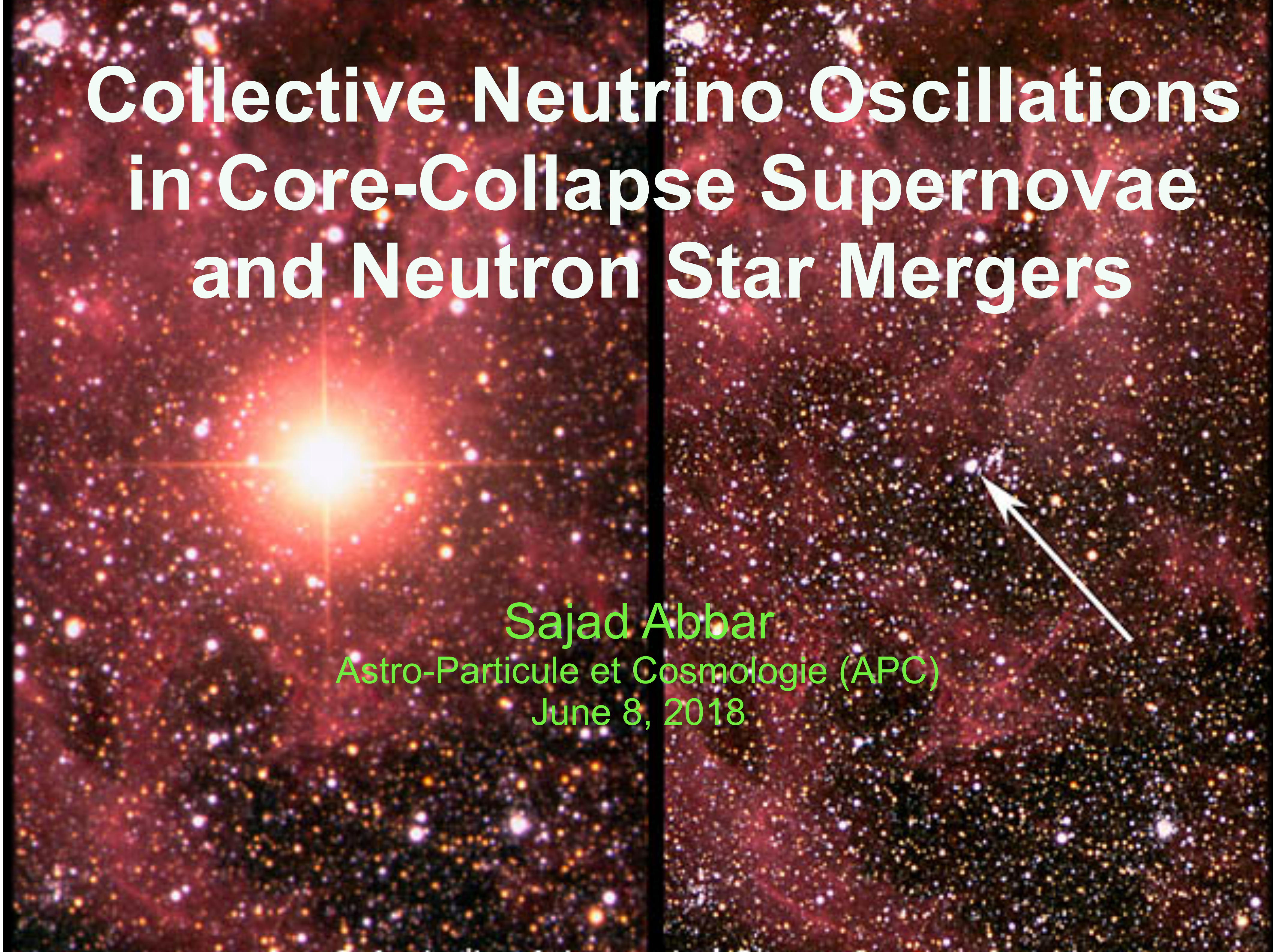


Collective Neutrino Oscillations in Core-Collapse Supernovae and Neutron Star Mergers

Sajad Abbar
Astro-Particule et Cosmologie (APC)
June 8, 2018

Outline

- Neutrino Oscillations in Vacuum and Matter
- Neutrino Oscillations in Dense Neutrino Media
- Core-Collapse Supernova Explosions and Neutron Star Mergers
- The Importance of Studying Neutrinos in CCSN and NS mergers
- Neutrino Oscillations in Dense Neutrino Media: Simplistic Models
- Too Simplistic Models ?!
- Summary

Neutrino Physics

- Neutrinos were first proposed by W. Pauli to account for the missing energy in beta decay $n \rightarrow p + e + \bar{\nu}_e$
- We have three flavors for neutrinos (antineutrinos) $\nu_{e}\ ,\mu,\ \tau$
- 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- … as

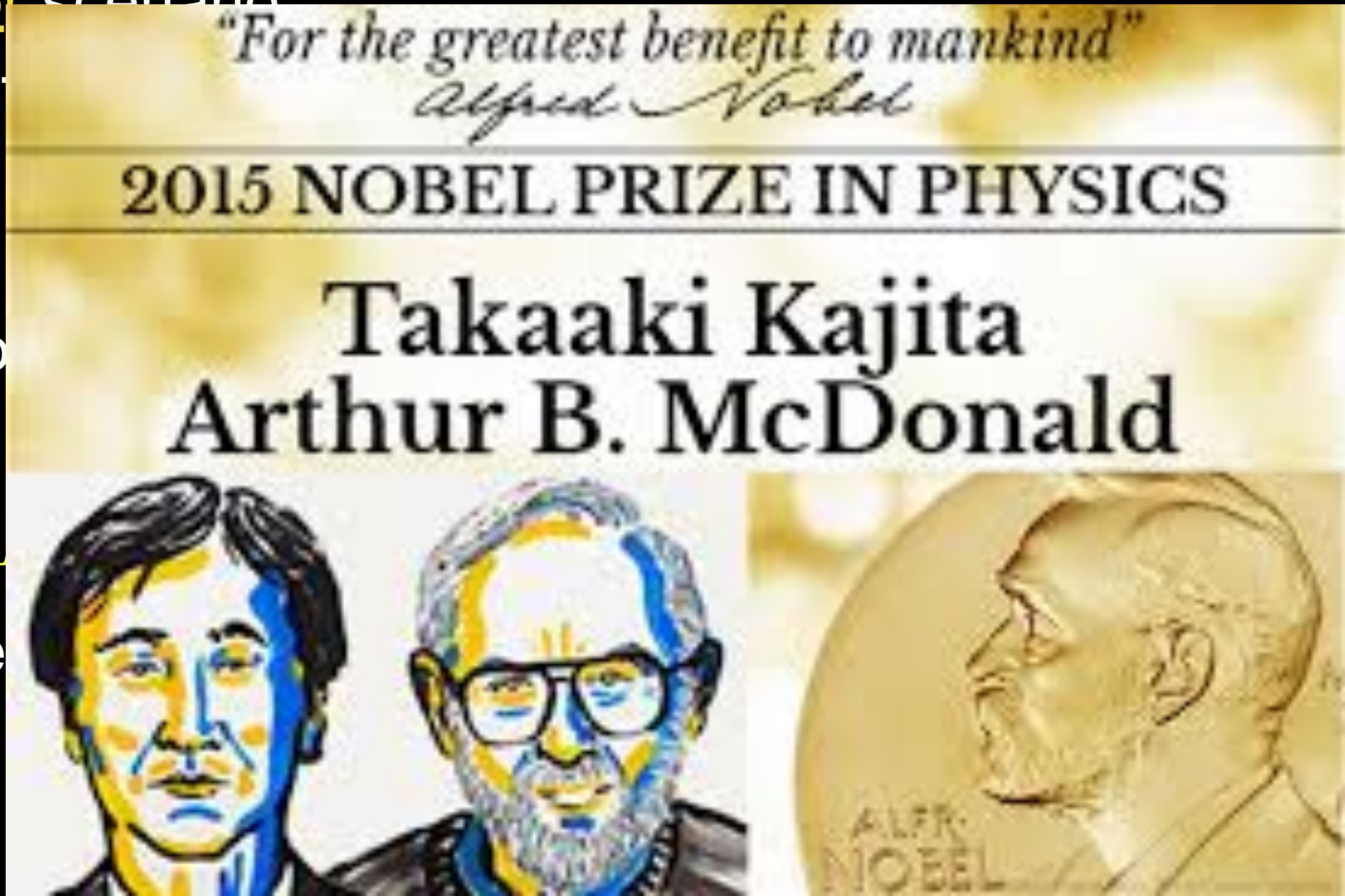
$$H = \frac{1}{2} \ldots$$

- In the two … eutrino produced …

$$P_{\nu_\alpha \to \nu_\beta}(\ldots$$

- When the … ian

$$H = \frac{1}{2} \ldots$$



- 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.

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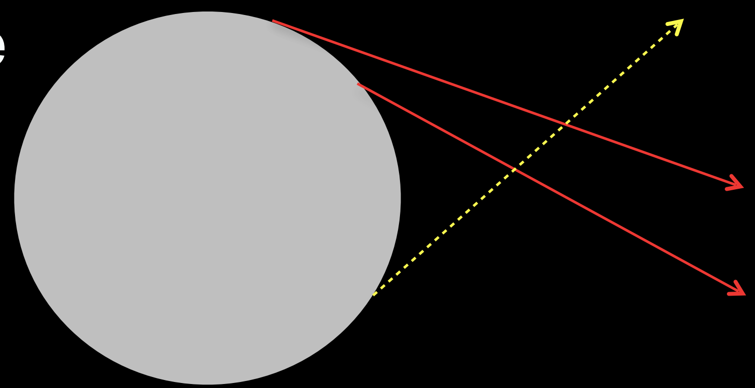
Neutrino Oscillations in Dense Media

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

$$H_{\nu\nu} = \sqrt{2}G_{\rm F}\int \underbrace{\mathrm{d}^3q}_{\text{correlation}}(1-\mathbf{v_p}\cdot\mathbf{v_q})(n_\nu \underbrace{\rho_q}_{\text{nonlinearity}} - n_{\bar\nu}\bar\rho_q)$$

correlation nonlinearity

- 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**



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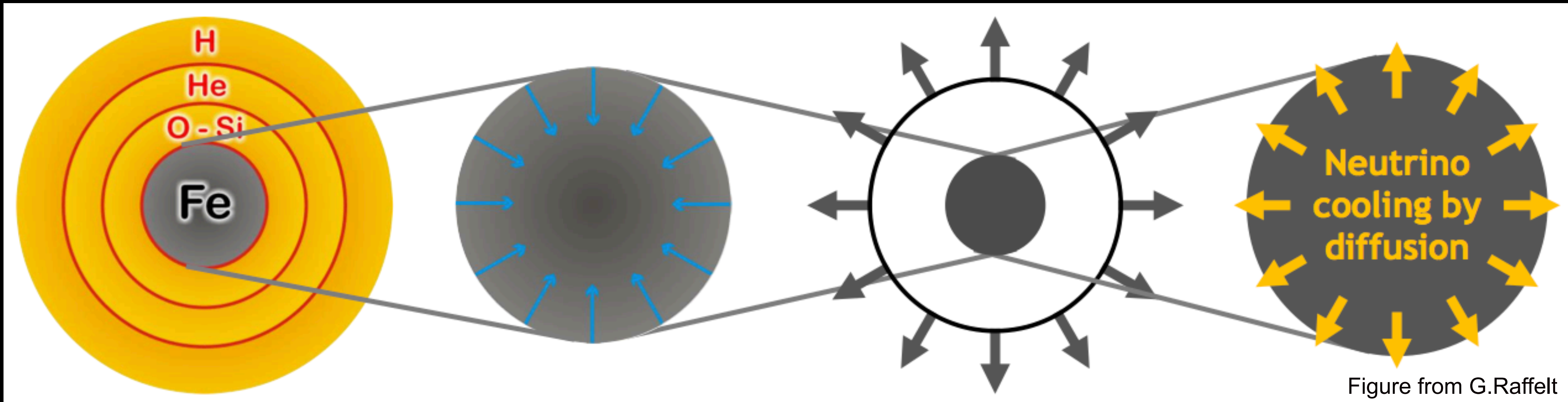
Core-Collapse Supernova



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.

Neutron Star Mergers

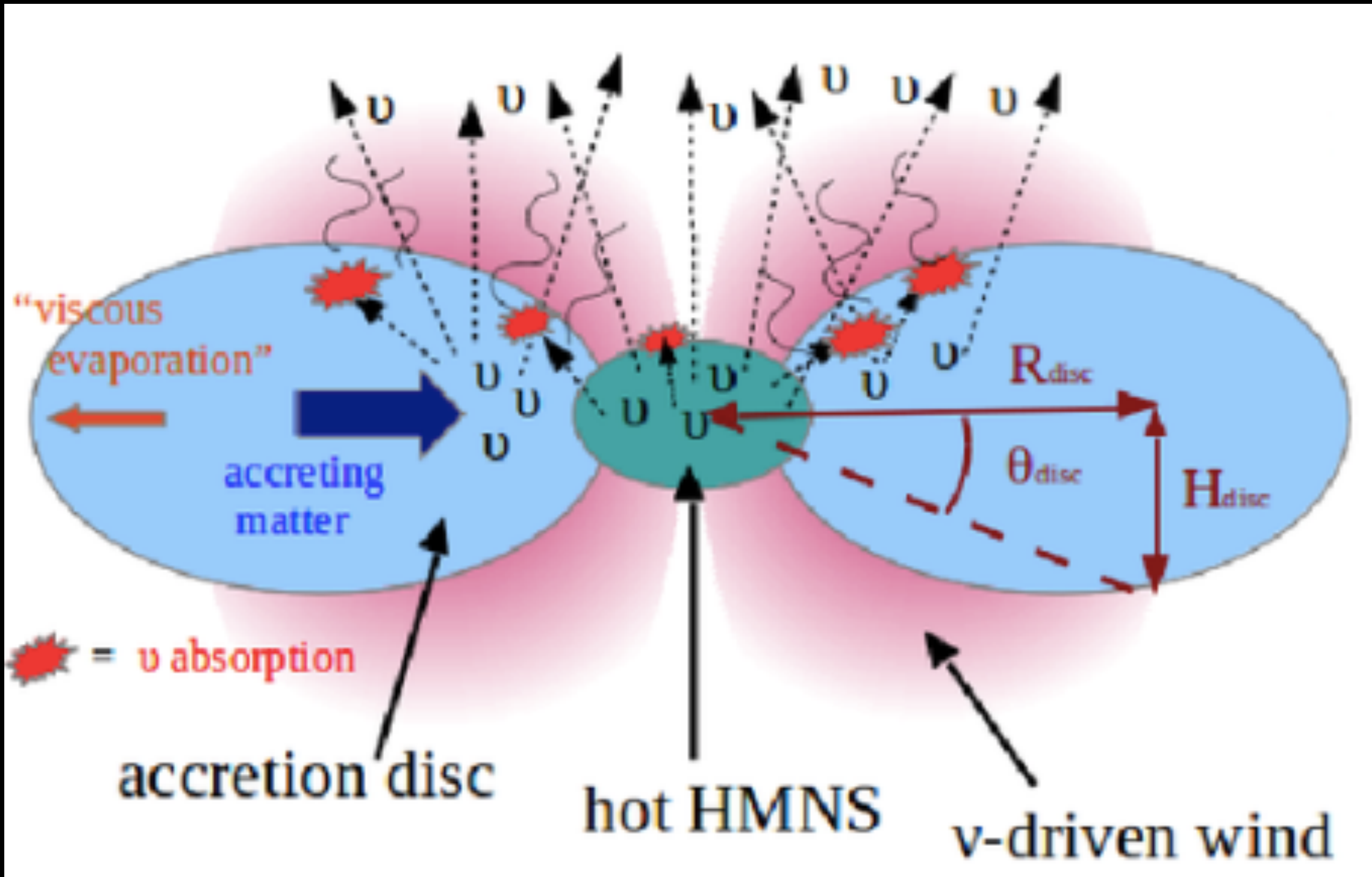


Figure from Perego et. al., arxiv: 1405.6730

- Hot hyper massive NS and the accretion disk emit a huge number of neutrinos

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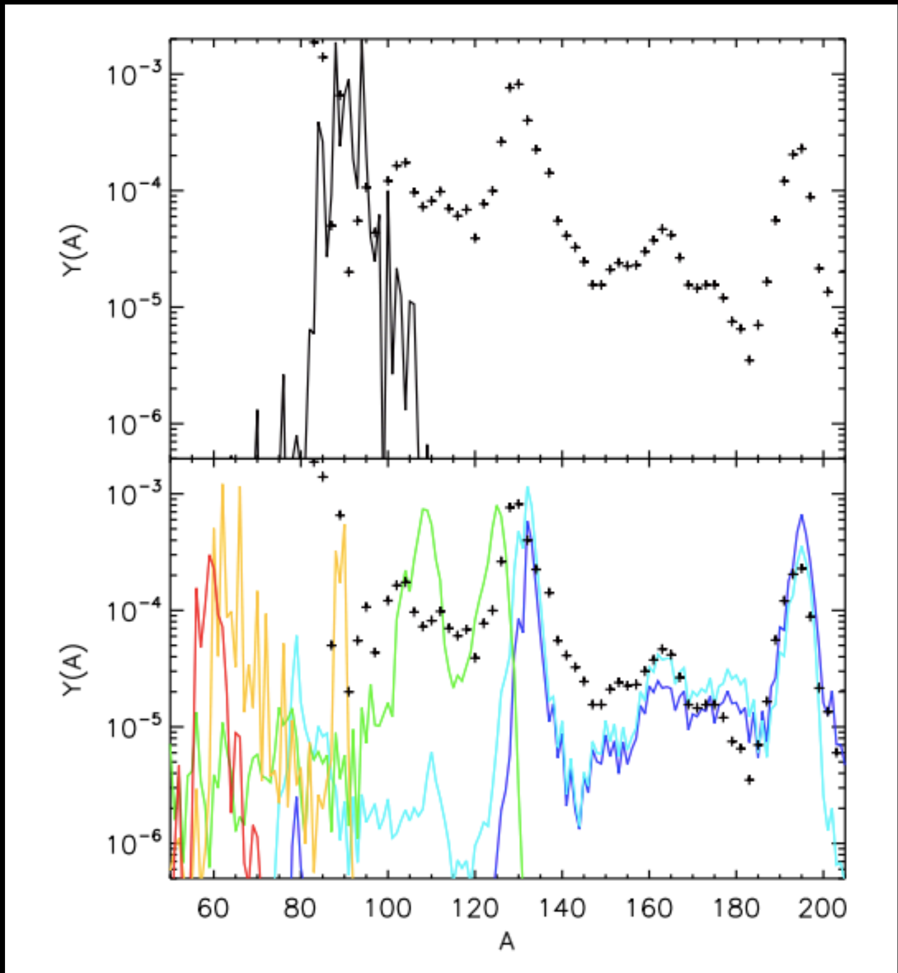
Why Studying Neutrino Oscillations

- Nearly half of elements with A>70 are produced in r-process
- The most promising candidate sites are CCSNe and NS mergers
- Neutrinos can change the neutron to proton ratio through the weak processes

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

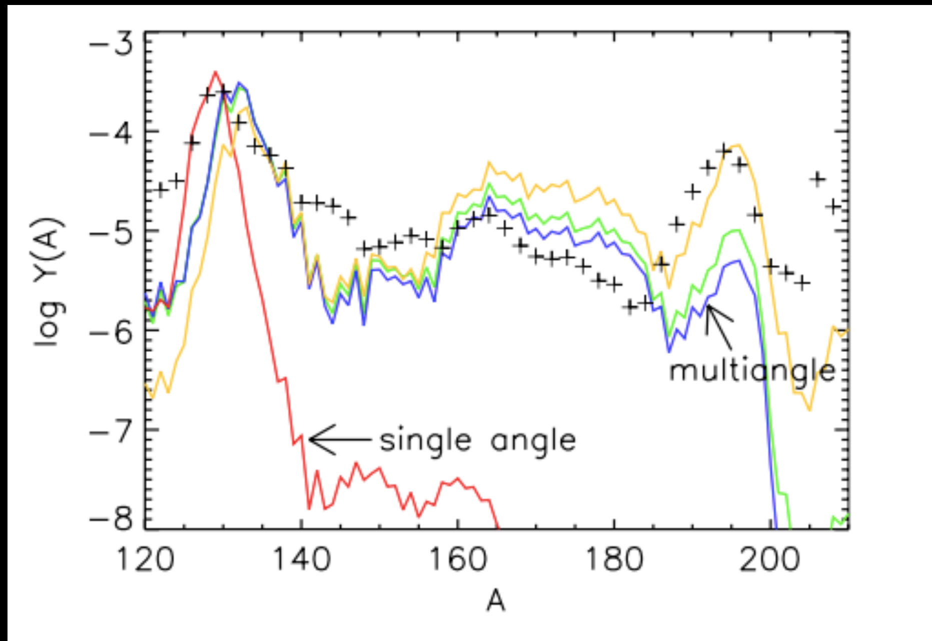
$$\nu_e + n \rightleftarrows p + e^-$$

NS Mergers



Malkus et al, Phys. Rev. D 93, 045021 (2016)

CCSN



Duan et al 2011 J. Phys. G: Nucl. Part. Phys. 38 035201

Why Studying Neutrino Oscillations

- 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 dynamics

  - Supernova dynamics: in delayed supernova explosion, shock wave is revive by the aid of neutrinos

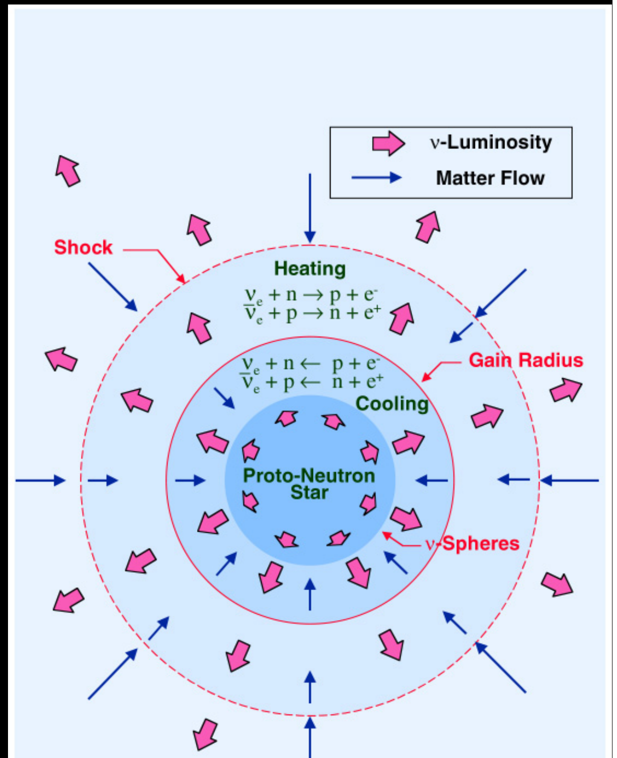


Image credit: TeraScale Supernova Initiative.

Why Studying Neutrino Oscillations?

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- Understanding neutrino flavor evolution can also be important to the dynamics.
  - **Supernova dynamics:** in delayed supernova explosion, shock wave is revive by the aid of neutrinos
  - **NS merger dynamics**

- Observation of a galactic supernova explosion
  - Determine neutrino hierarchy Wallace et. al., ApJ, 817, 182
  - Get some insight on explosion mechanism Loredo and Lamb, Phys.Rev.D65:063002,2002
  - Measure neutrino spectra parameters Rosso, Vissani & Volpe, 1712.05584
  - Measure PNS binding energy Rosso, Vissani & Volpe, JCAP11(2017)036
  - and maybe more …..!?

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  - Neutrinos can be essential to matter **composition**
  - Neutrinos can be important to **dynamics**
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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

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

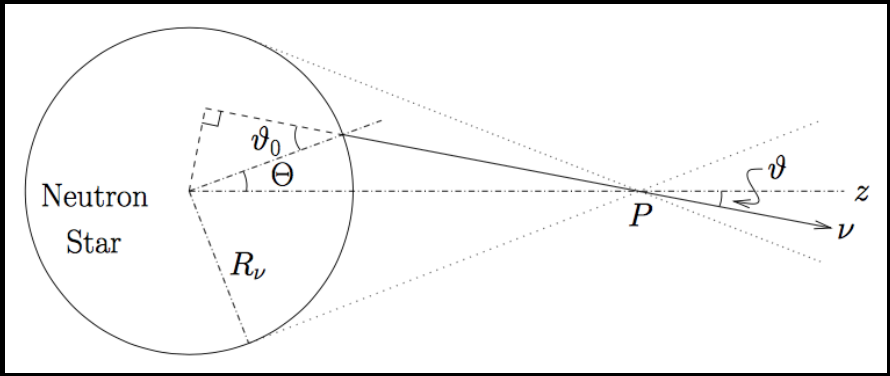
spherical symmetry & axial symmetry around radial direction

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

- *Neutrino Bulb Model:*

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

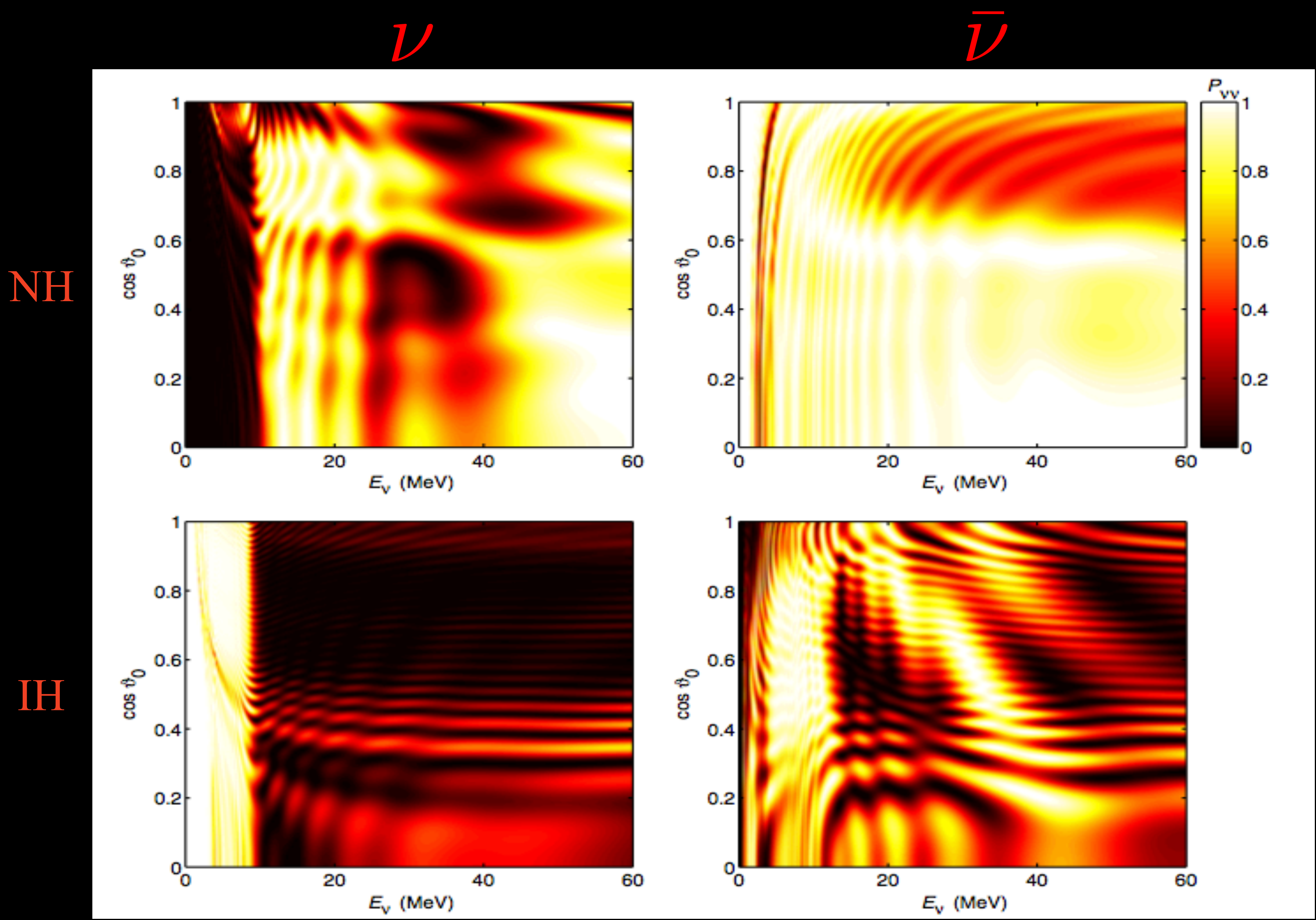
$$\rho(r; E, \theta)$$



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

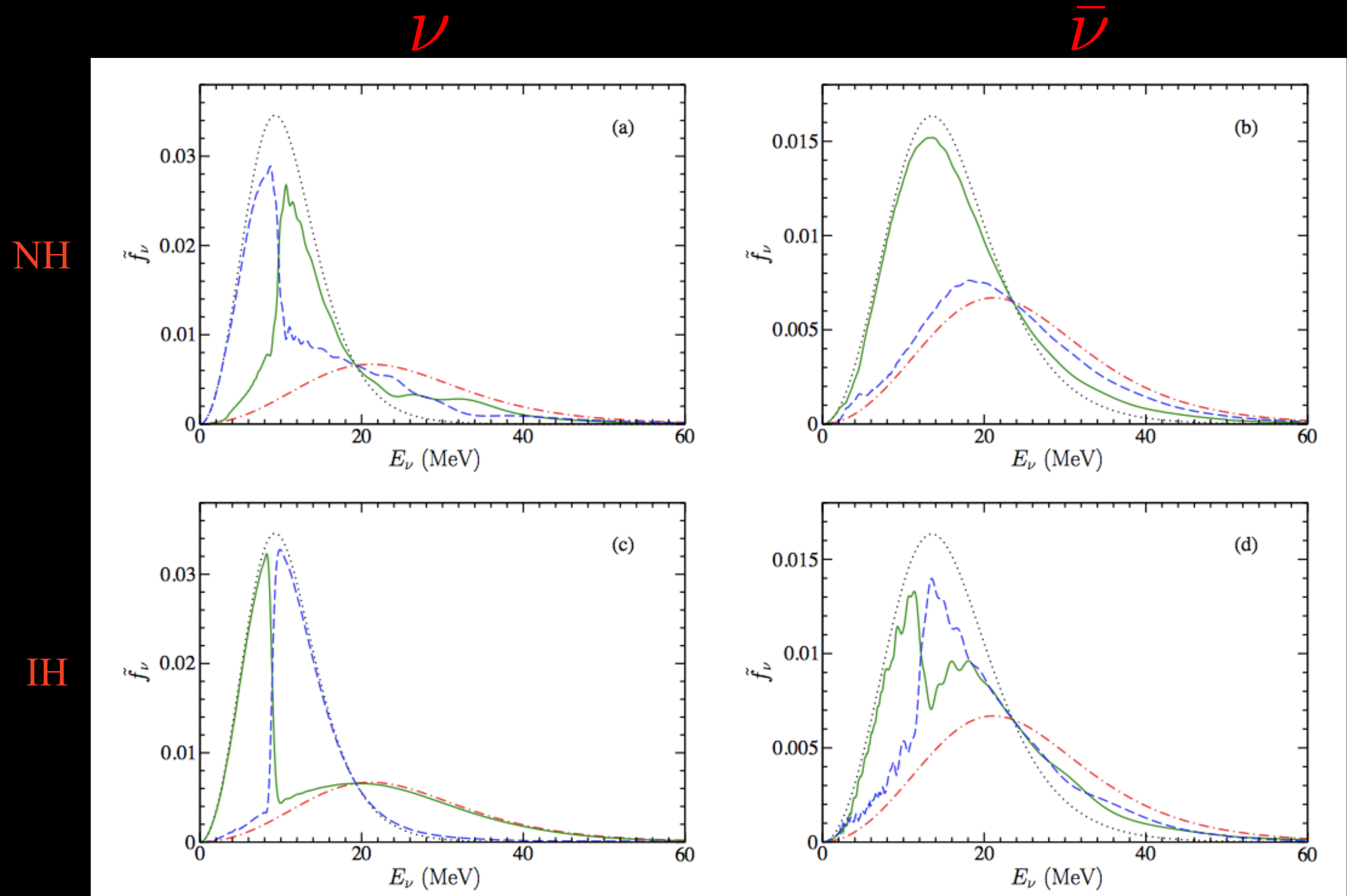
Neutrino Bulb Model

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



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

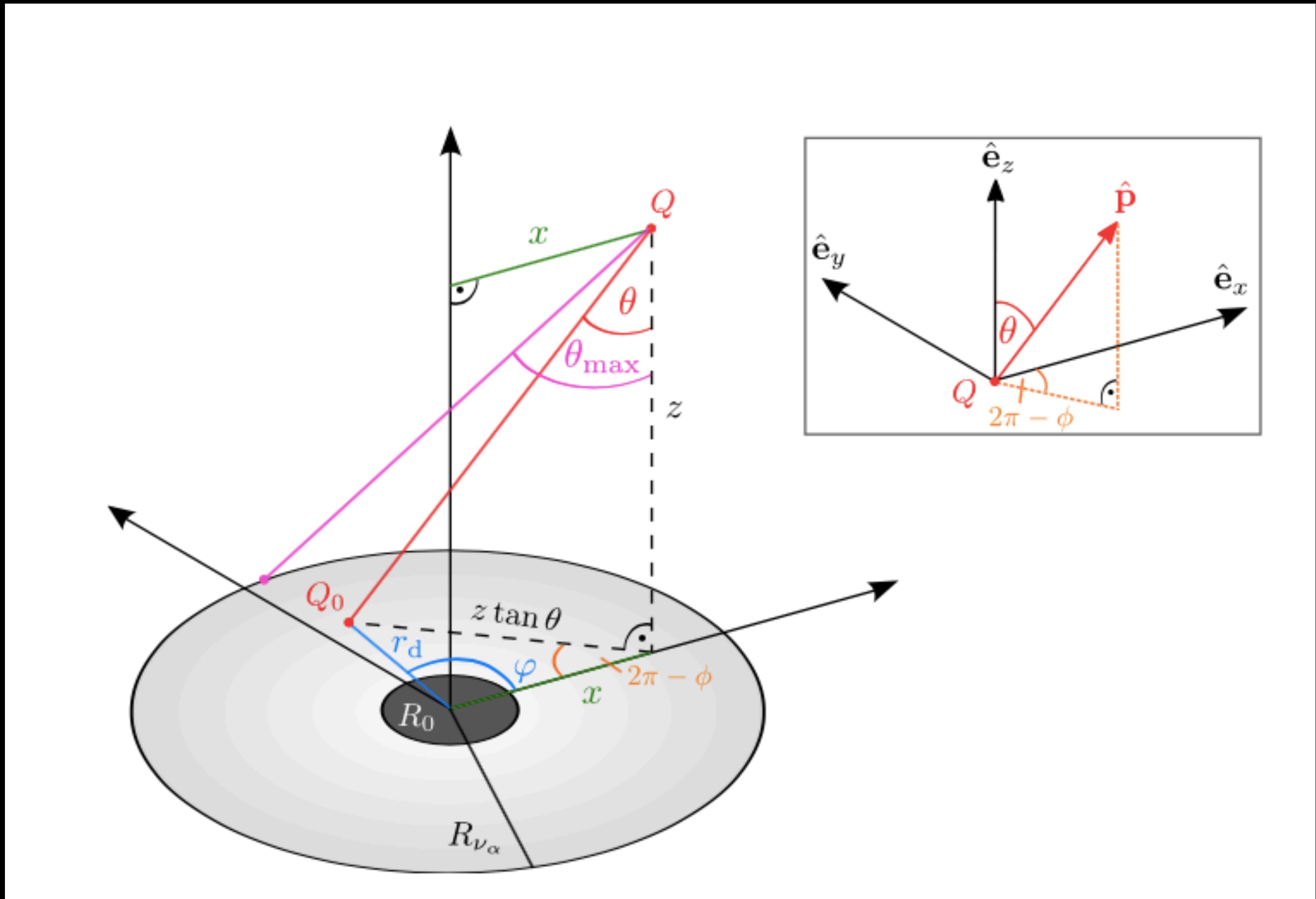
Neutrino Bulb Model



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

Single Angle Approximation in NS Mergers

- In the case of neutron star mergers, the geometry is much more complicated. One assumes that all of neutrino beams experience the same flavor evolution



Frensel et. al., Phys. Rev. D 95, 023011 (2017)

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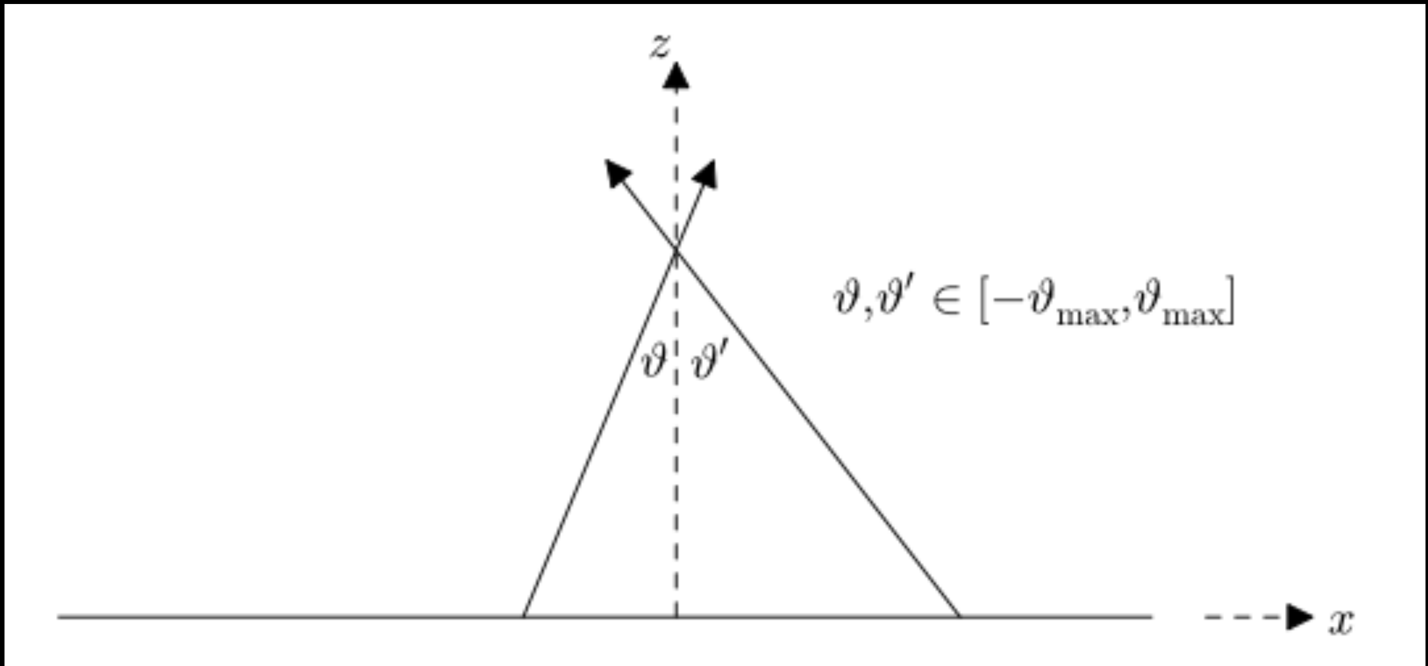
- Neutrino Oscillations in Dense Neutrino Media: Simplistic Models
  - To make the problem more tractable, we make several simplification
    SN: **spherical symmetry and stationarity** (*Neutrino Bulb Model*)
    NS mergers: single angle approximations
- Too Simplistic Models ?!

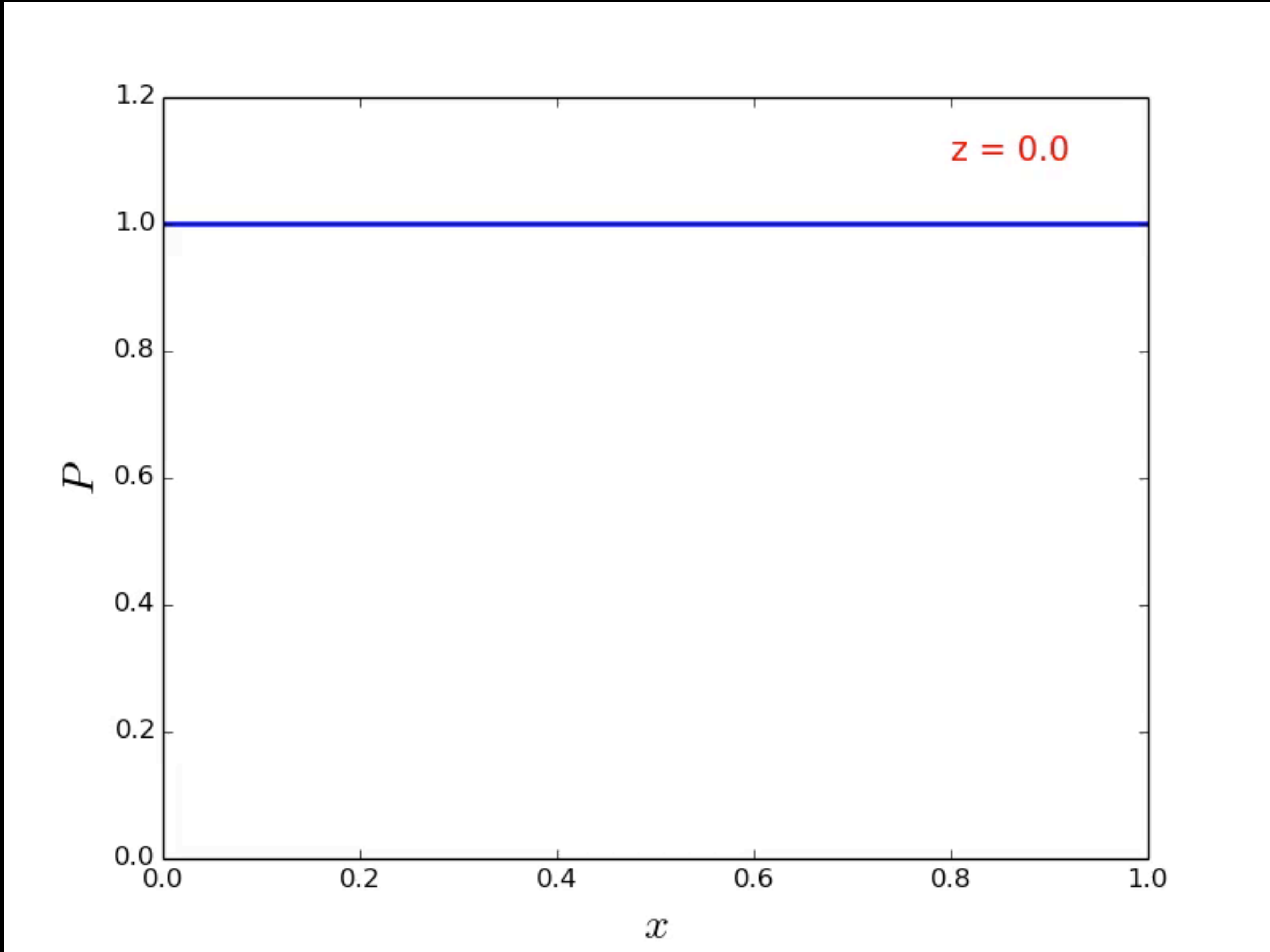
Too Simplistic Models ?!

- Our simplistic calculations are based on two important assumptions:
  - Neutrino evolution has time/special symmetries
  - Neutrinos are emitted isotropically

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)

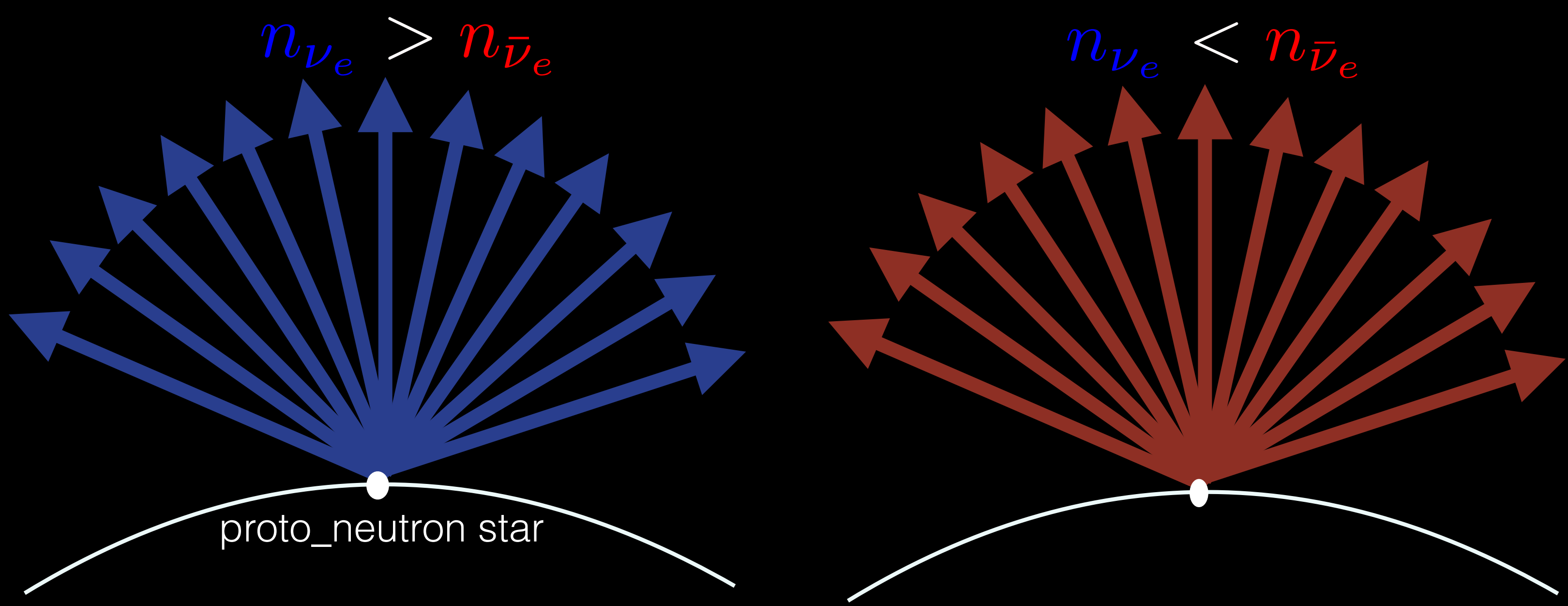
Symmetry Breaking




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

Anisotropic Neutrino Emission

- We assumed that neutrinos and antineutrinos are emitted isotropicall from the surface of the neutrino source
- $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$ is either always positive or negative

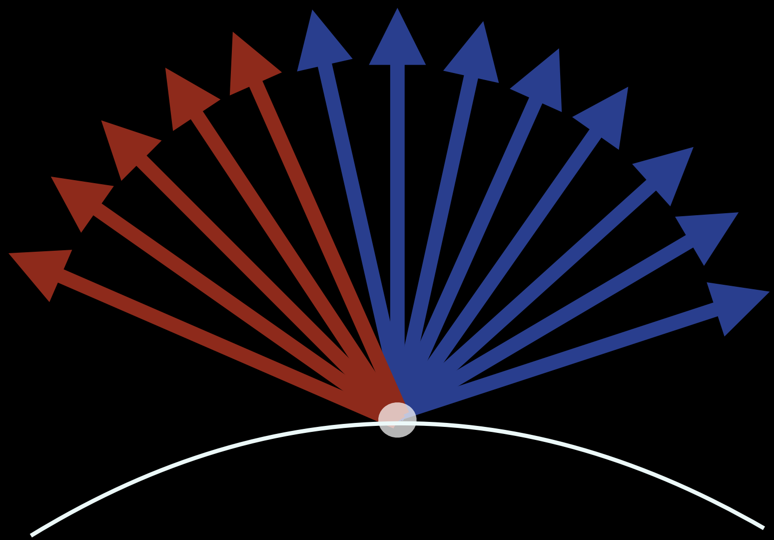


- This implies that the scales on which flavor conversion could occur is determined by vacuum frequency $\Delta m^2/2E \sim 1 \text{ km}^{-1}$

- At vary large matter densities, collective oscillations is irrelevant since collisions occur on much smaller scaler!

Anisotropic Neutrino Emission

- Fast modes could occur when there is crossing in $f_{\nu_e}(\theta) - f_{\bar{\nu}_e}(\theta)$

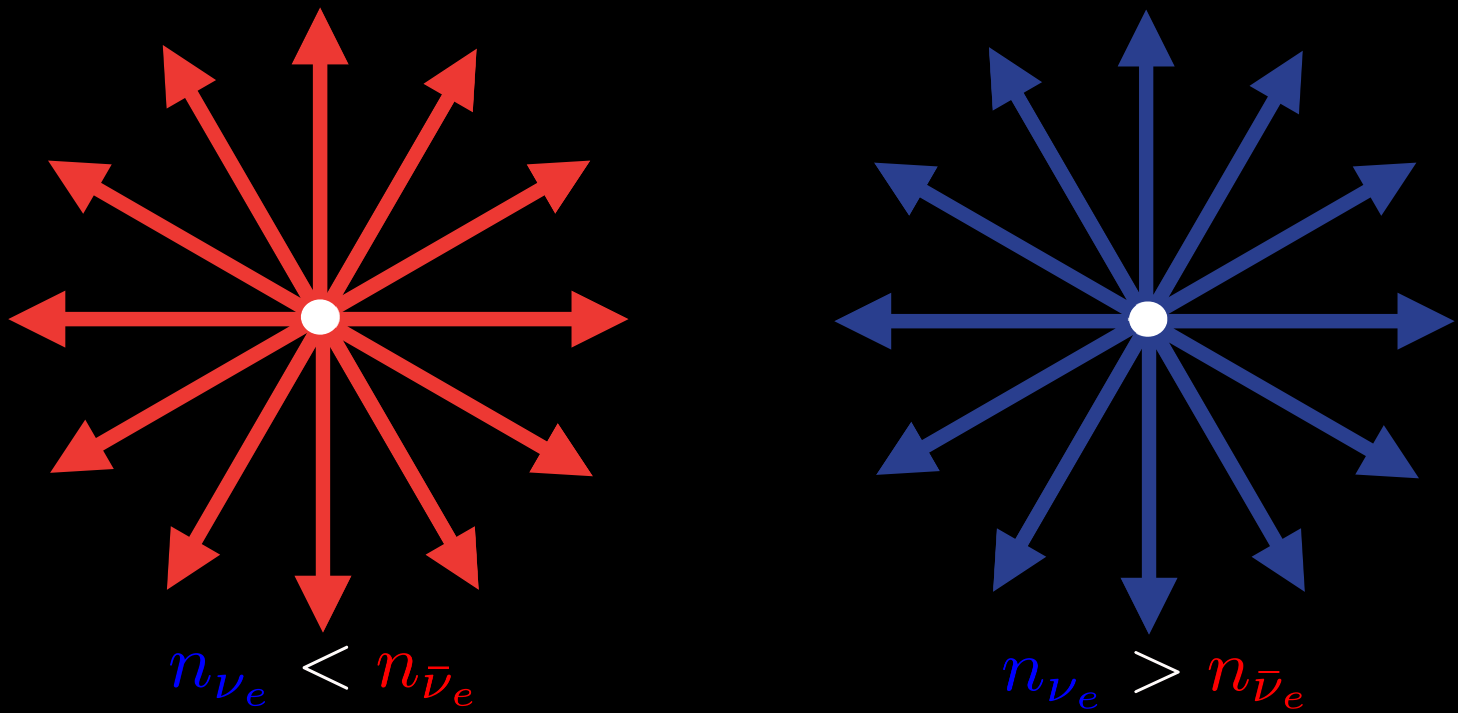


- Scales on which flavor conversion could occur is now determined by n_{ν_e} (n_e) and could be ~ 10 cm on the surface of proto-neutron star
- Neutrino oscillations could now occur in densities that has been long thought to be the realm of collisional and scattering processes

R. Sawyer, Phys.Rev.Lett. 116 (2016)
S. Chakraborty, R. Hansen, I. Izaguirre, G. Raffelt, JCAP 1603 (2016)
S. Abbar & H. Duan, arXiv: 1712.07013

Isotropic Neutrino Emission

- Fast modes could occur even in isotropic neutrino gas

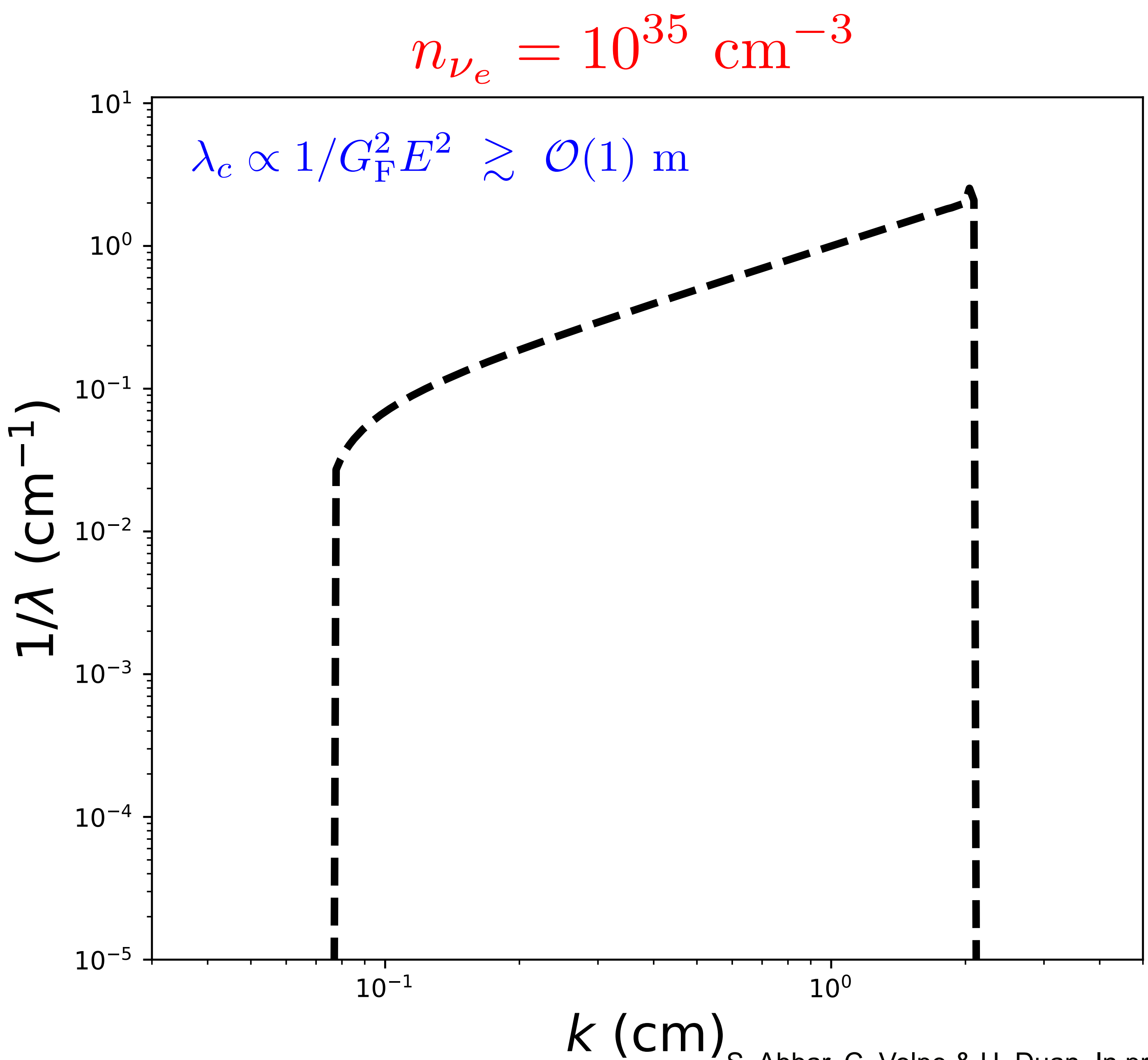


- Relevant for neutrino gas inside neutrino sphere

Isotropic Neutrino Emission

- Fast

- Relev



S. Abbar, C. Volpe & H. Duan, In preparation

Current Status and Future Directions

- Spatial and time symmetries in a dense neutrino gas are not consistent with collective neutrino oscillations.

  Breaking symmetries makes the problem very intense computationally

- Neutrinos could experience fast flavor conversion that occur on very small scales
- Collective neutrino oscillations might even occur inside the SN core
- Most of our understanding in in the linear regime. What happens in the nonlinear regime?
- How these new effects impact r-process nucleosynthesis, and neutrino spectra observed on earth