

Title: Neutron Star Mergers and AthenaK

Speakers: David Radice

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 27, 2025 - 9:00 AM

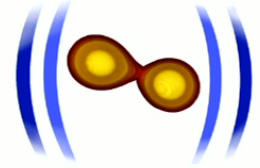
URL: <https://pirsa.org/25030086>

Abstract:

In this talk, I will explore key open questions in our understanding of neutron star mergers and their multi-messenger emission, highlighting recent progress made by our group. I will then introduce some of the first applications of AthenaK to compact binary mergers and outline our plans for its future development.



PennState
Eberly College of Science



CoRe collaboration

Neutron Star Mergers, **AICs**, and AthenaK

David Radice – March 27, 2025



Network for Neutrinos,
Nuclear Astrophysics,
and Symmetries

PHYSICS FRONTIER CENTER



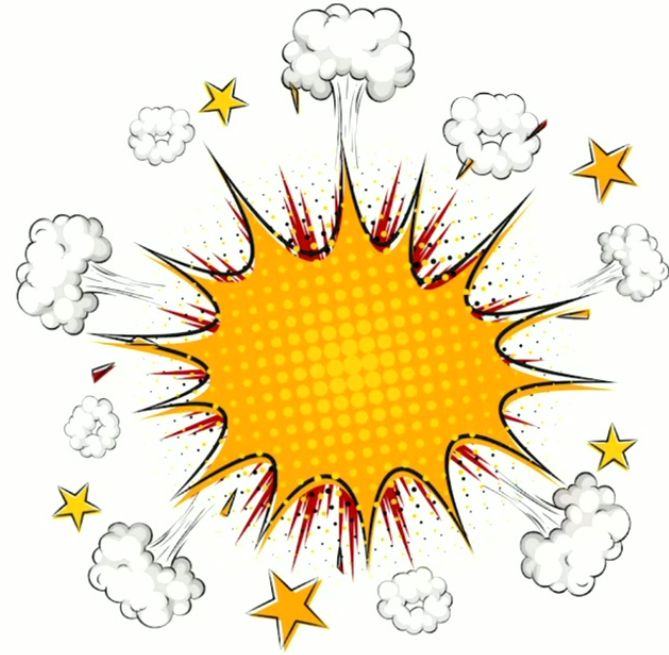
Recipe for making gold

- Take any material



Recipe for making gold

- Take any material
- Compress to twice nuclear density (*)
- Let it go!



(*) Do not do this at home!

Does it really work?

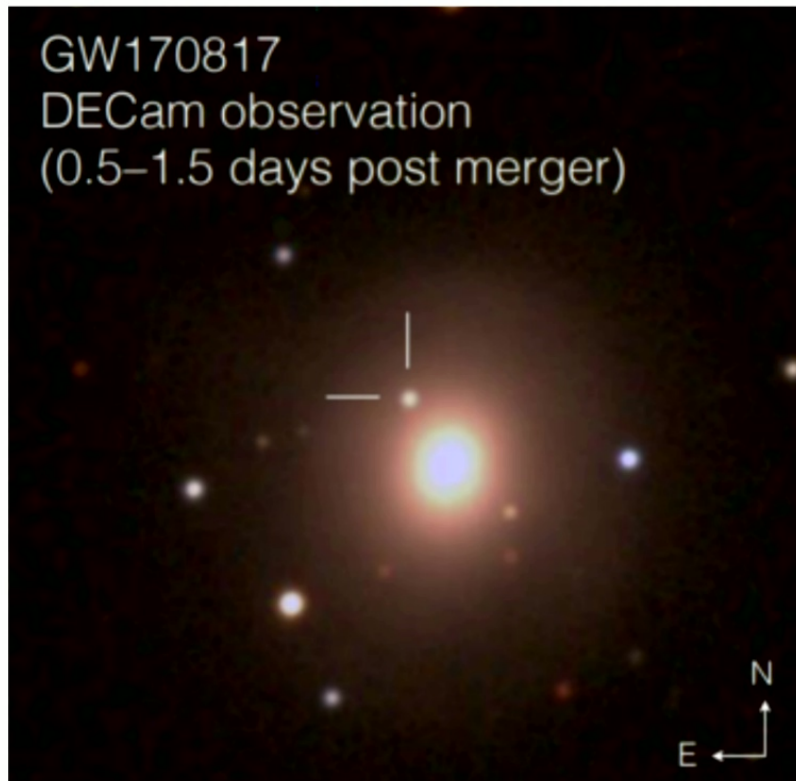


FRIB at MSU

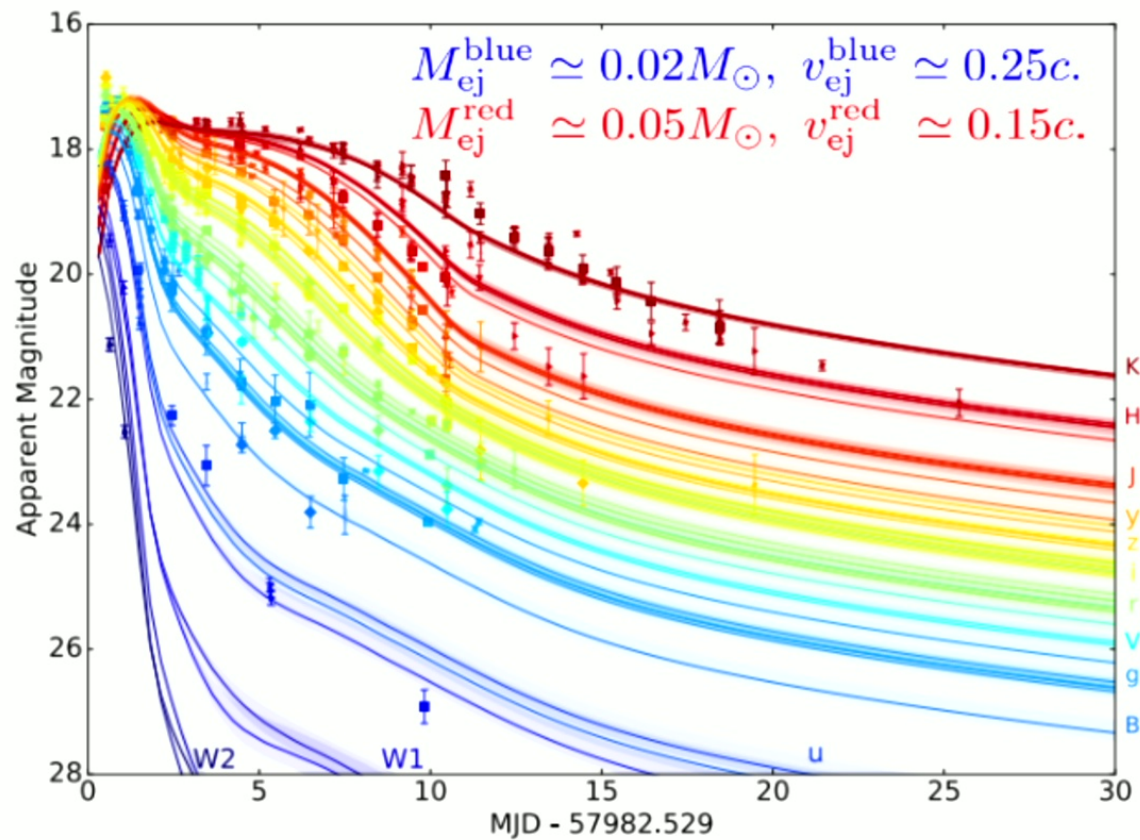


TRIUMF, Vancouver

R-process in neutron star mergers

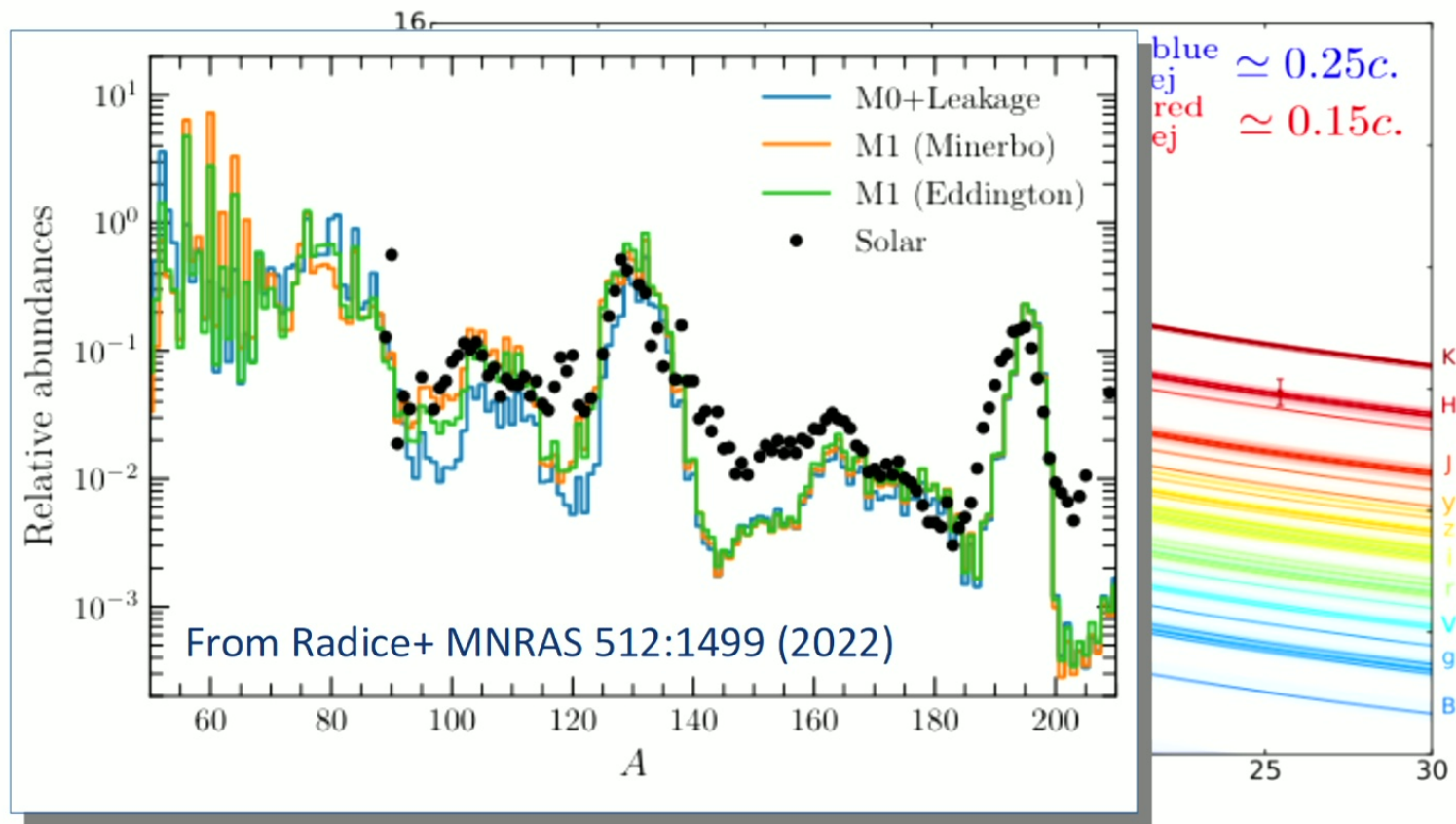


R-process in neutron star mergers

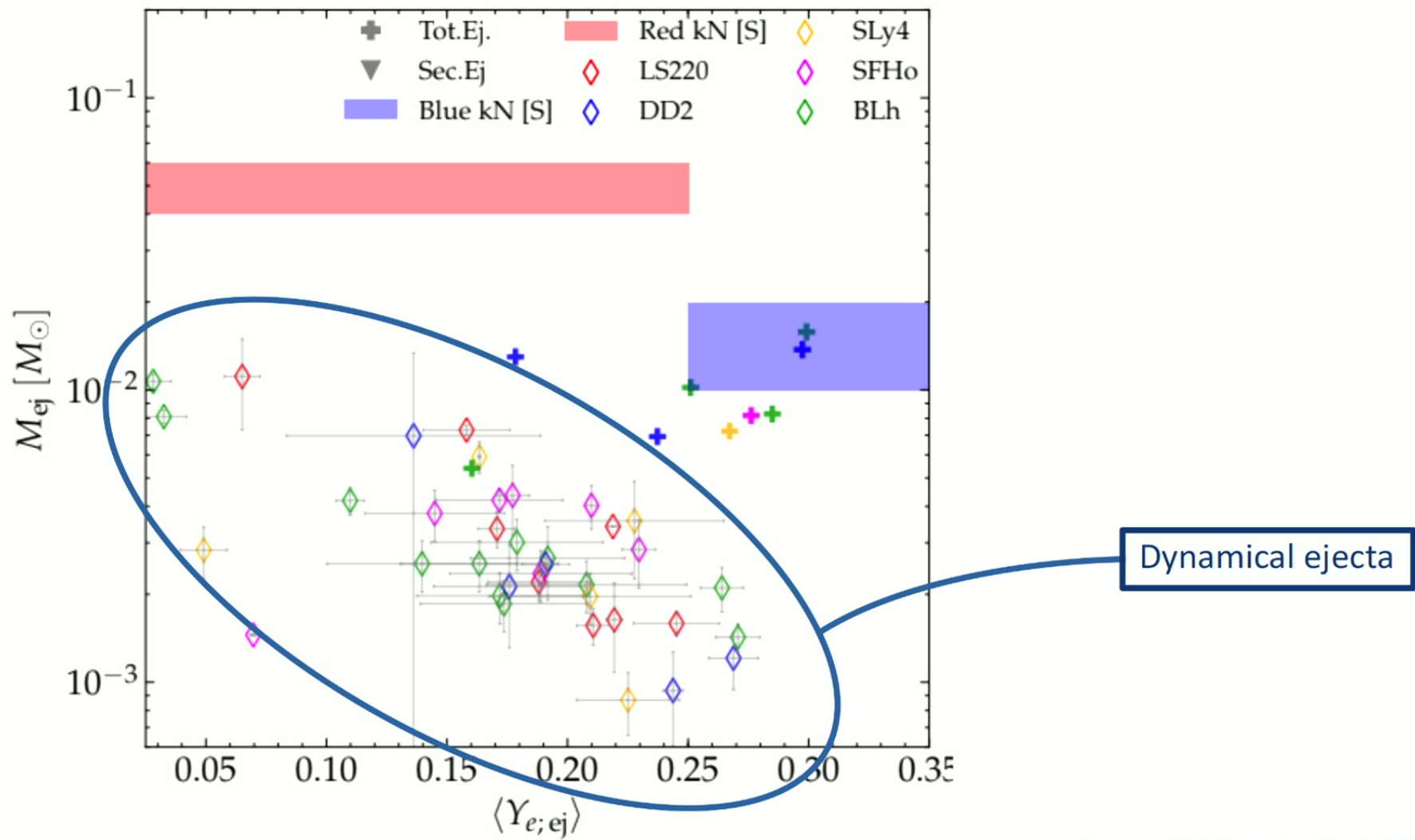


From Villar+ 2017

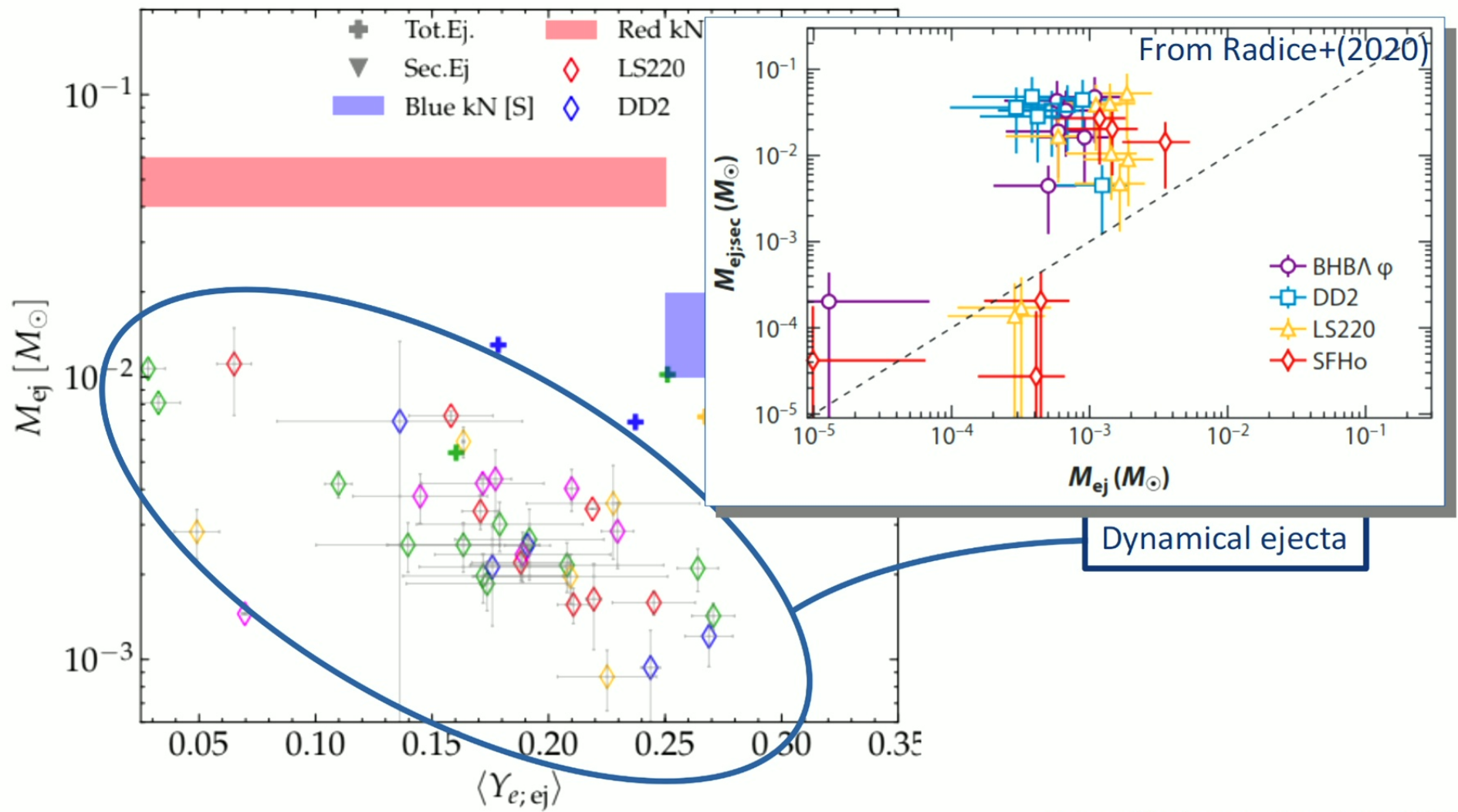
R-process in neutron star mergers



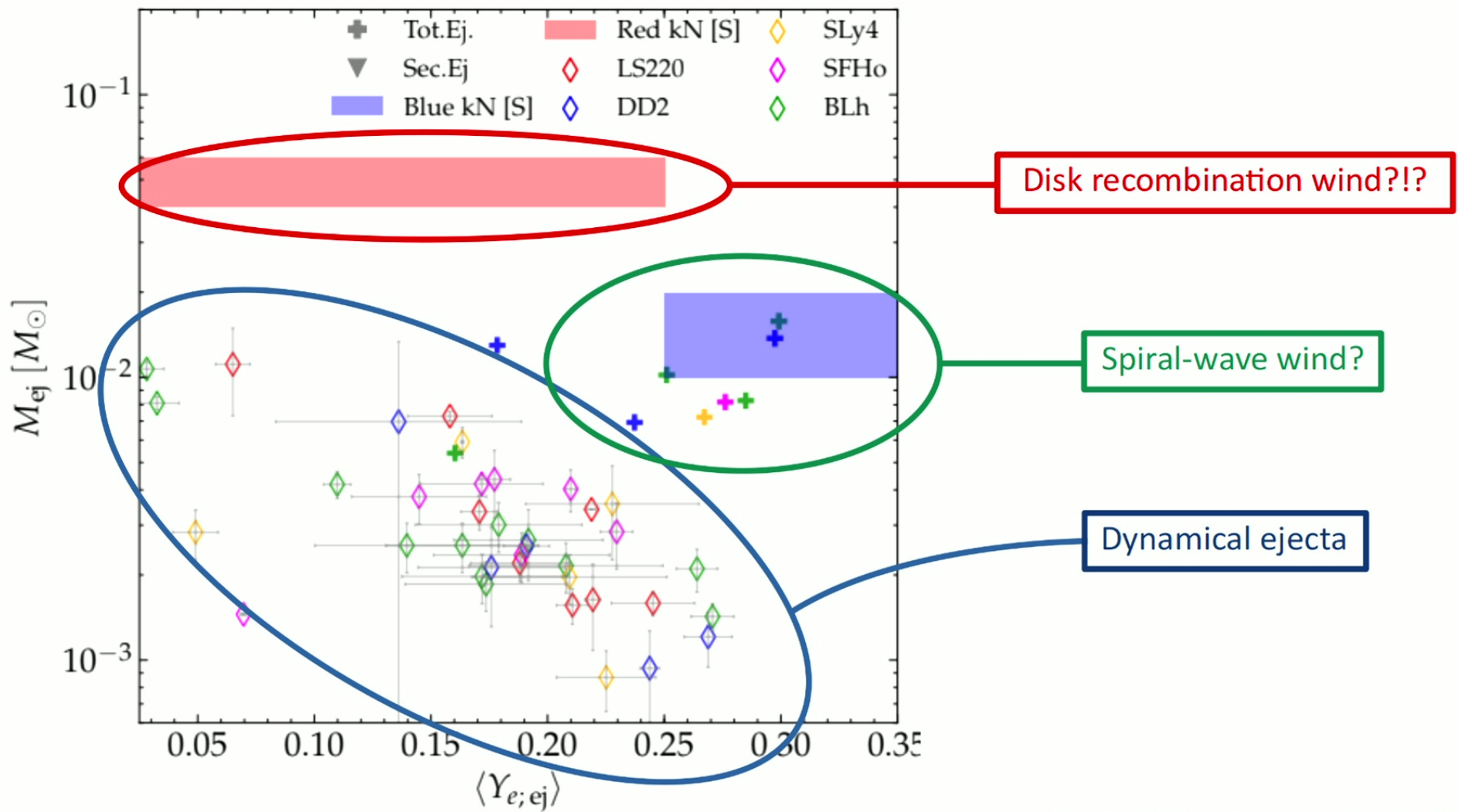
From Villar+ 2017



From Nedora+, ApJ 906:98 (2021)

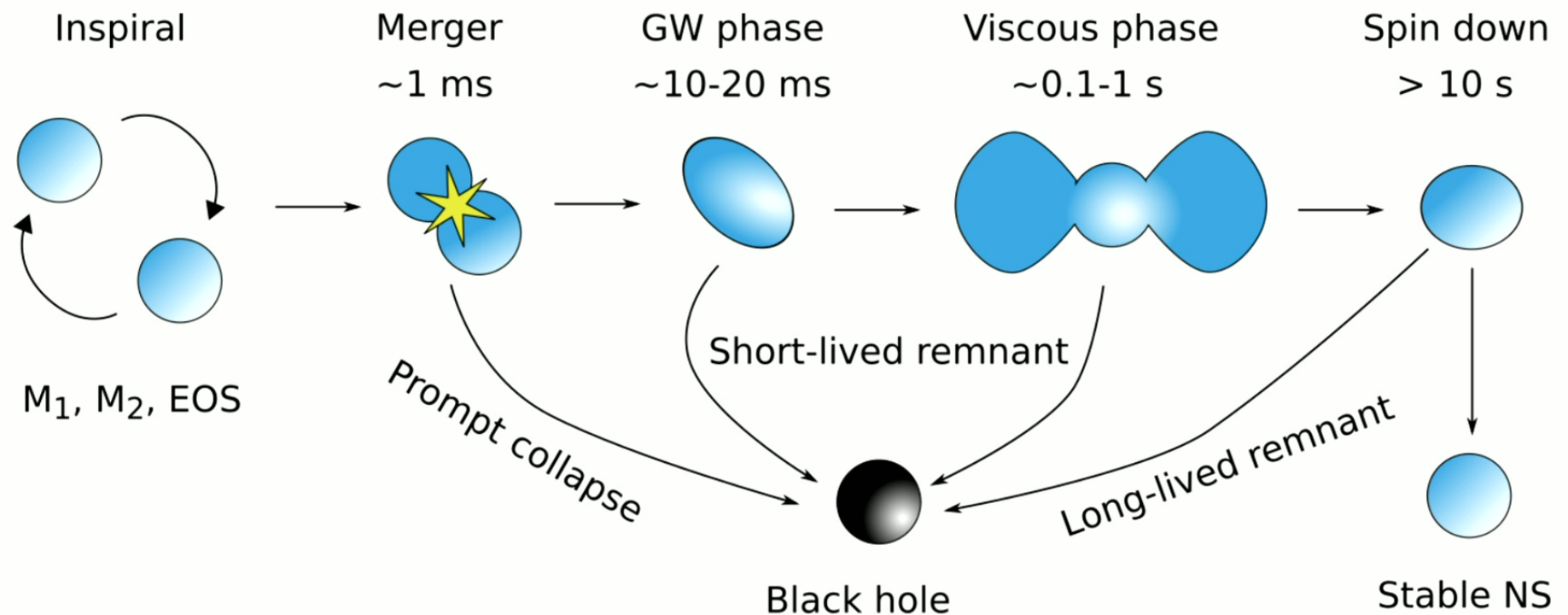


From Nedora+, ApJ 906:98 (2021)

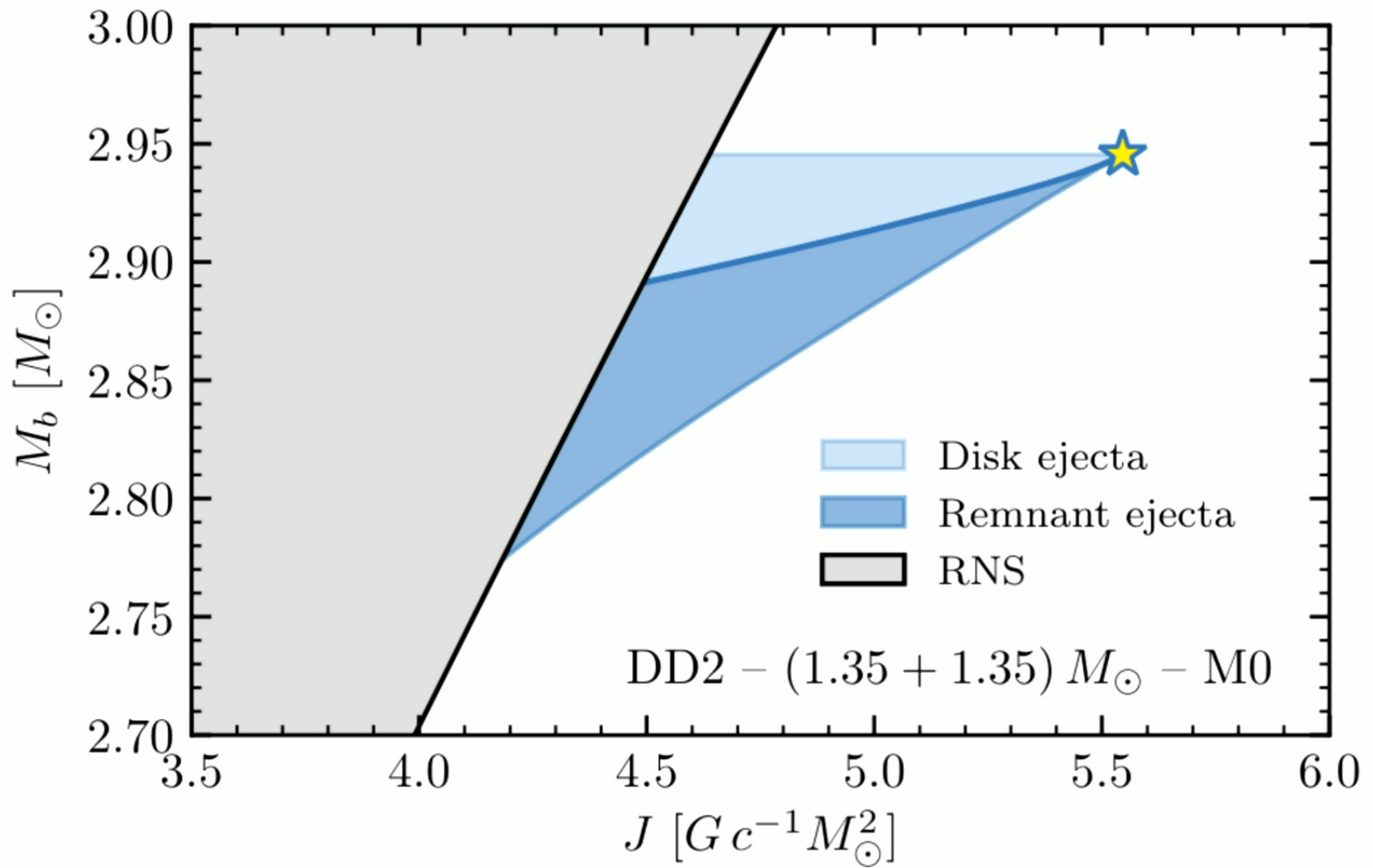


From Nedora+, ApJ 906:98 (2021)

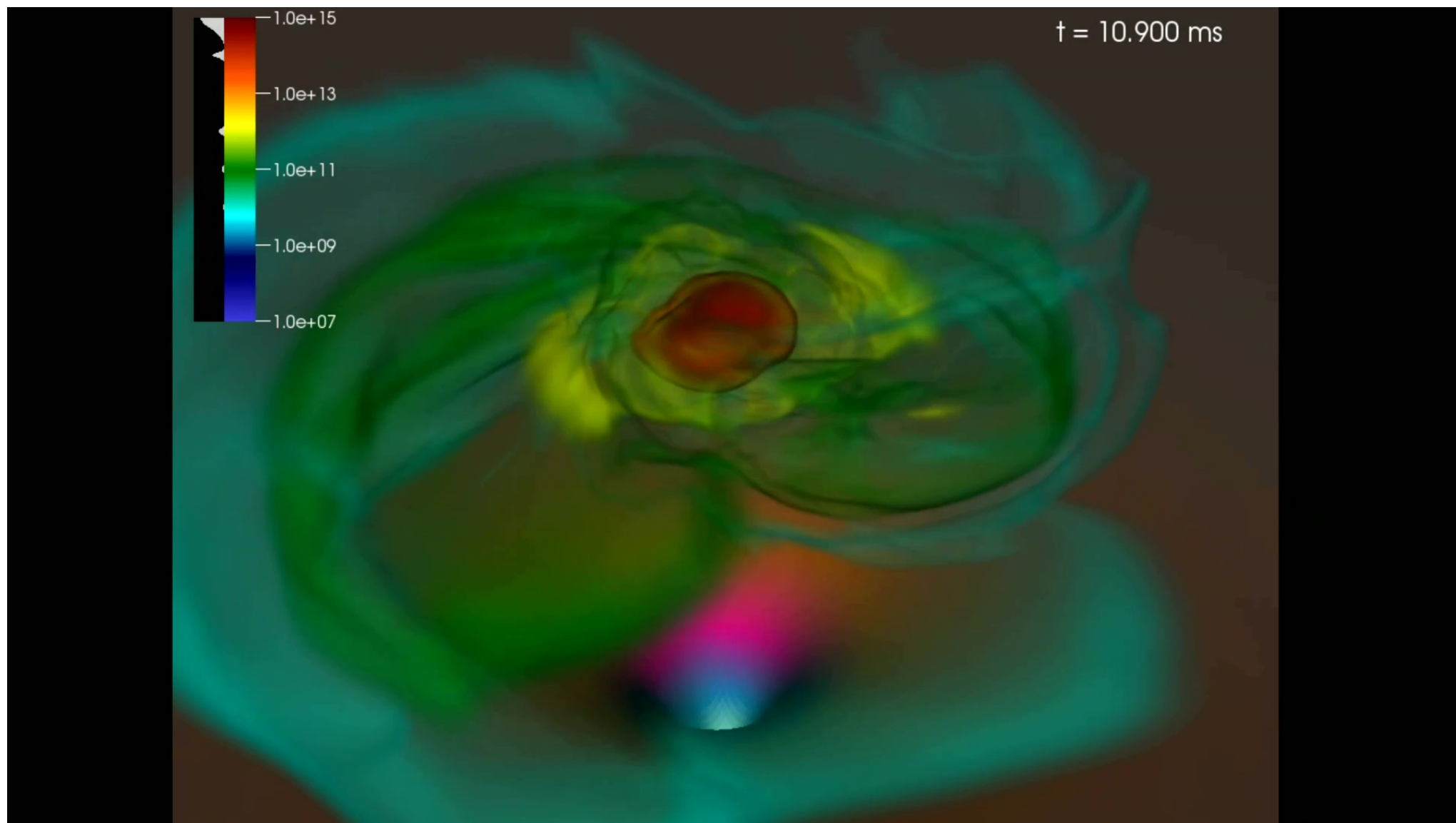
NS mergers road map



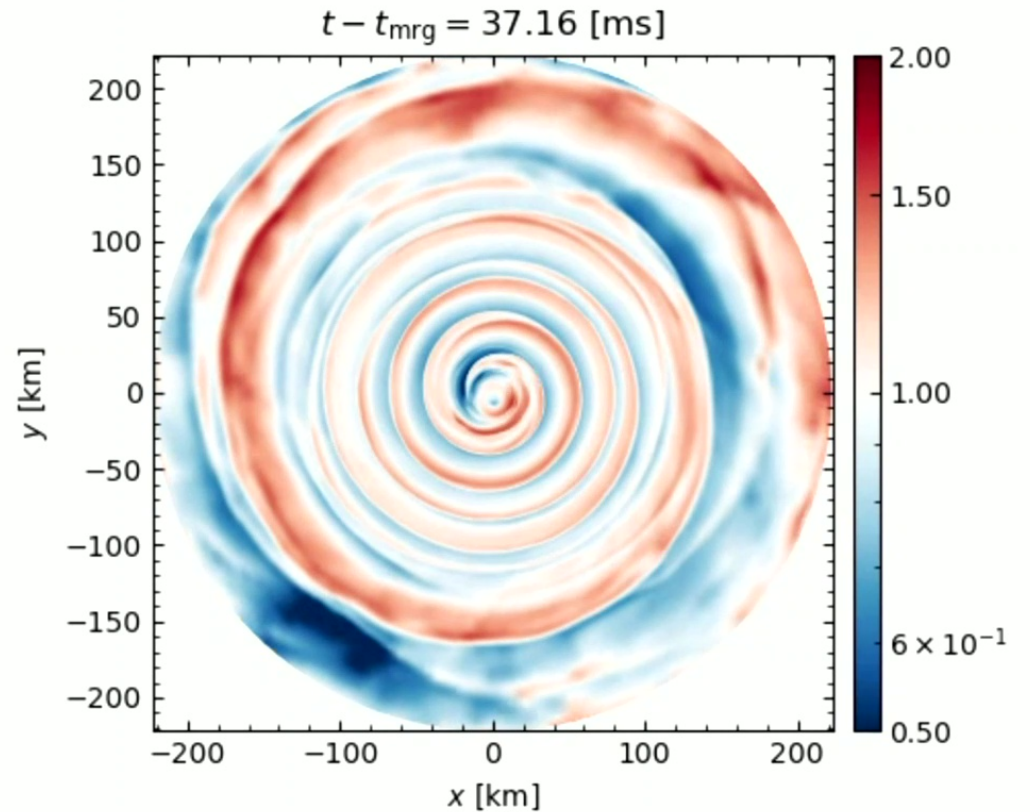
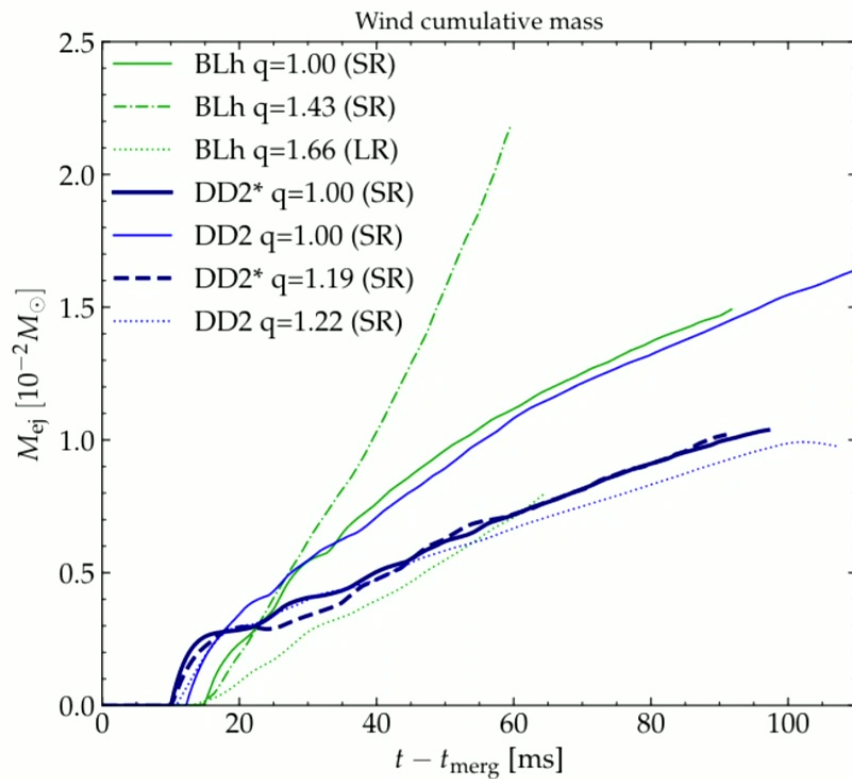
From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)



From Radice+ MNRAS 481:3670 (2018)



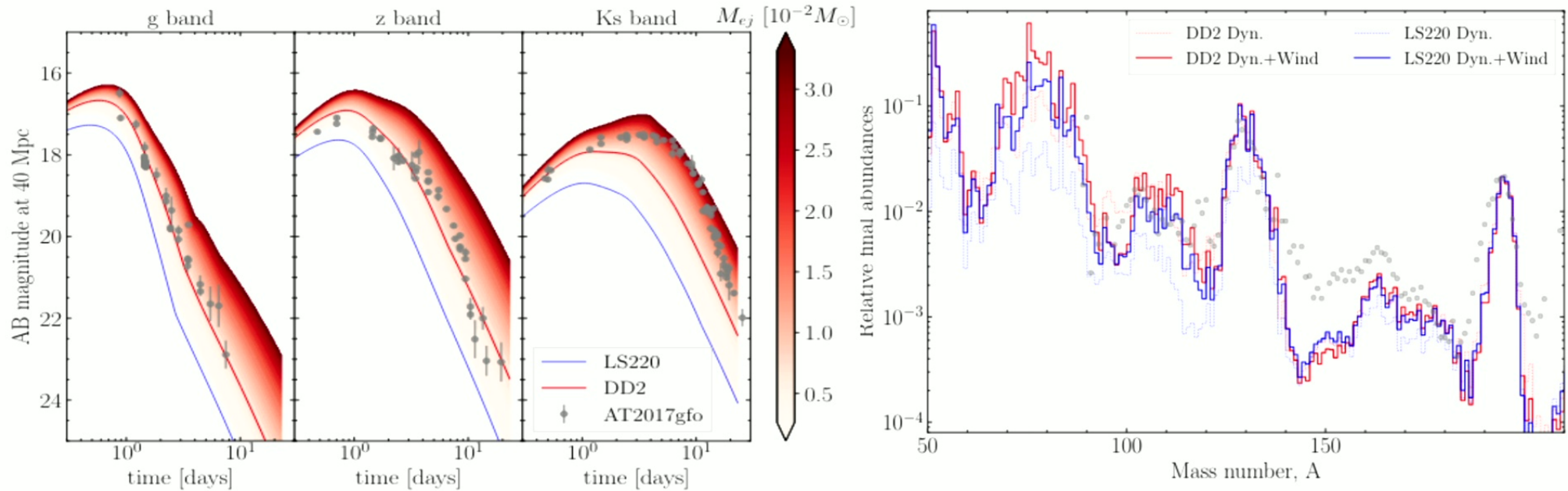
Spiral-wave wind



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

Nedora+ ApJ 906:98 (2021);
Radice+ ApJ 959:46 (2023)

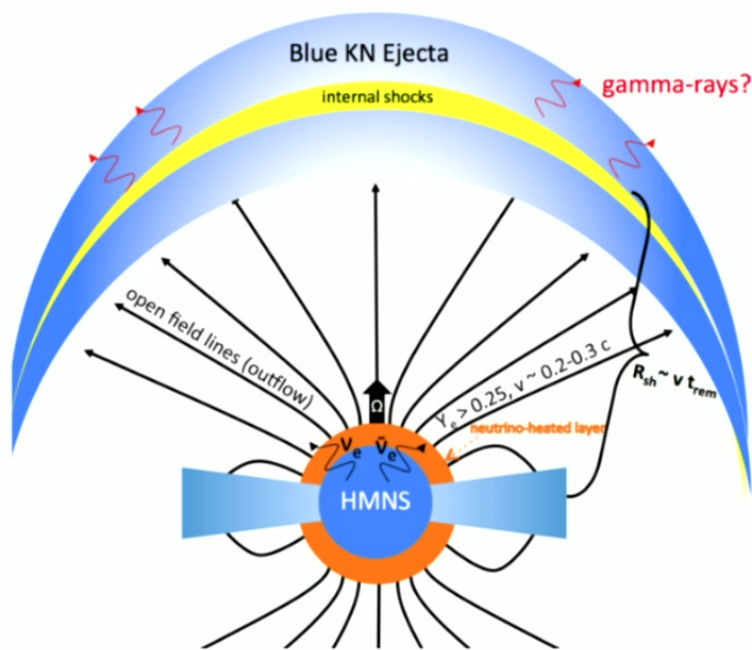
Numerical relativity results



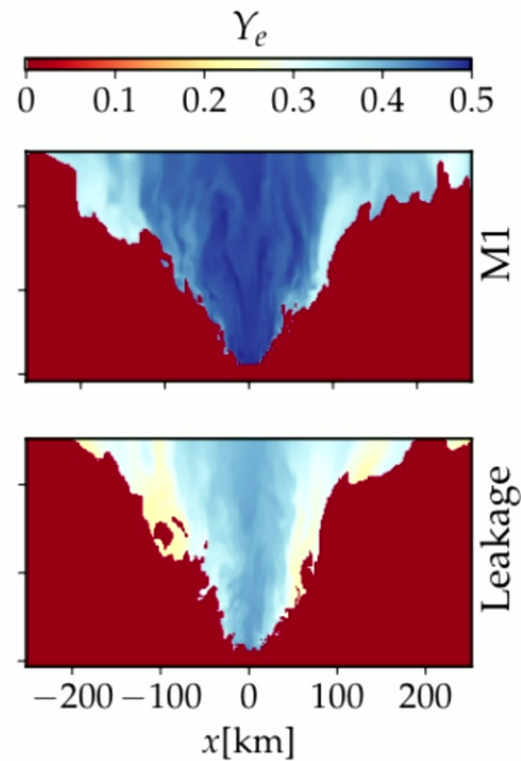
Postmerger winds **naturally** explain **blue** kilonova emission!

From Nedora+, ApJL 886:L30 (2019) & ApJ 906:98 (2021)

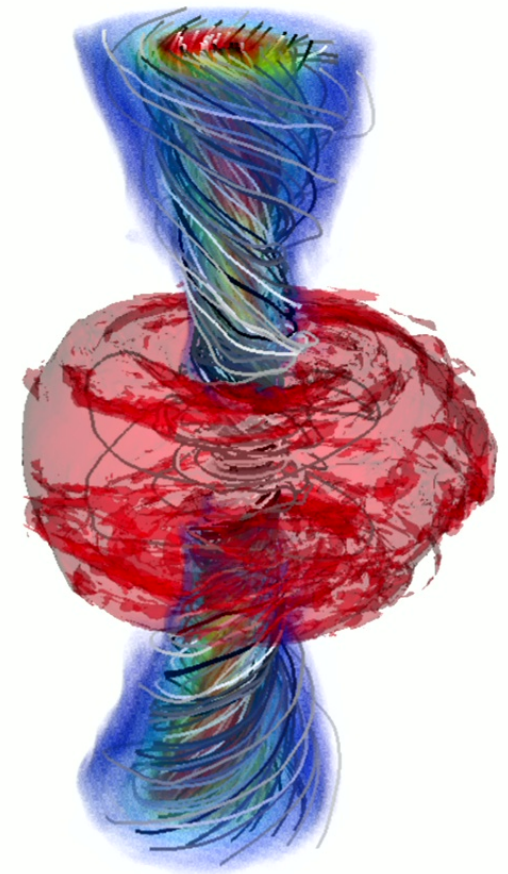
Magnetized winds (I)



Metzger+, ApJ 856:101 (2018)

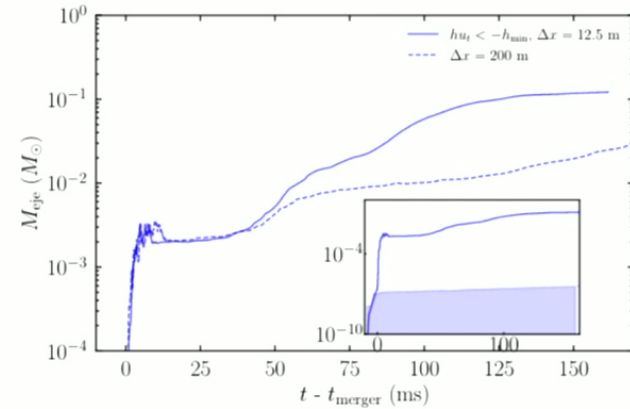
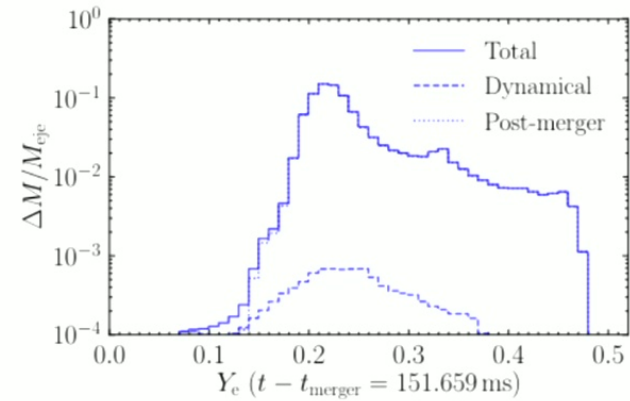
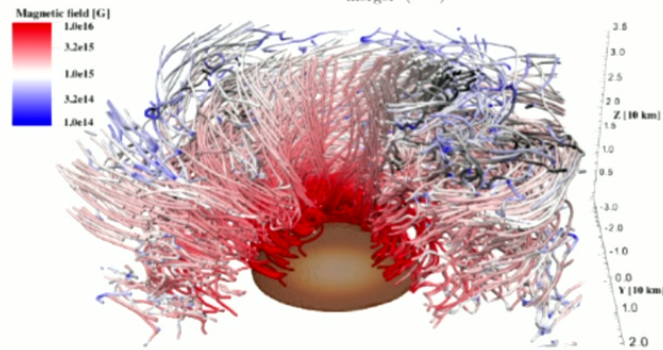
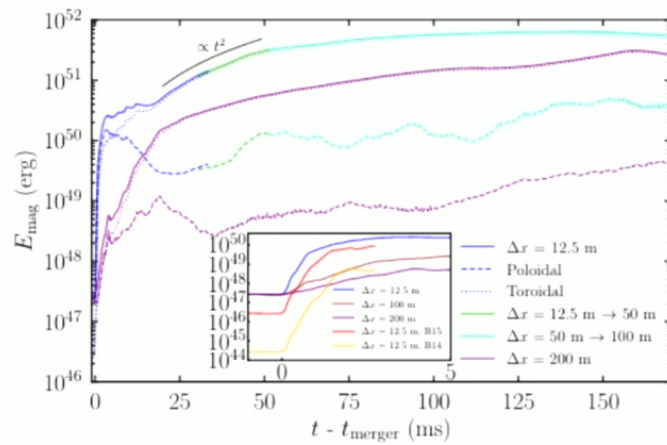


Curtis+, ApJL 961:L26 (2023)



Moesta+, ApJL 901:L37 (2020)

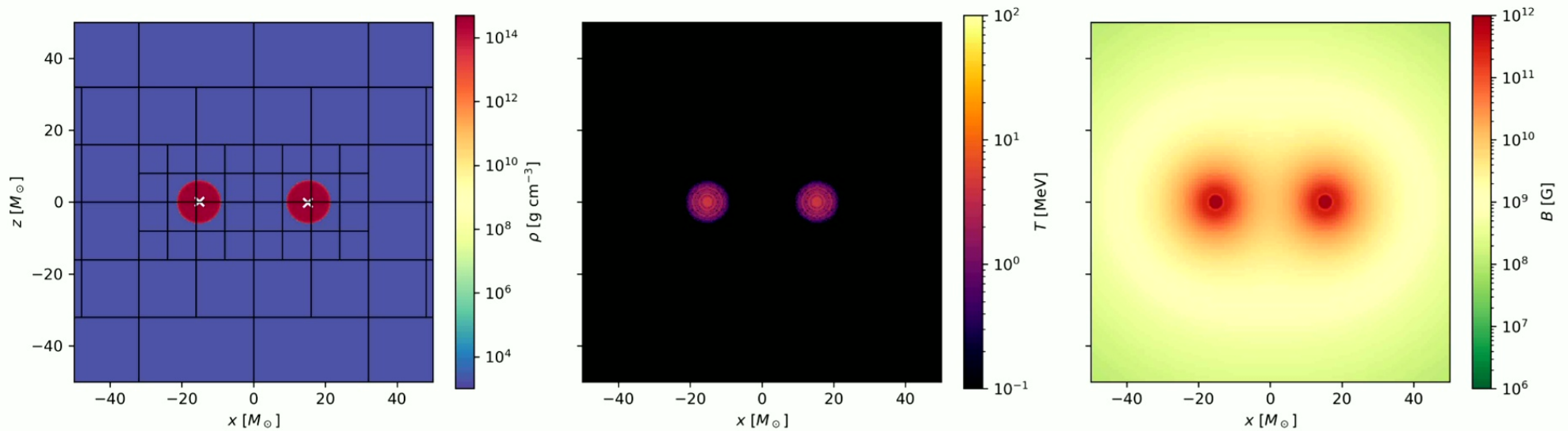
Magnetized winds (II)



See also Siegel & Combi PRL 131:231402 (2023)

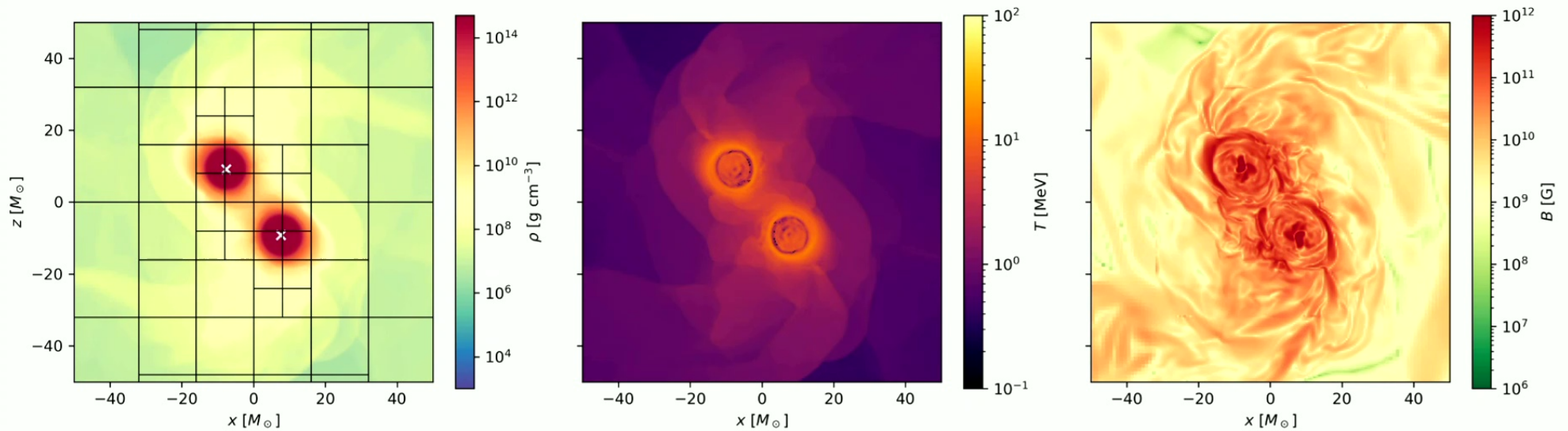
From Kiuchi+ Nat. Astron. 8:298 (2024)

GRMHD simulations



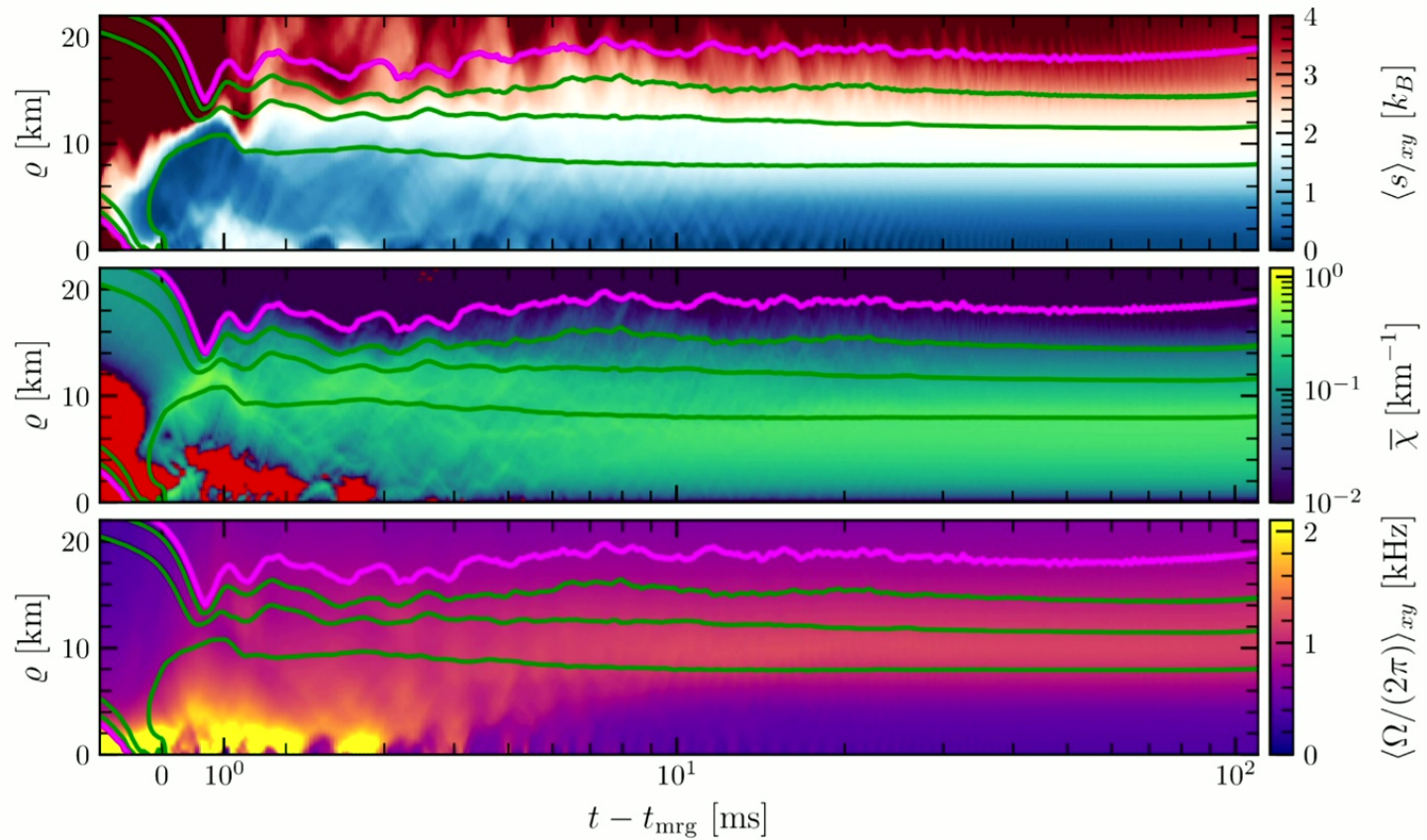
Simulation and visualization: Eduardo Gutiérrez

GRMHD simulations



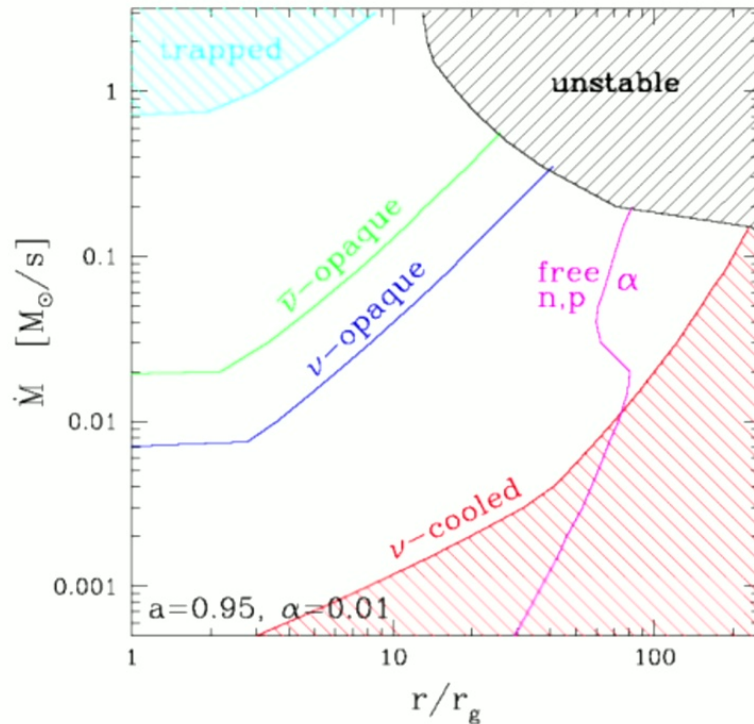
Simulation and visualization: Eduardo Gutiérrez

Structure of long-lived remnants

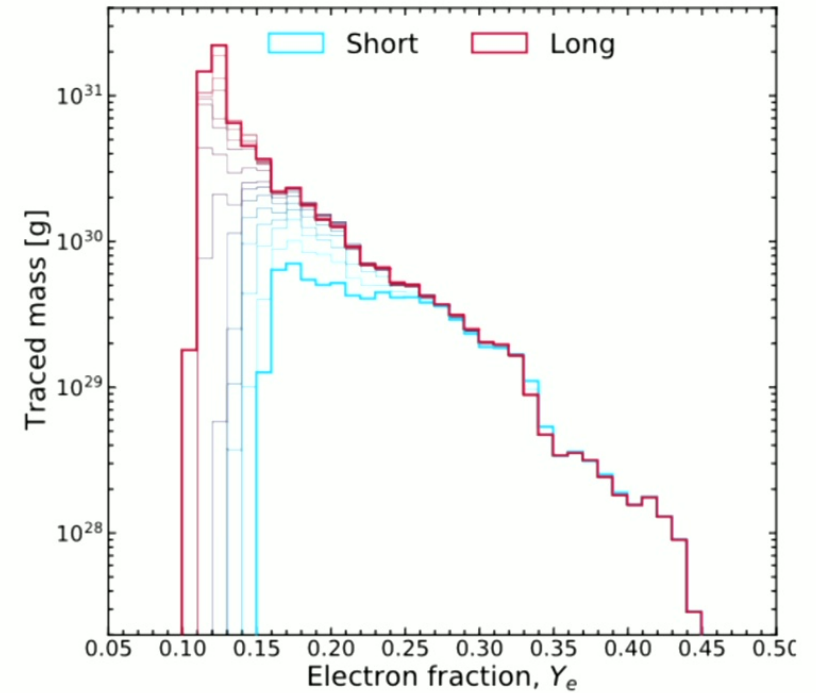


From Radice+ ApJ 959:46 (2023)

The red kilonova



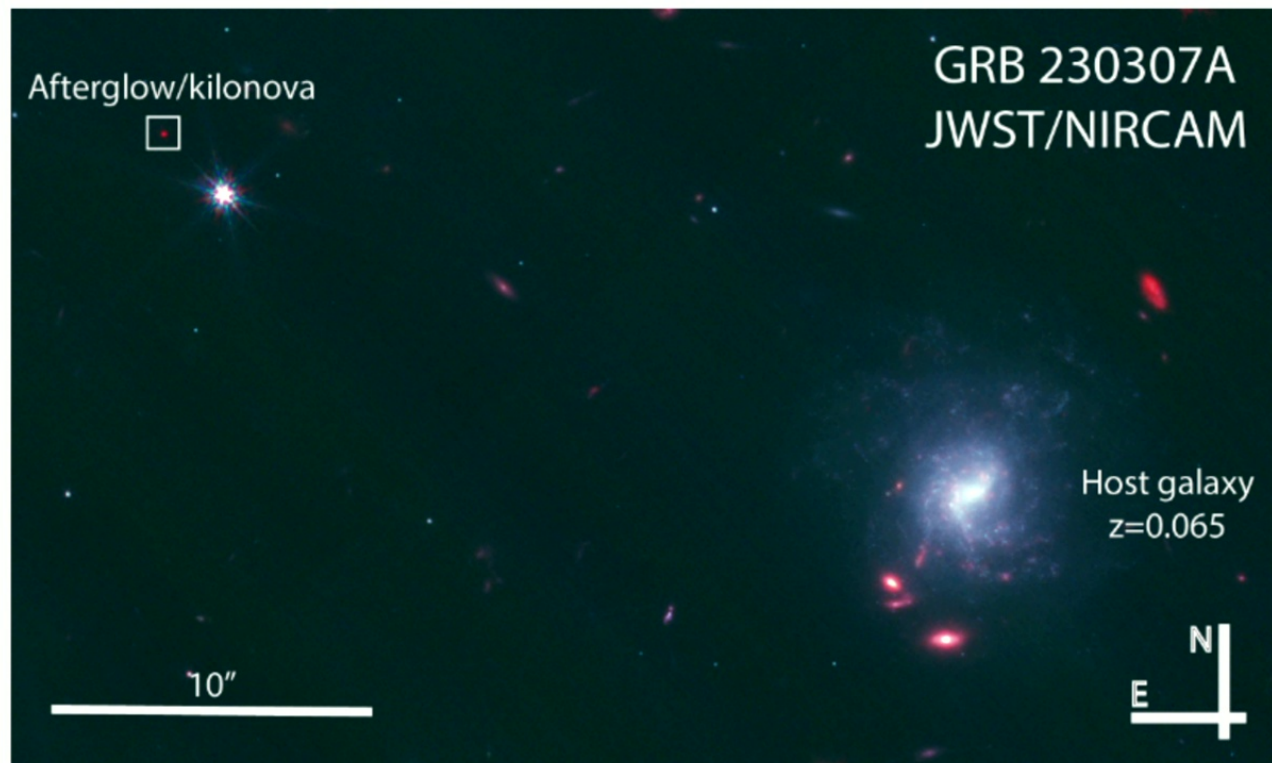
From Beloborodov AIP Conf.Proc. 1054 (2008)



From Sprouse+ ApJ 962:79 (2024)

See also Beloborodov (2003); Fernandez+ (2013); Metzger+ (2014); Perego+ (2014); Siegel+ (2017); ...

Kilonovae from long-GRBs?!?



See also Mei+ 2022; Rastinejad+ 2022; Troja+2022; Yang+ et al. 2022; ...

From Levan+, Nature (2023)

White dwarf mergers

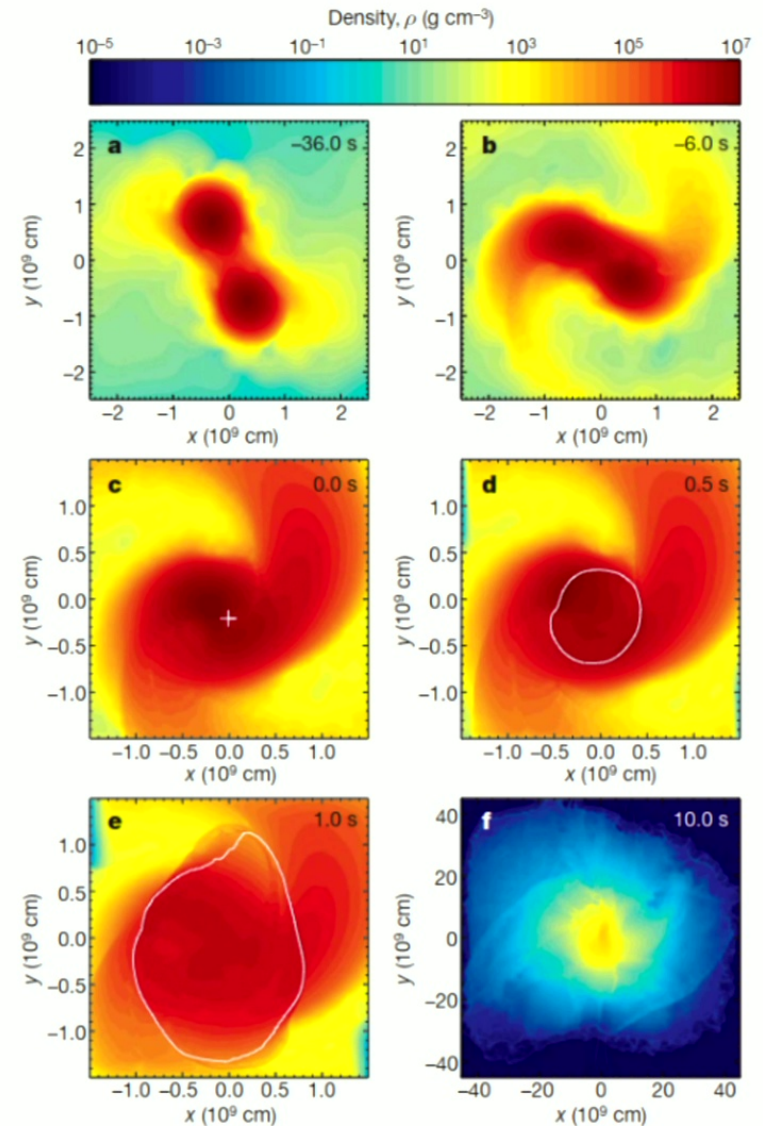
Two outcomes:

- complete burning: type Ia supernova
- weak explosion: lax + accretion-induced collapse (AIC) to neutron star

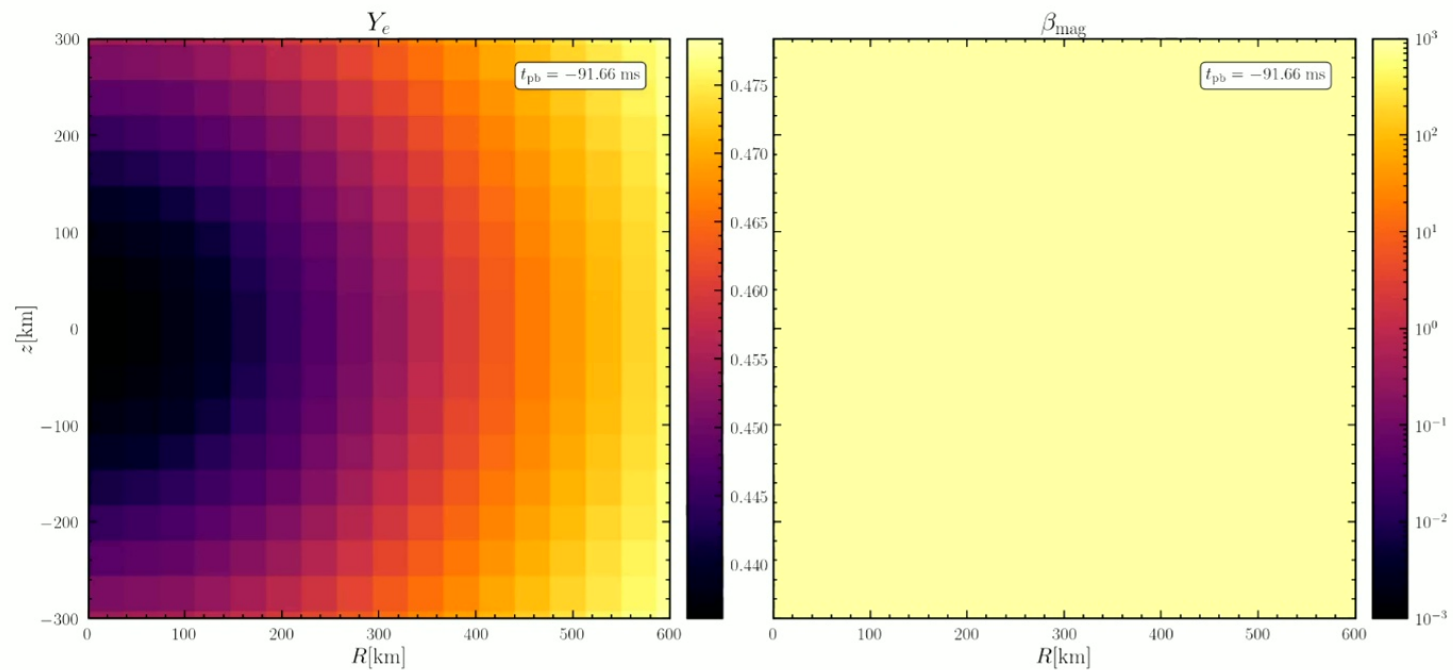
AIC have been invoked to explain:

- pulsars in globular clusters
- fast blue optical transients (FBOTs)
- fast radio bursts
- possible progenitors have been recently discovered
- production of **r-process elements**

From Pakmor+, Nature 463:61 (2010);
See also Roy+ 2022; Zhang+ 2024; **Cheung talk later today**



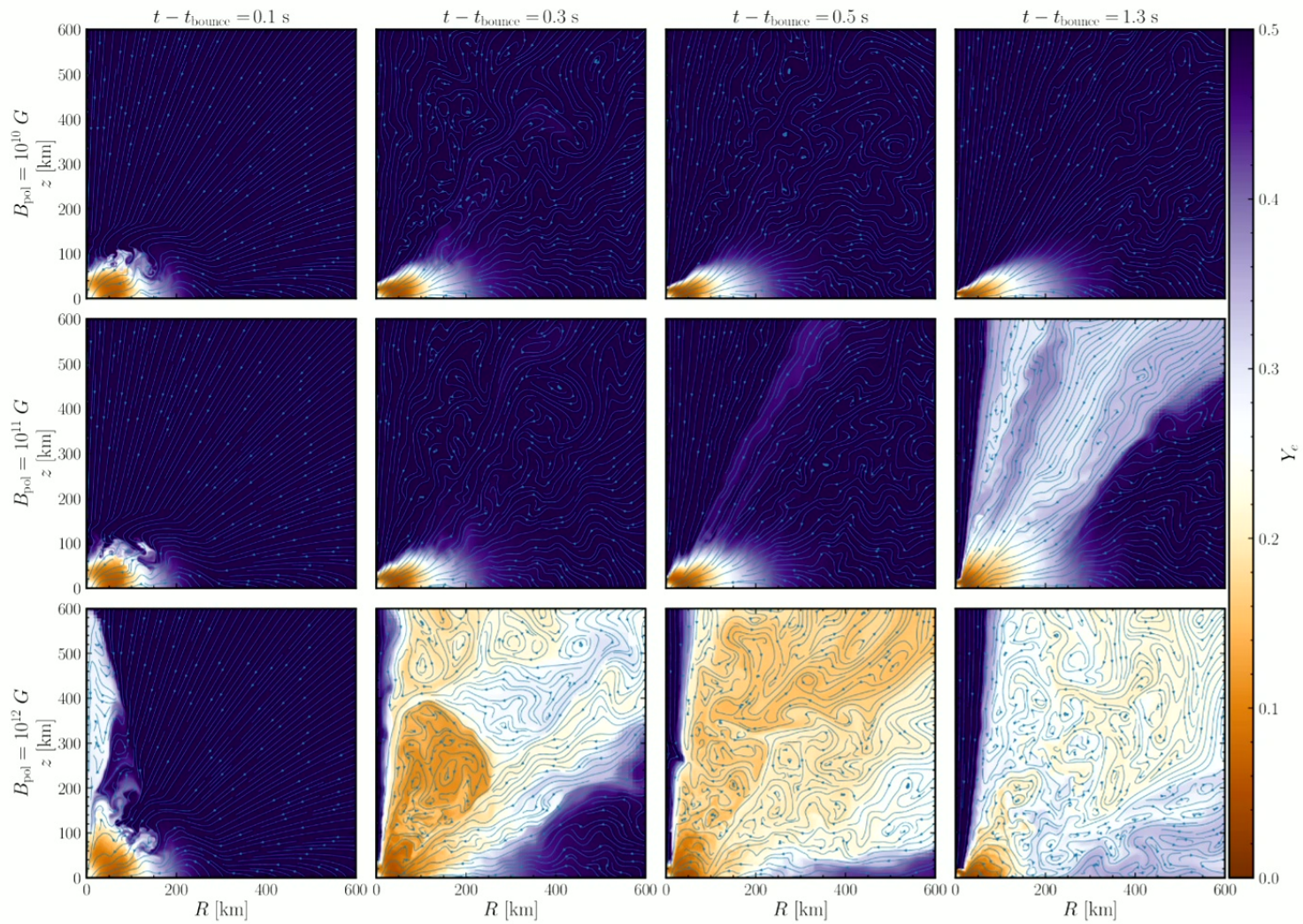
GRMHD simulations of AICs



Simulation and visualization: Tetyana Pitik

See also Batziou+ 2024; Chan+ 2025; Kuroda+ 2025; ...

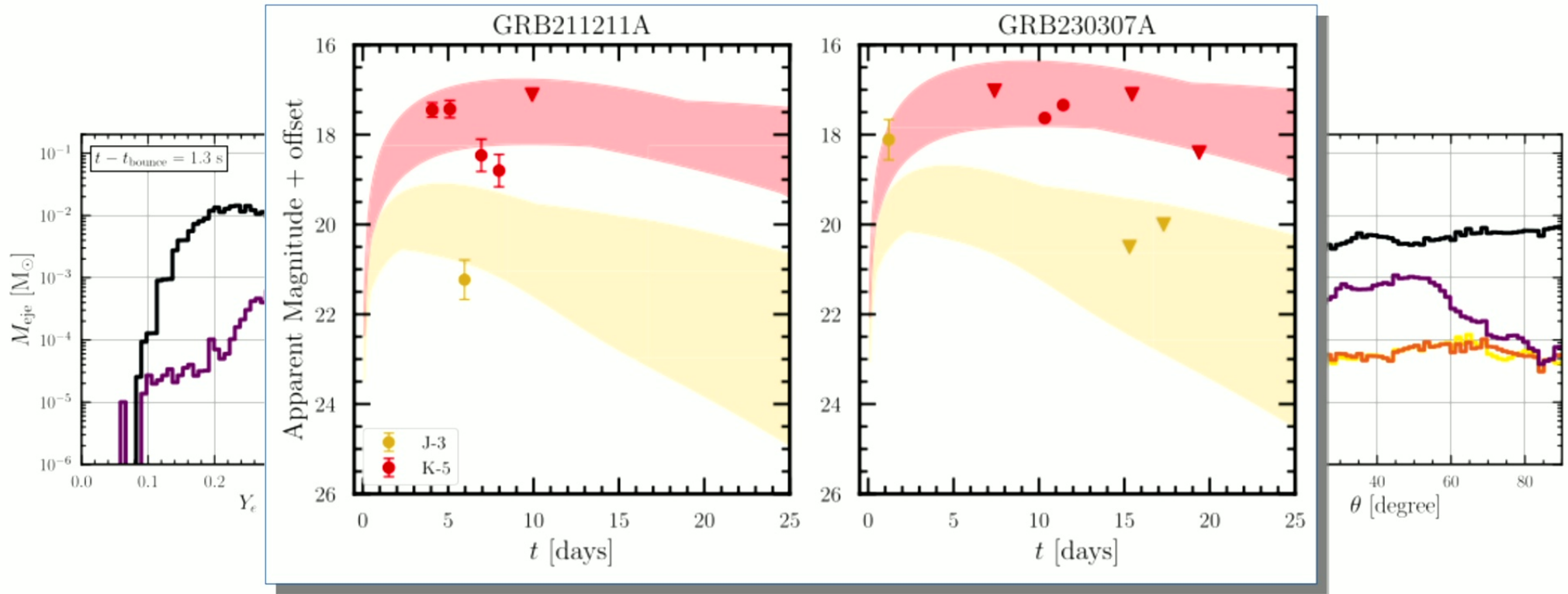
From Cheong+ ApJL 978 (2025)



See also Batziou+ 2024; Chan+ 2025; Kuroda+ 2025; ...

From Cheong+ ApJL 978 (2025)

Kilonova from AIC

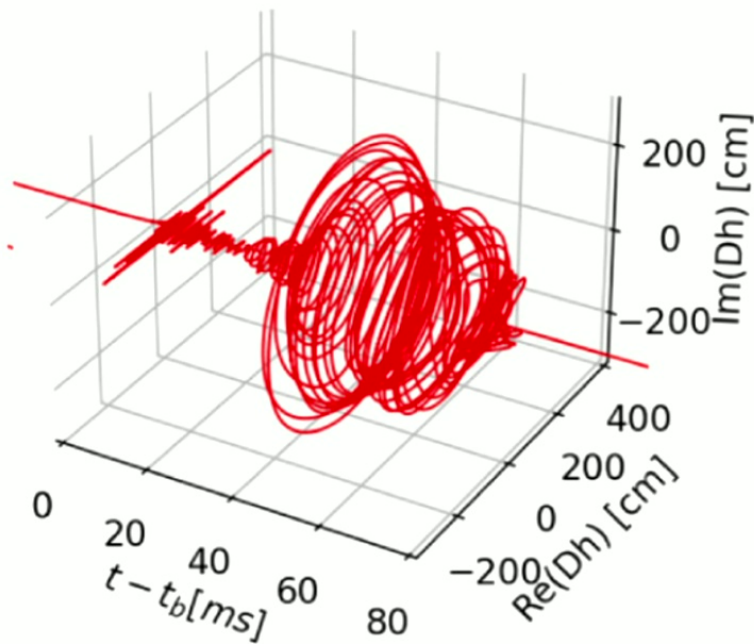


See also Batziou+ 2024; Chan+ 2025; Kuroda+ 2025; ...

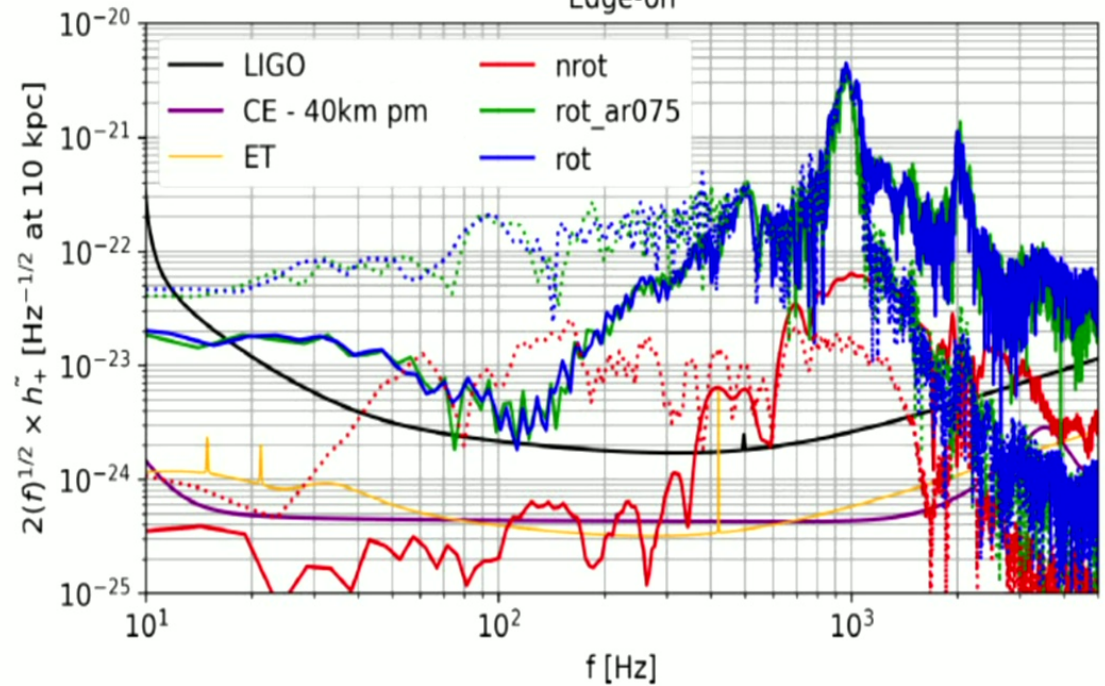
From Cheong+ ApJL 978 (2025)

Gravitational-waves from AICs

rot, edge-on



Edge-on



See also Chan+ 2025; Kuroda+ 2025

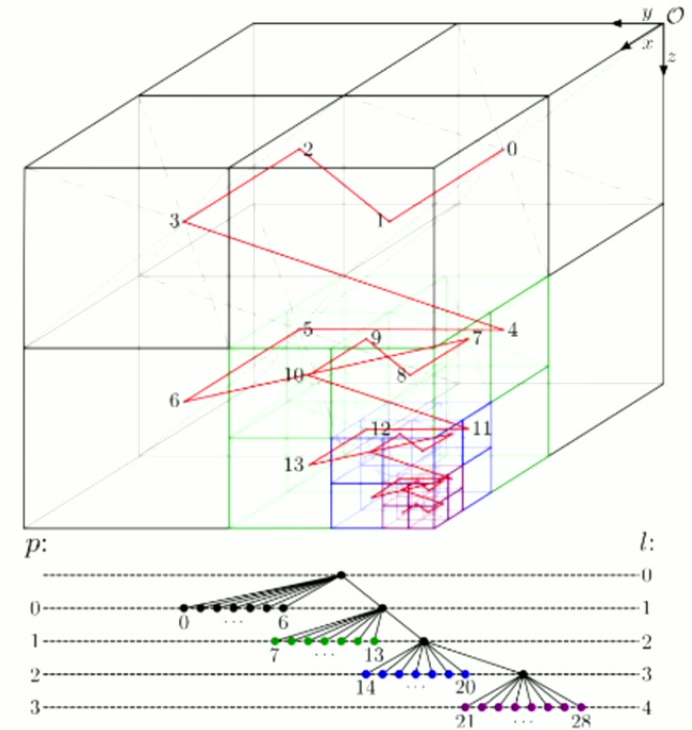
From Longo+, MNRAS 525:6359 (2023)

Numerical relativity with AthenaK

Building on top of the Octree-AMR algorithm of Athena++/AthenaK

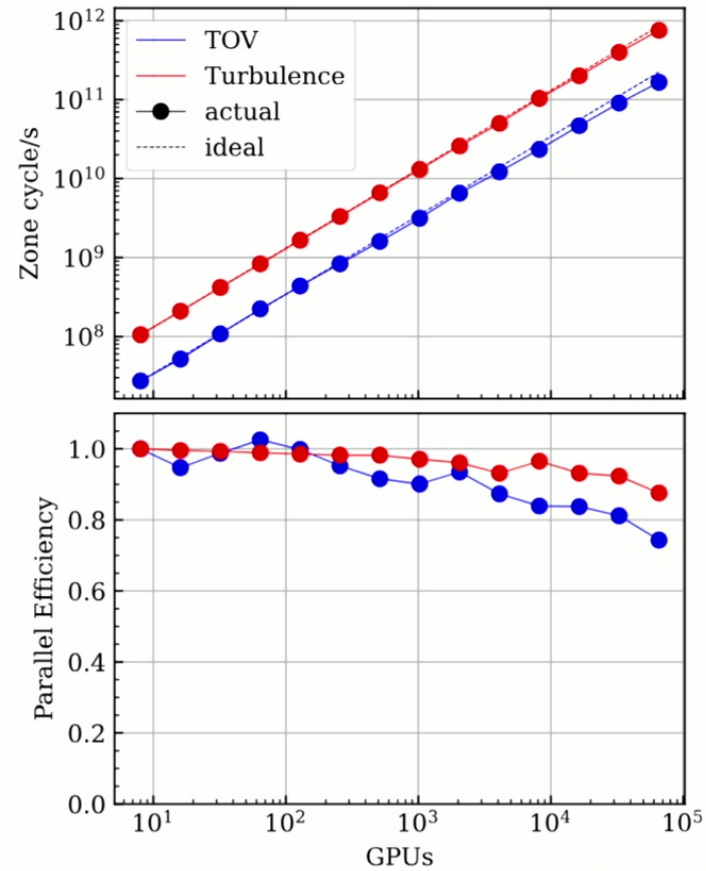
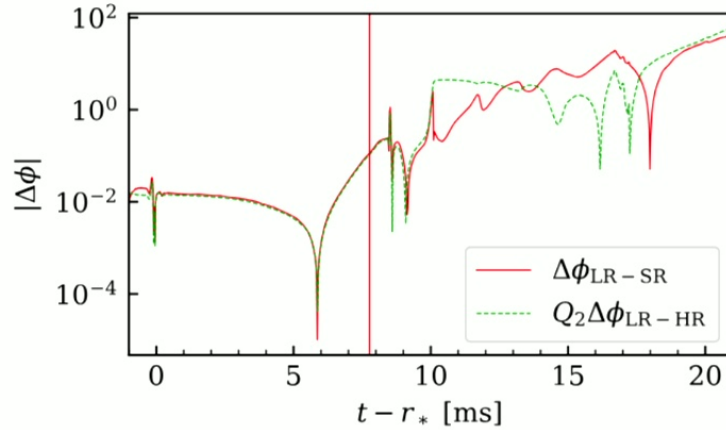
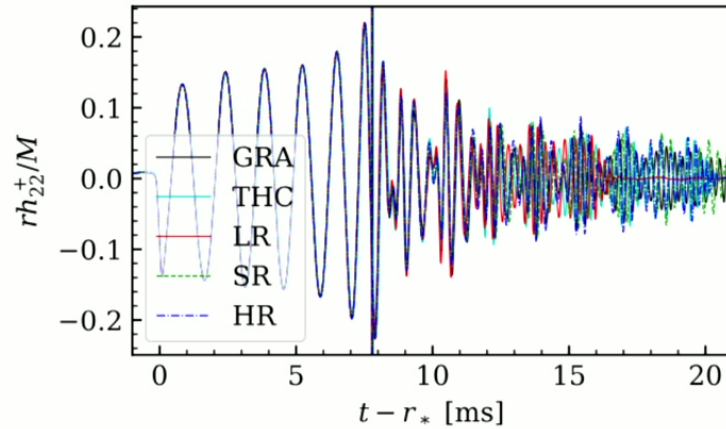
- Written in **Kokkos**, optimized for GPUs
- Spacetime evolution: **Z4c** with high-order FD
- Interface with SpECTRE ID and CCE
- Interface with ET for AH finder/analysis
- **GRMHD** in dynamical spacetimes with high-resolution shock capturing methods
 - Upwind constrain transport for B-field
 - Refluxing of fluxes / re-circulation of E-field
- Neutrino radiation: **M1** and FP_N (in progress)

Daszuta+ 2021, 2024; Cook+ 2023; Zhu+ 2024; Fields+ 2024
See also: **Stone+ 2020, 2024**



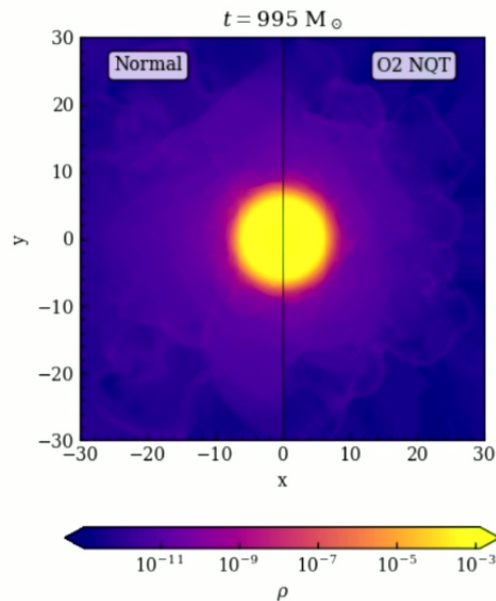
From Daszuta+ ApJS 257 (2021)

Binary neutron star mergers

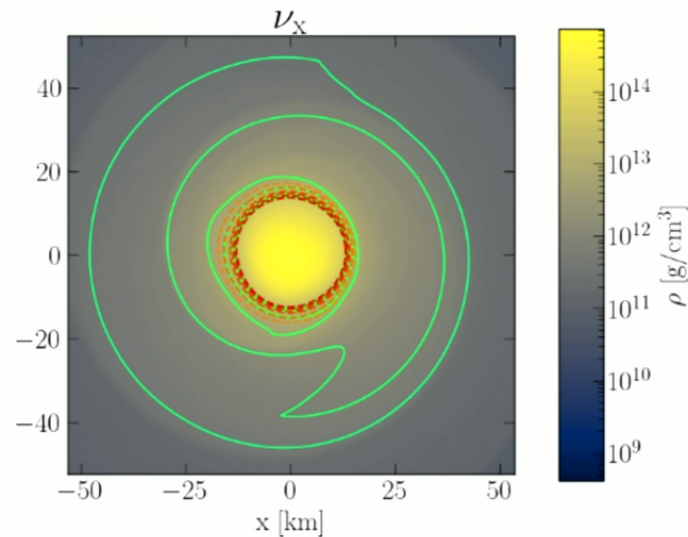


From Fields+ ApJS 276 (2025)

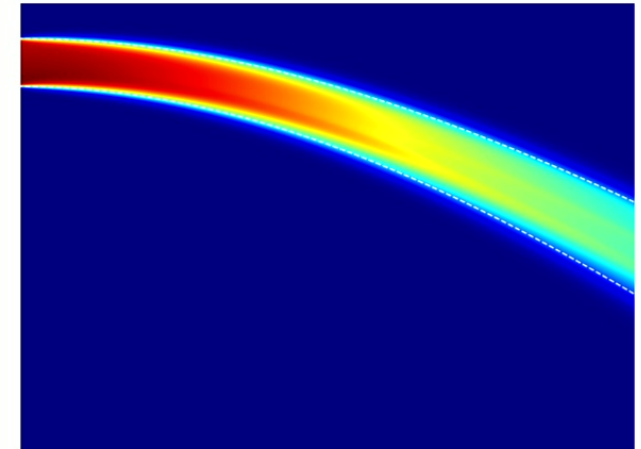
Microphysics on GPUs



From Hammond+ 2501.05410



From Chiesa+, Phys.Rev.D 111 (2025)



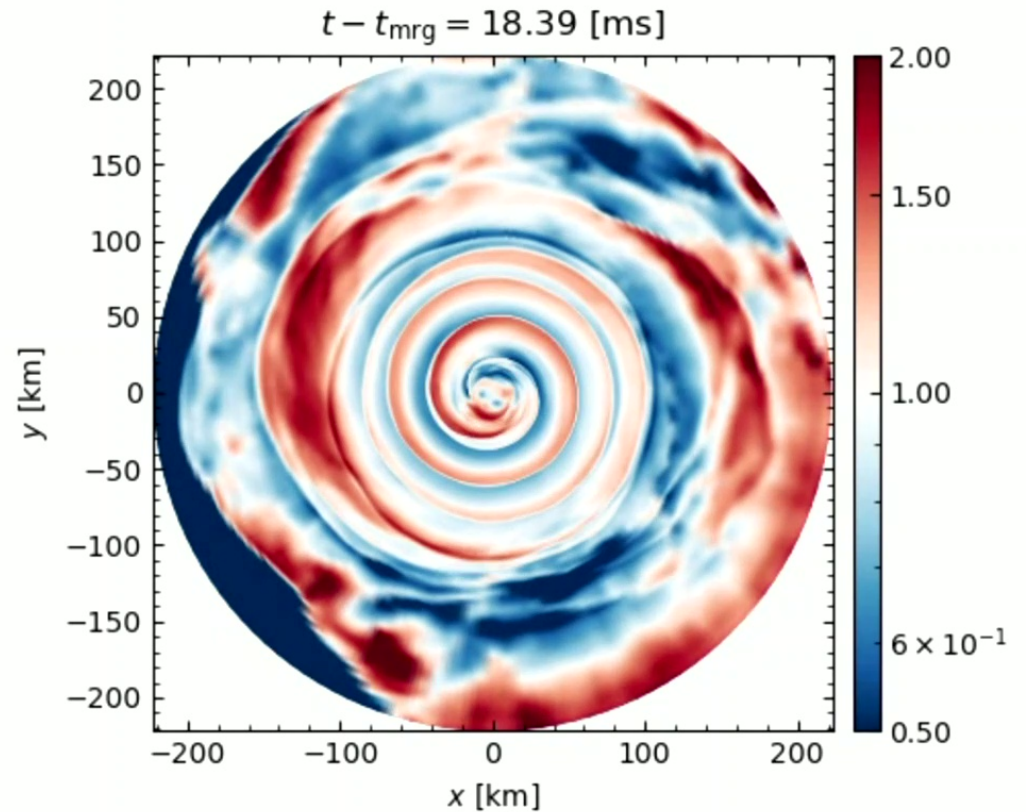
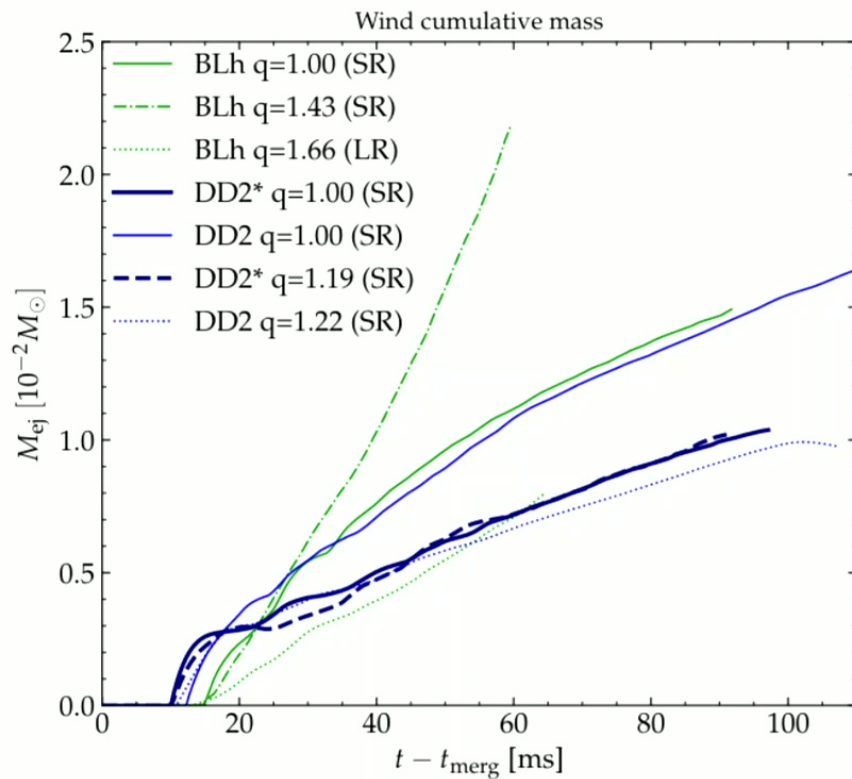
From Bhatthacharyya+ in prep

- Efficient log-like interpolation of thermodynamic quantities
- Neutrino opacities computed on the fly, reconstruction of neutrino spectra
- M1 should be production ready within a few weeks, FP_N in progress

Conclusions

- Theoretical models broadly reproduce AT2017gfo, but we do not yet have models that **quantitatively** match the data
- Kilonovae in association with **LGRBs**: mergers, AIC, or ...?
- **AthenaK** is designed to bring numerical relativity into the exascale era and address these and other questions in theoretical astrophysics

Spiral-wave wind



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

Nedora+ ApJ 906:98 (2021);
Radice+ ApJ 959:46 (2023)