PennState
Eberly College of Science

CoRe collaboration

# Neutrinos ~~and Dark Matter~~ in Neutron Star Mergers

David Radice – May 13, 2025

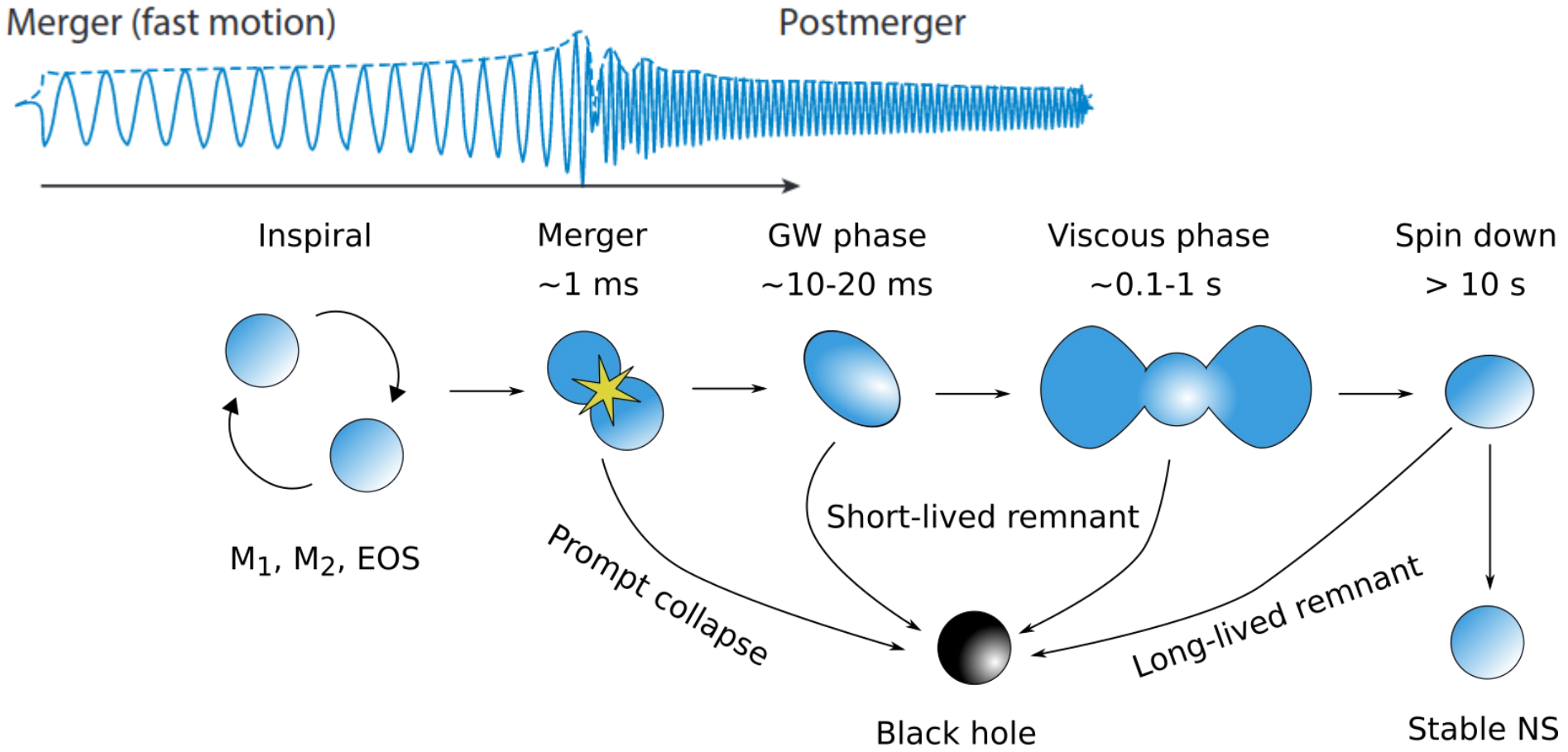
NP3M

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

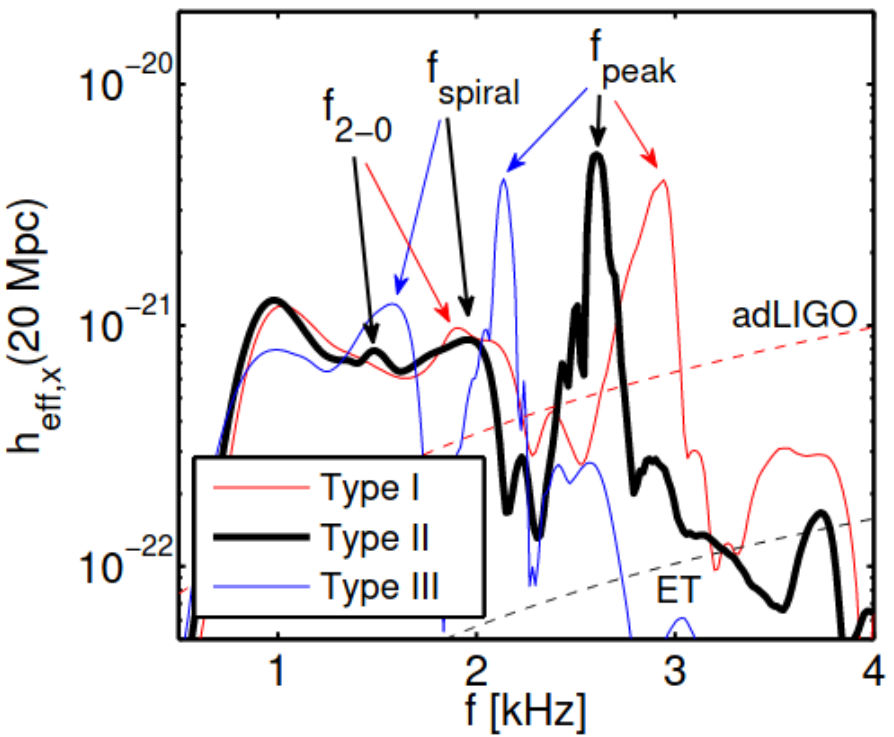
NASA



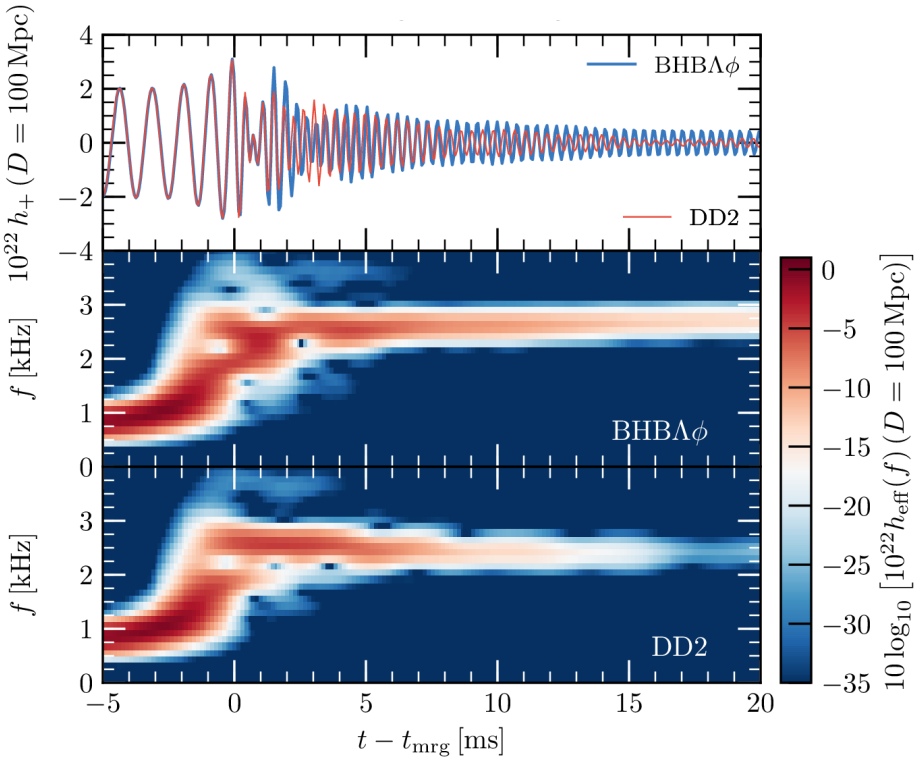

From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)

# Postmerger GW signal

From Bauswein+ 2015

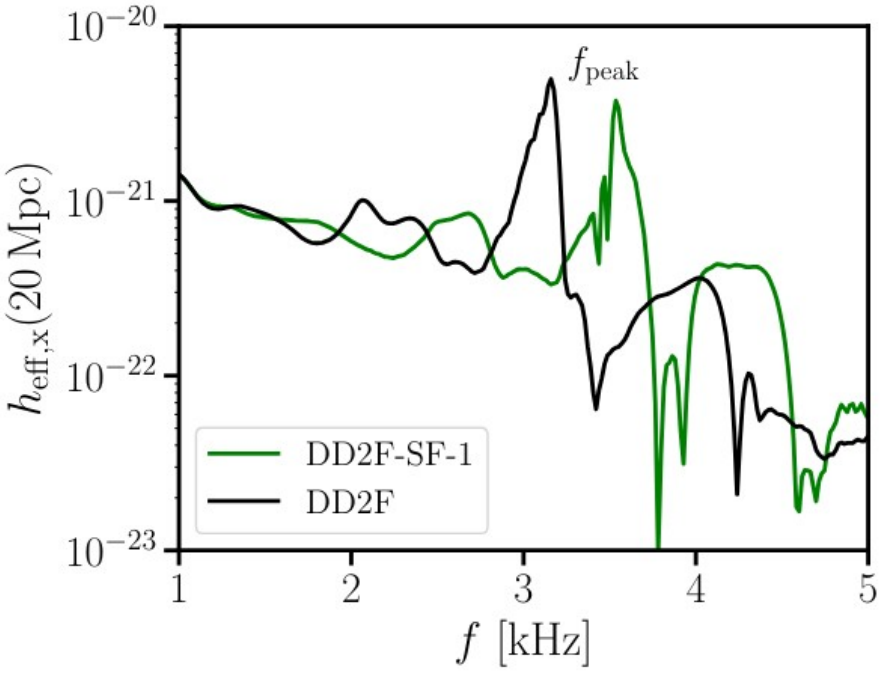



From Radice+ 2017

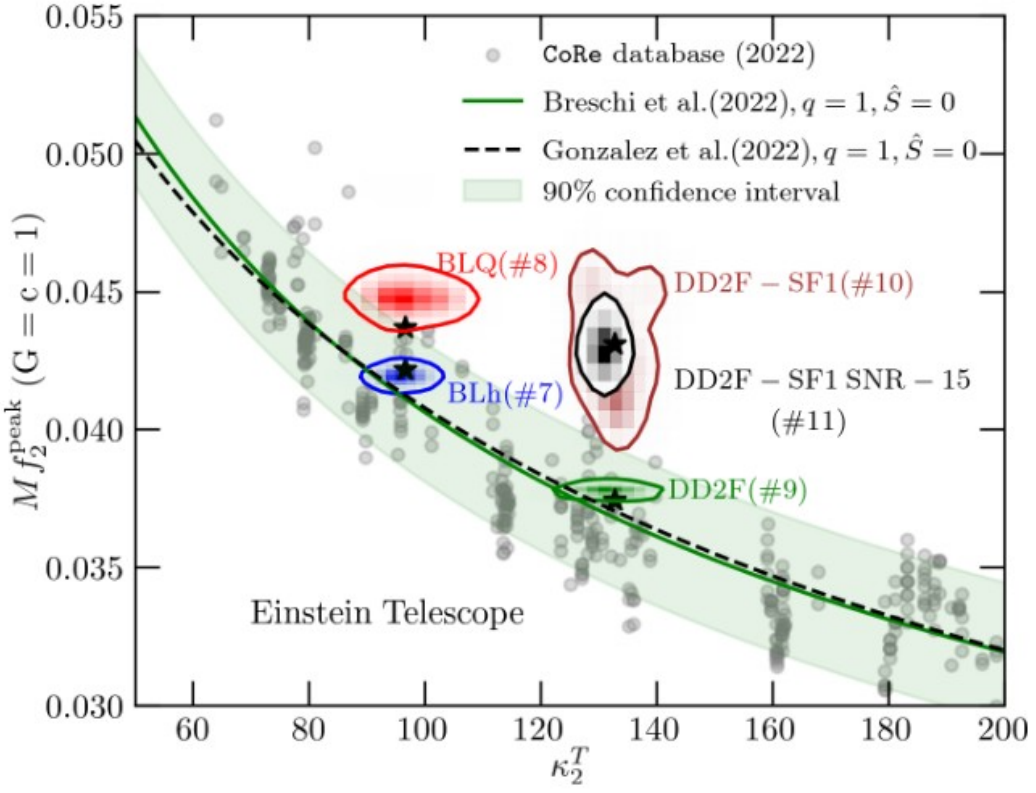



See also Takami+ 2014; Bernuzzi 2015, Rezzolla+ 2016; Dietrich+ 2016; Breschi+ 2019; Bauswein+ 2019; …

# QCD phase transitions



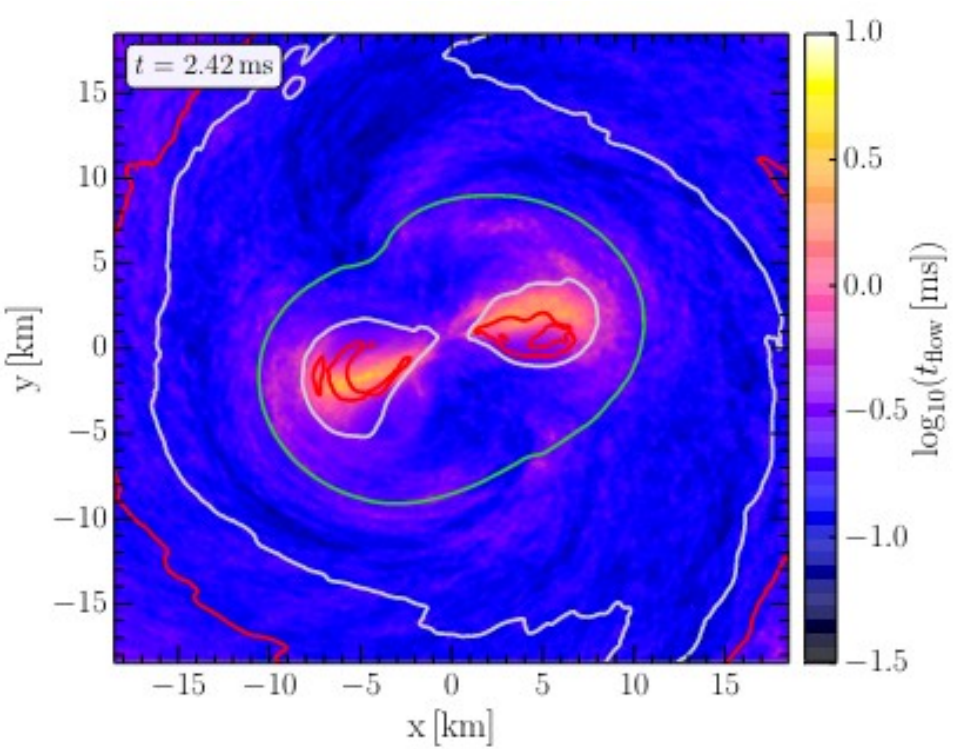

From Bauswein+, PRL 122:061102 (2019)




From Prakash+ PRD 109:103008 (2023)

See also: Bauswein+ 2020; Most+ 2019, Weigh+ 2019; Blacker+ 2020; Liebling+ 2021; Prakash+ 2021 ...

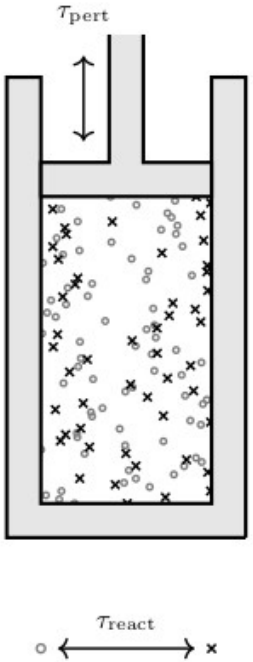
# Out of equilibrium effects?

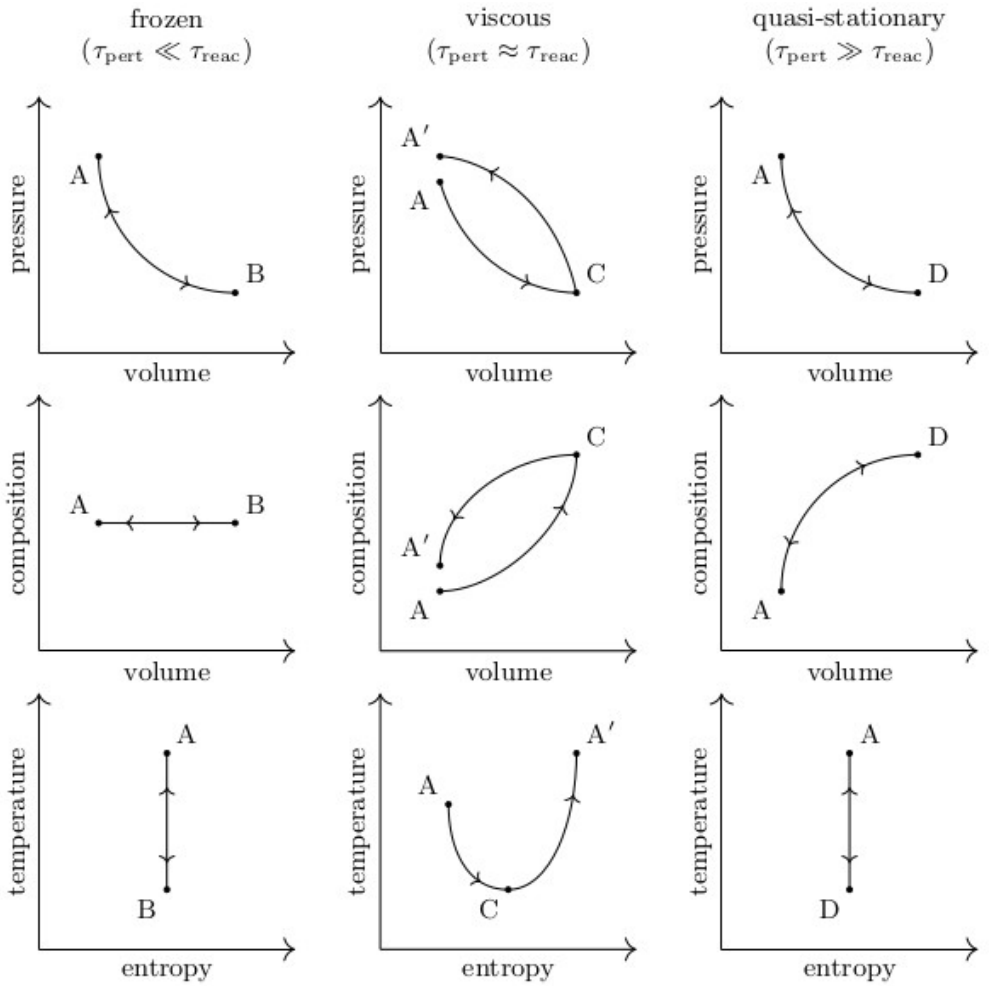



From Alford+ 2017

- When dense matter is compressed it undergoes strong and weak reactions
- $t_{strong} << t_{hydro}$, so strong reactions are always in equilibrium
- $t_{weak} \approx 10^{-3}$ ms $\approx t_{hydro}$: potentially out of equilibrium
- Could result in non-ideal effects (eg., bulk viscosity)

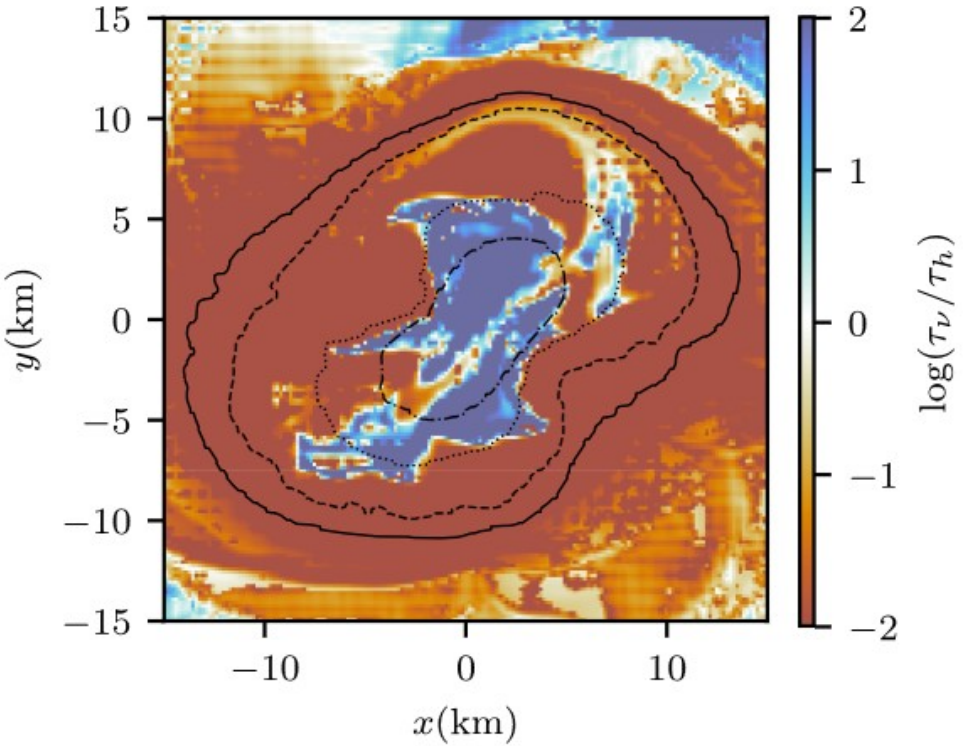
See also Perego+ 2019; Most+ 2021, 2022, 2024; Hammond+ 2021; Radice+ 2021; Espino 2024; ...

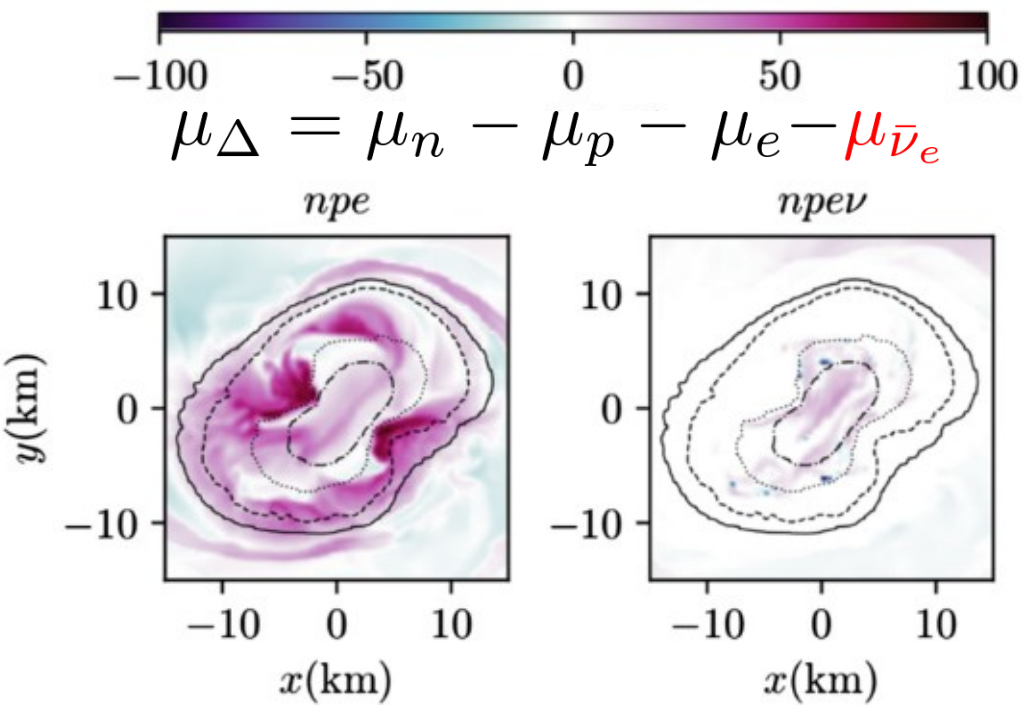



From Camelio+ PRD 107:103031 (2022) & 107:103032 (2022)

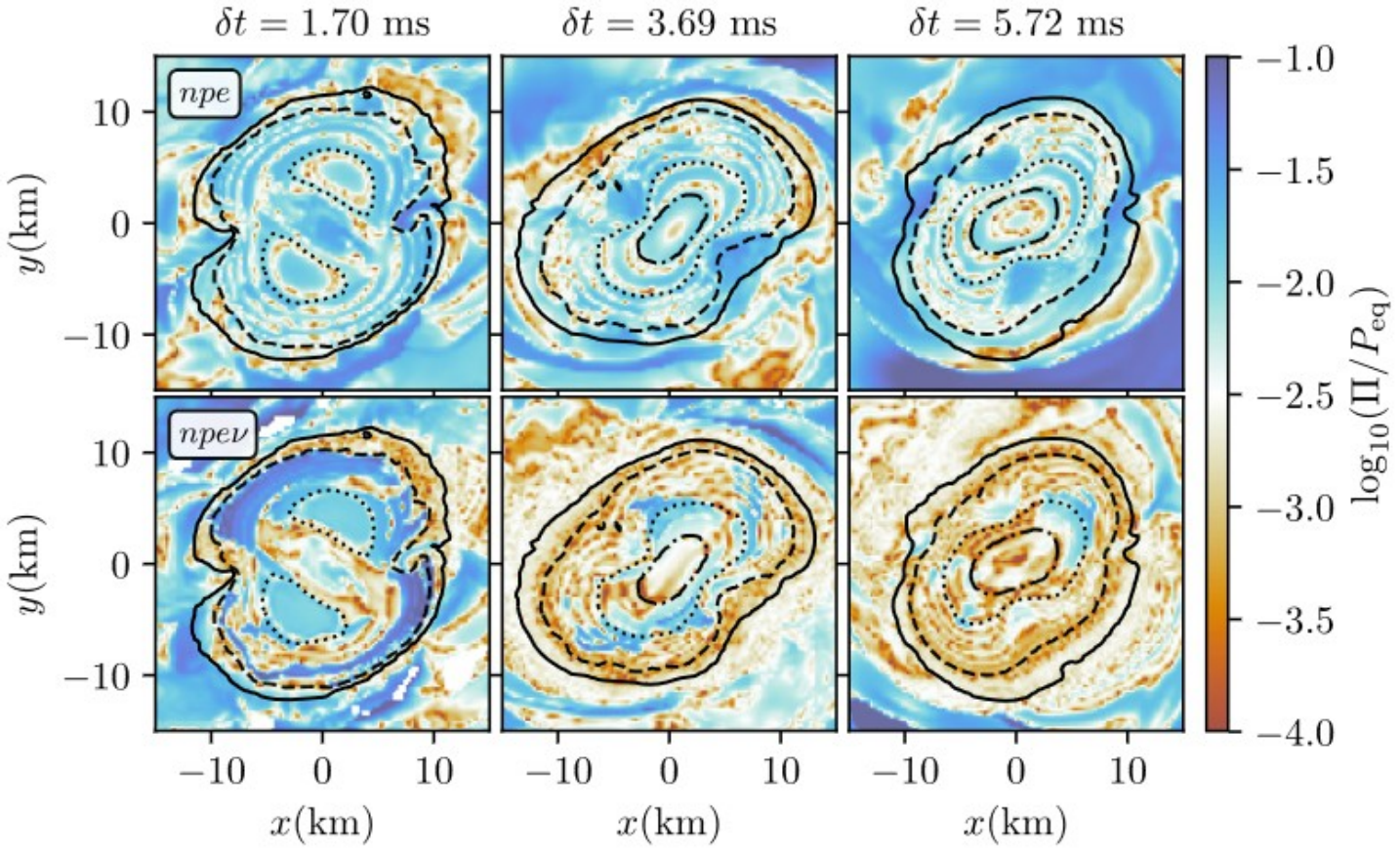
# Thermodynamic equilibrium




From Espino+ PRL 132:211001 (2024)

# Bulk-viscous pressure: $\Pi = p - p(T^*, Y_e^*)$




From Espino+ PRL 132:211001 (2024)

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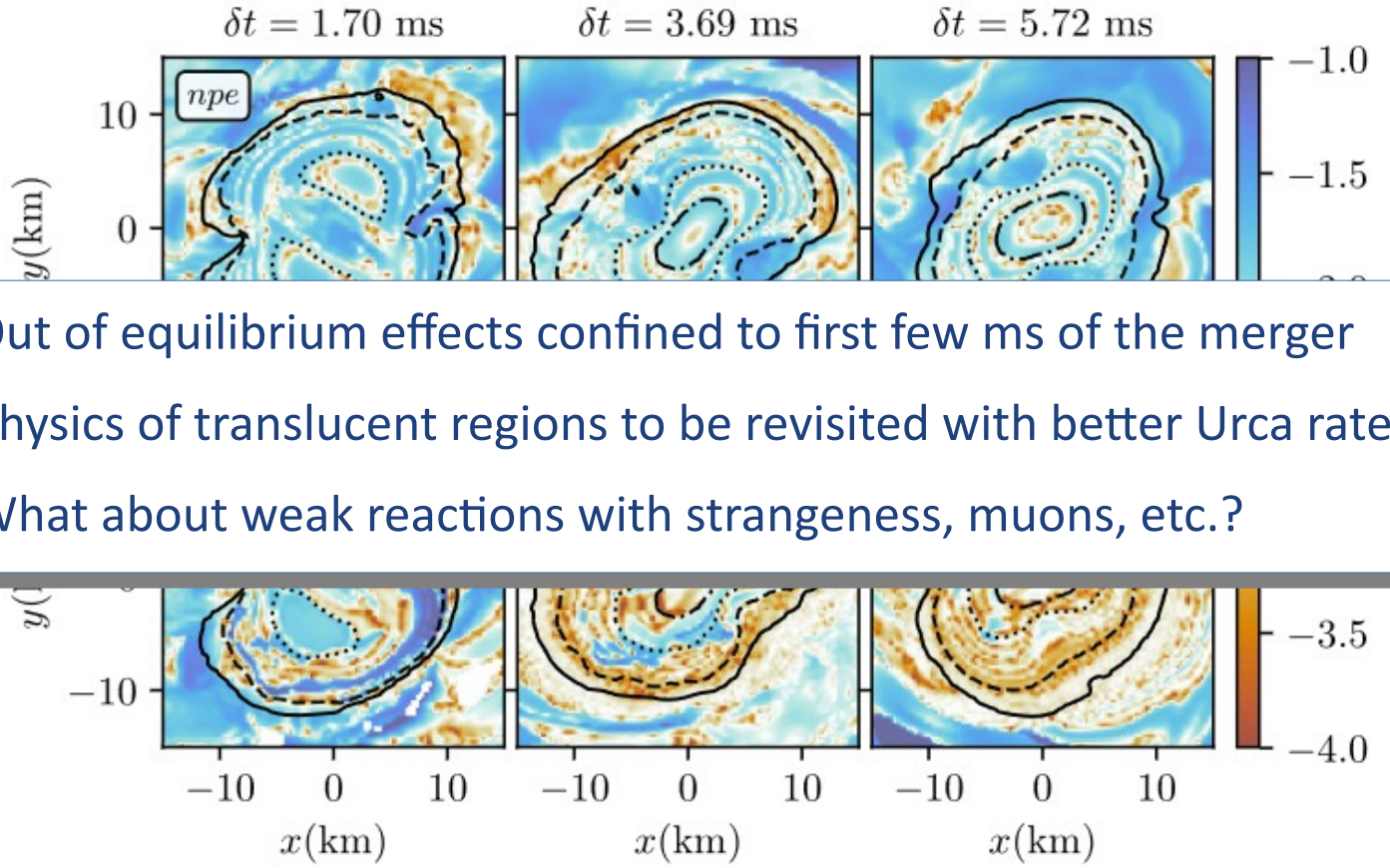
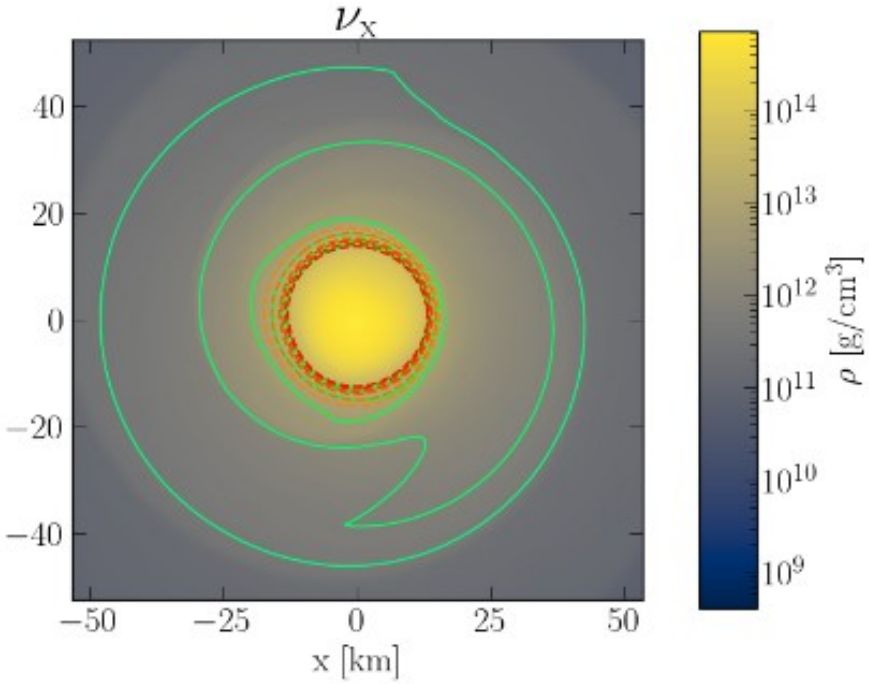
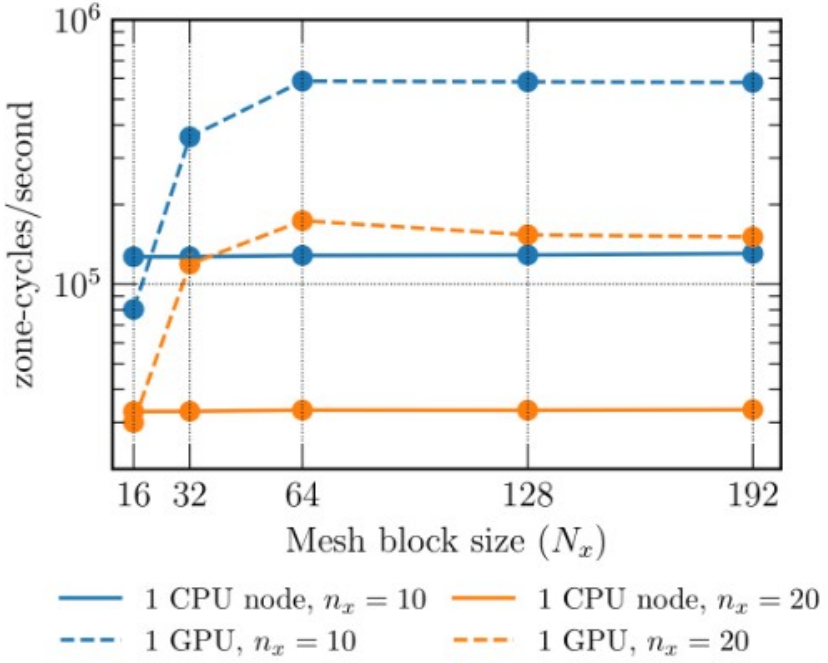



- Out of equilibrium effects confined to first few ms of the merger
- Physics of translucent regions to be revisited with better Urca rates
- What about weak reactions with strangeness, muons, etc.?

From Espino+ PRL 132:211001 (2024)

# bns_nurates

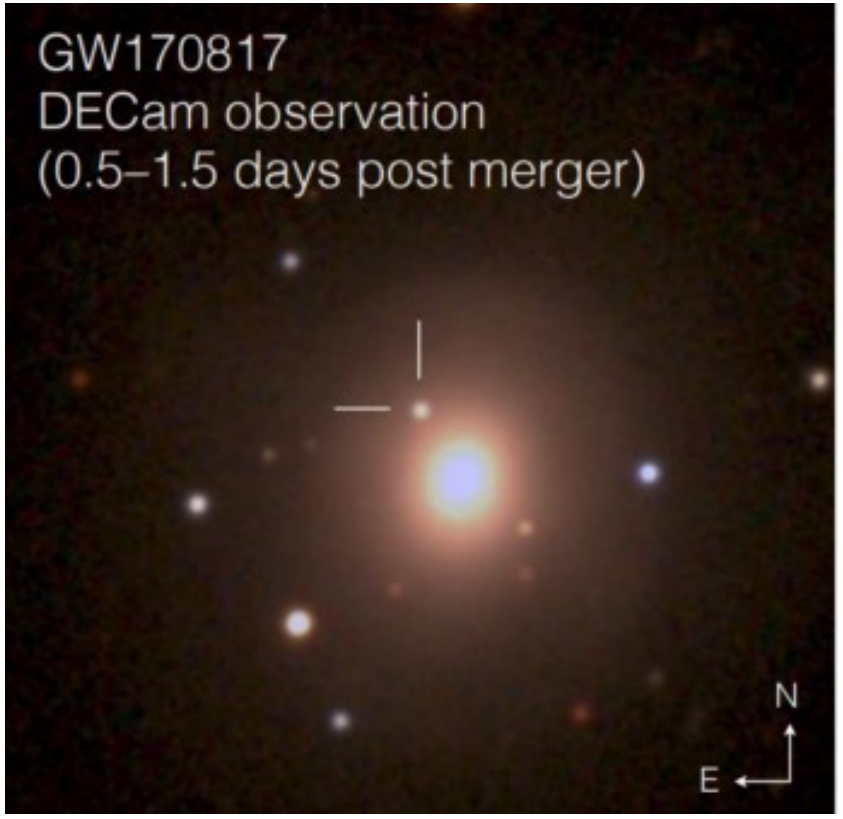


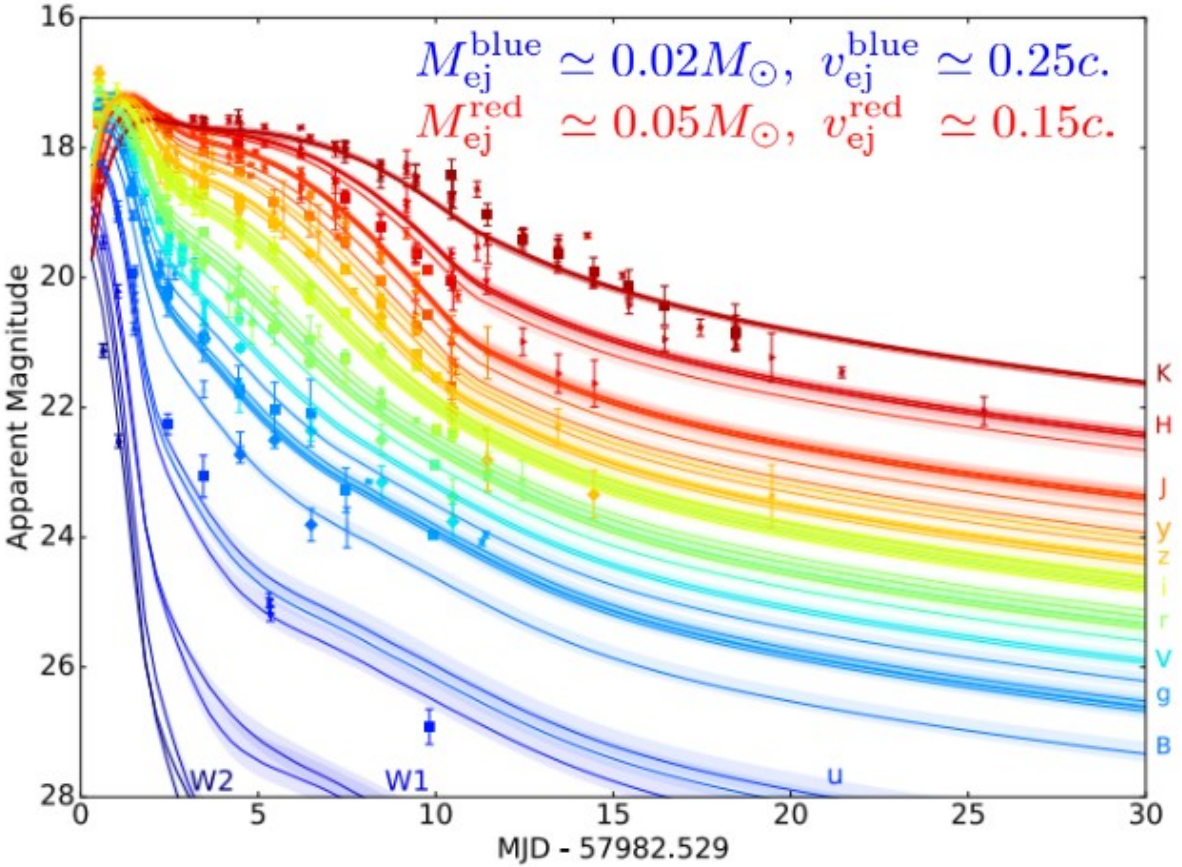

From Chiesa+ (2025), PRD 111:063053 (2025)

https://github.com/RelNucAs/bns_nurates

# Neutrinos in neutron star mergers

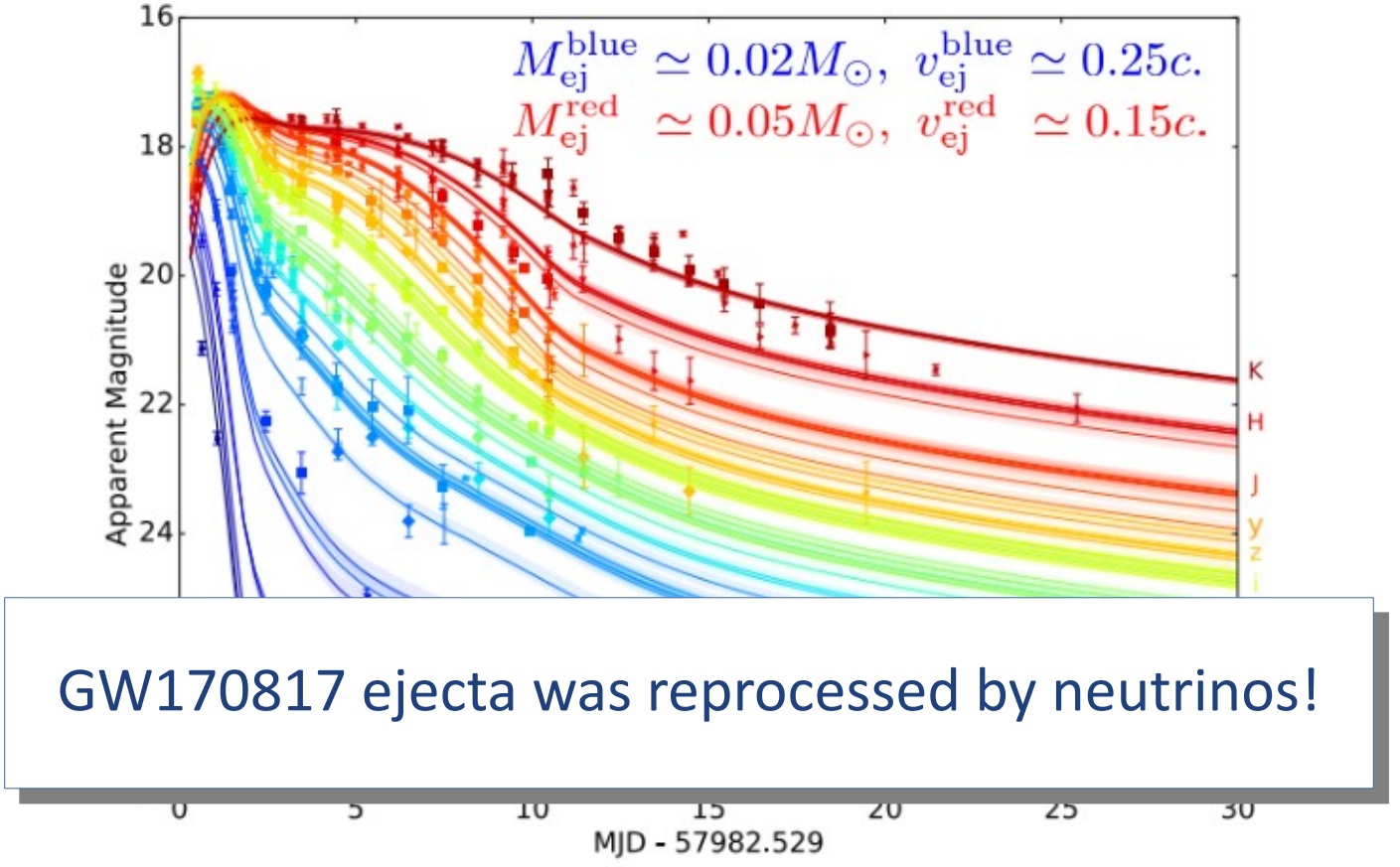



# Neutrinos in neutron star mergers



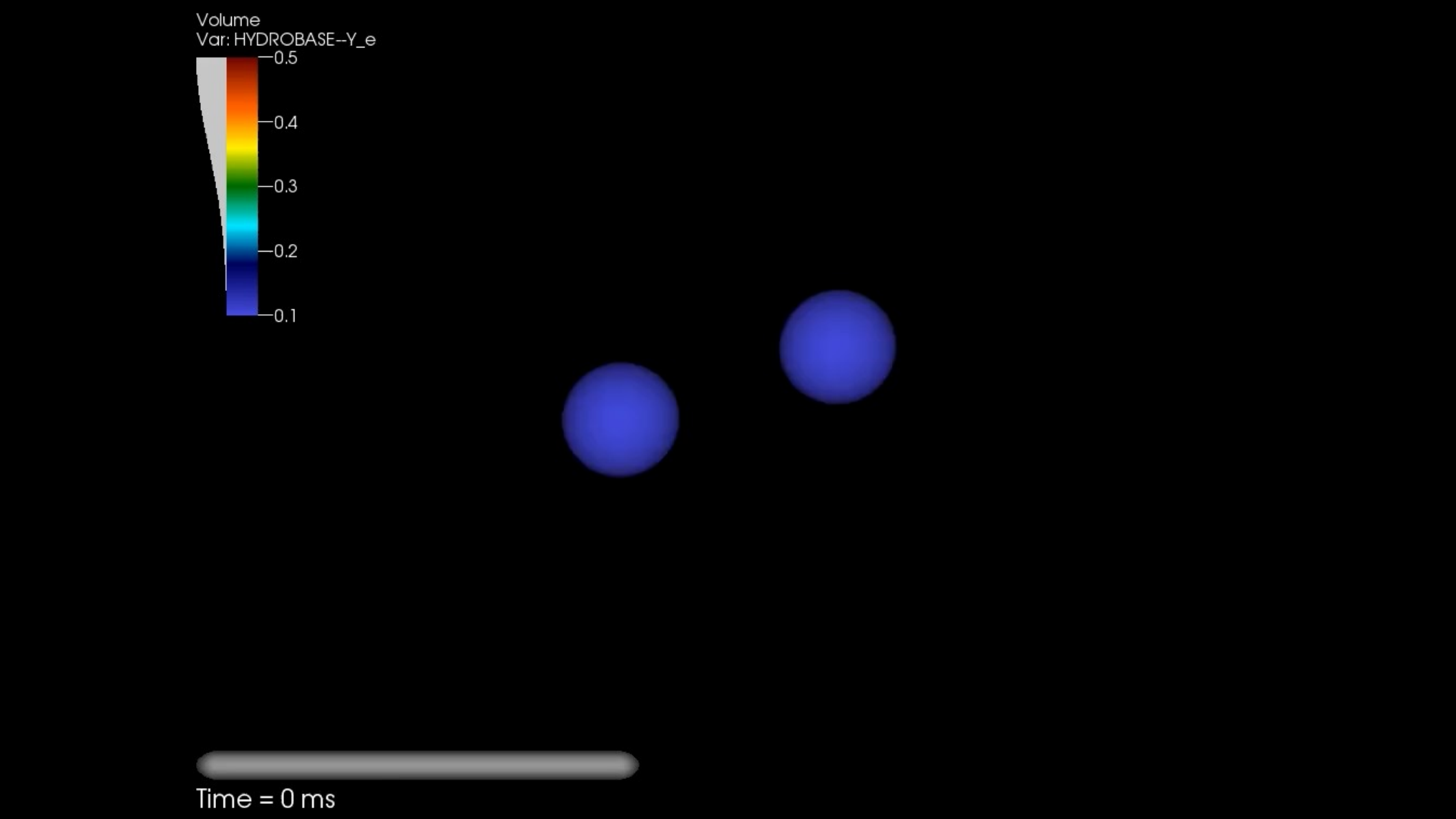

From Villar+ 2017

# Neutrinos in neutron star mergers

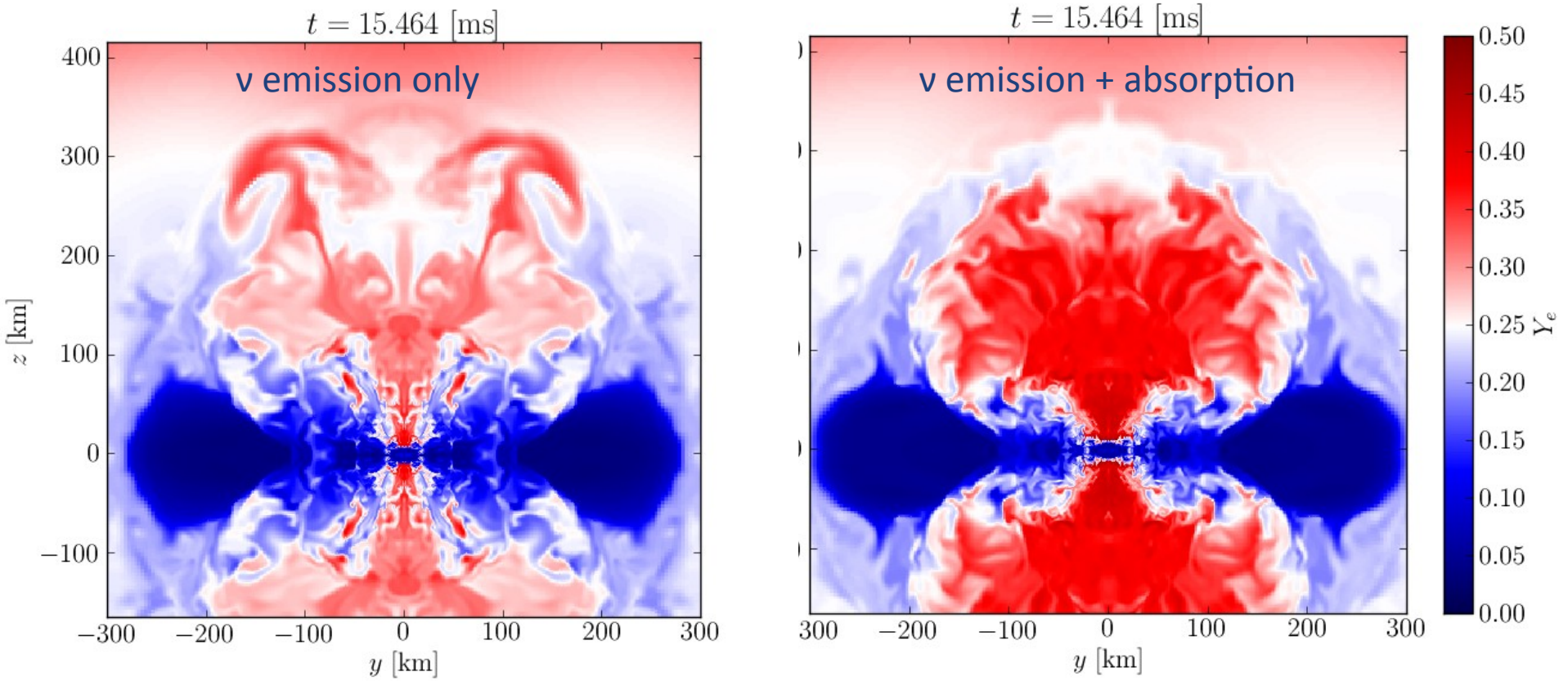



GW170817 ejecta was reprocessed by neutrinos!

From Villar+ 2017


Volume
Var: HYDROBASE--Y_e
0.5
0.4
0.3
0.2
0.1
Time = 0 ms

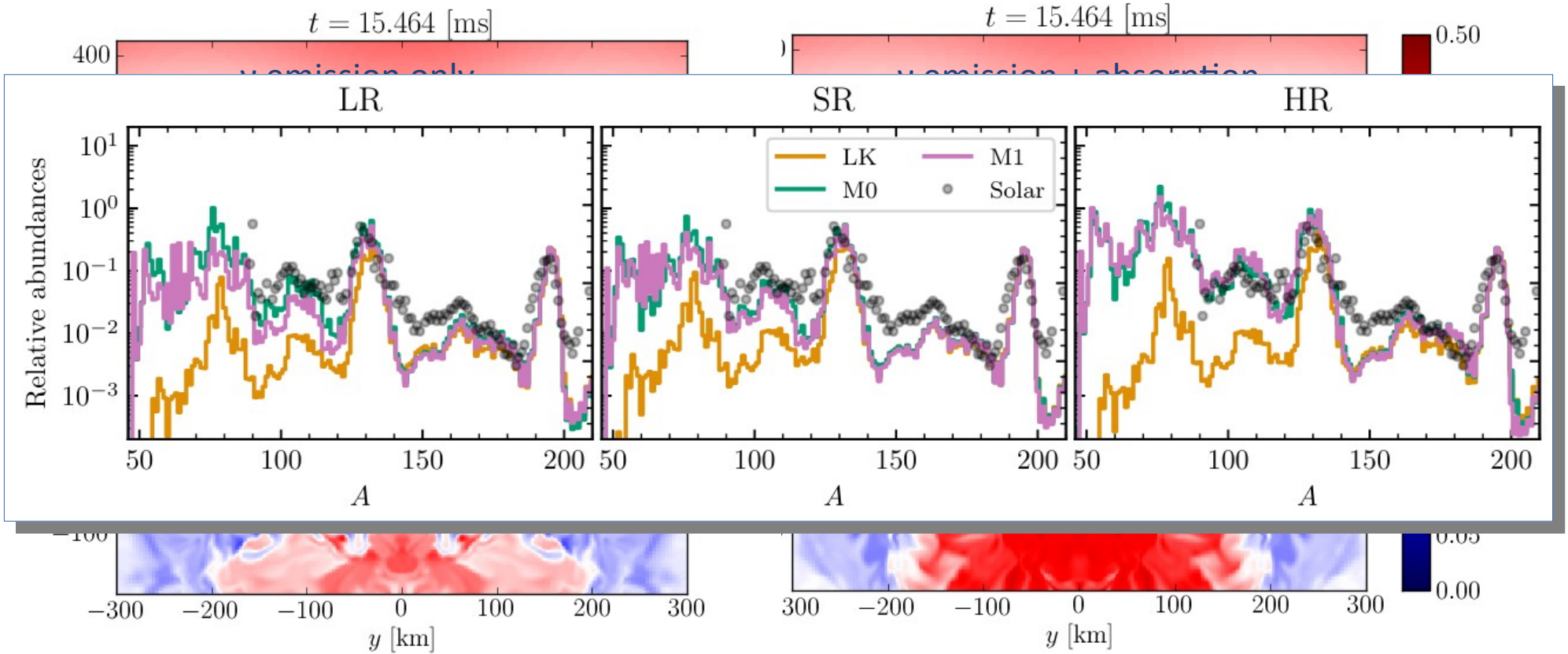
# Neutrino effects on the eiecta




See also Sekiguchi+ 2015; Foucart+ 2016;
Combi+ 2023; Foucart+ 2024; ...

Radice+, MNRAS 460:3255 (2016)
Zappa+, MNRAS 520:1481 (2023)

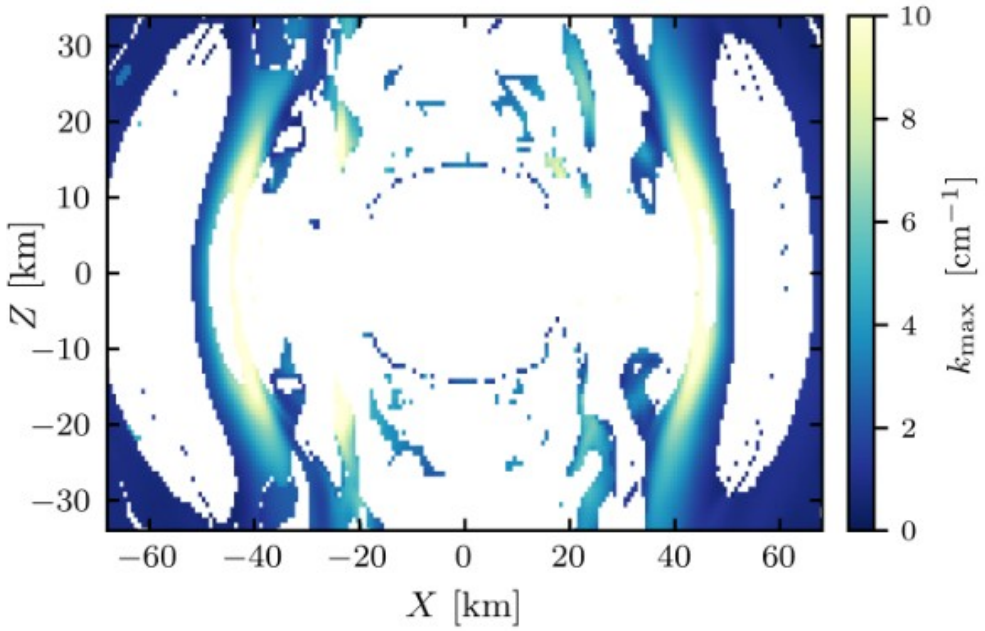
# Neutrino effects on the eiecta



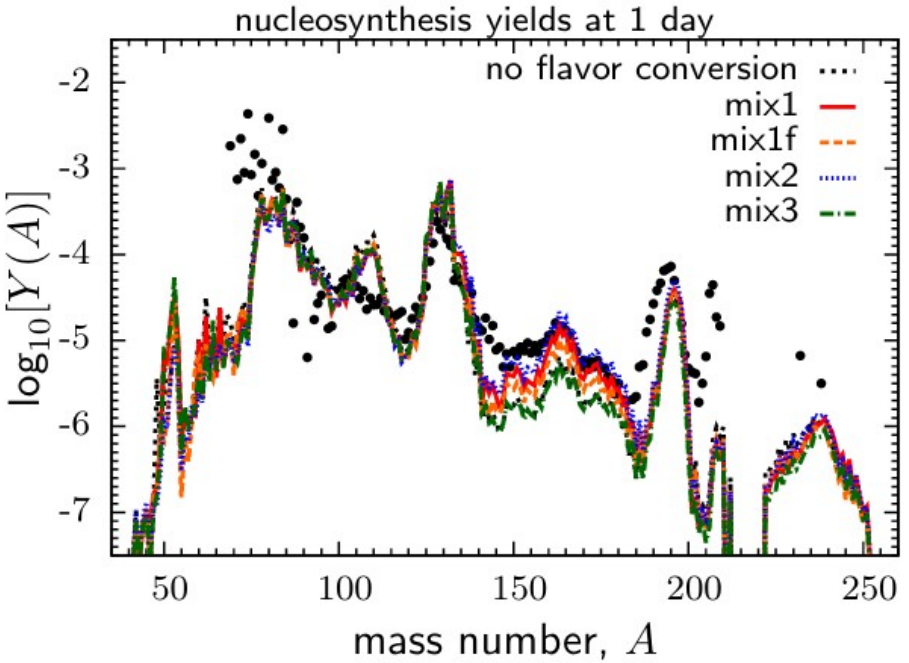

See also Sekiguchi+ 2015; Foucart+ 2016; Combi+ 2023; Foucart+ 2024; ...

Radice+, MNRAS 460:3255 (2016)
Zappa+, MNRAS 520:1481 (2023)

# Neutrino flavor transformations



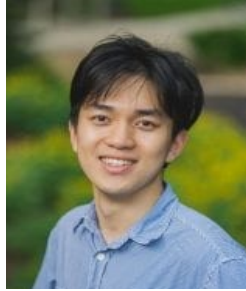

From Froustey+ 2025




From Just+ 2022

See also Li & Siegel 2023; Fernandez+ 2022; Lund+ 2025

# Flavor transformation model



We consider a flavor transformation scenario that can be solved using simple thermodynamics

BGK approximation

$$-i[H, f] \rightarrow \frac{1}{\tau(\rho)}(f^a - f)$$

Detailed balance

$$\nu_x \overline{\nu}_x \leftrightarrows \nu_y \overline{\nu}_y$$

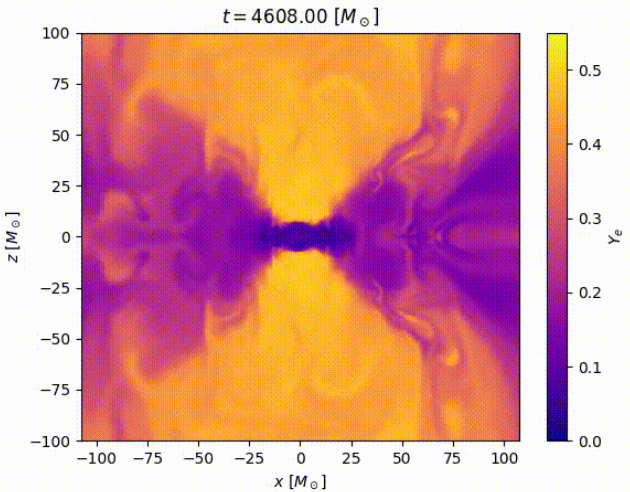
We are currently exploring FFI-inspired setups

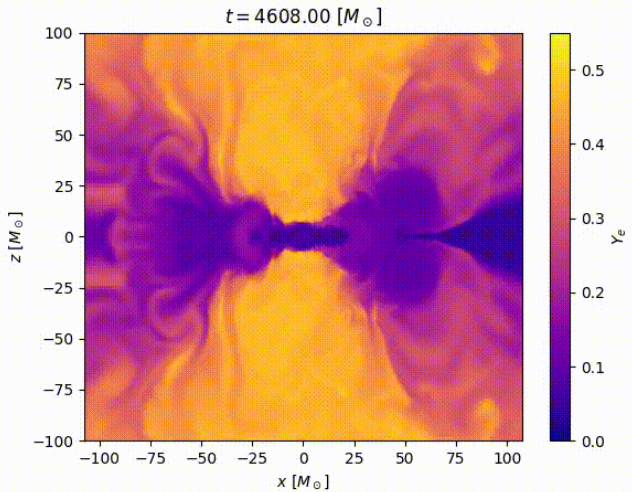
See Nagakura+ 2023, Martin+ 2023, Johns 2024, Ehring+ 2024

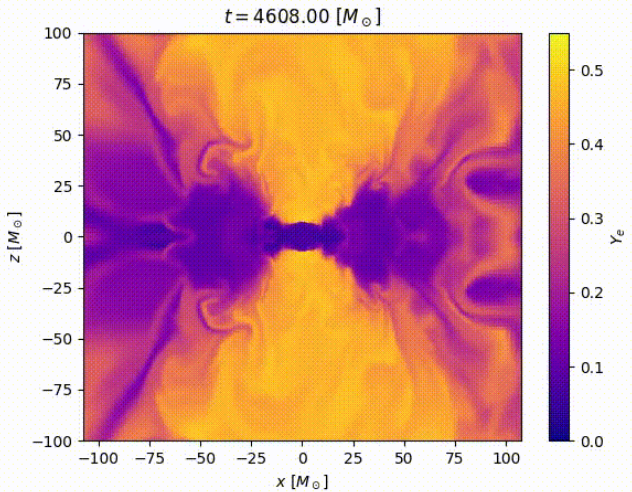
$\tau = \infty$

$\tau \propto \theta_{11}(\rho)$

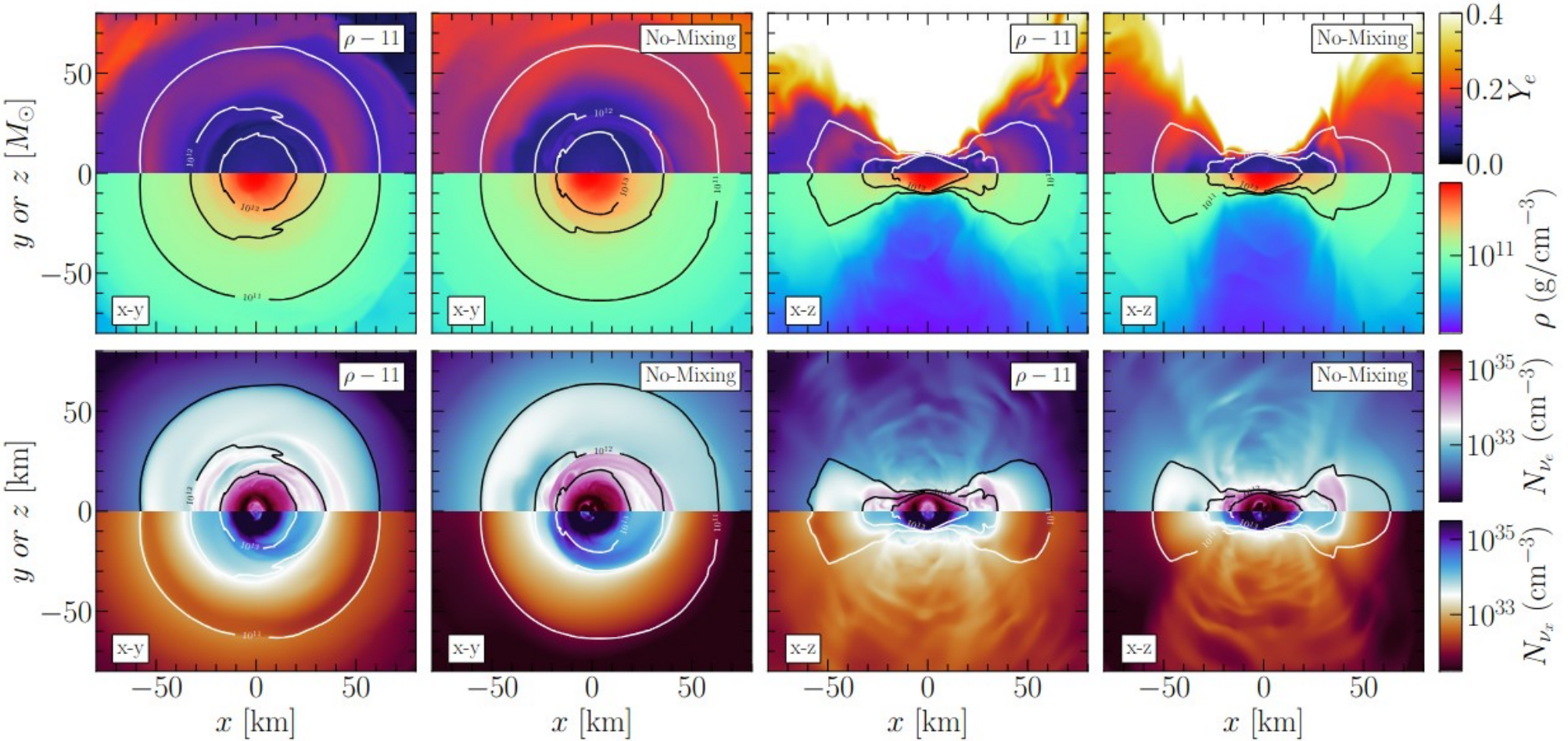
$\tau \propto \theta_{13}(\rho)$



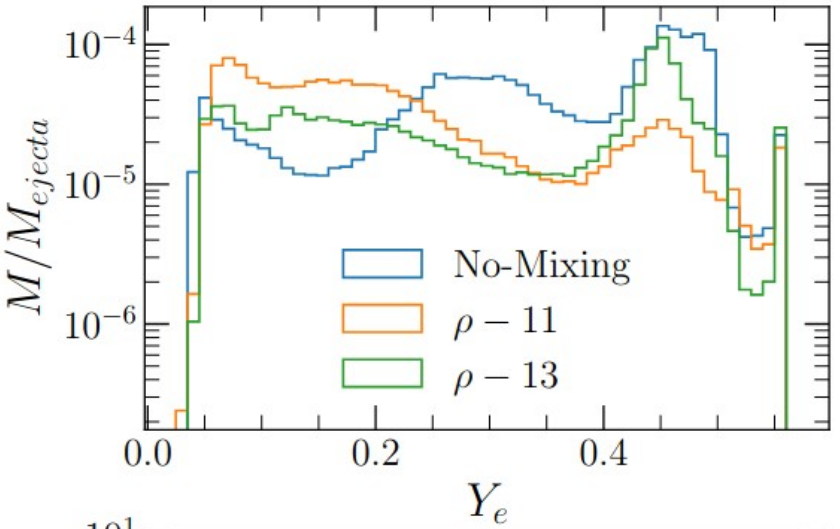



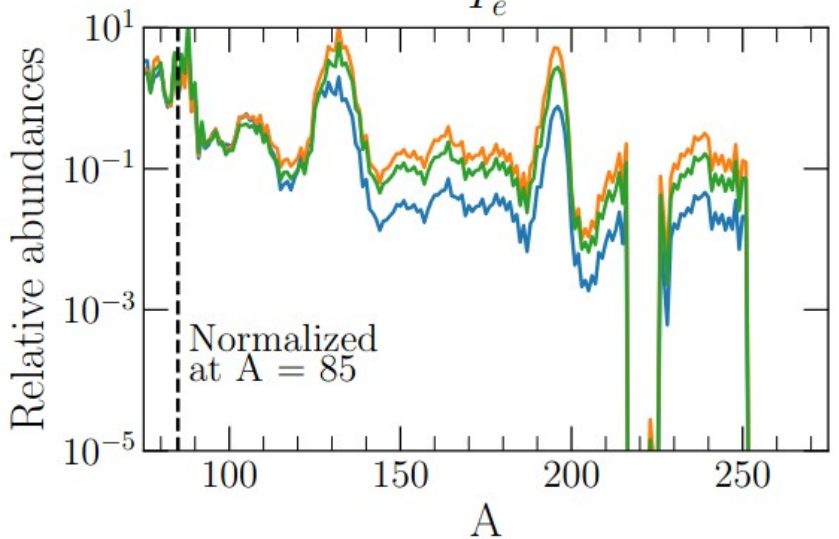

From Qiu+, 2503.11758

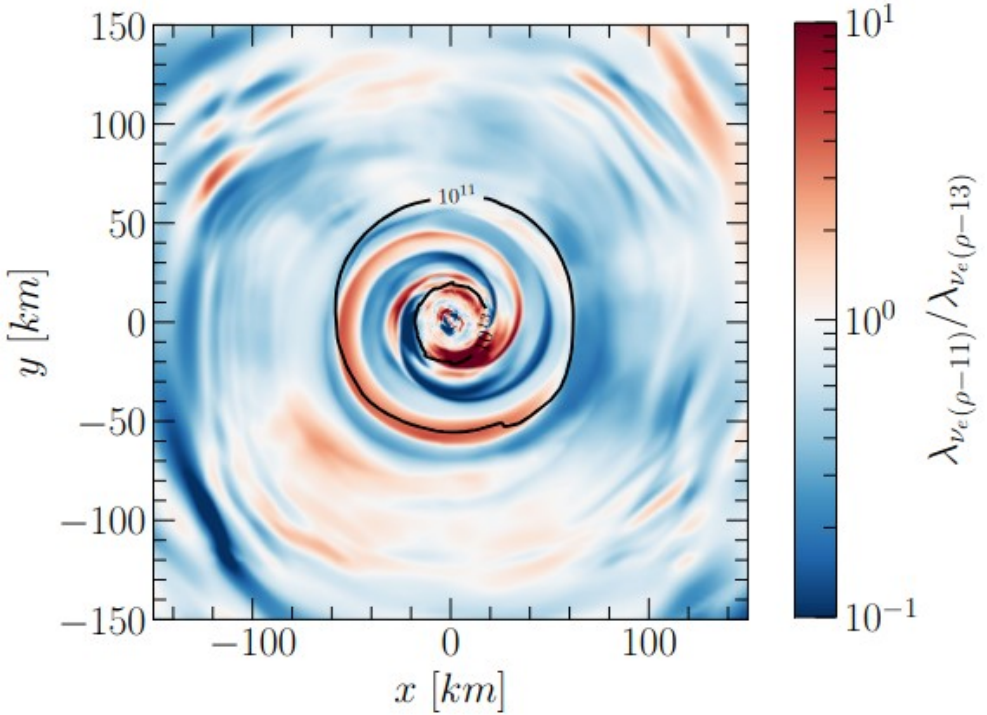



From Qiu+, 2503.11758

# Nucleosynthesis

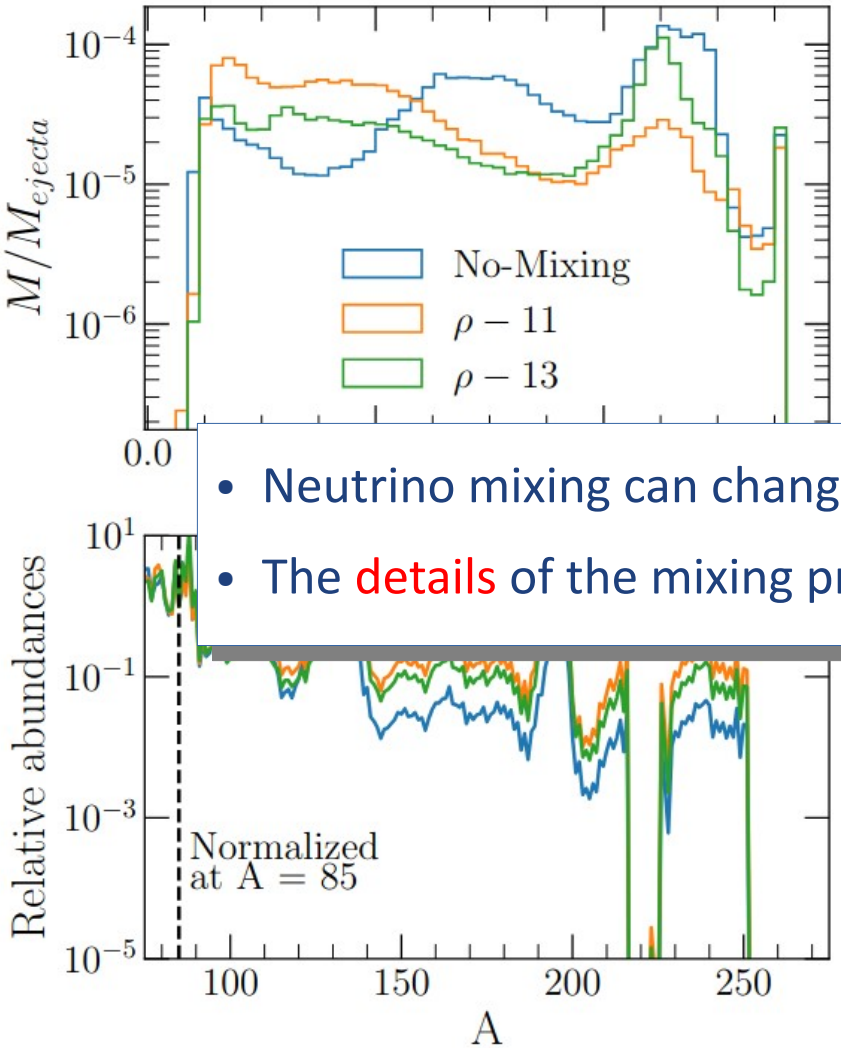


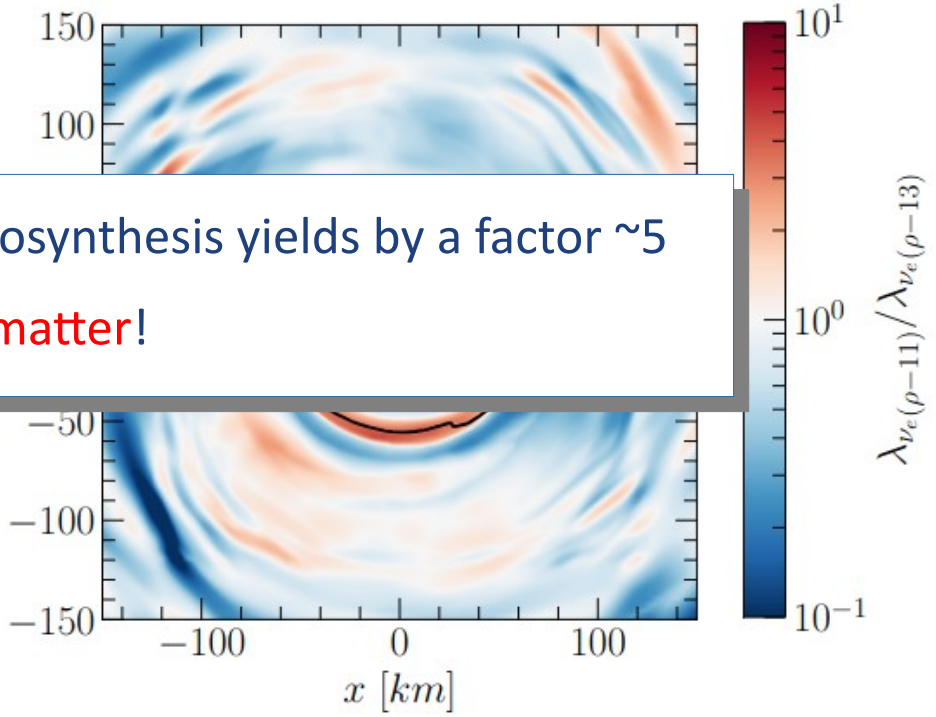




From Qiu+, 2503.11758

# Nucleosynthesis

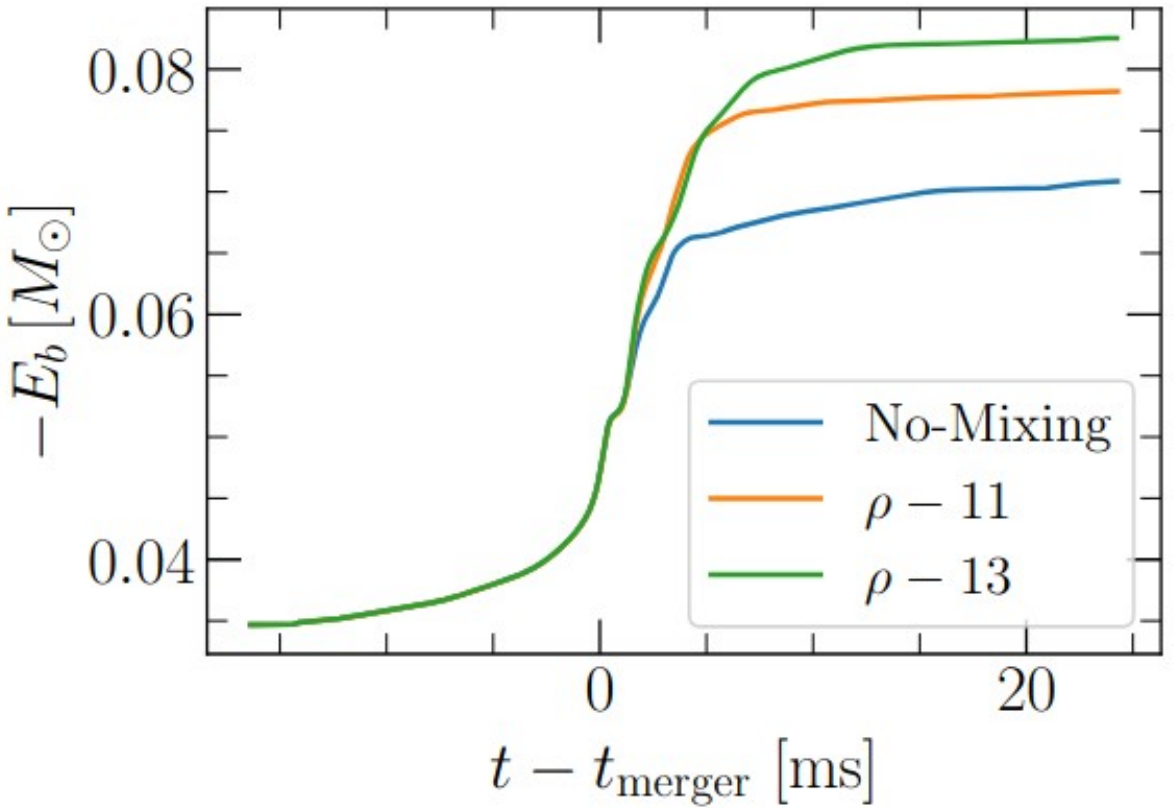



- Neutrino mixing can change nucleosynthesis yields by a factor ~5
- The details of the mixing process matter!

From Qiu+, 2503.11758

# Impact on dynamics



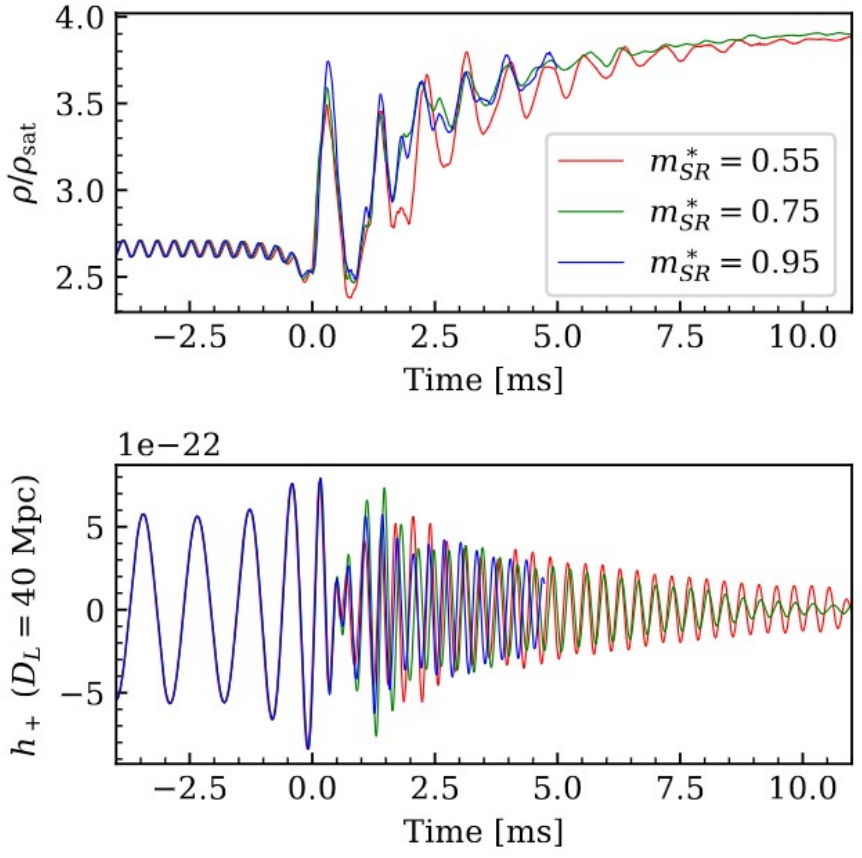

See also Ehring+ 2024

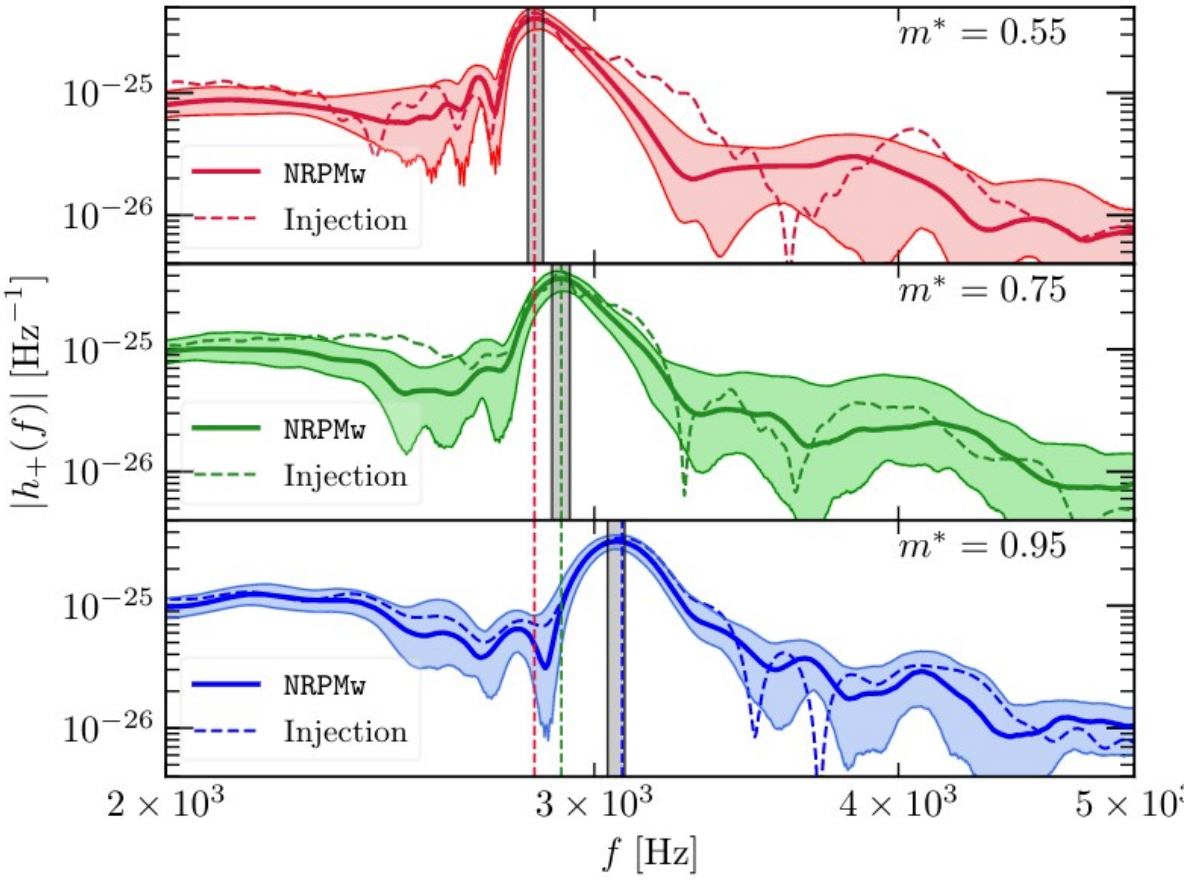
From Qiu+, 2503.11758

# Conclusions

- Thermal O(10 MeV) neutrinos impact the postmerger dynamics (GWs), and the properties of the ejecta (EM & nucleosynthesis)
- The window for effective bulk viscosity to be active due to weak reactions is of only a few milliseconds postmerger
- Other non-ideal thermodynamics effects cannot be excluded
- Neutrino flavor transformation have a significant impact on observables

# Thermal effects

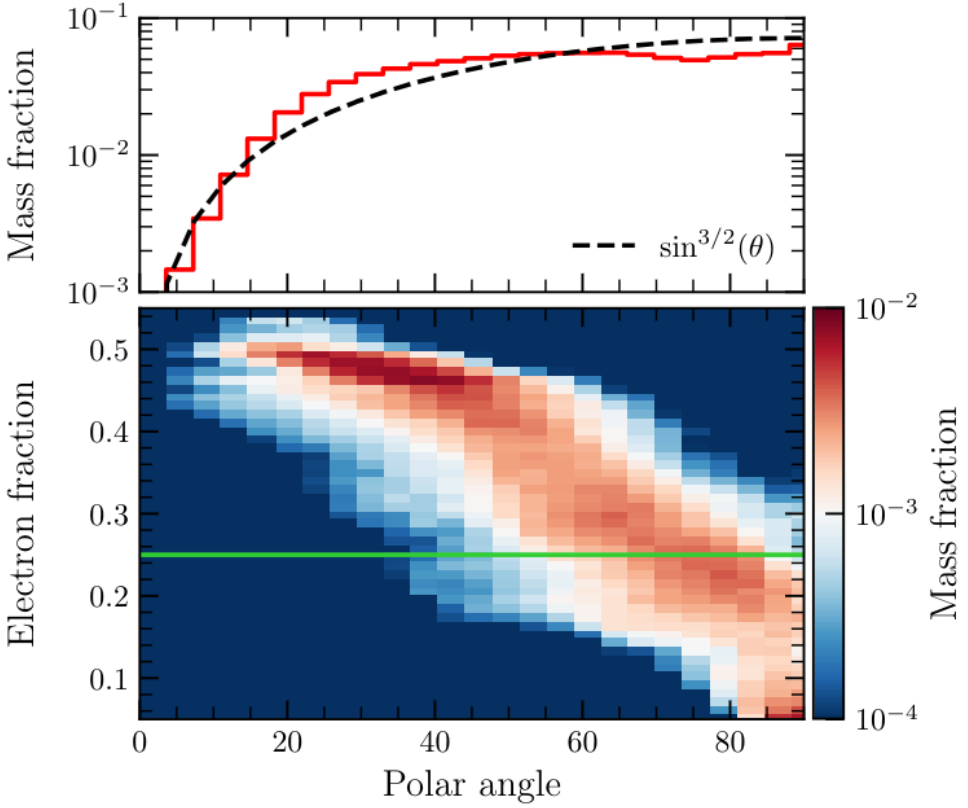


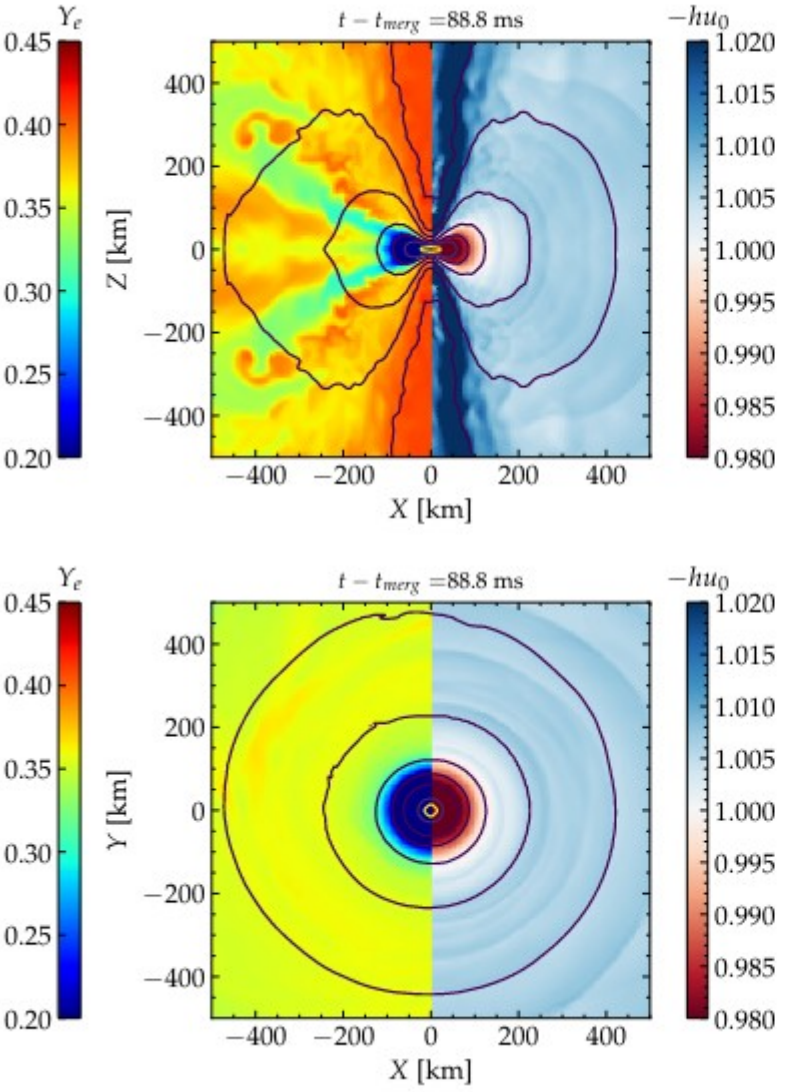

See also Raithel+ 2021, 2022

From Fields+ ApJL, 952:L36 (2023)

# Secular outflows

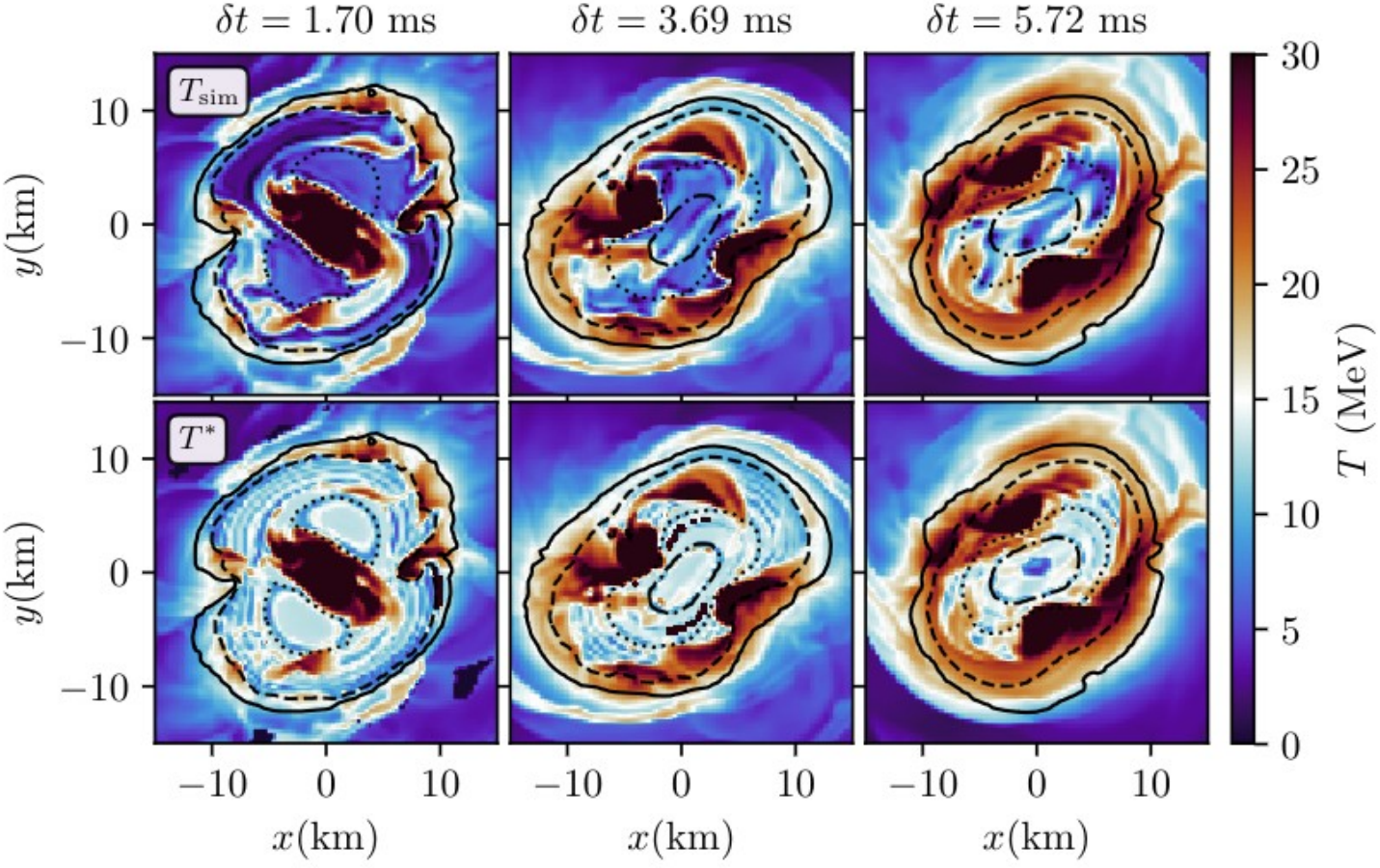



From Radice+ 2310.09934




From Nedora+, ApJ 906:98 (2021)

# Equilibrium temperature




From Espino+ PRL 132:211001 (2024)