

Neutrino Oscillations in Neutron Star Merger Simulations



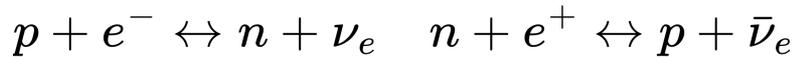
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Main points

1. Neutrino oscillations could have huge impacts on BNS merger
2. We are still very limited in terms of modeling/understanding their effects

Binary neutron star merger ejecta

- BNS mergers are major sites for rapid neutron capture (**r-process**) nucleosynthesis
- Ejecta electron fractions influenced by neutrinos through weak interactions, e.g.,

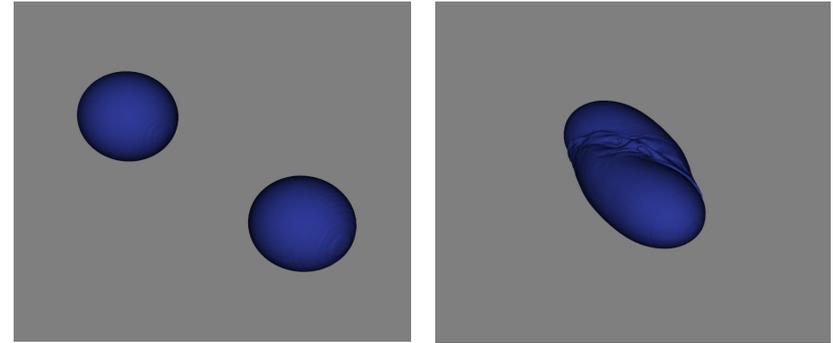


- Previous studies on **accretion disks** and **core-collapse supernovae** found that **neutrino oscillations**

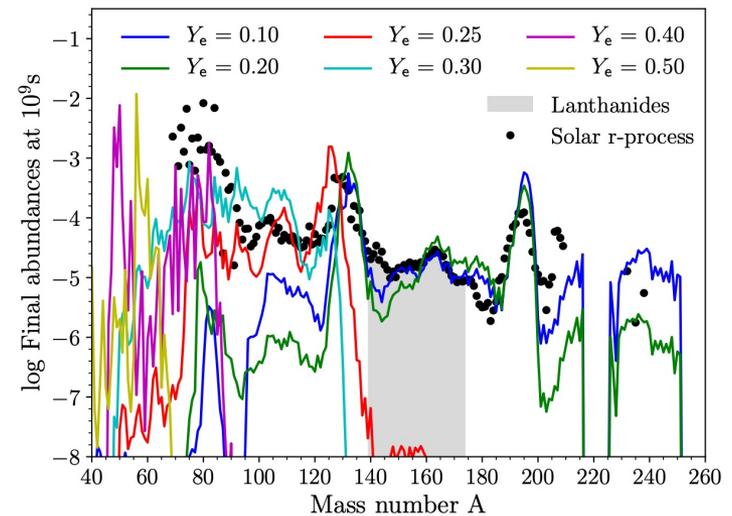
- Alter the ejecta properties
- Change nucleosynthesis yields

See Li+, Just+, Fernandez+, Ehring+, Lund+
See also in Meng-Ru, Jacob and Kyohei's talks

- Neutrino flavor conversion (FC) effect is **not** considered/understood in **dynamical phase** -> what about BNS merger from inspiral phase?



$Y_e = n_e/n_B \approx n_p/(n_p + n_n)$: electron fraction



Perego+(2021)

Fast flavor conversions in BNS

Neutrino “fast” flavor instability (FFI)

$H_{\text{neutrino}}^{-1} \sim (\sqrt{2}G_F n_{\nu_e})^{-1} \sim \mathbf{ns}$
 timescale (fast) flavor conversions

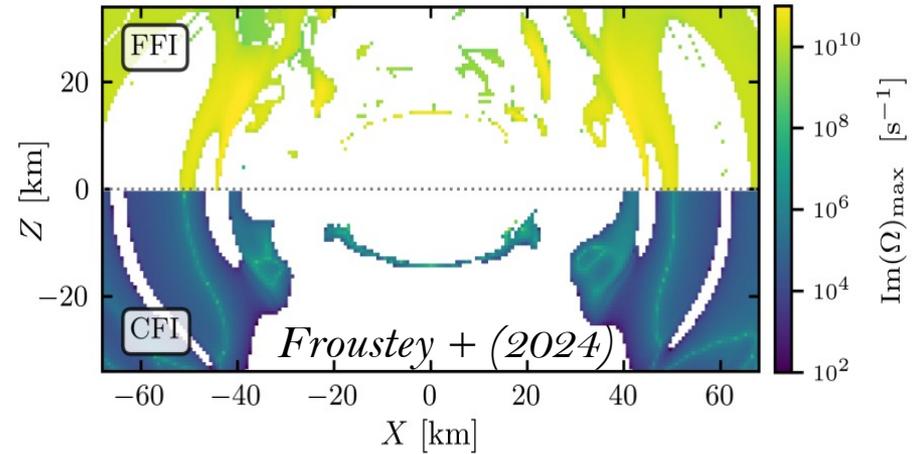
See also Sawyer, Duan+, Wu+,
 Richers+, Johns+, Tamborra+,
 Fiorillo+, Abbar+, Xiong+, Volpe

$\frac{1}{\tau_a} (f - f^a)$ relaxation time
 mixing equilibrium state

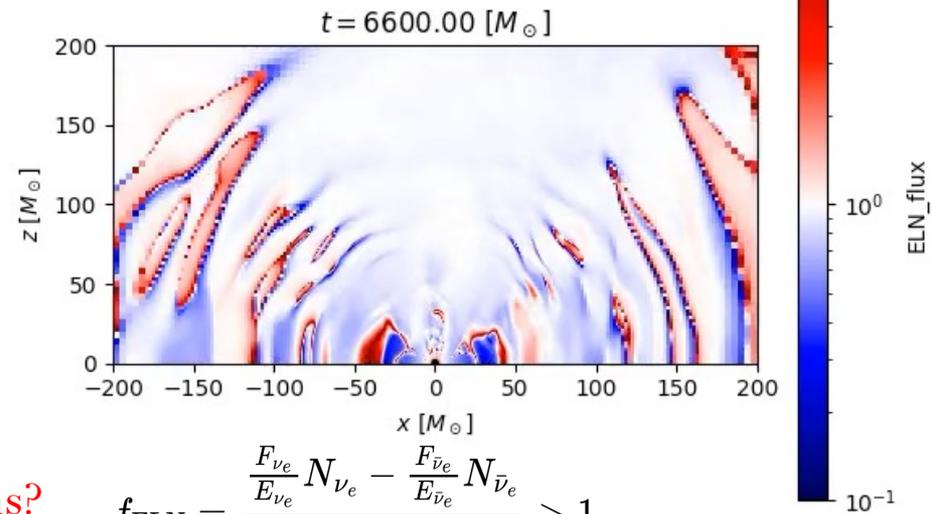
Bhatnagar-Gross-Krook (BGK)
 subgrid model

See also Nagakura+, Liu+

Where/how do we model neutrino oscillations?



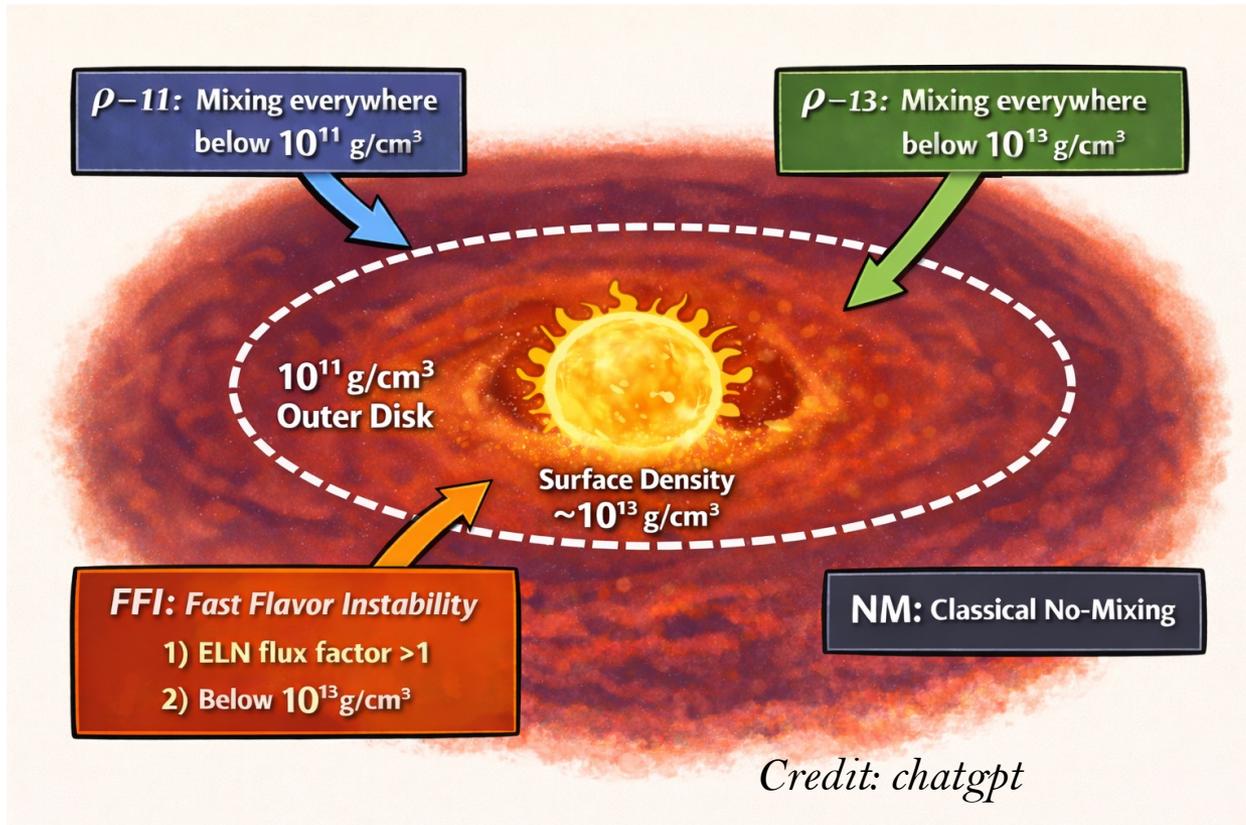
Electron lepton number (ELN) flux factor



$$f_{\text{ELN}} = \frac{\frac{F_{\nu_e}}{E_{\nu_e}} N_{\nu_e} - \frac{F_{\bar{\nu}_e}}{E_{\bar{\nu}_e}} N_{\bar{\nu}_e}}{N_{\nu_e} - N_{\bar{\nu}_e}} > 1$$

See also Abbar+, Richers

Neutrino mixing models



- Equilibrium states satisfy

- Many body (MB)

$$n_e^{\text{eq}} \bar{n}_e^{\text{eq}} = \frac{1}{4} n_x^{\text{eq}} \bar{n}_x^{\text{eq}}$$

Martin + (2023)

- Maximal mixing (MX)

$$n_e^{\text{eq}} = N/6 + N_e/2$$

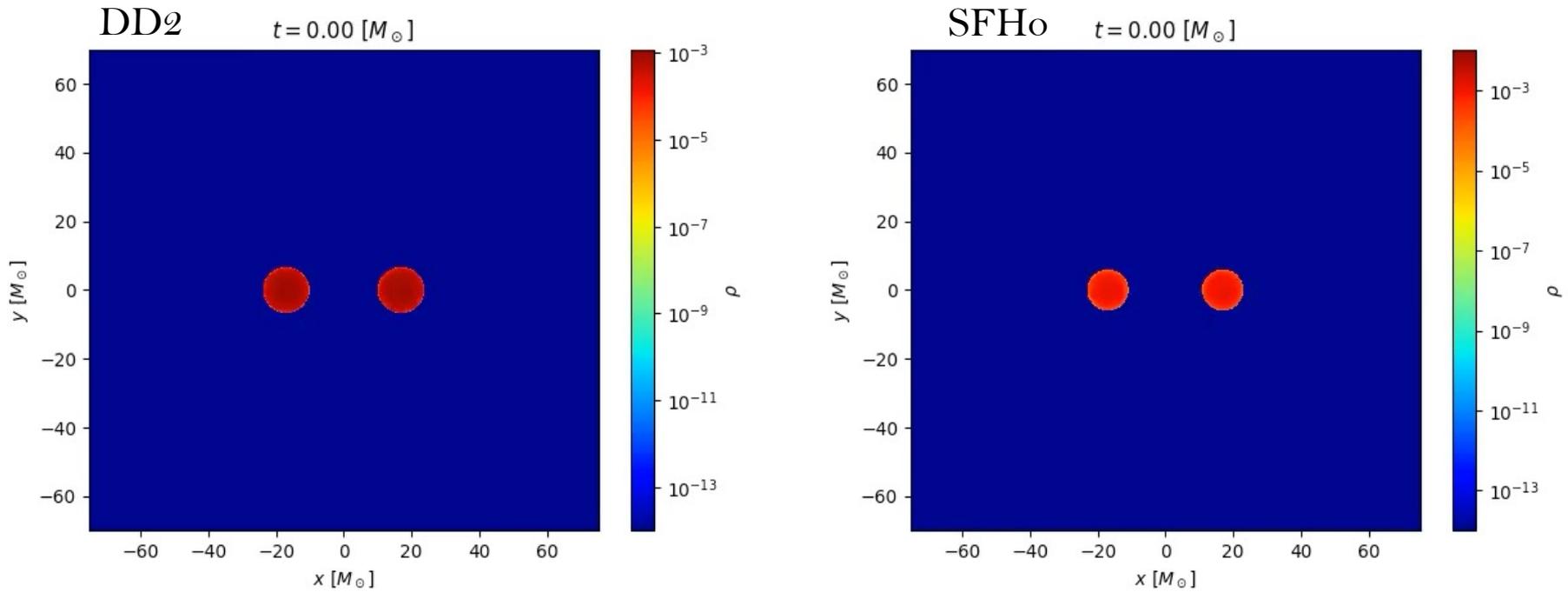
$$\bar{n}_e^{\text{eq}} = N/6 - N_e/2$$

$$n_x^{\text{eq}} = N/3 + N_x/2$$

$$\bar{n}_x^{\text{eq}} = N/3 - N_x/2$$

- 4 neutrino species, i.e., $\nu_e, \nu_x, \bar{\nu}_e, \bar{\nu}_x$
- Relaxation time: fixed at 0.5 ns (need small enough for proof-of-concept study)
- Flavor mixing **conserves** total lepton, heavy and electron lepton numbers
- FFI models use **MX**, other (density dependent) mixing models use **MB**

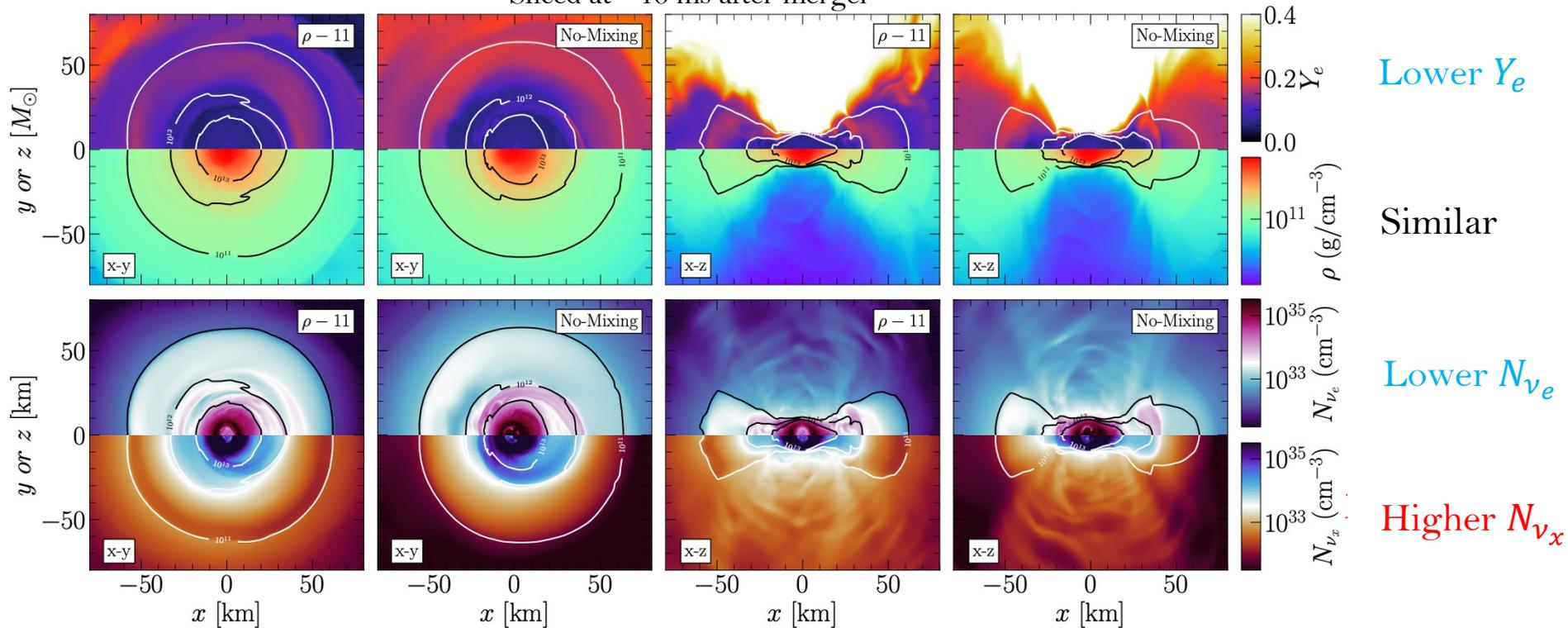
Binary neutron star merger simulations



- WhiskyTHC M1 transport + general relativistic hydrodynamics (Radice+)
- Equal mass ($1.35 M_{\odot}$) non-rotating BNS, with initial separation of 45km, run till $\sim 25\text{-}30\text{ms}$ after merger
- Two equations of state: DD2 and SFHo
- Two (low/standard) resolutions (LR/SR), with spacing 246 m/184 m
- Now let's see mixing vs. no-mixing!

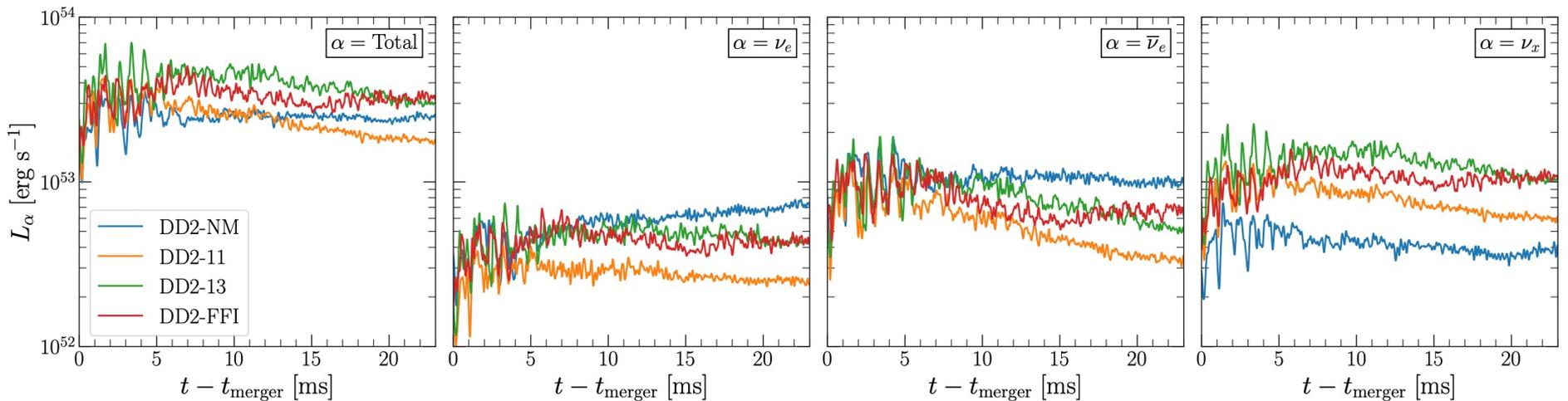
General dynamics

Sliced at ~ 10 ms after merger

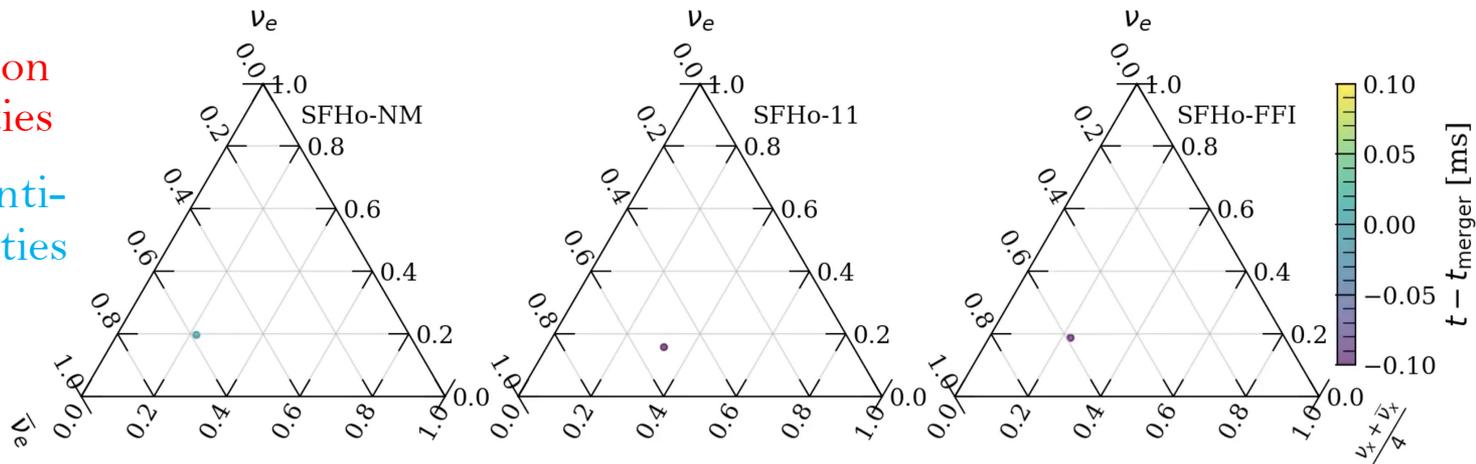


- Flavor conversions of $\nu_e, \bar{\nu}_e \rightarrow \nu_x, \bar{\nu}_x$
- What about the neutrino luminosities?

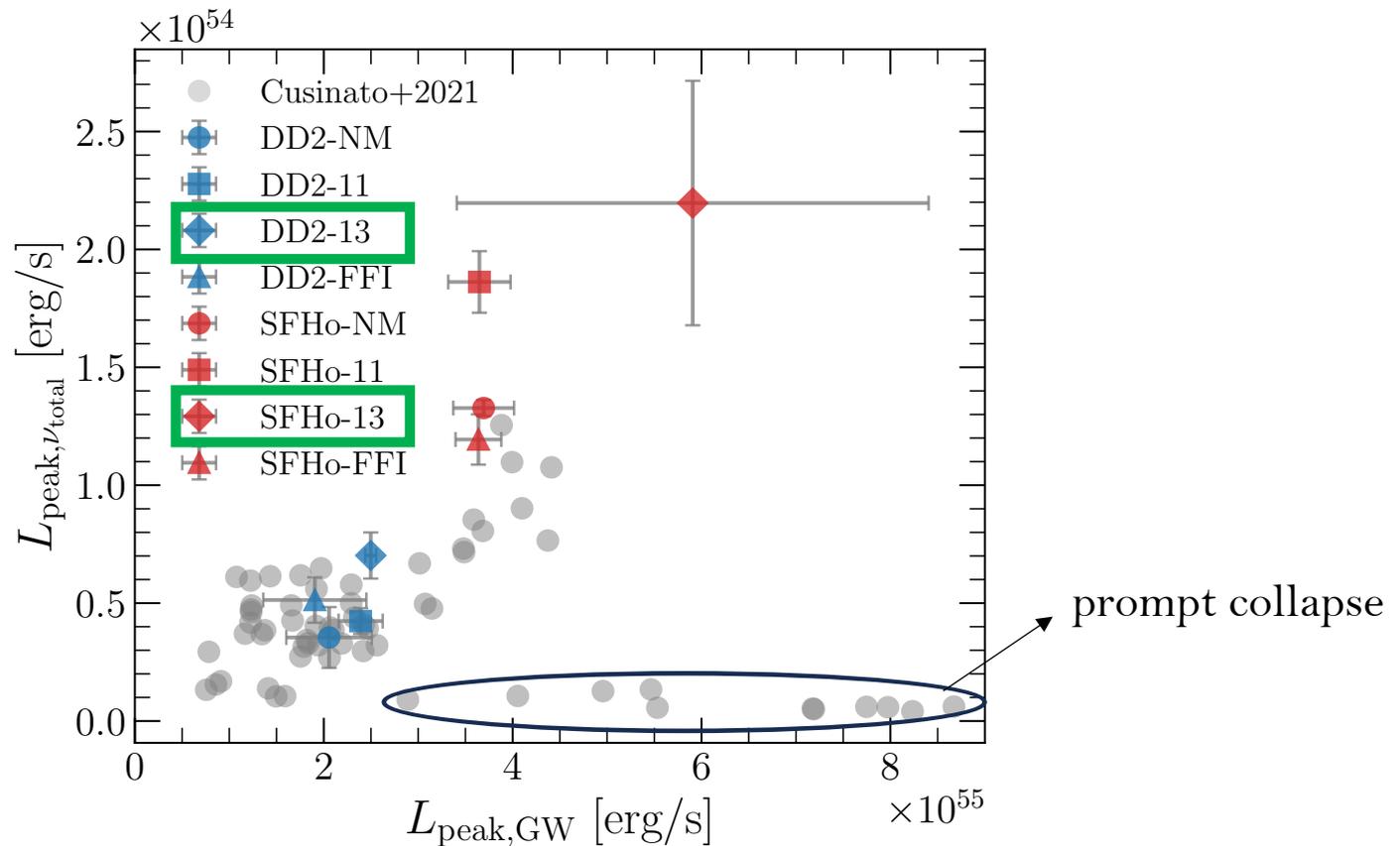
Neutrino luminosities



- Higher heavy lepton neutrino luminosities
- Lower electron (anti-)neutrino luminosities
- Final flavor distribution more “equipartition”

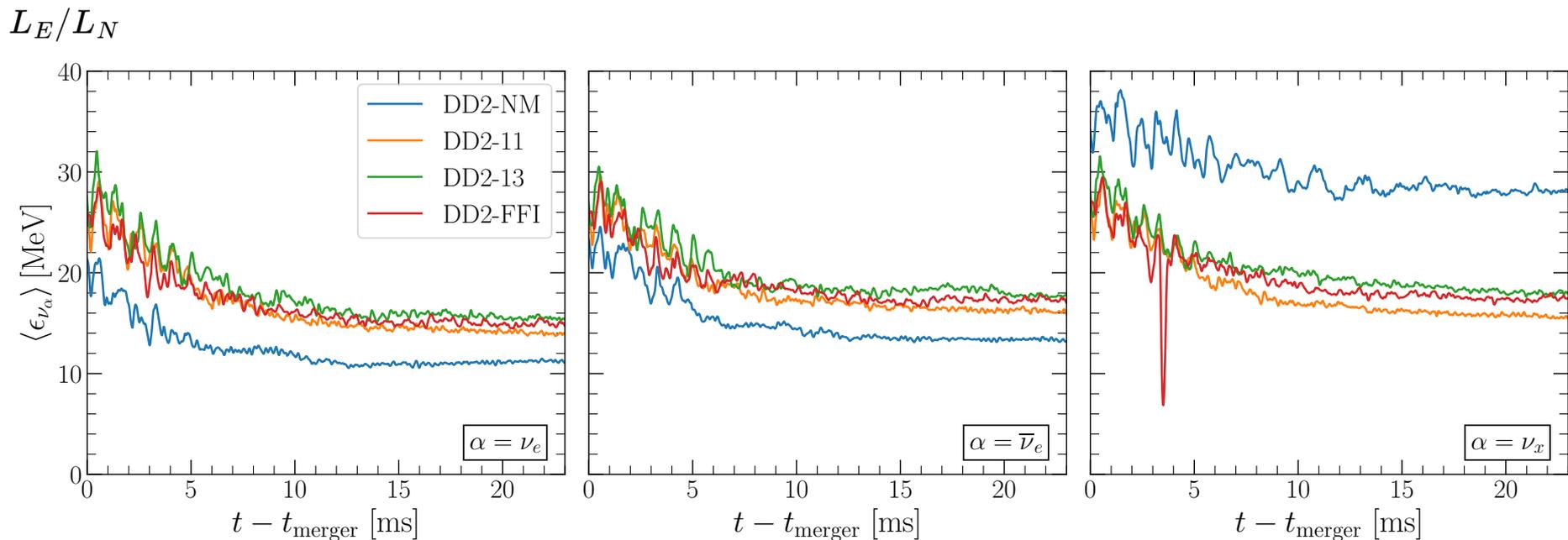


Multimessenger signatures



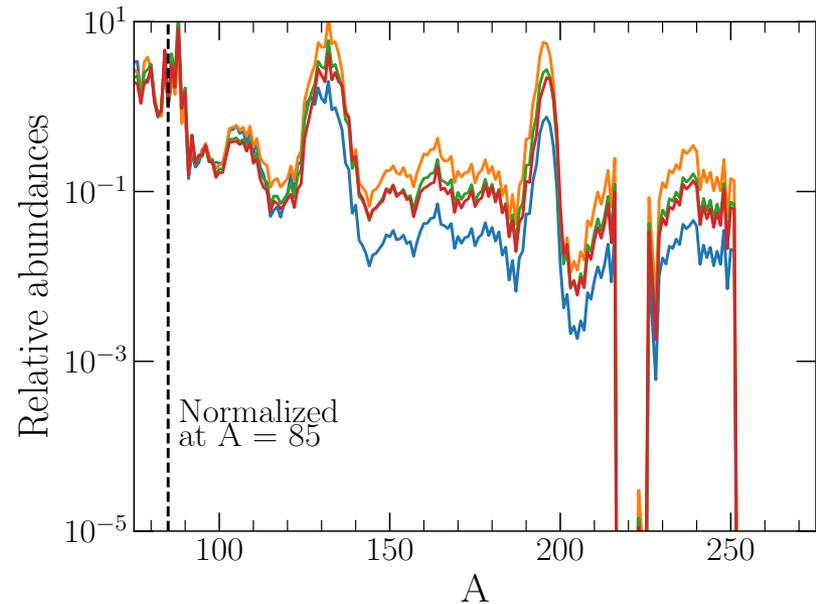
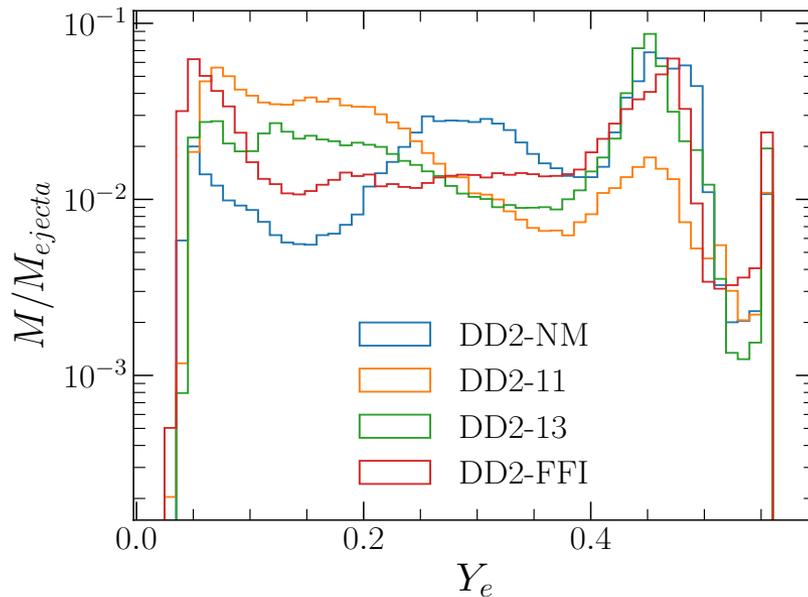
- Correlation between **neutrino** and **GW** emissions
- Flavor conversions at **high density regions** increase peak luminosities
- Next: mean energies of neutrinos?

Neutrino mean energies



- Without flavor conversions, higher ν_x , lower $\nu_e, \bar{\nu}_e$
- With flavor conversions, all flavors comparable
- Flavor mixing effectively alter the decoupling surfaces of neutrinos
- Next: ejecta properties?

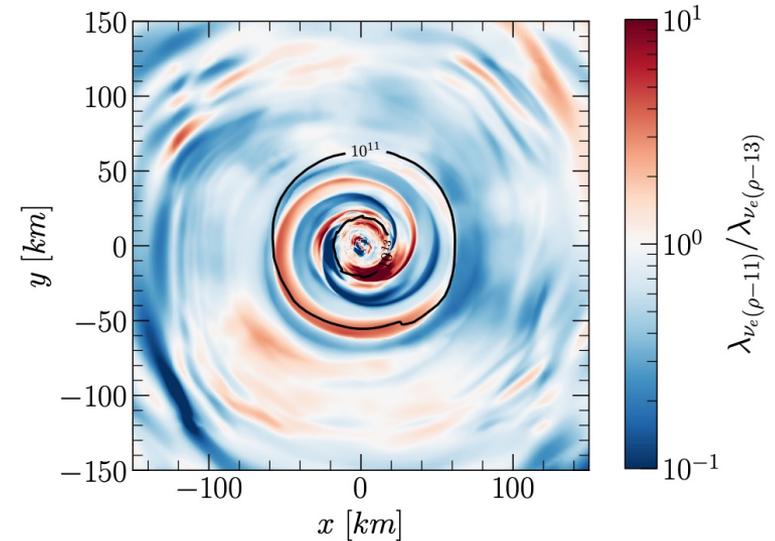
Impacts on the ejecta and nucleosynthesis



- Flavor conversions of $\nu_e, \bar{\nu}_e \rightarrow \nu_x, \bar{\nu}_x$ reduce neutrino reabsorption $\nu_e + n \rightarrow p + e^-$
- Flavor conversions \rightarrow up to **5 times more very neutron-rich** ($Y_e < 0.15$) material in dynamical ejecta, **approximately 200% to 1000% more heavy element synthesis**
- Exceed the reported $\sim 30\%$ numerical uncertainties in Foucart+(2024)
- Next: why different flavor mixing conditions lead to quantitatively different results?

Comparisons of different mixing conditions

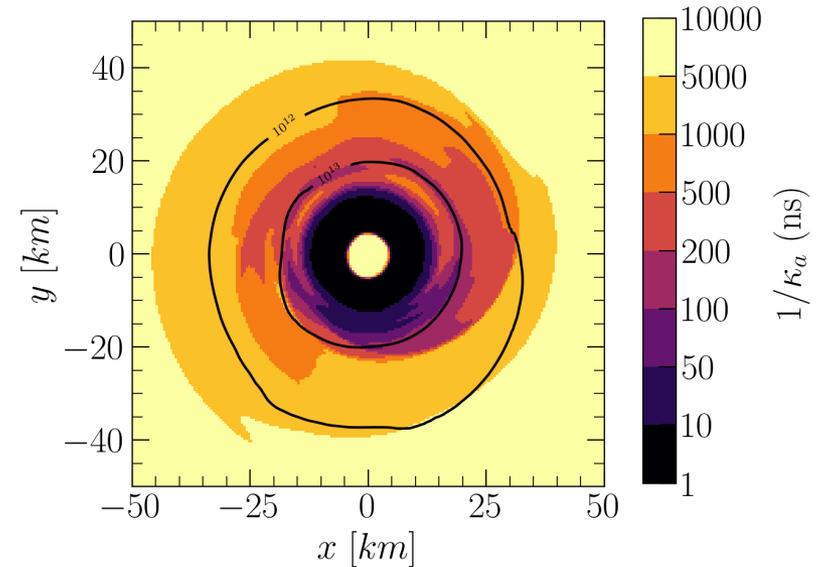
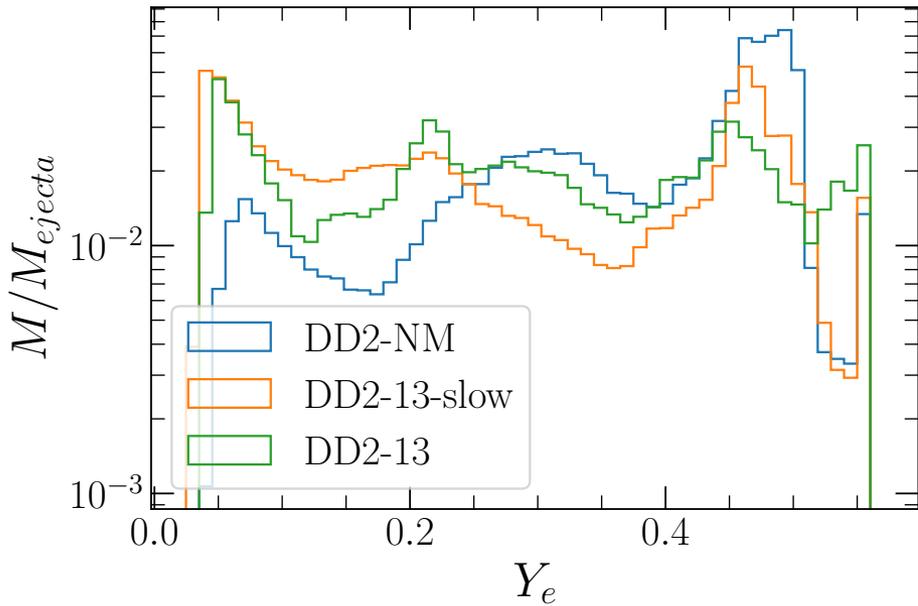
- Why $\rho - 11$ more neutron rich than $\rho - 13$?
- **Inner disk** (between 10^{11} and 10^{13} g/cm³)
 - $\nu_e, \bar{\nu}_e \rightarrow \nu_x, \bar{\nu}_x$
 - $\nu_e, \bar{\nu}_e$ trapped, $\nu_x, \bar{\nu}_x$ optically thin
- **Outer disk** (below $\rho = 10^{11}$ g/cm³)
 - Some $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$
 - More $\nu_e + n \rightarrow p + e^-$
 - Less neutron rich ejecta



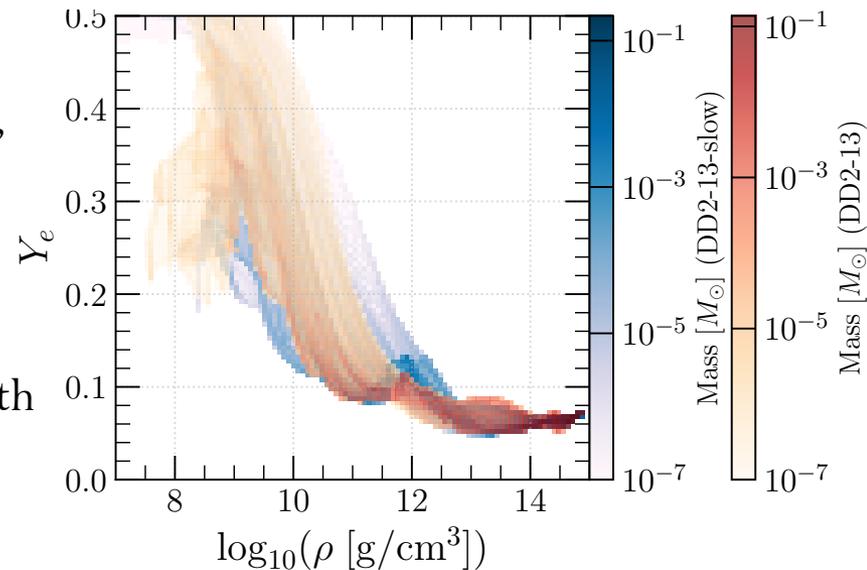
$$\frac{dY_e}{dt} = \lambda_{\nu_e}(1 - Y_e) - \lambda_{\bar{\nu}_e}Y_e \approx \lambda_{\nu_e}$$

Y_e in $\rho - 13$ increase faster!

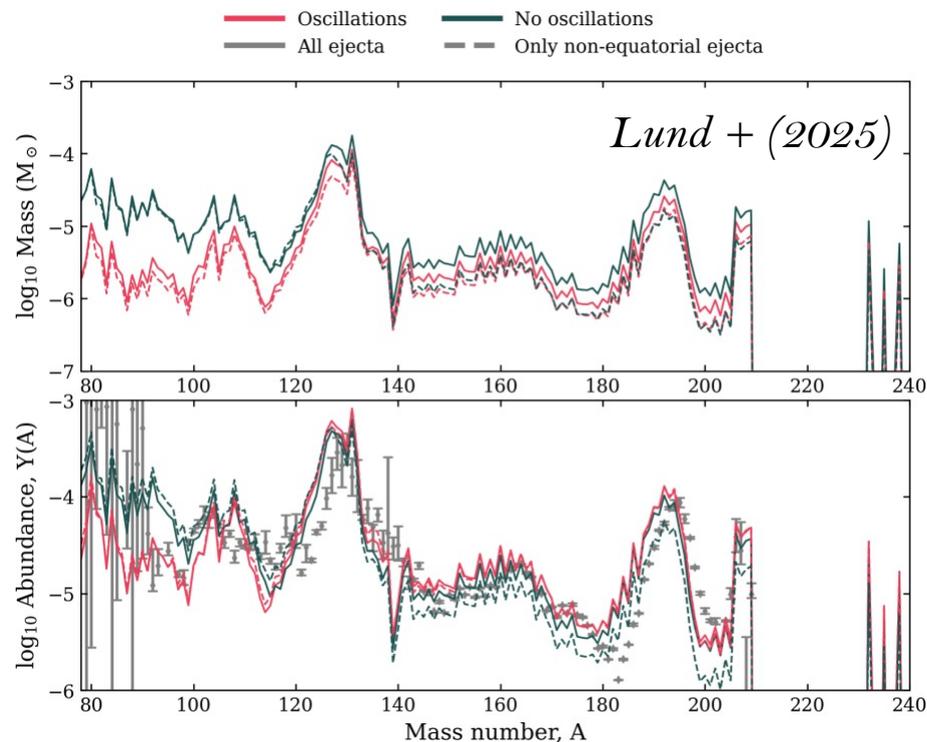
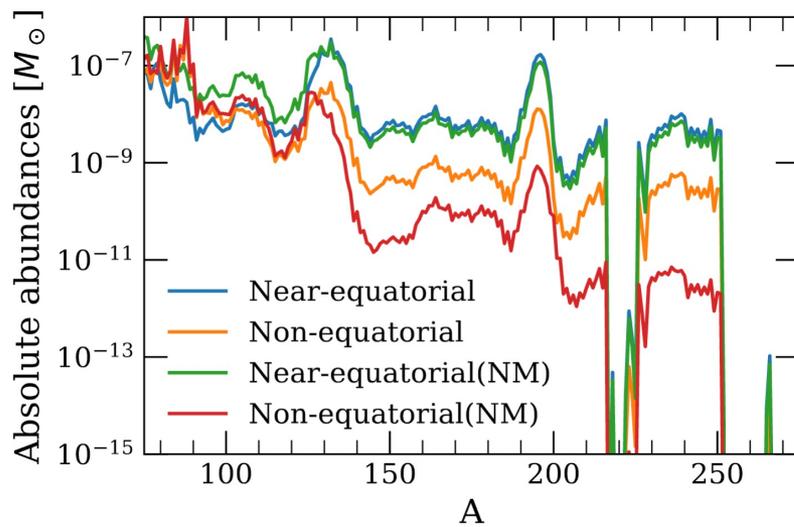
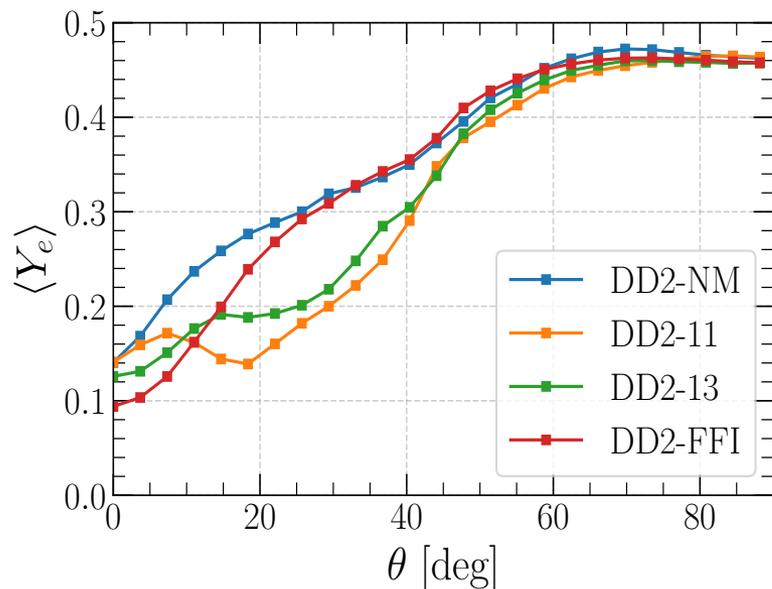
Comparisons of different relaxation times



- DD2-13-slow uses **50 ns** flavor relaxation time, **100x** than the default 0.5 ns used in DD2-13
- Slower flavor equilibration model's ejecta more neutron rich than that of DD2-13?
- Flavor conversions at **high density** compete with thermodynamics



Angular dependence



- Materials **near equatorial plane** and intermediate latitudes show **larger** differences between no-mixing and mixing simulations
- Substantial differences in **polar regions** also, however it is not the main contribution to the boost in r-process

Takeaways

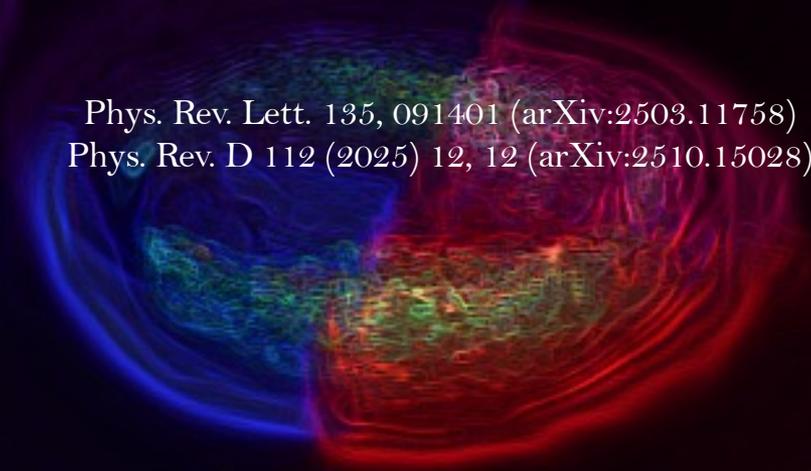
- Neutrino flavor conversions change the neutrino luminosities, mean energies and **flavor hierarchy**, and increase the **neutrino** and **GW peak luminosities**. Neutrino flavor conversions, give rise to a **more neutron rich** dynamical ejecta and **boost the heavy element** production
- *Where* and *how* neutrino flavor conversion happens change the results quantitatively -> we need better theoretical understanding to model them!

Limitations/Future work

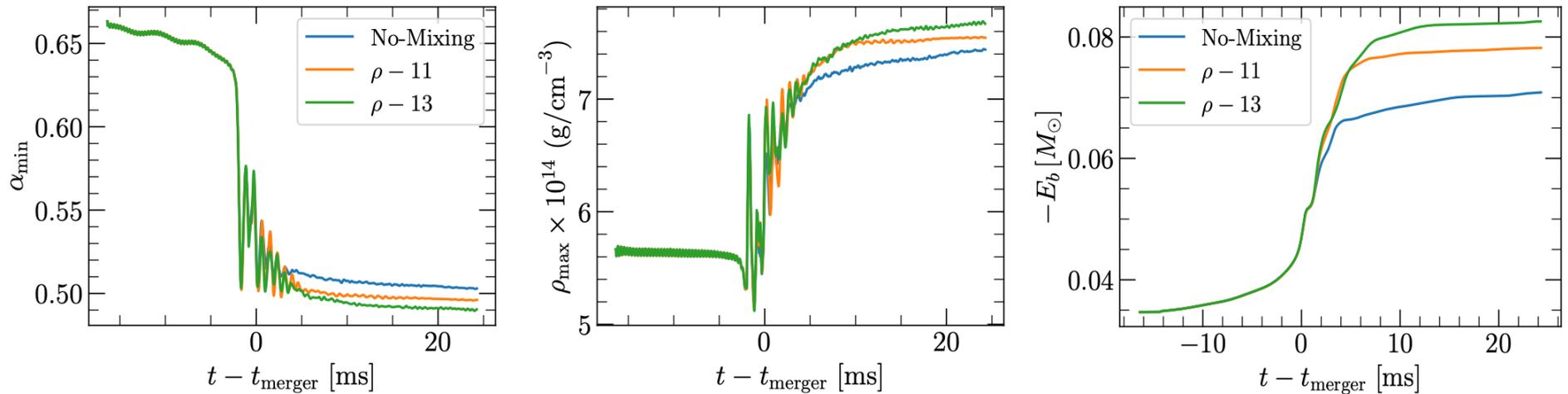
- Neutrino mixing
 - Better modeling? (see Richers+2024, Abbar+2024, Johns+2025, Lund+2025, Laraib+2025, Urquilla+2025)
- Microphysics
 - Muonic interactions? (see Gieg+2024, Pajkos+2024, Ng+2024)
 - Pair processes and inelastic scattering (see Cheong+2024, Chiesa+2024, Kawaguchi+2025)
- Magnetic field
 - Affect dynamics? (see Bamber+2024, Jiang+2025, Most+2025)
 - Change **neutrino opacities**? (see Kumamoto+2025)
- Equation of states
 - Phase transition in the cores? (see Prakash+2023)
- CPU --> GPU (potentially 10x speed up!)
 - **AthenaK (open-source)** (see Fields+2025, Zhu+2025)

Thank you!

Phys. Rev. Lett. 135, 091401 (arXiv:2503.11758)
Phys. Rev. D 112 (2025) 12, 12 (arXiv:2510.15028)

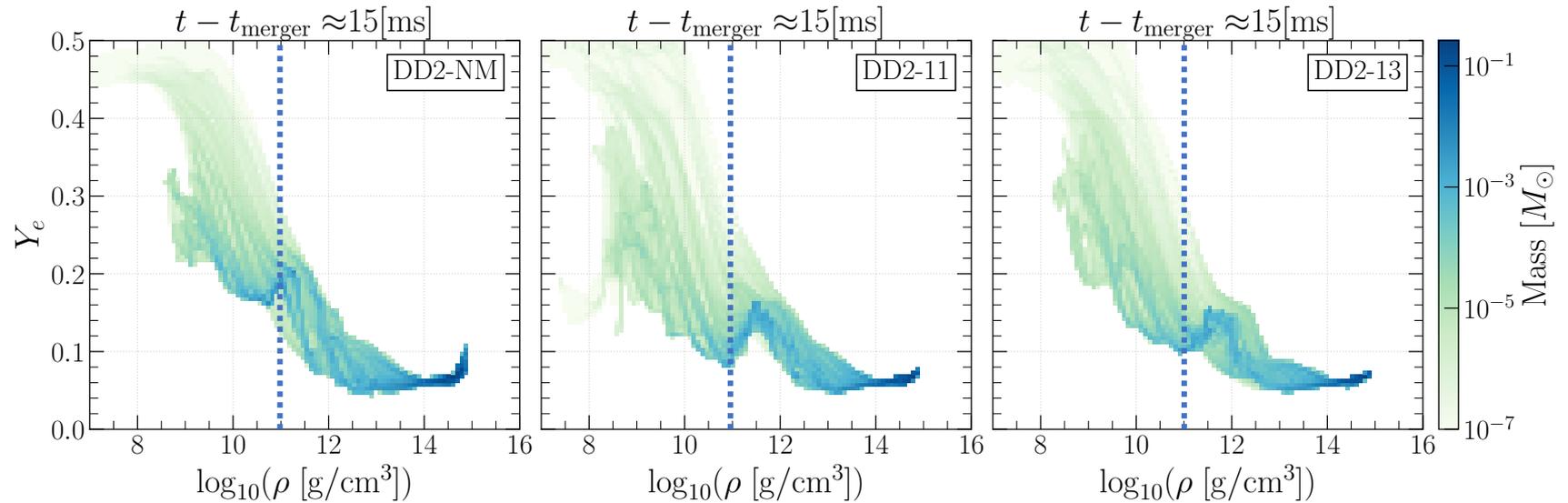


Impacts on the remnants



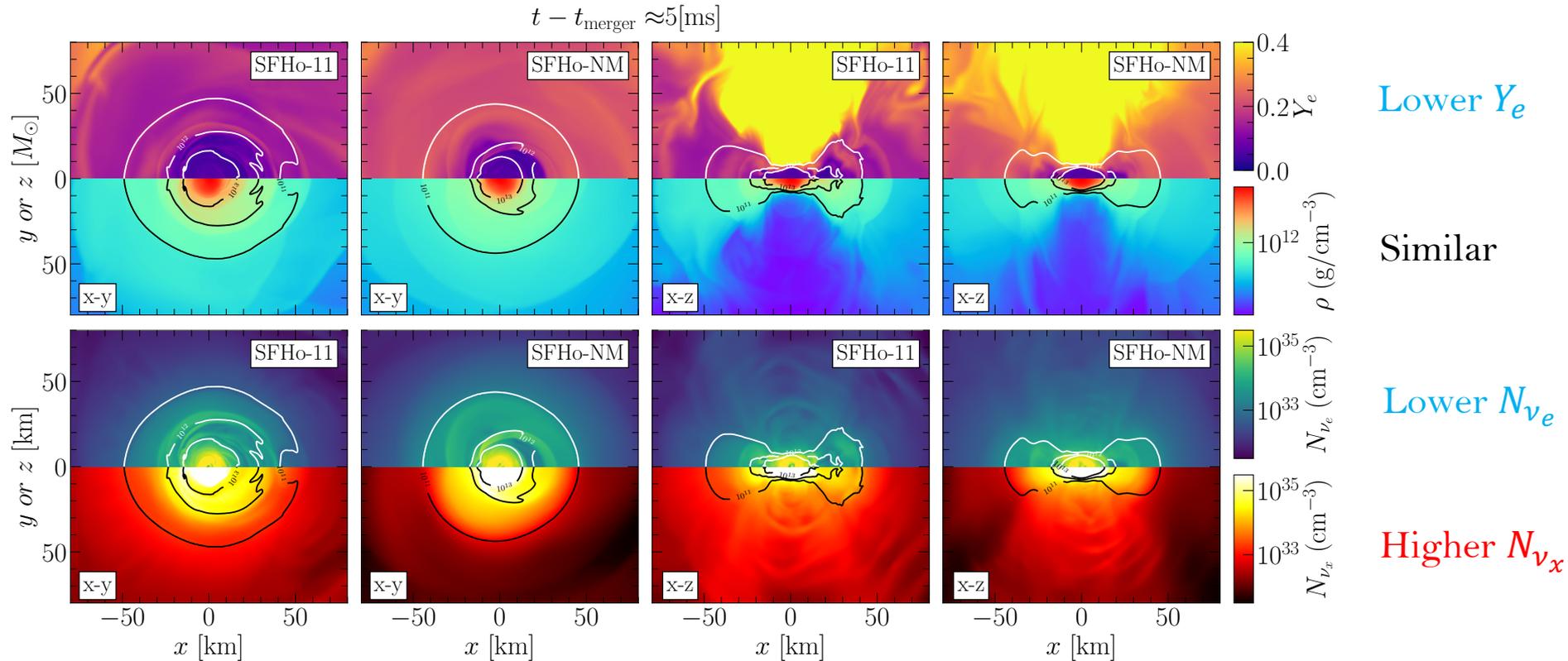
- More neutrino mixings \rightarrow **more compact** remnants
- Flavor conversions alter electron type neutrinos number \rightarrow affect convection \rightarrow **higher GW binding energy** (also seen in Ehring et al. 2024)

Density dependence



- Difference between no-mixing and mixing models mainly appear at **low density** regions (below 10^{11} g/cm^3)

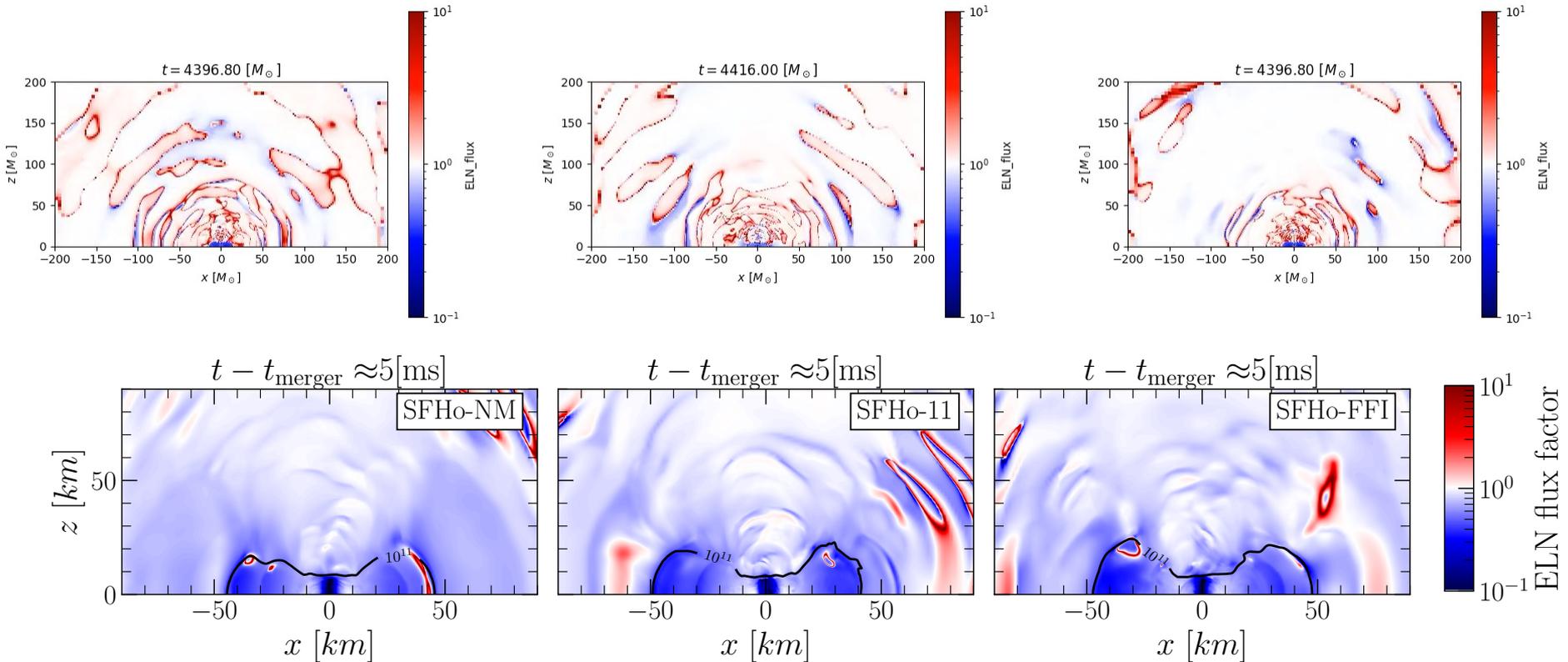
General dynamics (SFHo)



- Flavor conversions of $\nu_e, \bar{\nu}_e \rightarrow \nu_x, \bar{\nu}_x$
- Next: observational characteristics?

Fast flavor instability

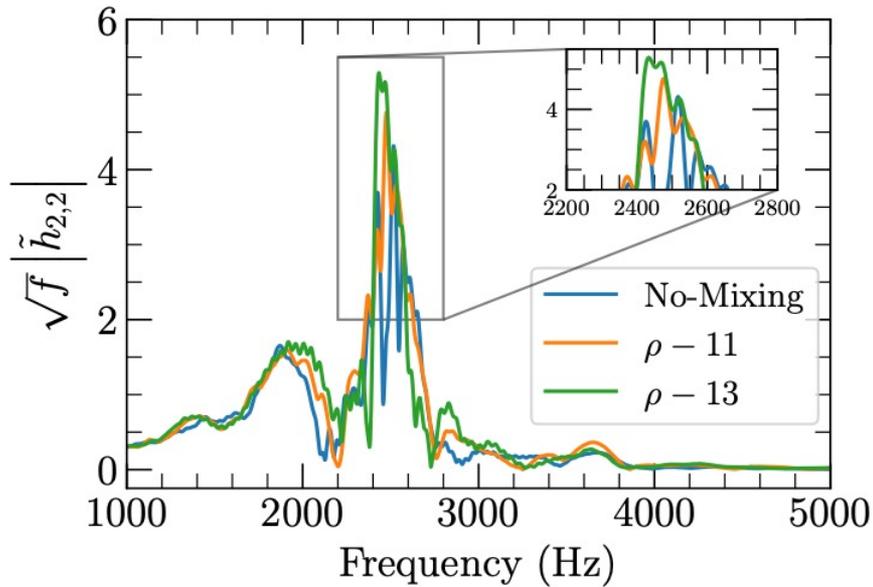
Remnant collapses at $\sim 7000 M_{\odot}$



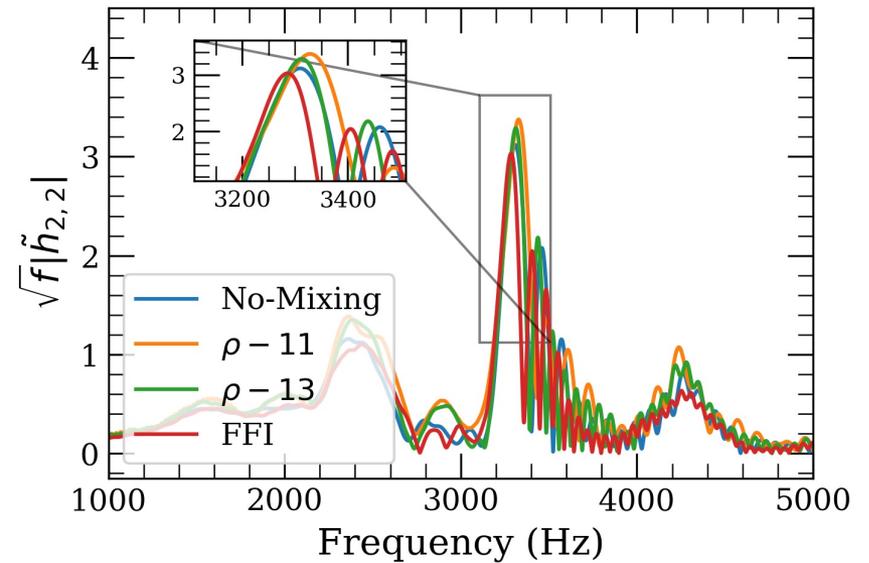
- ELN flux factor represents instabilities
- Fast flavor conversion instability targeted model still shows instabilities
- Dynamical effects like advections possibly regenerate the instabilities rapidly

Changes in gravitational waves

DD2



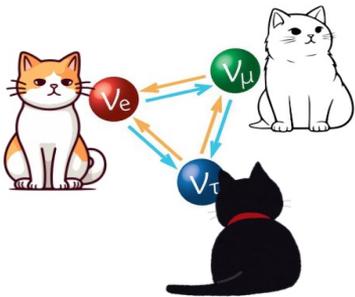
SFHo



- Frequency discrepancy up to 100 Hz

Neutrino mixing

What about neutrino **flavor mixing** (oscillation/conversion/transformation)?



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Master (Boltzmann) equation in matter

$$\frac{d\rho}{dt} = -i[H, \rho] + S, \quad \rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

Here ρ is the density matrix, S is the collisional term, the Hamiltonian is often decomposed as

$$H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{neutrino}}.$$

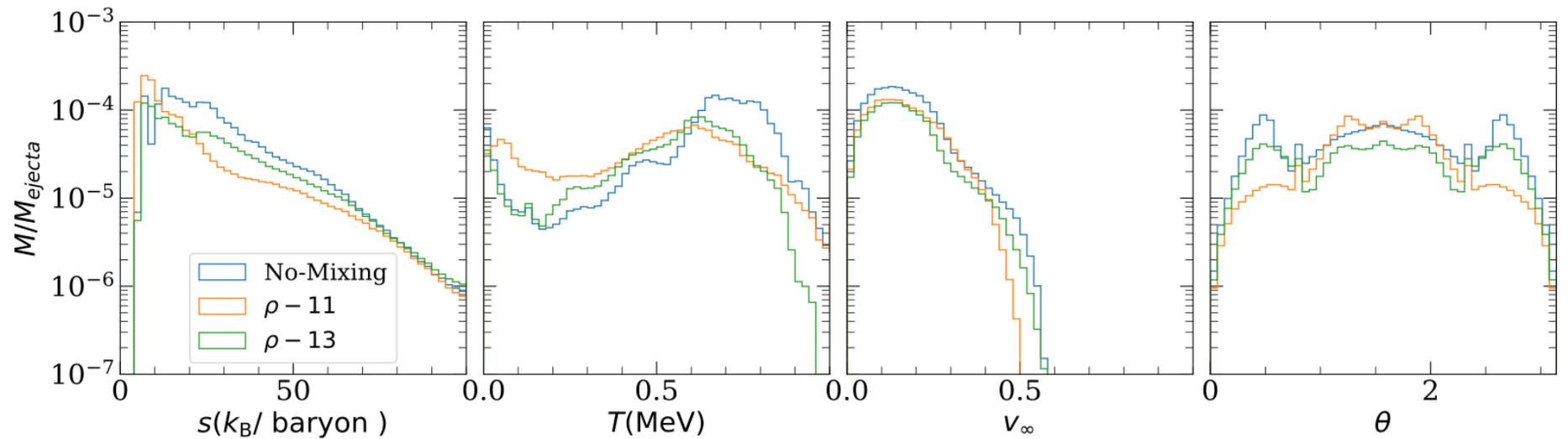


Credit: Richers (2021)

Impacts on the ejecta and nucleosynthesis

Simulation	Resolution	EoS	ρ_{mixing} [g/cm ³]	τ_a [ns]	Prescription	$t_{\text{coll}} - t_{\text{merg}}$ [ms]	$M_{\text{total}}^{\text{ej}}$ [10 ⁻² M_{\odot}]	$M_{Y_e < 0.25}^{\text{ej}}/M_{\text{total}}^{\text{ej}}$ [%]	$M_{Y_e < 0.15}^{\text{ej}}/M_{\text{total}}^{\text{ej}}$ [%]	v_{∞} [c]
DD2-NM	LR	DD2	–	–	–	–	0.1730	20.88	10.22	0.1530
DD2-11	LR	DD2	10 ¹¹	0.5	MB	–	0.1480	59.45	28.29	0.1704
DD2-13	LR	DD2	10 ¹³	0.5	MB	–	0.08940	43.38	22.99	0.1673
DD2-FFI	LR	DD2	10 ¹³	0.5	MX	–	0.08761	25.84	17.60	0.1617
DD2-13-slow	LR	DD2	10 ¹³	50.0	MB	–	0.1351	52.32	31.36	0.1714
DD2-NM	SR	DD2	–	–	–	–	0.2096	22.40	10.44	0.1657
DD2-11	SR	DD2	10 ¹¹	0.5	MB	–	0.1676	71.19	39.50	0.1608
DD2-13	SR	DD2	10 ¹³	0.5	MB	–	0.1312	43.22	23.40	0.1631
DD2-FFI	SR	DD2	10 ¹³	0.5	MX	–	0.1077	43.23	30.71	0.1888
SFHo-NM	LR	SFHo	–	–	–	10.26	0.6900	39.51	10.19	0.2267
SFHo-11	LR	SFHo	10 ¹¹	0.5	MB	8.215	0.5420	77.85	40.82	0.2082
SFHo-13	LR	SFHo	10 ¹³	0.5	MB	14.55	0.4517	69.62	39.27	0.2189
SFHo-FFI	LR	SFHo	10 ¹³	0.5	MX	17.27	0.5387	38.71	8.703	0.2345
SFHo-NM	SR	SFHo	–	–	–	8.078	0.5889	46.72	17.52	0.2102
SFHo-11	SR	SFHo	10 ¹¹	0.5	MB	11.15	0.4244	67.95	32.14	0.2239
SFHo-13	SR	SFHo	10 ¹³	0.5	MB	5.513	0.5252	74.89	38.70	0.2517
SFHo-FFI	SR	SFHo	10 ¹³	0.5	MX	5.607	0.6885	65.76	25.93	0.1829

Backup slide: more diagnostics



Backup slide: closure and LR vs. SR

the neutrino radiation pressure in different optical depth regimes [43]

$$P_{\alpha\beta} = \frac{3\chi - 1}{2} P_{\alpha\beta}^{\text{thin}} + \frac{3(1 - \chi)}{2} P_{\alpha\beta}^{\text{thick}}, \quad (3)$$

where $\chi \in [\frac{1}{3}, 1]$ is the Eddington factor. Using Minerbo closure [110], we express χ as

$$\chi(\xi) = \frac{1}{3} + \xi^2 \left(\frac{6 - 2\xi + 6\xi^2}{15} \right), \quad \xi^2 = \frac{\tilde{F}_\alpha \tilde{F}^\alpha}{\tilde{E}^2} \quad (4)$$

where the $\tilde{\cdot}$ quantities are the radiation fields in the fluid co-moving frame. In this work, we use the following ansatz for P^{thick}

$$\tilde{P}_{\alpha\beta}^{\text{thick}} = \frac{1}{3} \tilde{E} (g_{\alpha\beta} + u_\alpha u_\beta) \quad (5)$$

where u^α is the fluid four-velocity, $g_{\alpha\beta}$ is the spacetime metric. In addition, we use

$$P_{\alpha\beta}^{\text{thin}} = \frac{F_\alpha F_\beta}{E} \quad (6)$$

in the optically thin limit [43, 111].

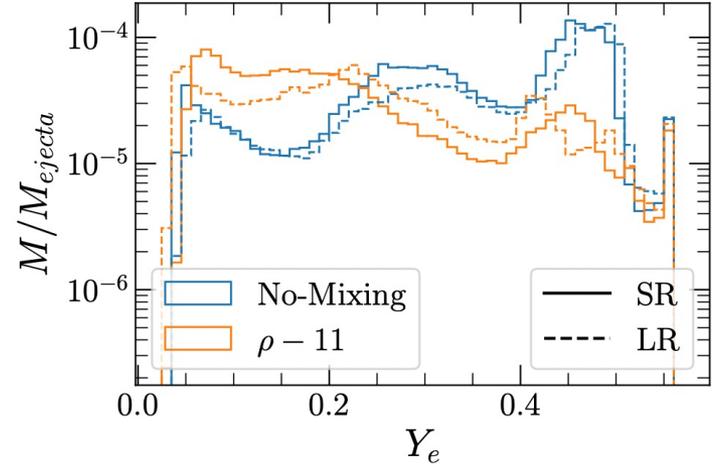
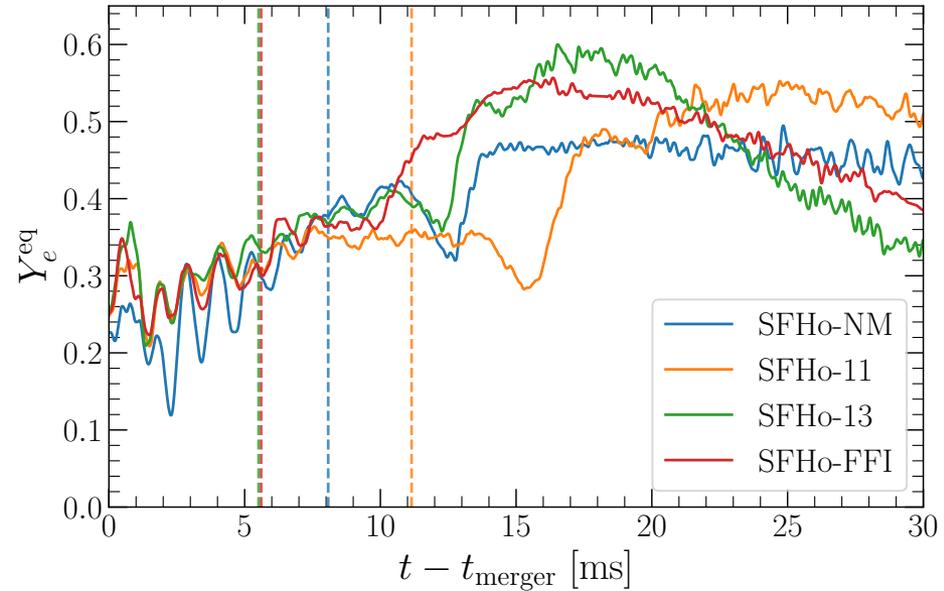
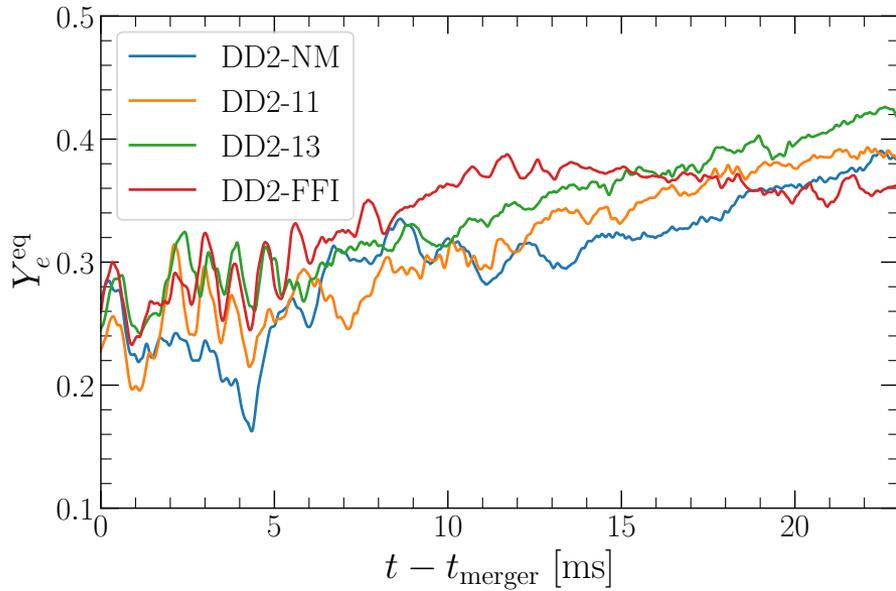


Figure 9. The electron fraction distributions of the dynamical ejecta in the **No-Mixing** and the $\rho - 11$ simulations for both standard (solid) and low (dashed) resolutions. We see in both LR and SR that, the ejecta is generally neutron-richer in the $\rho - 11$ simulation than that in the **No-Mixing** simulation, showing good consistency against resolutions.

Supplemental Materials in arXiv:2503.11758

Equilibrium Y_e



- Flavor conversions **increase** the equilibrium $Y_e \approx \left(1 + \frac{L_{\bar{\nu}_e} \langle \epsilon_{\bar{\nu}_e} \rangle}{L_{\nu_e} \langle \epsilon_{\nu_e} \rangle}\right)^{-1}$
- Ejecta Y_e being lower means the new equilibrium are determined by the **combination of flavor conversions and matter interactions**