Neutrinos in/from supernovae

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Neutrinos in Supernova

- Neutrinos are incredibly important in core-collapse supernovae.
  - They are the transporters of energy/momentum and lepton number.

- In order to correctly compute how a supernova explodes, a great deal of attention and effort is directed to the neutrinos.
  - neutrino transport is Hard: neutrinos are not everywhere in thermal equilibrium with the matter plus there are quantum effects

- Neutrinos are also the messengers which can tell us how the supernova explodes.
  - In 1987 we detected 20 neutrinos from a SN in the LMC which confirmed the basic paradigm
  - If a SN occurs tomorrow in the Milky Way we will detect 10's of thousands of neutrinos and be able to answer more detailed questions.

The physics in supernova neutrinos

Nuclear / Supernova

- Progenitor and structure,
- Neutrino opacities,
- Equation of State,
- Shock position / velocity,
- Standing Accretion Shock Instability,
- LESA
- Stalled shock duration,
- Nucleosynthesis conditions,
- ….

Neutrinos

- Neutrino mass ordering
- Number of ν flavors
- Self-interaction effects,
- MSW effects,
- Turbulence effects
- Non-standard interactions,
- Magnetic moments,
- SUSY contribution,
- ….

- If you want to understand supernovae, you have to understand neutrinos.

Neutrino transport

- The generalized (6x6) neutrino density matrix *F* for a given momentum evolves according to

$$i\frac{dF}{d\lambda}-[H,F]=iC[F]$$

- *H* is the generalized Hamiltonian, *C* is the generalized collision term.

Volpe, Väänänen & Espinoza, PRD **87**, 113010 (2013)

Vlasenko, Fuller & Cirigliano, PRD **89** 105004 (2014)

- The diagonal elements of *F* are the occupation numbers of the neutrino flavors, the off-diagonal are the coherences.

- The neutrino Hamiltonian is made up of several terms:
  - the vacuum H_V term,
  - the matter potential H_M,
  - the self-interaction H_{SI},

- The vacuum term is

$$H_V = \frac{1}{2E} U_V \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U_V^\dagger$$

- E is the neutrino energy, m_1, m_2 and m_3 are the neutrino masses.
- U_V is the mixing matrix parameterized by three mixing angles θ_{12}, θ_{13} and θ_{23}.

- In the presence of matter the neutrinos gain a potential energy.
- For mixing between active flavors we only need consider the Charged Current potential.

$$H_M = \pm \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_{CC} = \sqrt{2} G_F n_e$$

- Not included is the small potential $V_{\mu\tau}$.
  - In the standard model $V_{\mu\tau} \approx 10^{-5} V_{CC}$ but in some SUSY models the $\mu\tau$ term can be $V_{\mu\tau} \approx 10^{-2} V_{CC}$.
- Beyond the Standard Model physics can modify this matter term.

Stapleford *et al*, PRD **94** 093007 (2016)

Esteban-Pretel *et al*, PRD **81** 063003 (2010)

- So many neutrinos are emitted in a supernova the Hamiltonian includes a term due to neutrino self-interactions.

- At a given location and time, the self-interaction Hamiltonian due to the Standard Model V-A interaction is

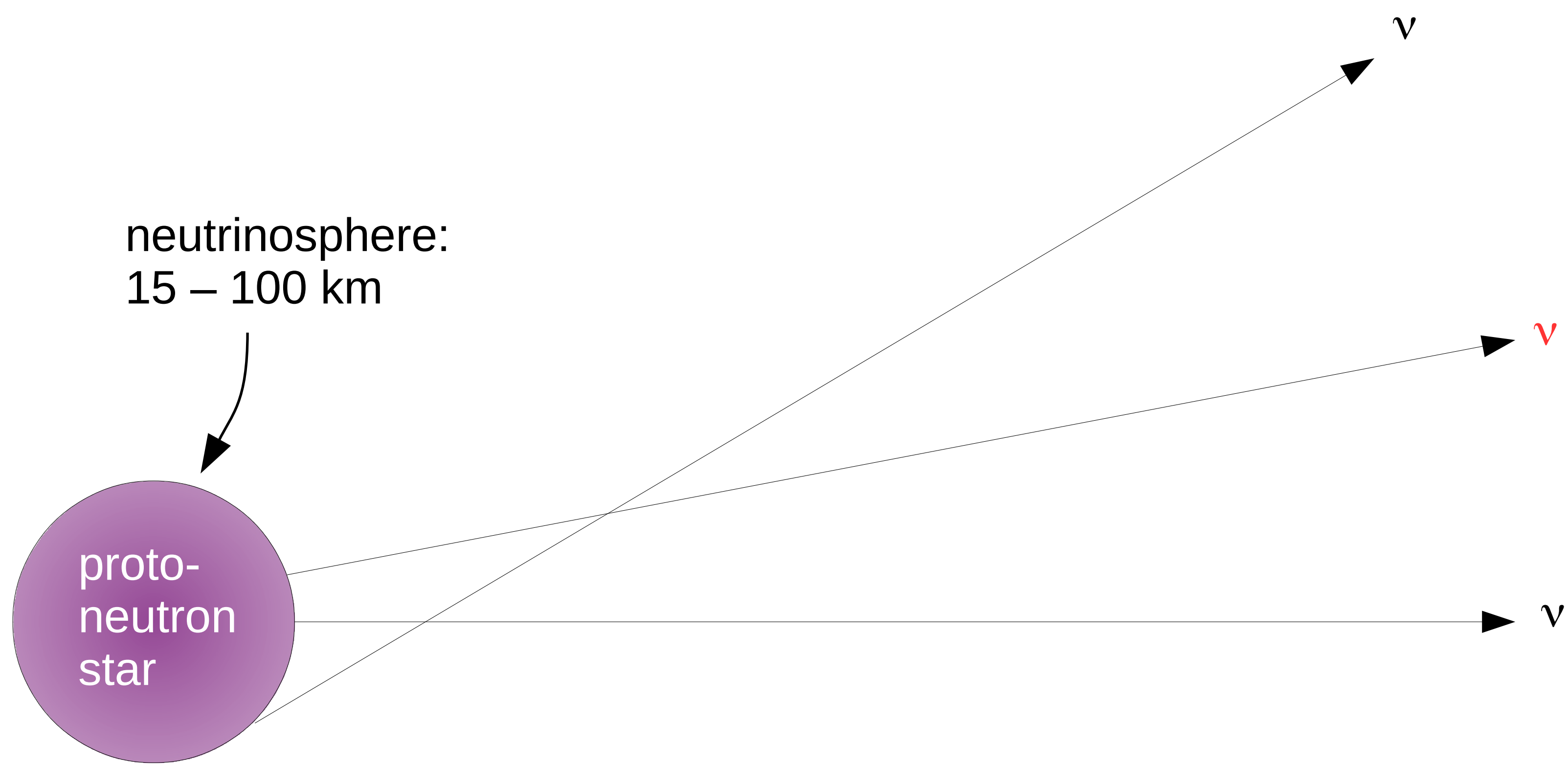
$$H_{SI}(\boldsymbol{q}) = \sqrt{2}\, G_F \int \frac{d^3 q'}{(2\pi)^3} \left(1 - \hat{\boldsymbol{q}} \cdot \hat{\boldsymbol{q}}'\right) \left(\rho(\boldsymbol{q}') - \bar{\rho}^*(\boldsymbol{q}')\right)$$

- Beyond the Standard Model physics can modify this term.

Blennow, Mirizzi & Serpico, PRD **78**, 113004 (2008)

Das, Dighe & Sen, JCAP **5** 051 (2017)

Yang & Kneller, PRD **97** 103018 (2018)



- The evolution of a single neutrino becomes dependent upon every other neutrino emitted even if they never meet!

Free-streaming neutrino propagation

- Efforts to solve the QKEs in supernovae and compact object mergers are still in the early stages.

Capozzi *et al*, PRL **122** 091101 (2019)

Richers *et al*, PRD **99** 123014 (2019)

- For free-streaming neutrinos the absorption/emission/collision term is unimportant.
- The density matrix at some spacetime location λ is related to the initial state at λ_0 by a unitary matrix *S*.

$$\rho(\lambda) = S(\lambda, \lambda_0)\, \rho(\lambda_0)\, S^{\dagger}(\lambda, \lambda_0)$$

- The probability that an initial state *j* is detected as state *i* at λ is

$$P(\nu_j \rightarrow \nu_i) \equiv P_{ij} = |S_{ij}|^2$$

The Bulb Model

- The current State Of The Art for free-streaming neutrinos is the Bulb model and so-called Multi-Angle calculations.

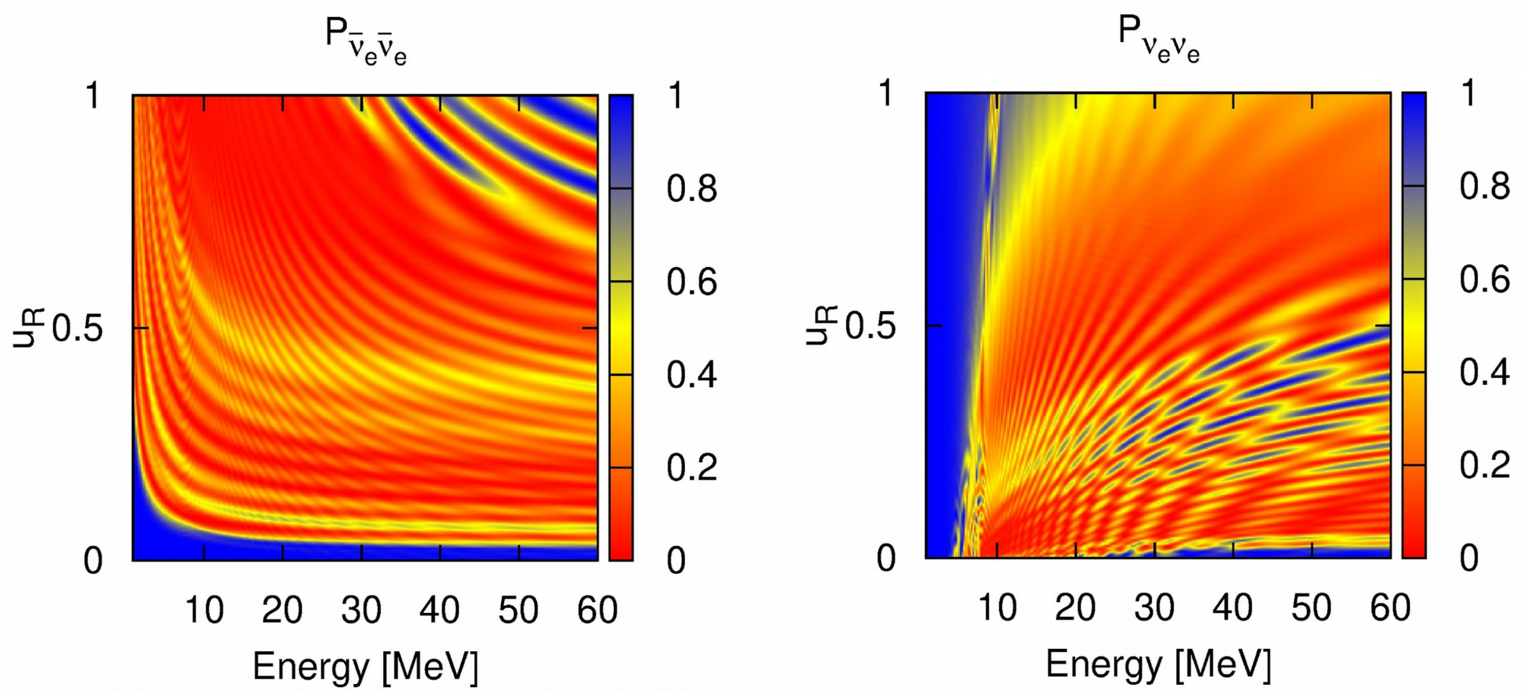
  Duan et al PRL **97** 241101 (2006)

  - The neutrinosphere is treated as a hard surface with spherically symmetric neutrino emission (originally half isotropic).
  - There are no collisions or absorption/emission beyond the neutrinosphere.
  - The neutrino field is in steady state – the time derivative is zero.
  - The neutrino field has axial symmetry around the radial direction.

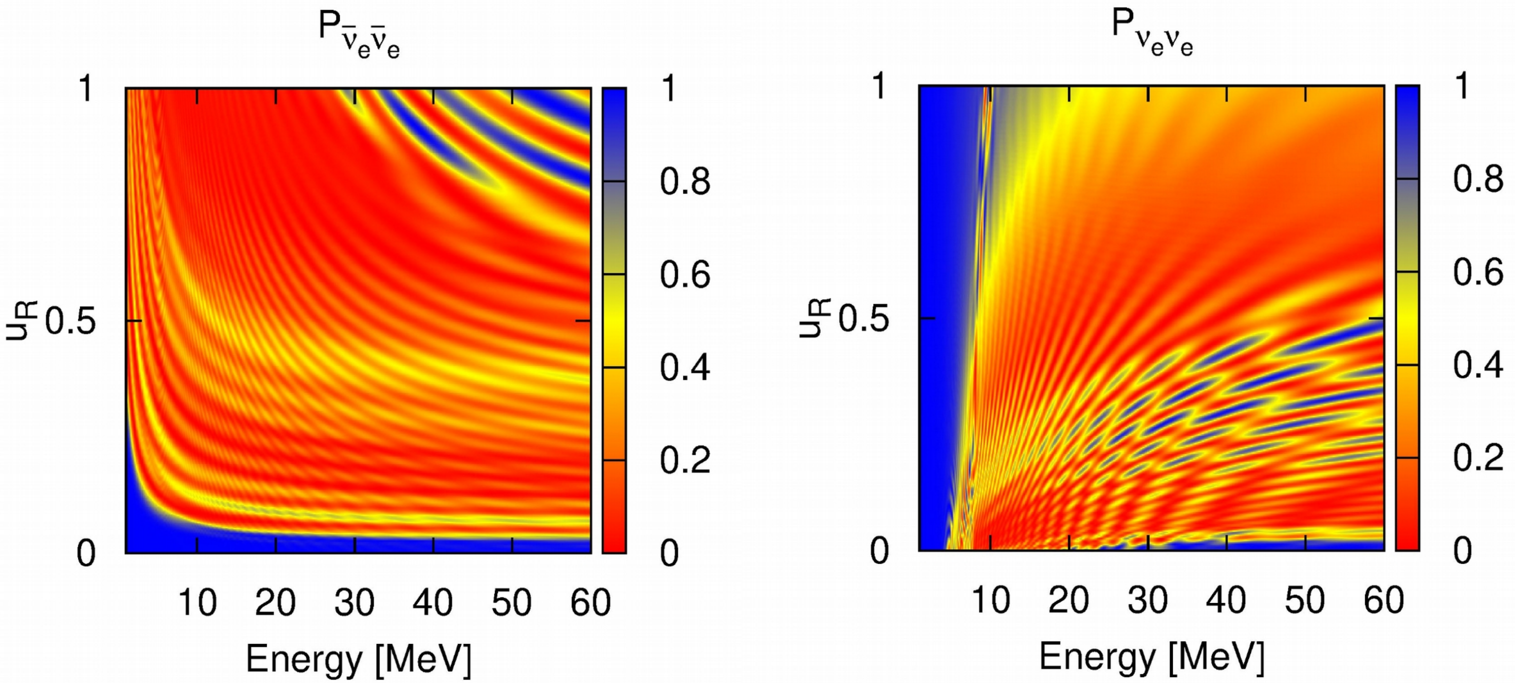
- This turns the neutrino transport into an initial-value problem.
- The imposed symmetries leave just two free variables:
  - The neutrino energy
  - The angle of emission at the neutrino sphere.

- Where do we start?
- How many energy bins N_E?
- How many angle bins N_A?

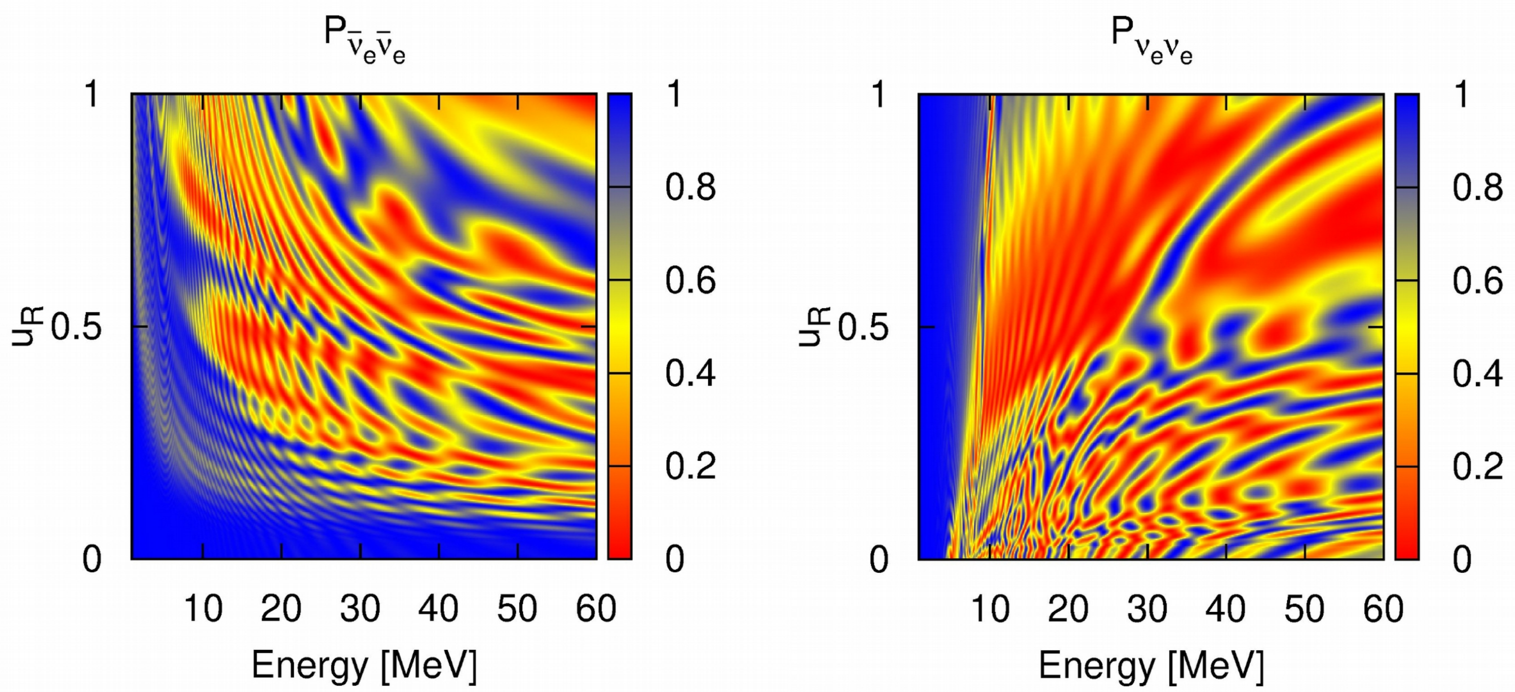
- E.g. using a snapshot at 0.7 s postbounce of the 10.8 $M_\odot$ simulation from Fischer *et al*, A&A **517** A80 (2010)



- 40 km, N_E = 296 (0 to 60 MeV), N_A = 181 (0 to 90°)



- 40 km, N_E = 591 (0 to 60 MeV), N_A = 181 (0 to 90º)



- 40 km, $N_E = 591$ (0 to 60 MeV), $N_A = 361$ (0 to 90°)

Matter effects

- Beyond ~1000 km, the flavor evolution is due to matter effects.
  - MSW conversion plus shock effects and turbulence at later epochs.

Dighe & Smirnov, PRD **62** 033007 (2000)

Schirato & Fuller, arXiv:astro-ph/0205390

Kneller, McLaughlin & Brockman, PRD **77** 045023 (2008)

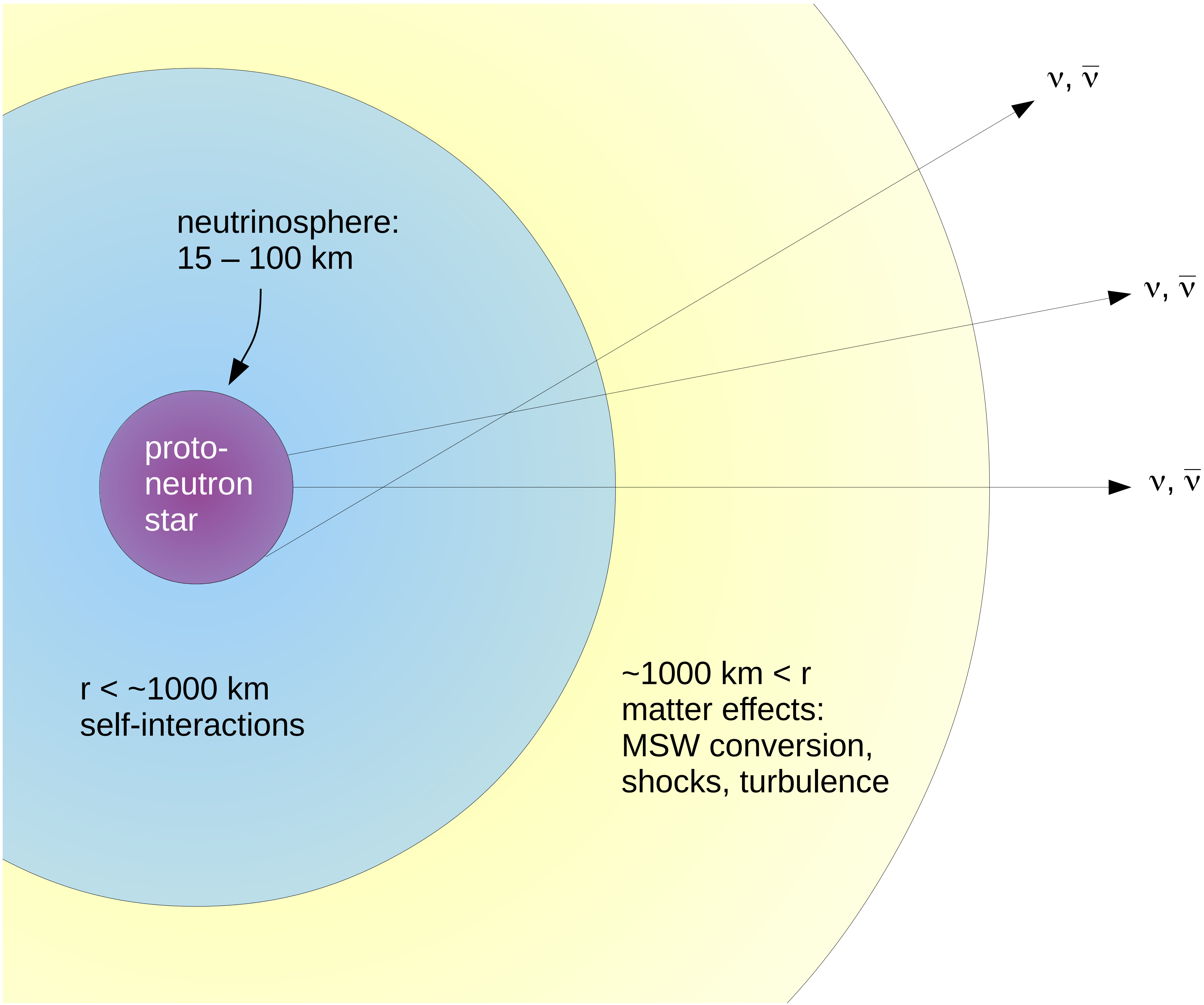
Kneller & Volpe, PRD **82** 123 004–+ (2010)

Lund & Kneller, PRD **88** 023008 (2013)

Capozzi *et al*, JCAP **4** 43 (2016)

Patton, Kneller & McLaughlin, PRD **89** 073022 (2014)

- MSW conversion and shock effects are easy to compute;
  turbulence effects require more work.


neutrinosphere:
15 – 100 km
proto-
neutron
star
r < ~1000 km
self-interactions
~1000 km < r
matter effects:
MSW conversion,
shocks, turbulence
ν, ν̄
ν, ν̄
ν, ν̄

Beyond the Bulb model

- We need to go beyond the Bulb model:
  - Neutrinospheres are not hard surfaces
  - Collisions and emission are not negligible above the neutrinosphere (there are backwards going neutrinos)
  - The symmetries can be spontaneously broken.
  - There is no feedback into the hydro.

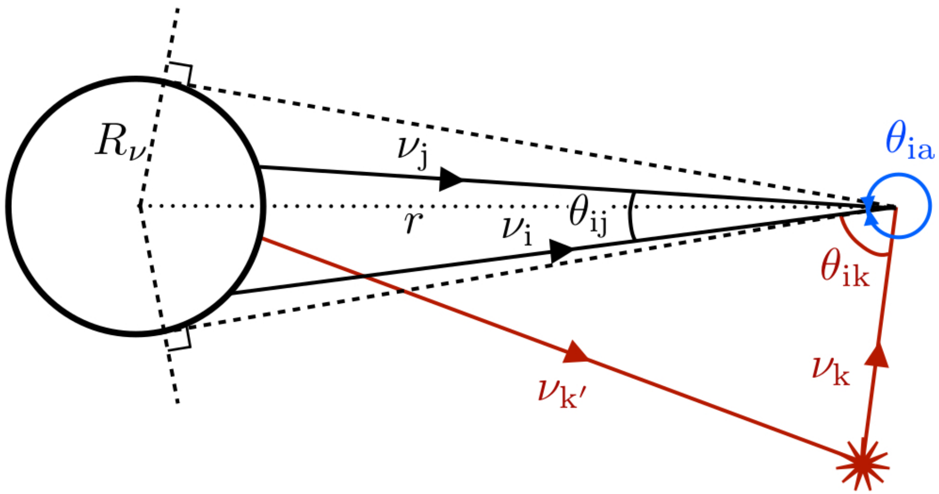
- Hansen & Smirnov showed the finite thickness of the neutrino decoupling region suppresses the neutrino coherence.

Hansen & Smirnov arXiv:1905.13670

  - The width of the neutrinosphere is 8-10 orders or magnitude larger than the oscillation length.

- Scattering can produce a diffuse neutrino halo.

Cherry *et al*, PRL **108** 261104 (2012)



  - The self-interaction from unscattered neutrinos scales as ~ $1/r^4$ because of the 1-cos θ term in the potential.

- But the same high density which creates the halo also suppress the flavor oscillations.

Sarikas *et al*, PRD, **85** 113007 (2012)

Stability Analysis

- In recent years a new tool has been developed that can indicate where the neutrinos will undergo flavor transformation.

Banerjee, Dighe, & Raffelt, PRD **84** 053013 (2011)

- The idea is to compute how a small perturbation of a fixed-point density matrix evolves.

- Consider a density matrix at some spacetime point and a small ‘perturbation’ to it.

$$i \frac{d(\rho_0 + \delta\rho)}{d\lambda} = [H_0 + \delta H, \rho_0 + \delta\rho]$$

- Linearize the equation

$$i\frac{d(\delta\rho)}{d\lambda}=[H_0,\delta\rho]+[\delta H,\rho_0]$$

- The perturbation to the Hamiltonian can be written as

$$\delta H=\frac{\partial H}{\partial\rho}\delta\rho+\frac{\partial H}{\partial\bar{\rho}}\delta\bar{\rho}$$

- Consider a perturbation of the form

$$\delta\rho=A e^{i[\vec{K}\cdot\vec{r}-\Omega t]}+A^{\dagger}e^{-i[\vec{K}\cdot\vec{r}-\Omega t]}$$

- Vectorize the equation in A and you end up with an eigenvalue equation for Ω

$$\Omega \vec{A} = S \vec{A}$$

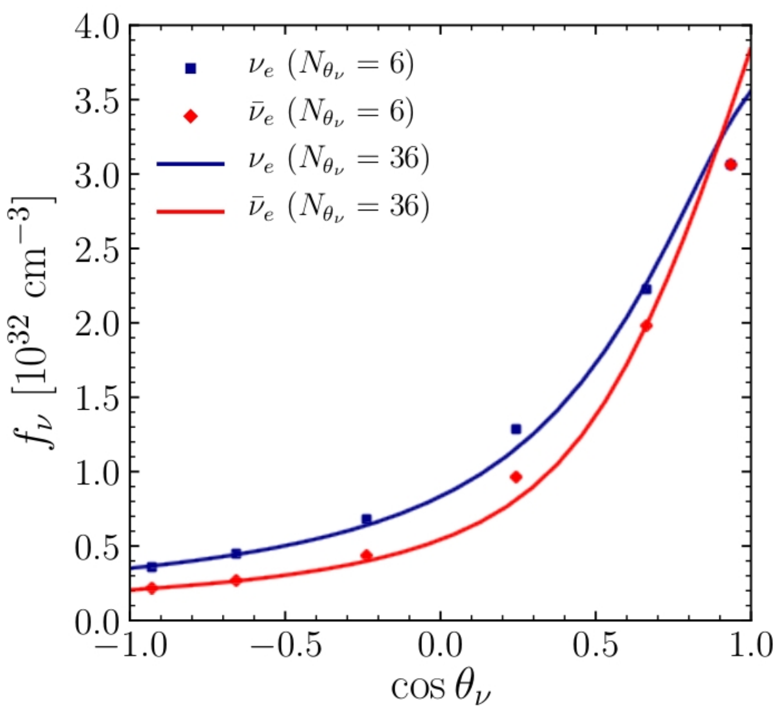
- S is the stability matrix.
- If all the eigenvalues of S are real, the ‘amplitude’ of A stays fixed and the mode rotates in the Argand plane.
- If some of the eigenvalues are complex, the amplitude of the mode with positive imaginary components grow.

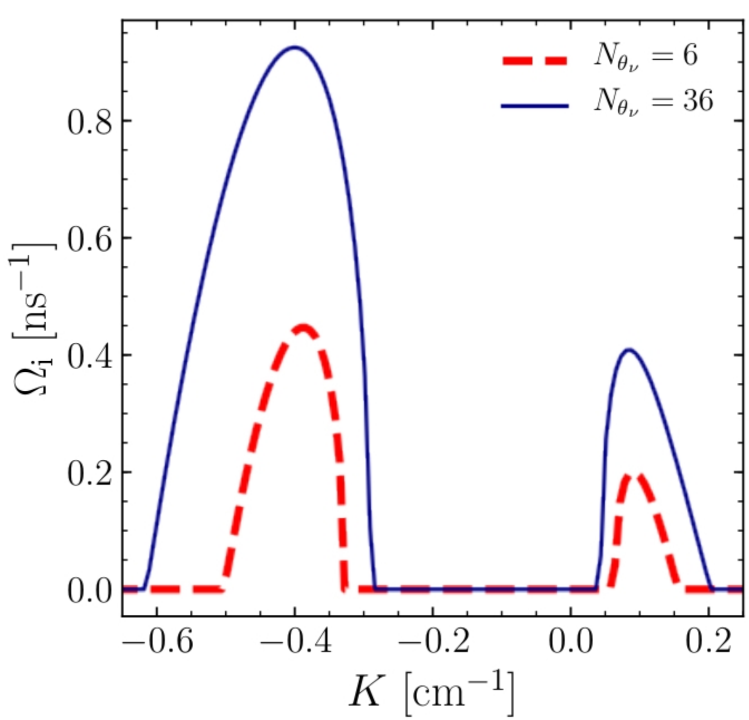
- Without collisions the eigenvalues come in complex conjugate pairs, collisions add a negative imaginary component i.e. collisions shift them ‘down’ in the Argand plane.

- Stability analysis does not impose any symmetries so it can be used with 2D or 3D simulation data.
- It has been found that the neutrinos are unstable to axial perturbations (spontaneous symmetry breaking).

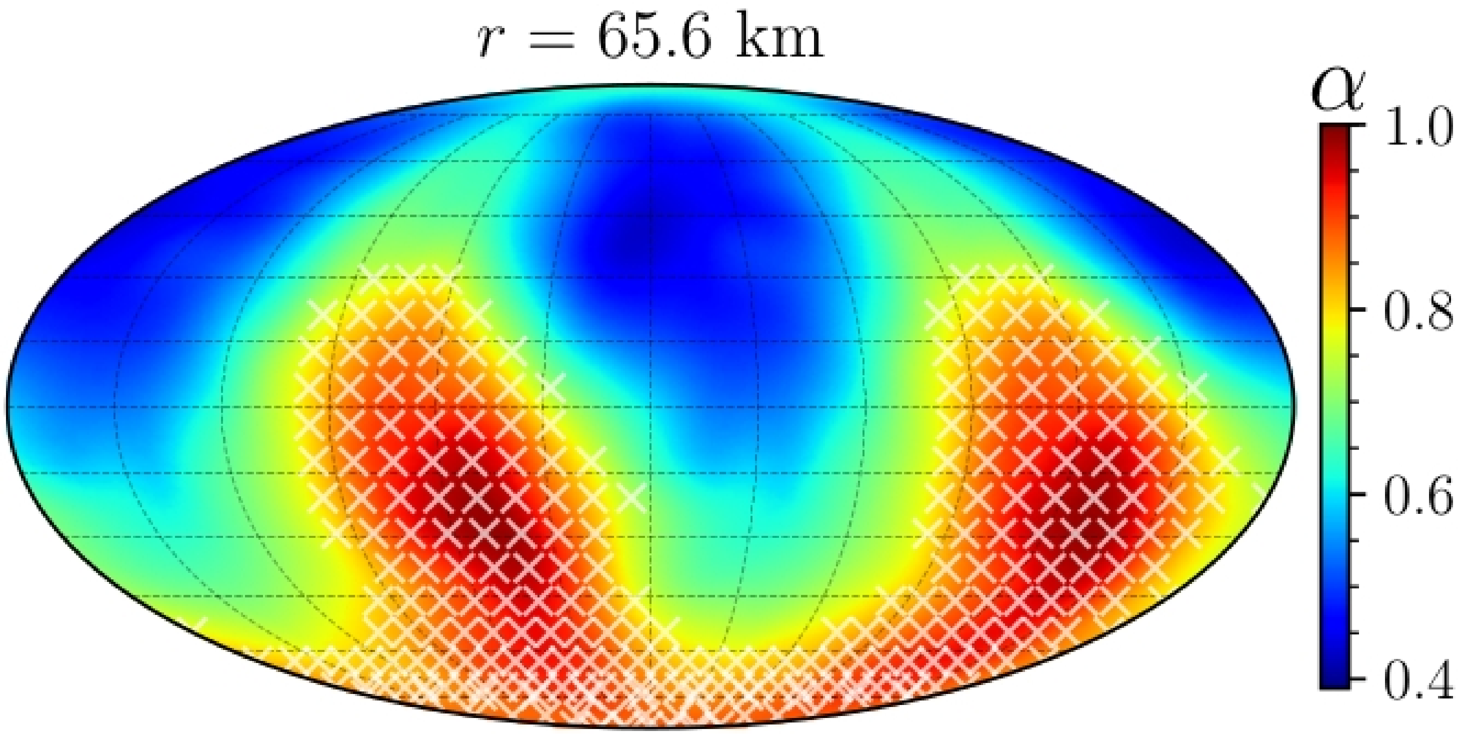
Fast Flavor Oscillations

- Fast Flavor Oscillations (FFO) were originally discovered by Sawyer PRD **72** 045003 (2005).
- A previous study did not find FFO in a 1D simulation but recently Abbar et al examined a 2D and 3D simulation.





Abbar et al, arXiv:1812.06883



- The Fast Flavor Instability occurs where the flux of antineutrinos is close to the neutrino flux.
  - globally more neutrinos than antineutrinos are emitted.
- This requires something like the LESA.

Where next?

- Is throwing more silicon at the QKEs the only way to make progress?

- Are there approximations that make the problem easier?
  - Do we need to solve the QKEs everywhere?

- Are there ideas we can steal from other fields (such as condensed matter, quantum optics)?

Summary

- Supernova neutrinos are a challenging problem.
- We know the equations we have to solve and, IMHO, I think we have a good sense of their difficulties.
- Numerical issues are significant obstacles.
- Over the next few years expect significant steps.