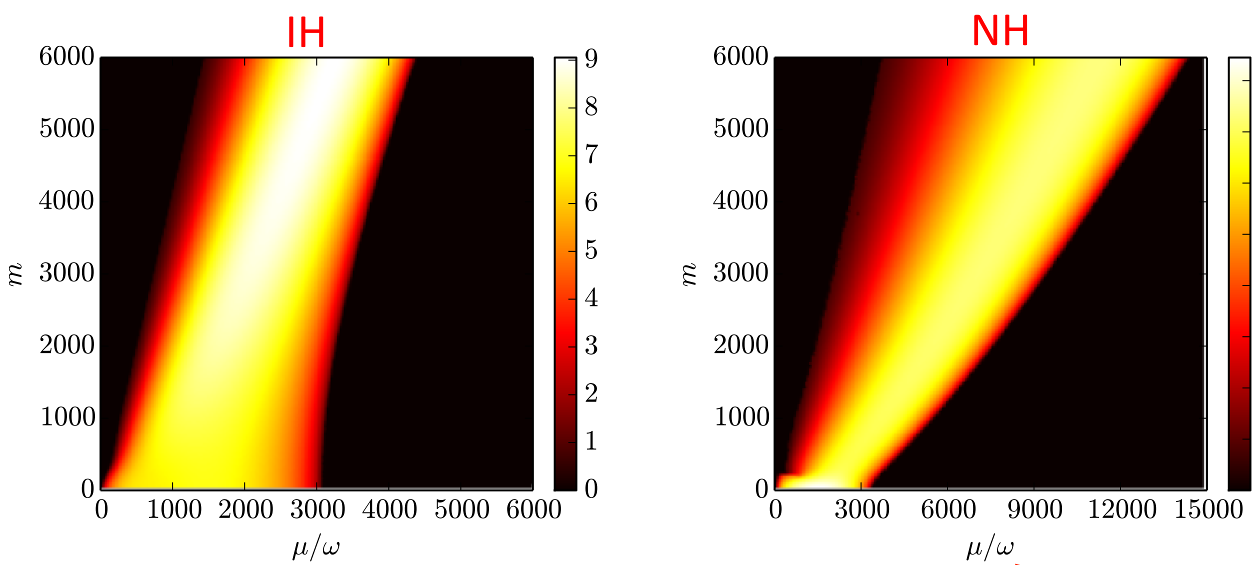
- Solutions of the equations for collective flavor oscillations does not have the symmetries of initial condition on the surface of the proto-neutron star!

Spatial symmetry breaking

$$\rho(\cancel{t};\ r, \overset{?}{\cancel{\Theta}}, \overset{?}{\cancel{\Phi}};\ E, \theta, \overset{?}{\cancel{\phi}})$$

$$\rho_{m,\theta}(z) = \frac{1}{L}\int_0^L e^{\frac{i2\pi m x}{L}} \rho_{x,\theta}(z)dx$$





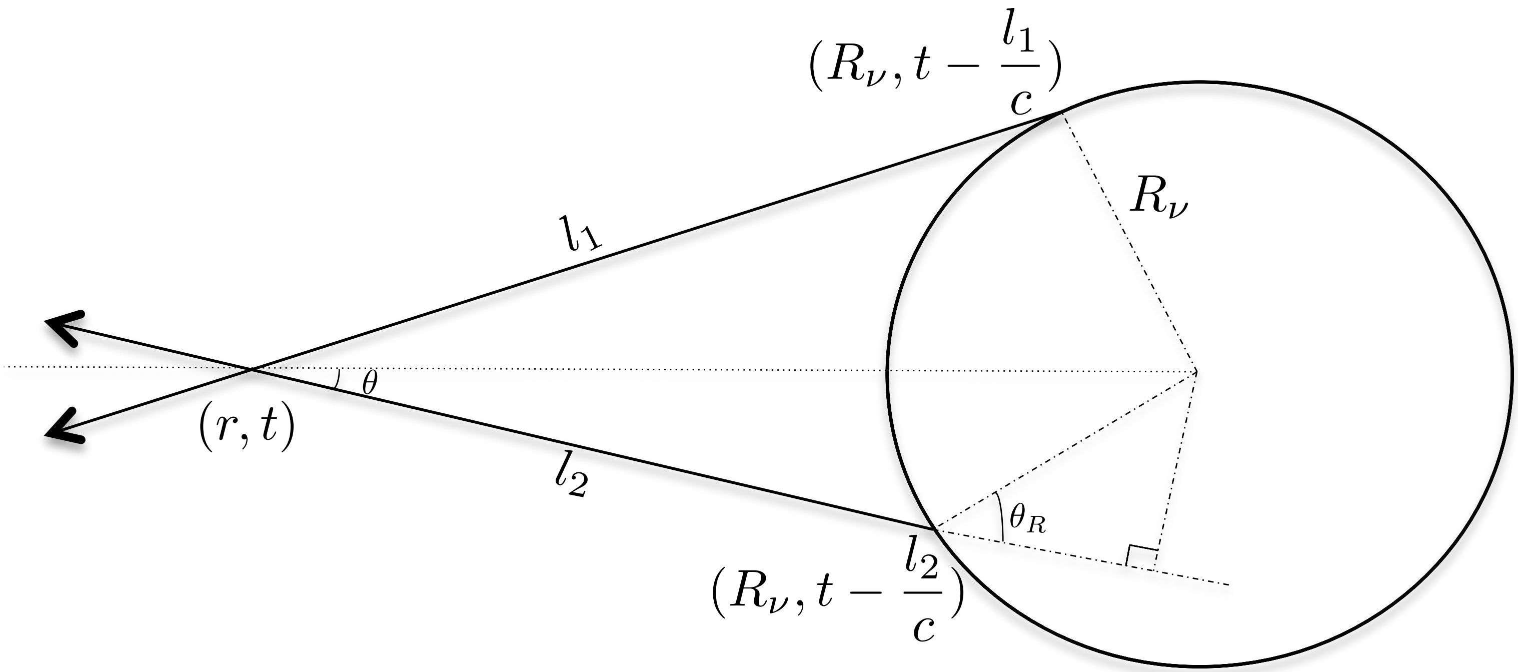
$\mu \propto n_\nu$

Duan & Shalgar, Phys.Lett. B747 (2015) 139-143
Abbar, Duan & Shalgar, Work in progress (2015)

Time-Dependent Bulb Mode

- All the previous studies are based on the assumption that neutrino gas outside the proto-neutron star is stationary.
- Does stationary neutrino flux at the surface of the proto-neutron star mean that the flux remain stationary at large radii?

Time-Dependent Bulb Mode



$$i(\partial_t + \cos\theta\,\partial_r)\rho = [H, \rho]$$

$$\rho_\zeta(r) = \int \mathrm{d}\zeta\, e^{-i\zeta t} \rho(r, t)$$

Time-Dependent Bulb Mode

- Neutrinos are emitted in flavor eigenstates

$$\boldsymbol{\rho_\xi} \sim \begin{bmatrix} \delta(\xi) & \epsilon_\xi(r) \\ \epsilon^*_{-\xi}(r) & 0 \end{bmatrix}$$

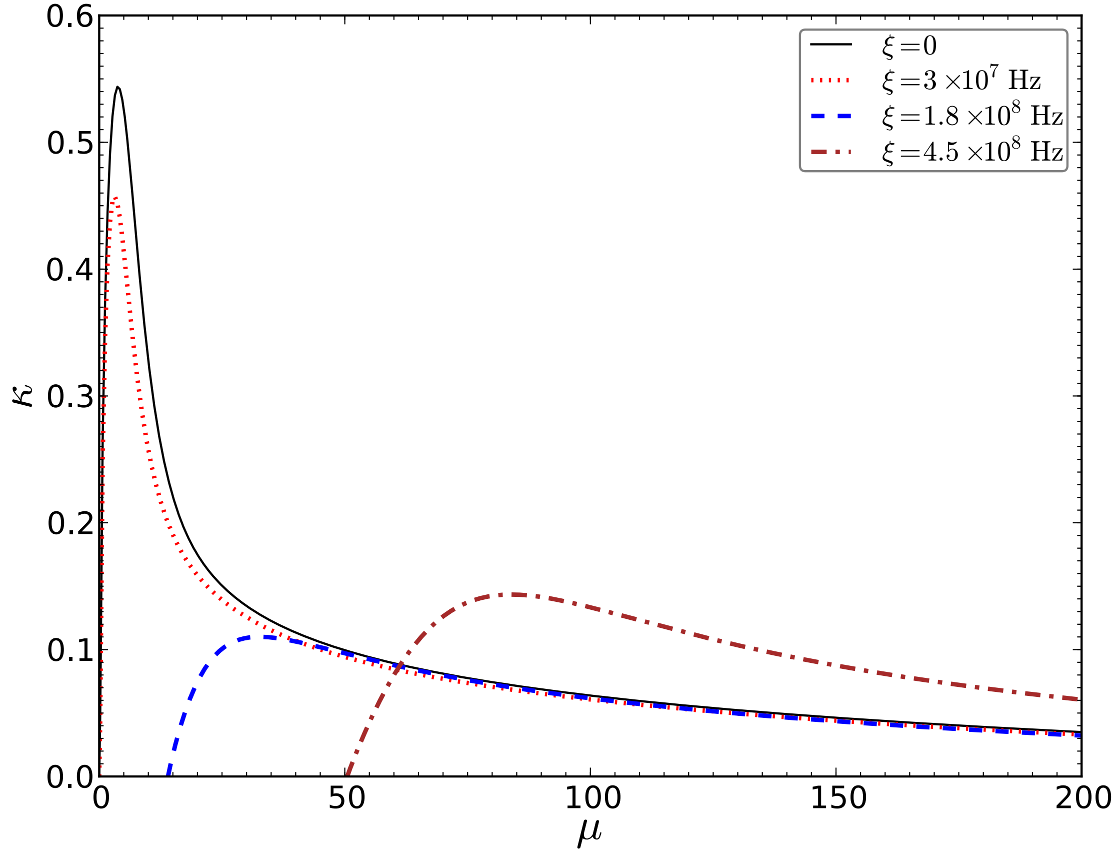
- Linearized EoM

$$[i\cos\theta\partial_r - \xi]\epsilon_\xi(r) = 2[H_{00}\epsilon_\xi(r) - H_{01}]$$

$$\epsilon_\xi \propto e^{\kappa r}$$

- A positive exponent means that perturbation grows exponentially

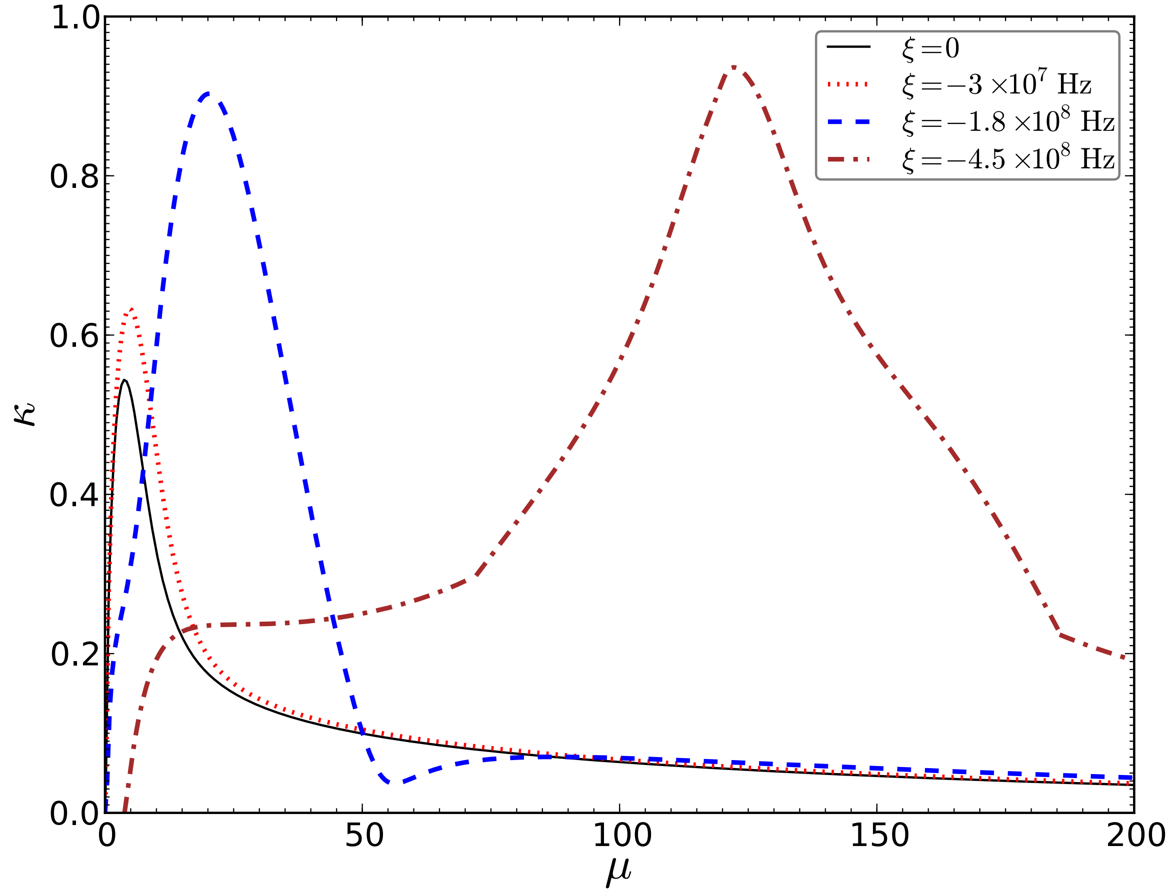
Time-Dependent Bulb Mode



Abbar & Duan, Work in progress (2015)

- Frequencies that can significantly modify the densities for which we have collective oscillations are very large
- Density of frequencies are very large around $\xi = 0$

Time-Dependent Bulb Mode



Abbar & Duan, Work in progress (2015)

- Negative frequencies seem to be more unstable

Summary

- Time translation symmetries is broken
  - The neutrino densities for which collective oscillations occur are not affected significantly by time dependence
  - Neutrino collective oscillations is a time-dependent phenomenon
  - Negative frequencies seem to be more unstable
- Combining breaking of time translation symmetry with spatial and axial symmetry breaking ......

we are back to the 7-D problem