PennState
Eberly College of Science

CoRe collaboration

Neutrinos in Neutron Star Mergers

David Radice – July 15, 2024

NP3M

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

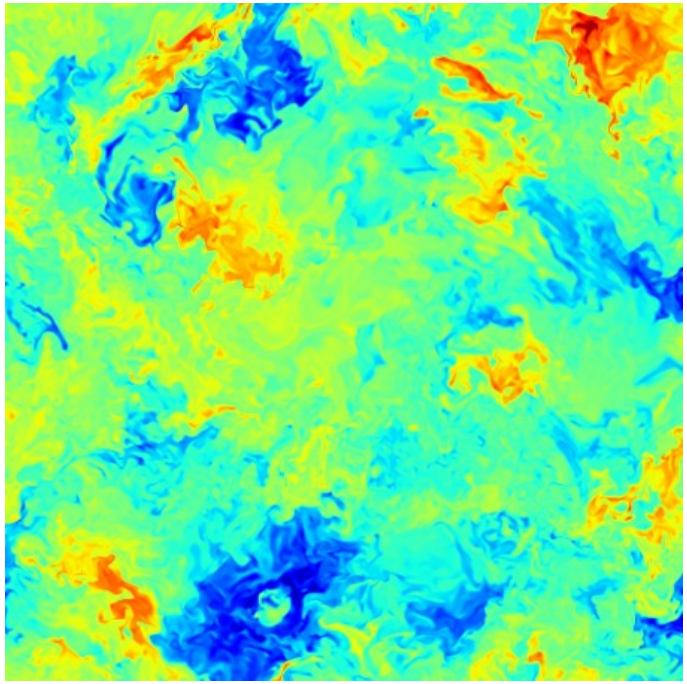
NSF

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NASA

WhiskyTHC

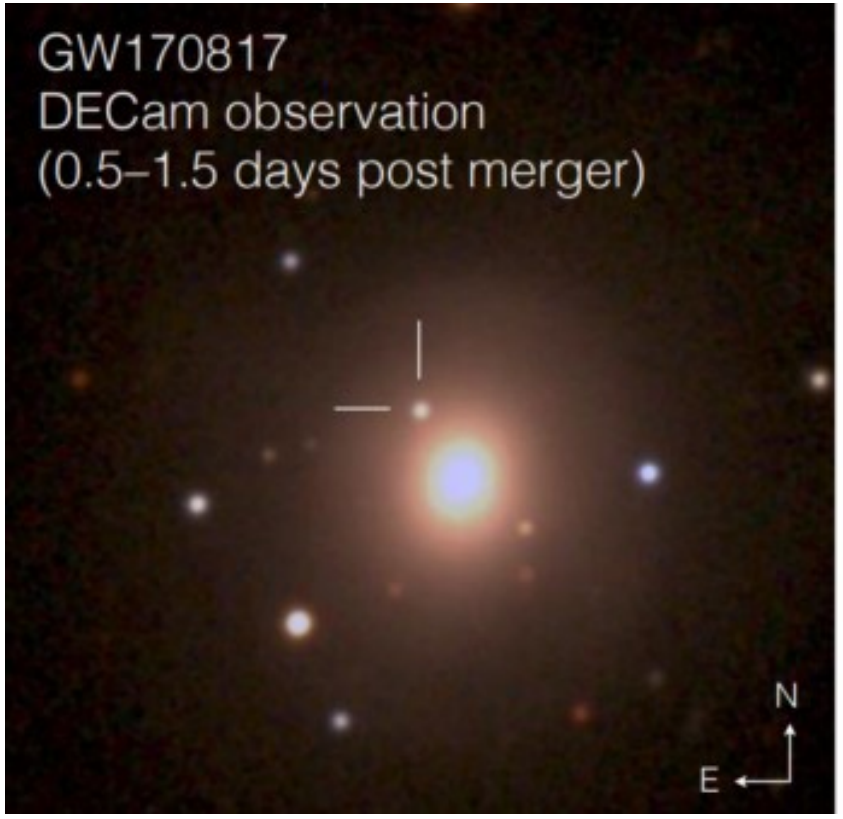
https://personal.science.psu.edu/dur566/whiskythc.html



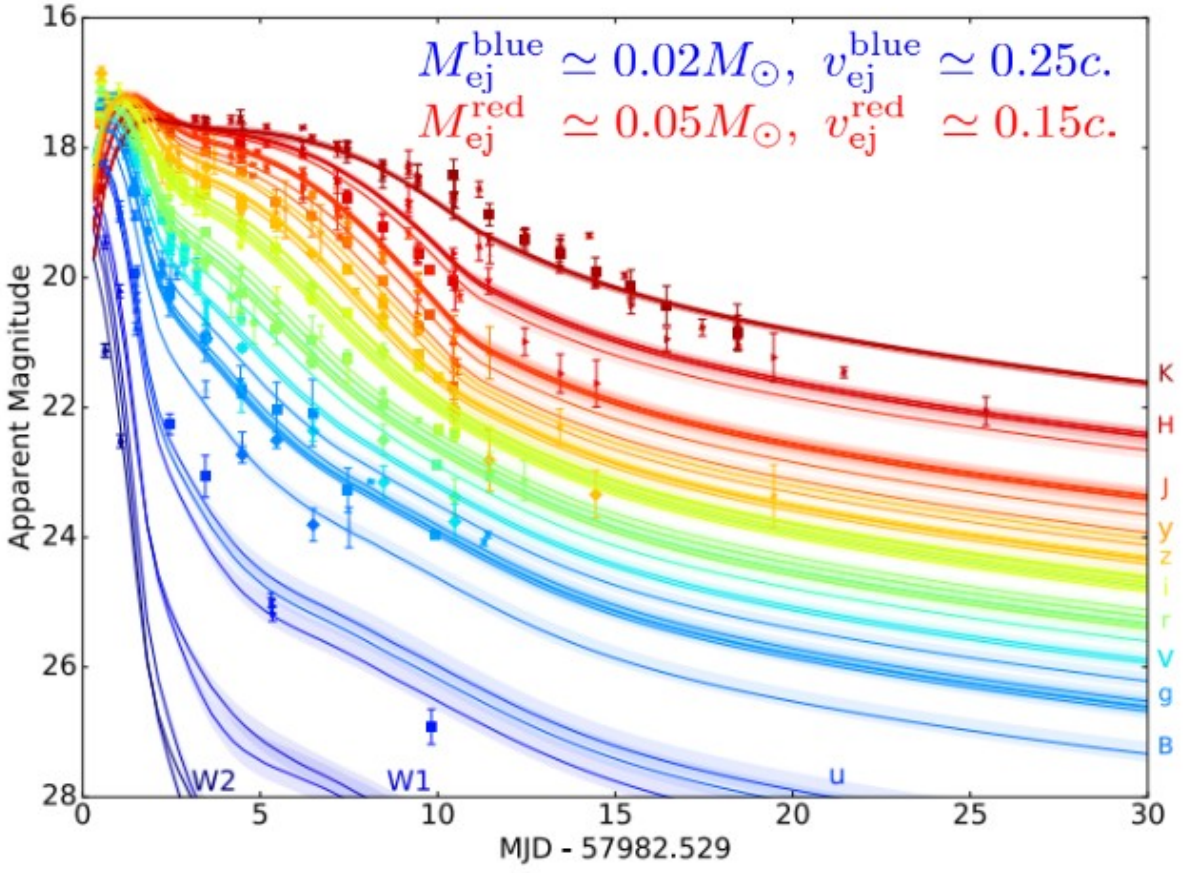
- Full-GR dynamical spacetime
- GRHD with tabulated EOS:
  2nd order KT / 5th order HRSC FD
- M0 & M1 neutrino transport
- Subgrid turbulence modeling
- Builds on top of the Einstein Toolkit and open source*

THC: Templated Hydrodynamics Code

Neutrinos in neutron star mergers

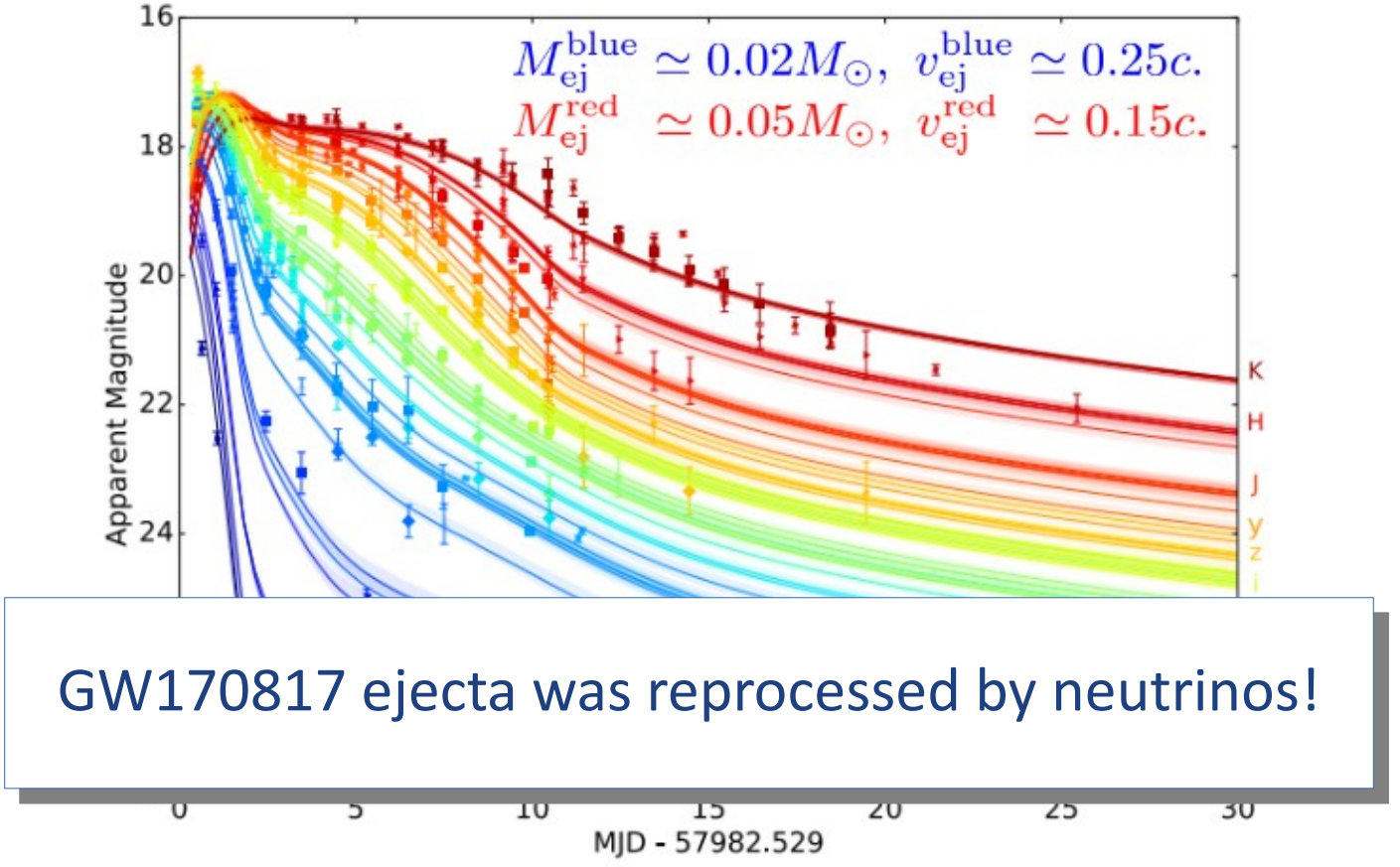


Neutrinos in neutron star mergers



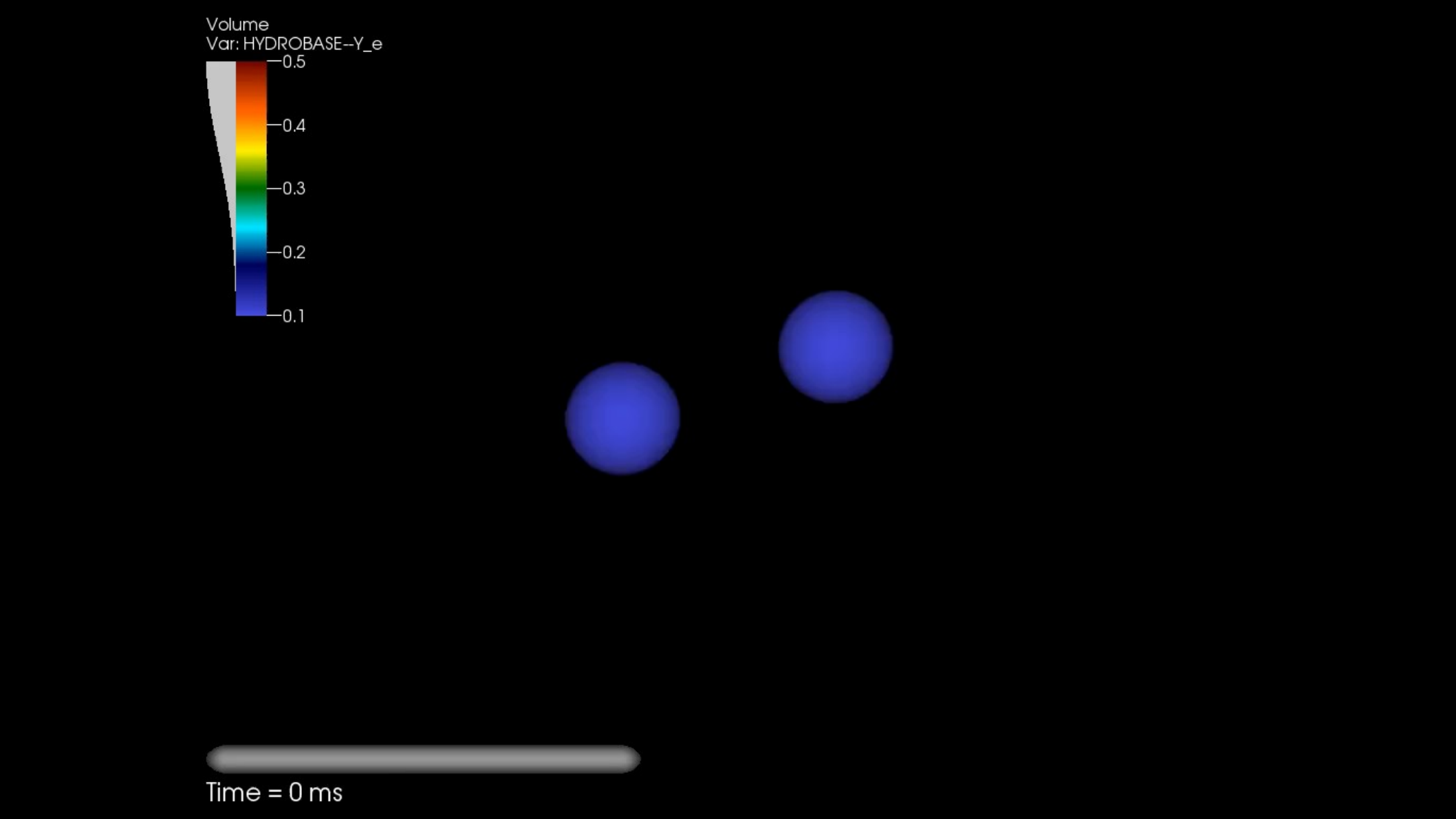
From Villar+ 2017

Neutrinos in neutron star mergers

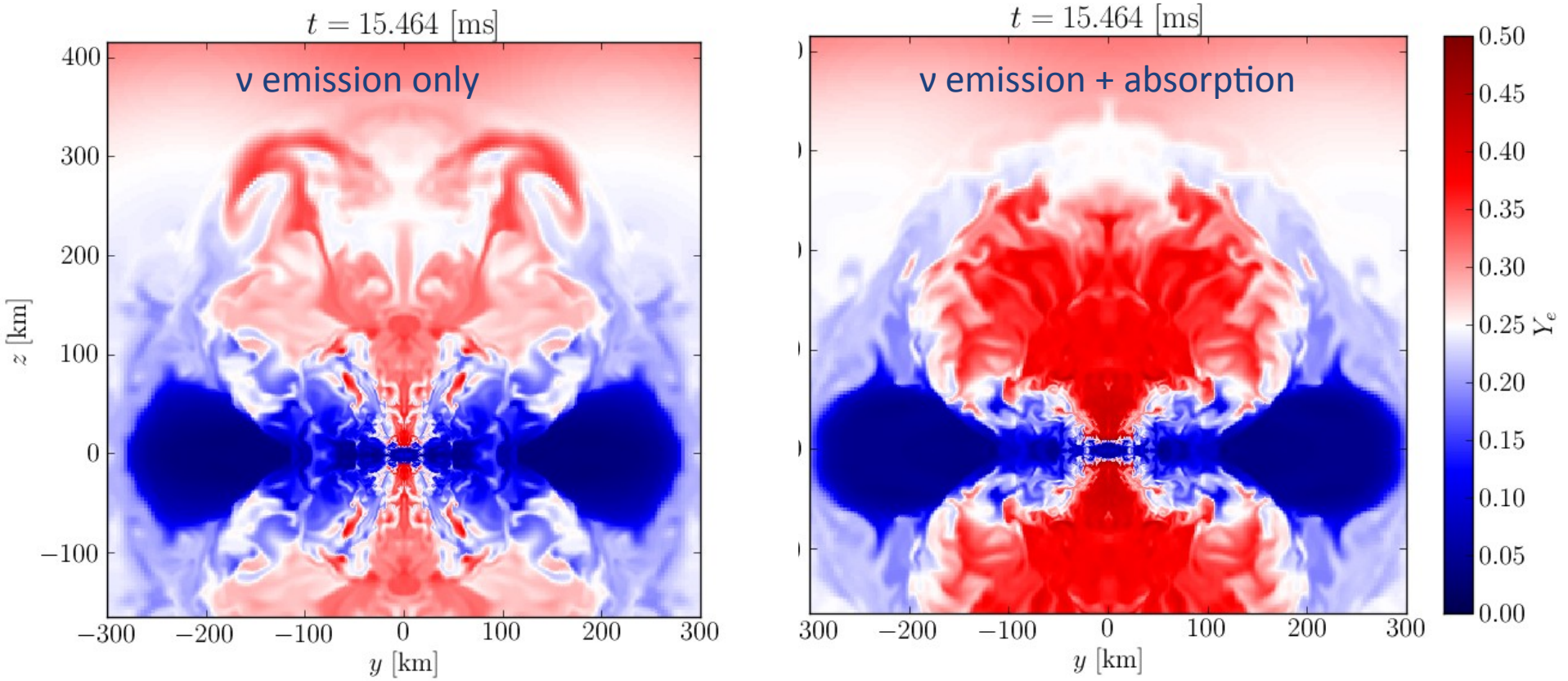


GW170817 ejecta was reprocessed by neutrinos!

From Villar+ 2017


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

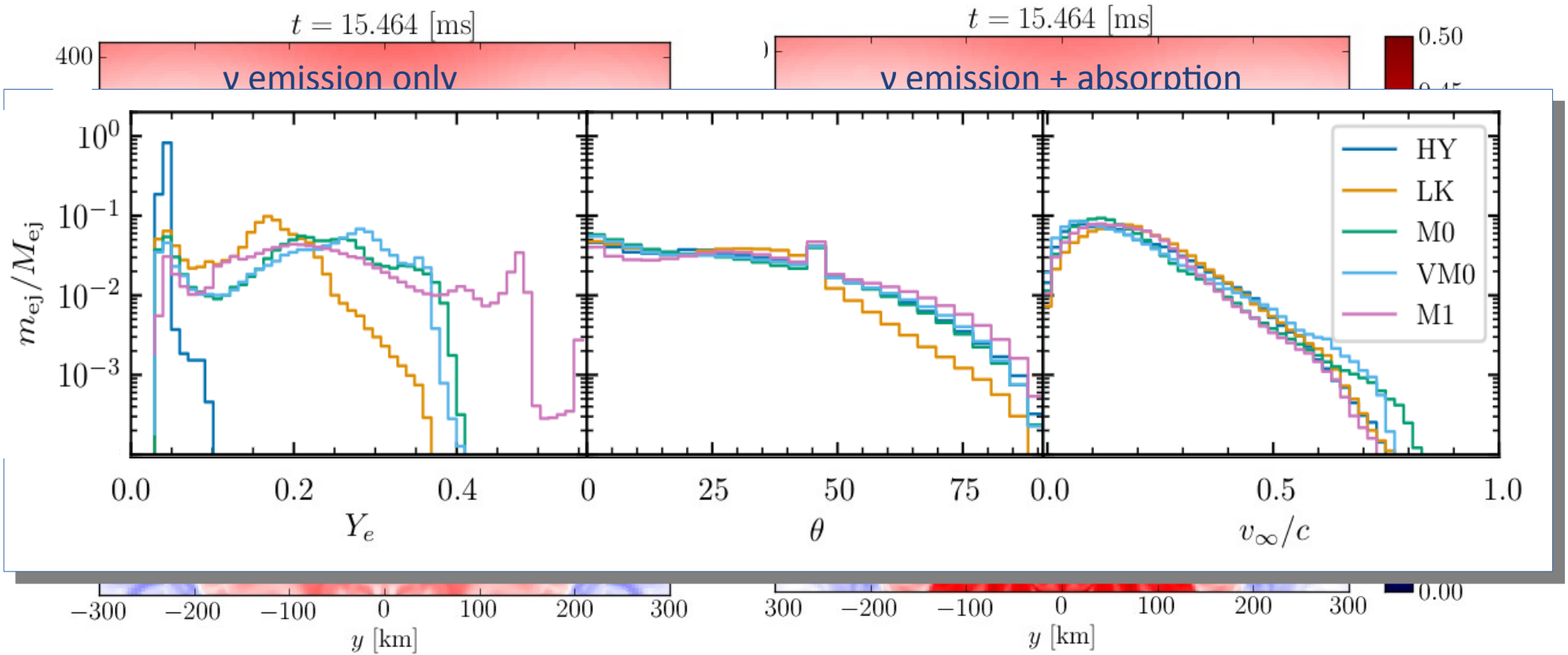
Neutrino effects on the eiecta



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

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

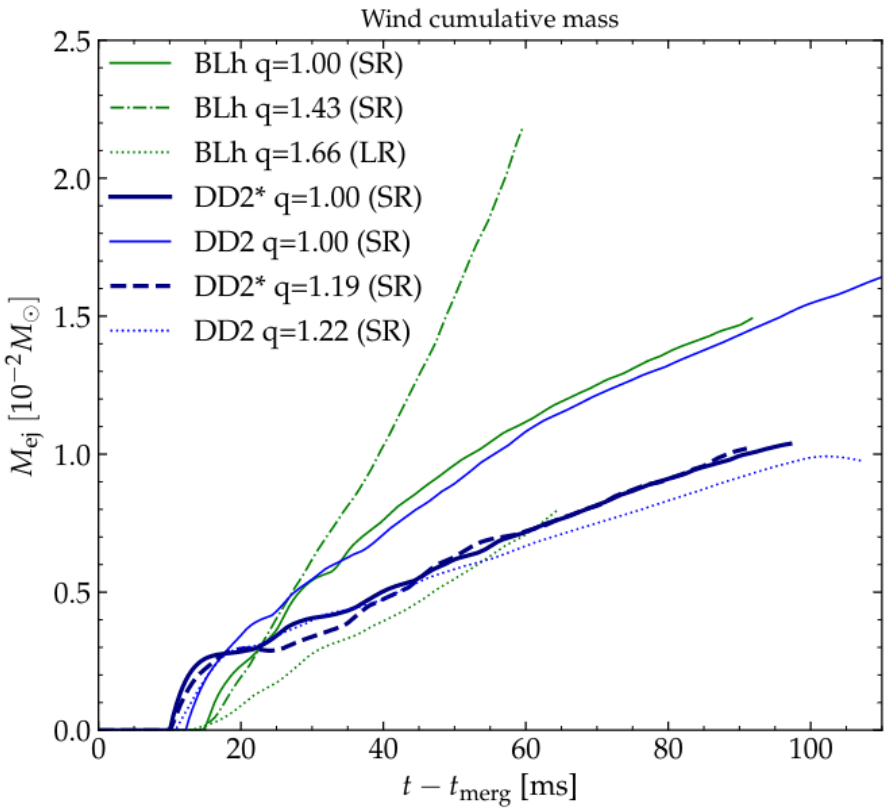
Neutrino effects on the eiecta

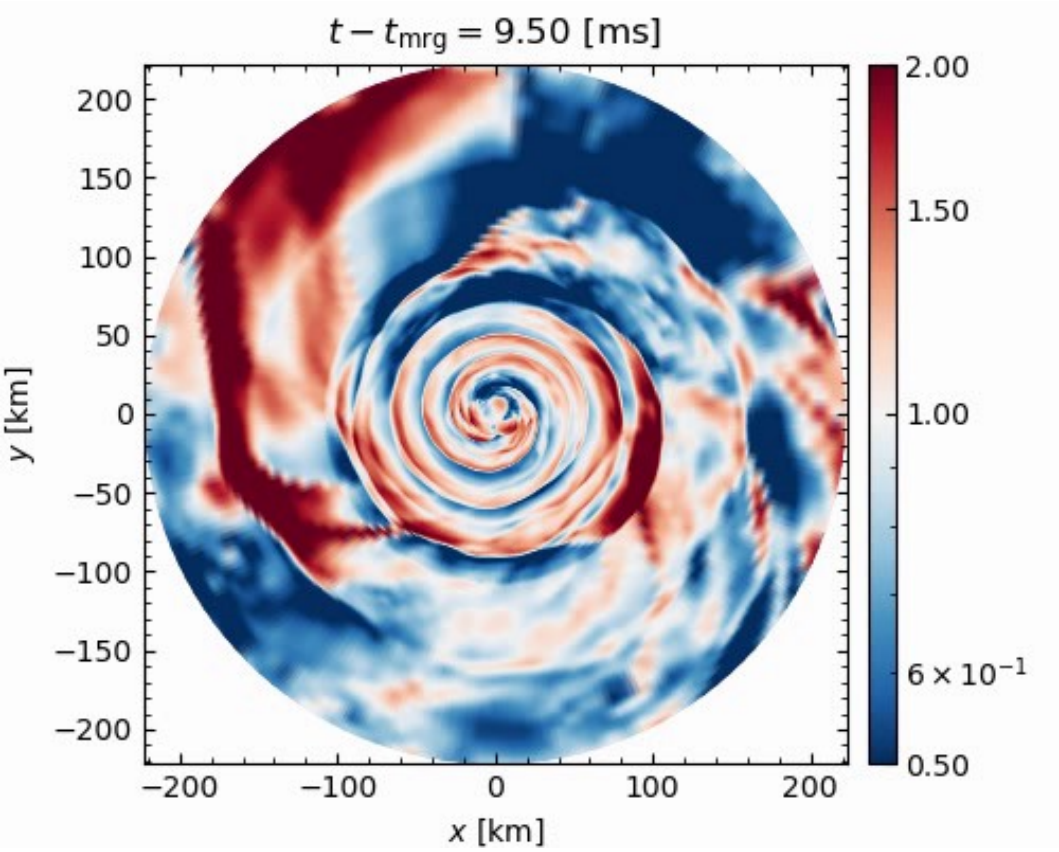


Radice+, MNRAS 460:3255 (2016)
Zappa+, MNRAS 520:1481 (2023)

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

Post-merger winds

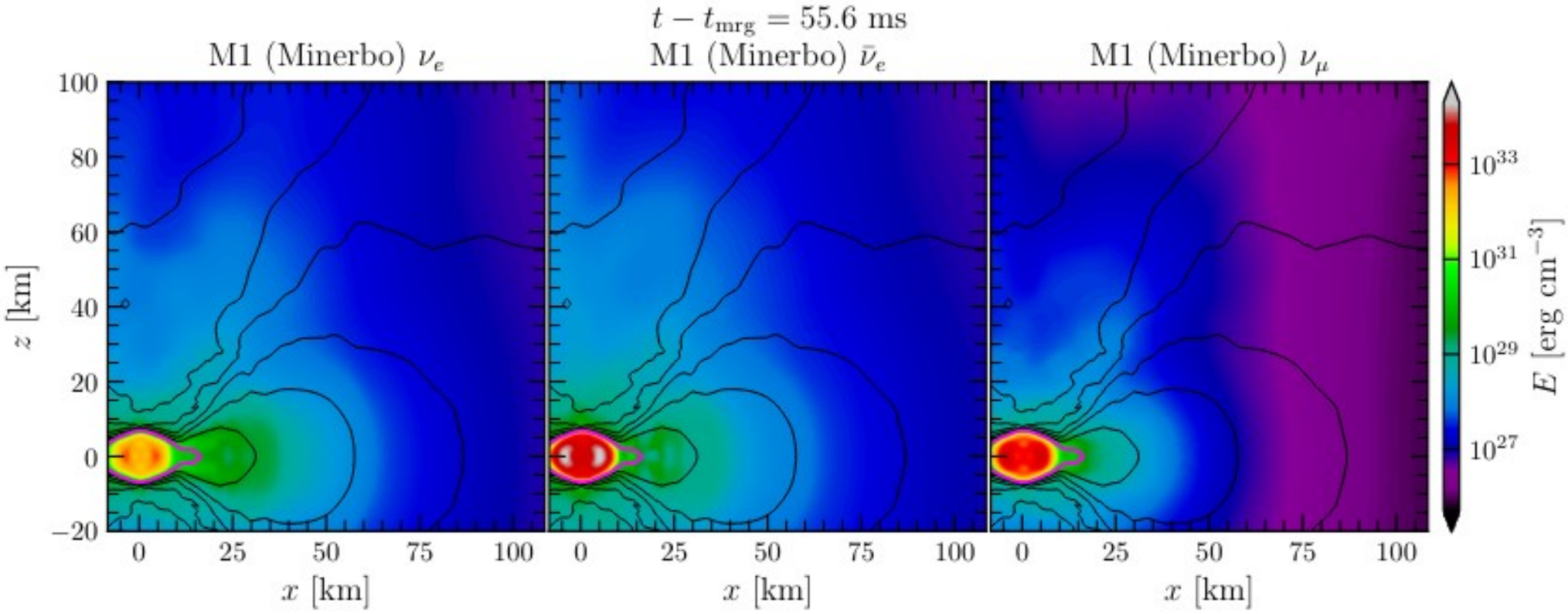




See also Siegel+ 2017; Fujibayashi+ 2018-2023; Radice+ 2018; Mösta+ 2020; Curtis+ 2023; Combi+ 2023; ...

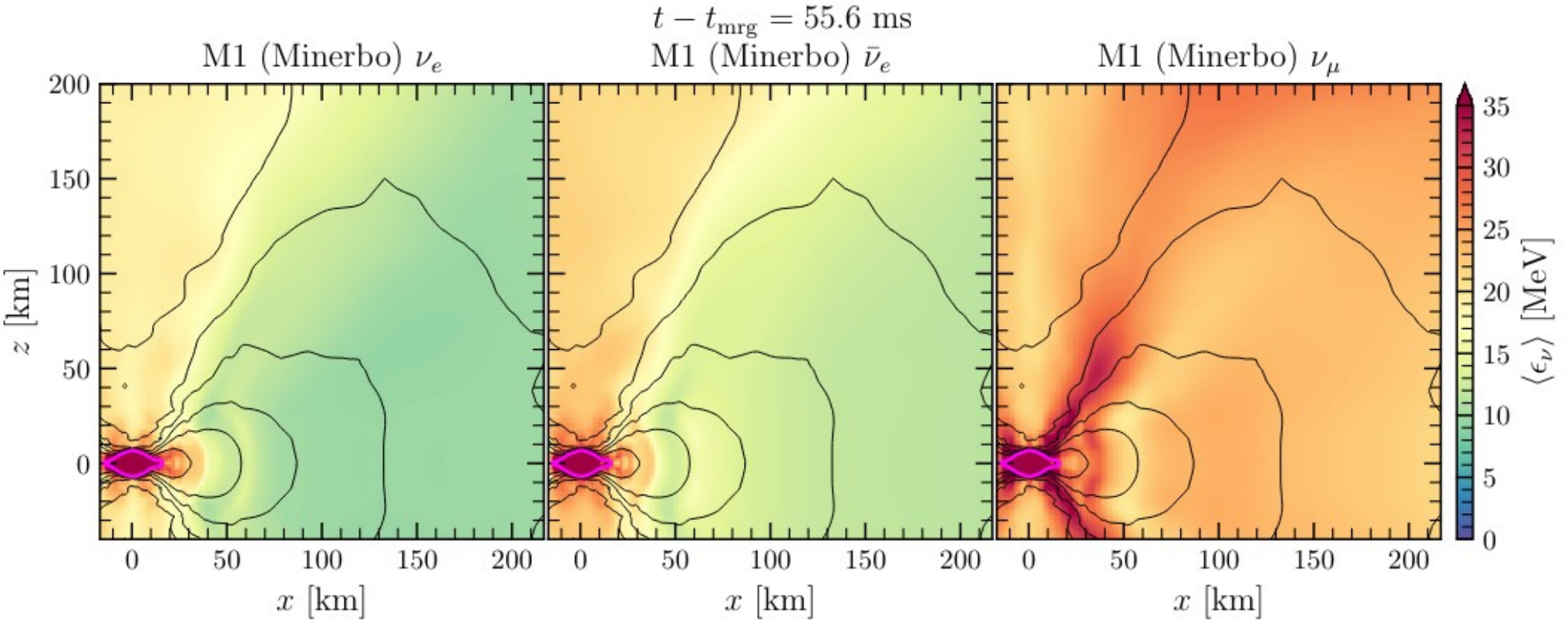
From Nedora+, ApJ 906:98 (2021); Radice+ 2306.13709

Neutrino field (I)



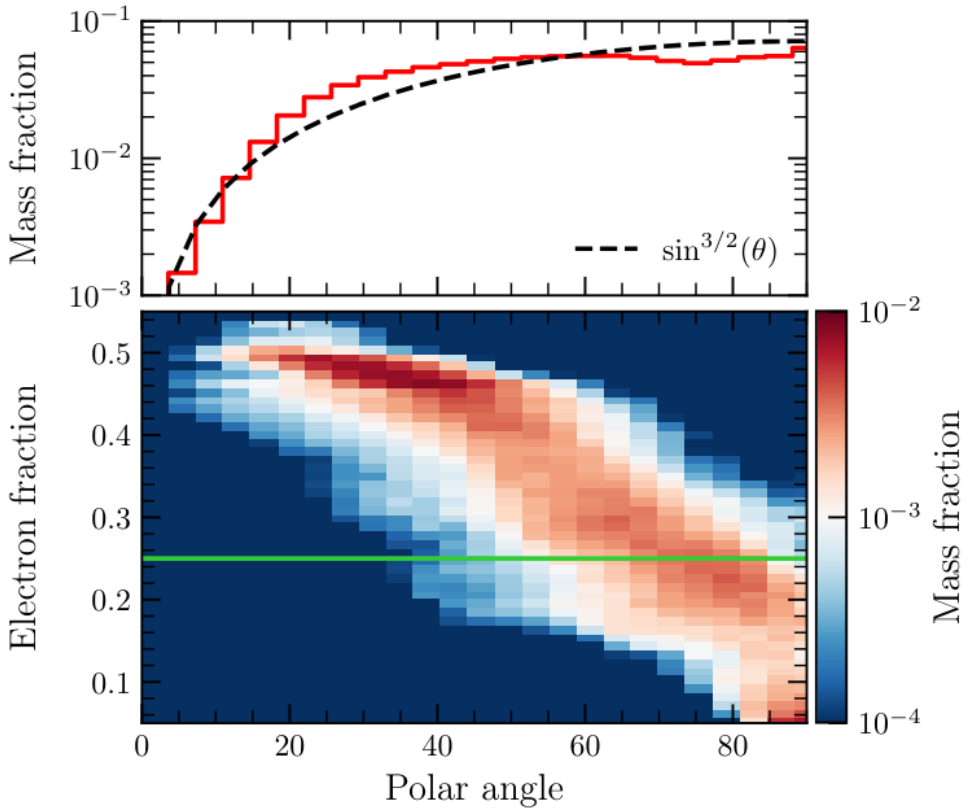
From Radice+ MNRAS 512:1499 (2022)

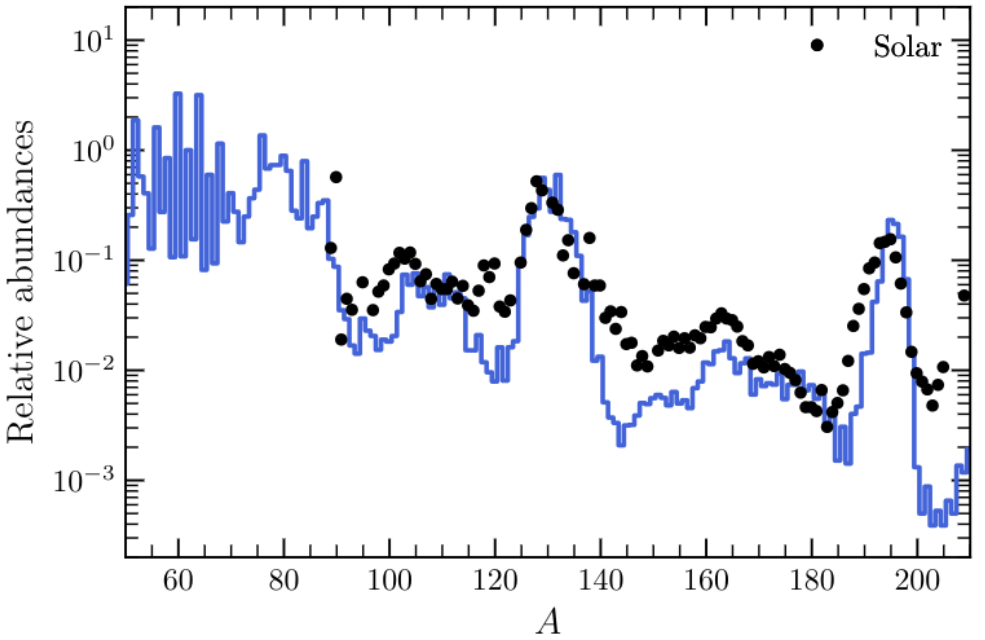
Neutrino field (II)



From Radice+ MNRAS 512:1499 (2022)

Secular outflows

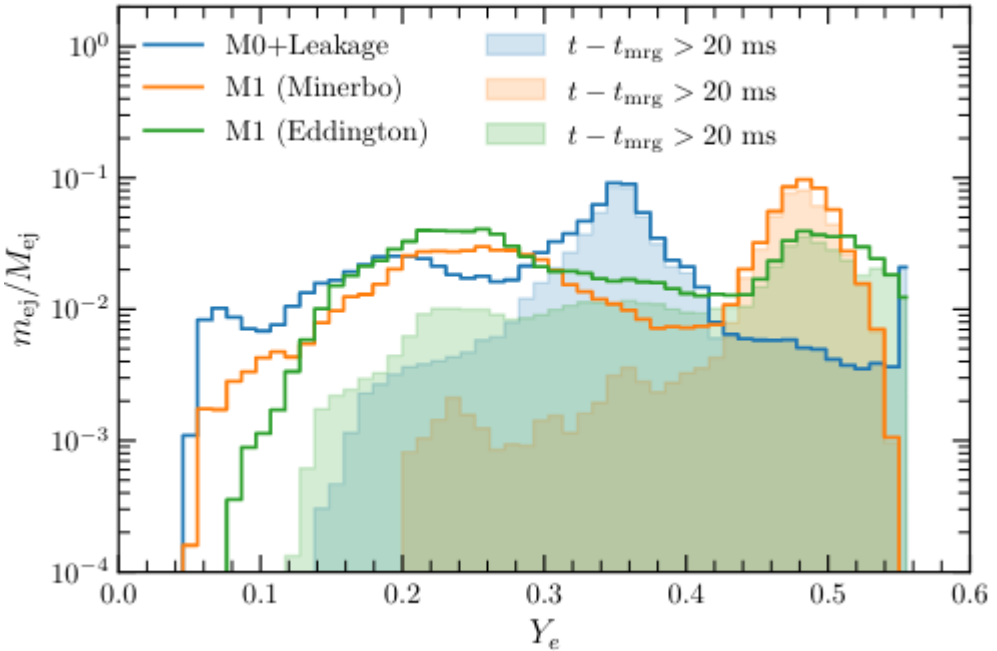


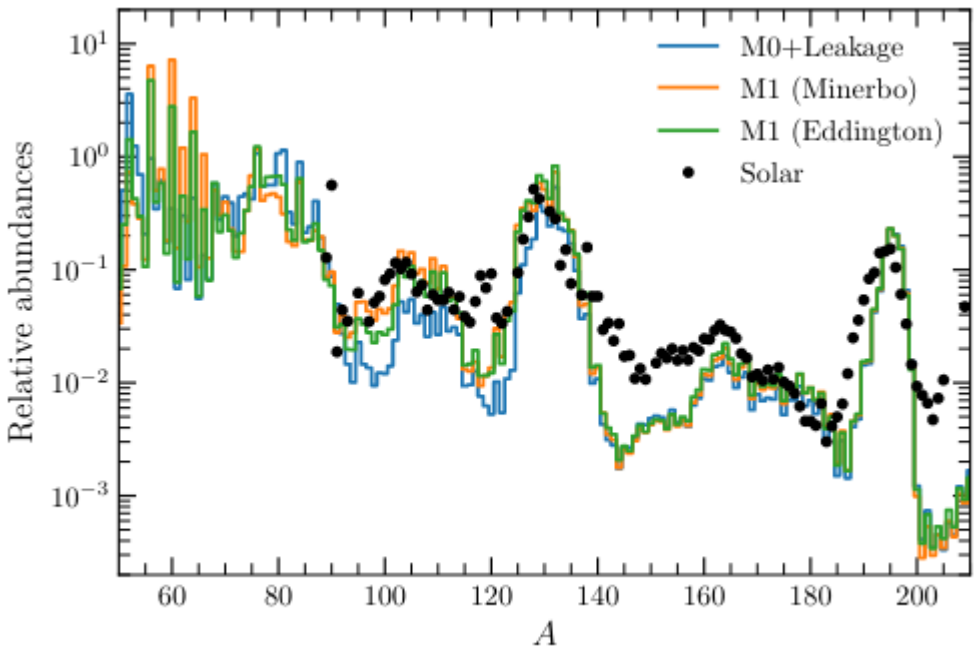


Spiral-wave wind naturally explains the blue kilonova and produces Solar r-process pattern

From Radice+ 2310.09934

Impact of neutrino treatment





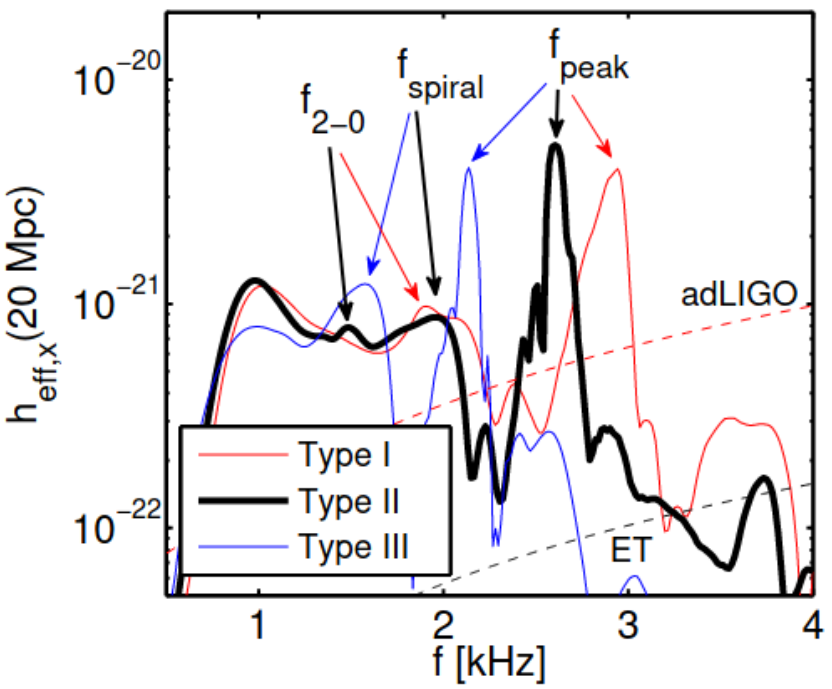
Accurate neutrino treatment is needed to calculate wind ejecta properties

See also Foucart+ 2016, 2020, 2021, Zappa+ 2023

From Radice+ MNRAS 512:1499 (2022)

Postmerger GW signal

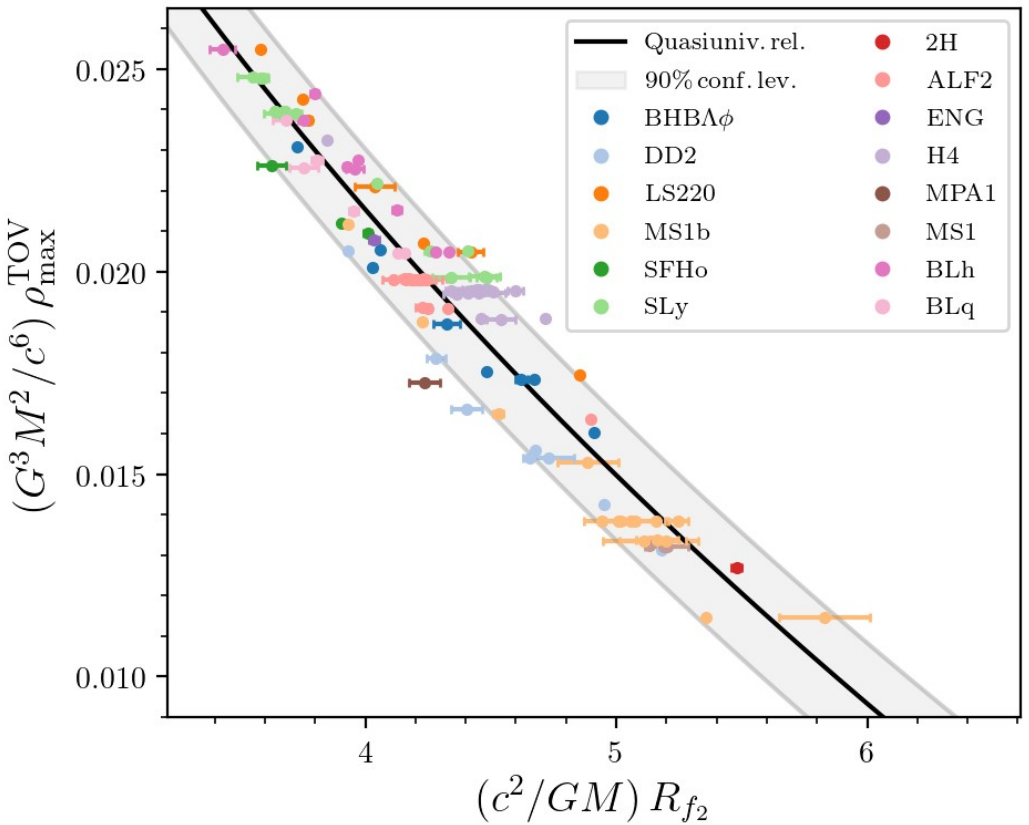
From Bauswein+ 2015

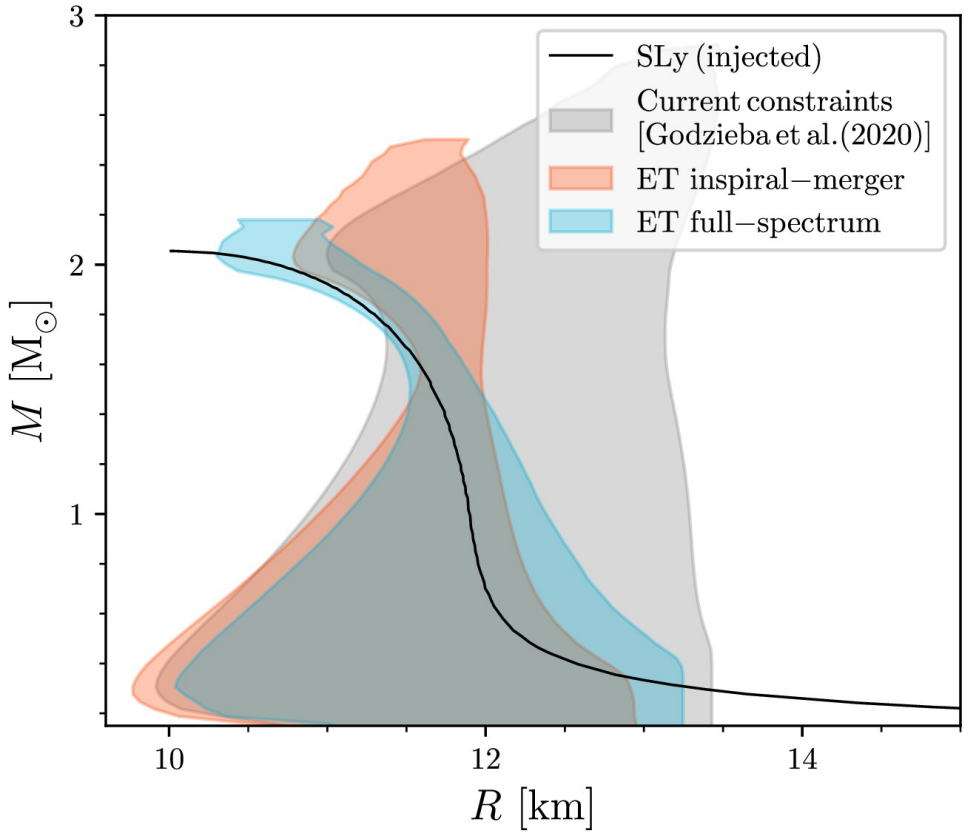


- Postmerger signal characterized by dominant frequency f_{peak}
- Need next gen. GW experiments, or very close (rare) events
- What can we learn from f_{peak}?
- Many ideas in the literature

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

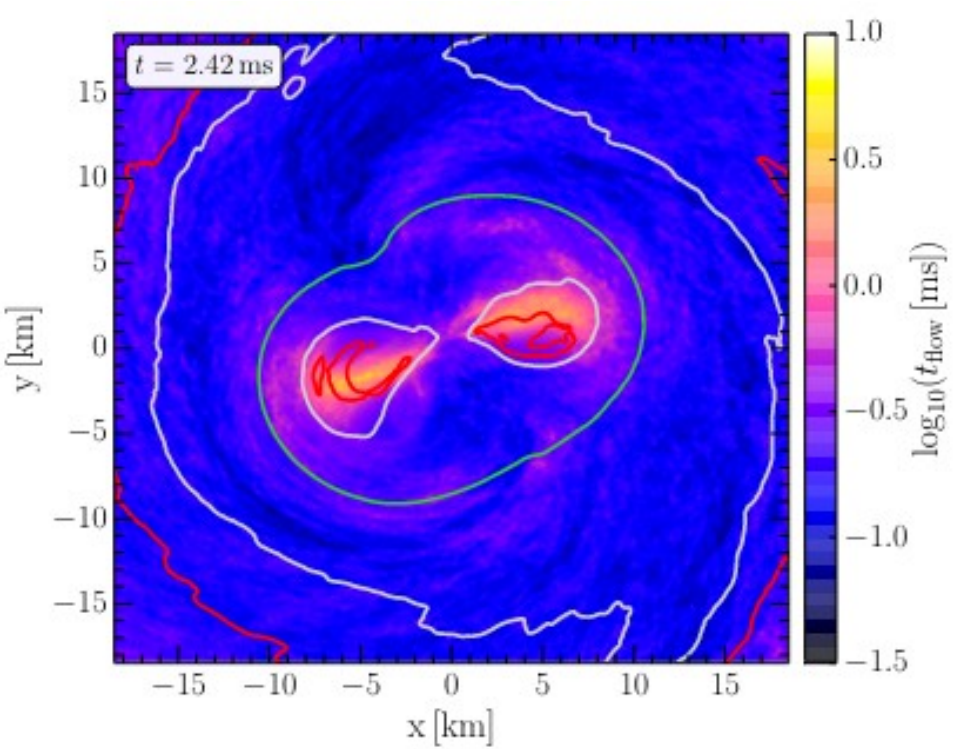
Universal relations





From Breschi+ PRL **128**:161102 (2022)

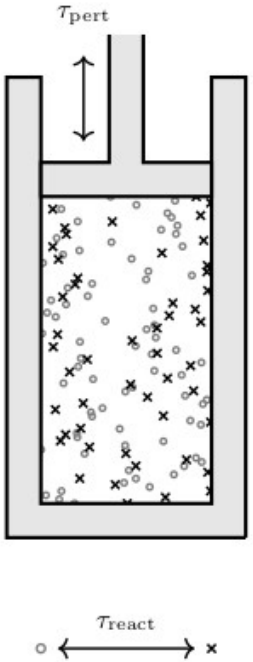
Bulk viscosity?

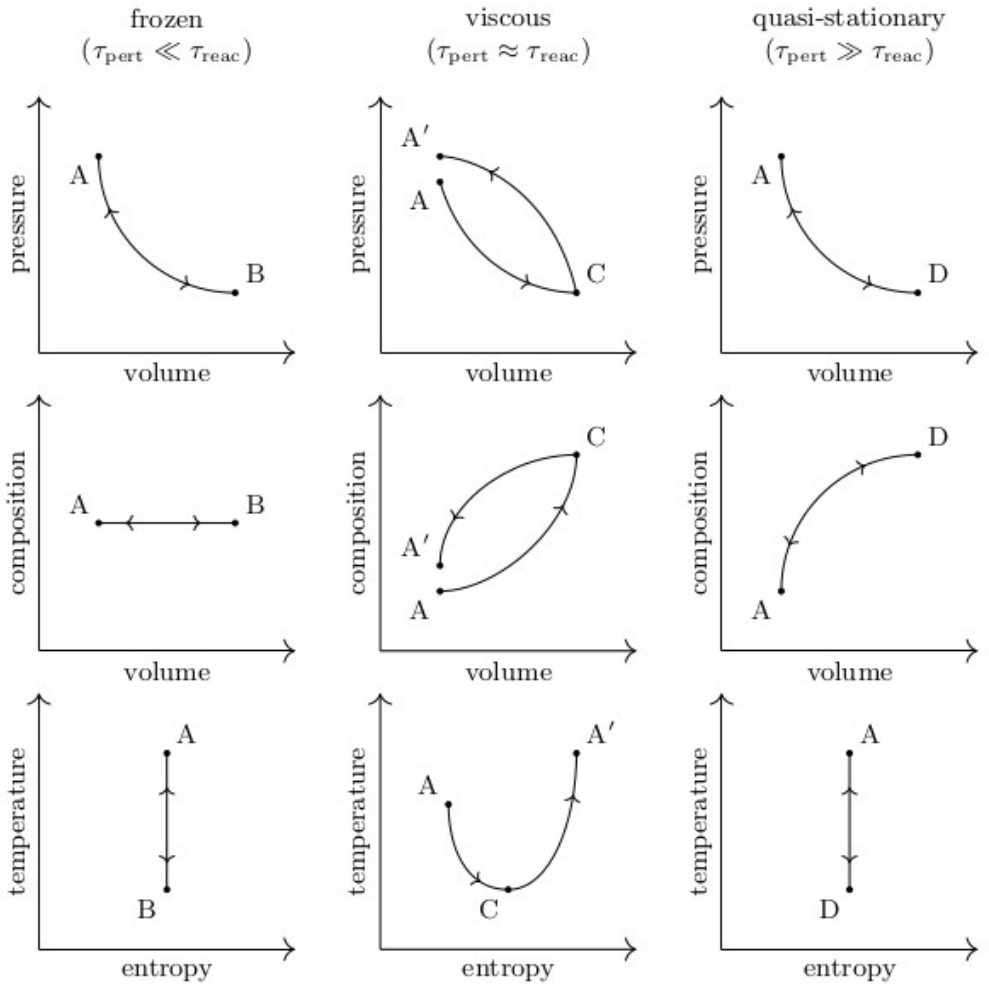


From Alford+ 2017

- 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
- Analogous to ε-mechanism in stars

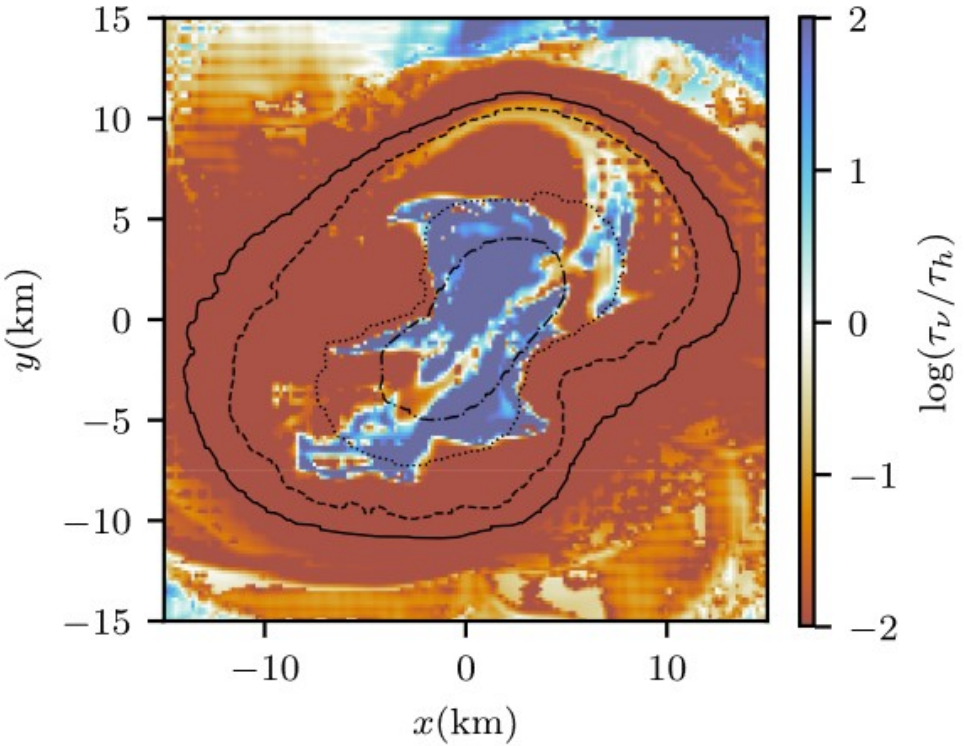
See also Perego+ 2019; Most+ 2021, 2022, 2024; Hammond+ 2021; Radice+ 2021; Espino 2024; ...

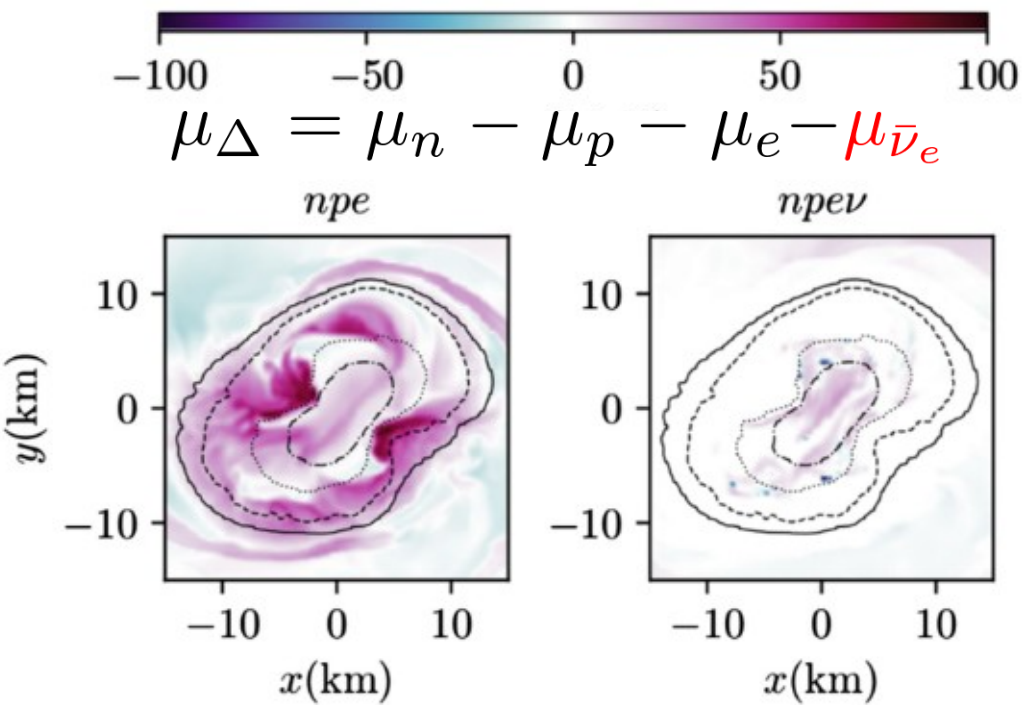




From Camelio+ PRD 107:103031 (2022) & 107:103032 (2022)

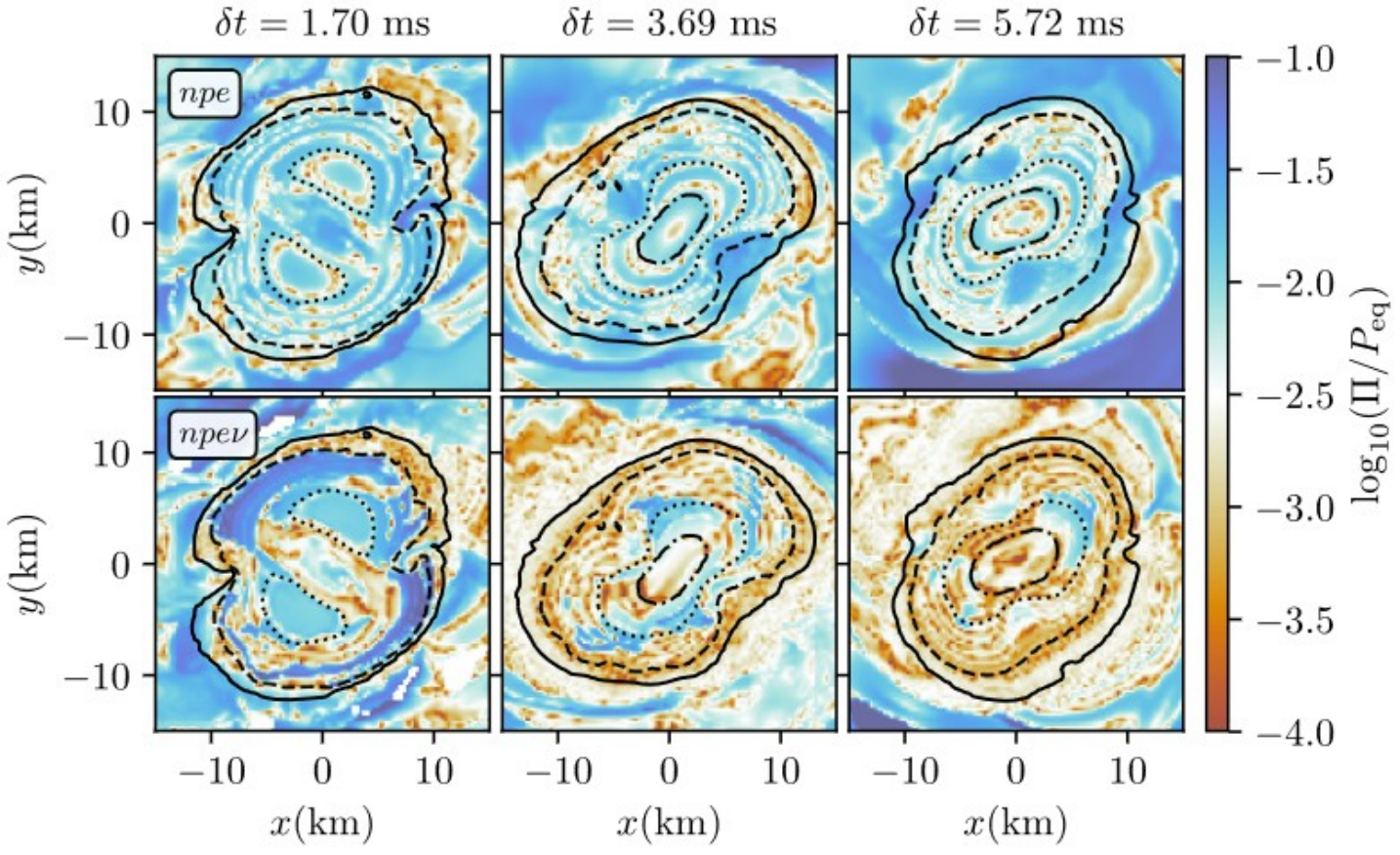
Thermodynamic equilibrium





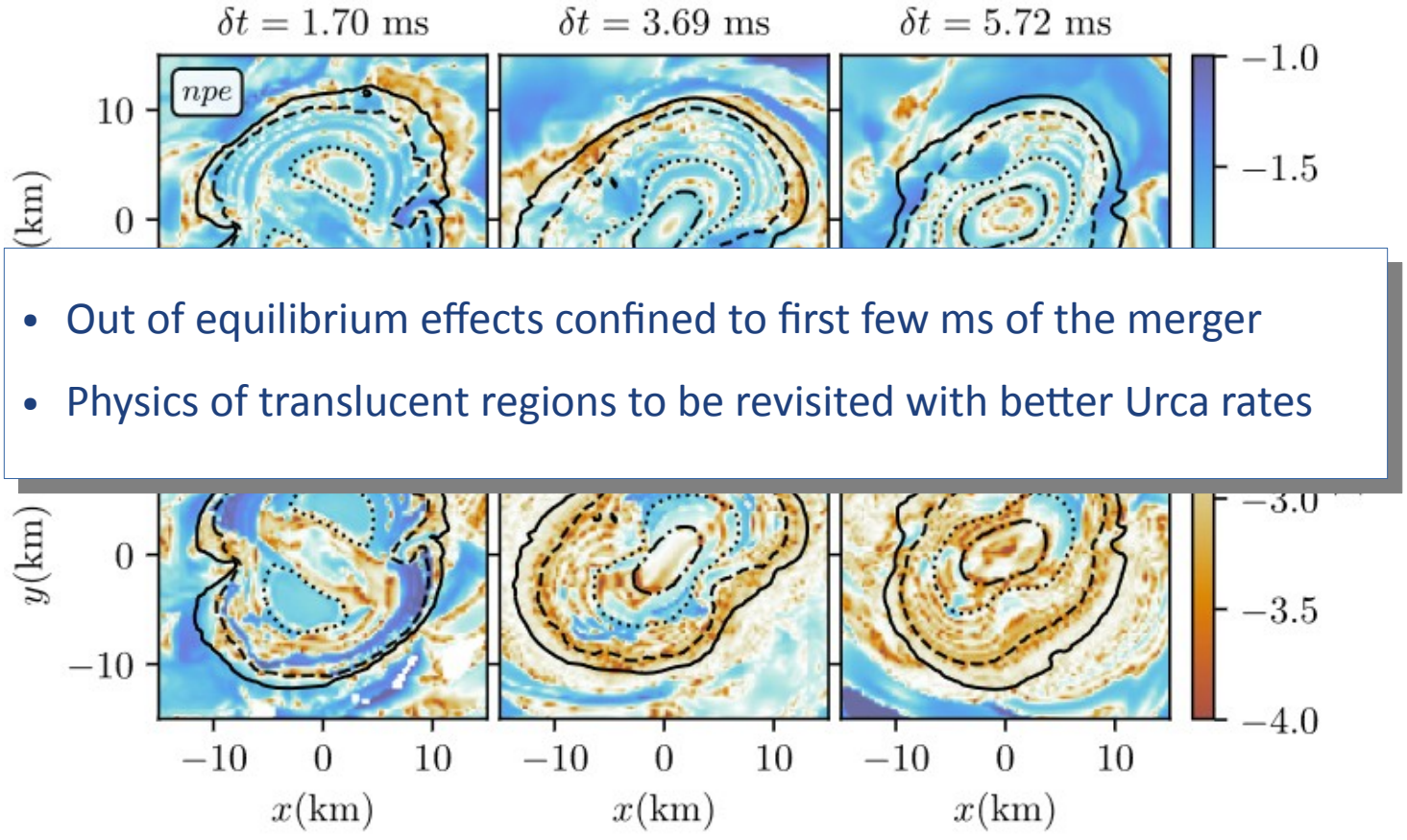
From Espino+ PRL 132:211001 (2024)

Bulk-viscous pressure



From Espino+ PRL 132:211001 (2024)

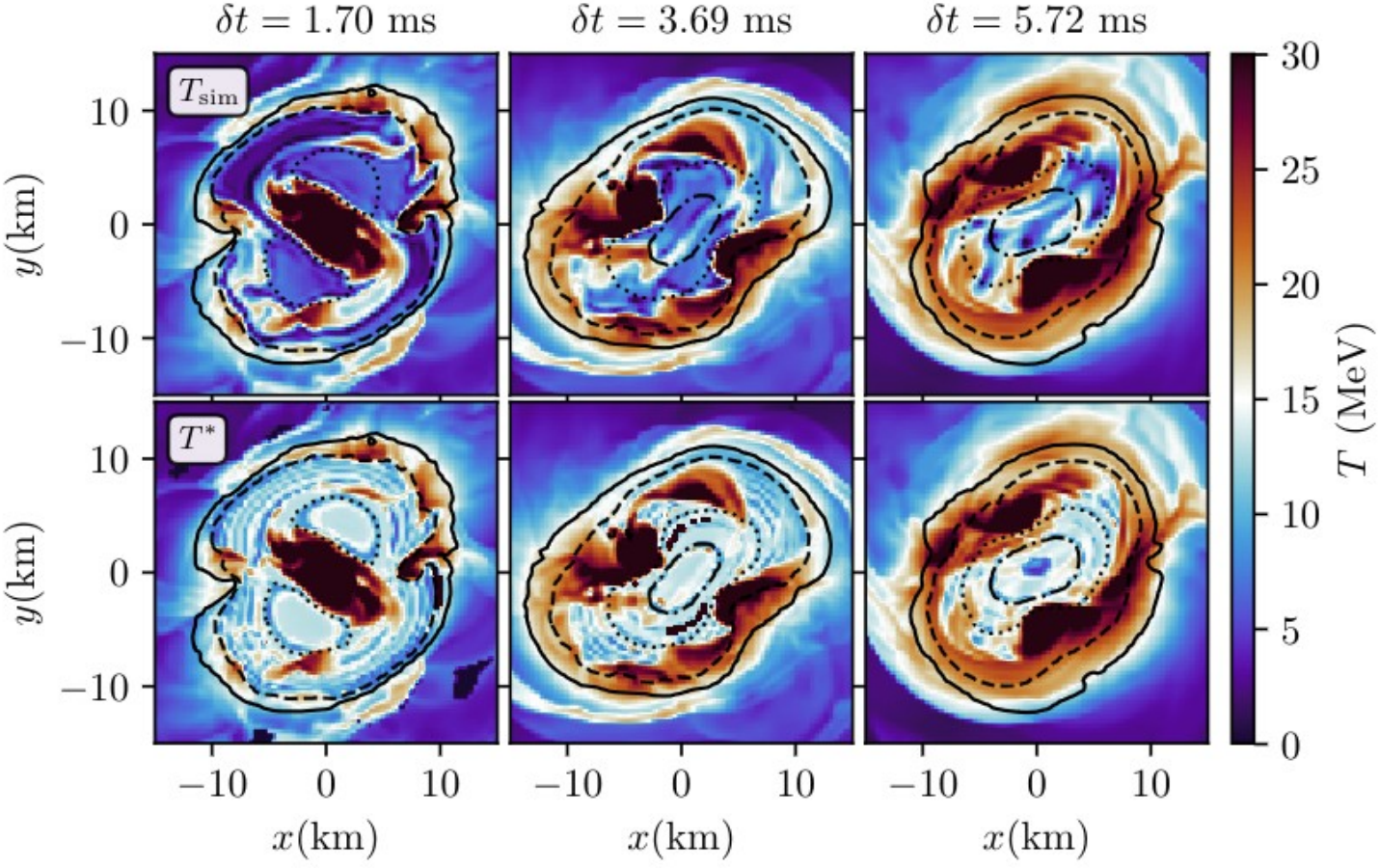
Bulk-viscous pressure



- Out of equilibrium effects confined to first few ms of the merger
- Physics of translucent regions to be revisited with better Urca rates

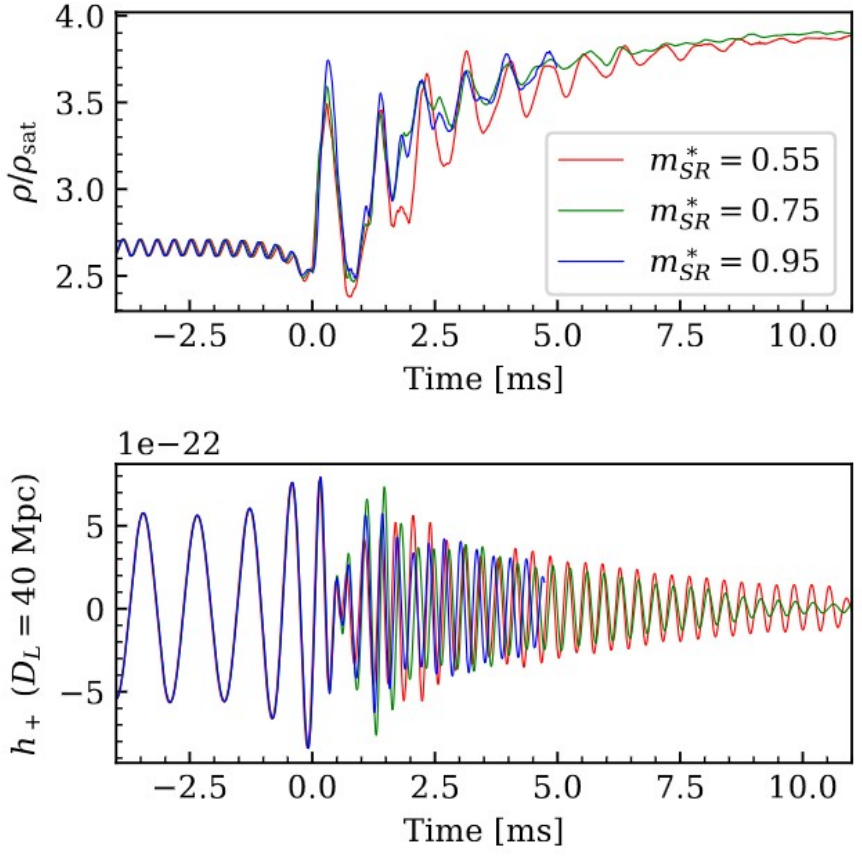
From Espino+ PRL 132:211001 (2024)

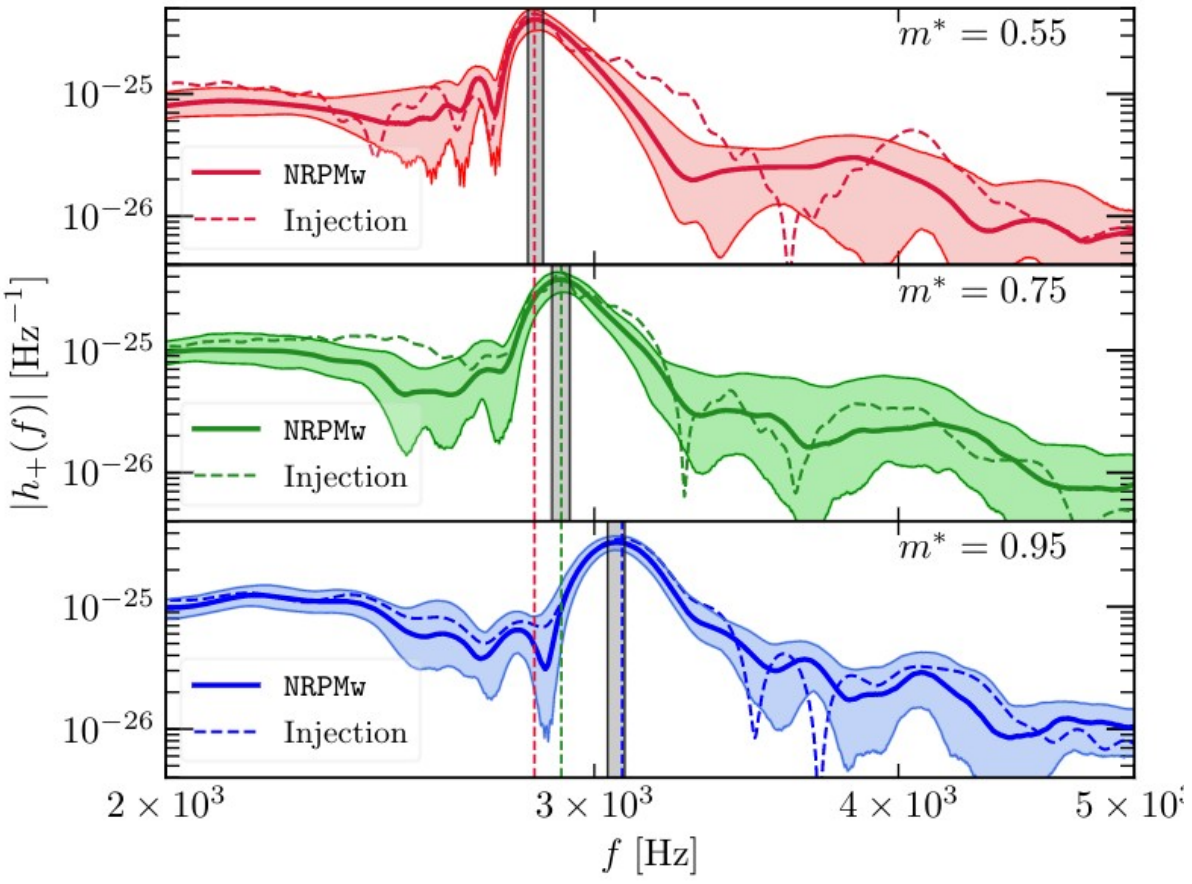
Equilibrium temperature



From Espino+ PRL 132:211001 (2024)

Thermal effects

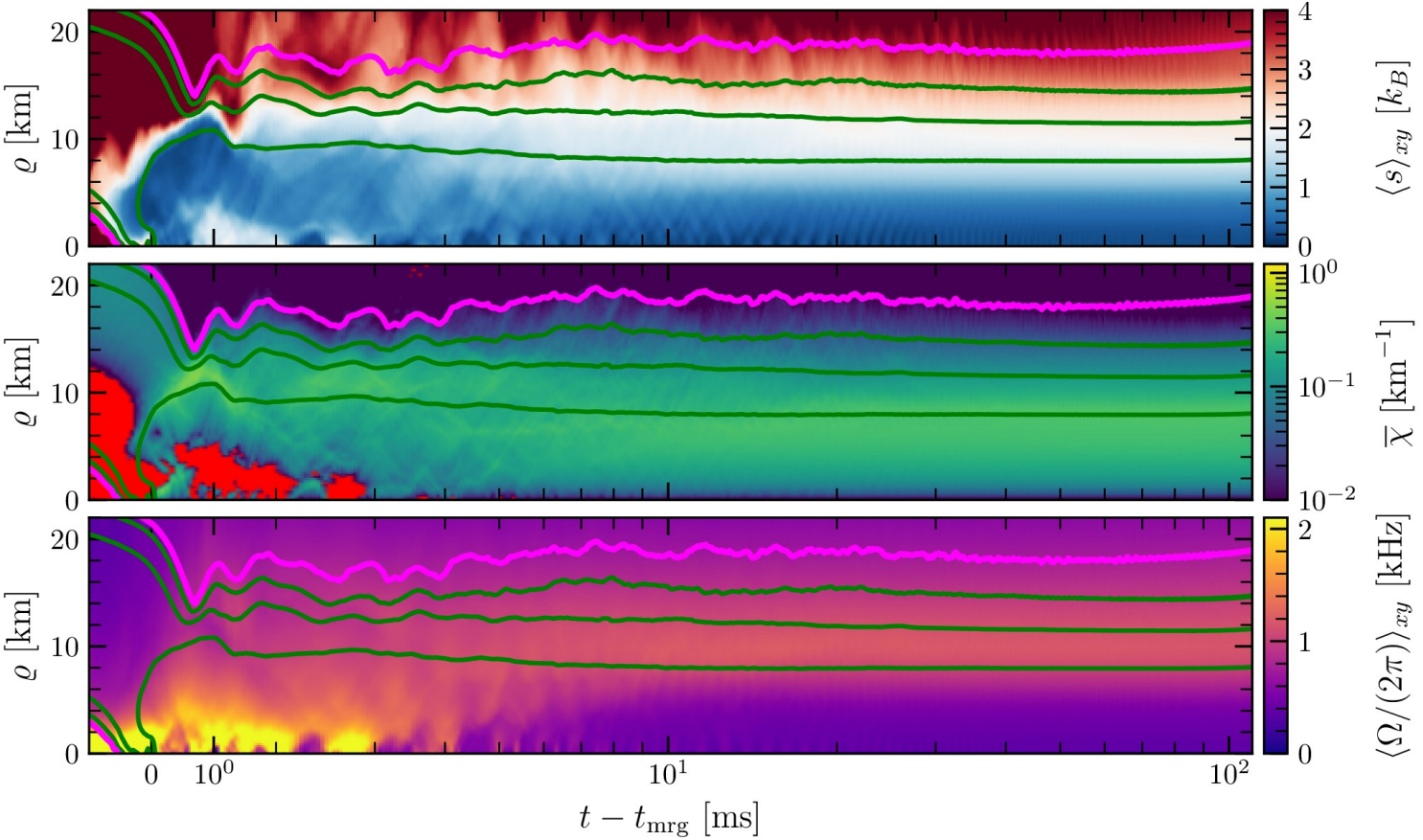




See also Raithel+ 2021, 2022

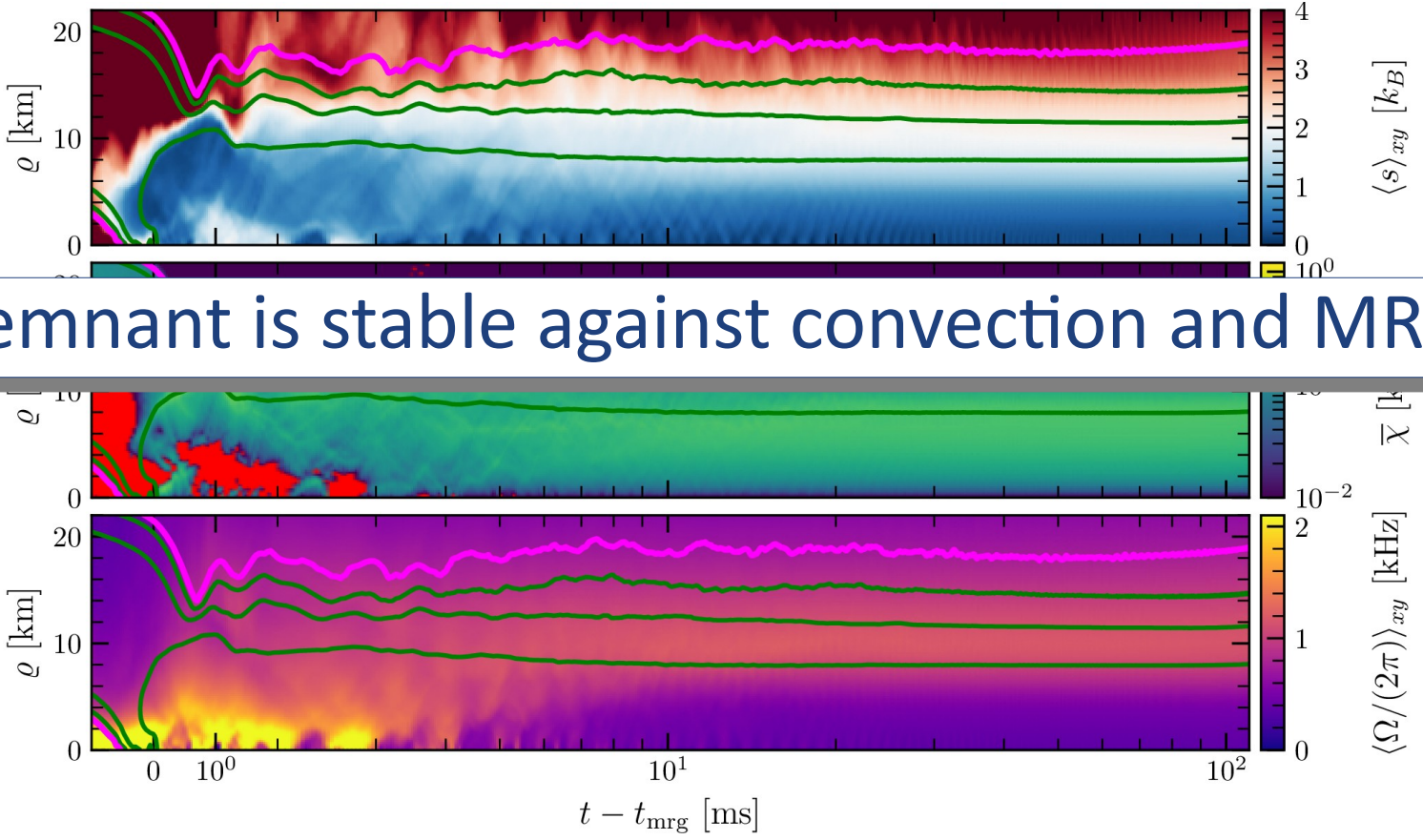
From Fields+ ApJL, 952:L36 (2023)

Structure of long-lived remnants



From Radice+ 2306.13709

Structure of long-lived remnants

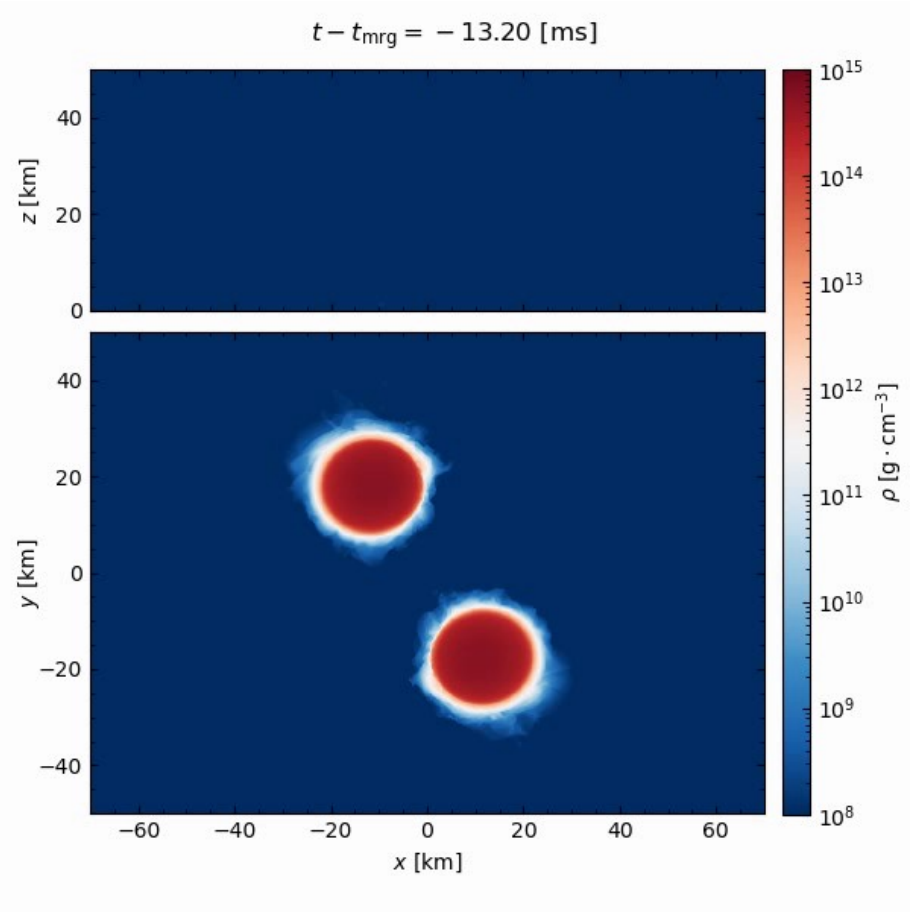


Remnant is stable against convection and MRI!

From Radice+ 2306.13709

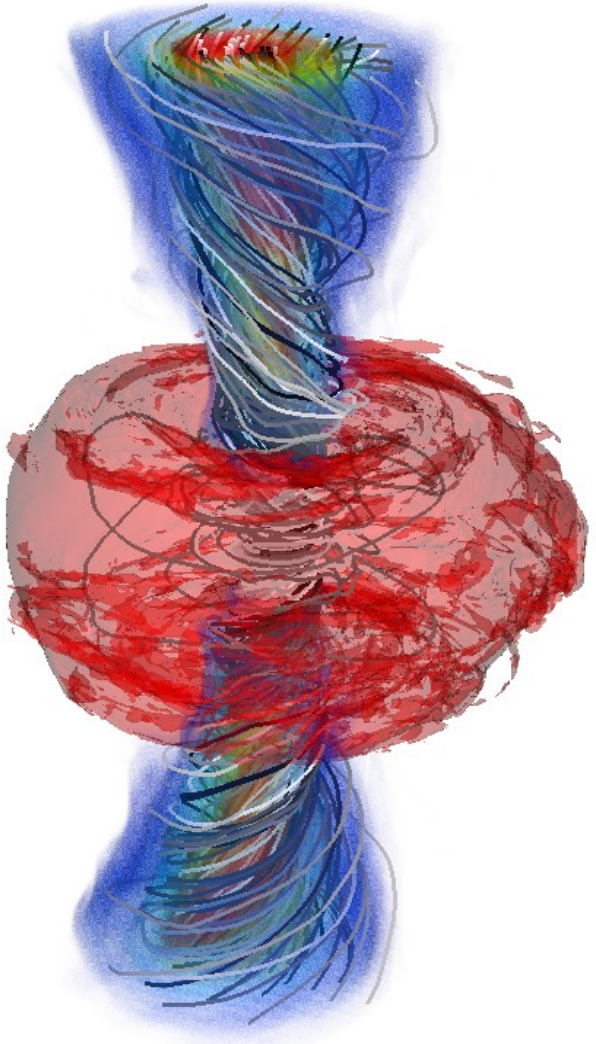
Conclusions

- Neutrinos impact the dynamics and outflow composition in NS mergers
- Neutrinos and matter are in thermodynamic equilibrium in the remnant
- Finite temperature effects in the postmerger will be detectable with next-generation GW experiments
- Good qualitative agreement between simulations and kilonova observations



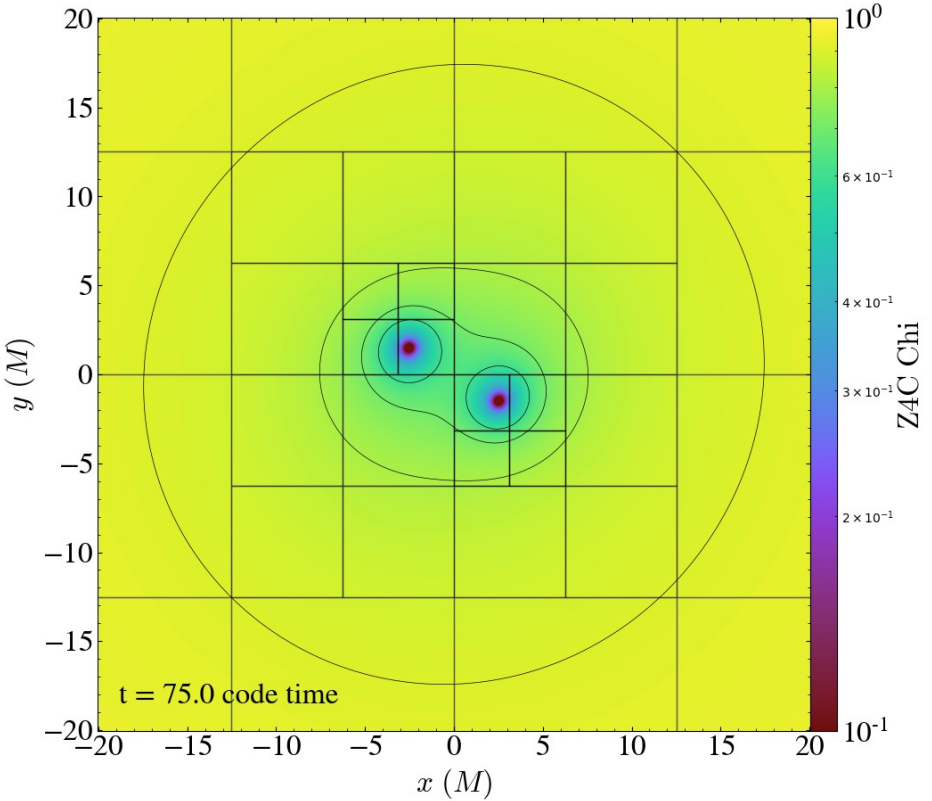
Challenges

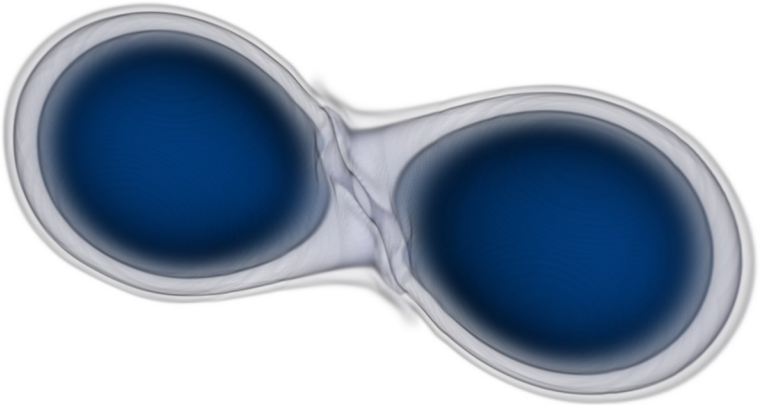
- Long-term GRMHD simulations to understand the full extent of the mass ejection from remnants
- Capture MHD turbulence and dynamo processes in the remnant
- Urca rates in merger conditions neutrino radiation transport
- Neutrino flavor conversion

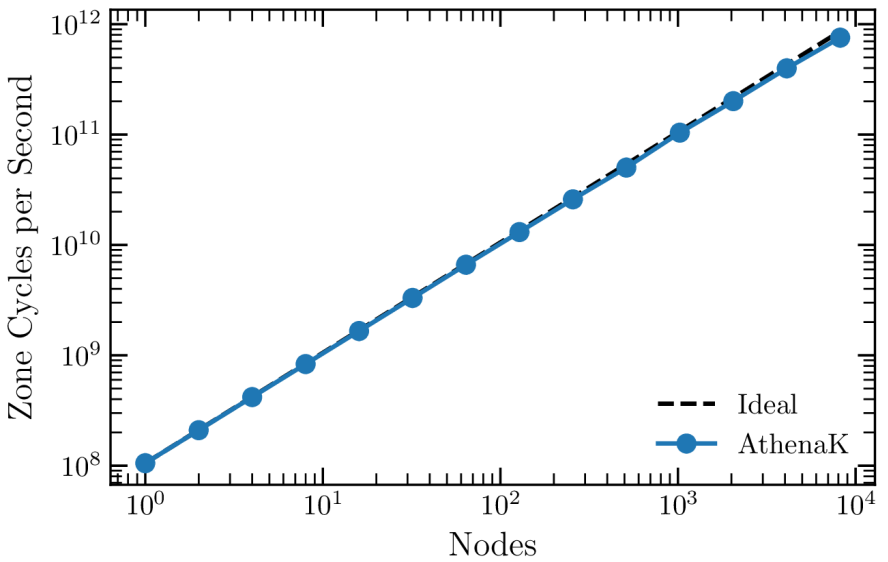


From Moesta+ ApJL, 901:L37 (2020)

AthenaK







From Zhu in prep; Fields in prep