Flavor conversions of supernova neutrinos

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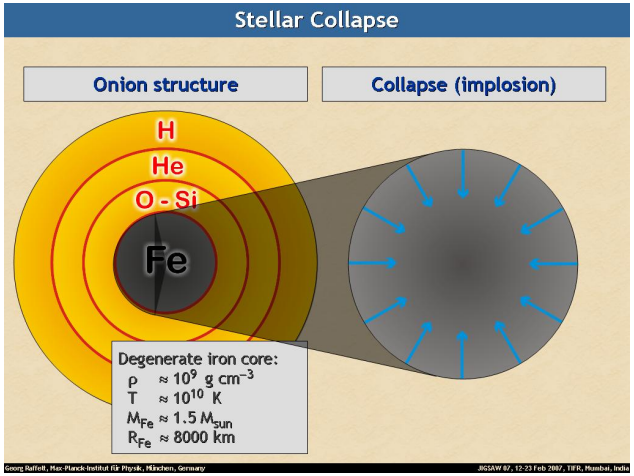
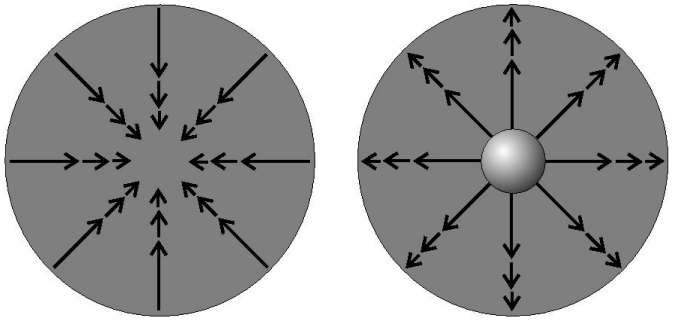
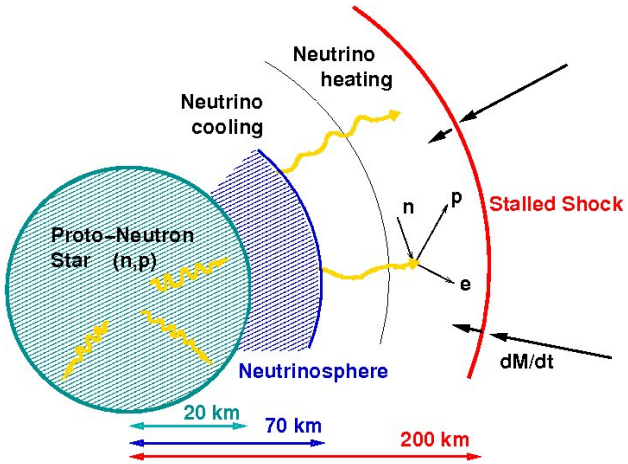
Supernova explosion



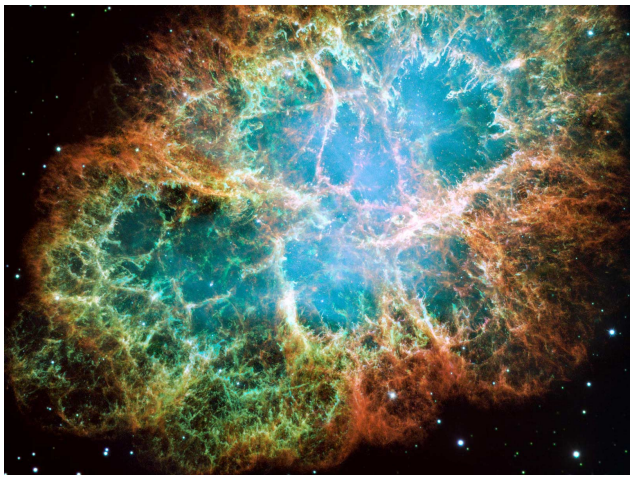
Explosion of a massive $6 - 8\ M_\odot$ star



Collapse of degenerate core. Bounce and Shock.



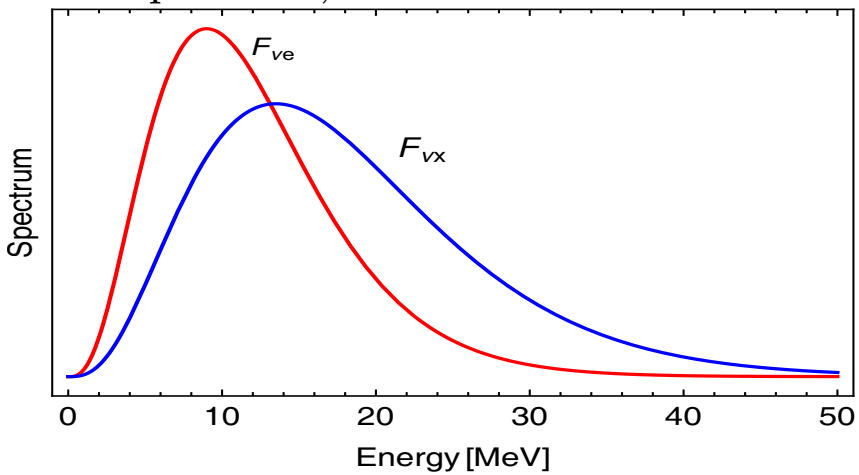
Stalled shock and accretion. 99% energy emitted as νs.



Explosion!

Flavor Oscillations in dense media: Why do we care?

- Flavor evolution in a dense media → non-linear complicated problem → can lead to collective effects.
- Neutrino spectrum, as a result of oscillations?

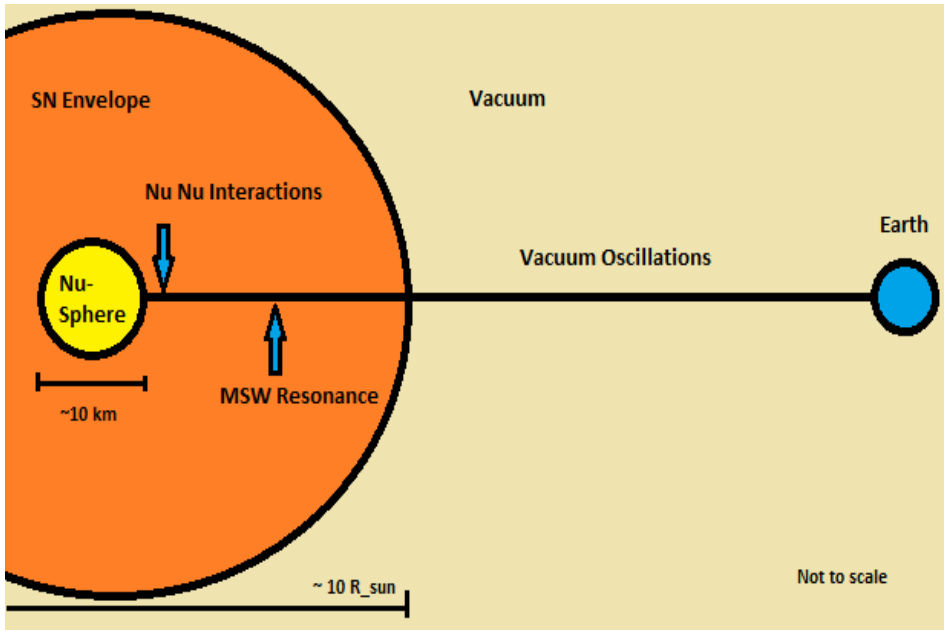


$\Longrightarrow$ **Final Spectra ??**

- Can confirm our idea of SN dynamics.
- Neutrino oscillations can have important impact on explosion dynamics as well as nucleosynthesis.

Prelude : Facts and Trivia

- Flavor conversions of supernova(SN) neutrinos - neutrino flavor conversions during the gravitational collapse of a massive star.



Illustrative of different length scales involved.

$$R_{\nu\text{-sphere}} \simeq 10 \text{ km} \ , \ R_{\text{coll}} \simeq 100 \text{ km} \ , \ R_{\text{MSW}} \simeq 1000 \text{ km}$$

- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$ where $x = \mu, \tau$. Avg ν energy $\sim$ 10 MeV.

Ways to describe flavor oscillations

- Work with 2 flavors ν_e and ν_x.
- Neutrino flavor density matrix

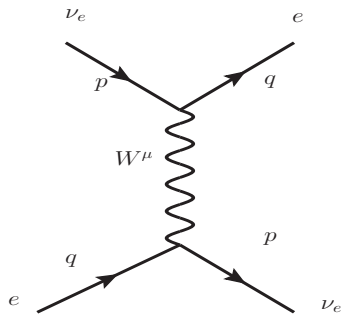
$$\rho = \begin{bmatrix} \langle \nu_e | \nu_e \rangle & \langle \nu_e | \nu_x \rangle \\ \langle \nu_x | \nu_e \rangle & \langle \nu_x | \nu_x \rangle \end{bmatrix} .$$

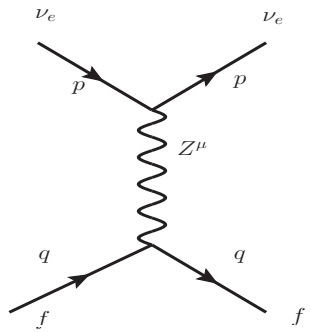
  Use EoM : $\mathrm{i}\, \mathrm{d}_t \rho = [H, \rho]$.

- Diagonal element ρ_{ii}= Survival Probability of the i^{th} flavor.
- Off-diagonal element ρ_{ii} encodes oscillation information.

Interacting Hamiltonian

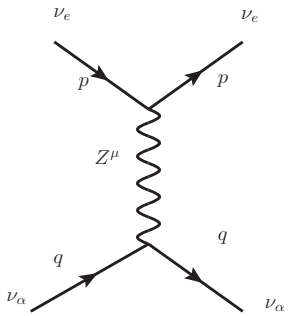
- Vacuum oscillation.
- Matter effect : forward scattering with electrons.

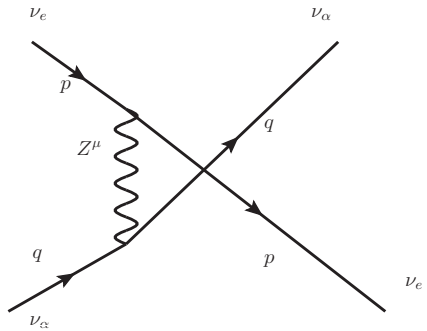




L. Wolfenstein (1977), S. Mikheyev, A. Smirnov (1985)

- $\nu - \nu$ interaction : scattering with same/different flavors. Important in dense media!





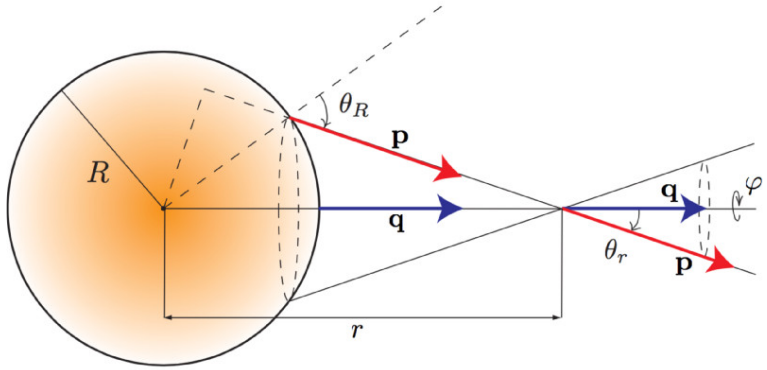
J. Pantaleone (1992)

Non-linearity from neutrino-neutrino interactions

- Effective Hamiltonian $H = H_{vac} + H_{MSW} + H_{\nu\nu}$ where

$$\begin{aligned} H_{\rm vac} &= \omega = \frac{M^2}{2E_p} \\ H_{\rm MSW} &= \lambda = \sqrt{2} G_F N_e \;\; {\rm diag}\{1,0,0\} \\ H_{\nu\nu} &= \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} \; (1 - \vec{v_p}.\vec{v_q})(\rho_q - \bar{\rho_q}) \end{aligned}$$

Define $\mu = \sqrt{2} G_F N_\nu$.

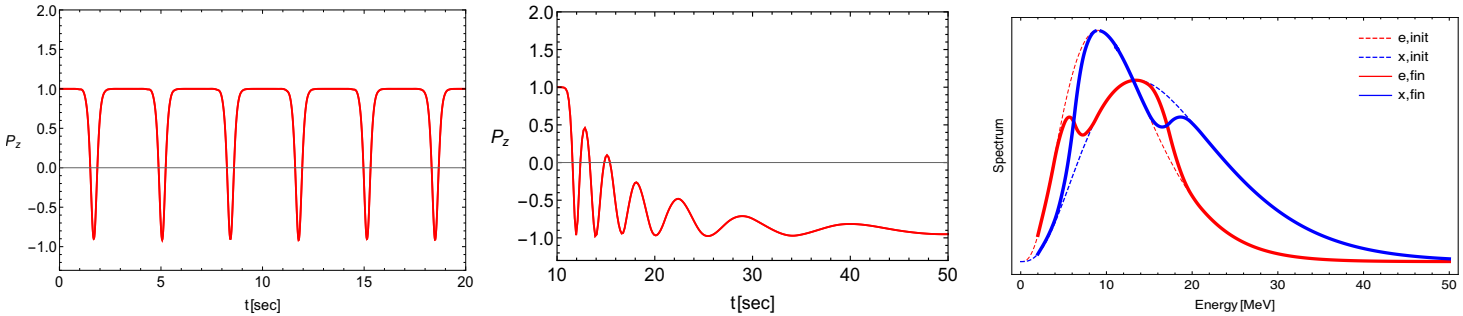


H. Duan *et al.*(2006)

- Hierarchy of scales $\mu > \lambda > \omega$.

Collective effects : new phenomena

- Synchronized oscillations: ν and $\bar{\nu}$ of all energies oscillate with the same frequency.



- Coherent $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations. Intermediate μ.
- Realistic declining μ can cause complete conversion.
- ν_e and ν_x spectra swap completely, but only within certain energy ranges. Occurs in both hierarchies.

G. Raffelt *et al.*(2007), B. Dasgupta *et al.*(2009)

Bipolar Oscillations : Linear stability analysis

- Deep inside $\rightarrow$ high density $\rightarrow$ flavor and mass states almost equal. ρ is almost identity.
- Expand the matrices

$$\rho = \frac{\mathrm{Tr}\rho}{2} + \frac{g_{\omega v \phi}}{2} \begin{bmatrix} s & S \\ S^* & -s \end{bmatrix}$$

  Drop trace since net flavor conserved.
- Linearize in off-diagonal element to get eigenvalue equation.

$$\begin{aligned} i(\partial_t + \vec{v} \cdot \vec{\nabla}_r) S_{\omega v z} &= \left(\omega + \lambda + \mu \int \frac{d\Gamma'}{(2\pi)} \left(1 - v_z v'_z - \vec{v_T}.\vec{v_T}'\right) g_{\omega' v' \phi'} \right) S_{\omega v z} \\ &\quad -\mu \int \frac{d\Gamma'}{(2\pi)} \left(1 - v_z v'_z - \vec{v_T}.\vec{v_T}'\right) g_{\omega' v' \phi'} S_{\omega' v' z'} \end{aligned}$$

A. Dighe *et al.*(2011)

- Check for exponentially growing $S \rightarrow$ instability.

Historical Detour

- Pre-2006 : Flavor conversions mainly in MSW regions $r \sim O(10^3)$ km. MSW conversions $\propto \omega$
- Post-2006 : Collective effects. Significant flavor conversions at $r \sim O(10^2)$ km from neutrinosphere. Rates $\propto \sqrt{\omega\mu}$.
- Faster conversions: $\propto \mathcal{O}(\mu) \sim 10^5\,\omega$? Can occur for massless neutrinos. Non-trivial angular distributions? Near the source??

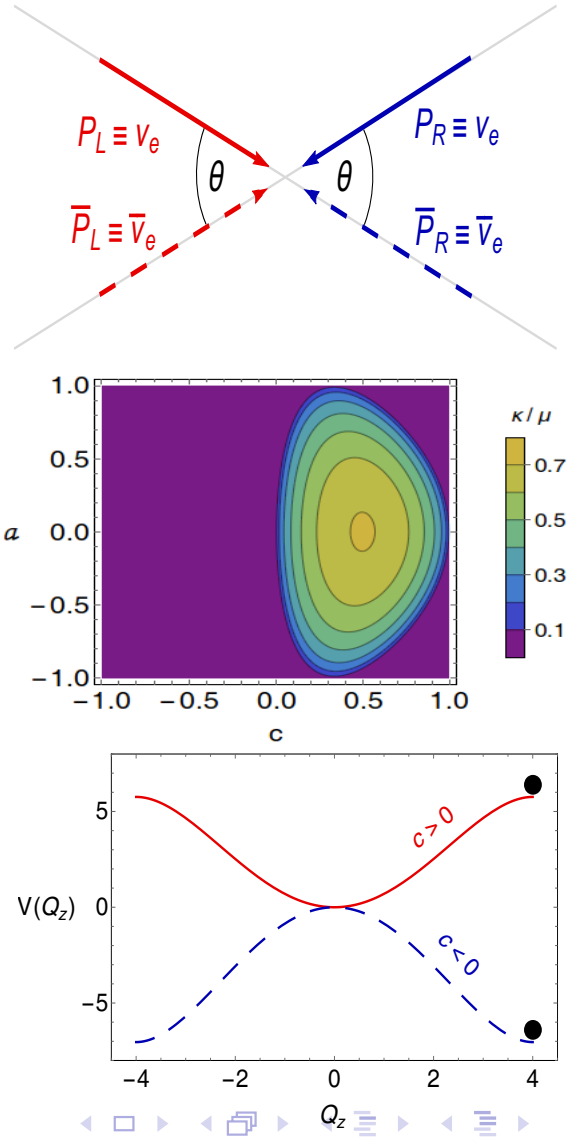
R.F Sawyer(2015), G. Raffelt *et al.*(2016), M. Sen *et al.*(2016)

Fast Oscillations

- Simplest system which shows fast conversions.
- Occurs near the core, even for massless neutrinos.
- Conversions obtained for $c \equiv \cos\theta > 0$.

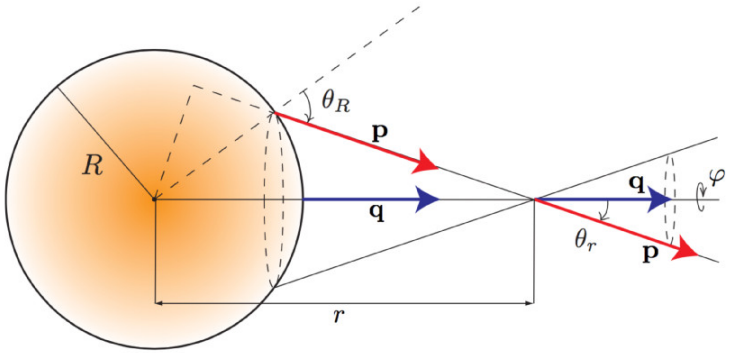
  G. Raffelt et. al. (2016)
- Classical analogy: particle in a quartic potential!

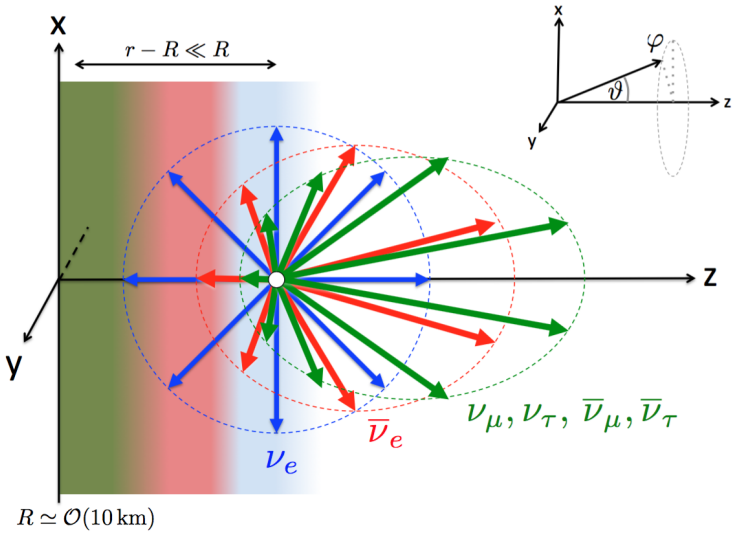
  M. Sen et. al. (2017)



Modelling a realistic SN

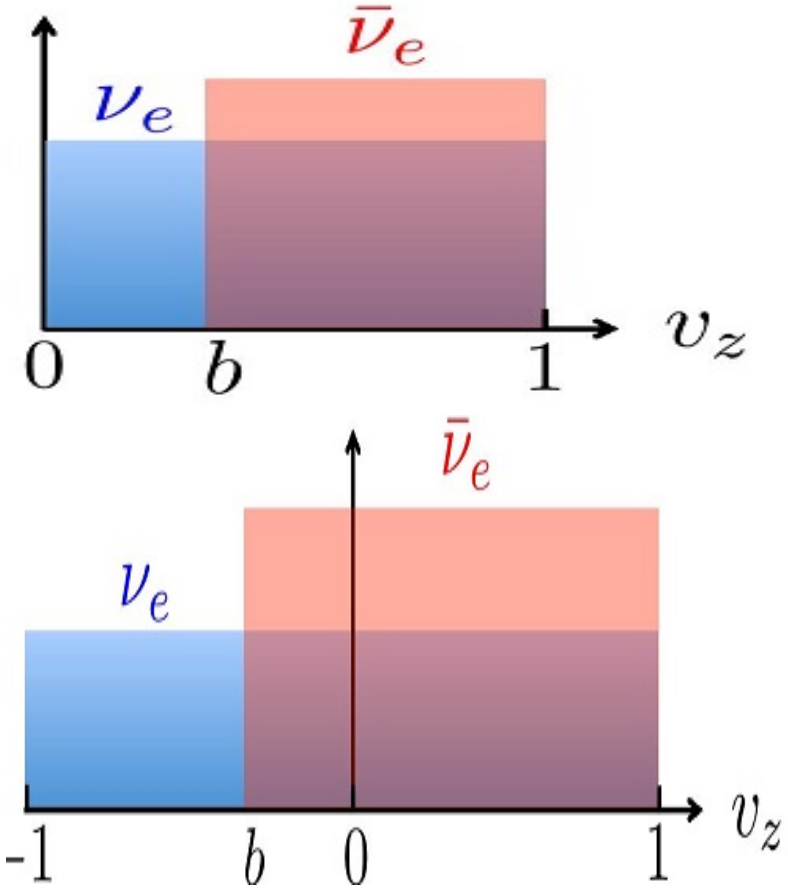
- Different flavors of neutrinos have different rates of interactions. Decouple at different times.
- Discard the "bulb model", and because of the near field effect, model the source as an infinitely long plane.

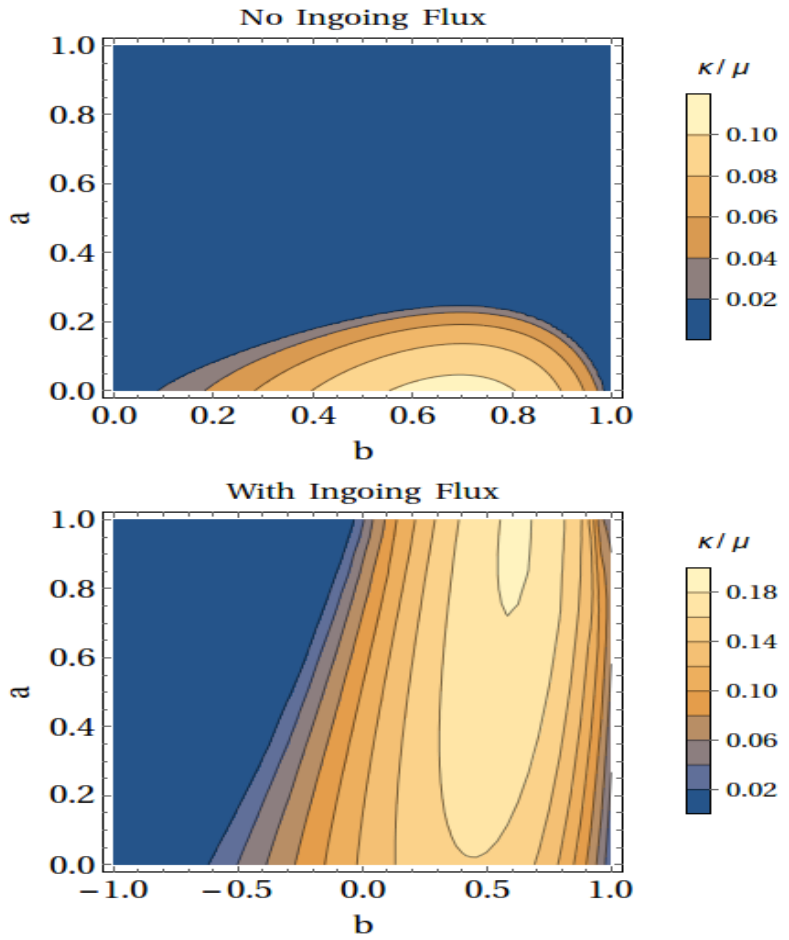




- Use flavor dependent angular spectrum. Realistic approximation.
- Consider different cones of emission for ν and $\bar{\nu}$. Can consider inward going rays also.

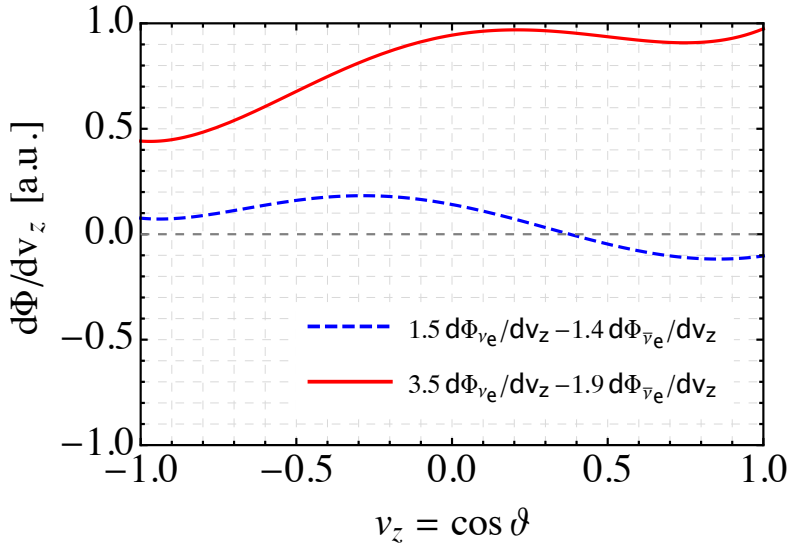
Fast growths ubiquitous

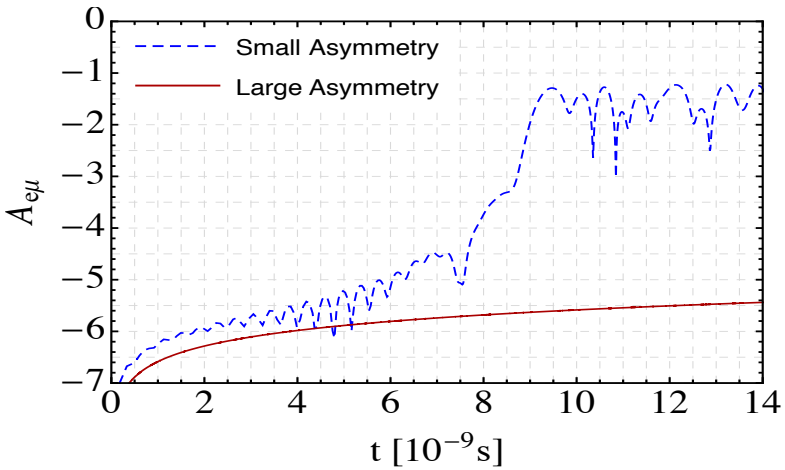


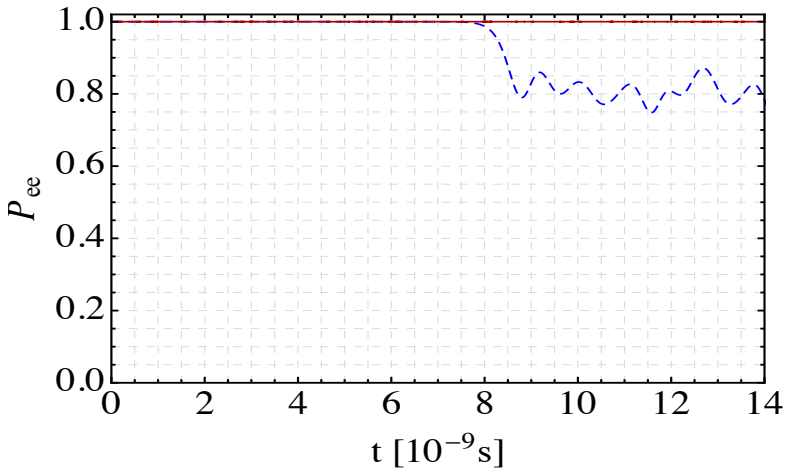


Backward modes makes fast conversion faster!

Crossing in Angular spectrum!







Conclusion

- Find fast conversions at a distance of $\sim O(1\text{ m})$ from the neutrinosphere.
- Flavor dependent angular spectrum seem to be essential for these fast conversions. Need a crossing??

  B. Dasgupta et. al. (2017)
- Effect of new physics??

  M. Sen et. al. (2017)
- Fast conversions lead to averaging of flavor information. Can collisions be important?
- Can be crucial for SN explosion and nucleosynthesis!

THANK YOU