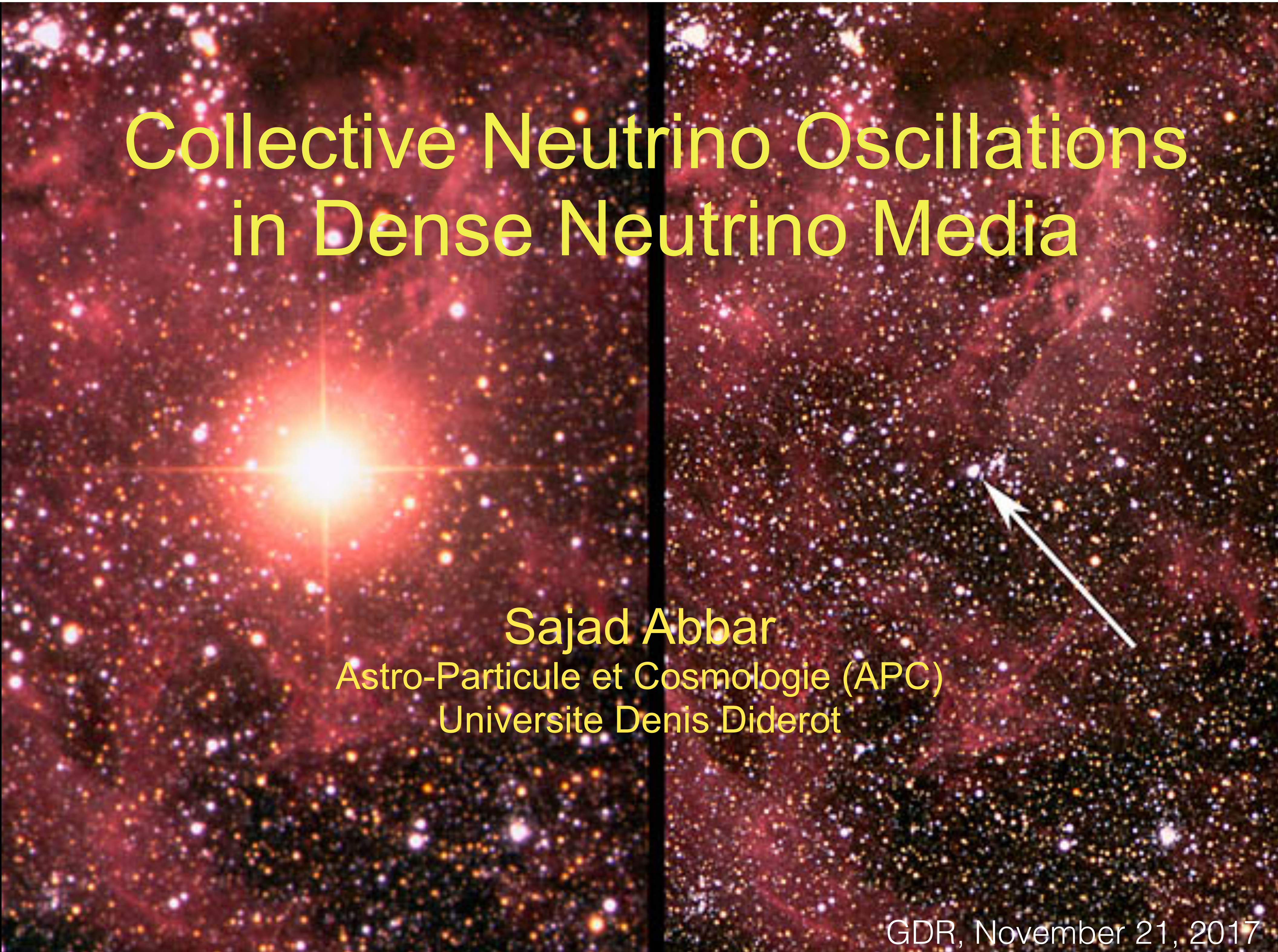

Collective Neutrino Oscillations in Dense Neutrino Media

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GDR, November 21, 2017

Neutrino Physics

- Neutrinos were first proposed by W. Pauli to account for the missing energy in beta decay $n \to p + e + \bar{\nu}_e$
- We have three flavors for neutrinos (antineutrinos)
- No electrical charge, interact weakly
- Only left-handed neutrinos participate in weak interaction
- They have very small masses
- Flavor (production) eigenstates and mass (propagation) eigenstates are not the same. This leads to neutrino oscillations

Neutrino Oscillations

- Since the mass-squared difference are different by more than one order of magnitude, the three-flavor problem reduces to an effective **two-flavor** scenario.
- In the two-flavor scenario, the Hamiltonian can be written as

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta \end{bmatrix}, \quad \omega = \pm\frac{\Delta m^2}{2E}$$

- In the two flavor scenario, the transition probability for a neutrino produced in flavor alpha after traveling the distance *L*

$$P_{\nu_\alpha\to\nu_\beta}(L) = \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$$

- When there is matter, we have a new term in the Hamiltonian

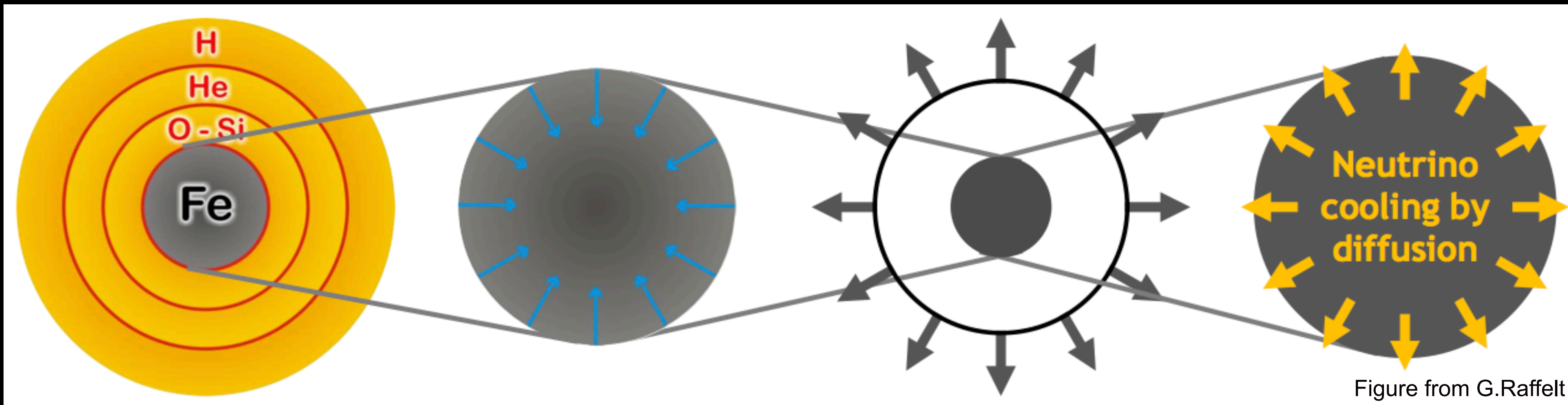
$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\mathrm{F}}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\mathrm{F}}n_e \end{bmatrix}$$

- Note that there is **resonance** in which the diagonal term can become zero and we can have maximum mixing. This can cause **significant flavor conversion**. This is called the **MSW** effect.

Core-Collapse Supernova

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\mathrm{F}}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\mathrm{F}}n_e \end{bmatrix} + H_{\nu\nu}$$

Core-Collapse Supernova



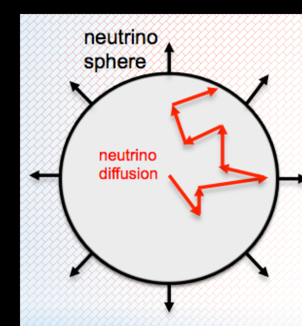
Stars burn lighter elements into heavier ones until the core reaches **Iron**.

When the mass of the core becomes larger than the **Chandrasekhar** mass the collapse starts.

Neutrinos are trapped inside the **neutrino sphere**.

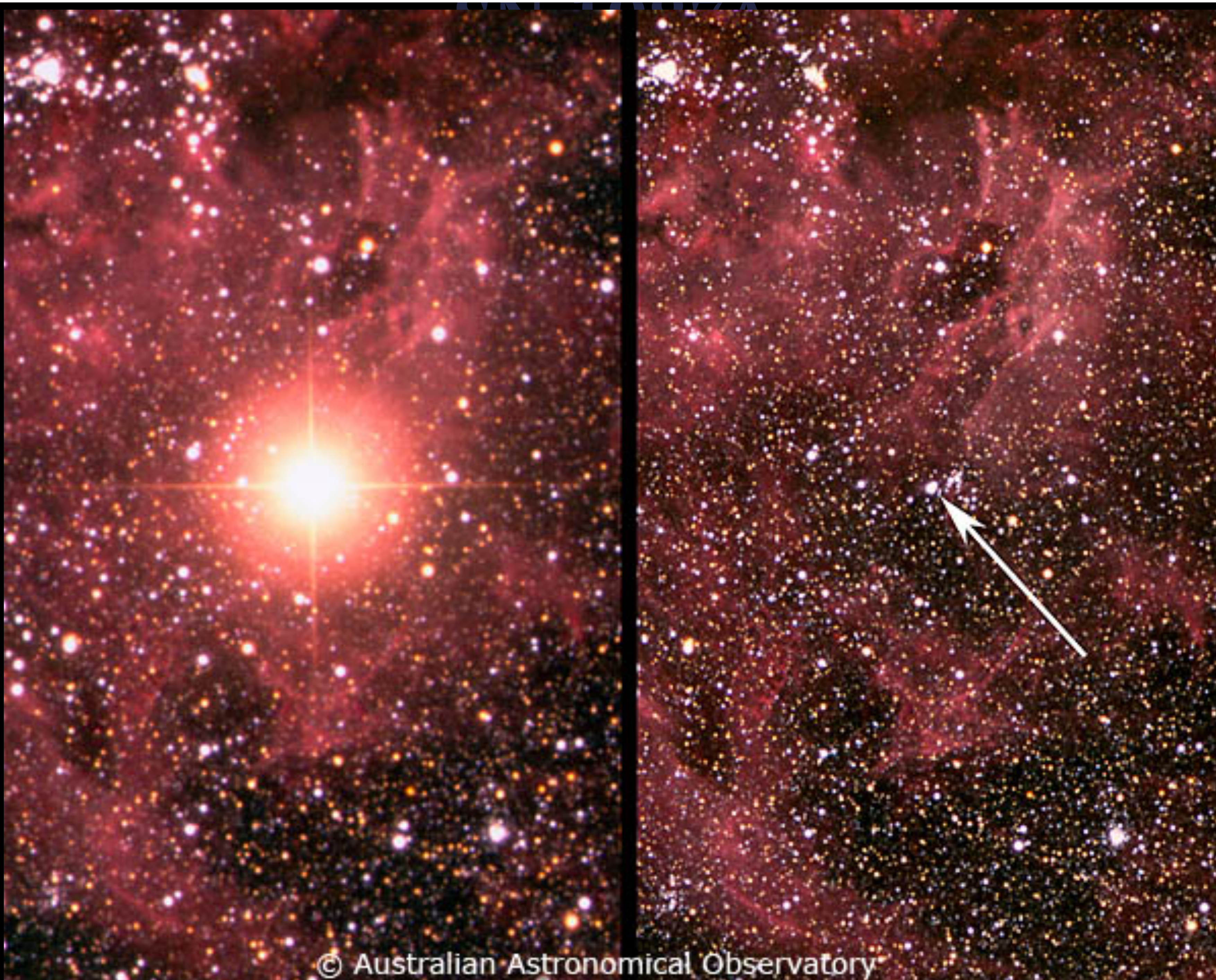
The collapse is **halted** when the inner core reaches density of order of nuclear density.

- A huge amount of energy (~10^{53} ergs (10^{46} joule), 99% of the total released energy) is released in the form of neutrinos of all flavors.



- The explosion can outshine the host galaxy.

- Core-collapse supernovae are different form type Ia supernovae.



Supernova 1987A that exploded on 23 February 1987 in the Large Magellanic Cloud (LMC)

Figure from the website of Australian Astronomical Observatory

Supernova Neutrinos

- Neutrinos can be important to the composition of matter. They can change the neutron to proton ratio through the weak processes

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

$$\nu_e + n \rightleftarrows p + e^-$$

- Understanding neutrino flavor evolution can also be important to the supernova dynamics.

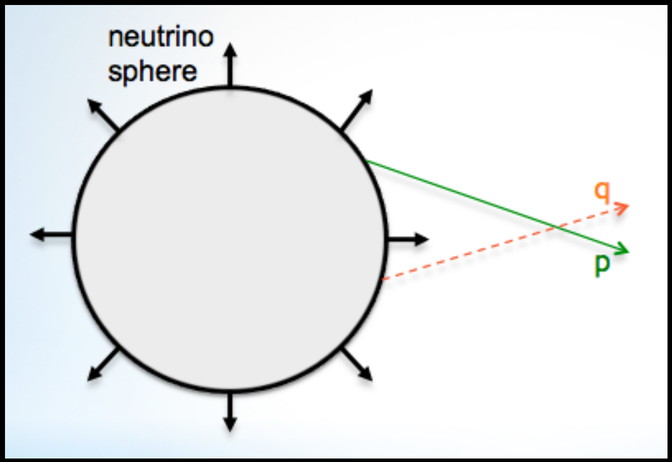
- Observation of a galactic supernova explosion

Supernova Neutrinos

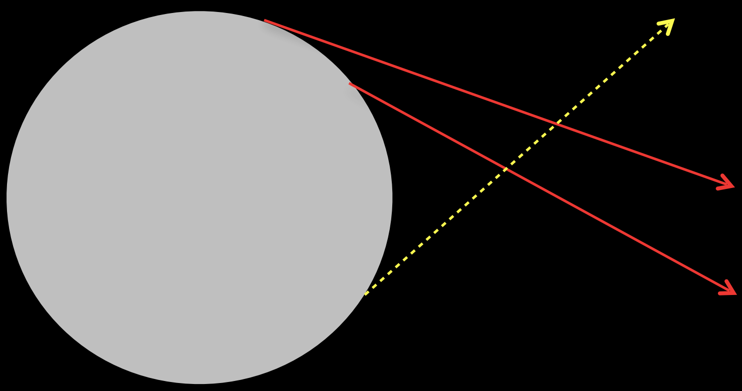
- The effective Hamiltonian has a new term due to the neutrino-neutrino weak interaction

$$H = \frac{1}{2}\begin{bmatrix} -\omega\cos 2\theta + \sqrt{2}G_{\mathrm{F}}n_e & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - \sqrt{2}G_{\mathrm{F}}n_e \end{bmatrix} + H_{\nu\nu}$$

$$\sqrt{2}G_{\mathrm{F}}\int \mathrm{d}^3q(1-\mathbf{v_p}\cdot\mathbf{v_q})(n_\nu\rho_q - n_{\bar\nu}\bar\rho_q)$$



- This new term is **different** from the vacuum and matter terms in the sense that: It **correlates** neutrinos with trajectories and energies
  It brings up **nonlinearity**



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

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

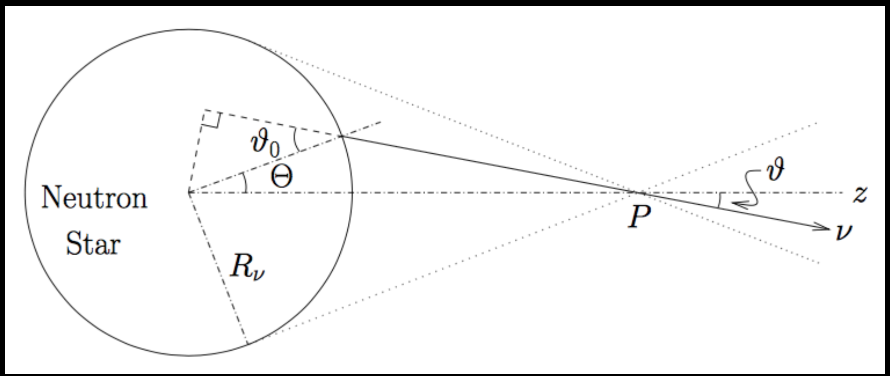
spherical symmetry & axial symmetry around radial direction

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

- *Neutrino Bulb Model:*

neutrinos are emitted isotropically from the surface of porto-neutron star

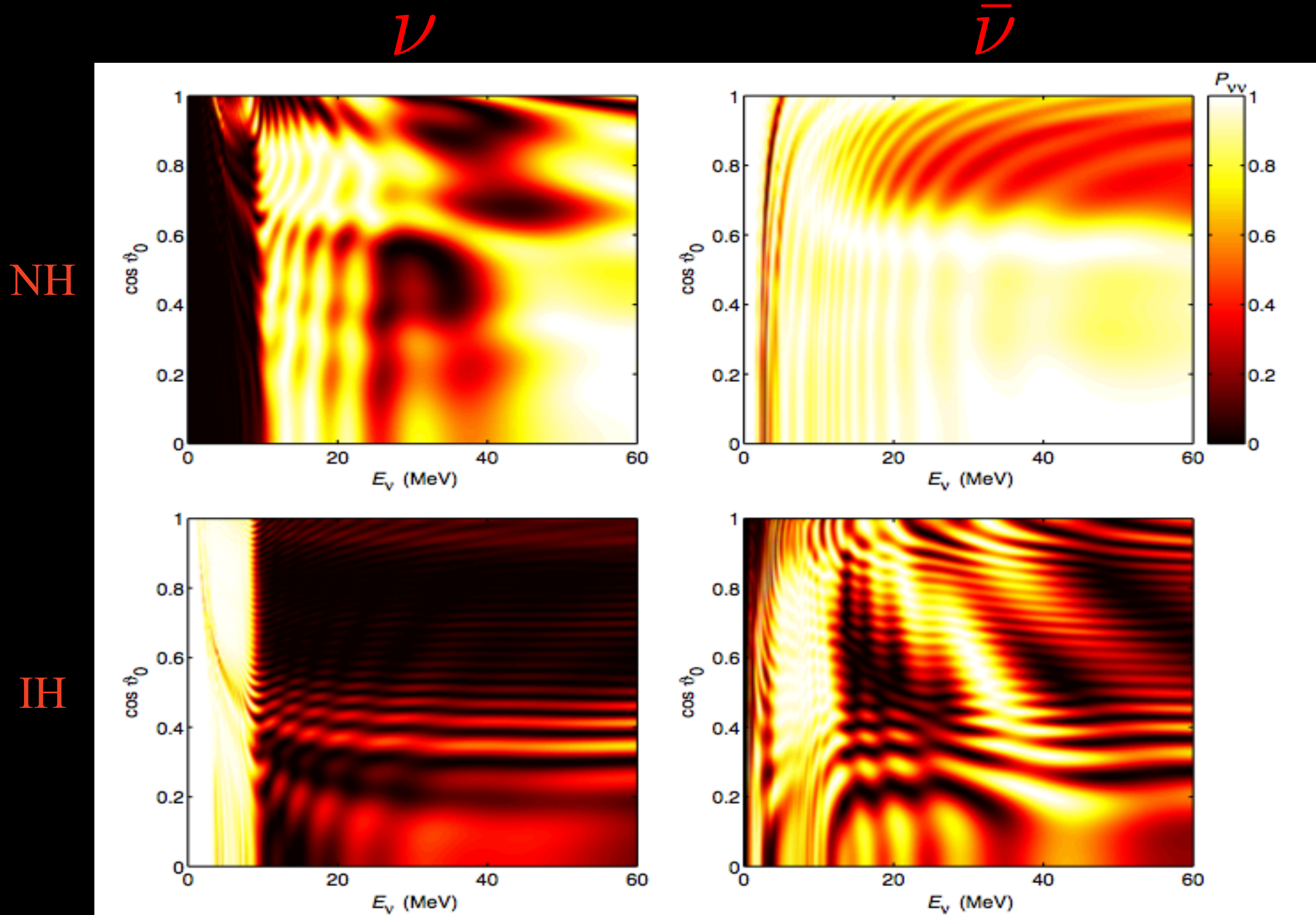
$$\rho(r; E, \theta)$$



Duan et al., PRD 74, (2006) 105014

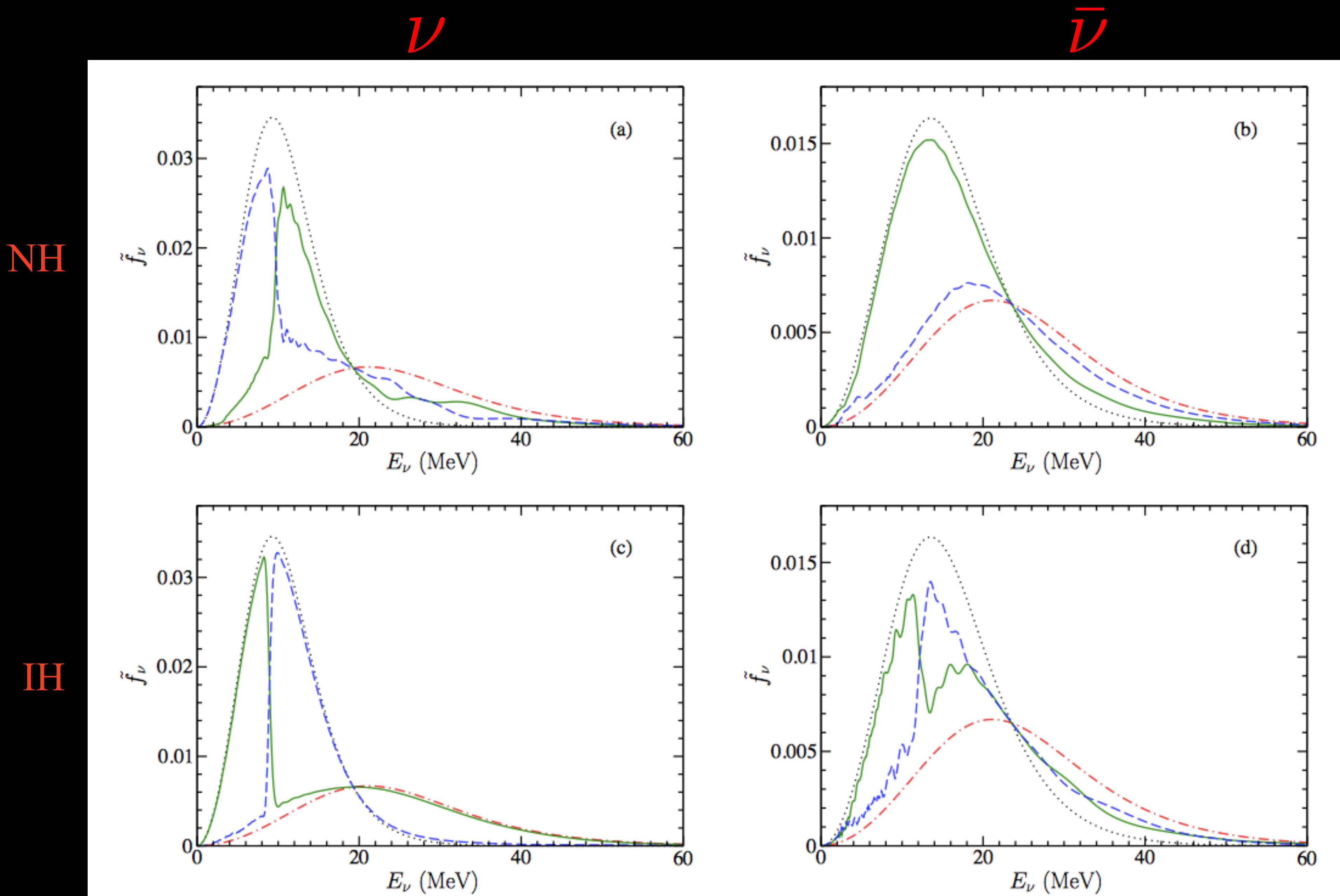
Neutrino Bulb Model

- Even for this simple model, we have to solve ~10^6 nonlinear differential equations simultaneously



Duan et al., PRL 97, (2006) 241101

Neutrino Bulb Model



Duan et al., PRL 97, (2006) 241101

Neutrino Bulb Model

- Neutrino bulb model is based on two important assumptions:
    - Neutrino evolution has time/special symmetries
    - Neutrinos are emitted isotropically

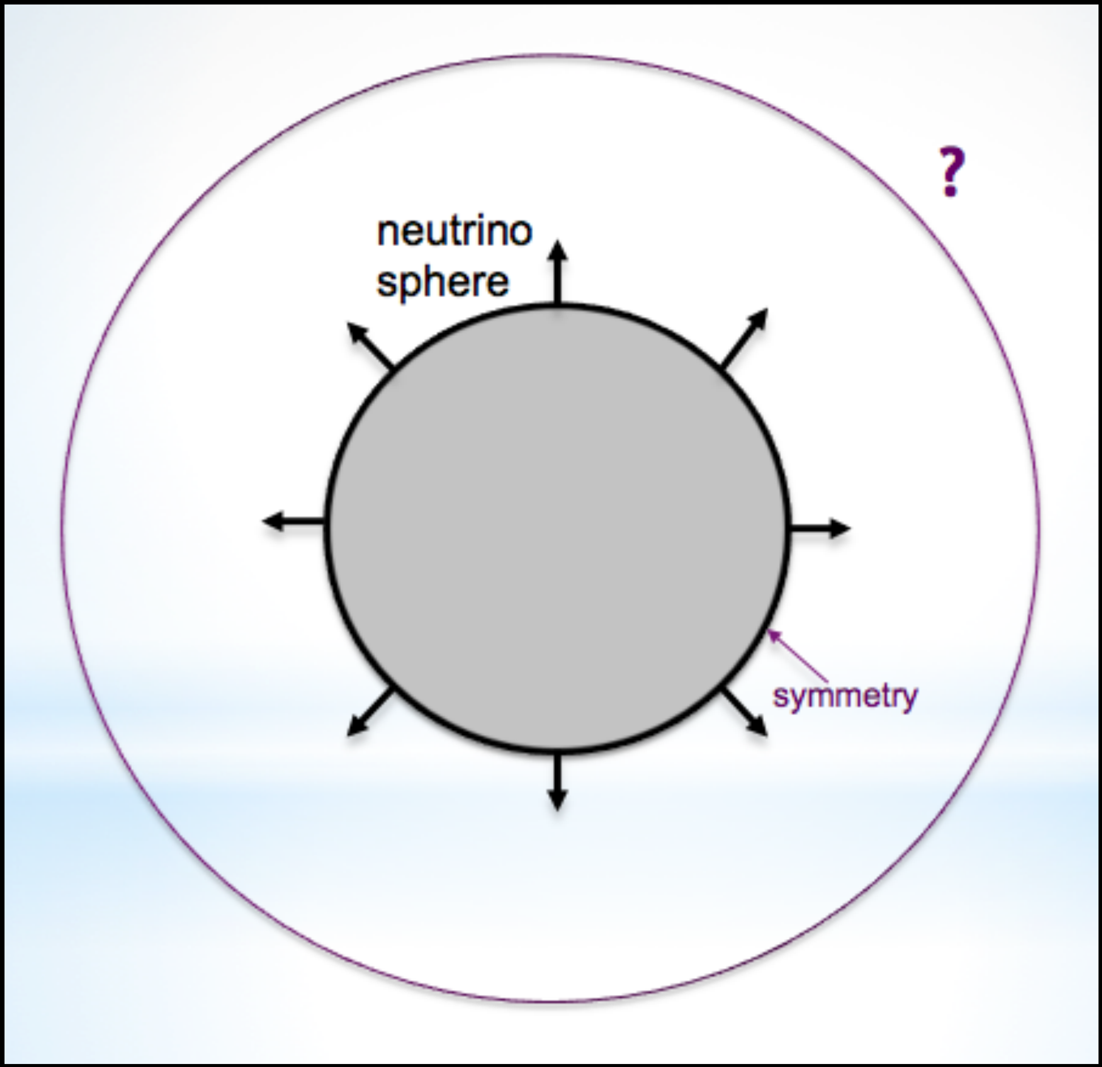
Symmetry Breaking

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

- Are the symmetries in the neutrino bulb model consistent with collective neutrino oscillations?

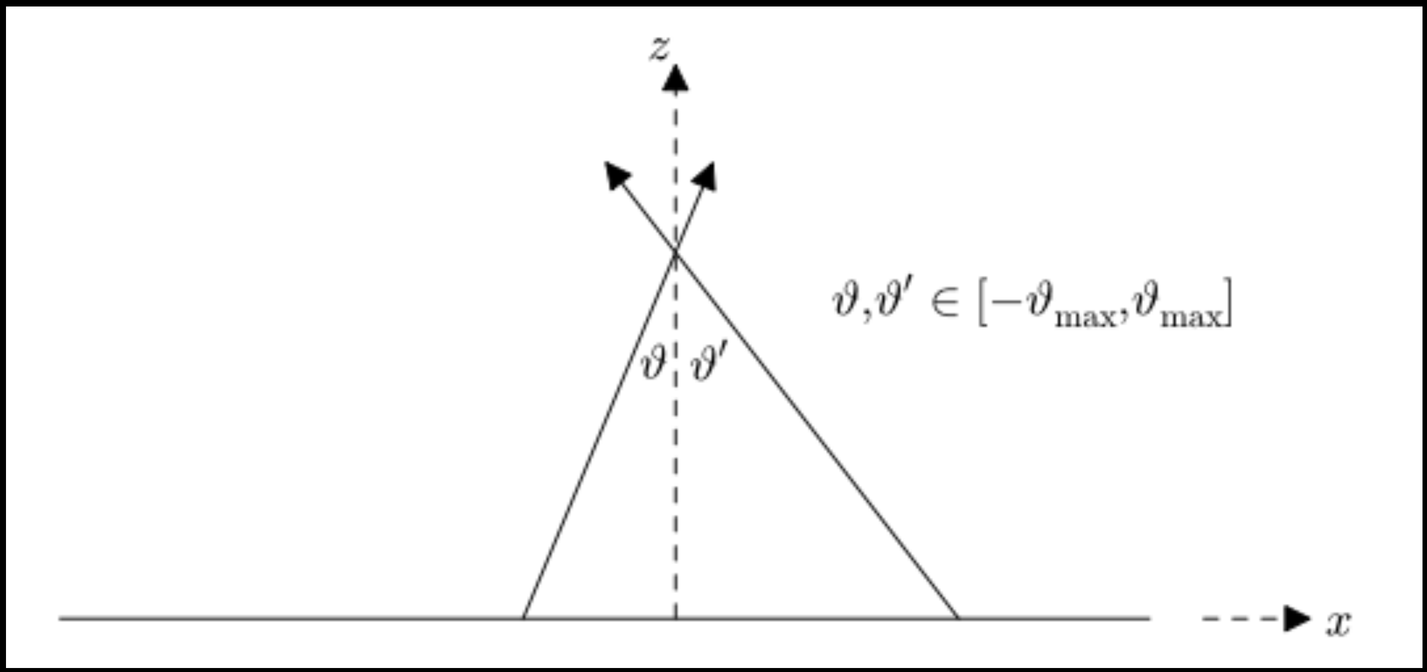
- Suppose we assume the spatial and time symmetries on the neutrino sphere. Do the symmetries survive at larger radii?

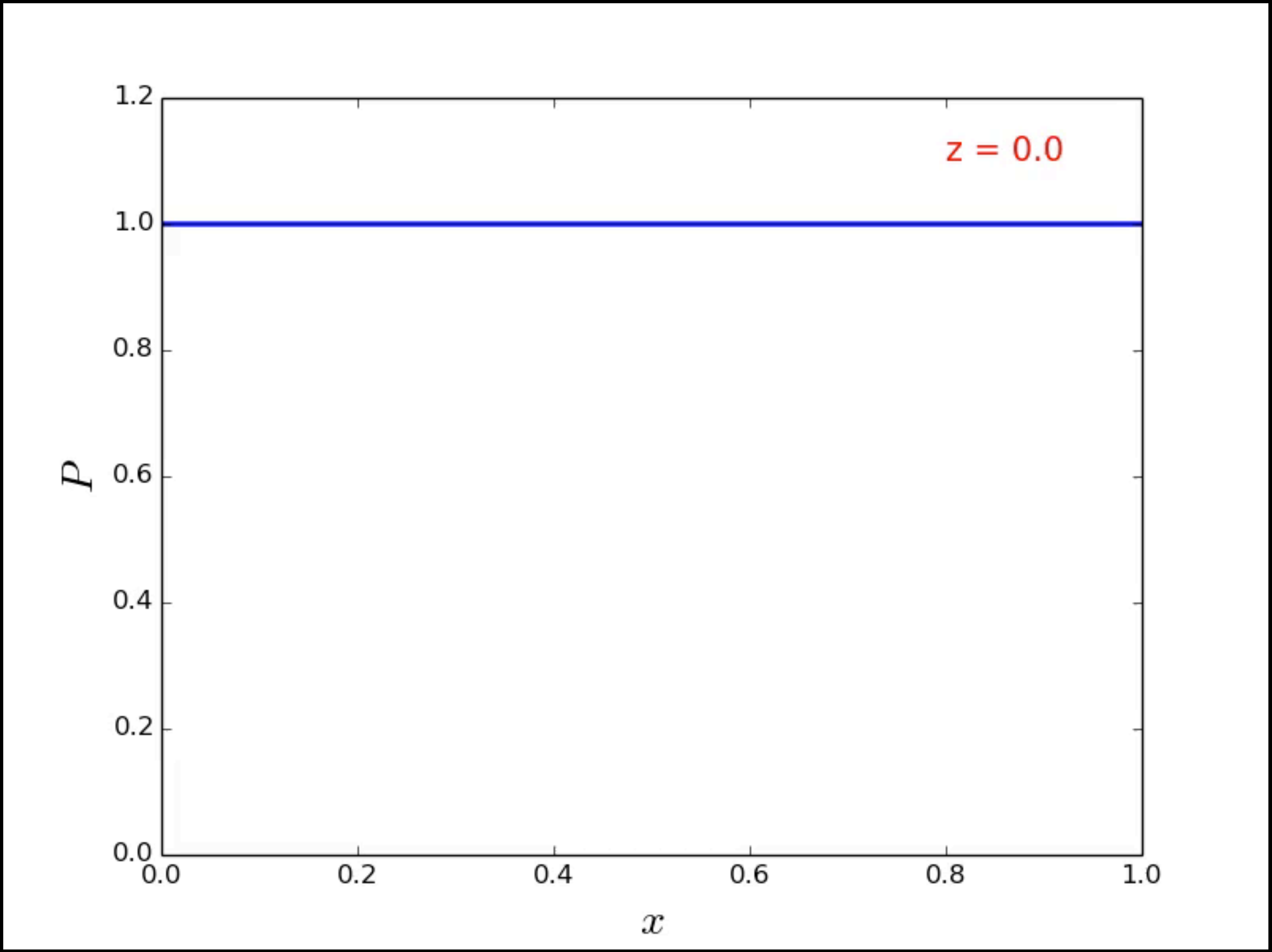
- Study the stability of asymmetric perturbations



G. Raffelt, S. Sarikas, D. S. Seixas, PRL 111, 091101 (2013)
H. Duan & S. Shalgar, PLB 747, 2015
S. Abbar, H. Duan & S. Shalgar, PRD 92, (2015) 065019
S. Abbar & H. Duan, PLB 751, 2015
A. Mirizzi, G. Mangano & N. Saviano, PRD 92, 021702 (2015)

Symmetry Breaking

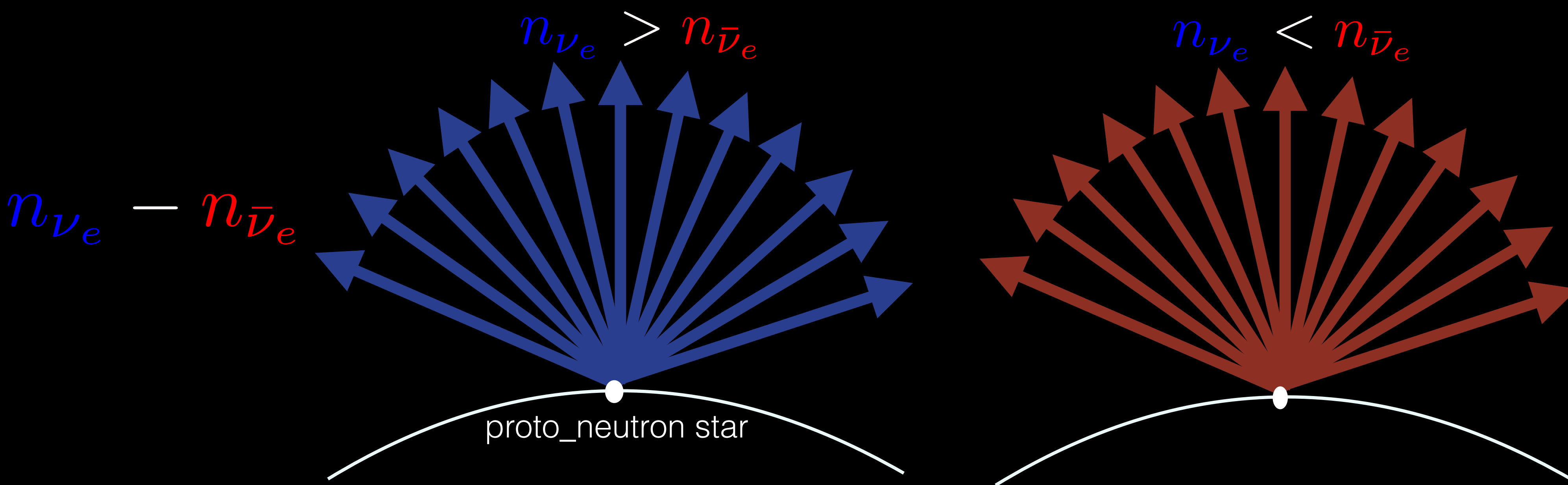




z = 0.0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
P
0.0
0.2
0.4
0.6
0.8
1.0
x

Anisotropic Neutrino Emission

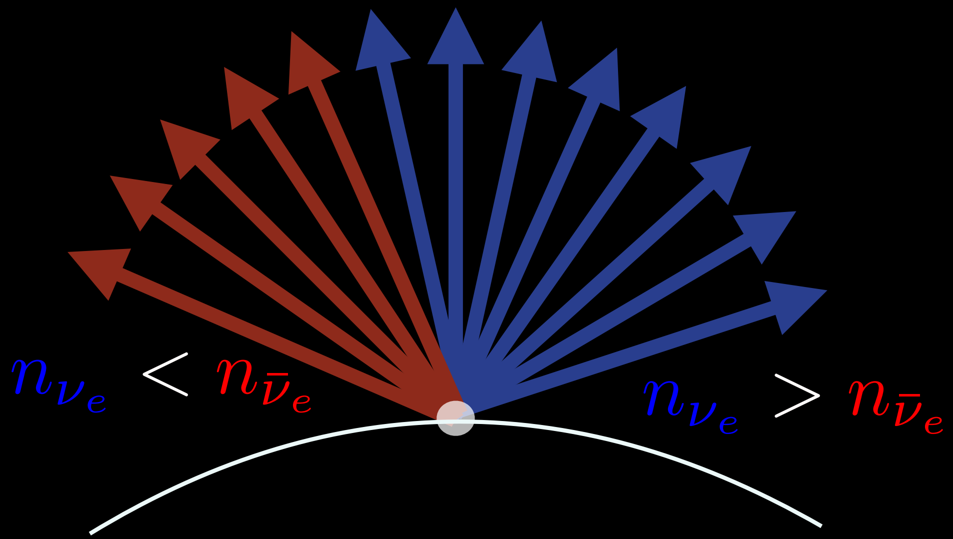
- In the bulb model, it assumed that neutrinos and antineutrinos are emitted isotropically from the surface of the proto-neutron star



- This implies that the scales on which flavor conversion could occur is determined by vacuum frequency $\Delta m^2/2E \sim 1\ \mathrm{km}^{-1}$

Anisotropic Neutrino Emission

- Fast modes could occur when there is crossing in $n_{\nu_e} - n_{\bar{\nu}_e}$



- Scales on which flavor conversion could occur is now determined by n_{ν_e} (n_e) and could be < 1 cm on the surface of proto-neutron star
- Neutrino oscillations could occur even for $\omega = 0$

R. Sawyer, Phys.Rev.Lett. 116 (2016)
S. Chakraborty, R. Hansen, I. Izaguirre, G. Raffelt, JCAP 1603 (2016)

Current Status and Future Directions

- Breaking symmetries makes the problem very intense computationally

- Binary neutron stars are also dense in neutrinos, but the geometry is complicated

A. Malkus, J. P. Kneller, G. C. McLaughlin &, R. Surman, PRD 86, 085015
M. Fresnel, M. R. Wu, C. Volpe & A. Perego, PRD 95, 023011

- For the fast modes, crossing in “ $n_{\nu_e} - n_{\bar{\nu}_e}$“ is necessary.
  But it is not understood well if the crossing in the spectrum exists

- How these new effect impact r-process nucleosynthesis, and neutrino spectra observed at earth

- New interaction terms could modify the evolution of neutrinos
  - Spin/helicity coherence terms
  - Nonstandard neutrino interactions

J. Serreau & C. Volpe, PRD 90, 125040
Velasenko, Fuller & Cirigliano, Phys. Rev. D 89, 105004

A. Chatelain & C. Volpe, arXiv:1710.11518
C. J. Stapleford et. al., PRD 94, 093007