Neutrino quantum kinetics and r-process nucleosynthesis in stellar explosions

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中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA

NSTC 國家科學及技術委員會
National Science and Technology Council

NCTS

Outline

- Collective neutrino (ν) oscillations and neutrino quantum kinetics
- Numerical solutions of neutrino quantum kinetic equation
- r-process nucleosynthesis – nuclear heating and neutrino annihilation
- Summary

please feel free to enter your inputs for the discussion session on "Neutrino oscillations" by scanning this QR code

ν transport in core-collapse supernovae and neutron star mergers

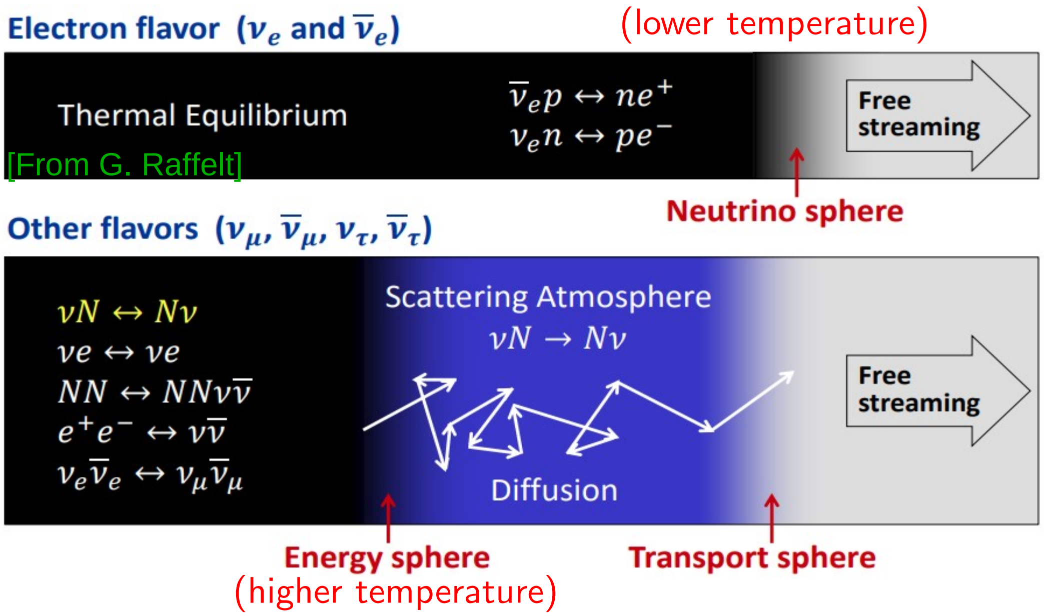
$E_\nu \sim E_G \gtrsim 10^{53}$ erg$\gg E_{\rm expl} \sim 10^{51}$ erg

$\rightarrow$ accurate modeling of non-equilibrium, multi-species ν transport is needed

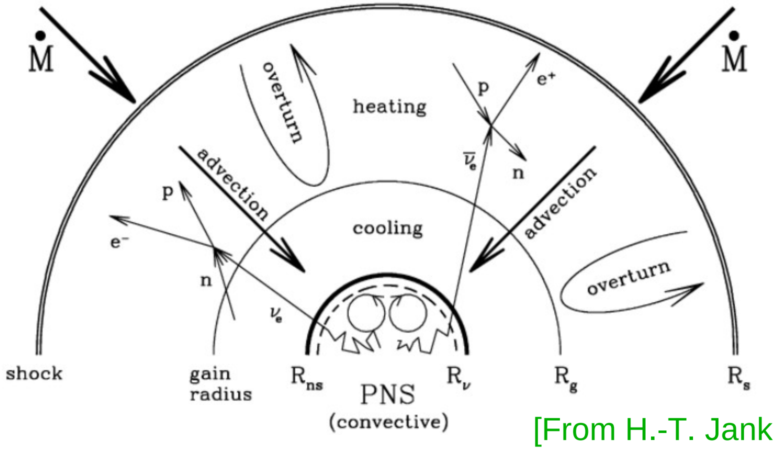
Most (nearly all) supernova & neutron star merger simulations assume that neutrinos stay in their "flavor eigenstates" after production and remain so in propagation

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}}) f_{\nu_\alpha}(\mathbf{x},\mathbf{p},t) = \mathcal{C}$$

Key processes $\nu_e + n \leftrightarrow p + e^-$ and $\bar\nu_e + p \leftrightarrow n + e^+$ are flavor/species dependent



[From G. Raffelt]



[From H.-T. Janka]

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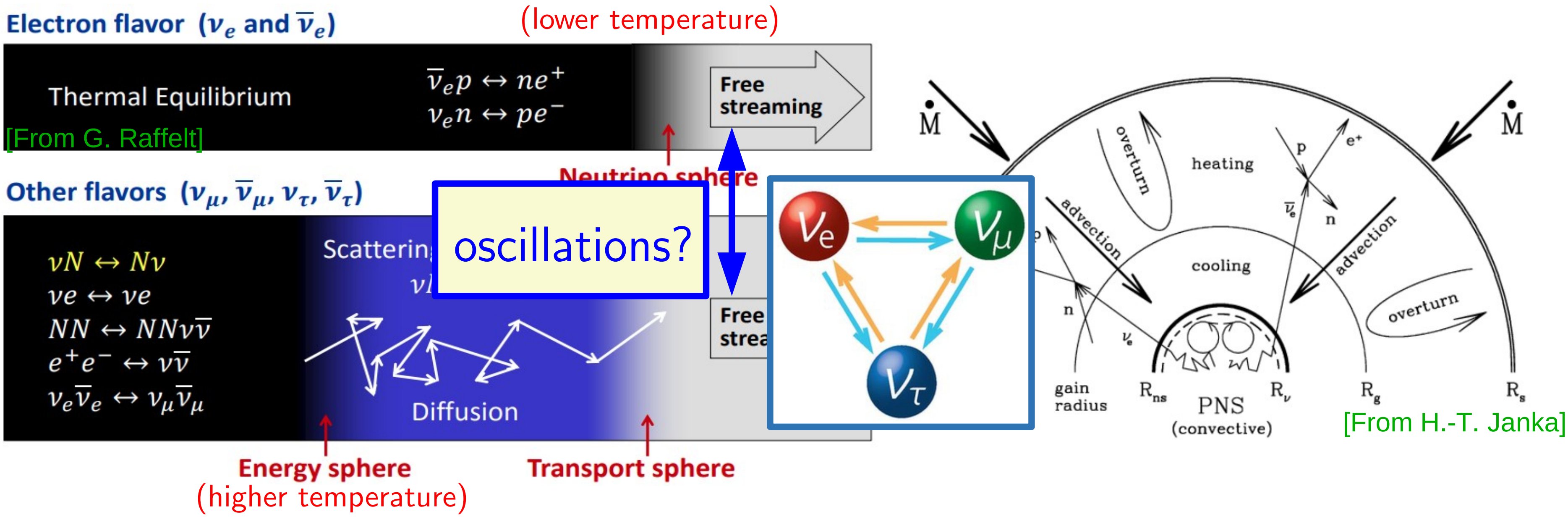
Can flavor oscillations occur in SN's or merger's deep interior to affect the dynamics? If so: How do they occur? How to incorporate them in simulations? What's the impact?



[From G. Raffelt]

[From H.-T. Janka]

The oscillation “problem”

Oscillations (quantum nature of ν) → density matrix $\varrho(t, \mathbf{x}, \mathbf{p}) = \left[\begin{array}{ccc} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{array} \right]$

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→ requires solving (at least) the neutrino quantum kinetic equation (νQKE):

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[\underbrace{H_{\rm vac} + \overbrace{H_{\rm m}}_{\text{function of } |\mathbf{p}| \text{ and } n_e\text{, no non-linearity, nearly diagonal}} + H_{\nu\nu}}^{\text{sourced by medium correction to neutrino's dispersion relation}}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

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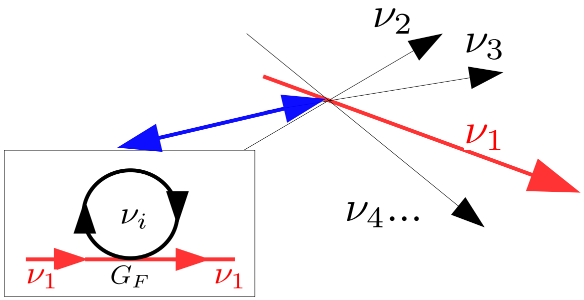
Neutrino-neutrino forward scattering:

$$H_{\nu\nu}(\mathbf{x}, \hat{\mathbf{p}}, t) = \frac{\sqrt{2}G_F}{(2\pi)^3} \int d^3q(1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}})[\varrho(\mathbf{x}, \mathbf{q}, t) - \bar{\varrho}^*(\mathbf{x}, \mathbf{q}, t)]$$

- non-linear (depends on the integral of ρ of all momenta)
- carries strong directional dependence
- introduce a scale $L_\text{SI}^{-1} \sim G_F n_\nu \gg |H_\text{vac}|$



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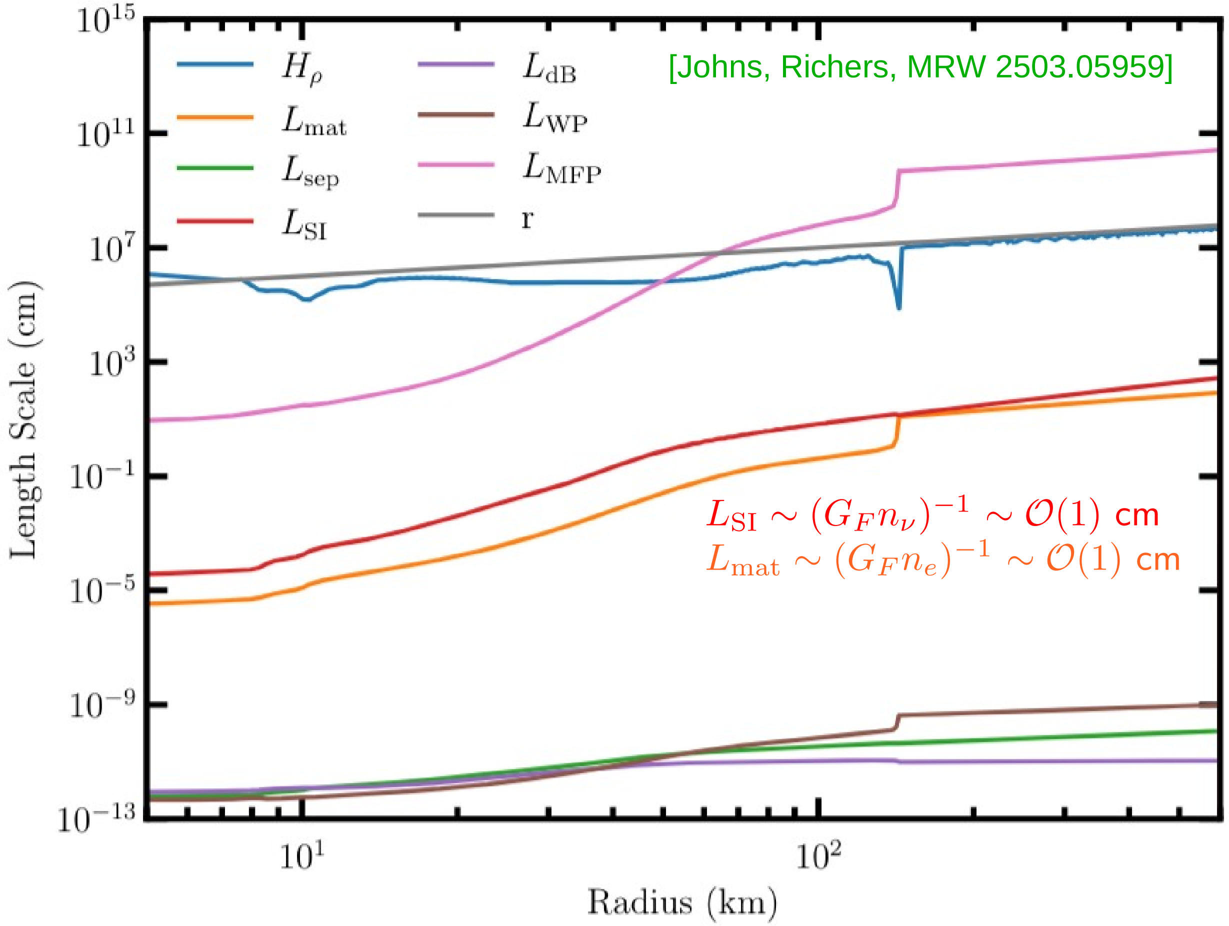

[Johns, Richers, MRW 2503.05959]

$L_{\rm SI} \sim (G_F n_\nu)^{-1} \sim \mathcal{O}(1)$ cm

$L_{\rm mat} \sim (G_F n_e)^{-1} \sim \mathcal{O}(1)$ cm

(scale height, mean-free path, ...)
macroscopic scale
$\sim \mathcal{O}$(km)

(oscillation length)
mesoscopic scale
$\sim \mathcal{O}$(cm)

(particle separation, wave packet,...)
microscopic scale
$\sim \mathcal{O}$(pm)

A “complete” modeling of neutrino flavor oscillations in SNe & mergers requires resolving the mesoscopic oscillations at length scale of $L_{\rm SI} \sim (\sqrt{2} G_F n_\nu)^{-1} \sim \mathcal{O}(1)$ cm

The oscillation "problem"

$$H_{\nu\nu}(\mathbf{x}, \hat{\mathbf{p}}, t) = \frac{\sqrt{2}G_F}{(2\pi)^3} \int d^3q(1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}})[\varrho - \bar{\varrho}^*]$$

Q: Neutrinos are produced in flavor eigenstates, shouldn't $H_{\nu\nu}$ be nearly diagonal and do not matter?

A: Unfortunately no – the system can be "collectively unstable" against small perturbations in $\rho_{\alpha\beta}$

Collective neutrino flavor oscillations

Assuming $|\rho_{\alpha\beta}|/f_{\nu_\alpha} \ll 1$, linearization of the EoM allows to find the dispersion relation of collective modes:

[Banerjee+ 2011, Raffelt+ 2013, Izaguirre+ 2017...]

$$|\varrho_{\alpha\beta}| \propto \exp(ik^\mu x_\mu) \longrightarrow \text{EoM} \longrightarrow \mathcal{D}(\omega, \vec{k}) = 0$$

complex frequency ↔ unstable collective modes

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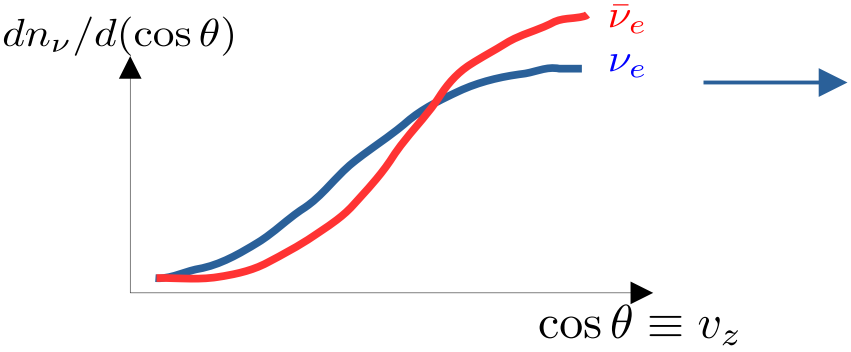
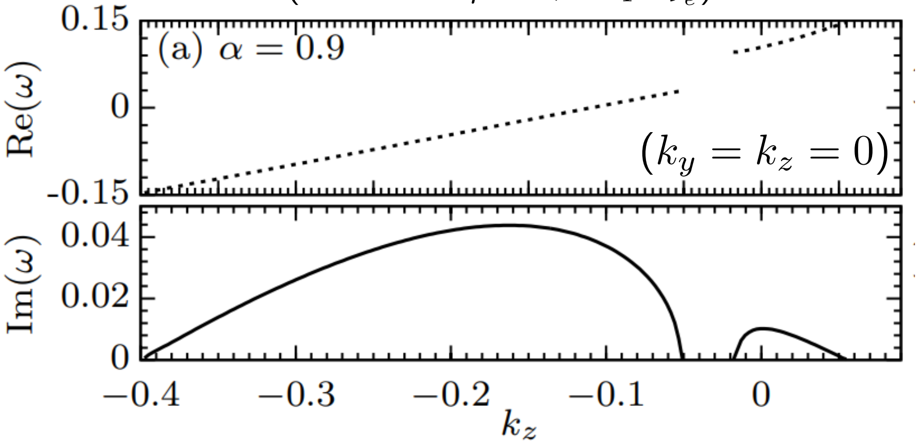
[MRW, George, Lin, Xiong 2108.09886]

An example: existence of a "crossing" in neutrino angular distributions

(fast flavor instabilities / conversions)



(in units of $\mu \equiv \sqrt{2}G_F n_{\nu_e}$)



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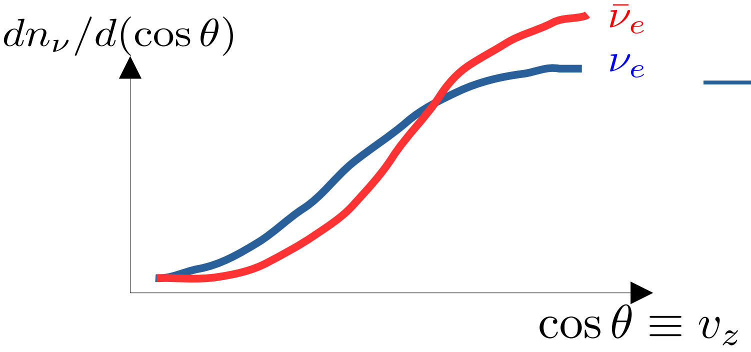

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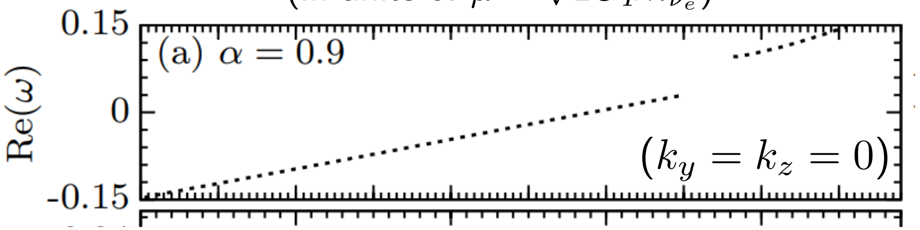
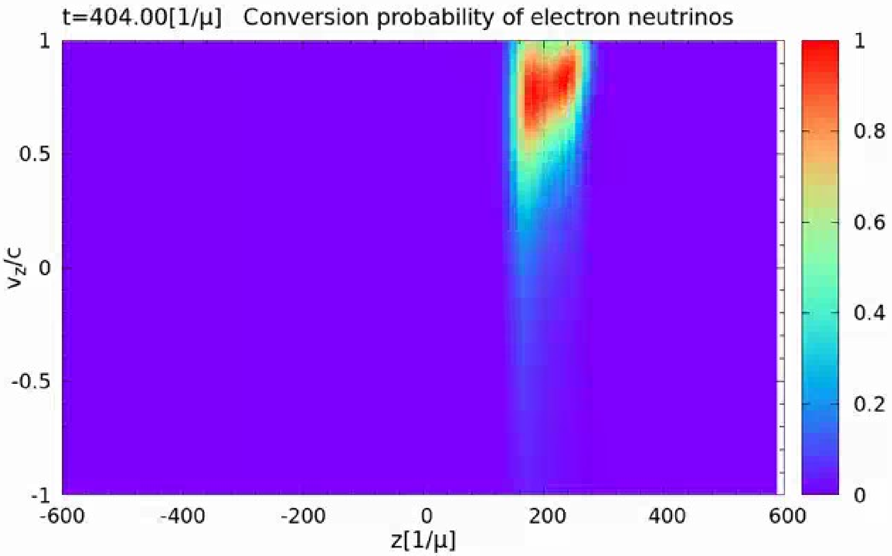




these collective unstable modes can grow in nanoseconds and lead to "flavor waves" of centimeter wavelengths (mesoscopic scale!)

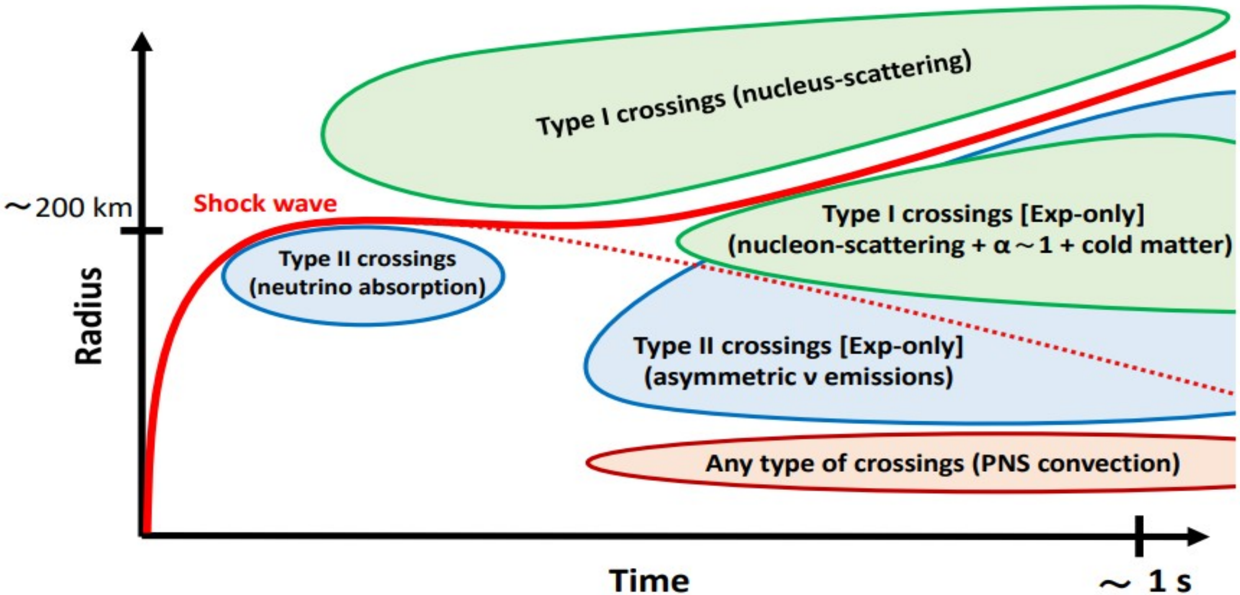
[See Fiorillo & Raffelt, 2502.06935 for the language of "flavomon" + a very nice series of papers using plasma physics approach]

Fast flavor instabilties in SNe?

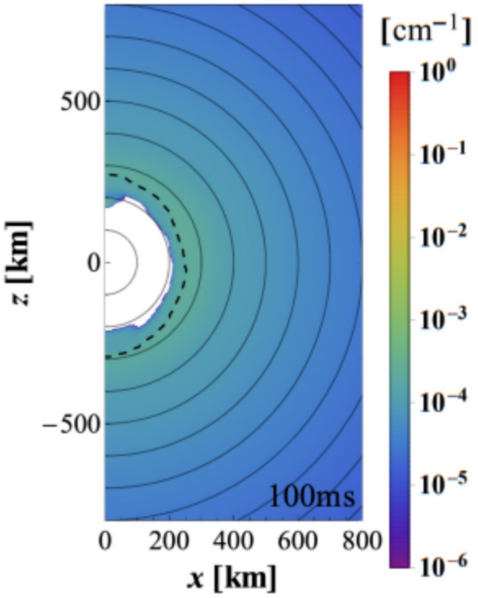
Post-processing analyses based on SN simulation snapshots WITHOUT including oscillations suggest the presence of neutrino angular crossings hence the fast instabilities

[Abbar+, Glas+, Nagakura+, Akaho+, ...]

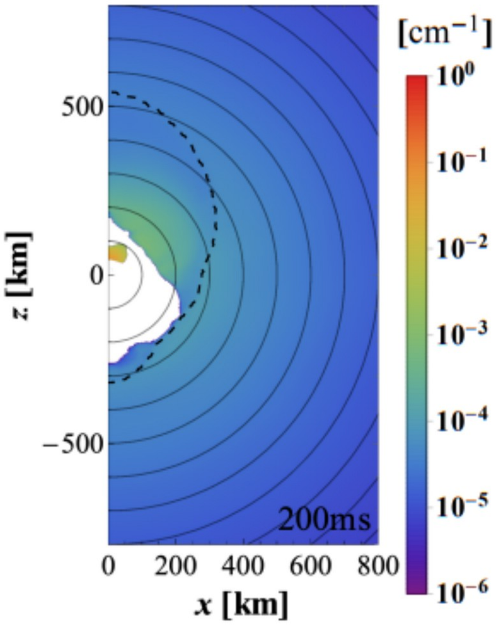
Space-time diagram of ELN-angular crossings in CCSNe



[Nagakura+ 2108.07281]



[Nagakura+ 1910.04288]



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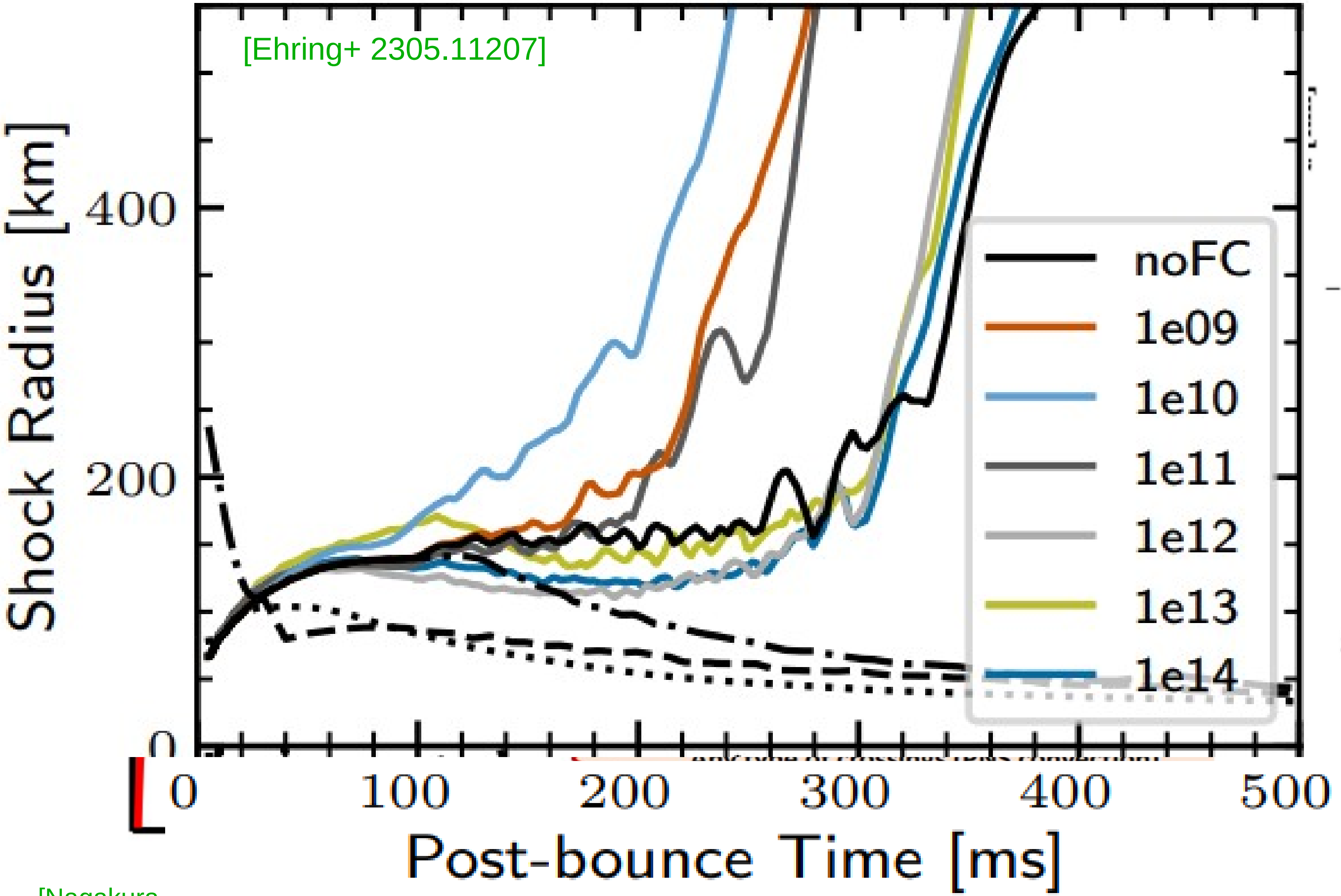
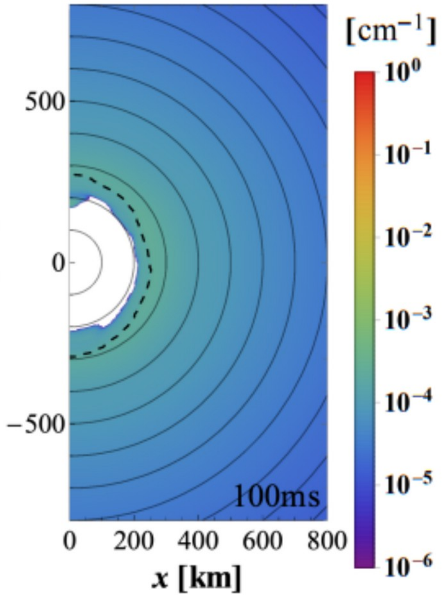


[Ehring+ 2305.11207]

[Nagakura-



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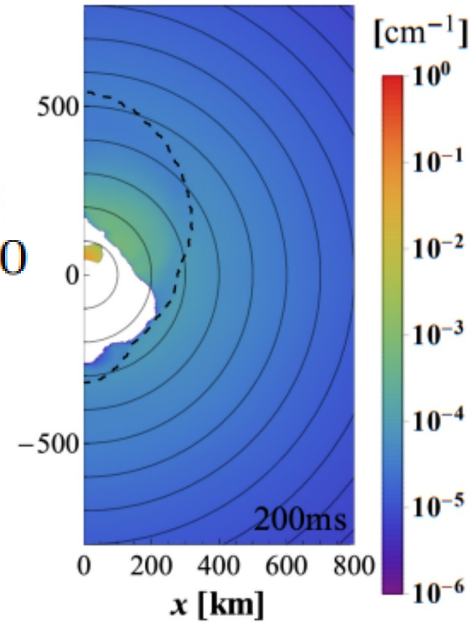


preliminary studies suggest potential impact on explosion, nucleoynthesis, pulsar kick, neutrino & GW signals...

[Ehring+, Mori+, Wang+, Xiong+, Nagakura+, Akaho+,...]

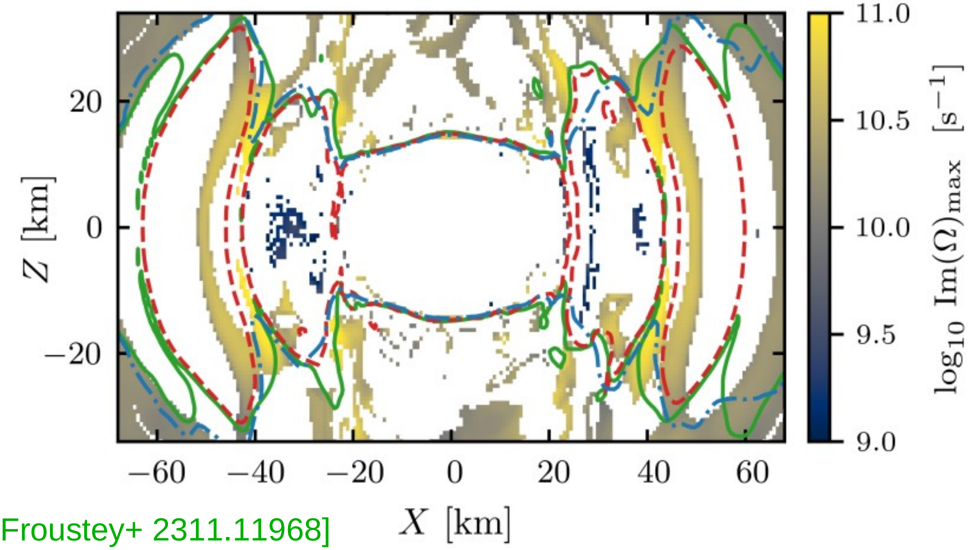
(see Jakob Ehring's talk)

Fast flavor instabilties in NSM?

Similar analyses indicate that fast flavor instabilities exist even more robustly in NSM remnants, related to their “protonization”

[MRW+, Abbar+, Richers+, Froustey+, Nagakura+,...]

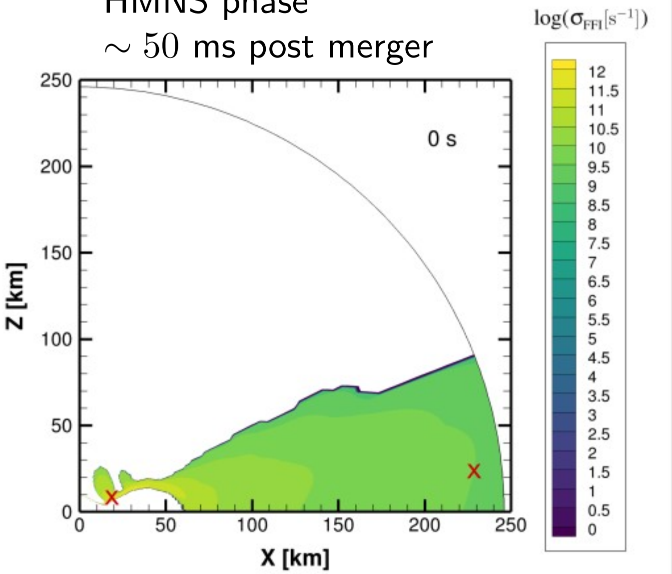
dynamical phase ~ 5 ms post merger



[Froustey+ 2311.11968]

HMNS phase

~ 50 ms post merger



[Nagakura+ 2504.20143]

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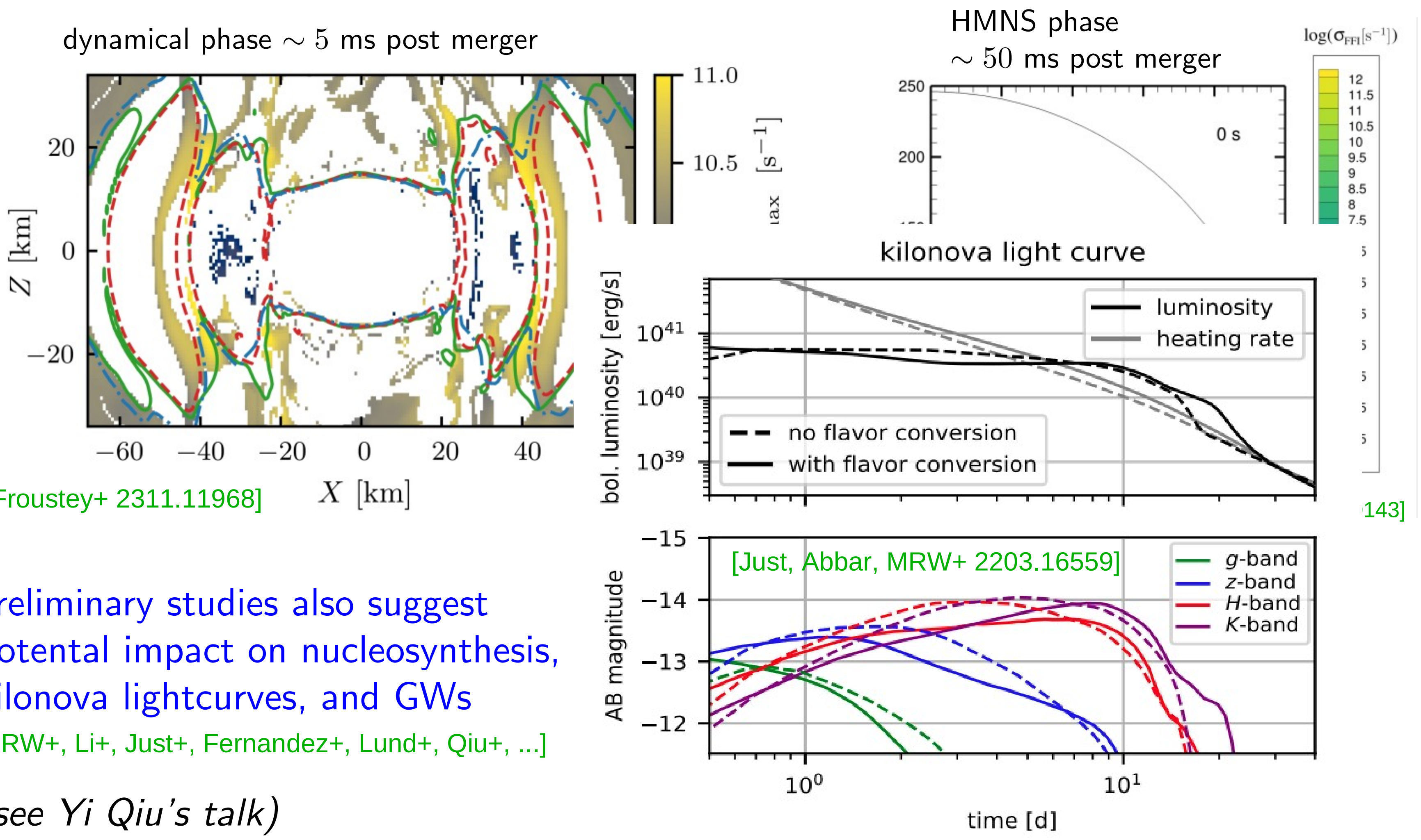


dynamical phase ~ 5 ms post merger

[Froustey+ 2311.11968]

HMNS phase
~ 50 ms post merger

kilonova light curve

[Just, Abbar, MRW+ 2203.16559]

preliminary studies also suggest potental impact on nucleosynthesis, kilonova lightcurves, and GWs

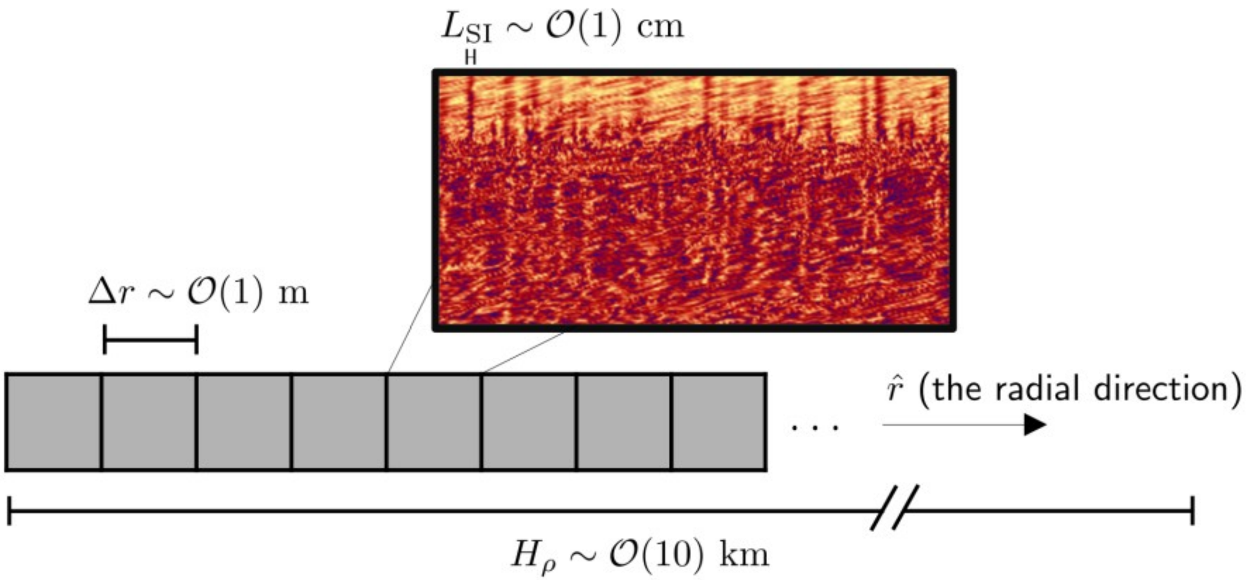
[MRW+, Li+, Just+, Fernandez+, Lund+, Qiu+, ...]

(see Yi Qiu’s talk)

Approaches to resolve the “oscillation problem”

Q: Obviously it’s not possible to directly solve the νQKE in SN or NSM simulations, can one construct surrogate models that incorporate oscillation physics in a satisfactory way?

→ likely will involve the development of **subgrid-scale** models.



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- understand QKE dynamics and study their coarse-grained properties.

  $\rightarrow$ numerical studies:

  - local periodic-box (nearly homogeneous) simulations [Martin+, Bhattacharyya+, Richers+, MRW+, Nakagura+, Zaizen+, Fiorillo+, Liu+,...]
  - local or global simulations taking fixed (Dirichlet) boundaries [Nakagura+, Shalgar+,...]
  - "realistic" global simulations [Nakagura+, Xiong+, Shalgar+,...]

  $\rightarrow$ analytical advancement:

  - quasi-linear theory [Fiorillo+]
  - "misci-dynamics" [Johns+]

- explore new closure relations for QKE.

  - analytical "quantum M1" closure relations [Kneller+, Grohs+, Froustey+,...]

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Numerical exploration of νQKE dynamics

Local quasi-equilibrium state of fast flavor conversion

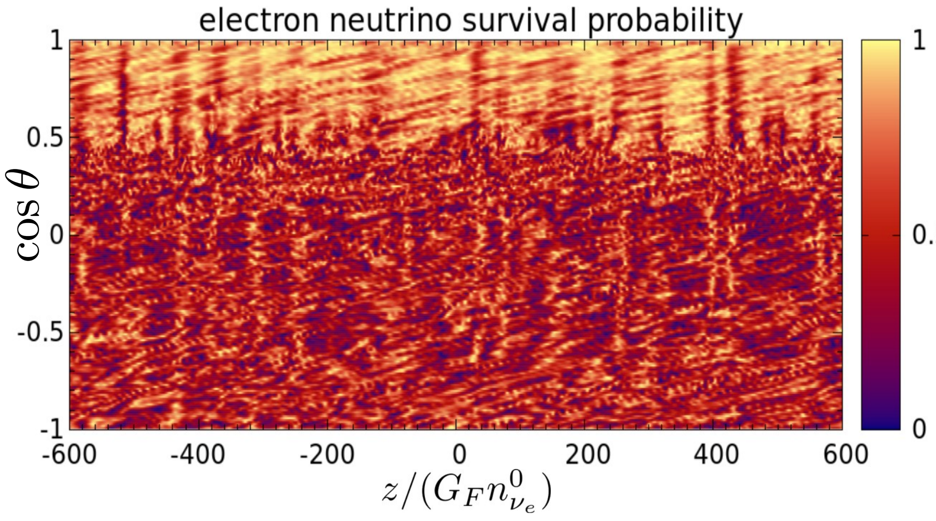
Simulations of fast flavor conversions in “local” periodic boxes found:

[see also Bhattacharyya+, Richers+, Nagakura+, Cornelius+, Delfan Azari+, ...]

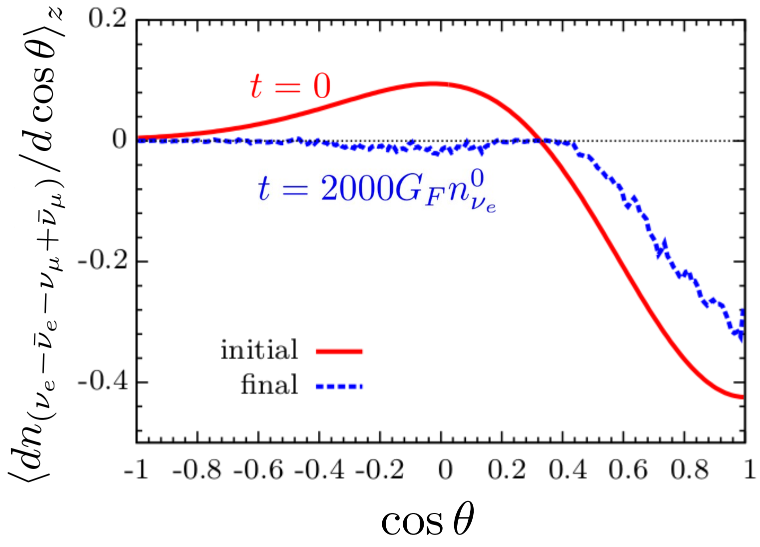
nonlinear flavor wave interaction
→ kinematic decoherence
→ coarse-grained equilibrium
→ near flavor equipartition in one side of the angular domain

$$\langle \frac{dn_{\nu_e}}{d\cos\theta} \rangle_z \simeq \langle \frac{dn_{\nu_\mu}}{d\cos\theta} \rangle_z, \; \langle \frac{dn_{\bar\nu_e}}{d\cos\theta} \rangle_z \simeq \langle \frac{dn_{\bar\nu_\mu}}{d\cos\theta} \rangle_z \text{ for } \cos\theta \lesssim 0.35$$

[MRW, George, Lin, Xiong, 2108.09886]



averaging over space



Is this the general outcome?

(Our code – Collective Oscillation Simulation Engine for Neutrinos (`COSE`ν) available at https://github.com/cosenu/cosenu)

Local quasi-equilibrium state of fast flavor conversion

Net electron-minus-muon neutrino number is a conserved quantity:

$\int d(\cos\theta)\langle dn_{(\nu_e-\bar{\nu}_e-\nu_\mu+\bar{\nu}_\mu)}/d\cos\theta\rangle_z =$ constant (with periodic b.c.)

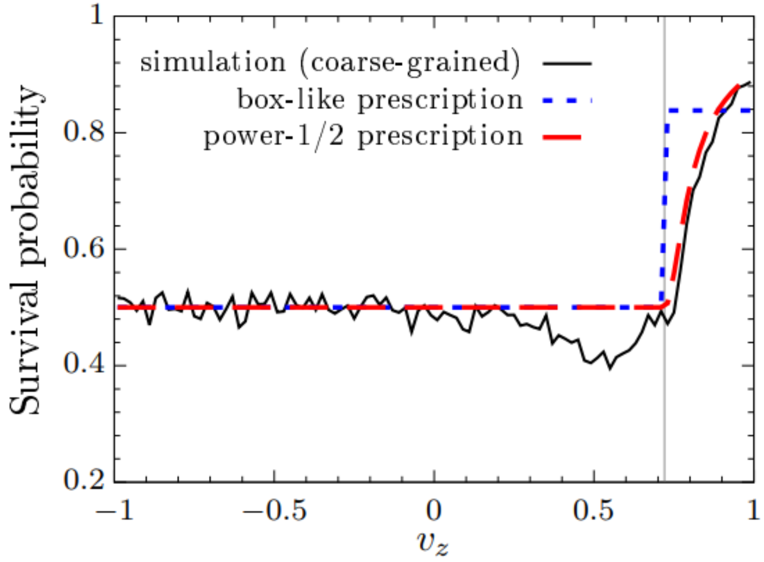
$\rightarrow$ allows analytical parametrization for the coarse-grained survival probabiity $\langle P_{ee}\rangle$:

[Zaizen+, Xiong+, Bhattaharyya+, Richers+,...]

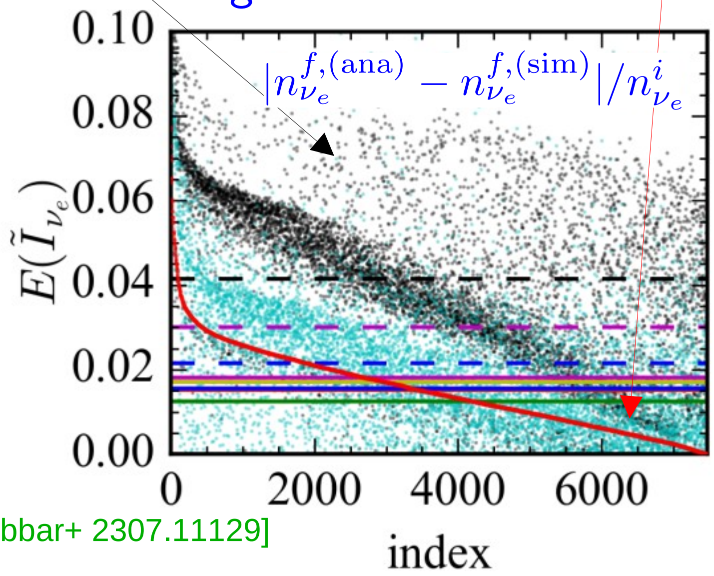
– on the flavor-equipartition side: $\langle P_{ee}\rangle = 0.5$

– on the other side: $\langle P_{ee}(v_z)\rangle = 1 - 0.5h(|v_z - v_c|/a)$, where $h(x) = (x^2+1)^{-1/2}$ (power-1/2)

or $=$ *constant* (box-like)



For $\sim 10^4$ different initial angular functions:



[Xiong, MRW, Abbar+ 2307.11129]

Moving beyond local box – global νQKE simulations

Although it is not possible to fully solve νQKE with required resolution, one can artifically quench $H_{\nu\nu}$ to solve the νQKE with static SN profiles [Nagakura+, Xiong+, Shalgar+]

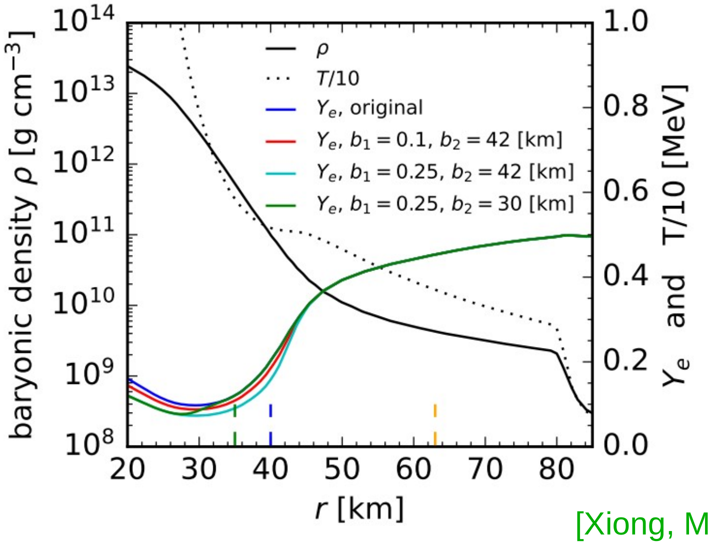
– Take SN matter background profiles $(\rho_b, T, Y_e, \ldots)$ from spherically symmetric SN simulations

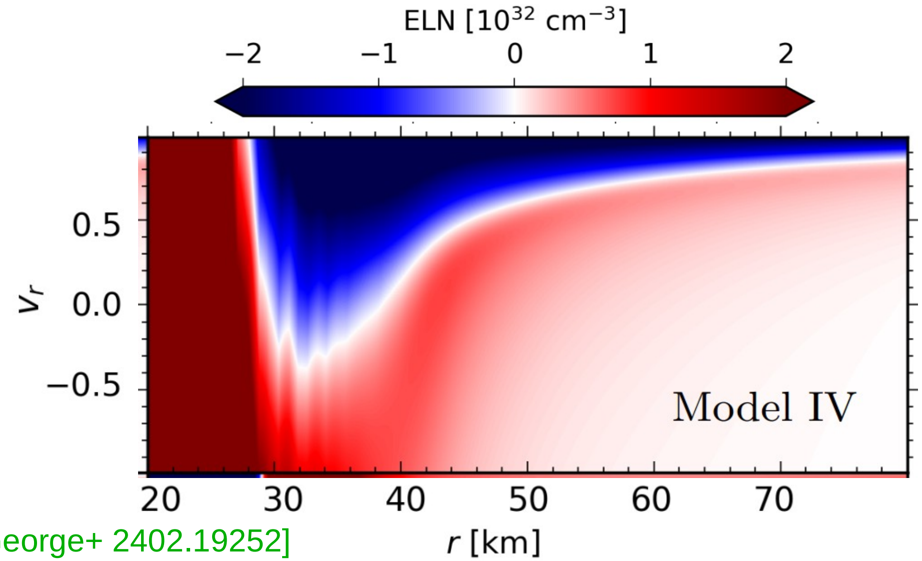
– Solve classical neutrino transport equations to obtain neutrino distributions without considering flavor oscillations

$$(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})f_\nu = \mathcal{C}$$

– Use the above steady-state solution as initial condition for νQKE simulations

$$(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})\varrho_\nu = -i[H_{\rm vac} + H_{\rm m} + aH_{\nu\nu}, \varrho_\nu] + \mathcal{C} \text{ with } a \sim 10^{-3}$$

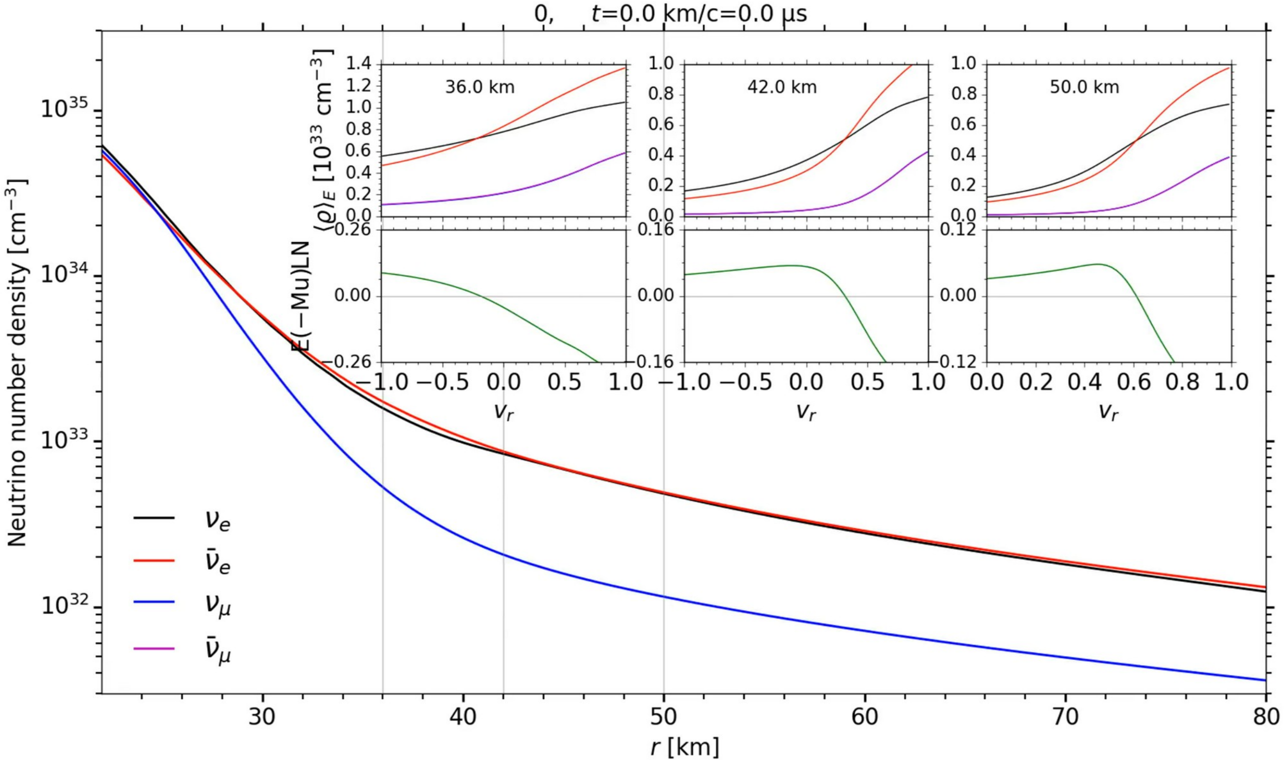




[Xiong, MRW, George+ 2402.19252]

Moving beyond local box – global νQKE simulations

- FFC occurs promply and erase $e-\mu$ crossings across all radii
- neutrino emissions/absorptions inside the neutrinosphere replenish ν_e and $\bar{\nu}_e$, driving gradual evoluton of $e-\mu$ distributions, but no new $e-\mu$ crossings appear



[Xiong, MRW, George+ 2402.19252]

Local state of the system seem to be well described by the local quasi-equilibrium states found with periodic boundary condition

Is this the nature consequnence of scale speration?

Effective classical transport model including FFC

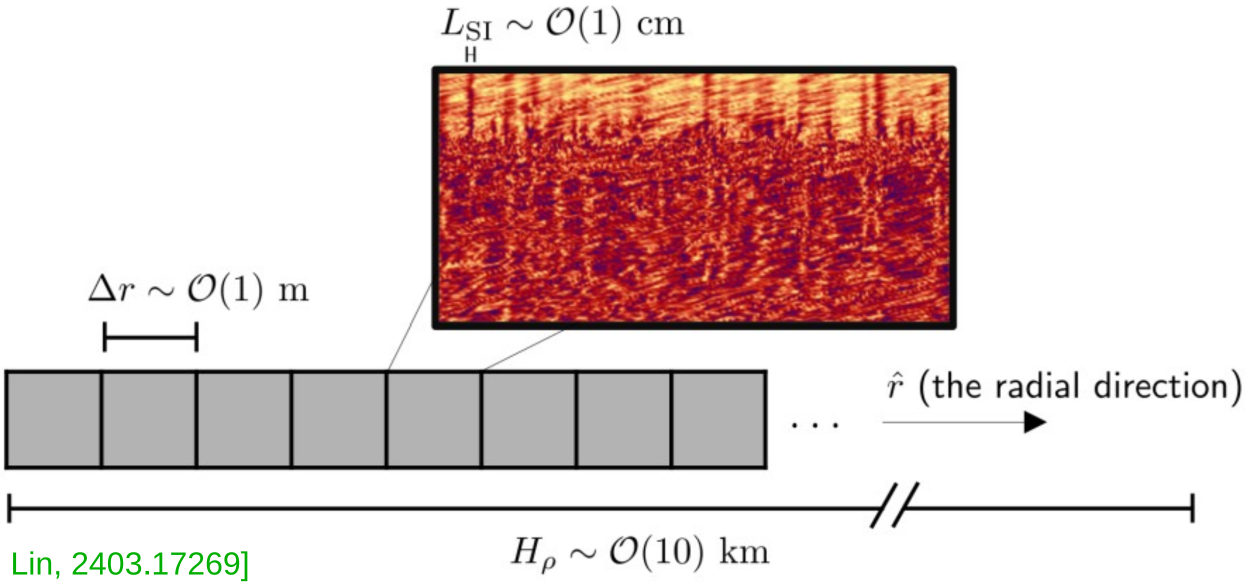
- Full νQKE: solves $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})\varrho_\nu = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho_\nu] + \mathcal{C}$

$$H_{\nu\nu}(\mathbf{x},\mathbf{p},t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*], \quad \varrho(t,\mathbf{x},\mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{e\mu}^* & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho_{e\tau}^* & \varrho_{\mu\tau}^* & f_{\nu_\tau} \end{bmatrix}$$

- Effective transport: solves $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})f_\nu = \mathcal{C}$ with:

  f_ν replaced by $f_\nu^{\rm eq}$ computed using the analytical formula at each time and location where $e-\mu$ crossing is found

  (a special case of Bhatnagar–Gross–Krook model; see also Nagakura+ 2312.16285)



[Xiong, MRW, George, Lin, 2403.17269]

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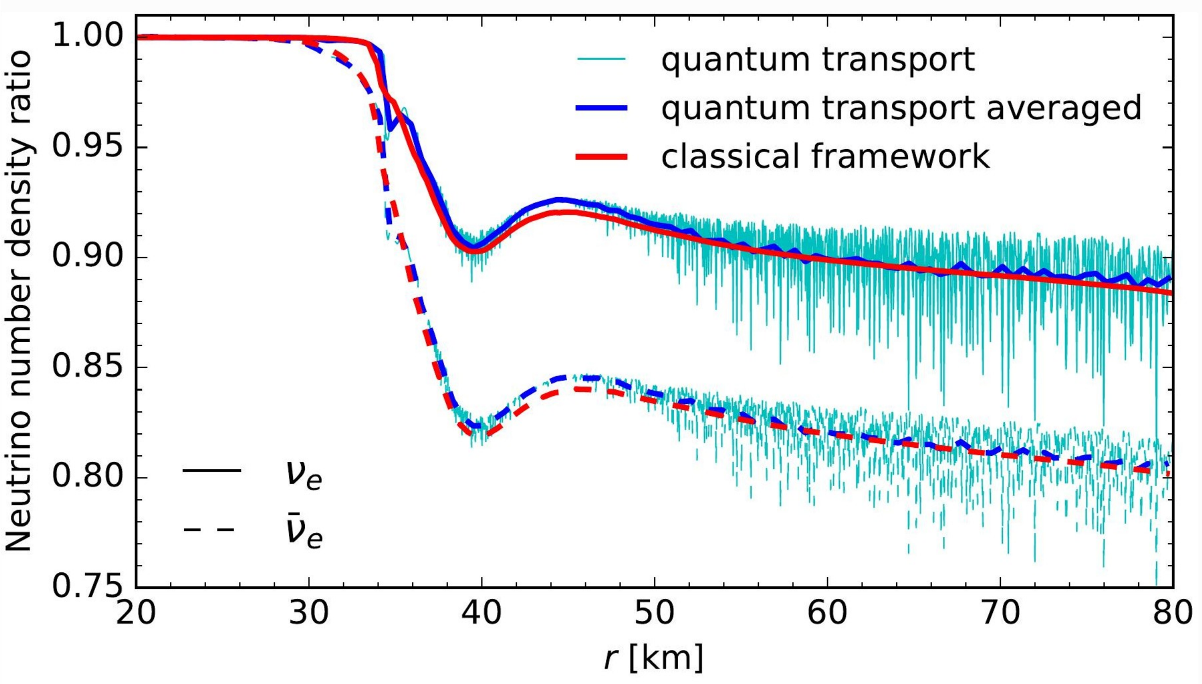
$$H_{\nu\nu}(\mathbf{x}, \mathbf{p}, t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1 - \hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*], \quad \varrho(t, \mathbf{x}, \mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

- Effective transport: solves $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})f_\nu = \mathcal{C}$ with:

f_ν replaced by $f_\nu^{\rm eq}$ computed using the analytical formula at each time and location where $e - \mu$ crossing is found

[Xiong, MRW, George, Lin, 2403.17269]



Is this generally valid?

Other collective flavor instabilities

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

The fast instability is driven by the presence of angular crossing & $H_{\nu\nu}$

Q: is the system always “stable” when no angular crossings exist?

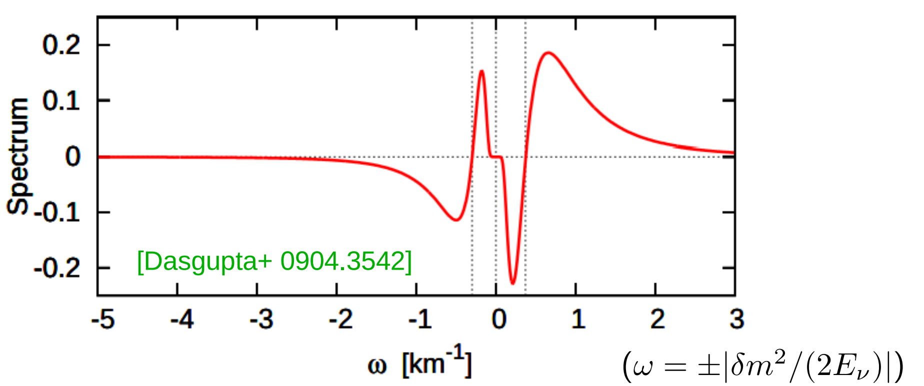
Other collective flavor instabilities

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\text{vac}} + H_{\text{m}} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

Crossings in the neutrino “inverse energy” spectrum can trigger “slow” flavor instabilities

antineutrino $E_\nu^2[f_{\bar\nu_\mu}(E_\nu) - f_{\bar\nu_e}(E_\nu)](\frac{dE_\nu}{d\omega})$

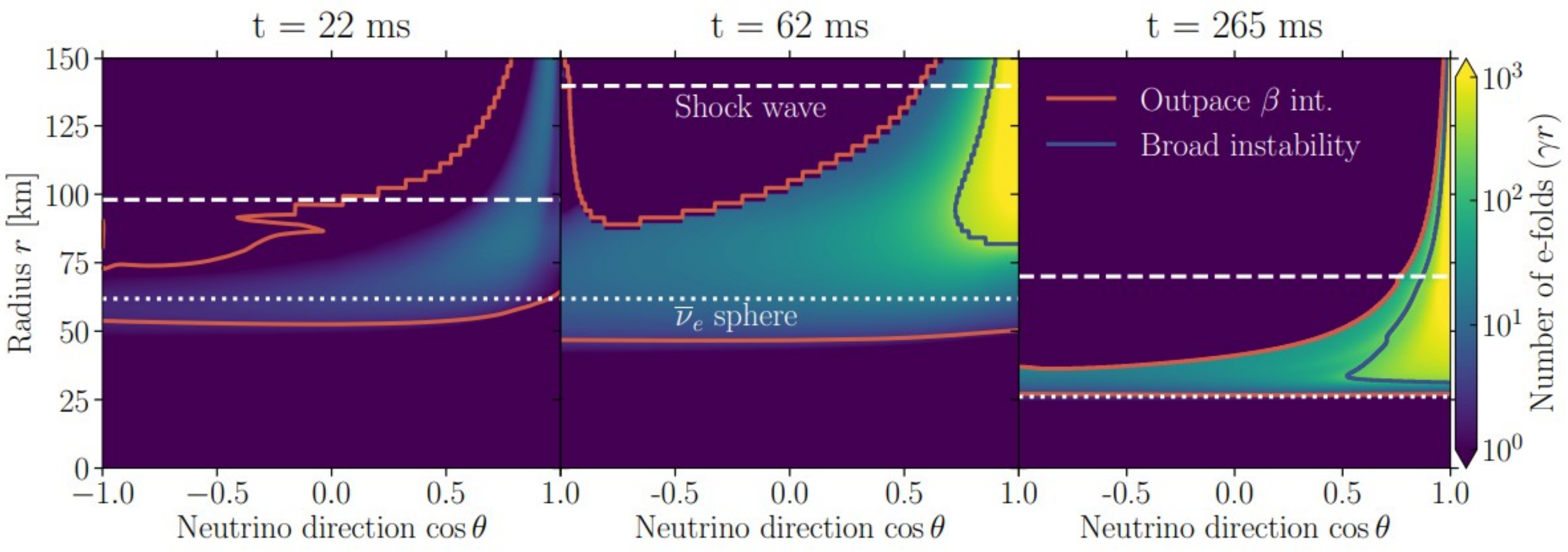
neutrino $E_\nu^2[f_{\nu_e}(E_\nu) - f_{\nu_\mu}(E_\nu)](\frac{dE_\nu}{d\omega})$



[Dasgupta+ 0904.3542]

$(\omega = \pm|\delta m^2/(2E_\nu)|)$

perhaps the first instability that appears in SNe? How about mergers?



[Fiorillo+ 2507.22985]

Local equilibration solution of slow flavor conversion?

Q: Does slow flavor conversion also lead to a similar local equilibrium state?

Local equilibration solution of slow flavor conversion?

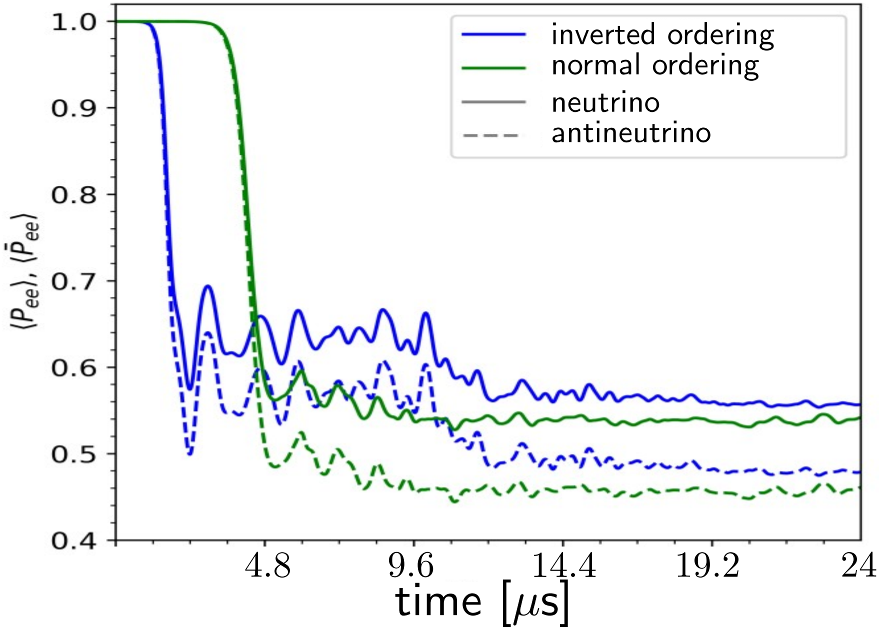
Q: Does slow flavor conversion also lead to a similar local equilibrium state?

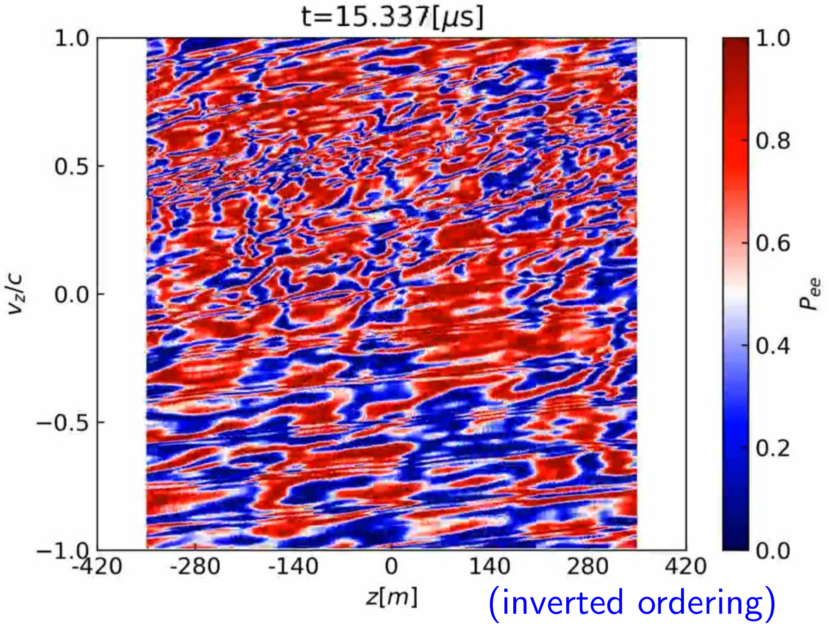
Set-up: a (small) box + perioic boundary condition + homogeneity (except for small perturbation), no $(e-\mu)$LN angular crossing

→ coarse-grained equilibration driven by phase-space kinematic decoherence also occurs within $\sim \mathcal{O}(1-10)\ (\delta m^2/(2E_\nu))^{-1}$ ∼ sub-millisecond to remove the instability

[Padilla-Gay, Chen, Abbar, MRW, Xiong, 2505.11588]

$$\alpha = n_{\bar{\nu}_e}/n_{\nu_e} = 0.85,\ E_{\nu_e} = E_{\bar{\nu}_e} = 9.5\ \mathrm{MeV},\ n_{\nu_e} \simeq 10^{29}\ \mathrm{cm}^{-3}$$





(inverted ordering)

Is this a general outcome? Can this be any useful for global transport modeling?

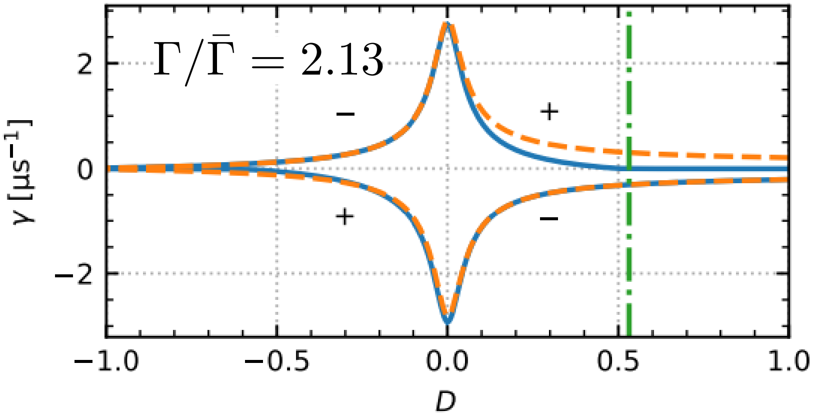
Collision-induced flavor instabilities

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

[Xiong, Johns, MRW, Duan, 2212.03750]

Asymmetry in collision rates of neutrinos and antineutrinos can curiously drive the "collisional flavor instability"

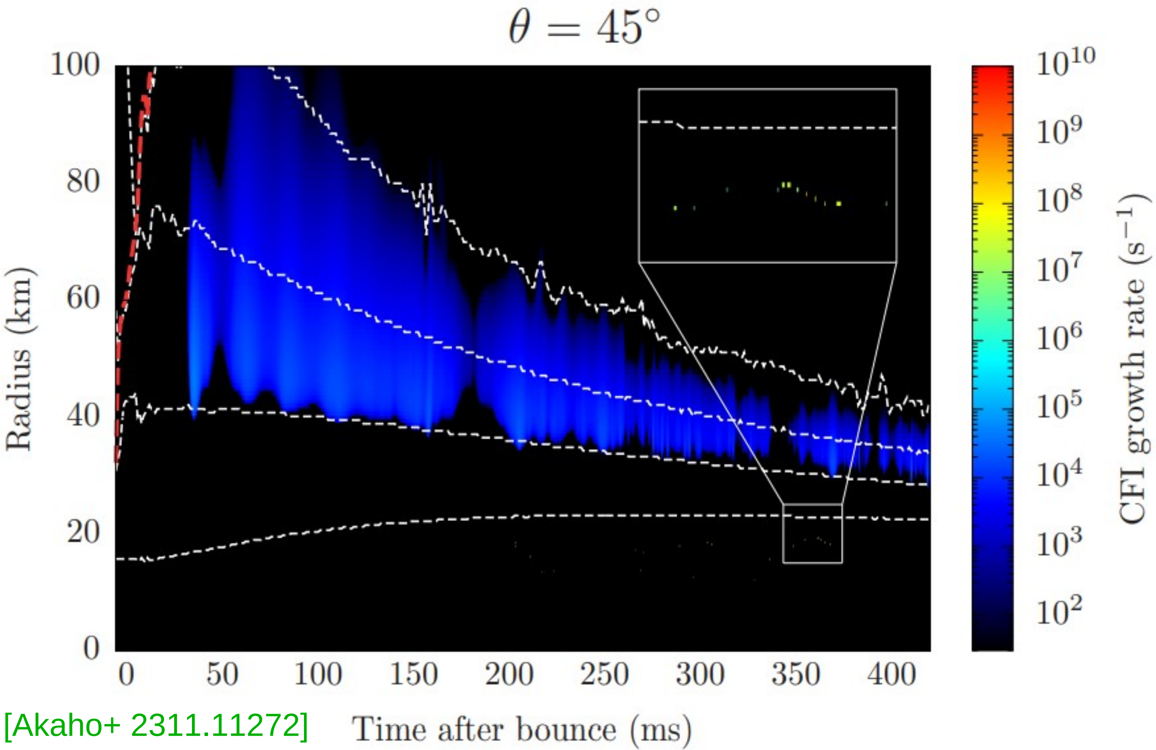
[Johns+, Xiong+, Liu+,...]



Γ: averaged neutrino emission/absorption rate

$\bar{\Gamma}$: averaged antineutrino emission/absorption rate

$D = 1 - (n_{\bar{\nu}_e} - \bar{\nu}_{\bar{\nu}_\mu})/(n_{\nu_e} - n_{\nu_x})$



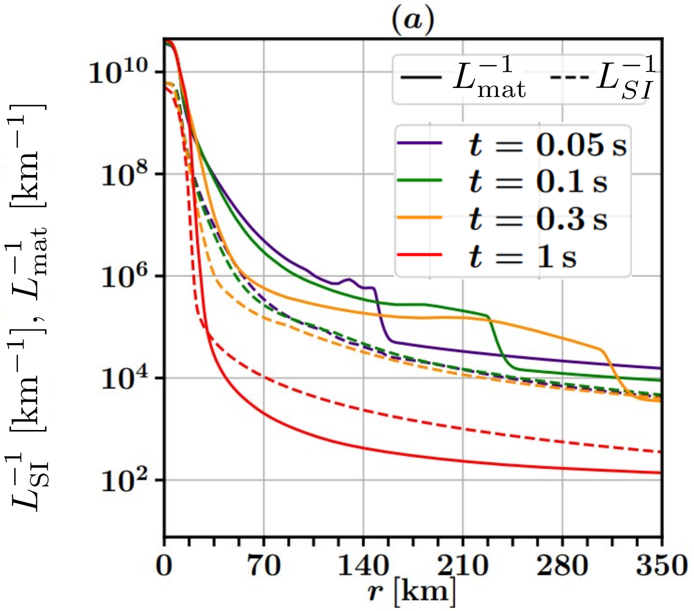
[Akaho+ 2311.11272]

the detail dynamics and relevance are under intense study

Impact of inhomogeneous matter profile

In SNe, the ν-matter forward scattering potential ($L_{\rm mat}^{-1} \sim G_F n_e$) may be $\mathcal{O}(10)$ larger than the ν-ν self-interacting potential $L_{\rm SI}^{-1} \sim G_F n_\nu$

If the spatial variation rate of λ is too large to be ignored, how does it affect flavor conversion?



[Bhattacharyya, MRW, Xiong, 2504.11316]

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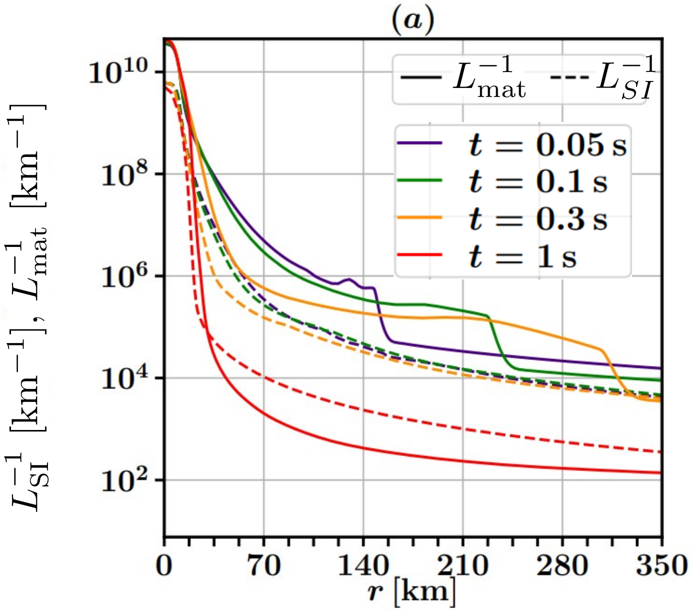
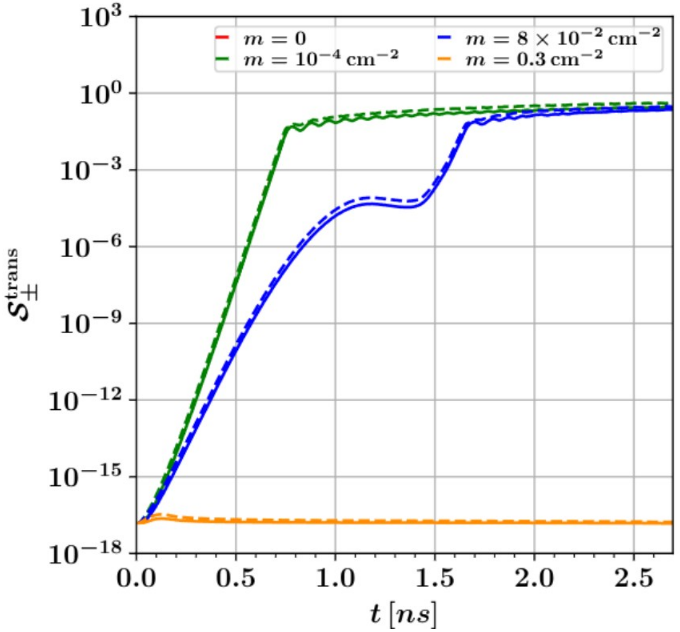


[Bhattacharyya, MRW, Xiong, 2504.11316]

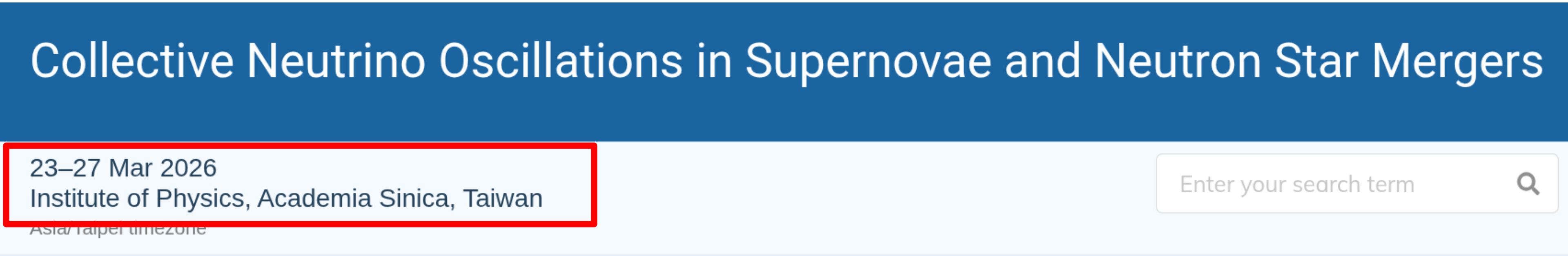
Approximating $L_{\rm mat}^{-1} \propto mr$ as a linear function, we found a critical m_c, above which the spatial dependence of $L_{\rm mat}^{-1}$ suppresses flavor conversions

$$m_c \sim \Omega(\Delta K)$$

(Ω: growth rate of flavor instability
ΔK: characteristic unstable K range in Fourier space)



$\rightarrow$ implies that the gradient of matter potential cannot be simply neglected



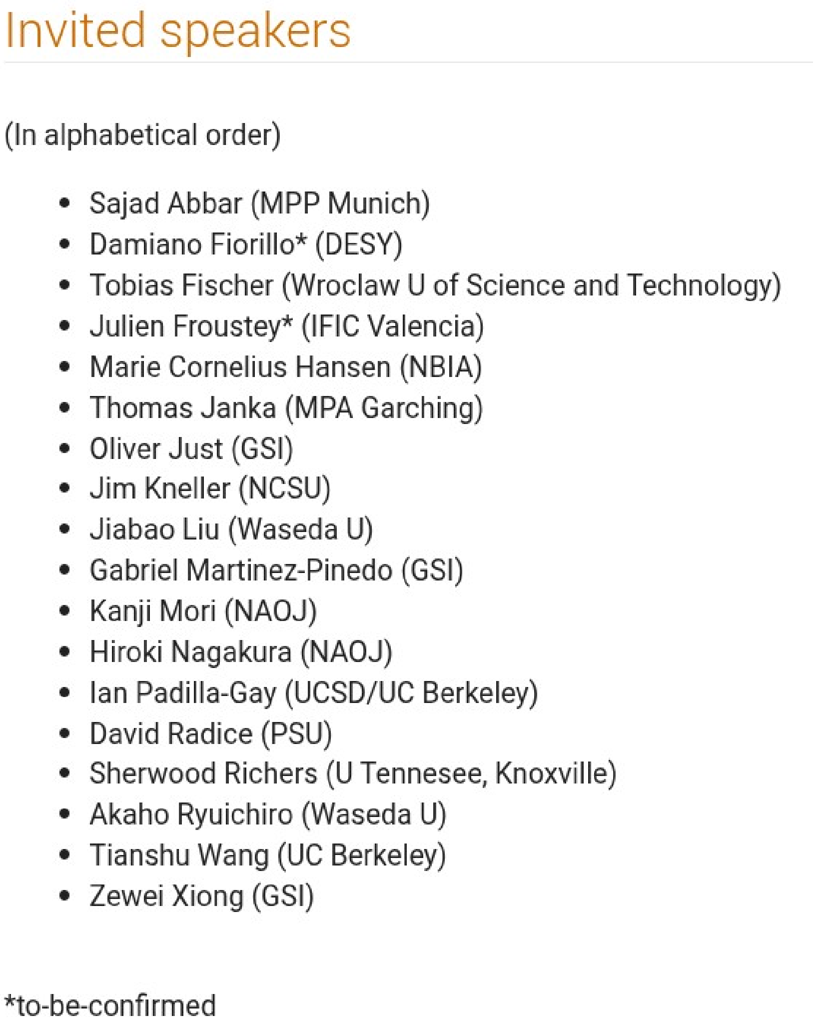
Collective Neutrino Oscillations in Supernovae and Neutron Star Mergers

23–27 Mar 2026
Institute of Physics, Academia Sinica, Taiwan
Asia/Taipei timezone

to discuss very rapid progress in this field:
– various approaches to overcome the multi-scale challenge,
– possible ways to integrate flavor conversions in hydro simulations,
– potential impact on physical observables,
– …

https://indico.phys.sinica.edu.tw/event/345/

registration deadline: Feb 8, 2026



Invited speakers

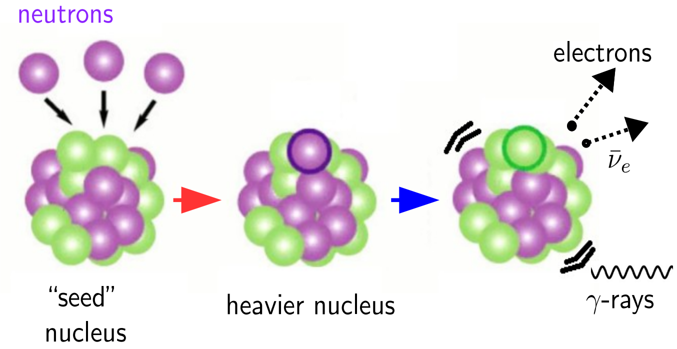
(In alphabetical order)

- Sajad Abbar (MPP Munich)
- Damiano Fiorillo* (DESY)
- Tobias Fischer (Wroclaw U of Science and Technology)
- Julien Froustey* (IFIC Valencia)
- Marie Cornelius Hansen (NBIA)
- Thomas Janka (MPA Garching)
- Oliver Just (GSI)
- Jim Kneller (NCSU)
- Jiabao Liu (Waseda U)
- Gabriel Martinez-Pinedo (GSI)
- Kanji Mori (NAOJ)
- Hiroki Nagakura (NAOJ)
- Ian Padilla-Gay (UCSD/UC Berkeley)
- David Radice (PSU)
- Sherwood Richers (U Tennesee, Knoxville)
- Akaho Ryuichiro (Waseda U)
- Tianshu Wang (UC Berkeley)
- Zewei Xiong (GSI)

*to-be-confirmed

Some topics related to r-process nucleosynthesis

r-process and their decay product



For $M_{\rm ej} \sim 0.05\ M_\odot$, the available nuclear energy amounts to $\sim 6 \times 10^{50}$ erg $\times(1 - 2Y_e^0)$

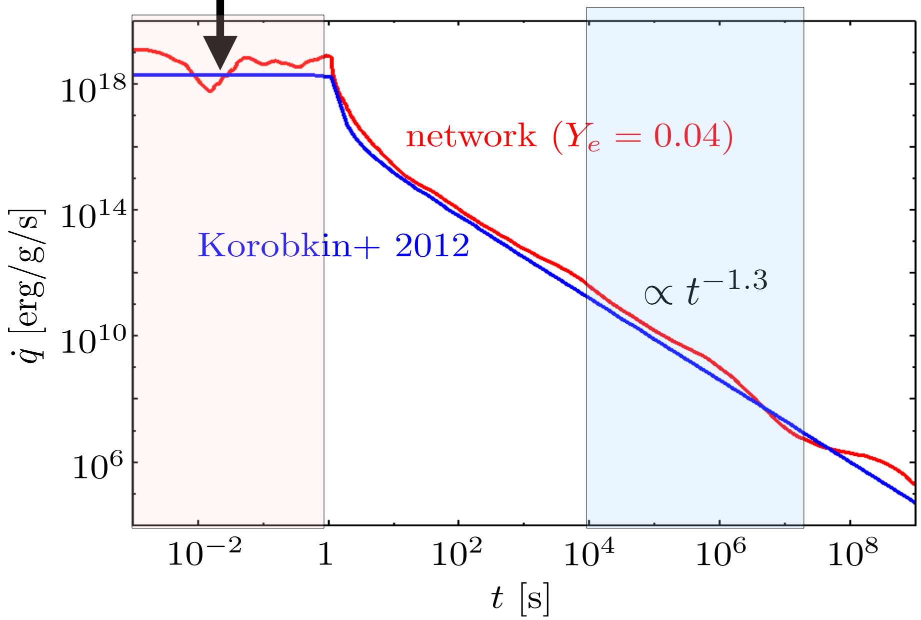
$\rightarrow$ comparable to the inferred kinetic energy of GW170817

(specific kinetic energy of $0.1c \simeq 4.5 \times 10^{18}$ erg/g)

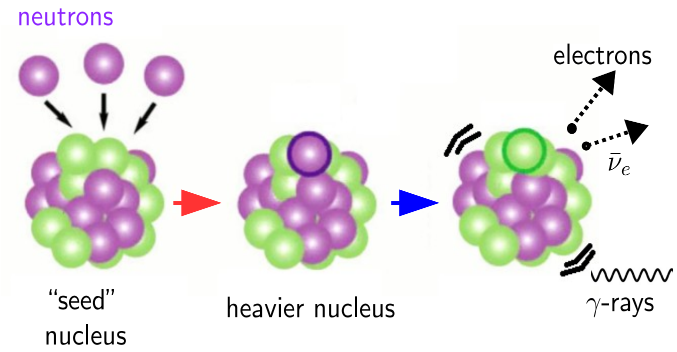
The late-time decay heating powers the kilonova emission at $\gtrsim$ days.

Q: Any potential impact at earlier times?

$\sim (1-10)$ MeV/nuc/s
during r-process



r-process and their decay product



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The late-time decay heating powers the kilonova emission at $\gtrsim$ days.

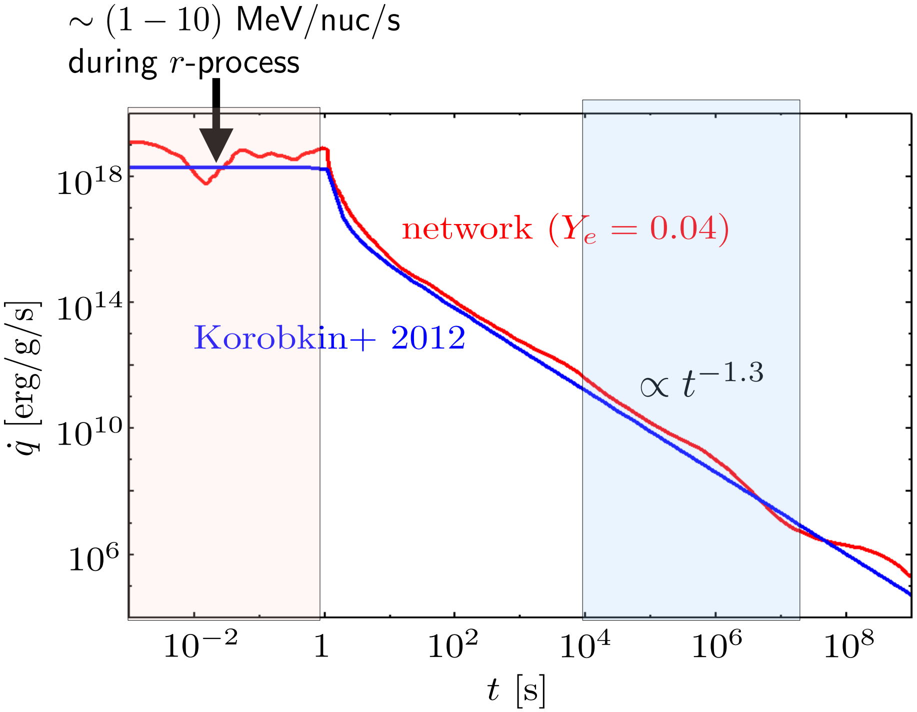
Q: Any potential impact at earlier times?

- How does the early-time nuclear energy release affect the ejecta property?

  [MRW+, Klion+, Foucart, Haddadi, Kawaguchi+, Just+, Ma+,...]

- How may decay antineutrinos affect the high-energy neutrinos co-produced at the same site?

  [Guo, Qian, MRW, 2212.08266]



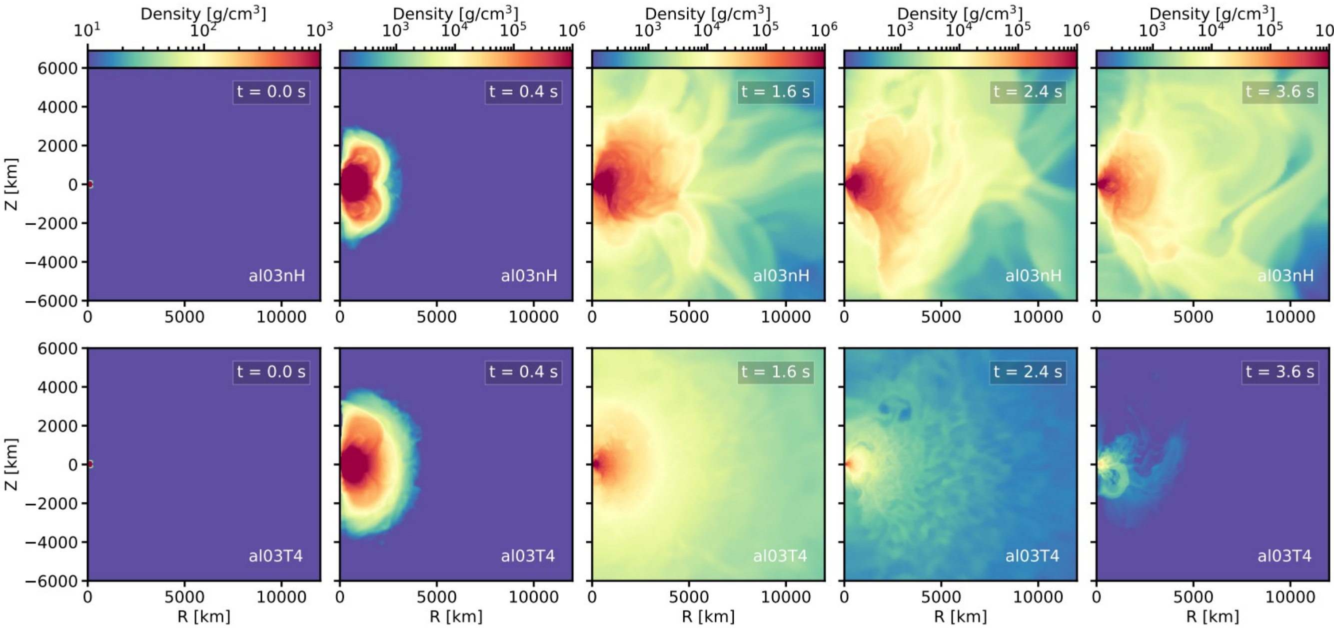
r-process heating and ejecta kinematics

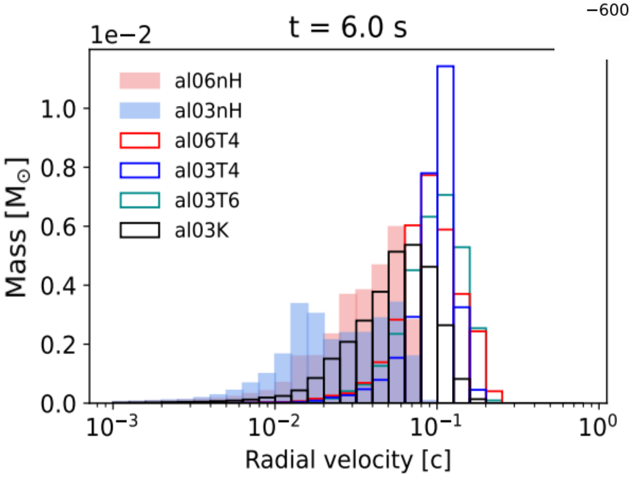
We couple a composition and temperature dependent r-process heating rate given by tracer particles with hydrodynamical simulations of post-merger black-hole accretion disks

[Ma, Pan, MRW, Fernandez, 2508.15288]

without r-process heating

with r-process heating

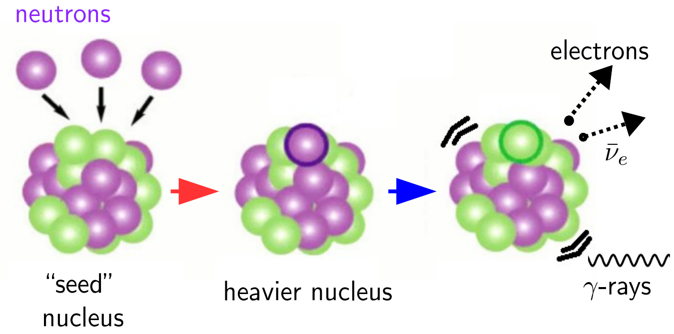




r-process heating enhances the ejecta velocity by $\sim$ a factor of 2 and mass by $\sim 10\%$

(broadly consistent with Just+ 2025; see O. Just's talk)

Annihilation of low- and high-energy neutrinos?



The decay of r-process nuclei also produce $\bar{\nu}_e$ with $E_L \sim 5 - 10$ MeV

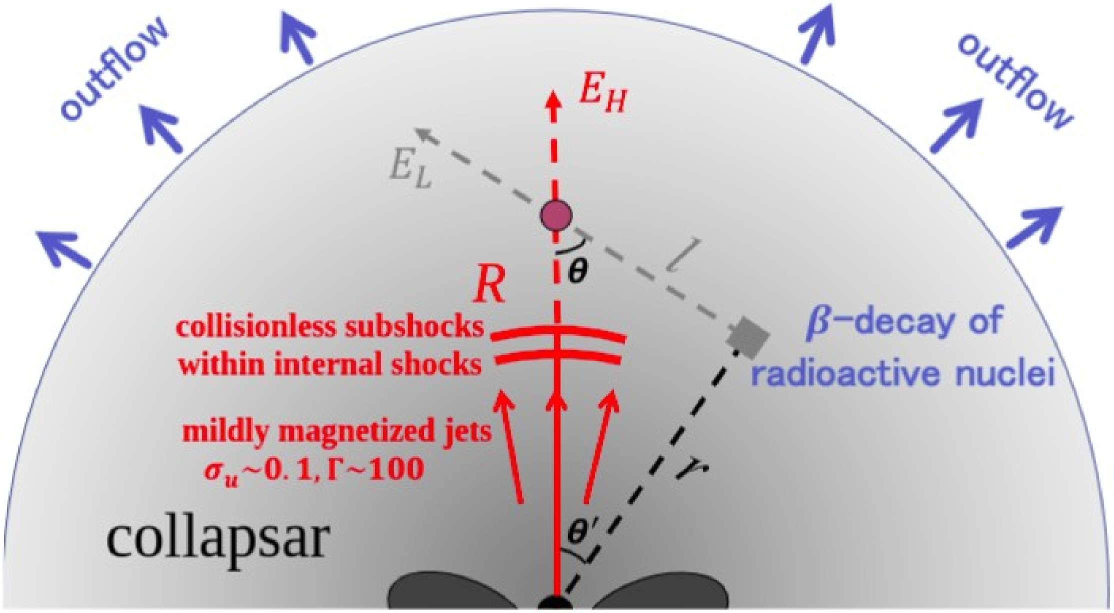
They can oscillate to different flavors and annihilate resonantly with HE neutrinos of $E_H \sim 100 - 1000$ TeV if HE neutrinos can be produced at $\sim 10^{10}$ cm

At $R \sim 10^{10}$ cm, $n_{\bar{\nu},\mathrm{LE}} \sim 10^{23}\ \mathrm{cm}^{-3} \left(\frac{\dot{M}}{0.02 M_{\odot}/\mathrm{s}}\right)\left(\frac{0.05c}{v_{\mathrm{ej}}}\right)\left(\frac{10^{10}\ \mathrm{cm}}{R}\right)^2$

With $\sigma_{\mathrm{res}} \sim 10^{-31}$ cm^2 for $2E_H E_L \simeq m_Z^2$

$\rightarrow \sigma_{\mathrm{res}} n_{\bar{\nu},\mathrm{LE}} R \gg \mathcal{O}(1)$

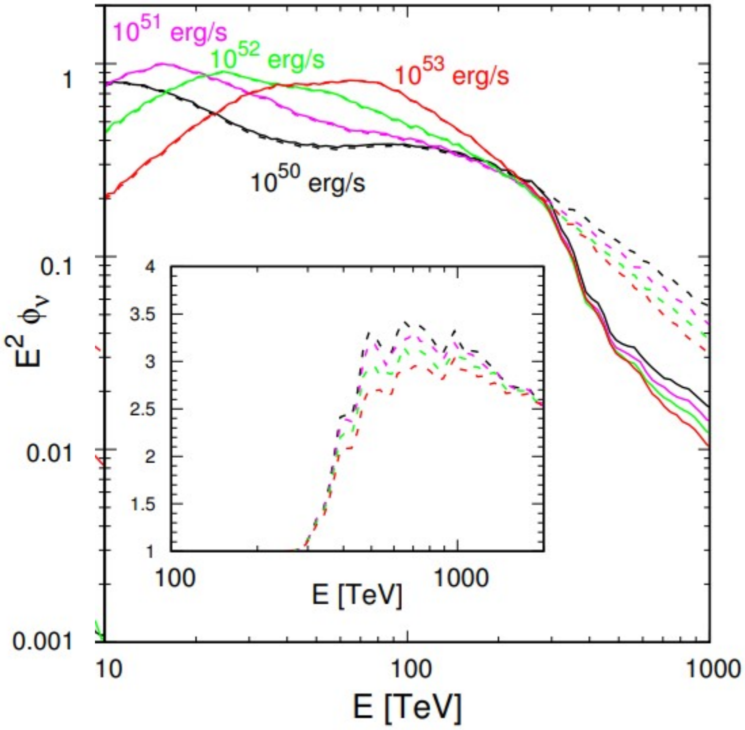
efficient annhiliation



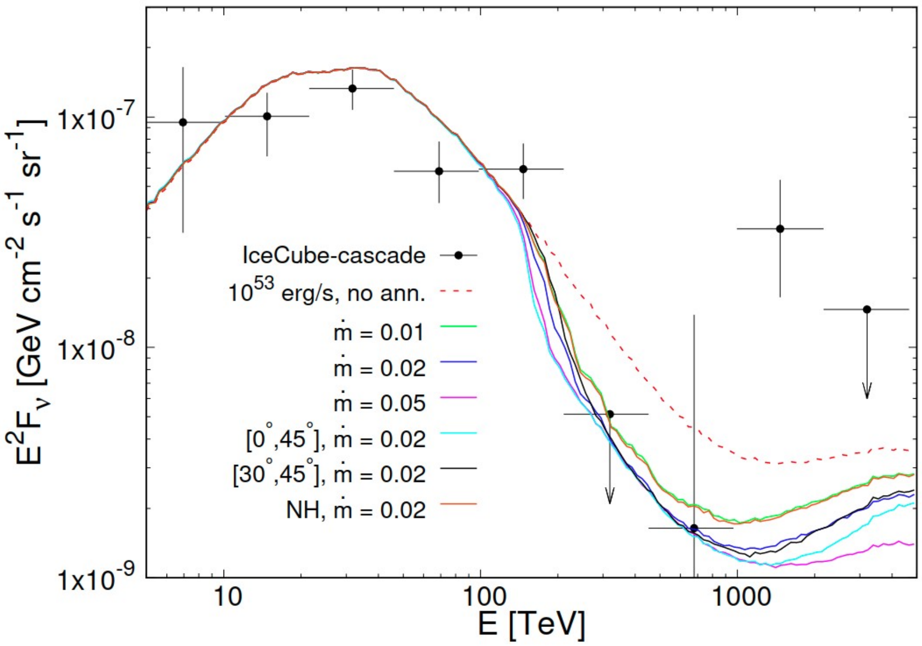
[Guo, Qian, MRW, 2212.08266]

Potential effect of ν pair annhiliation on HE ν?

For a wide range of jet power or different $\dot{M}_{\rm ej}$, annihilation can suppress the HEν flux substantially above $\sim 200 - 300$ TeV



[Guo, Qian, MRW, 2212.08266]



Can this be relevant for potential HE neutrino productions associated with mergers or other scenarios?

Take-home-messages

• Collective neutrino flavor oscillations driven by **various instabilities** can occur deep inside the supernova and neutron star merger remnants. The associated **length scale is sub-centimeter**, which makes a direct inclusion of neutrino quantum kinetic equation in astrophysical simulations challenging.

• Significant progress has been carried to not only understand the detailed **dynamics and equilibration**, but also trying to find alternative ways (probably some kind of **sub-grid models**) to overcome the multi-scale challenge.

• The r-process **decay heating** not only dominates the kilonova lightcurves at late times, but can also **affect the the ejecta property** from early times. The decay **antineutrinos** can potentially also introduce interesting **annihilation** effects, if **high-energy neutrinos** are produced close enough to the central engine.