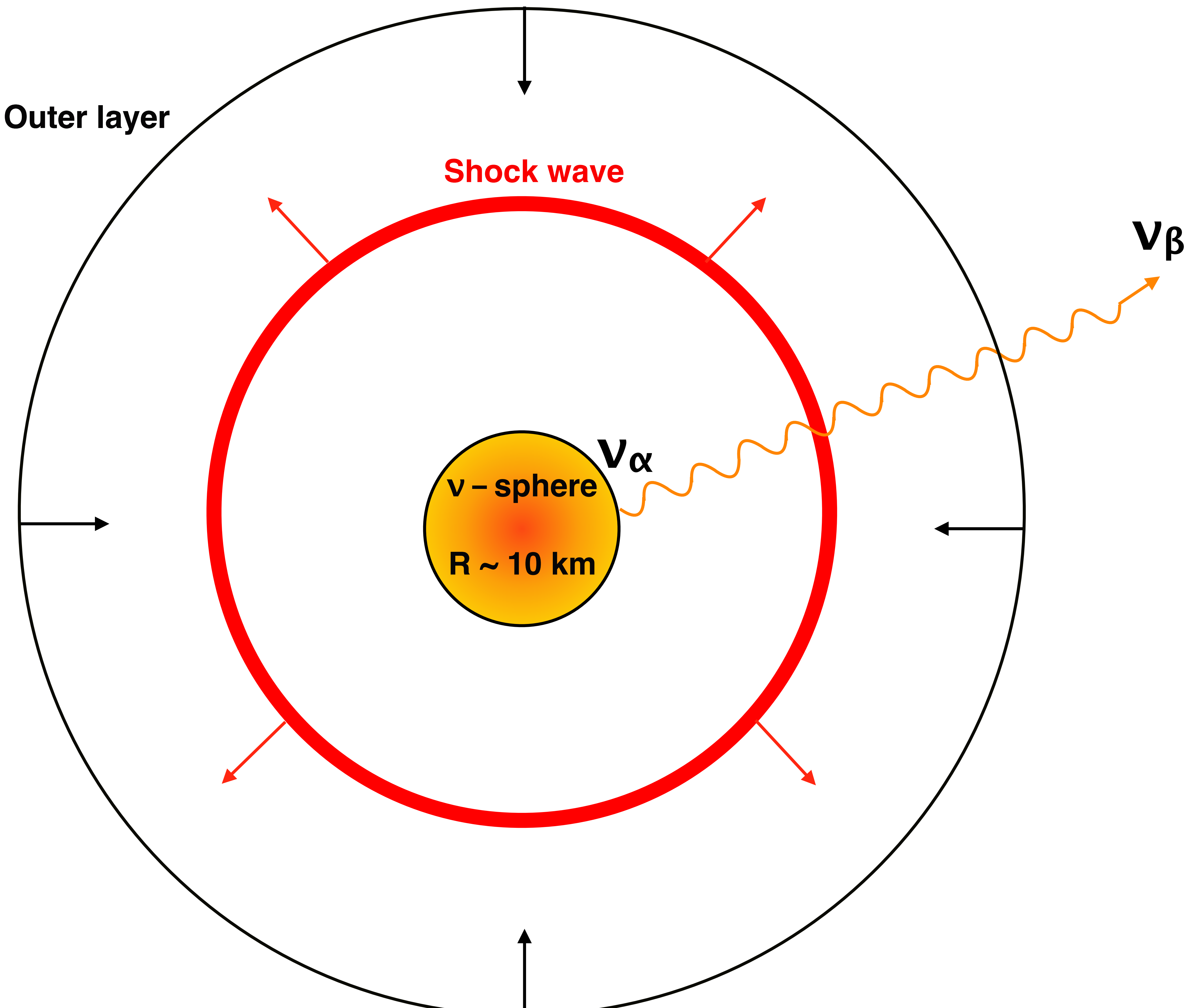
Fast neutrino flavour conversion near the supernova core

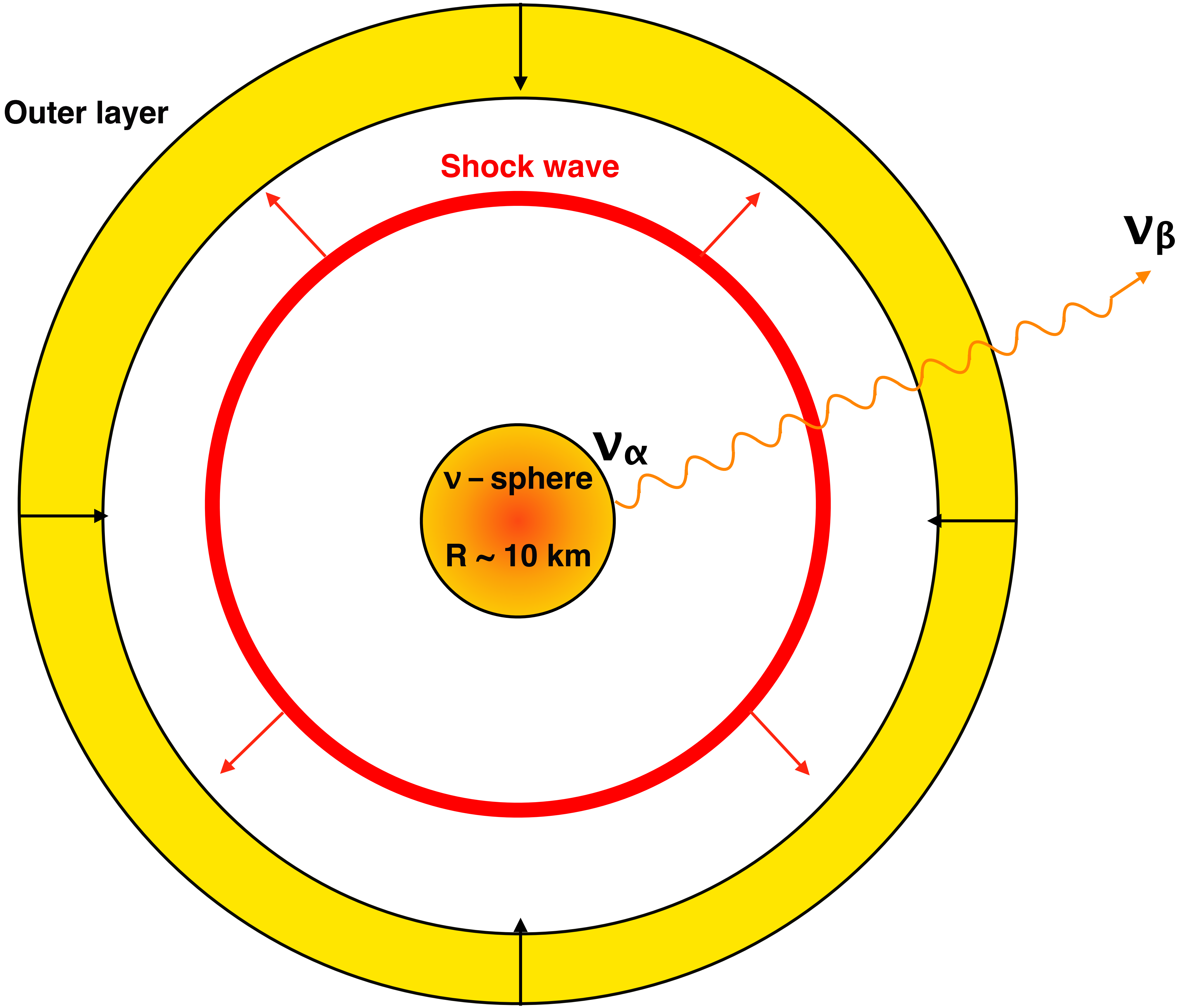
based on arXiv:1706.03360, with B. Dasgupta, E. Lisi, A. Marrone, A. Mirizzi

FRANCESCO CAPOZZI

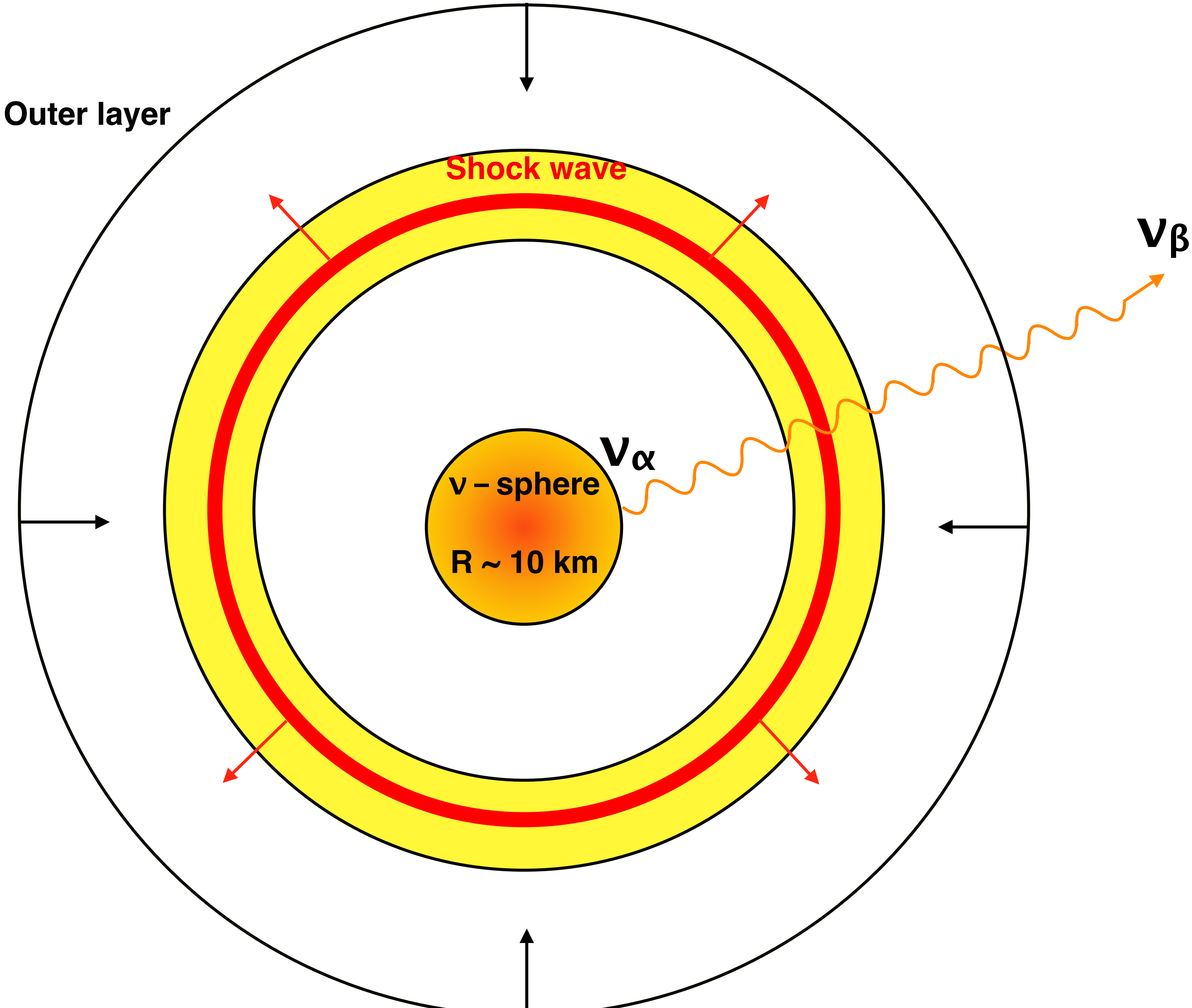
Flavour conversion: an overview


Outer layer
Shock wave
ν_β
ν_α
ν – sphere
R ~ 10 km

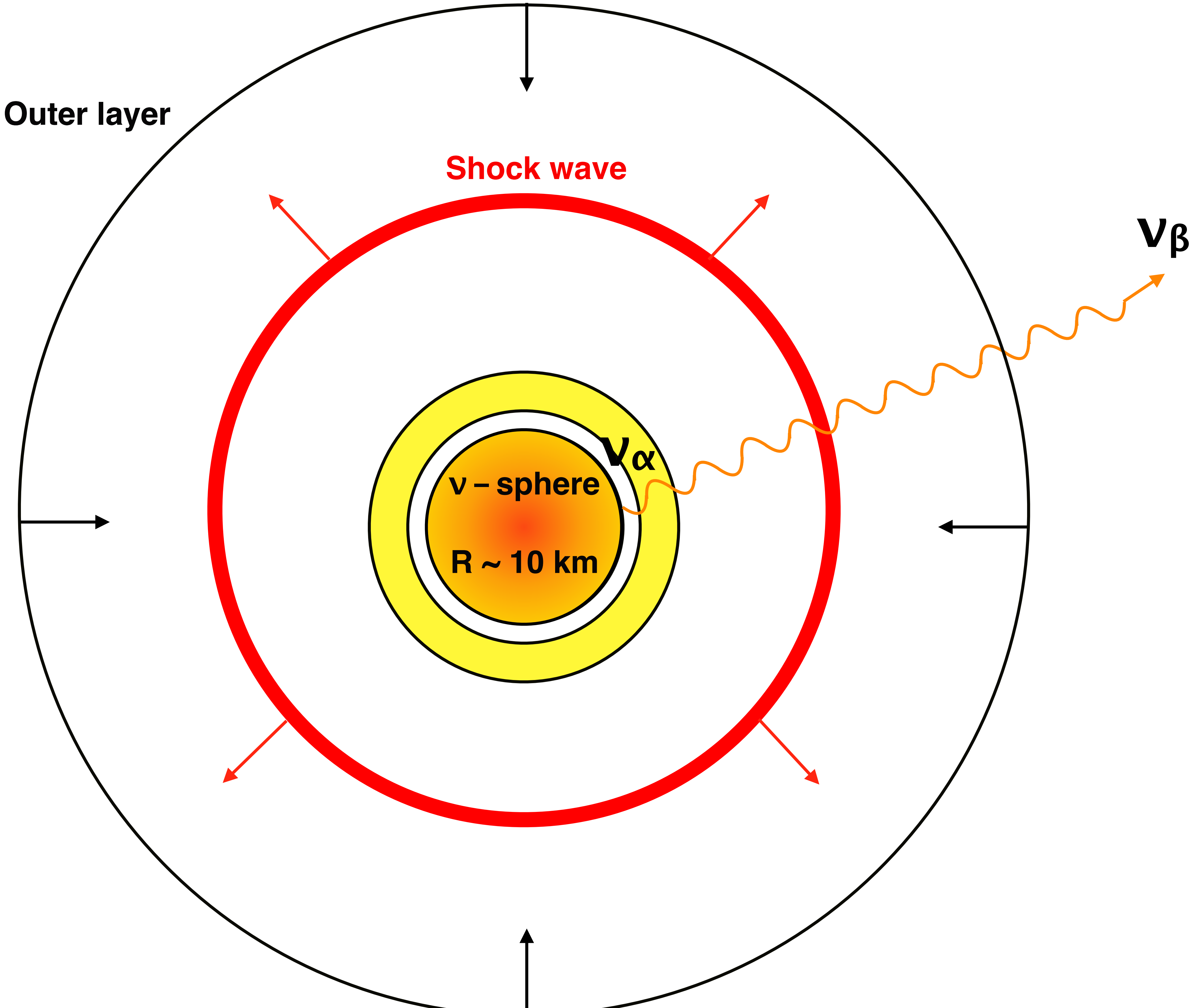
MSW effects



Collective effects



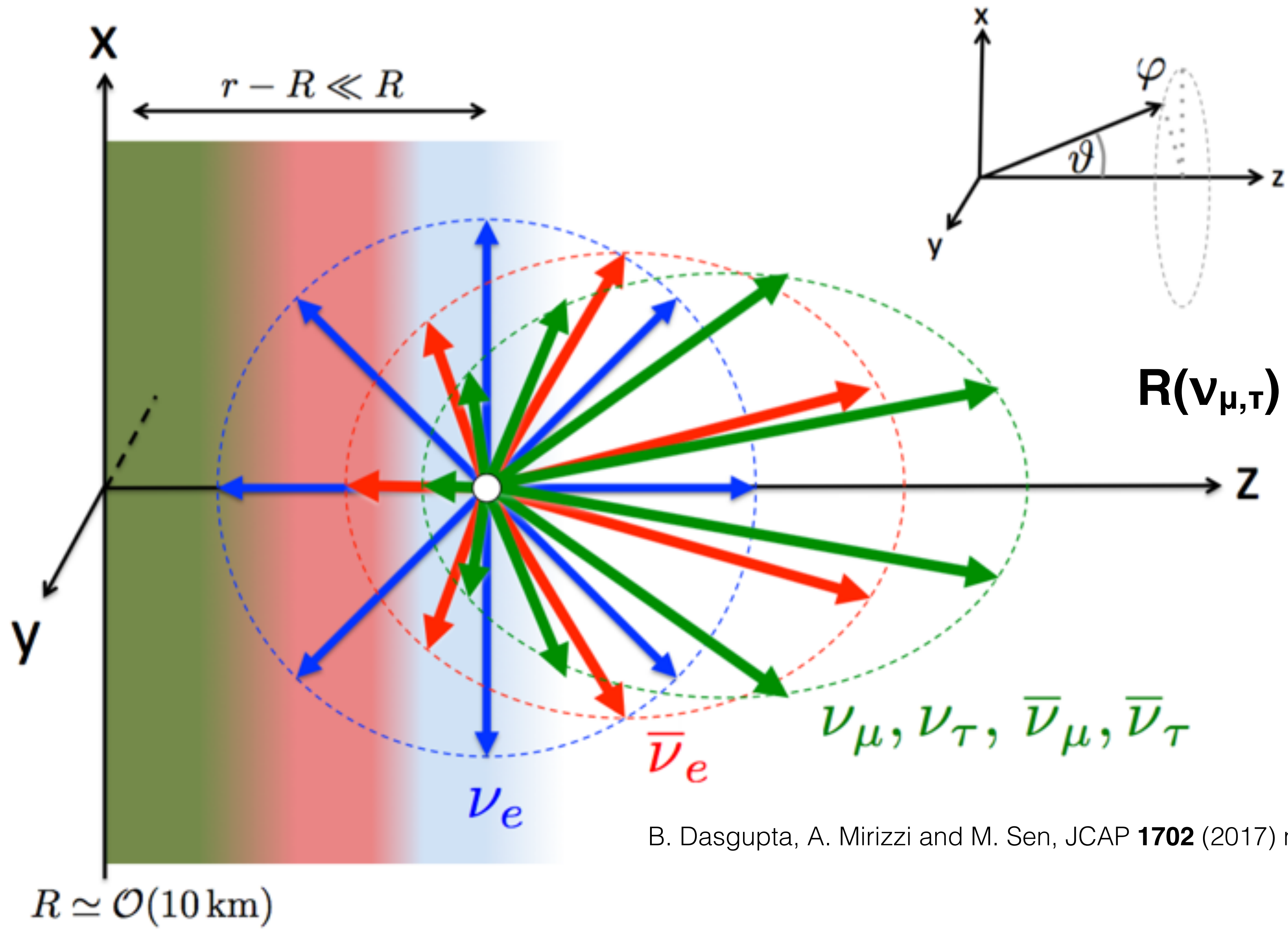
Fast flavour conversions



Fast flavour conversions: current status

What is causing fast flavour conversions?

Different angular distributions for the different flavors can speed-up conversions



$R(\nu_{\mu,\tau}) > R(\overline{\nu}_e) > R(\nu_e)$

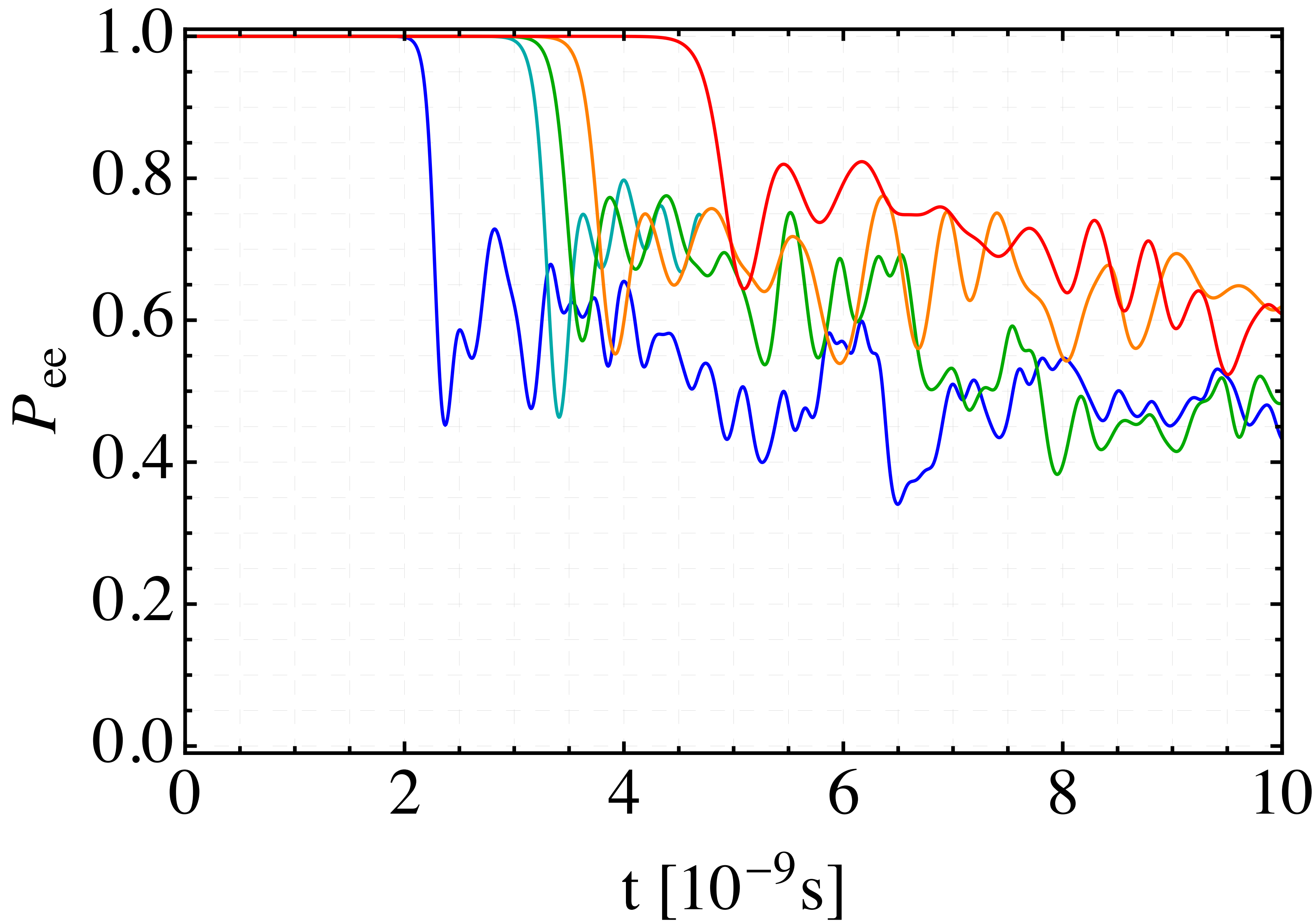
B. Dasgupta, A. Mirizzi and M. Sen, JCAP **1702** (2017) no.02, 019

Different angular distributions can be found near the ν_e - neutrinosphere

Outcome of fast flavour conversions

Survival probability for ν_e

B. Dasgupta, A. Mirizzi and M. Sen, JCAP **1702** (2017) no.02, 019



Flavour equilibration is a possible outcome

How do we simulate flavour conversions?

Numerical approach

The equation of motion is written in terms of the density matrix ρ

$$\partial_t \varrho_{\mathbf{p},\mathbf{x},t} + \mathbf{v}_\mathbf{p} \cdot \nabla_\mathbf{x} \varrho_{\mathbf{p},\mathbf{x},t} = -i[H_{\mathbf{p},\mathbf{x},t}, \varrho_{\mathbf{p},\mathbf{x},t}]$$

$$\varrho = \frac{f_{\nu_e} - f_{\nu_x}}{2} \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

INITIAL CONDITIONS

$$S \ll 1 \qquad\qquad s \sim 1$$

Numerical approach

The equation of motion is written in terms of the … matrix ρ

$$\partial_t \varrho_{\mathbf{p},\mathbf{x},t} + \mathbf{v}_\mathbf{p} \cdot \nabla_\mathbf{x} \varrho_{\mathbf{p},\mathbf{x},t} \ldots {}_{\mathbf{x},t}\, , \varrho_{\mathbf{p},\mathbf{x},t}]$$

$$\varrho = f \ldots \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

UNSOLVABLE!!!!

INITIAL CONDITIONS

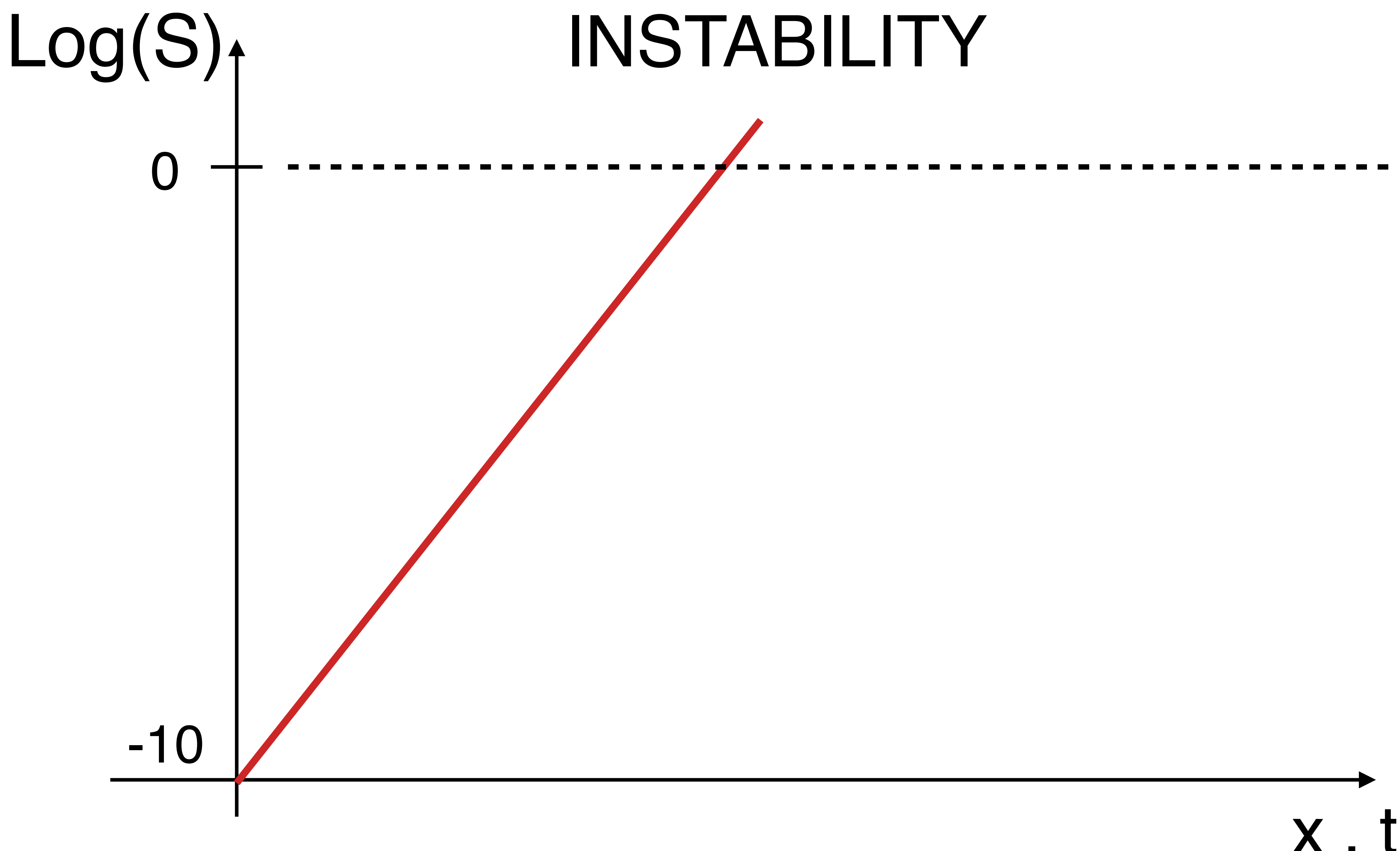
$$\ll 1 \qquad\qquad s \sim 1$$

Linear stability analysis

We linearise in S and look only for the onset of flavour conversion

$$S_{\mathbf{v}}(t,\mathbf{x}) = Q_{\mathbf{v}} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}$$

INSTABILITY



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DISPERSION RELATION

$$\boxed{D(\omega,k) = 0}$$

Two ways of solving the DR:

$$\omega = \Omega(k) \qquad \omega \in \mathbb{C}, k \in \mathbb{R}$$

TEMPORAL STABILITY

$$k = K(\omega) \qquad k \in \mathbb{C}, \omega \in \mathbb{R}$$

SPATIAL STABILITY

Instability theory applied to supernova neutrinos

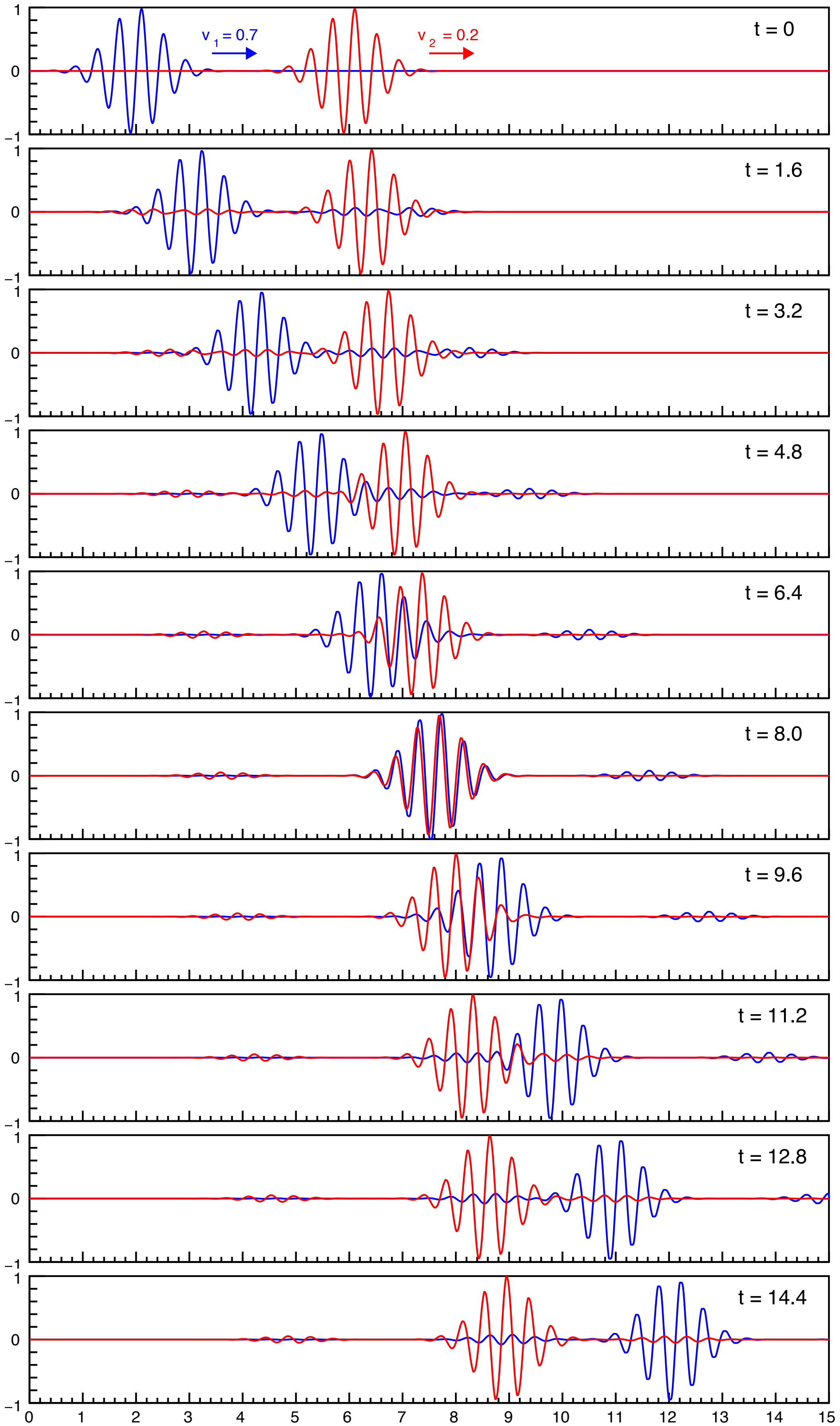
Two beam model

crossing: $N_\nu > N_{\bar{\nu}}$ for v_1 and $N_\nu < N_{\bar{\nu}}$ for v_2

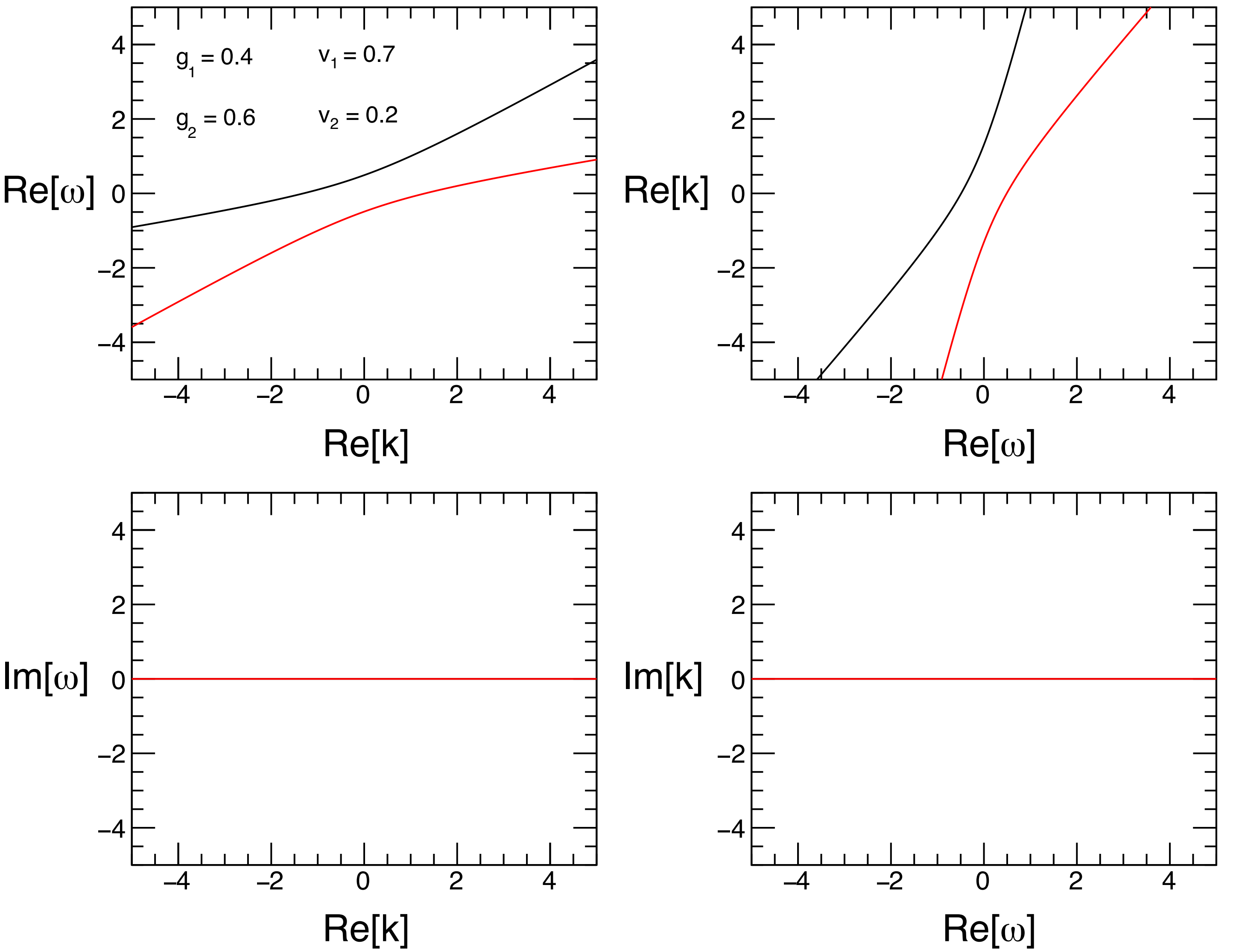
$\varepsilon>0$: no crossing

$\varepsilon<0$: crossing

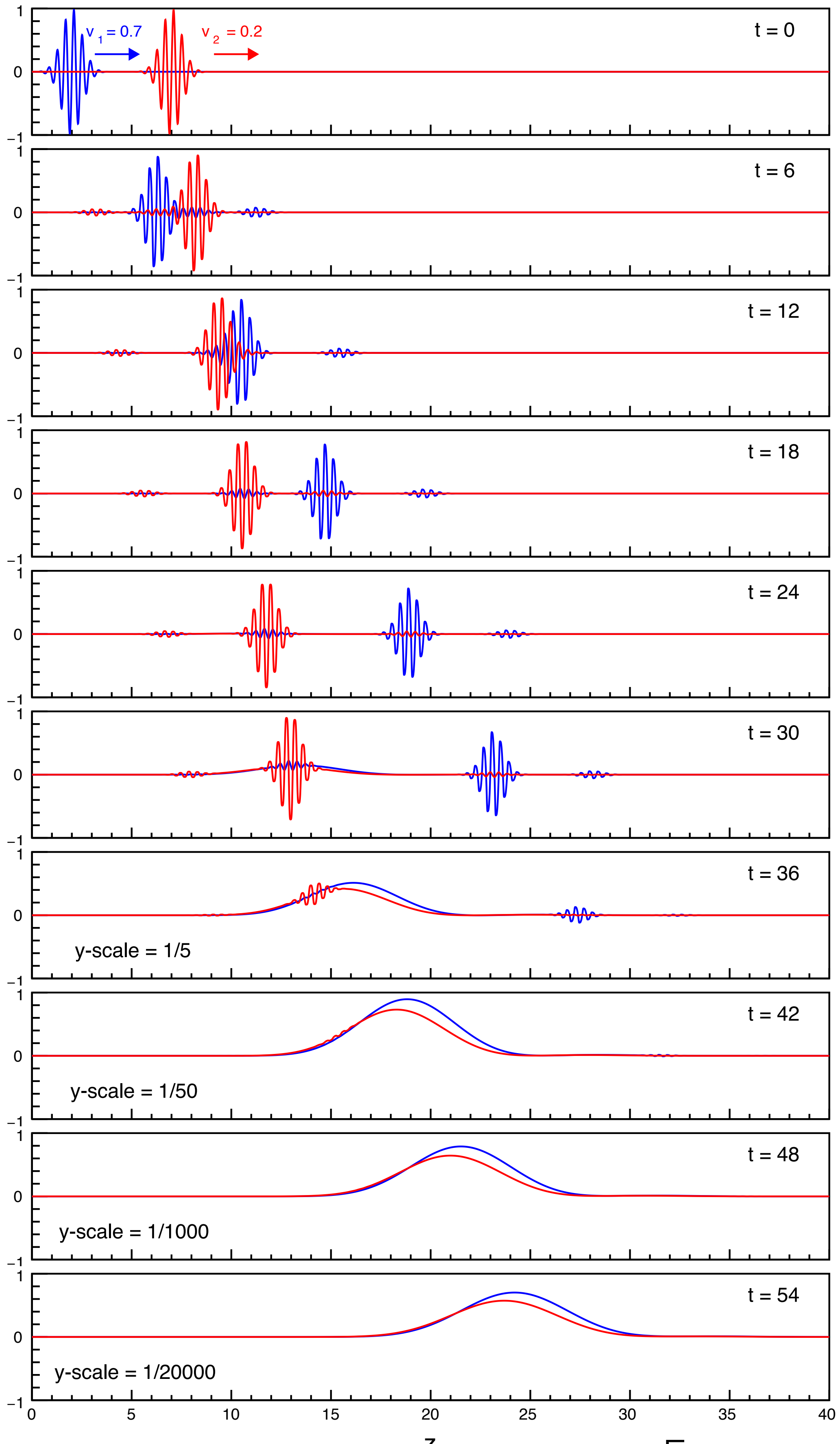
Pure stability



$v_1 = 0.7$
$v_2 = 0.2$
$\varepsilon > 0$



Convective instability



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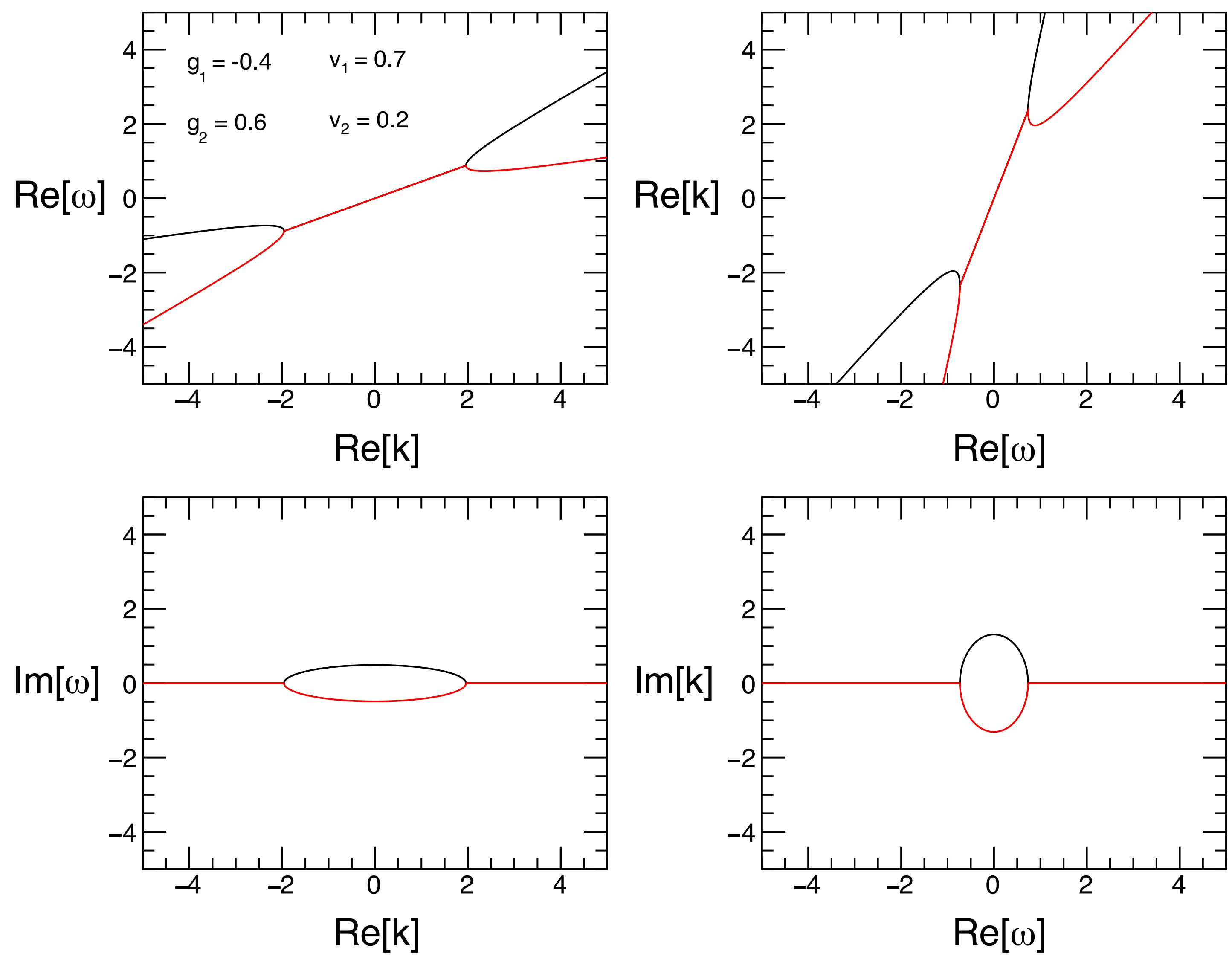
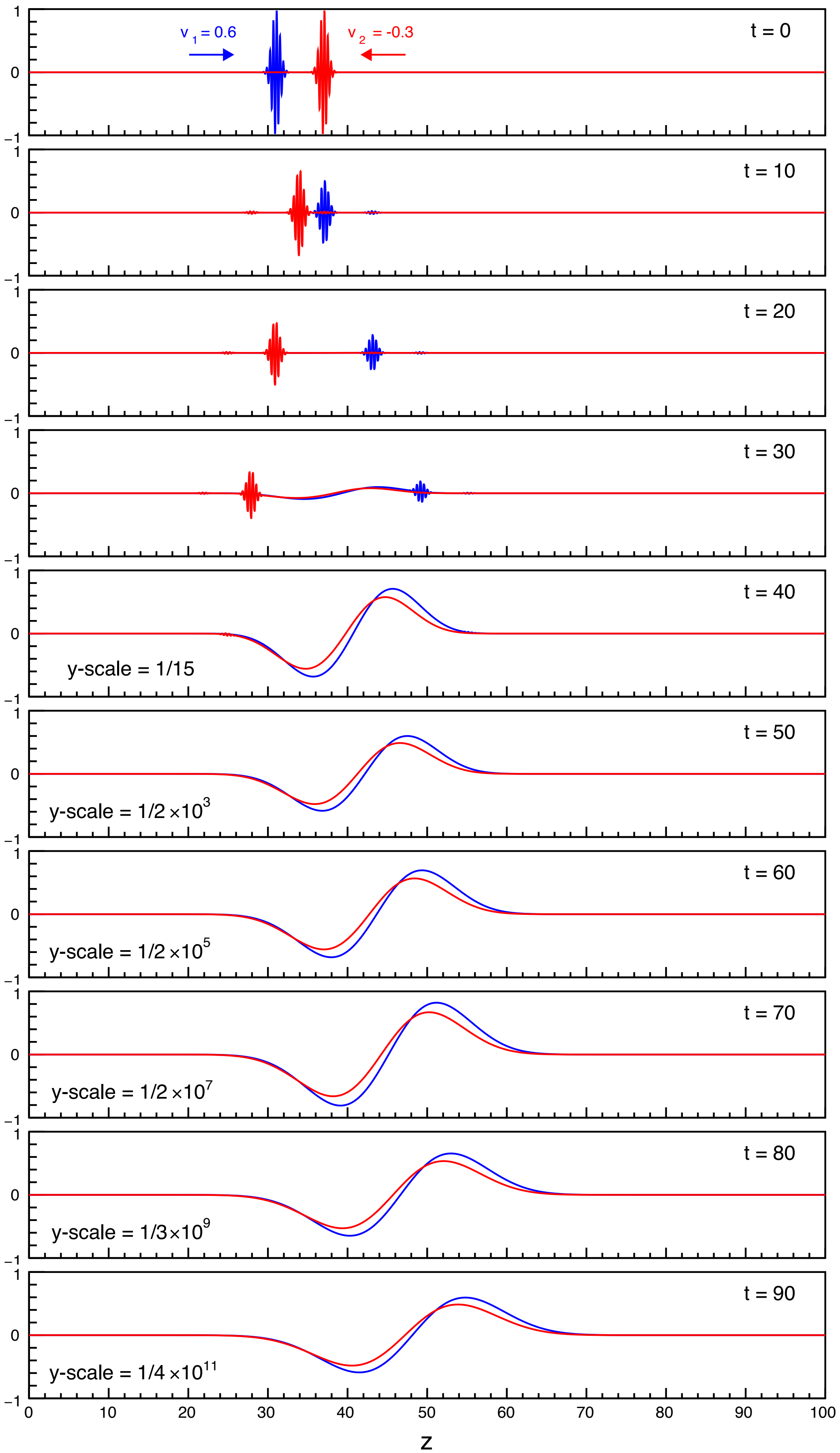


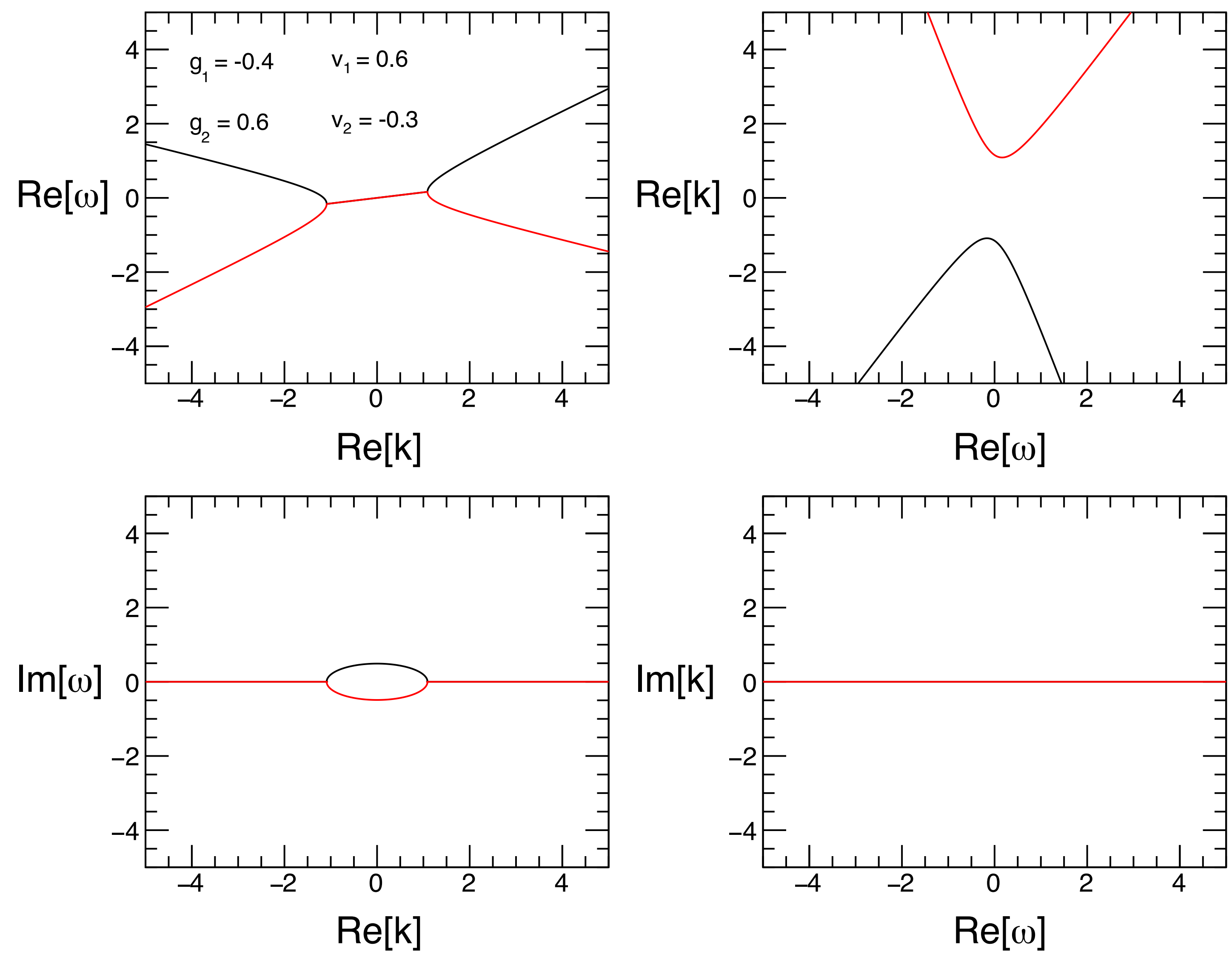
Absolute instability



$v_1 = 0.6$

$v_2 = -0.3$

$\varepsilon < 0$



Conclusions

Flavour conversions near the supernova core are possible.

Impact on SN explosion and r-processes

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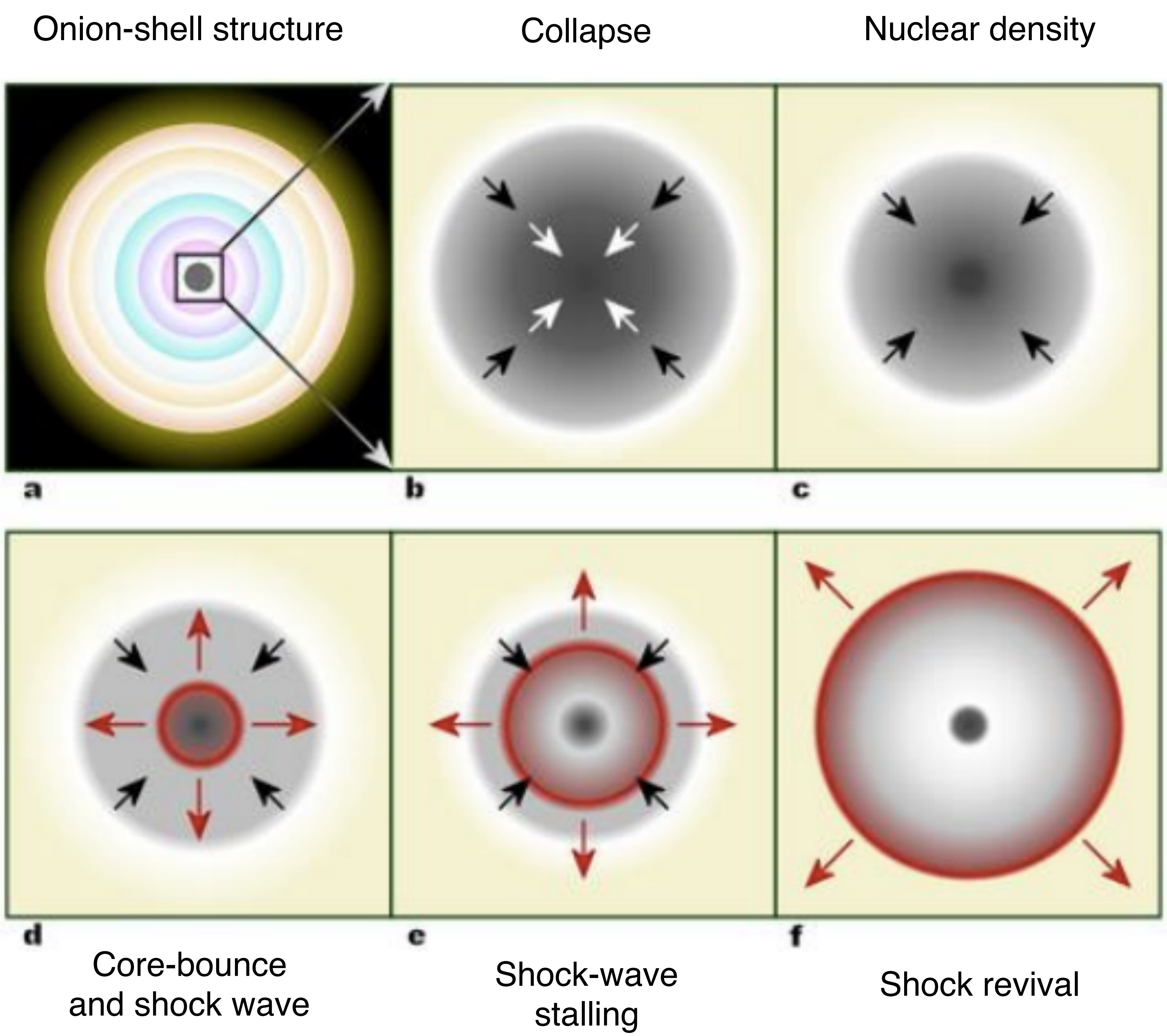
Linear stability analysis through DR is a **powerful tool** if used correctly

Non-linear simulations are mandatory to study possible flavor equilibrium

Thank you

Supernova collapse

Core-collapse supernovae are the final explosion of stars with $M > 8M_{\odot}$



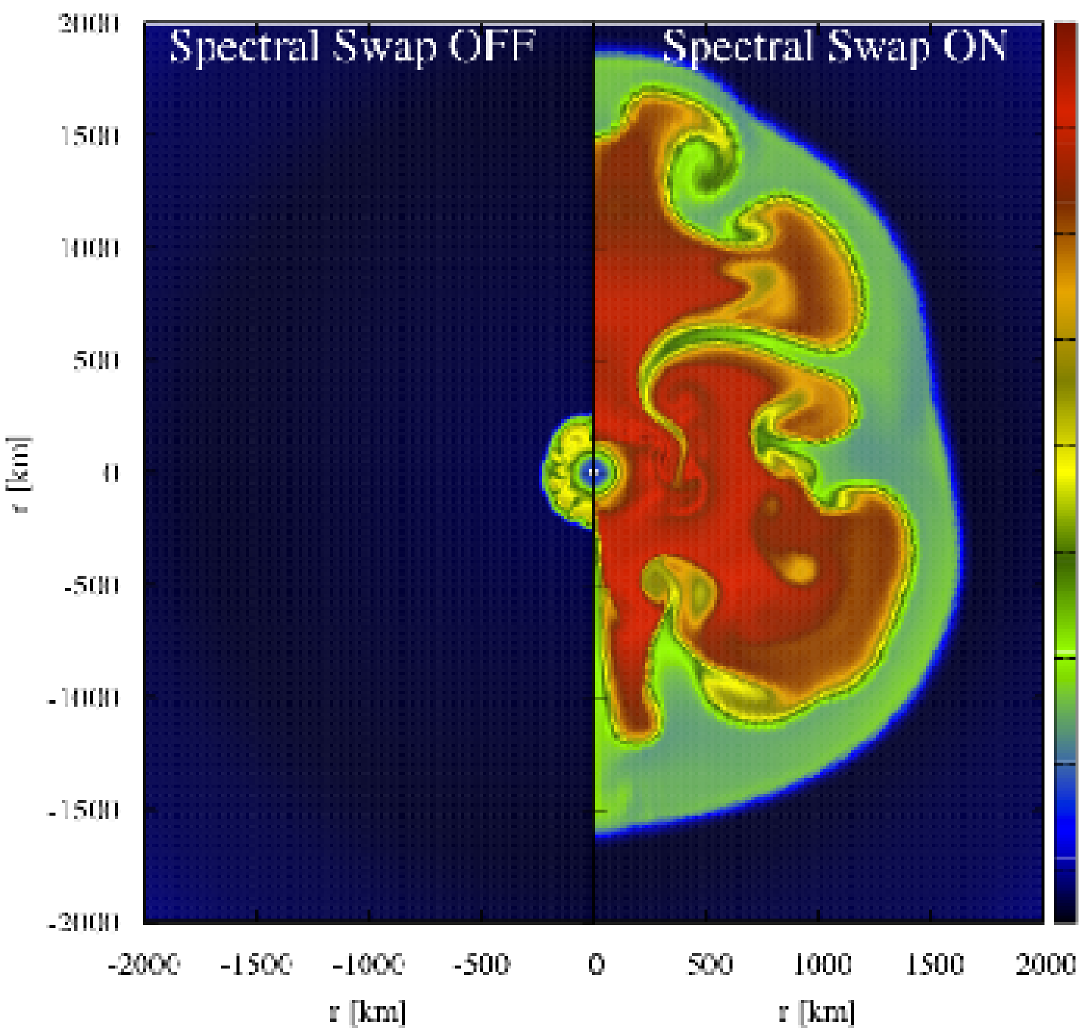
99% of binding energy ~10^{53} erg emitted through neutrinos $\nu_e, \bar{\nu}_e, \nu_x$

Emission time ~10 s

Average ν energy ~10 MeV

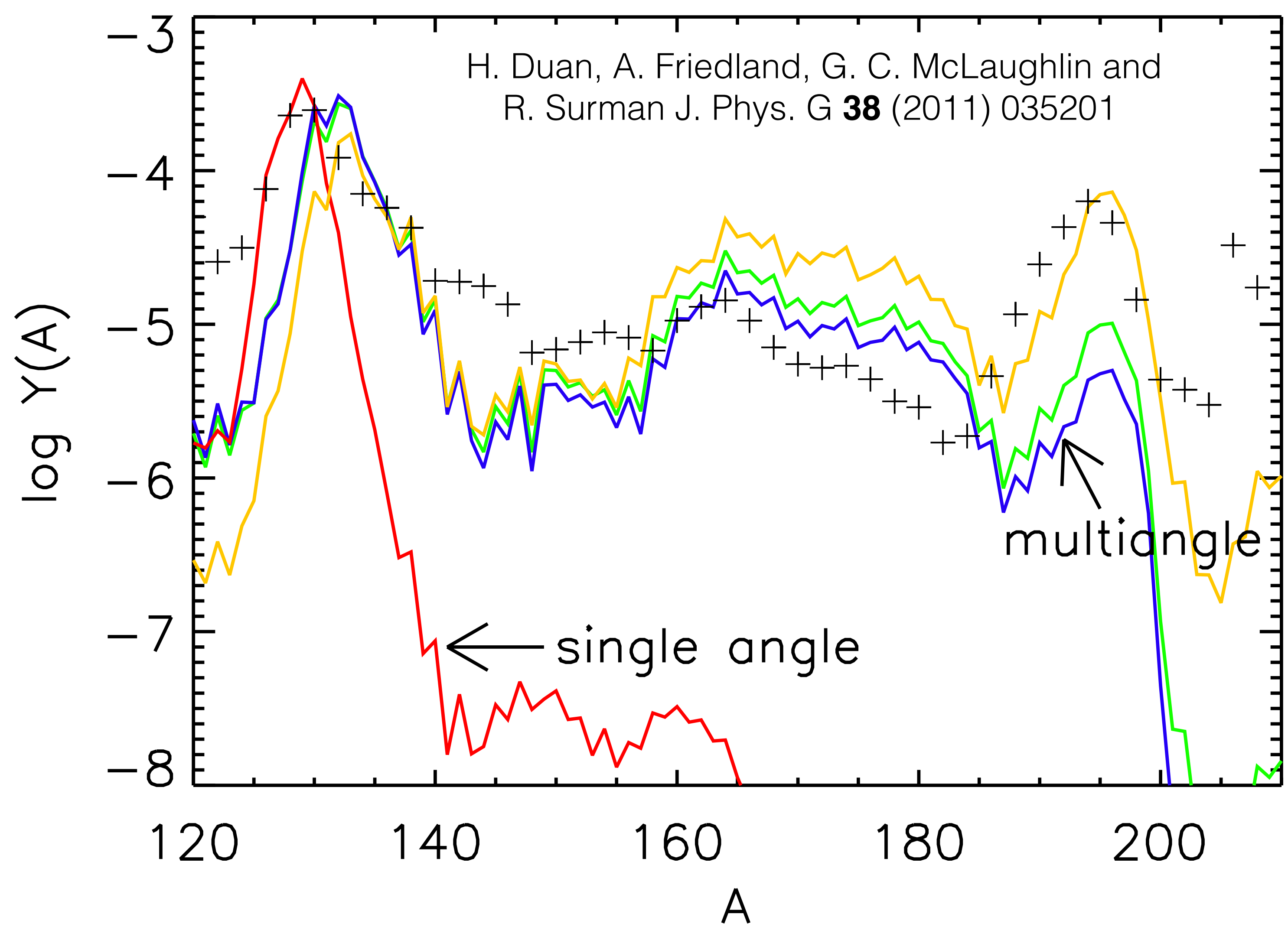
Flavour conversions: why study them?

Impact on neutrino heating of the shock



Y. Suwa, K. Kotake, T. Takiwaki, M. Liebendorfer and K. Sato, Astrophys. J. **738** (2011) 165

Impact on nucleosynthesis (r-process)



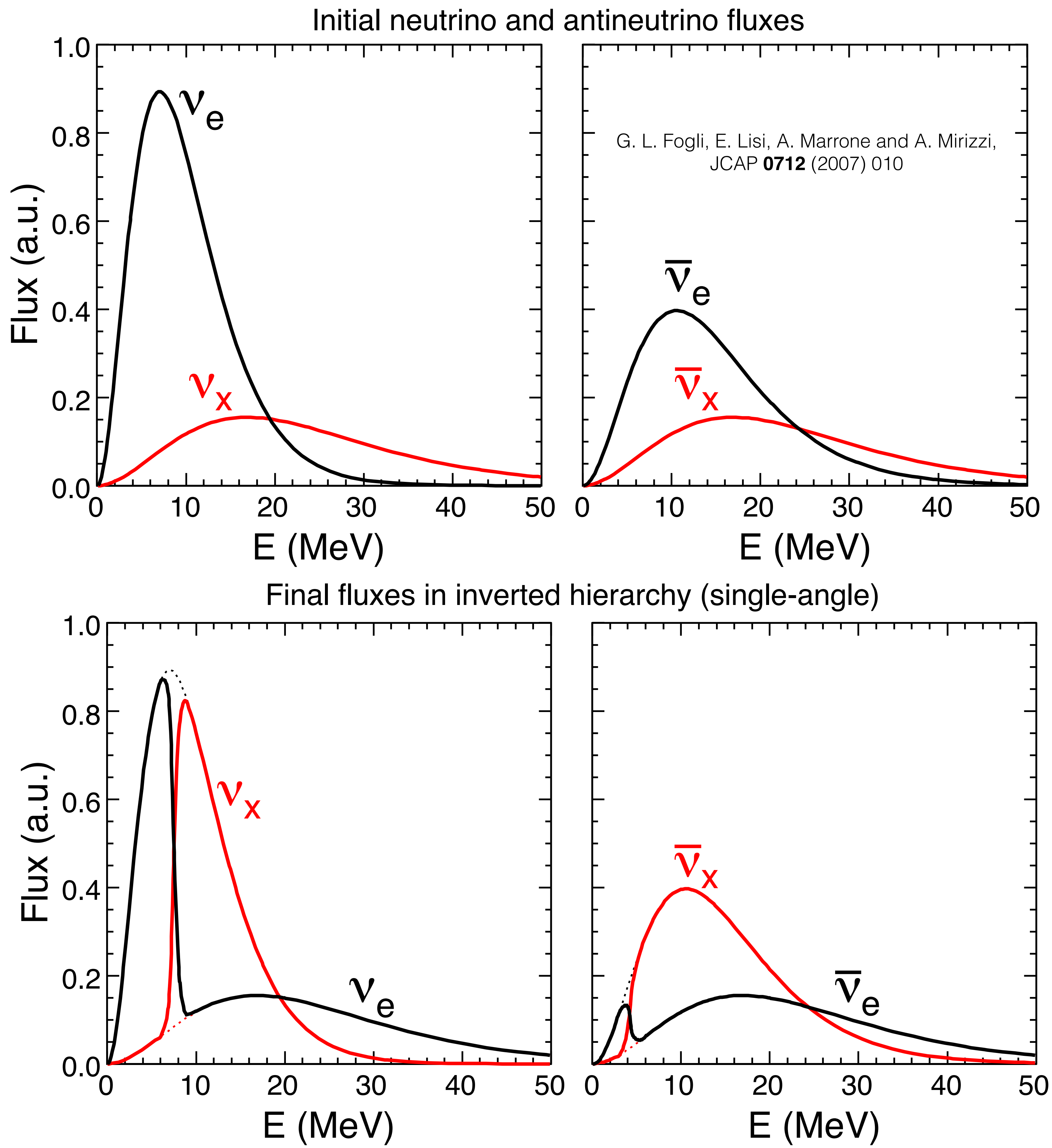
Flavour conversions: an overview

The rich phenomenology can be classified according to:

$$\lambda = \sqrt{2} G_F n_e$$

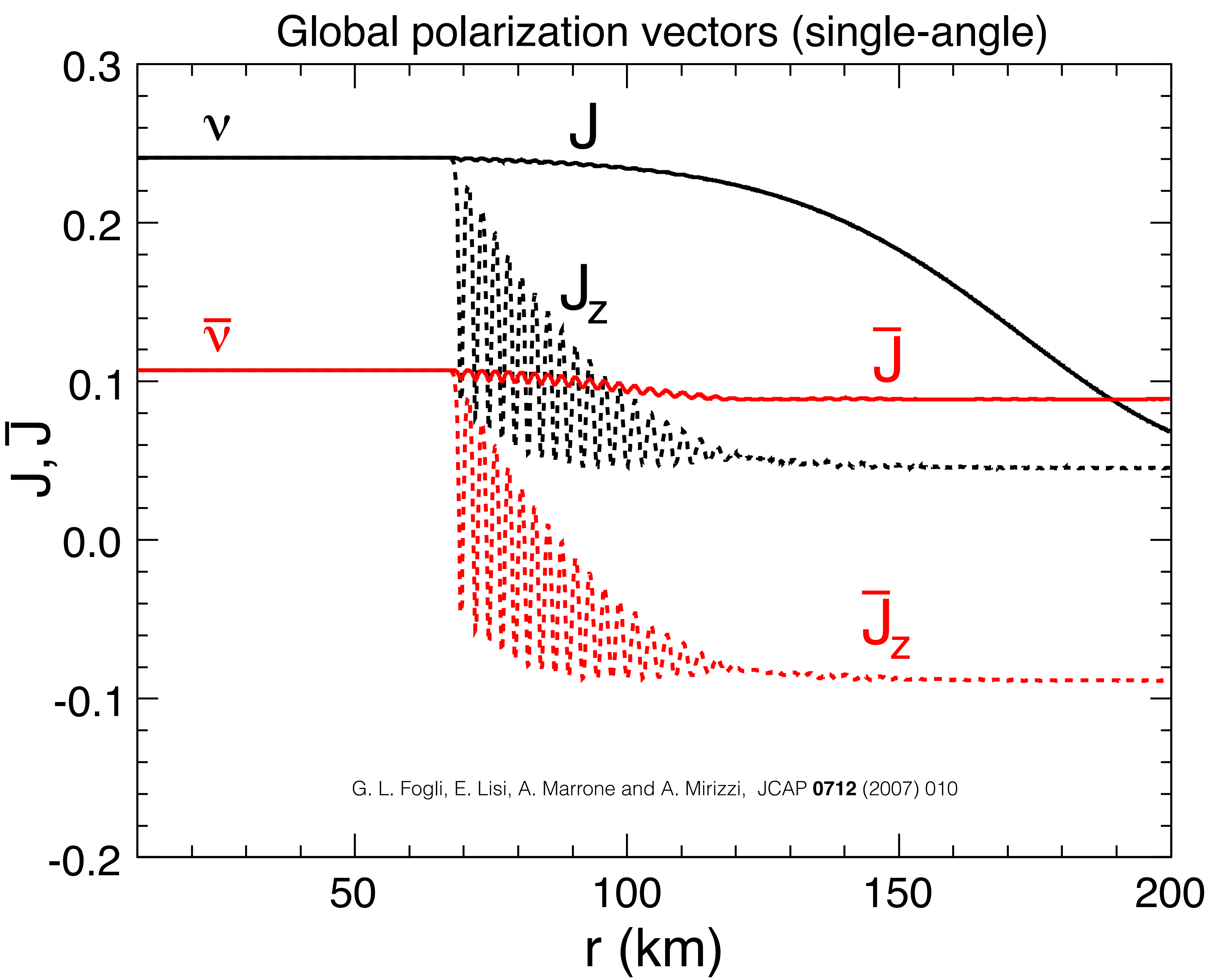
$$\mu = \sqrt{2} G_F n_\nu$$

Collective effects



Collective effects

Development time ~ $(\omega\mu)^{1/2}$



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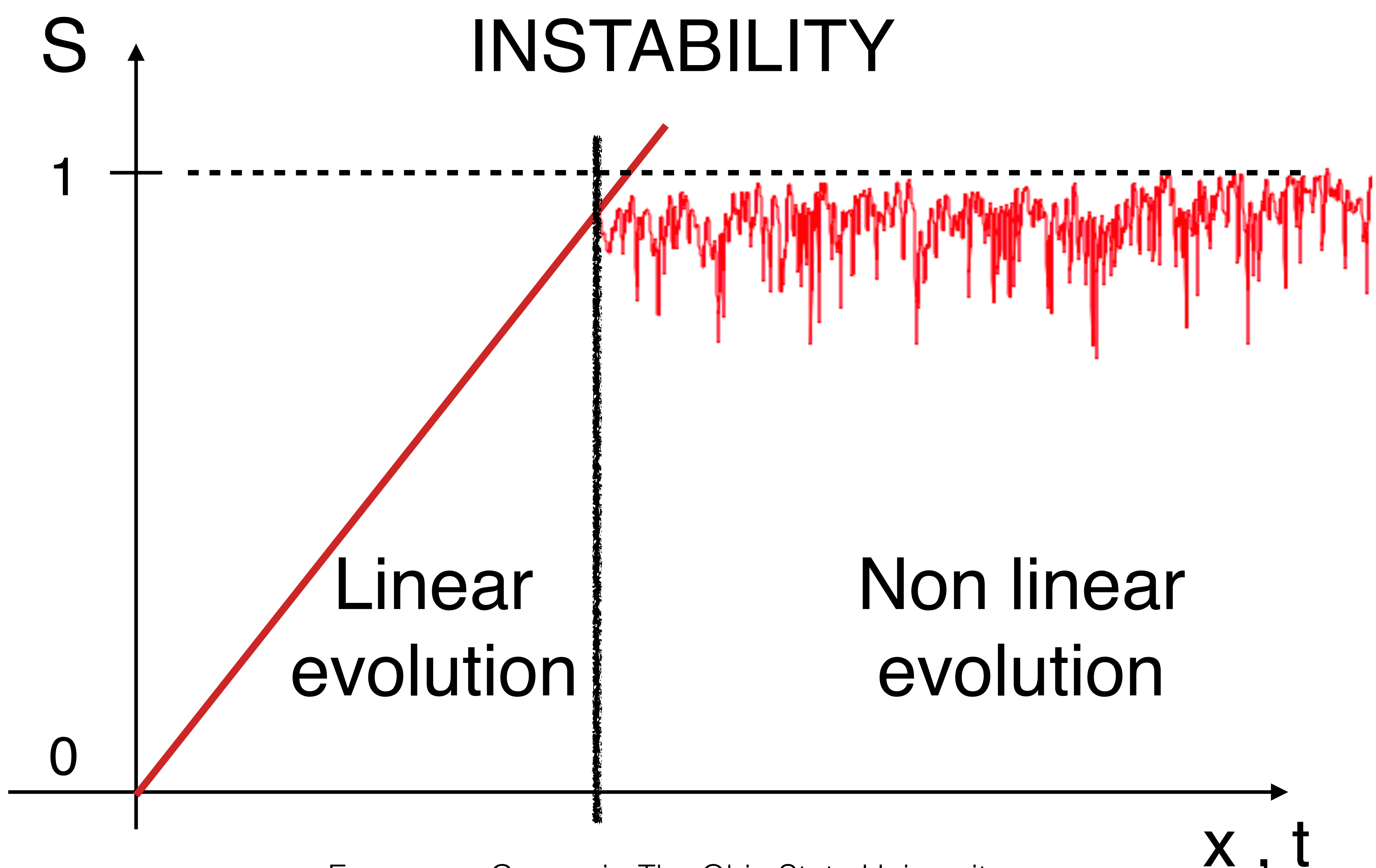
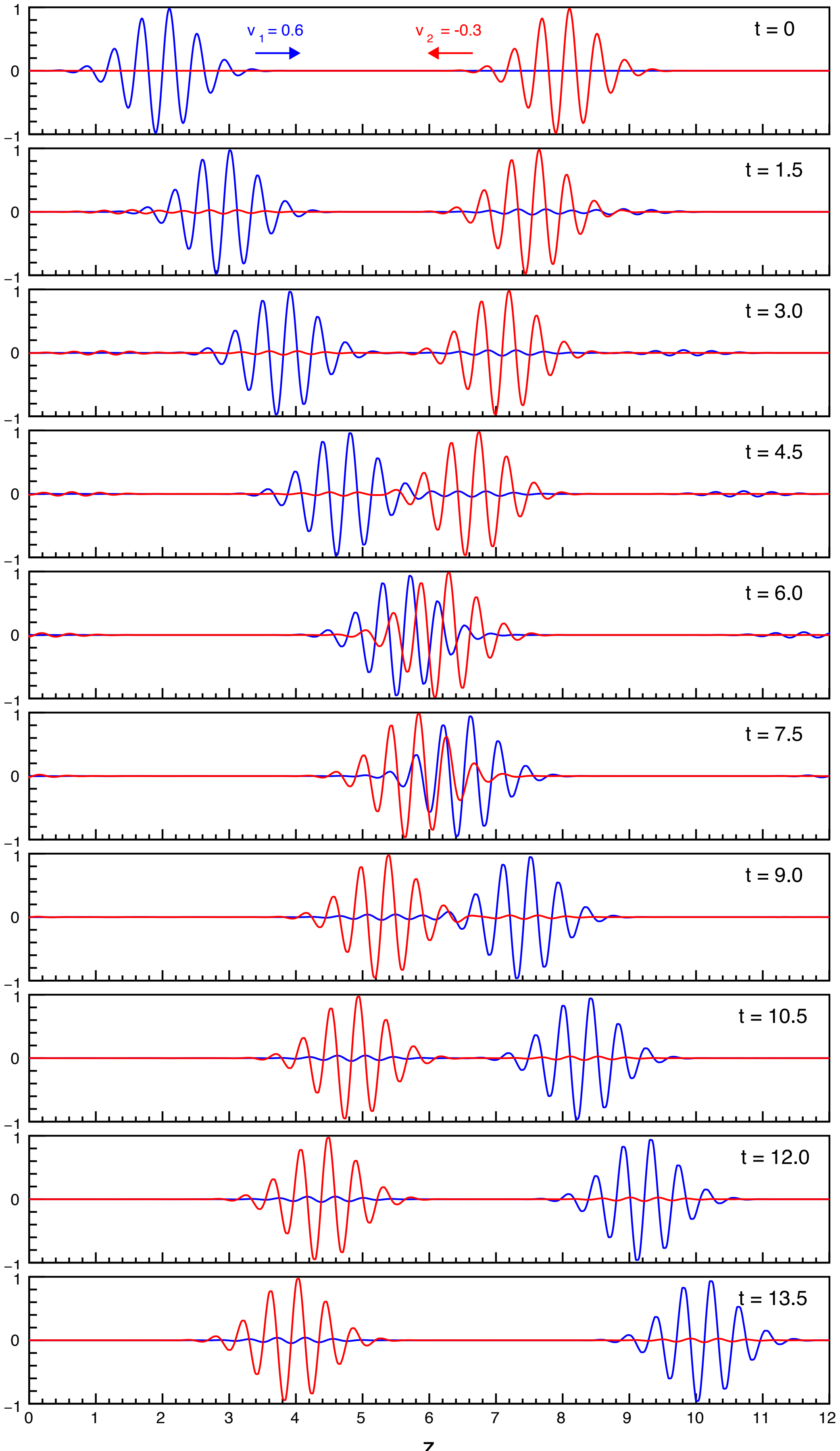


Damped instability



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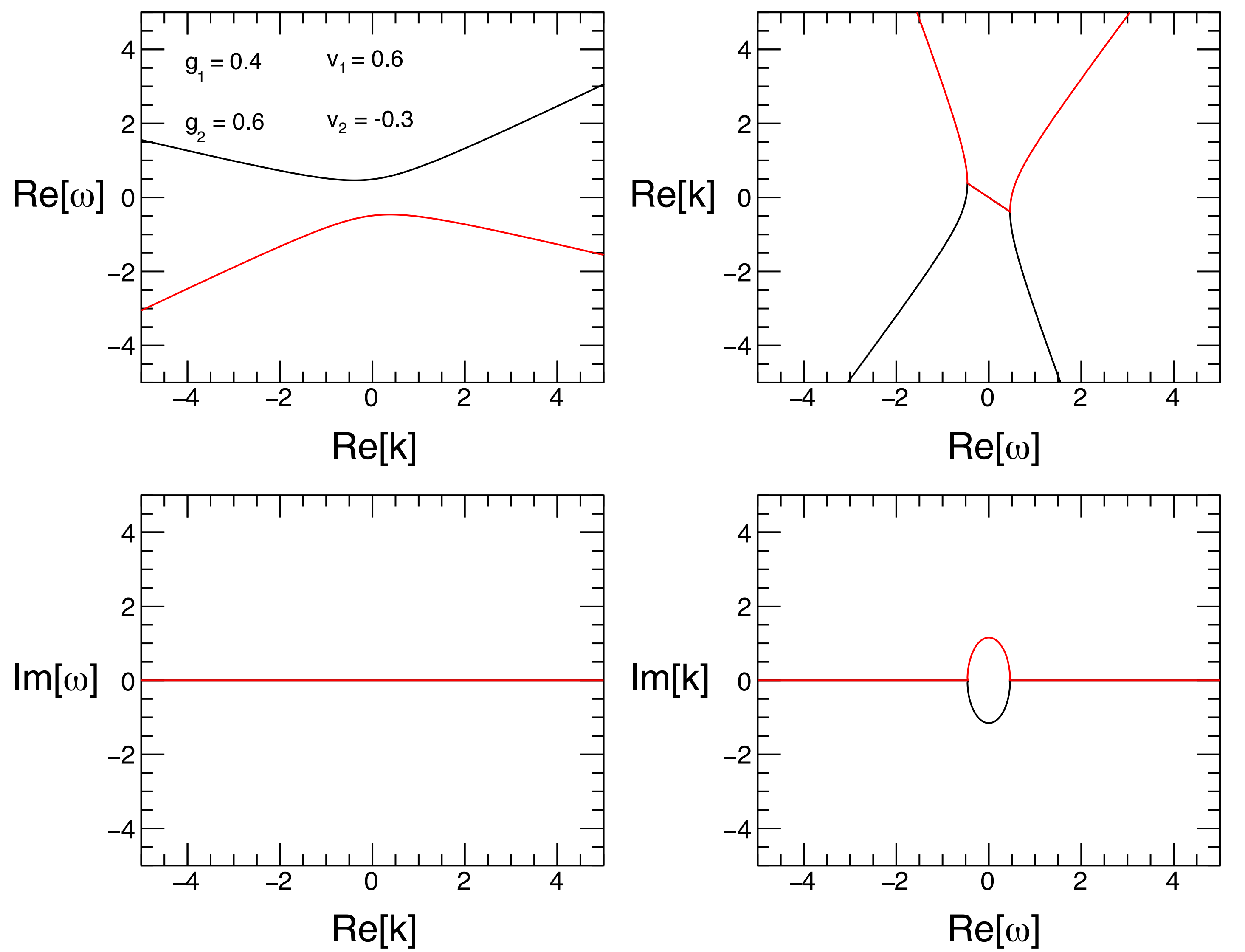

Can we have crossing in a SN?