Linear Analysis of Fast-Pairwise collective neutrino oscillations in Core-Collapse Supernovae Based on the results of realistic Boltzmann Simulations

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Delfan Azari et al. (arXiv: 1902.07467)

March 19-20 *RIKEN-RESCEU joint seminar 2019* The University of Tokyo

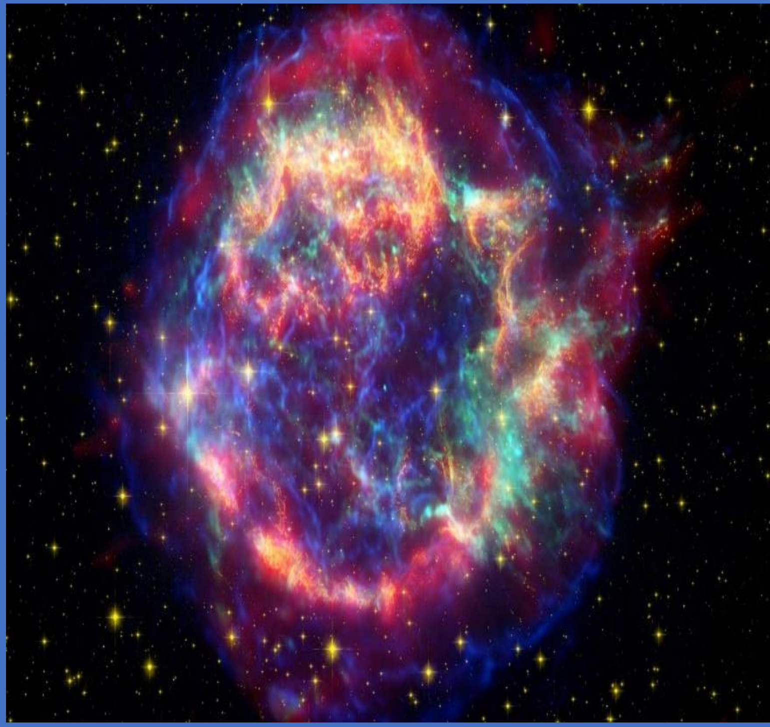
Fate of a star depends on its Mass

SN 1987A

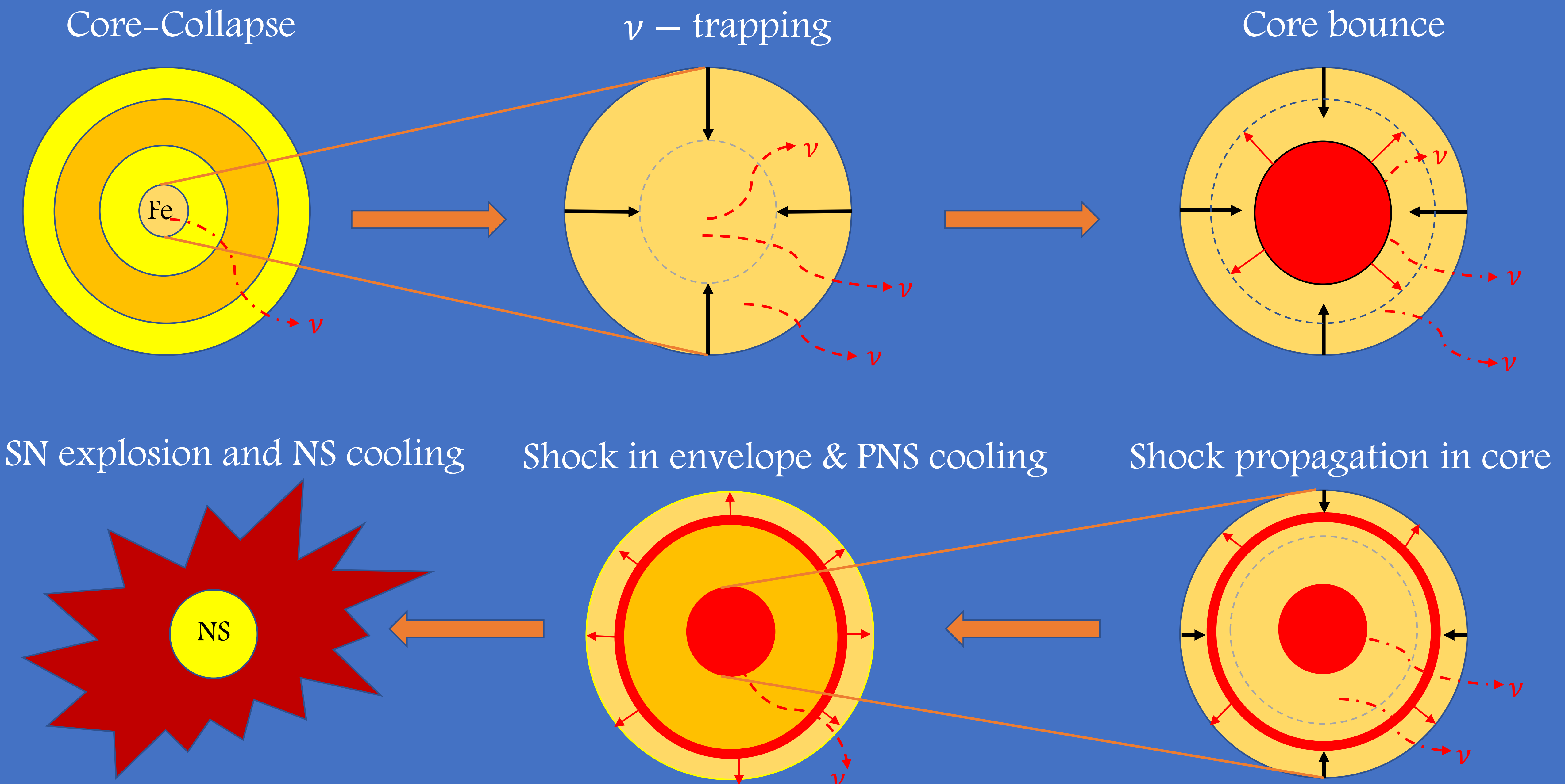
$$M_{star} \gtrsim 8\ M_{sun}$$

Core-Collapse

Supernovae



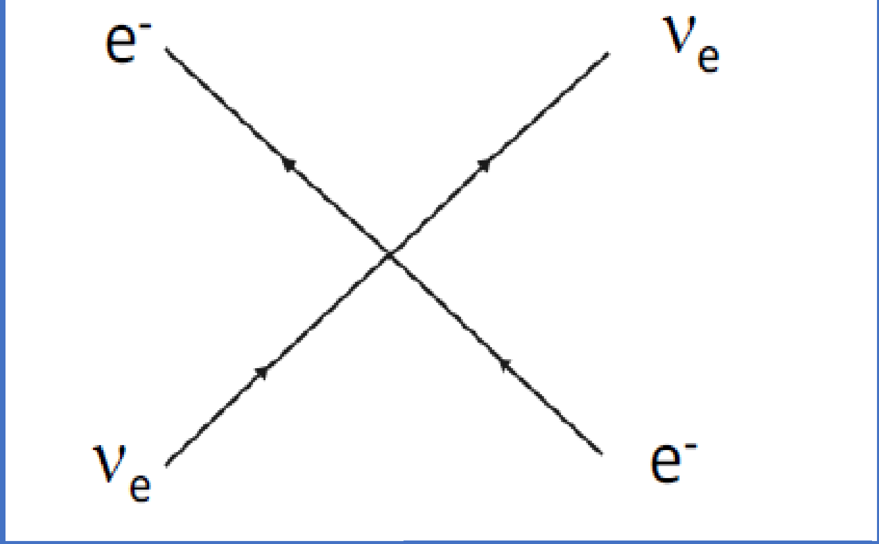
Cassiopeia A


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

Why neutrinos ?

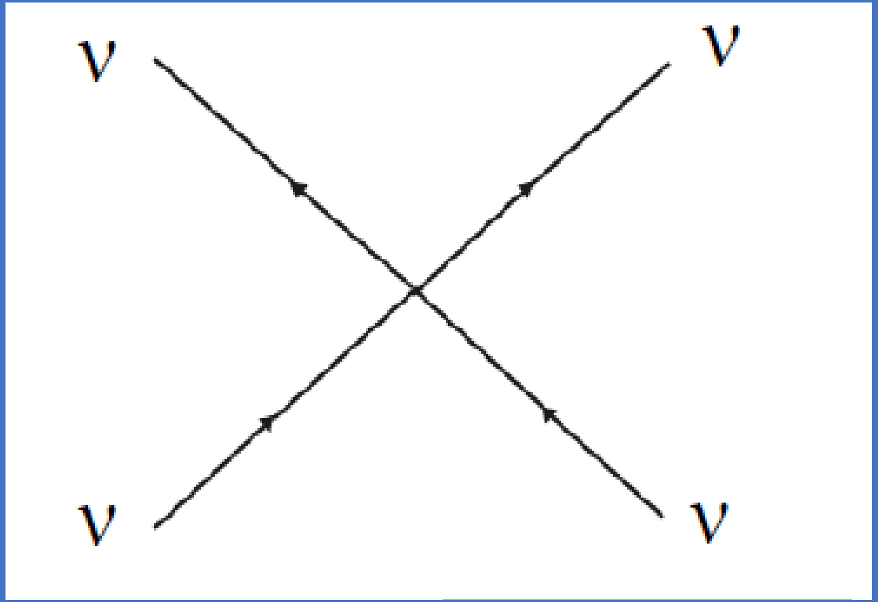
- ✓ almost all of the binding energy of NS liberated in the gravitational collapse is emitted in the form of neutrinos and the kinetic energy of matter in the supernova explosion is just 1% of this energy.

- ✓ In the $\nu -$ heating mechanism, a fraction of the electron-type neutrinos and anti-neutrinos are re-absorbed by the matter between the shock front and the so-called gain radius and deposit their energy to push the stagnated shock again.



Matter effect $r >\sim 10^3$ km

Wolfenstein PRD 17, 2369, 1978



$\nu - \nu$ self interaction $r \sim 10^2$ km

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

✓Why?

Because it is difficult !

Motivation

✓ Problems remaining;

- No successful explosion model for CCSNe

and

- Collective neutrino oscillation has been ignored

✓ Our goal;

Study the collective neutrino oscillations and see whether they effect the explosion mechanism or no

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:

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

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

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

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

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

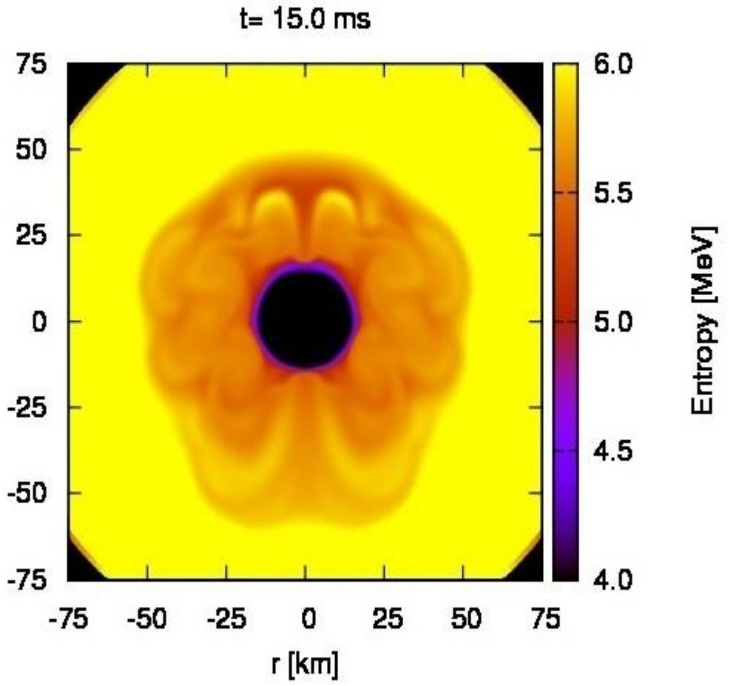
$$\Pi^{\mu\nu}(\omega, \mathbf{k}) \, a_\nu = 0$$

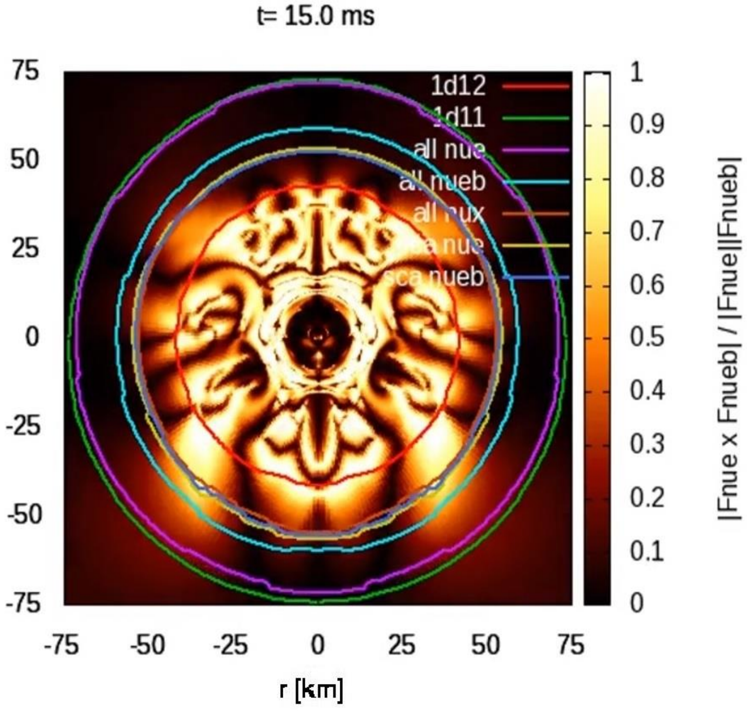
Polarization tensor $\Pi^{\mu\nu} = \eta^{\mu\nu} + \int \frac{dV}{4\pi} G_V \frac{v^\mu v^\nu}{\omega - V.k}$

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

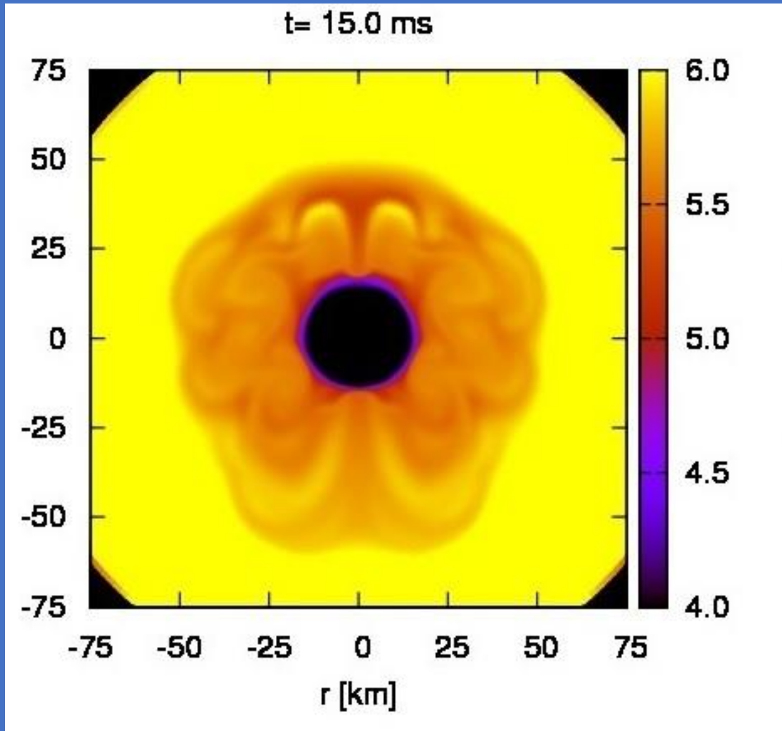
Background Numerical Model

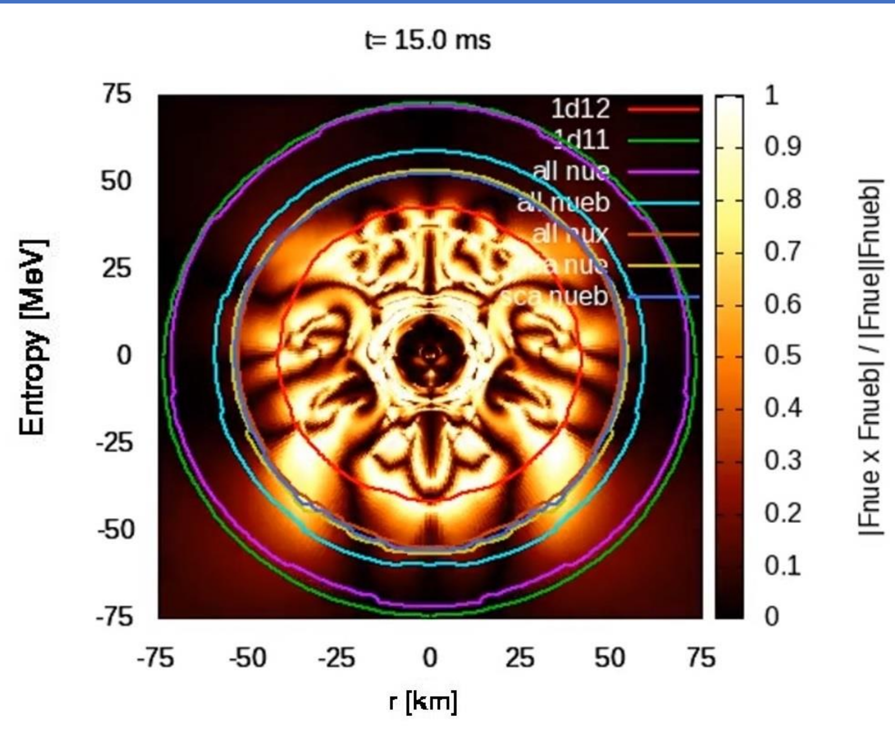
- ✓ Results of the realistic 2D simulations on the K-Supercomputer Nagakura et al., ApJ 854, 136 (2018)
- ✓ For non-rotating progenitor model of M_{star}=11.2 $M_{\odot}$
  Woosley et al., Reviews of Modern Physics 74, 1015 (2002)
- ✓ With the Boltzmann equation for neutrino transport being solved and 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.

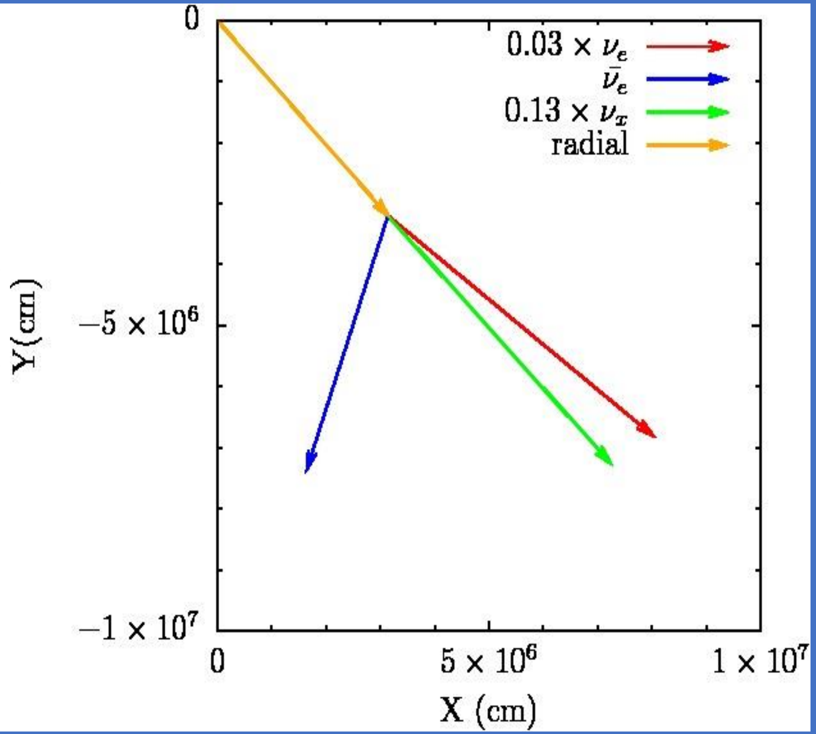




Method







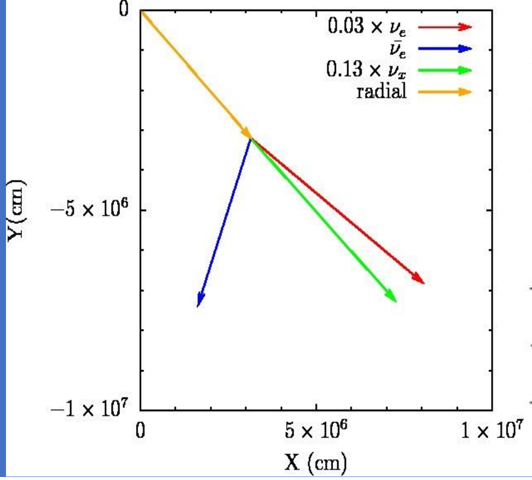
Entropy distributions at the central part of the core

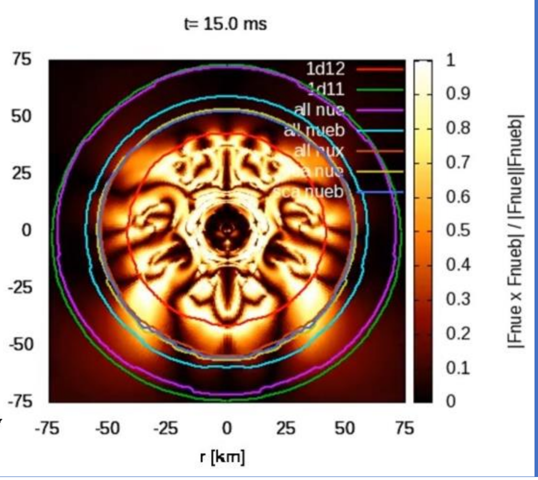
Outer product of ν_e and $\bar{\nu}_e$ (Misalignment between ν_e and $\bar{\nu}_e$)

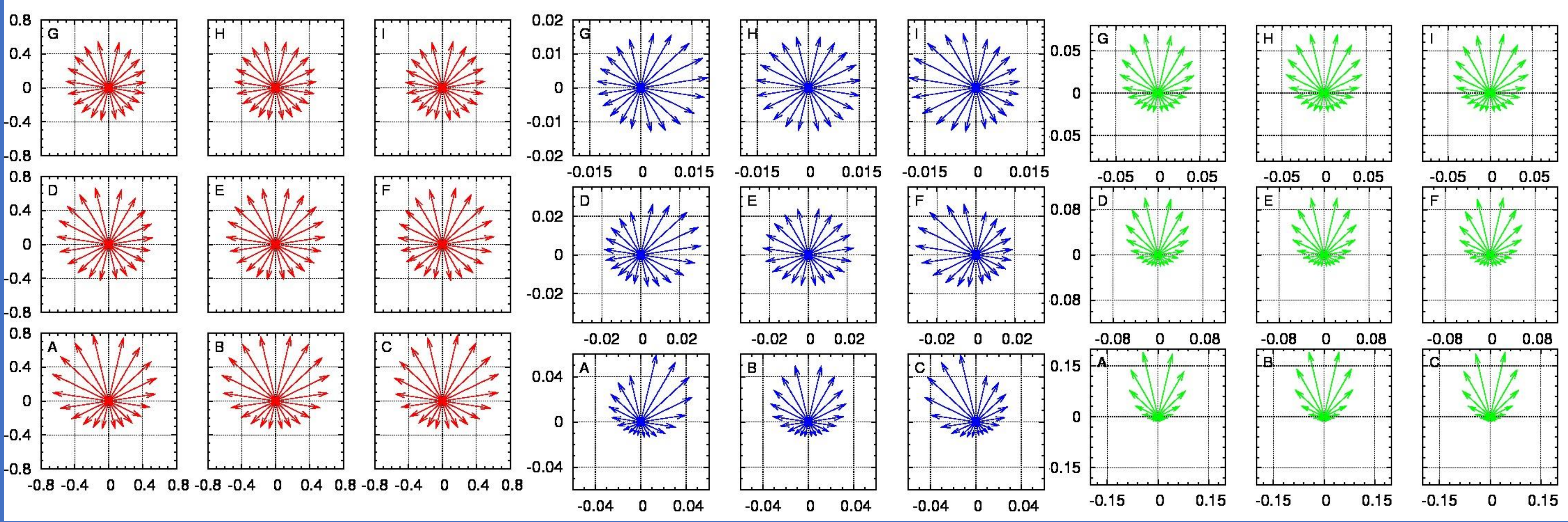
Energy integrated of fluxes of different neutrinos at the radial point at r= 44.8 km

Method

r= 44.8 km and t= 15.0 ms post bounce



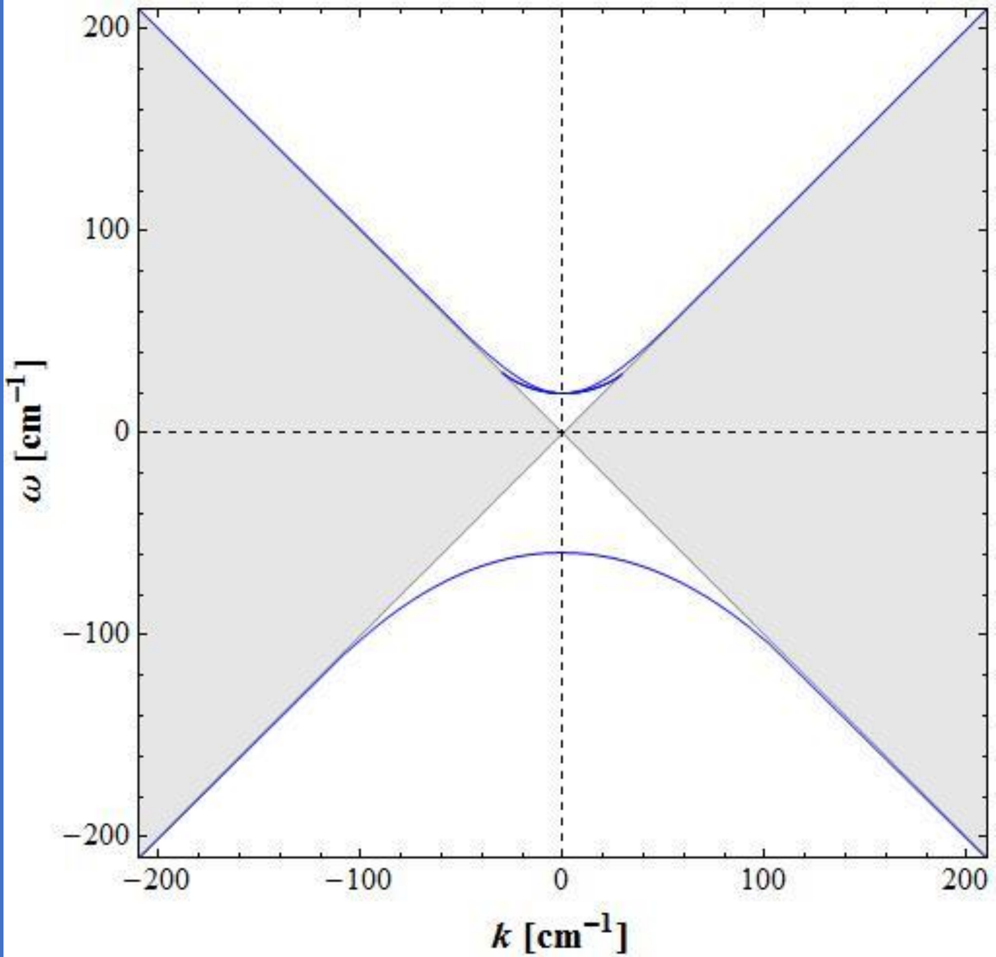




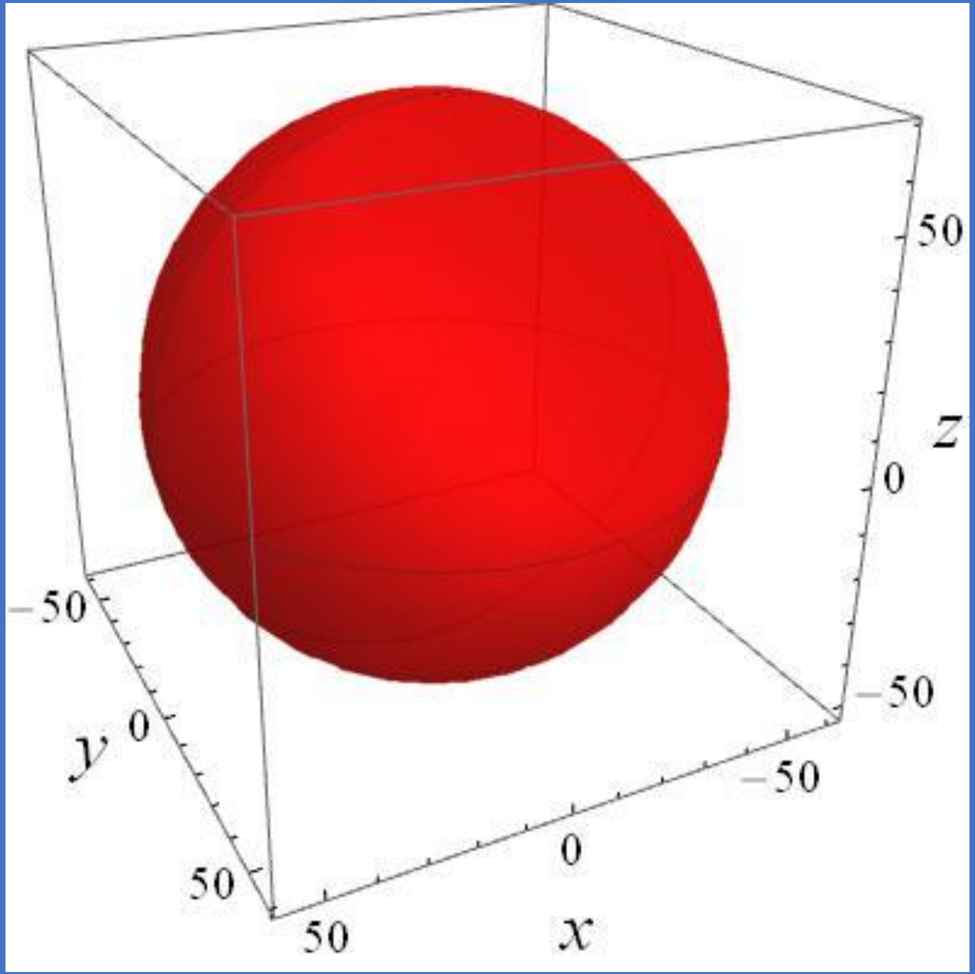
Angular distributions of ν_e, $\bar{\nu}_e$ & ν_x in meridian section at different azimuthal axis.

Results – Realistic data

Dispersion relation



Rendering of the neutrino distribution

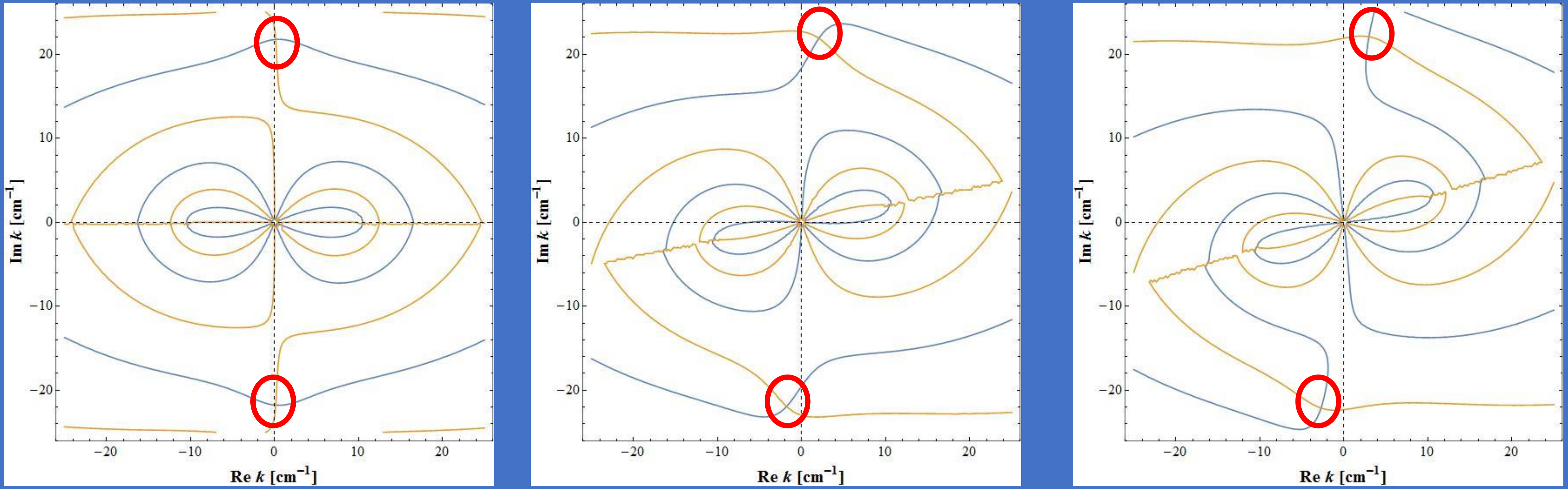


$\det[\Pi] = 0$

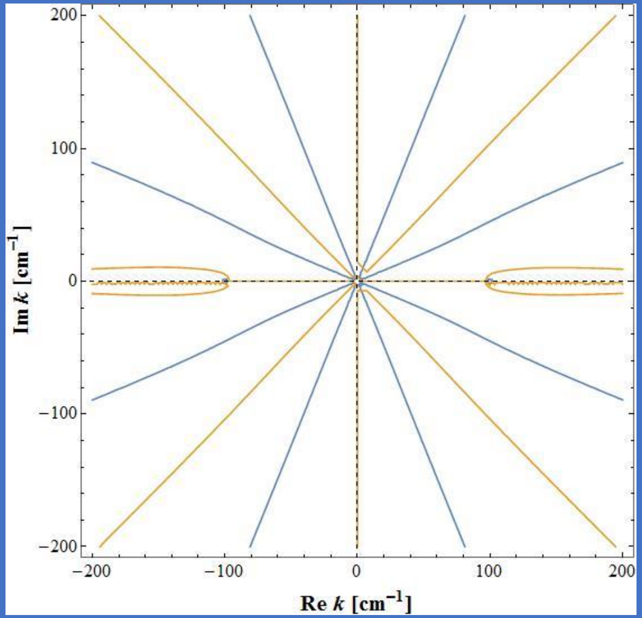
Real part of $\det \Pi = 0$

Imaginary part of $\det \Pi = 0$

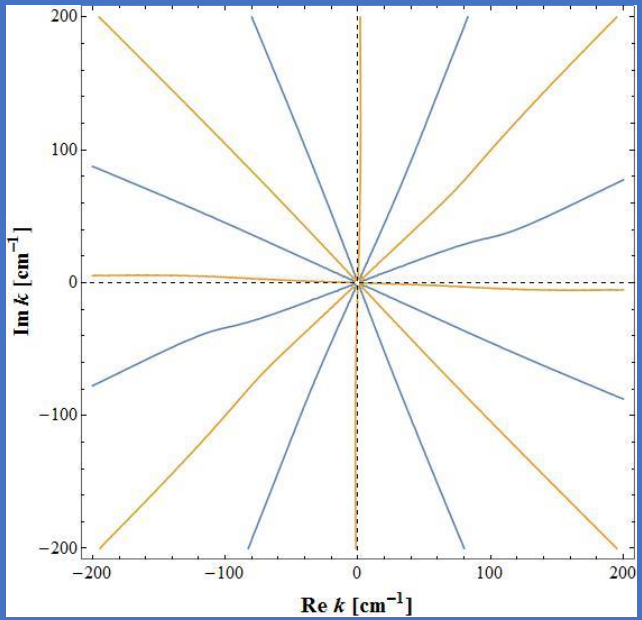
$\omega = 10$ $\qquad$ $\omega = 10 + i\,10$ $\qquad$ $\omega = 10 + i\,20$



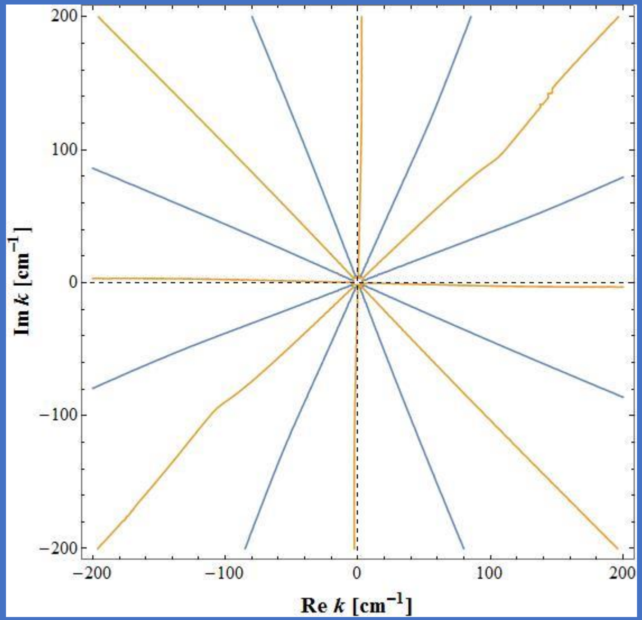
NO crossing in Re k, Means NO instability is expected



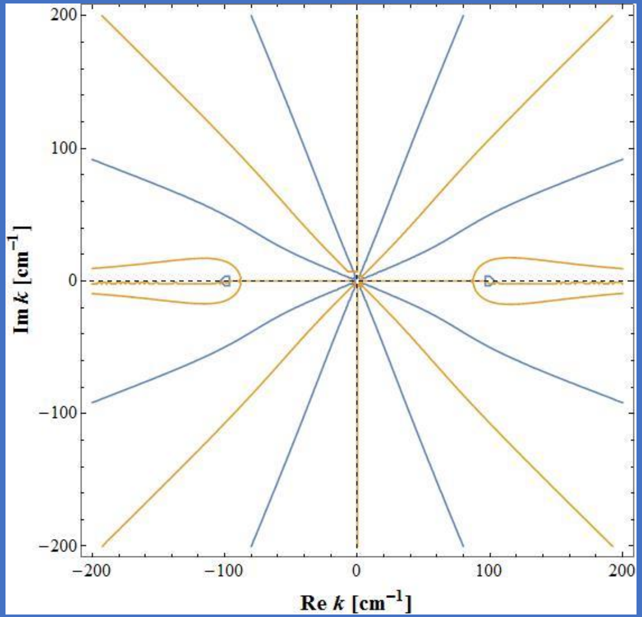
$\omega = 100$



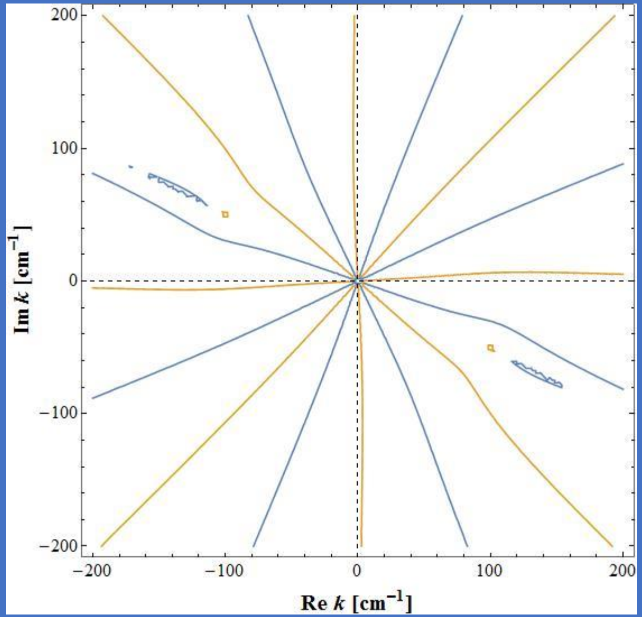
$\omega = 100 + i\,50$



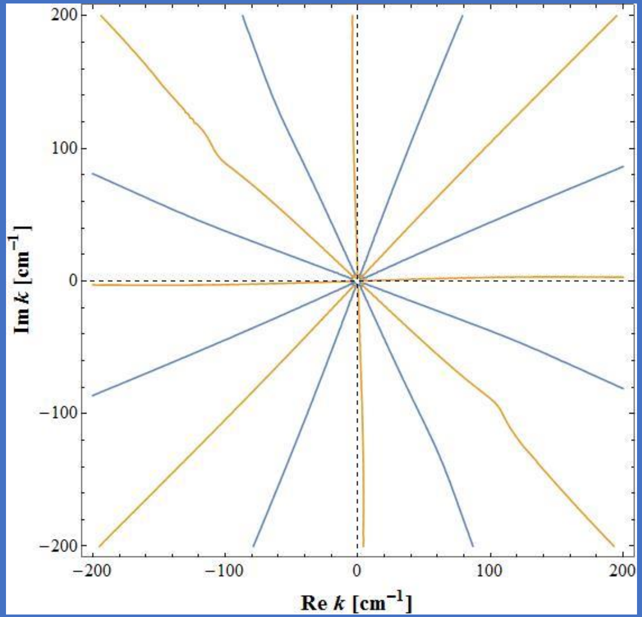
$\omega = 100 + i\,100$



$\omega = -100$



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

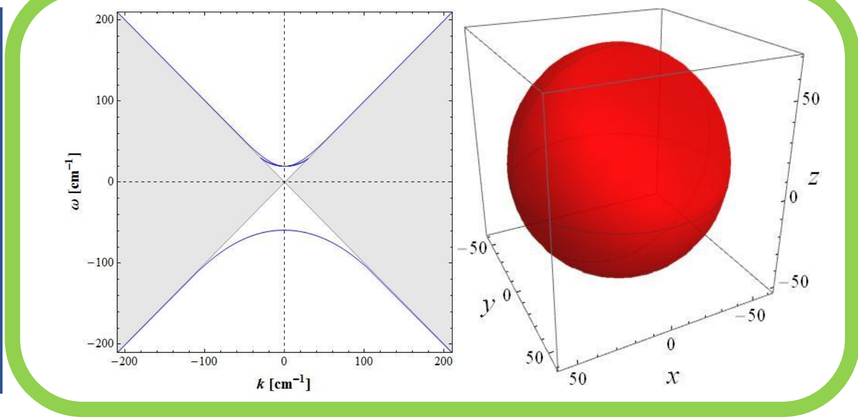


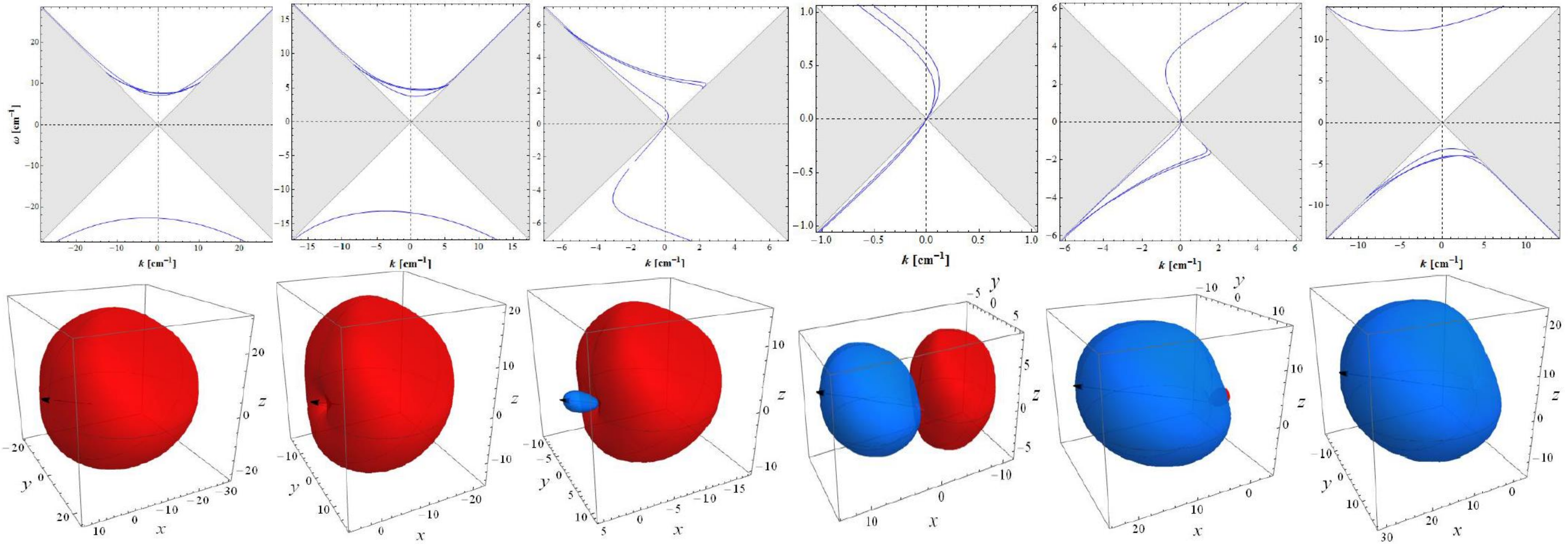
$\omega = -100 + i\,50$

No oscillation so far ….

How & under what condition can we obtain the oscillation?

Results- Scaled data (**k**- towards crossing)

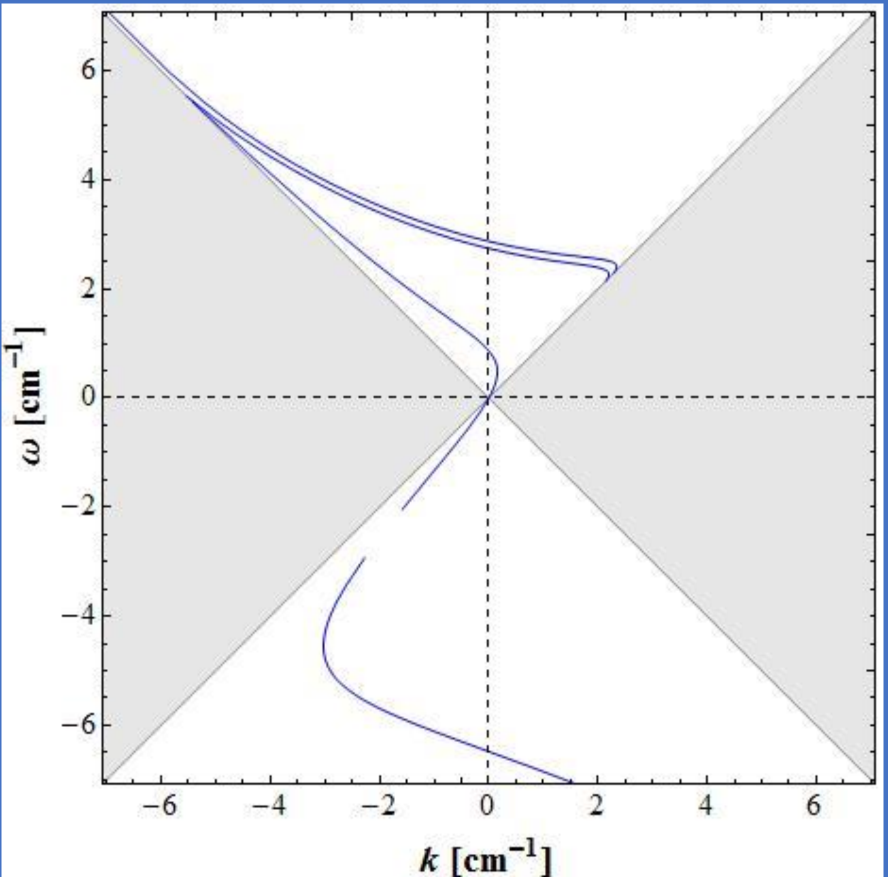




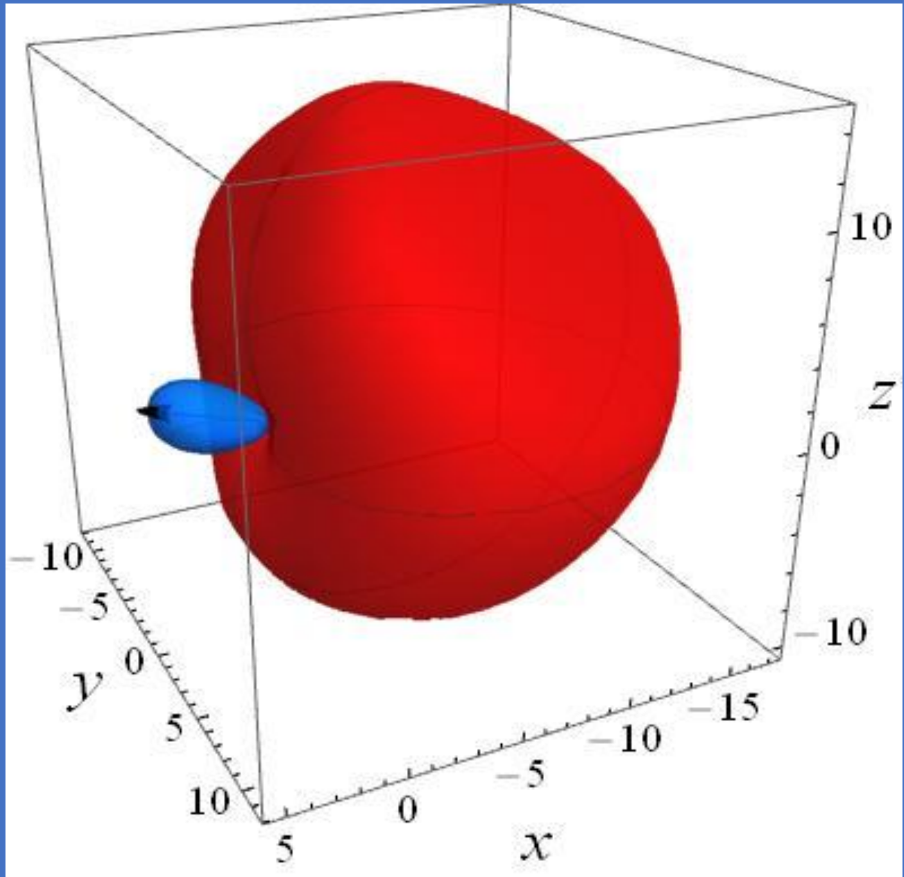
25 31 35 39.5 45 49

Modified data

Dispersion relation



Neutrino distribution



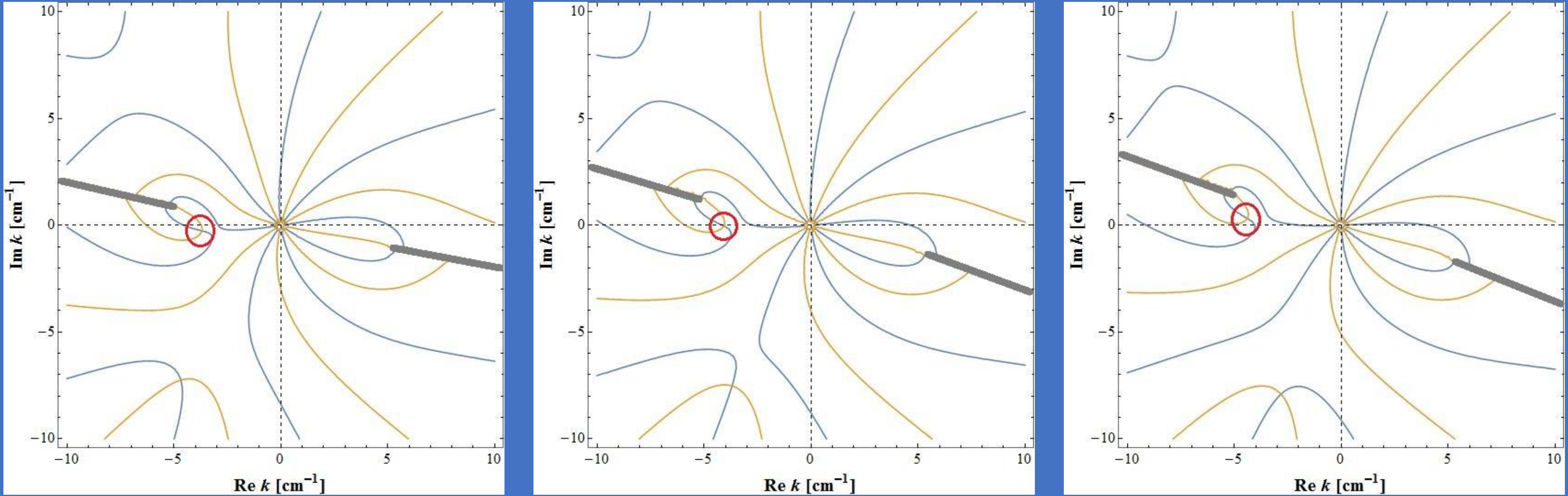
Solution

Zone of avoidance

Real part of det $\Pi = 0$

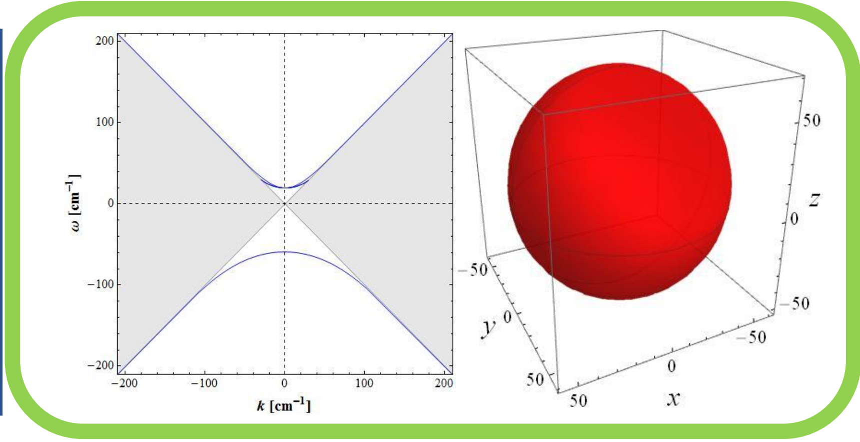
Imaginary part of det $\Pi = 0$

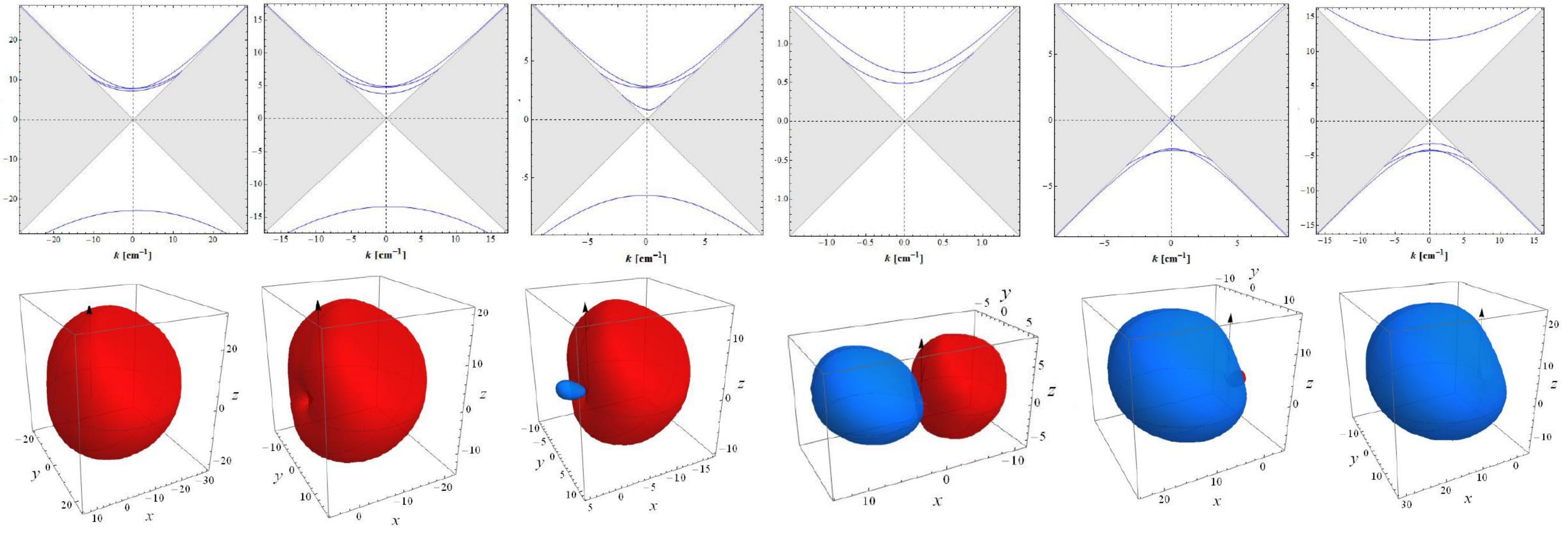
$\omega = -5 + i\,1$ $\omega = -5 + i\,1.3$ $\omega = -5 + i\,1.6$



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

Results- Scaled data (k- towards z-direction)

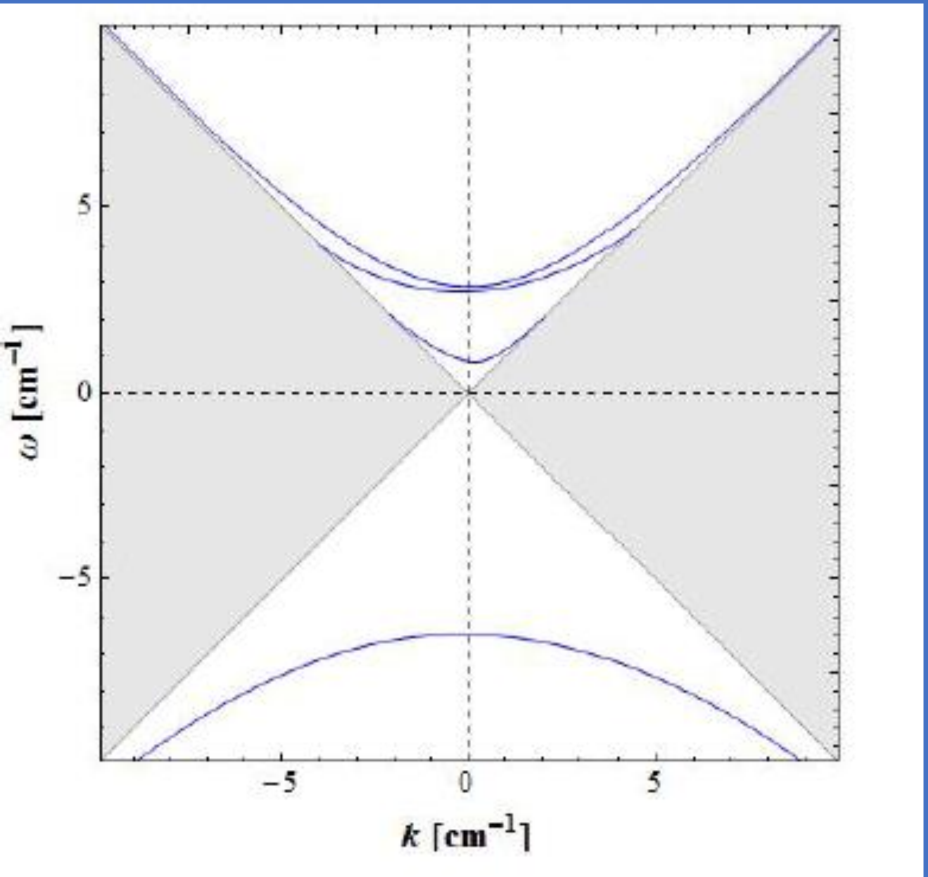




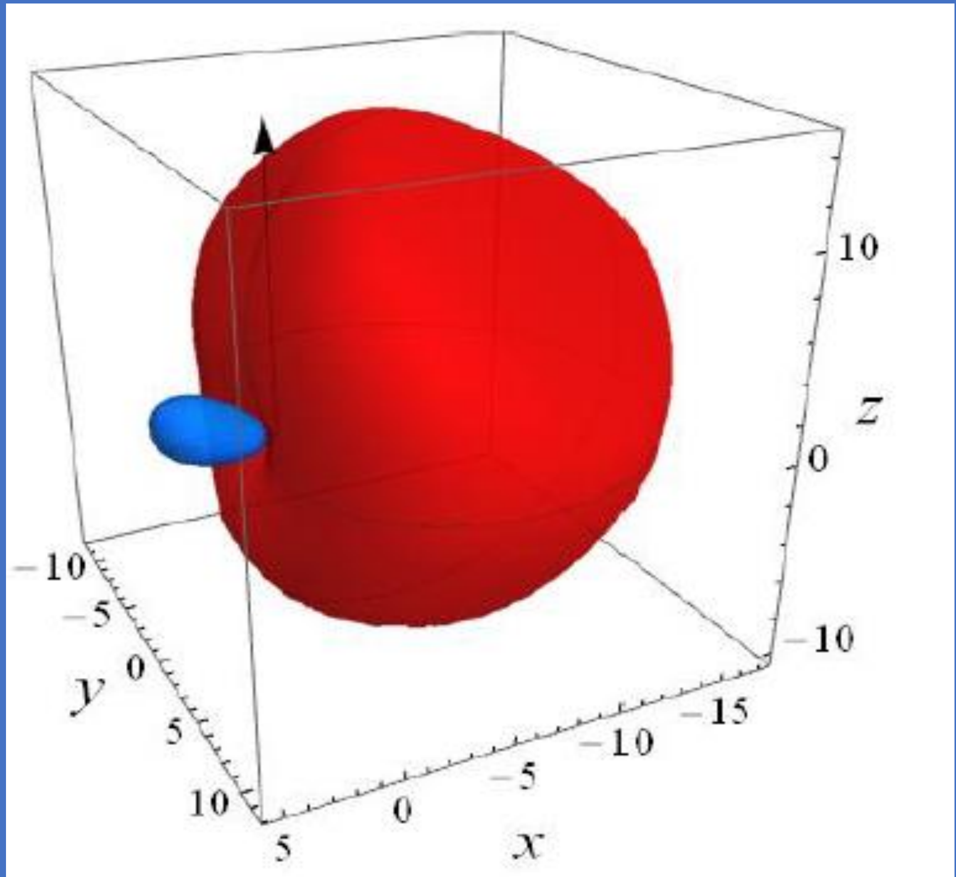
25 31 35 39.5 45 49

Modified data

Dispersion relation



Neutrino distribution



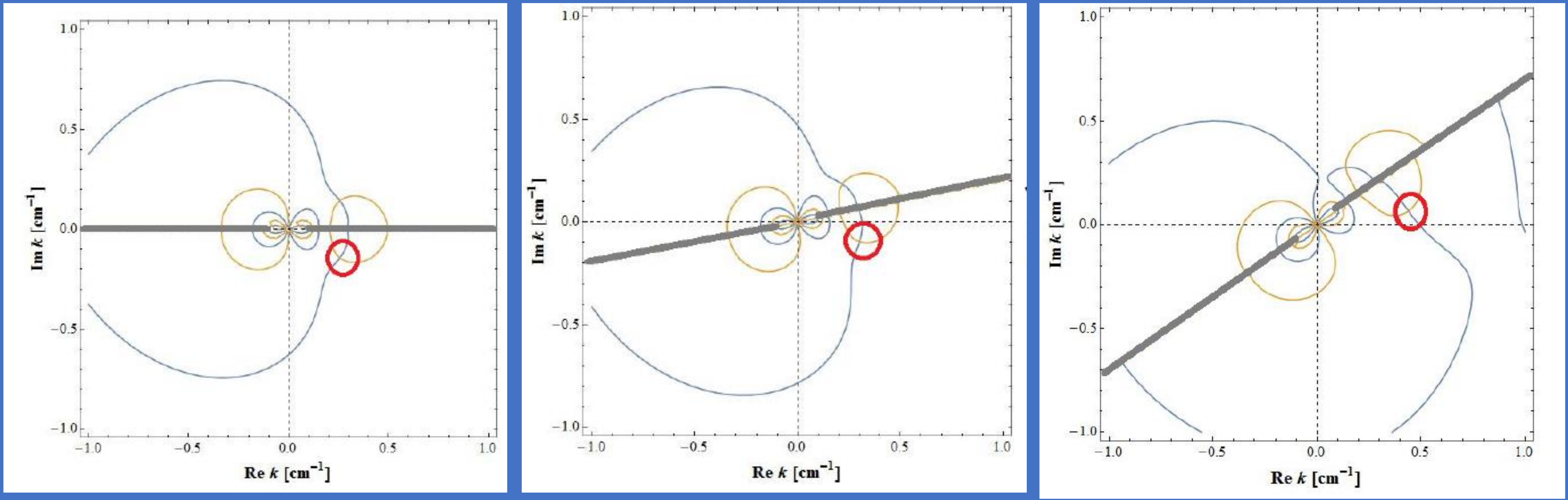
Solution

Zone of avoidance

Real part of det $\Pi = 0$

Imaginary part of det $\Pi = 0$

$\omega = 0.1 + i\,0$ $\omega = 0.1 + i\,0.02$ $\omega = 0.1 + i\,0.07$



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

Summary and future works

- ✓ Fast-pairwise 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.
- ✓ A systematic survey for all radii based on the angular distributions difference between the electron-neutrinos and anti-electron type neutrinos.
- ✓ As recently some data for the 3D simulations from my colleagues is available, the similar investigations might be a point of interest.
- ✓ 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.