Linear Analysis of Fast Pairwise Neutrino Oscillations In Core-Collapse Supernovae Based on Realistic Data

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第31回 理論懇シンポジウム 宇宙物理の標準理論：未来へ向けての再考

Introduction

Fate of a star depends on its **Mass**

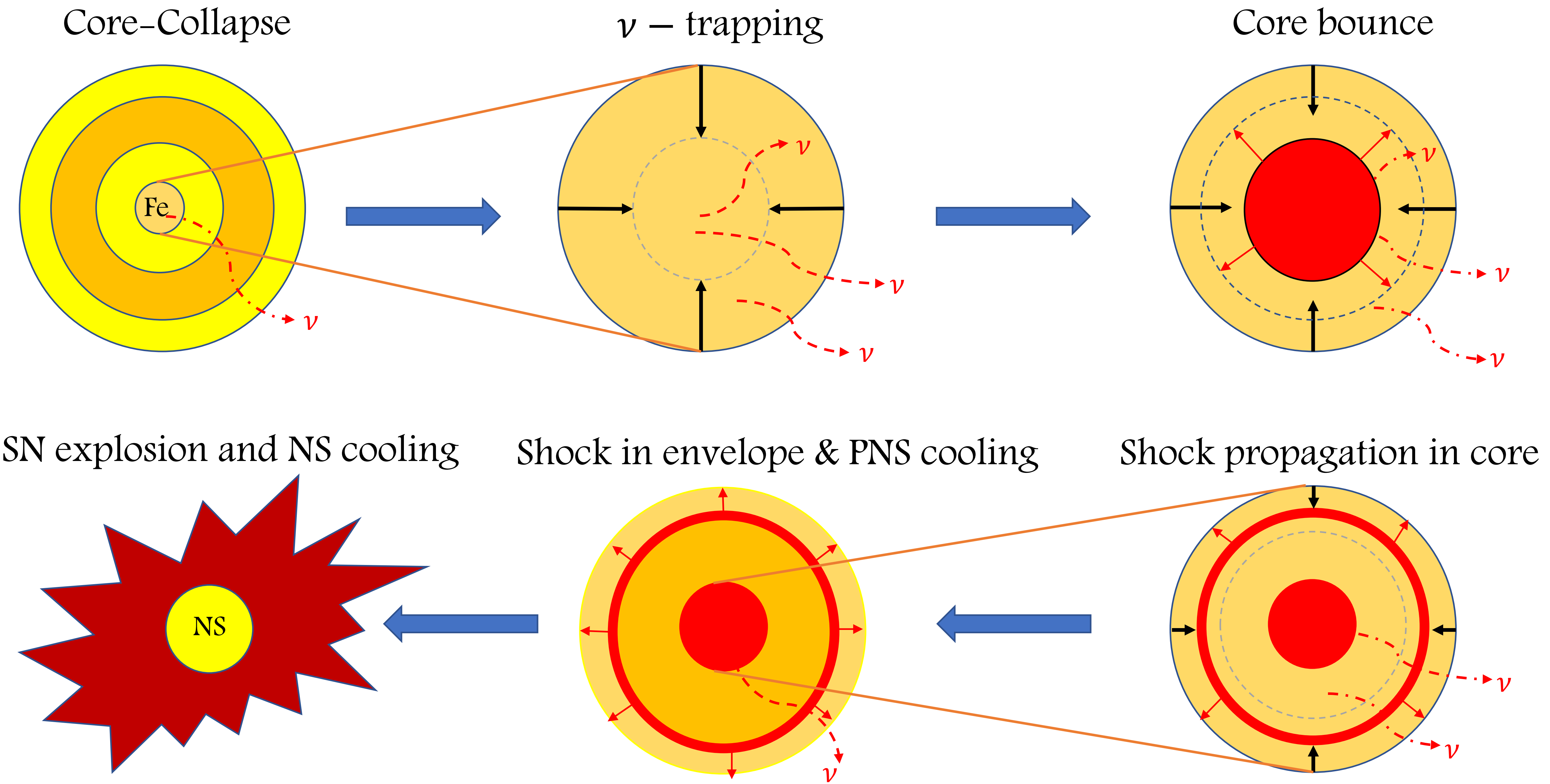
SN 1987A

$M_{star} \gtrsim 8\ M_{sun}$

Core–Collapse

Supernovae

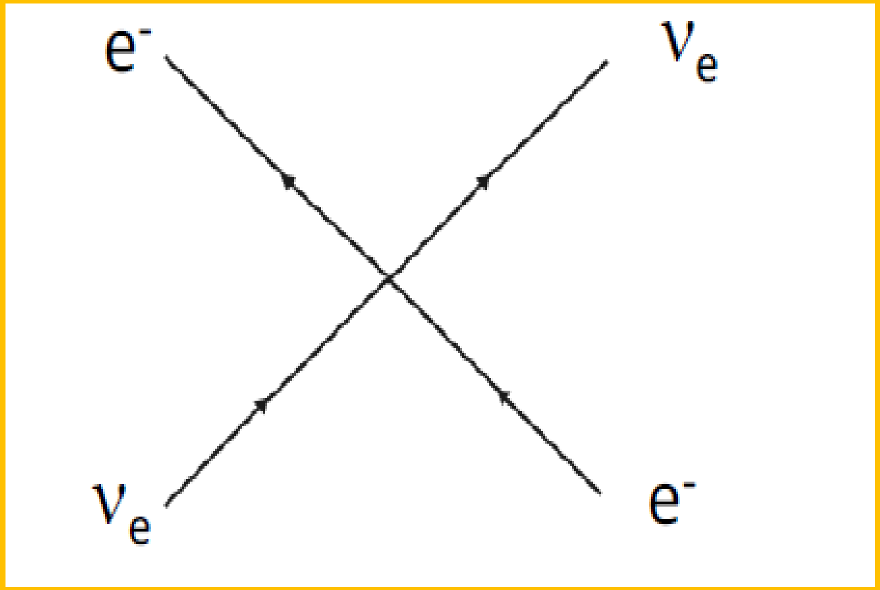
Cassiopeia A


Core-Collapse
Fe
ν
ν − trapping
ν
ν
ν
Core bounce
ν
ν
ν
SN explosion and NS cooling
NS
Shock in envelope & PNS cooling
ν
Shock propagation in core
ν
ν

Why neutrinos are important ?

- ✓ almost all of the binding energy of NS liberated in the gravitational collapse is emitted in the form of neutrinos and the kinetic energy of matter in the supernova explosion is just 1% of this energy.

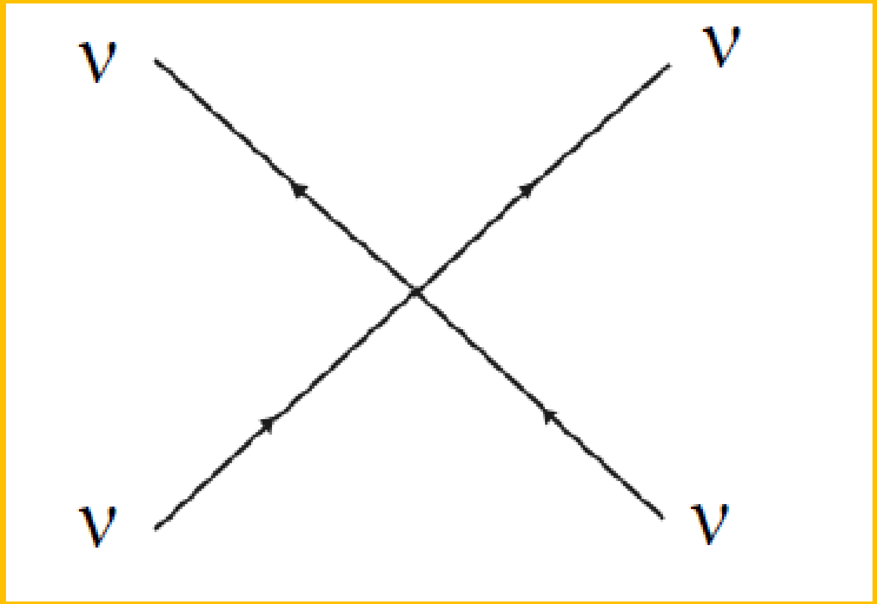
- ✓ a fraction of the electron-type neutrinos and anti-neutrinos are re-absorbed by the matter between the shock front and the so-called gained radius and deposit their energy to push the stagnated shock again.



$r >\sim 10^3$ km

Matter effect

Wolfenstein PRD 17, 2369, 1978



$r \sim 10^2$ km

$\nu - \nu$ self interaction

Duan et al., PRD 74, 105014, 2006

What fast pairwise means?

- ✓ Collective pair conversion $\nu_e\bar{\nu}_e \rightleftarrows \nu_x\bar{\nu}_x$ by forward scattering maybe generic for SN neutrino transport

- ✓ Depending on the angular intensity, this rate is “Fast”

Motivation

✓ Problems remaining;

- No successful explosion model for CCSNe

and

- Collective neutrino oscillation has been ignored

✓ Our goal;

Study the collective neutrino oscillations quantitatively.

Basic Equations and Formulae

Equation of Motion:

$$(\partial_t + v.\nabla_r)\rho = i[\rho, H]$$

$$\rho = \frac{f\upsilon_e + f\upsilon_x}{2} + \frac{f\upsilon_e - f\upsilon_x}{2}\begin{pmatrix} s & S \\ S^* & -s \end{pmatrix},$$

$$H = \frac{M^2}{2E} + v^\mu \Lambda_\mu \frac{1}{2}\sigma_3 + \sqrt{2}G_F \int d\Gamma' v^\mu v'_\mu \rho'$$

Kinetic Hamiltonian — Vacuum Oscillation

Matter Hamiltonian — MSW Oscillation

Neutrino-Neutrino Hamiltonian — Collective Oscillation

M^2: Mass-squared matrix

v^μ : (1,**v**)

Λ^μ : $\sqrt{2}G_F(n_e - n_{e^+})u^\mu$

$d\Gamma'$ =d**v**'/4π

Basic Equations and Formulae

Linearized Equation of Motion:

$$i(\partial t + v.\nabla_r)S_v = v^\mu(\Lambda_\mu + \Phi_\mu)S_v - \int \frac{d\mathbf{v}'}{4\pi} v^\mu v'_\mu G_{v'} S_{v'}$$

$$G_v = \sqrt{2} G_F \int_0^\infty \frac{dE E^2}{2\pi^2}\left[f_{\nu_e}(E,\mathrm{v}) - f_{\bar{\nu}_e}(E,\mathrm{v})\right]$$

$$\Phi^\mu \equiv \frac{d\mathbf{v}}{4\pi} G_v v^\mu$$

Assuming the solutions in the form of ;

$$S_v(t,r) = Q_v(\Omega, K)e^{-i(\Omega t - K.r)}$$

$$v^\mu k_\mu Q_v = a^\mu$$

where ; $a^\mu \equiv -\int \frac{d\mathbf{v}'}{4\pi} v^\mu v'_\mu G_{v'} Q_{v'}$

$k^\mu = K^\mu - \Lambda^\mu - \Phi^\mu$ with $k^\mu = (\omega, \mathbf{k})$

$$\Pi^{\mu\nu}(\omega, \mathbf{k})\, a_\nu = 0$$

Polarization tensor $\Pi^{\mu\nu} = \eta^{\mu\nu} + \int \frac{dV}{4\pi} G_V \frac{v^\mu v^\nu}{\omega - V.k}$

$$\mathrm{D}(\omega, \mathbf{k}) \equiv \det[\Pi] = 0$$

Background Numerical Model

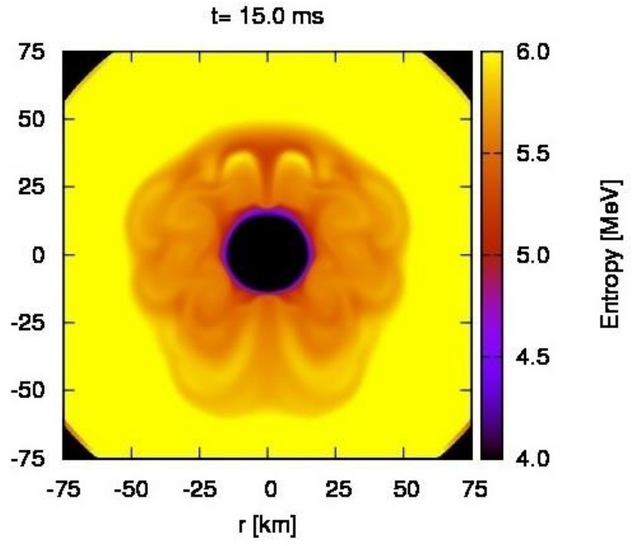
✓ Results of the realistic 2D simulations on the K-Supercomputer Nagakura et al., ApJ 854, 136 (2018)

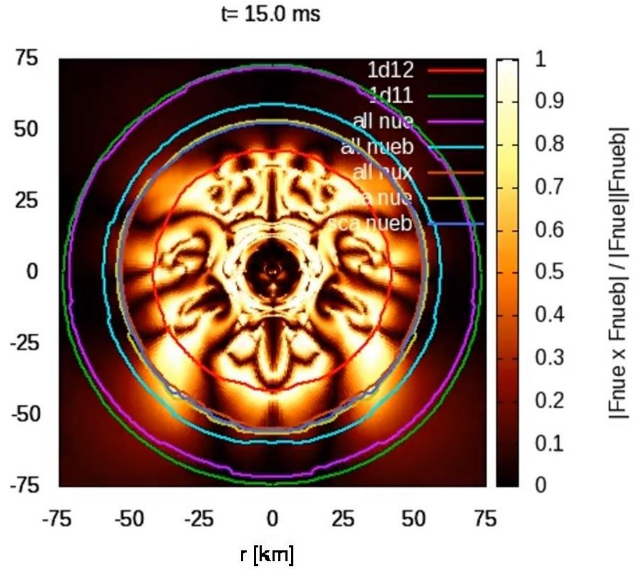
✓ For non-rotating progenitor model of $M_{star}=11.2\ M_{\odot}$

Woosley et al., Reviews of Modern Physics 74, 1015 (2002)

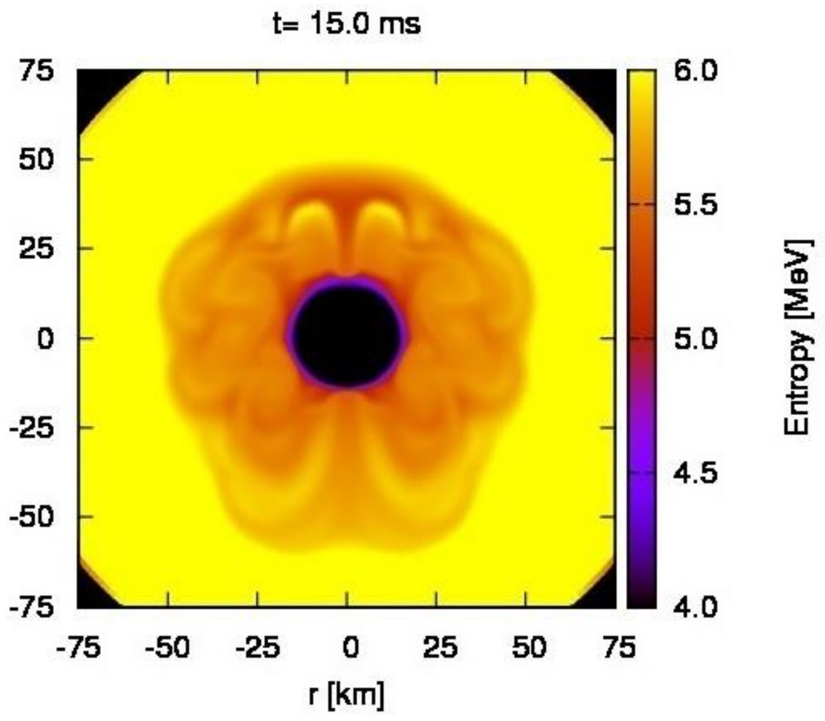
✓With the Boltzmann equation for neutrino transport being solved and special relativistic effect with a two energy grid technique. Nagakura et al., ApJS 214,16 (2014)

✓ Newtonian hydrodynamical equations & the Poisson equation for self-gravity were solved simultaneously.

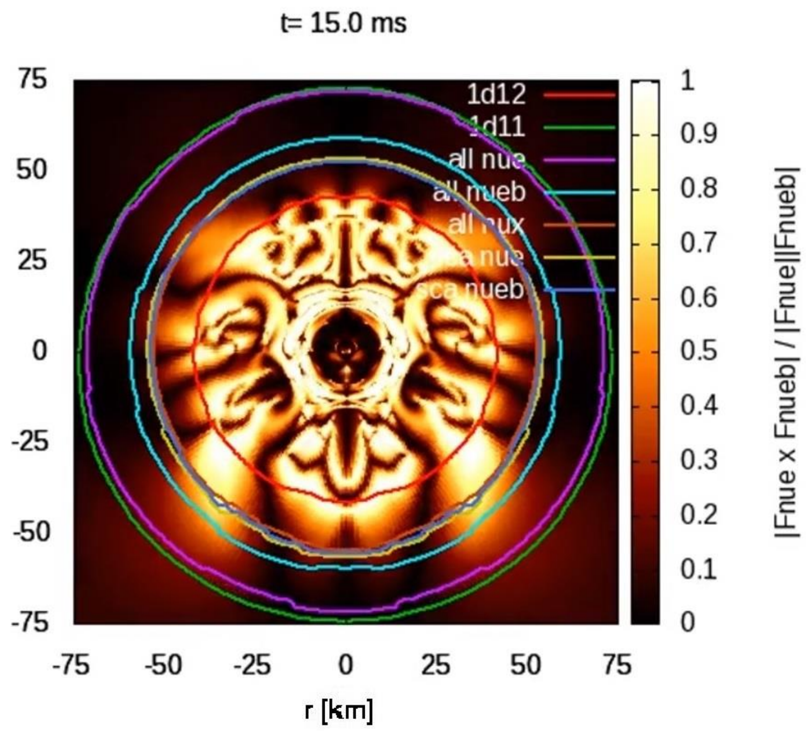




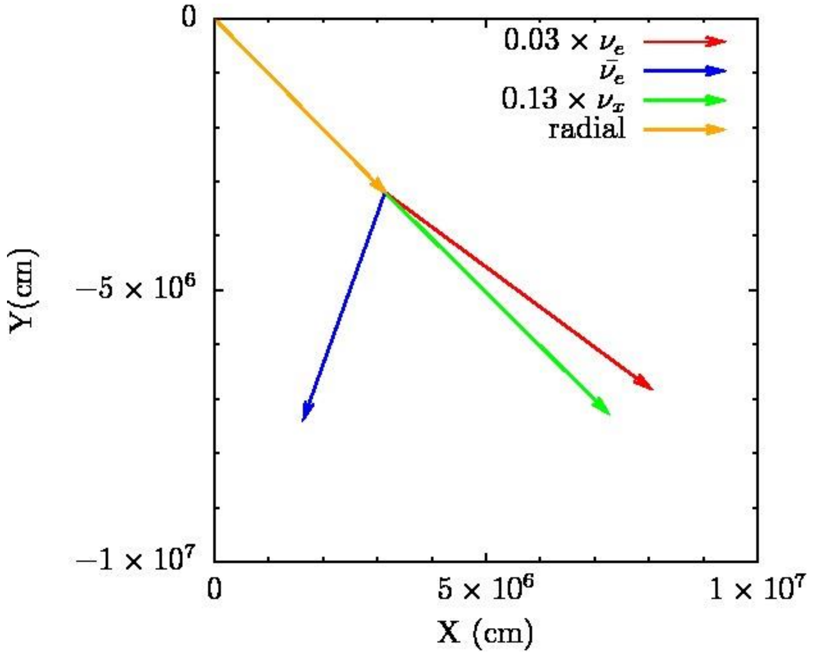
Method



Entropy distributions at the central part of the core



Outer product of ν_e and $\bar{\nu}_e$

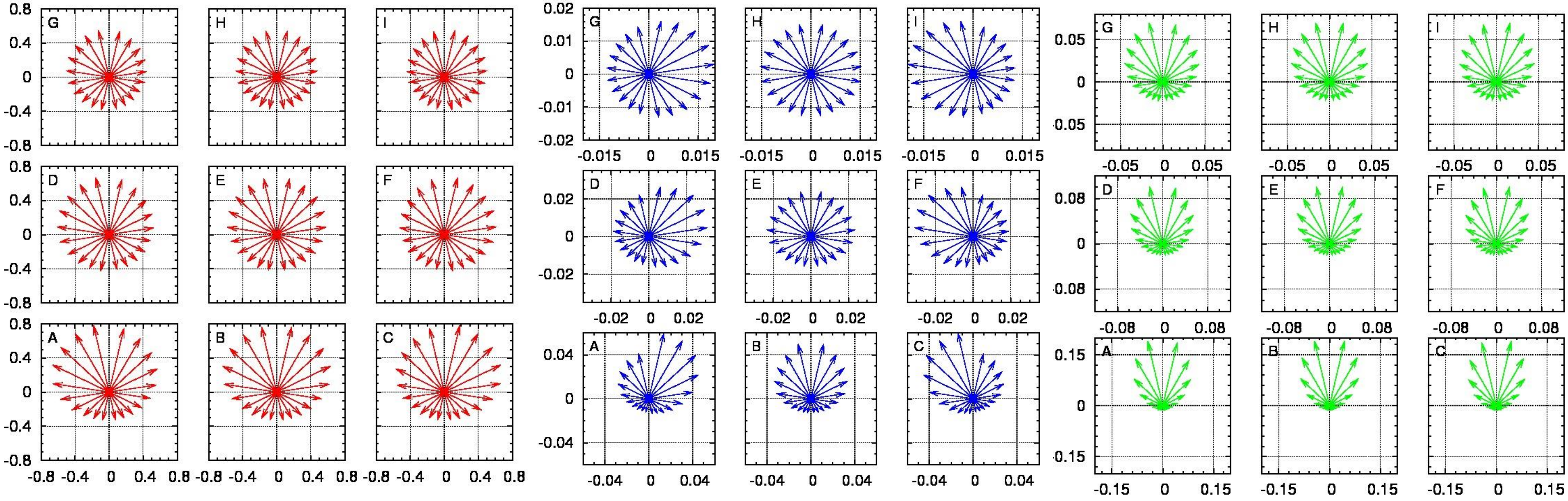


Neutrino fluxes with compared to the radial direction at r= 44.8 km

Method

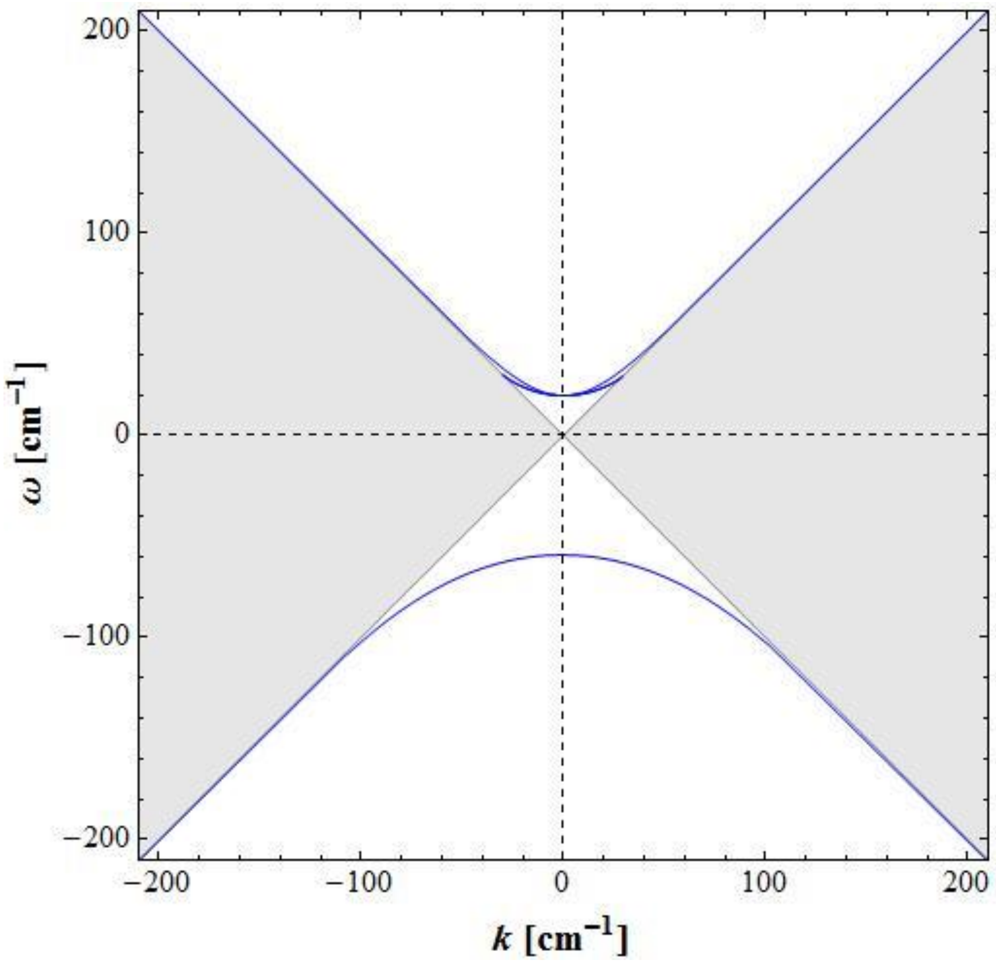
Angular distributions of ν_e, $\bar{\nu}_e$ & ν_x in meridian section at different azimuthal axis.

r= 44.8 km and t= 15.0 ms post bounce

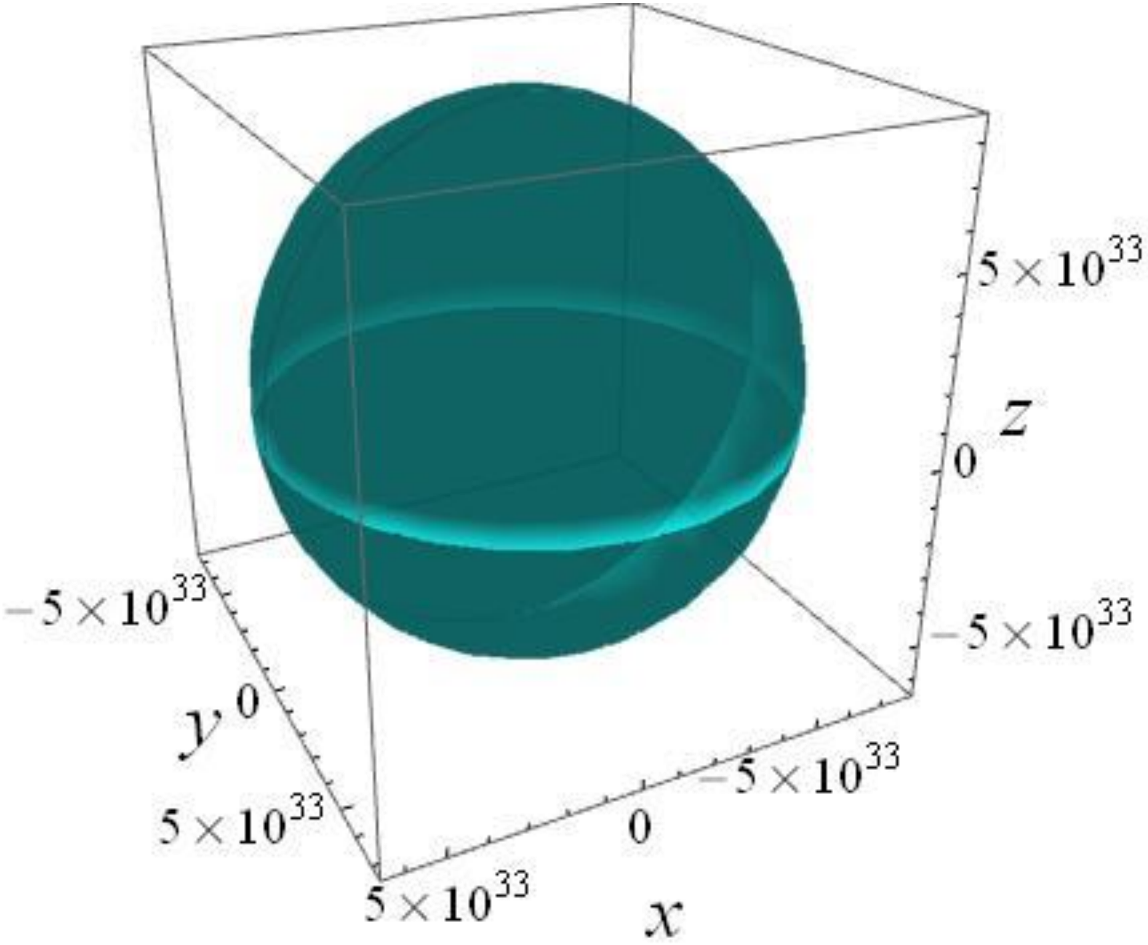


Results

Dispersion relation



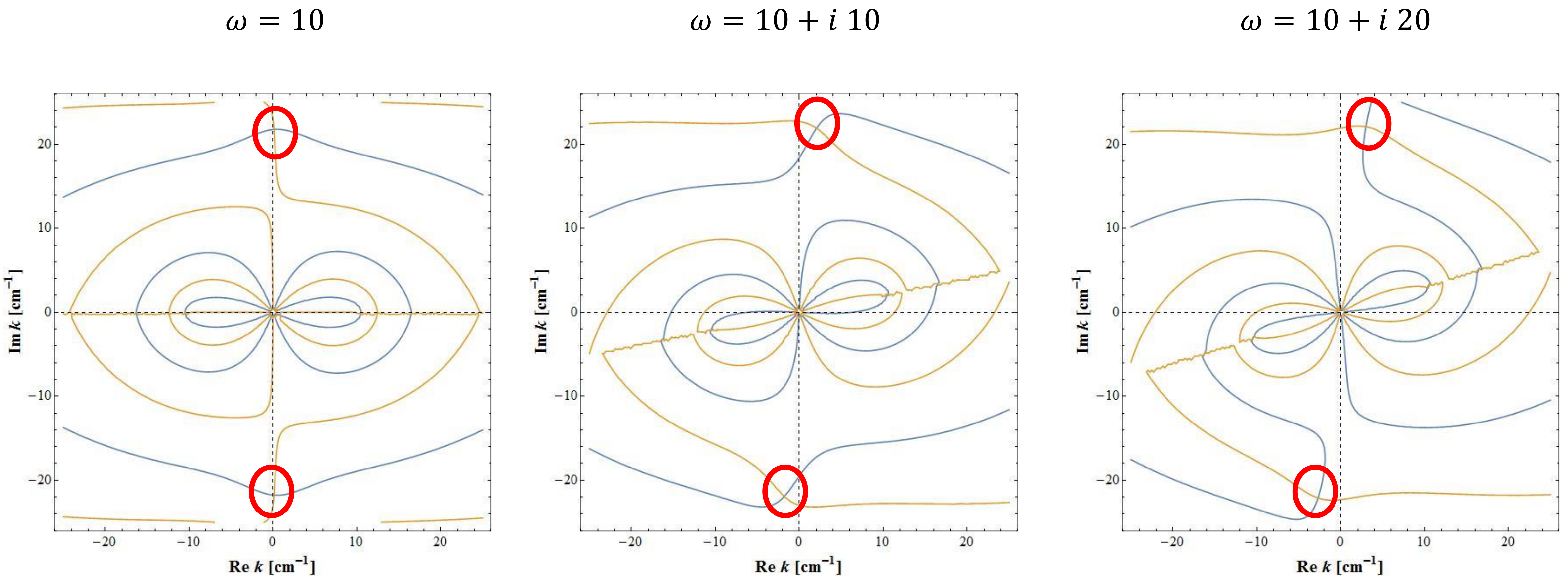
Rendering of the neutrino distribution



$\det[\Pi] = 0$

Real part of $\det \Pi = 0$

Imaginary part of $\det \Pi = 0$

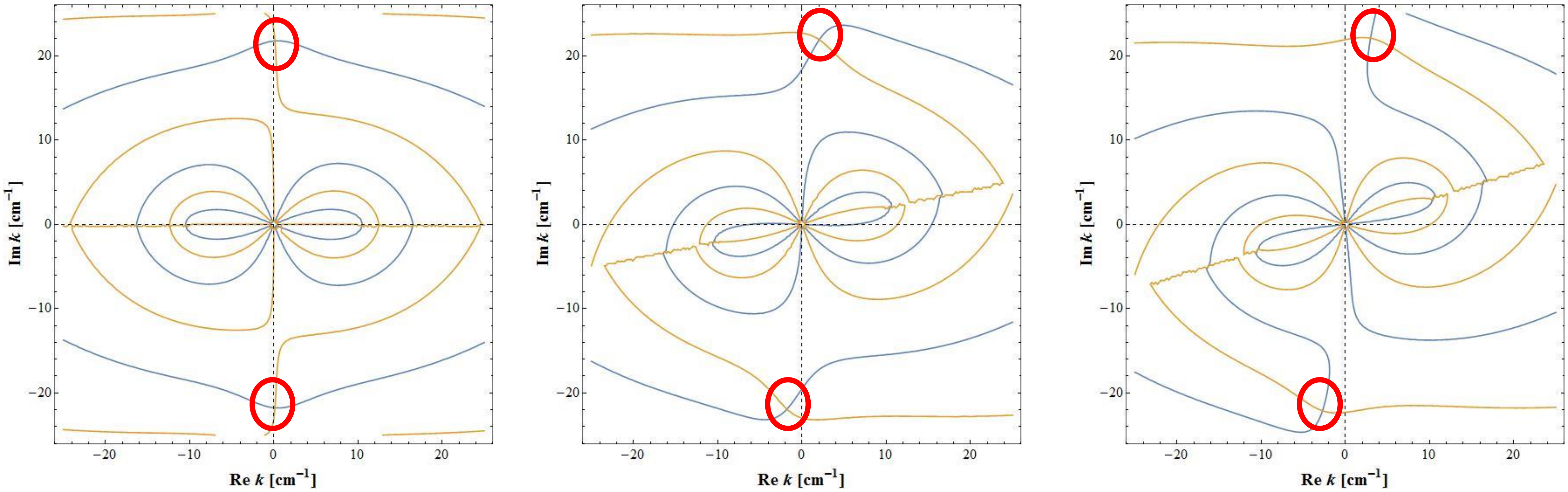


$\det[\Pi] = 0$

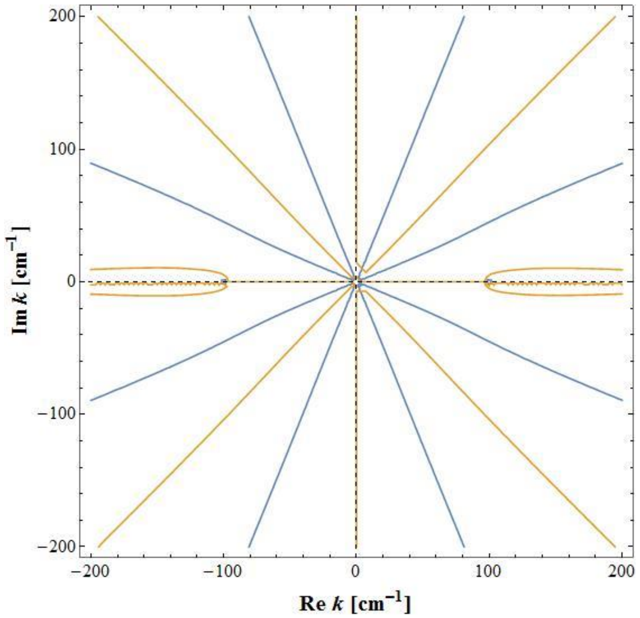
Real part of $\det \Pi = 0$

Imaginary part of $\det \Pi = 0$

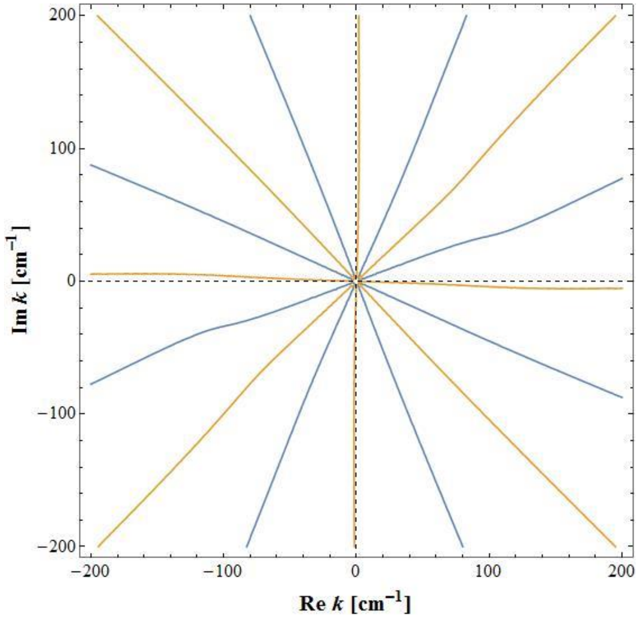
$\omega = 10$ $\omega = 10 + i\,10$ $\omega = 10 + i\,20$



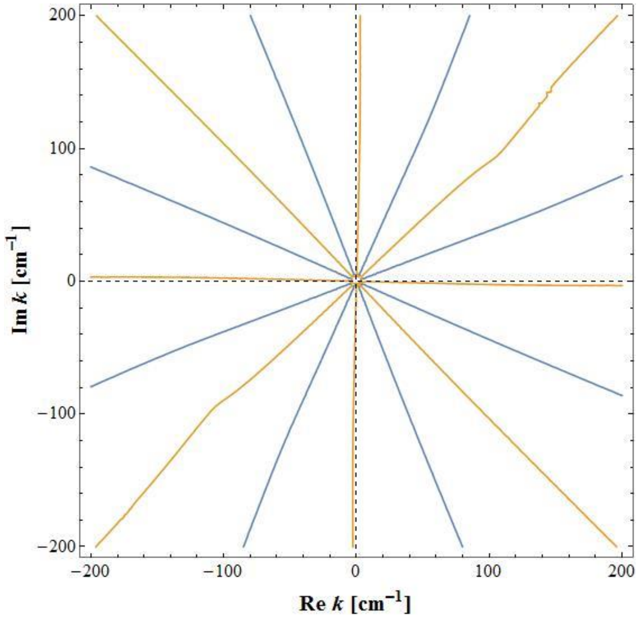
NO crossing in Re k, Means NO instability is expected



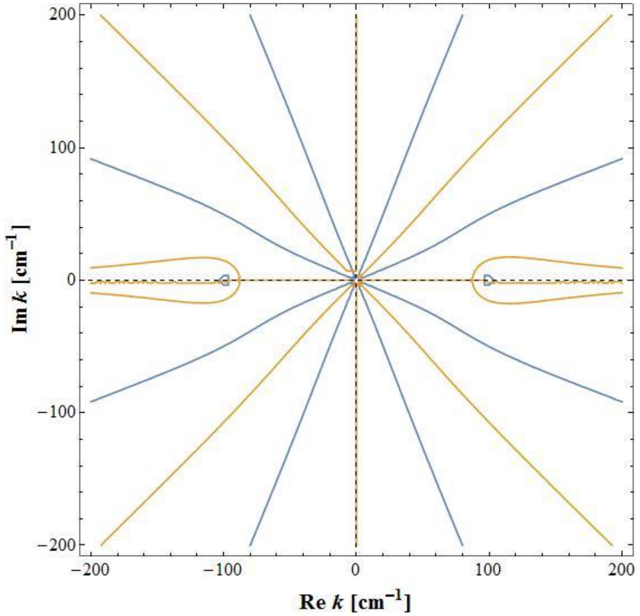
$\omega = 100$



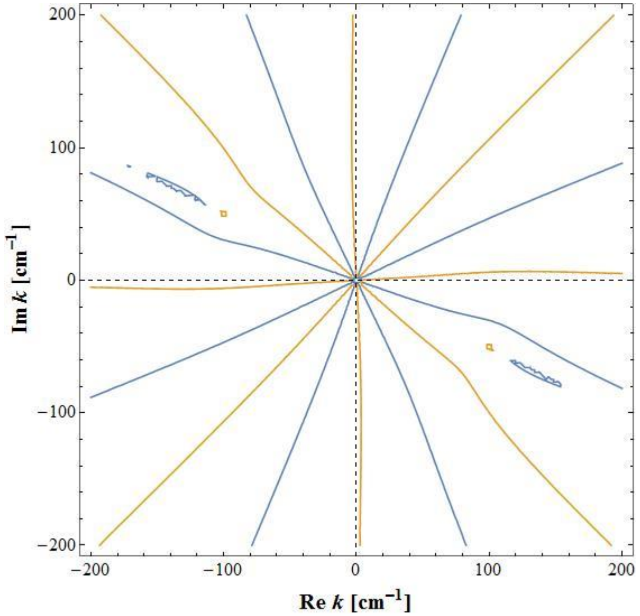
$\omega = 100 + i\,50$



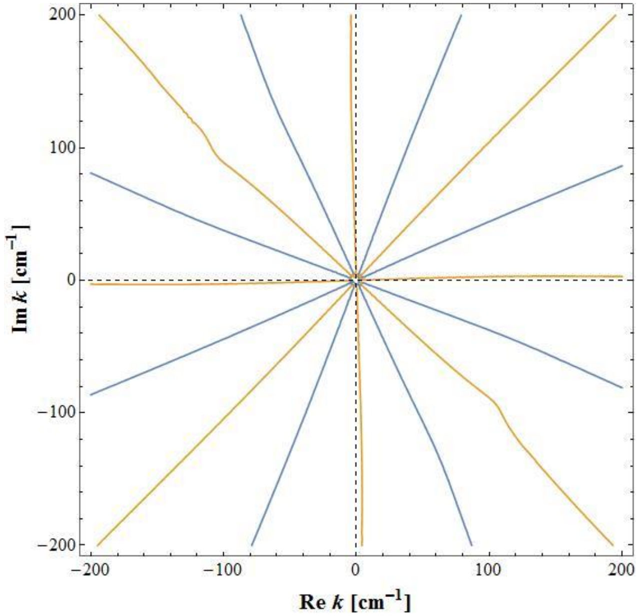
$\omega = 100 + i\,100$



$\omega = -100$



$\omega = -100 + i\,50$



$\omega = -100 + i\,50$

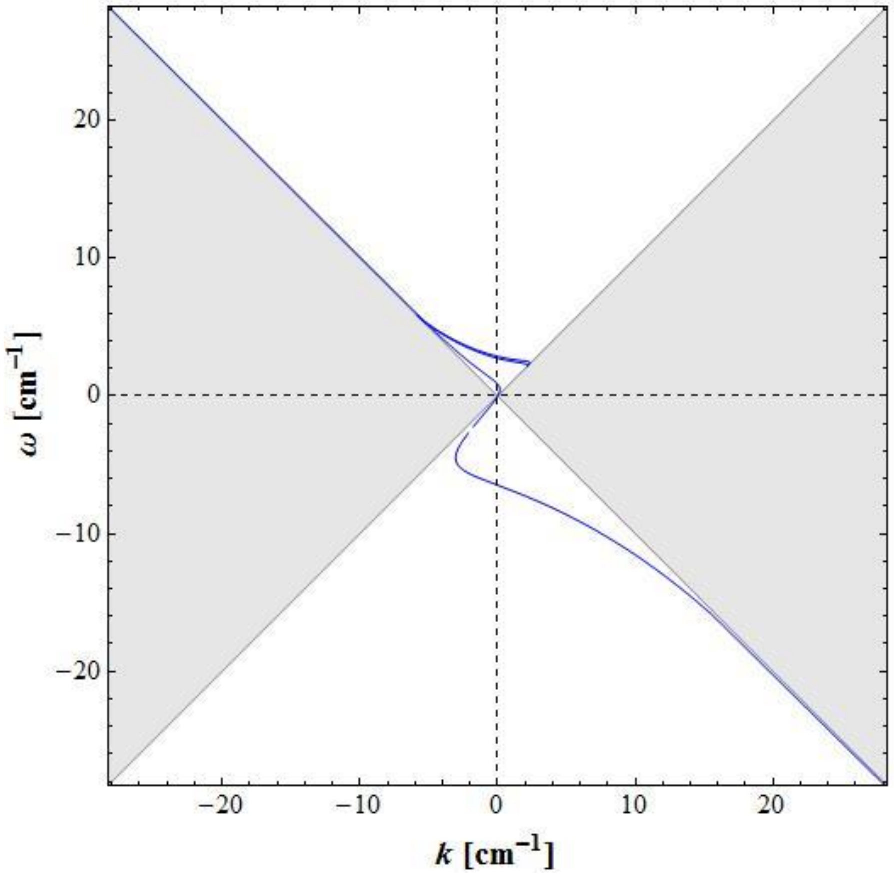
No oscillation so far ….

No oscillation so far ….

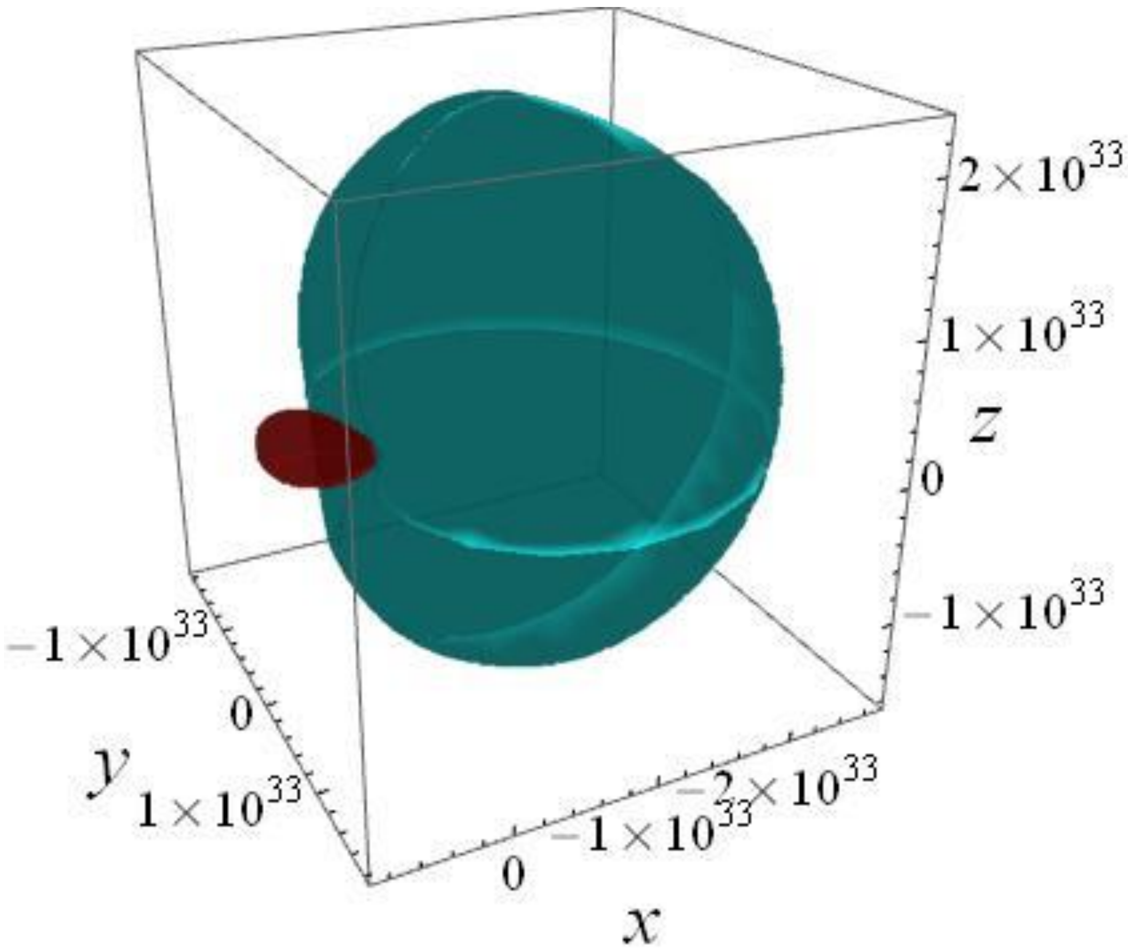
How & under what condition can we obtain the oscillation?

Modified data

Dispersion relation



Rendering of the neutrino distribution

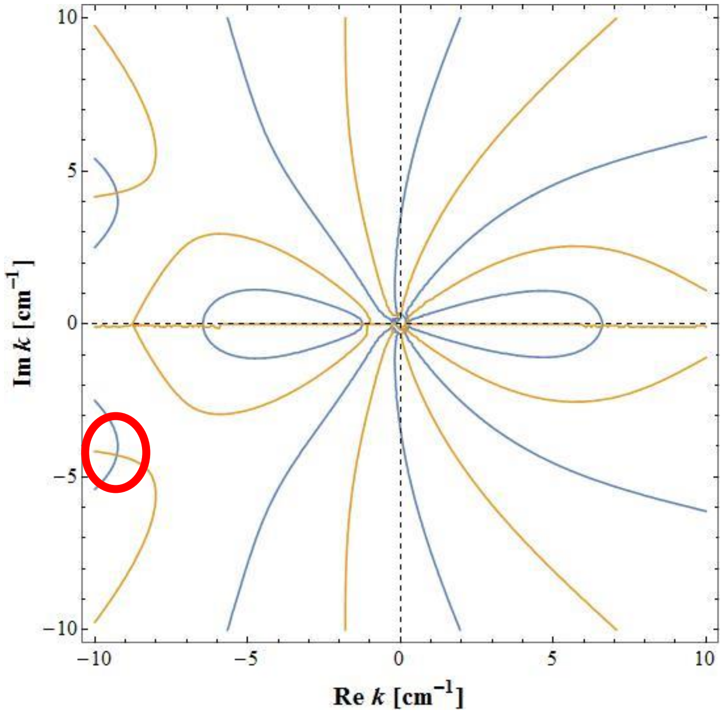


$\det[\Pi] = 0$

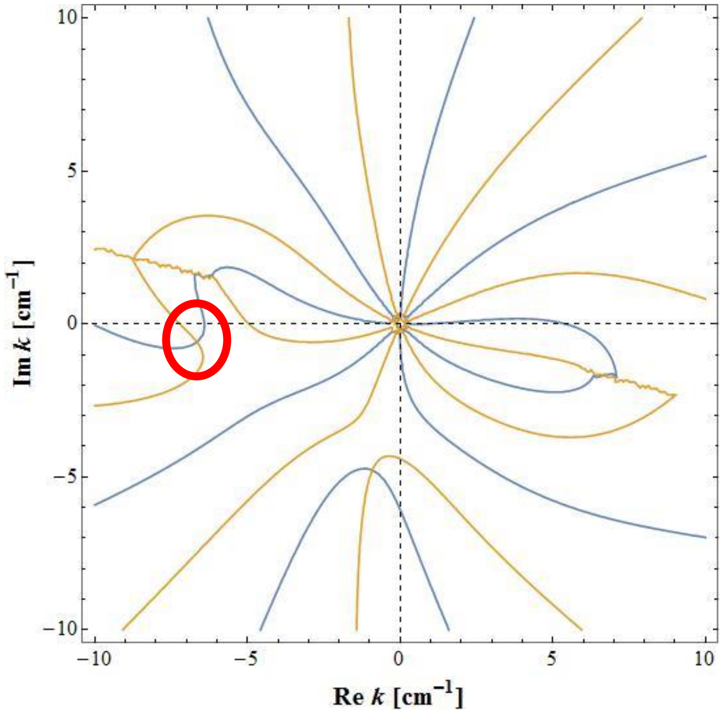
Real part of $\det \Pi = 0$

Imaginary part of $\det \Pi = 0$

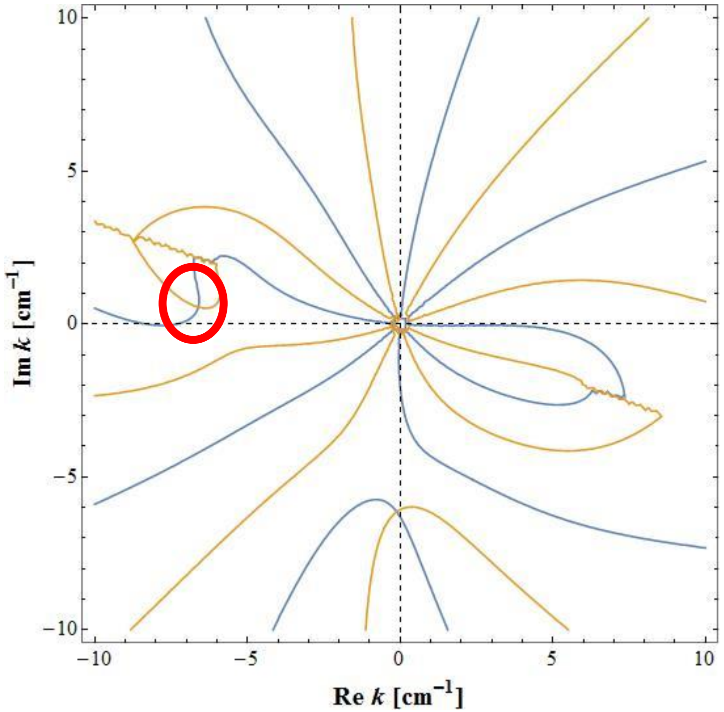
$\omega = -7$



$\omega = -7 + i\ 1.5$



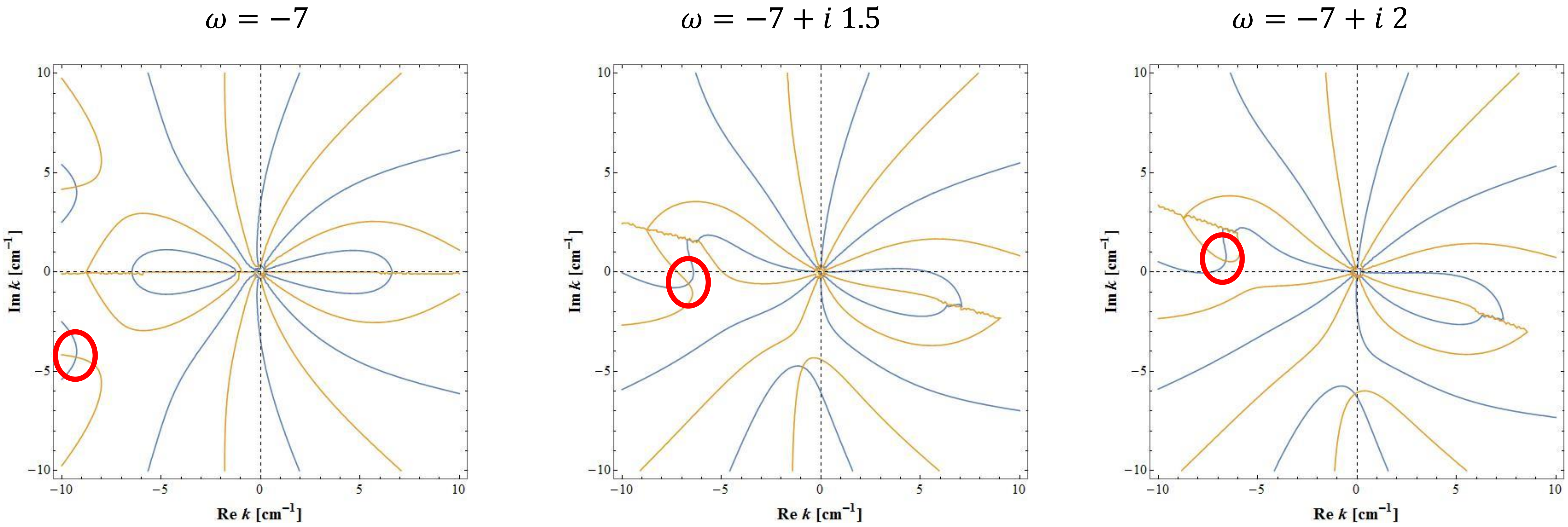
$\omega = -7 + i\ 2$



$\det[\Pi] = 0$

Real part of $\det \Pi = 0$

Imaginary part of $\det \Pi = 0$



There **is** crossing in Re k, Means; instability **is** expected

Summary and future works

- ✓Collective neutrino oscillations in core-collapse supernovae has been studied quantitatively.
- ✓We confirm that there is no sign of instability which leads to the conversion in case of the realistic data analysis.
- ✓The possible oscillation conditions in different radii and time steps has been studied.
- ✓This method might be applicable to other astrophysical objects such as NS-mergers disks, etc. We plan to investigate the conversion possibilities in these objects in near future.