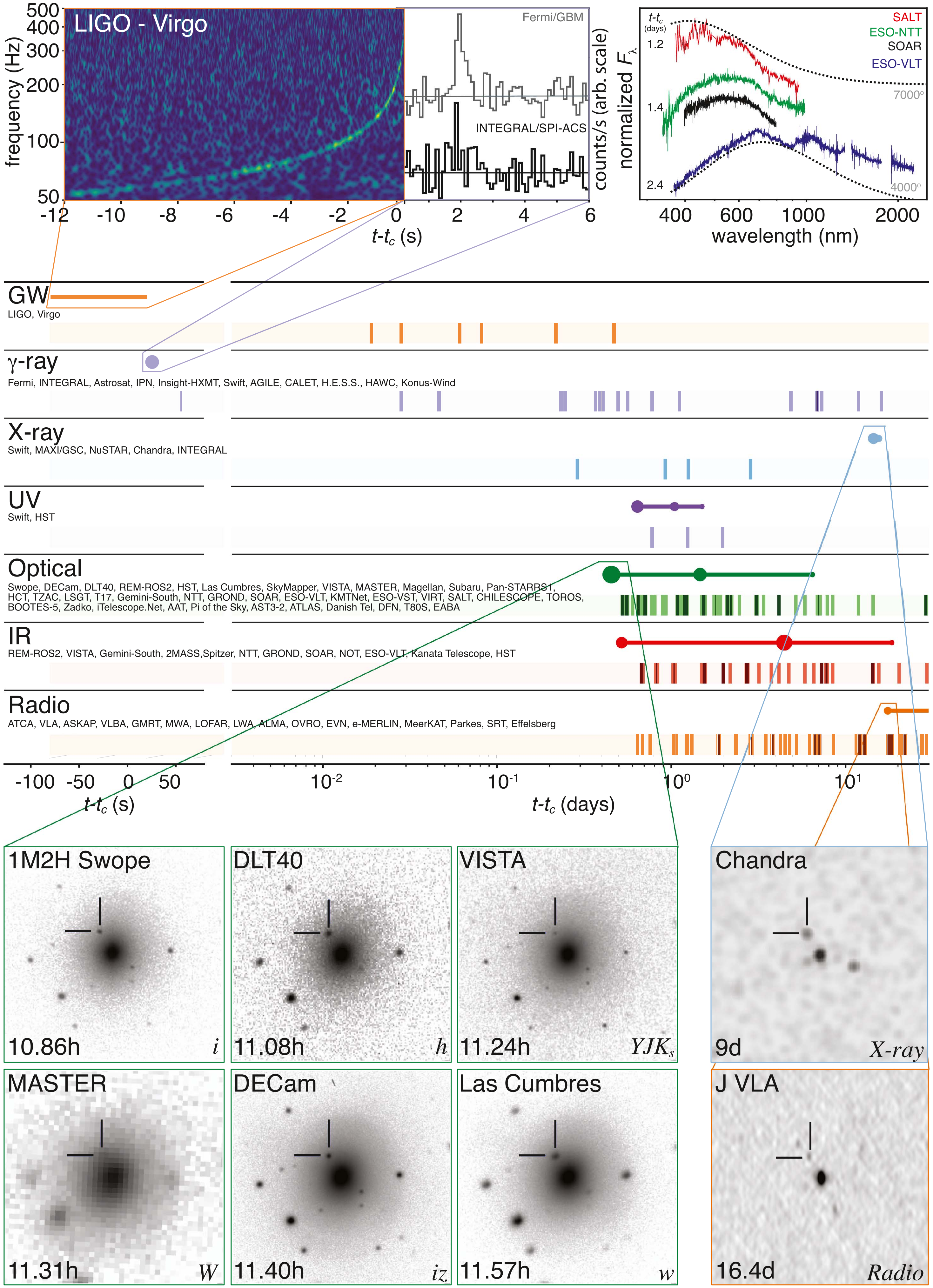
PennState
Eberly College of Science

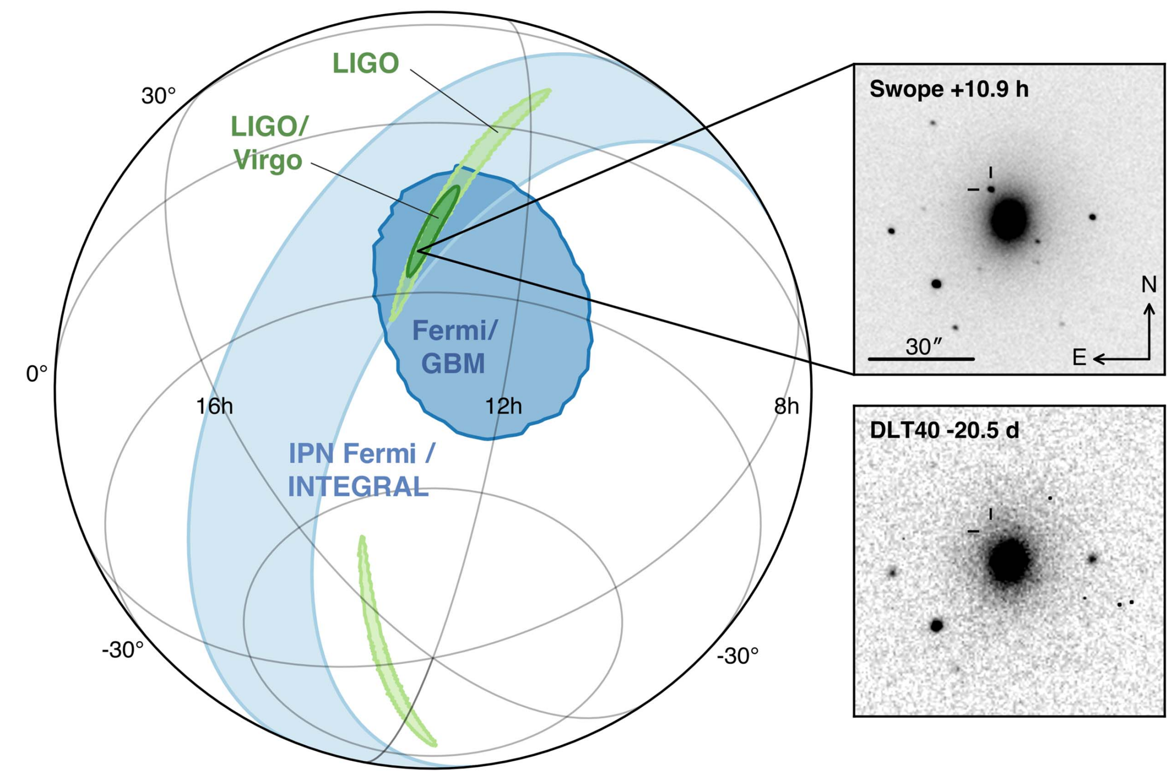
Neutron Star Merger Dynamics

www.computational-relativity.org

arXiv:2002.03863

David Radice — October 27, 2020

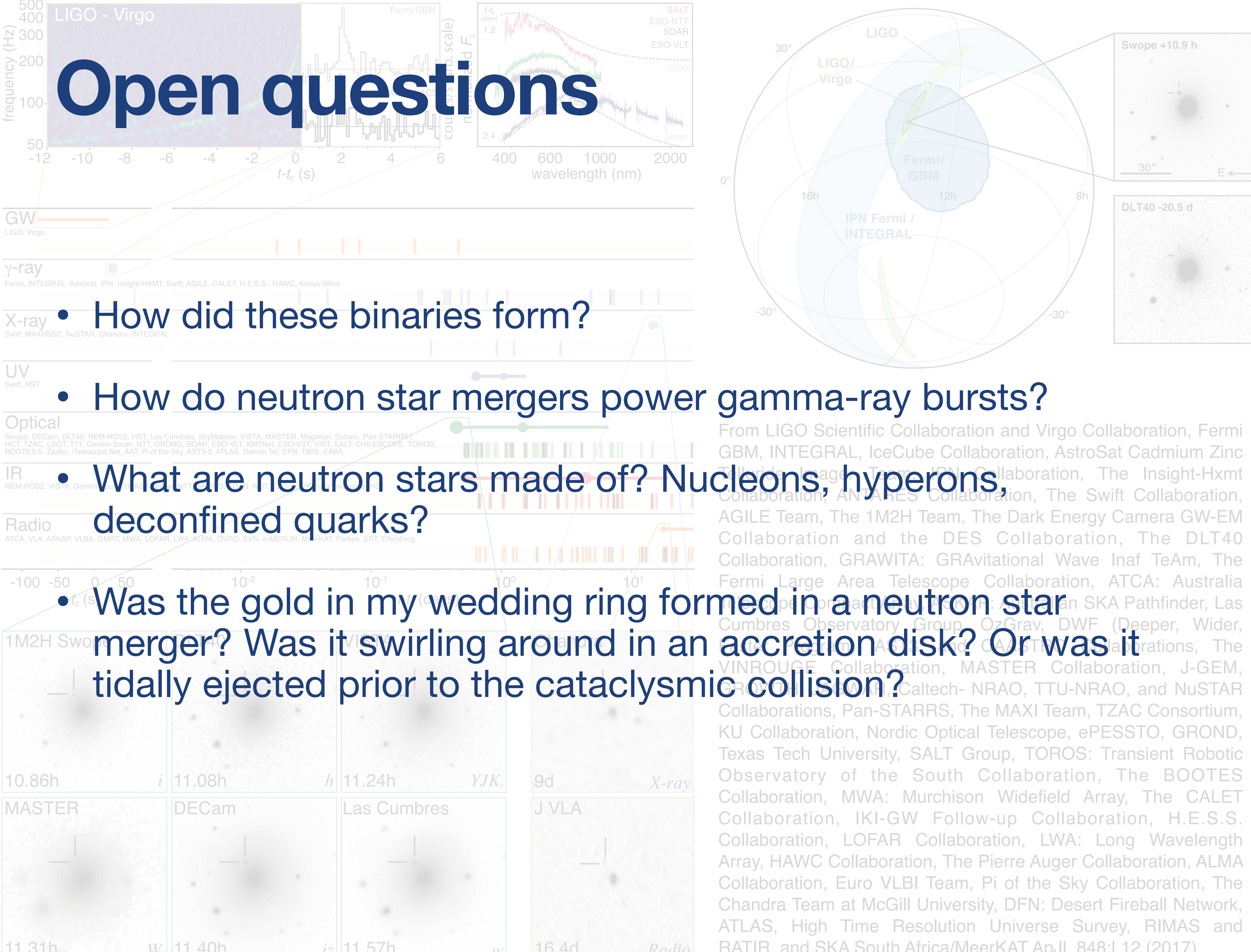




From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM 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)

Open questions

- How did these binaries form?
- How do neutron star mergers power gamma-ray bursts?
- What are neutron stars made of? Nucleons, hyperons, deconfined quarks?
- Was the gold in my wedding ring formed in a neutron star merger? Was it swirling around in an accretion disk? Or was it tidally ejected prior to the cataclysmic collision?



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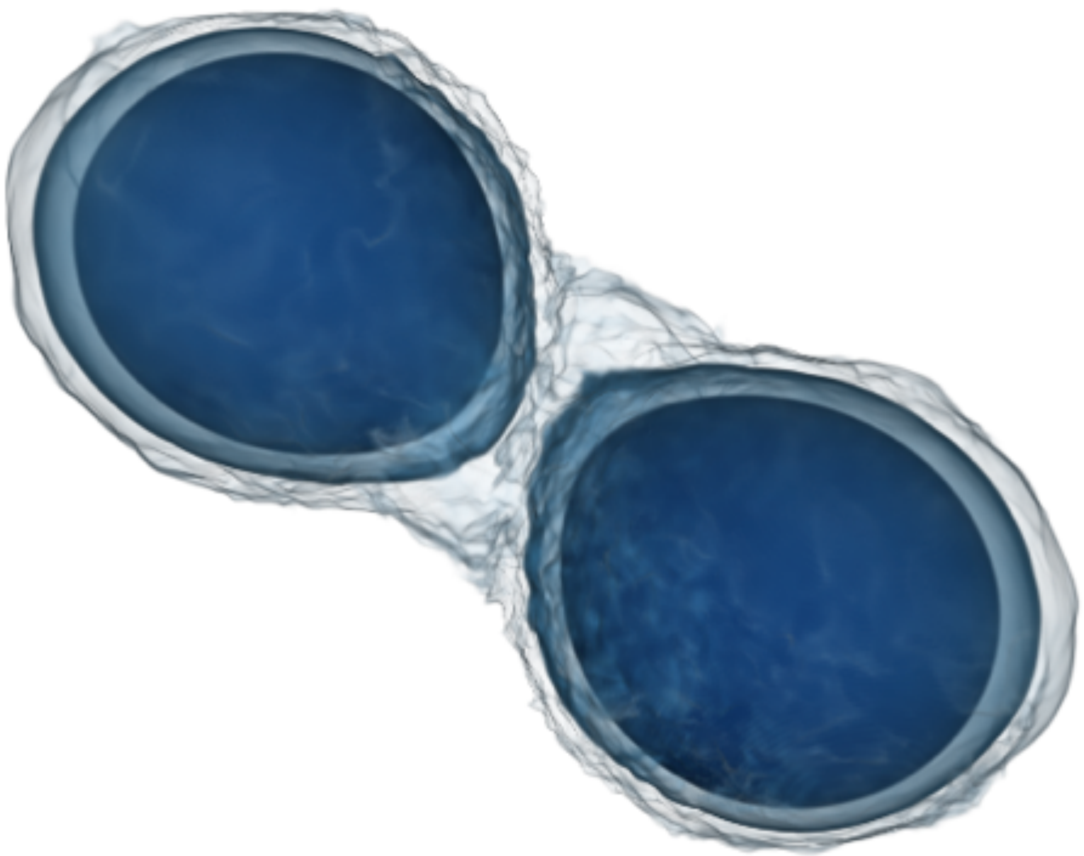
WhiskyTHC

http://personal.psu.edu/~dur566/whiskythc.html



- Full-GR, dynamical spacetime*
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics
- Open source!

* using the Einstein Toolkit metric solvers

THC: Templated Hydrodynamics Code

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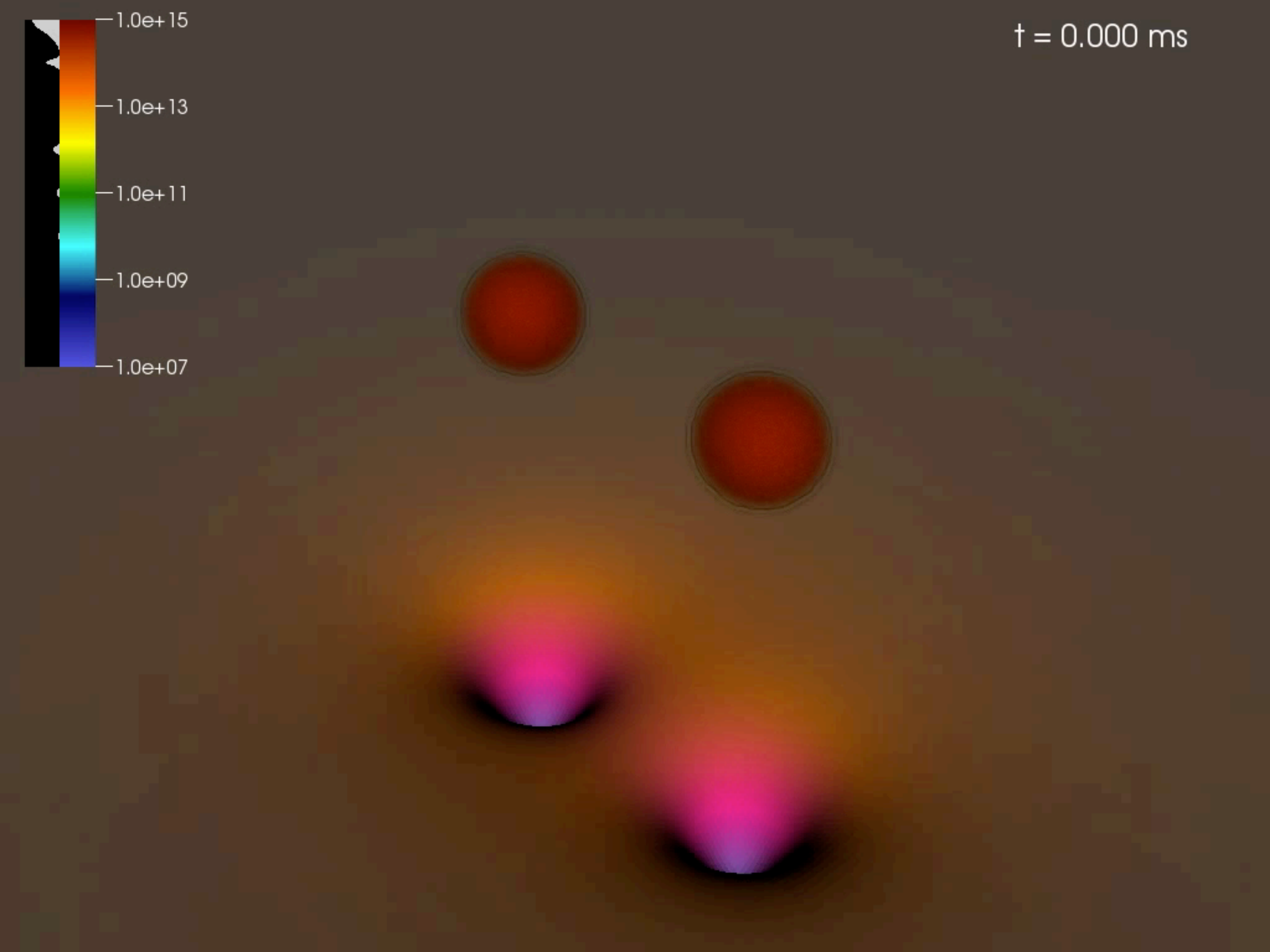
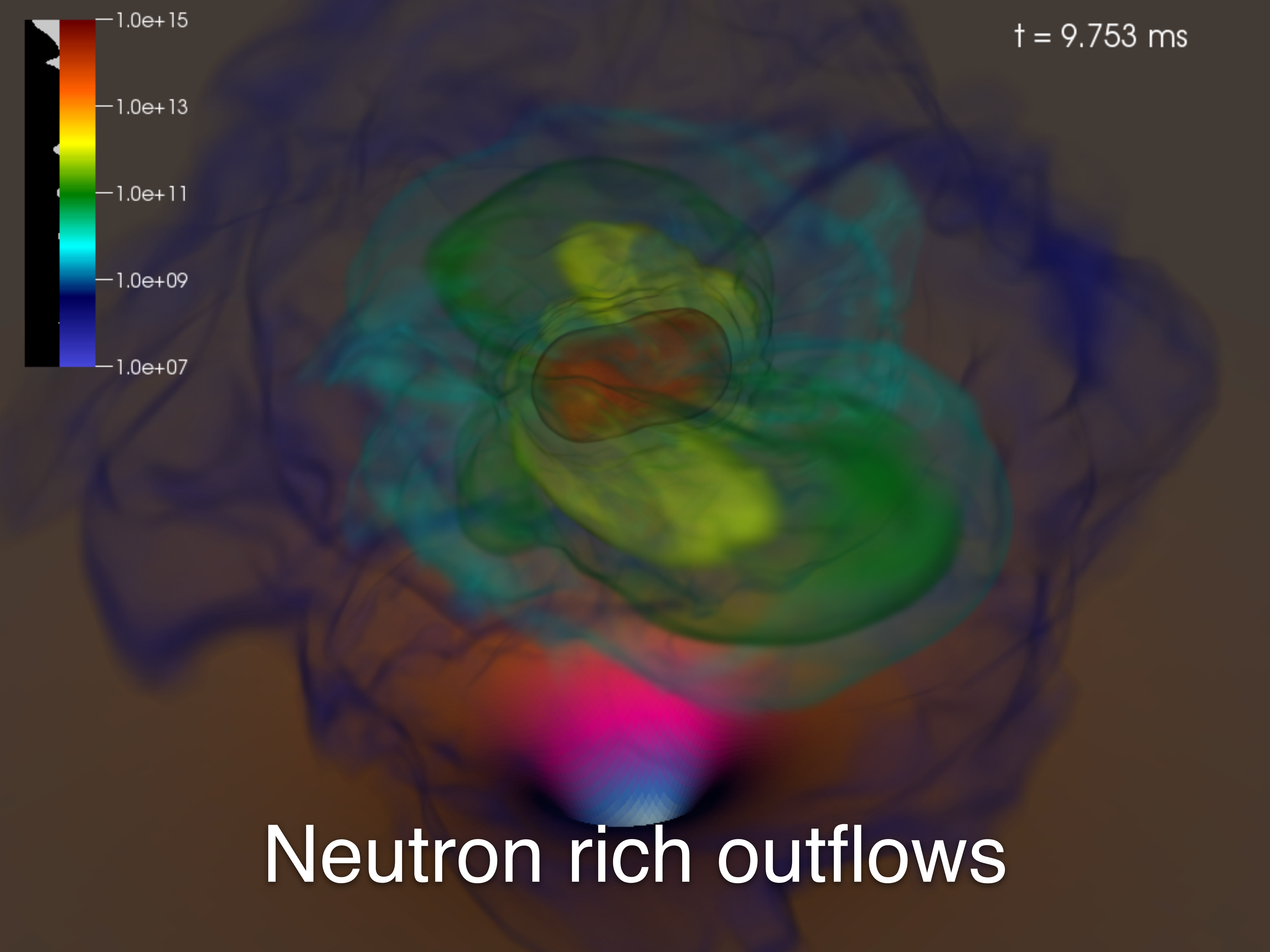
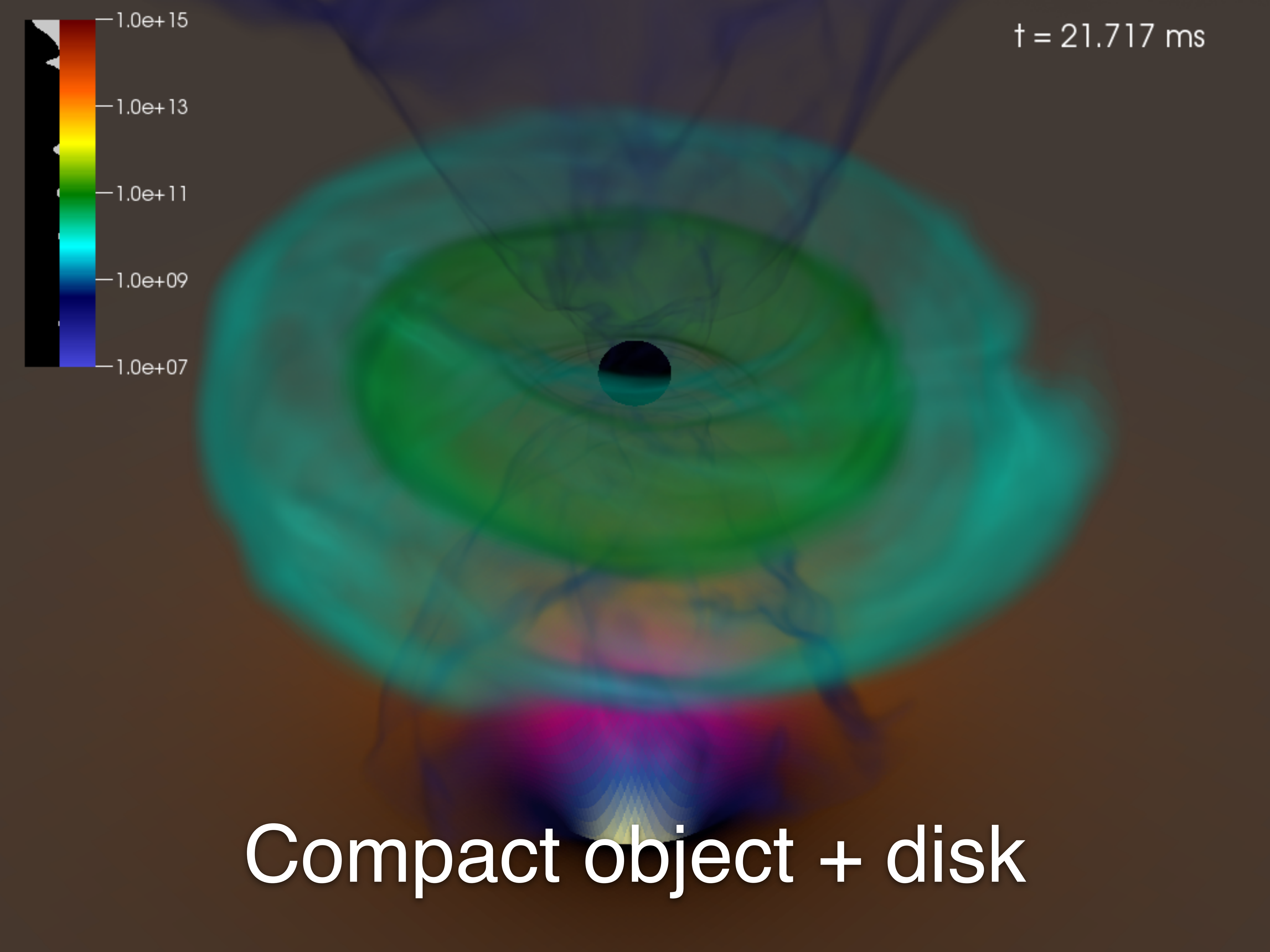

1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 0.000 ms

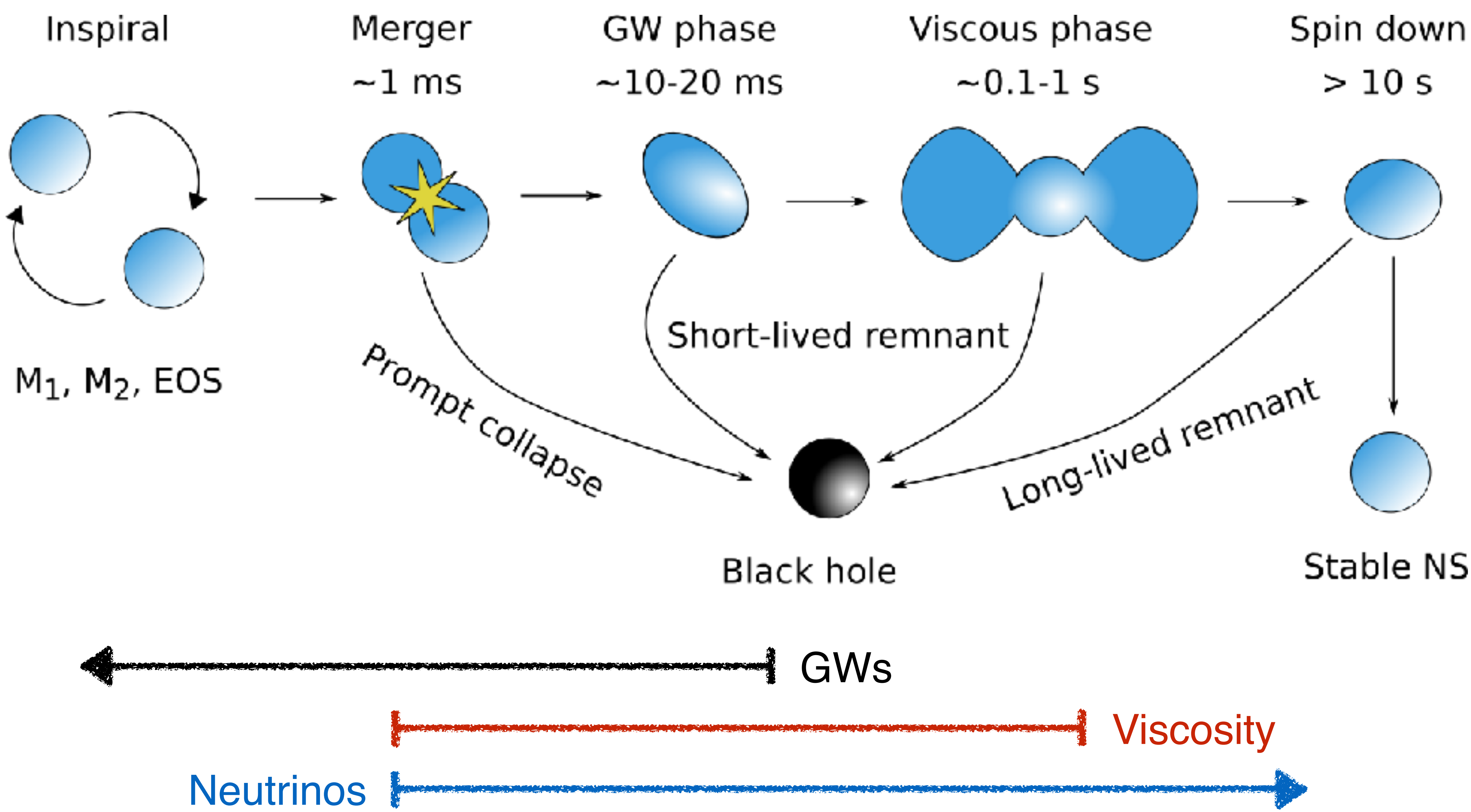


Neutron rich outflows

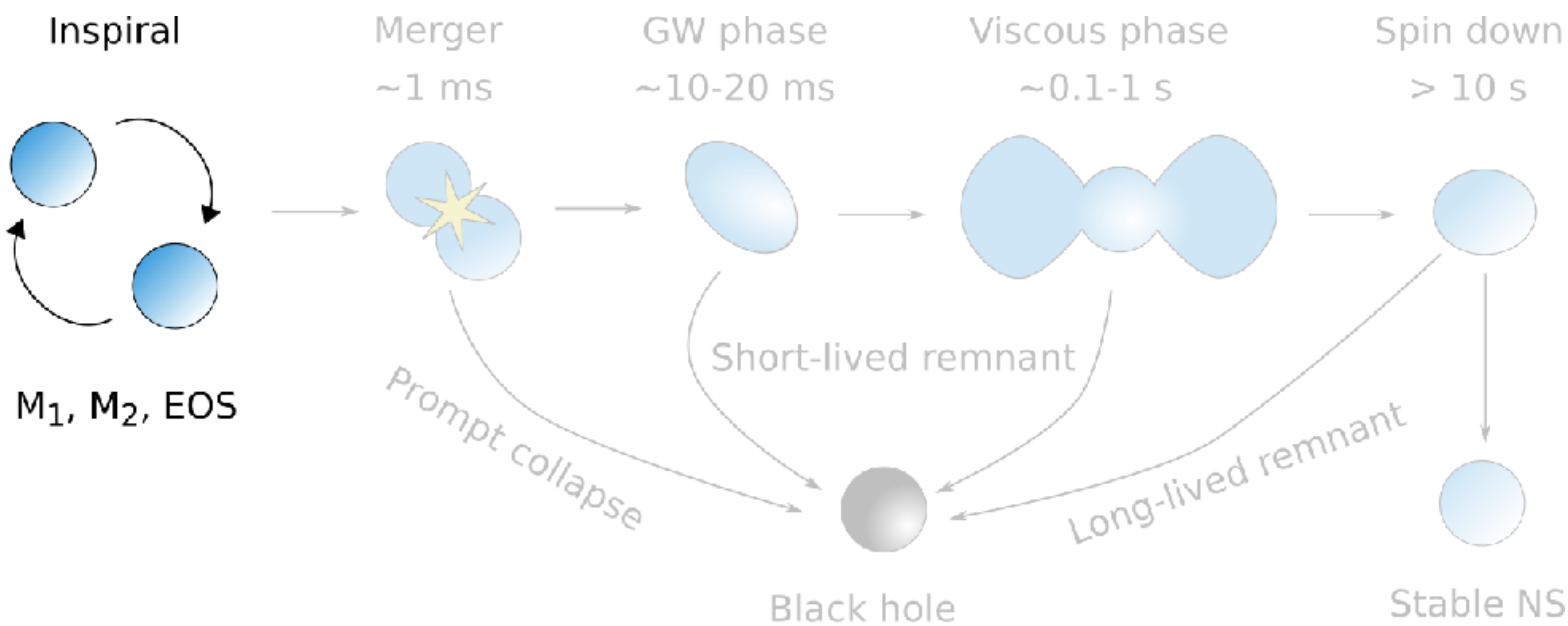


Compact object + disk

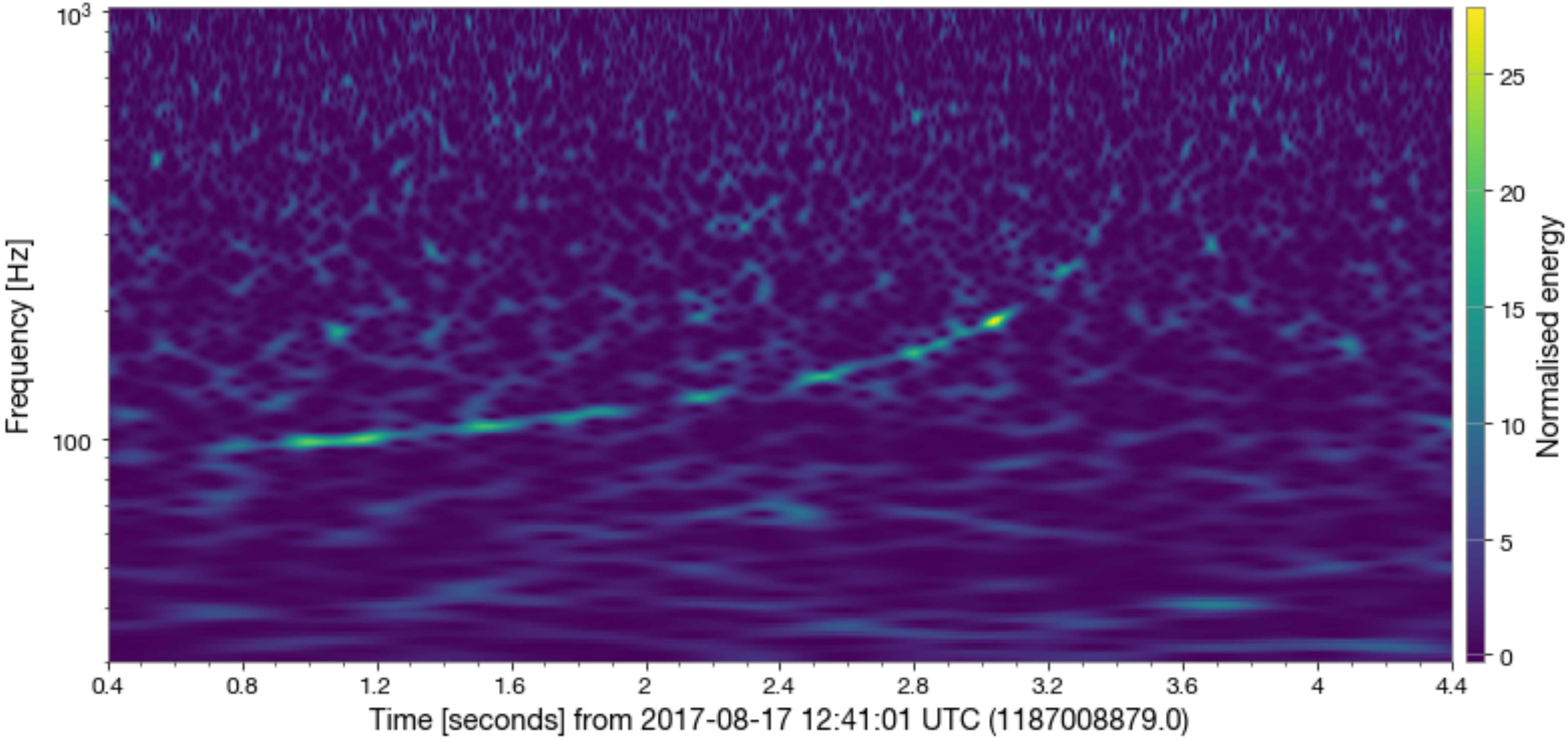
Neutron star merger evolution



The inspiral phase



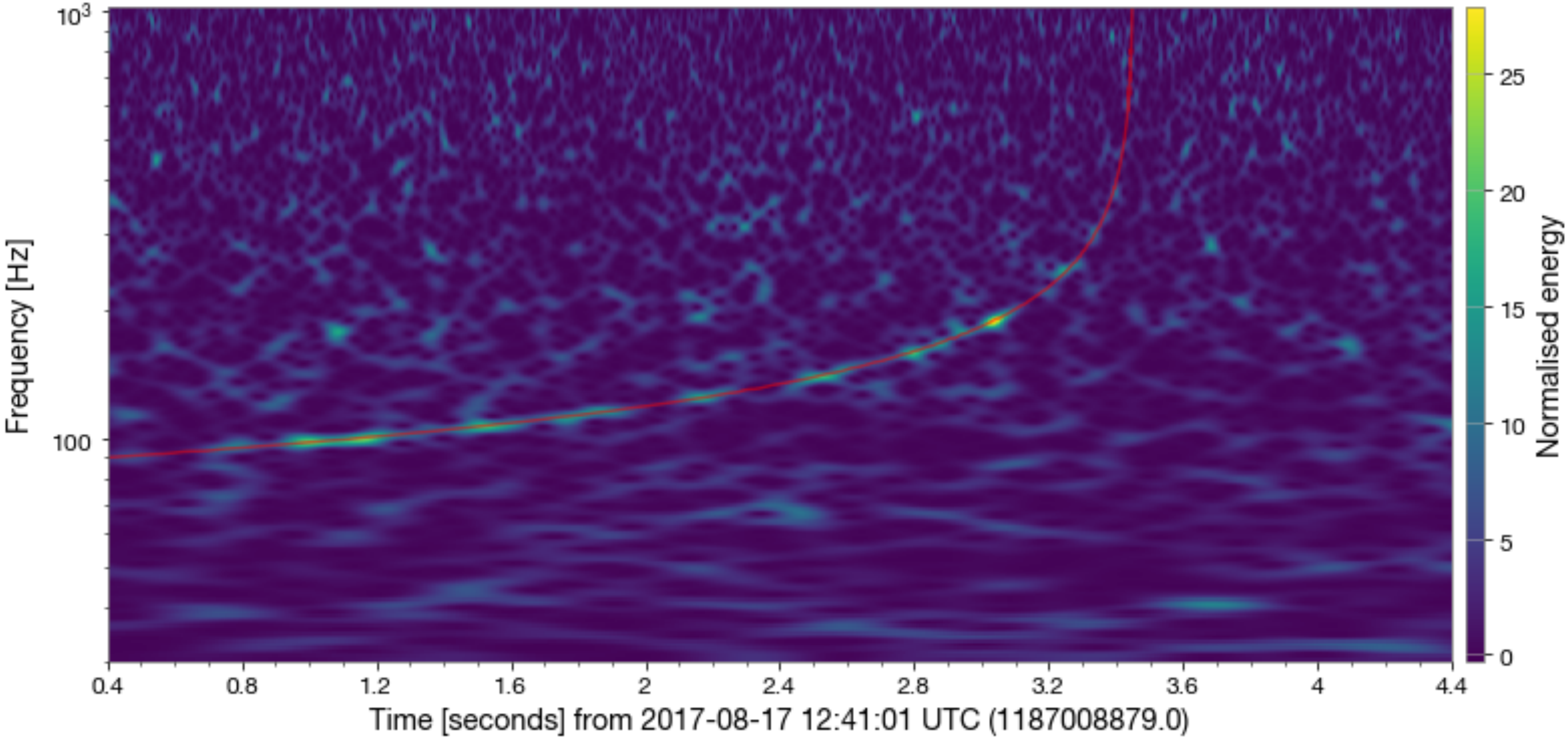
Gravitational waves



GW170817 — In the frequency domain vs theory prediction

https://teobresums.github.io/gwevents/

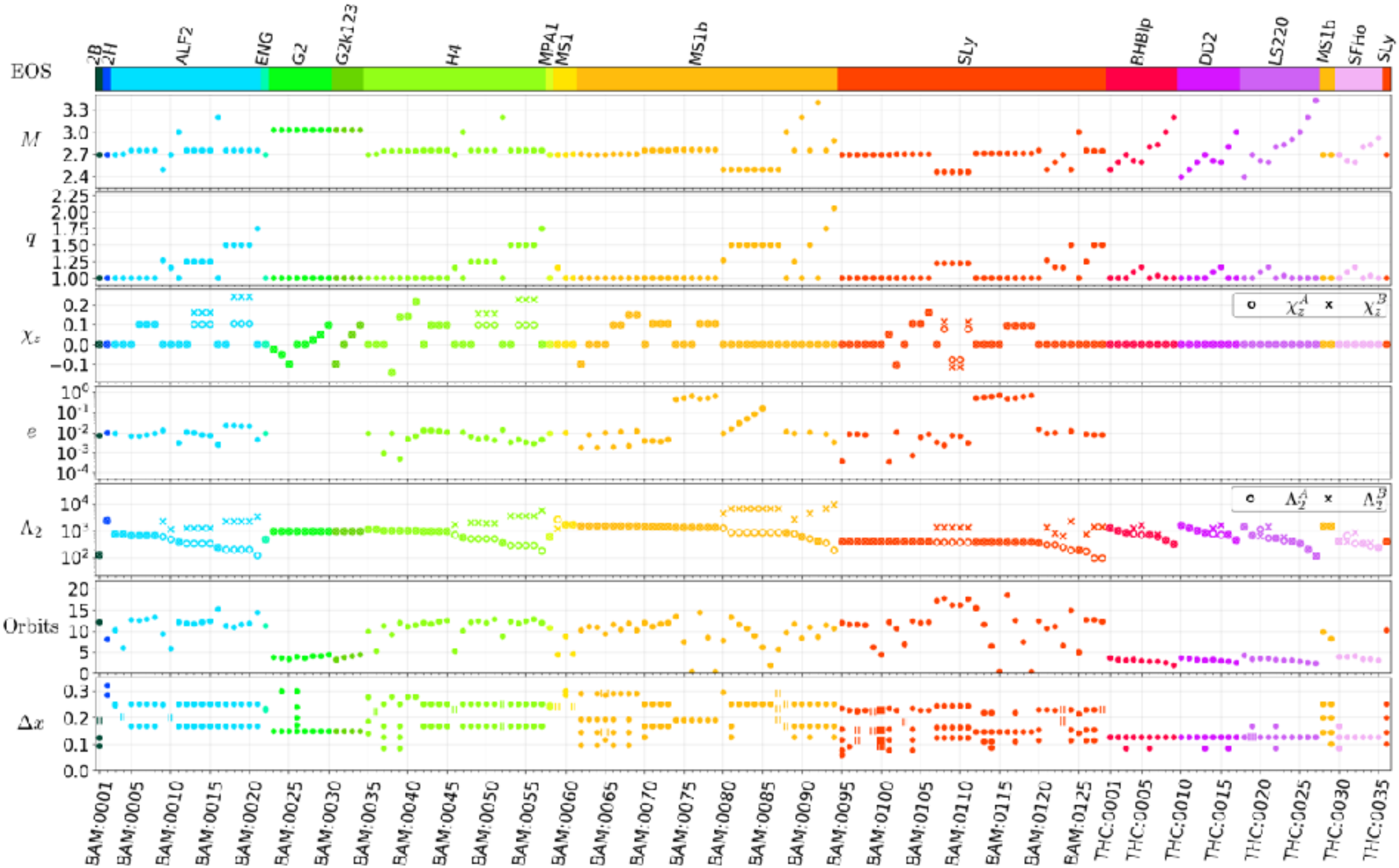
Gravitational waves



GW170817 — In the frequency domain vs theory prediction

https://teobresums.github.io/gwevents/

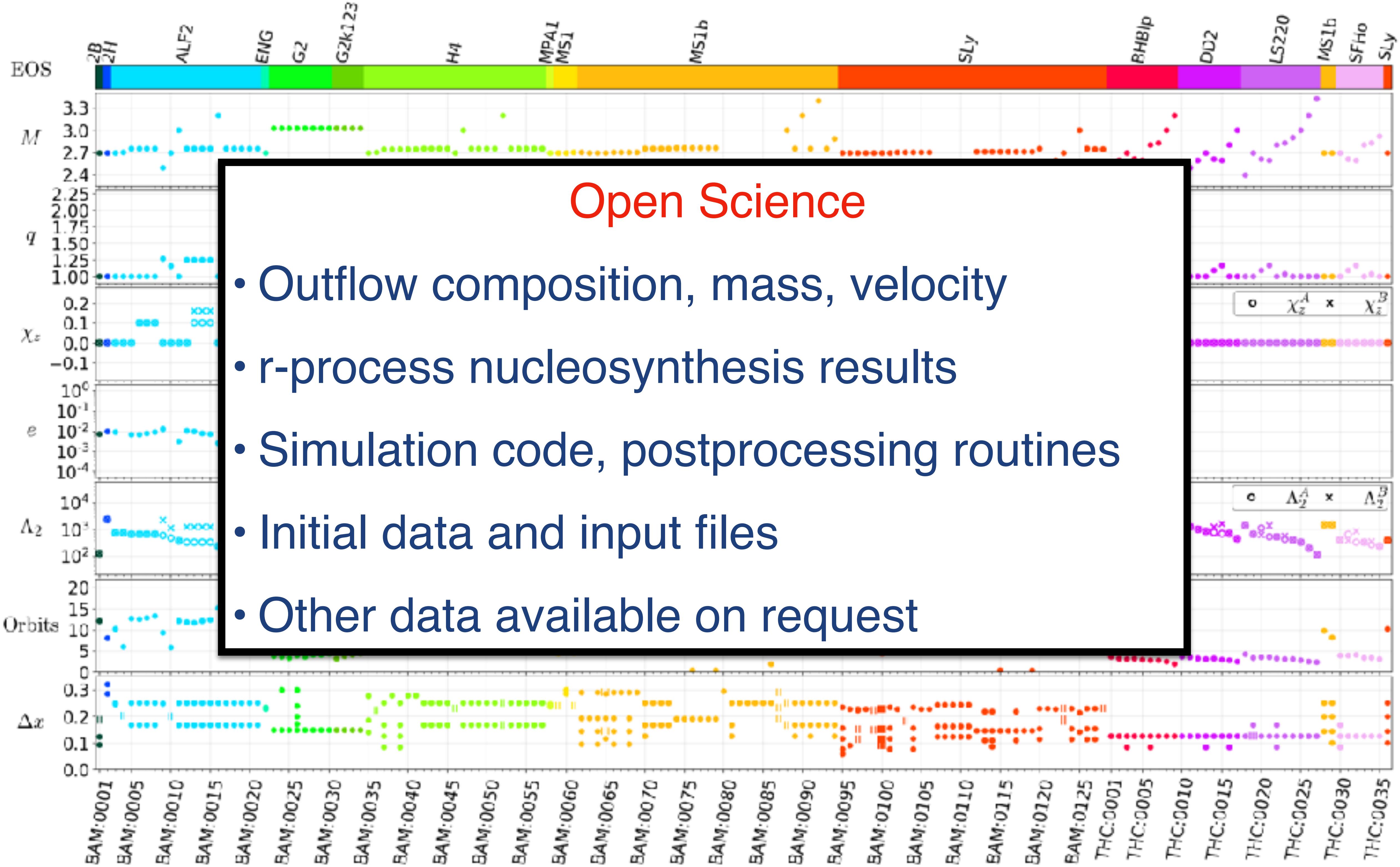
The CoRe database



www.computational-relativity.org

Dietrich, **DR**, Bernuzzi+ CQG 35:LT01 (2018)

The CoRe database



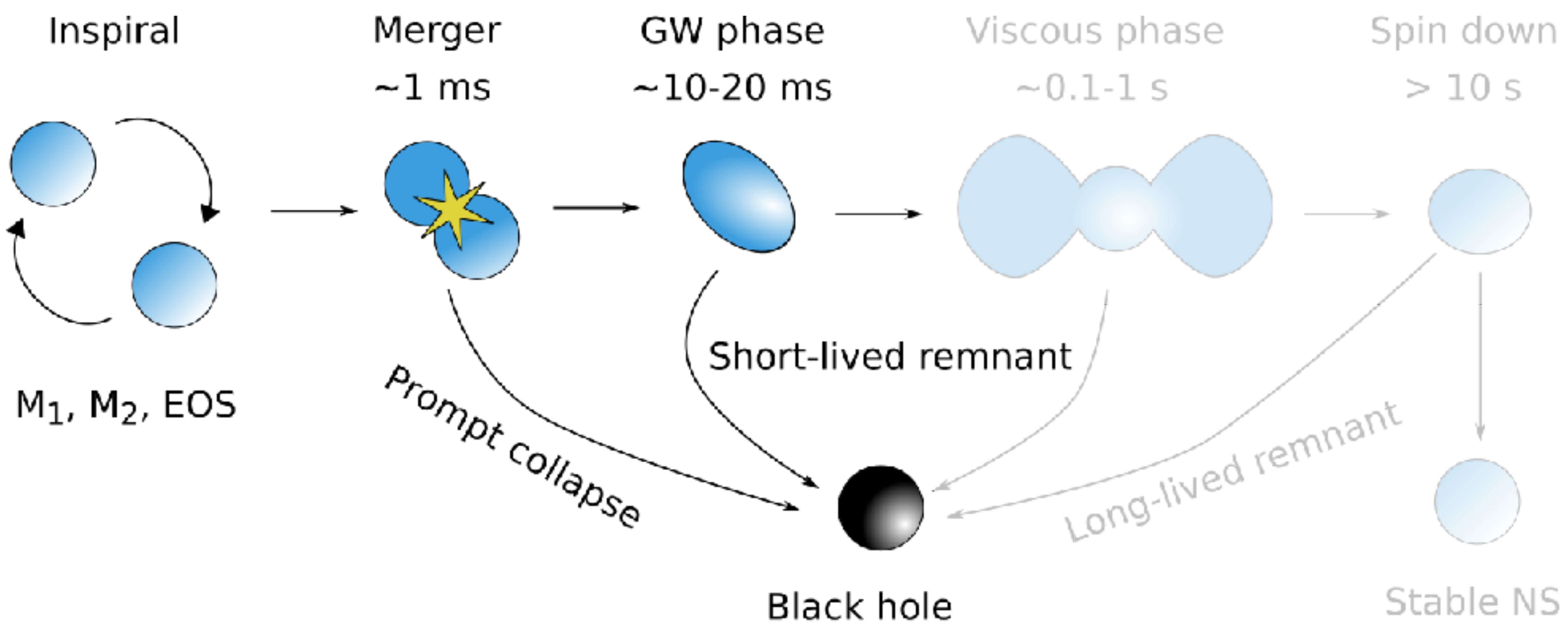
Open Science

- Outflow composition, mass, velocity
- r-process nucleosynthesis results
- Simulation code, postprocessing routines
- Initial data and input files
- Other data available on request

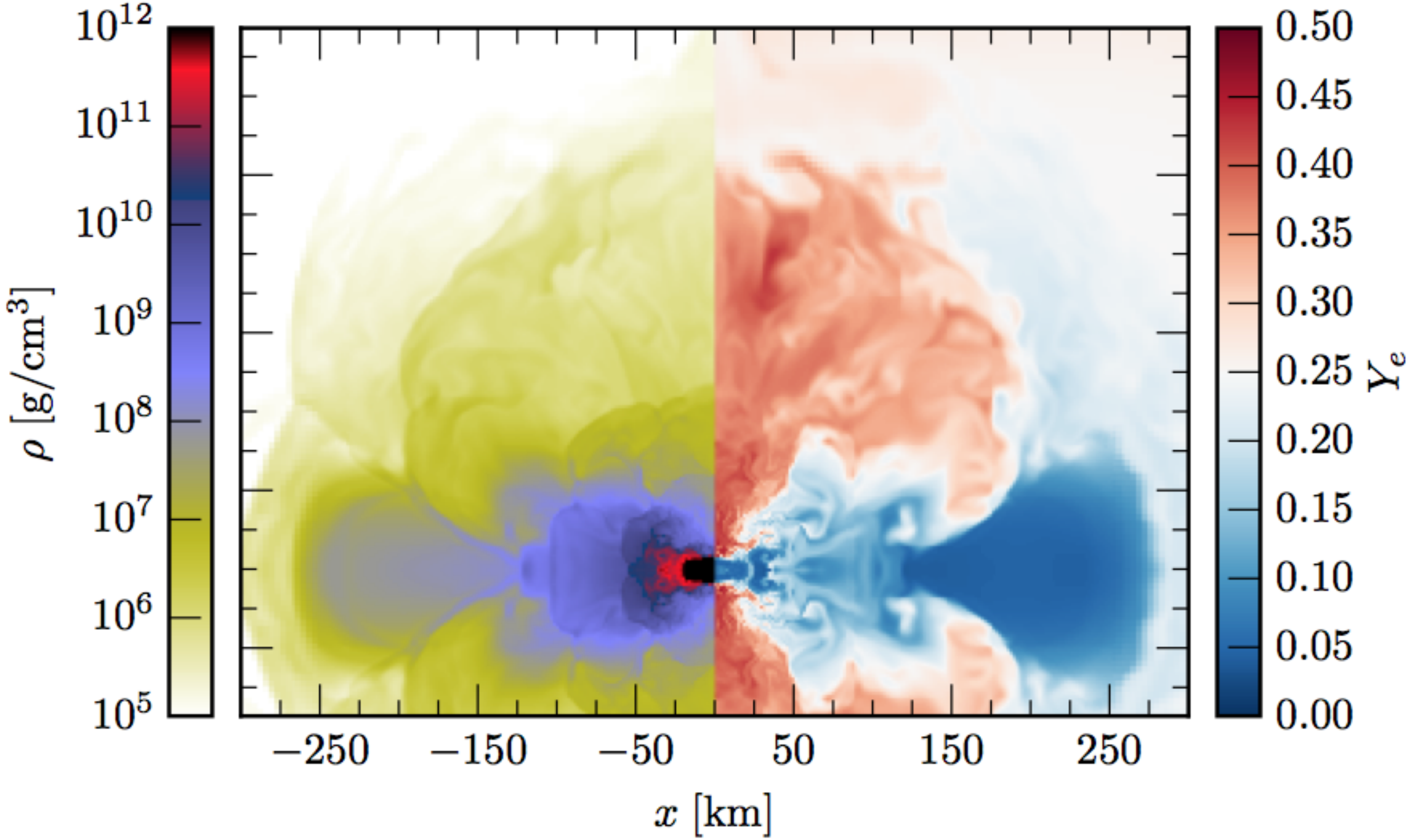
www.computational-relativity.org

Dietrich, **DR**, Bernuzzi+ CQG 35:LT01 (2018)

Early postmerger evolution



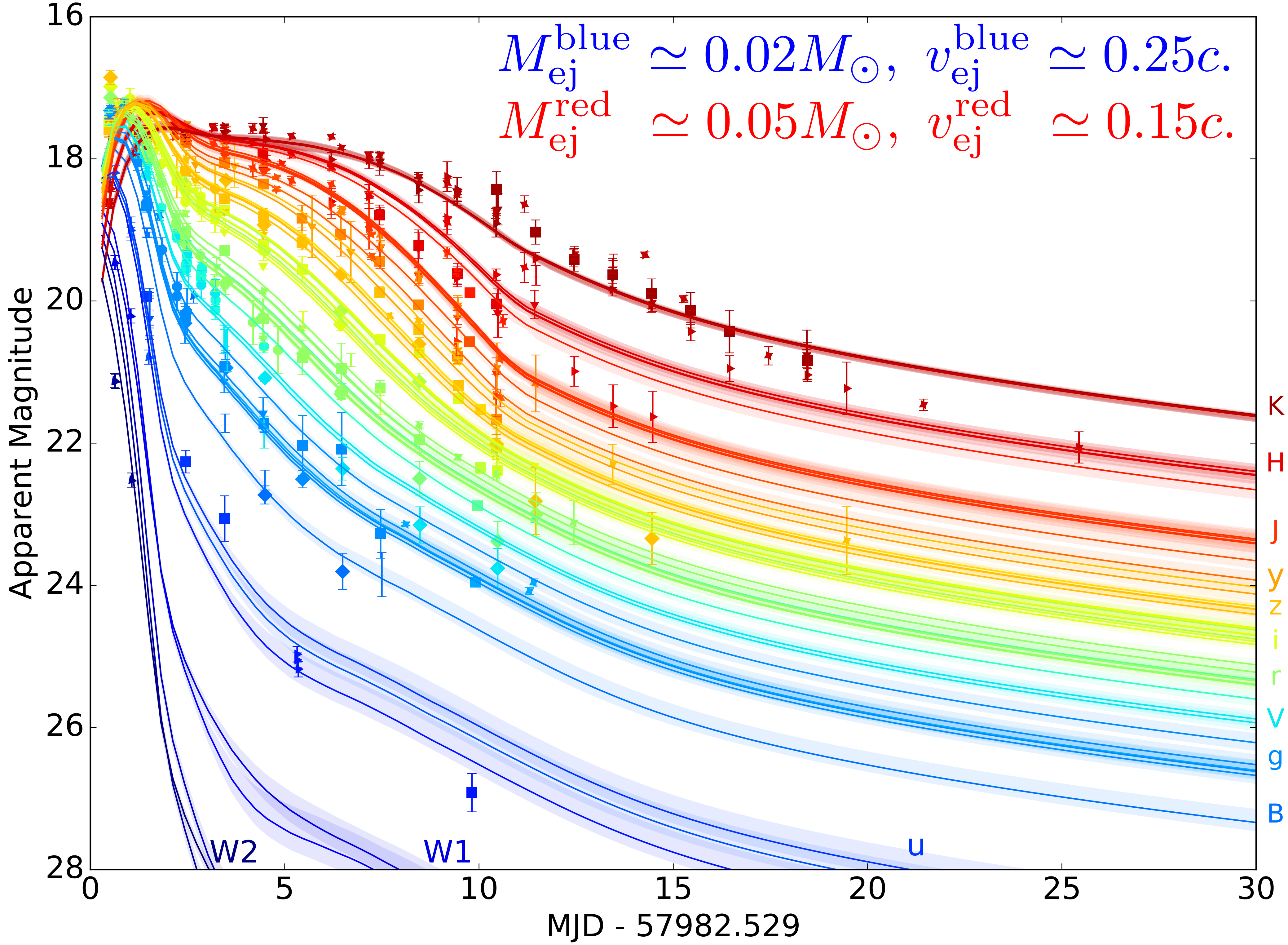
Dynamical mass ejection



See also Bausswein+ 2013, Hotokezaka+ 2013, Wanajo+ 2014, Sekiguchi+ 2015, 2016, Foucart+ 2016, Lehner+ 2016, Dietrich+ 2016, **DR**+ 2018, …

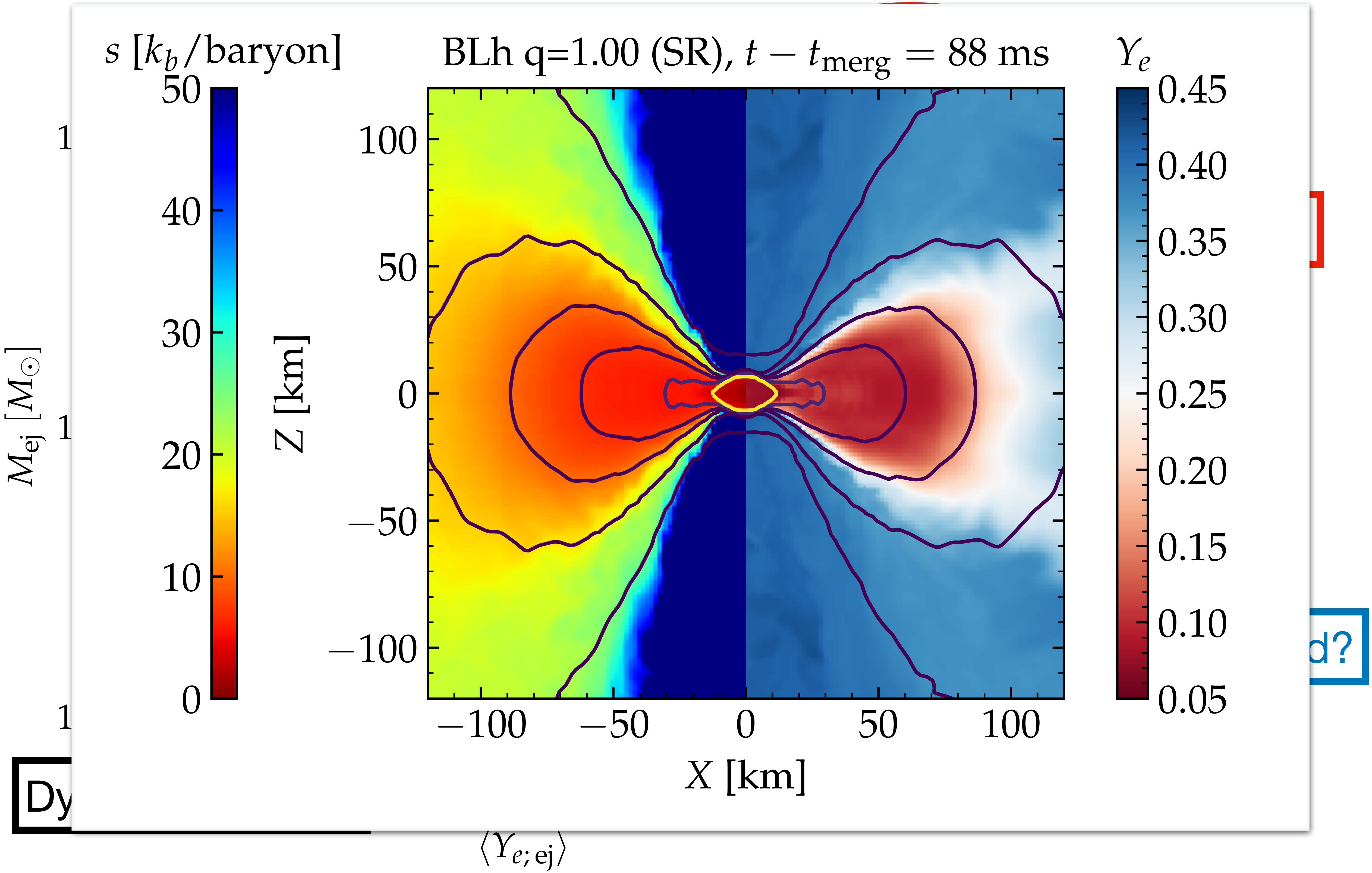
DR, Galeazzi+ MRAS 460:3255 (2016)

The kilonova in GW170817



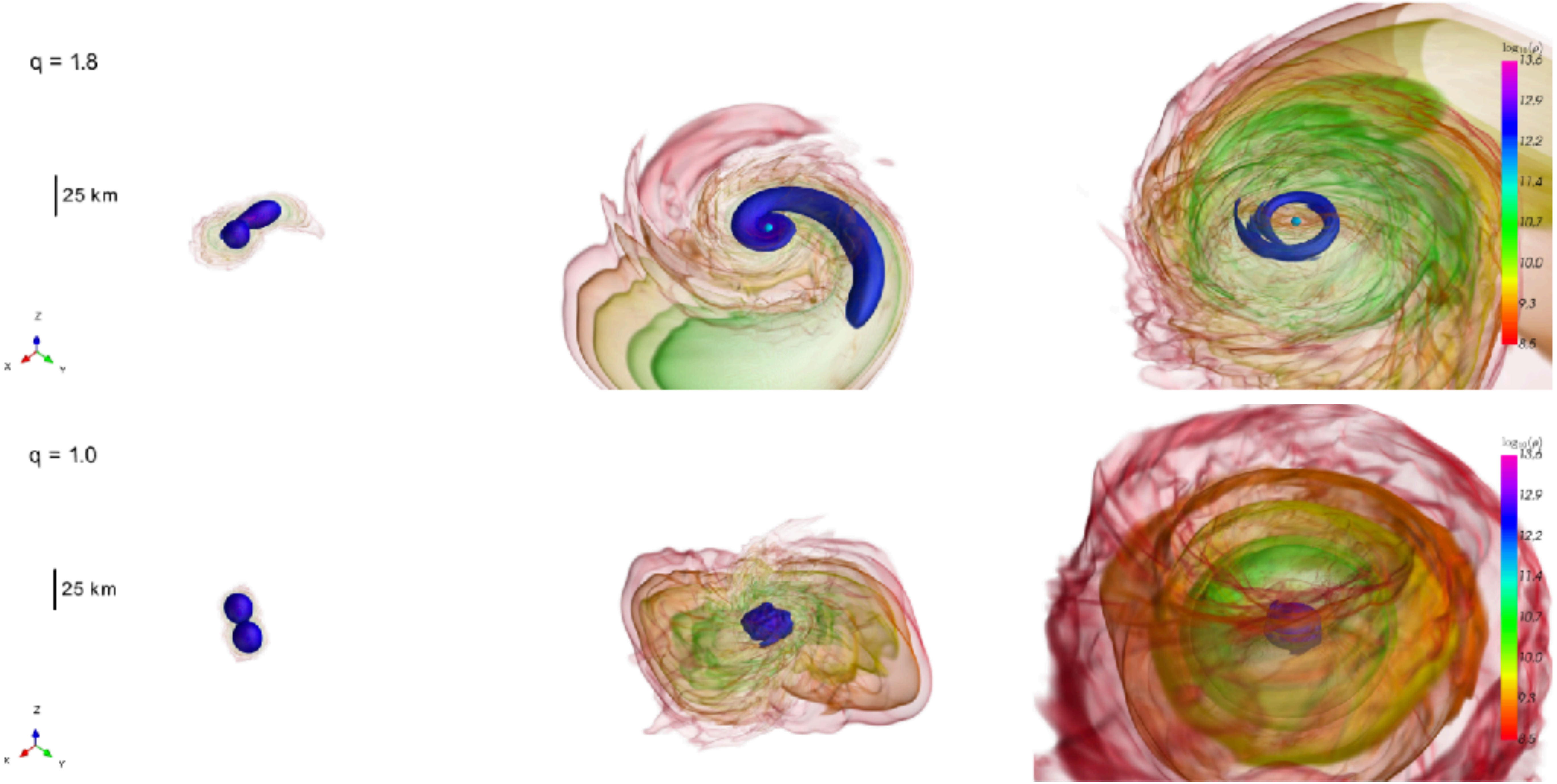
From Villar et al. ApJL 851:L21 (2017)

Theory vs observations



From Nedora, Bernuzzi, **DR**+, 2008.04333

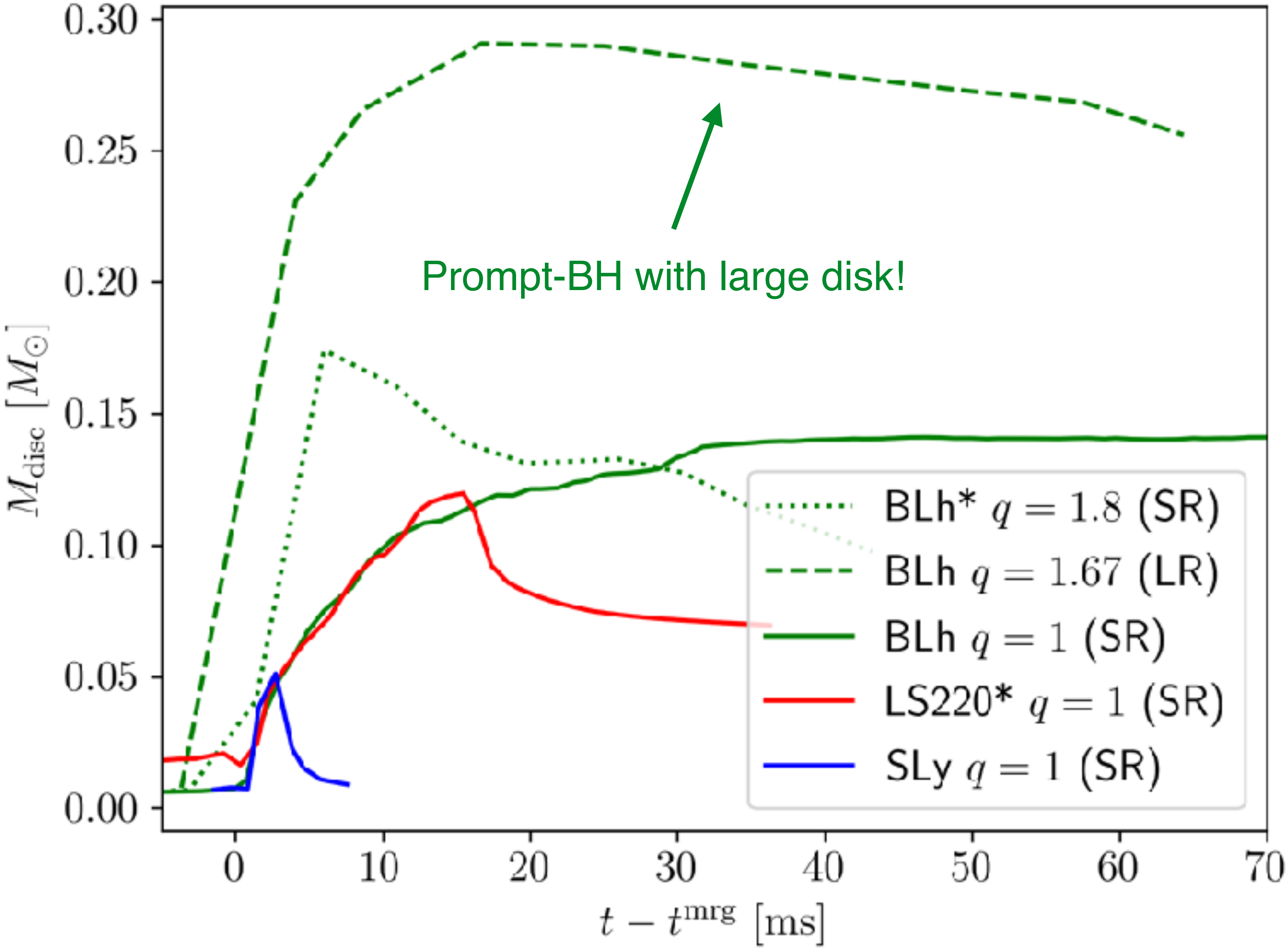
Disk formation I



$$\mathcal{M}_{\rm chirp} = 1.188\ M_\odot$$

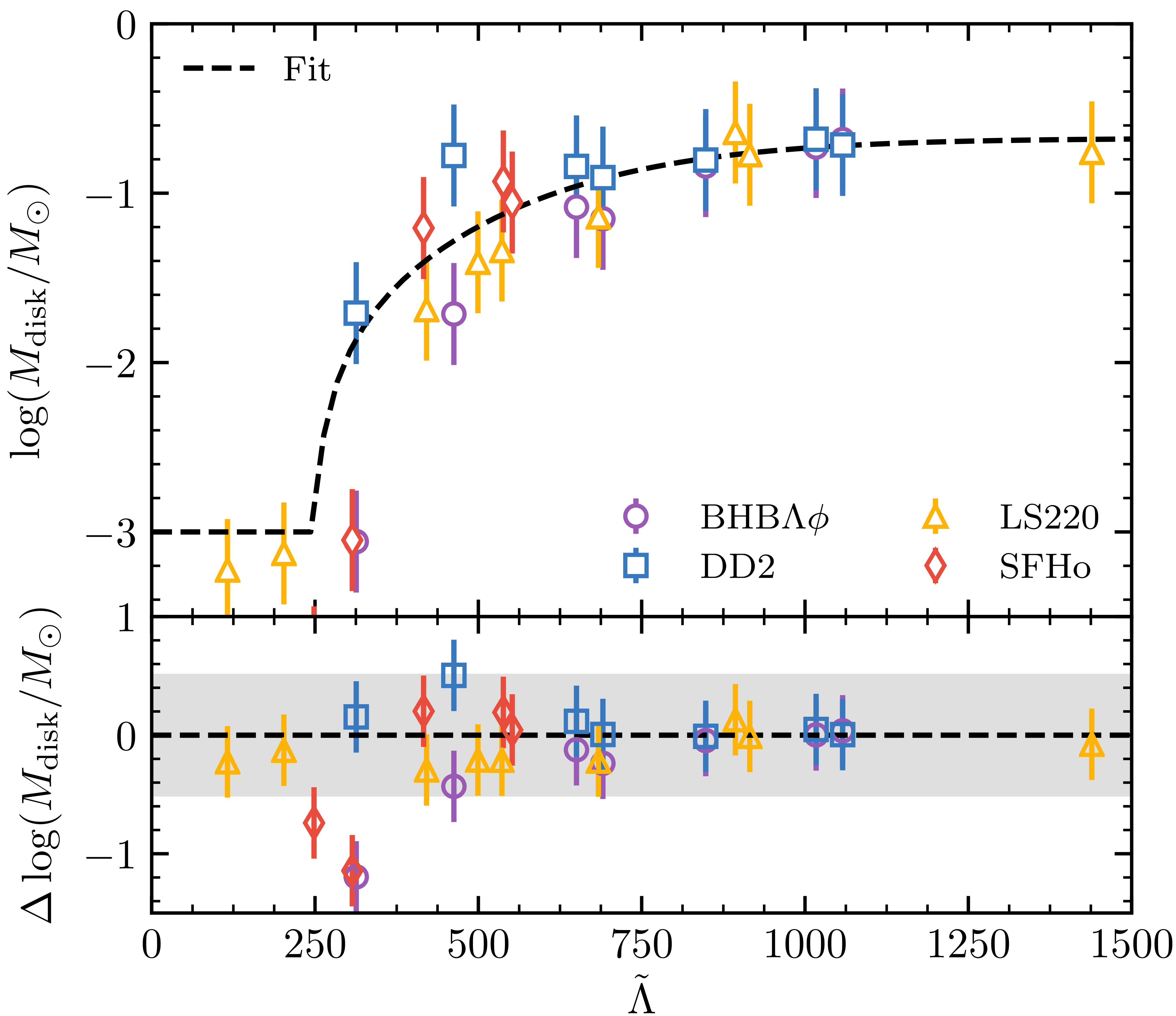
Bernuzzi, …, **DR**+, arXiv:2003.06015

Disk formation II



Bernuzzi, …, **DR**+, arXiv:2003.06015

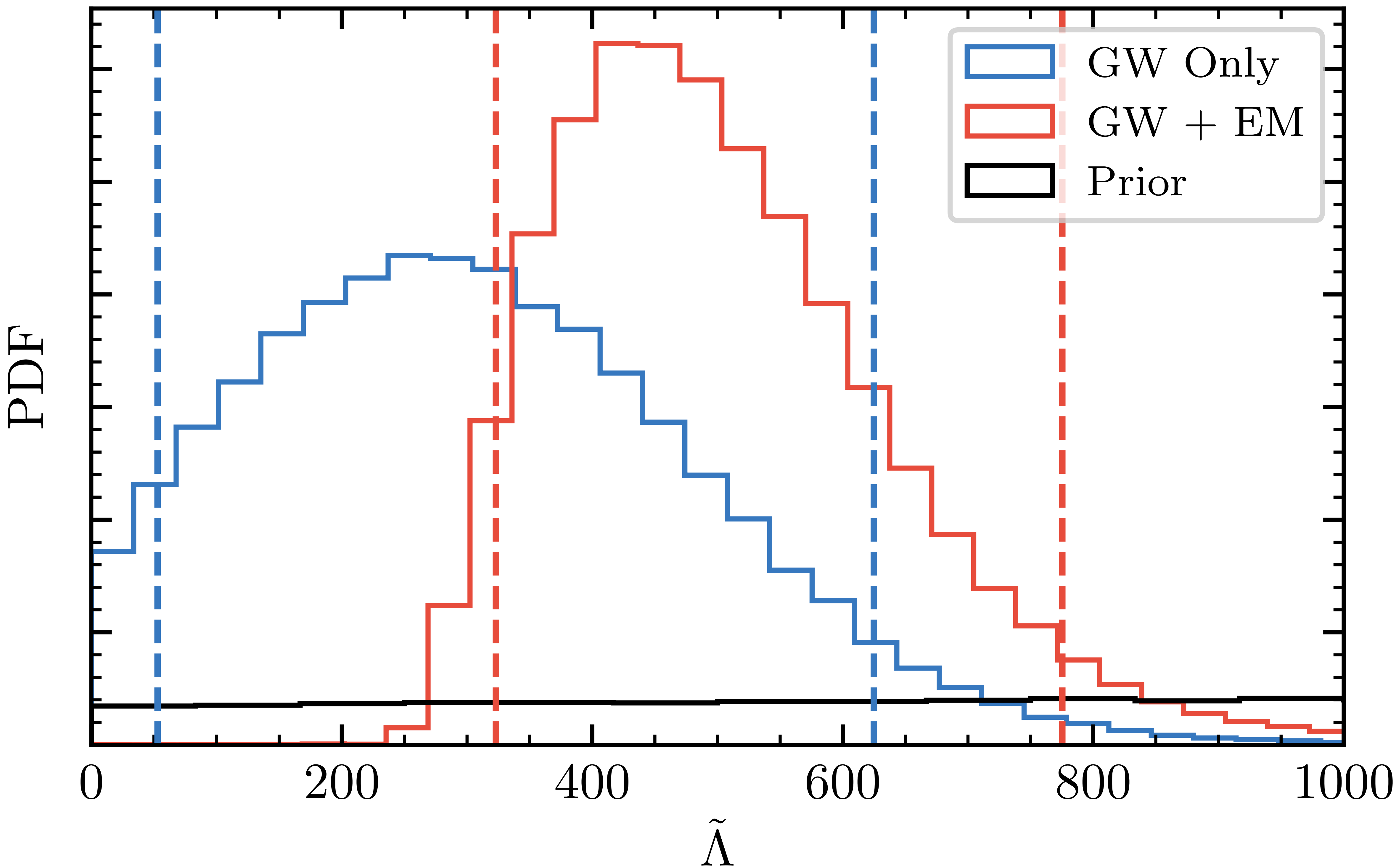
Disk masses



See also Krüger+ 2020; Salafia+ 2020; …

DR, Perego+ ApJL 852:L29 (2018);
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

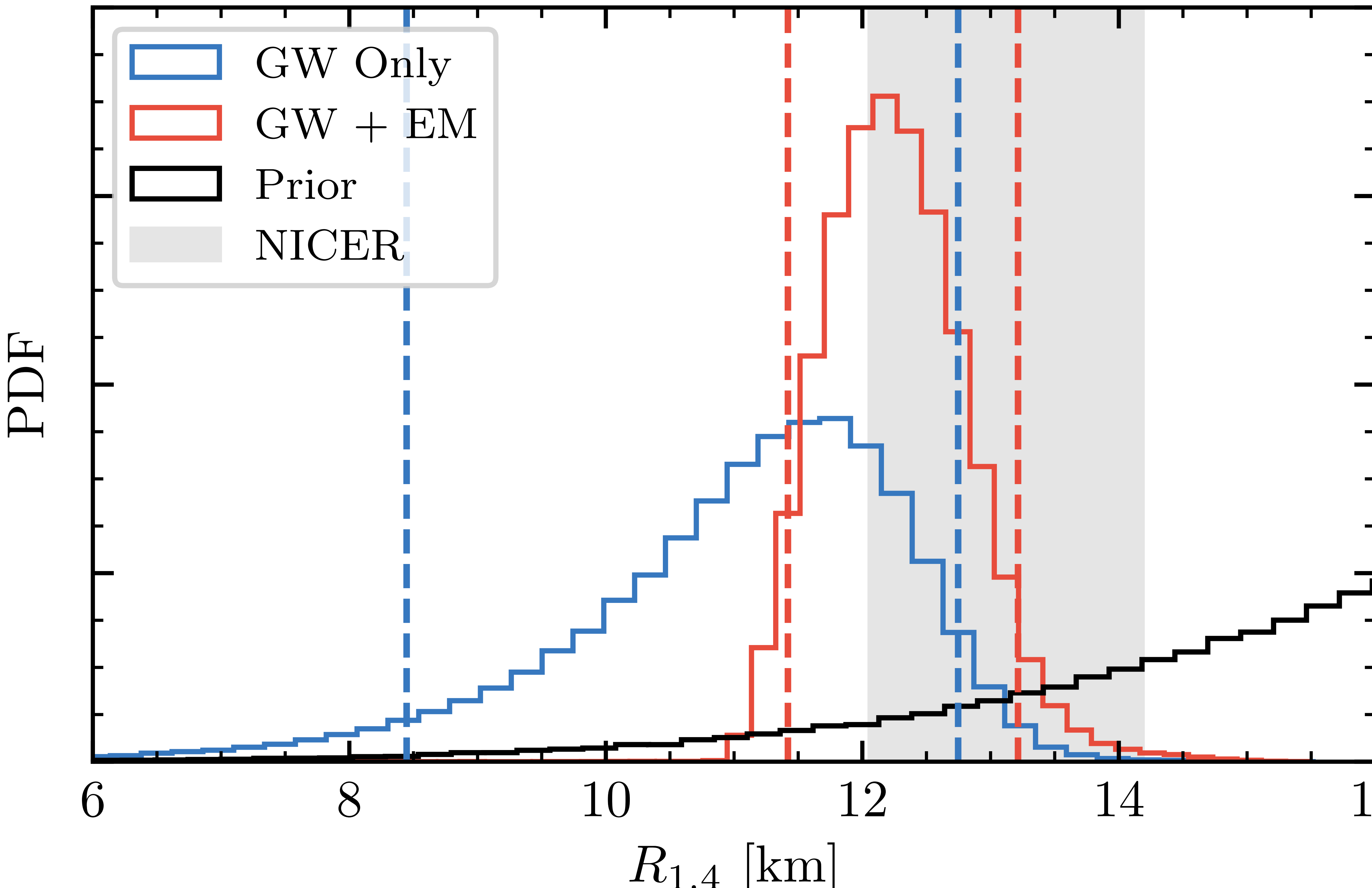
Equation of state constraints



See also Gamba+ 2020

DR, Perego+ ApJL 852:L29 (2018);
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

Equation of state constraints



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DR & Dai, Eur. Phys. J. A 55: 50 (2019)

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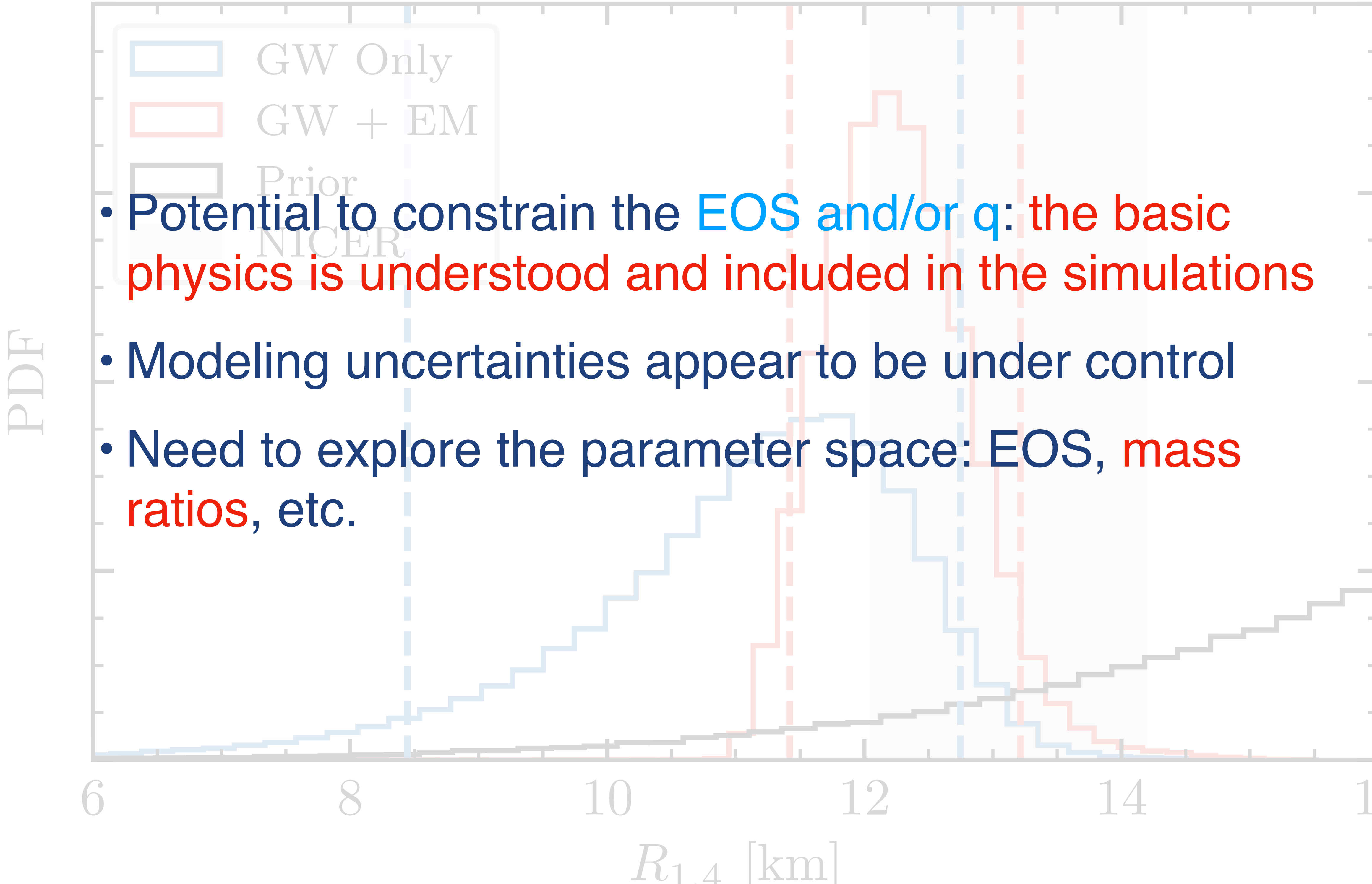
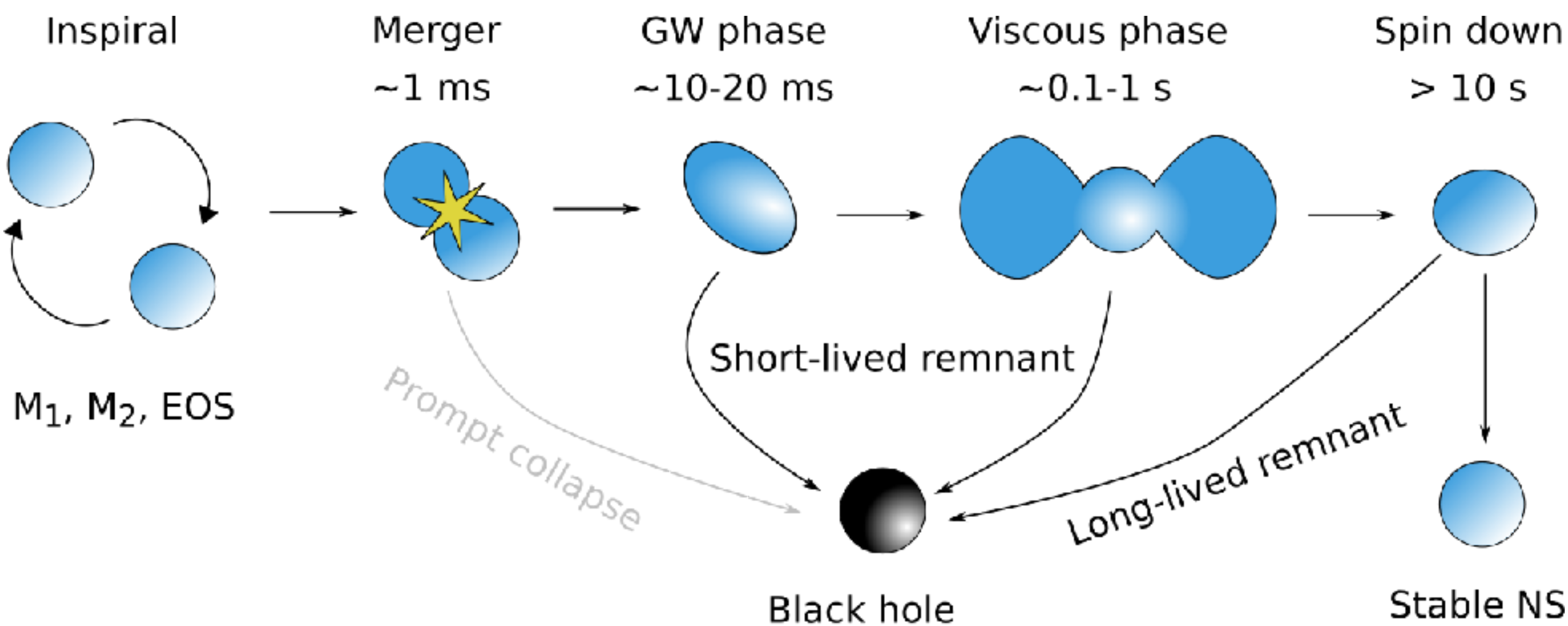


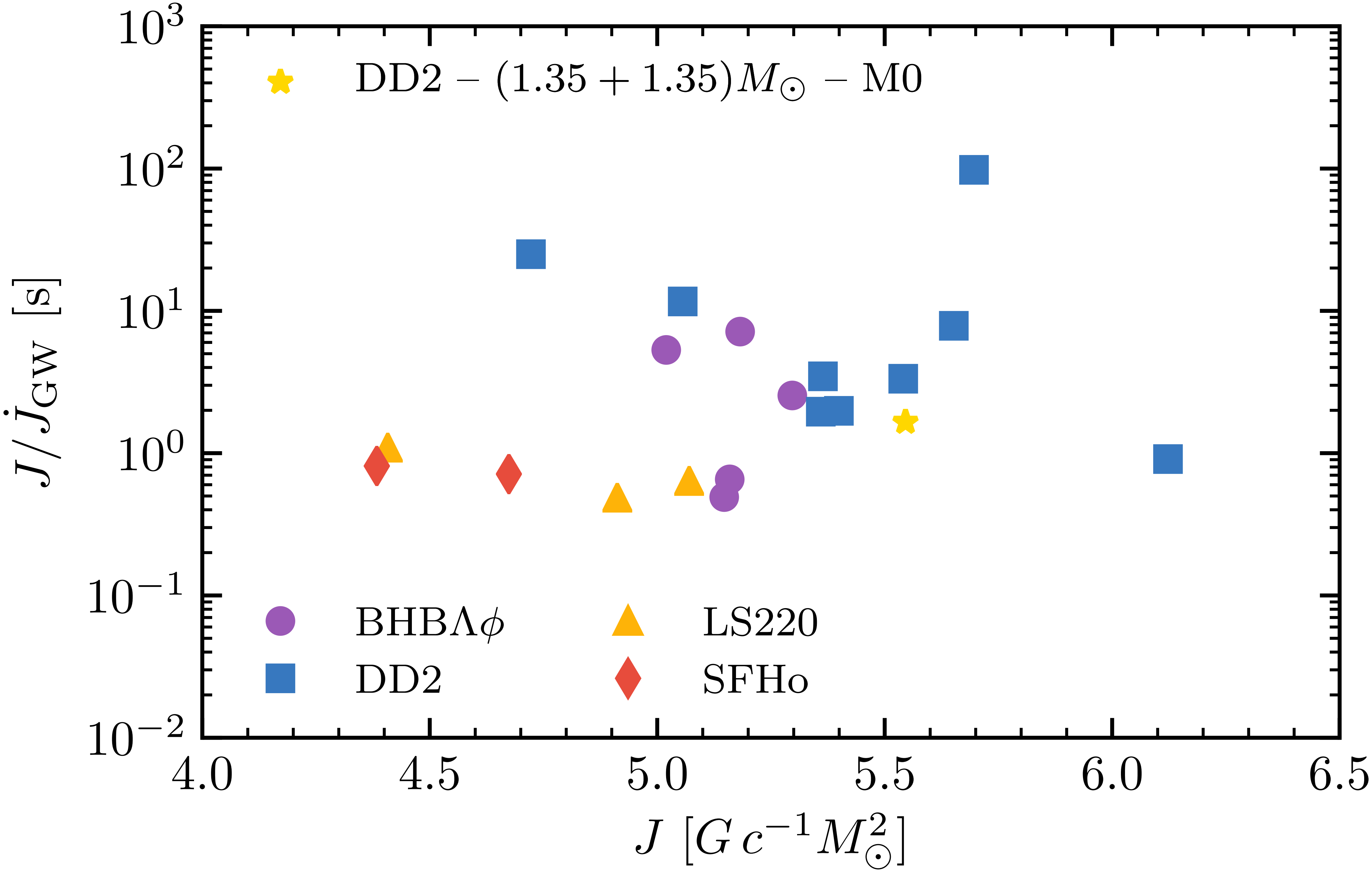
- Potential to constrain the EOS and/or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Need to explore the parameter space: EOS, mass ratios, etc.

DR, Perego+ ApJL 852:L29 (2018);
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

Long-term evolution

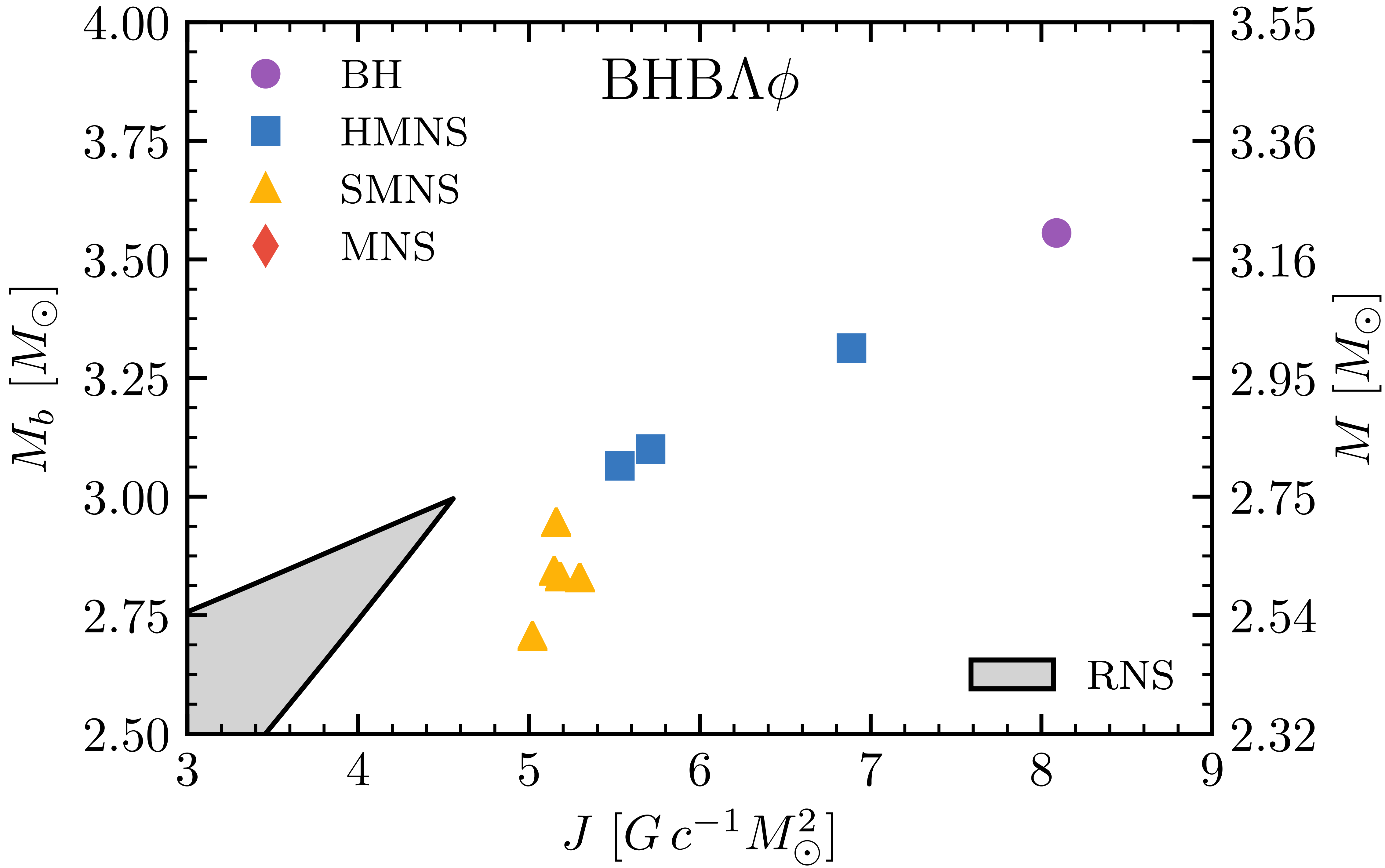


End of the GW-driven phase

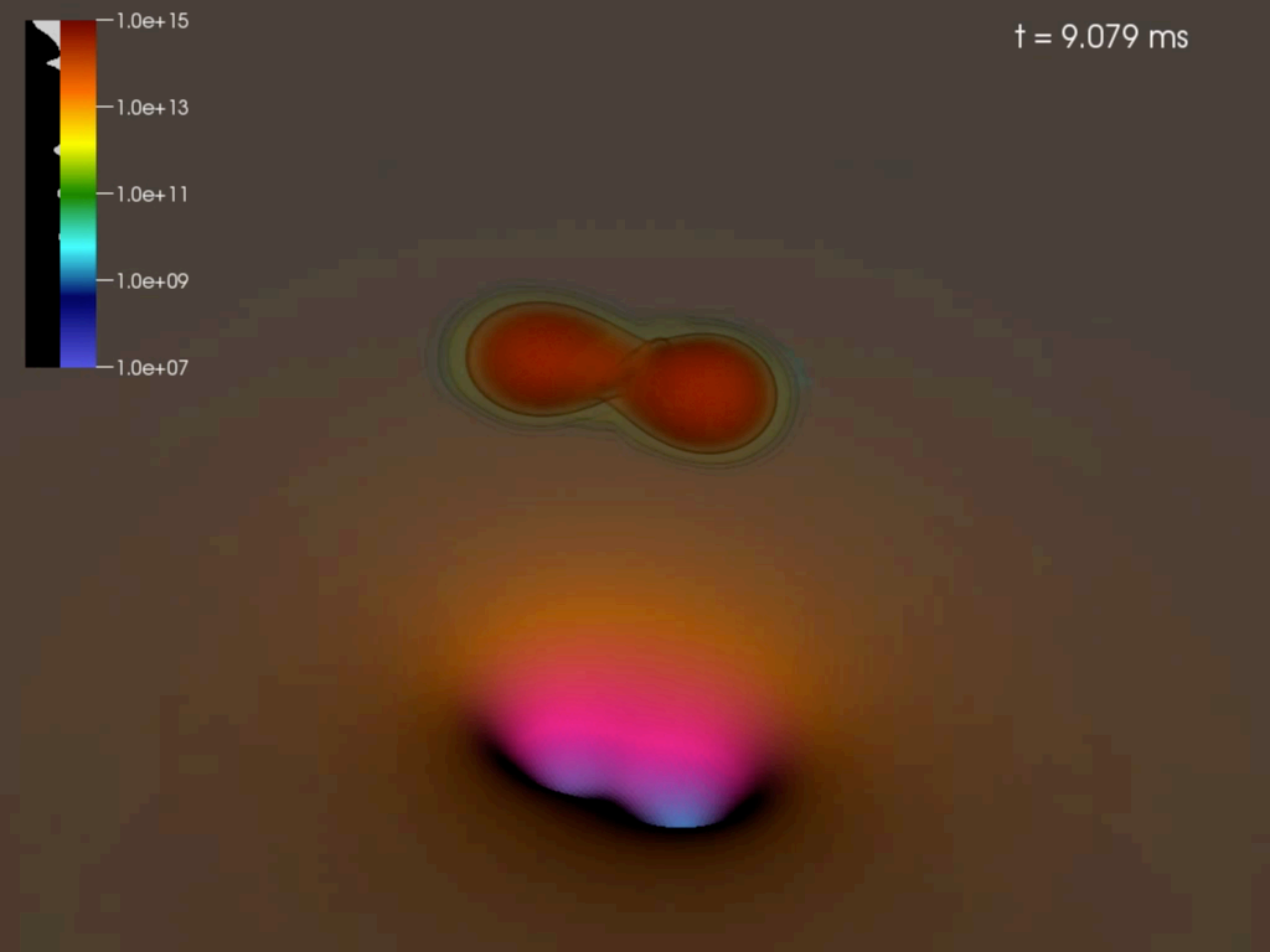


DR, Perego, Bernuzzi, Zhang, MNRAS 481:3670 (2018)

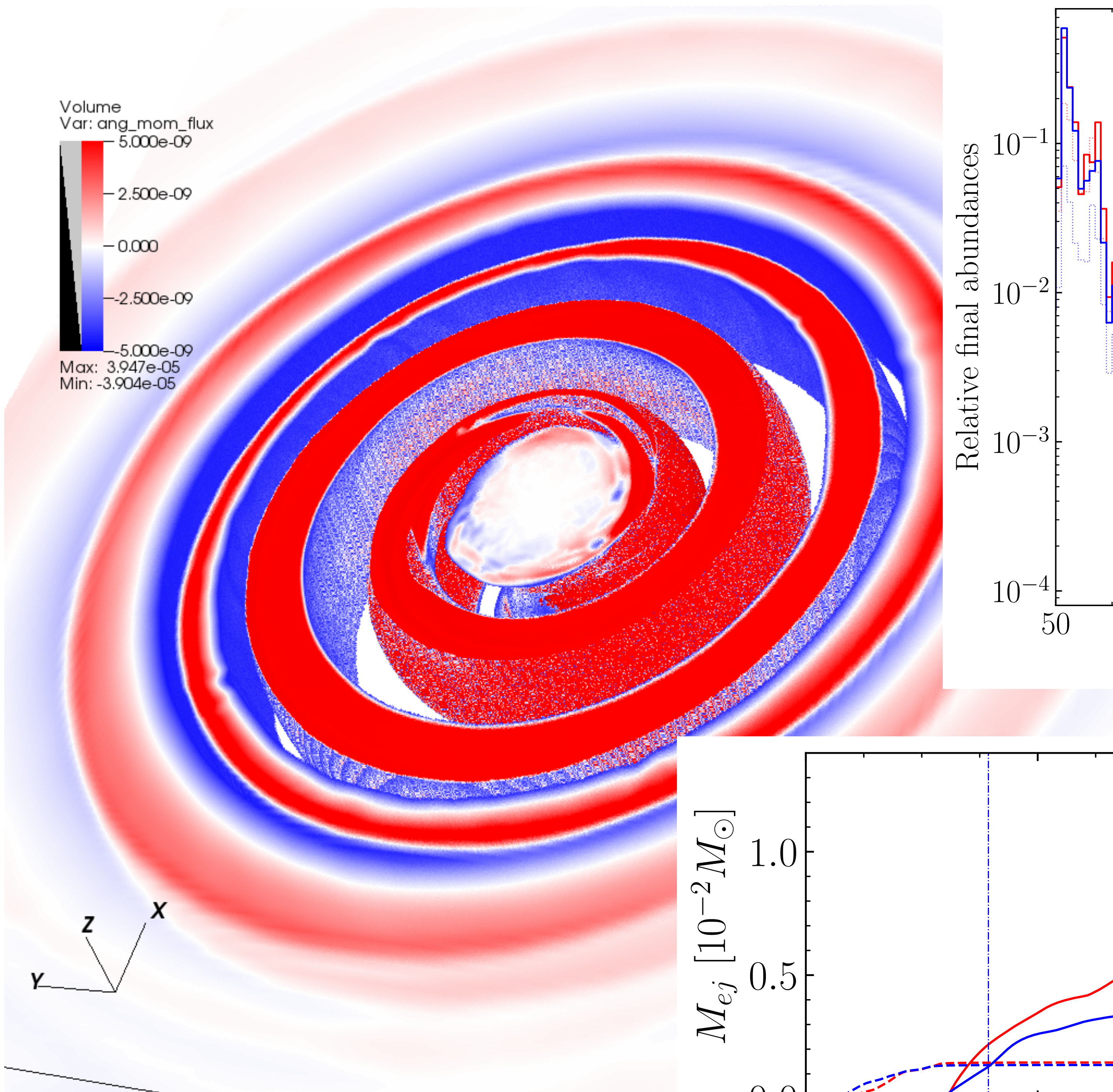
Secular evolution: NS remnants

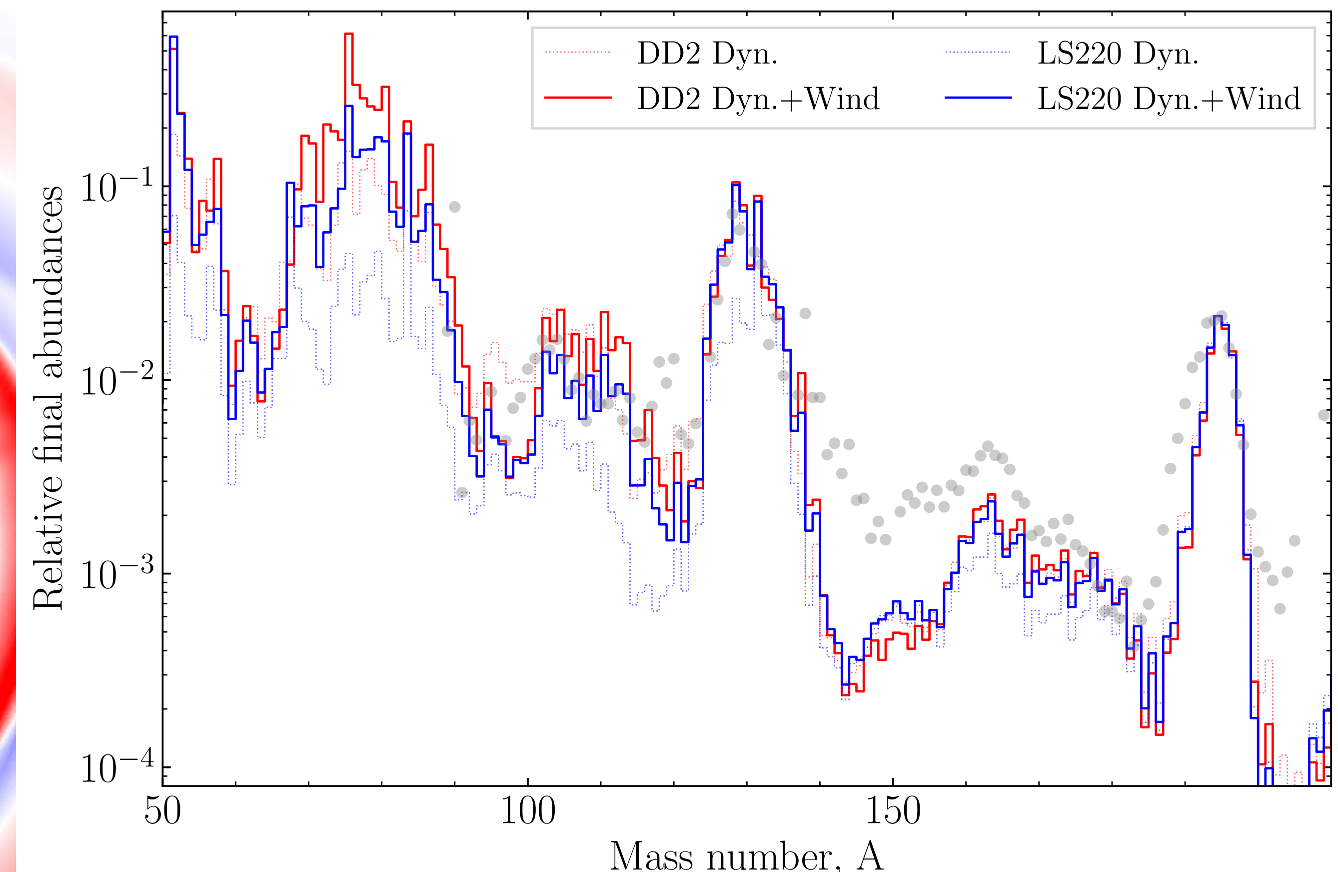


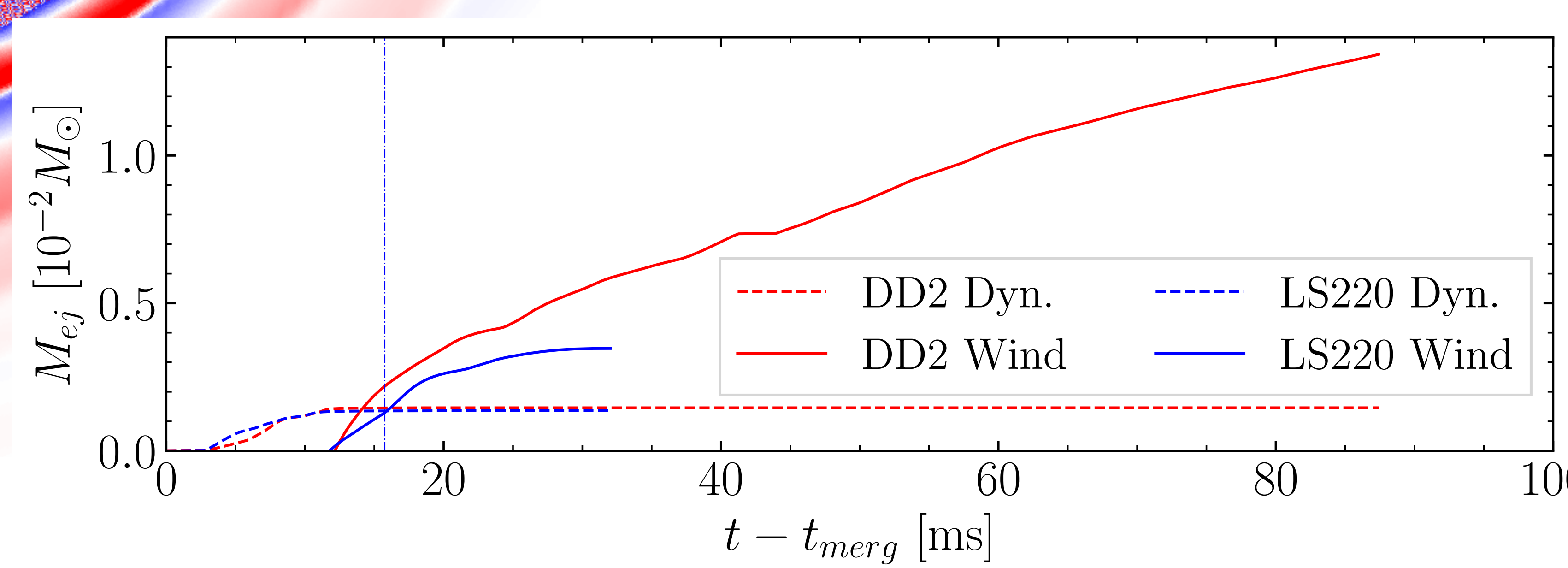
DR, Perego, Bernuzzi, Zhang, MNRAS 481:3670 (2018)


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 9.079 ms

Spiral-wave wind (I)

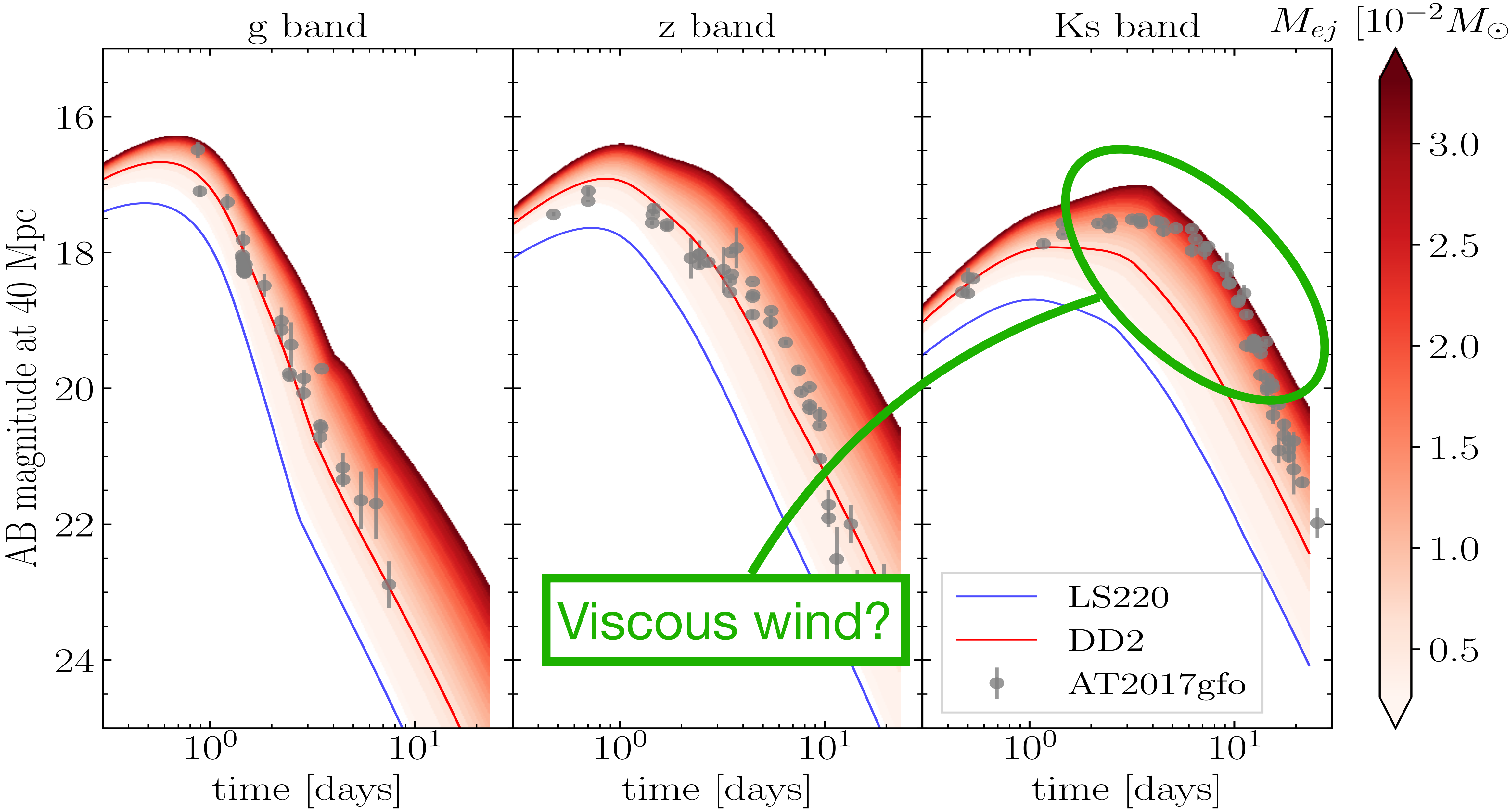






From Nedora, Bernuzzi, **DR**+, ApJL 886:L30 (2019)

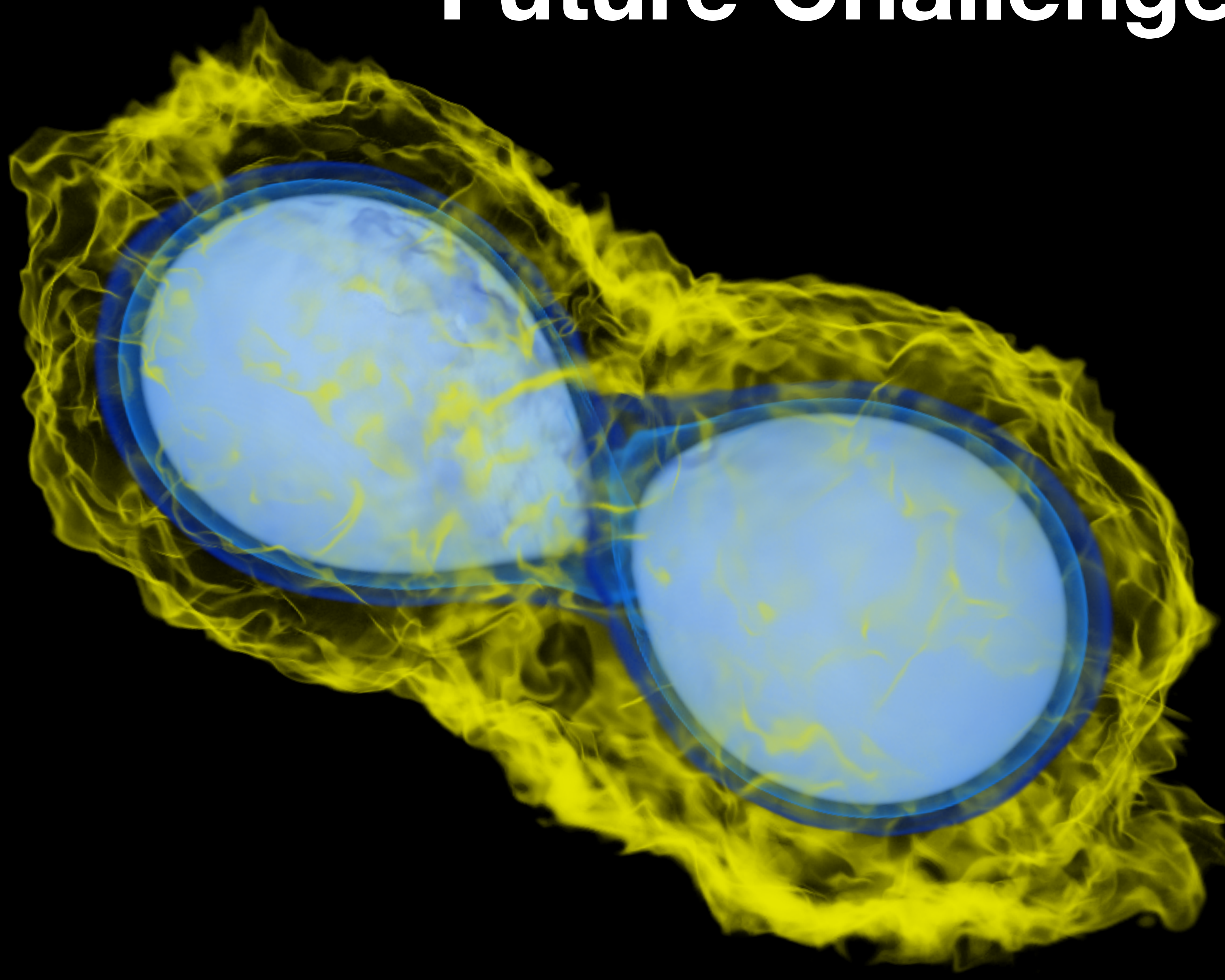
Spiral-wave wind (II)



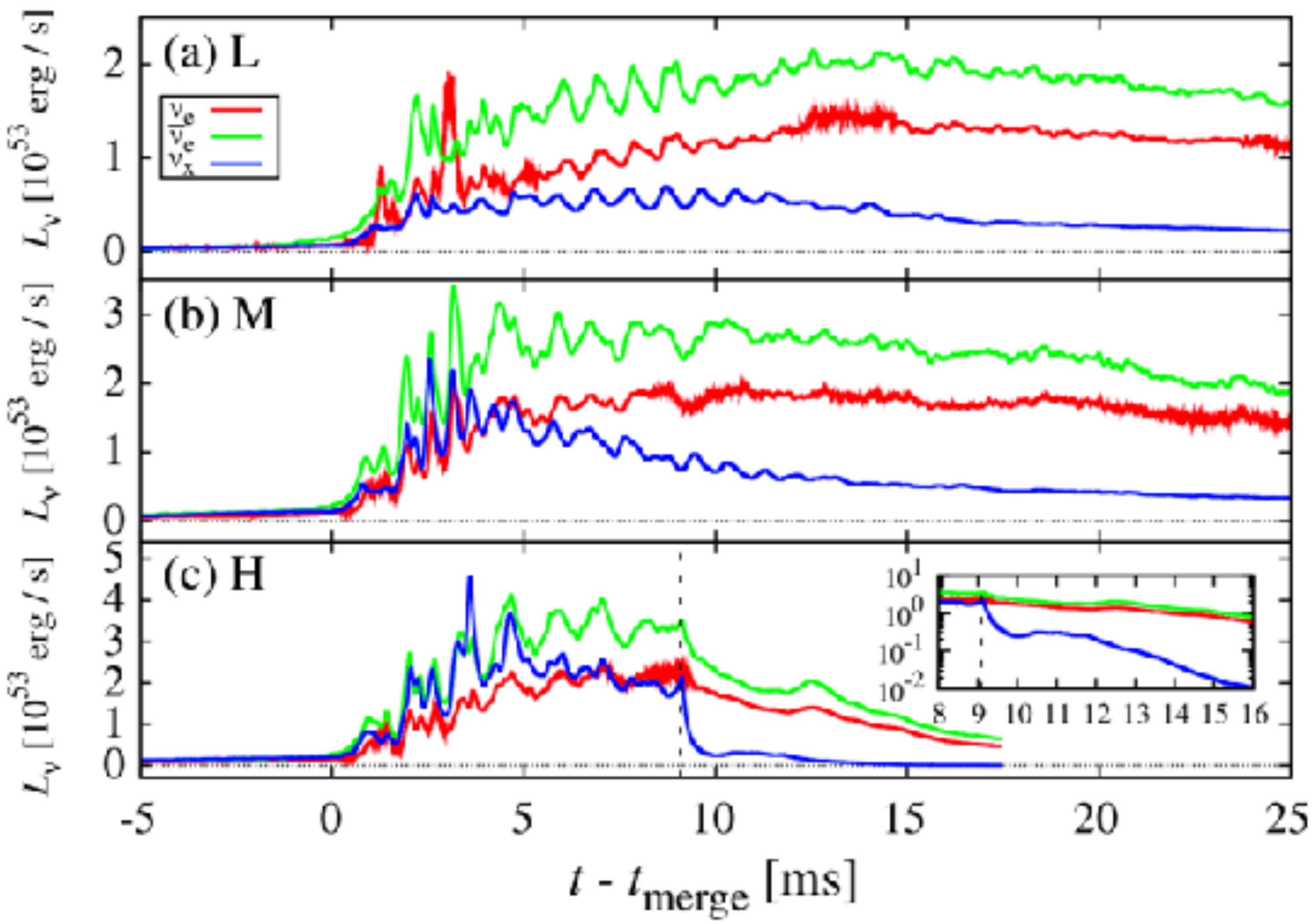
Promising, but incomplete, and not the only possible explanation

From Nedora, Bernuzzi, **DR**+, ApJL 886:L30 (2019)

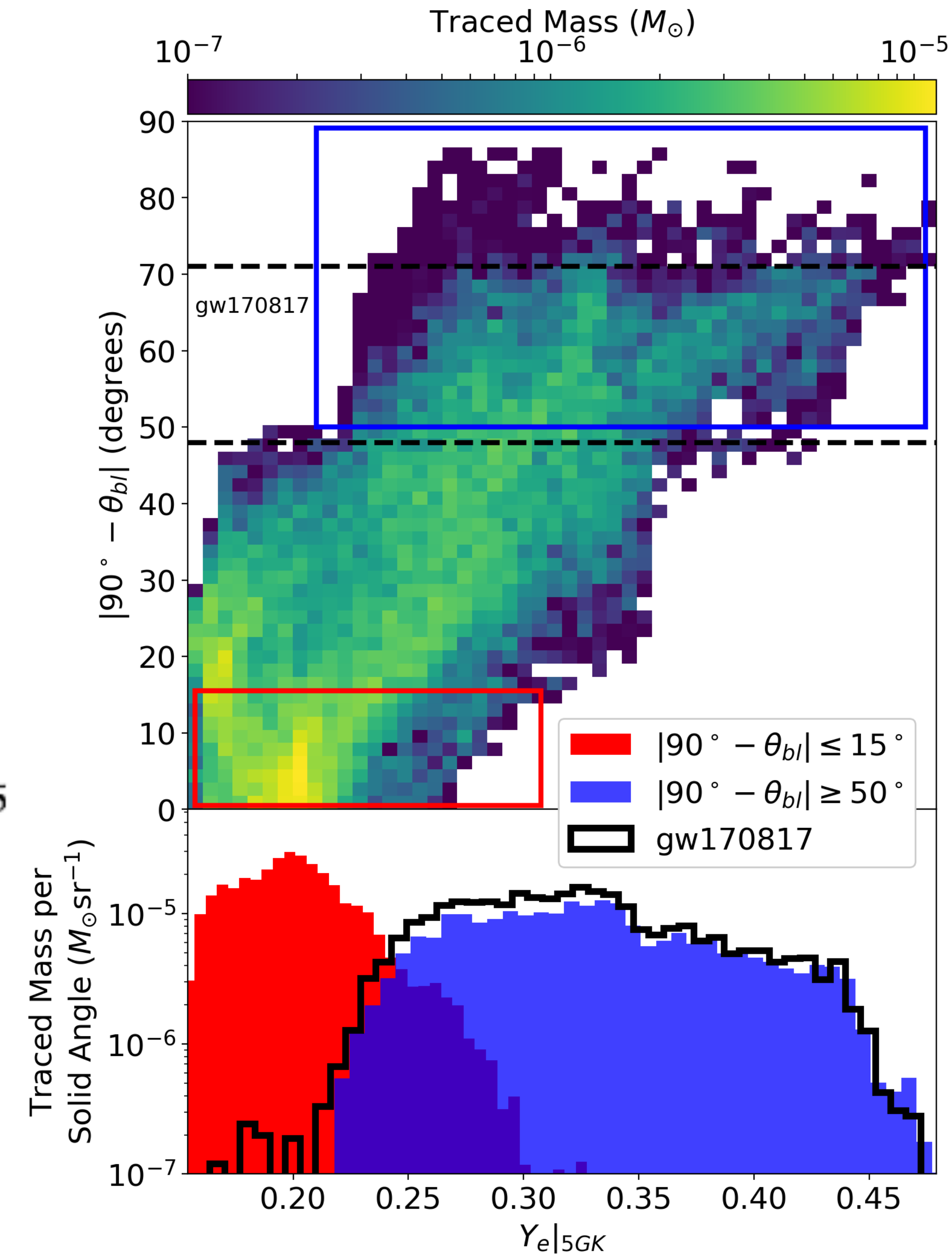
Future Challenges



Neutrino physics



From Sekiguchi+ 2011

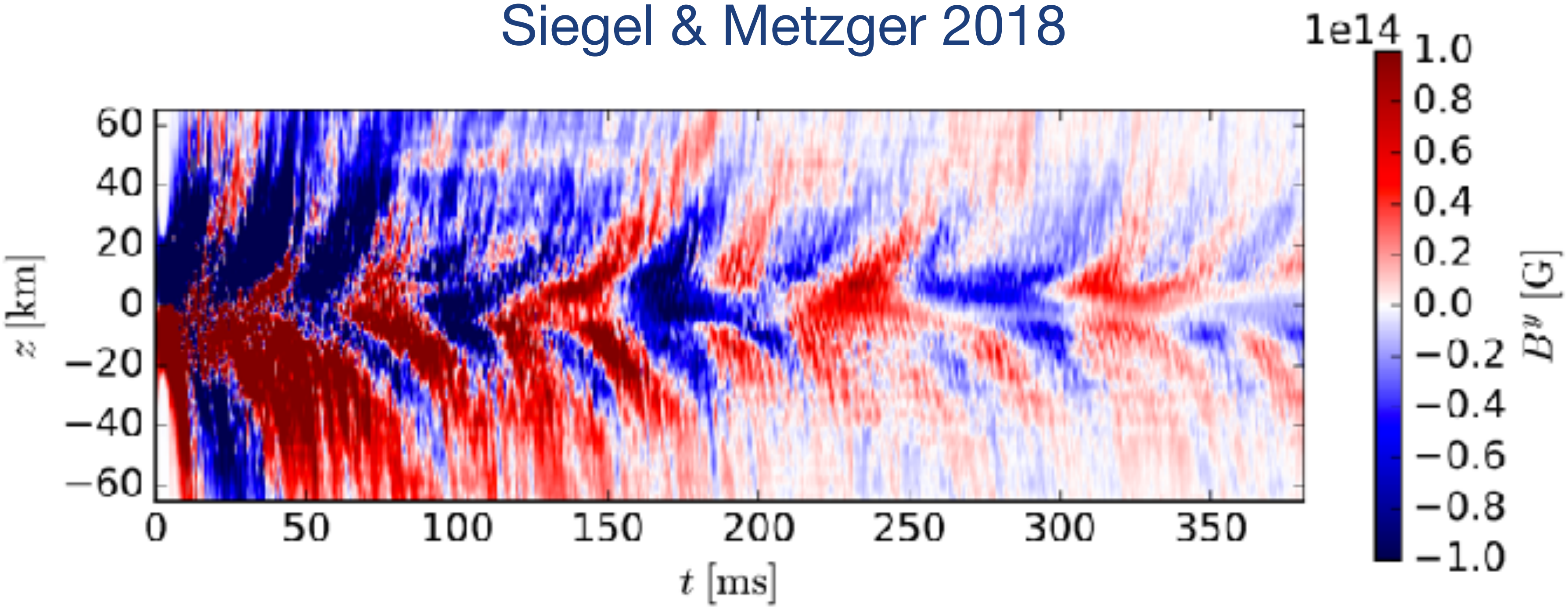


From Miller+ 2019

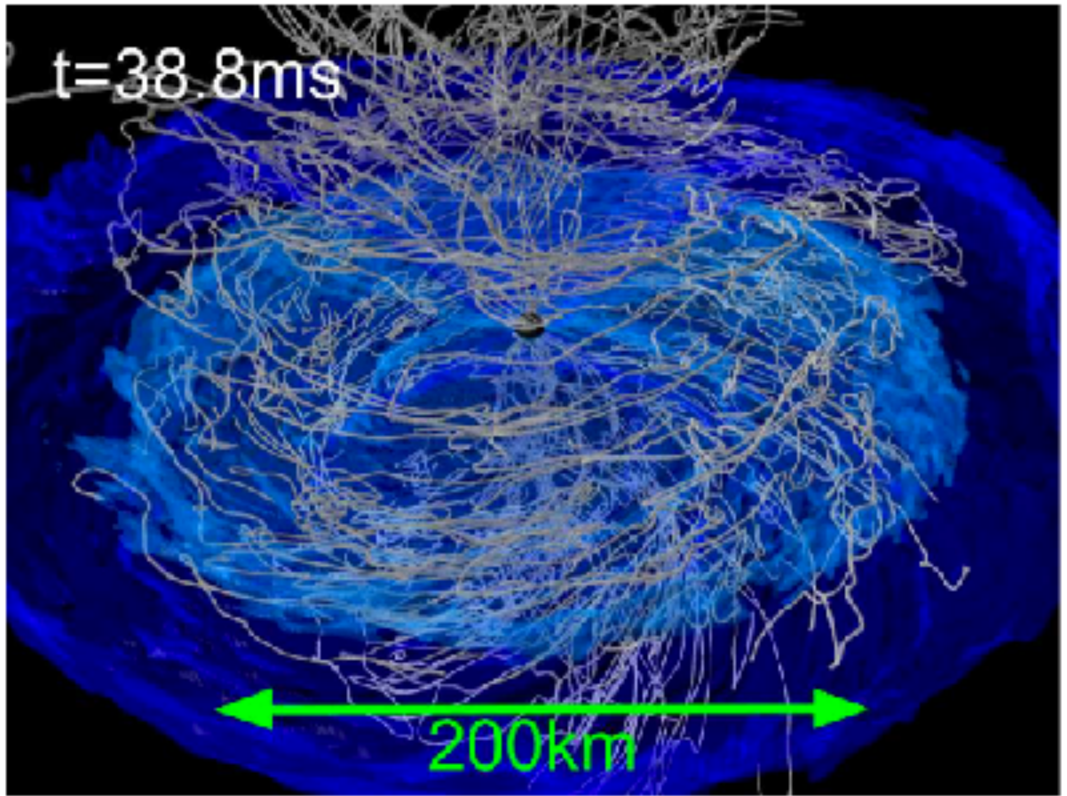
See also: Dessart+ 2008, Perego+ 2014, Just+ 2015, Metzger+ 2014, Foucart+ 2016, Siegel & Metzger 2018, Fujibayashi+ 2017, 2020 …

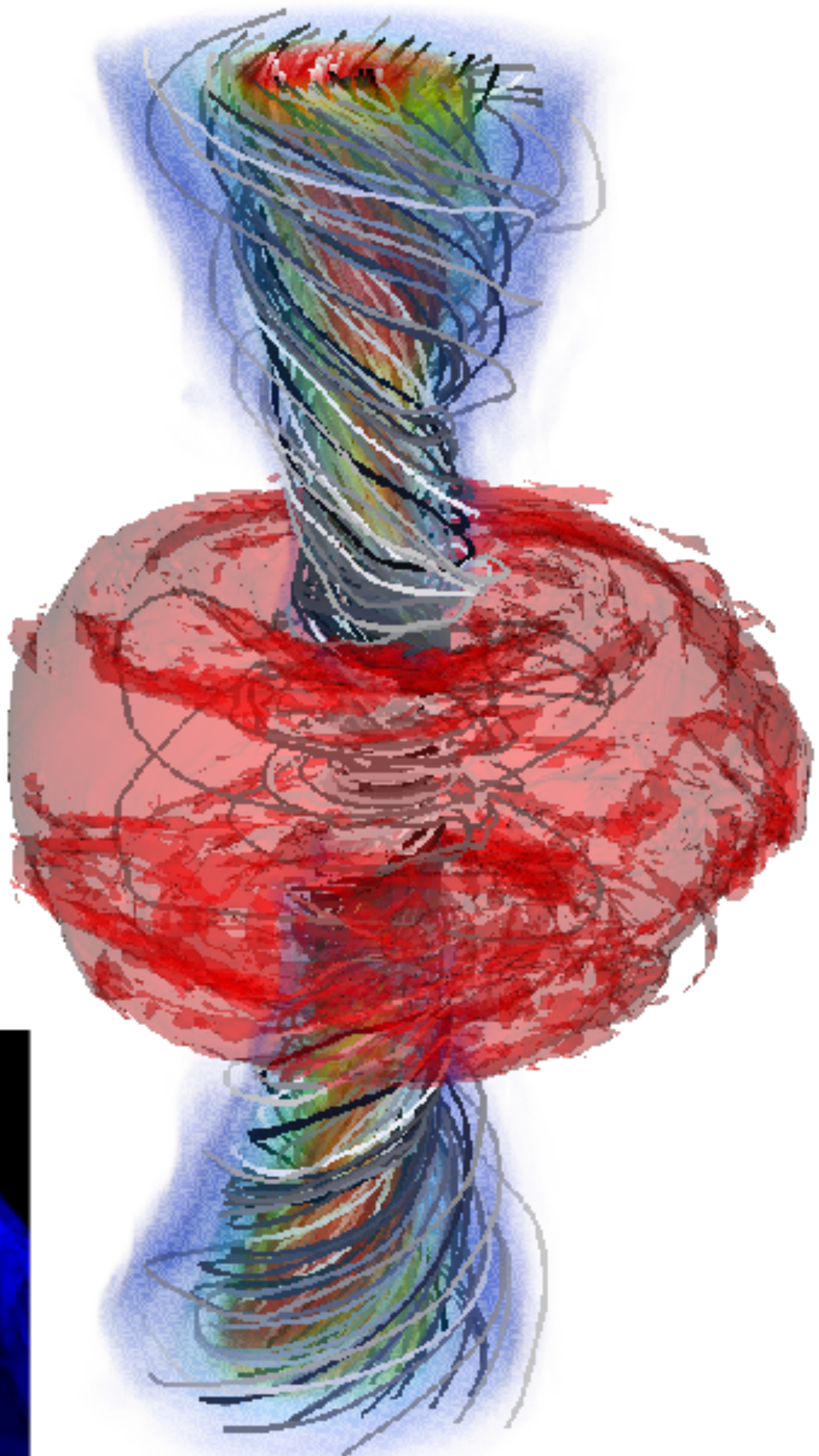
MHD turbulence

Siegel & Metzger 2018



Kiuchi+ 2014



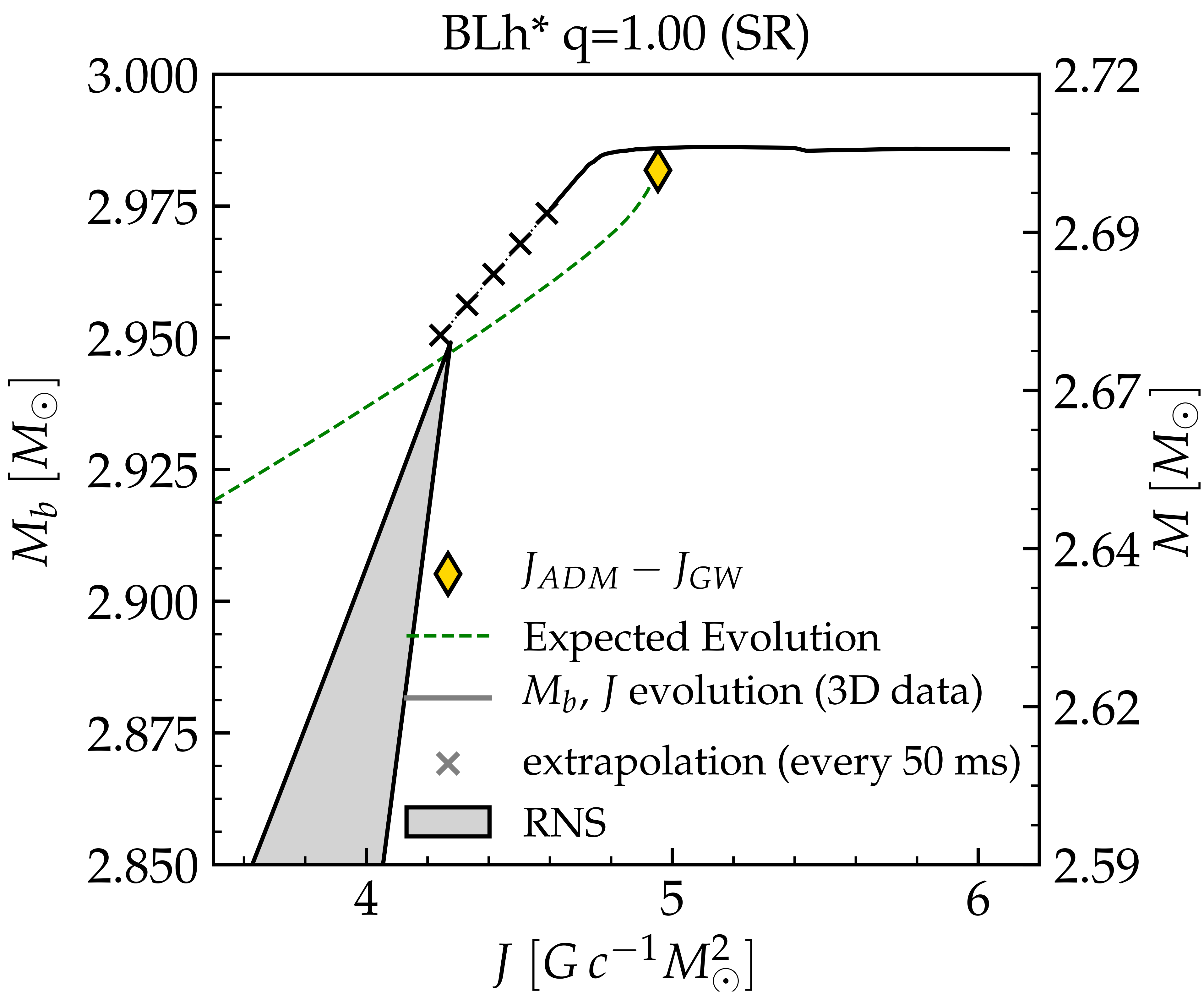


Mösta, **DR**+, ApJL 2020

See also

Price & Rosswog 2006;
Andreson+ 2008;
Etienne+ 2011;
Endrizzi+ 2014;
Giacomazzo+ 2015;
Ruiz+ 2016;
Palenzuela+ 2016;
Fernandez+ 2018;
Ciolfi+ 2019; …

Merger outcome



From Nedora, Bernuzzi, **DR**+, 2008.04333

Conclusions

- Inspiral and early postmerger are better understood, but there is still a vast parameter space volume to explore.
- We can already do multimessenger astrophysics!
- The physics becomes increasingly complex on longer timescales in the postmerger. Higher resolution, longer, and more sophisticated simulations are needed.