PennState
Eberly College of Science

CoRe collaboration

Multimessenger Astrophysics with Neutron Star Mergers

David Radice – Feb. 4, 2026

NP3M

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

NSF

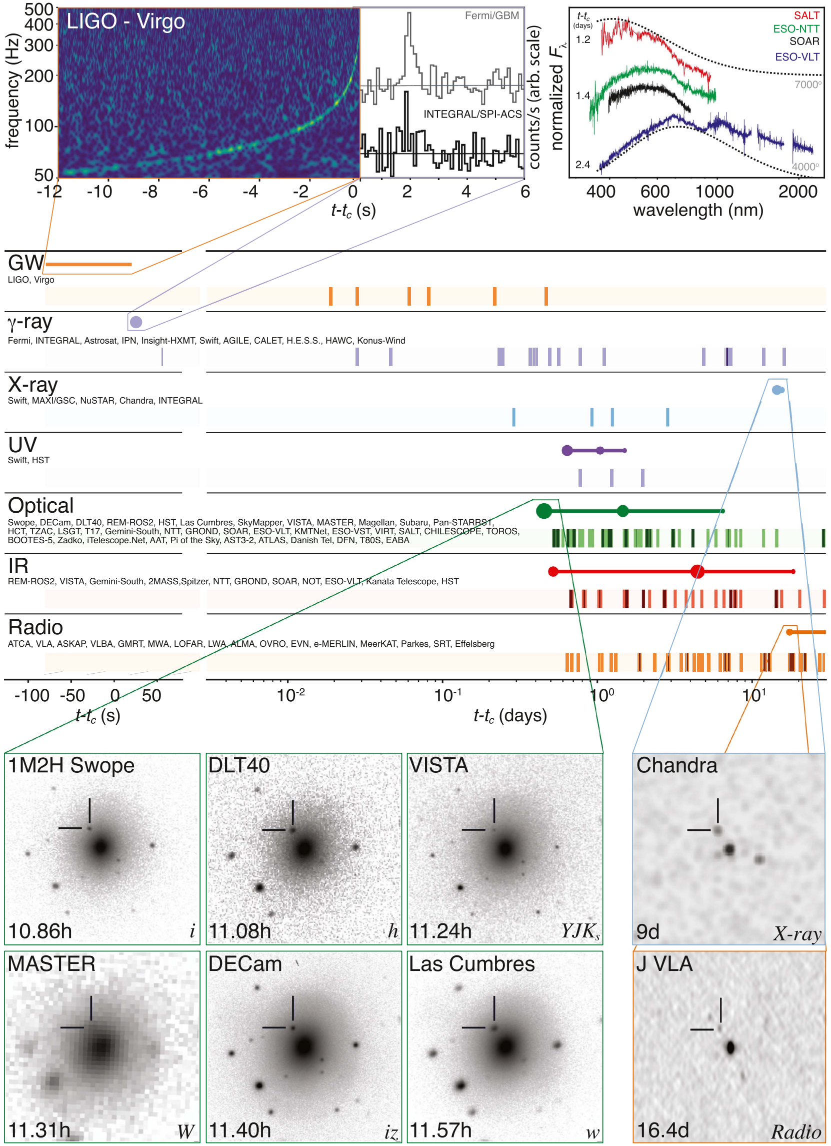
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

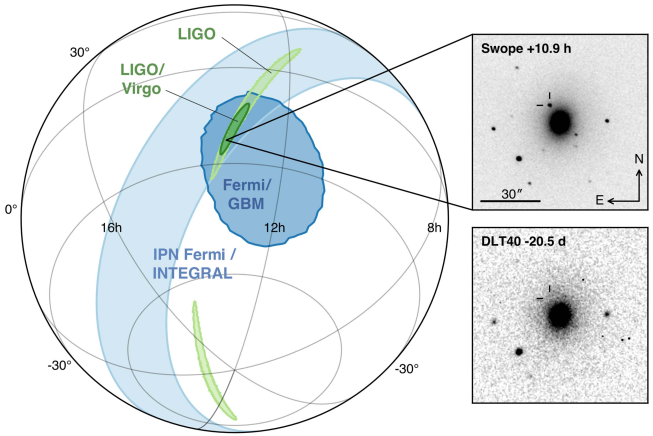
NASA

Part I: Multimessenger Astrophysics

Learning about dense matter, gravity, GRBs, and the r-process

GW170817



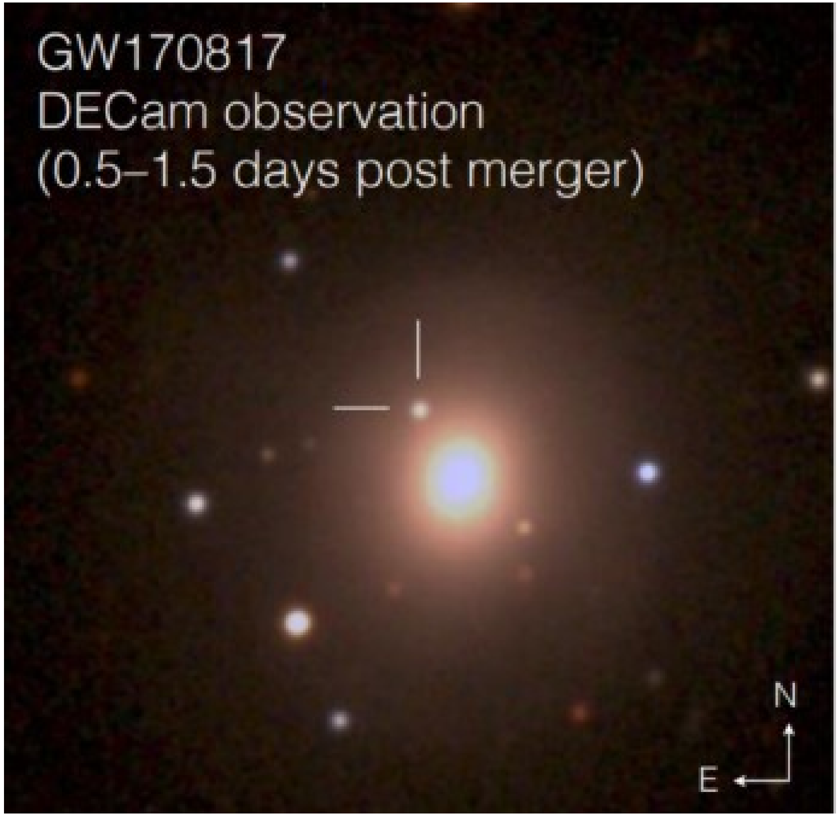


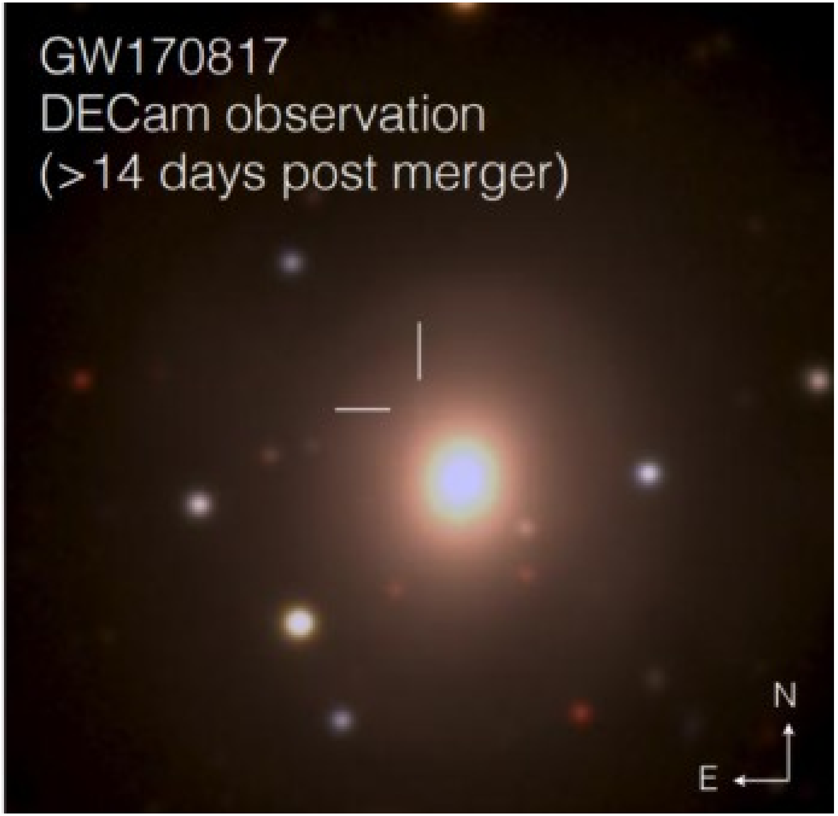
From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech- NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT ApJL 848:L12 (2017)

Questions

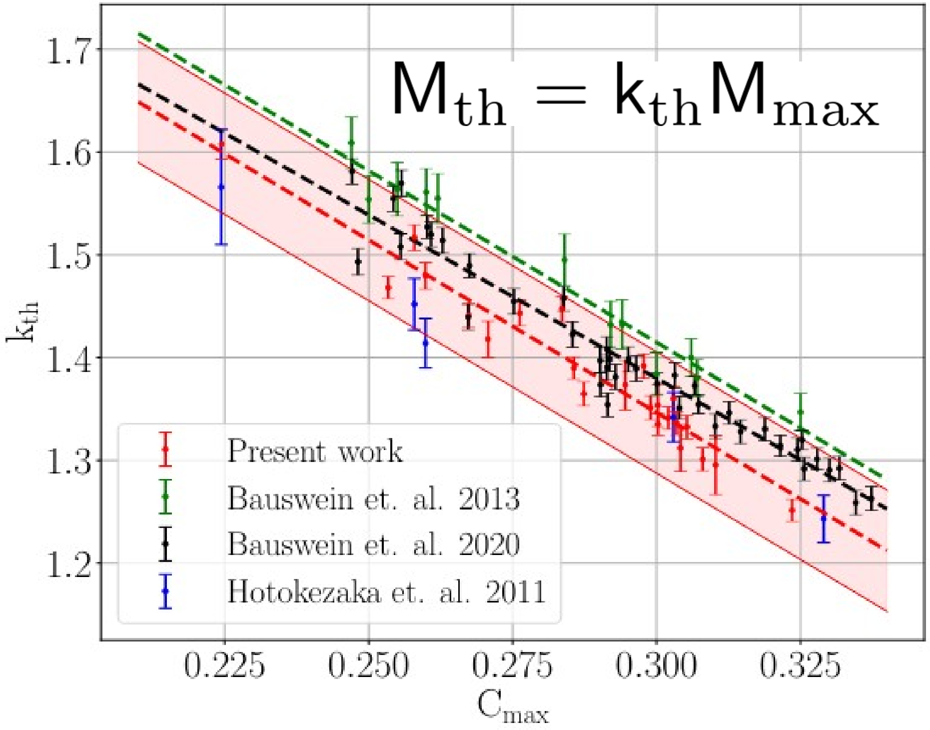
- What are the possible outcomes of binary NS mergers?
- What are the physical processes that determine them?
- How are they reflected in the EM and GW signals?
- What can we learn about the properties of dense matter?
- What is the astrophysical site of the r-process?

AT2017gfo


GW170817
DECam observation
(0.5–1.5 days post merger)
N
E


GW170817
DECam observation
(>14 days post merger)
N
E

Prompt collapse: q ≈ 1

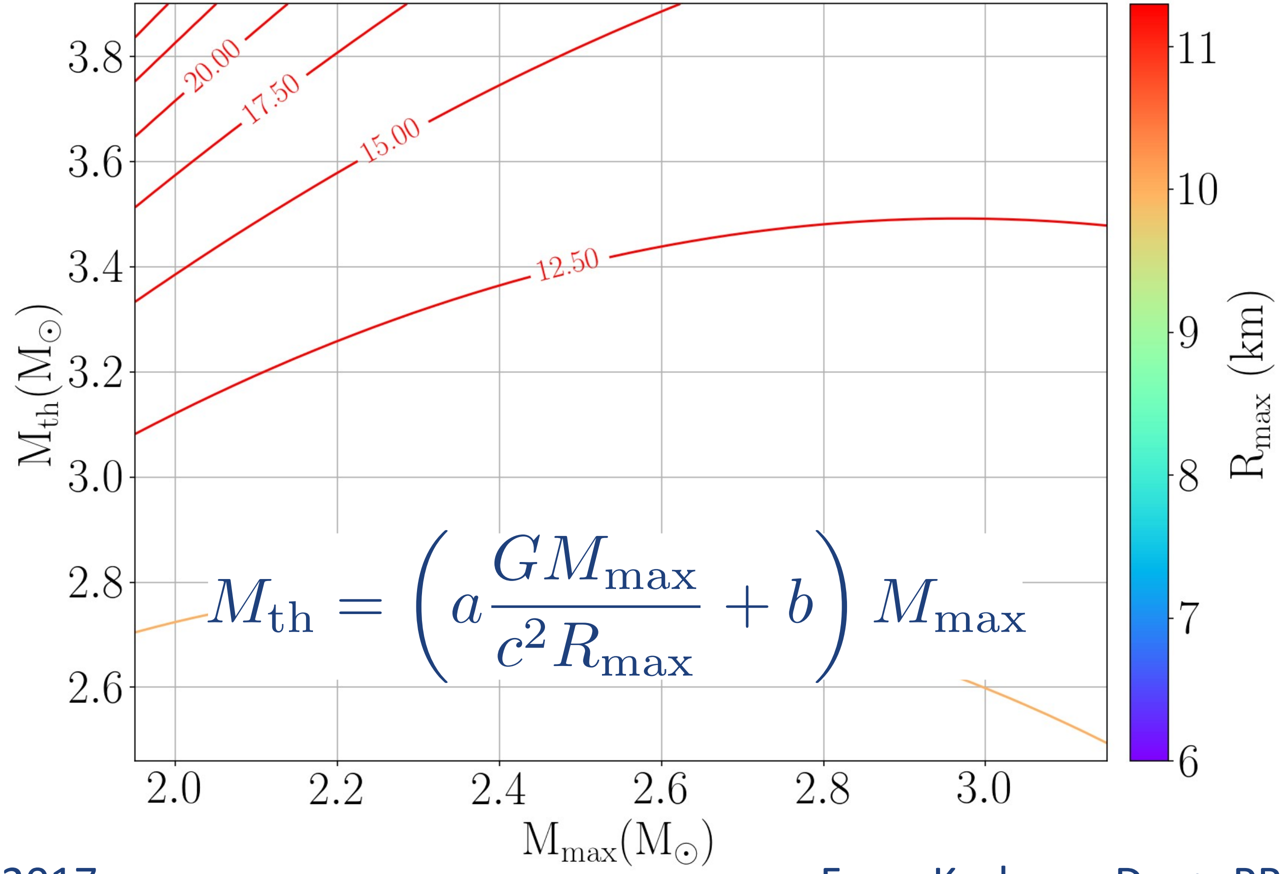


- Prompt collapse: no bounce after merger, direct BH formation
- EOS has a qualitative impact
- If $q \simeq 1$ expected to be EM quiet
- Alternative: use postmerger GWs (likely with 3G)
- Needs of high-quality NR data

See also Hotokezaka+ 2011, Bauswein 2013, 2020, Koeppel 2019, ...

From Kashyap, Das+, PRD 105 103022 (2022)

Prompt collapse: equal masses

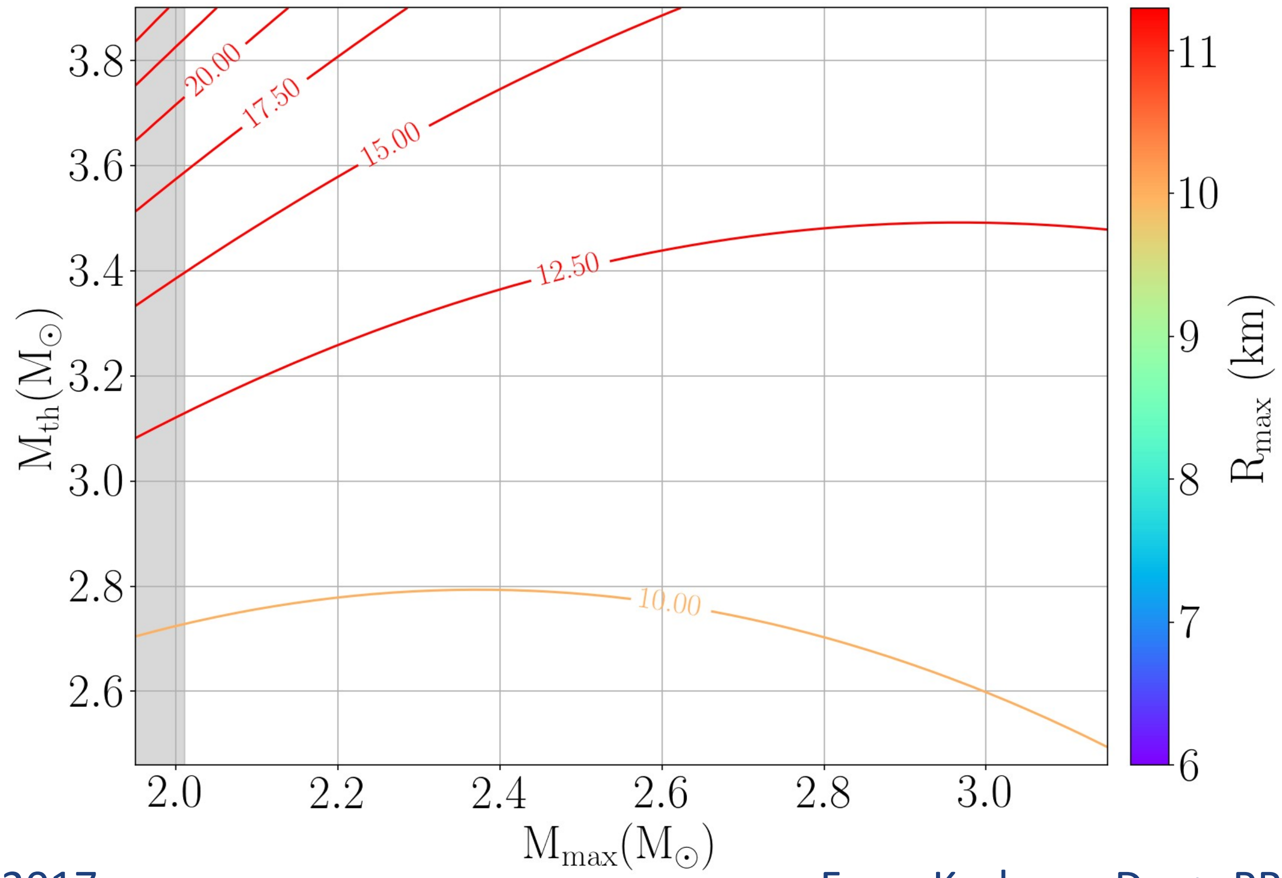


$$M_{\rm th} = \left(a \frac{G M_{\rm max}}{c^2 R_{\rm max}} + b \right) M_{\rm max}$$

See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

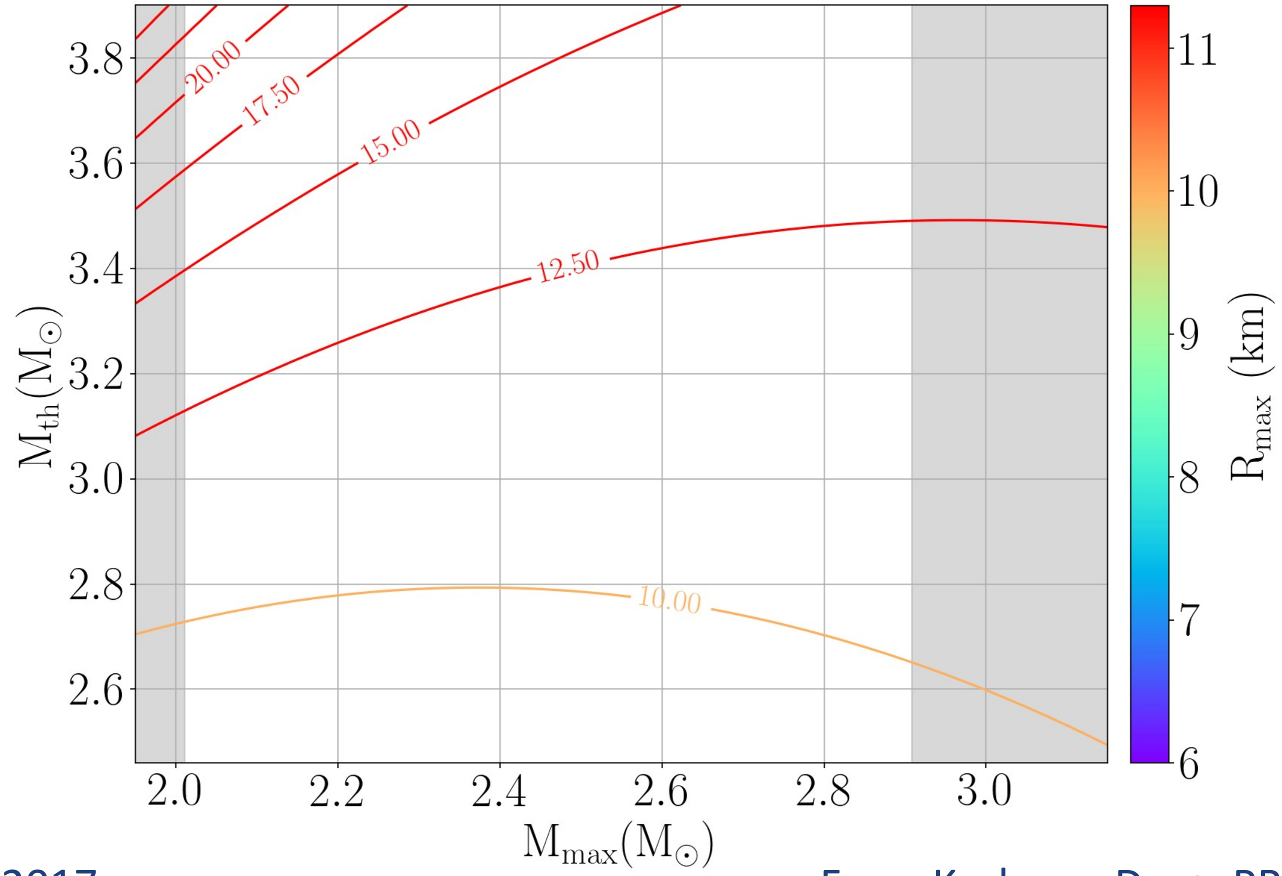
Prompt collapse: equal masses



See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

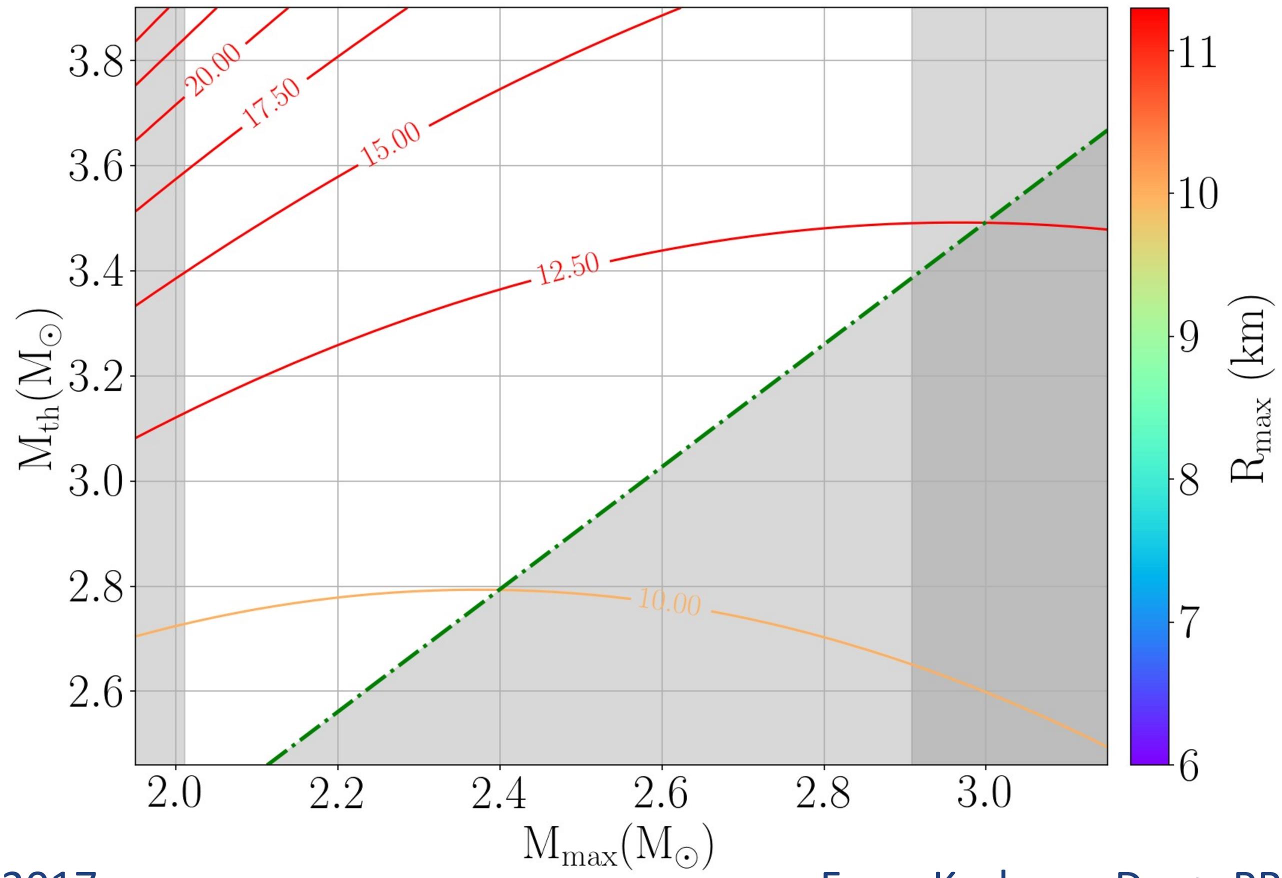
Prompt collapse: equal masses



See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

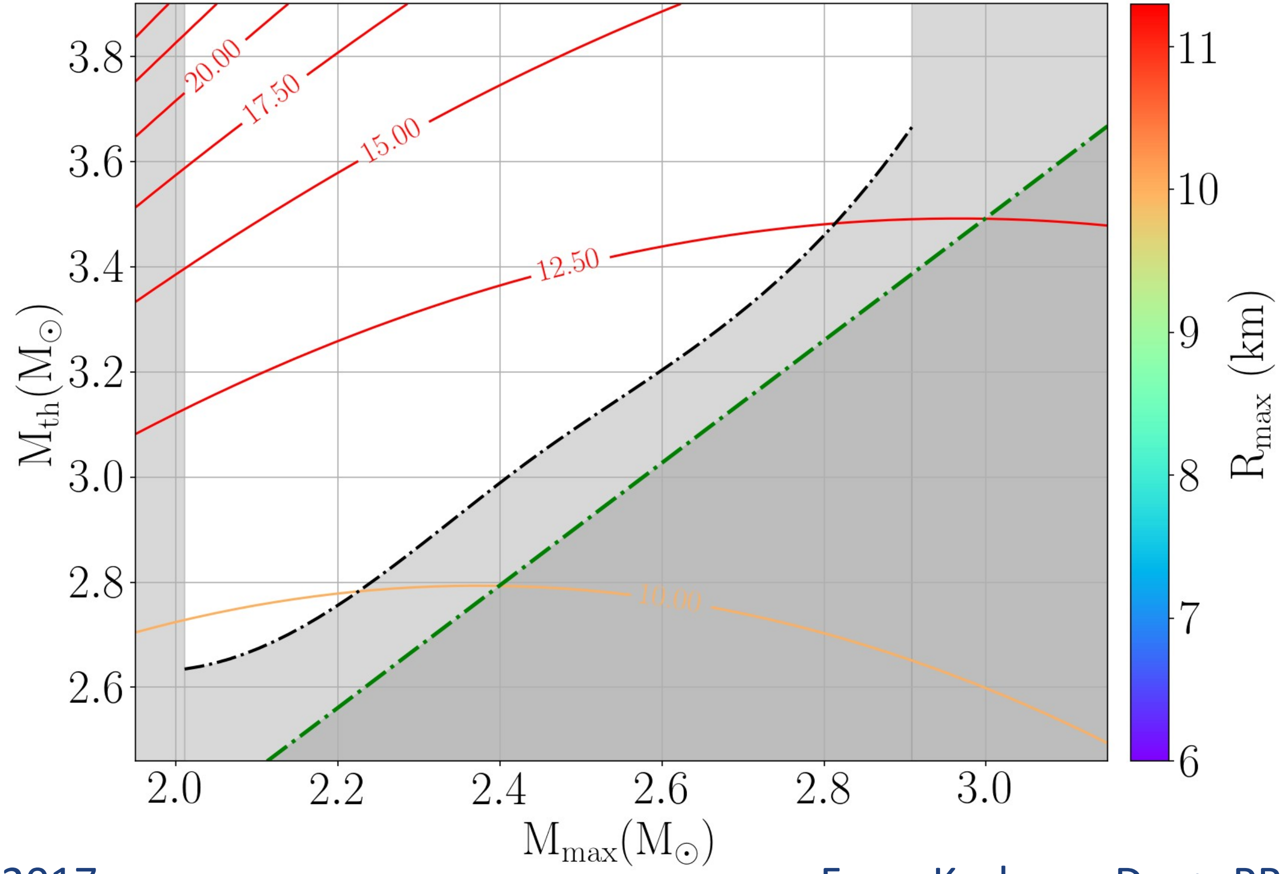
Prompt collapse: equal masses



See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

Prompt collapse: equal masses



See also Bauswein+ 2017

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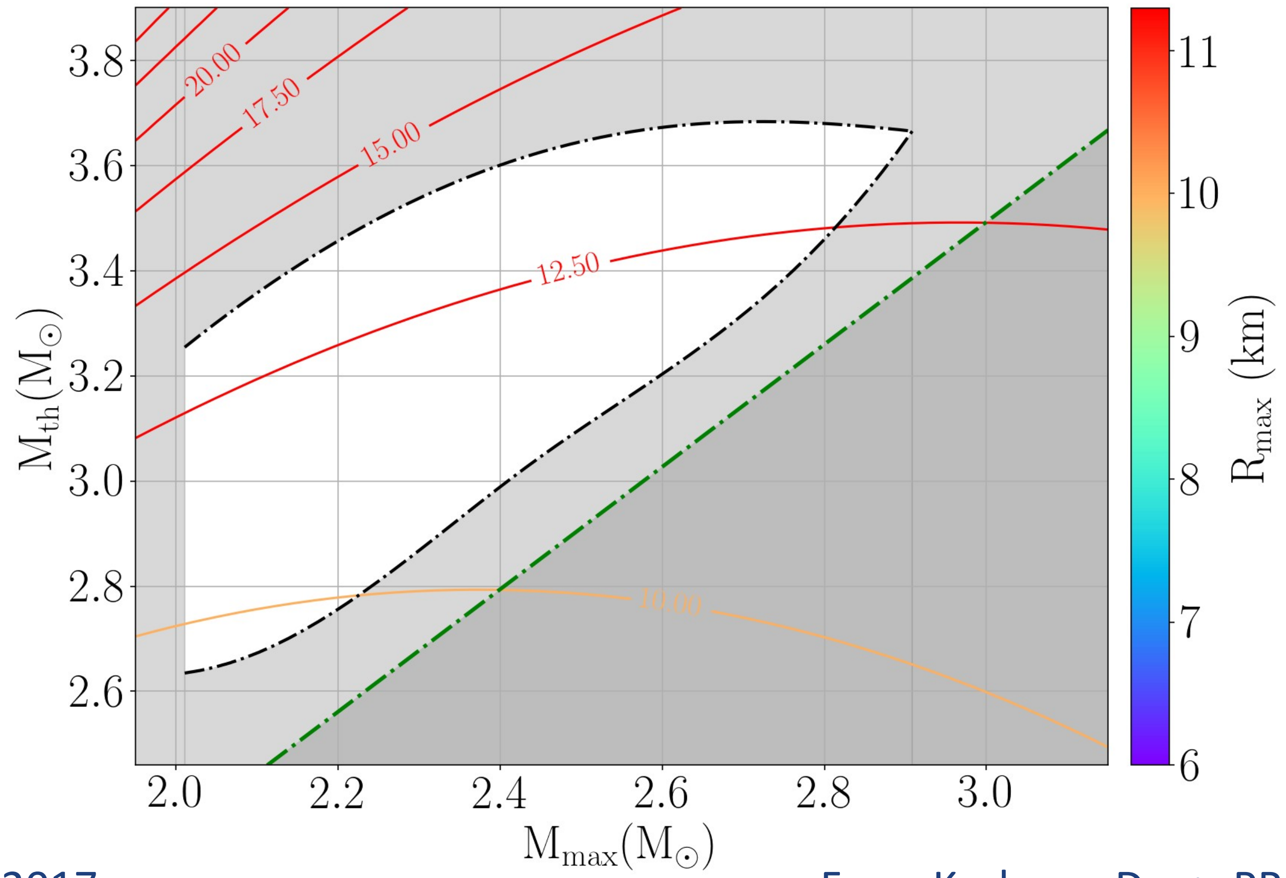
Prompt collapse: equal masses



See also Bauswein+ 2017

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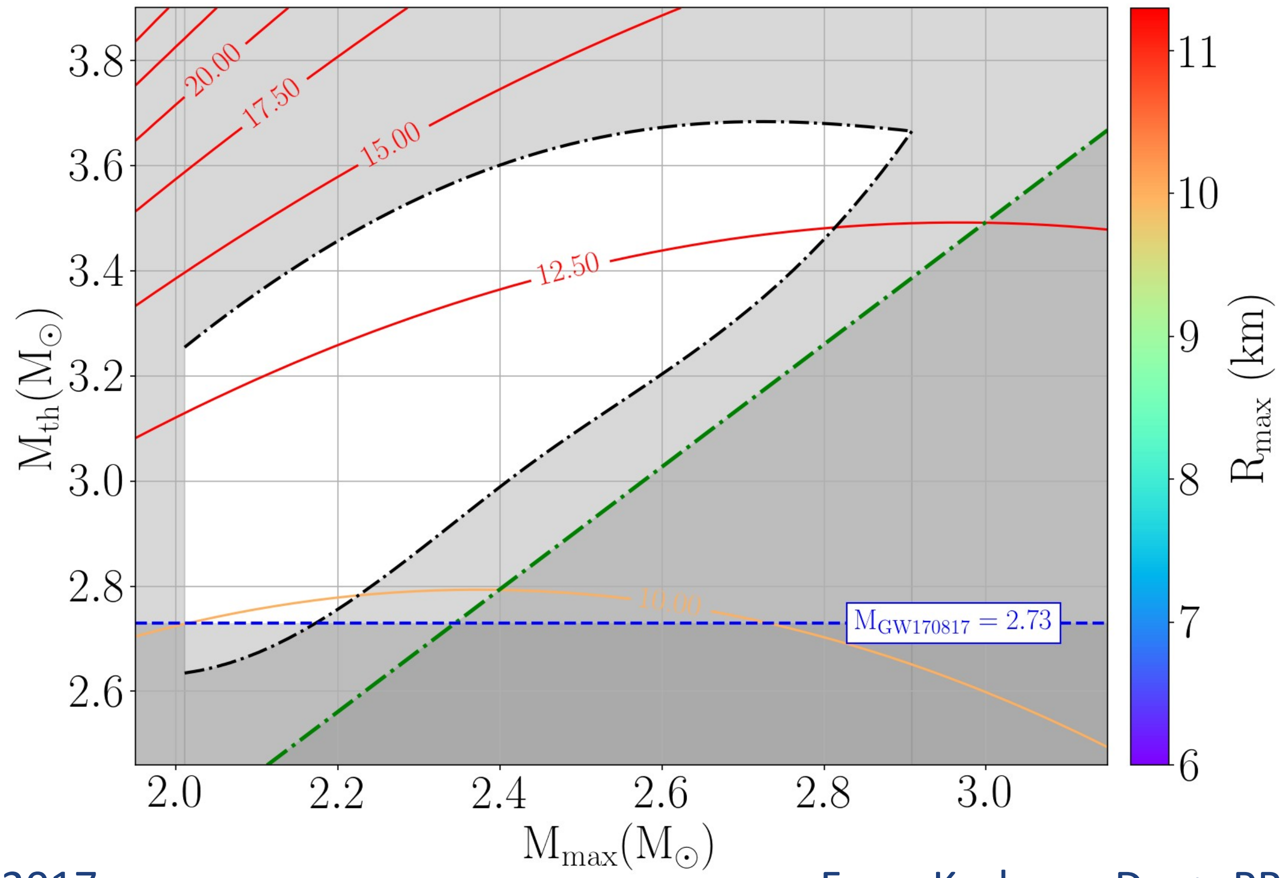
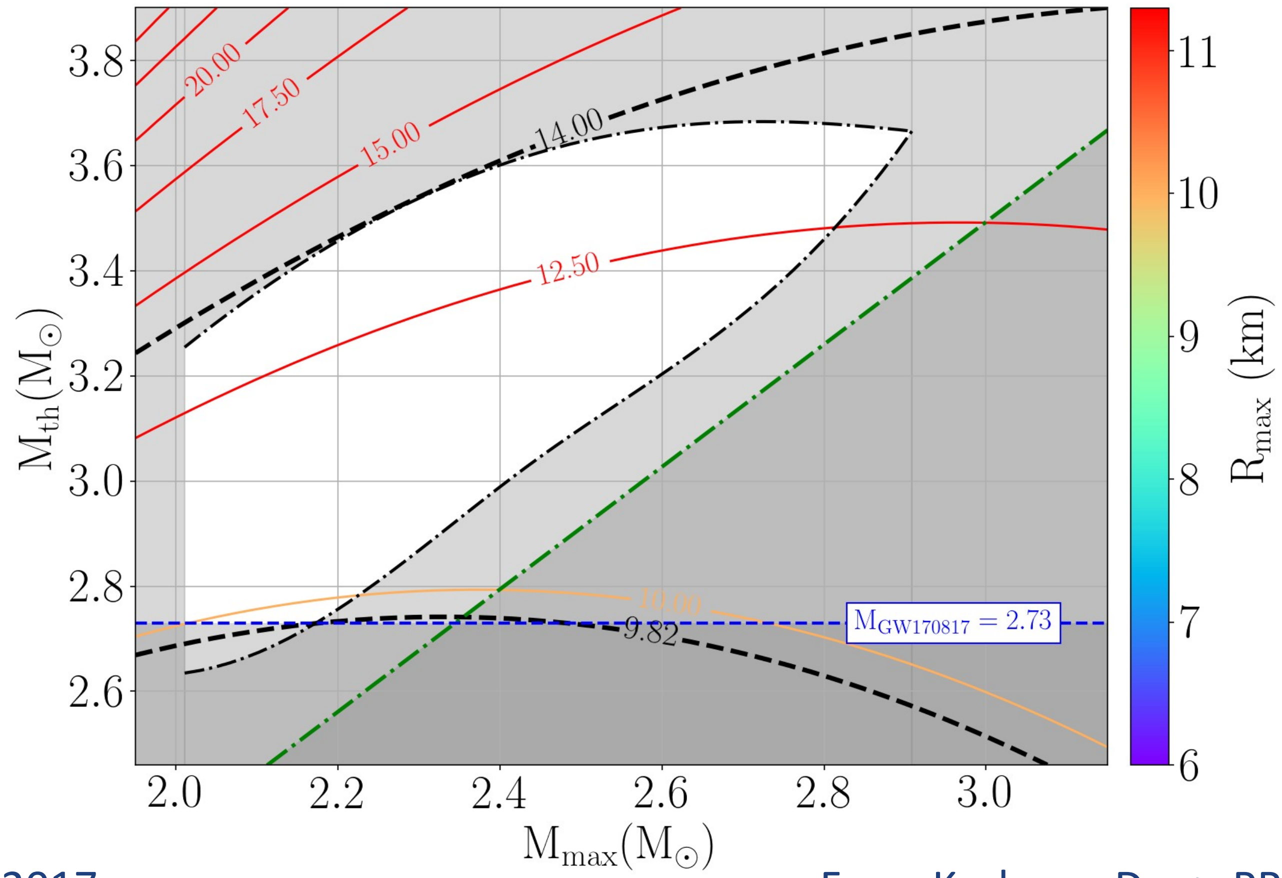
Prompt collapse: equal masses



See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

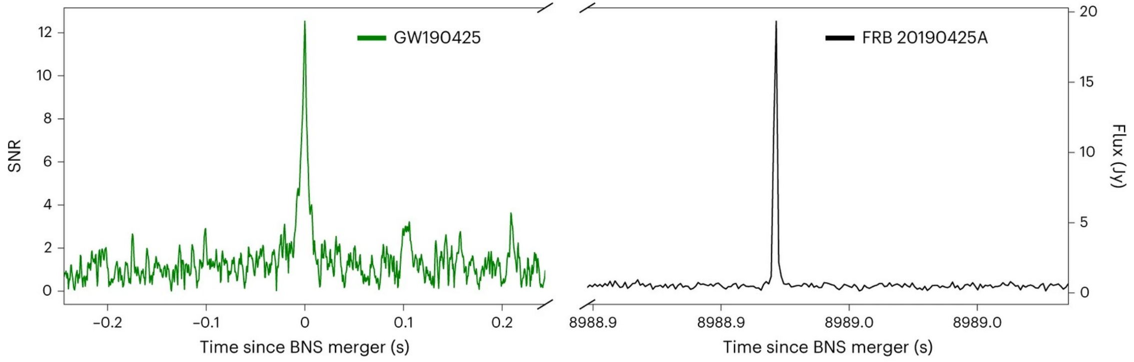
Prompt collapse: equal masses



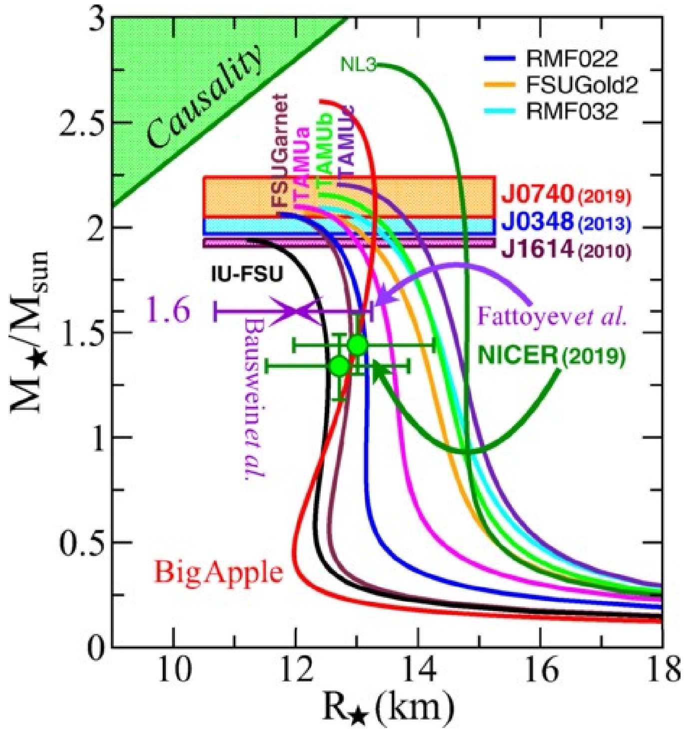
See also Bauswein+ 2017

From Kashyap, Das+, PRD 105 103022 (2022)

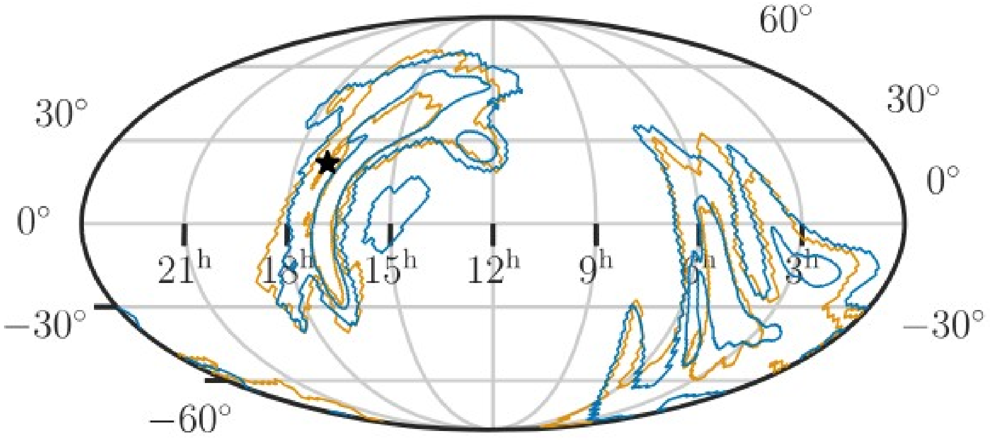
GW190425



Moroianu+ 2023

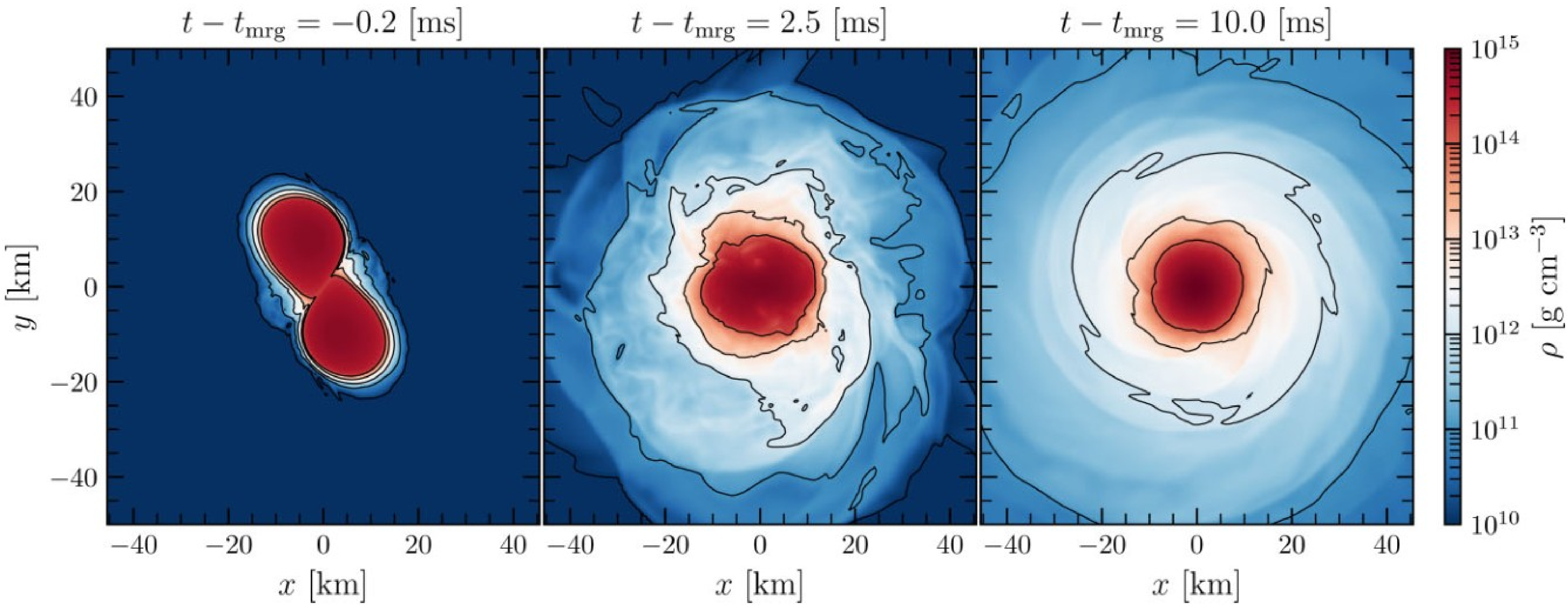


Fattoyev+ 2020



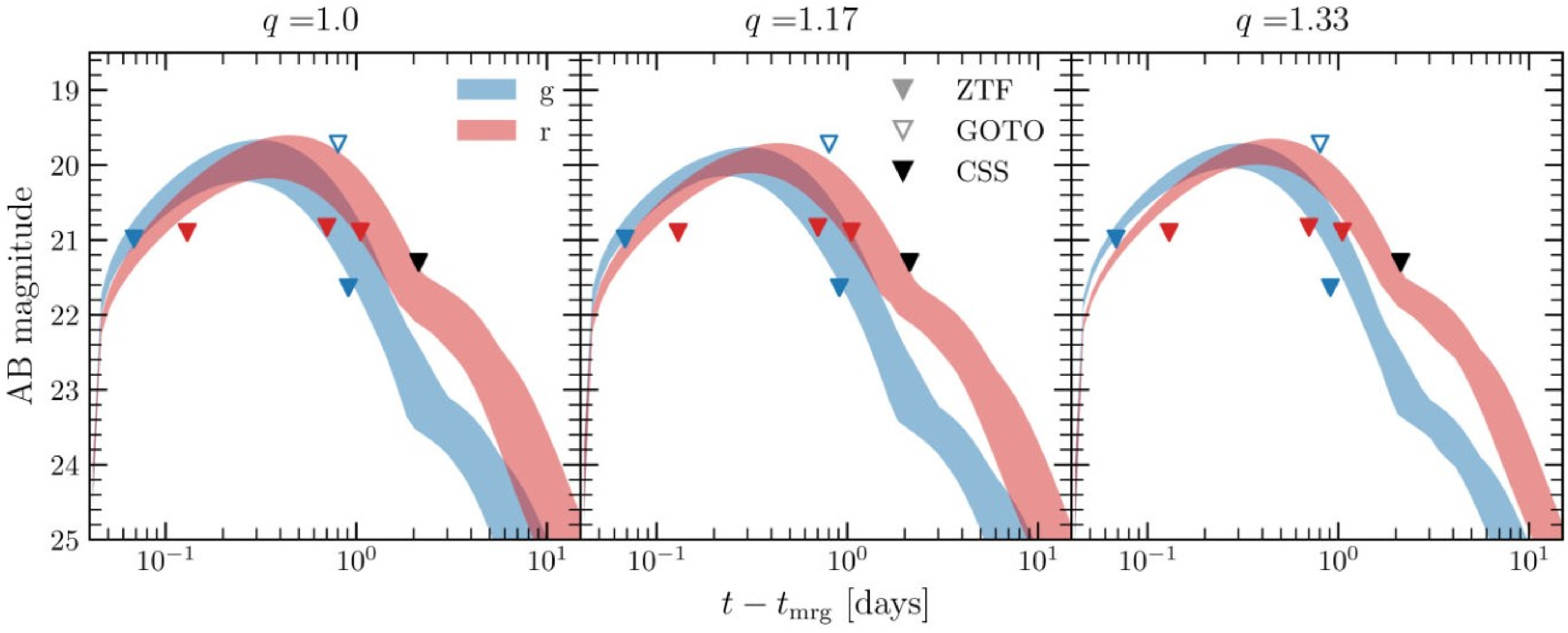
Bhardwaj, Palmese+ 2024

GW190425



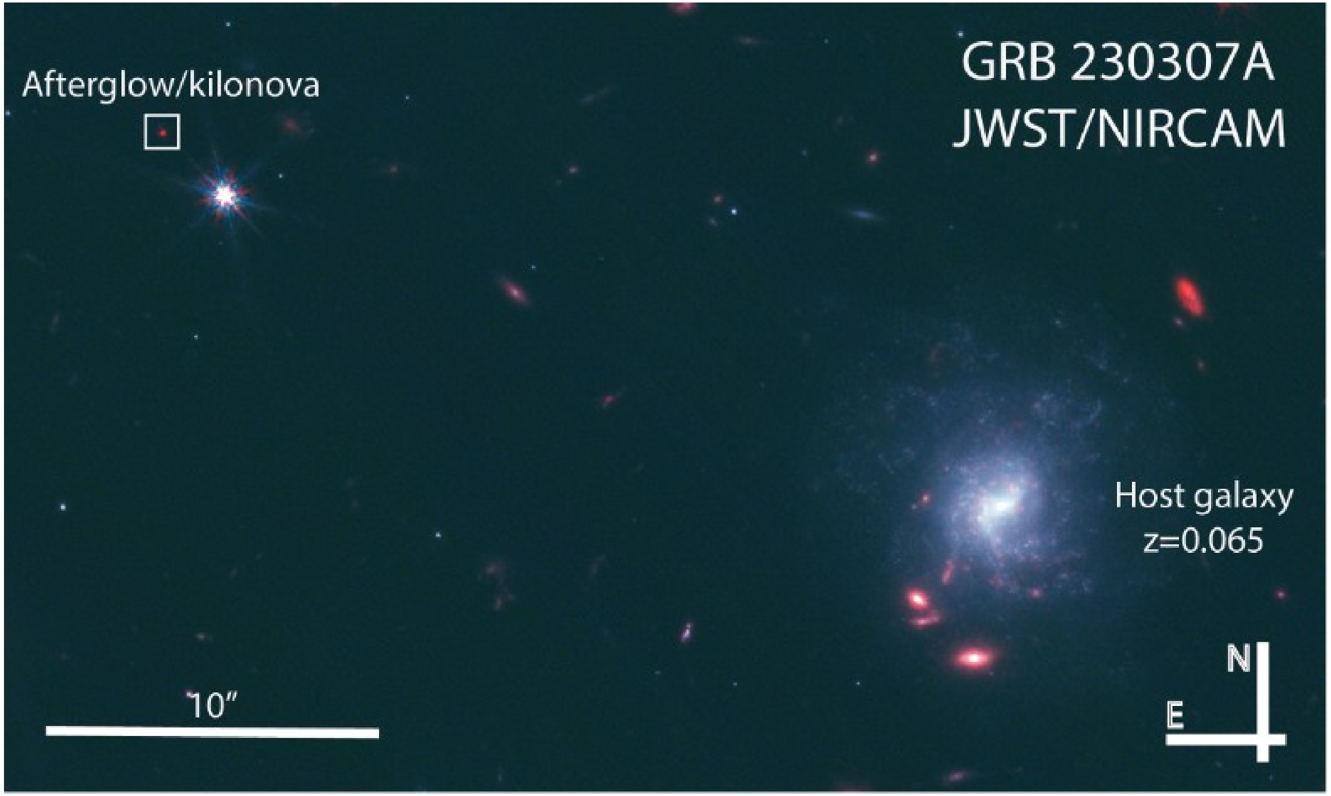
From Radice+ MNRAS 528:5836 (2024)

GW190425



From Radice+ MNRAS 528:5836 (2024)

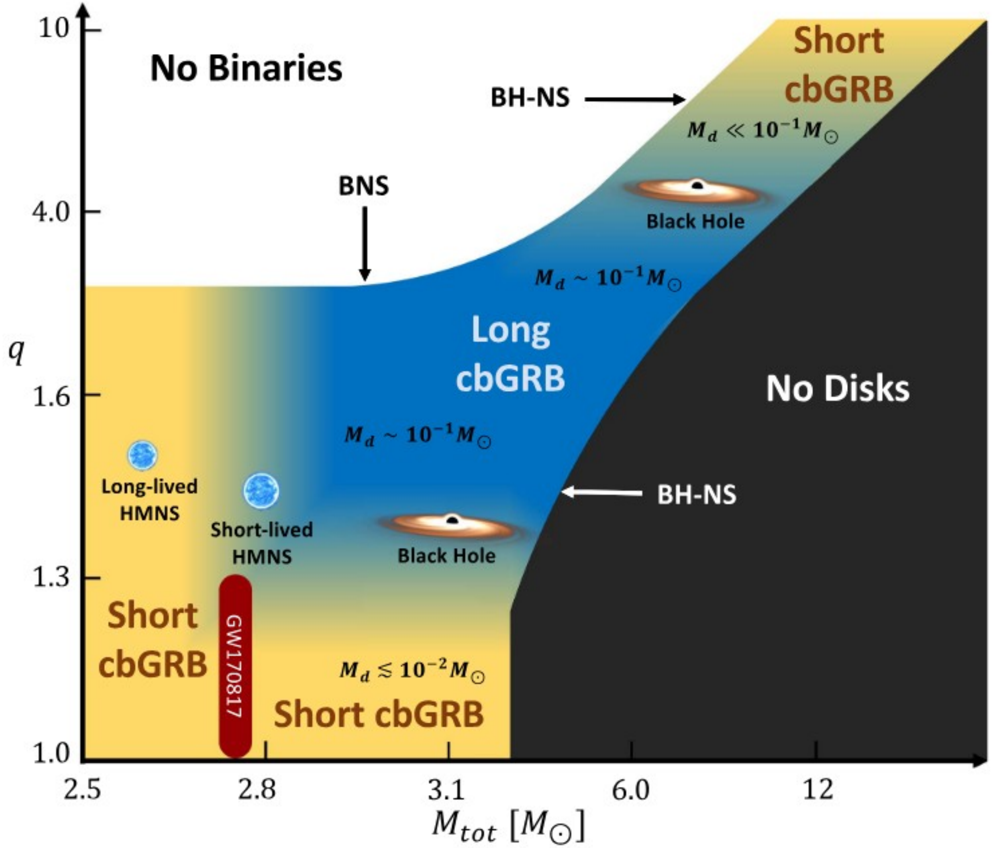
Kilonovae from long-GRBs?!?



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

From Levan+, Nature (2023)

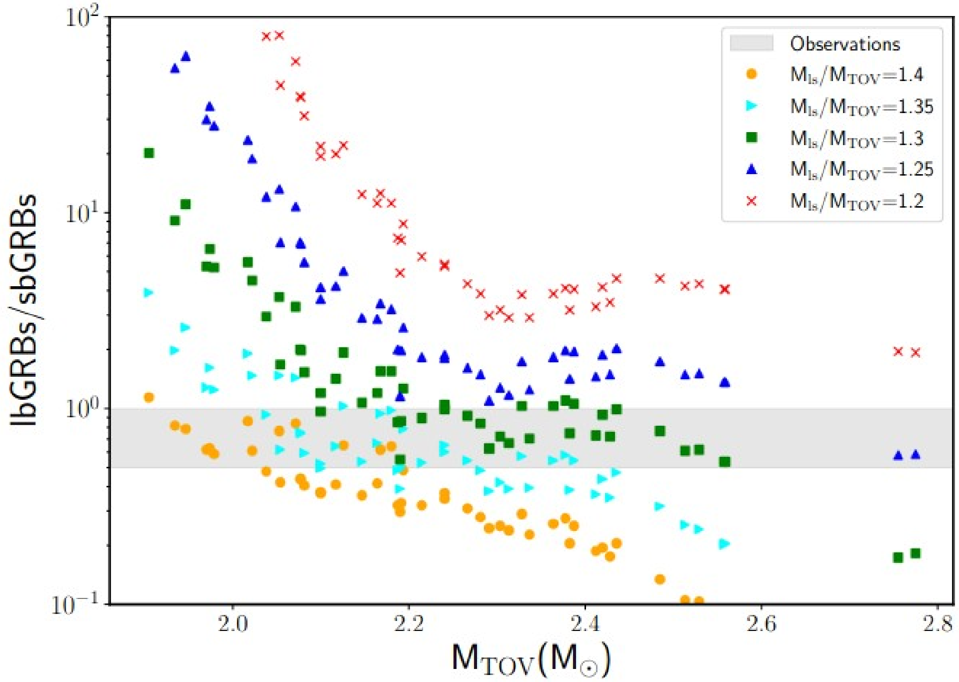
Long vs short bursts from mergers

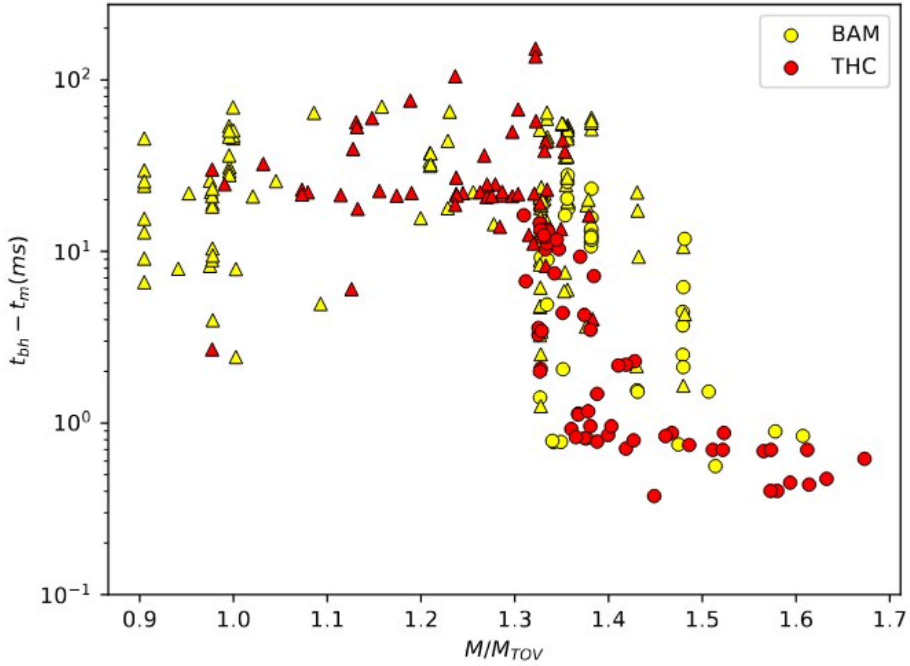


From Gottlieb+, ApJL 2023

- Mergers forming small disks power short-GRBs
- Mergers producing large disks power long-GRBs
- Ration of long to short merger GRBs can tell us about ratio of long to short lived remnants

Implication for NS mergers

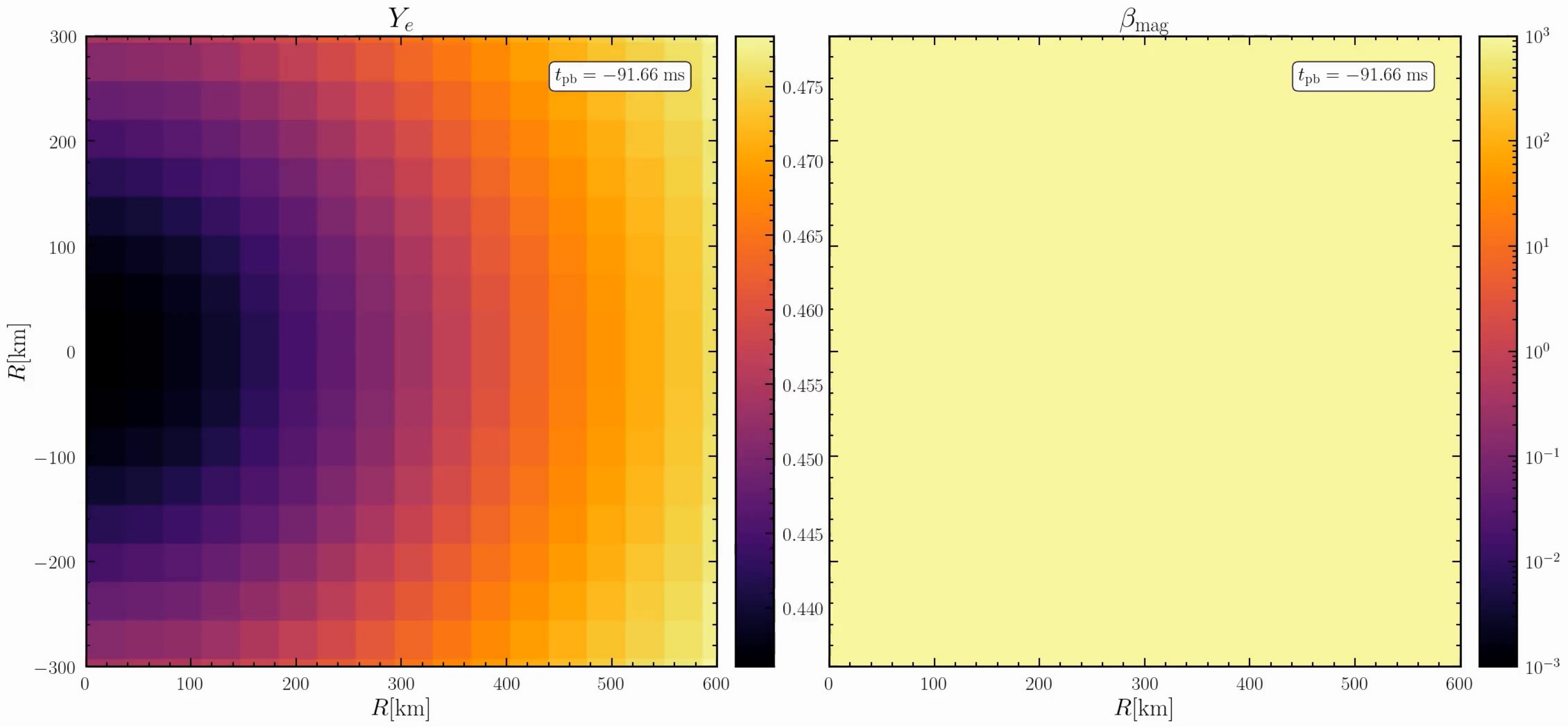




The ratio of long to short compact-binary GRBs could constrain k_{long}

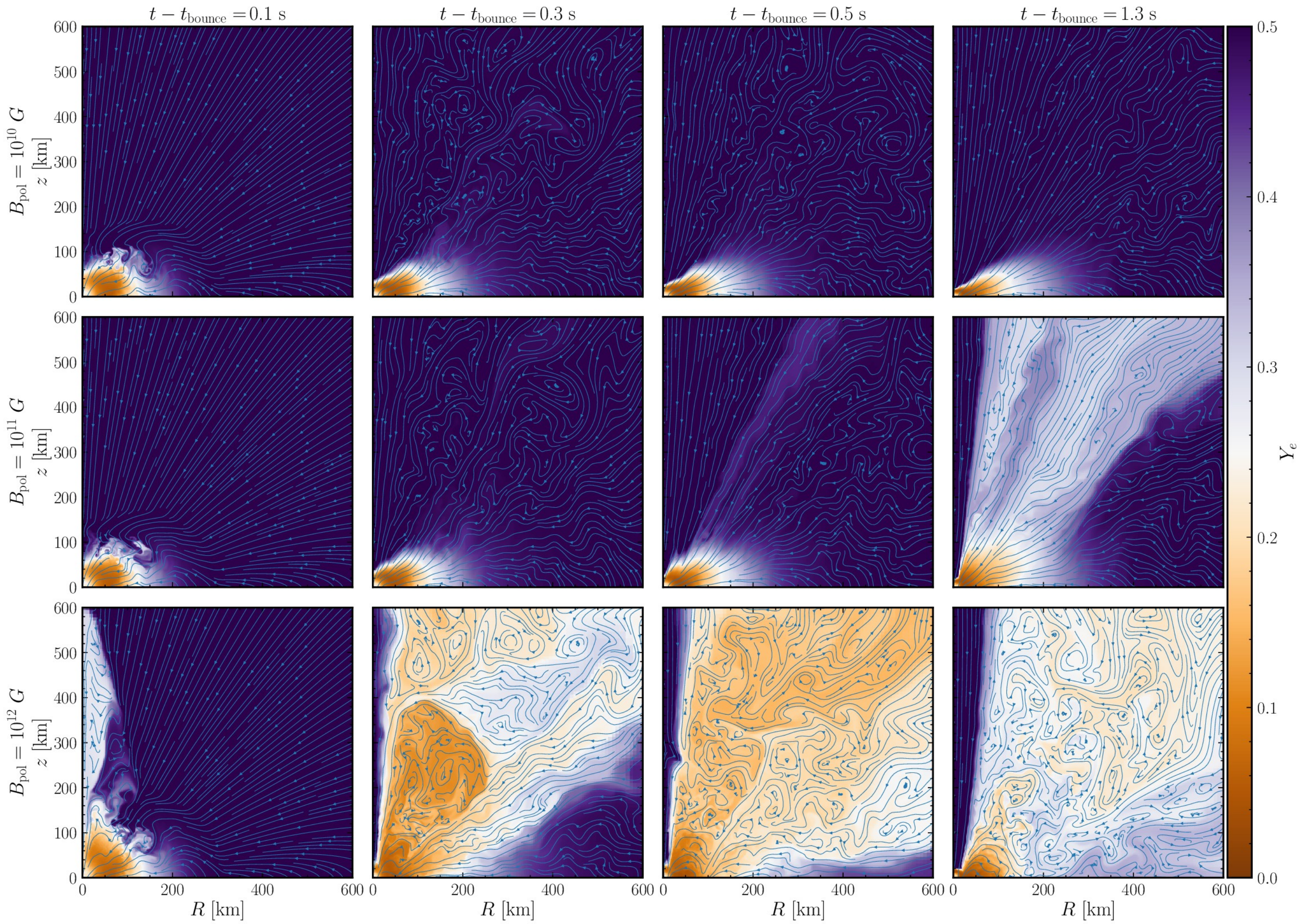
From Perna+ PRD 111:063015 (2025)

An alternative progenitor: AIC



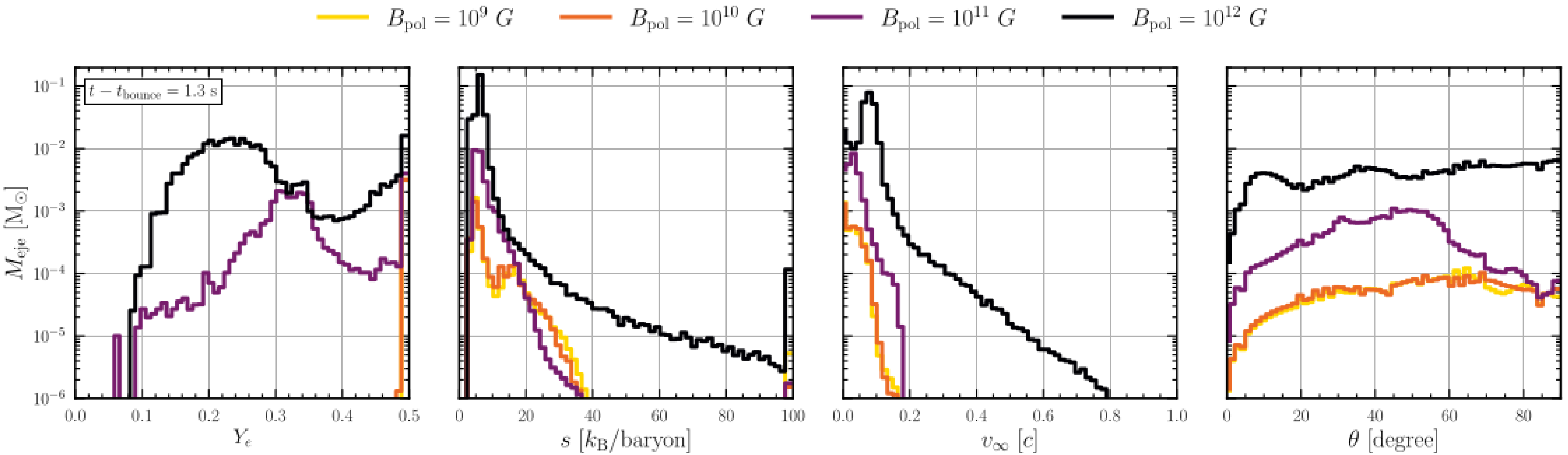
Simulation and visualization: Tetyana Pitik

From Cheong+ ApJL 978 (2025)

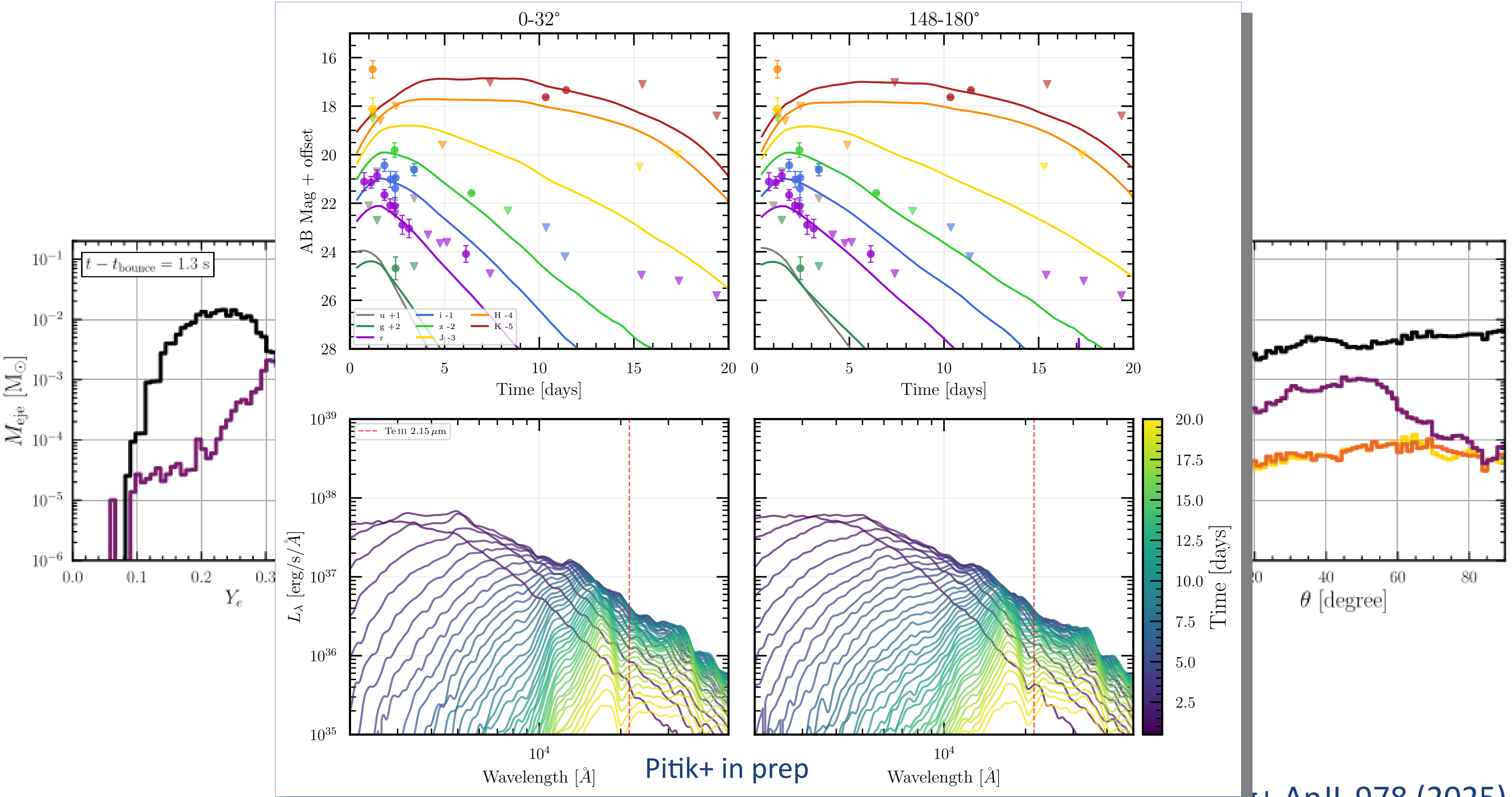


See also Batziou+ 2024; Chan+ 2025; Kuroda+ 2025; Combi+ 2025; ... From Cheong+ ApJL 978 (2025)

Kilonova from AIC

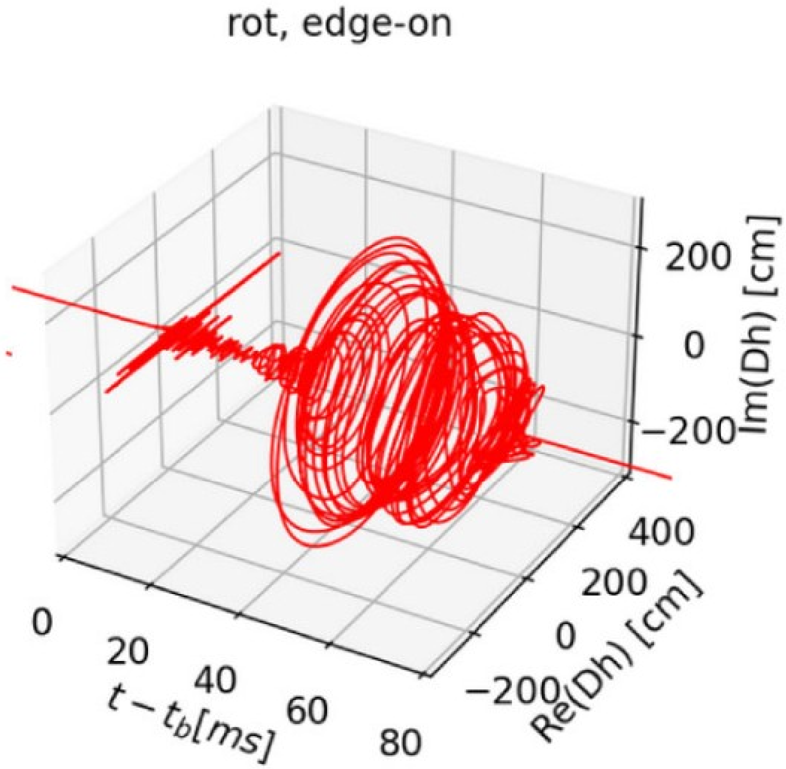


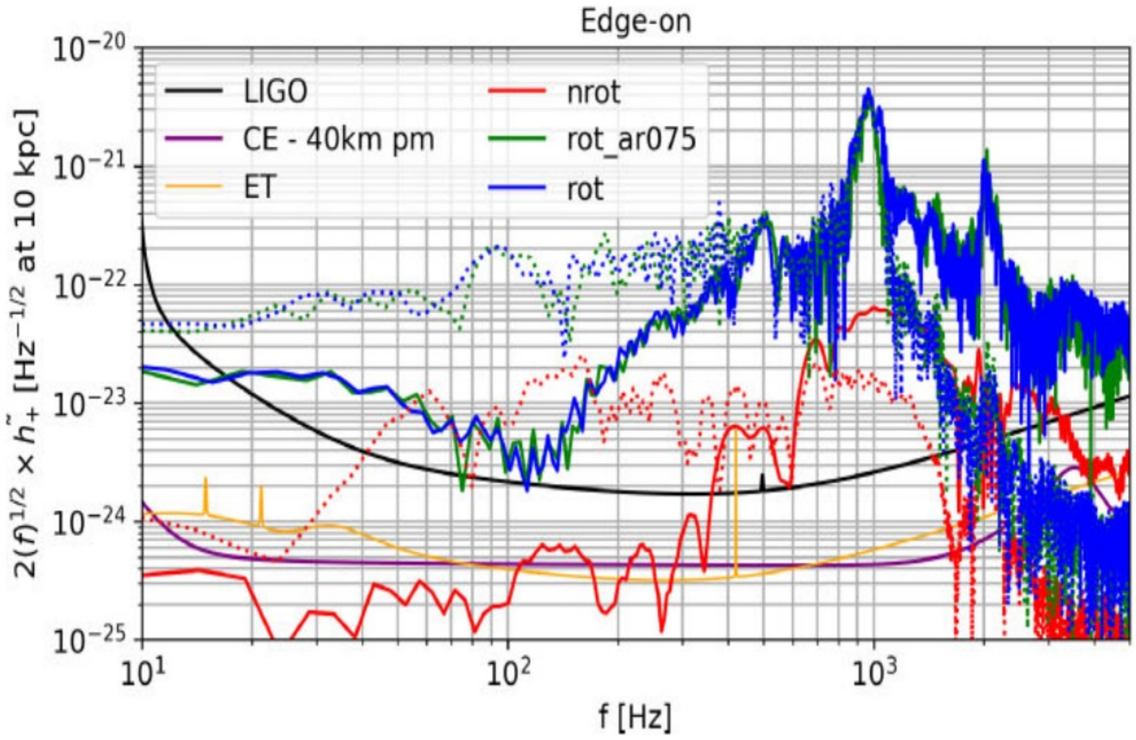
From Cheong+ ApJL 978 (2025)



g+ ApJL 978 (2025)

Gravitational-waves from AICs



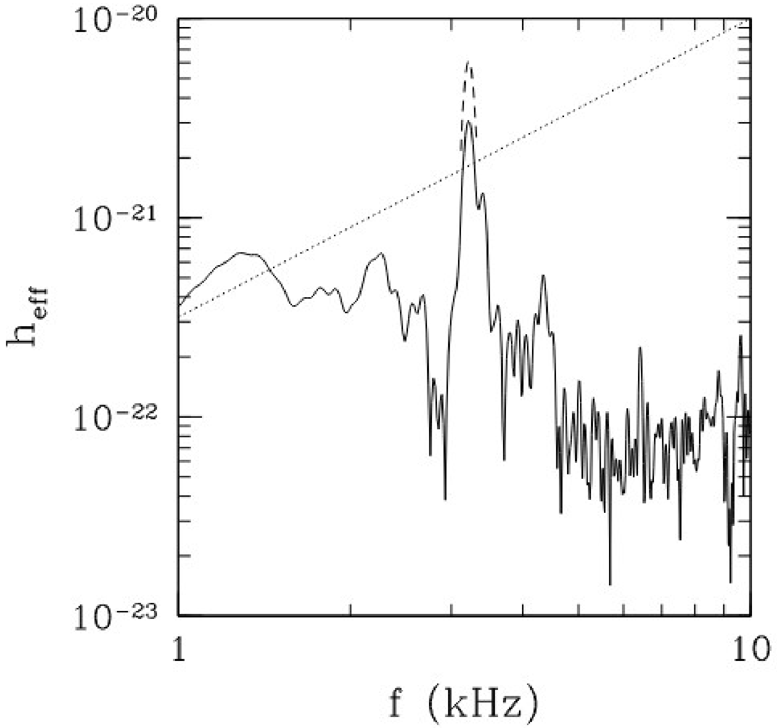


See also Shibagaki+ 2020, 2021, 2023; Shibata 2026

From Longo+, MNRAS 525:6359 (2023)

Postmerger GW signal

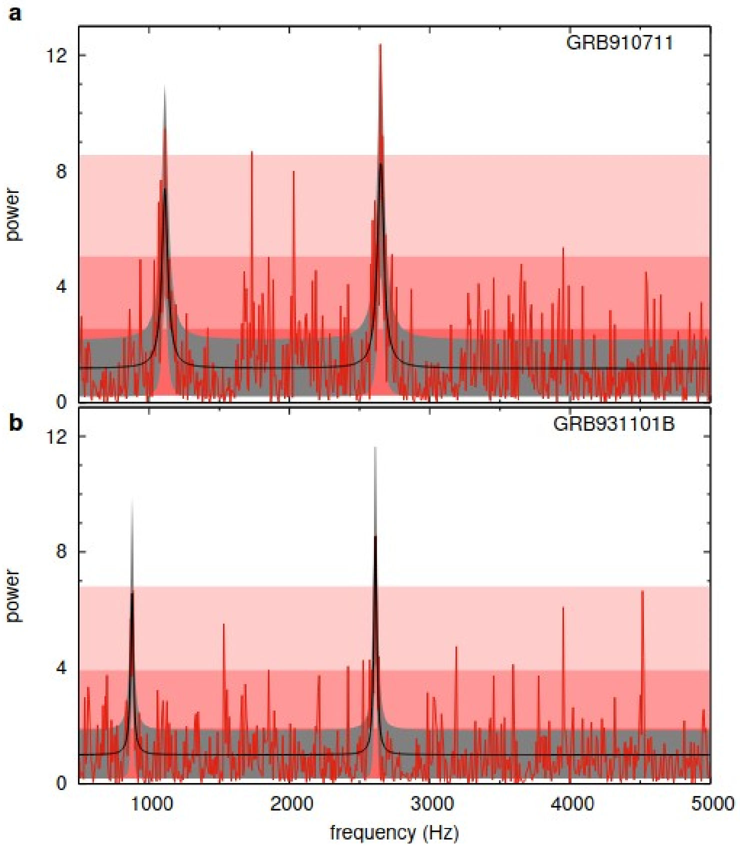
From Shibata 2005



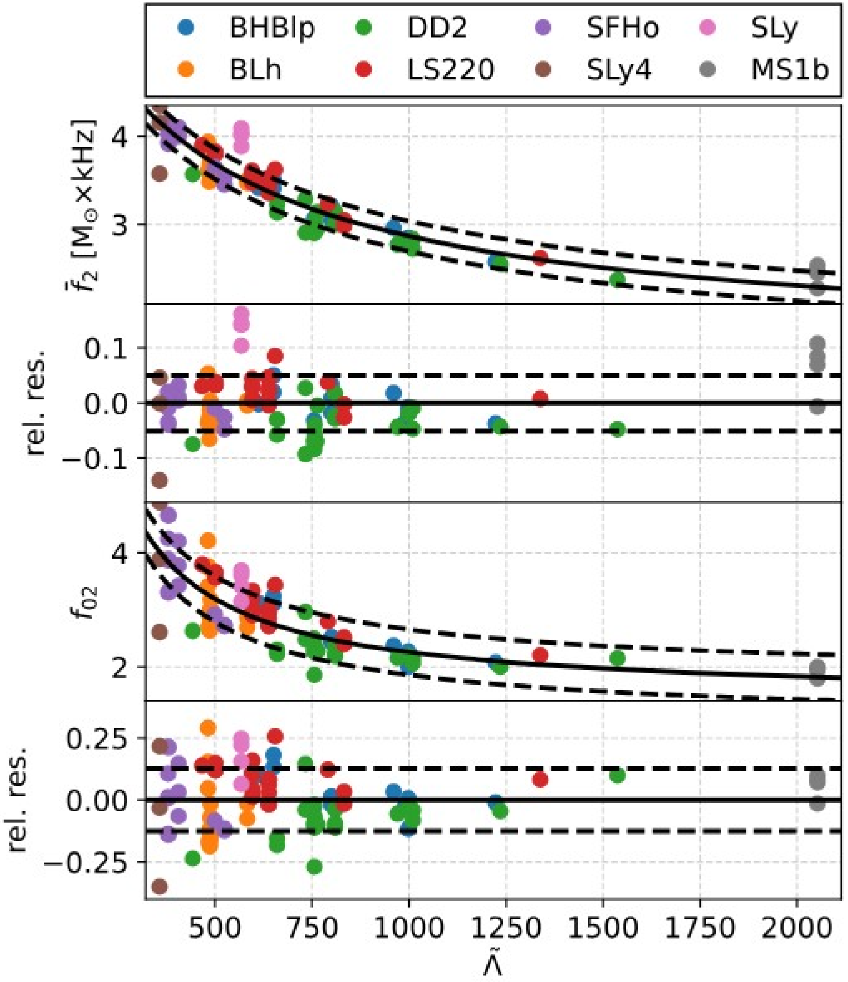
- Postmerger signal characterized by dominant frequency f_{peak}
- Need next gen. GW experiments, or very close (rare) events
- What can we learn from f_{peak}?
- Many ideas in the literature (many more papers than ideas)

See also Shibata+ 2005; Takami+ 2014; Bernuzzi 2015, Rezzolla+ 2016; Dietrich+ 2016; Radice+ 2017; Breschi+ 2019; Bauswein+ 2019; …

QPOs from SGRBs?

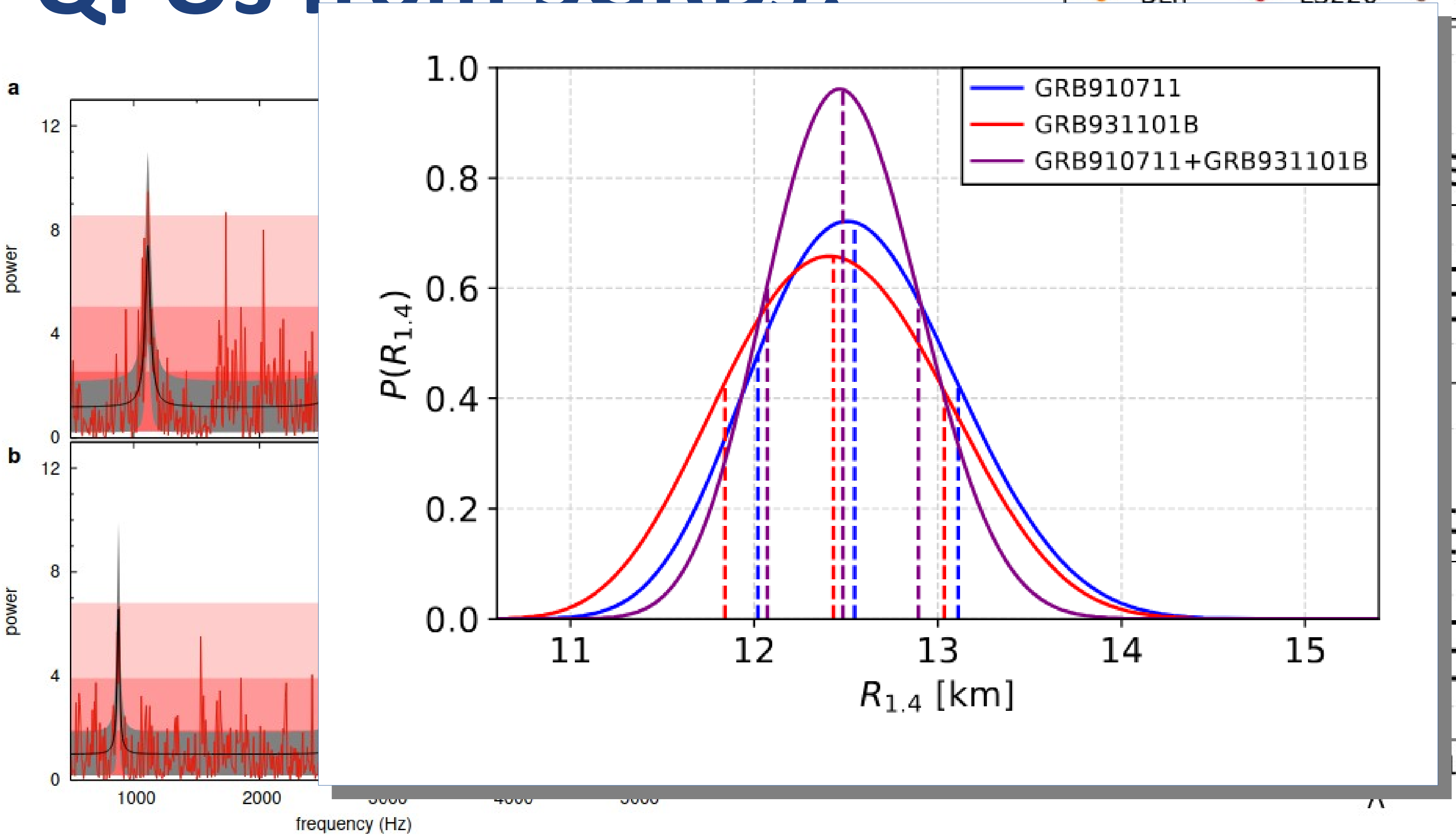


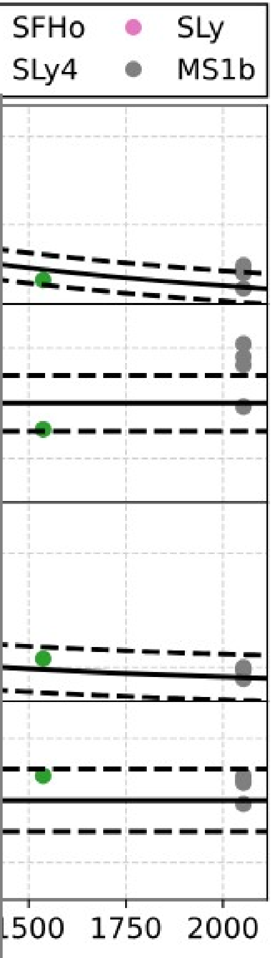
Chirenti+ Nature 613:7943 (2023)



Guedes+ ApJ 983 (2025)

QPOs from SGRBs?

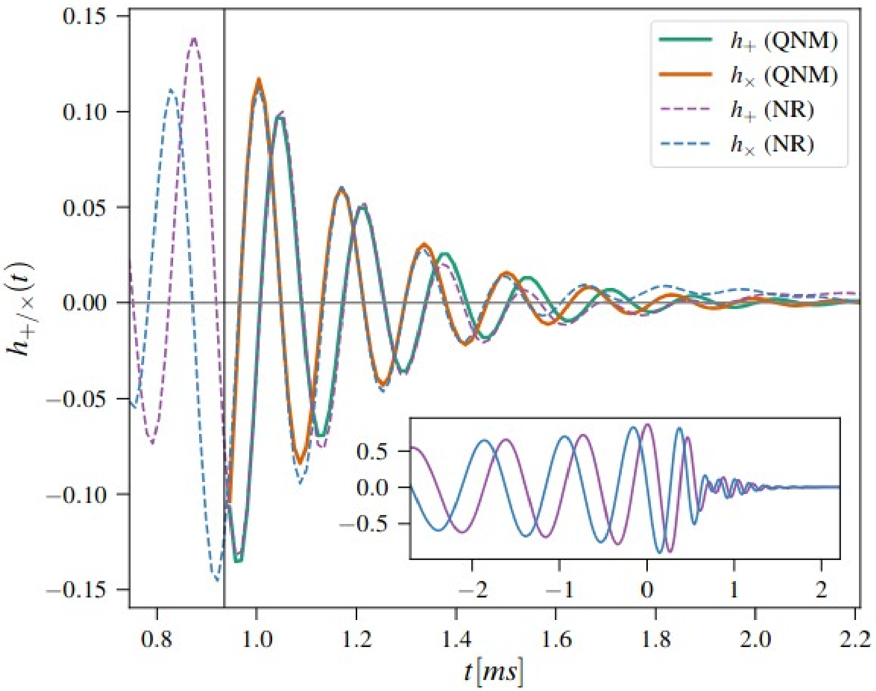


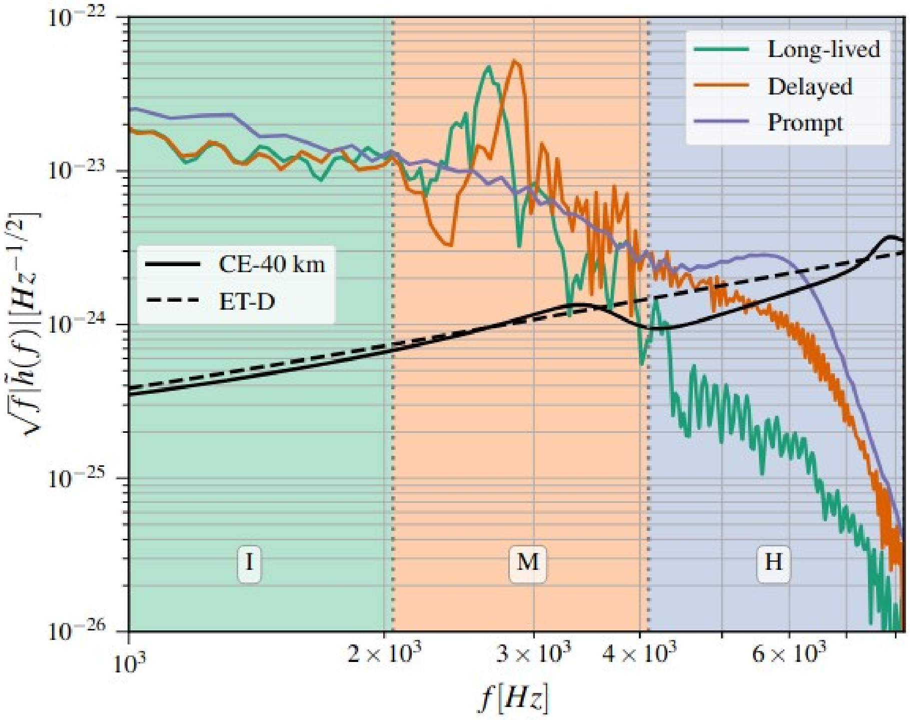


Chirenti+ Nature 613:7943 (2023)

Guedes+ ApJ 983 (2025)

GWs from BH formation

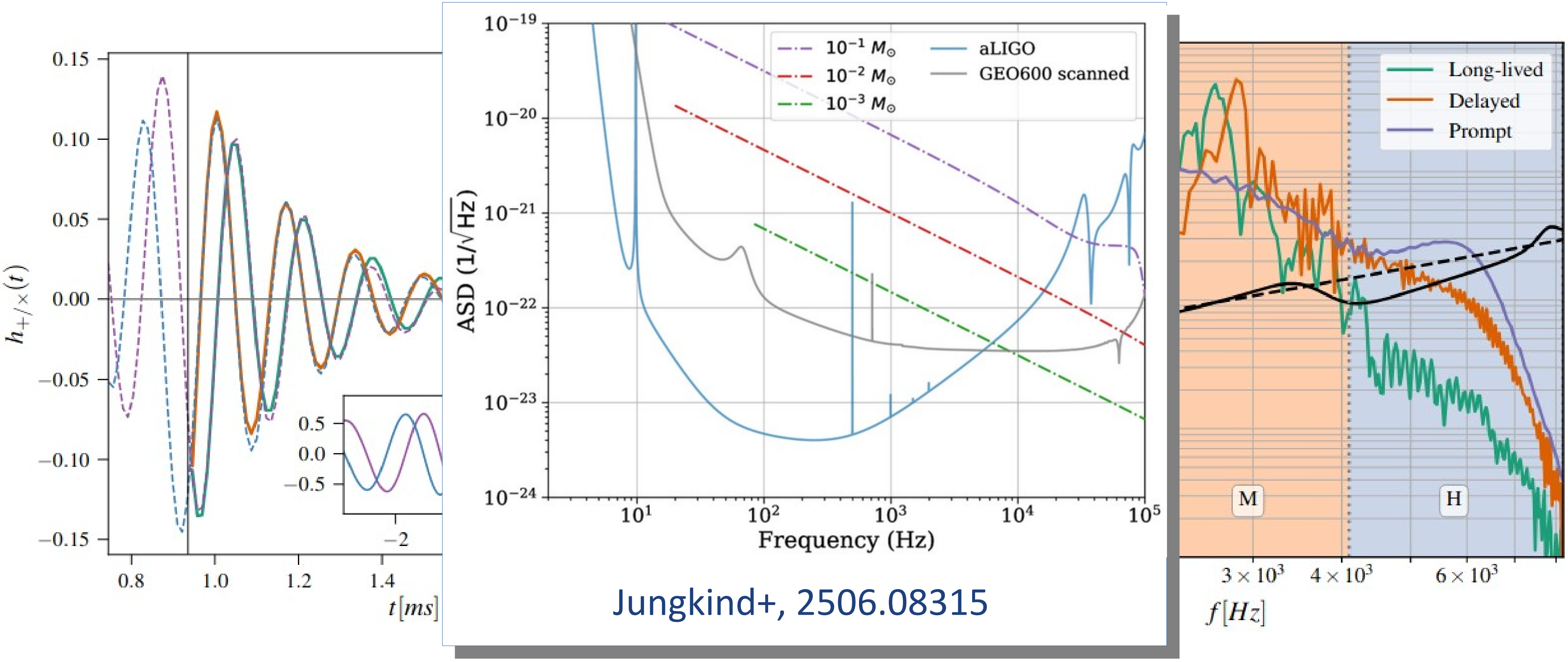




See also Shibata 2005; Zhang+ 2021

From Dhani, DR+, PRD 109:044071 (2024)

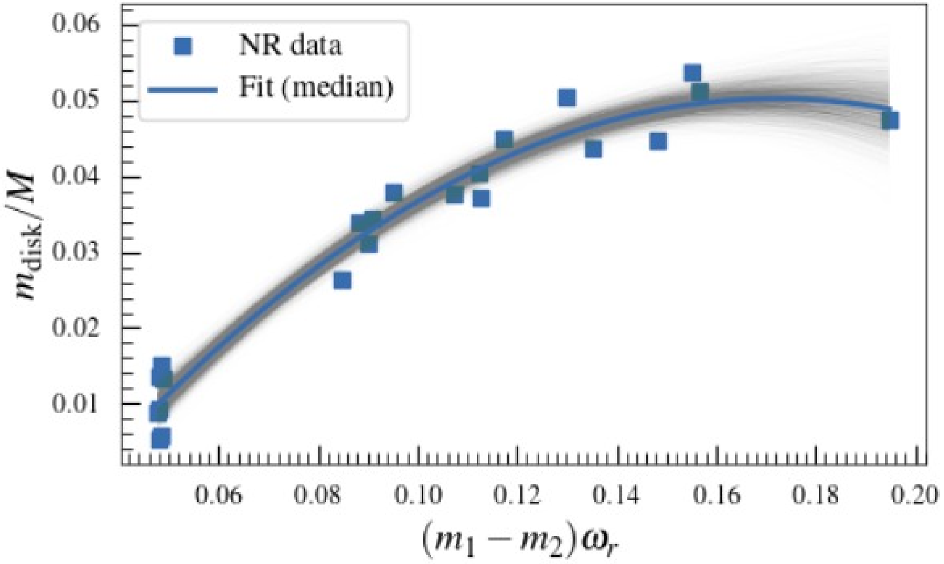
GWs from BH formation

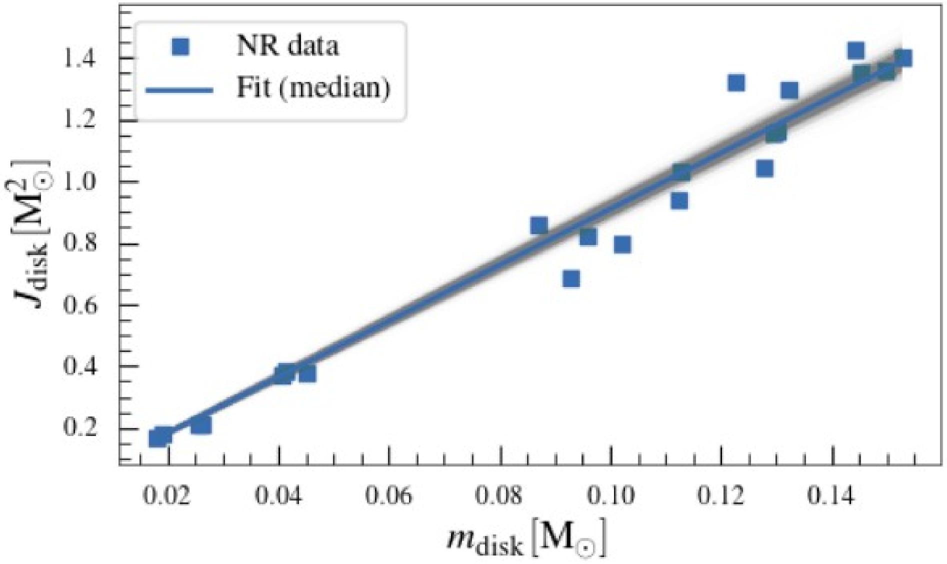


See also Shibata 2005; Zhang+ 2021

From Dhani, DR+, PRD 109:044071 (2024)

Measuring the disk mass with GWs

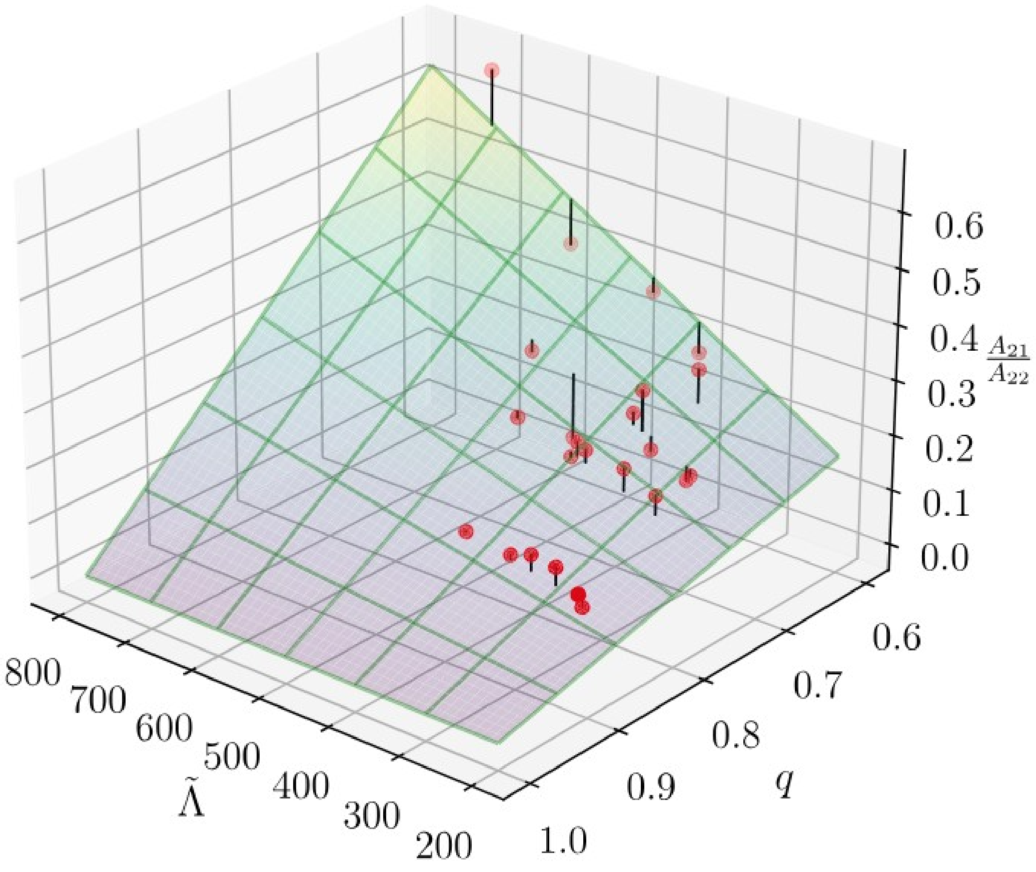


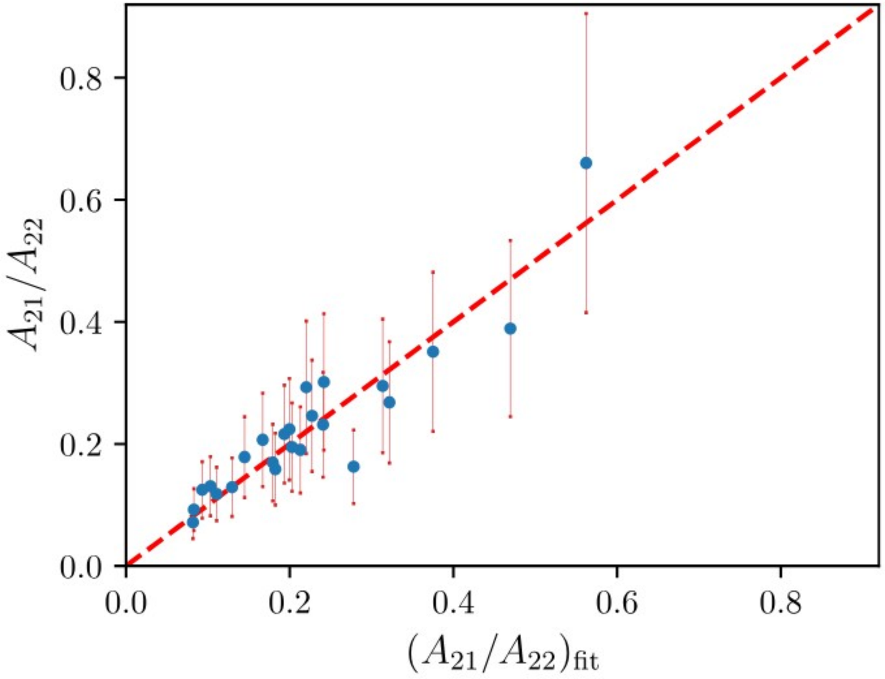


We could measure the disk mass with a precision of ~10% at SNR of 5!

From Dhani, arXiv:2507.14071

Mode amplitudes





From Bandyopadhyay+, CQG 41:145006 (2024)

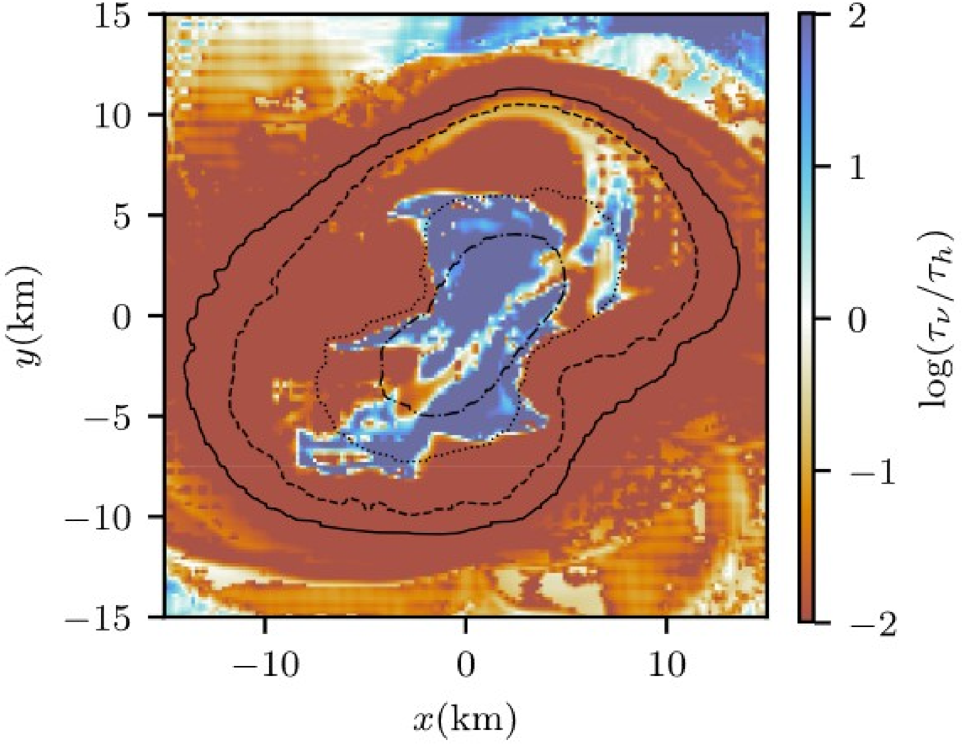
Part II: The Fine Print

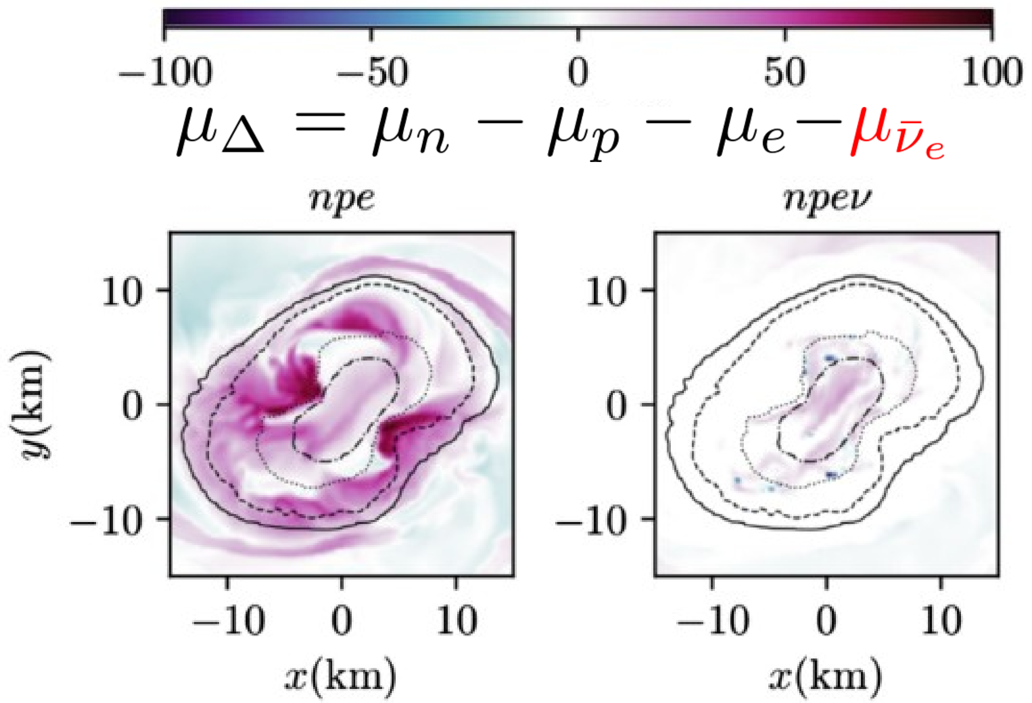
Some open problems and theory opportunities

Theory challenges

- Simulations cover small region of parameter space
- Most simulations are too short
- MHD turbulence and dynamo action in mergers: how do we model?
- Can we model neutrinos and weak interactions sufficiently well in mergers?
- What about non-ideal effects (viscosity, crust, BSM physics)?

Can we use hydrodynamics?

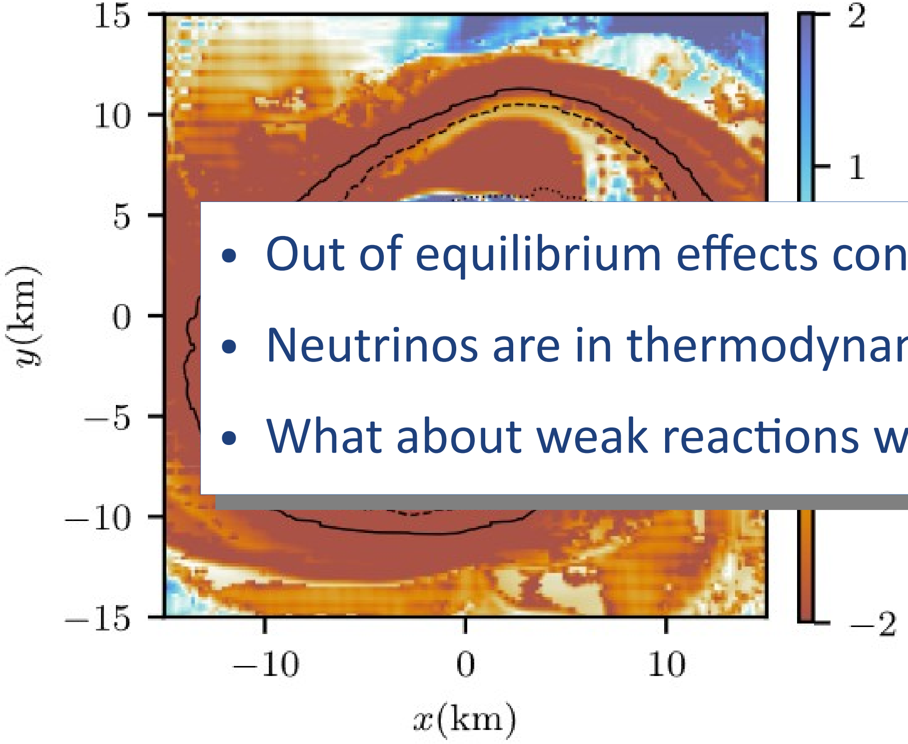


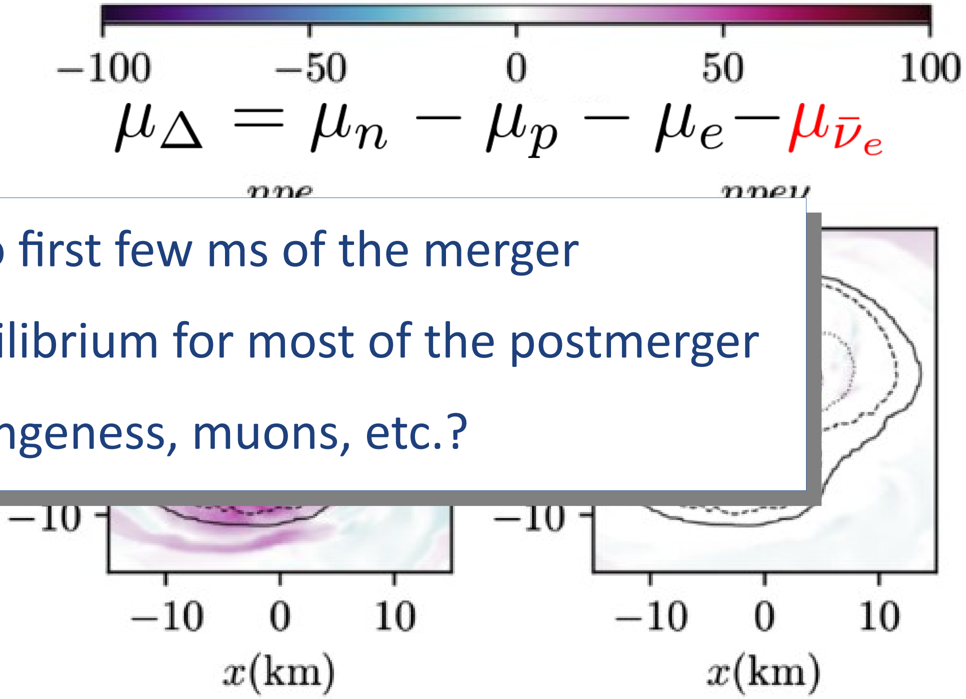


See also Alford+ 2017; Perego+ 2019;
Most+ 2021, 2022, 2024; Hammond+ 2021; ...

From Espino+ PRL 132:211001 (2024)

Can we use hydrodynamics?



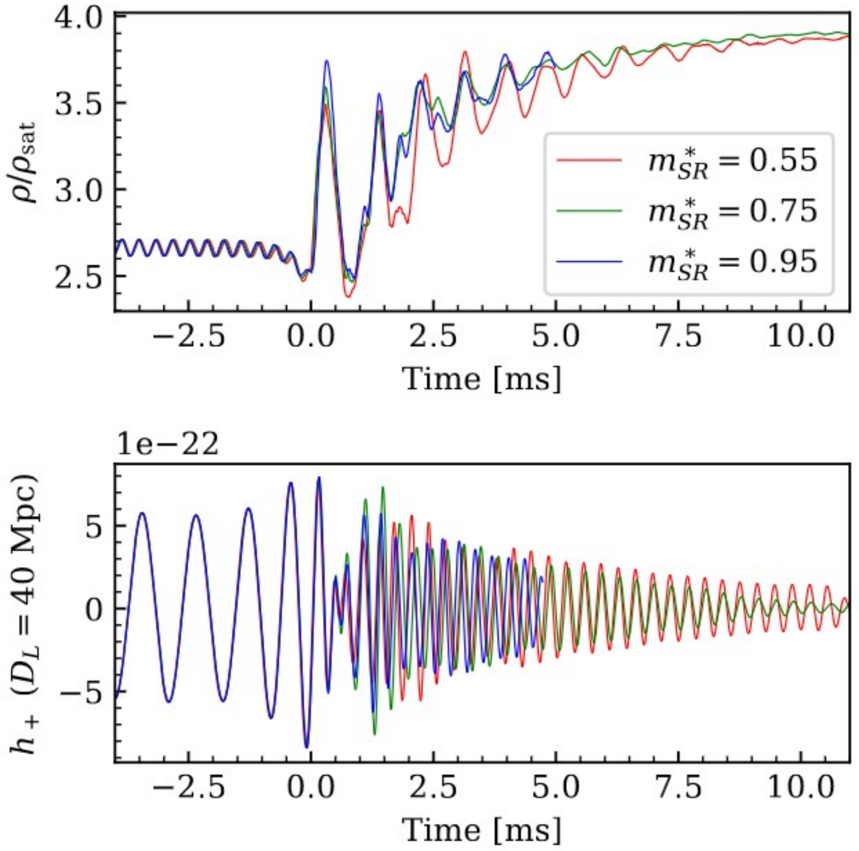


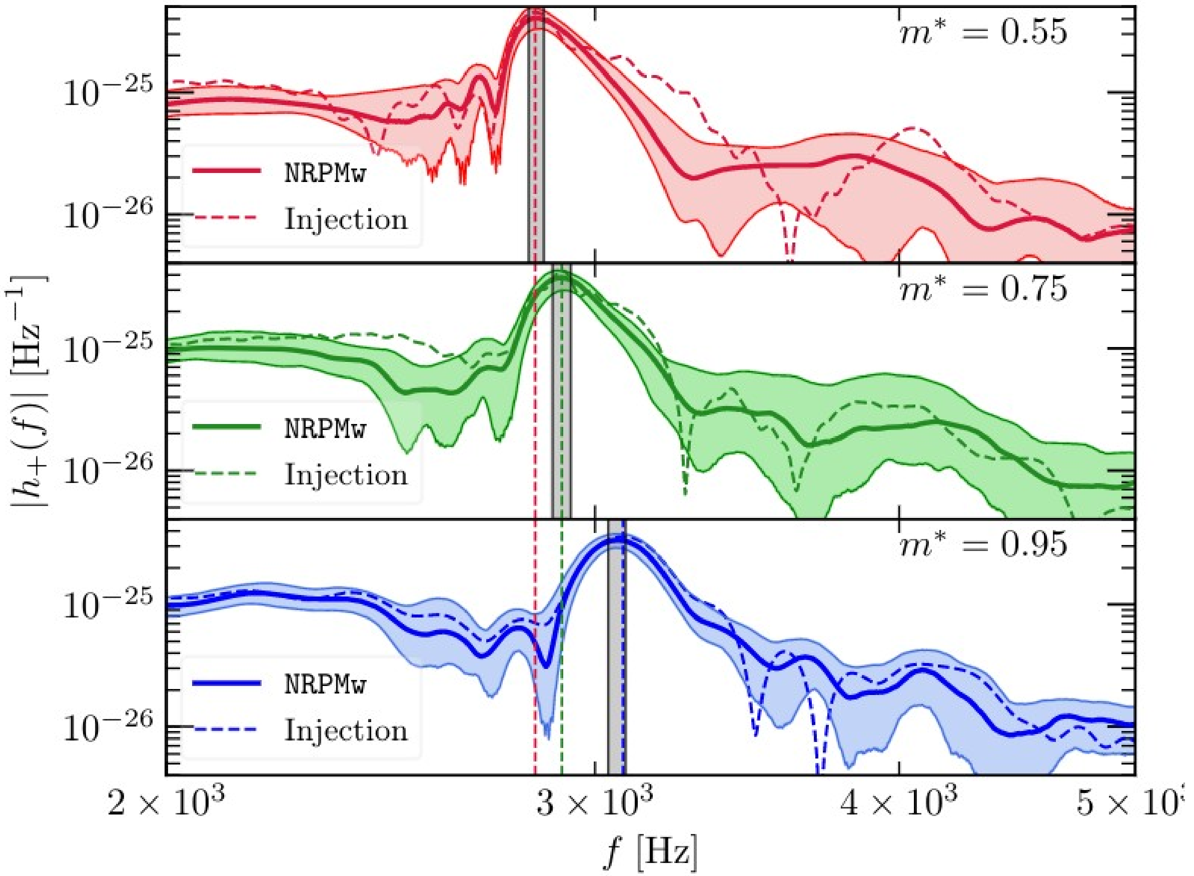
- Out of equilibrium effects confined to first few ms of the merger
- Neutrinos are in thermodynamic equilibrium for most of the postmerger
- What about weak reactions with strangeness, muons, etc.?

See also Alford+ 2017; Perego+ 2019;
Most+ 2021, 2022, 2024; Hammond+ 2021; ...

From Espino+ PRL 132:211001 (2024)

Thermal effects





See also Raithel+ 2021, 2022

From Fields+ ApJL, 952:L36 (2023)

Quantum neutrino effects

Quantum kinetic equation: $$\frac{Df}{D\lambda} = -i[H, f] + \mathbb{C}[f]$$

We consider a flavor transformation scenario that can be solved exactly

BGK approximation

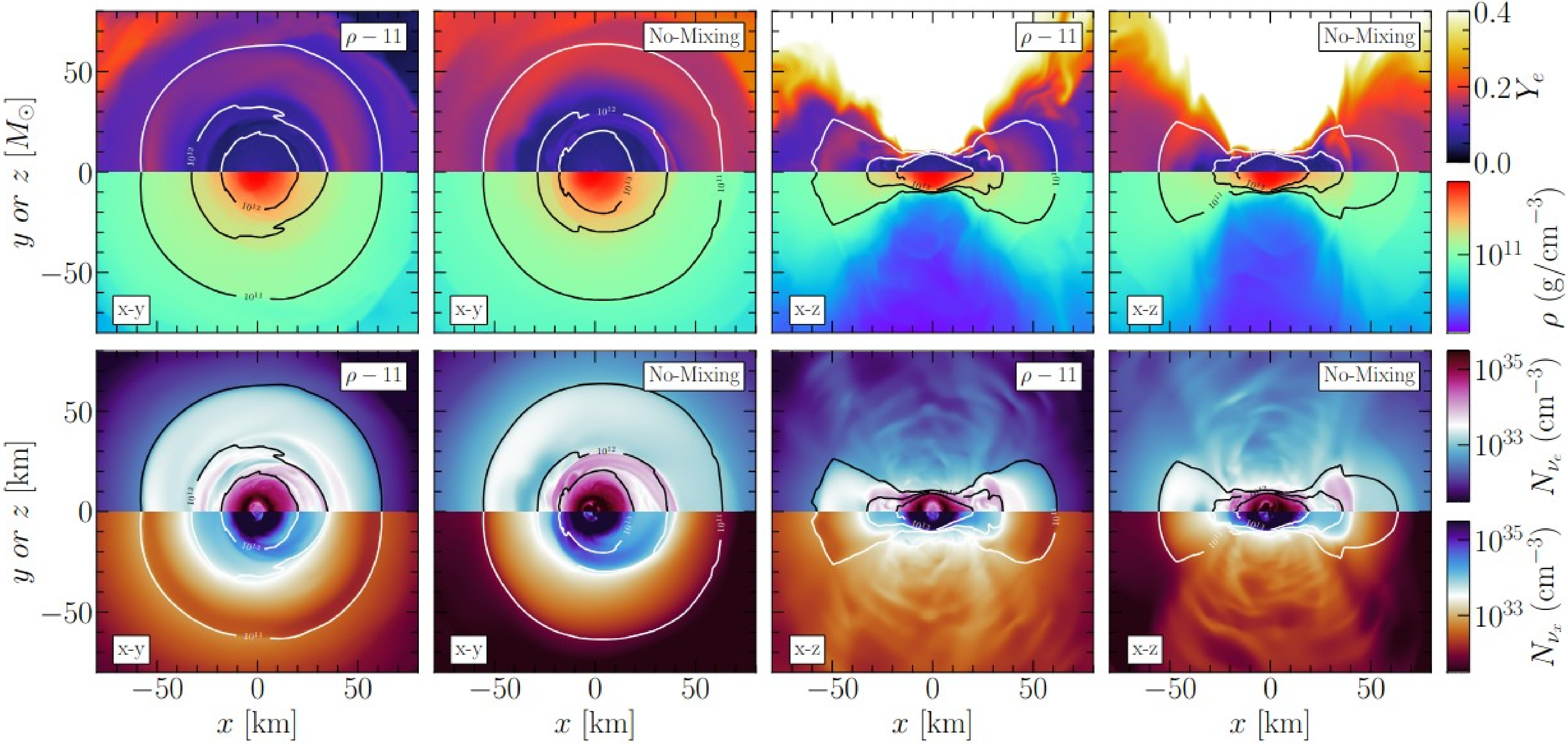
$$-i[H, f] \rightarrow \frac{1}{\tau(\rho)}(f^a - f)$$

Detailed balance

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

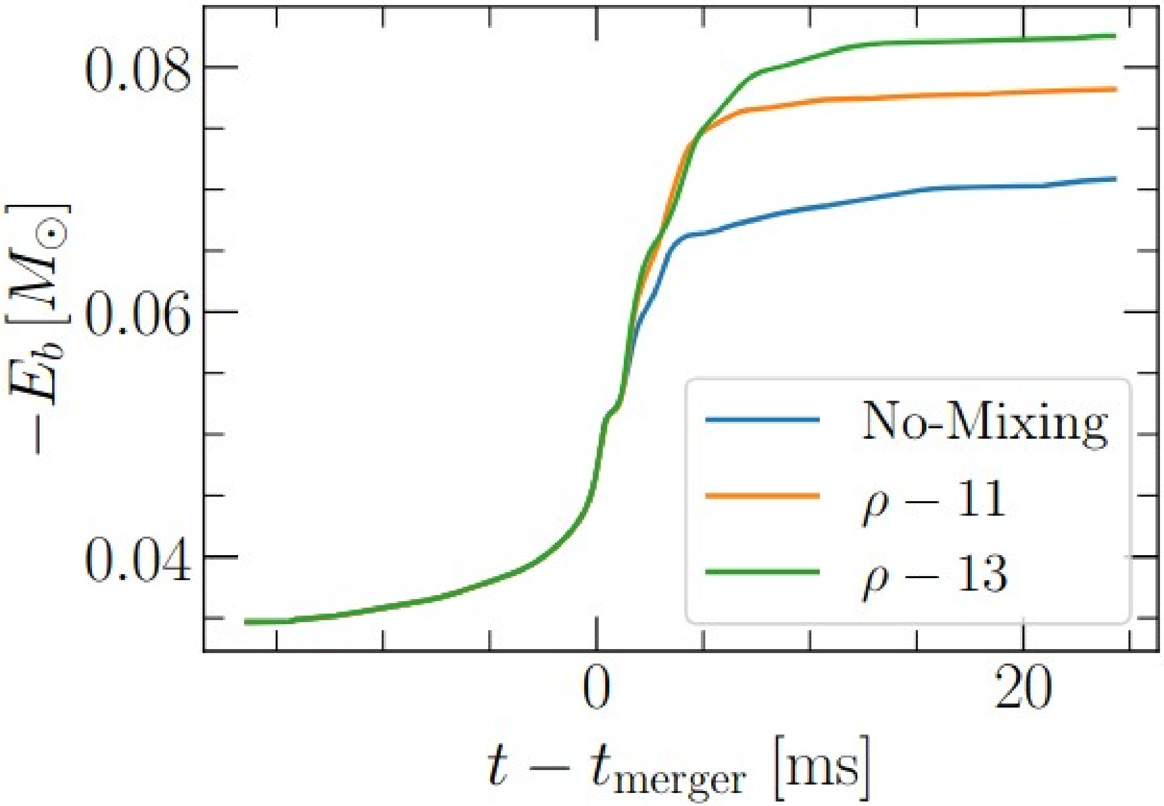
See Nagakura+ 2023; Martin+ 2023; Johns 2024; Ehring+ 2024; Larib & Richers 2025; Lund+ 2025; Qiu+ 2025a,b; ...

Yi Qiu's talk on Thursday!



From Qiu+, PRL 135:091401 (2025)

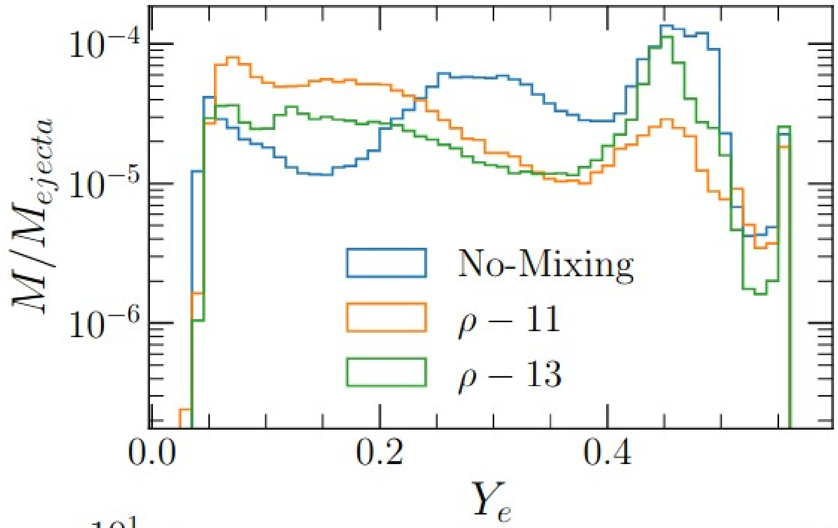
Impact on dynamics

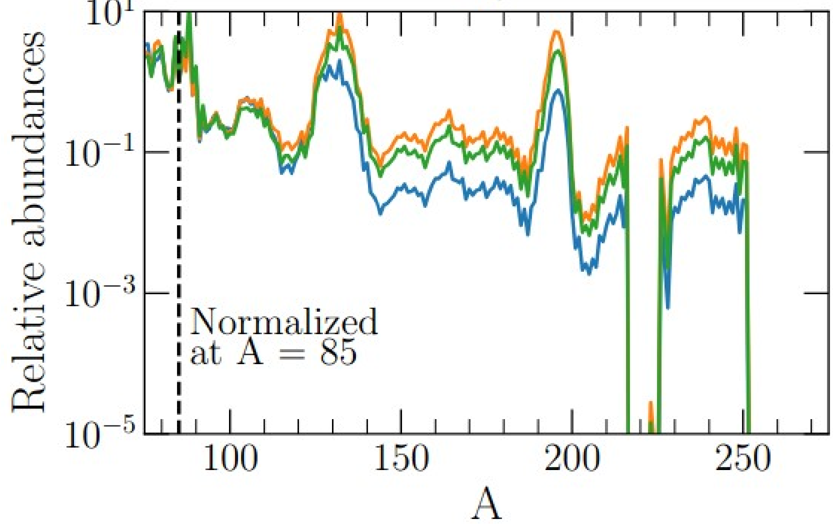


See also Ehring+ 2024

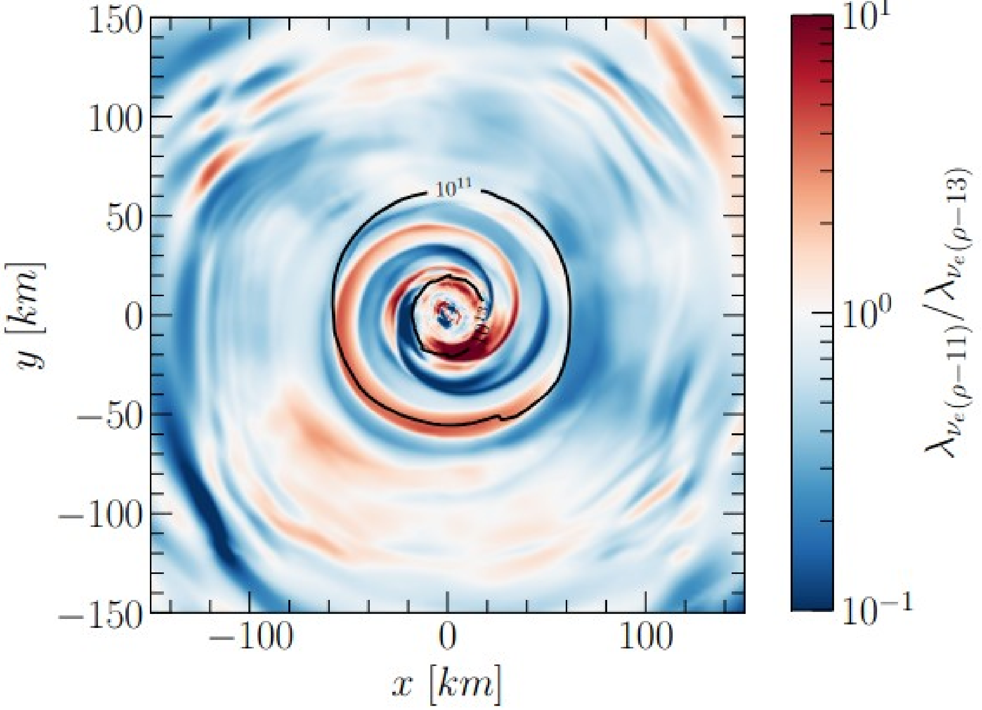
From Qiu+, PRL 135:091401 (2025)

Nucleosynthesis



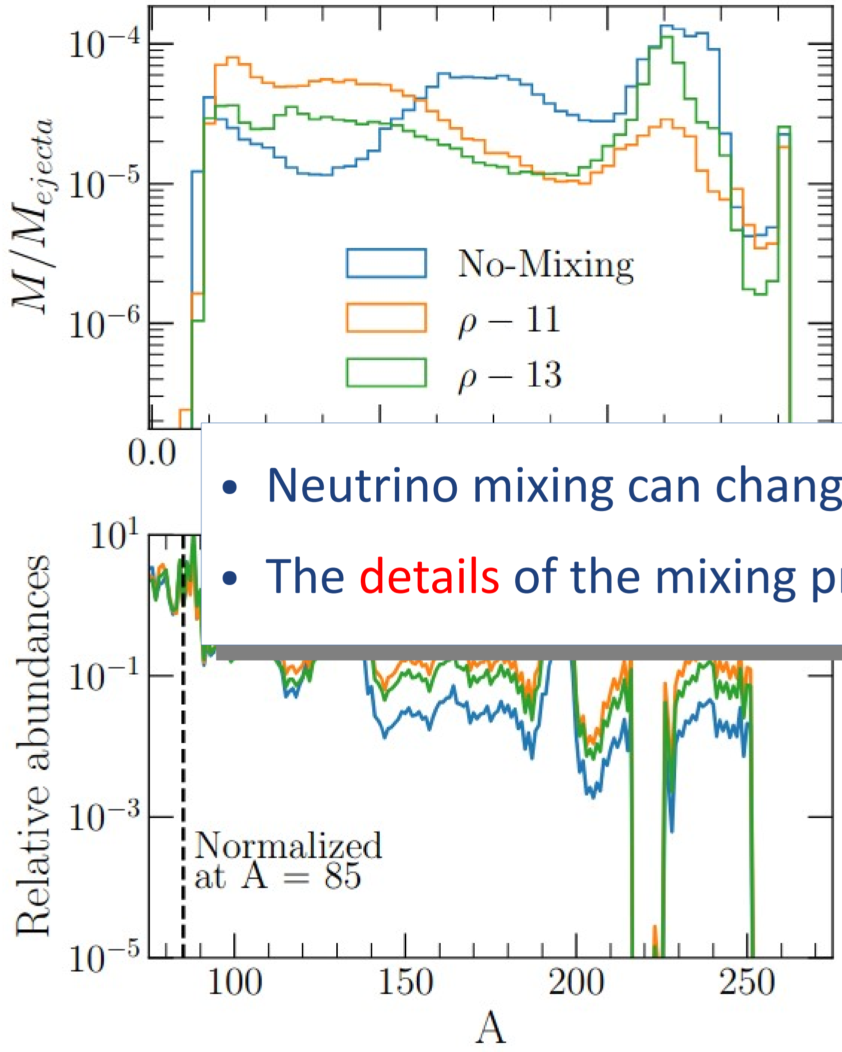


$\dot{Y}_e \sim \lambda_{\nu_e}$

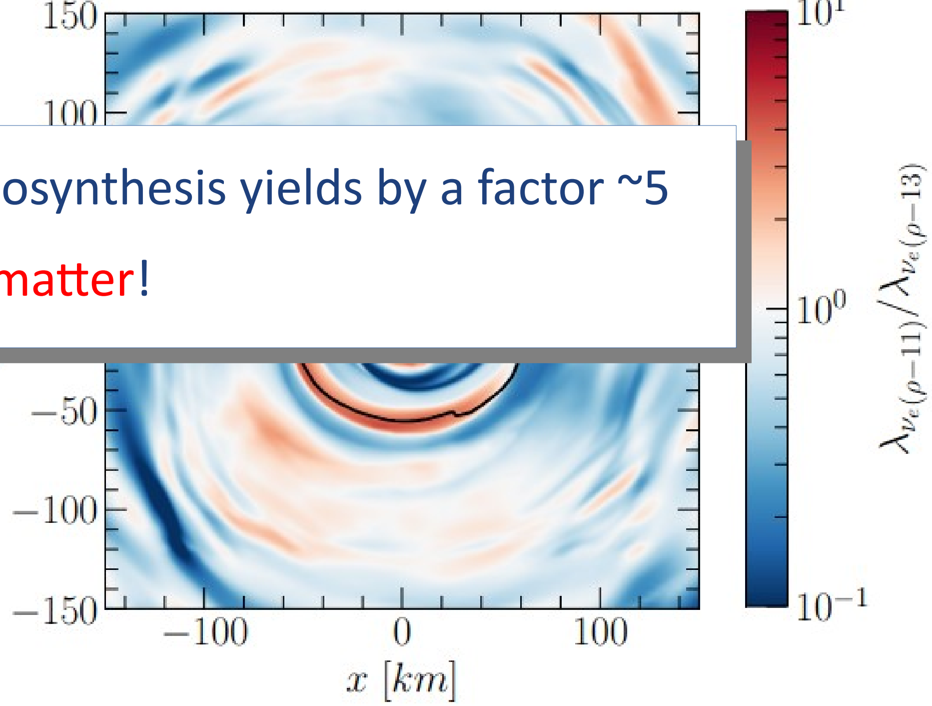


From Qiu+, PRL 135:091401 (2025)

Nucleosynthesis



$\dot{Y}_e \sim \lambda_{\nu_e}$

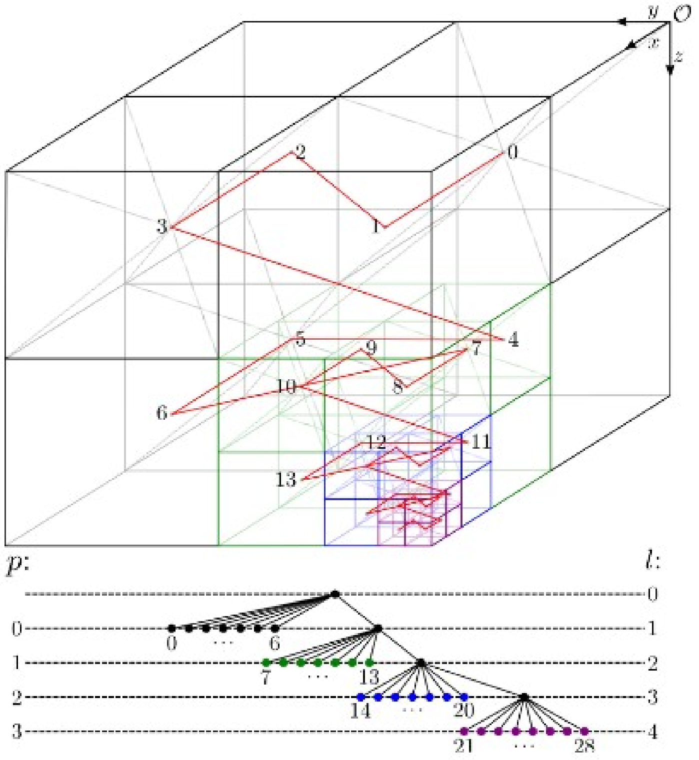


- Neutrino mixing can change nucleosynthesis yields by a factor ~5
- The details of the mixing process matter!

From Qiu+, PRL 135:091401 (2025)

AthenaK

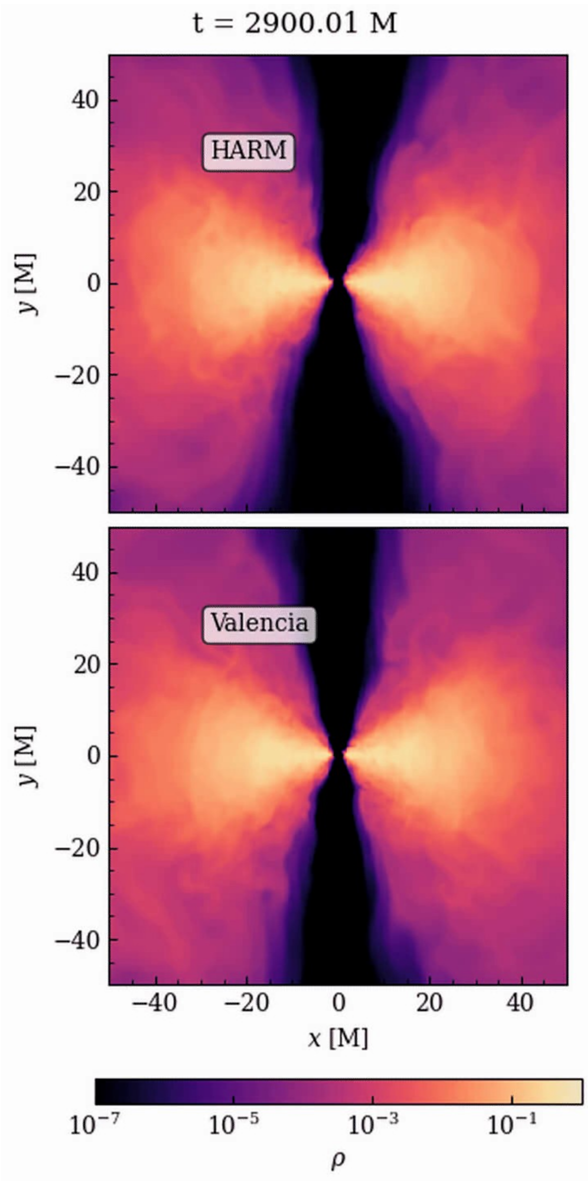
- Spacetime evolution: Z4c with high-order FD
- GRMHD in dynamical spacetimes with high-resolution shock capturing methods
  - Upwind constrain transport for B-field
  - Refluxing of fluxes / re-circulation of E-field
  - WENO-Z+HLLE / MOOD (1st order)
  - HLLD in progress
- Interface with SpECTRE ID and CCE
- Interface with ET for AH finder/analysis (post-processing)
- Neutrino radiation: M1, S_N and FP_N (in progress)

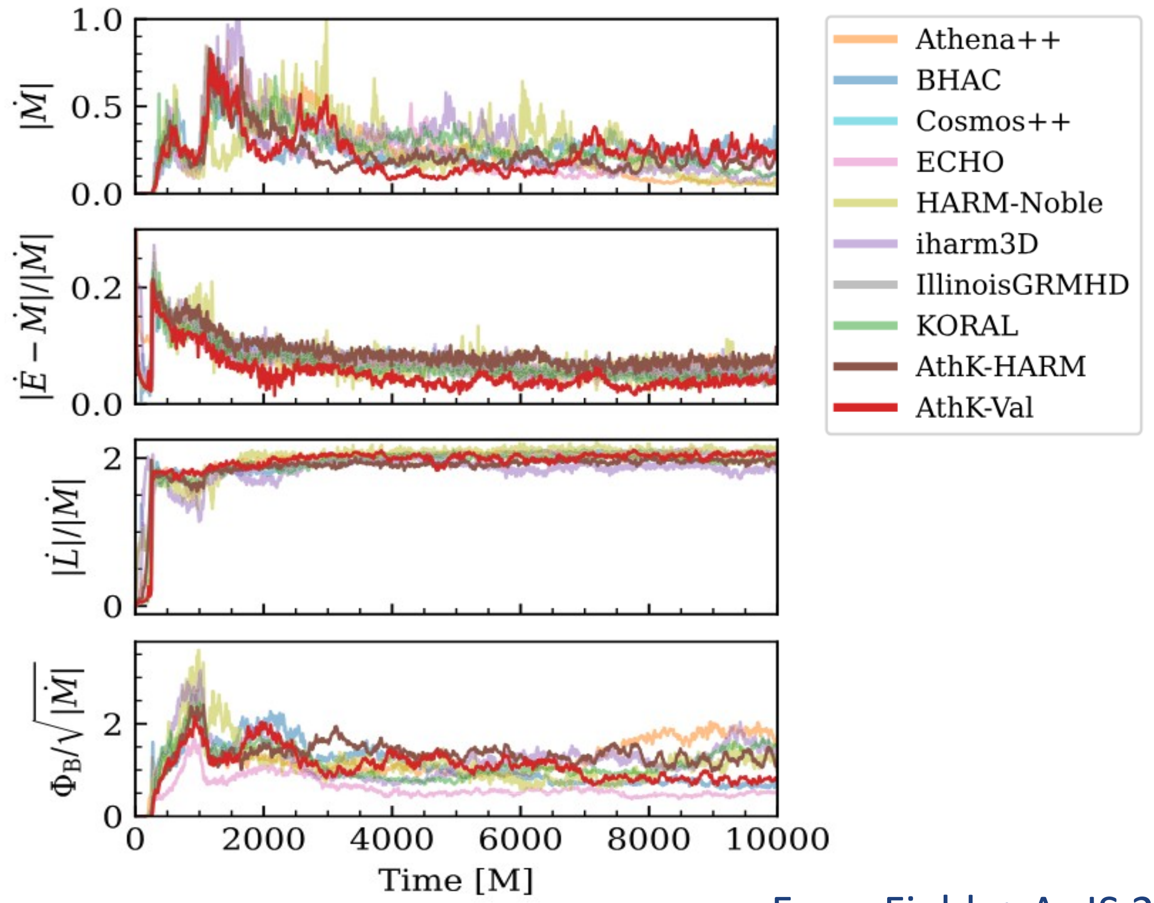


From Daszuta+ ApJS 257 (2021)

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

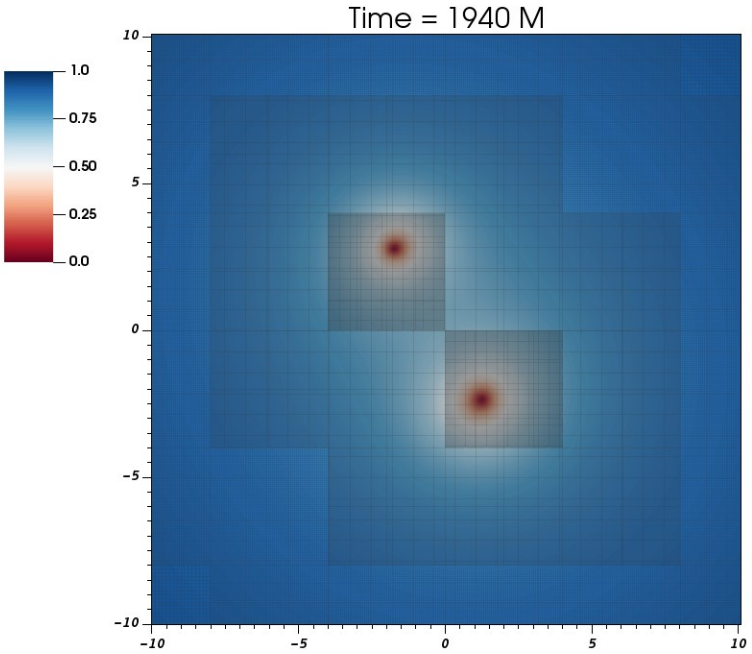
Magnetized torus test

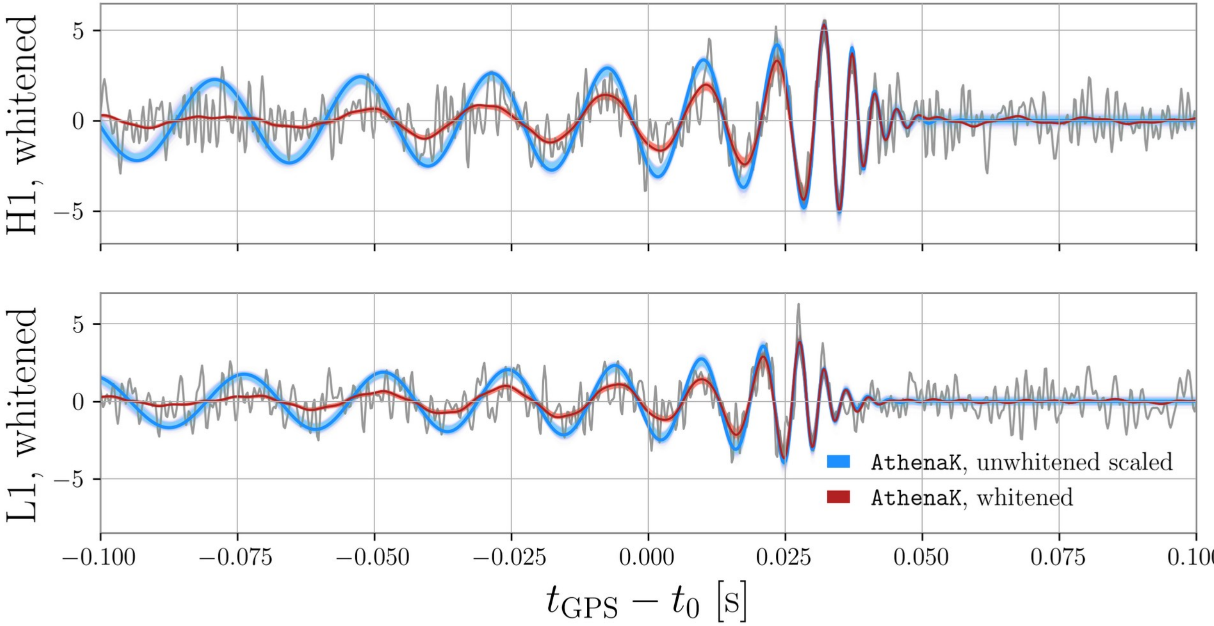




From Fields+ ApJS 276 (2025)

Binary BH mergers: GW150914

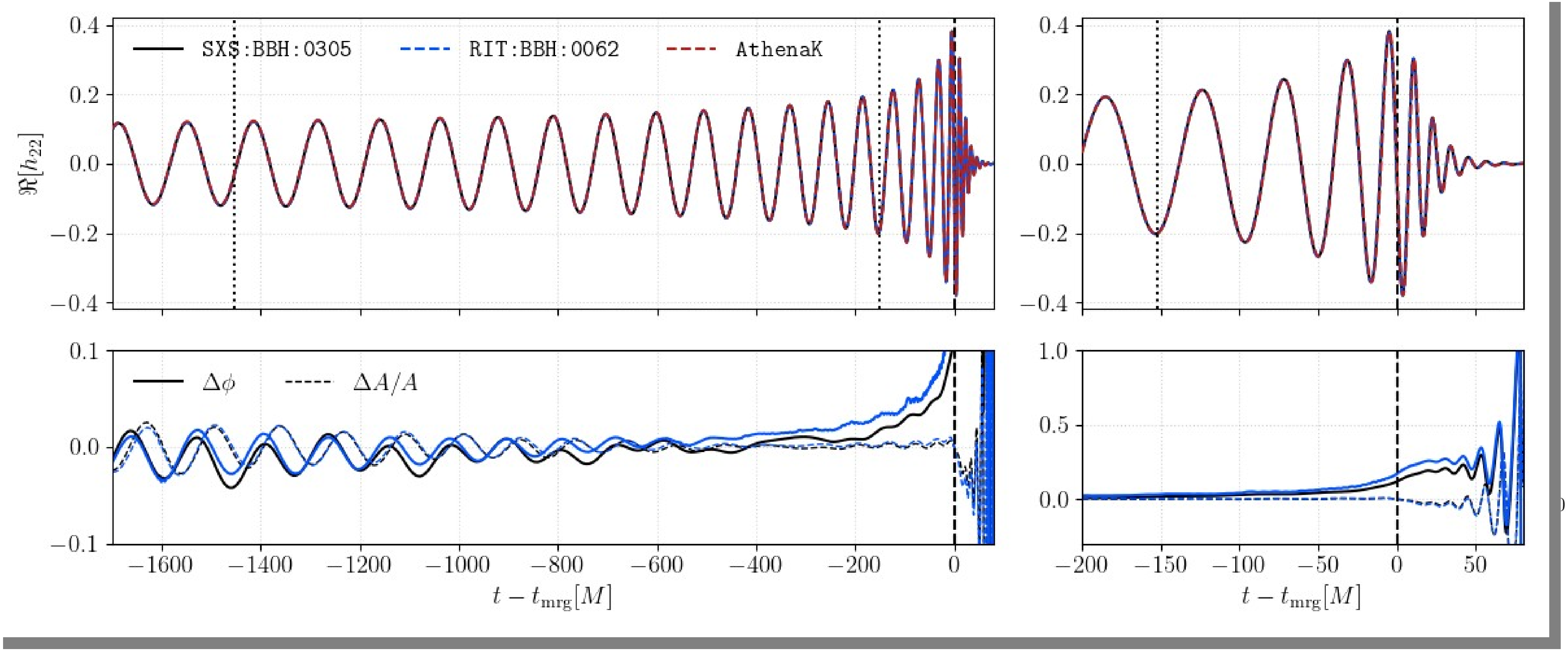




https://github.com/dradice/athenak-tutorial-gw150914/

From Radice+, CQG 2025

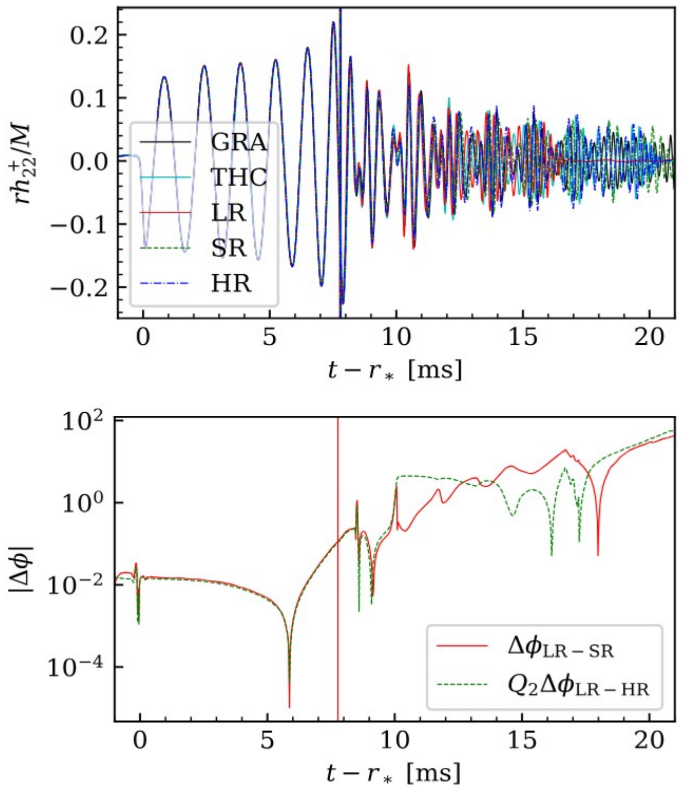
Binary BH mergers: GW150914

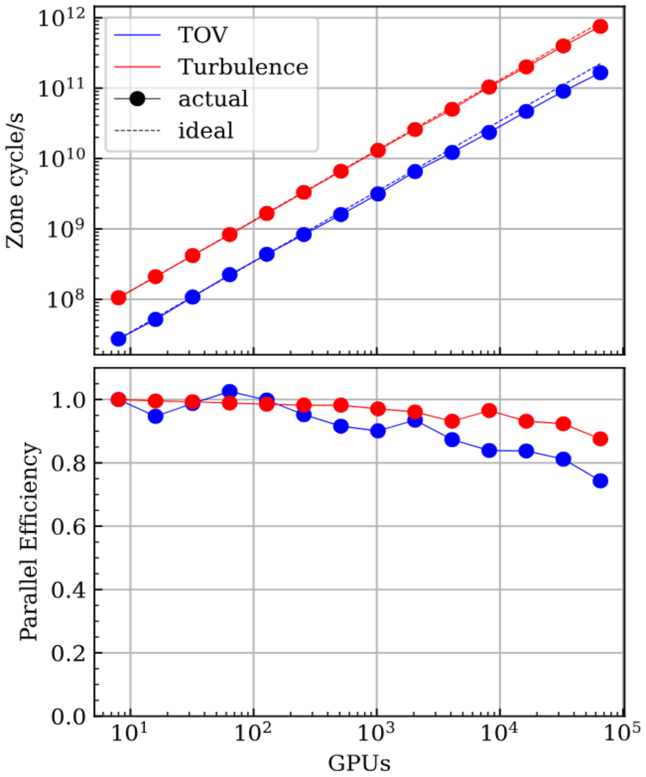


https://github.com/dradice/athenak-tutorial-gw150914/

From Radice+, CQG 2025

Binary neutron star mergers



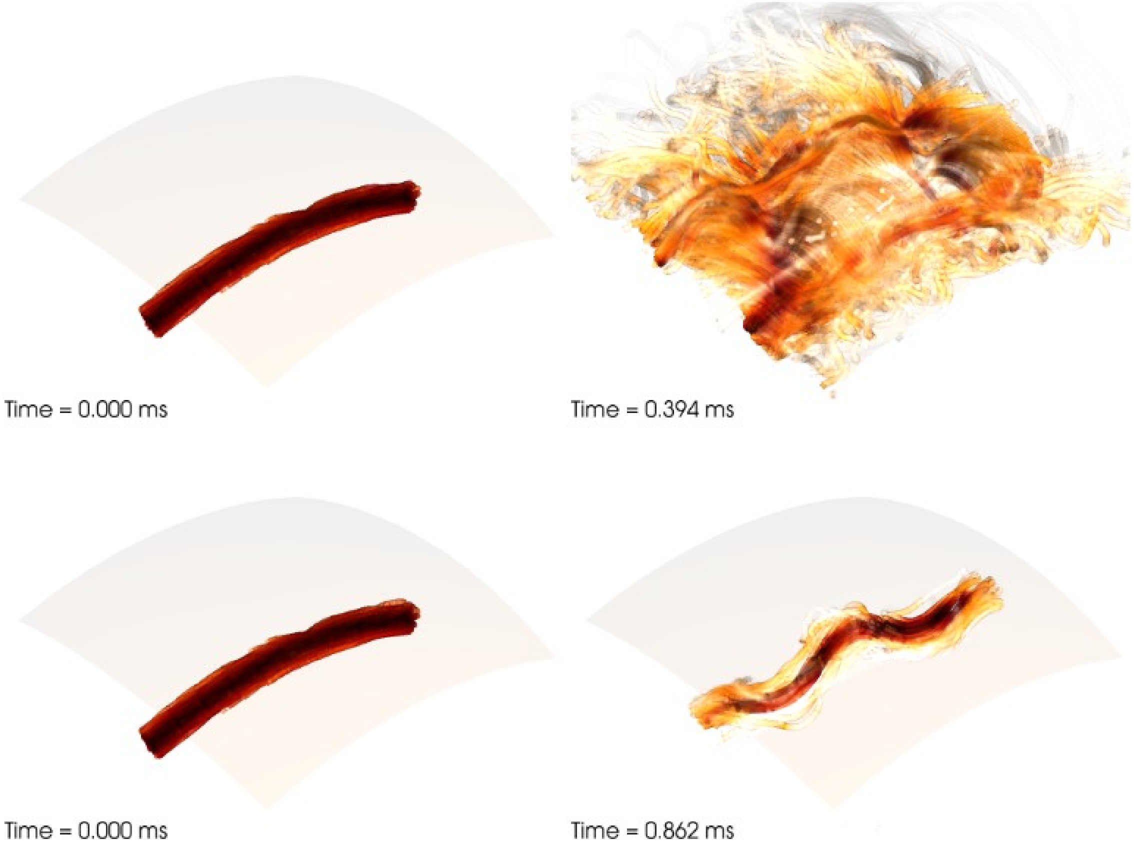


From Fields+ ApJS 276 (2025)

Flux emergence in NS mergers

$$B_{\rm max} = 7 \times 10^{17}\ \mathrm{G}$$

$$B_{\rm max} = 1 \times 10^{17}\ \mathrm{G}$$



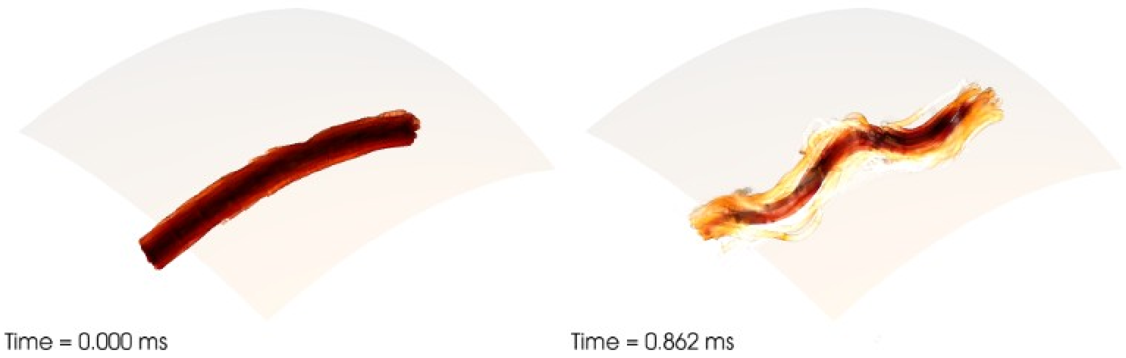
From Fields+, arXiv:2507.18695

Flux emergence in NS mergers

$B_{\mathrm{max}} = 7 \times 10^{17}\ \mathrm{G}$

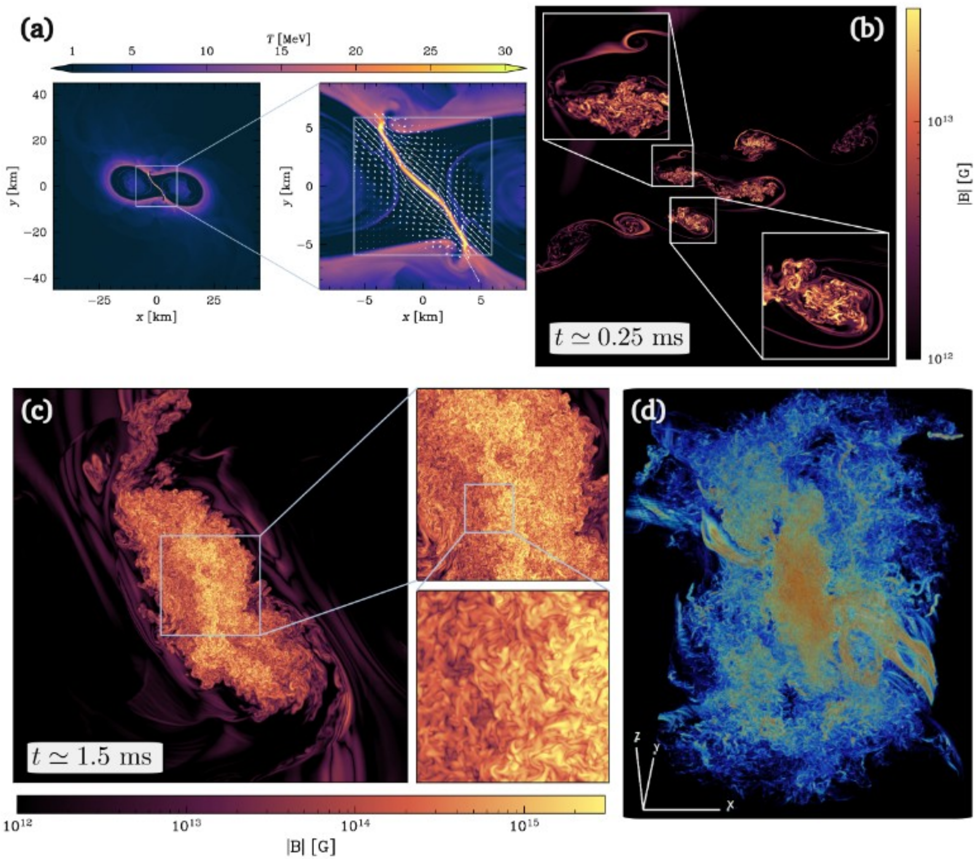
- Internal field within the NS is trapped, unless it is ultra-strong
- Need accretion disk MRI to do interesting things

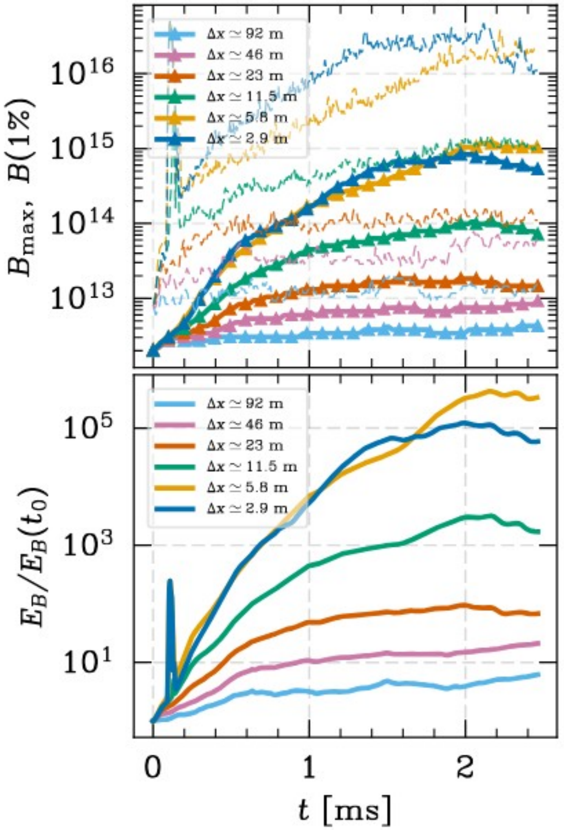
$B_{\mathrm{max}} = 1 \times 10^{17}\ \mathrm{G}$



From Fields+, arXiv:2507.18695

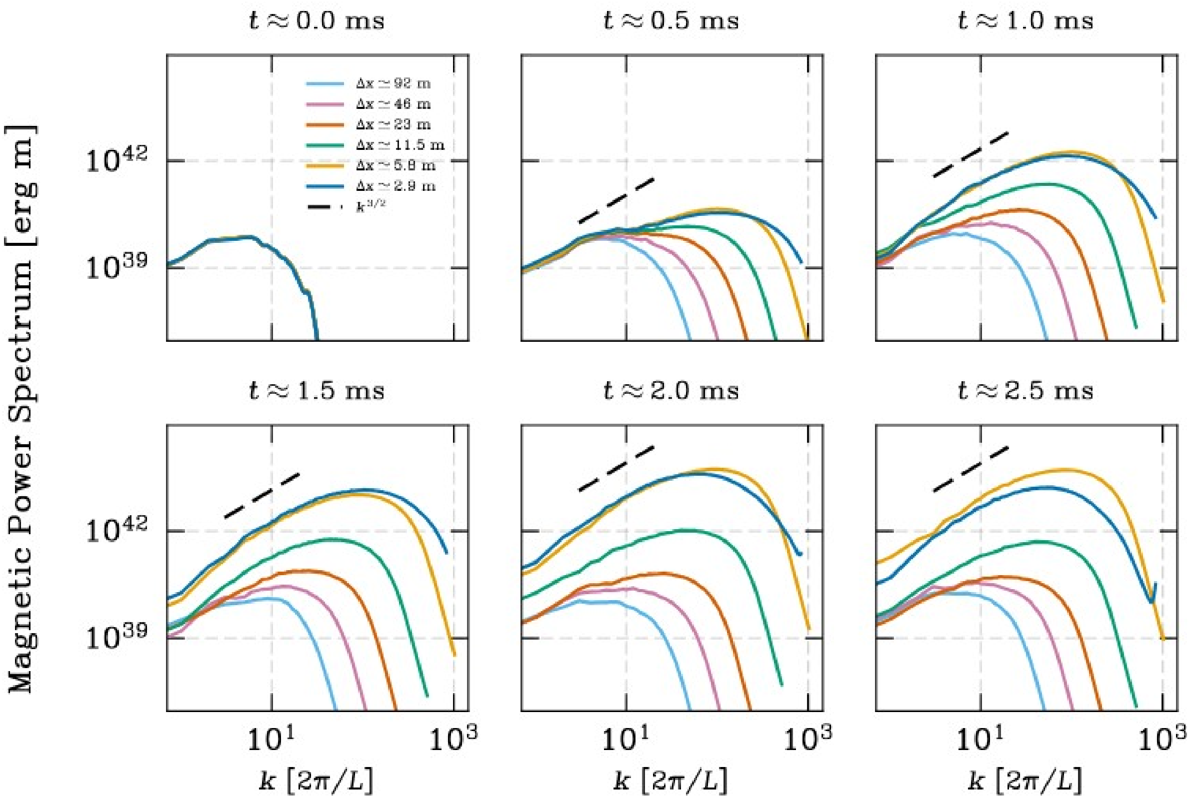
Zoom-in simulations of the KHI





Eduardo Gutiérrez's talk later today!

Turbulent dynamo action



See also Price & Rosswog 2006; Obergaulinger+ 2010;
Zrake+2013 Kiuchi+ 2014, 2025; ...

From Gutierréz+ in prep

Conclusions

- Multimessenger astronomy is already delivering important results!
- Theoretical uncertainties are still dominant… much work left to be done
- AthenaK is a new performance portable code for computational astrophysics and numerical relativity
  - Z4c/GRMHD solvers are well tested and are used in production
  - First applications: flux-emergence, KHI in merger
  - Tutorials, documentation, summer school(*), coming!

(*) July 7 to 17, 2026 at Penn State!

M. Campanelli, D. Fielding, G. Halevi, A. Lam, E. Ostriker, DR, J. Stone, Z. Zhu, ...