Theory of neutrino flavor plasma

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based on works with G. Raffelt, T. Janka, G. Sigl, M. Goimil-Garcia

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di Fisica Nucleare

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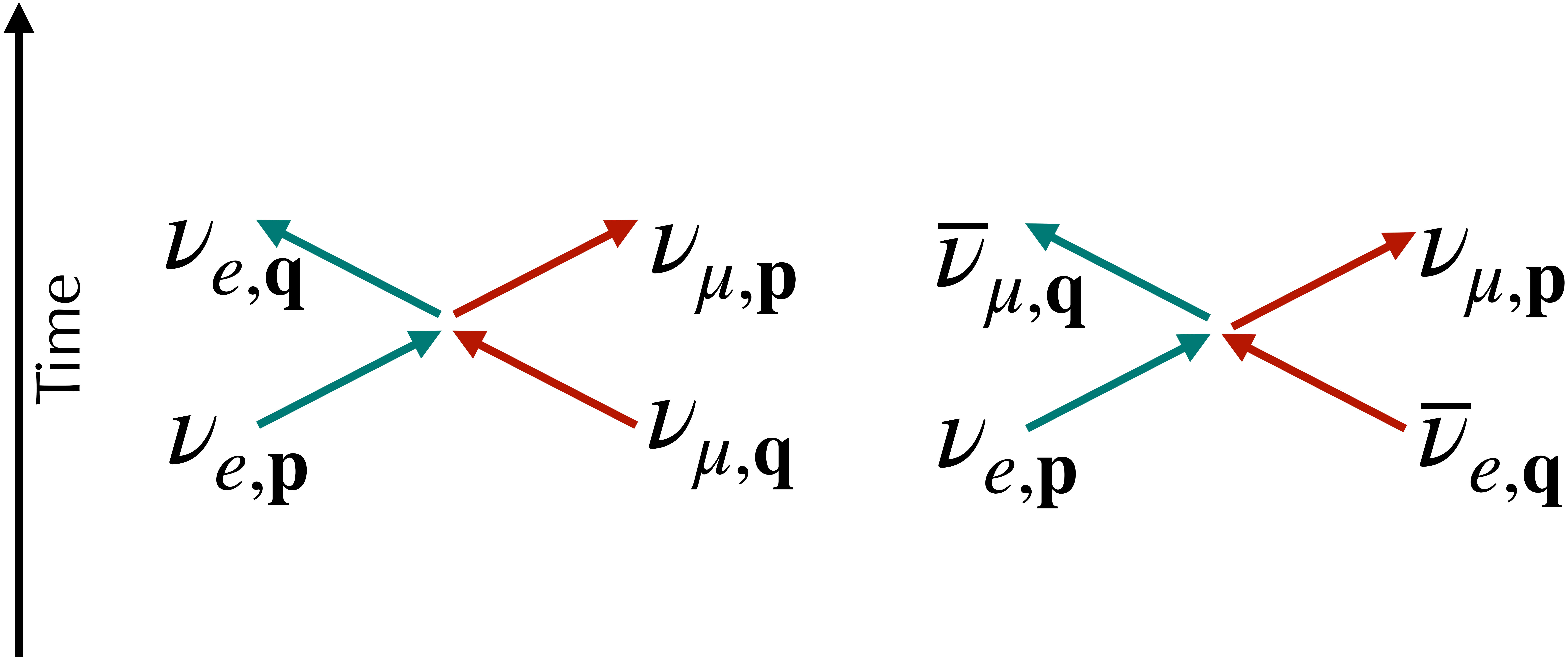
Collective flavor conversions



Time

$\nu_{e,\mathbf{q}}$ $\nu_{\mu,\mathbf{p}}$

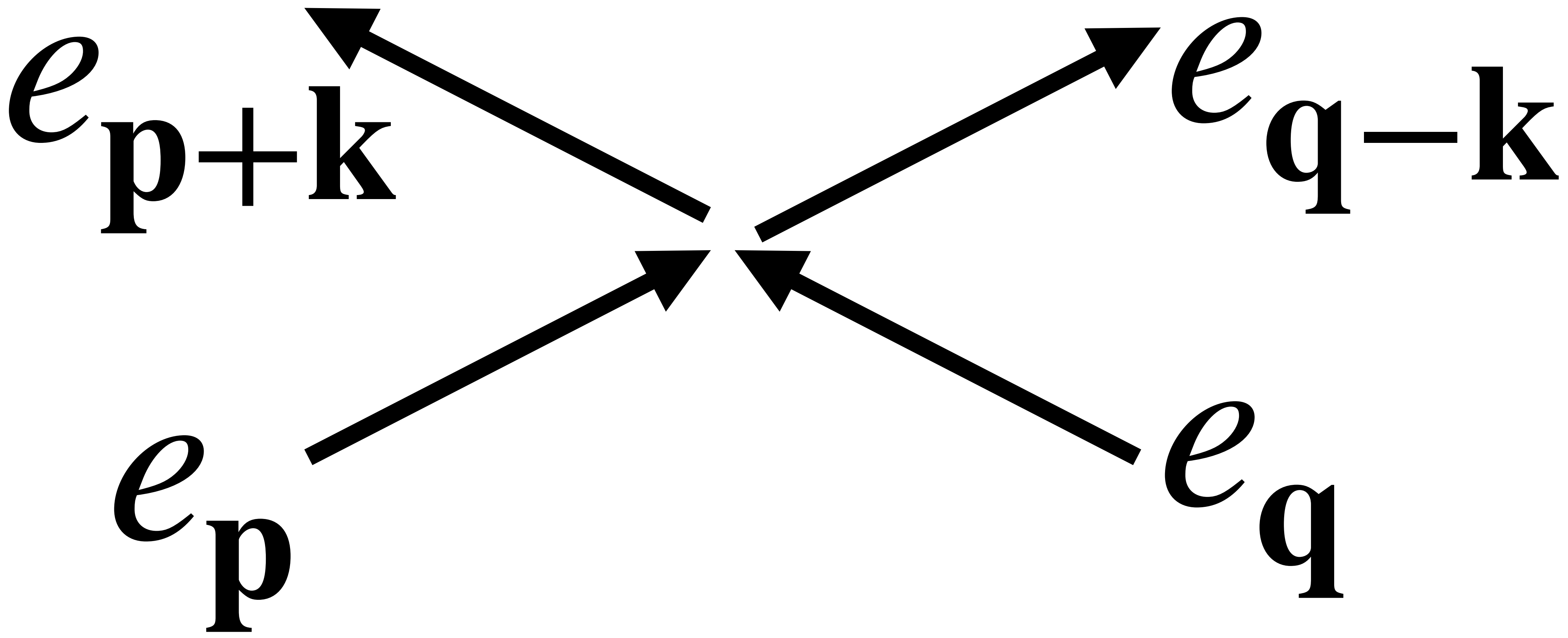
$\nu_{e,\mathbf{p}}$ $\nu_{\mu,\mathbf{q}}$

$\bar{\nu}_{\mu,\mathbf{q}}$ $\nu_{\mu,\mathbf{p}}$

$\nu_{e,\mathbf{p}}$ $\bar{\nu}_{e,\mathbf{q}}$

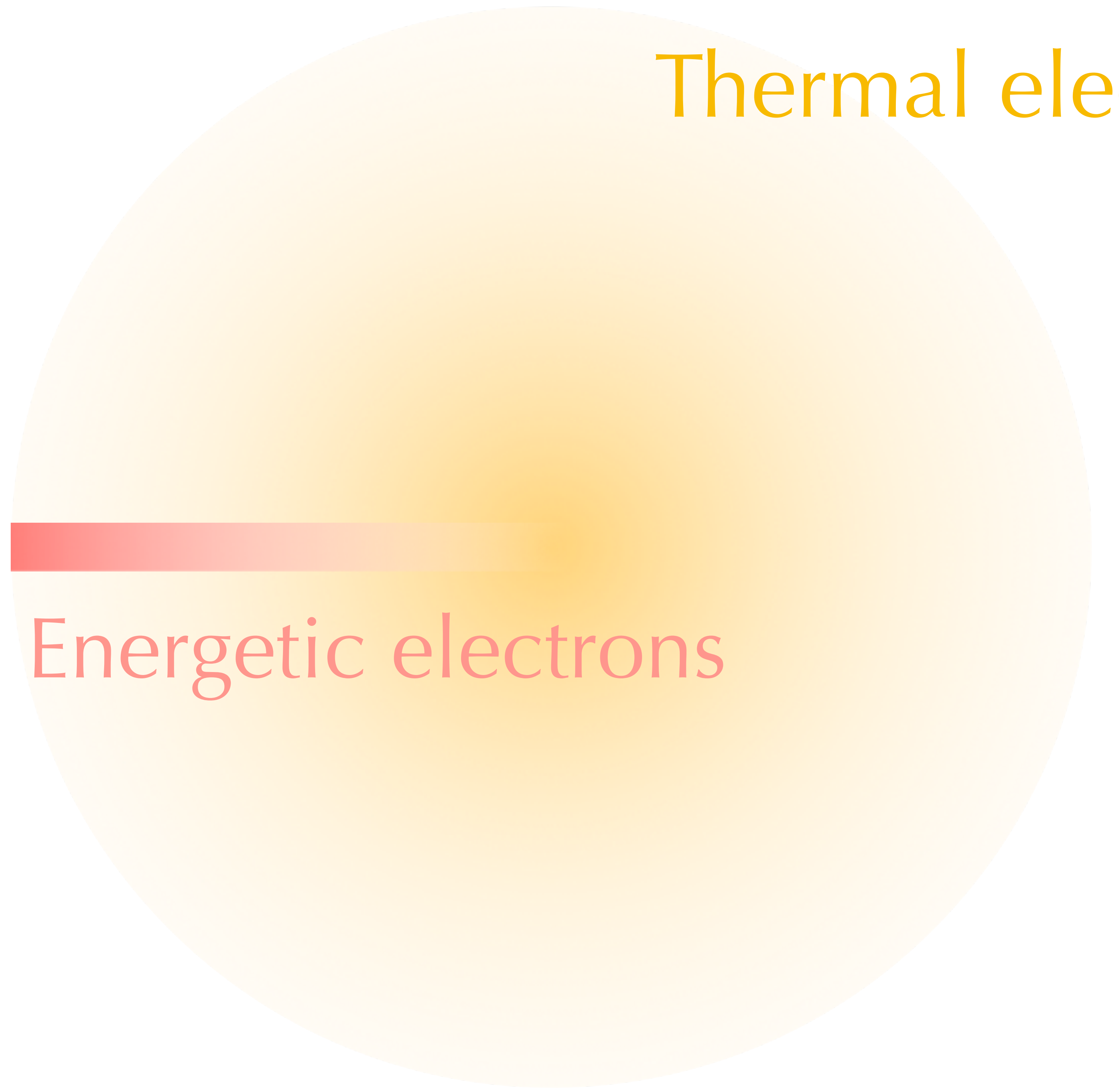
Scattering vs. collective

Coulomb scattering



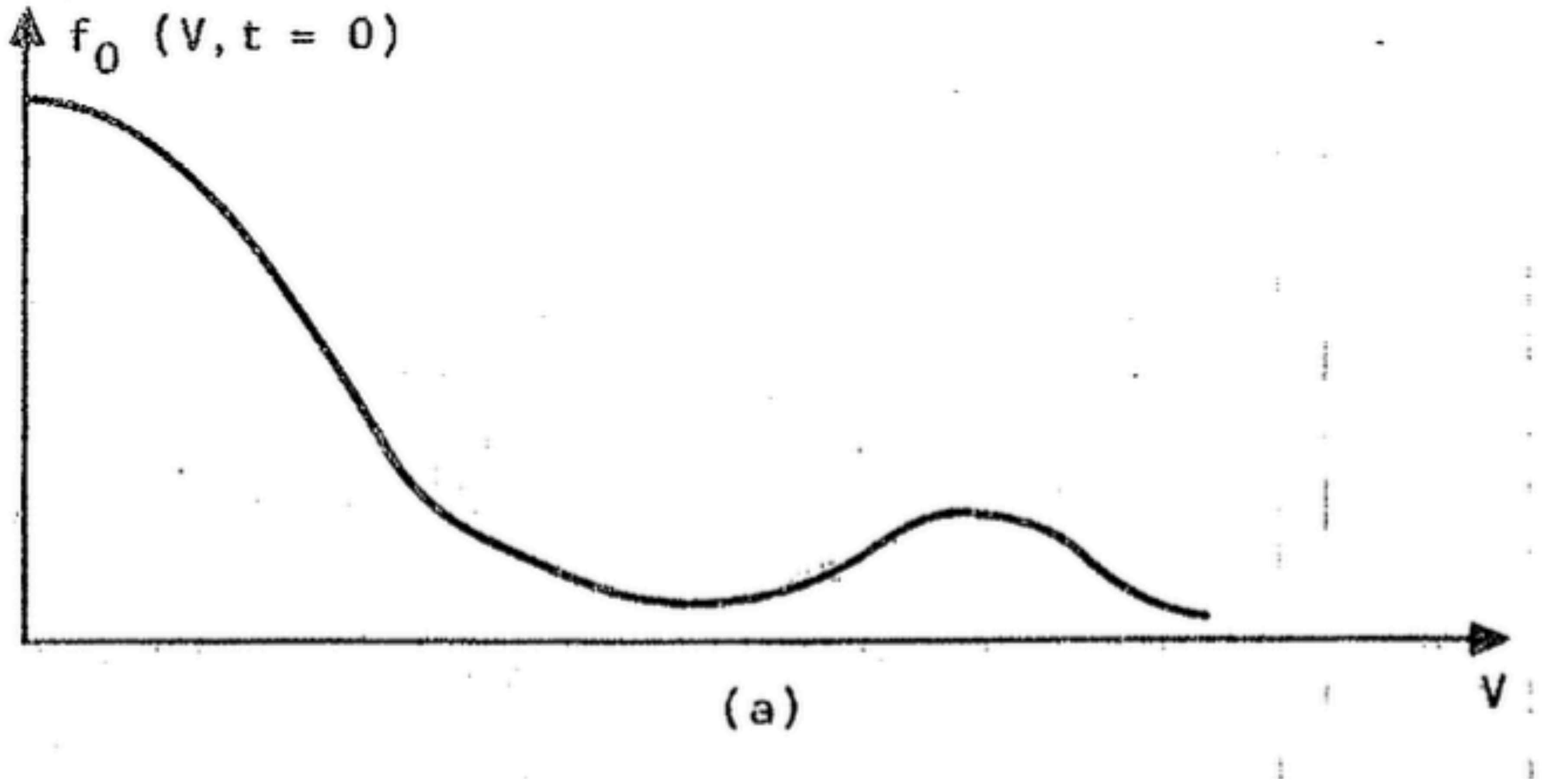
Rare, requires two electrons to come close together

Scattering vs. collective

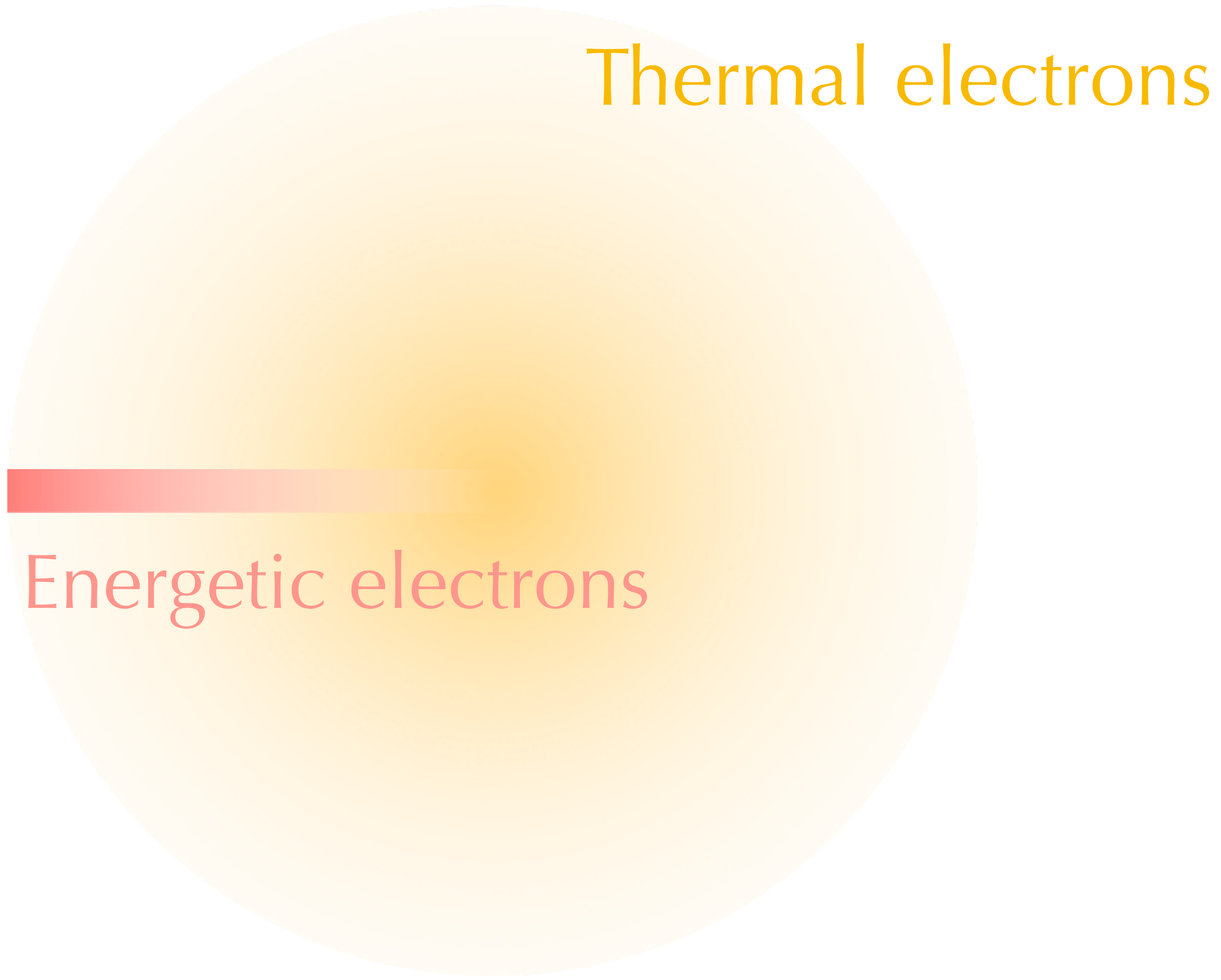


Thermal electrons

Energetic electrons

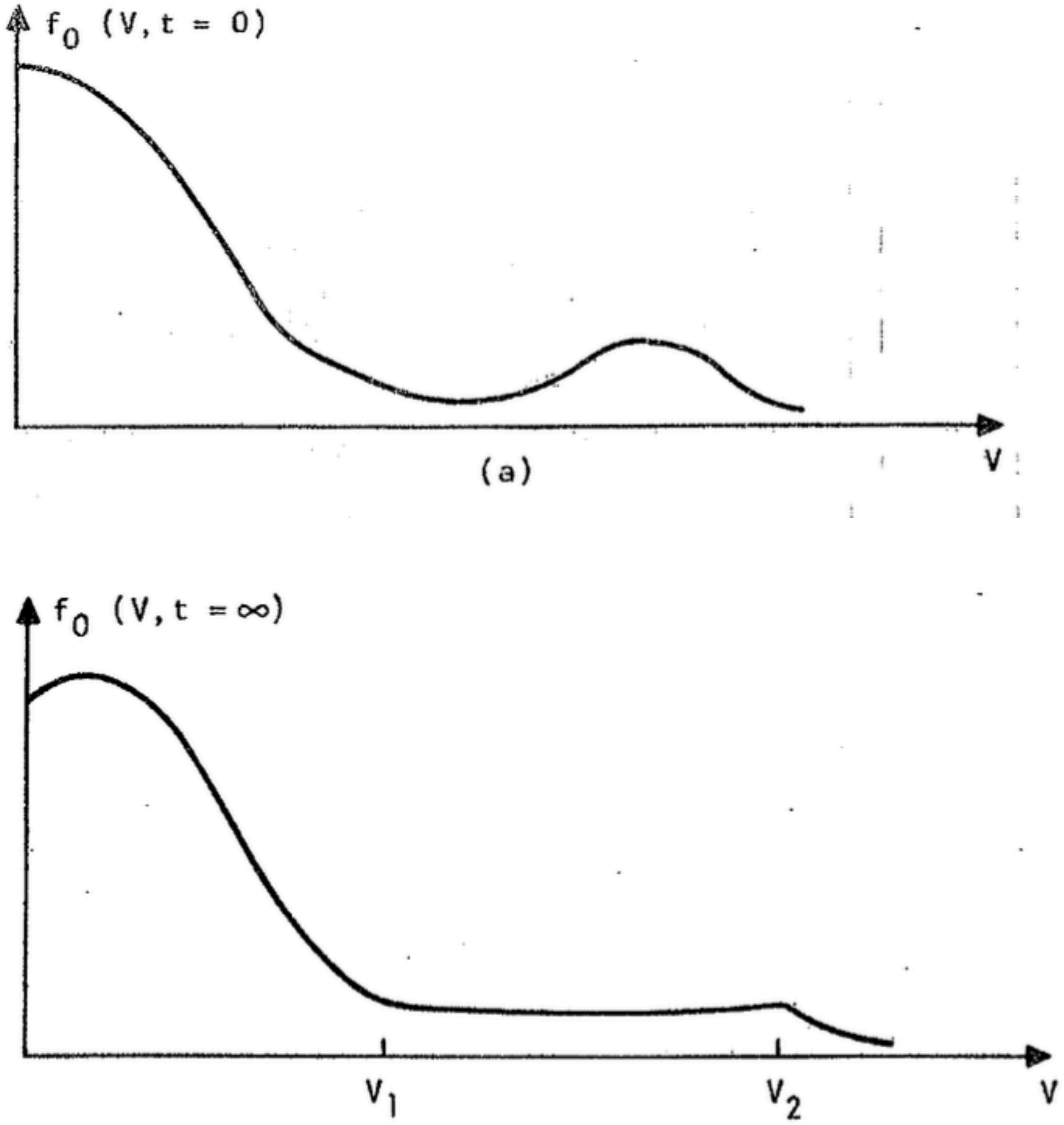


Scattering vs. collective

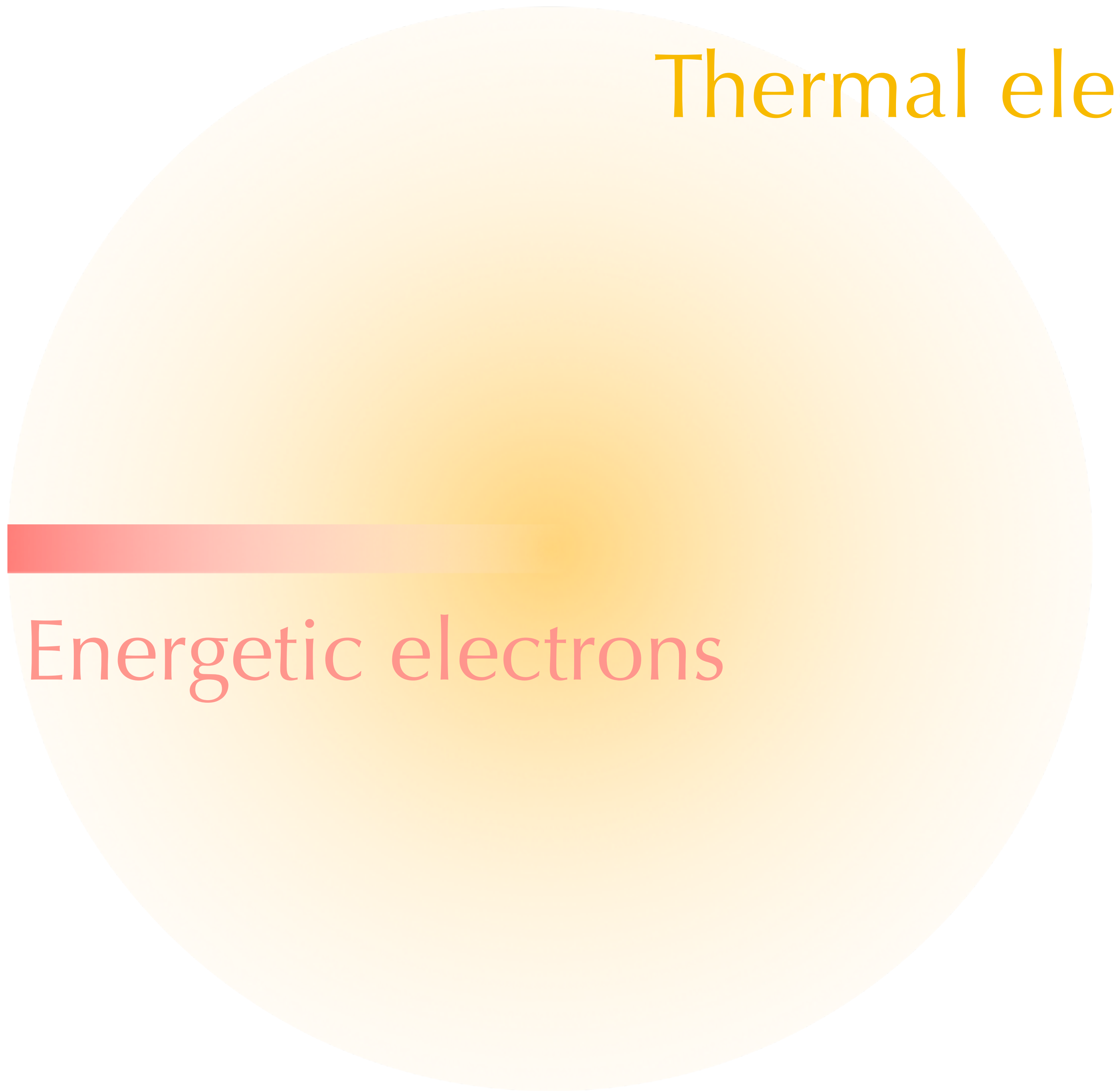


Thermal electrons

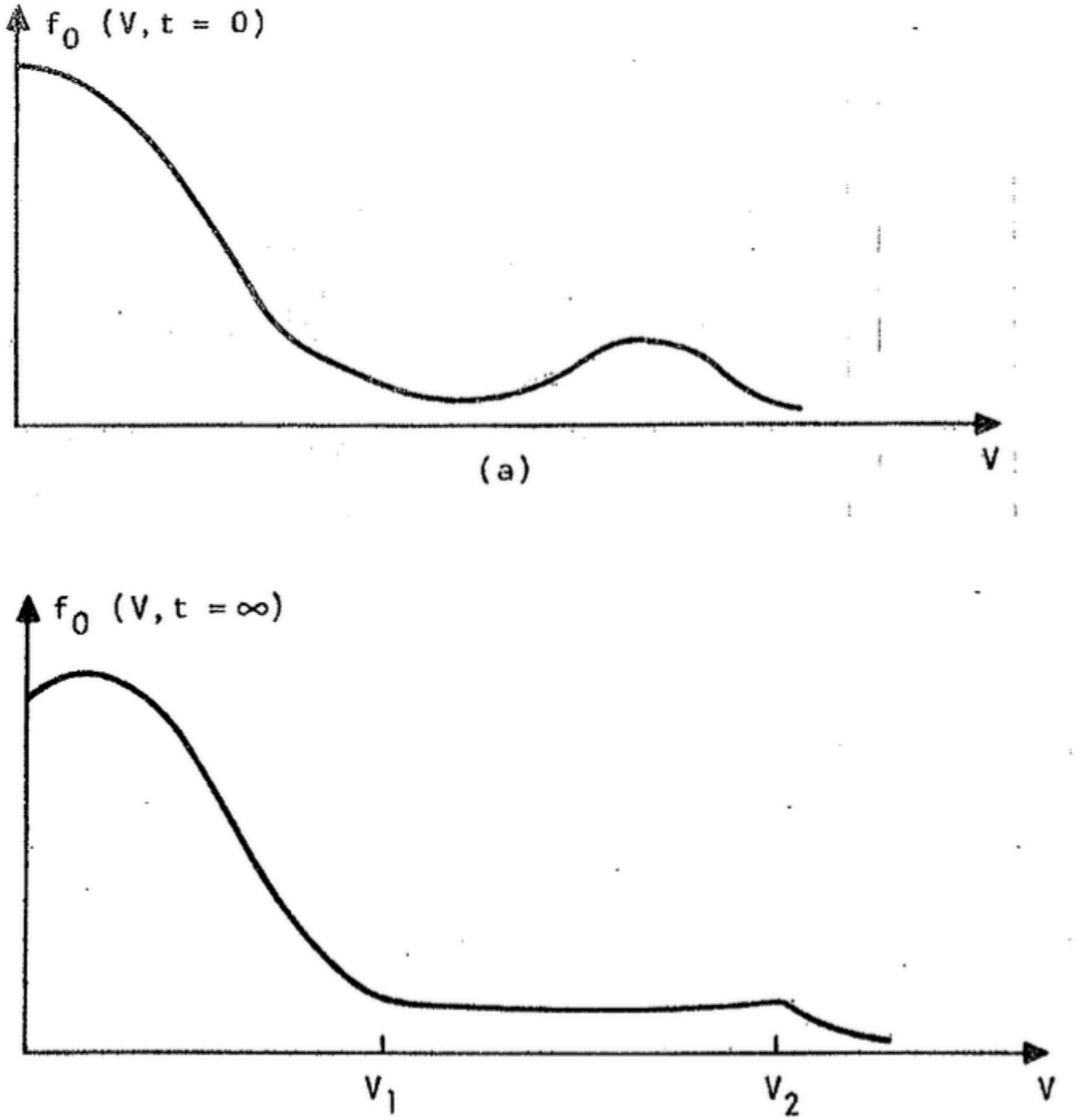
Energetic electrons



Scattering vs. collective



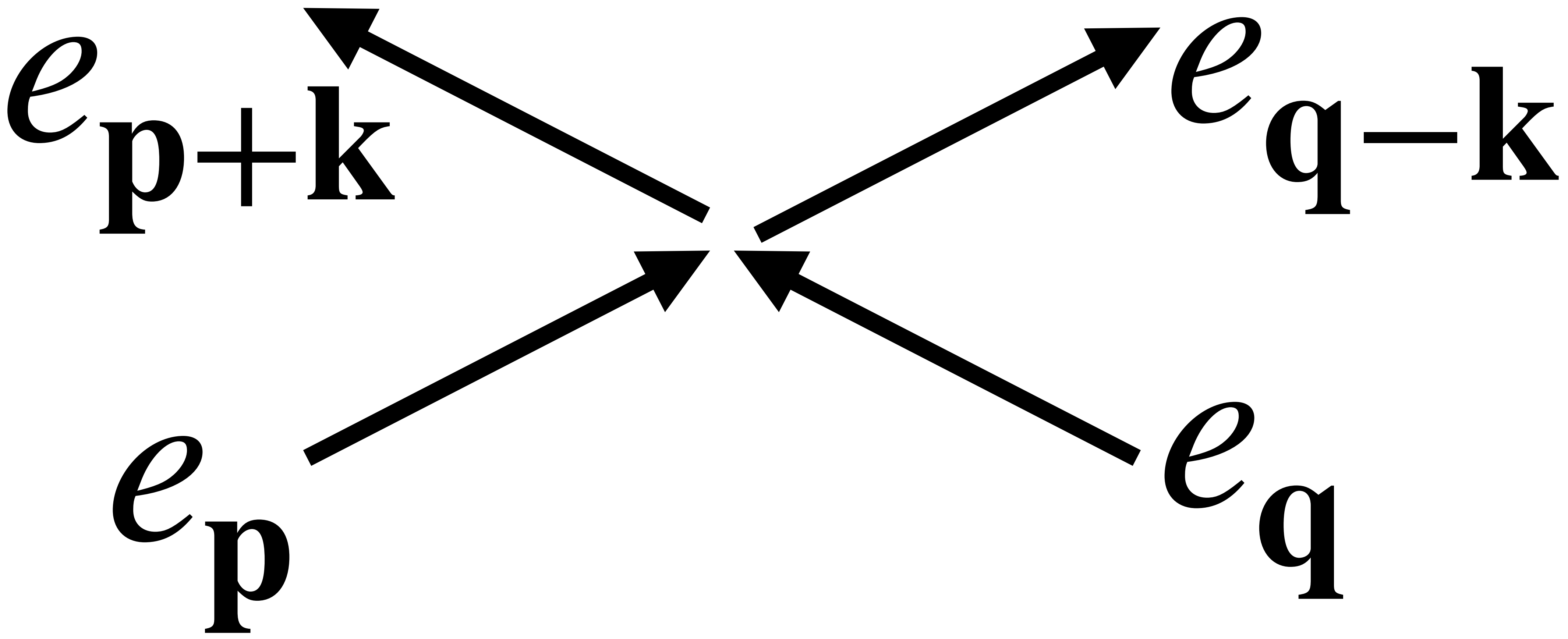
Plasma instabilities:
energetic electrons produce electric fields, mediating exchange with thermal electrons



Wave-particle interaction

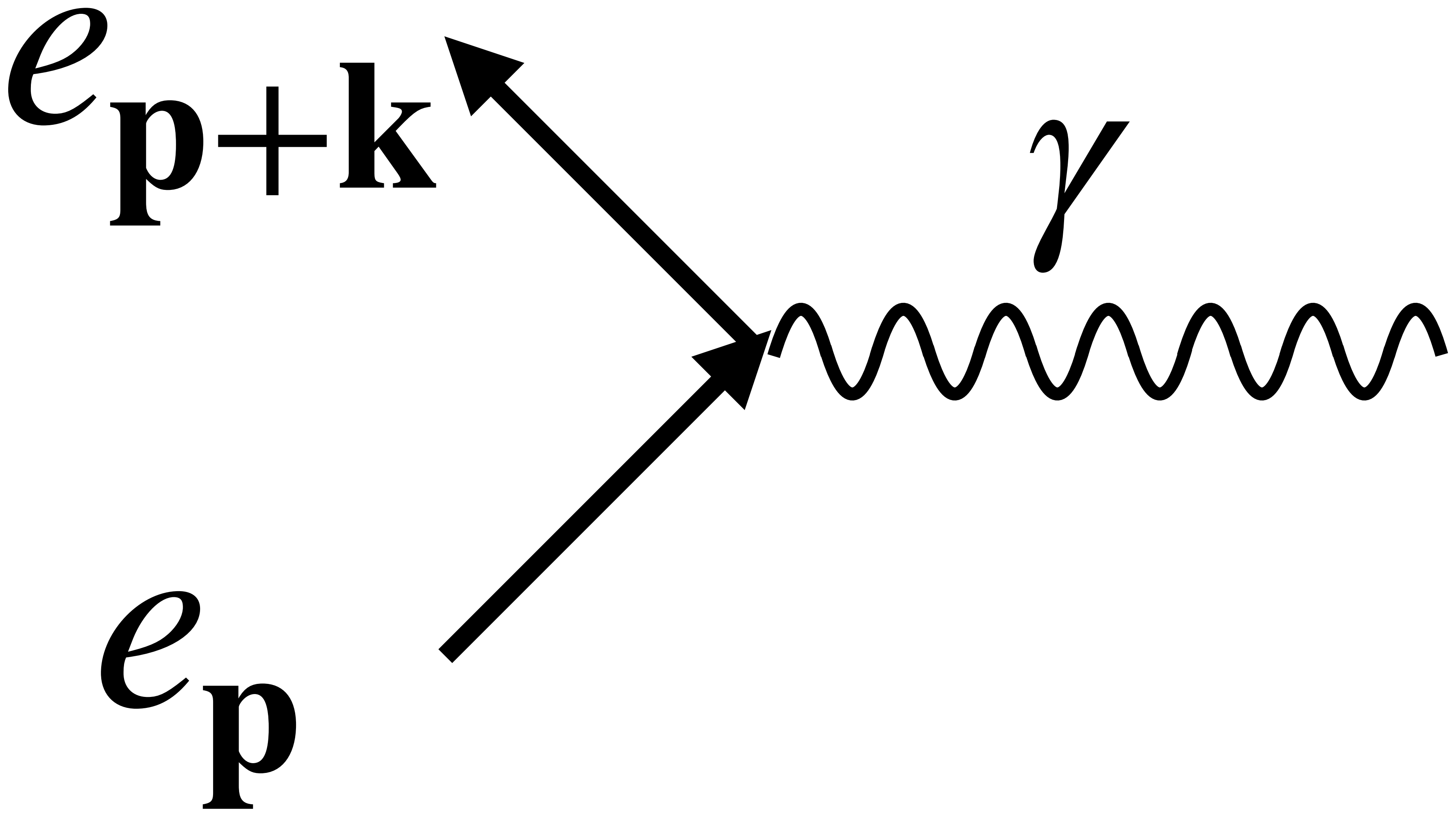
Scattering vs. collective

Coulomb scattering



Rare, requires two electrons to come close together

Electric field production

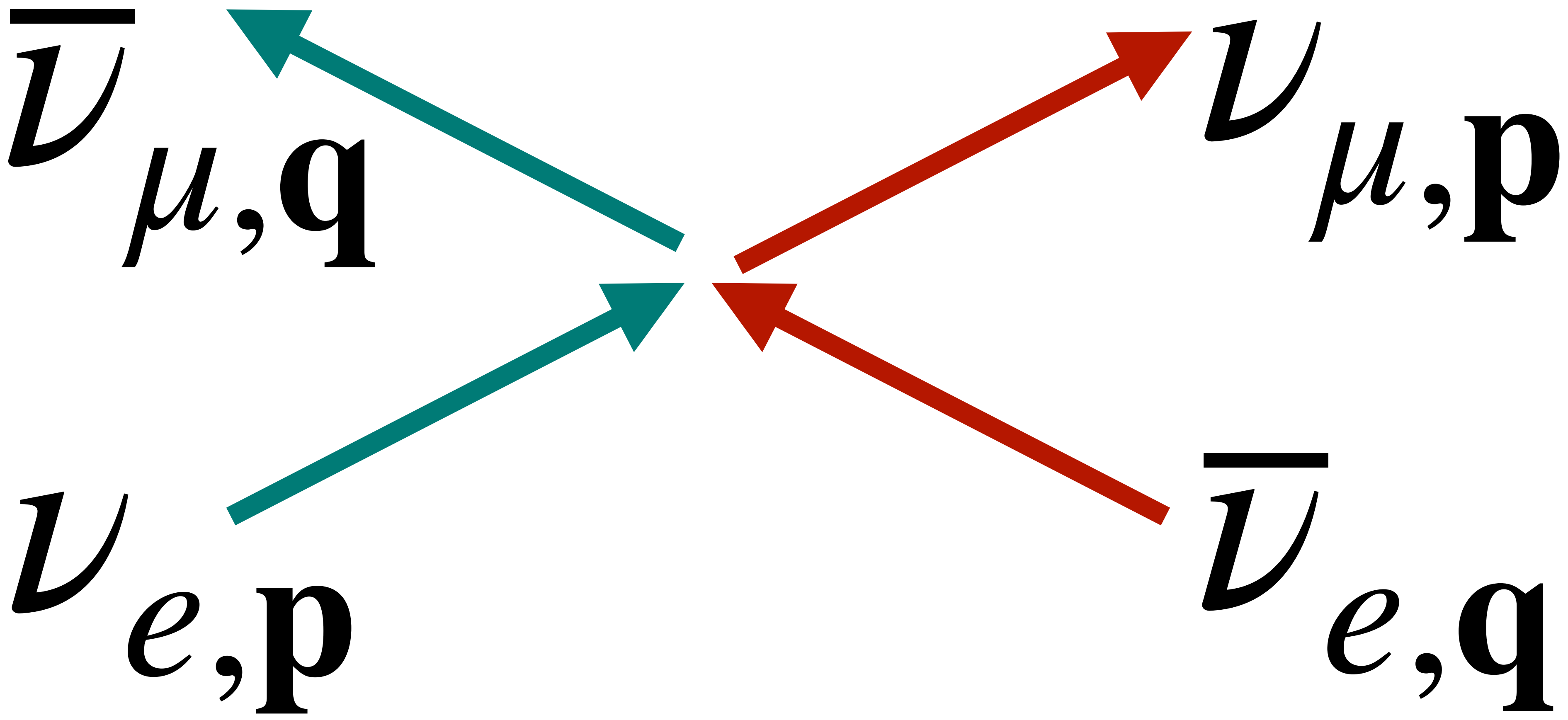


Plasmon emission — electron emits electric field

Inverse **Landau damping**

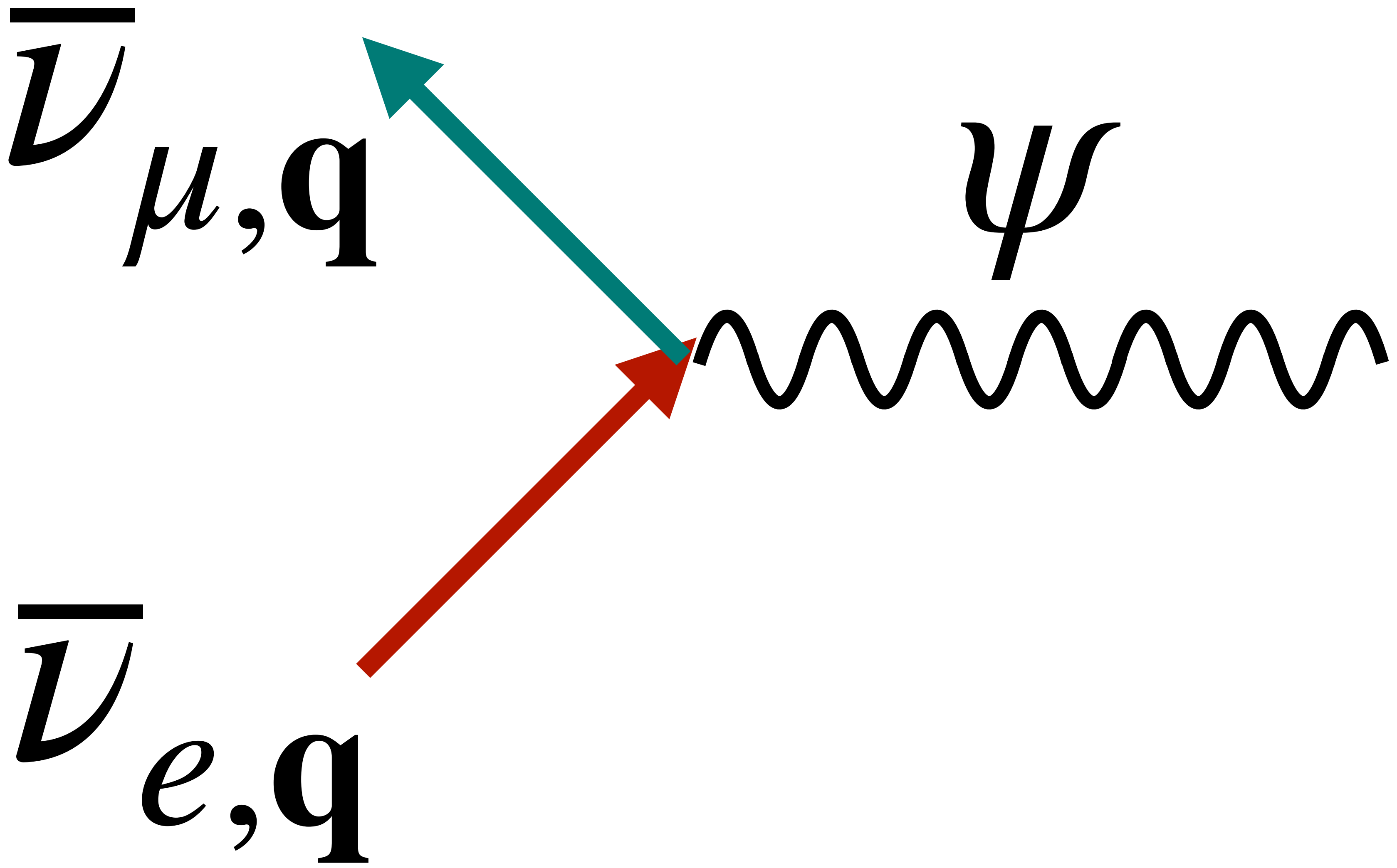
Scattering vs. collective

Neutrino scattering



Rare and irrelevant in SNe

Flavor field production



Flavomon emission

DF, *Raffelt, PRL, 2502.20389*

Theory of neutrino plasma

$$\lambda \sim 1 - 10\,\mathrm{mm}$$

$$\tau \sim 10 - 100\,\mathrm{ps}$$

Flavor waves

↓

Flavomons

Dispersion relation of **neutrino plasma** in ***DF***, *Raffelt, JHEP 2505.20389*

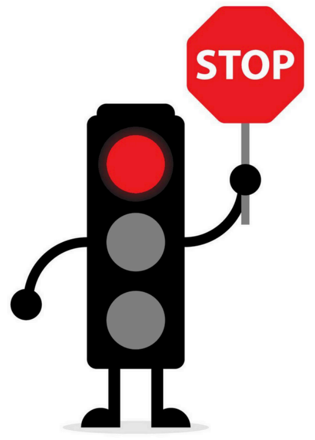
DF, *Raffelt, PRL, 2502.20389*

Quantum kinetic equations

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Sigl, Raffelt, Nucl. Phys. B, 1993

(See also *Vlasenko et al., PRD 1309.2628; Volpe et al., PRD 1302.2374; Serreau et al., PRD 1409.3591; Kartavtsev et al., PRD 1504.03230;* ***DF****, Raffelt, Sigl, PRD 2401.02478; PRL 2401.05278*)



$$\partial_t \rho \qquad + v\partial_r \rho \qquad = -i[\mathscr{H}, \rho]$$

Advection

Interaction

Interaction allows flavor exchange

Unstable growth of $\rho_{e\mu}$!

$$\mathscr{H} \propto \underbrace{\sqrt{2}G_F(n_\nu - n_{\bar{\nu}})}_{\mu\epsilon \sim (1\,\mathrm{cm})^{-1}} \sum_{'} \frac{\rho'}{(n_\nu - n_{\bar{\nu}})}$$

Flavor waves are real

Neutrinos have no partners to exchange flavor with

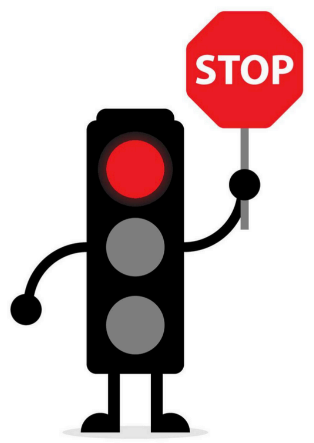
No crossing implies no instability
(Johns, PRD 2402.08896; ***DF****, Raffelt, JHEP 2406.06708)*

Flavomons ψ can only be absorbed ($\psi + \nu_e \to \nu_\mu$) but not produced, so **no conversion**

In a ν_e-dominated plasma, flavomons carry lepton number $\nu_\mu \overline{\nu}_e$

Flavor waves are real

In a ν_e-dominated plasma, flavomons carry lepton number $\nu_\mu\bar{\nu}_e$



Emission

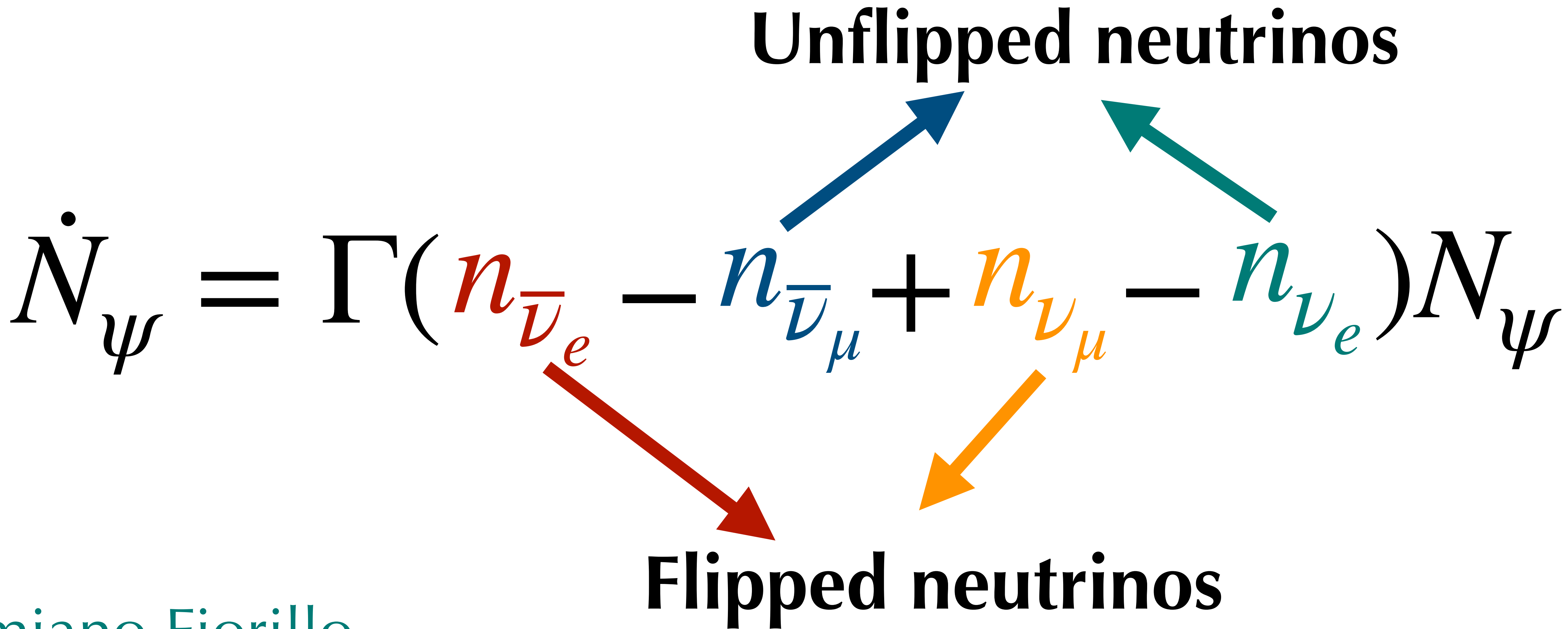
Absorption

Flavor waves are real

$$\dot{N}_\psi = \Gamma[(n_{\bar\nu_e} + n_{\nu_\mu})(1 + N_\psi) - (n_{\bar\nu_\mu} + n_{\nu_e})N_\psi]$$

Flavor waves are real

$$\dot N_\psi = \Gamma[(n_{\bar\nu_e}+n_{\nu_\mu})(1+N_\psi)-(n_{\bar\nu_\mu}+n_{\nu_e})N_\psi]$$



Unflipped neutrinos

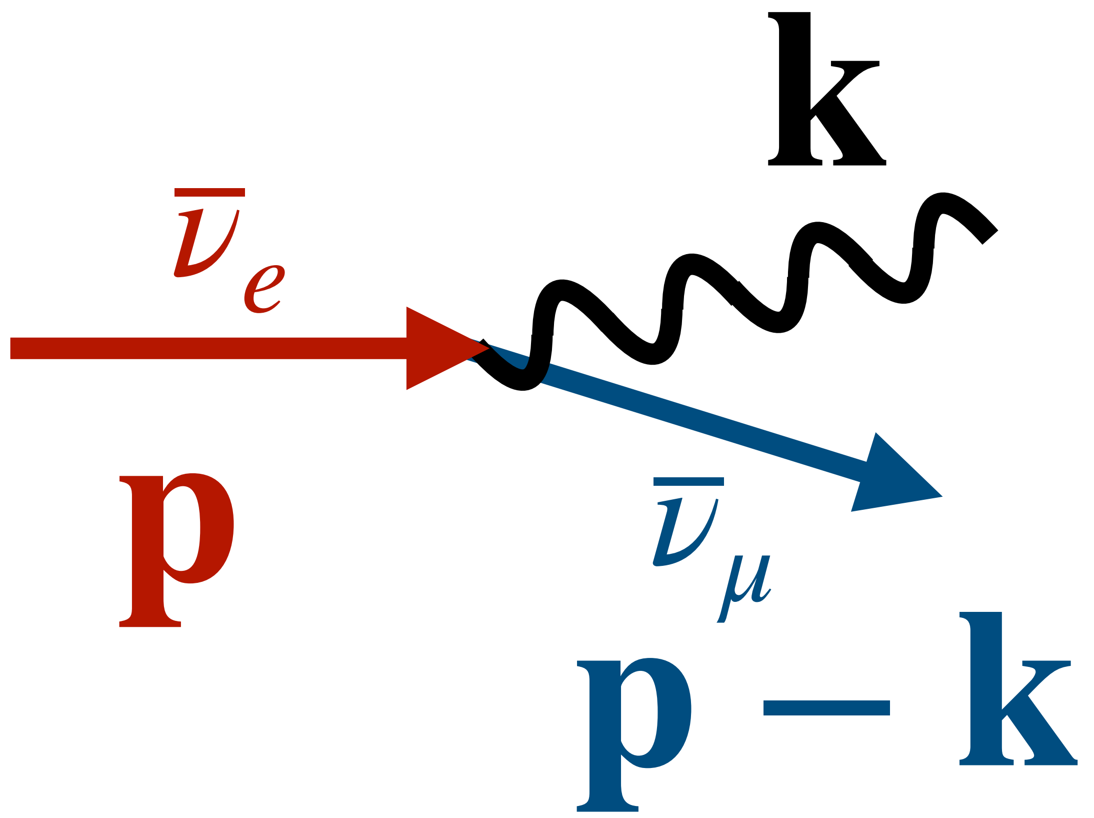
$$\dot N_\psi = \Gamma(n_{\bar\nu_e} - n_{\bar\nu_\mu} + n_{\nu_\mu} - n_{\nu_e})N_\psi$$

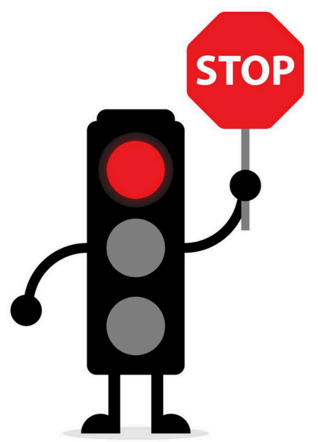
Flipped neutrinos

Find neutrinos kinematically able to emit flavomons (**resonant neutrinos**)

If **flipped** dominate over **unflipped**, **instability!**

Fast instability



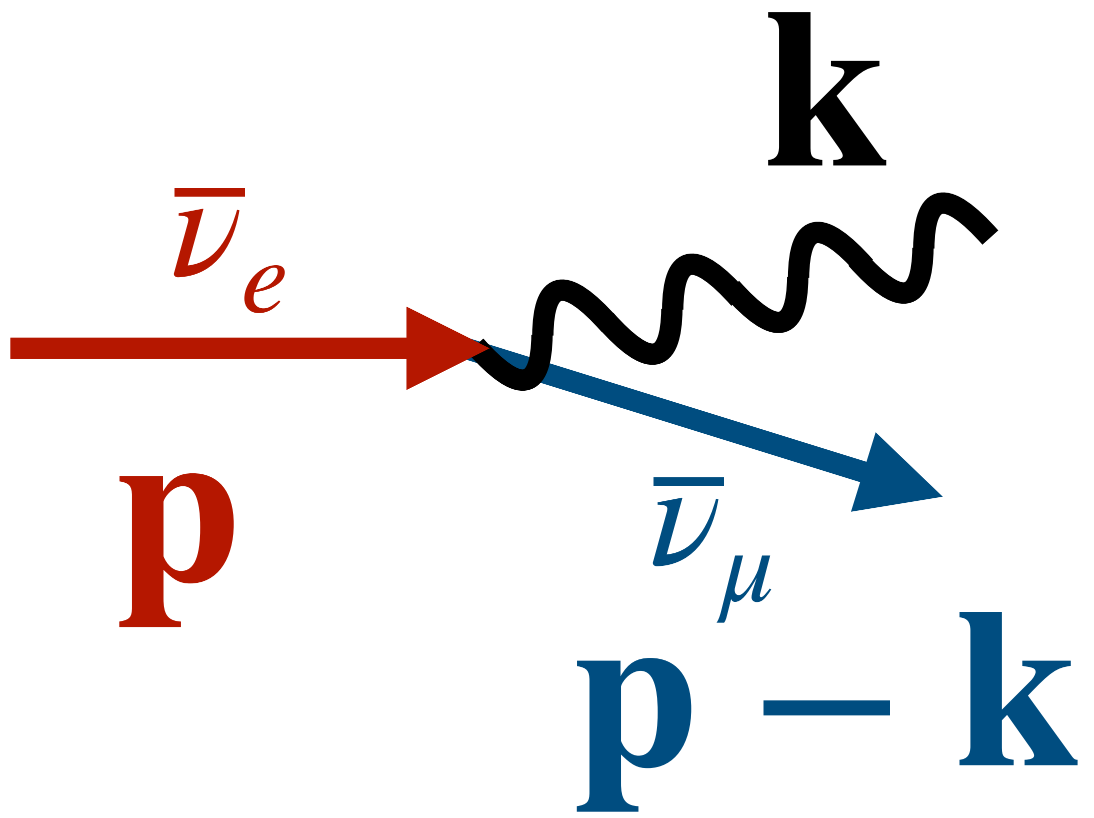


$$\omega_{\mathbf{k}} = E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{k}}$$

$$\omega_{\mathbf{k}} = \mathbf{v} \cdot \mathbf{k}$$

***DF**, Raffelt, PRL 2502.06935; PRL 2507.22987*

Fast instability



$$\omega_\mathbf{k} = E_\mathbf{p} - E_{\mathbf{p}-\mathbf{k}}$$

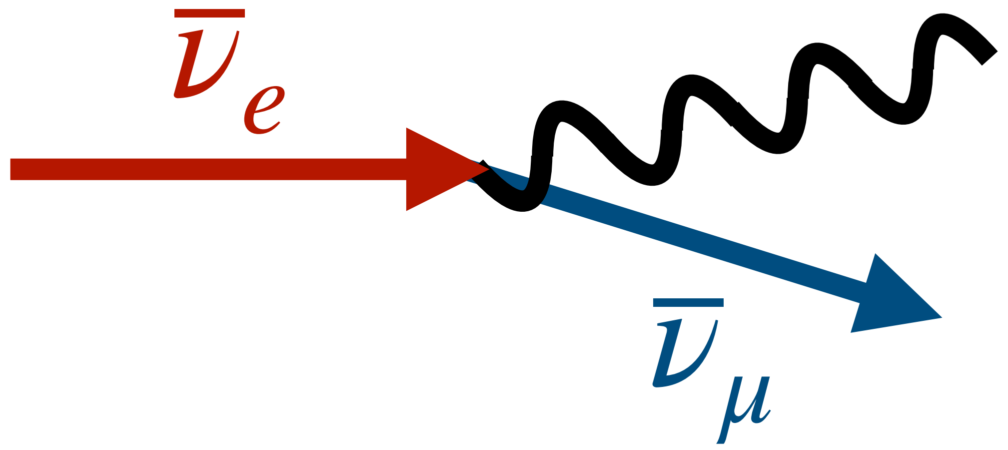
$$\omega_\mathbf{k} = \mathbf{v}\cdot\mathbf{k}$$

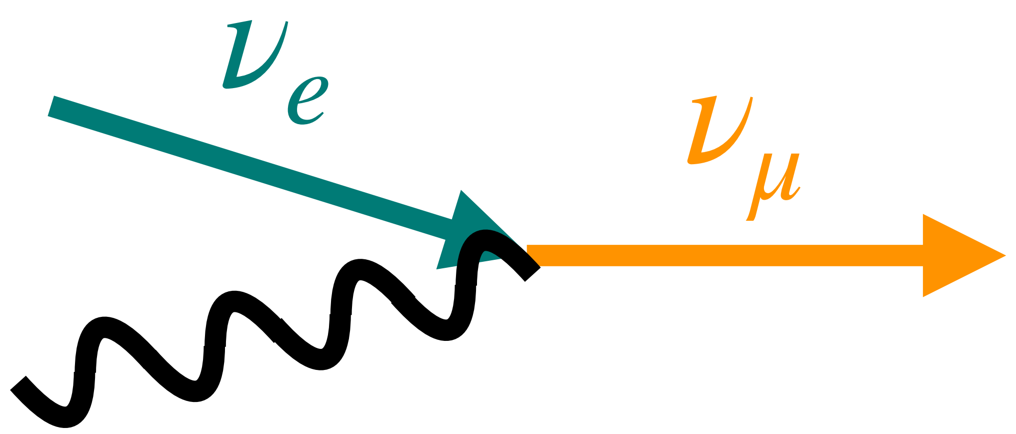
Incidentally, collective flavor conversions heat or cool the neutrino plasma (but only by $\mu\epsilon \sim 0.1\,\mathrm{meV}$)!

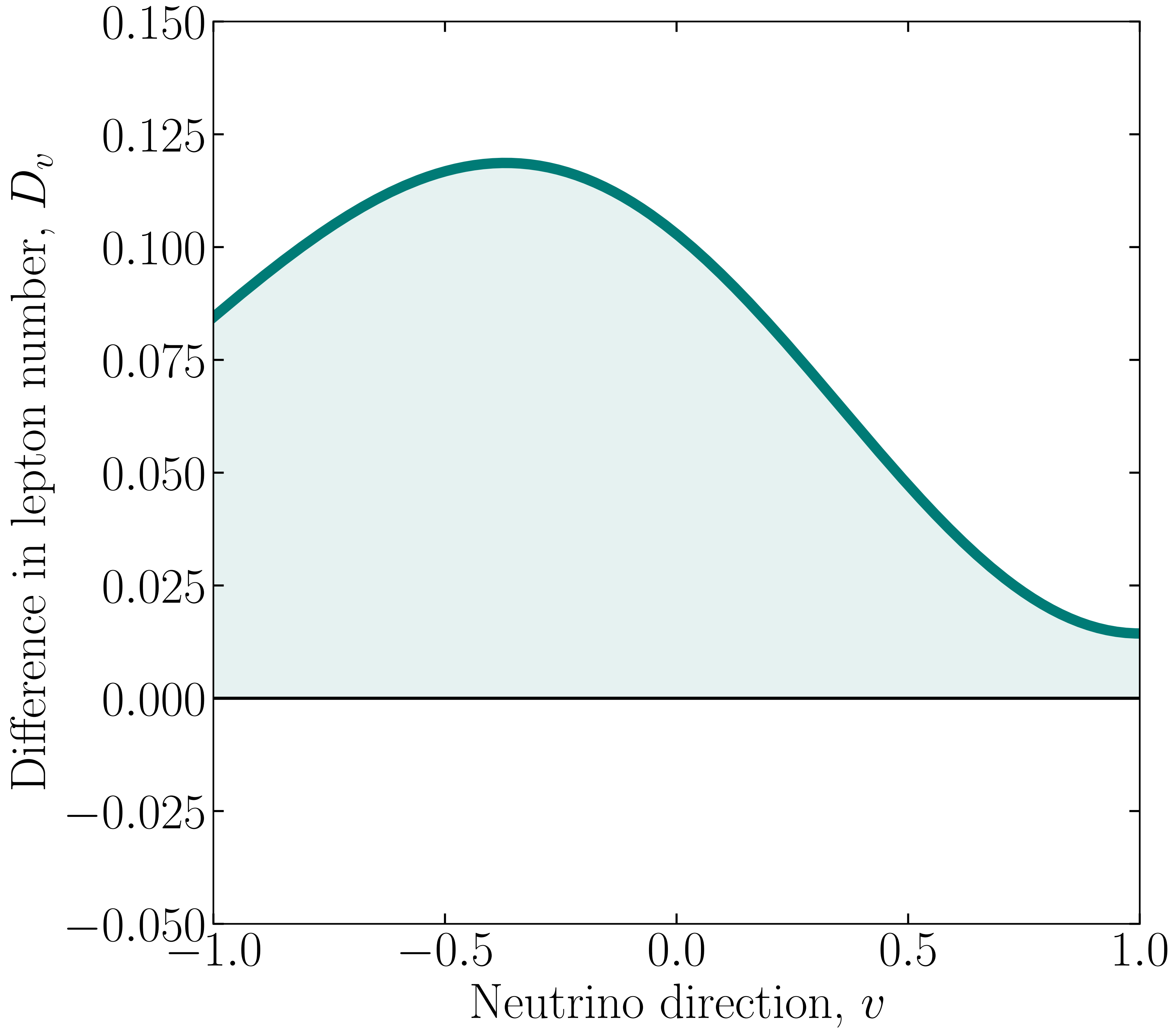
***DF**, Raffelt, Sigl, PRL 2401.05278*

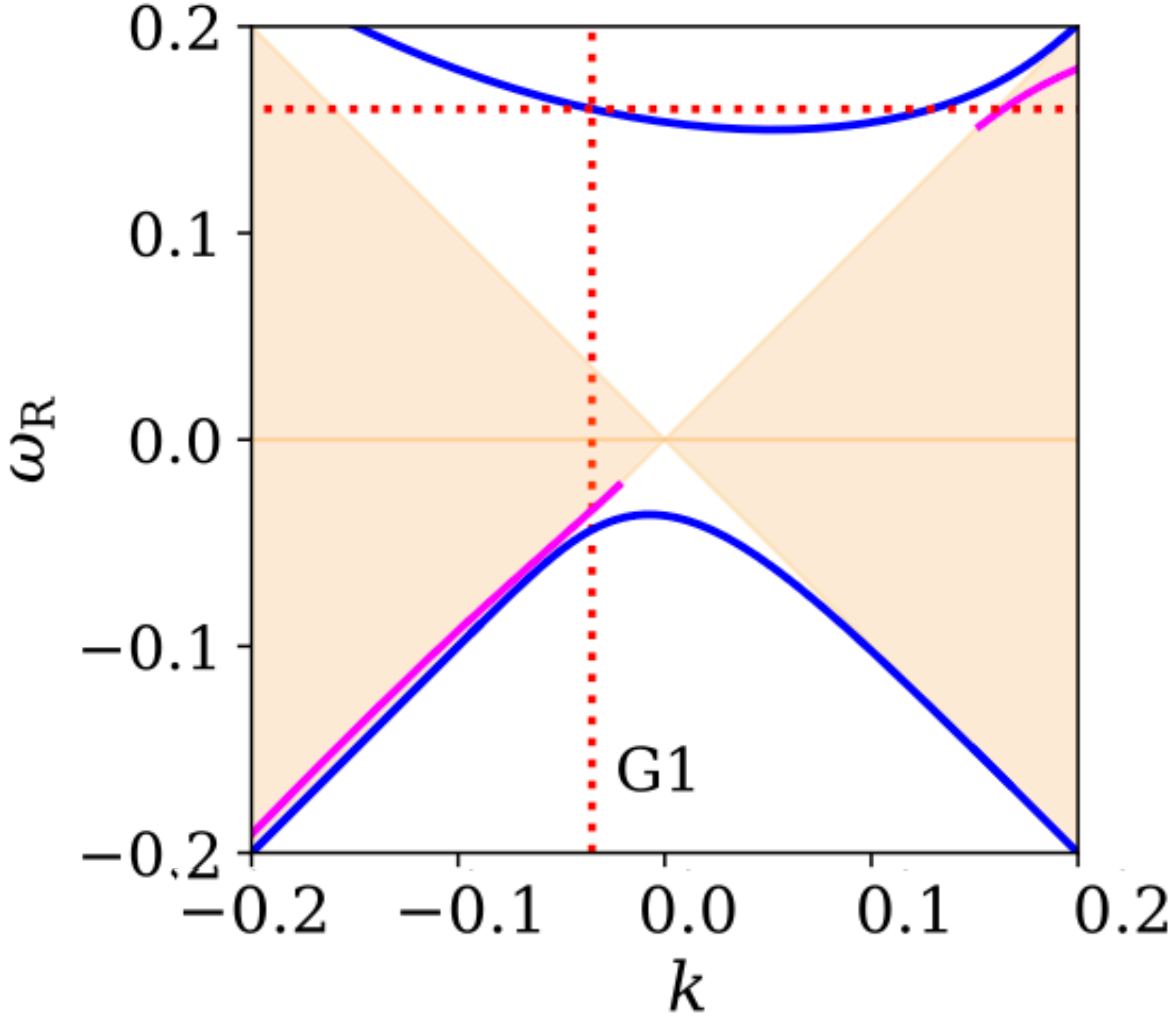
***DF**, Raffelt, PRL 2502.06935; PRL 2507.22987*

Fast instability





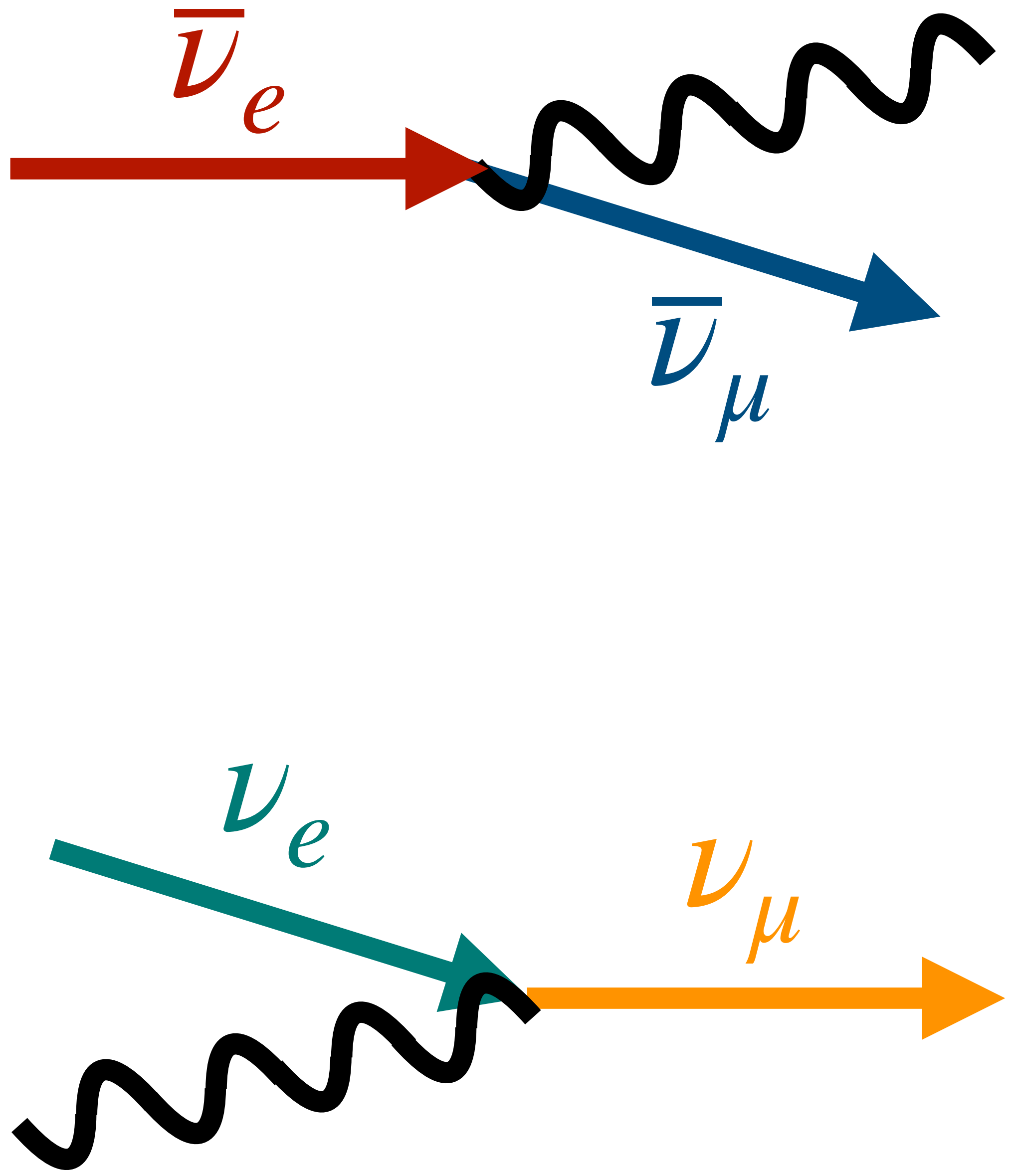


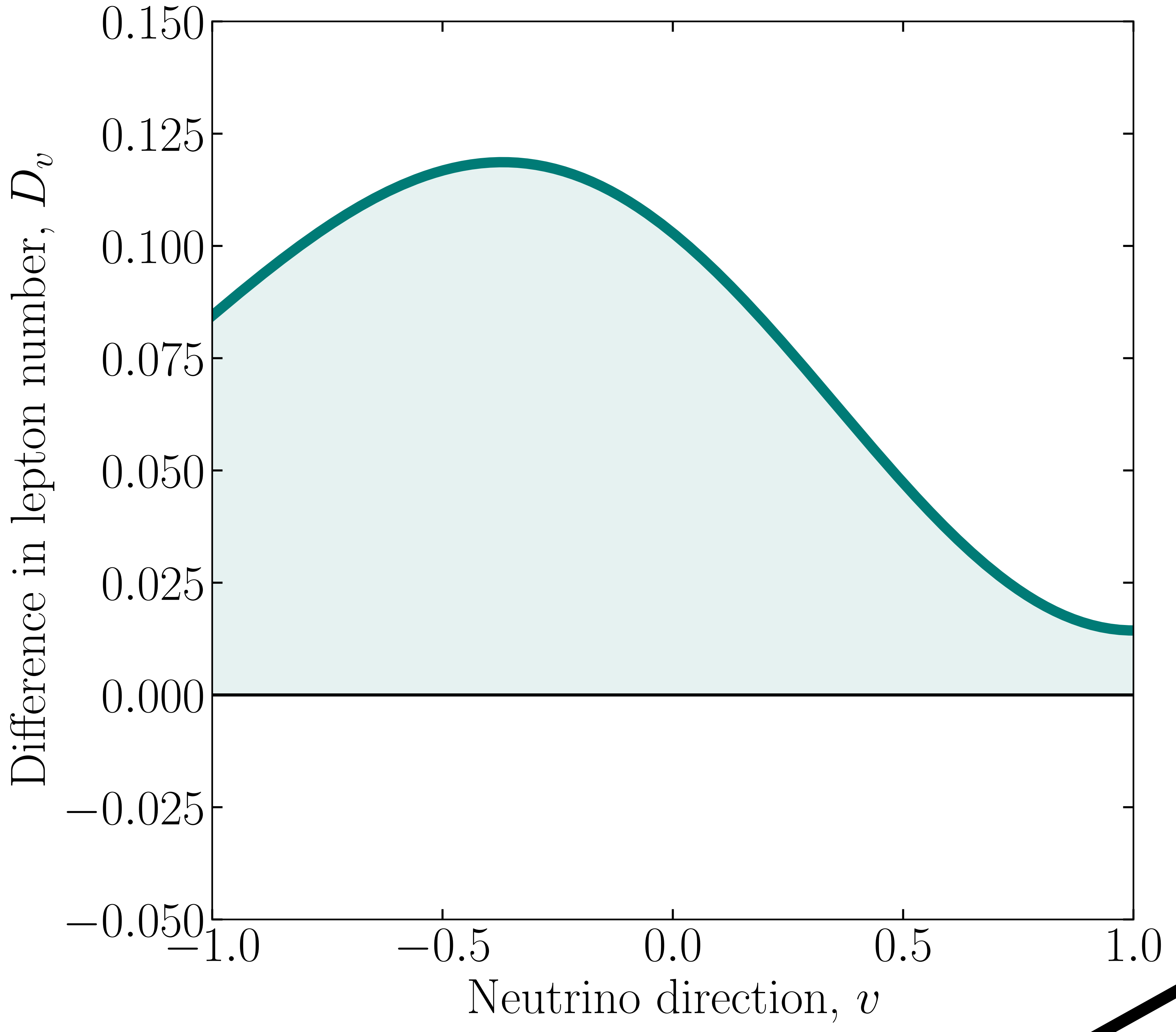


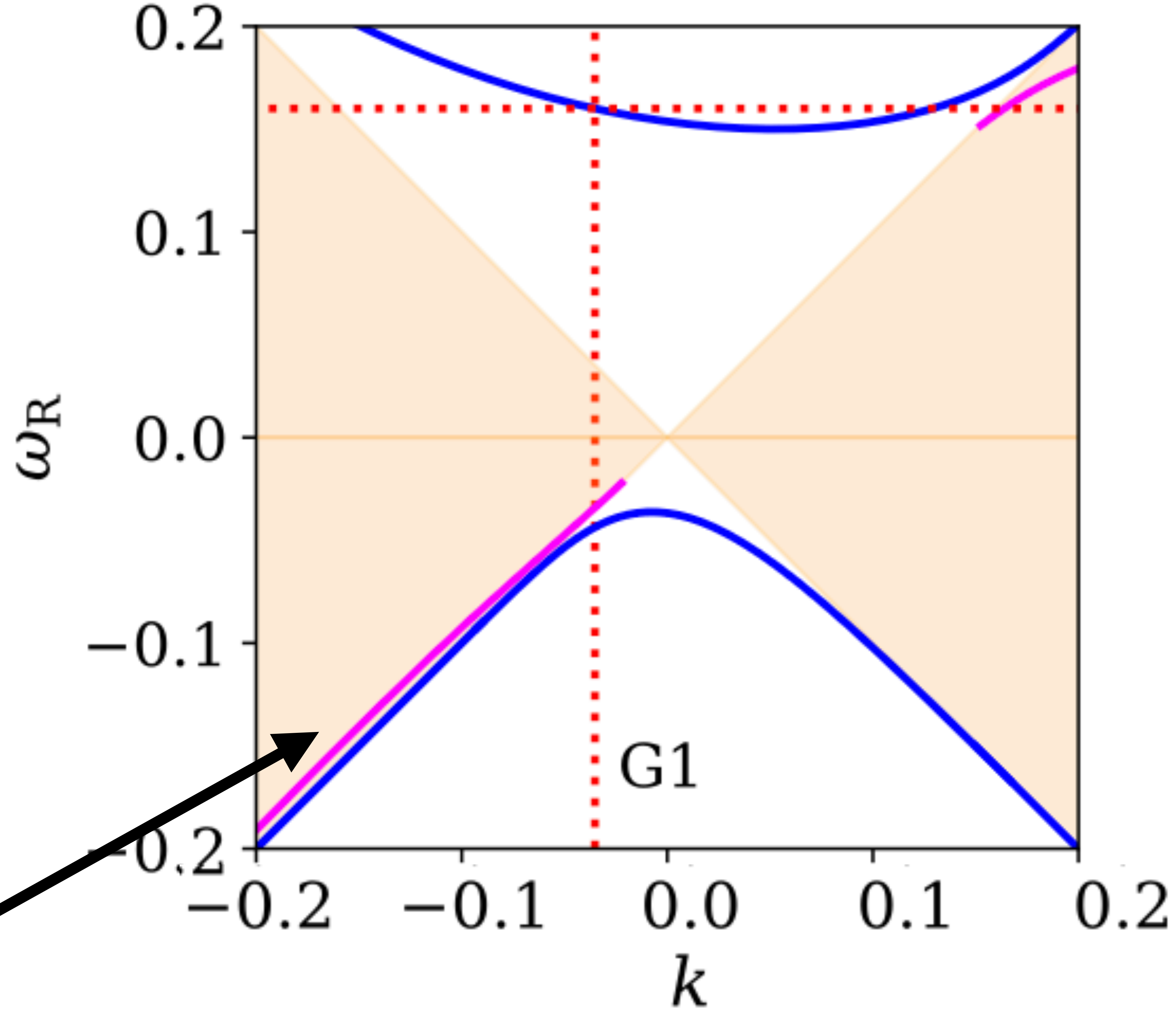
$$\cos\theta = \frac{\omega_{\mathbf{k}}}{k}$$

DF, *Goimil-Garcia, Raffelt, PRD 2412.09027*

Fast instability





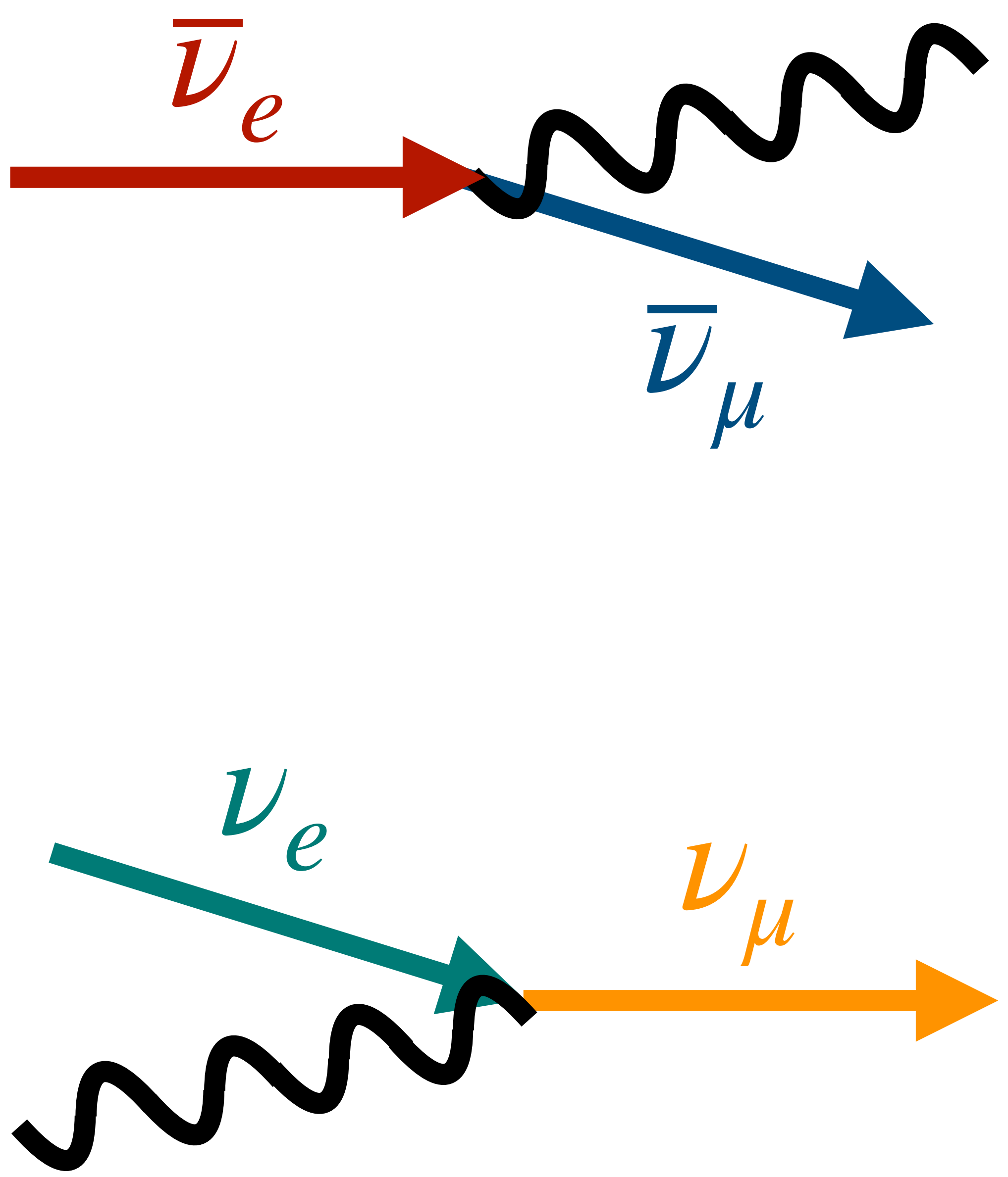


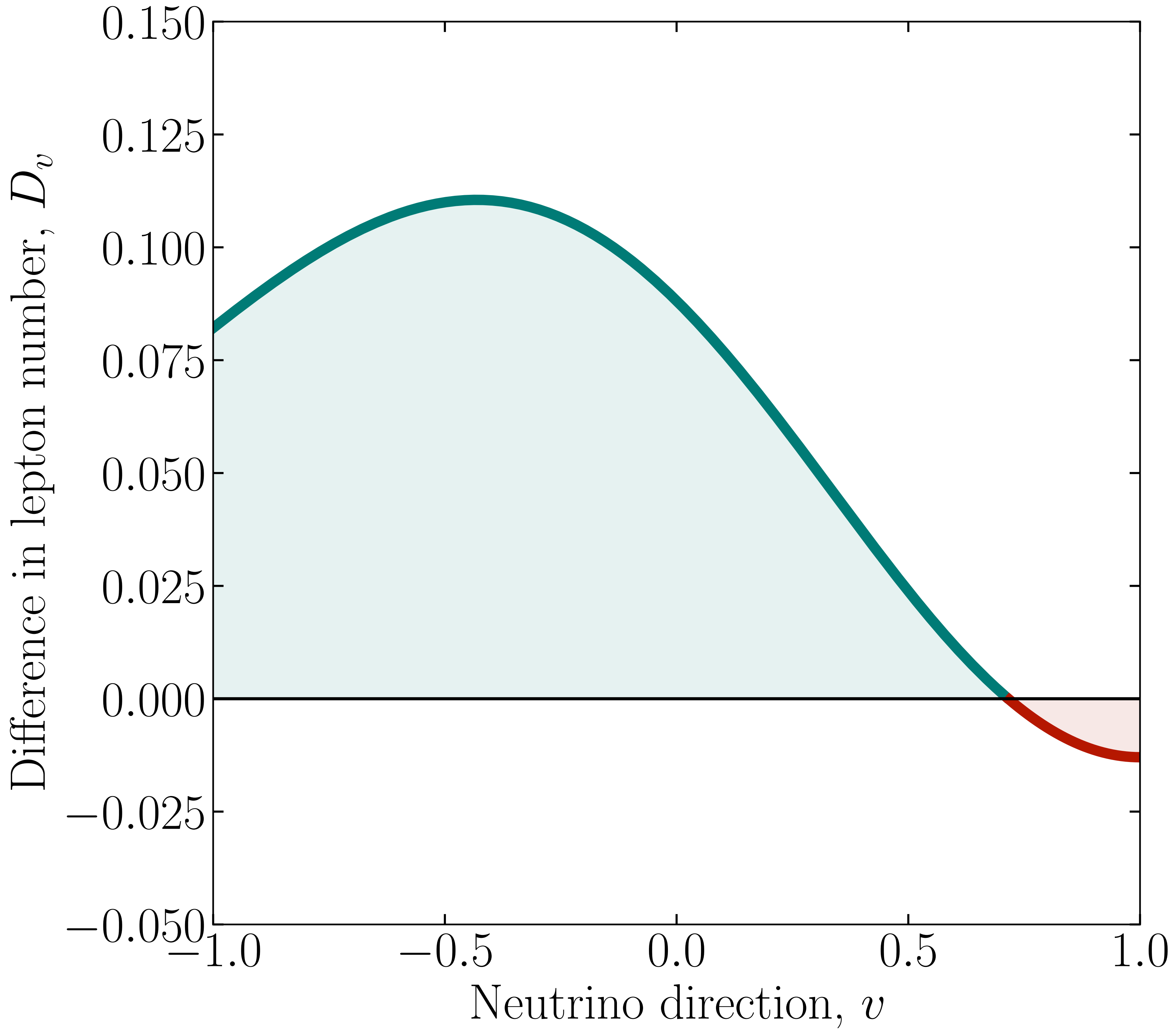
$$\cos\theta = \frac{\omega_{\mathbf{k}}}{k}$$

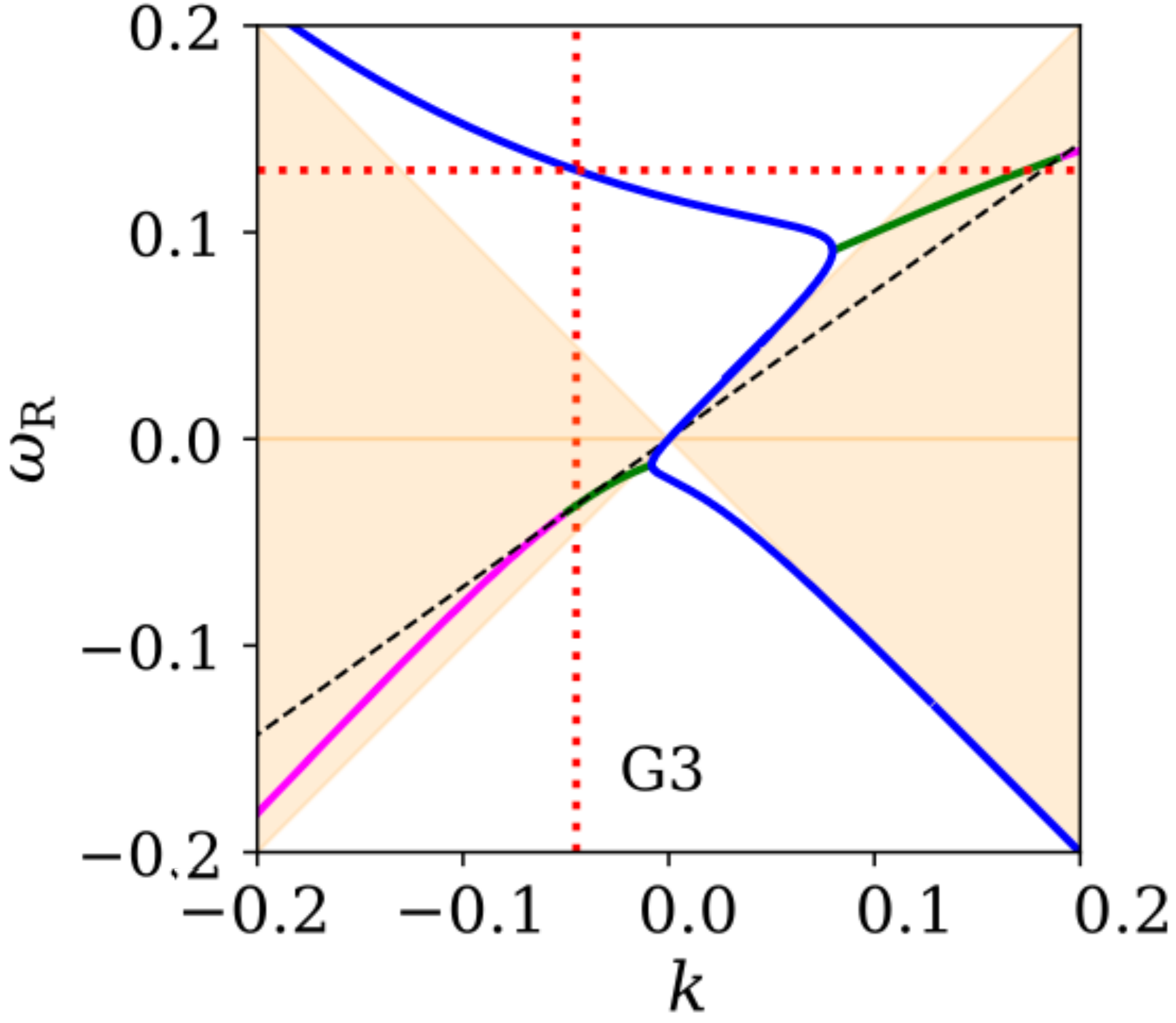
More ν_e than $\bar{\nu}_e$ (absorption!)

DF*, Goimil-Garcia, Raffelt, PRD 2412.09027*

Fast instability



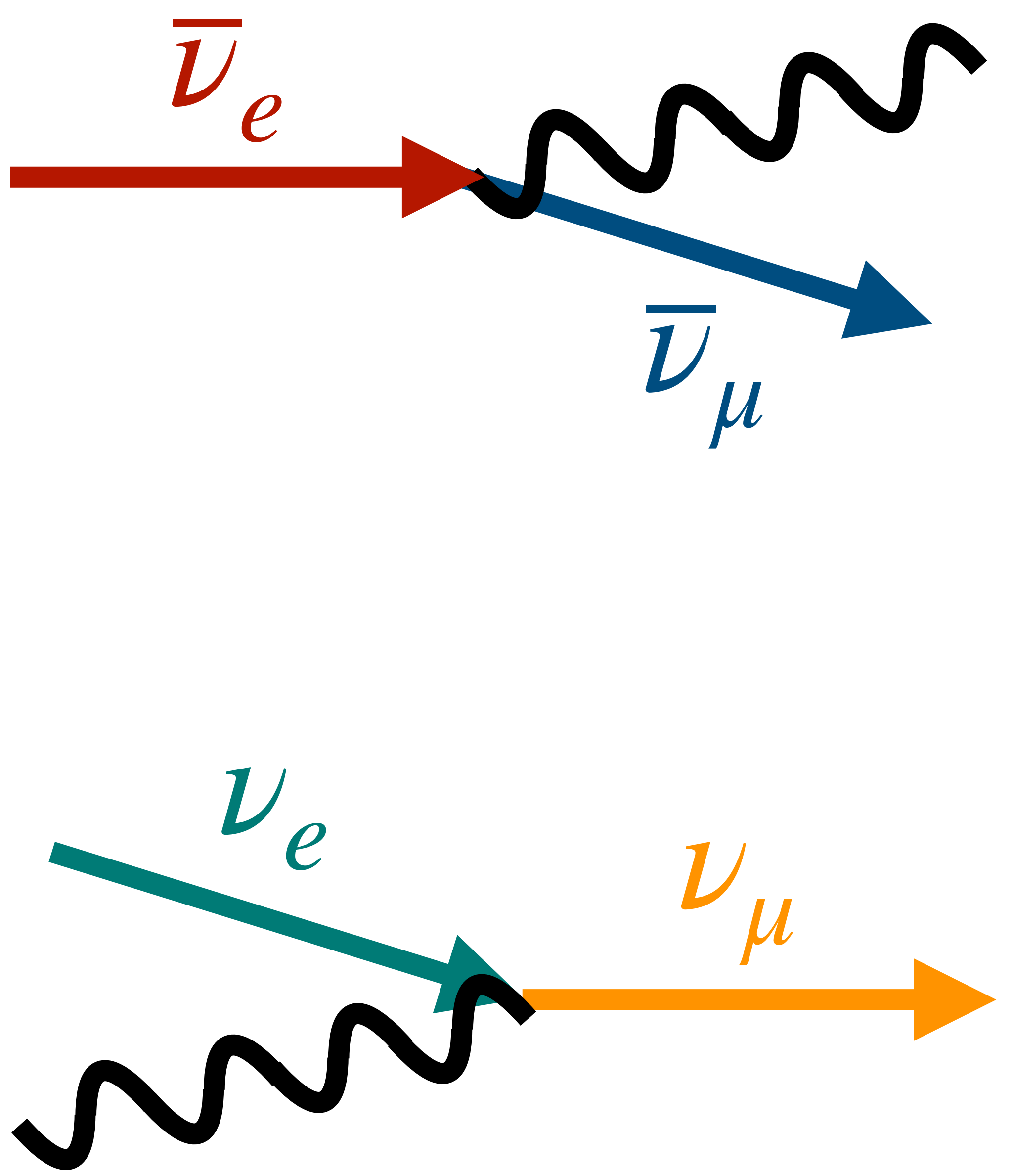


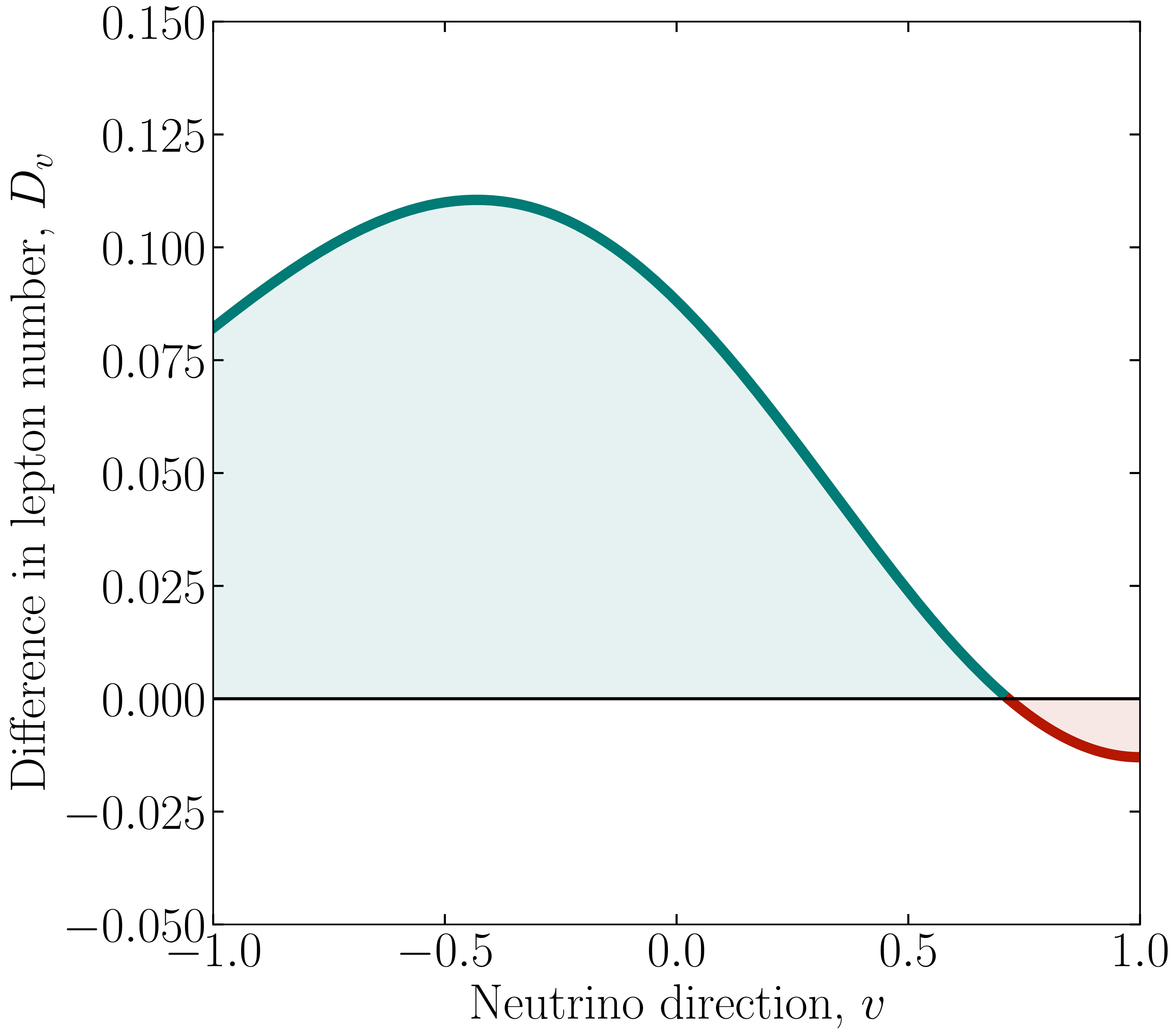


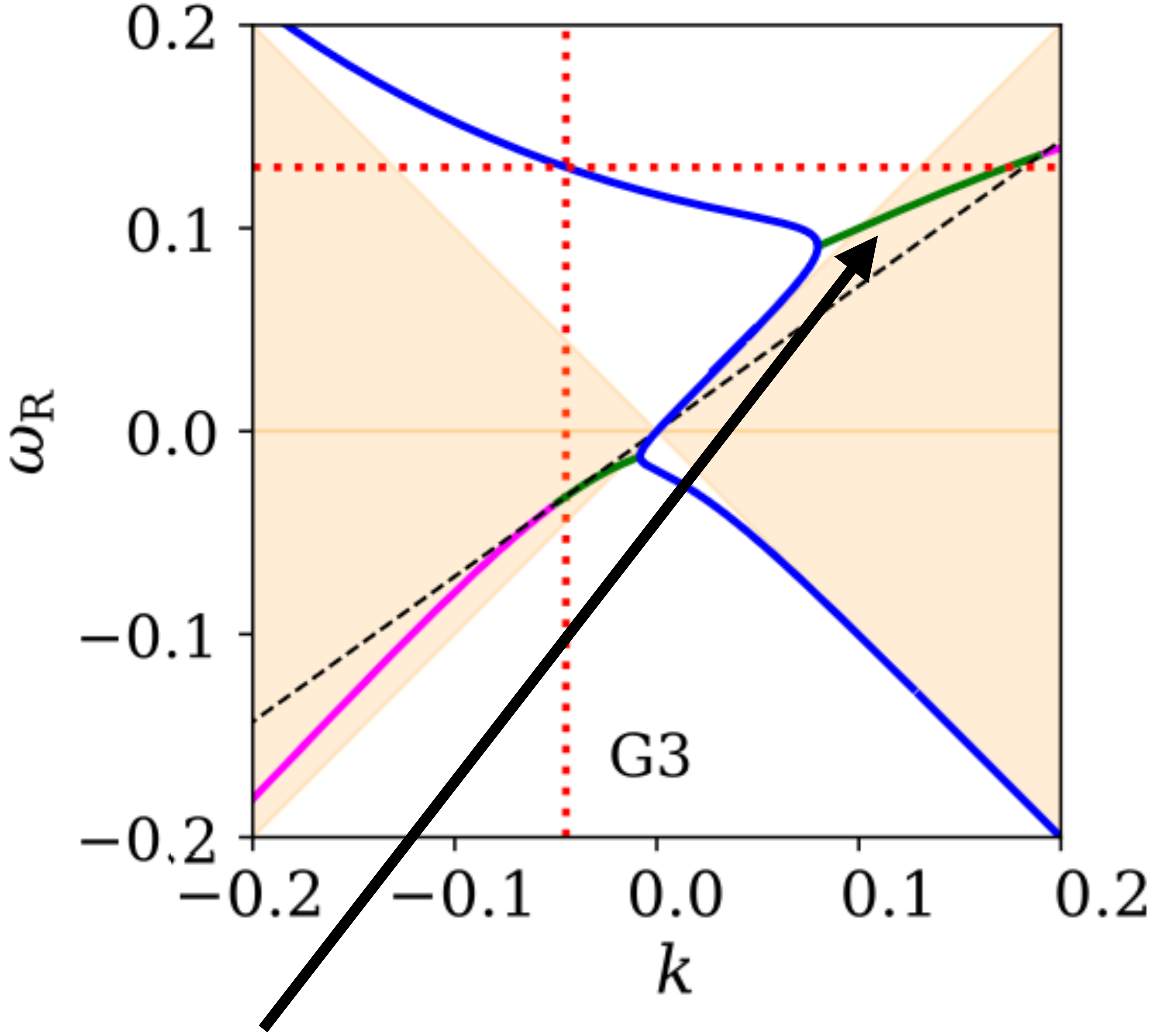
$$\cos\theta = \frac{\omega_{\mathbf{k}}}{k}$$

__DF__, Goimil-Garcia, Raffelt, PRD 2412.09027

Fast instability







$$\cos\theta = \frac{\omega_{\mathbf{k}}}{k}$$

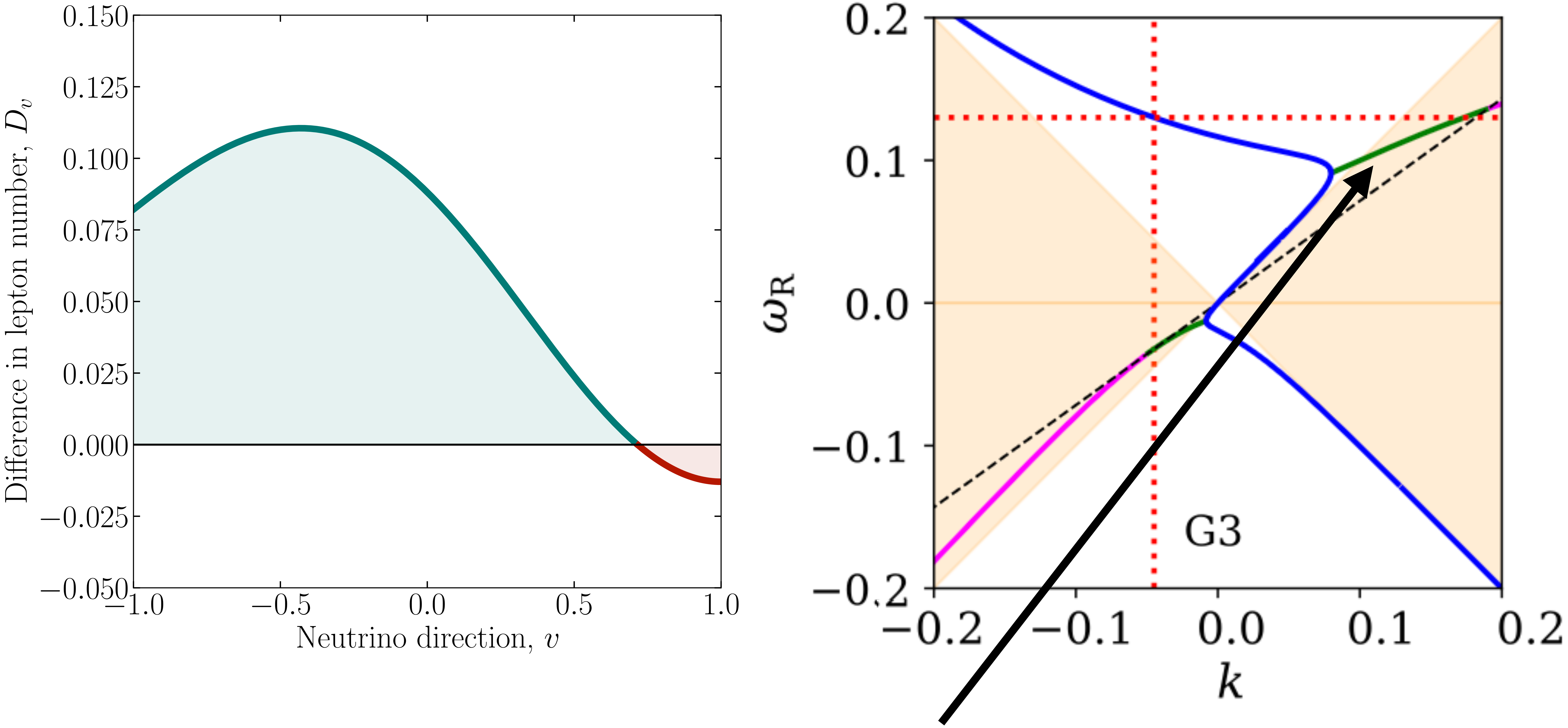
More $\overline{\nu}_e$ than ν_e (emission!)

DF, *Goimil-Garcia, Raffelt, PRD 2412.09027*

Fast instability

Angular crossing triggers instability

(Morinaga, PRD 2103.15267; Dasgupta, PRL 2110.00192; ***DF****, Raffelt, JHEP 2406.06708)*

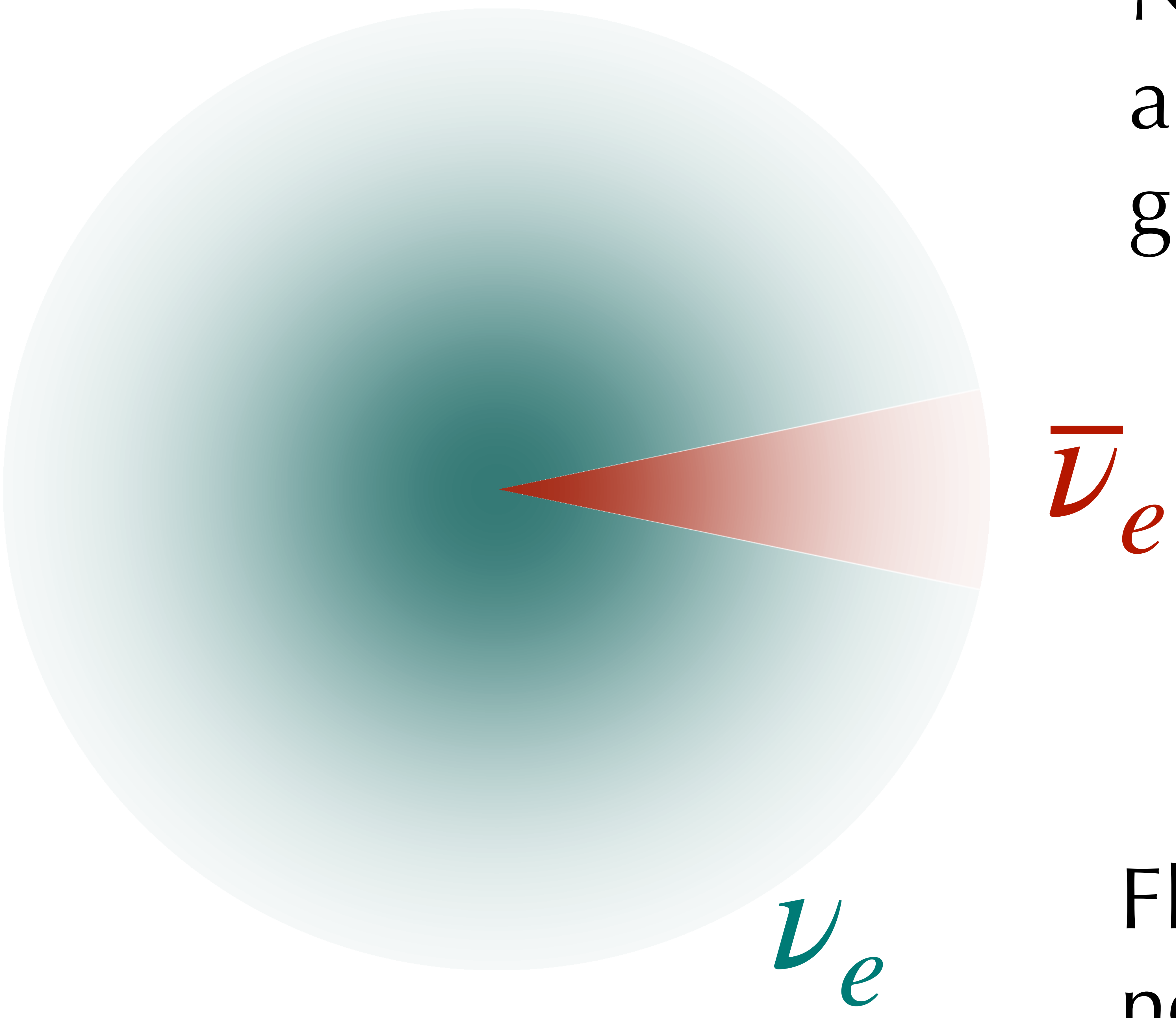


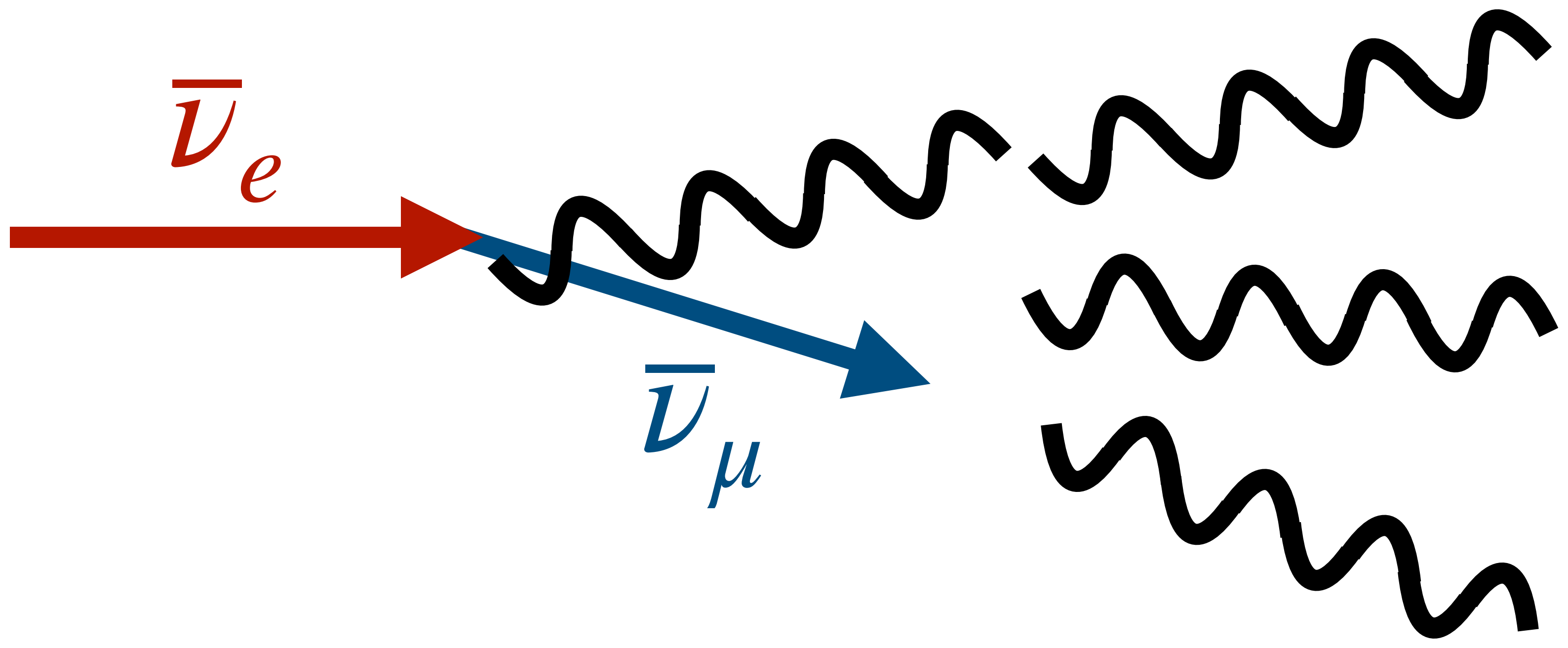
More $\overline{\nu}_e$ than ν_e (emission!)

DF*, Goimil-Garcia, Raffelt, PRD 2412.09027*

Fast instability

Not enough ν_e to absorb flavomons, grow exponentially!

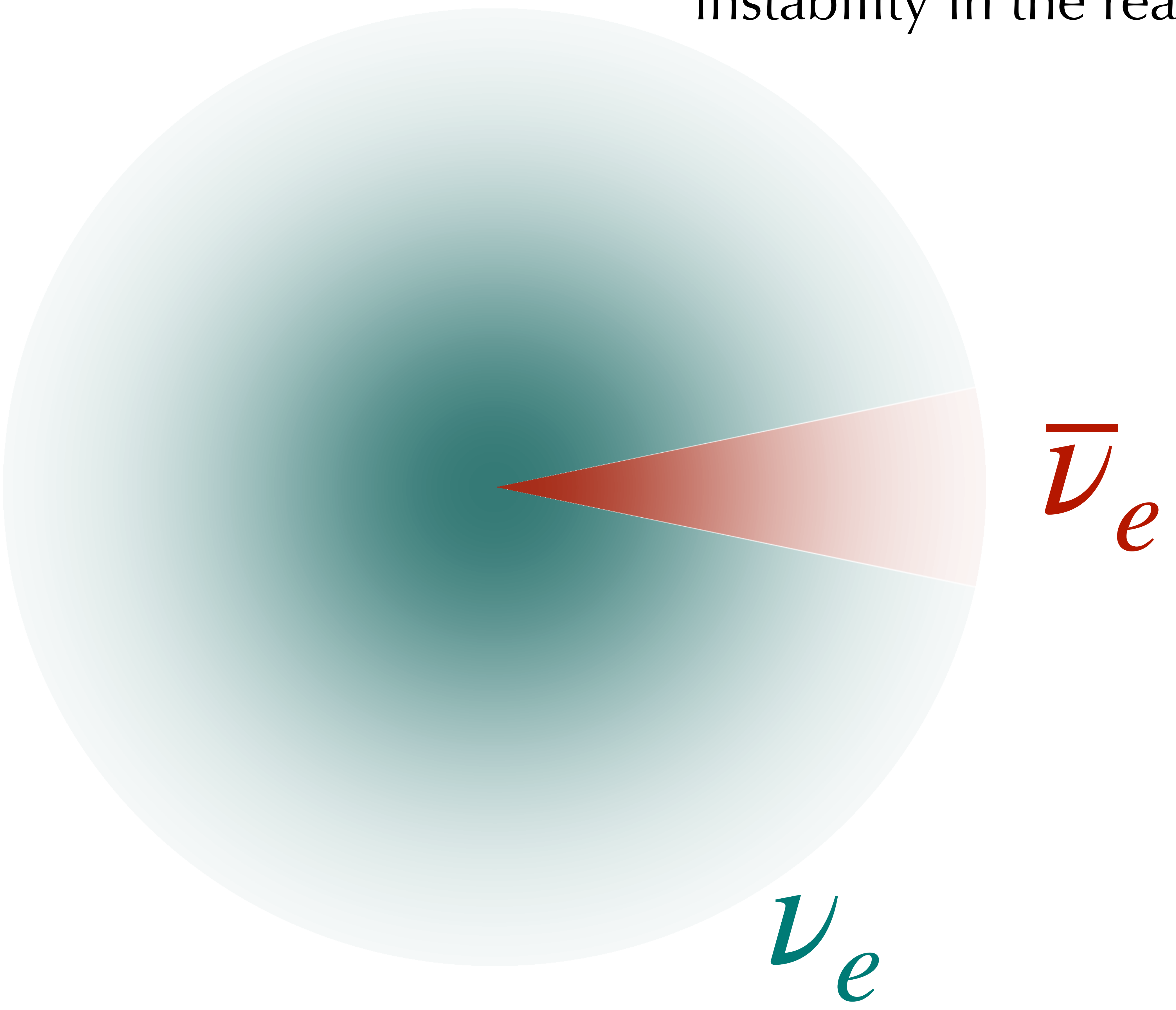


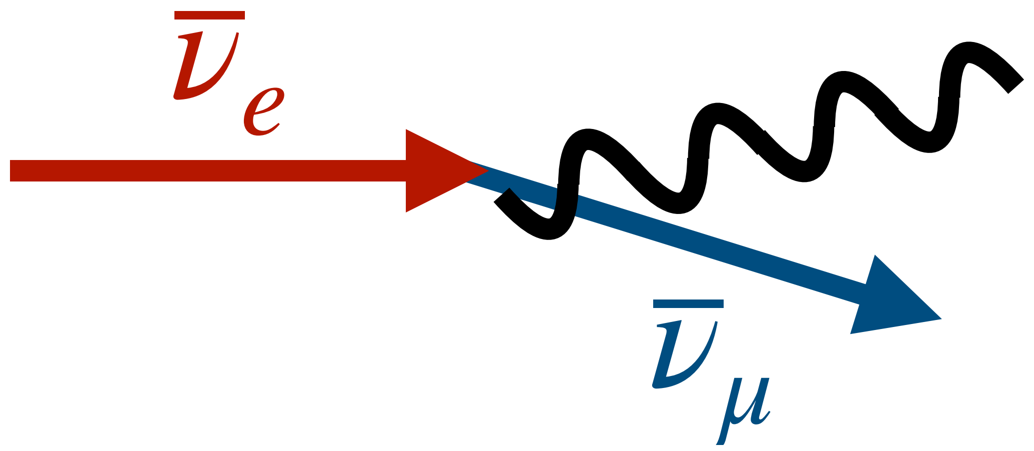


Flavomons produced collinearly with flipped neutrinos (**convective instability**, ***DF***, *Raffelt JHEP 2501.16423; see also Ma et al., PRD 1901.01546, Capozzi et al., PRD 1706.03660*)

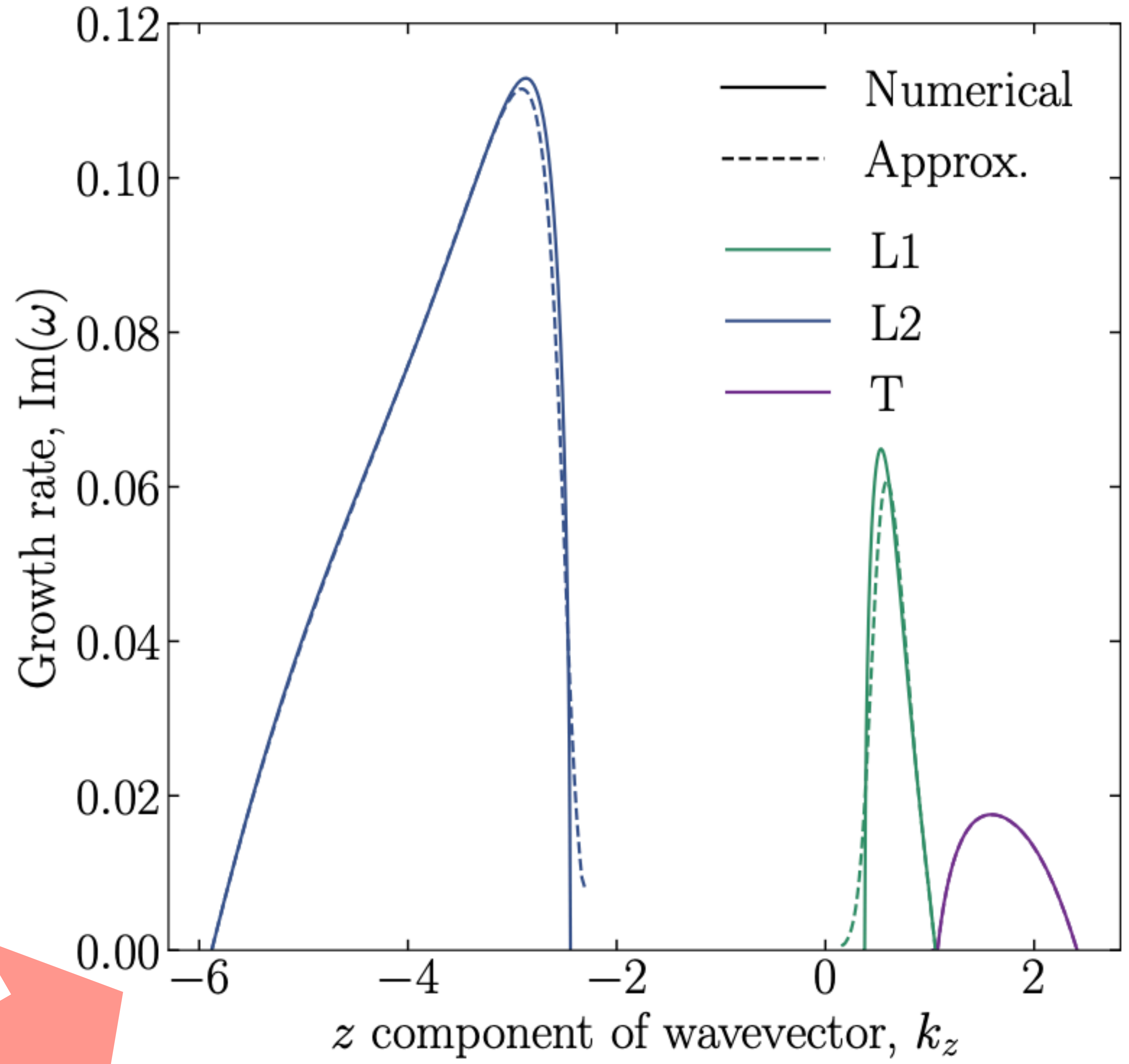
Fast instability

Agreement very good for weak instabilities (there is probably no such thing as a strong instability in the real world, *Johns, PRD 2401.15247;* ***DF****, Raffelt, PRL 2403.12189*)





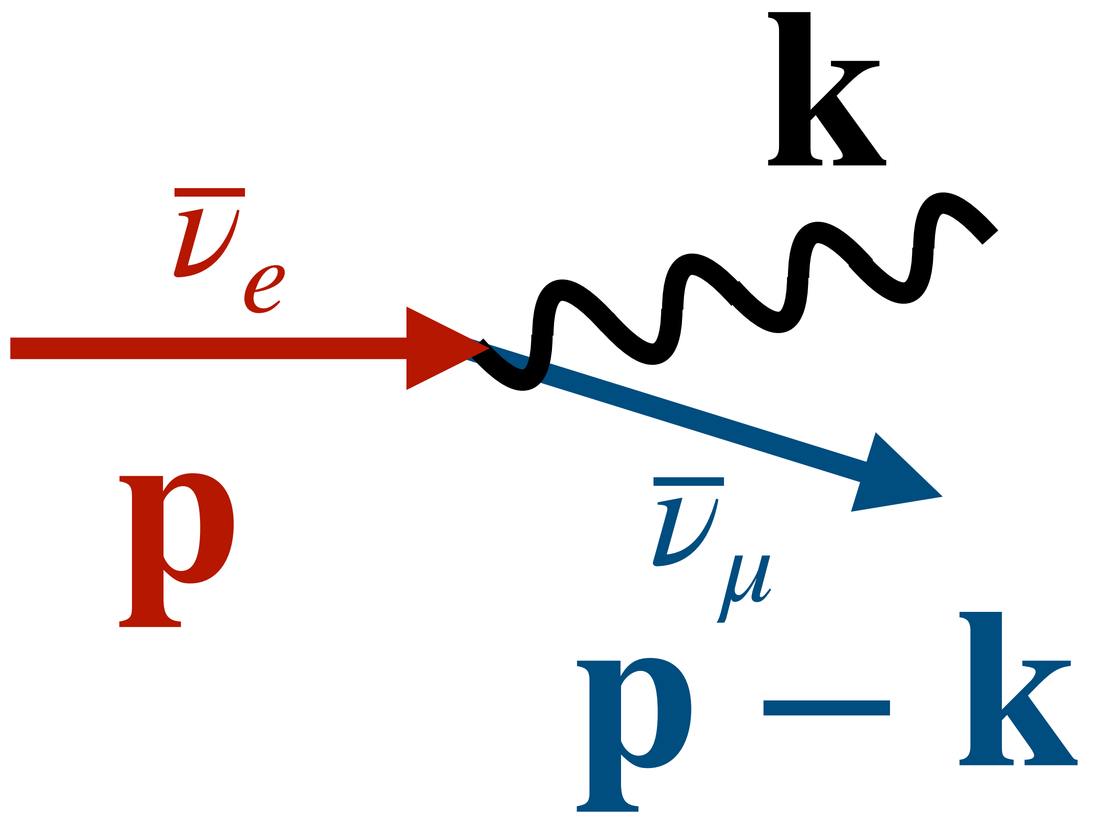
Feynman rules (***DF****, Raffelt, PRL 2502.06935)*



DF*, Raffelt, JHEP 2409.17232*

Massive neutrinos

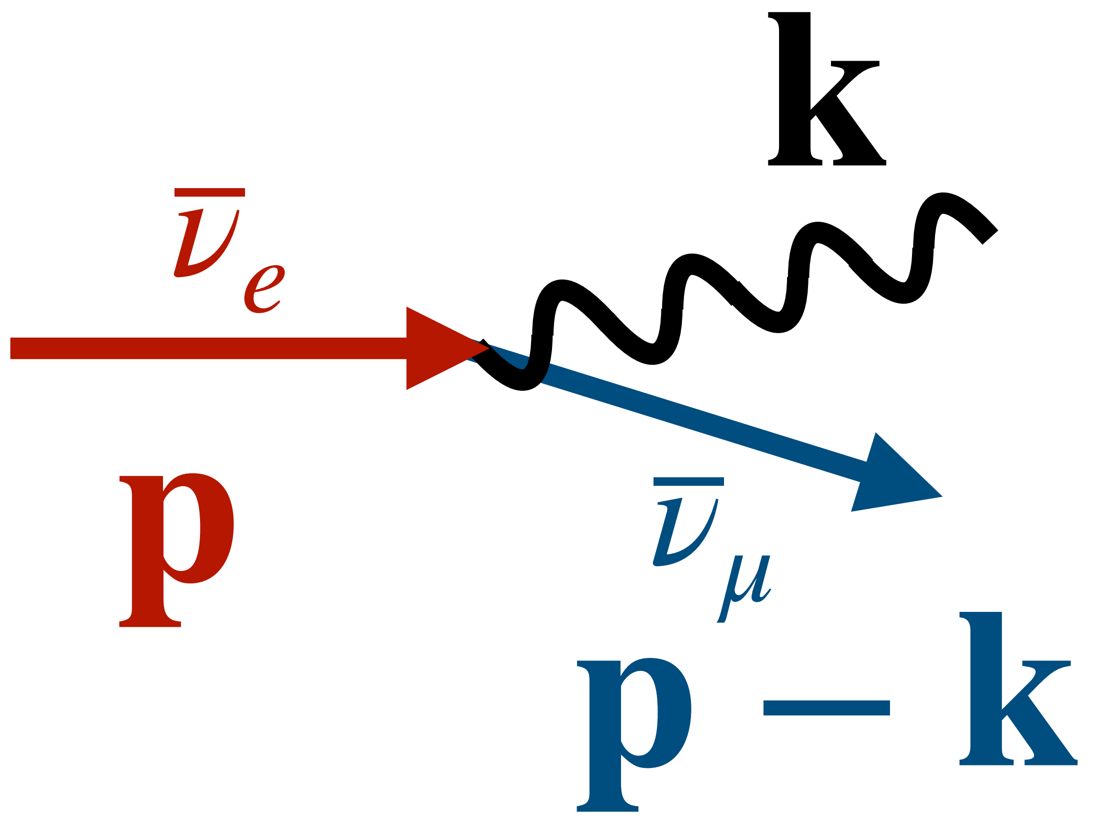
***DF**, Raffelt, PRL 2507.22987*



$$\omega_{\mathbf{k}} = E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{k}}$$

Massive neutrinos

***DF**, Raffelt, PRL 2507.22987*

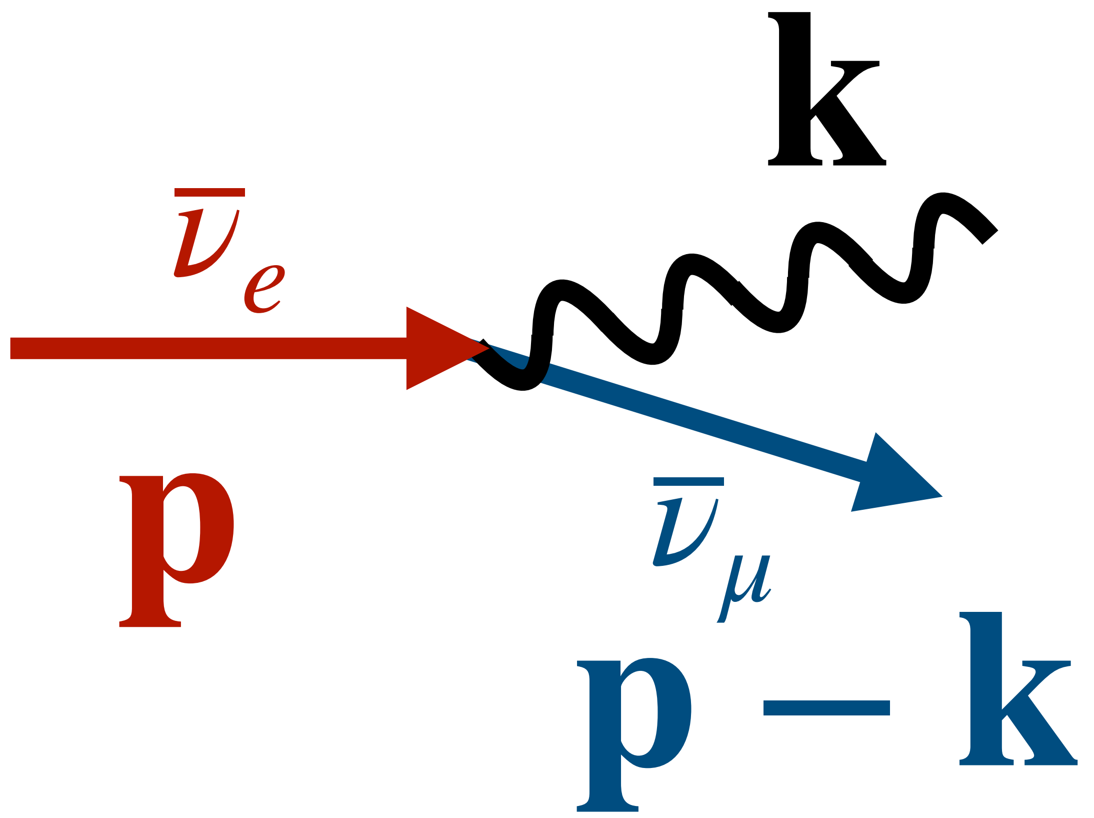


$\overline{\nu}_e$ are heavier than $\overline{\nu}_\mu$, so can decay!

$$\omega_{\mathbf{k}} = E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{k}} + \underbrace{\frac{\delta m^2 \cos 2\theta}{E}}_{= \tilde{\omega}_E \sim (1\,\mathrm{km})^{-1}}$$

Massive neutrinos

***DF**, Raffelt, PRL 2507.22987*



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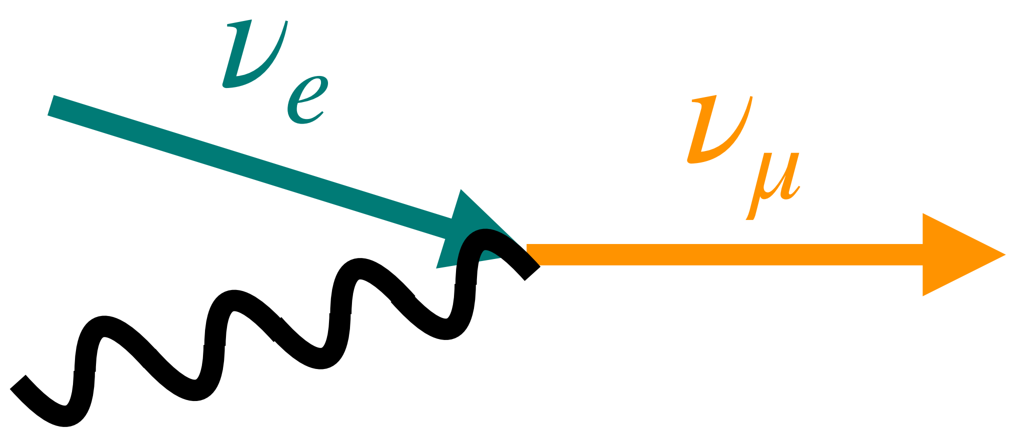


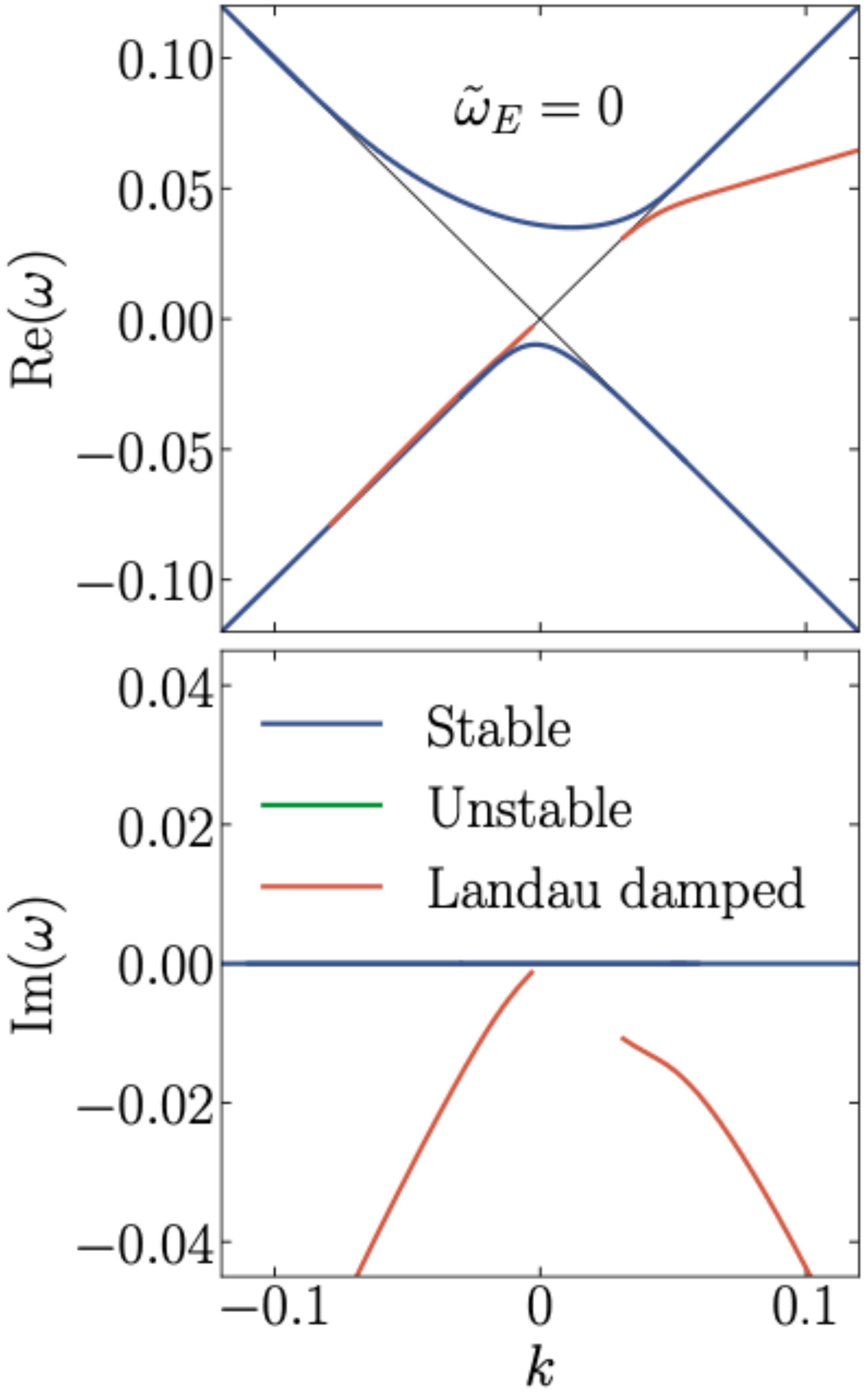
ν_e are also heavier than ν_μ, so no absorption!

$$\omega_{\mathbf{k}} = E_{\mathbf{p}} - E_{\mathbf{p}-\mathbf{k}} + \tilde{\omega}_E$$

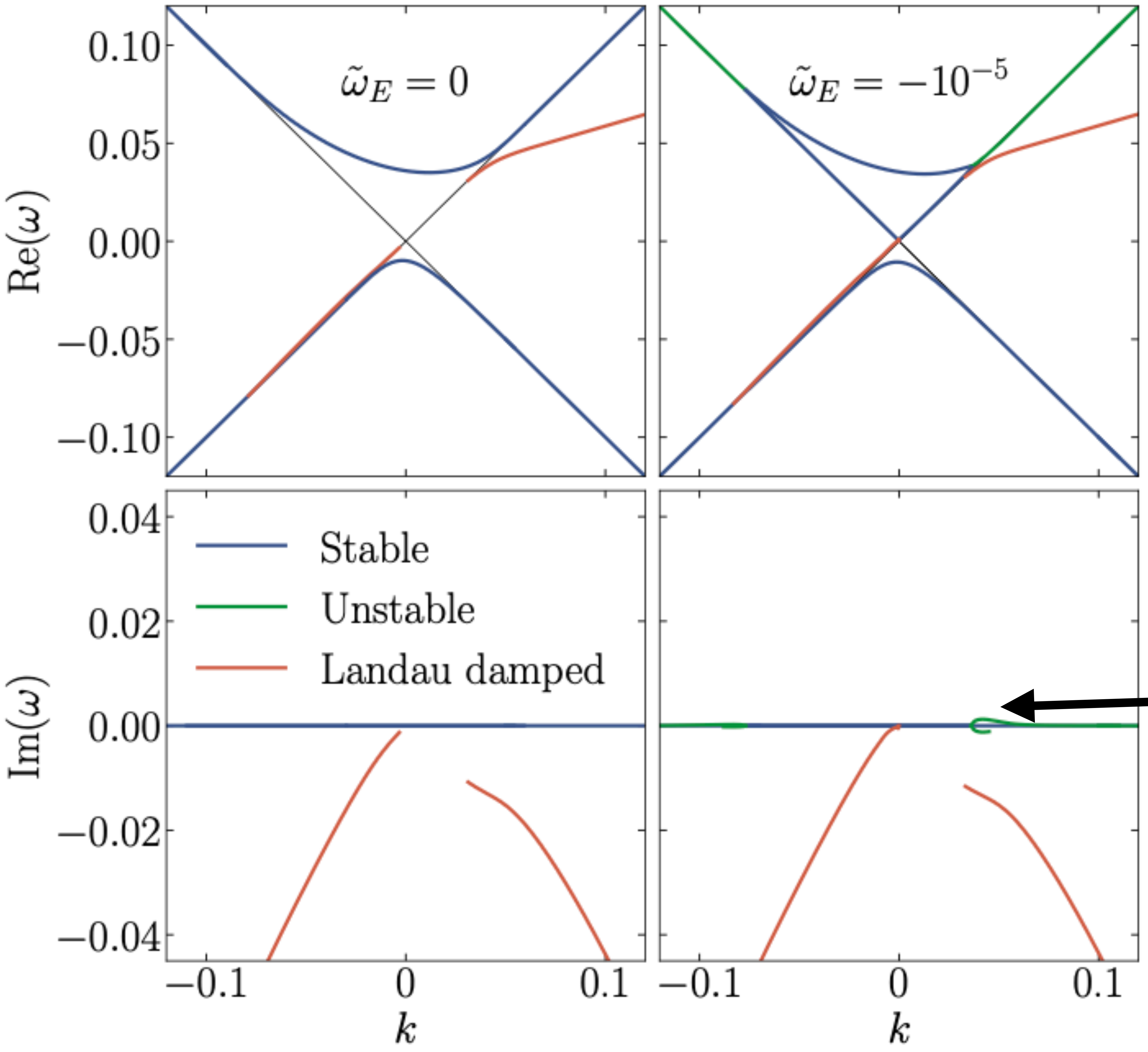
Positive-energy flavomons can be emitted without absorption!

Neutrino-mass-induced (slow) instabilities are just a heavy neutrino decaying to a lighter one

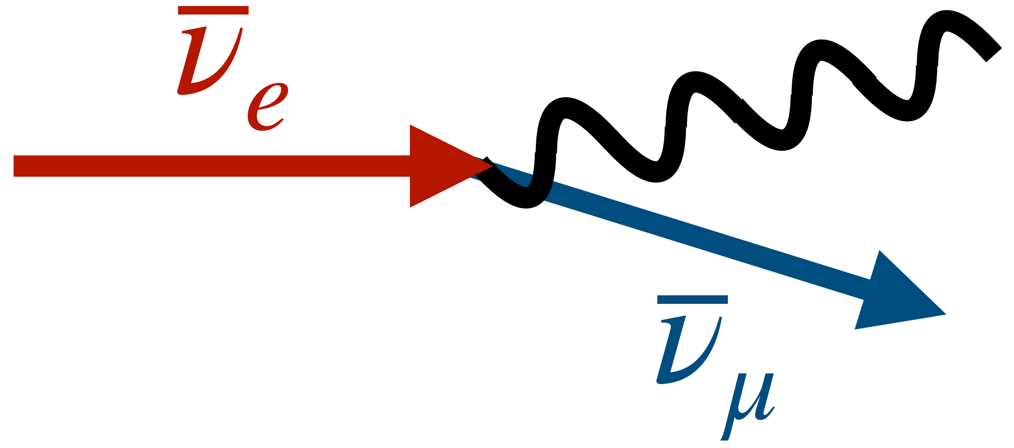
Slow instabilities



Slow instabilities



Narrow instability

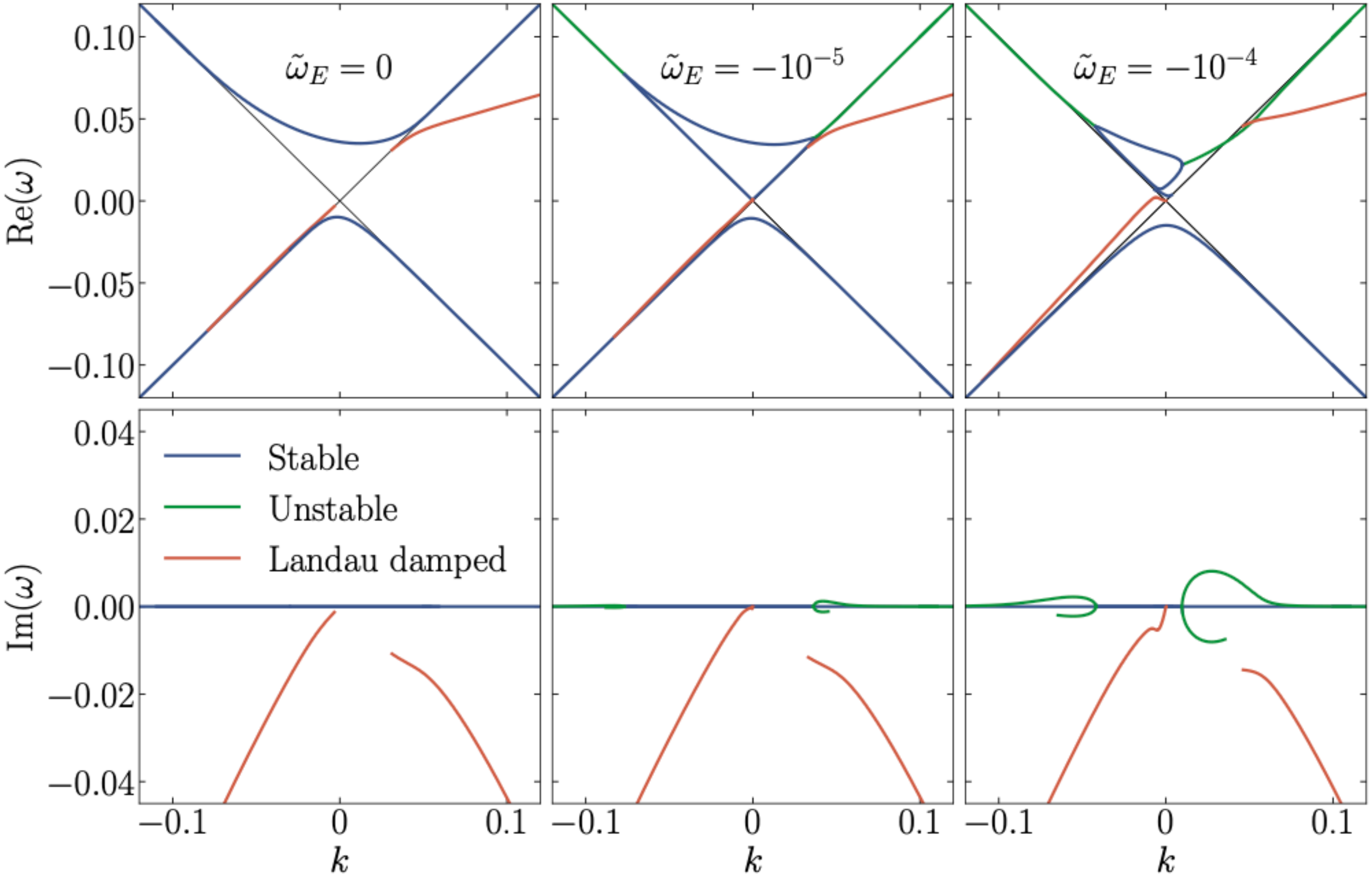


Directional decay

$$\gamma \sim \tilde{\omega}_E \, \frac{n_{\overline{\nu}_e} - n_{\overline{\nu}_\mu}}{n_{\overline{\nu}} - n_\nu}$$

Slowly growing,
but rapidly
oscillating!

Slow instabilities



Broad instability

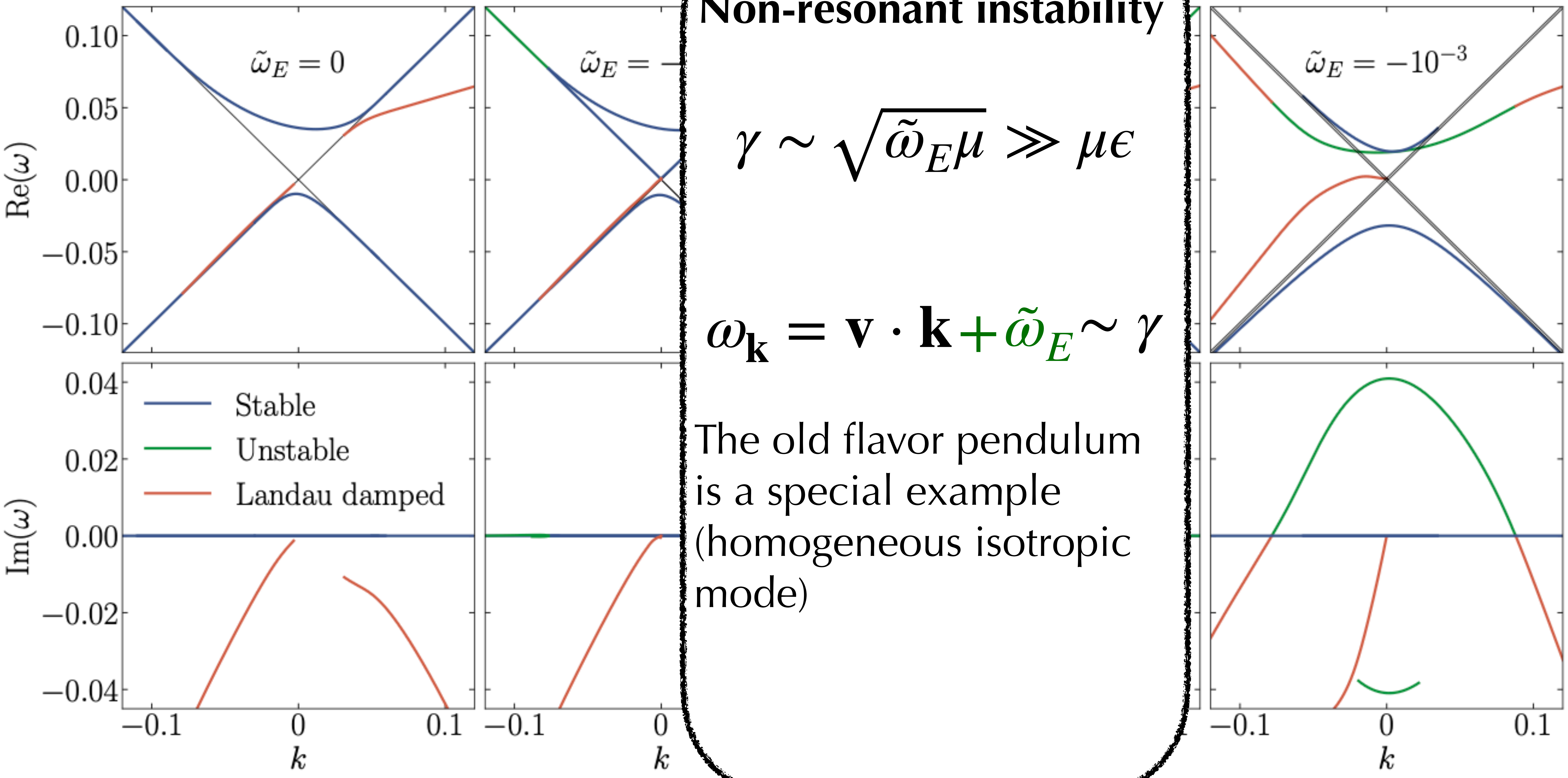
$$\gamma \sim \frac{\omega_E}{\epsilon} \gg \omega_E$$

Uncertainty principle

$$\omega_{\mathbf{k}} = \mathbf{v} \cdot \mathbf{k} + \tilde{\omega}_E \sim \gamma$$

Still a **directional** decay ($\gamma \ll \mu\epsilon$ so neutrinos decay collinearly)

Slow instabilities



Non-resonant instability

$$\gamma \sim \sqrt{\tilde{\omega}_E \mu} \gg \mu\epsilon$$

$$\omega_{\mathbf{k}} = \mathbf{v} \cdot \mathbf{k} + \tilde{\omega}_E \sim \gamma$$

The old flavor pendulum is a special example (homogeneous isotropic mode)

Slow instabilities

Narrow instability

$$\gamma \sim \tilde{\omega}_E \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu}}{n_{\bar{\nu}} - n_\nu}$$

Broad instability

$$\gamma \sim \frac{\omega_E}{\epsilon} \gg \omega_E$$

Non-resonant instability

$$\gamma \sim \sqrt{\tilde{\omega}_E \mu} \gg \mu\epsilon$$

Slow, but comparable to neutrino-nucleon collisions

Slow, but oscillate on centimeters and picoseconds

$\sqrt{\tilde{\omega}_E \mu}$ sometimes characterized as slow, but actually only applies when slow are faster than fast ($\sqrt{\omega_E \mu} \gg \mu\epsilon$)

Slow instabilities in SN core entirely different from flavor pendulum, spectral splits, …

Matter refraction does not prevent slow instabilities

Not induced by mixing, purely by kinematics!

Slow instabilities

Narrow instability

$$\gamma \sim \tilde{\omega}_E \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu}}{n_{\bar{\nu}} - n_{\nu}}$$

Broad instability

$$\gamma \sim \frac{\omega_E}{\epsilon} \gg \omega_E$$

Non-resonant instability

$$\gamma \sim \sqrt{\tilde{\omega}_E \mu} \gg \mu\epsilon$$

Several papers from Copenhagen group

Slow, but comparable to neutrino-nucleon collisions

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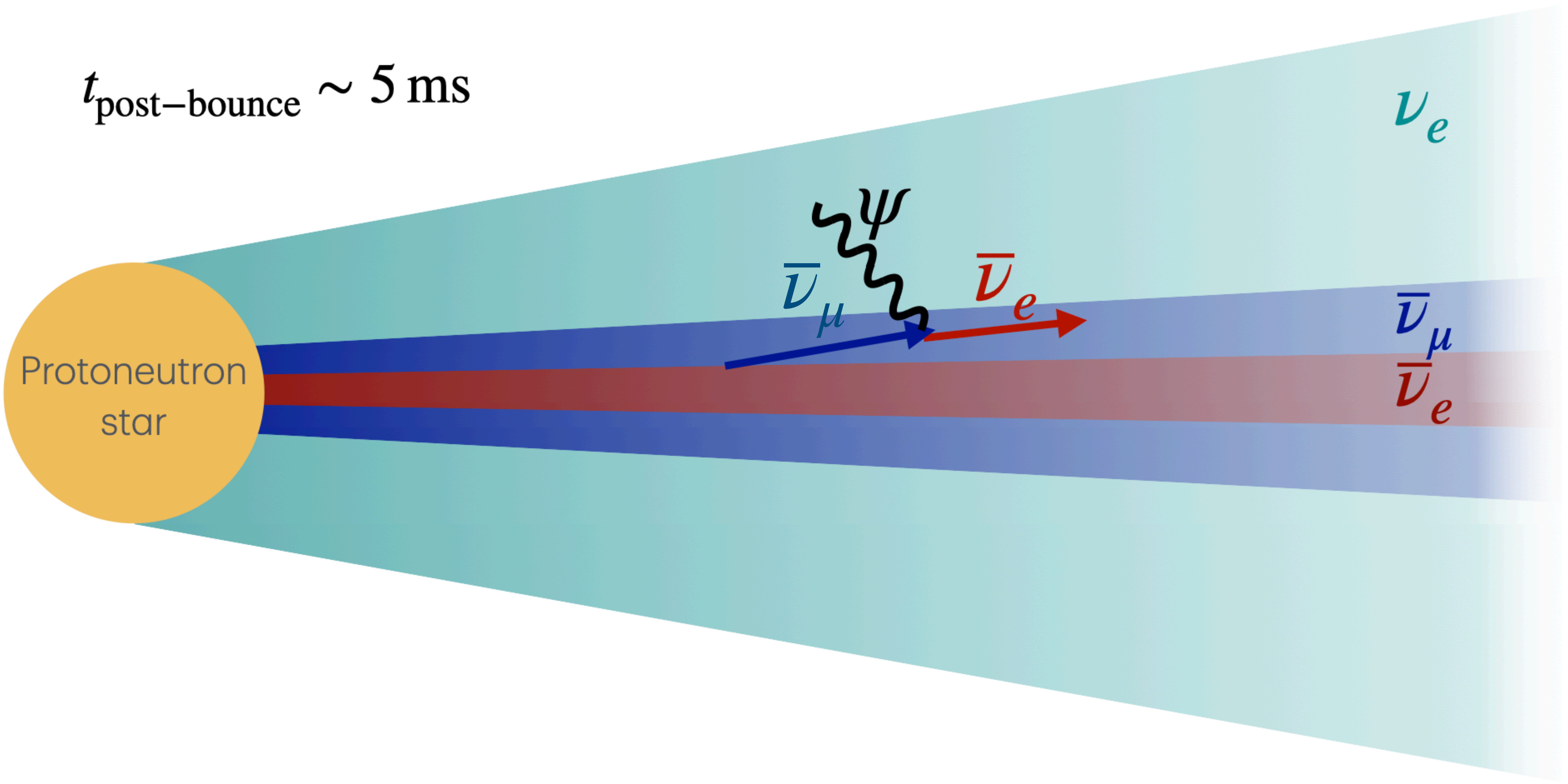
Slow instabilities in SN core entirely different from flavor pendulum, spectral splits, …

Matter refraction does not prevent slow instabilities

Not induced by mixing, purely by kinematics!

See also Ian’s talk and *Padilla-Gay et al., PRD 2505.11588*

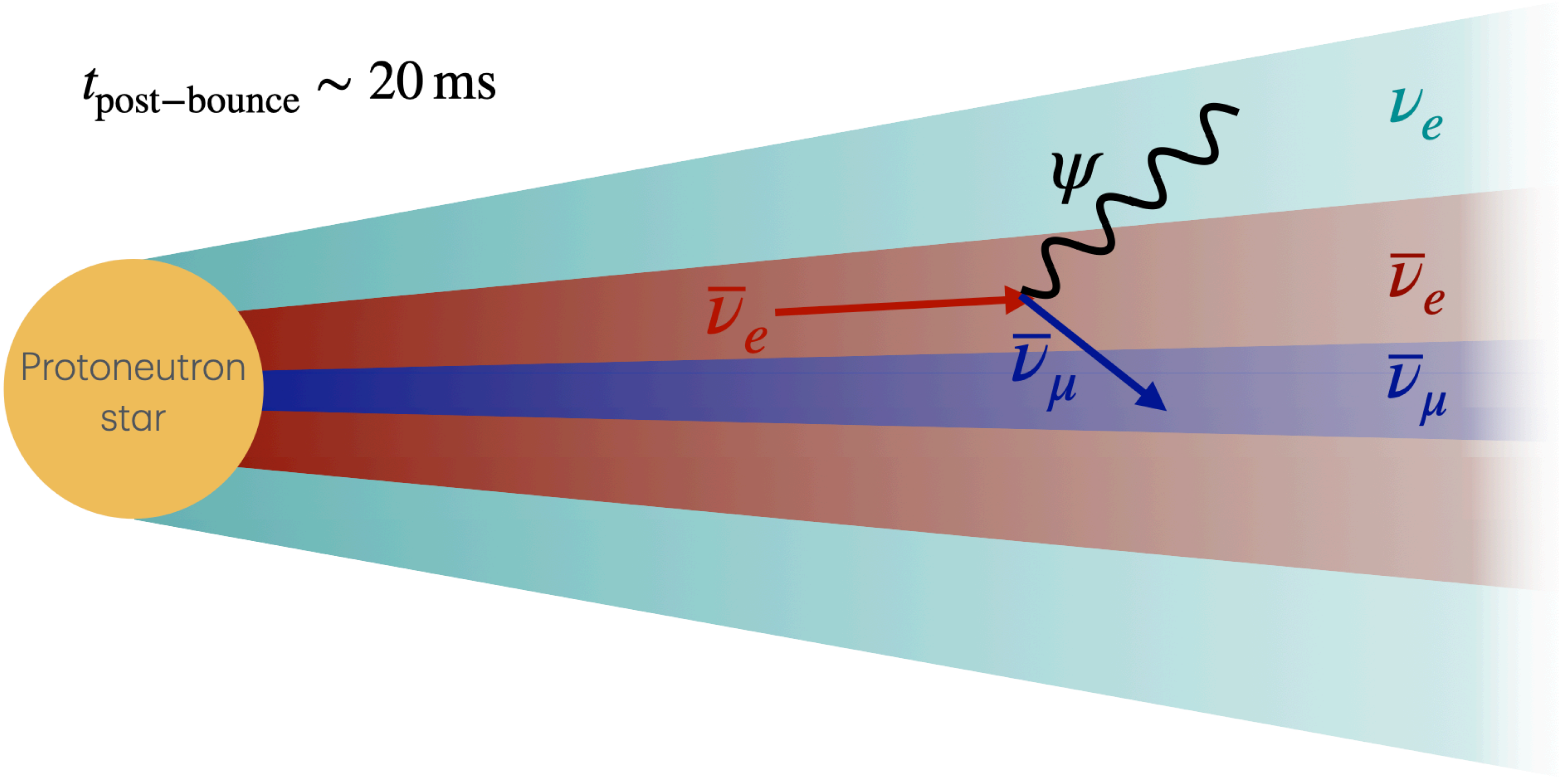
No instability initially



$t_{\text{post-bounce}} \sim 5\,\text{ms}$

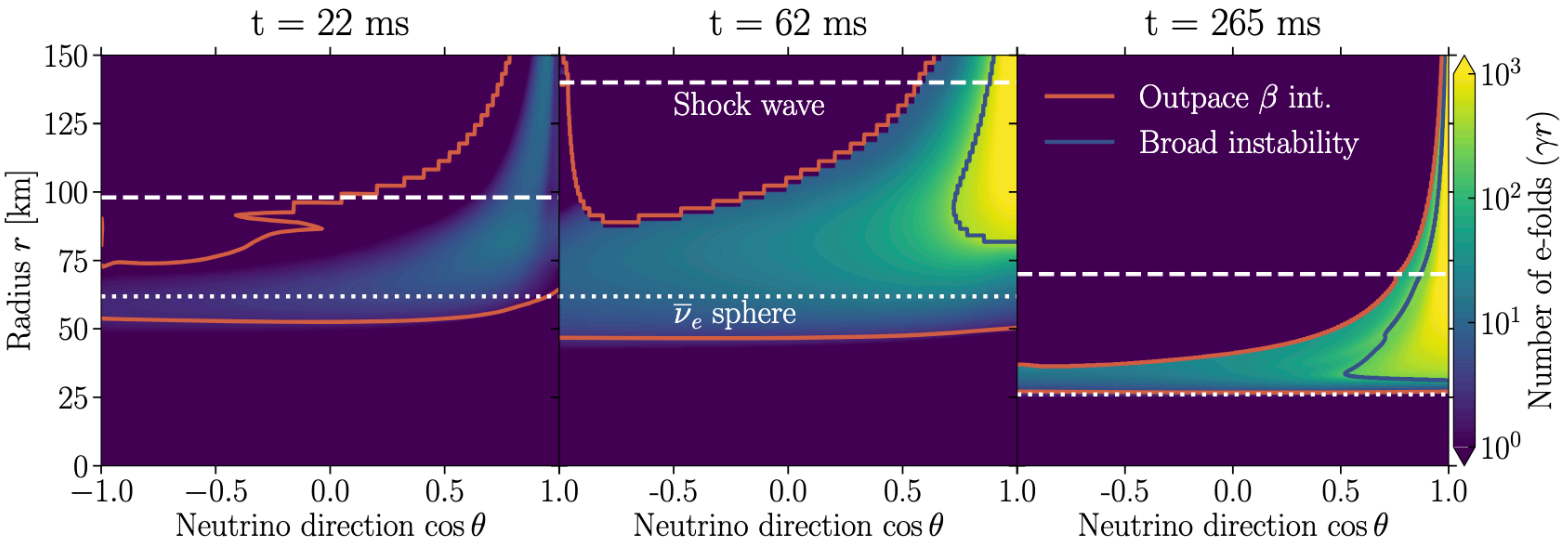
Accretion powers slow instabilities

$t_{\text{post-bounce}} \sim 20\,\text{ms}$



First beat fast: ubiquitous slow instabilities

Slow instabilities appear **much before** angular crossings

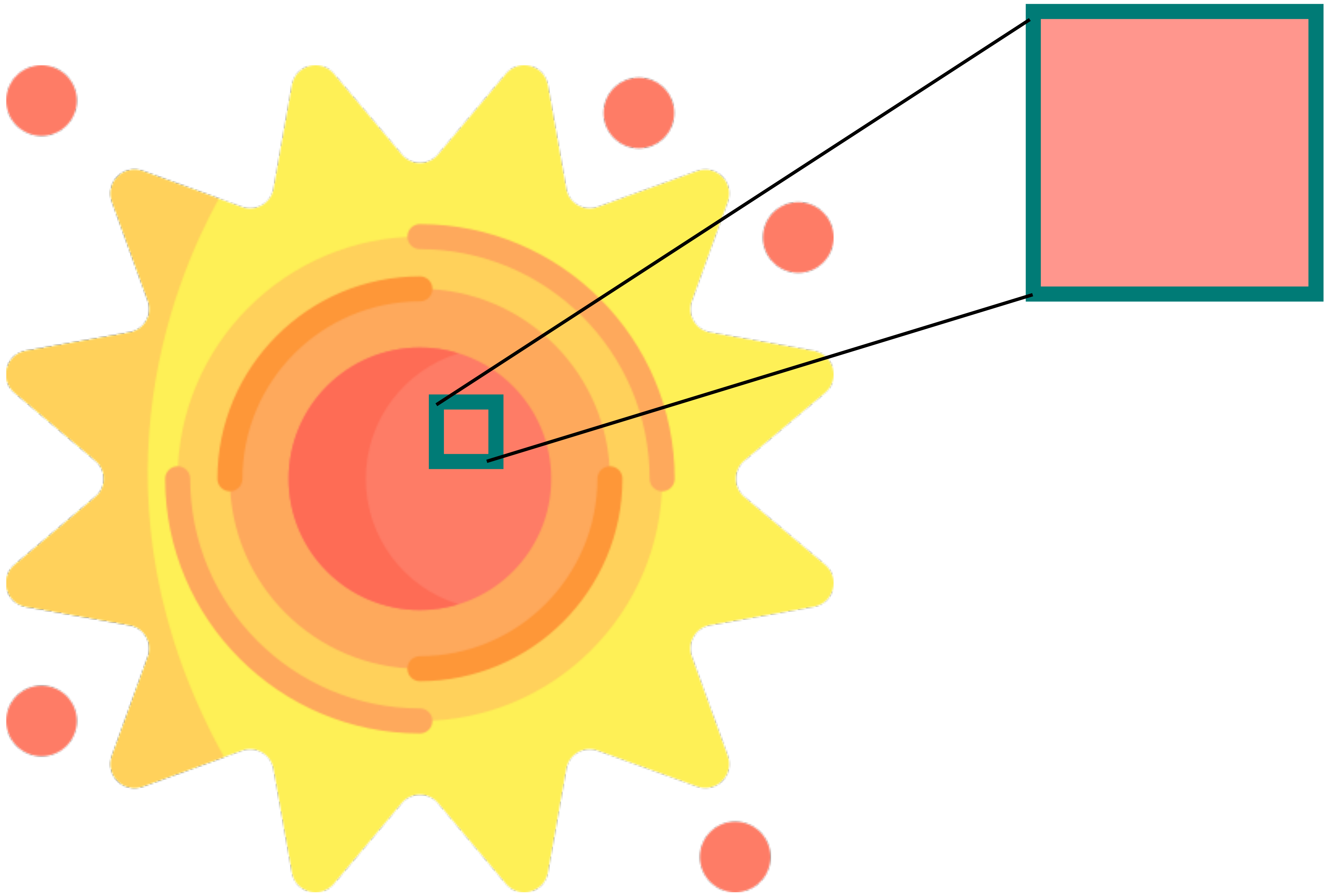


Damiano Fiorillo

***DF**, Janka, Raffelt, PRL, 2507.22985*

Non-linear small-scale dynamics

How to deal with them?



Local relaxation *(Bhattacharyya et al., PRL 2009.03337; Kato et al., ApJ Supp. 2108.06356; Richers et al., PRD 2101.02745; George et al., CPC 2203.12866; Richers et al., PRD 2205.06282; Xiong et al., PRD 2307.11129; Grohs et al., ApJ 2309.00972; Froustey et al., PRD 2311.11968; Richers et al., PRD 2409.04405 …)* based on numerical fits to small-scale simulation

Non-linear small-scale dynamics

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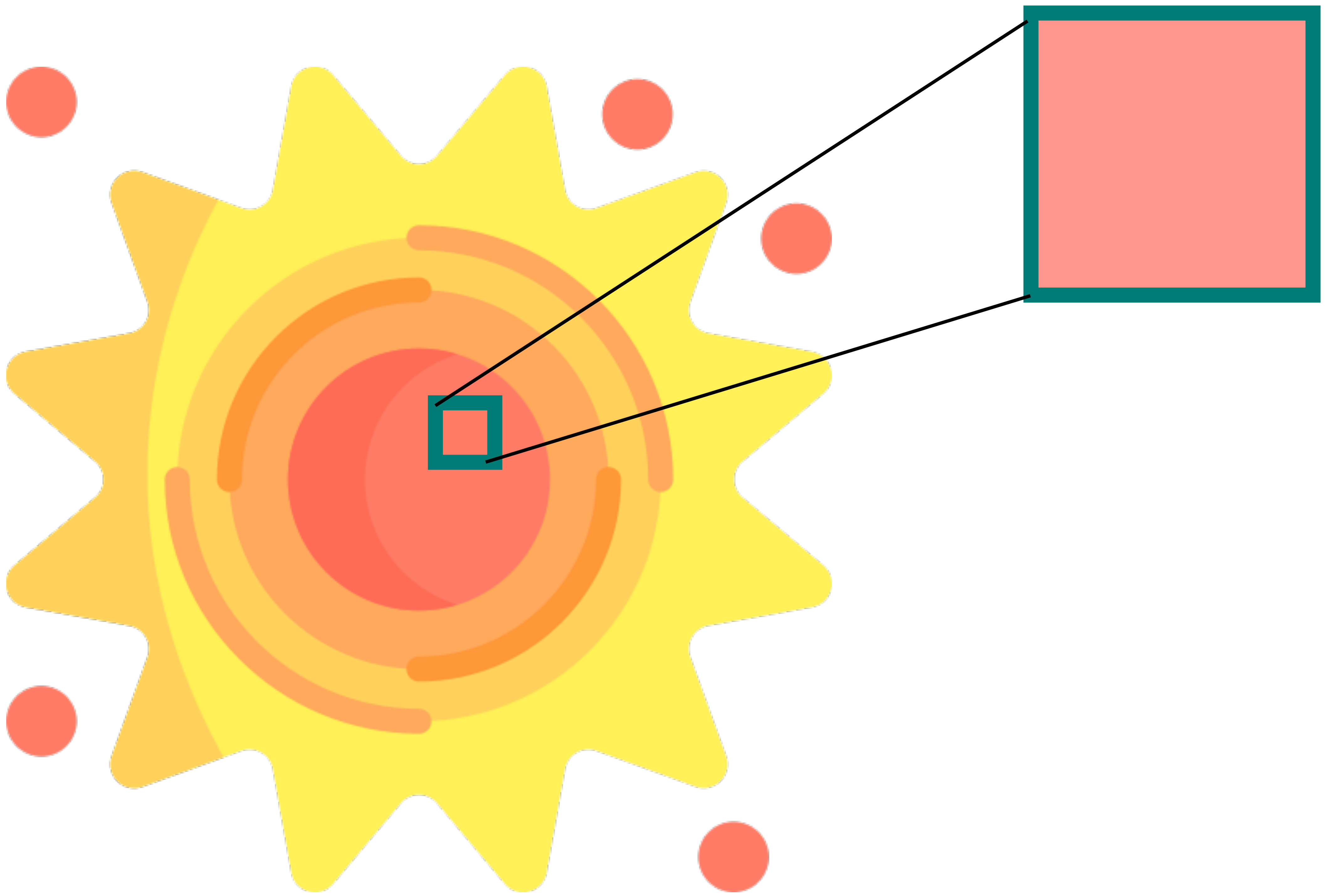

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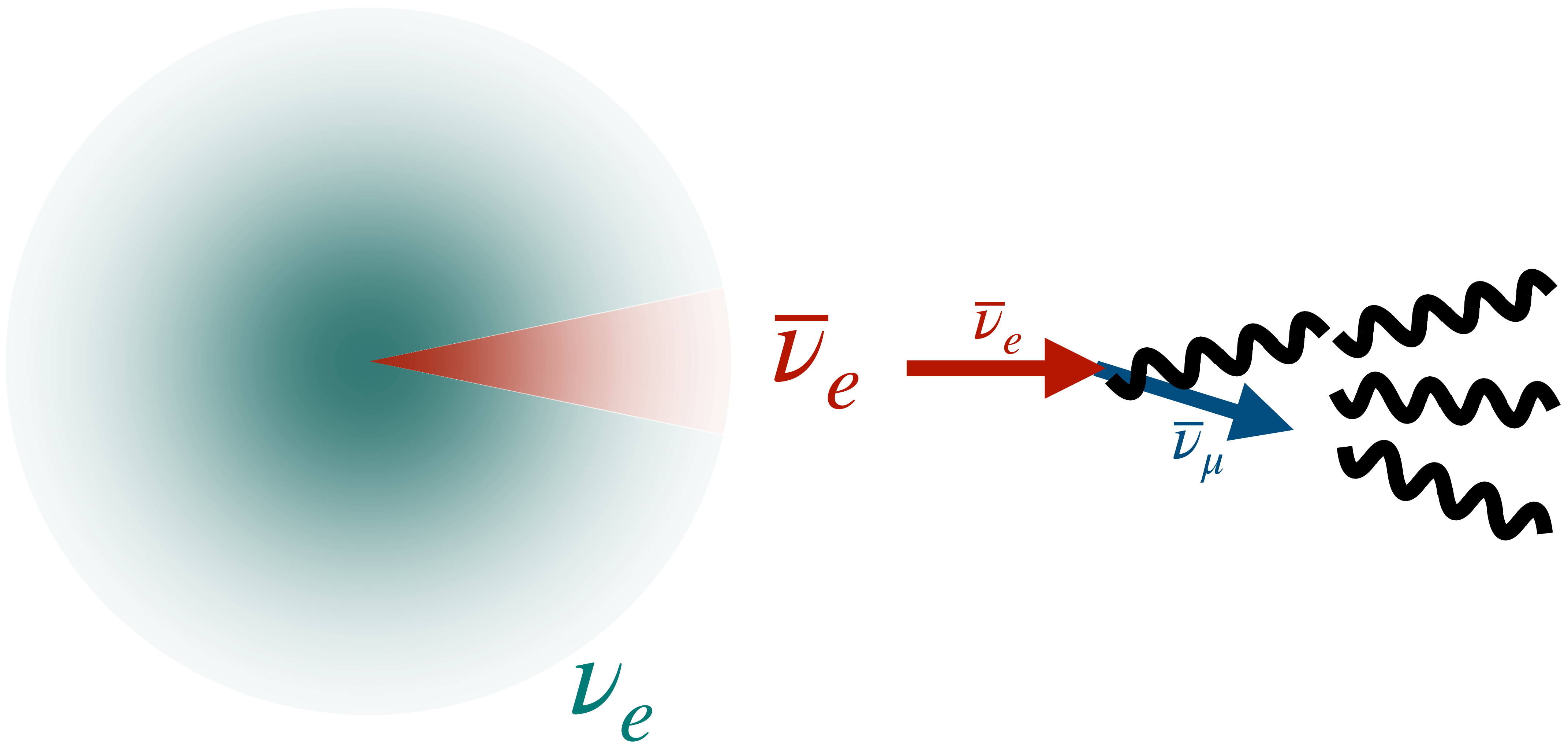
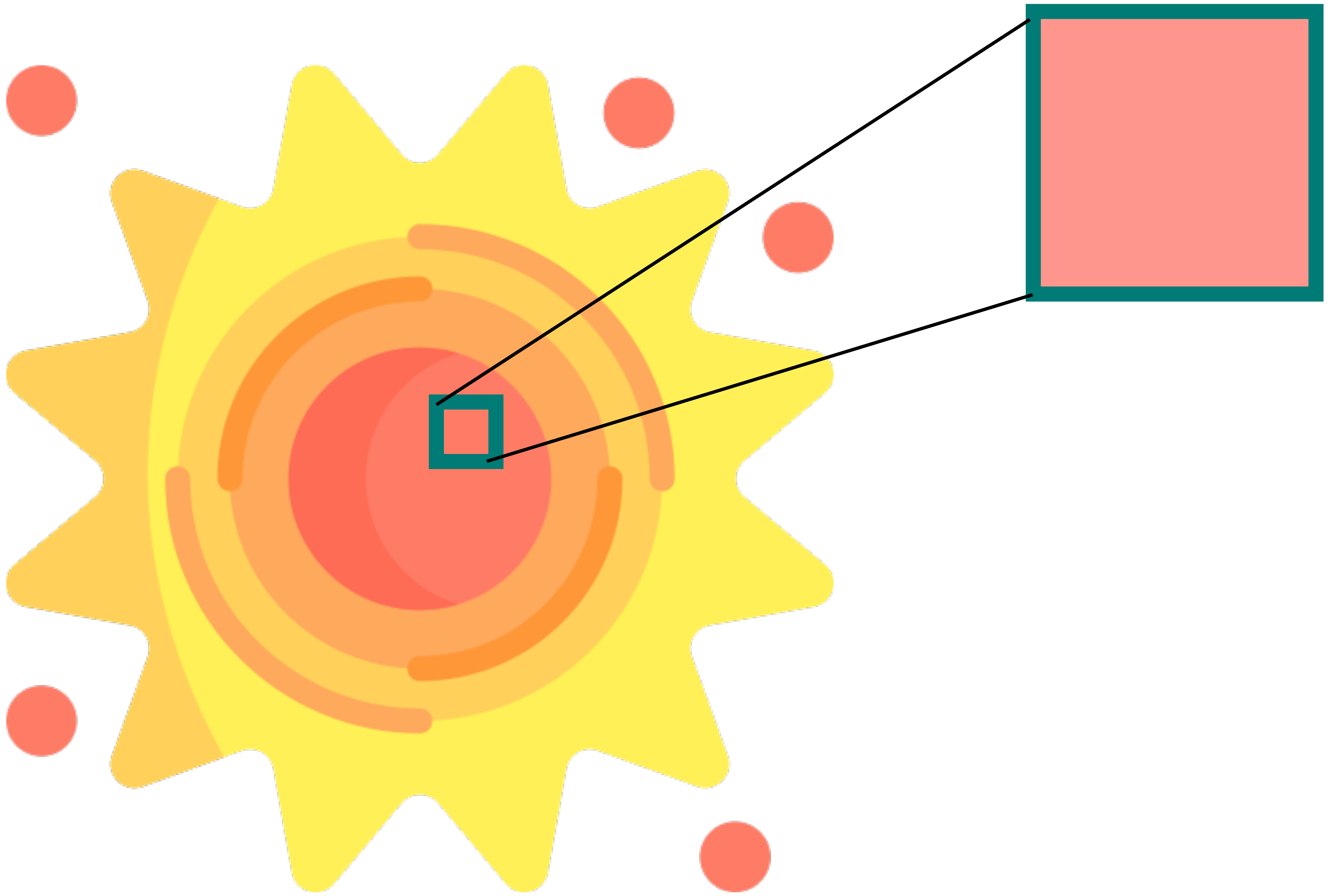
Waves are erased in this approach



DF*, Raffelt, JHEP 2501.16423*

Non-linear small-scale dynamics

How to deal with them?



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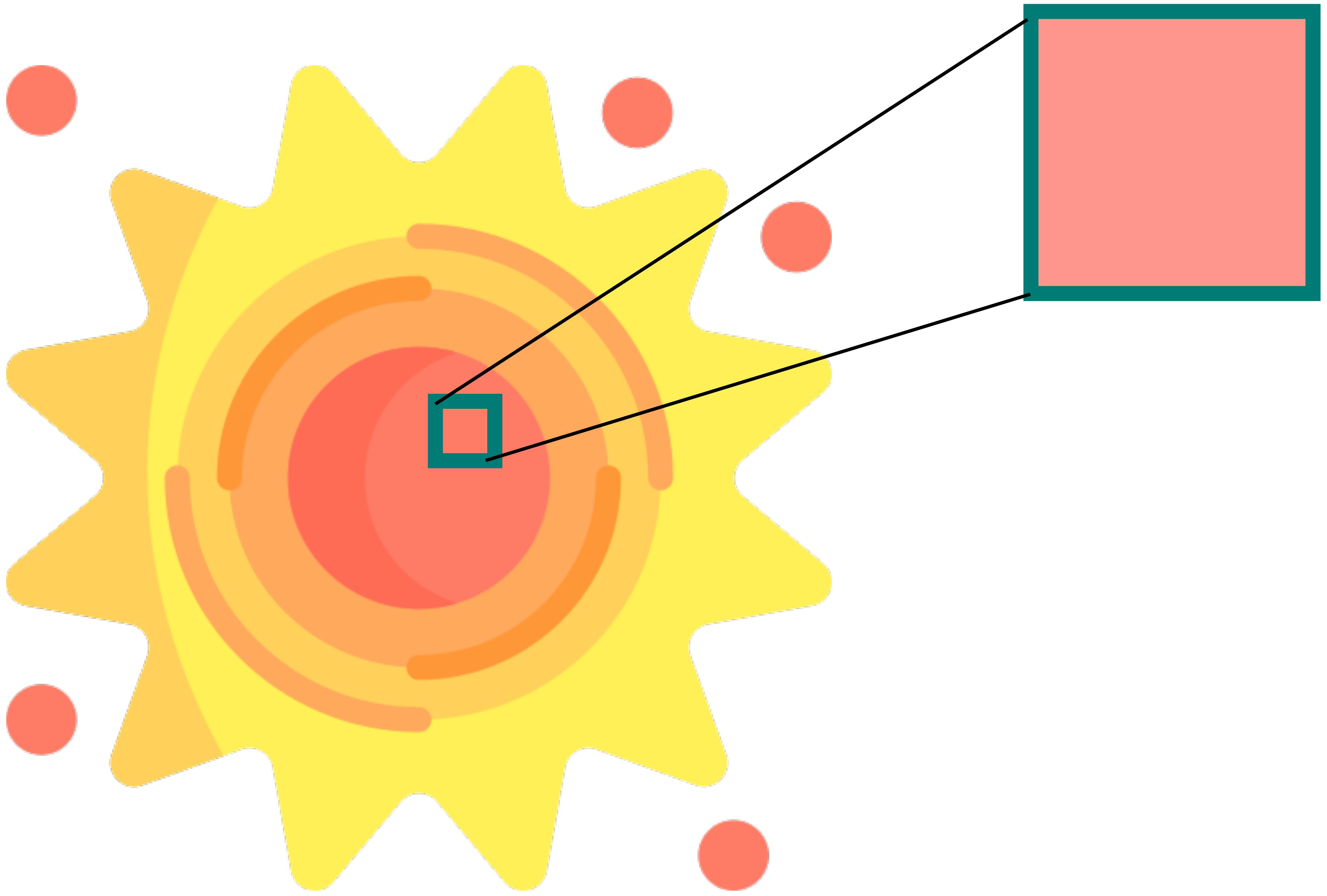
Waves are erased in this approach

Waves persisting in plasma can change even the neutrino flavor state as the instability is driven *(**DF**, Raffelt, PRL 2403.12189; Urquilla, Johns, 2510.23917)*

Non-linear small-scale dynamics

How to deal with them?



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Waves are erased in this approach

Waves persisting in plasma can change even the neutrino flavor state as the instability is driven *(**DF**, Raffelt, PRL 2403.12189; Urquilla, Johns, 2510.23917)*

Slow instabilities do not even relax locally in the first place!

Neutrino-flavomon relaxation

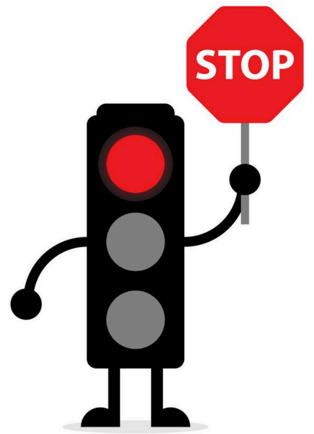
$$\dot{N}_\psi = \Gamma(n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu} + n_{\nu_\mu} - n_{\nu_e})N_\psi$$

Neutrino-flavomon relaxation

$$\dot{N}_\psi = \Gamma(n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu} + n_{\nu_\mu} - n_{\nu_e})N_\psi$$

$$\dot{n}_{\bar{\nu}_e} = -\Gamma(n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu})N_\psi$$

$$\dot{n}_{\nu_e} = -\Gamma(n_{\nu_e} - n_{\nu_\mu})N_\psi$$

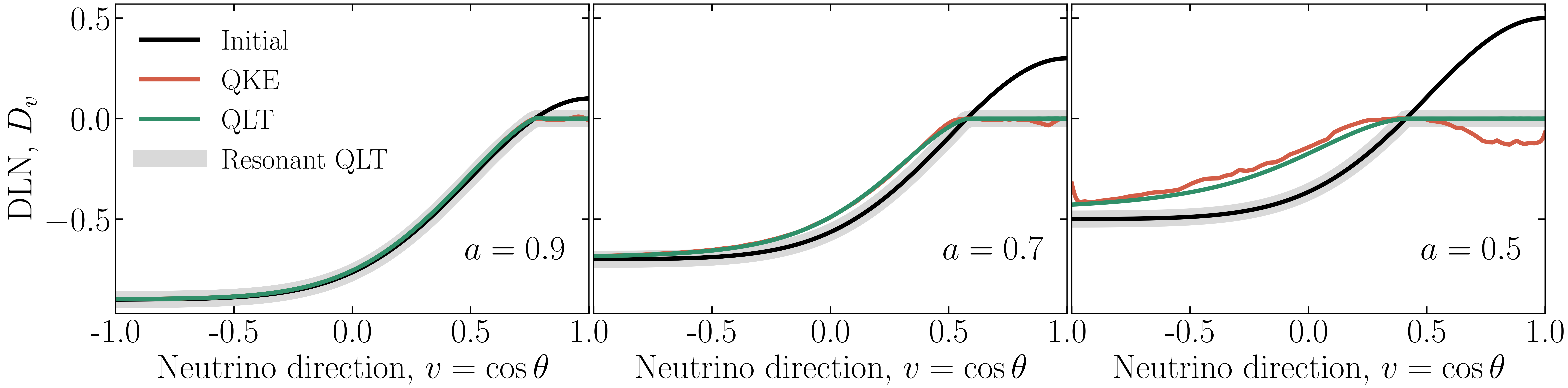


Instability saturates because every time a flavomon is emitted a flipped neutrino unflips!

Saturation driven by detailed balance — flipped neutrinos want to equipartition!

Quasi-linear theory developed in ***DF***, *Raffelt, PRL 2403.12189, 2502.06935*

Neutrino-flavomon relaxation



- ✦ Reproduces standard numerical results in homogeneous boxes!
- ✦ Equipartition of angular crossing — detailed balance!

***DF**, Raffelt, 2604.XXXX*

Take-away lessons

- Flavor waves are real — several predictions already drawn from this viewpoint (convergence of ideas with *Johns, Kost, 2506.03271*)
    - Growth rates from Feynman rules! (*Theory of Fast, Theory of Slow, Dispersion relation of the neutrino plasma)*
    - When and why is a distribution stable? *(Lepton-number crossings are insufficient)*
    - Neutrino-mass-induced instabilities easiest to achieve, earlier to appear in SNe (*When first beats fast)*
    - Instability saturation driven by detailed balance, with equipartition of angular crossing (*Edge of instability, CFCs are interactions with quantized flavor waves, Quasi-linear theory)*
    - Flavomon emission heats and cools the plasma *(Tracing the missing energy)*

A new state of matter

	Electron-ion plasma	Quark-gluon plasma	Neutrino plasma
Made of	Electrons, ions	Quarks, gluons	Neutrinos
Driven by	Electromagnetic interactions	Strong interactions	Weak interactions
Coll. excitations	Plasmons, phonons, magnetic waves	Gluonic plasmons	Flavomons, neutrino-plasmons
Their fate	Landau damping, plasma instability	Landau damping, color instability	Landau damping, flavor instability

***Theory of the neutrino plasma: DF**, Raffelt, JHEP, 2406.06708, 2409.17232, 2412.02747, 2501.16423, 2505.20389; PRL, 2403.12189, 2502.06935, 2507.22987; **DF**, Raffelt, Sigl, PRL, 2401.05278*

Backup slides

Collisional instabilities

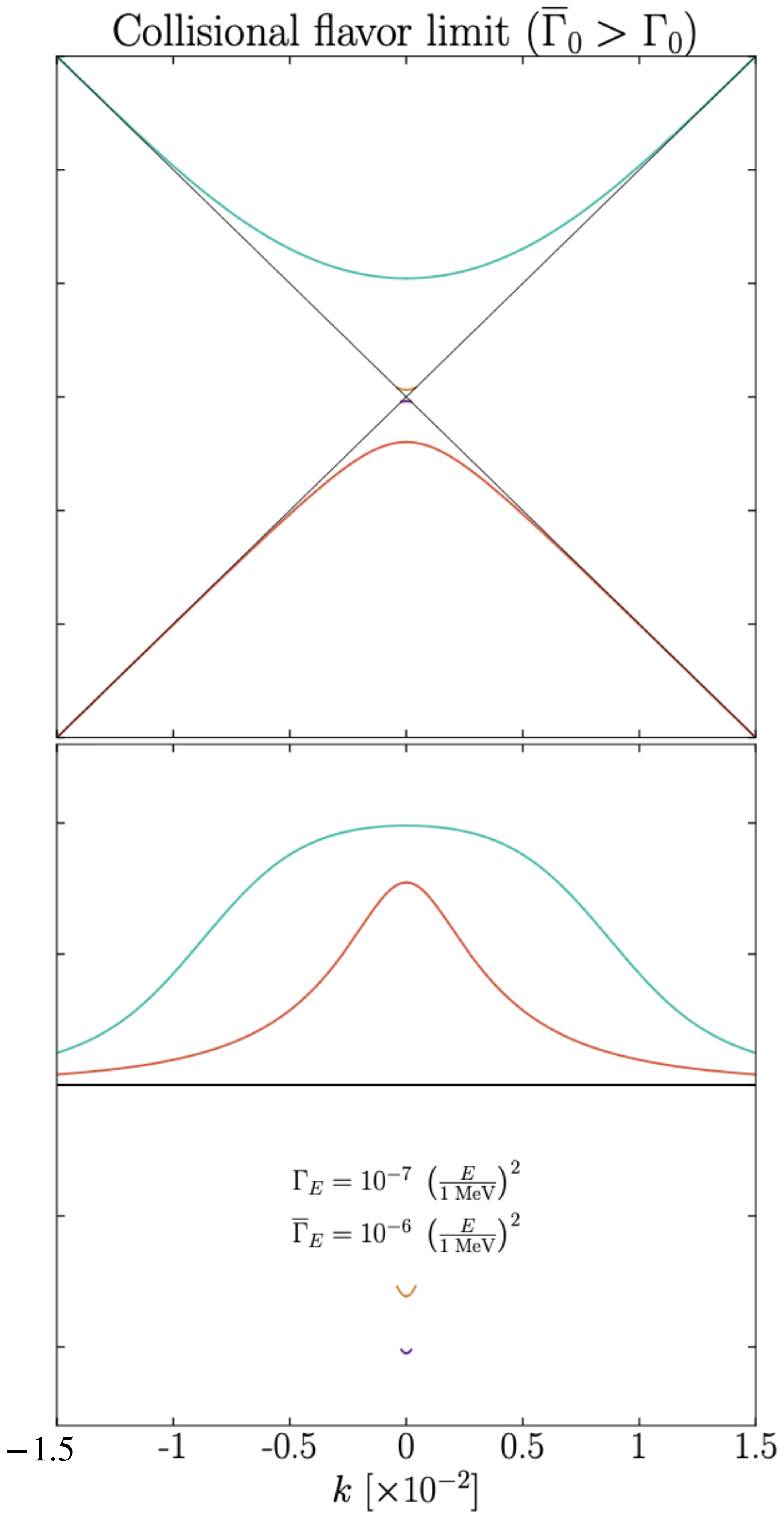
Neutrinos are strongly off-shell by an amount $\sim \Gamma$, so flavomon emission becomes kinematically possible

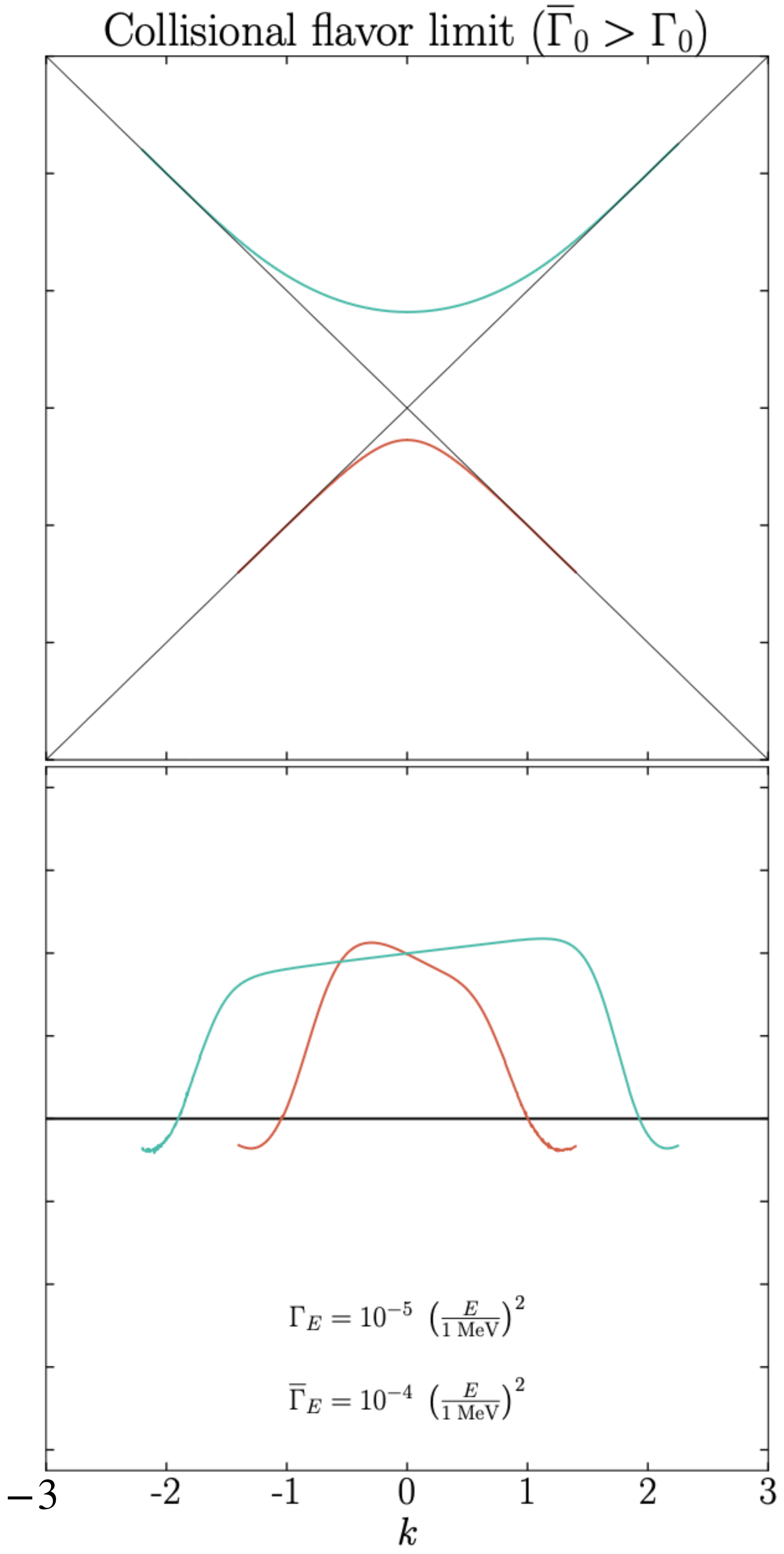
Many early studies use monochromatic or isotropic ansatz, and most focus on modes with $k = 0$

Introduced in *Johns, PRL 2104.11369*

Collisional instabilities

Instability in gapped modes: requires $\overline{\nu}_e > \nu_e$ (perhaps in mergers?)

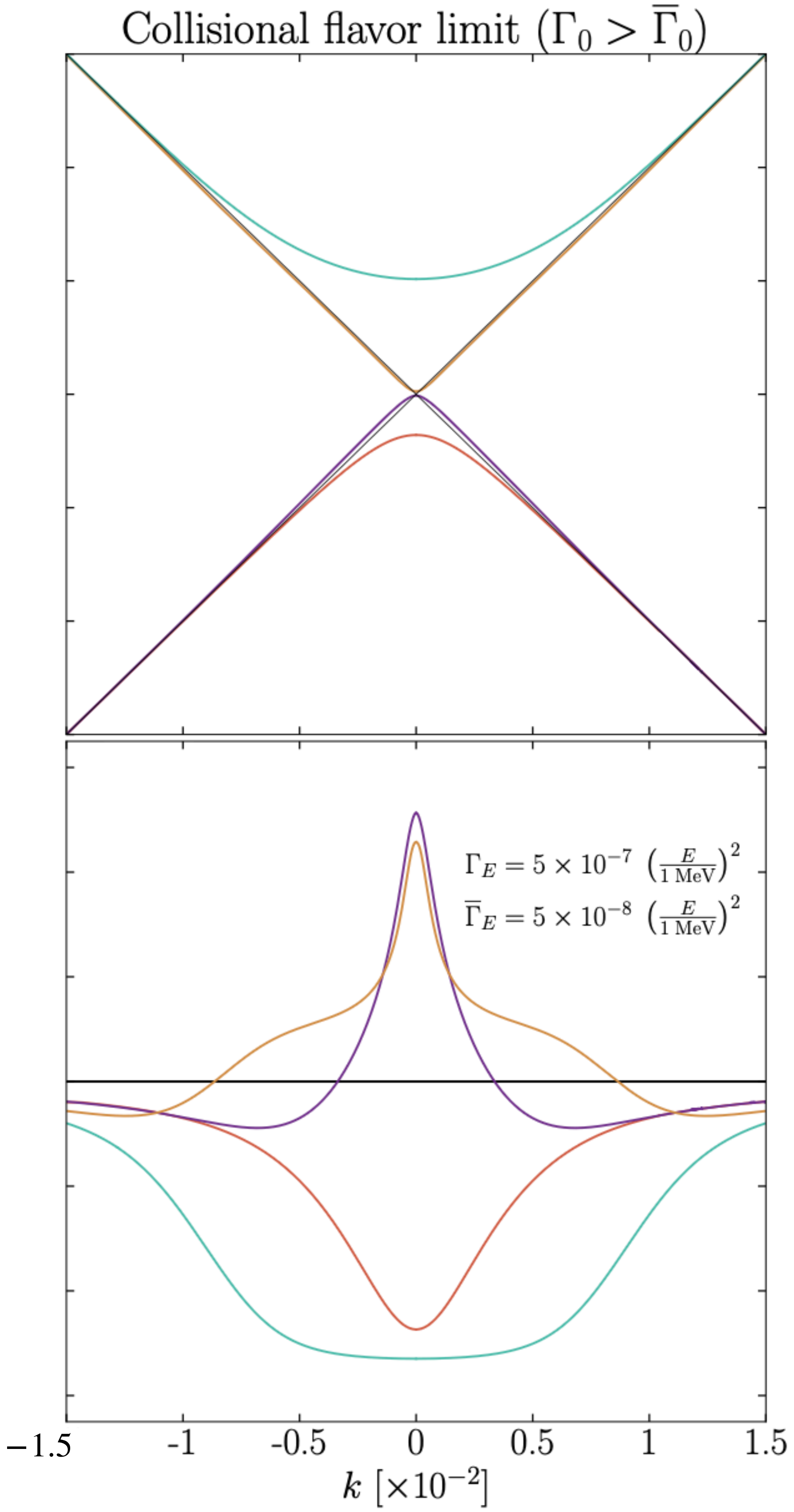


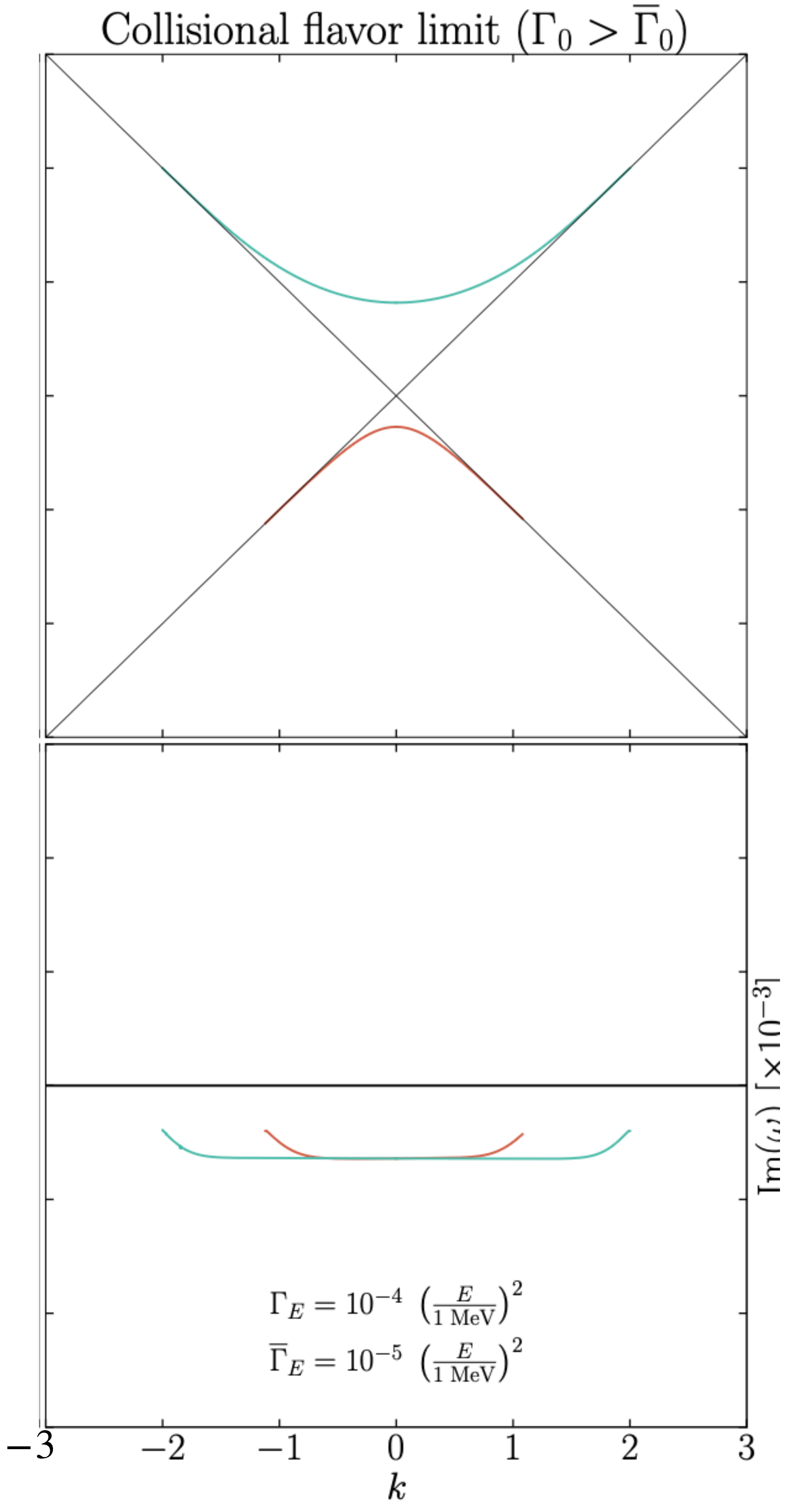


***DF**, Raffelt, JHEP*

Collisional instabilities

Instability in gapless modes: requires $\bar{\nu}_e < \nu_e$





***DF**, Raffelt, JHEP*

Collisional instabilities

Instability in gapless modes: requires $\bar{\nu}_e < \nu_e$

***DF**, Janka, Raffelt, PRL 2507.22985*

$$\frac{n_{\bar{\nu}_e}}{n_{\nu_e}} > \frac{\langle \Gamma_E^{-1} \rangle}{\langle \overline{\Gamma}_E^{-1} \rangle} \sim \frac{n_p}{n_n}$$

Threshold condition (***DF**, Raffelt, JHEP 2505.20389; Johns, PRL 2104.11369 for monochromatic distributions*)

Confirmed also by comparison with numerical SN simulations (*Wang et al., PRD 2507.01100*)

Slow instabilities have no threshold!

Collisional instabilities could still dominate within the neutrinosphere in regions where $\mu_{\nu_e} \sim \mu_{\bar{\nu}_e} (\sim 0?)$

Does it matter?

Does it happen? Yes!

Abbar et al., PRD 1812.06883; Li et al., PRL 2103.02616; Abbar et al., PRD 1911.01983; Abbar et al., PRD 2012.06594; Nagakura et al., PRD 2108.07281; Wu et al., PRD 1701.06580; ***DF*** *et al., PRL, 2507.22985*

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Does it affect neutrino observations? Yes!

Does it matter?

Does it happen? Yes!

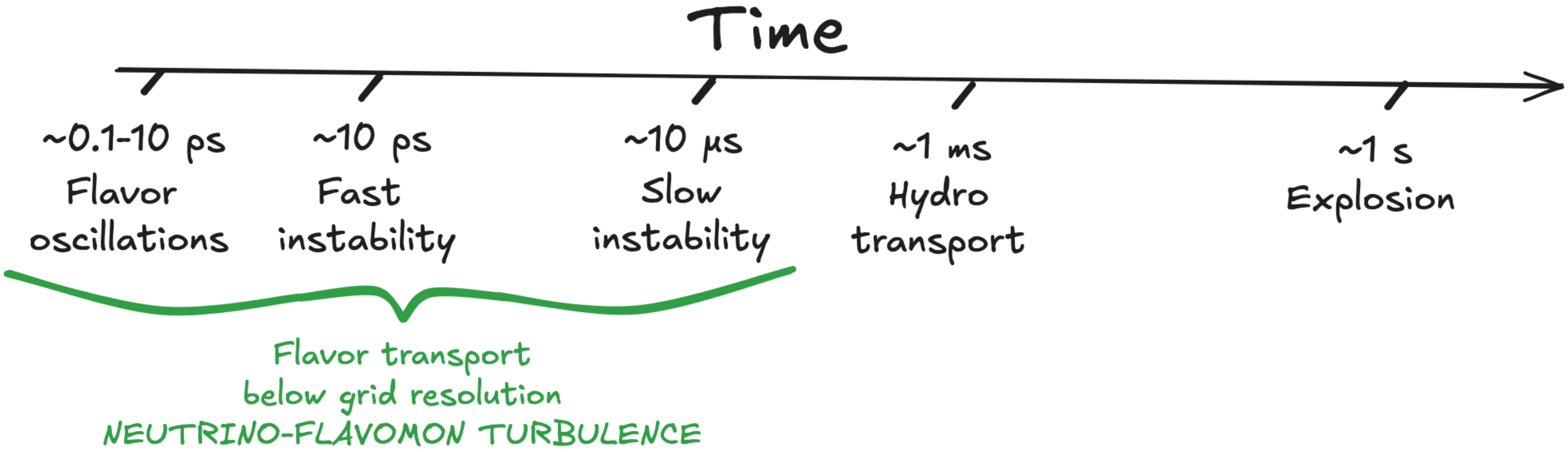
Abbar et al., PRD 1812.06883; Li et al., PRL 2103.02616; Abbar et al., PRD 1911.01983; Abbar et al., PRD 2012.06594; Nagakura et al., PRD 2108.07281; Wu et al., PRD 1701.06580; ***DF*** *et al., PRL, 2507.22985*

Does it affect neutrino observations? Yes!

Does it affect SN evolution? Likely yes!

Ehring et al., PRD 2301.11938, PRL 2305.11207; Wang et al., 2503.04896, …

How to move forward?



Time

~0.1-10 ps
Flavor oscillations

~10 ps
Fast instability

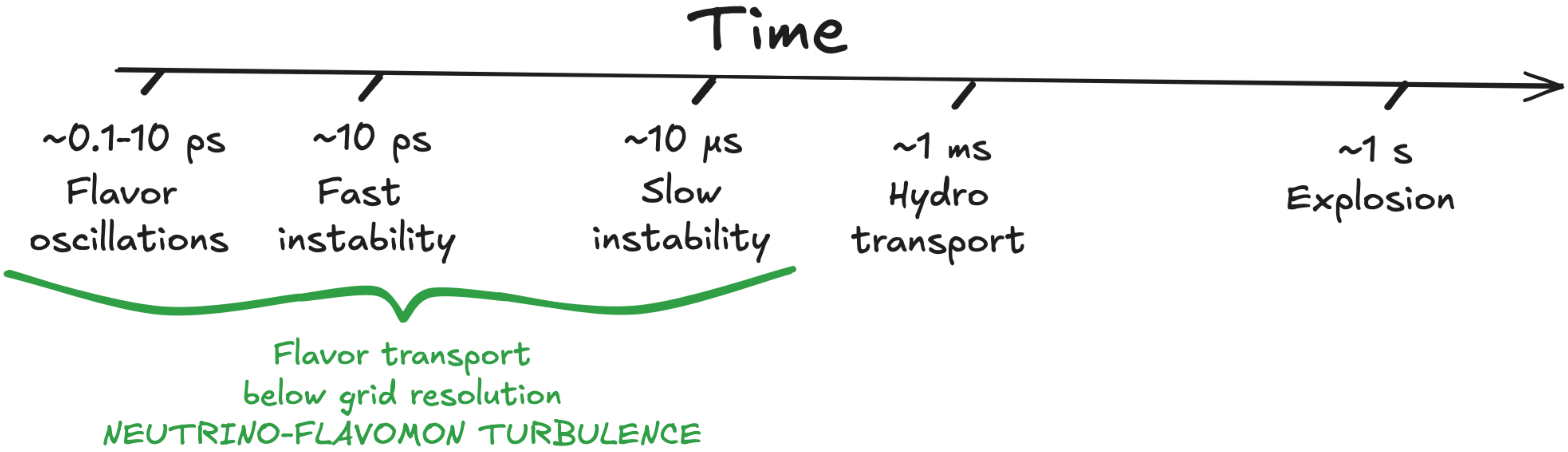
~10 μs
Slow instability

~1 ms
Hydro transport

~1 s
Explosion

Flavor transport
below grid resolution
NEUTRINO-FLAVOMON TURBULENCE

How to move forward?



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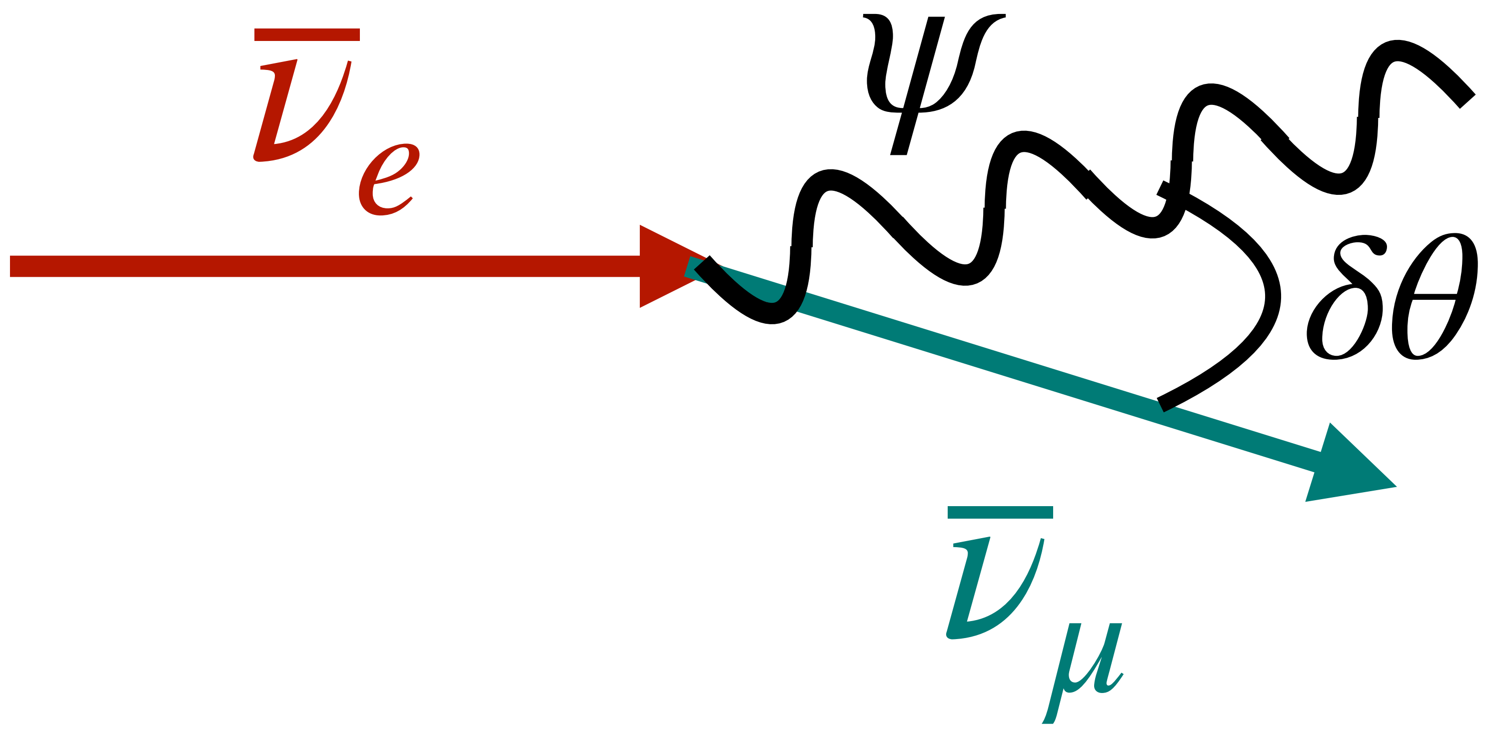
Flavor transport
below grid resolution
NEUTRINO-FLAVOMON TURBULENCE

Where, when, why do instabilities occur in SNe?

How do we describe their small-scale dynamics?

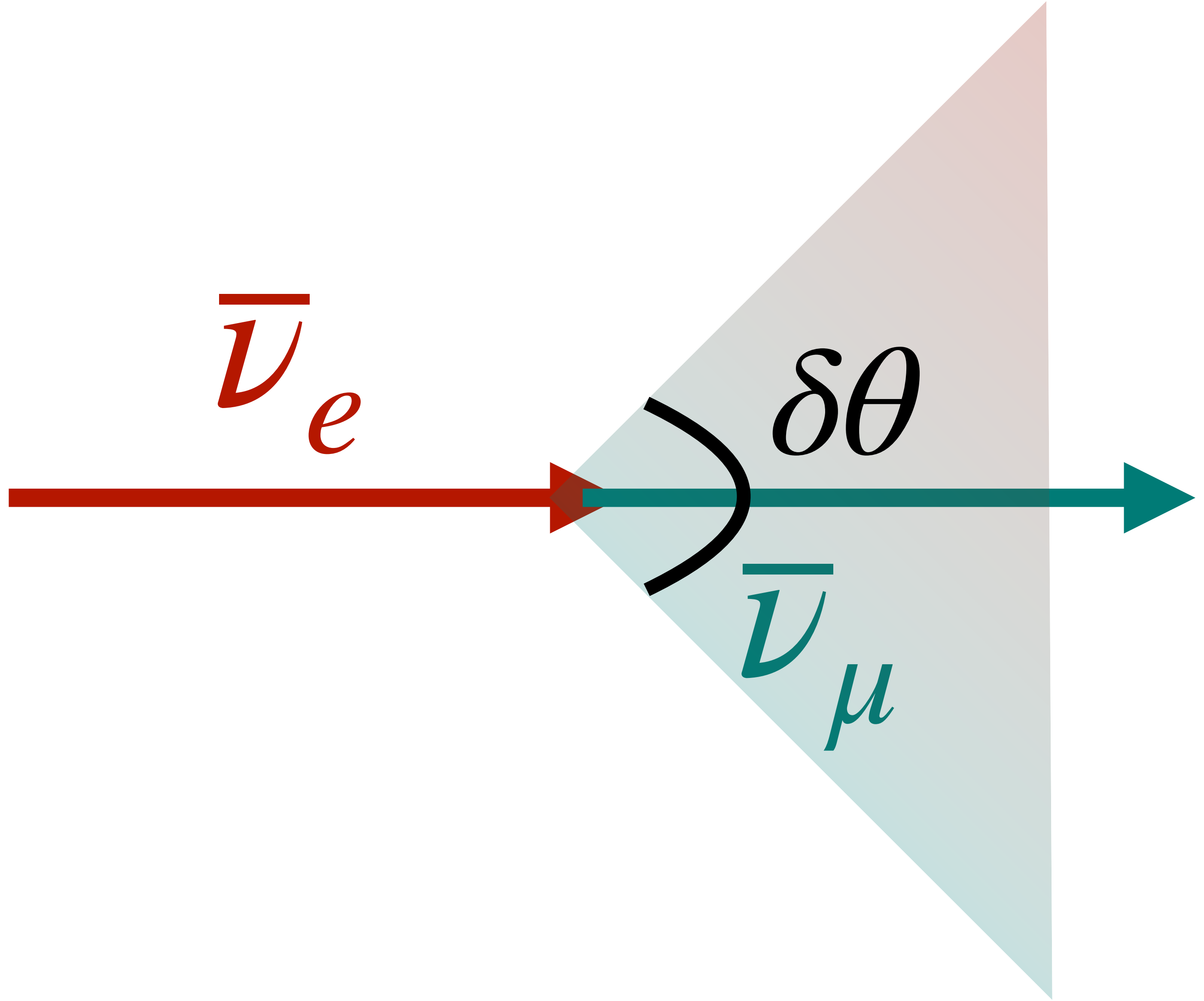
Wave-particle dualism

Decay to flavomons



Energy conservation

Cherenkov flavor-wave emission

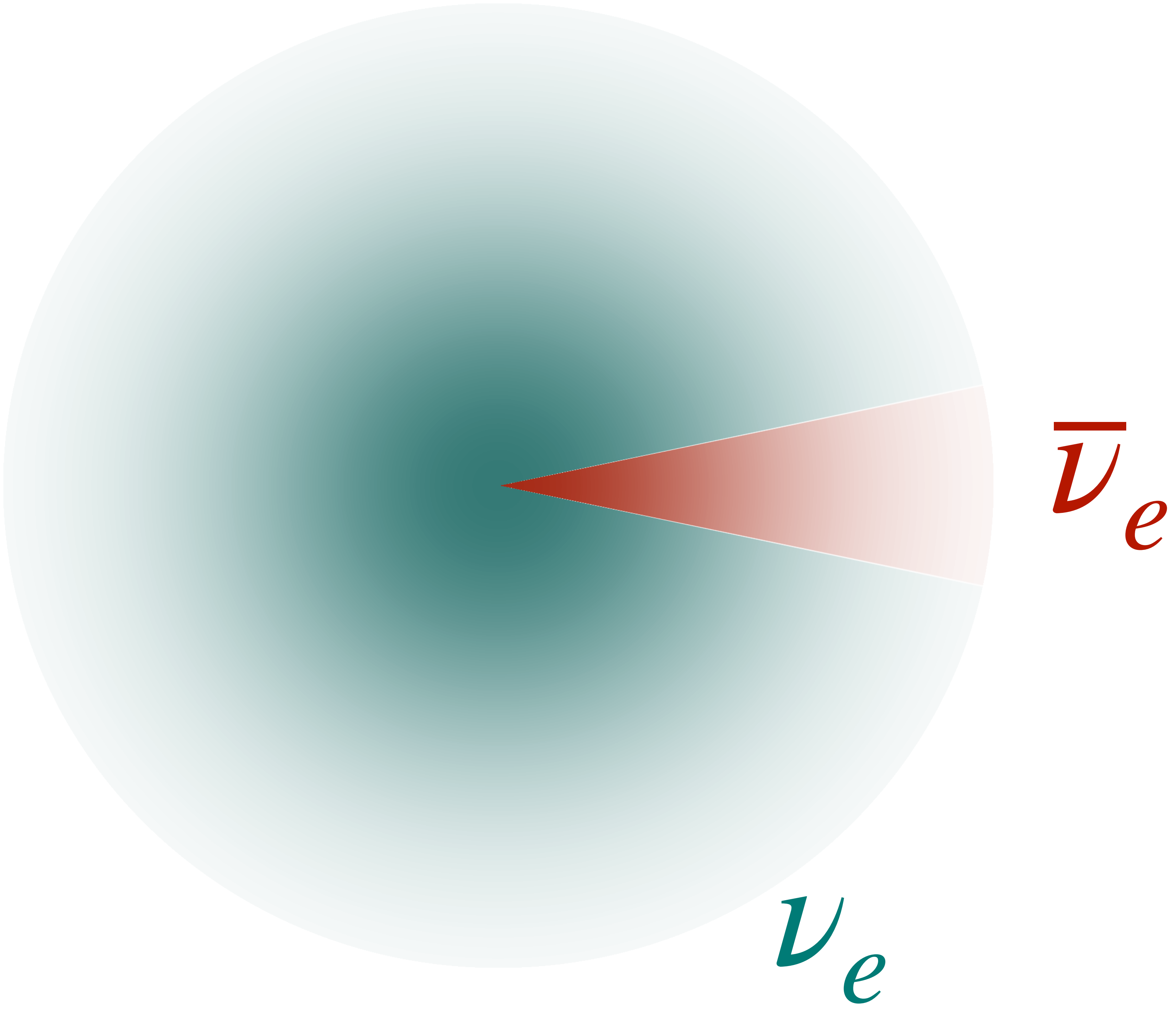


Cherenkov condition

$$\omega - \mathbf{v} \cdot \mathbf{k} = 0$$

$\delta\theta \sim \sqrt{1 - \omega/k} \ll 1$ Flavomons are emitted **collinearly**!

What instabilities occur?



Fast flavor instabilities

Search for angular crossing *(Tamborra et al., ApJ 1702.00060; Shalgar et al., ApJ 1904.07236; Morinaga et al., PRR 1909.13131; Capozzi et al., PRD 2012.08525; Cornelius et al., 2507.13429; Abbar et al., PRD 1812.06883; Delfan Azari et al., 1910.06176; Abbar et al., PRD 1911.01983; Glas et al., PRD 1912.00274; Abbar et al., PRD 2012.06594; Nagakura et al., PRD 2108.07281)*

Angular crossings emerge after 100 ms!

A new state of matter

- **Spontaneously broken symmetry —** flavor-mixed states without explicit flavor mixing, spontaneously broken homogeneity and isotropy (turbulence)
- **Emerging degrees of freedom —** flavor waves (flavomons)
- **Collisionless exchange —** mediated by wave-particle interaction, typical of plasmas

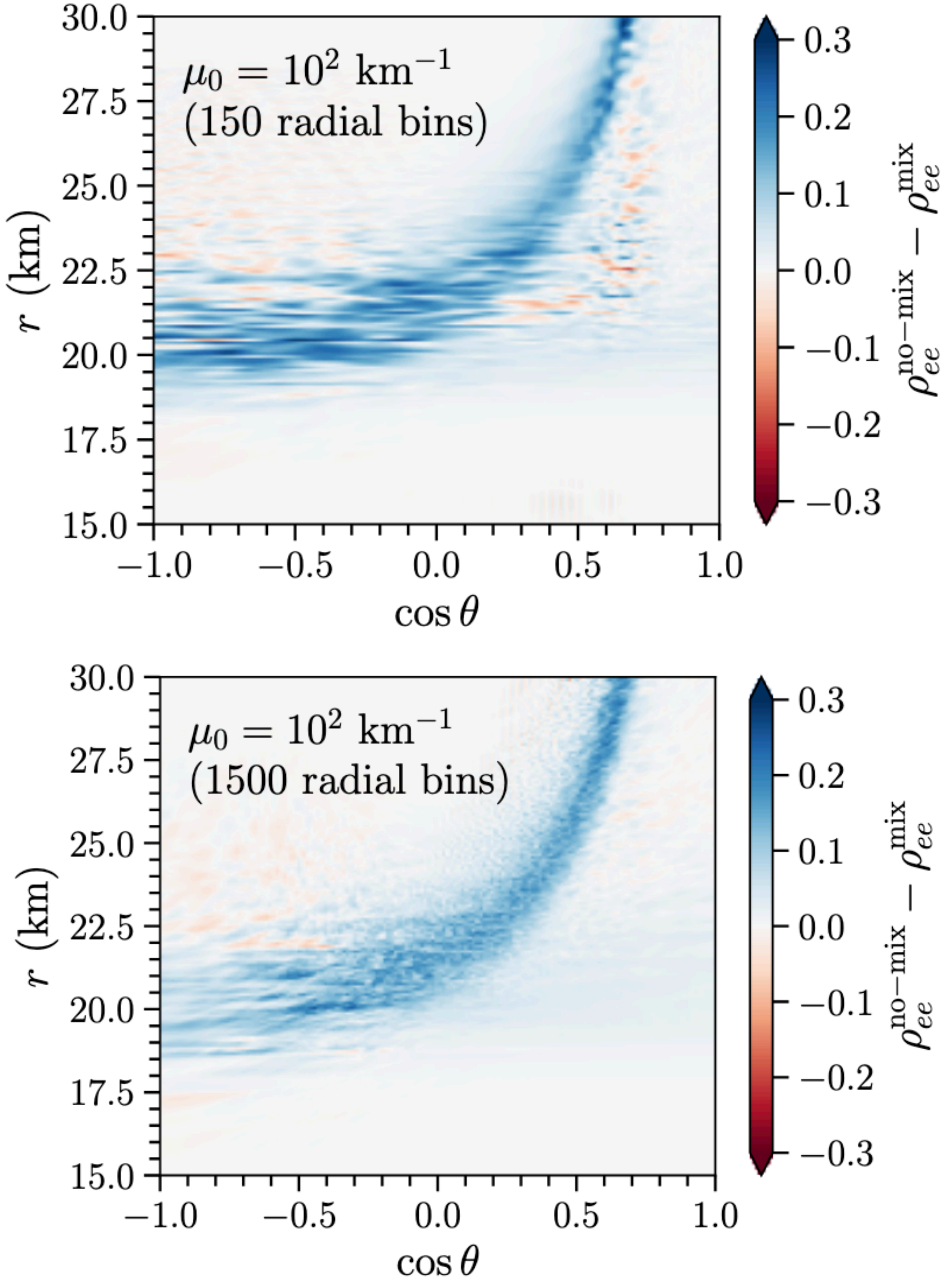
Under-resolved spatial grids

Large-scale simulations ($\sim 50\,\mathrm{km}$) with coarse resolution ($\sim 100\,\mathrm{m}$), much above the flavomon wavelength ($\sim 1-10\,\mathrm{mm}$)

Mainly driven by *Shalgar and Tamborra, PRD 2206.00676; PRD 2207.04058; PRD 2307.10366; JCAP 2407.04769; …*

Convergence only validated numerically, no theoretical understanding of why under-resolved grids should work, or under what conditions

For weakly unstable distributions, it should not work — unstable modes all have small wavelength



Shalgar and Tamborra, PRD 2206.00676

Moment-based methods

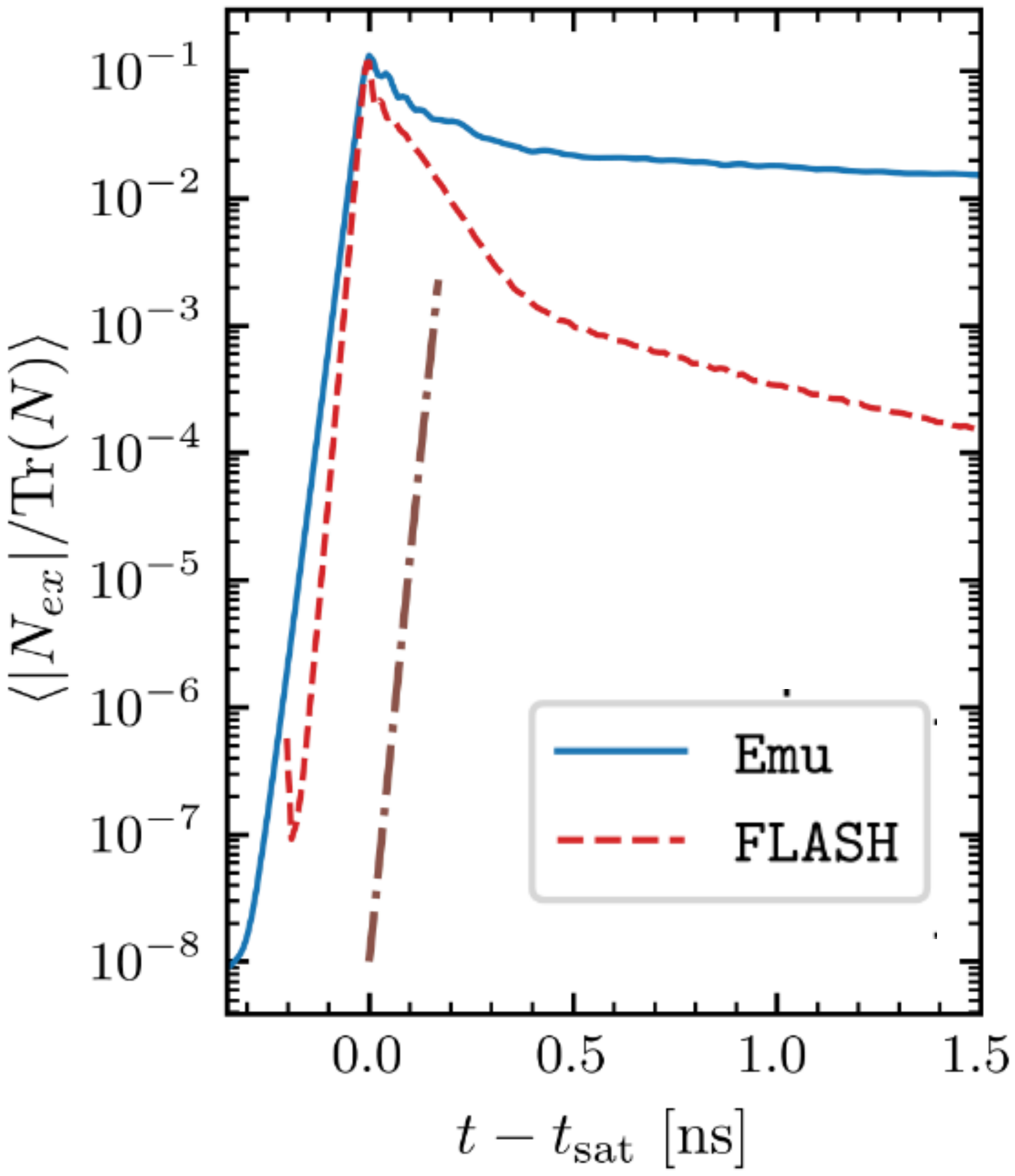
Replacing angular distribution with monopole and dipole moments — much less computational cost, avoiding a full angular distribution

Does not circumvent small-scale problem

Requires quantum closure

Pioneered by *Strack et al., PRD 0504035; Zhang et al., 1310.2164;* in fast conversion era, driven by *Myers et al., PRD 2111.13722; Grohs et al., ApJ 2309.00972; Froustey et al., PRD 2311.11968; …*

Weak instabilities — which are directional — likely require full angular distribution



Shalgar and Tamborra, PRD 2206.00676

Attenuation-based methods

- Artificially reducing the value of Fermi constant → Wavelength and period of flavomons become larger, easier to resolve
- Removes the small-scale difficulty
- Generally uncontrollable approximation — no theoretical justification, provides general guidance but requires extrapolation
- Mainly driven by *Nagakura et al., 2206.04097; 2211.01398; 2301.10785; 2306.10108*

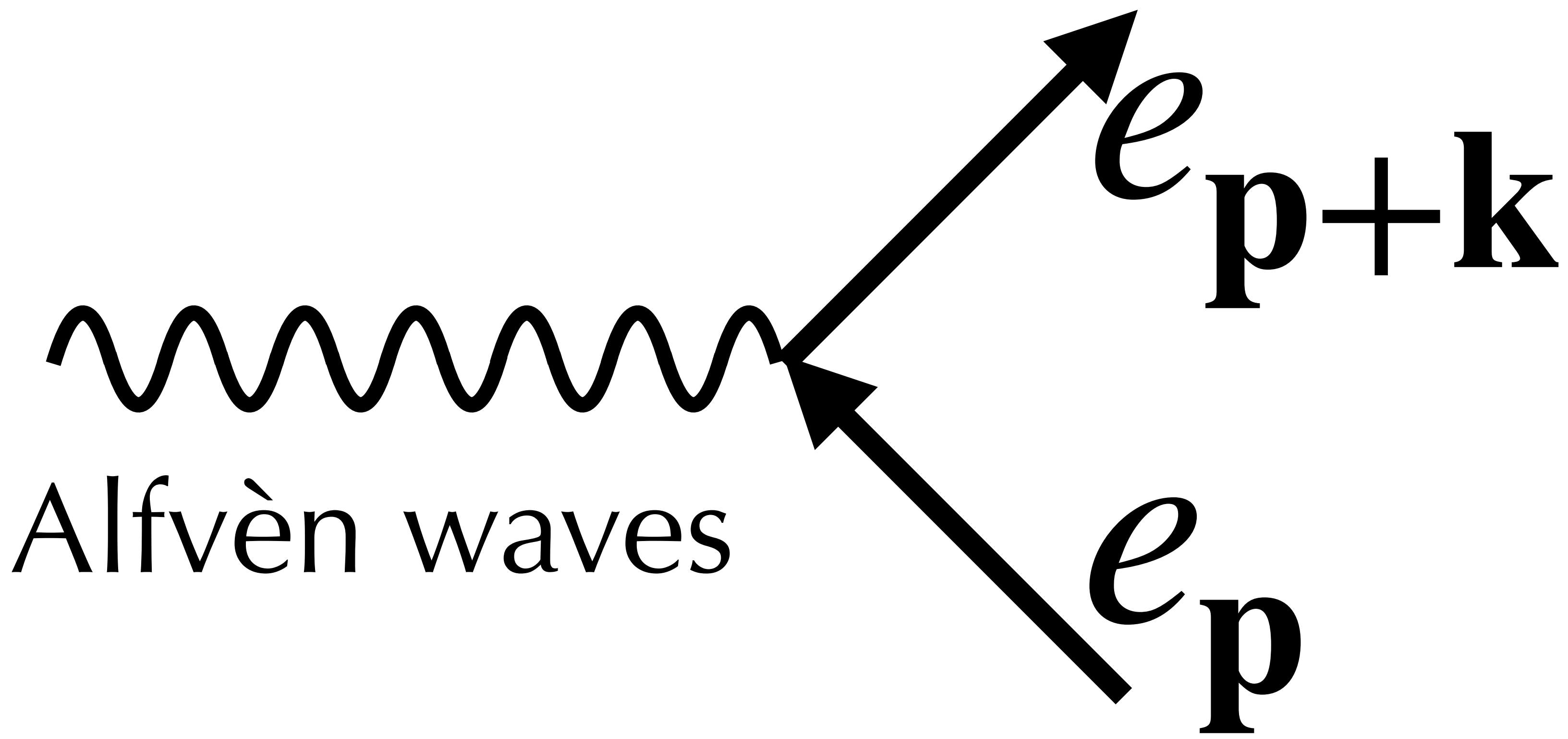
Box-based methods (local relaxation)

- Solving for flavor conversion exactly in cm-scale boxes
- The solution can map between an unstable configuration and its asymptotic relaxed version — ready to be implemented in a simulation!
- Many groups work along this direction — see main slides for representative list
- Ignores non-local effects due to transfer among boxes — but flavor waves can propagate among boxes (numerically observed in *Cornelius et al., JCAP 2312.03839*; proved in ***DF***, *Raffelt, JHEP 2501.16423*)
- For slow instabilities, waves grow over km-scale — a single box is not representative!

Neutrino plasma

- What are neutrinos in a SN, outside of the PNS?
- Not in regular lattice → **Not a solid**
- Not in thermal equilibrium → **Not a liquid**
- Exchange flavor more rapidly than they leave → **Not a gas**
- Collective dynamics of flavor waves → **Neutrino plasma!**

Ubiquitous collisionless interactions



Stochastic acceleration in weakly magnetized turbulence
(Fermi 2nd order acceleration)

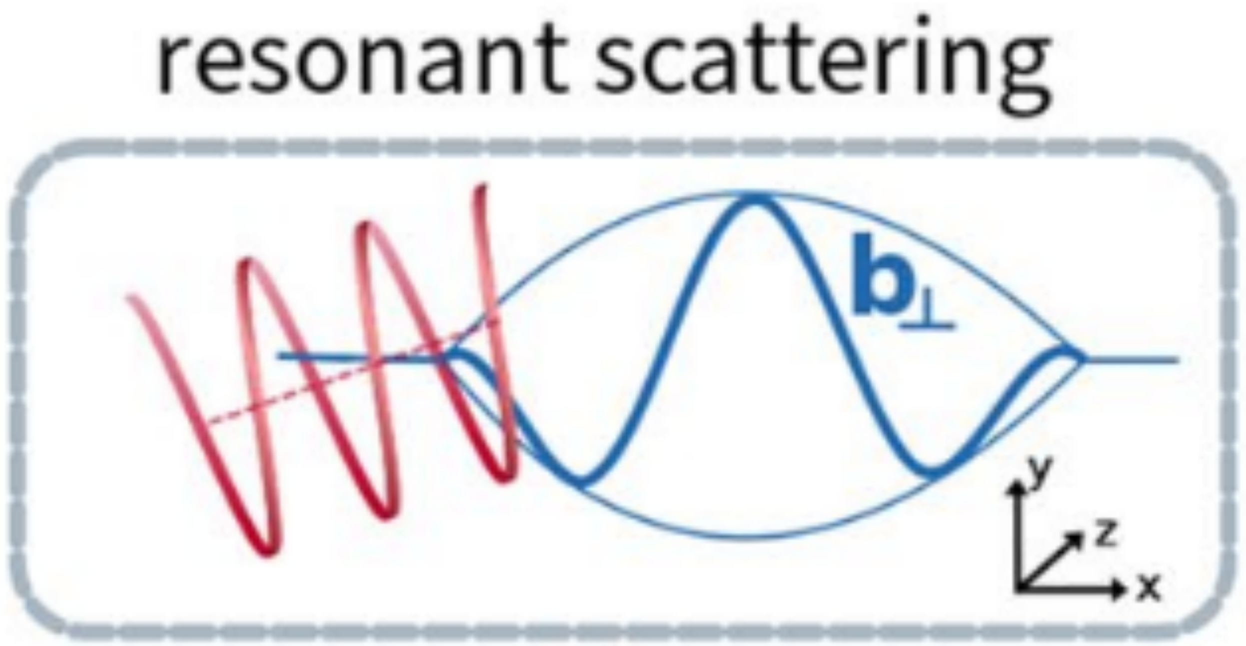
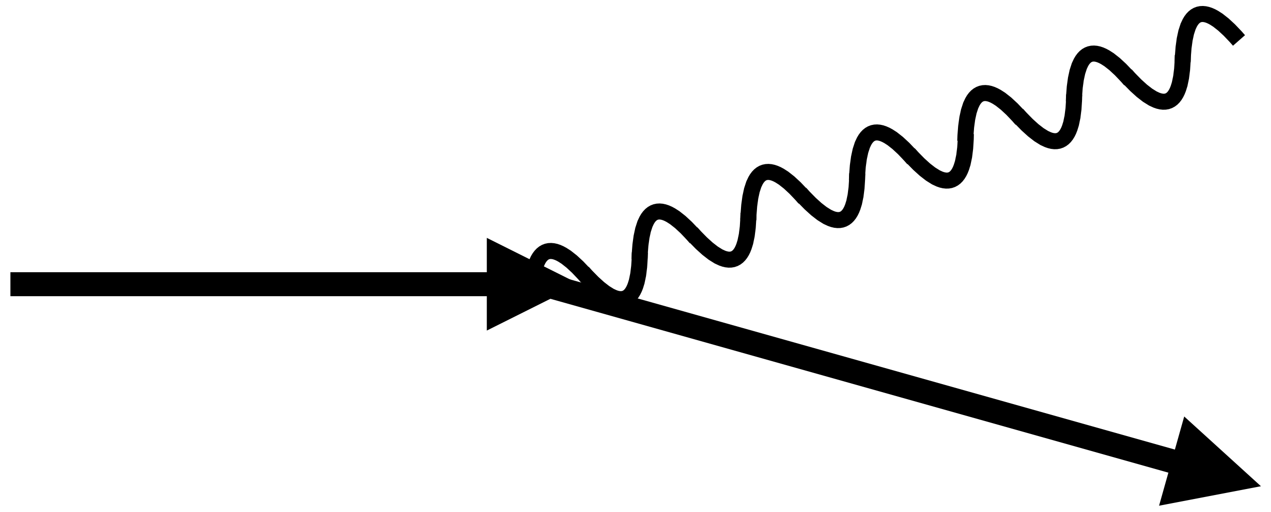


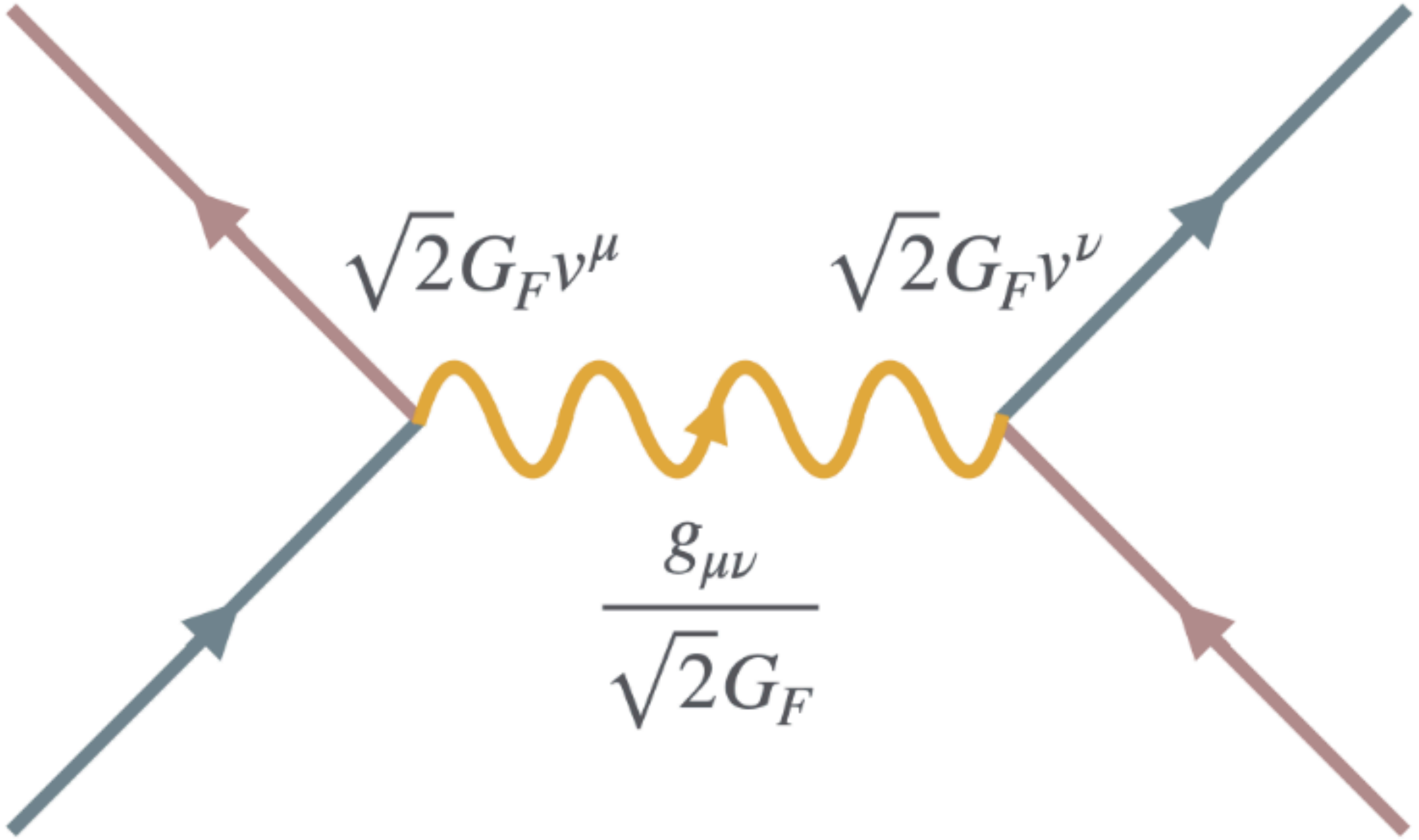
Fig. from
Reichherzer et al., SN App. Sc., 2021

Cosmic-ray diffusion by magnetic perturbations
(also responsible for **Fermi 1st order acceleration** at shock waves)

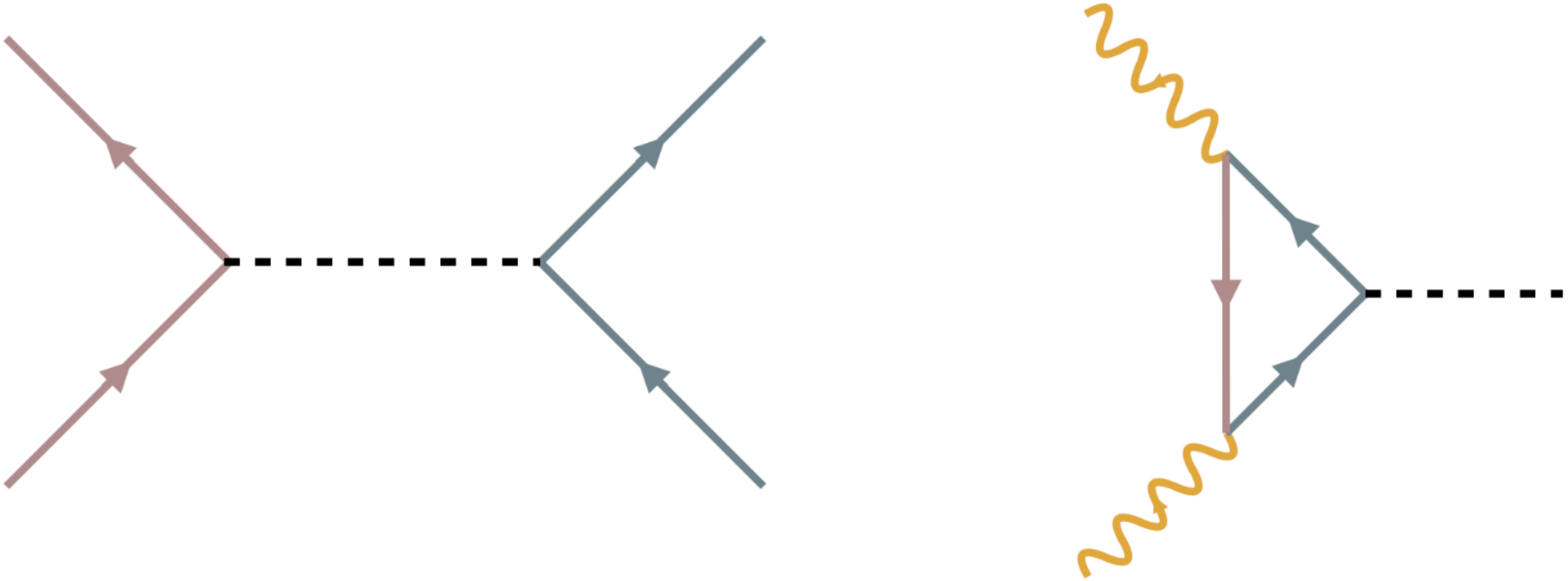


Cosmic-ray streaming instabilities
with self-generated turbulence

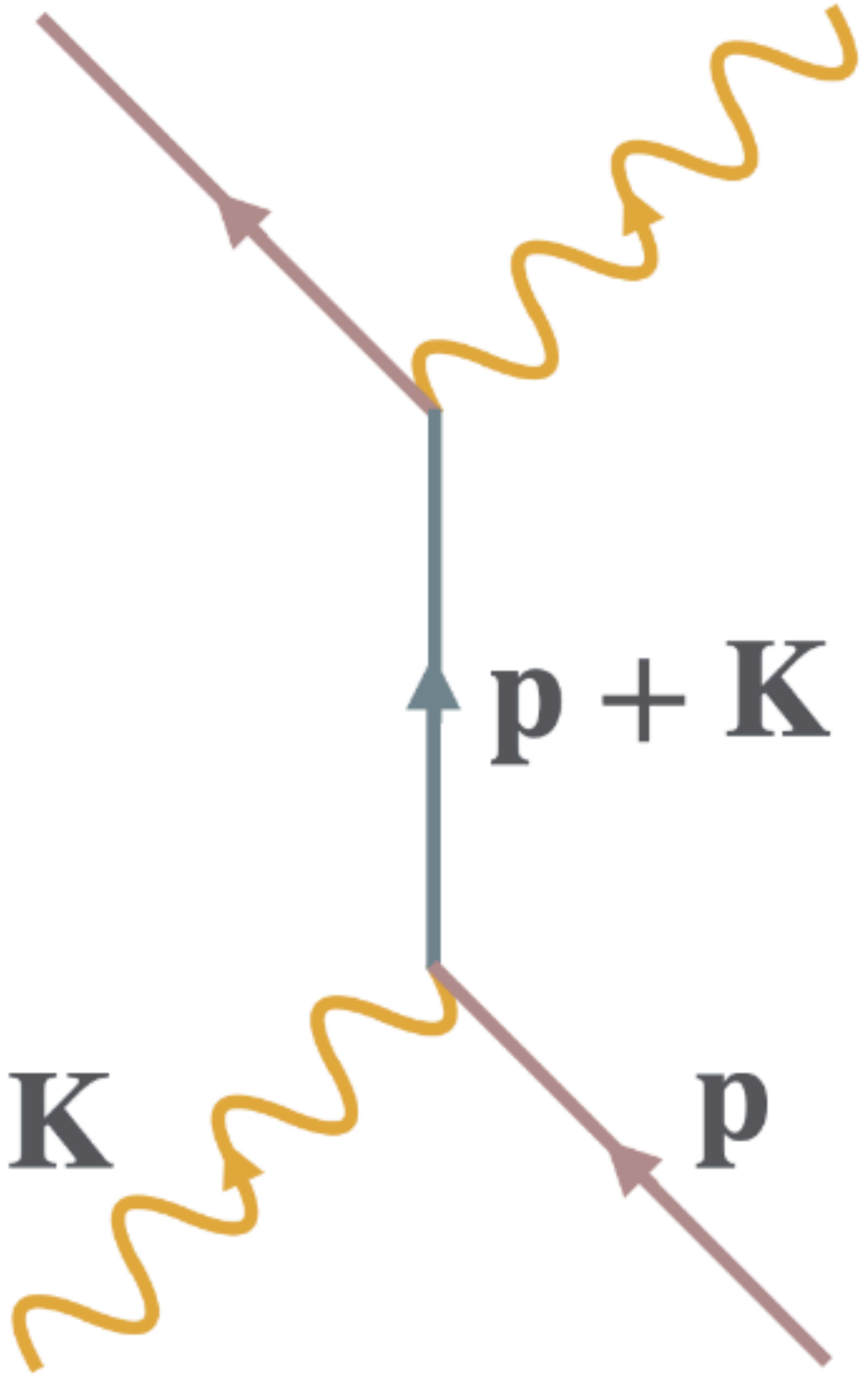
Neutrino-flavomon interactions

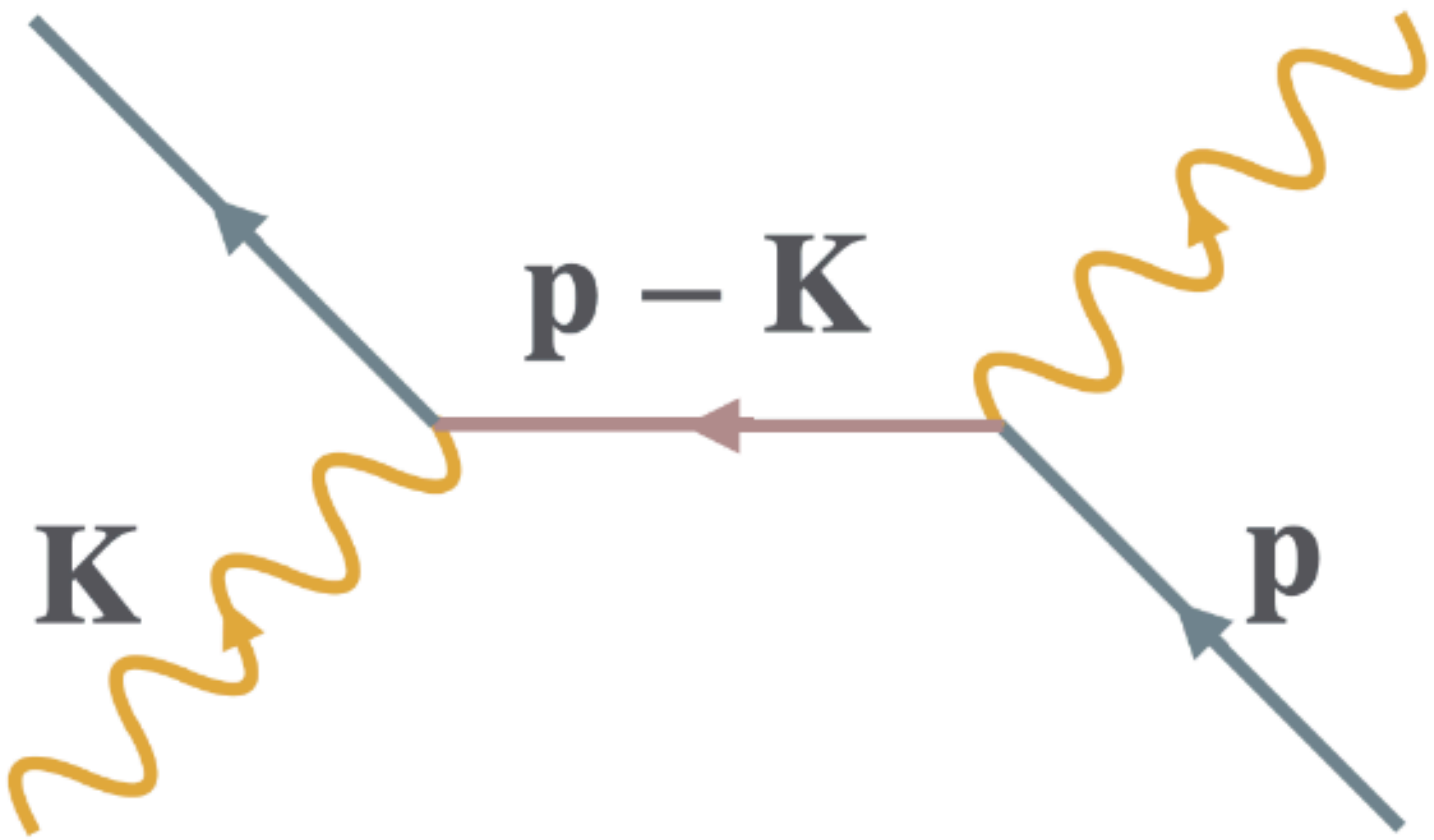


Neutrino-flavomon interactions



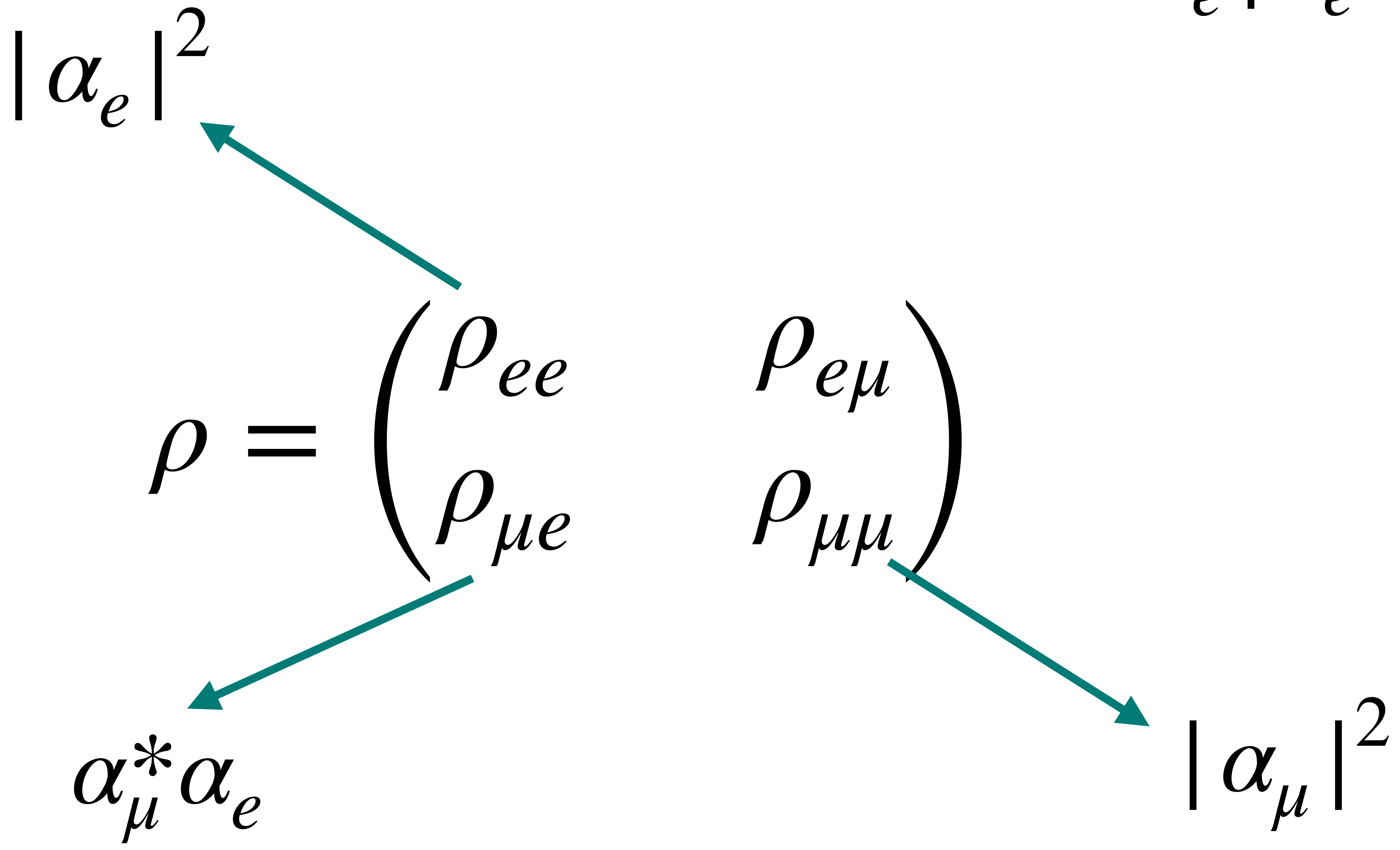
Neutrino-flavomon interactions





Quantum kinetic equations

$$\alpha_e |\nu_e> + \alpha_\mu |\nu_\mu>$$



$$|\alpha_e|^2$$

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

$$\alpha_\mu^* \alpha_e$$

$$|\alpha_\mu|^2$$

Quantum kinetic equations

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Dolgov, Sov. J. Nucl. Phys.,1981

Rudzsky, Astrophys. Space Sci., 1990,

Sigl, Raffelt, Nucl. Phys. B, 1993

$$\partial_t \rho \qquad + v \partial_r \rho \qquad = -i[\mathscr{H}, \rho]$$

Advection

Interaction

$|\overrightarrow{P}_\nu|$ conserved!

$$\mathscr{H} \propto \sqrt{2} G_F \sum_{\prime} \rho'$$

Quantum kinetic equations

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Instability driven by **advection** and **interaction** (similar to **plasma waves**)

$$\partial_t \rho \quad + v \partial_r \rho \quad = - i[\mathcal{H}, \rho]$$

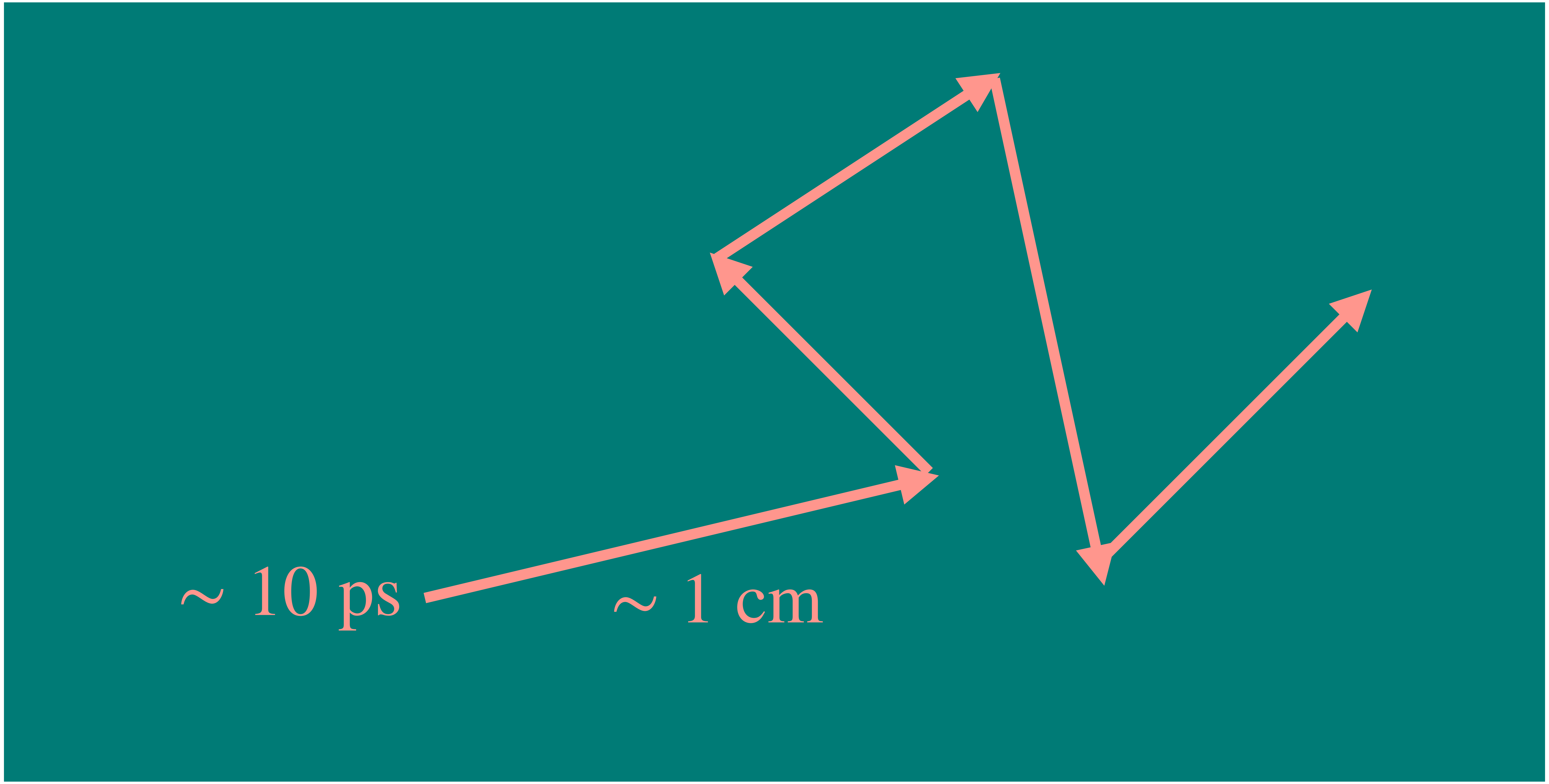
Advection

Interaction

$| \overrightarrow{P}_v |$ conserved!

$$\sim 10\ \mathrm{ps} \longrightarrow \mathcal{H} \propto \sqrt{2} G_F \sum_{'} \rho'$$

Quantum kinetic equations



Spontaneous breaking of homogeneity!

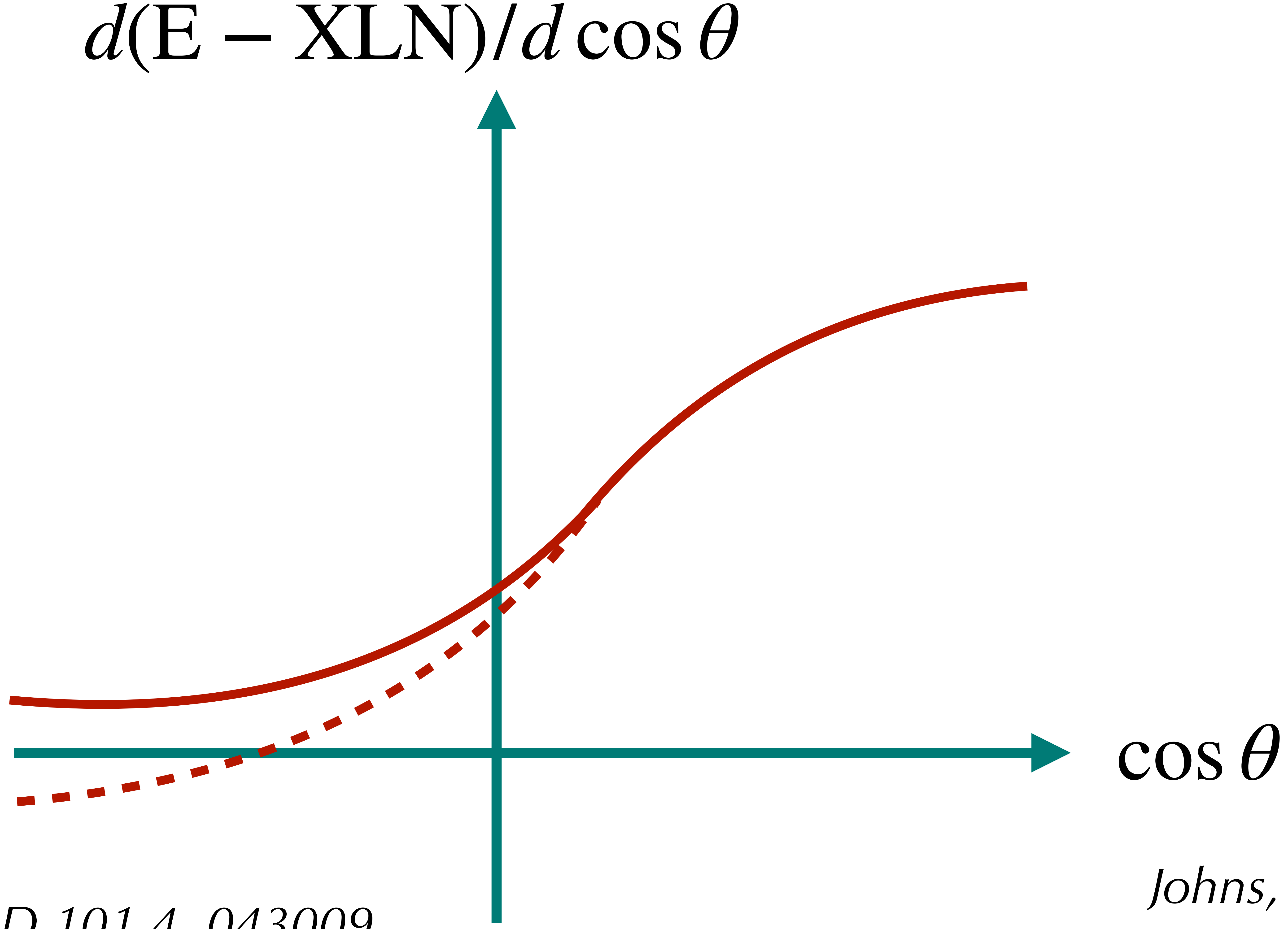
Conservation laws

$$(n_{\nu_e} - n_{\overline{\nu}_e}) - (n_{\nu_\mu} - n_{\overline{\nu}_\mu})$$

conserved!

E-XLN conservation

Conservation laws



Things can move

Instability? Only if no more conservation laws!

Simple counterexample: homogeneous system (infinite conservation laws)

Johns et al., PRD 101 4, 043009

***DF**, Raffelt, PRD 107 4, 043024; PRD 107 12, 123024*

Johns, 2402.08896

***DF**, Raffelt, 2406.06708*

Stable systems

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

$$\rho_{e\mu} \ll \rho_{ee}, \rho_{\mu\mu}$$

Neutrinos are mostly in flavor eigenstates!

Flavor waves

Stable systems

Stable systems

Stable systems

If $u \neq c \cos\theta$ no net effect!

Stable systems

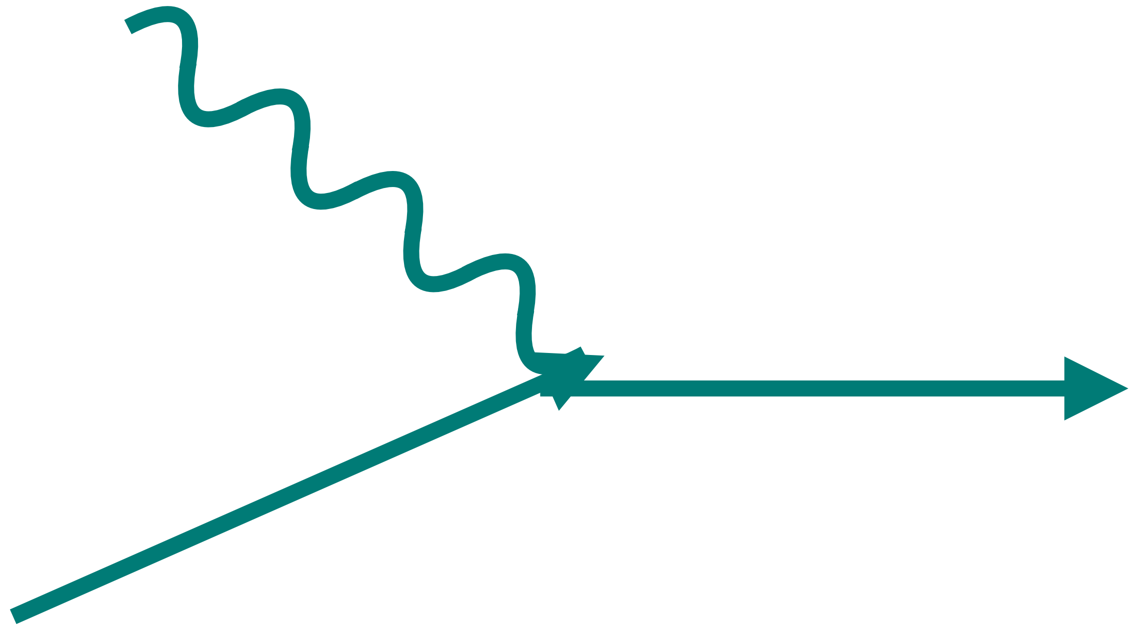
If $u = c\cos\theta$ resonance!

Damiano Fiorillo

Stable systems

Flavor waves can only be damped → **Landau damping!**

Resonant neutrinos move in phase with the wave

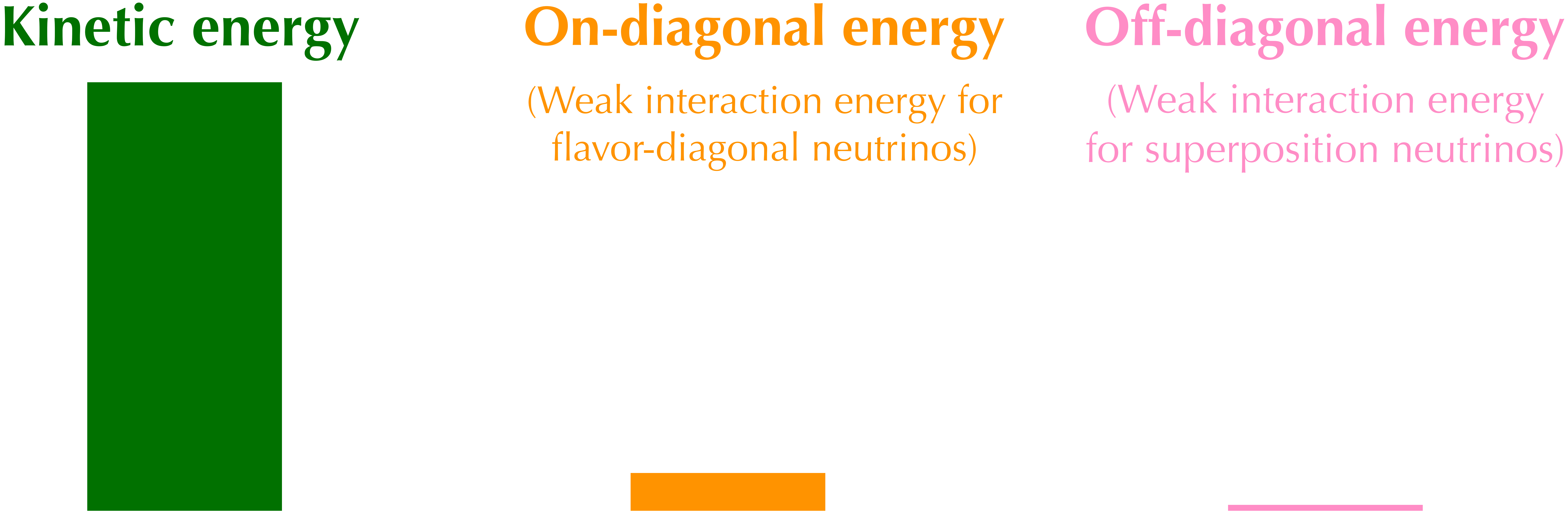


Cherenkov absorption causes damping

Stable systems

Flavor waves can only be damped ⟶ **Landau damping!**

Resonant neutrinos move in phase with the wave



Kinetic energy

On-diagonal energy

(Weak interaction energy for flavor-diagonal neutrinos)

Off-diagonal energy

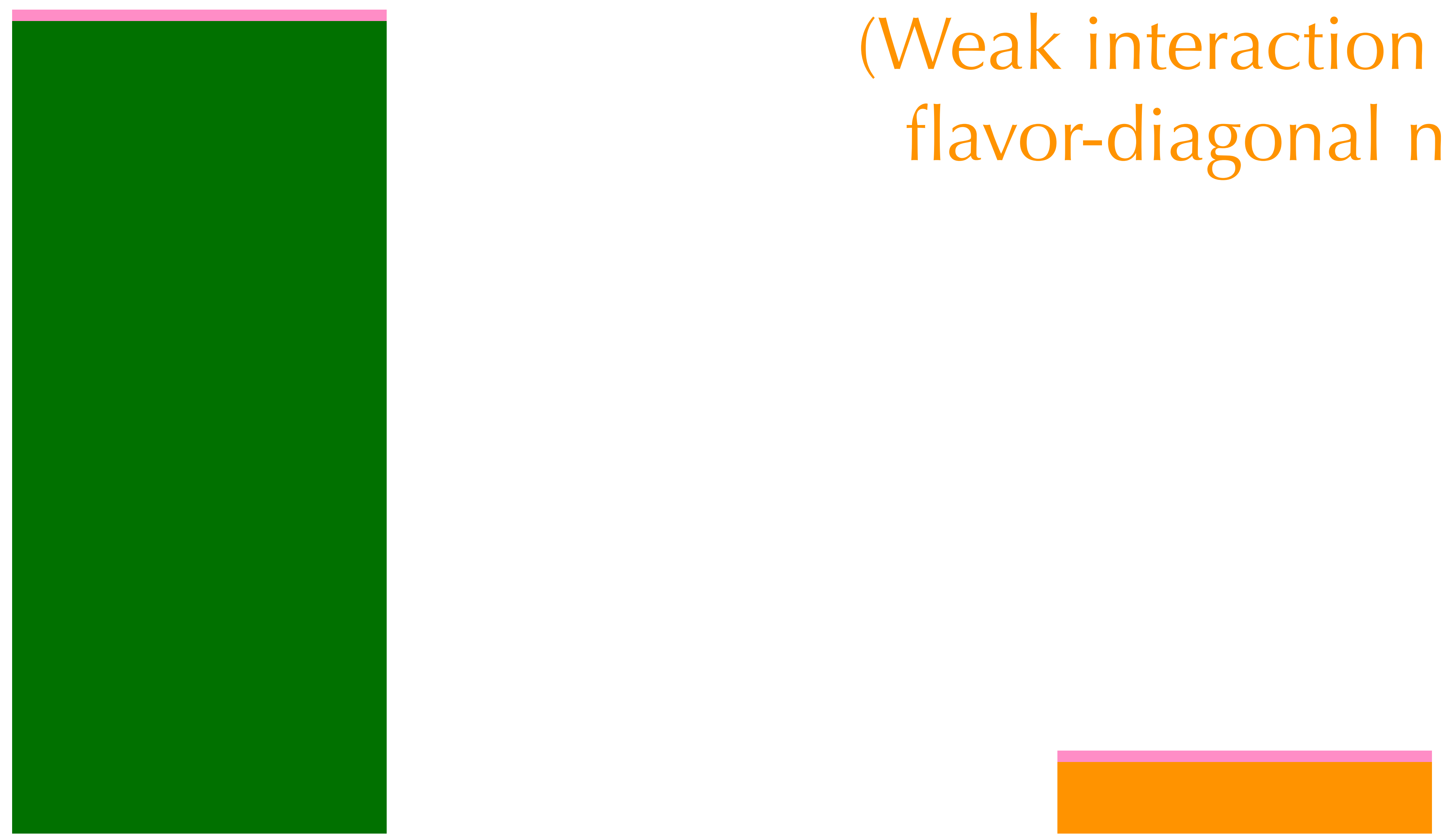
(Weak interaction energy for superposition neutrinos)

***DF**, Raffelt, Sigl, PRL 133 2, 021002*

Stable systems

Flavor waves can only be damped ⟶ **Landau damping!**

Resonant neutrinos move in phase with the wave



Kinetic energy

On-diagonal energy

(Weak interaction energy for flavor-diagonal neutrinos)

Off-diagonal energy

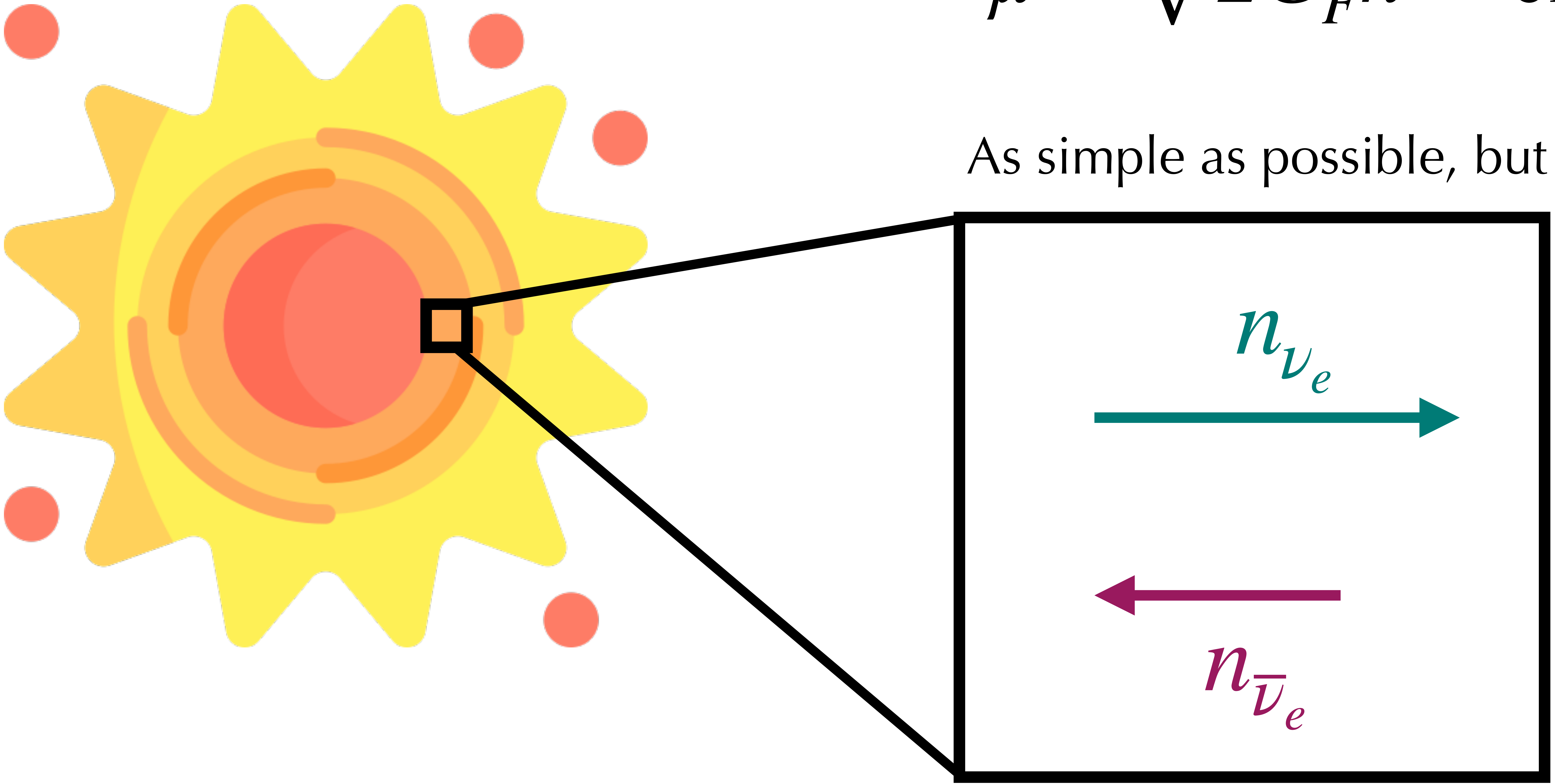
(Weak interaction energy for superposition neutrinos)

***DF**, Raffelt, Sigl, PRL 133 2, 021002*

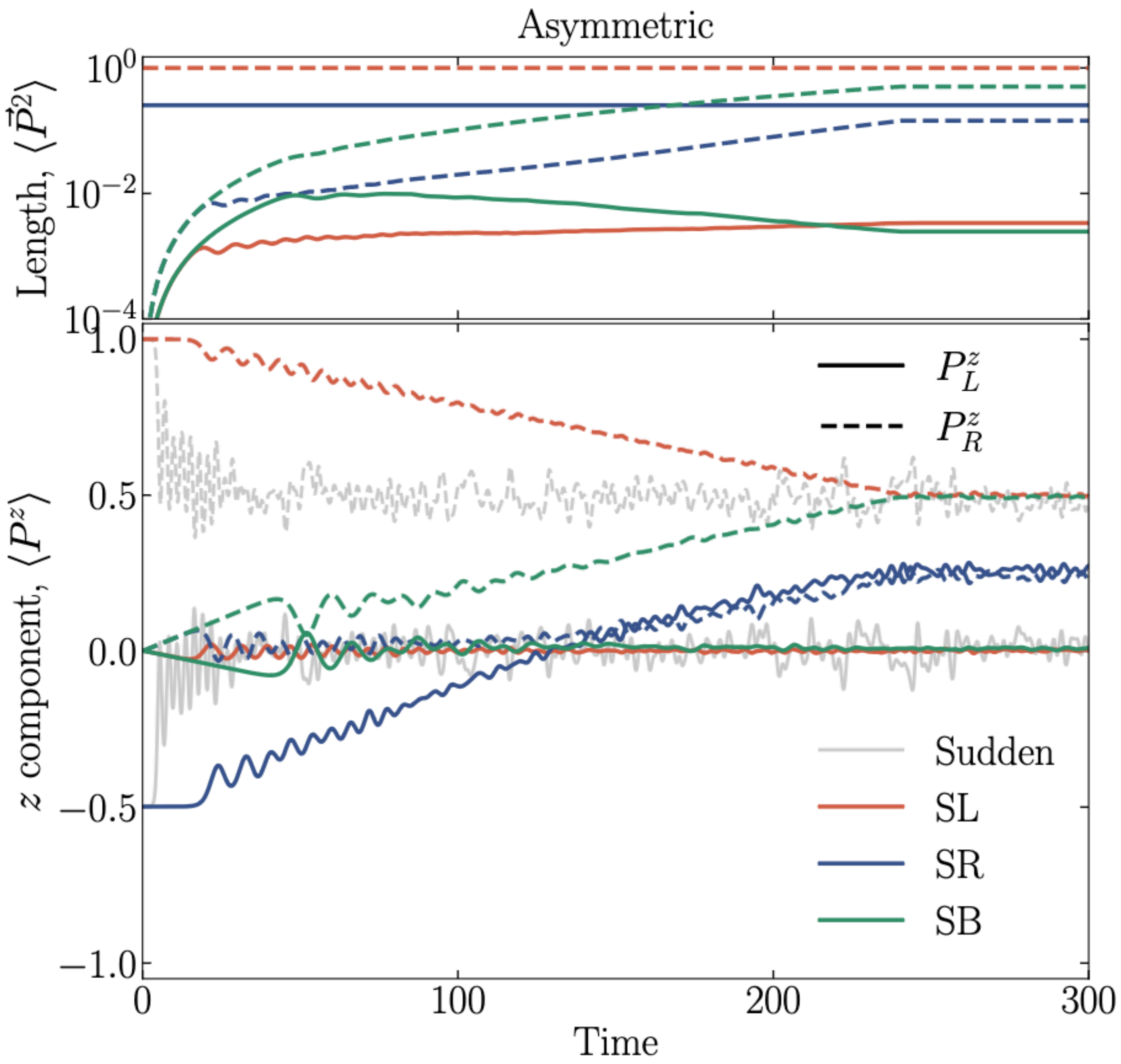
Relaxation of instability

$$\mu \simeq \sqrt{2} G_F n \simeq \mathrm{cm}^{-1}$$

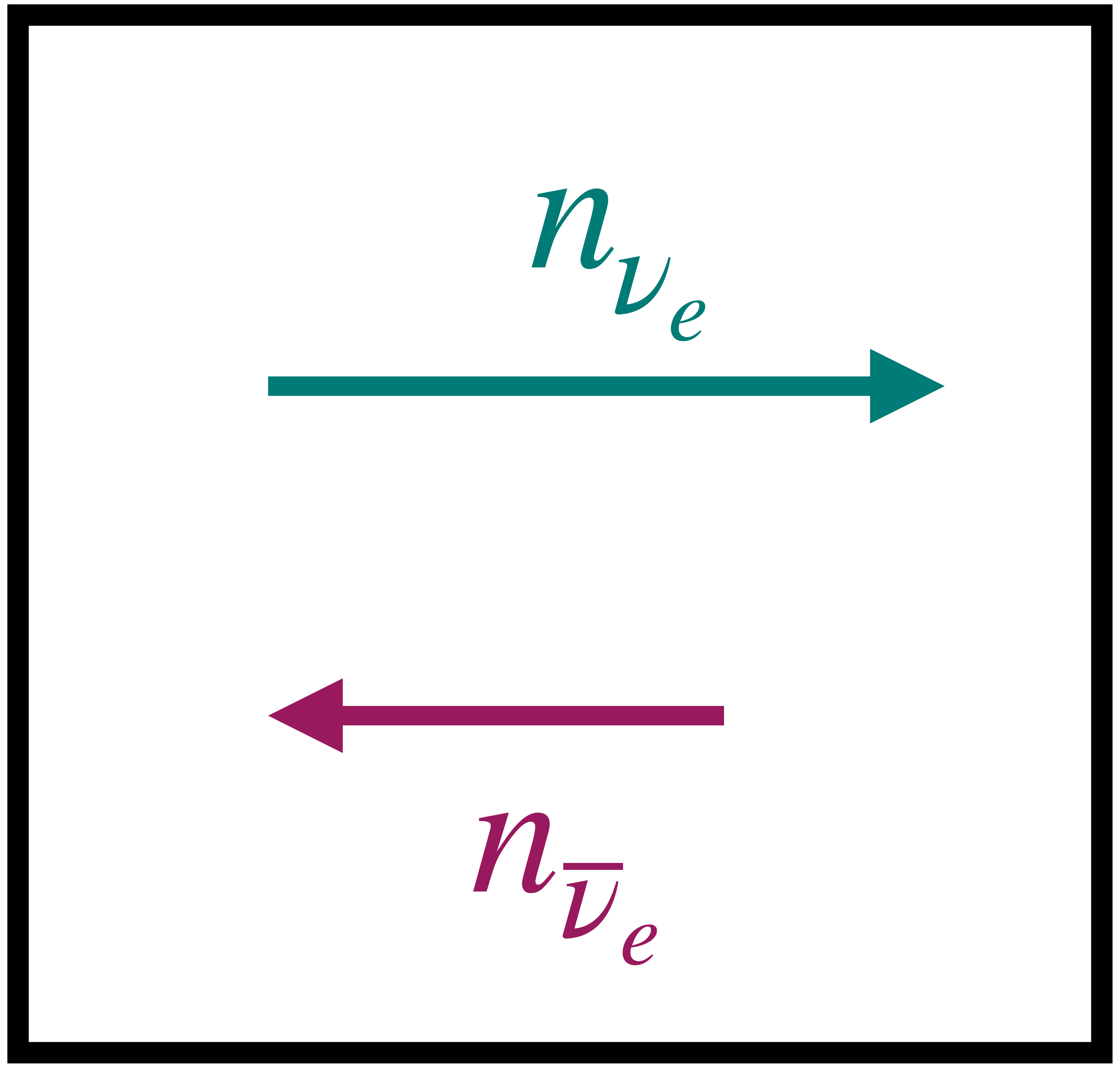
As simple as possible, but no simpler!



Relaxation of instability

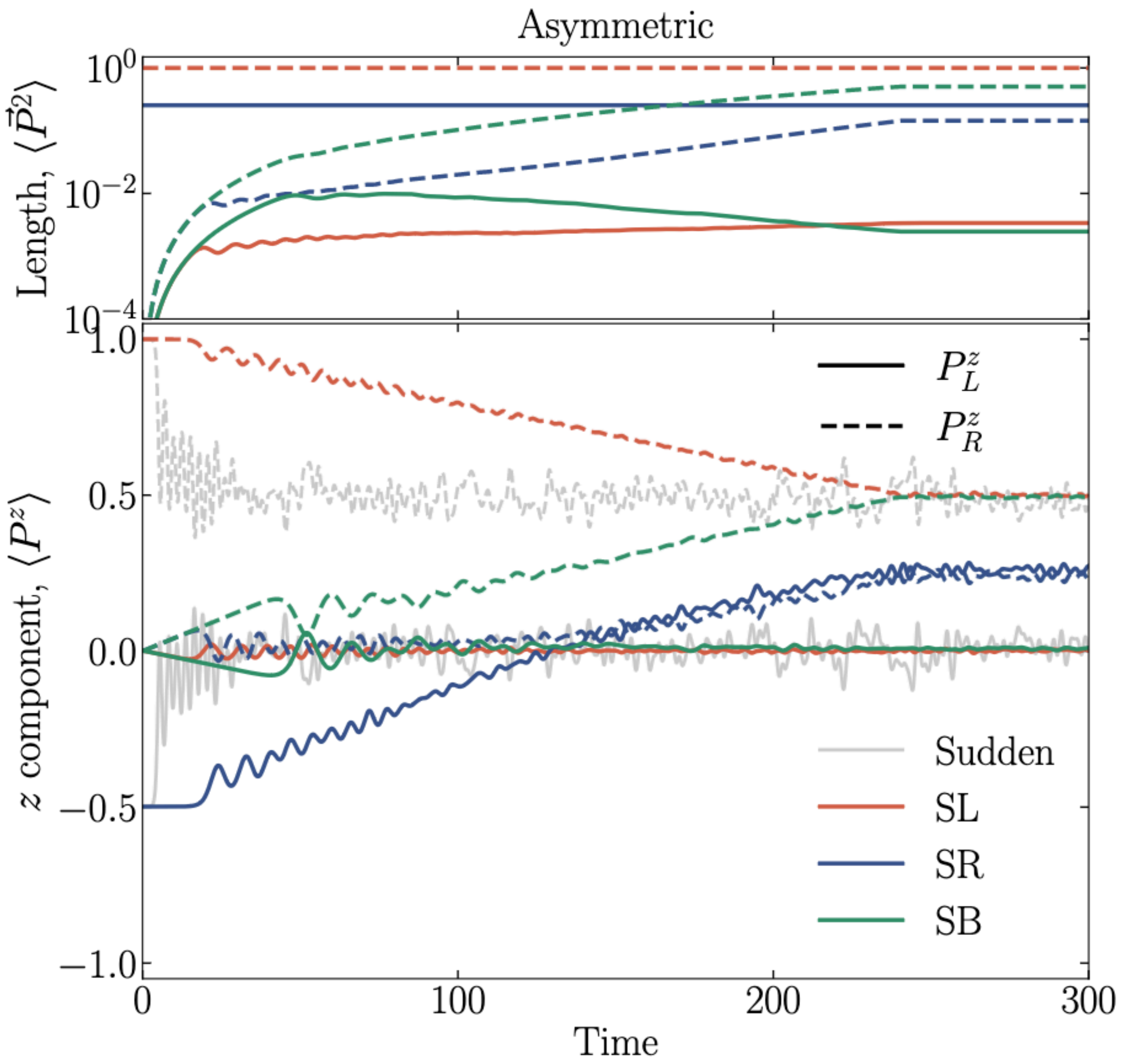


Space-time fluctuating, but average leads to **removal of angular crossing**

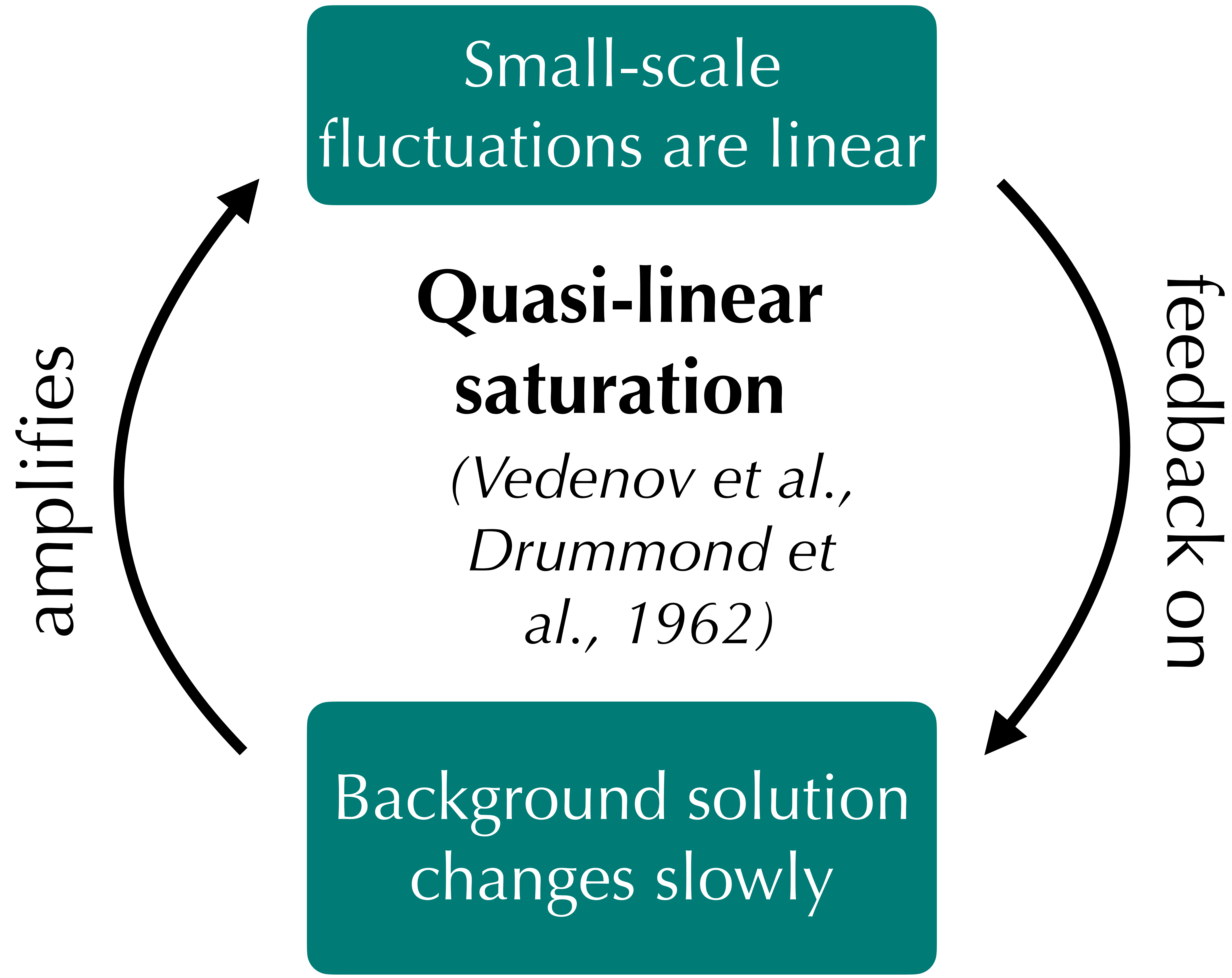


***DF**, Raffelt, PRL 2403.12189*

Relaxation of instability



System sticks to the closest stable state (which may depend on history!)



Small-scale fluctuations are linear

feedback on

Background solution changes slowly

amplifies

Quasi-linear saturation

(Vedenov et al., Drummond et al., 1962)

***DF**, Raffelt, PRL 2403.12189*

Quantum kinetic equations

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Density matrix

Nearly ν_e

$$P^z = \rho_{ee} - \rho_{\mu\mu}$$

$$P^x = \mathrm{Re}(\rho_{e\mu})$$

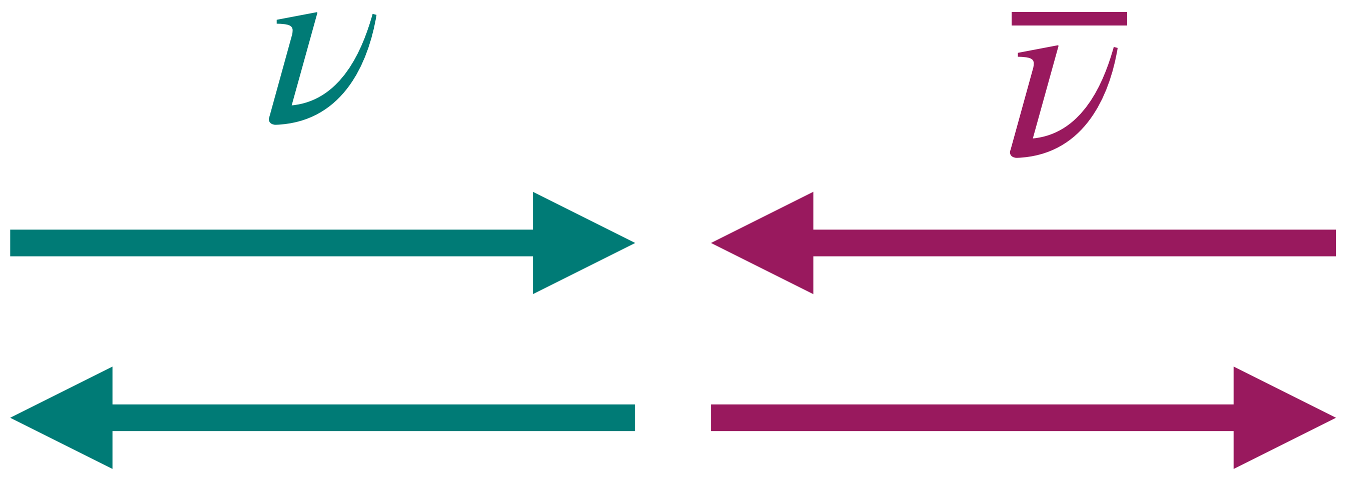
$$P^y = -\,\mathrm{Im}(\rho_{e\mu})$$

Nearly $\overline{\nu}_\mu$

$$P^z = \overline{\rho}_{\mu\mu} - \overline{\rho}_{ee}$$

A concrete example

Can conversions happen without flavor?

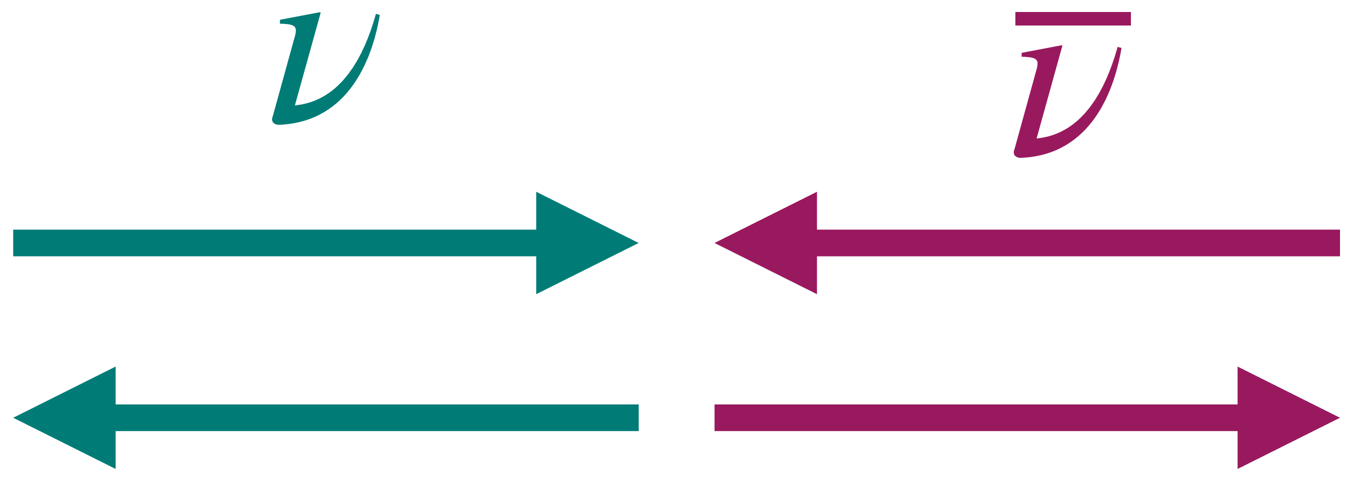


Neutrino-antineutrino collective oscillations?

Proposed in Sawyer, PRD 2023

A concrete example

Can conversions happen without flavor?



Neutrino-antineutrino collective oscillations?

Proposed in Sawyer, PRD 2023

Helicity violation!

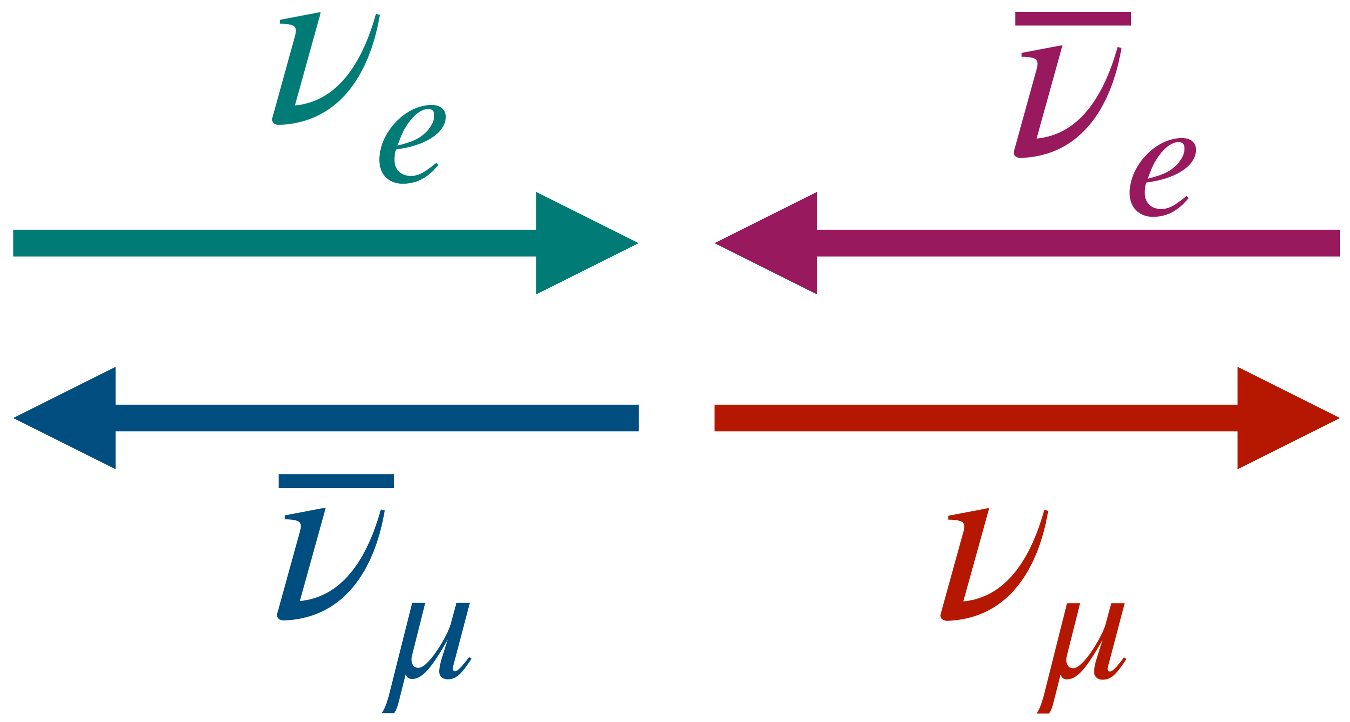
$\overline{\nu}\nu$ conversions can be neglected, but only by previously unnoticed argument!

***DF**, Raffelt, Sigl, 2401.02478*

A concrete example

Exponential growth of off-diagonal components

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$



Can we predict the final state of the system?

Are there **conserved quantities**?

Conserved quantities

$$\sum \rho = \begin{pmatrix} \rho_{ee} + \bar{\rho}_{\mu\mu} & \rho_{e\mu} + \bar{\rho}_{\mu e} \\ \rho_{\mu e} + \bar{\rho}_{e\mu} & \rho_{\mu\mu} + \bar{\rho}_{ee} \end{pmatrix}$$

Total lepton number

Homogeneous systems

Infinite conservation laws (**Gaudin invariants**) ***DF****, Raffelt, 2301.09650*

Broken for inhomogeneous, except special solutions (flavor solitons) ***DF****, Raffelt, 2303.12143*

Inhomogeneities grow!

Energy must be conserved (right?)

Energy in collective oscillations

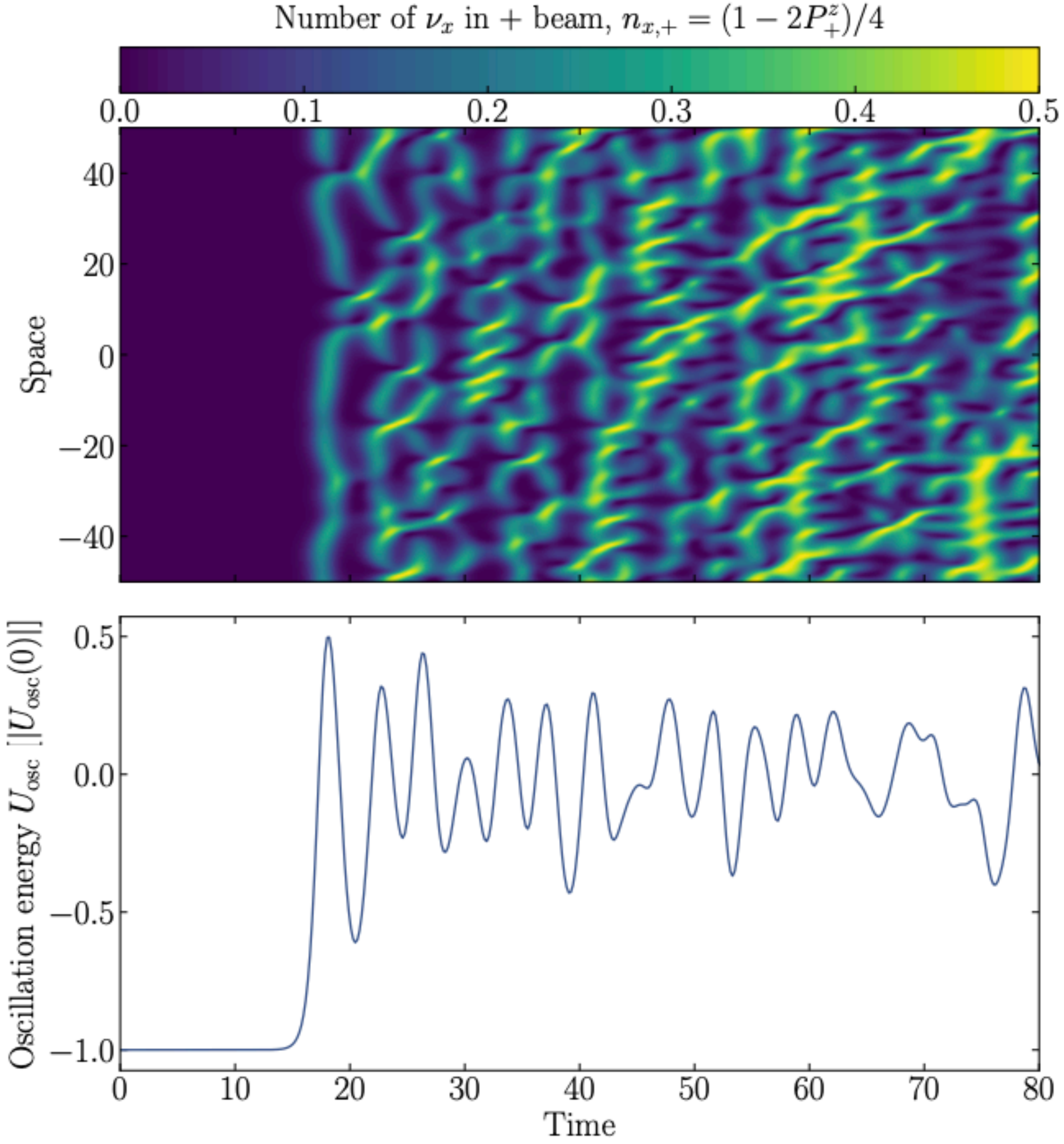
$$E = \mathrm{K} + U$$

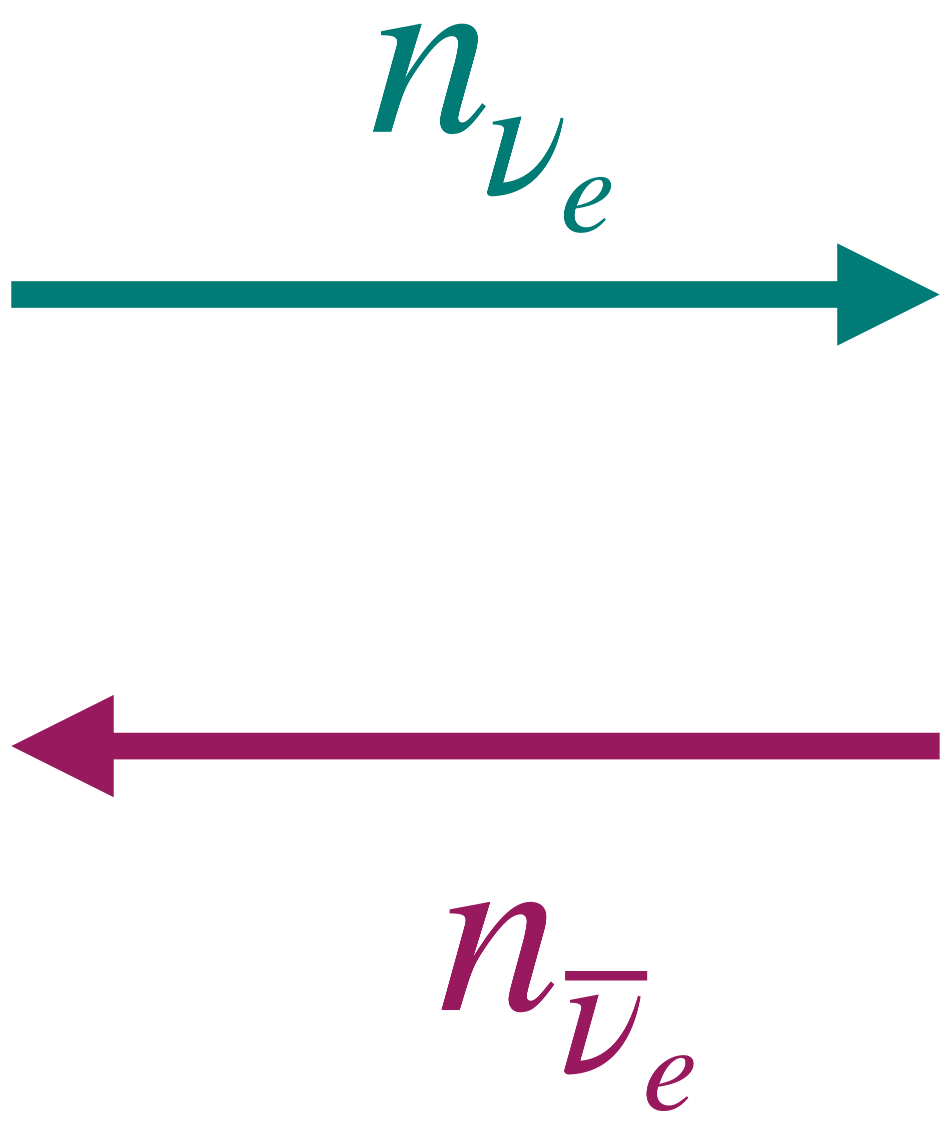
$$\sim 10\ \mathrm{MeV} \qquad \sim \mathrm{cm}^{-1} \sim 10^{-1}\ \mathrm{meV}$$

- ✦ Standard quantum kinetic equations
- ✦ Neutrino motion decoupled from collective conversions ($dK/dt = 0$)

$$\frac{dU}{dt} \neq 0!$$

Energy in collective oscillations





Initially

Average U was initially -1, finally oscillates around 0

Maximal energy violation!

__DF__, Raffelt, Sigl, 2401.05278

Energy in collective oscillations

$$E = \mathrm{K} + U$$

$$\sim 10\ \mathrm{MeV} \qquad\qquad \sim \mathrm{cm}^{-1} \sim 10^{-1}\ \mathrm{meV}$$

- ✦ Standard quantum kinetic equations
- ✦ Neutrino motion decoupled from collective conversions ($\xcancel{dK/dt = 0}$)

$$\frac{dU}{dt} \neq 0!$$

Energy in collective oscillations

Gradients in flavor composition → Force → Neutrinos accelerated (or slowed) by inhomogeneous flavor conversions!

Energy in collective oscillations

$$E = \quad \mathrm{K} \quad + \quad U$$

$\sim 10\ \mathrm{MeV}$ $\qquad$ $\sim \mathrm{cm}^{-1} \sim 10^{-1}\ \mathrm{meV}$

Interaction energy is not conserved!

Quasi-linear relaxation

$$\rho = \langle \rho \rangle + \delta\rho$$

Slowly-varying background

Rapidly-varying fluctuation

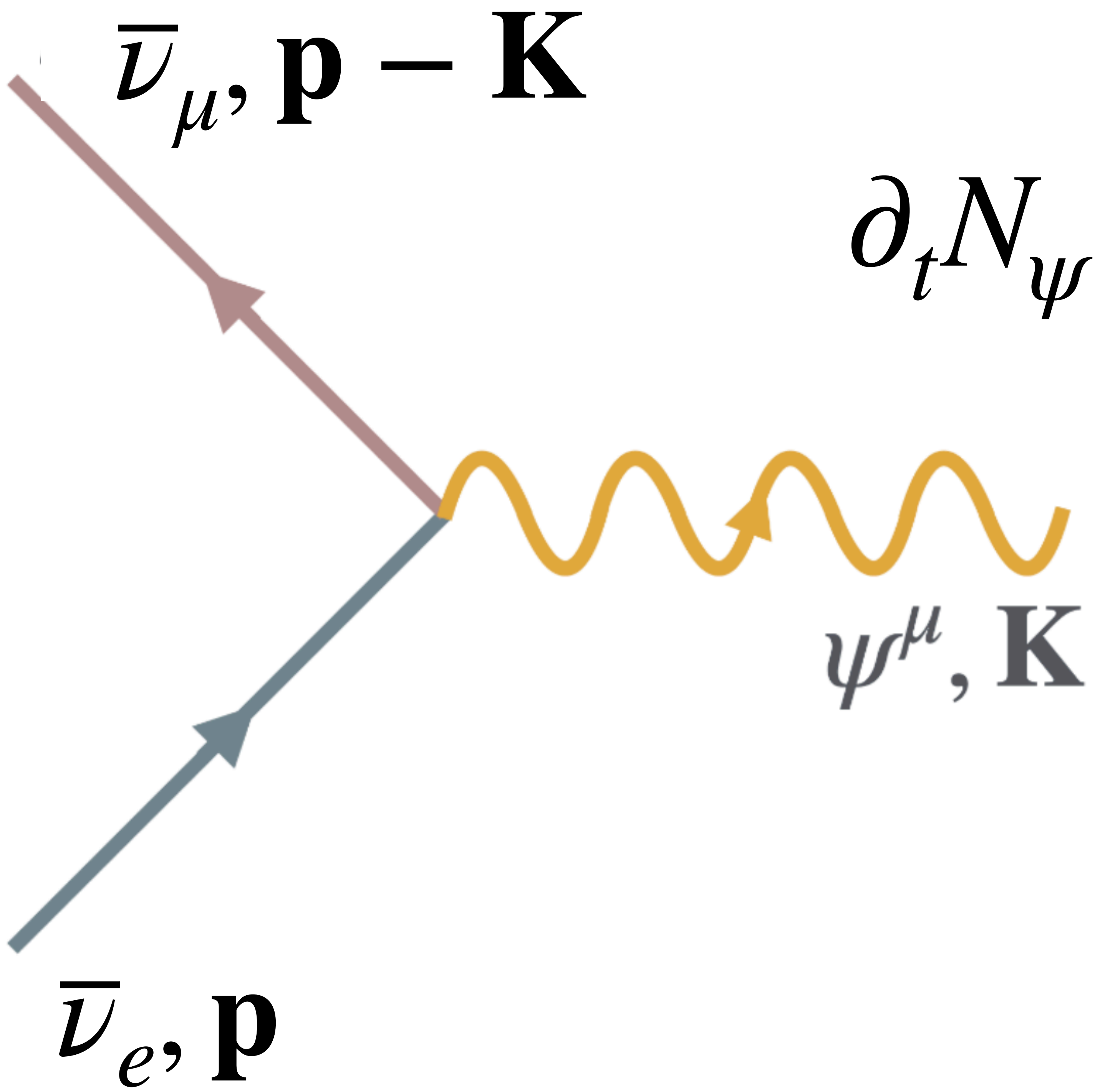
$$\partial_t \delta\rho + \vec{v} \cdot \overrightarrow{\nabla}\, \delta\rho = -\, i[\langle H \rangle, \delta\rho] - i[\delta H, \langle \rho \rangle]$$

Fluctuations are treated **linearly**

$$\partial_t \rho = -\, i \langle [\delta H, \delta\rho] \rangle$$

Fluctuations **non-linearly** feedback and lead to **background relaxation**

A theoretical framework



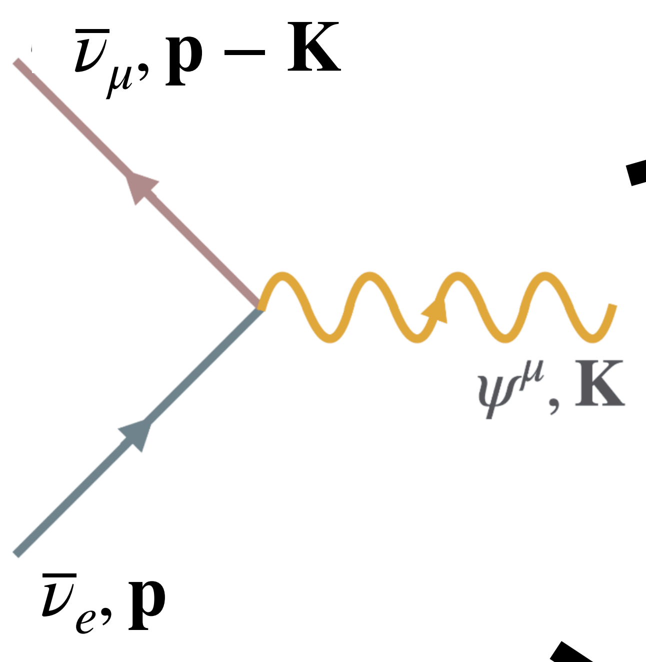
$\bar{\nu}_e \to \bar{\nu}_\mu \psi$ $\qquad$ $\bar{\nu}_\mu \psi \to \bar{\nu}_e$

$$\partial_t N_\psi = \Gamma \left[n_{\bar{\nu}_e}(1-n_{\bar{\nu}_\mu})(1+N_\psi) - N_\psi n_{\bar{\nu}_\mu}(1-n_{\bar{\nu}_e}) \right]$$

$$\simeq \Gamma(n_{\bar{\nu}_e} - n_{\bar{\nu}_\mu}) N_\psi$$

***DF**, Raffelt, 2502.06935*

A theoretical framework



Exponential growth *(Samuel, PRD 1993; Sawyer, PRD 0503013; Izaguirre et al., PRL 1610.01612; …)* = **Stimulated flavomon emission**

Appearance of instability *(Morinaga, PRD 2103.15267; Dasgupta, PRL 2110.00192;* ***DF****, Raffelt, JHEP 2406.06708; JHEP 2409.17232; 2412.02747)* = **More emission than absorption**

Saturation of instability *(empirically found in Nagakura et al., PRL 2206.04097; proved in* ***DF****, Raffelt, PRL 2403.12189)* = **Detailed balance**

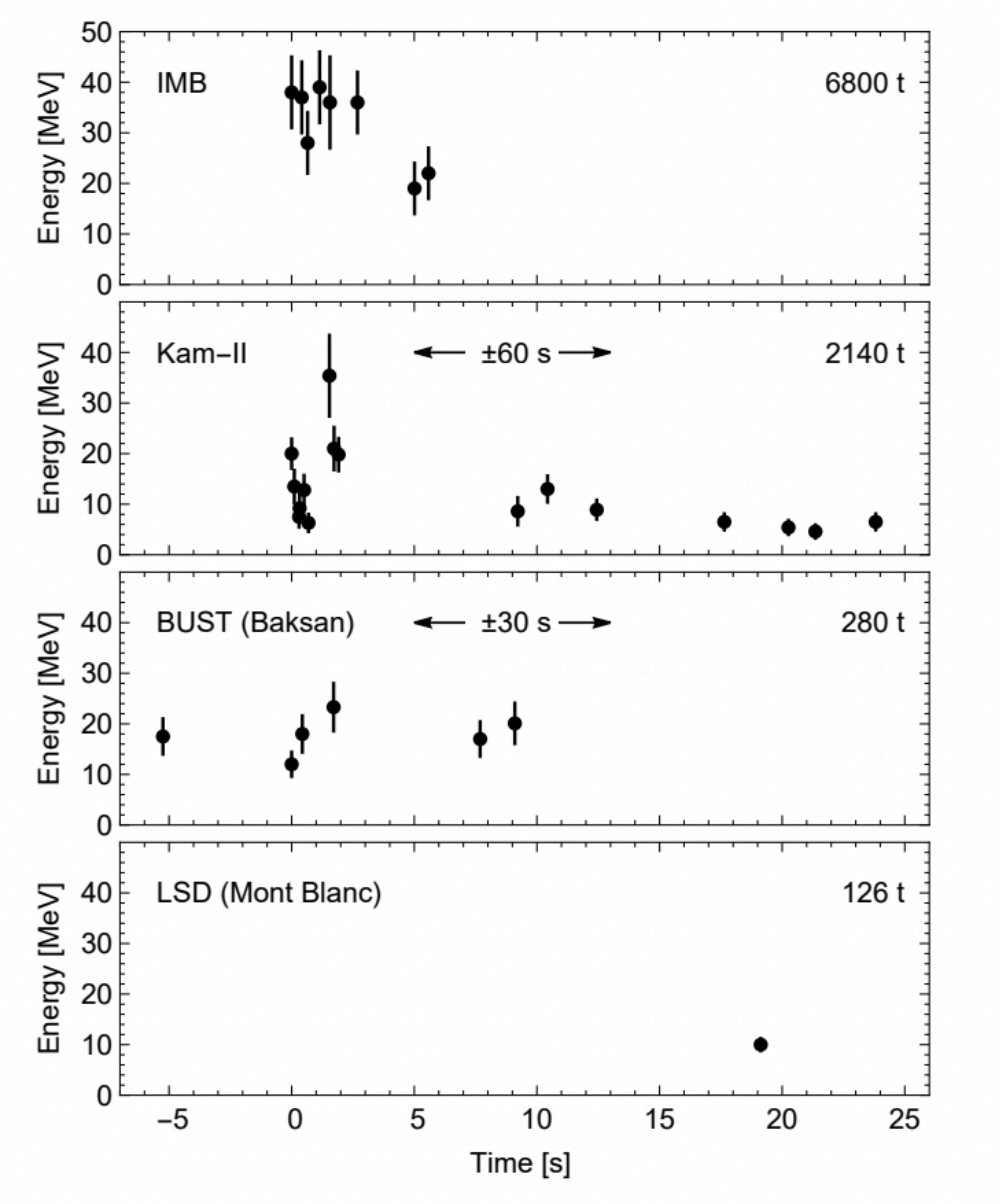
Energization of neutrinos *(****DF****, Raffelt, Sigl, PRL 2401.05278)* = **Flavomons carry energy**

Spreading of instabilities *(****DF****, Raffelt, JHEP 2501.16423)* = **Flavomon streaming**

Regular solutions and flavor pendula *(Hannestad et al., PRD 0608695; Padilla-Gay et al., PRL 2109.14627;* ***DF****, Raffelt, PRD 2301.09650; PRD 2303.12143)* = **Flavor solitons**

Damiano Fiorillo

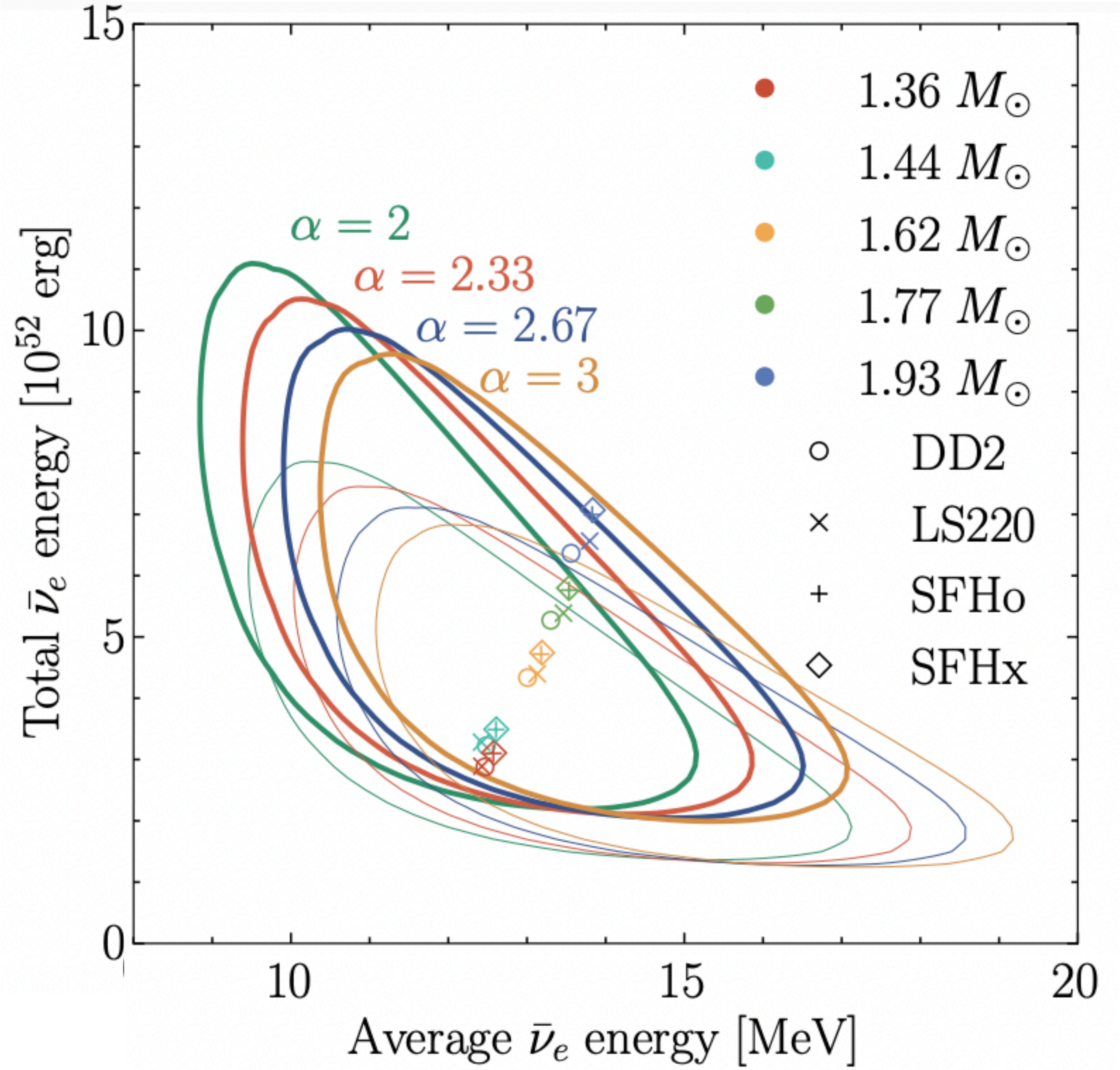
SN1987A neutrino observations



Several puzzles

- ✦ 7 seconds gap in Kamiokande
- ✦ Anisotropic angular distribution
- ✦ Precursor events at MontBlanc (not shown)

What did SN 1987A teach us?



- ✦ Very good agreement with current models for time-integrated signal
- ✦ Previous claims of tension (*Li et al., PRD 2306.08024*) from look-elsewhere effect — no statistically significant tension!

***DF**, Heinlein, Janka, Raffelt, Vitagliano, Bollig, PRD, 2308.01403*

What did SN 1987A teach us?

- Predicted duration 5-7 s
- Observed duration 9-12 s at Kam-II
- Potential later phase of emission (late-time accretion?)
- Will next galactic supernova show late emission?

***DF**, Heinlein, Janka, Raffelt, Vitagliano, Bollig, PRD, 2308.01403*

Many uncertainties

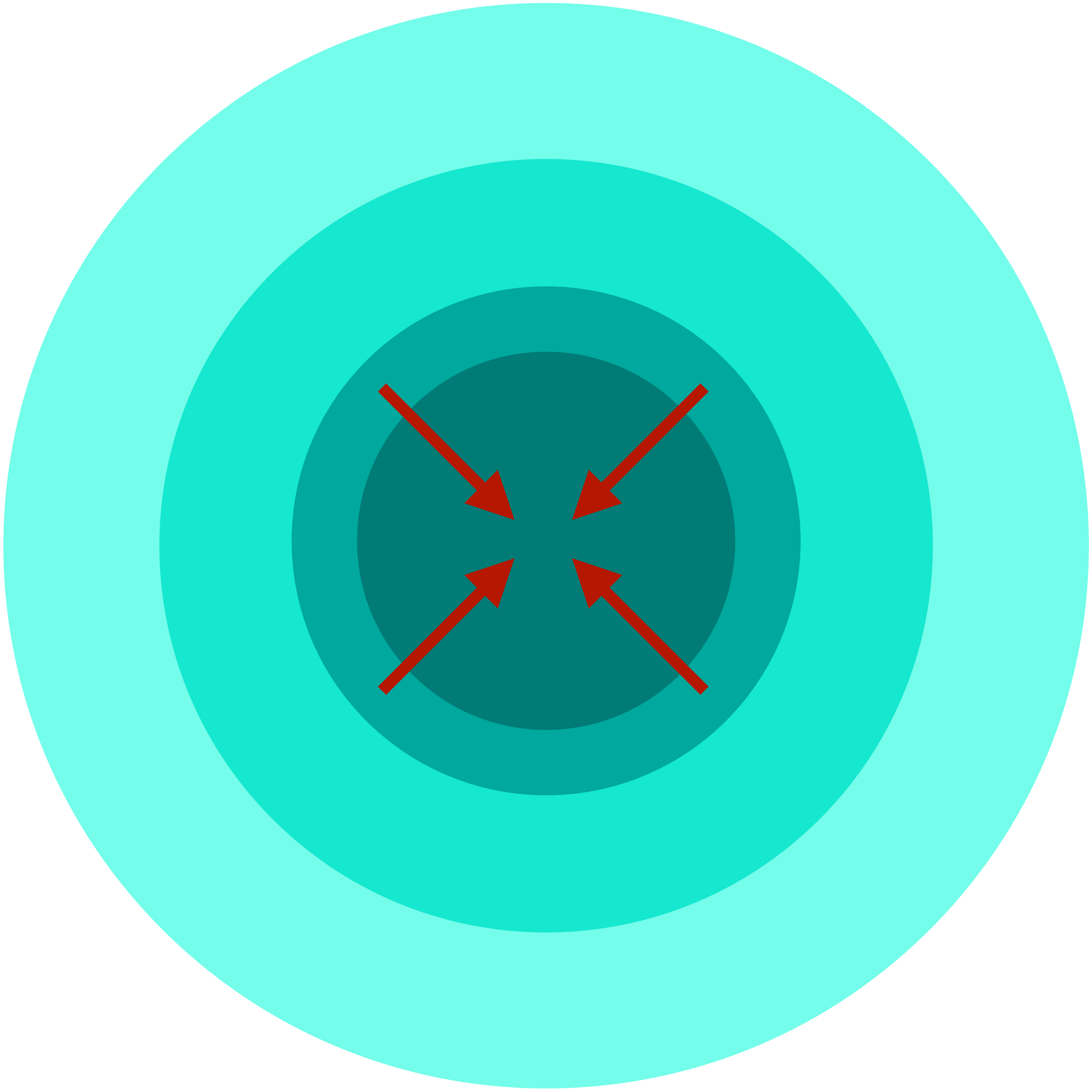
- Nuclear equation of state
- Neutrino-nucleon interactions
- Convection
- Three-dimensional instabilities (SASI, LESA, ...)
- Late-time accretion
- **Flavor conversions**

Nuclear physics

Hydrodynamics

Neutrinos!

Core-Collapse Supernovae

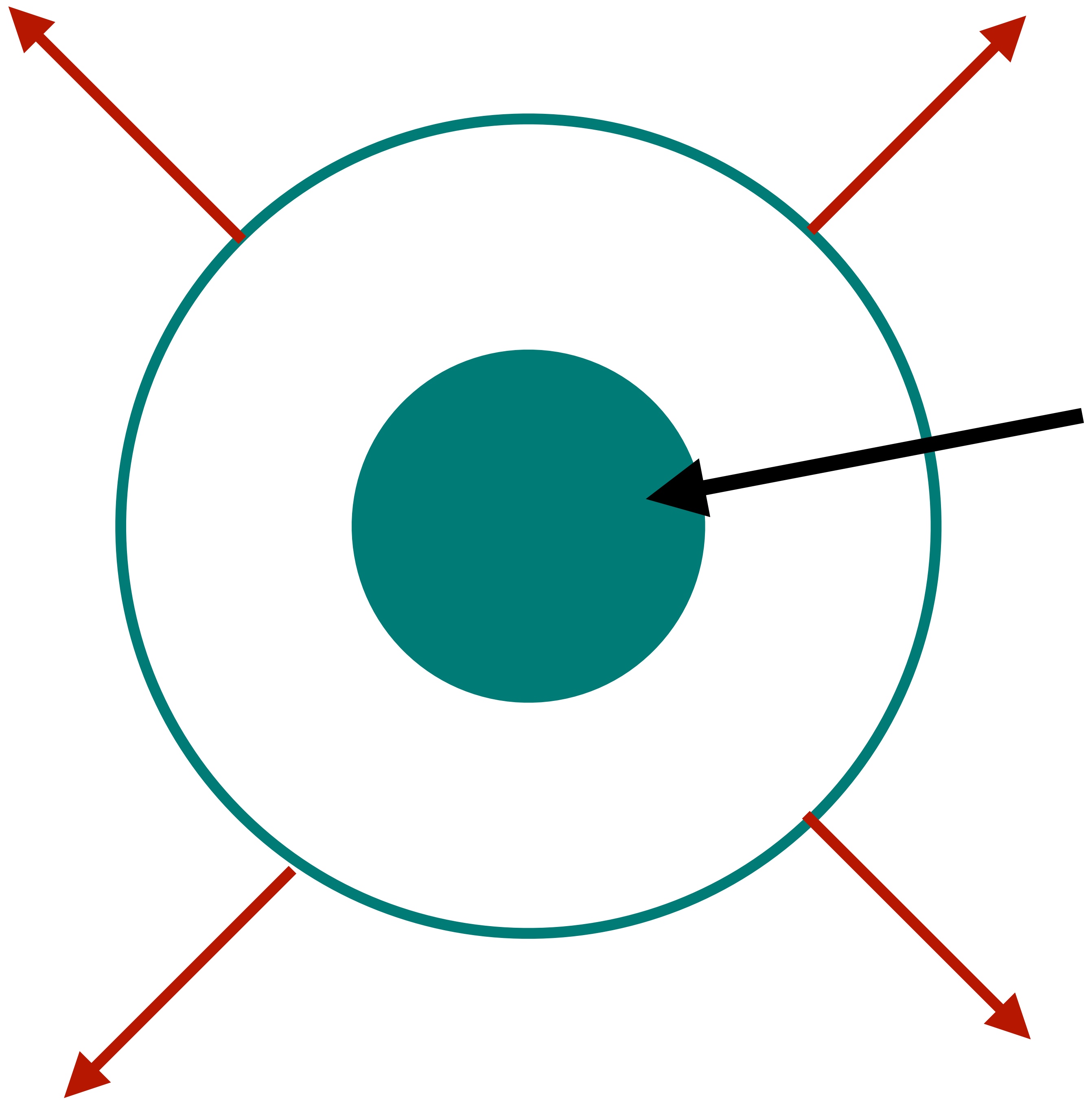


- Iron core without fusion
- Core collapses up to nuclear densities

$\rho \sim 10^{11}\ \mathrm{g\ cm^{-3}}$ Neutrinos are trapped

$\rho \sim 10^{14}\ \mathrm{g\ cm^{-3}}$ Rebounce

Core-Collapse Supernovae



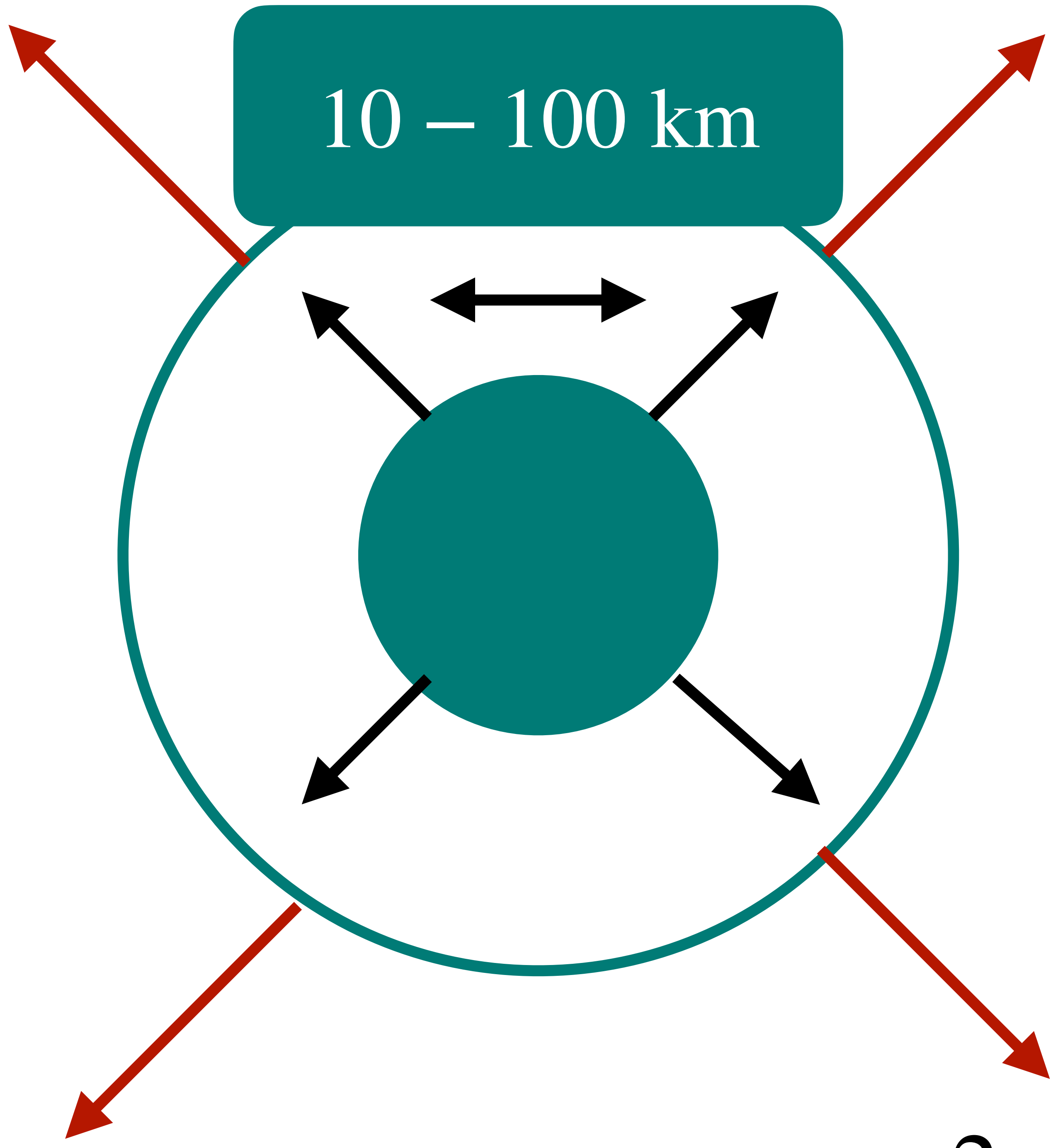
Neutrinos trapped and degenerate!

- Iron core without fusion
- Core collapses up to nuclear densities
- Rebounce launches shock wave, leaving **accreting** proto-neutron star (PNS) in the center
- Shock wave stalls, revived by neutrinos depositing energy

$$\Delta t \sim 100 - 500\,\mathrm{ms}$$

Core-Collapse Supernovae

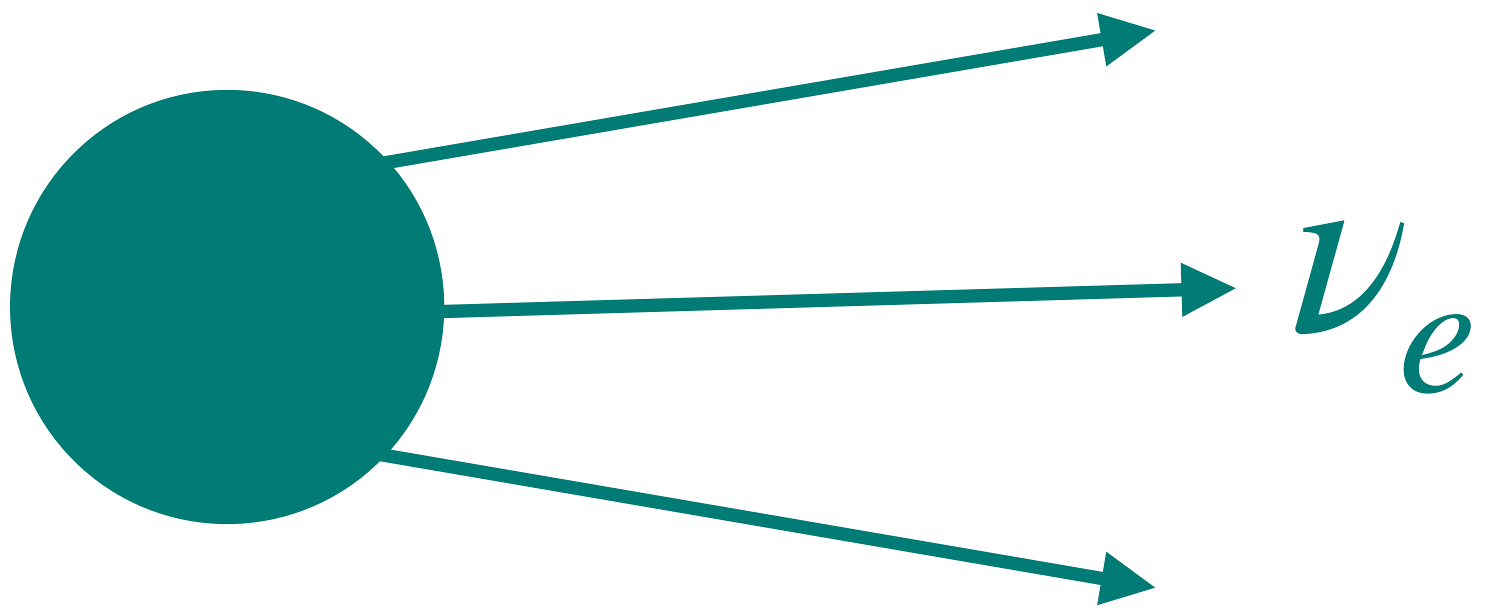
$$E_\nu \simeq 10^{53}\ \mathrm{erg}$$



$$\tau \simeq \frac{R^2}{\lambda_{\nu N}} \simeq 5-7\ \mathrm{s}$$

- Iron core without fusion
- Core collapses up to nuclear densities
- Rebounce launches shock wave, leaving **accreting** proto-neutron star (PNS) in the center
- Shock wave stalls, revived by neutrinos depositing energy
- Neutrino **cooling** of PNS

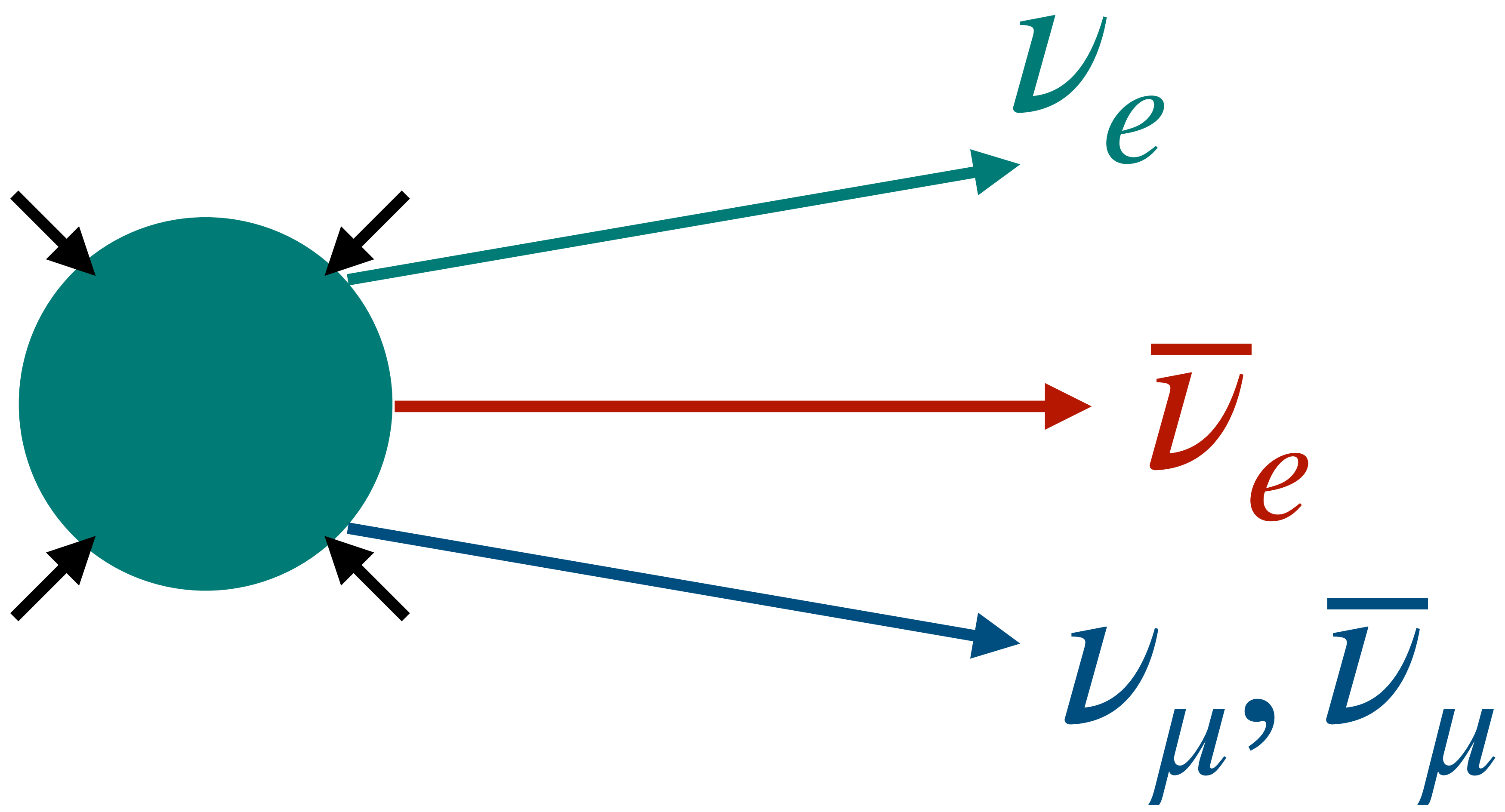
Neutrino emission

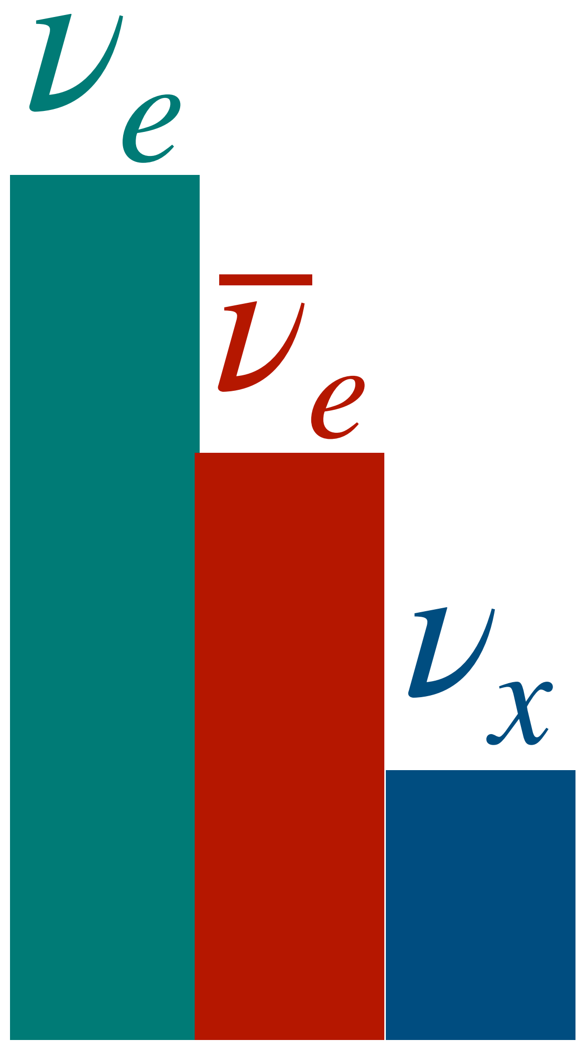


Neutronization burst

Trapped ν_e are suddenly released

$\sim 5 - 10\,\mathrm{ms}$



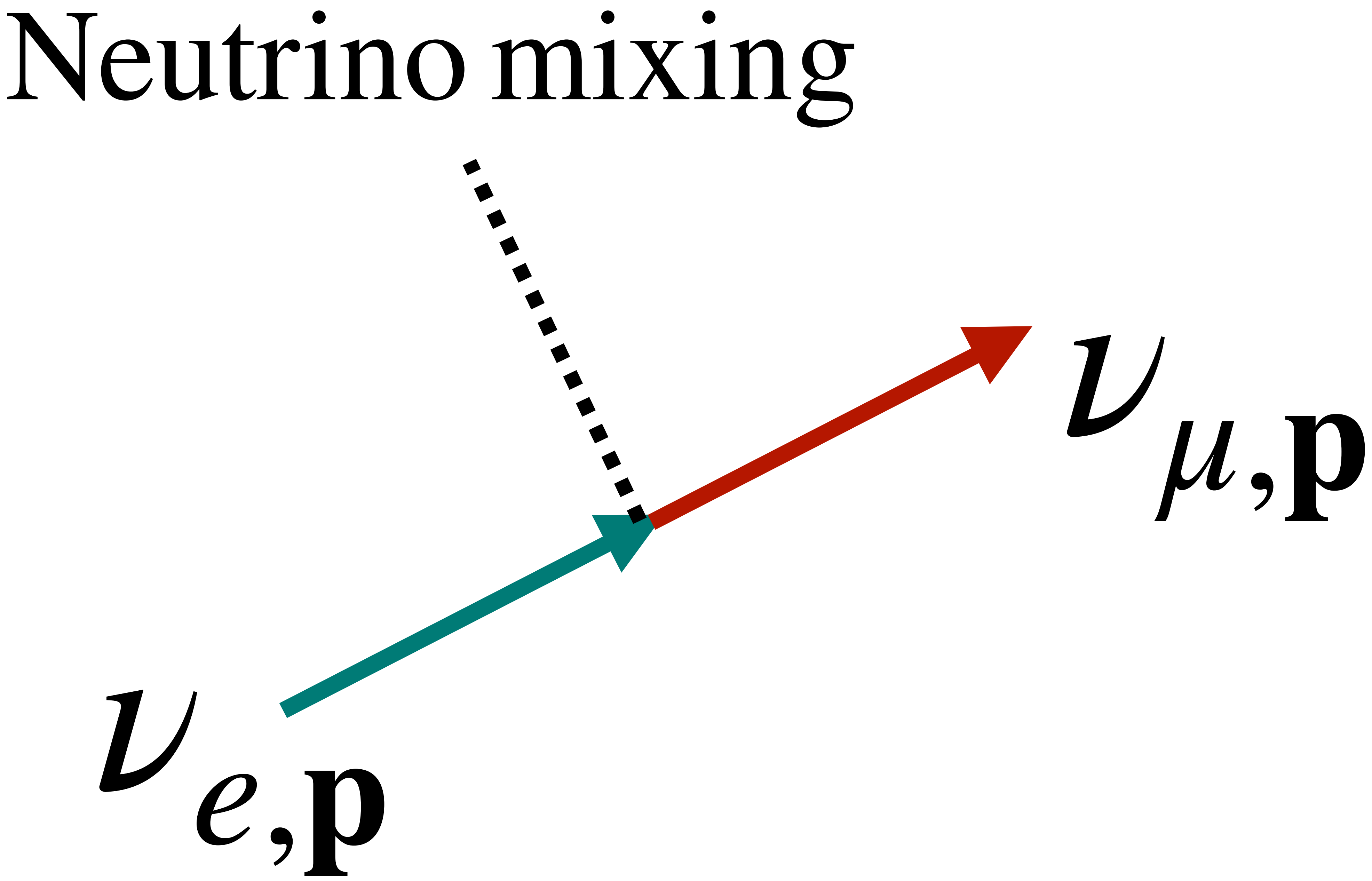


Accretion phase

Accreting matter powers neutrino emission through beta decay

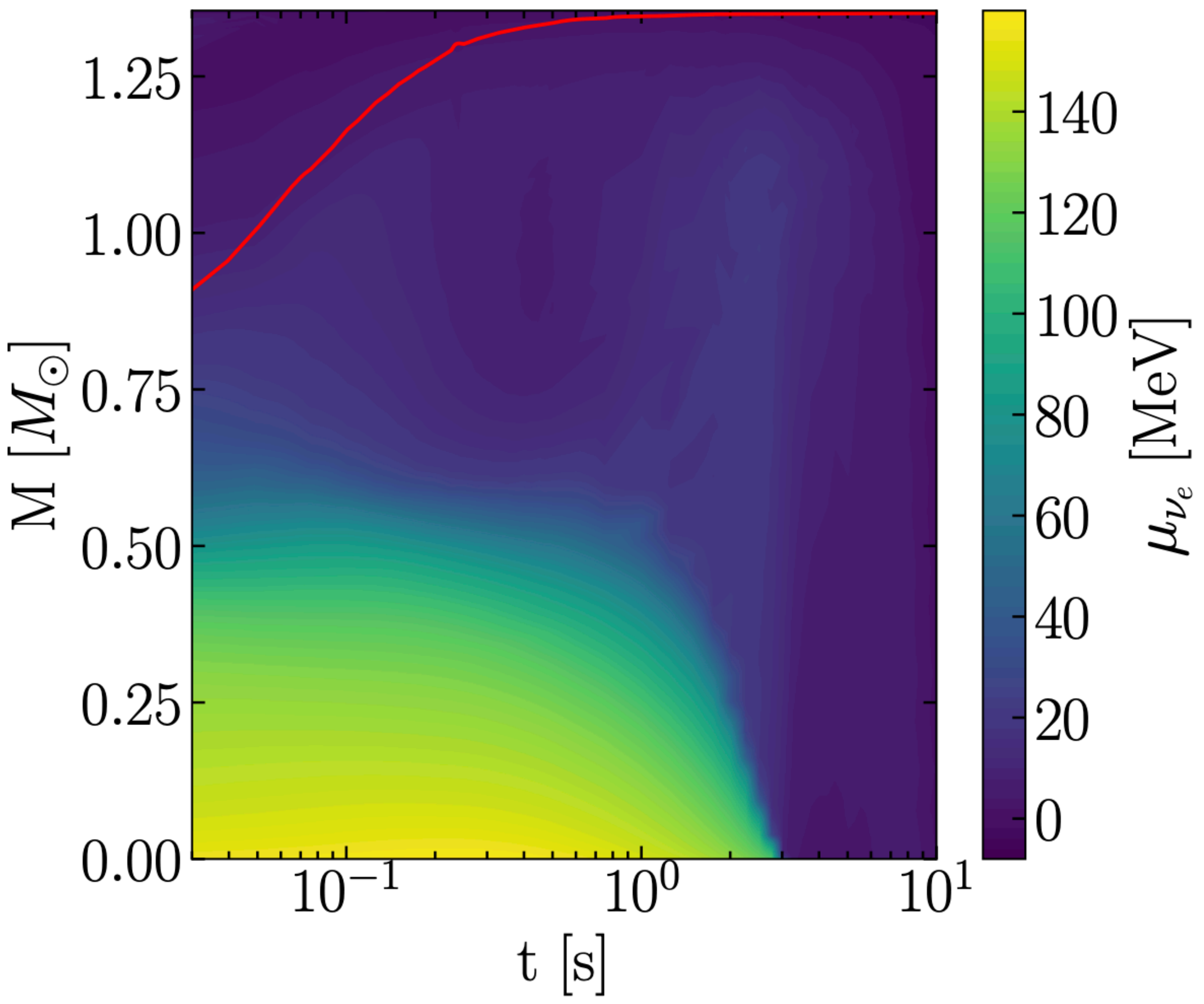
$\sim 10 - 500\,\mathrm{ms}$

Flavor conversions

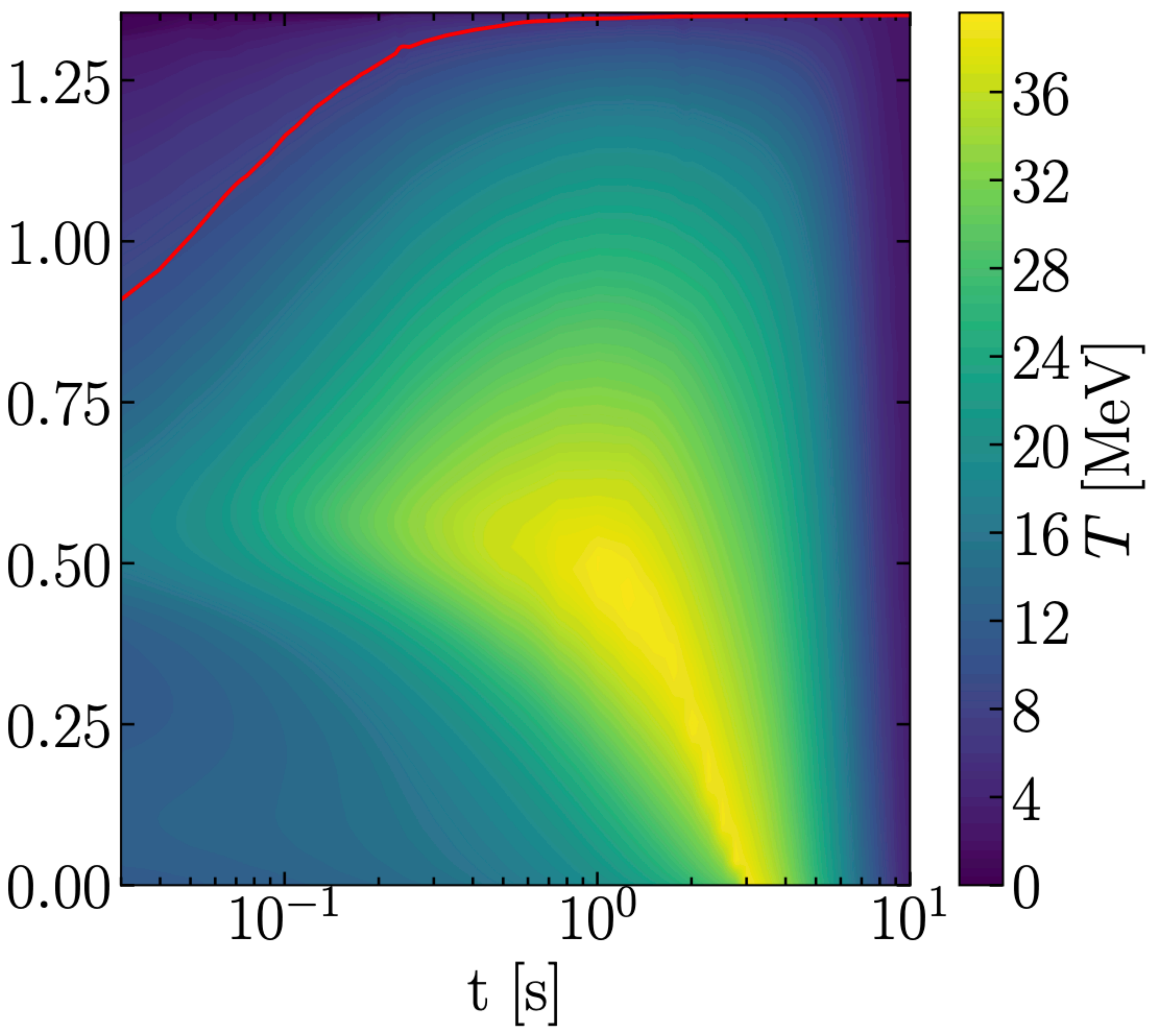


- Not happening in SNe due to matter refraction
- Not implemented in SNe

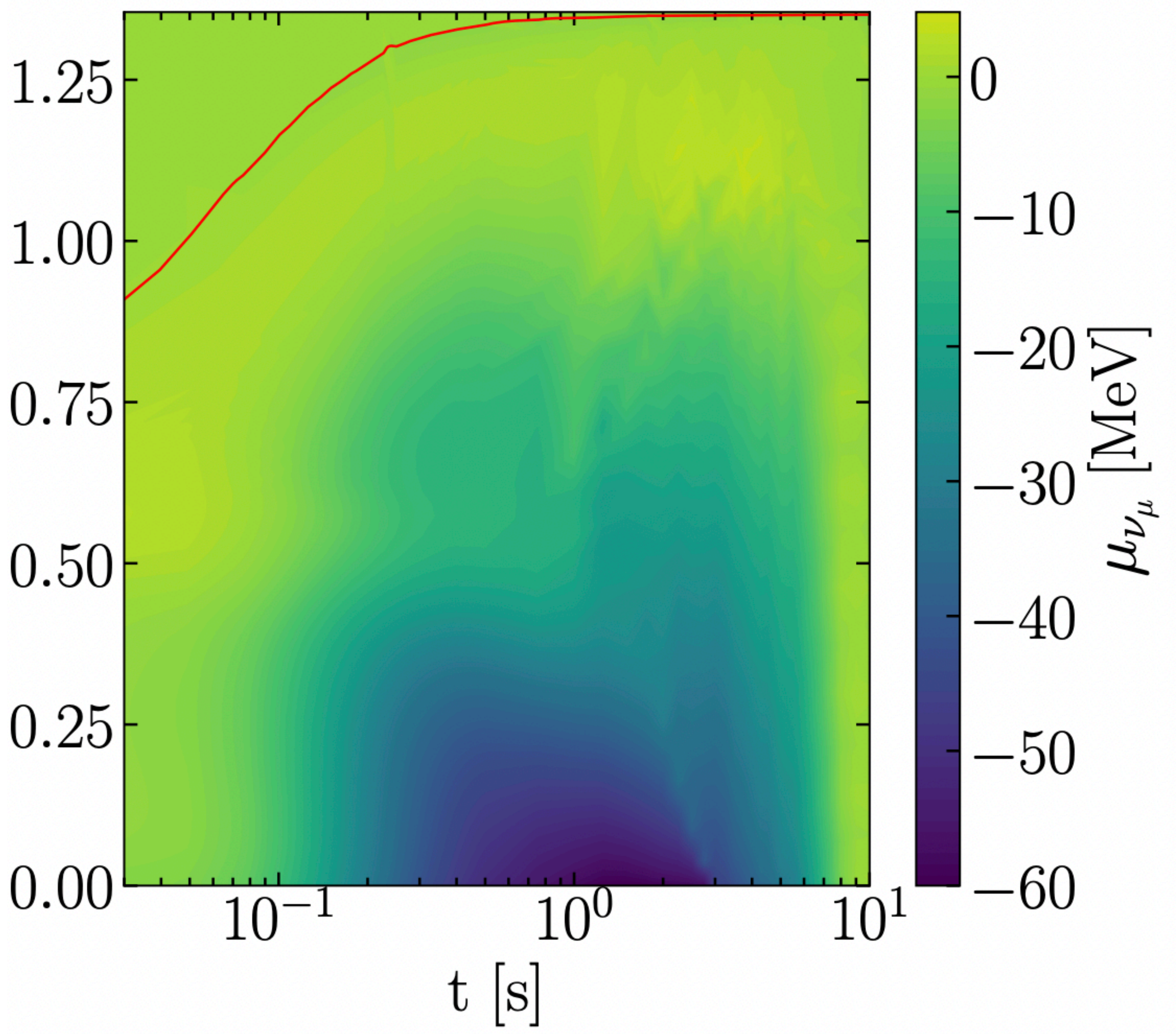
Core-Collapse Supernovae



PNS deleptonizes
and cools

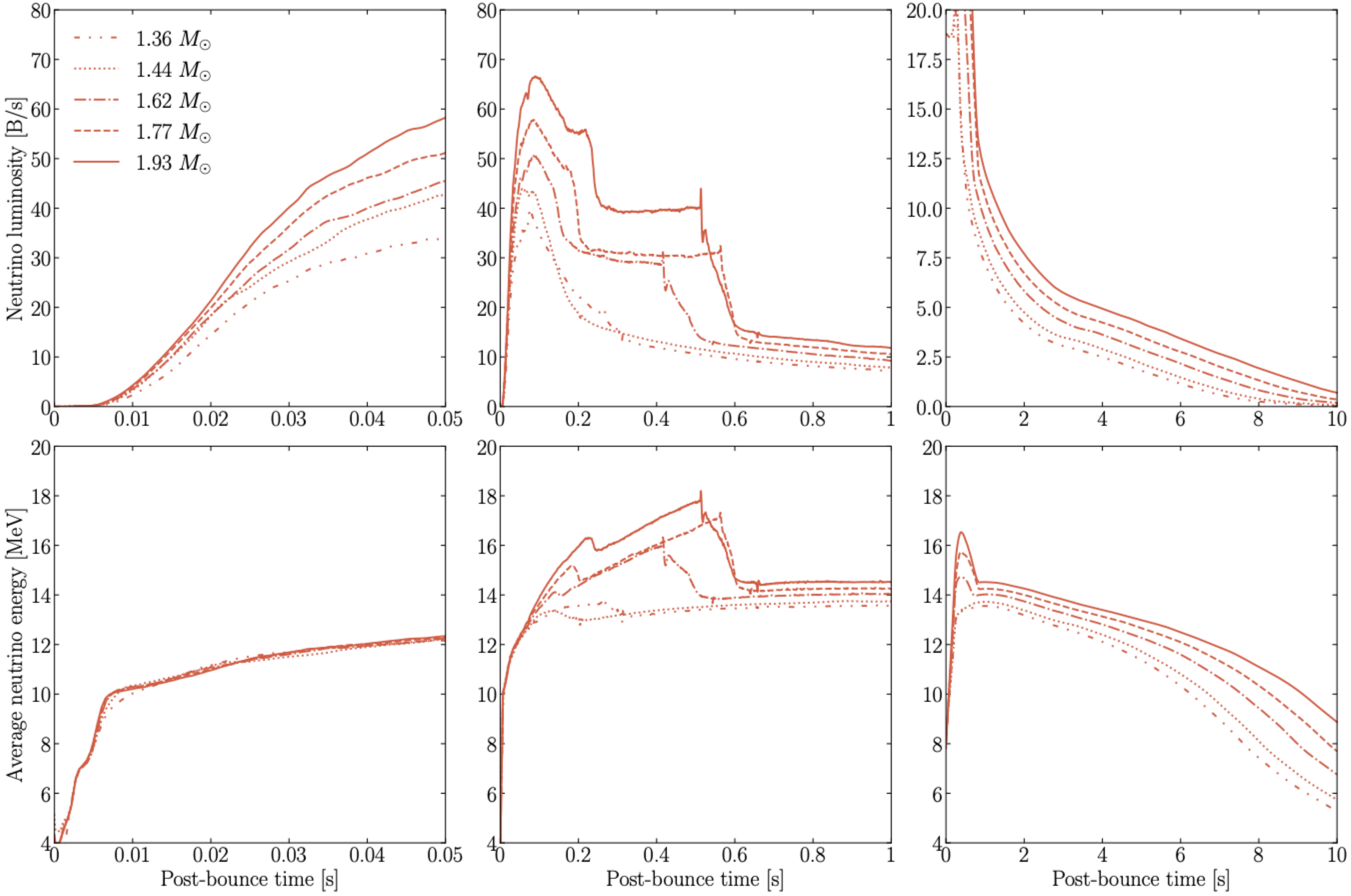


Heats up the
external material

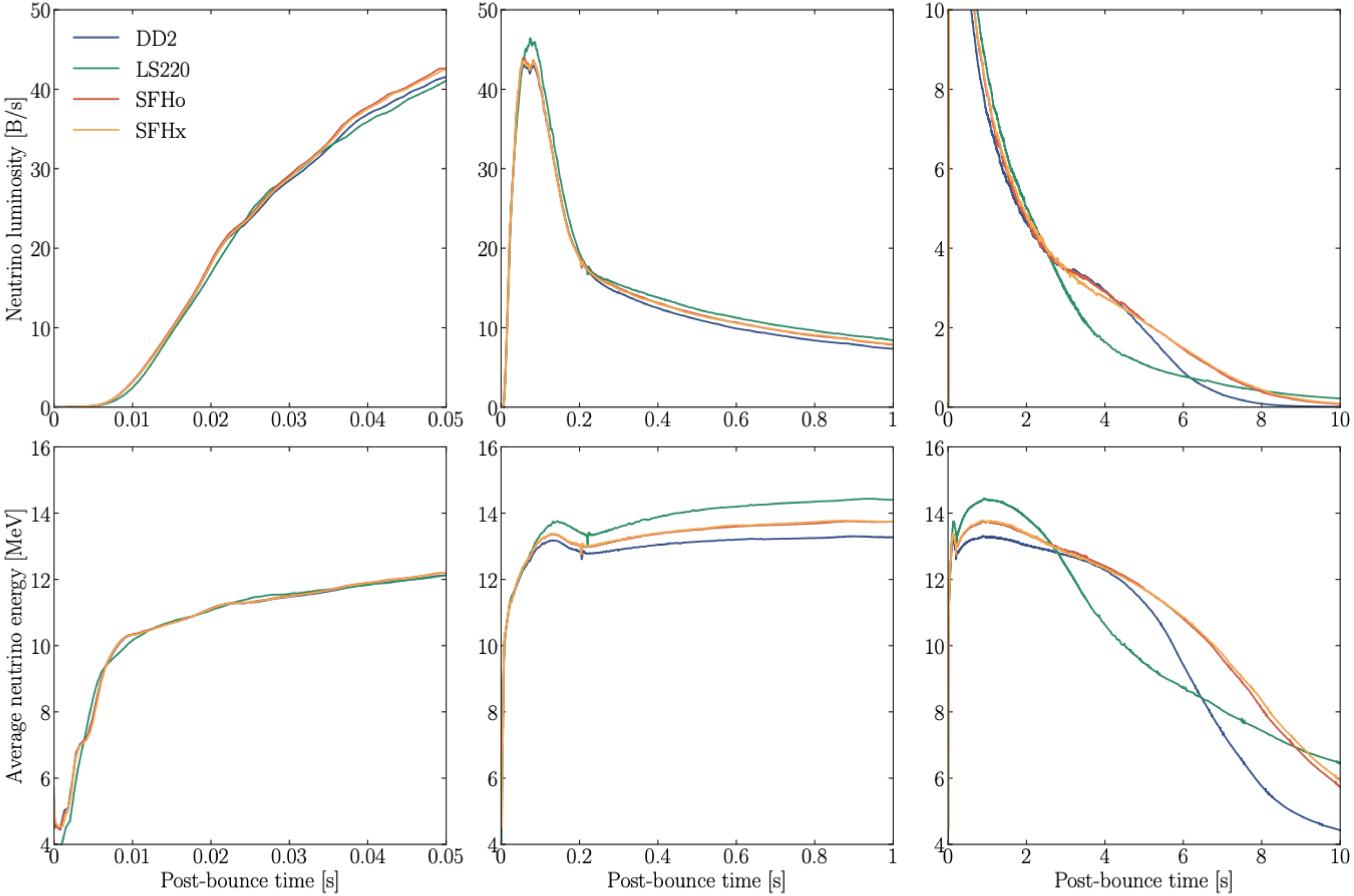


Produces muons
and muon
neutrinos

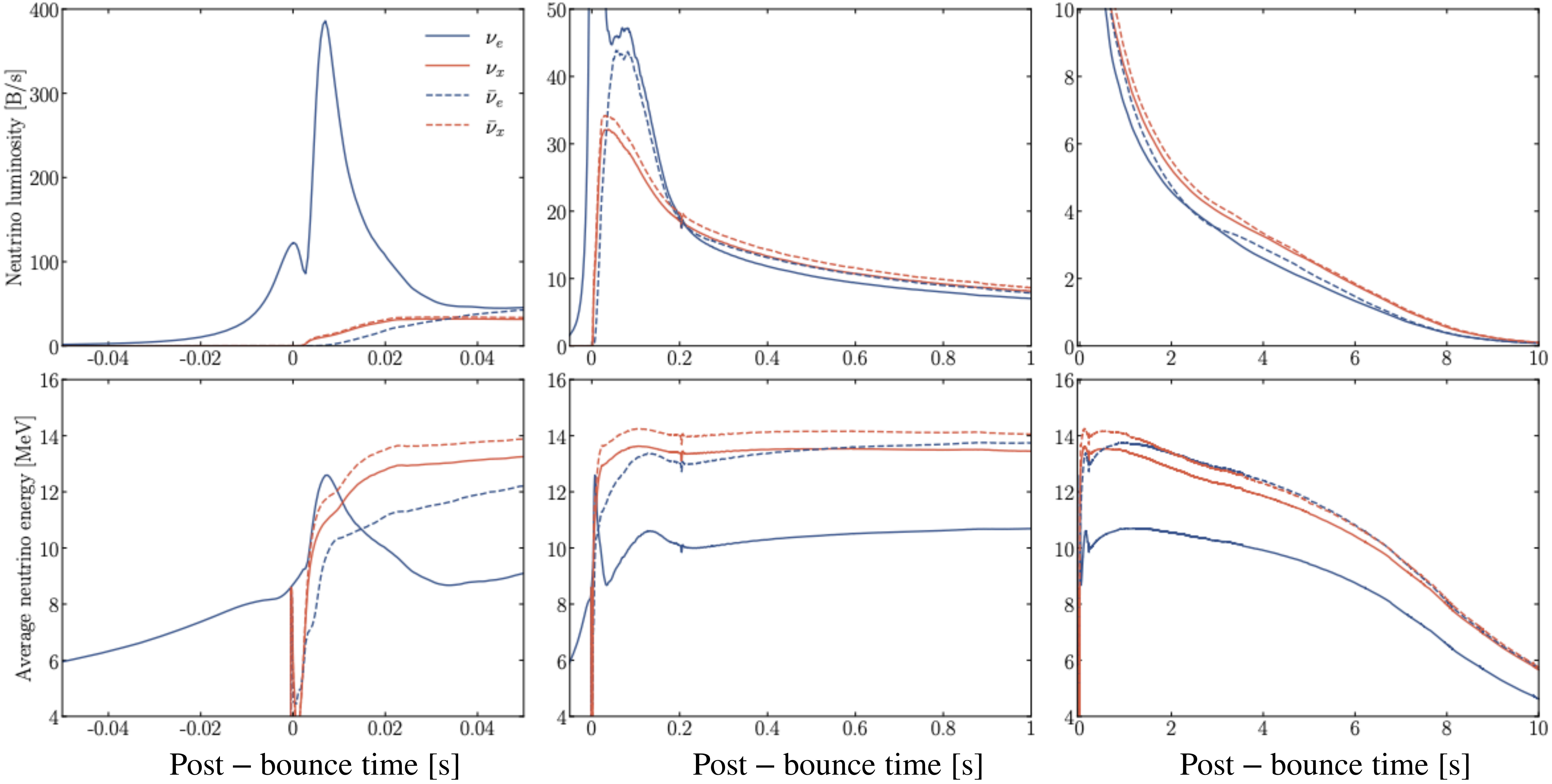
SN models - neutrino signal



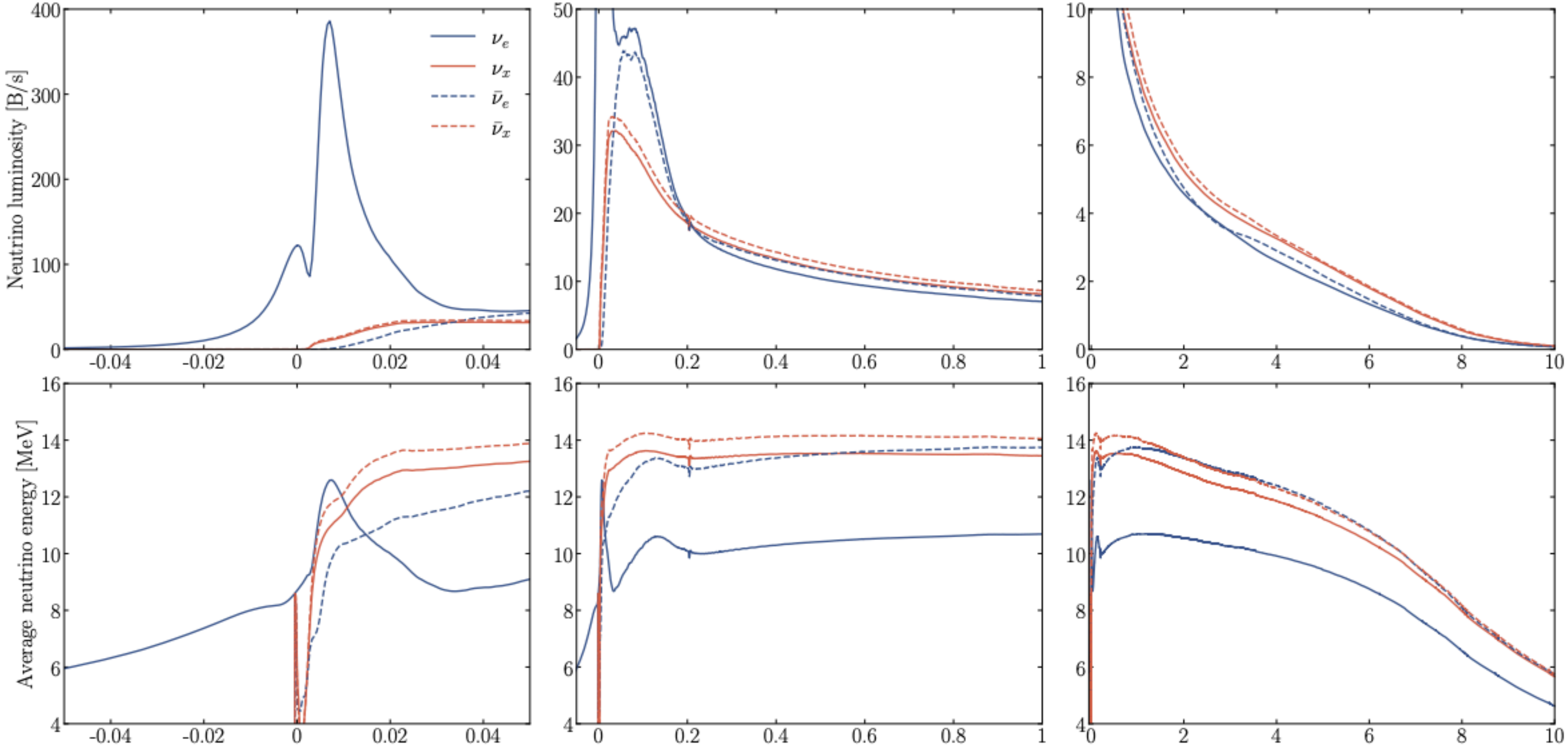
SN models - neutrino signal



Flavor dependence of neutrino signal



Neutrino signal



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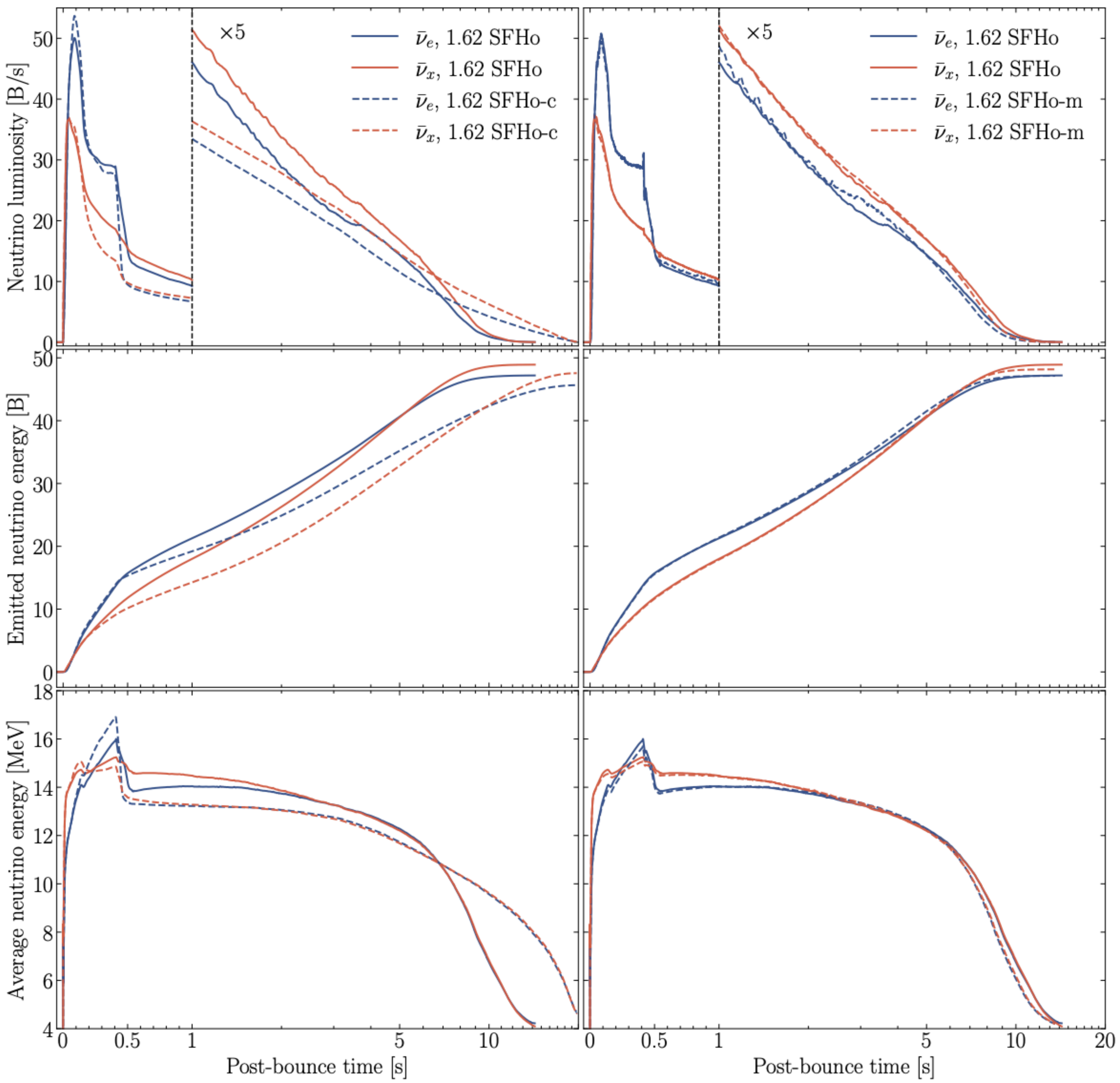
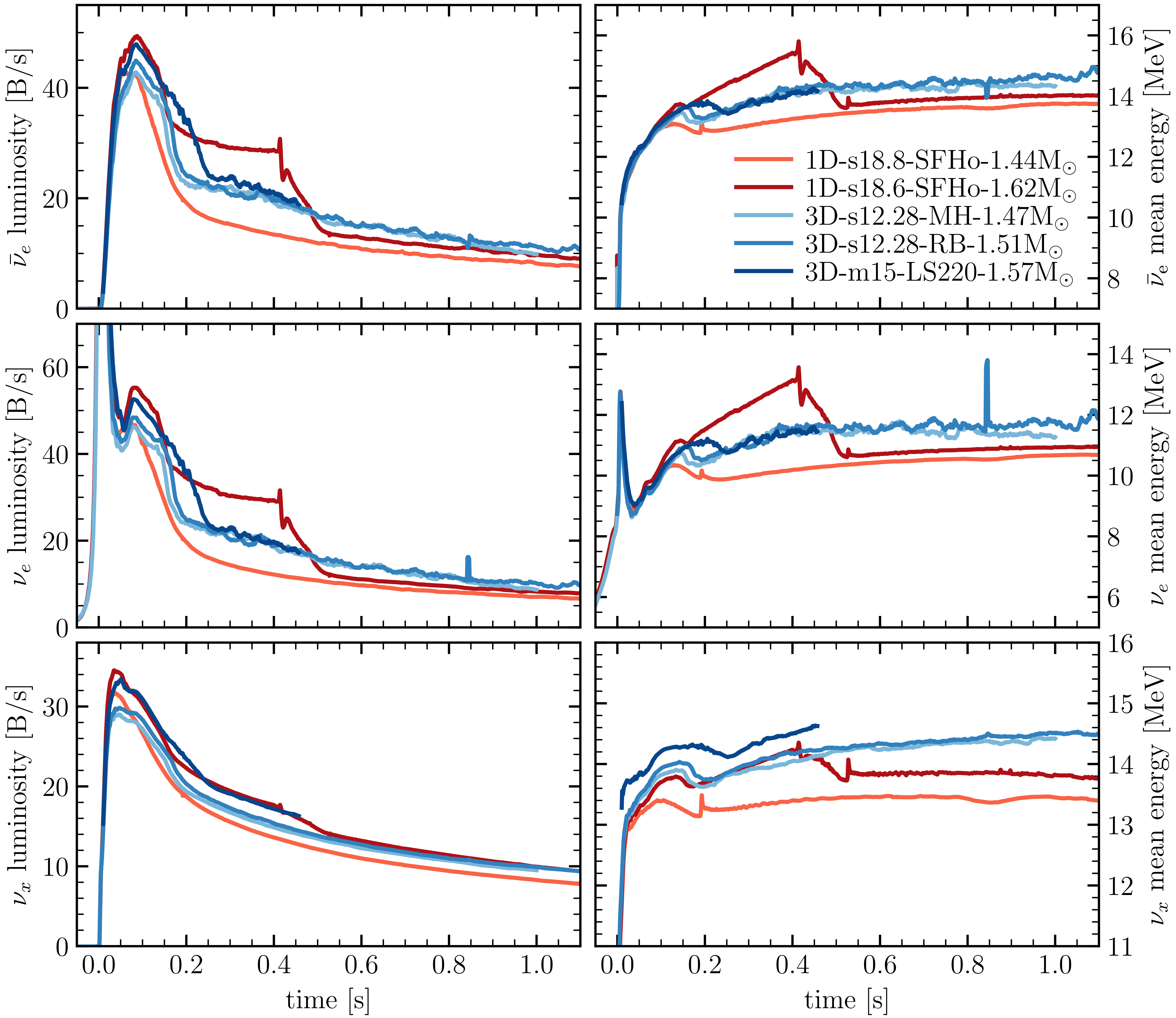
DF et al., *PRD*, arXiv:2308.01403

Convection vs. no convection



Comparison between 1D and 3D



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Model choice

PNS mass ($M_\odot$)

1.36 1.44 1.62 1.77 1.93

Equation of state (EoS)

DD2

LS220

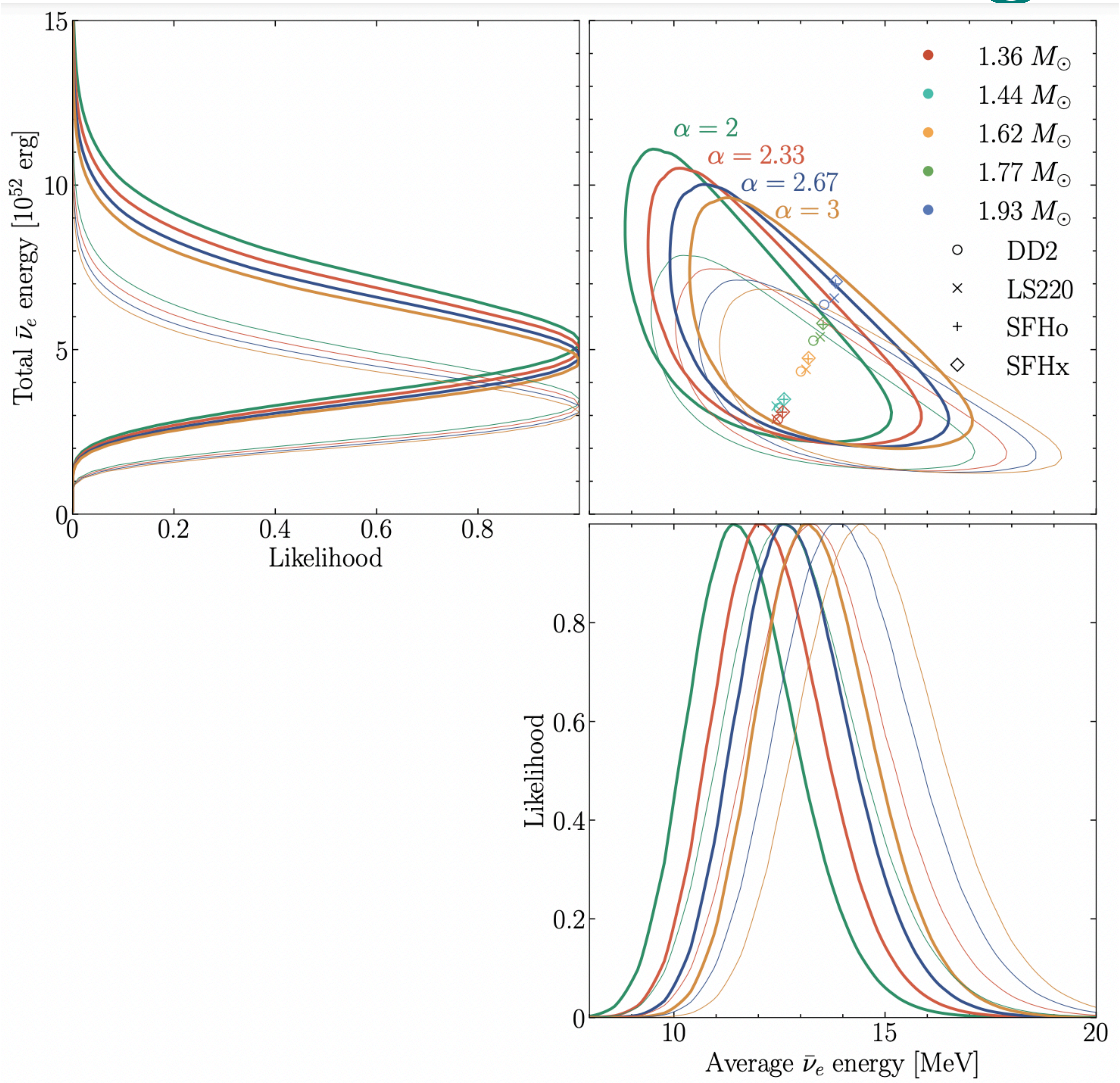
SFHo

SFHx

All 1D

- Reliable for the sparse data of SN 1987A
- Allows for systematic scan of PNS
- Can describe the entire signal

Time-integrated signal



- (Quasi)-blackbody spectrum

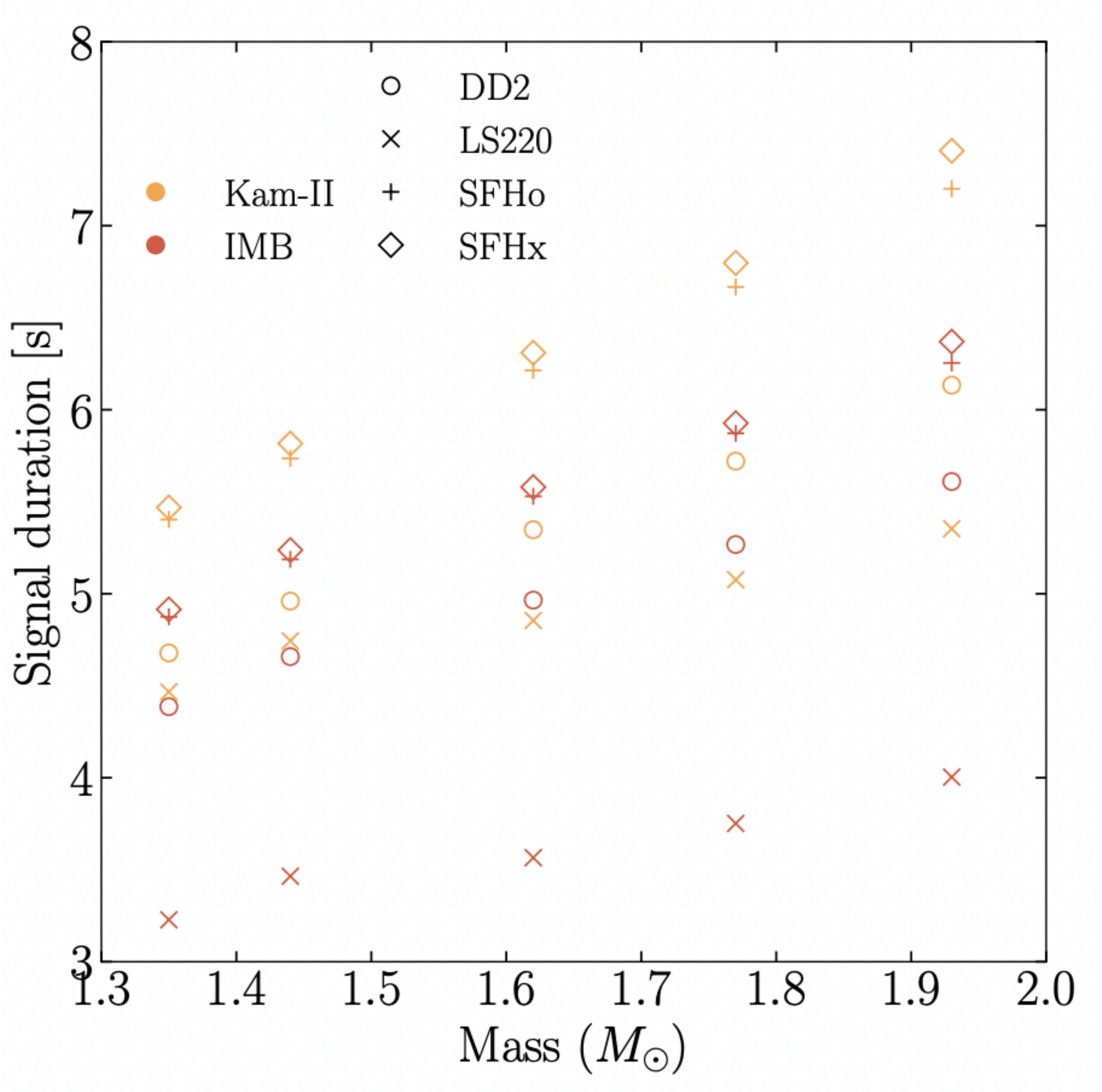
$$\frac{d\mathcal{F}_{\bar{\nu}_e}}{d\epsilon_\nu} = \frac{E_{\mathrm{tot}}^{\bar{\nu}_e}}{\Gamma_{1+\alpha}\bar{\epsilon}^2}\frac{(1+\alpha)^{1+\alpha}}{4\pi d_{\mathrm{SN}}^2}\left(\frac{\epsilon_\nu}{\bar{\epsilon}}\right)^\alpha e^{-(1+\alpha)\epsilon_\nu/\bar{\epsilon}}$$

- Most SN models lie within 2σ regions — consistency with data

- Tension with heavy PNS

***DF**, Heinlein, Janka, Raffelt, Vitagliano, Bollig, PRD, 2308.01403*

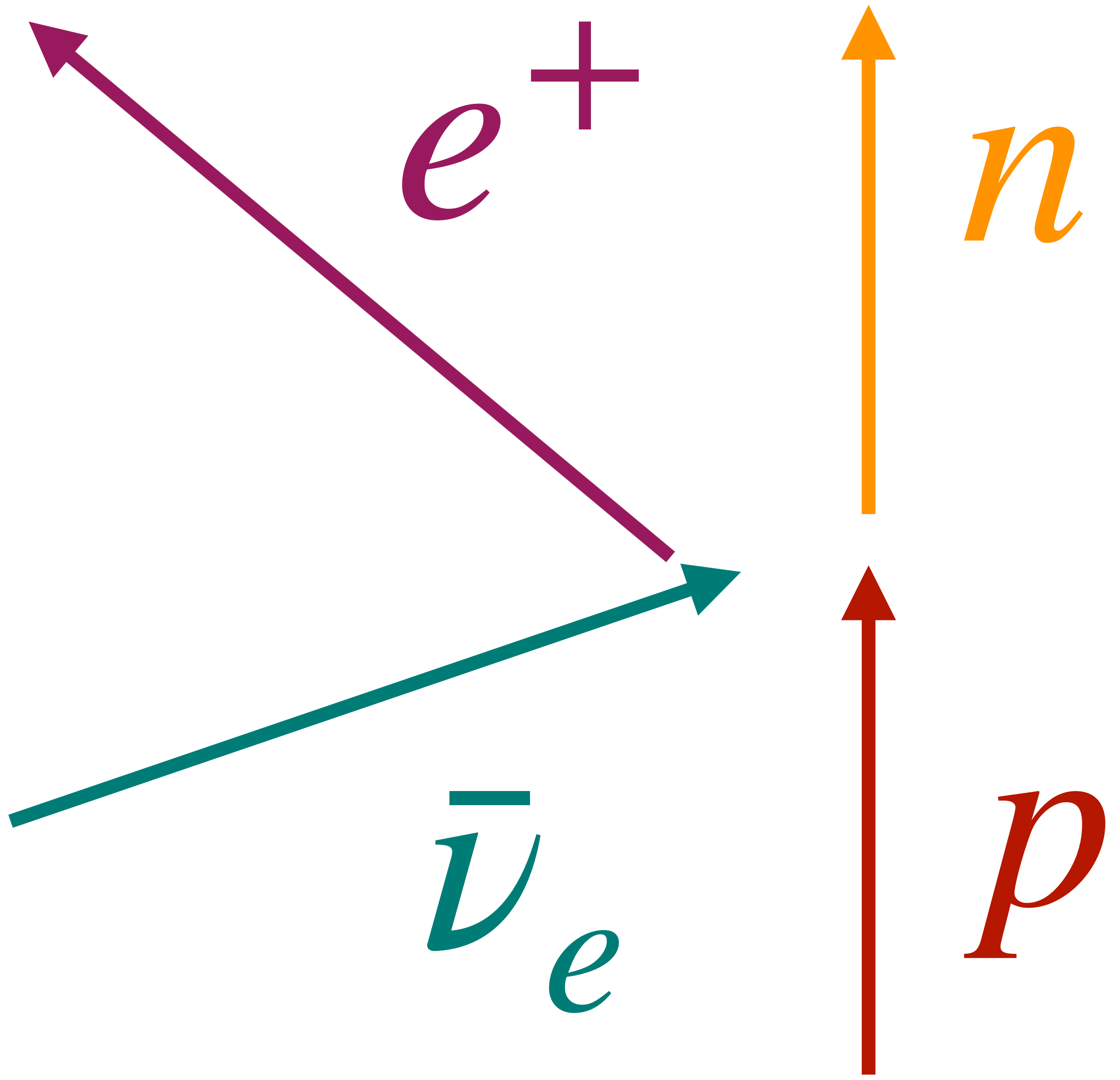
Time structure of the signal



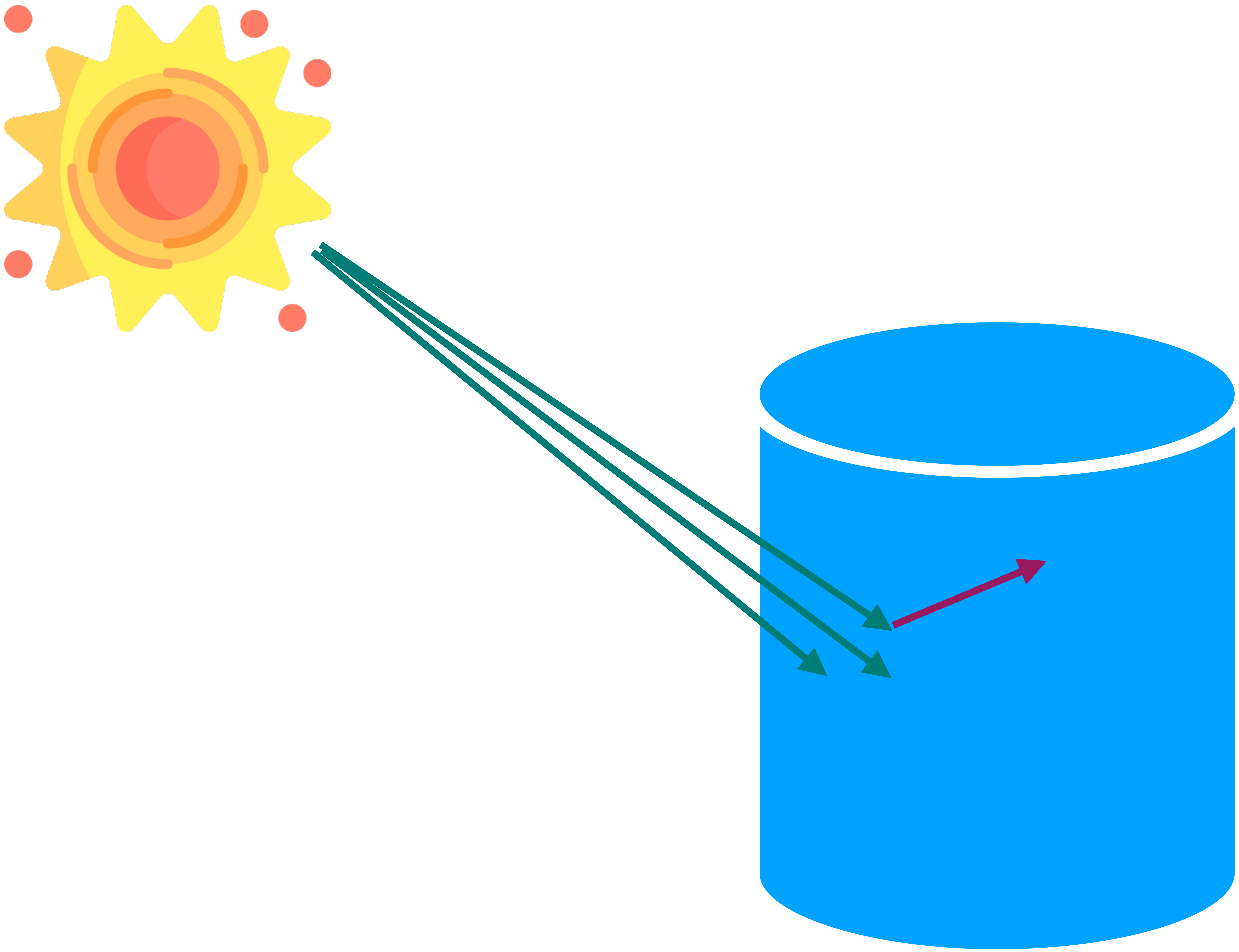
- ✦ Signal duration less than 8 seconds for **all** models
- ✦ Tension with late-time Kam-II events
- ✦ Key role played by convection and updated neutrino-nucleon opacities

__DF__, Heinlein, Janka, Raffelt, Vitagliano, Bollig, PRD, 2308.01403

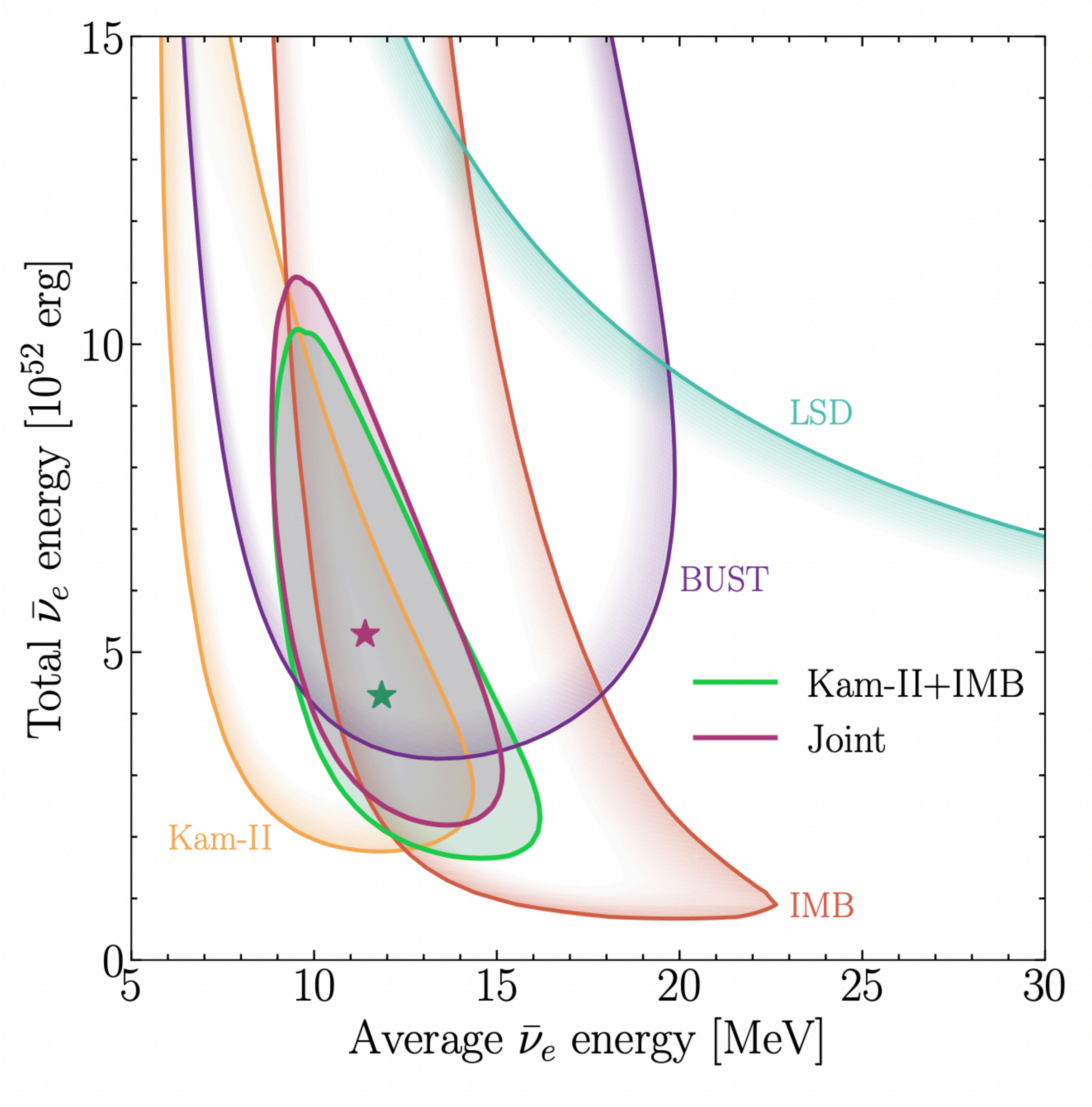
SN1987A neutrino observations



$$\sigma_{\nu p} \propto E_\nu^2$$

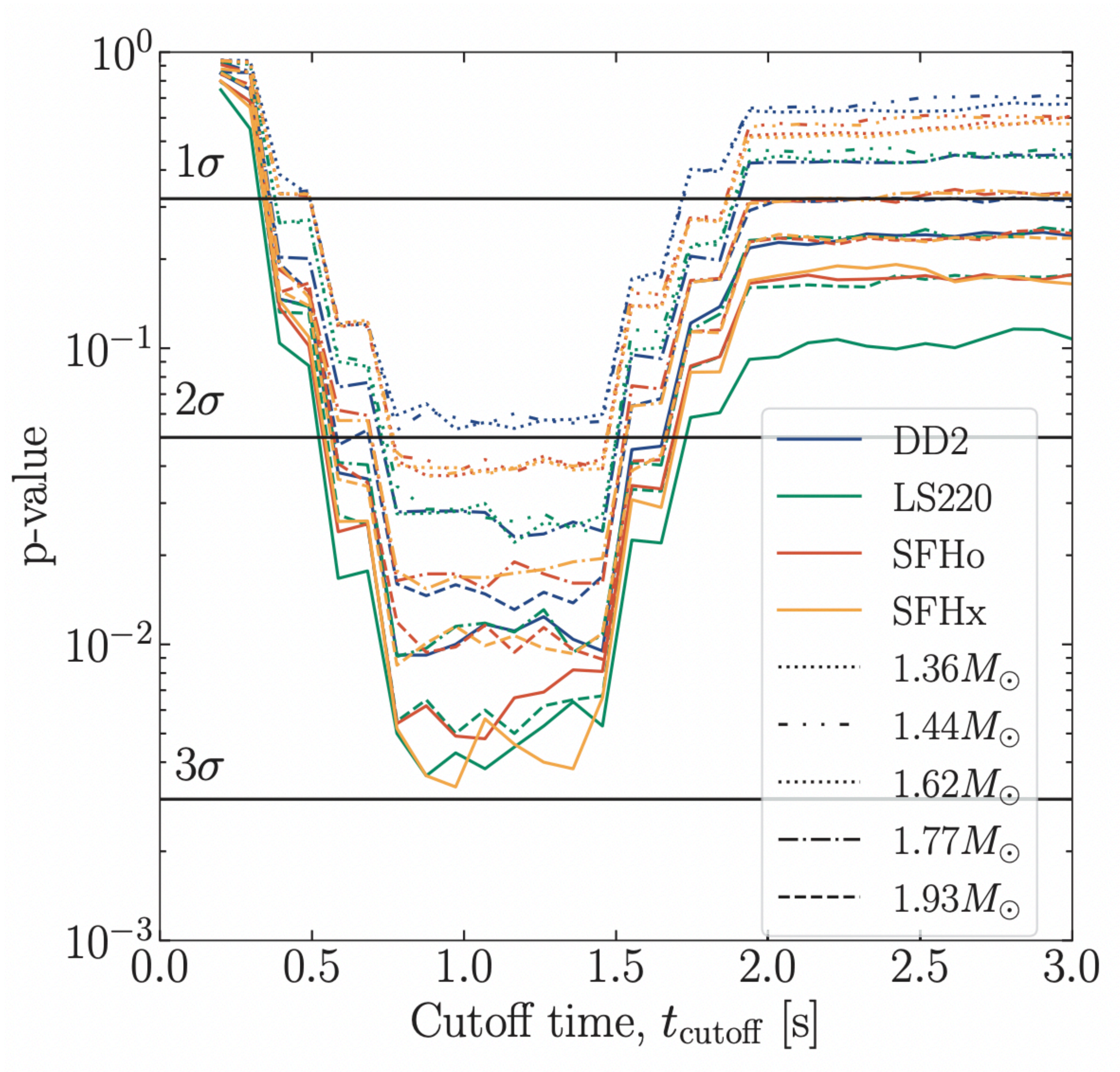


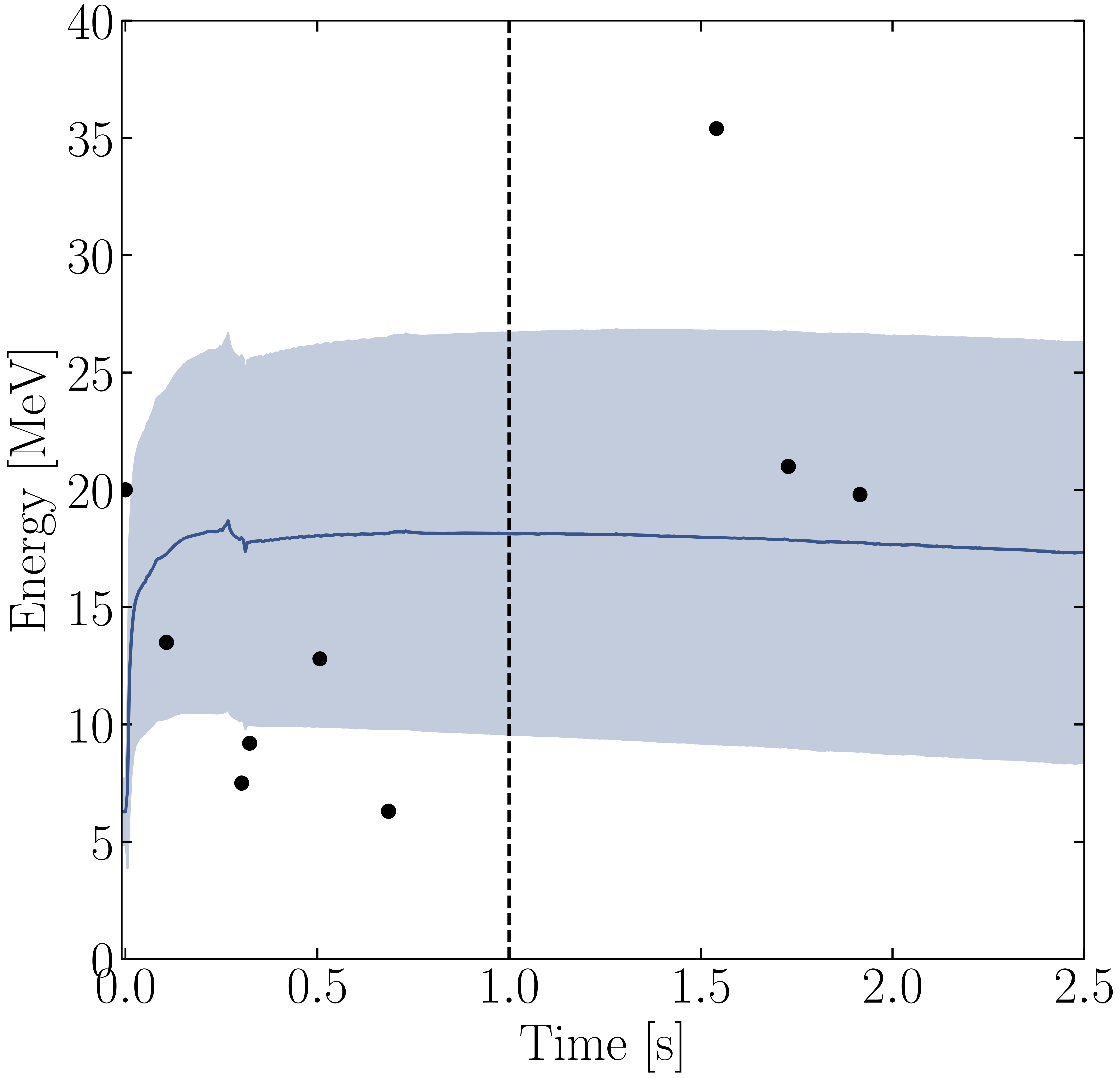
Time-integrated signal



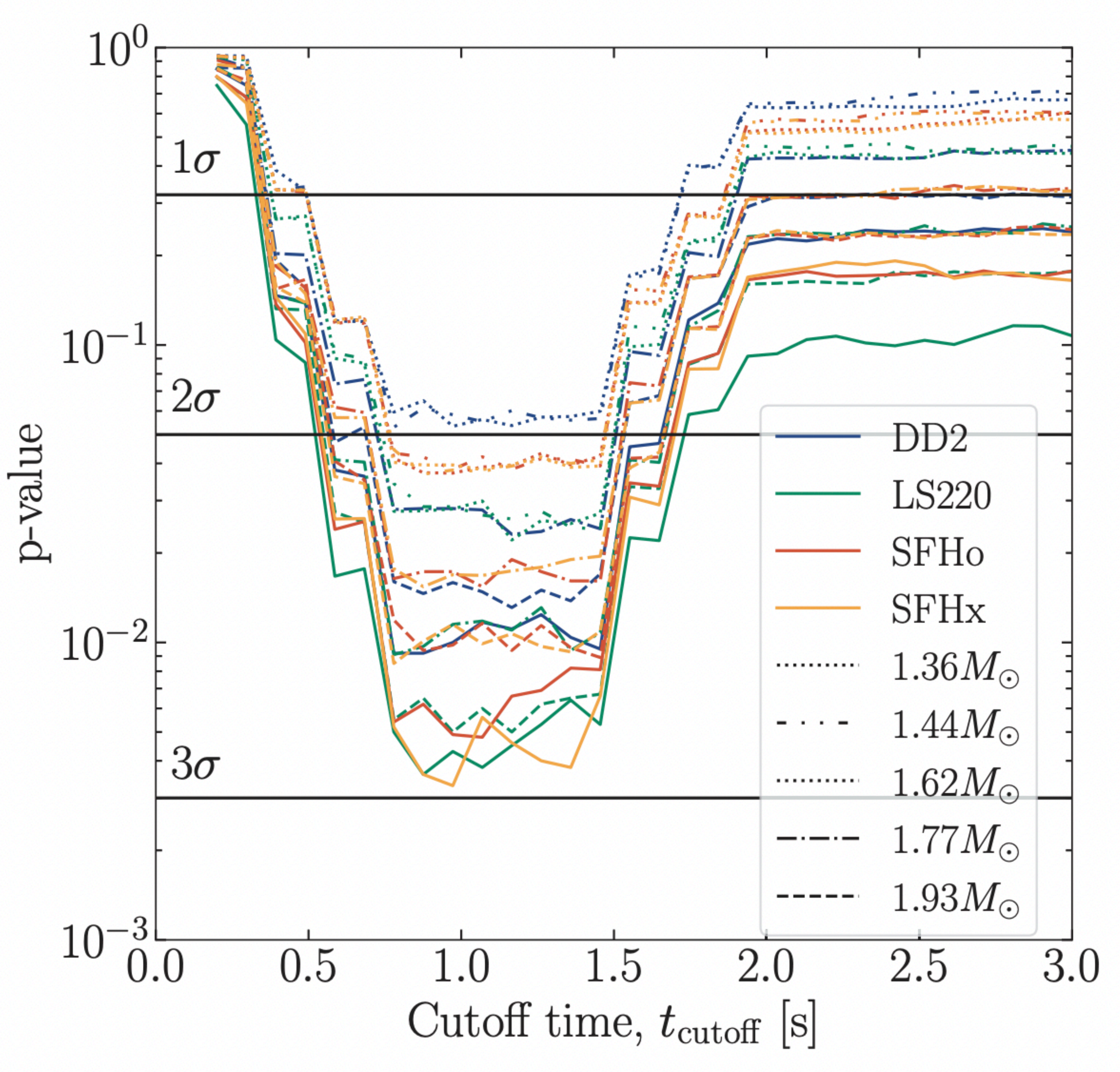
- Tension between Kam-II and IMB — slightly relieved, less than 2σ
- First combined analysis including all experiments!
- Assuming neutrino blackbody spectrum

First second of emission





First second of emission



- ✦ Kolmogorov-Smirnov on first-second events to compare with Li et al., 2306.08024
- ✦ Cutting at 1 s maximizes tension (events 3 and 4 have low energy), but globally insignificant
- ✦ Models with low PNS less than 2 sigma even cutting the events

Motivation

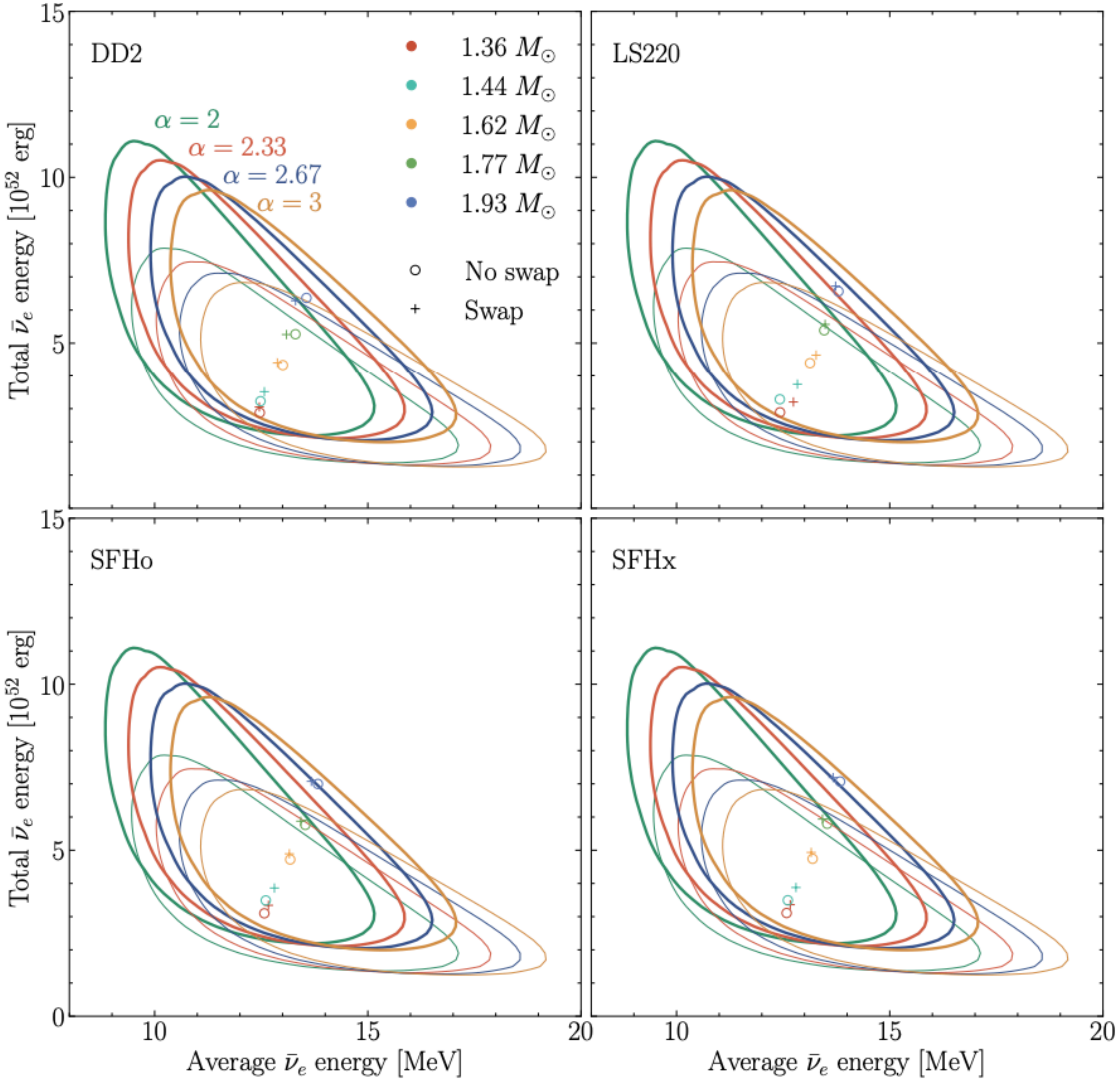
- Increased confidence in the neutrino delayed explosion mechanism - 3D simulations show self-consistent explosions
- Boost of activity in BSM bounds
- Significant updates to the simulations
    - **Convection**
    - **Updated neutrino-nucleon opacities**

arXiv:2108.08463: Olsen, Qian

arXiv:2301.11407: Dedin Neto, de Santos, de Holand, Kemp

arXiv:2306.08024: Li, Beacom, Roberts, Capozzi

Impact of flavor conversion



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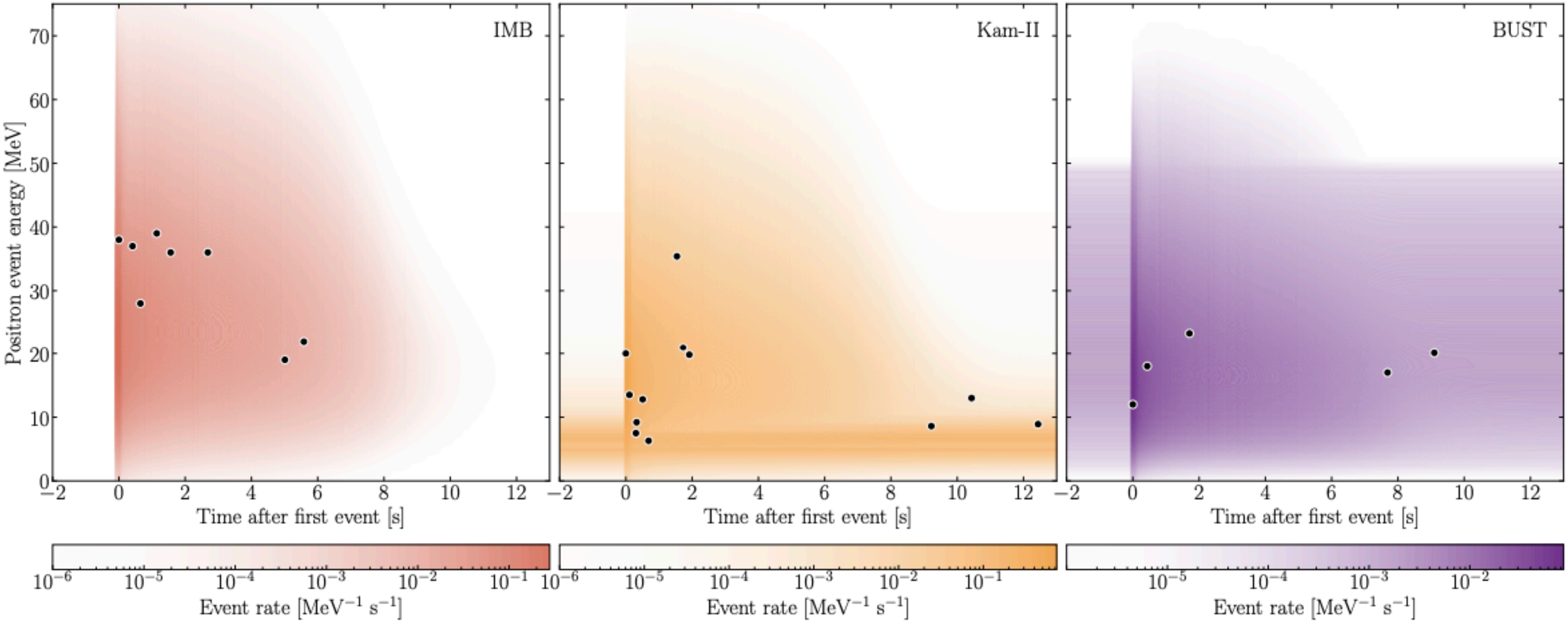
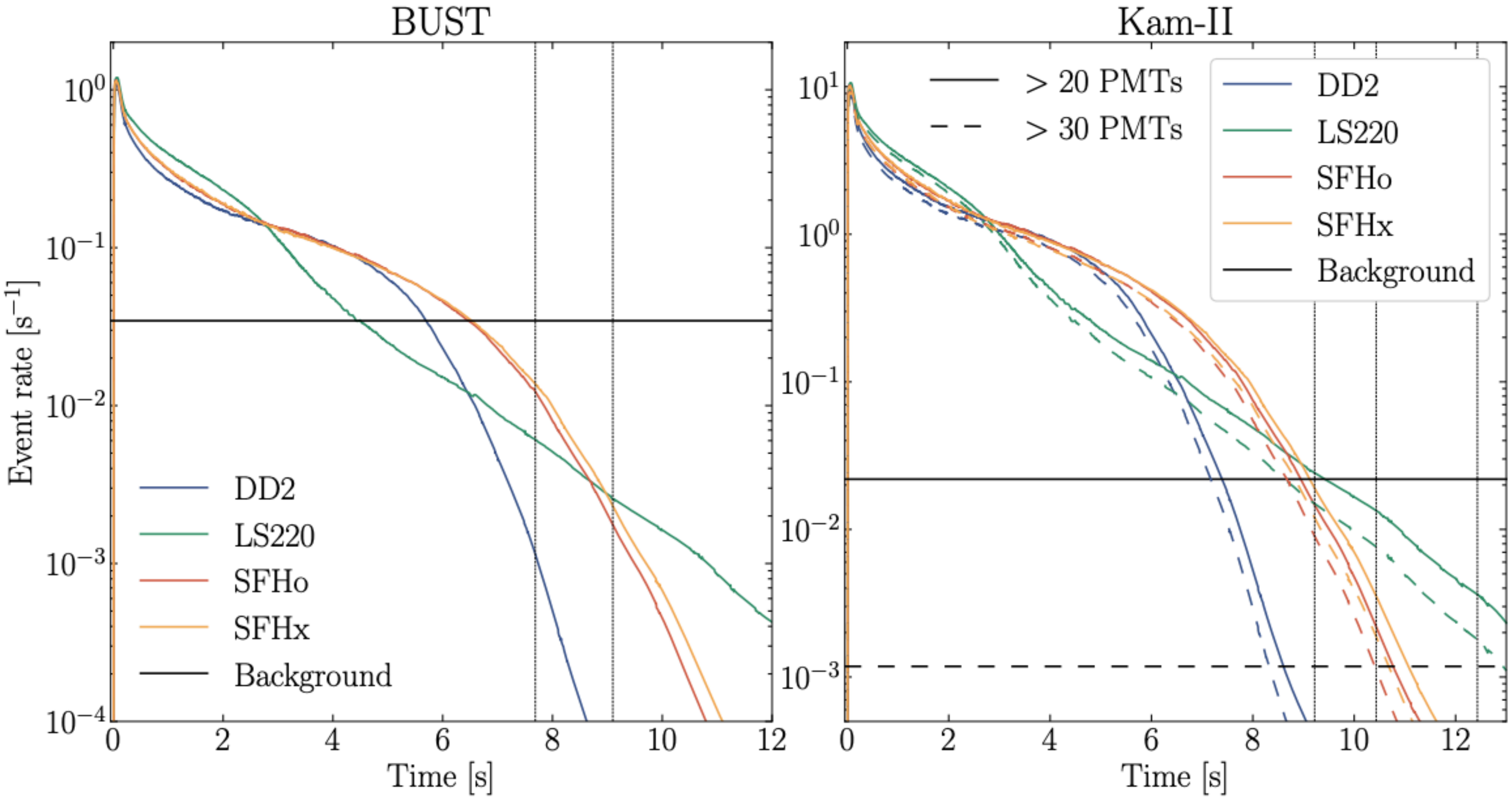
Event rates

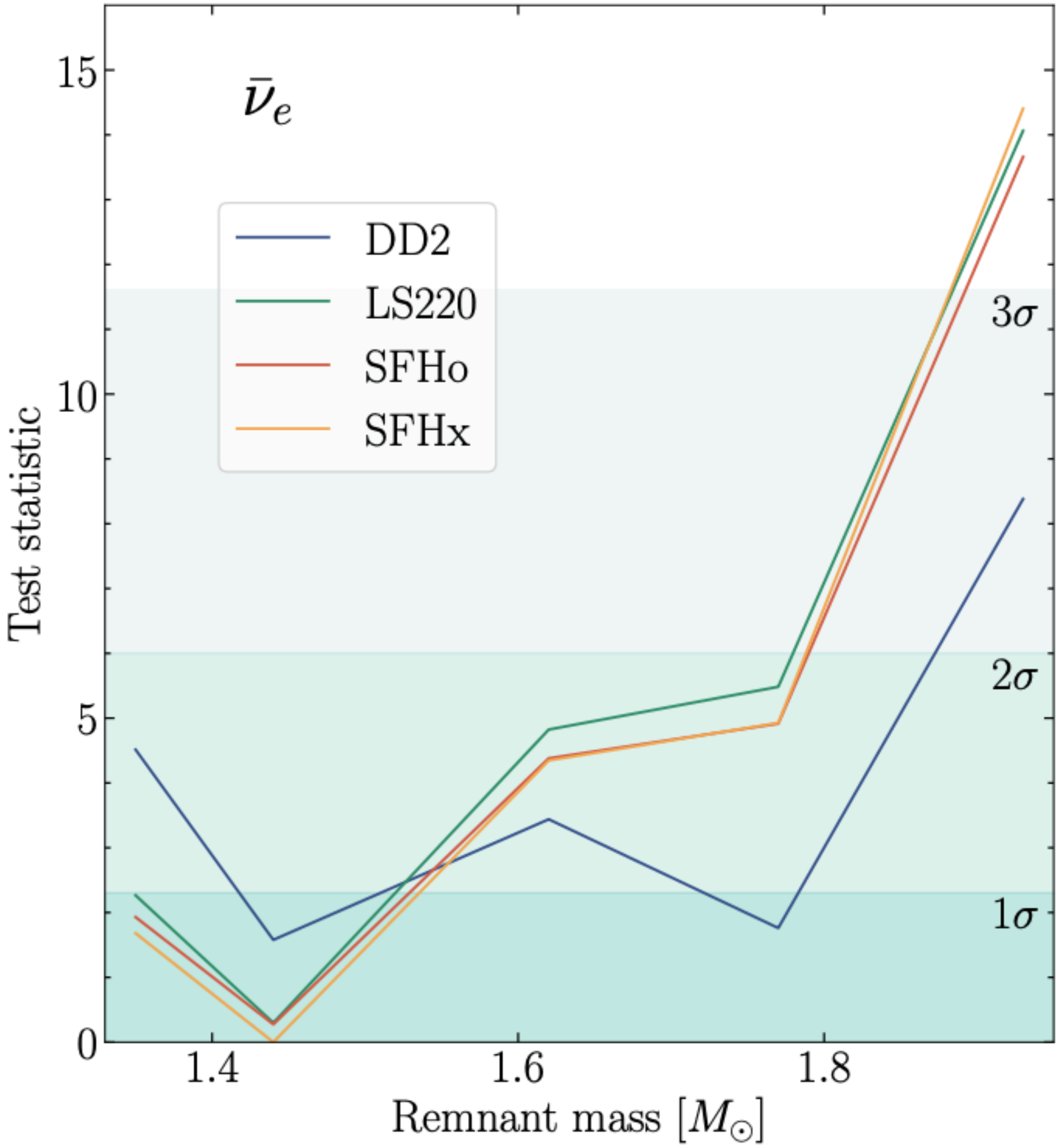


IMB
Kam-II
BUST
Positron event energy [MeV]
0
10
20
30
40
50
60
70
−2
0
2
4
6
8
10
12
Time after first event [s]
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Event rate [MeV^{-1} s^{-1}]

Late-time events

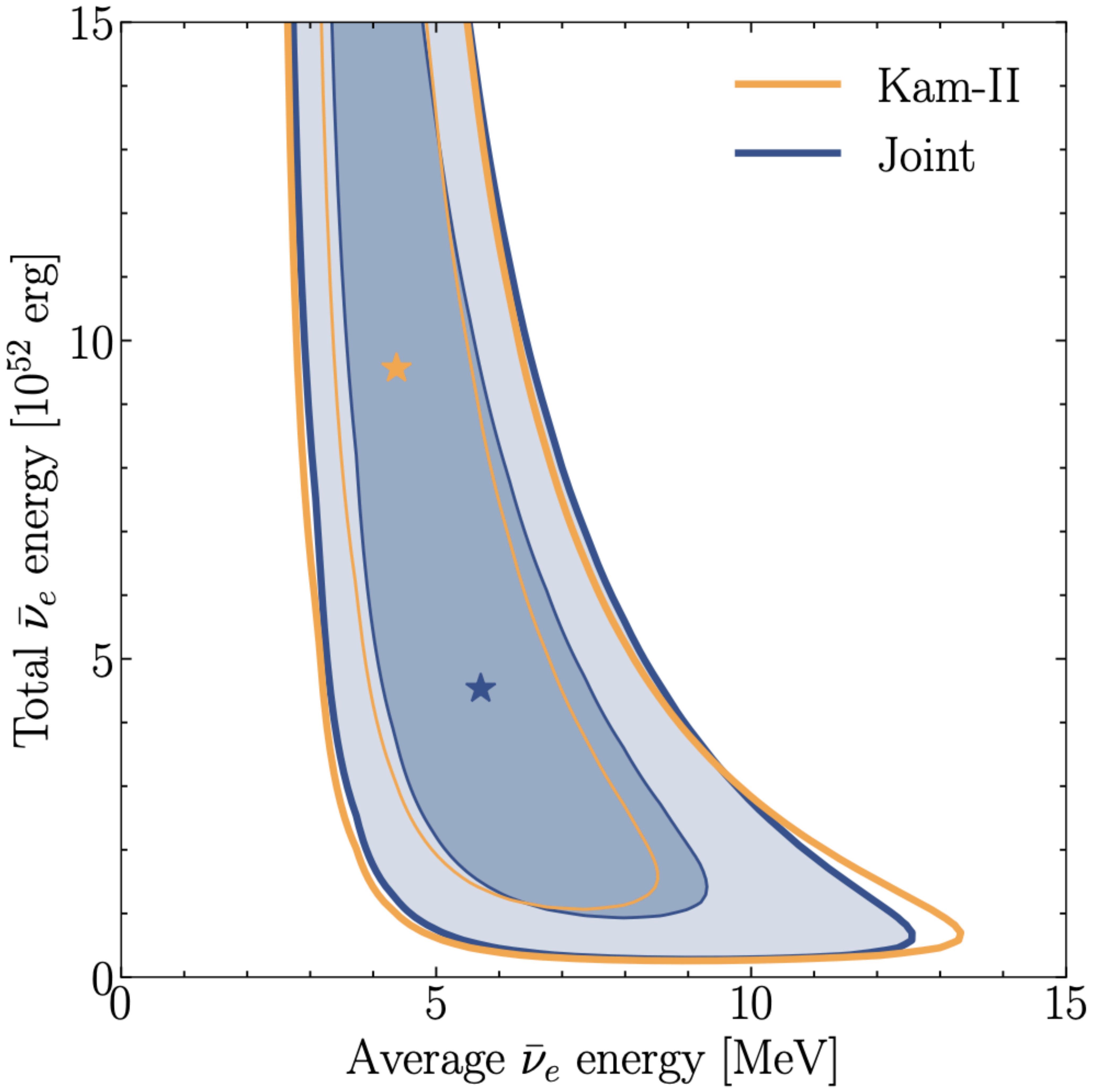


Full time and energy analysis



- ✦ Bimodal tendency — Kam-II and LSD point to light PNS, IMB and BUST to heavy PNS
- ✦ PNS mass of 1.93 $M_\odot$ excluded
- ✦ Weak sensitivity to EoS

Time structure of the signal



- Origin of late-time events is an open question
  - Background?
  - Late-time fallback accretion?