NP3M

NSF Focus Research Hub
Nuclear Physics from Multi-Messenger Mergers

www.computational-relativity.org

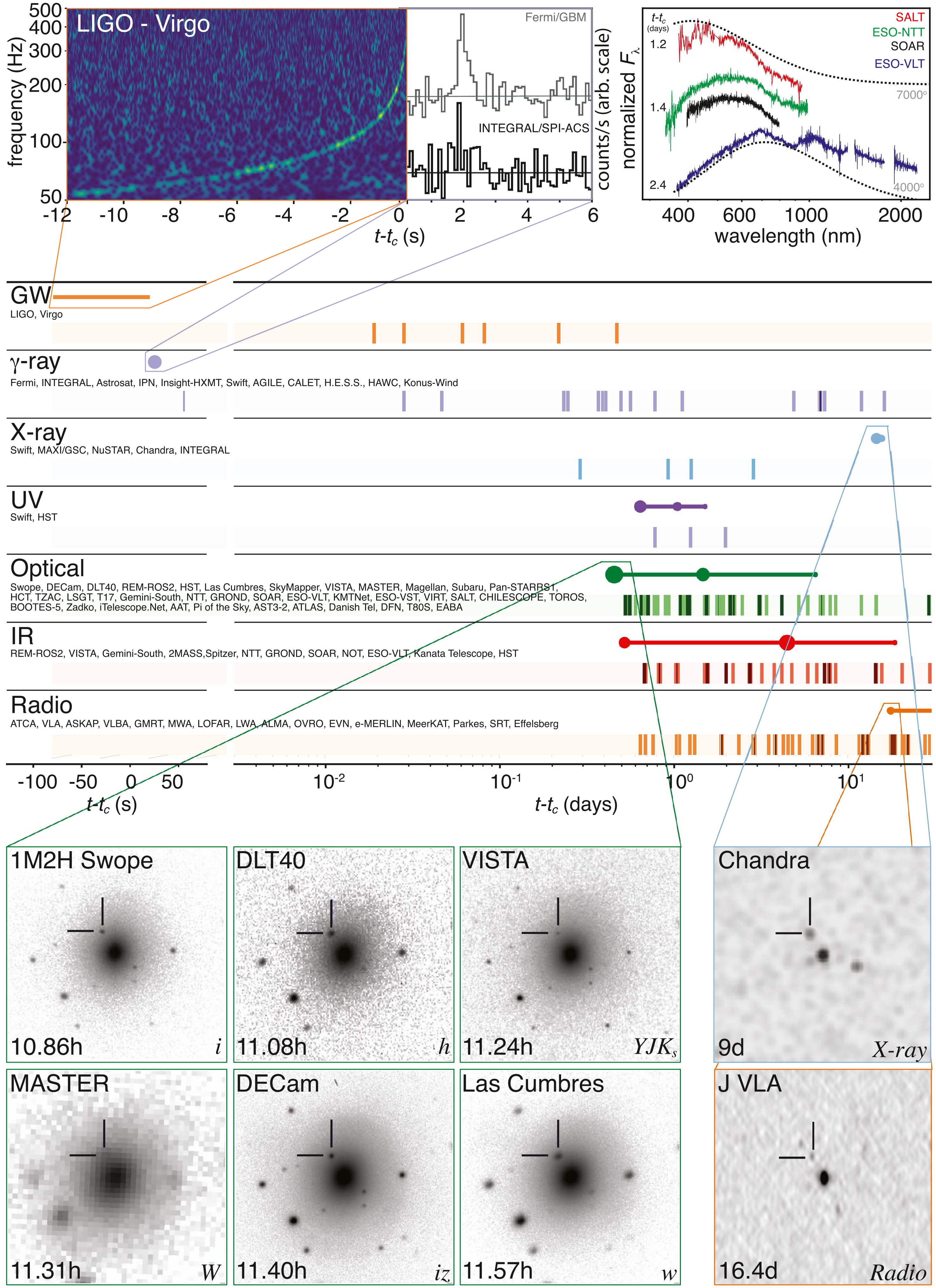
Binary Neutron Star Mergers

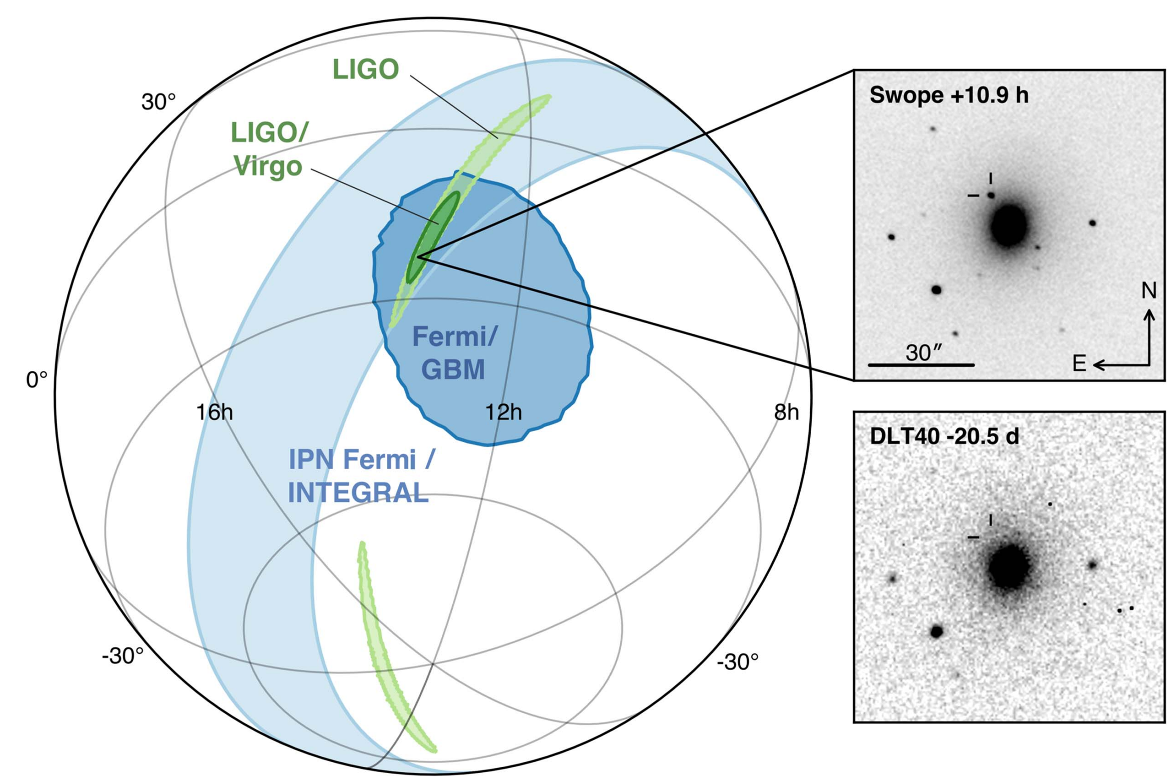
David Radice (PSU) — Oct. 4, 2021

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

Open questions

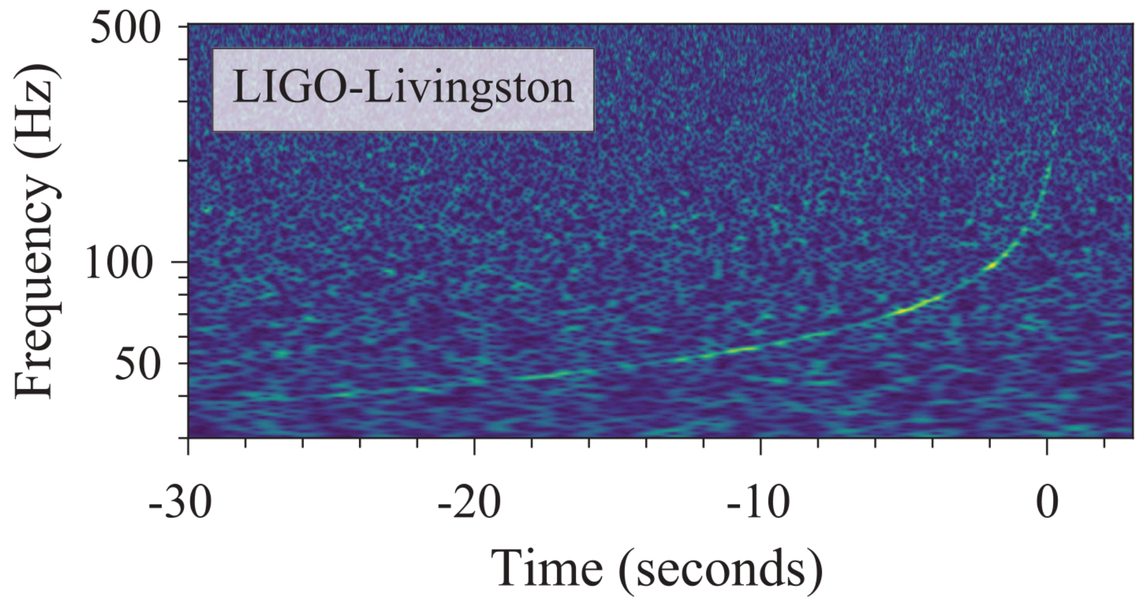
- How do binary NS system form and evolve?
- How do neutron star mergers power gamma-ray bursts?
- What are neutron stars made of? Nucleons, hyperons, deconfined quarks?
- Are neutron star mergers the site of production of the heaviest elements like gold and uranium?

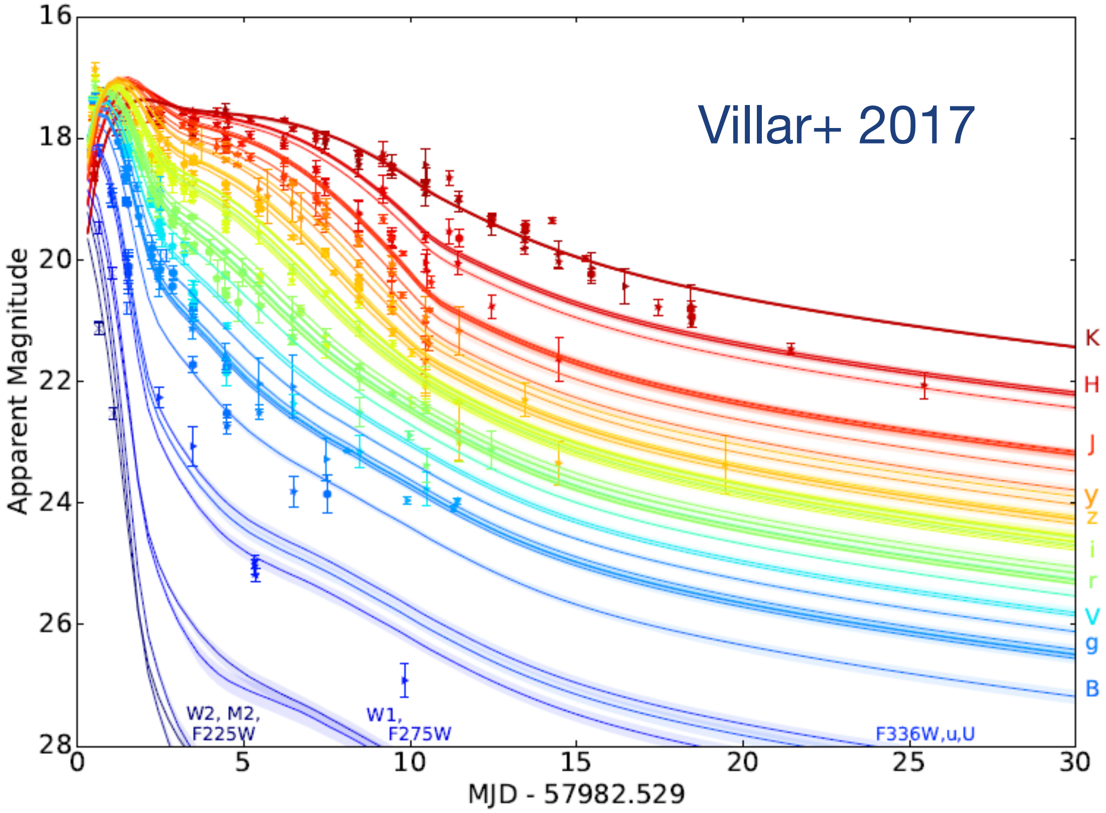




From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM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

How do we interrogate the data?





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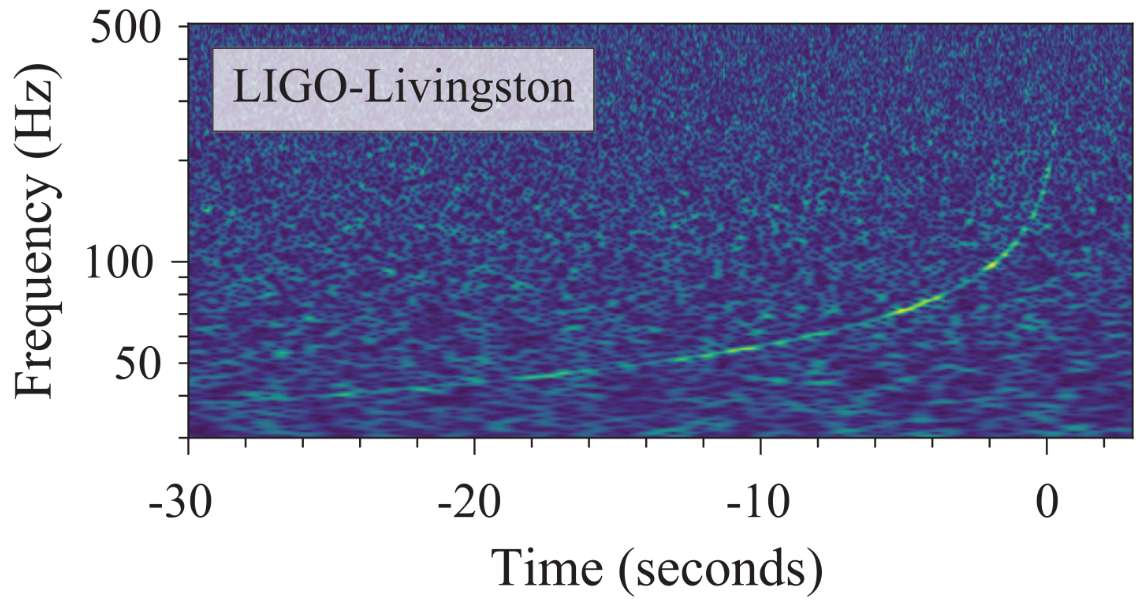
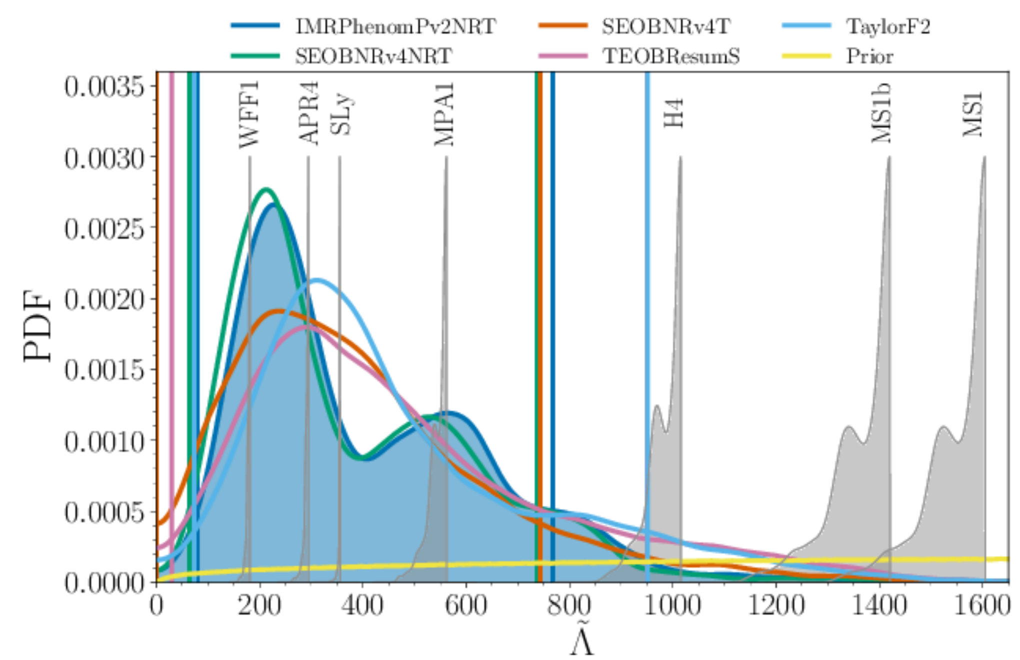
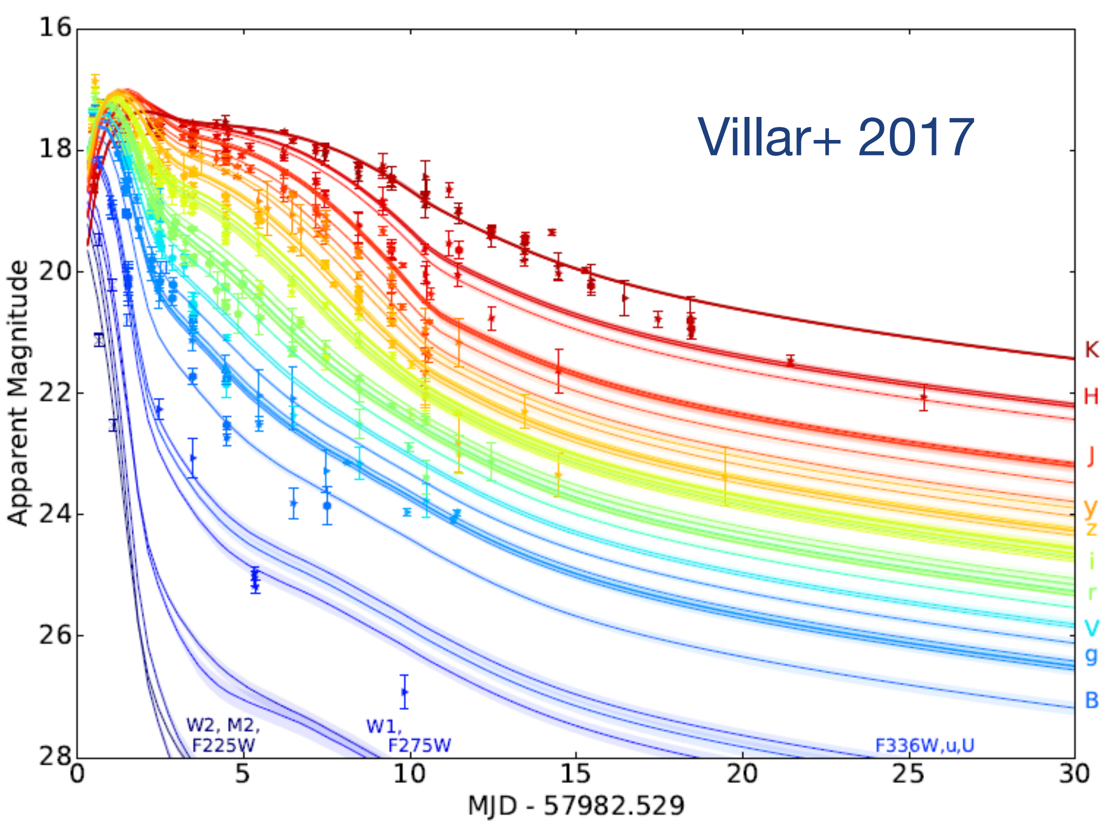


GW DA





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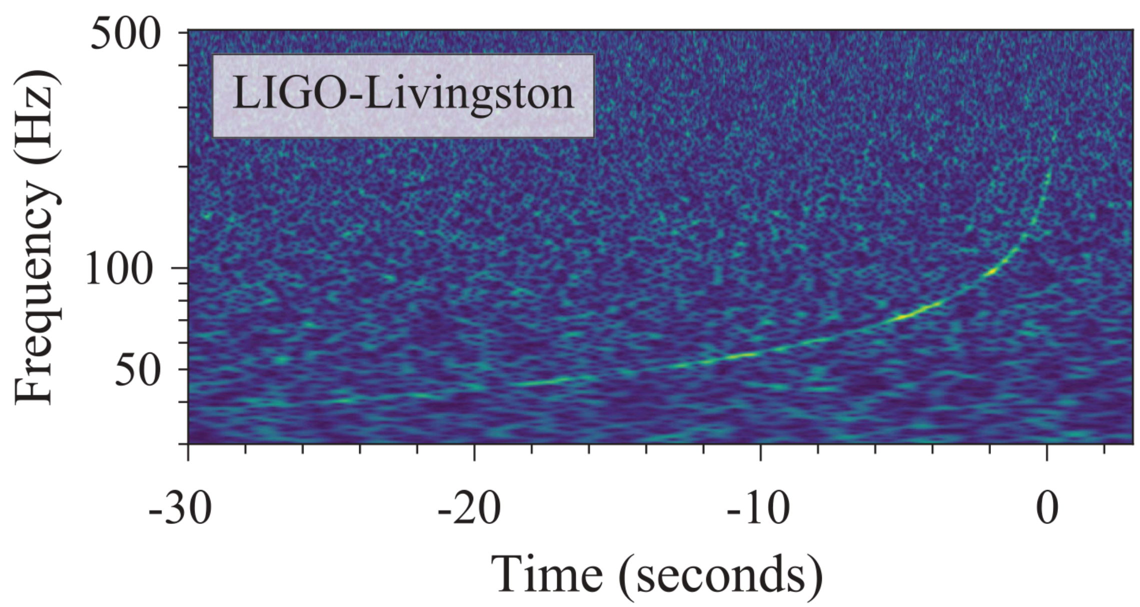

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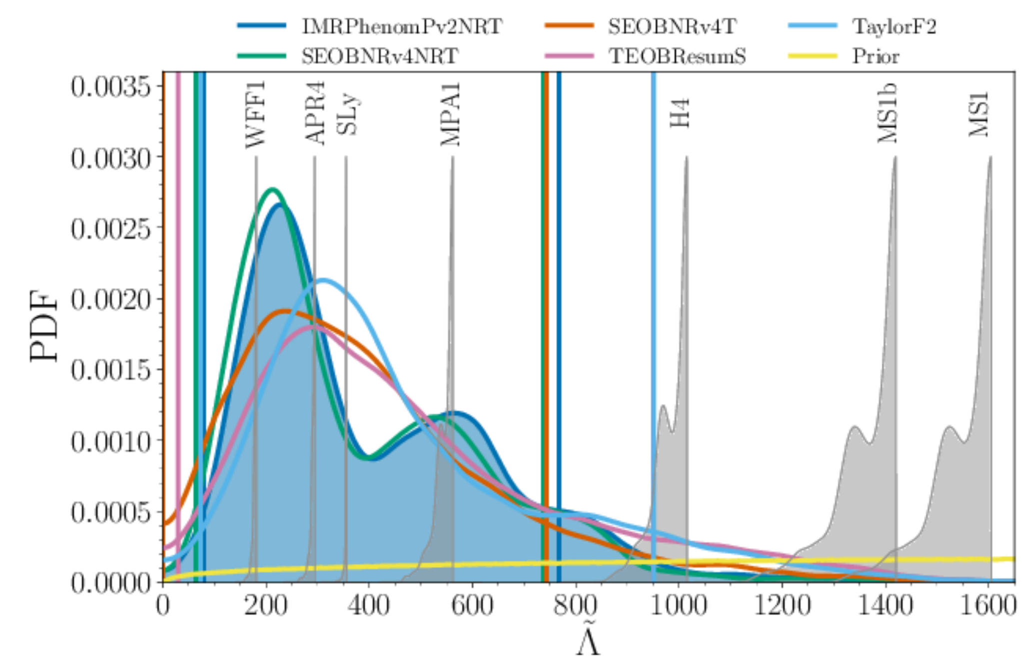
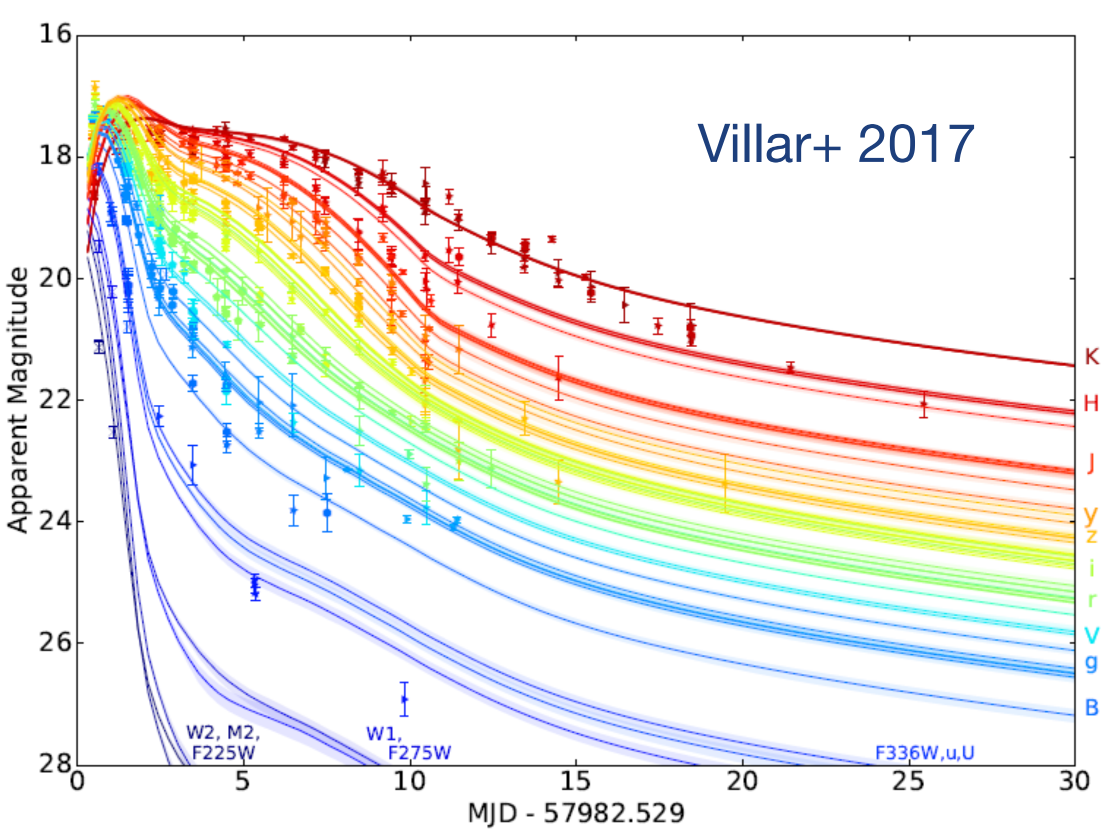
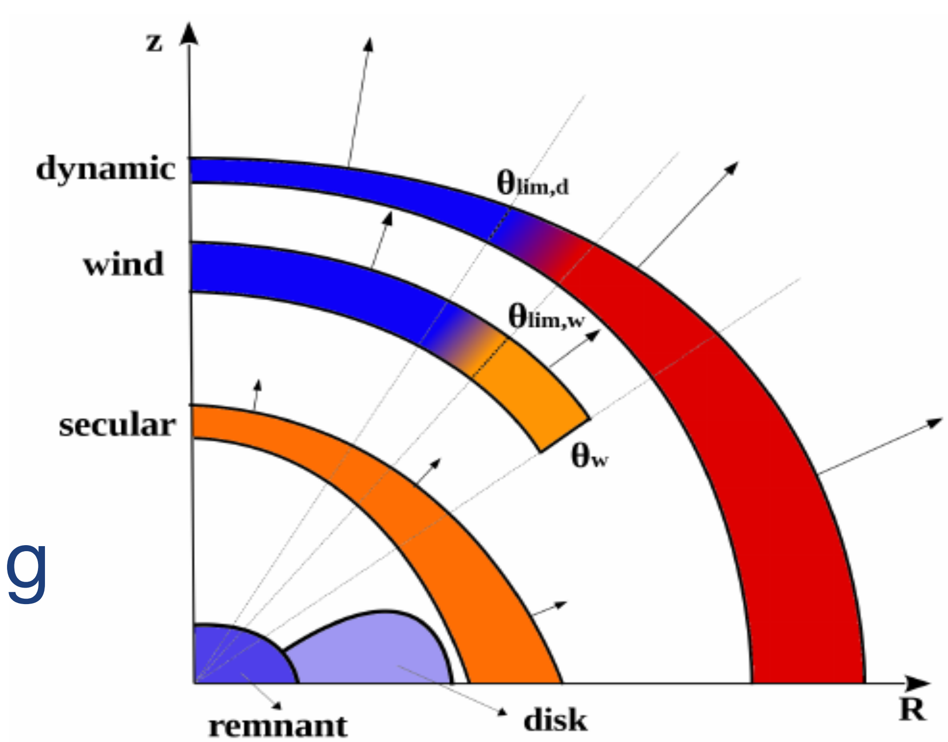




kN modelling



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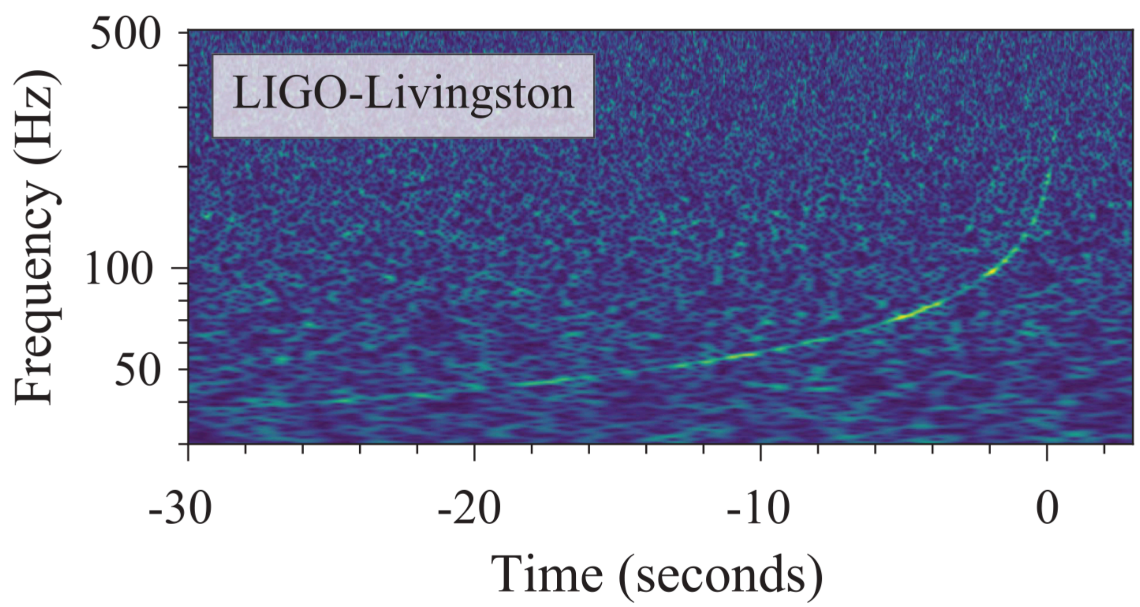

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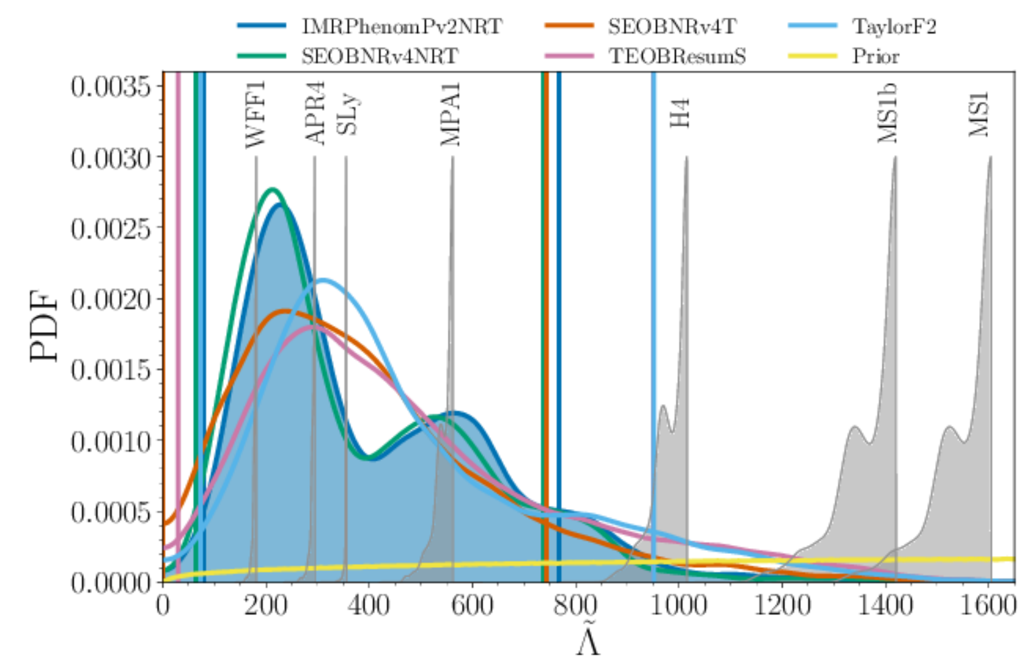

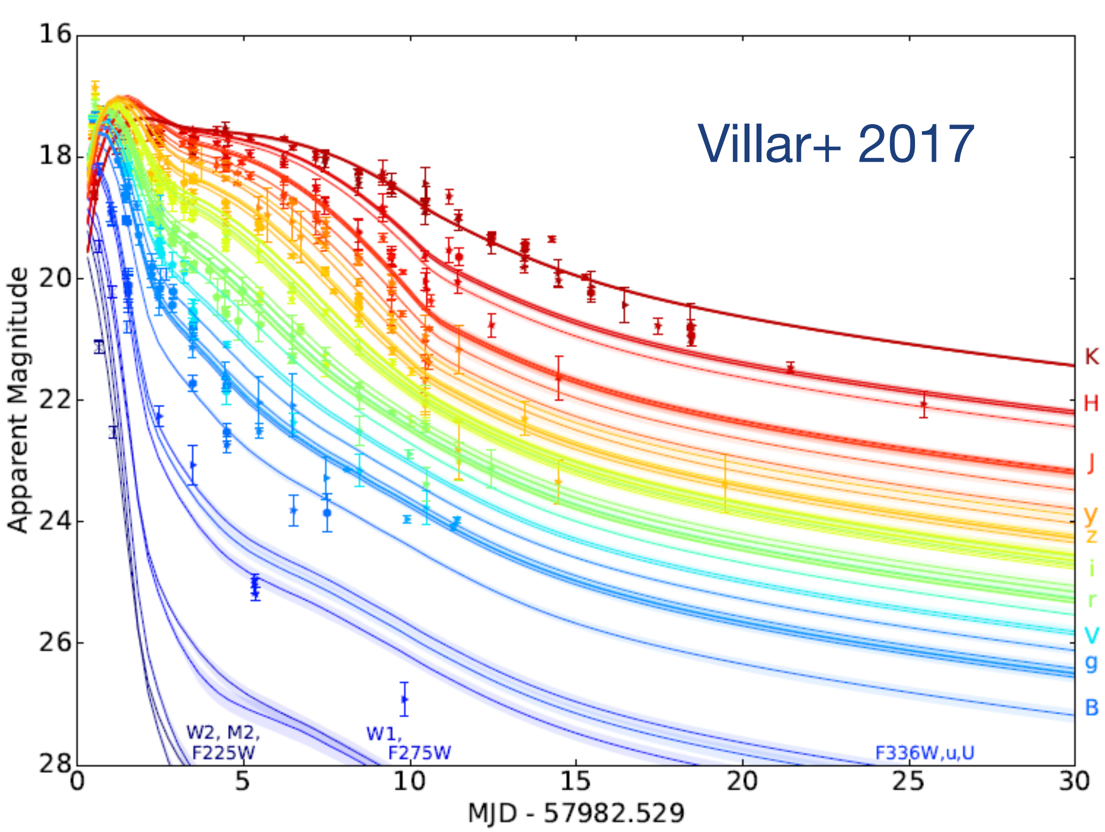

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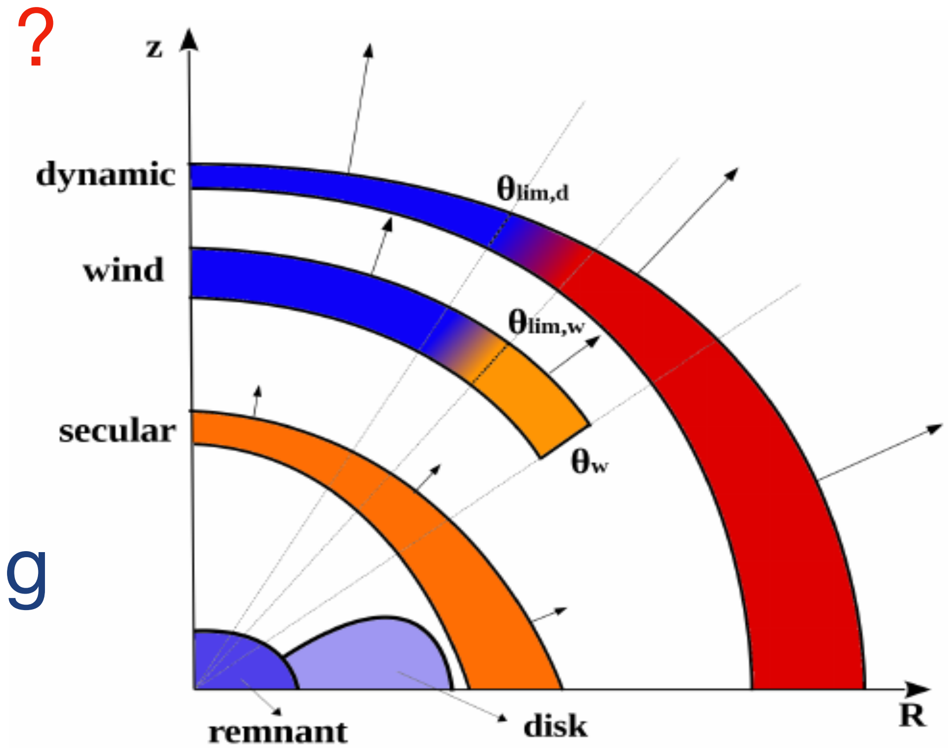
kN modelling



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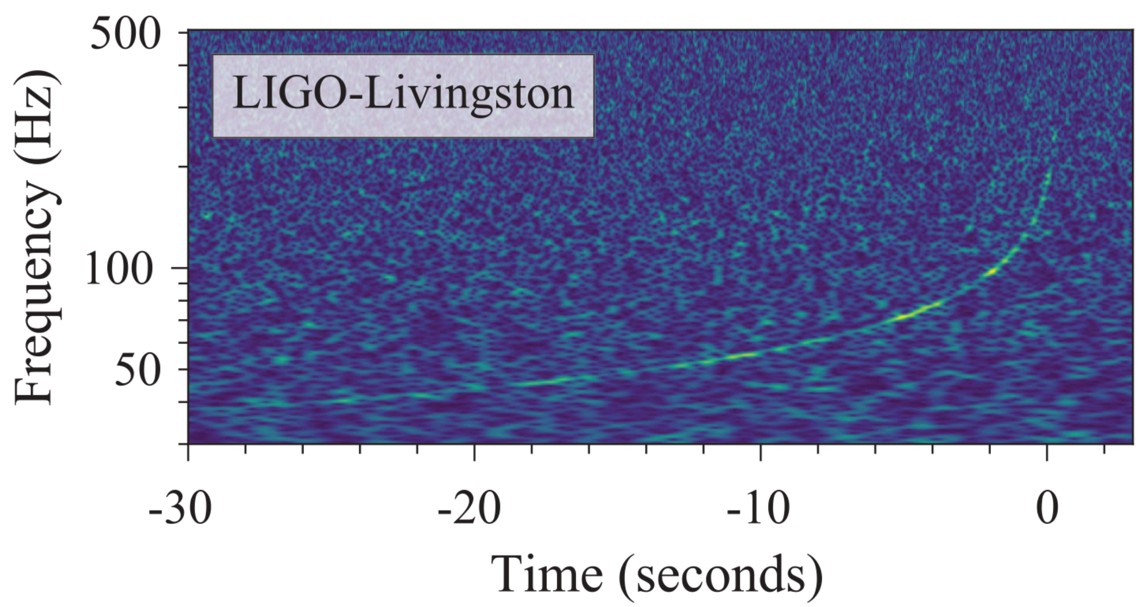

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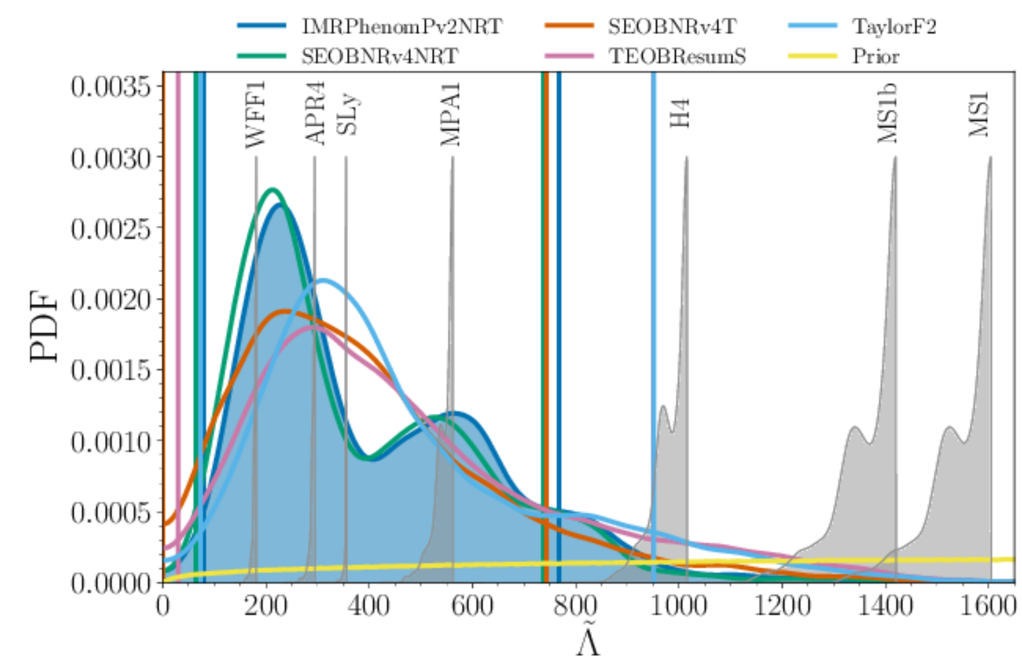

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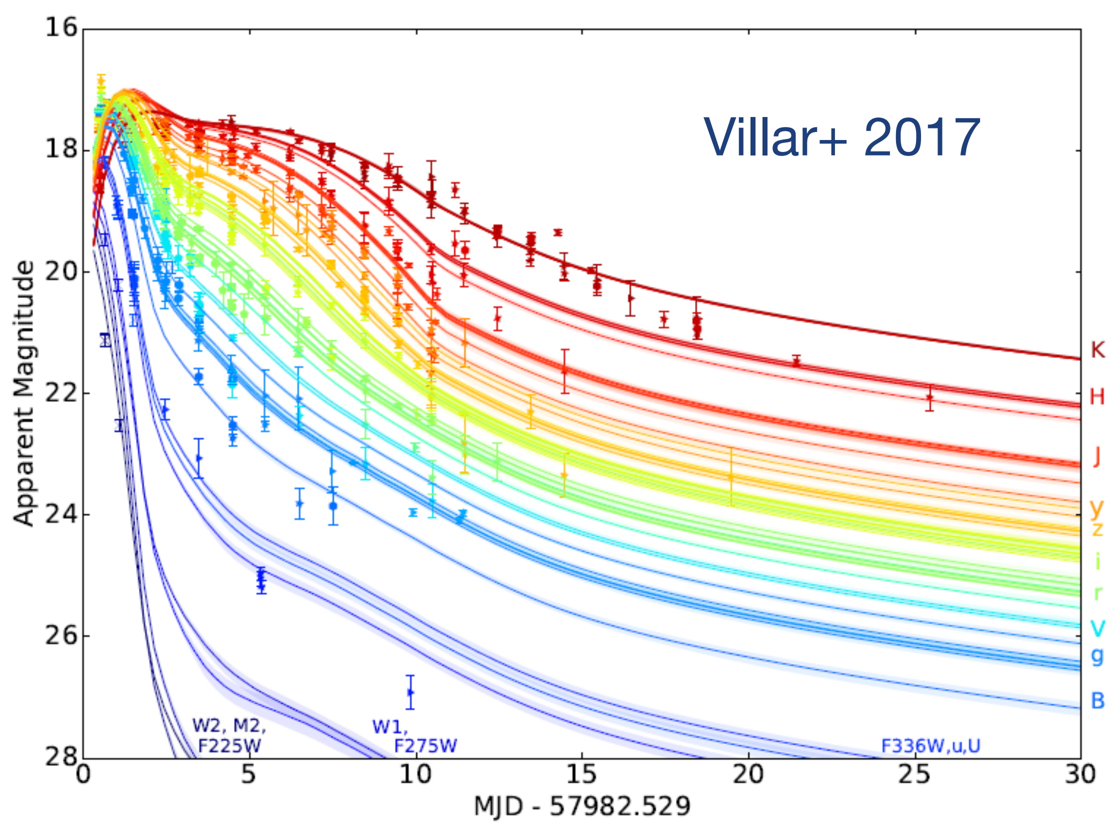
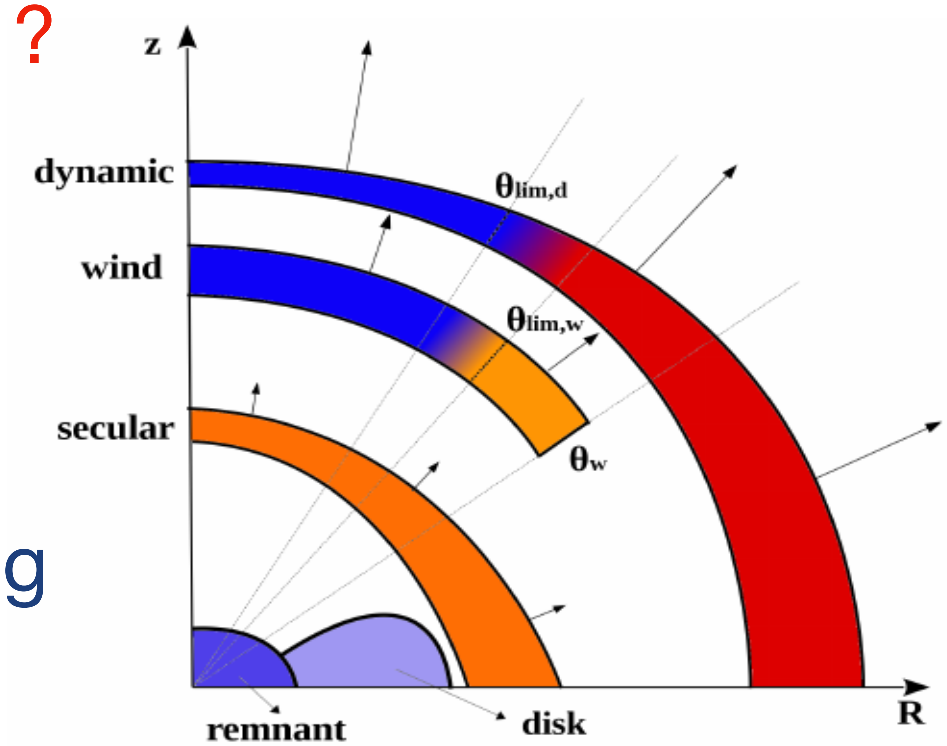


kN modelling



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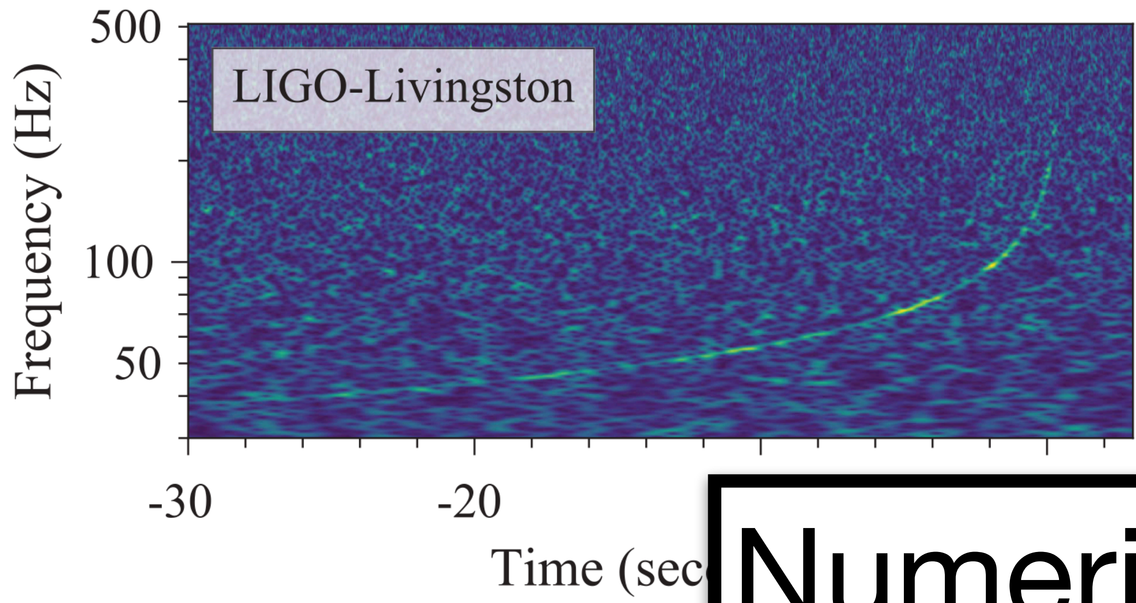
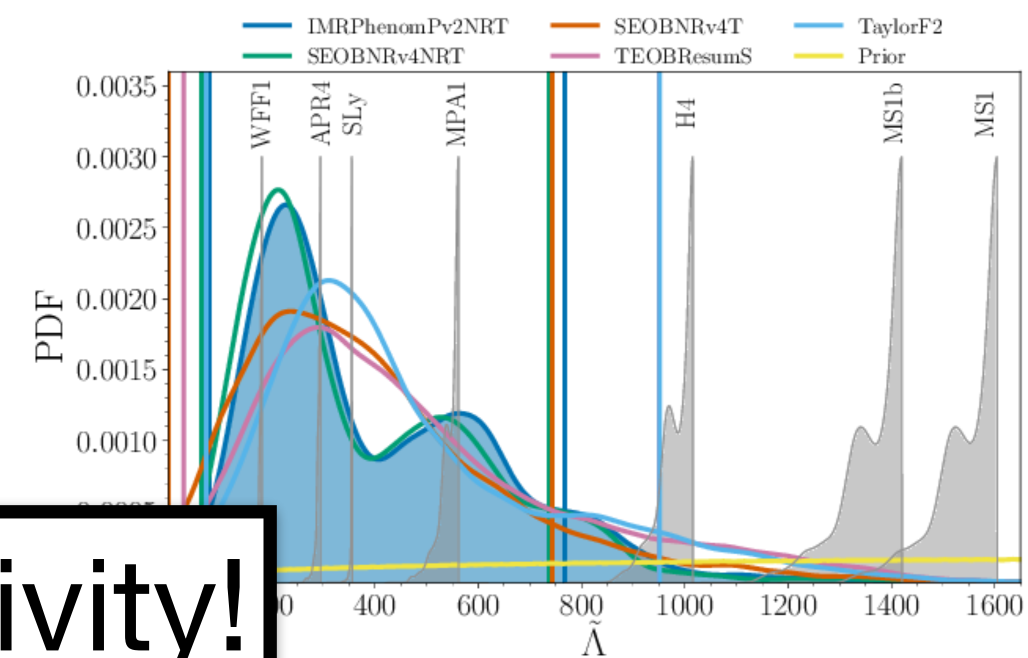


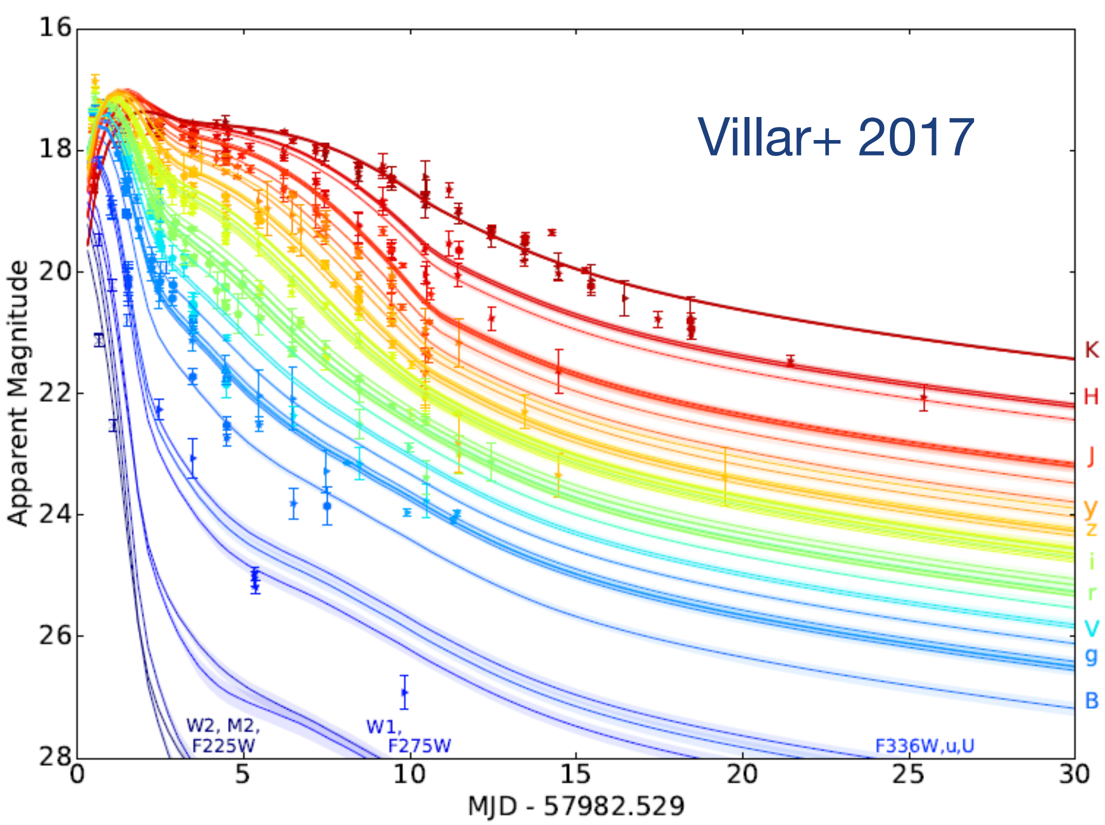
GW DA



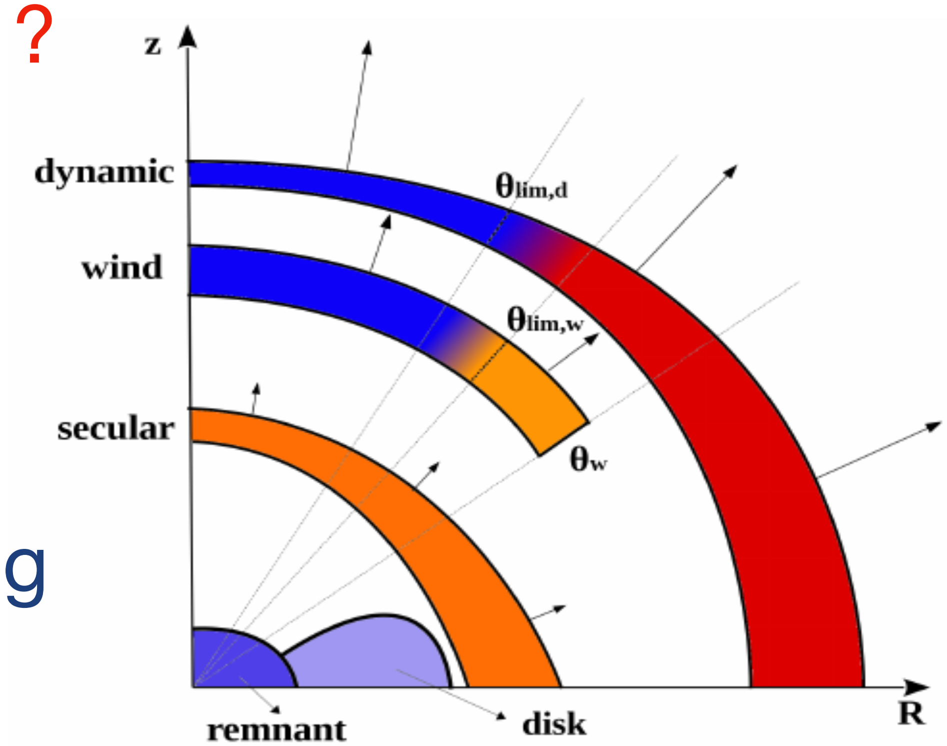
Numerical relativity!

???

?

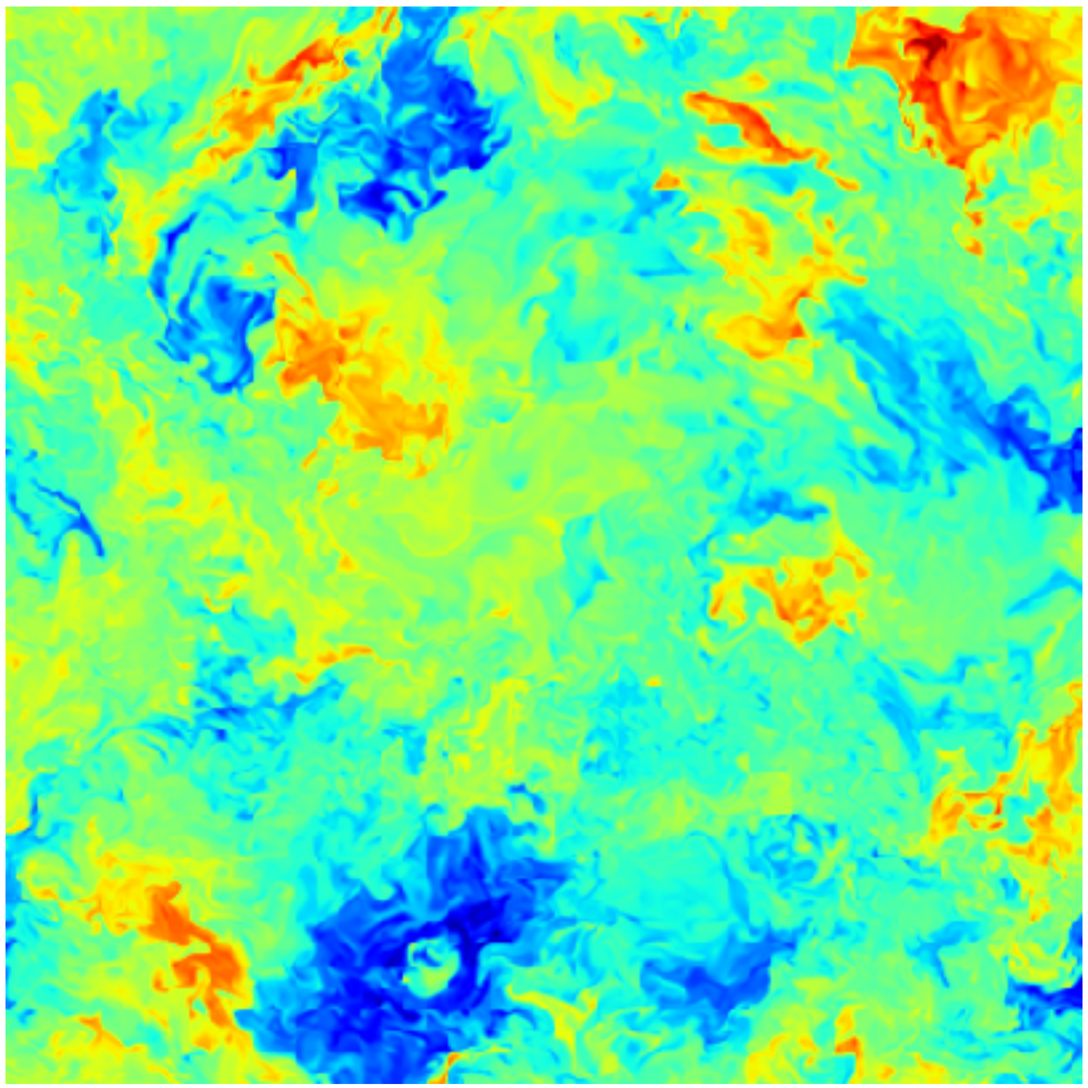


kN modelling



WhiskyTHC

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



- Full-GR, dynamical spacetime*
- Nuclear EOS
- M0 & M1 neutrino treatment
- High-order hydrodynamics
- Open source!

* using the Einstein Toolkit metric solvers

THC: Templated Hydrodynamics Code

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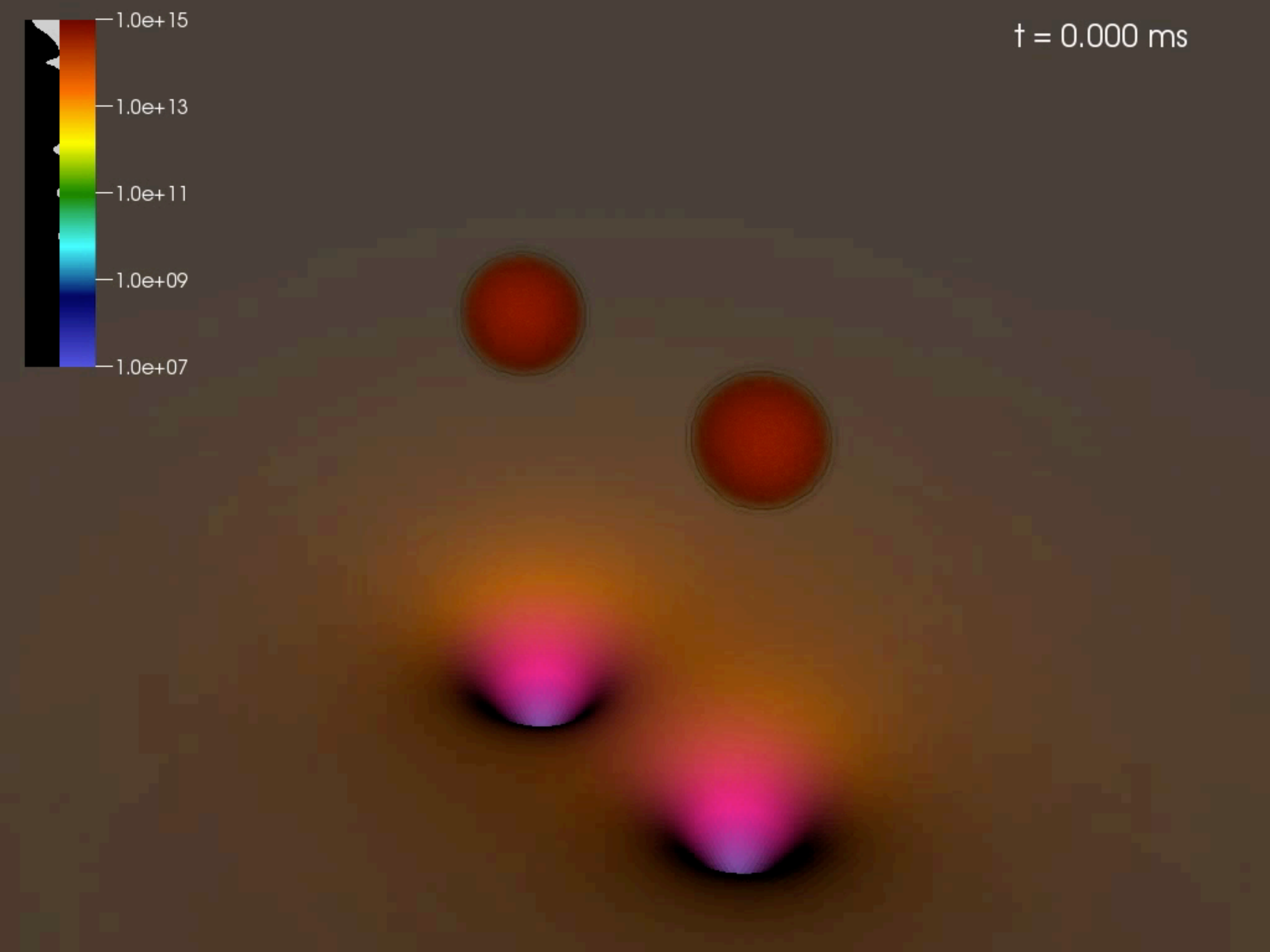

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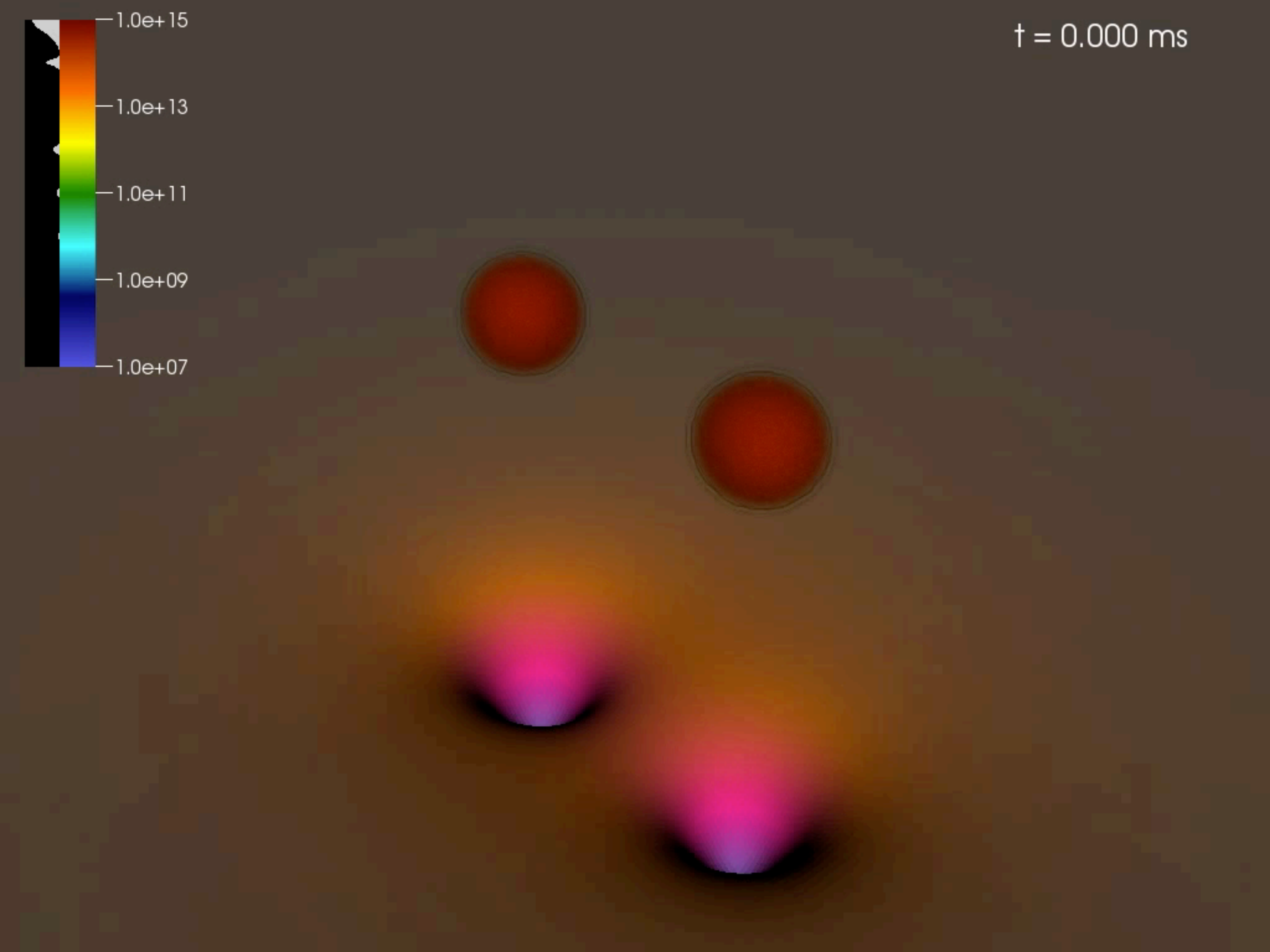
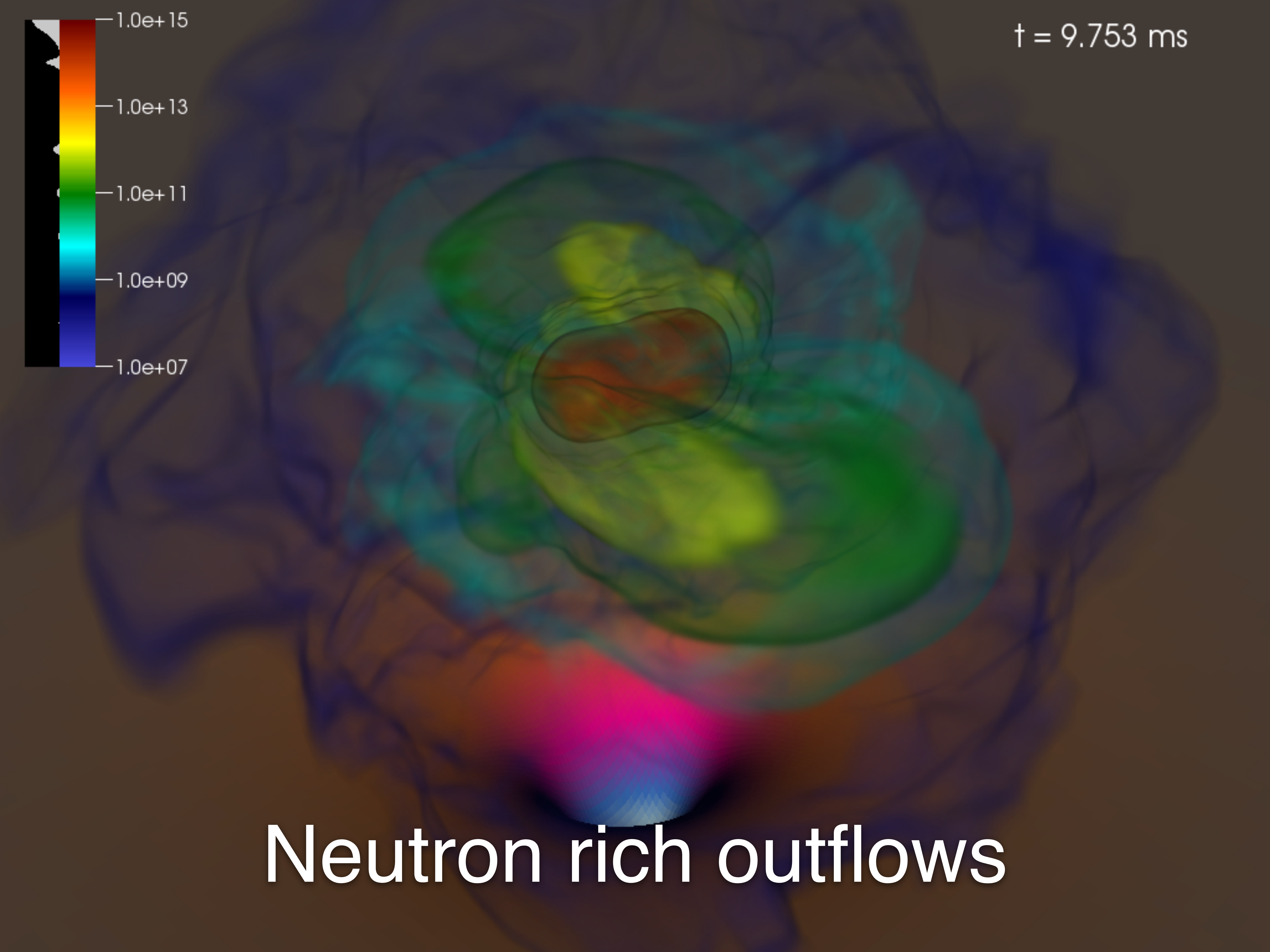
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 0.000 ms


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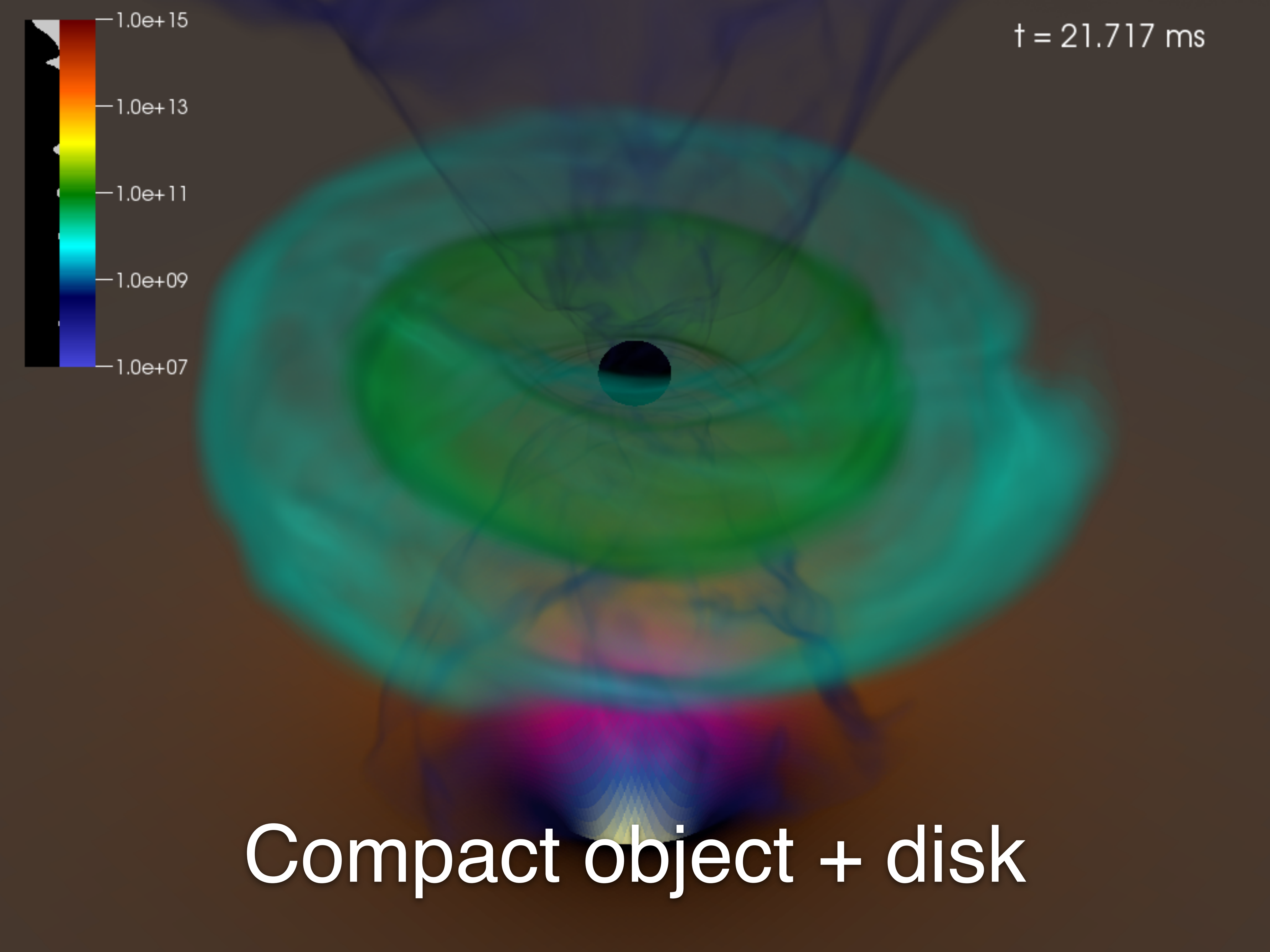
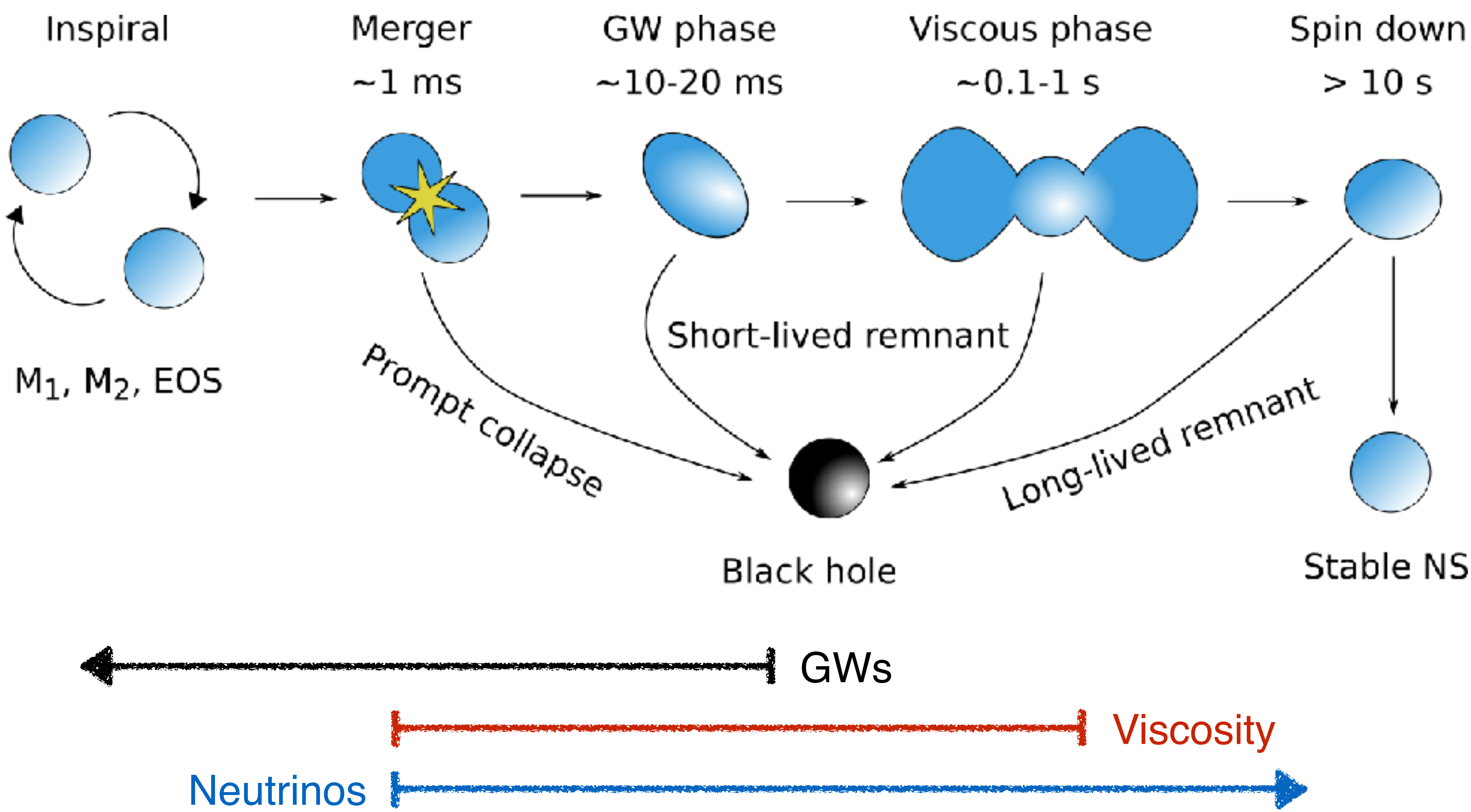
Neutron rich outflows

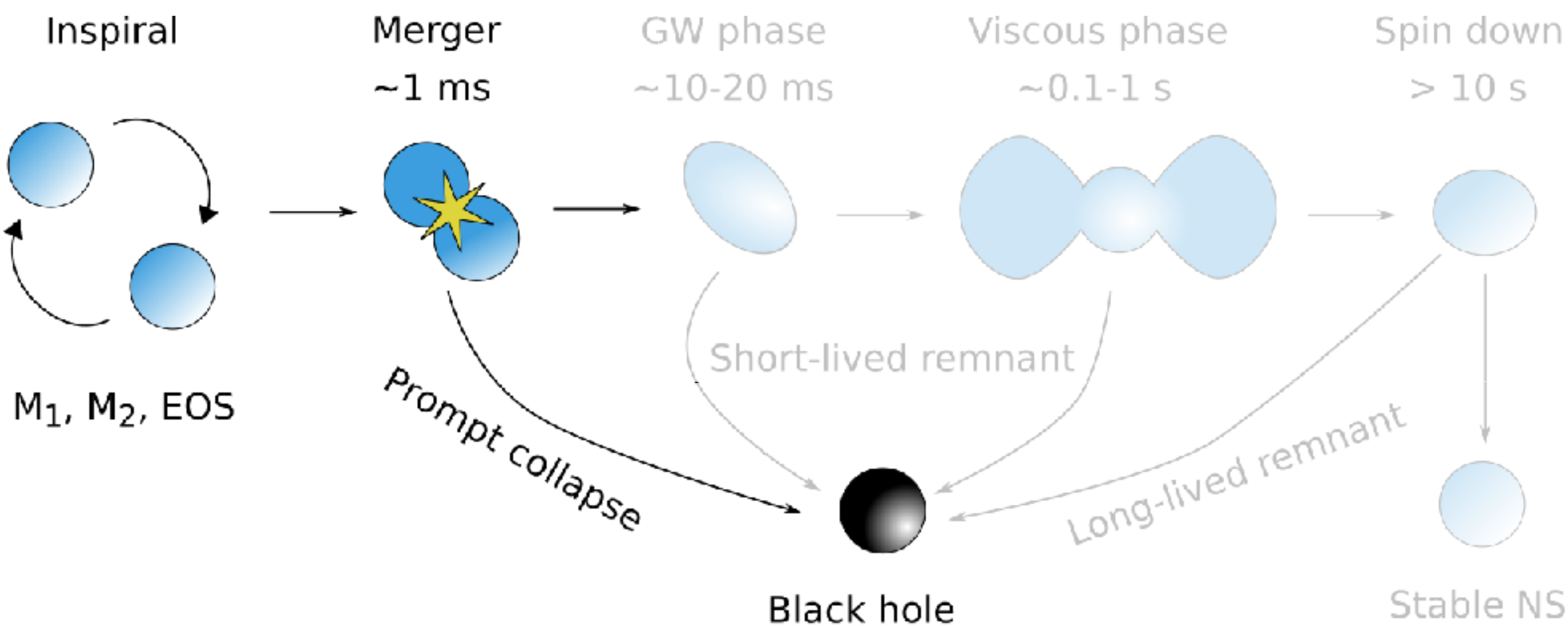


Compact object + disk

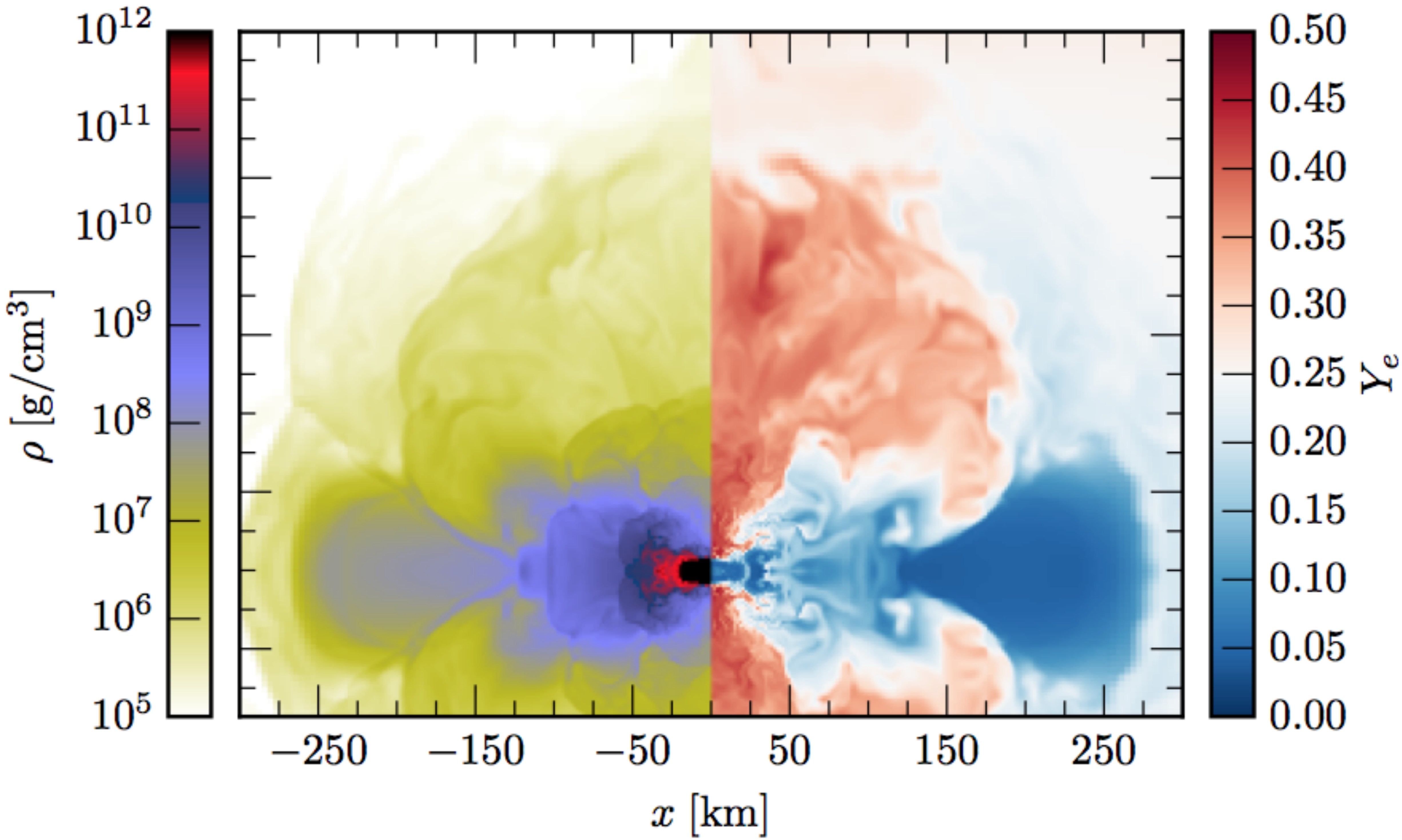
Neutron star merger evolution



Merger phase



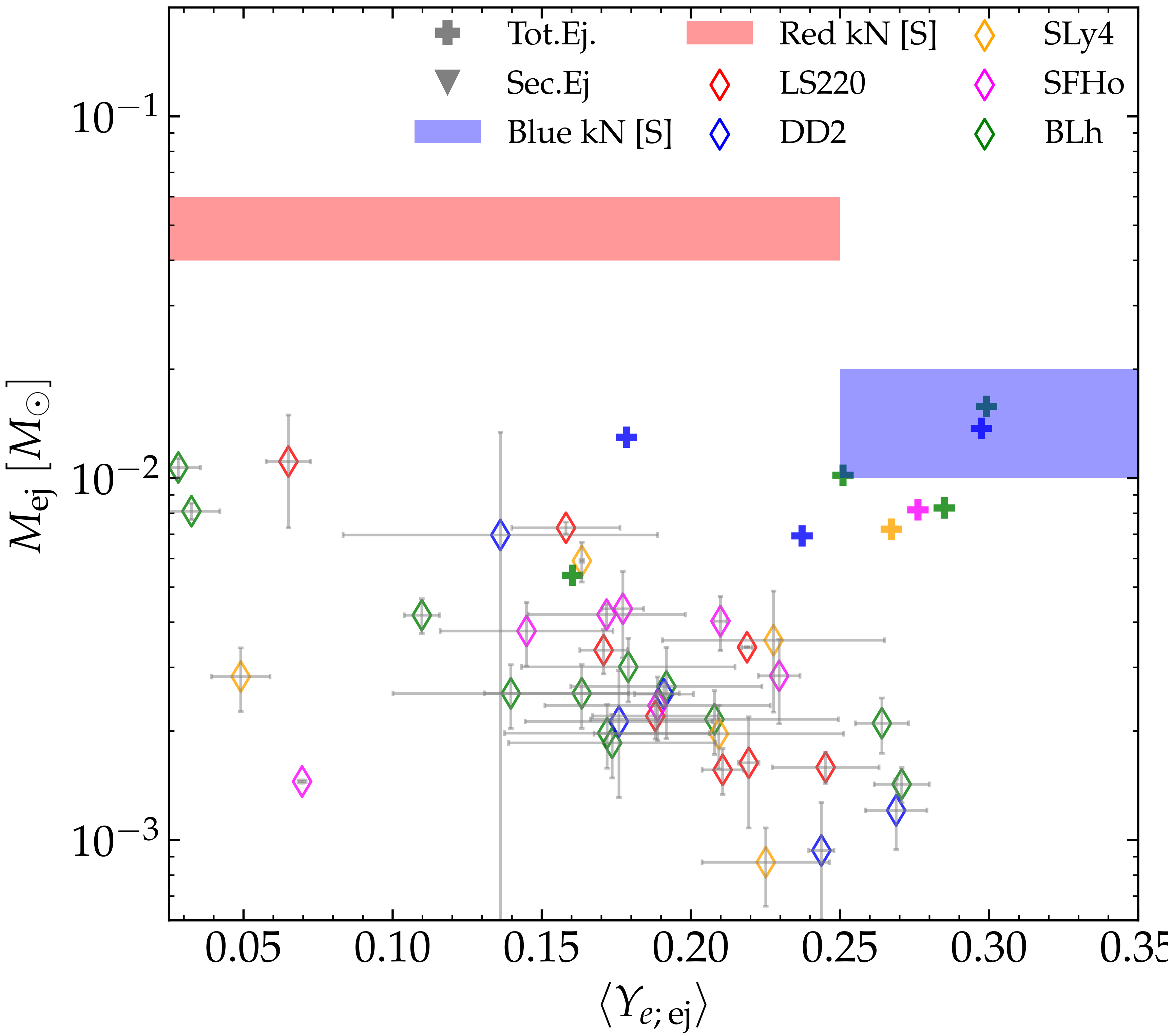
Dynamical mass ejection



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

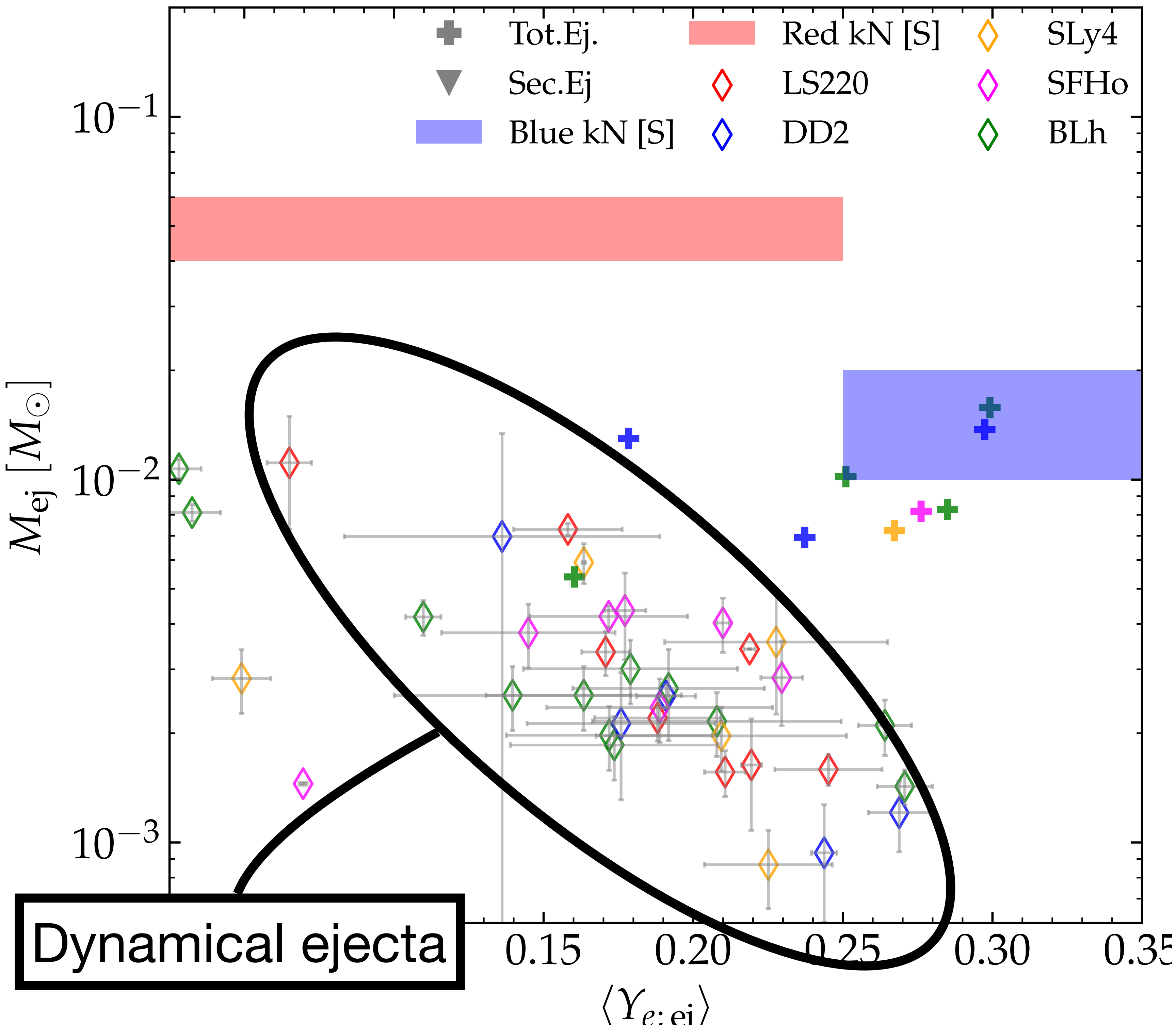
DR, Galeazzi+ MRAS 460:3255 (2016)

Dynamical and secular ejecta



From Nedora, Bernuzzi, **DR**+, ApJ 906:98 (2021)

Dynamical and secular ejecta



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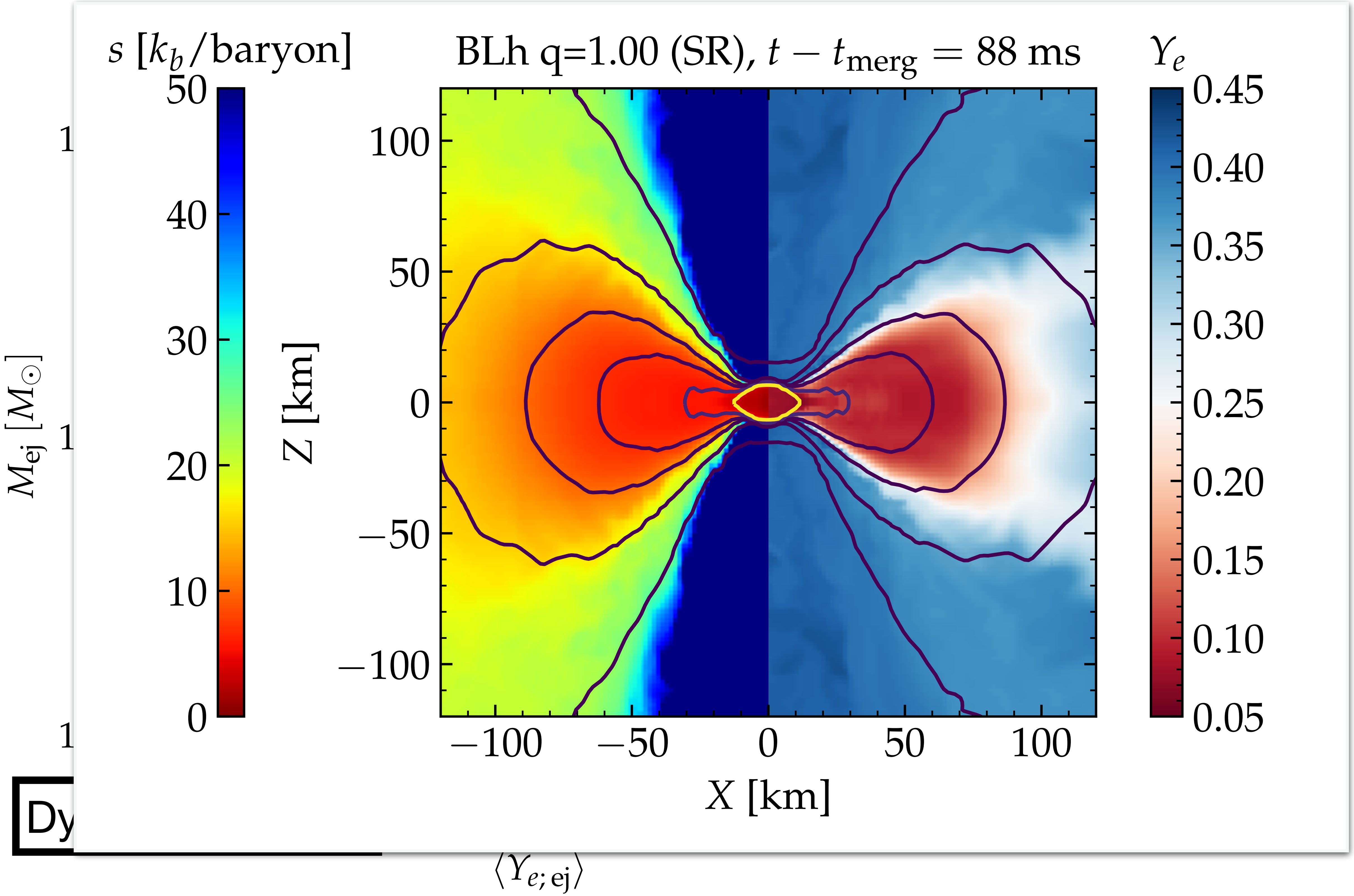
Dynamical and secular ejecta



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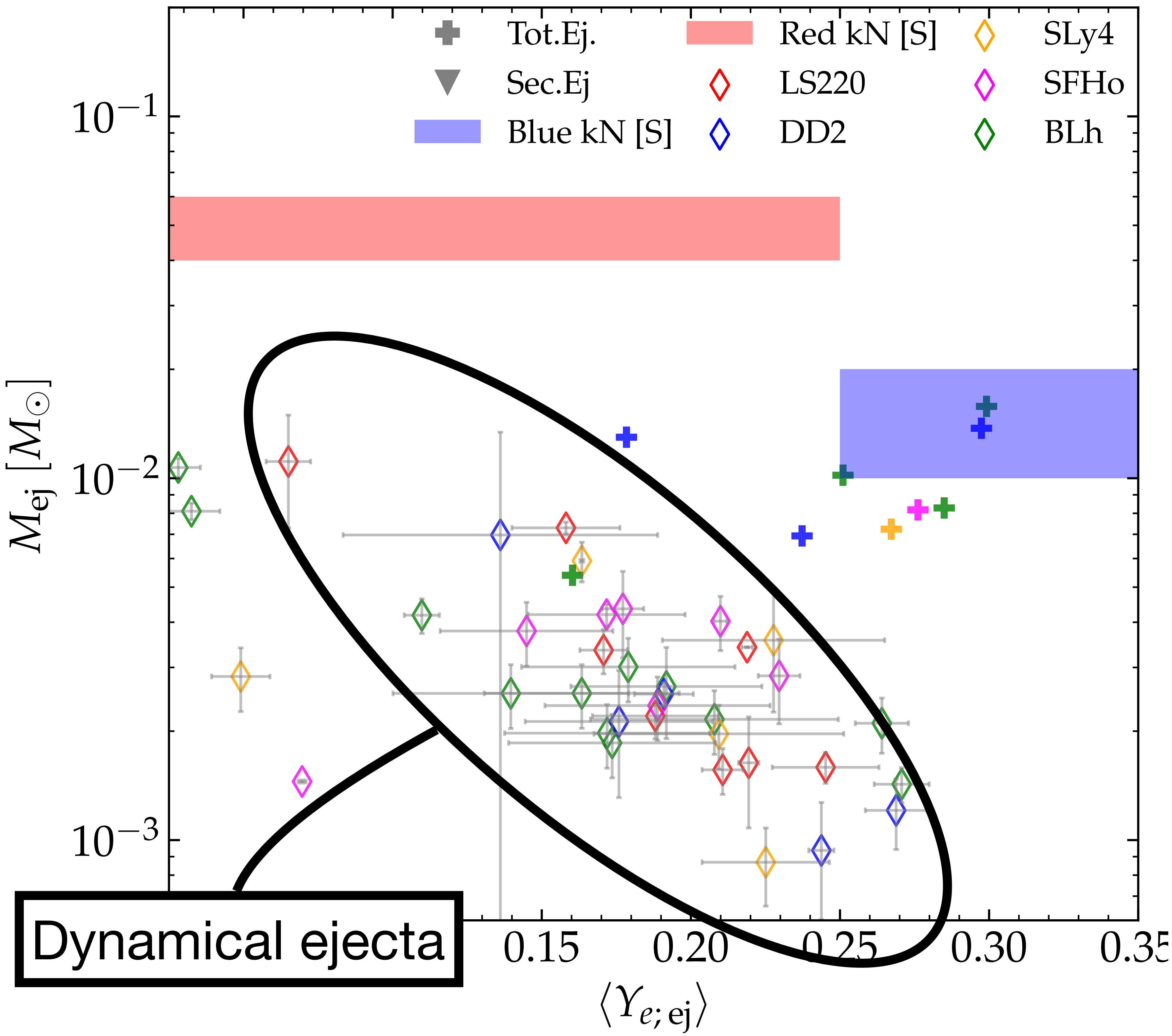
Dynamical and secular ejecta



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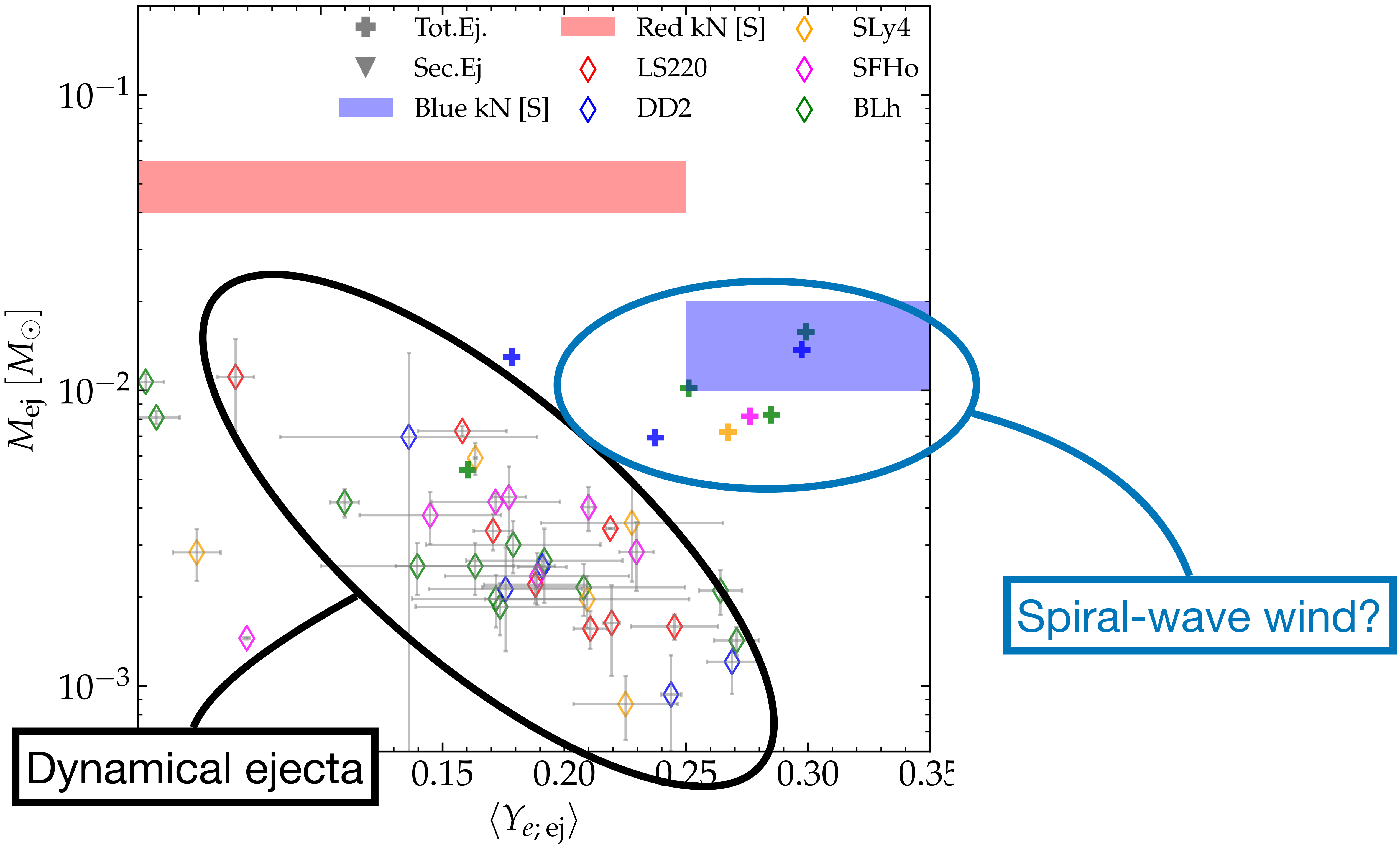

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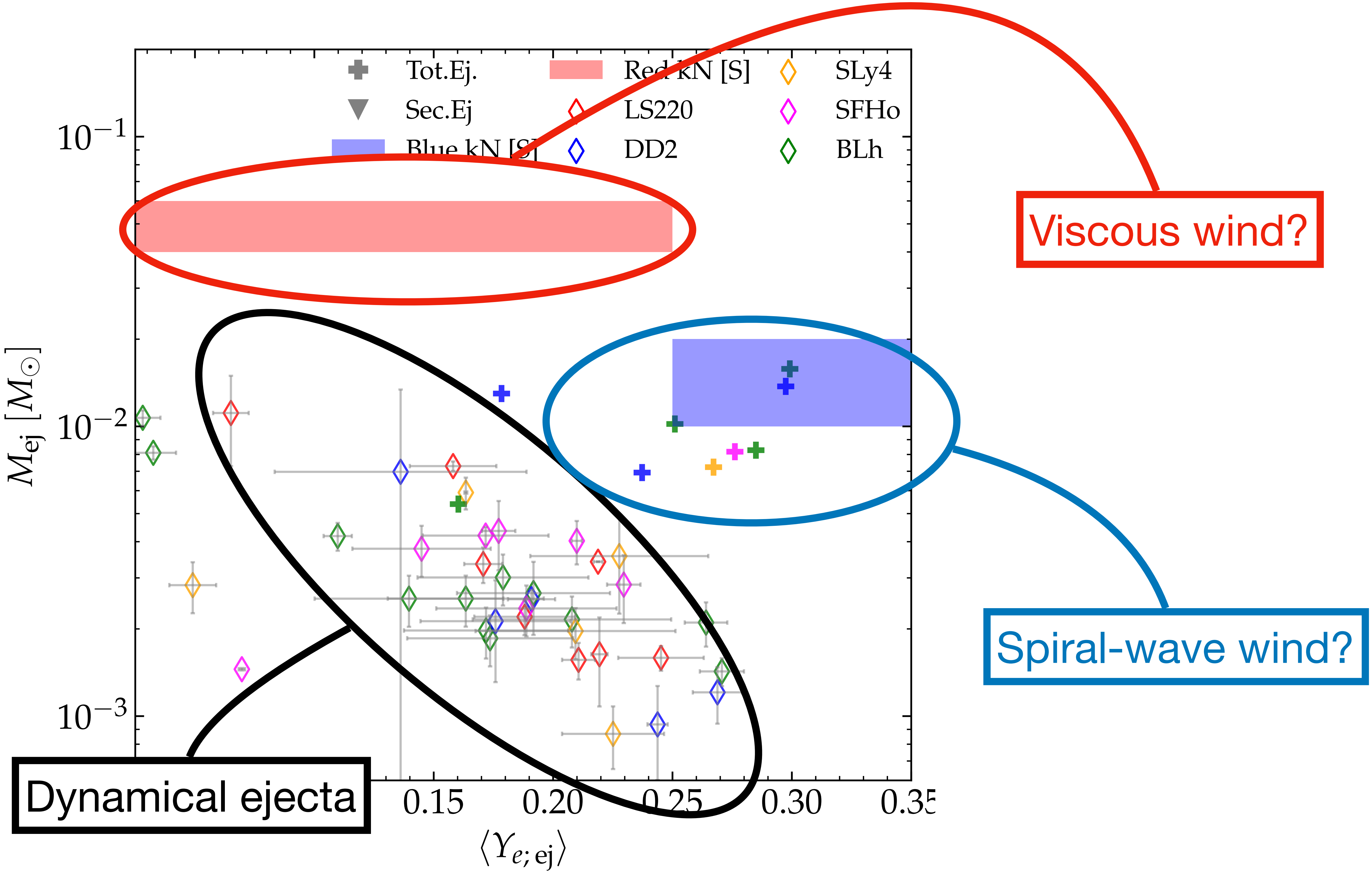
Dynamical and secular ejecta



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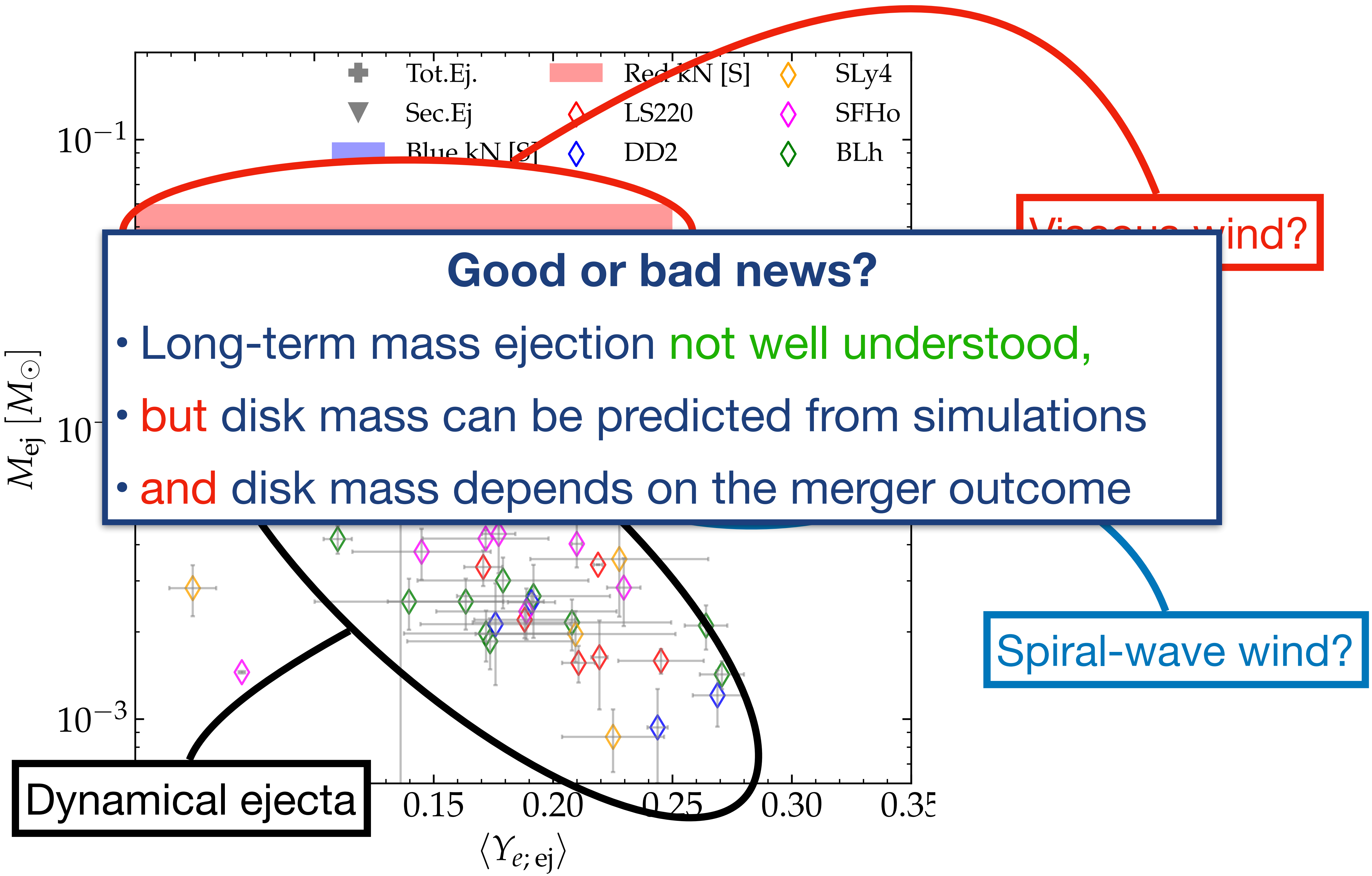
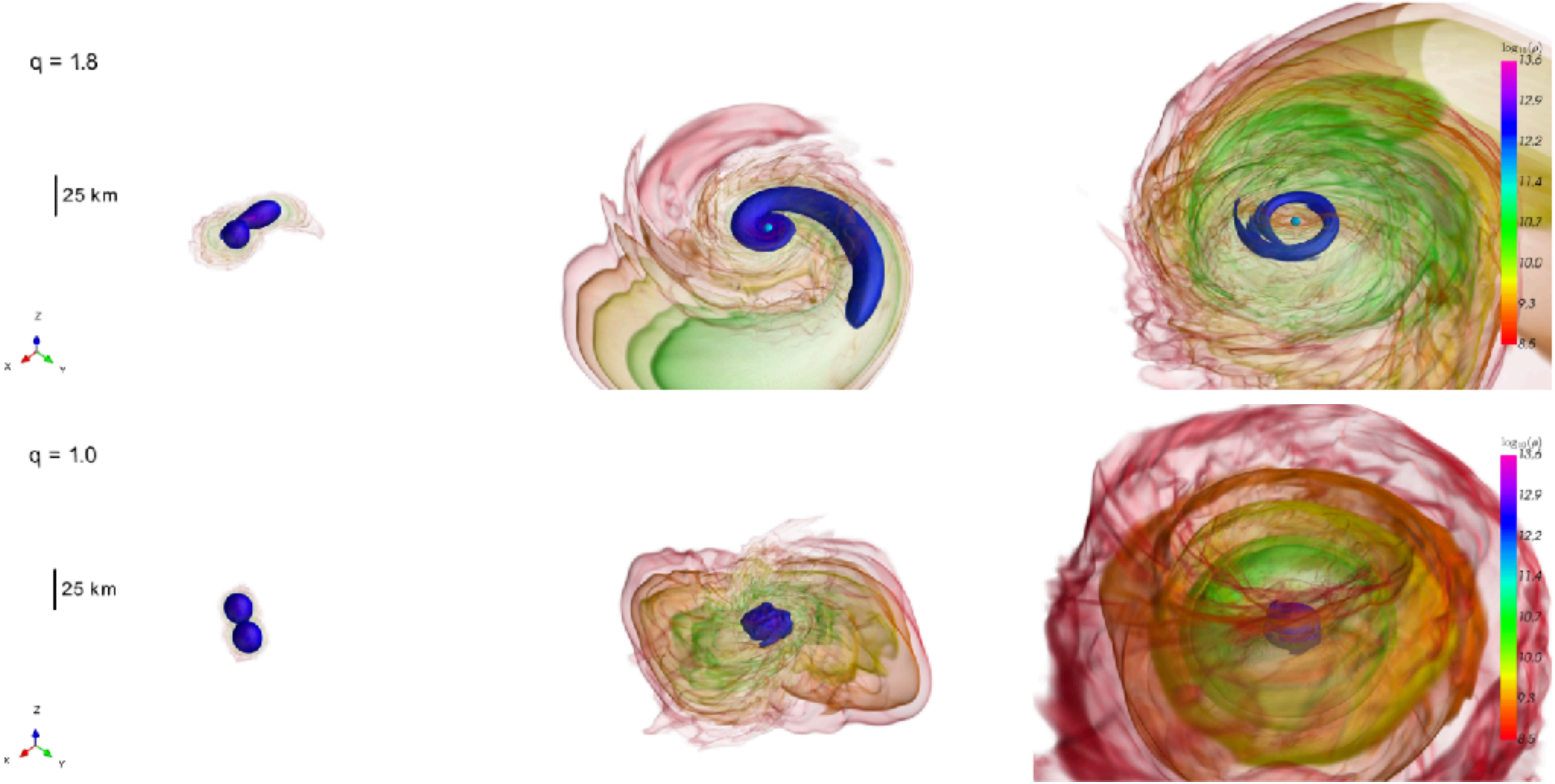


Good or bad news?

- Long-term mass ejection not well understood,
- but disk mass can be predicted from simulations
- and disk mass depends on the merger outcome

From Nedora, Bernuzzi, **DR**+, ApJ 906:98 (2021)

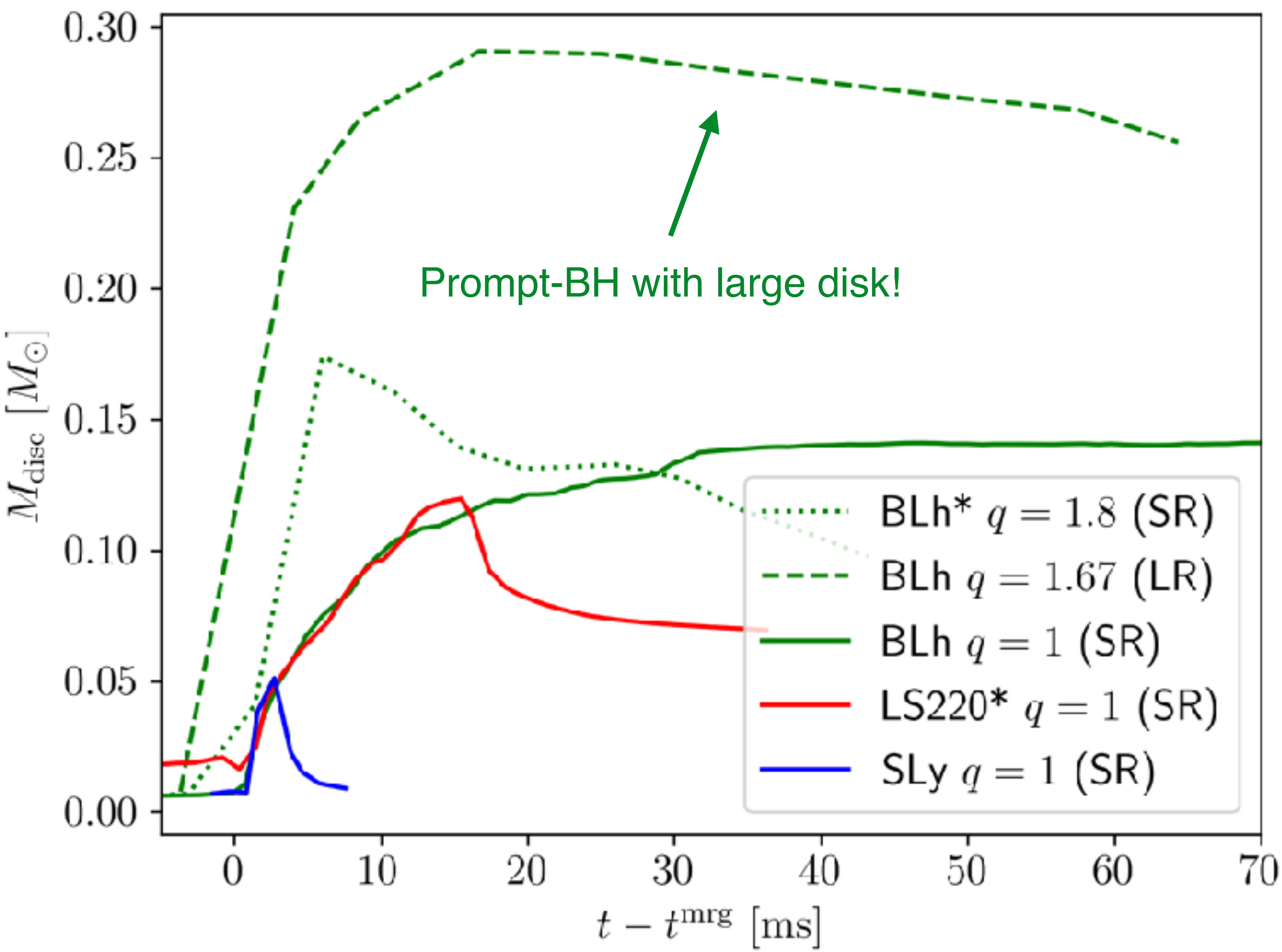
Disk formation I



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

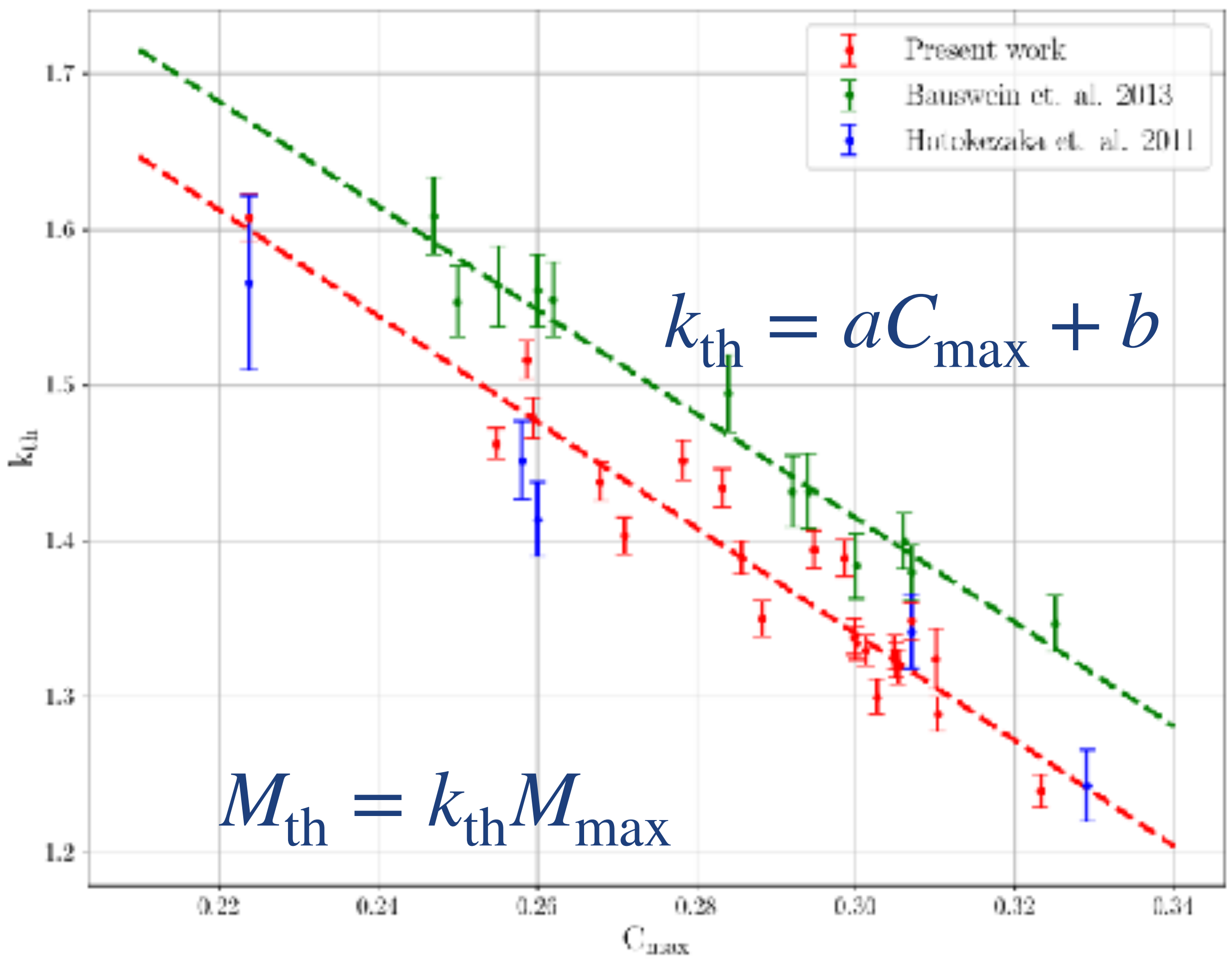
Bernuzzi, …, **DR**+, MNRAS 497:1488 (2020)

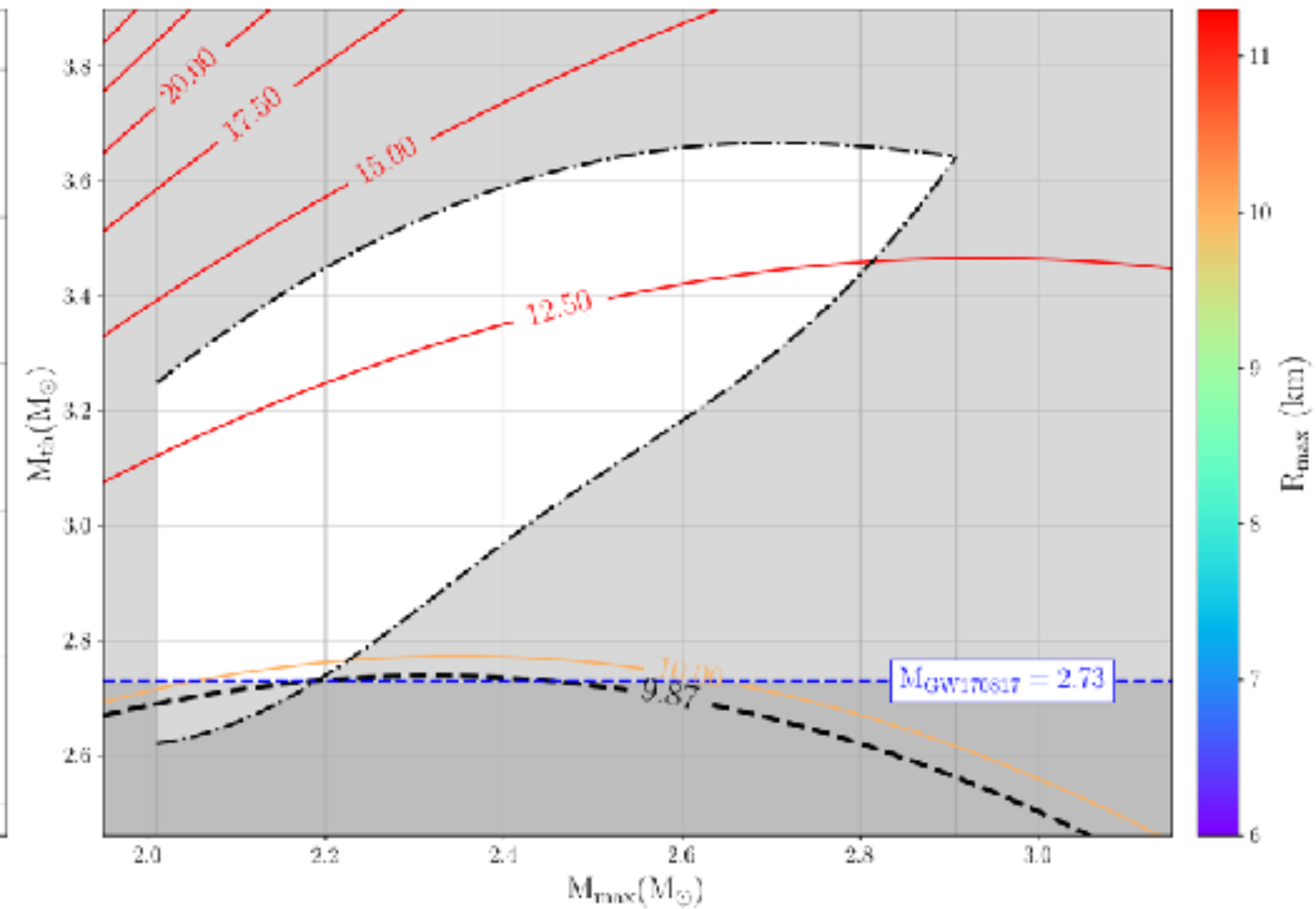
Disk formation II



Bernuzzi, …, **DR**+, MNRAS 497:1488 (2020)

Prompt collapse





- First proposed by Bauswein+ 2013, 2017
- Revised constraints: $R_{1.6} \geq 10.99^{+0.16}_{-0.04}$ km, $R_{max} \geq 9.87^{+0.14}_{-0.04}$ km
- Assumes $q \lesssim 1.25$

See also Köppel+ 2019, Agathos+ 2019, Bernuzzi+ 2020, Tootle+ 2021

Kashyap, Das, **DR**+, in prep

Multimessenger PE

$$P[\theta|d]$$

Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta]$$

Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]{\color{red}P[d_{\rm EM}|\theta]}$$

Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\mathrm{GW}}|\theta]\textcolor{red}{P[d_{\mathrm{EM}}|\theta]}$$

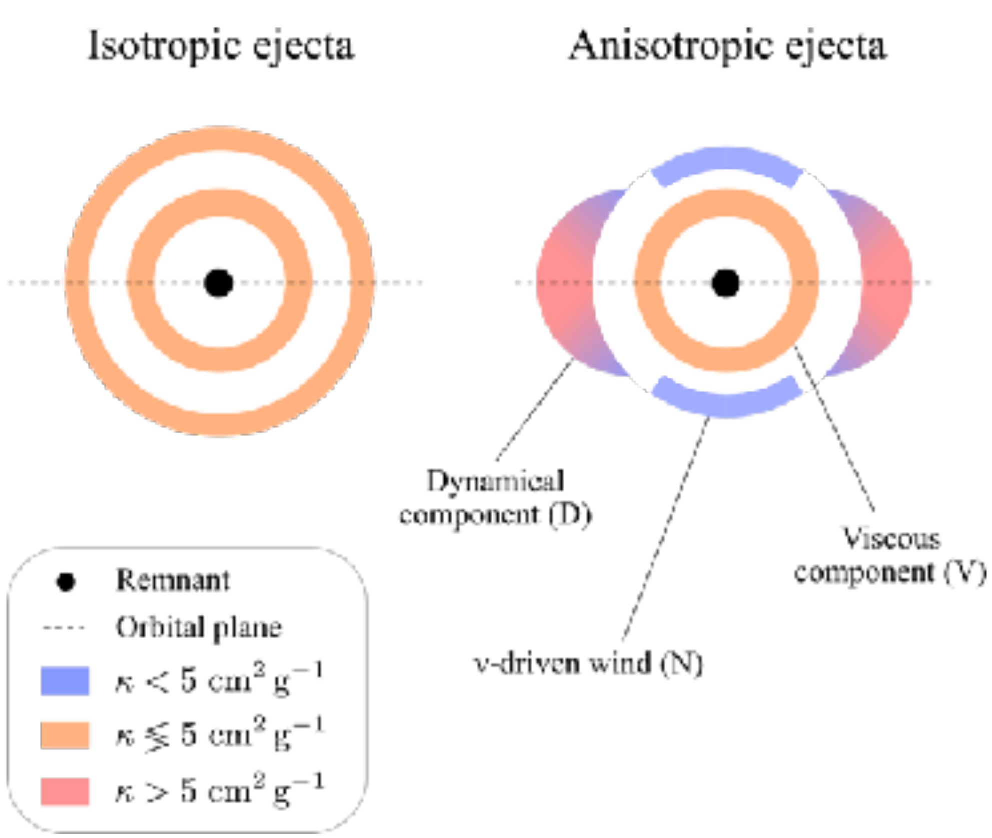
GW modeling
and data analysis

Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]\color{red}{P[d_{\rm EM}|\theta]}$$

GW modeling
and data analysis

kilonova modeling



Breschi+ 2021, MNRAS 505:1661 (2021)

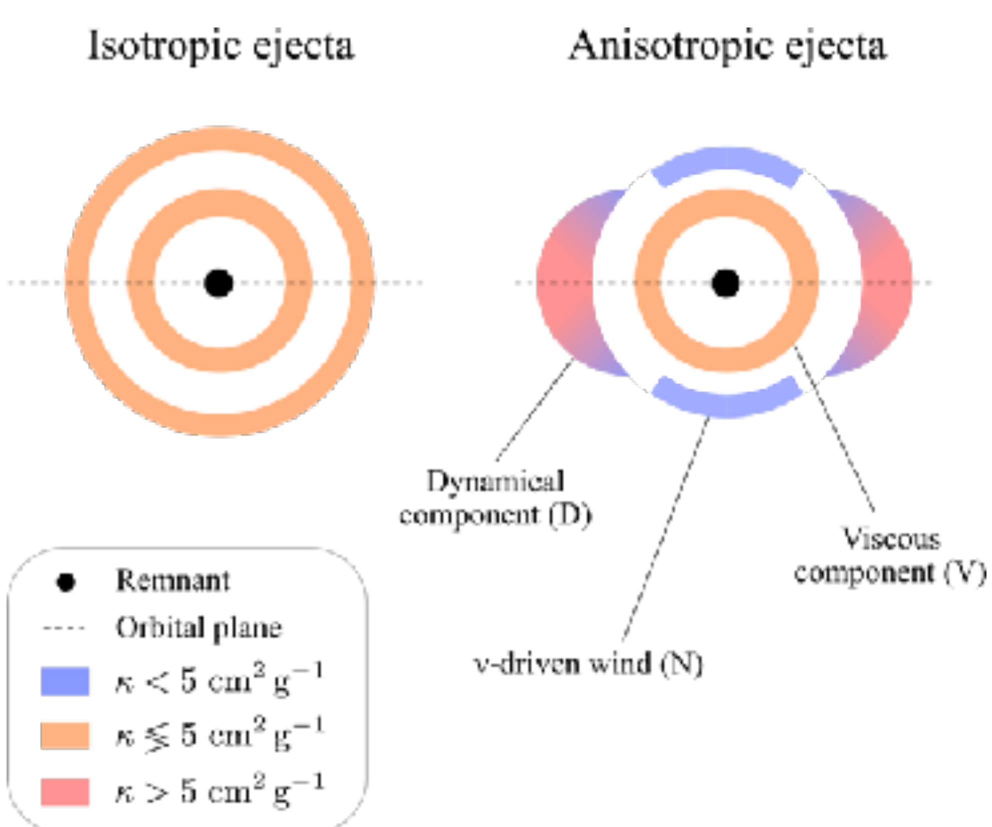
Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\mathrm{GW}}|\theta]\textcolor{red}{P[d_{\mathrm{EM}}|\theta]}$$

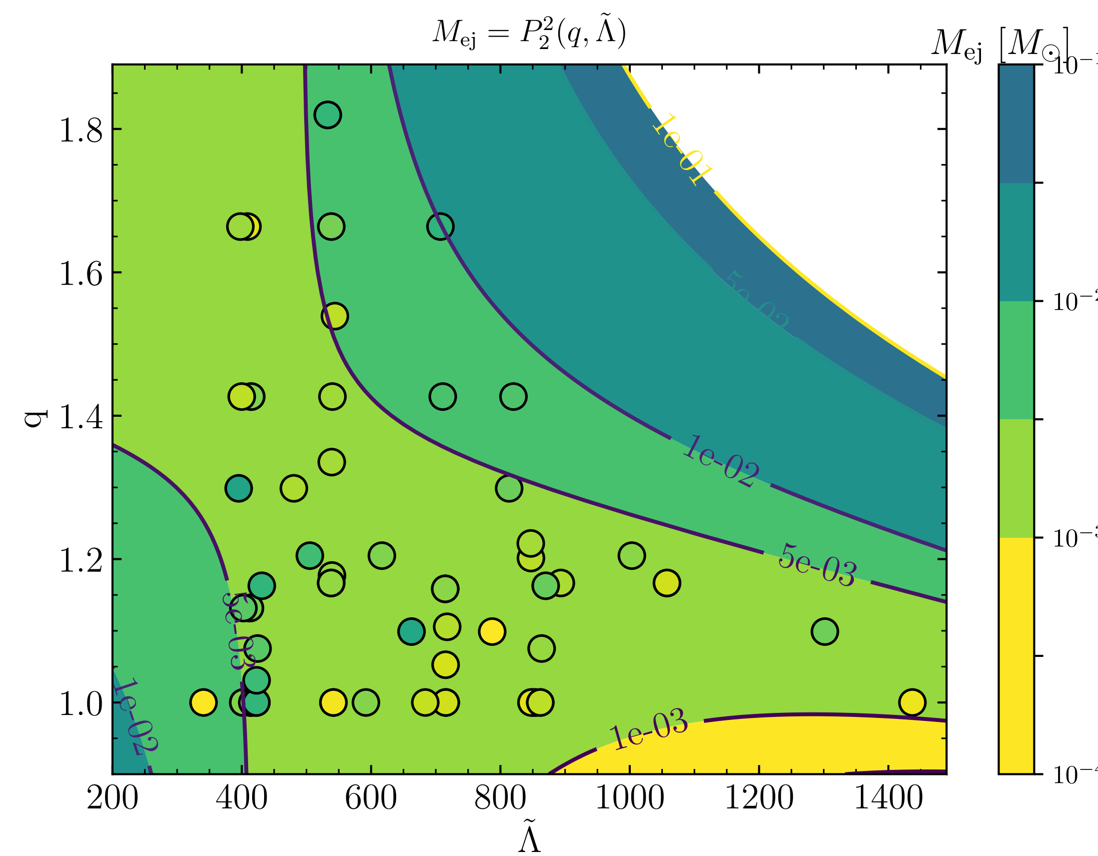
GW modeling
and data analysis

kilonova modeling

NR simulations



Breschi+ 2021, MNRAS 505:1661 (2021)



Nedora+ 2020, 2011.11110

Multimessenger PE

$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]\color{red}{P[d_{\rm EM}|\theta]}$$

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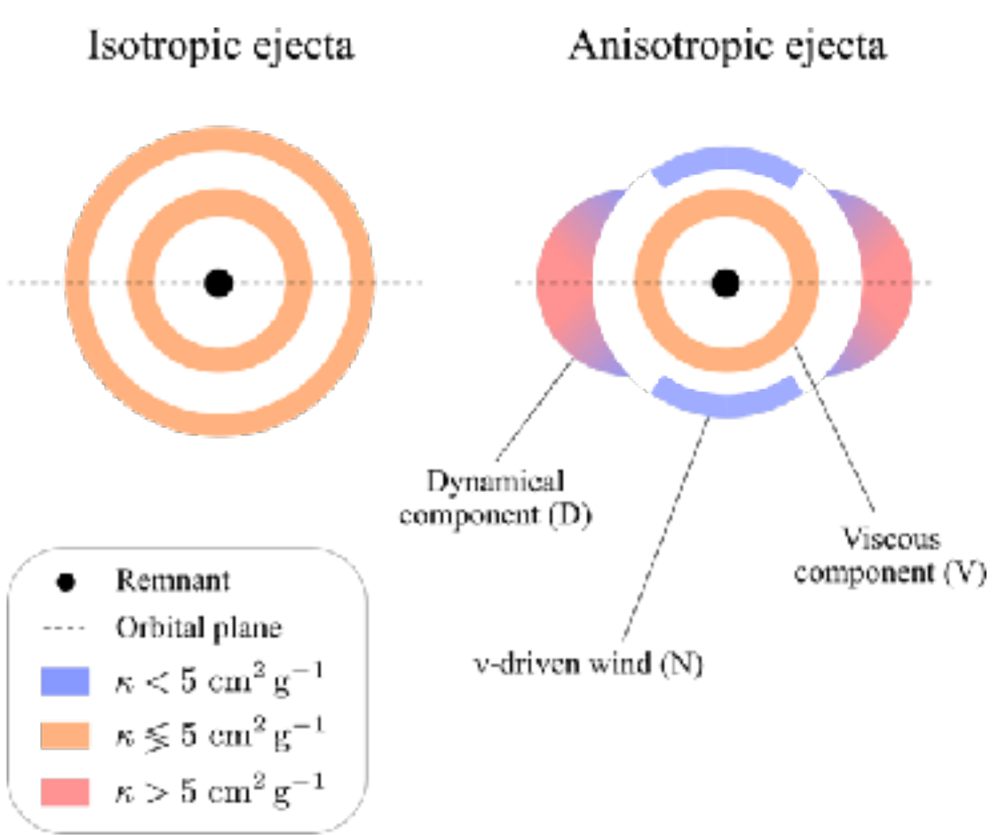
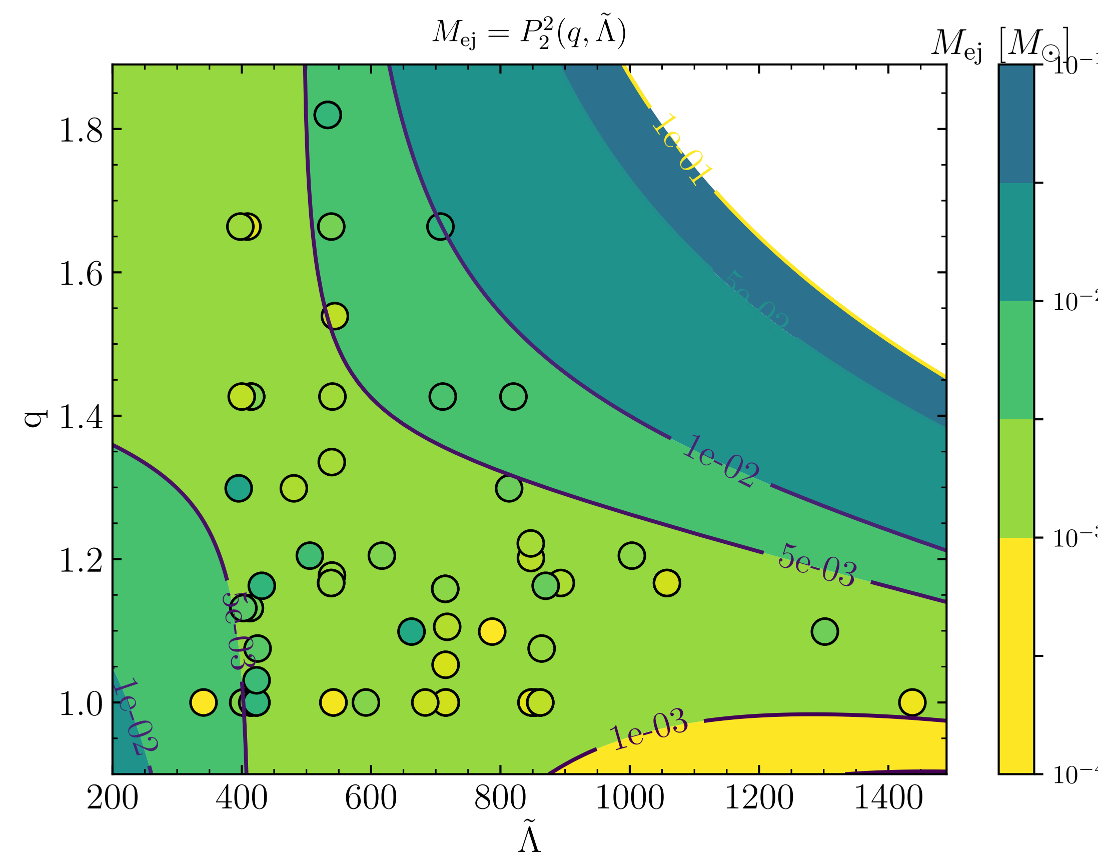
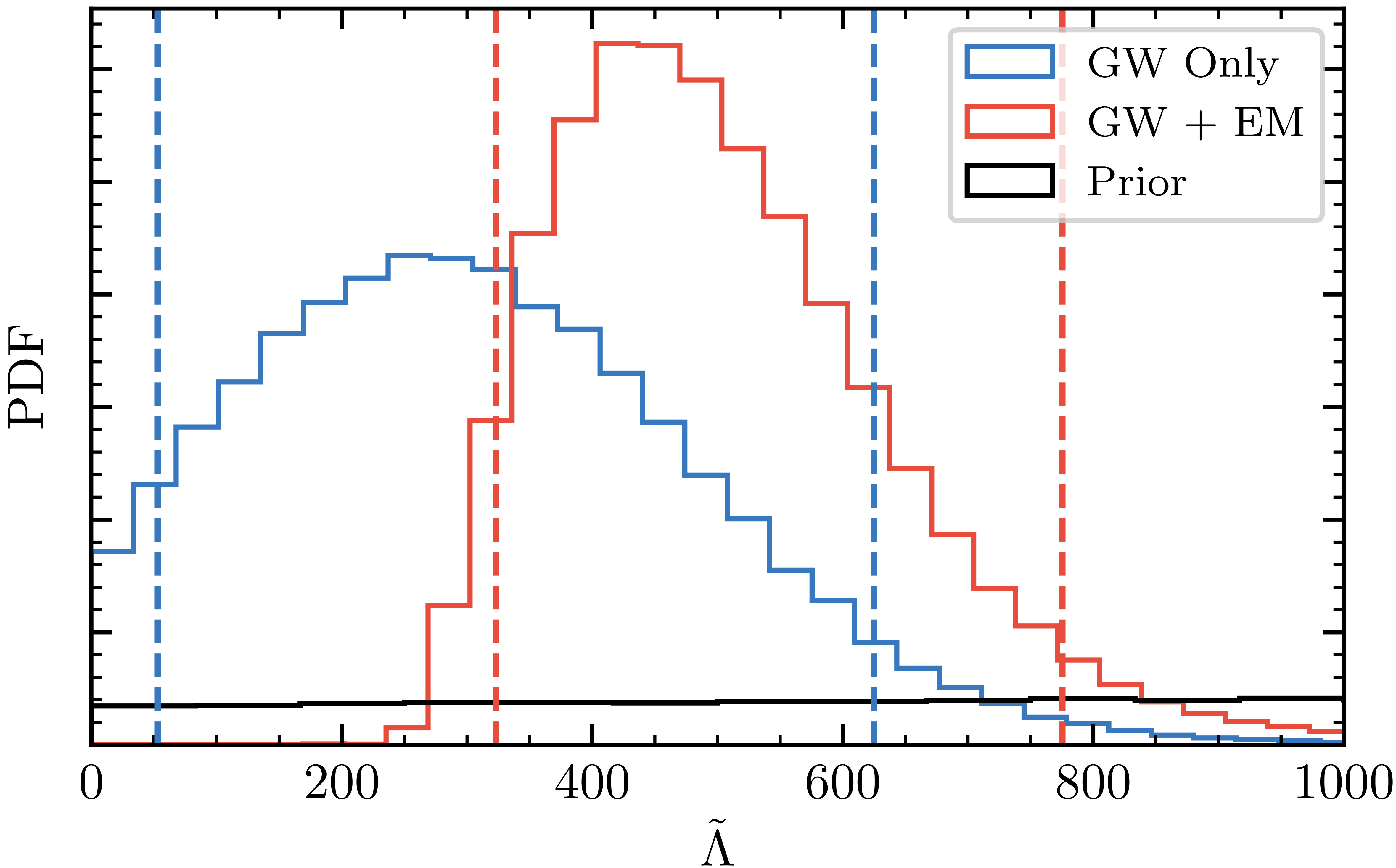


Breschi+ 2021, MNRAS 505:1661 (2021)



Nedora+ 2020, 2011.11110

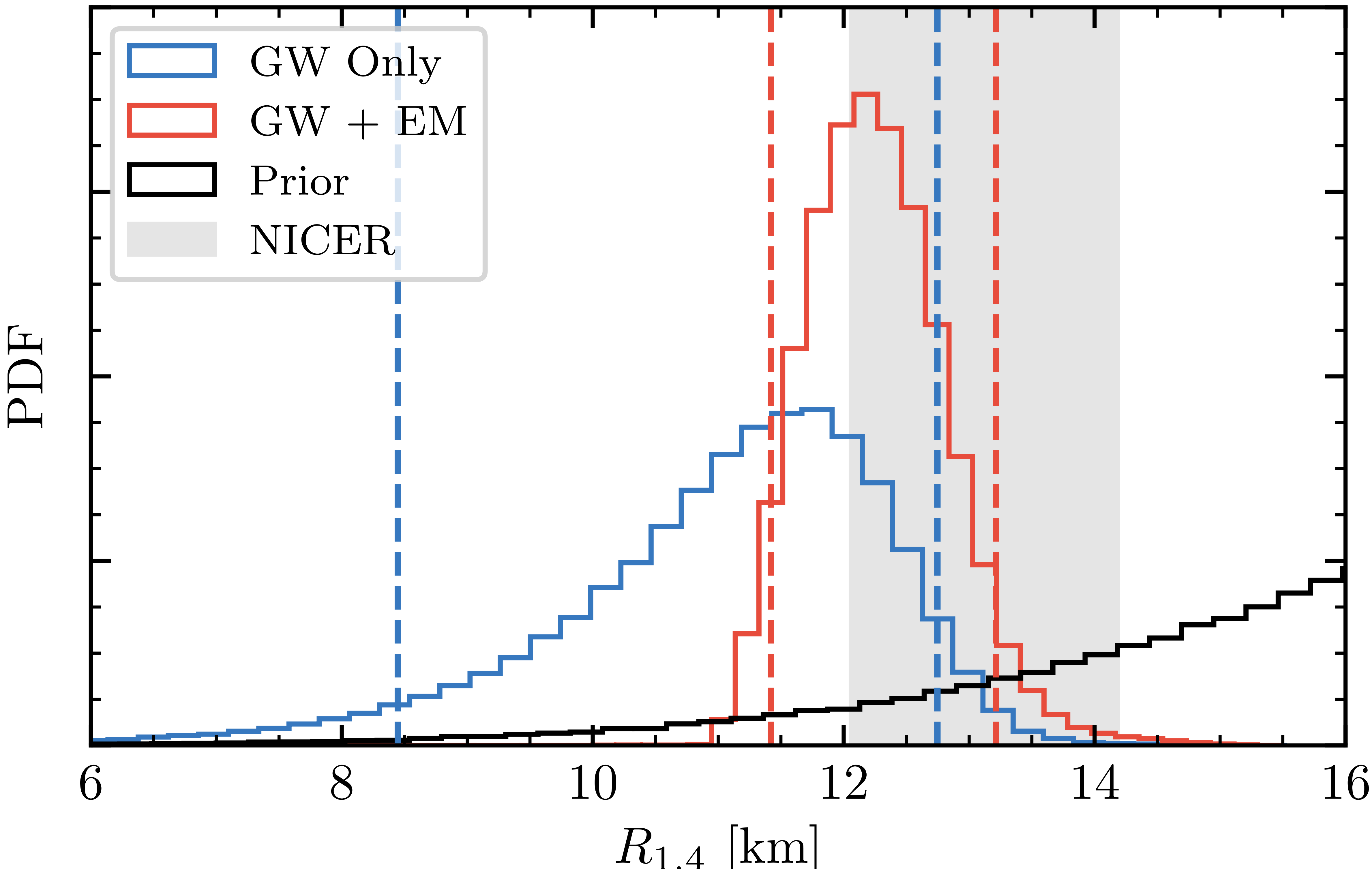
Equation of state constraints



See also Coughlin+ 2018; Capanno+ 2019; Dietrich+ 2020; Gamba+ 2020; …

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

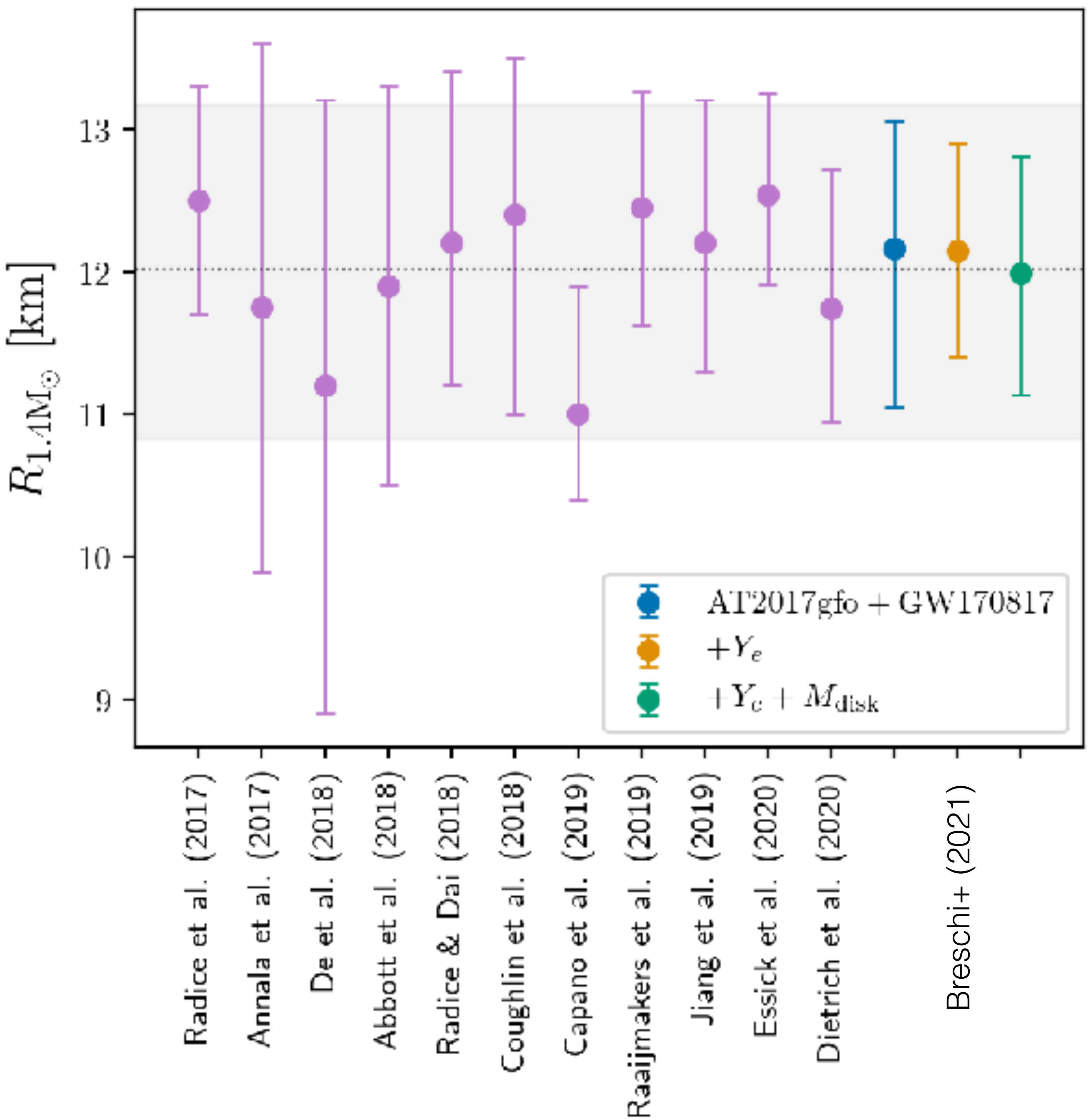
Equation of state constraints



See also Gamba+ 2020

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

Multimessenger constraints

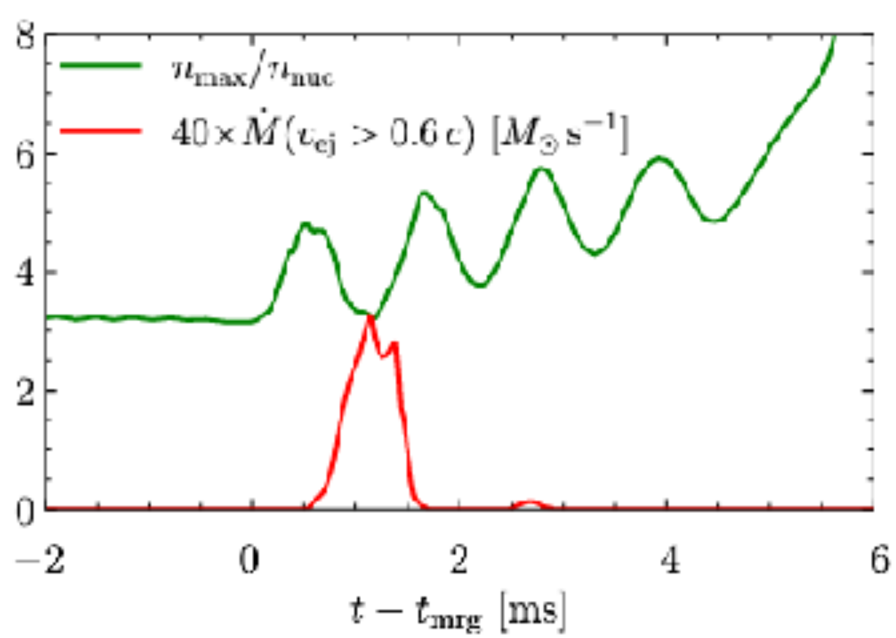


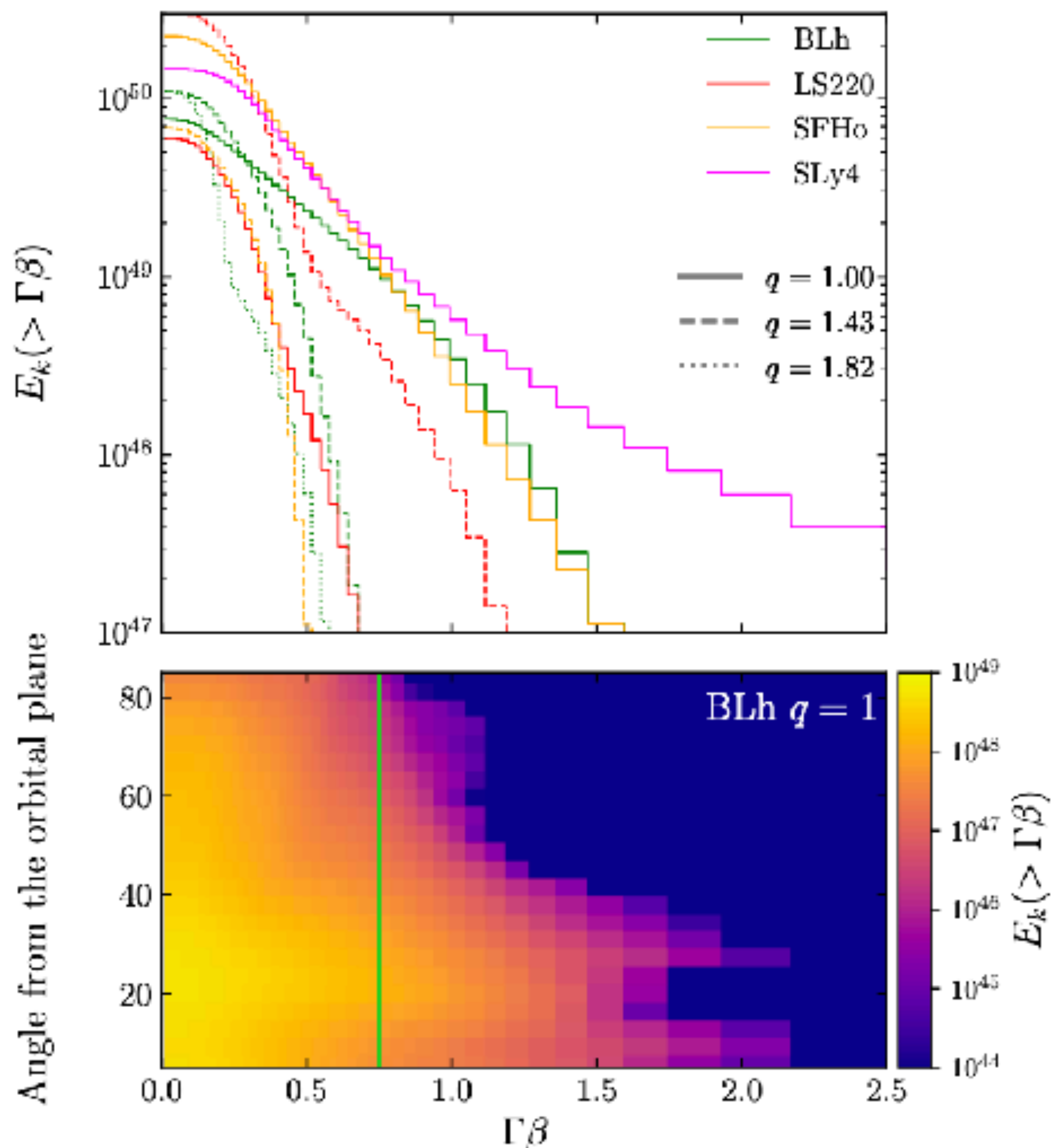
- Potential to constrain the EOS and/or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Systematic errors still dominant
- Need to explore the parameter space: EOS, mass ratios, etc.

Breschi+ 2021, MNRAS 505:1661 (2021)

Kilonova afterglow

- Shocks generated as the remnant bounces accelerate a small fraction of the ejecta to mildly relativistic velocities
- The ejecta drive a shock in the ISM
- Synchrotron emission from the shock produces an afterglow that evolves on timescales of years to decades

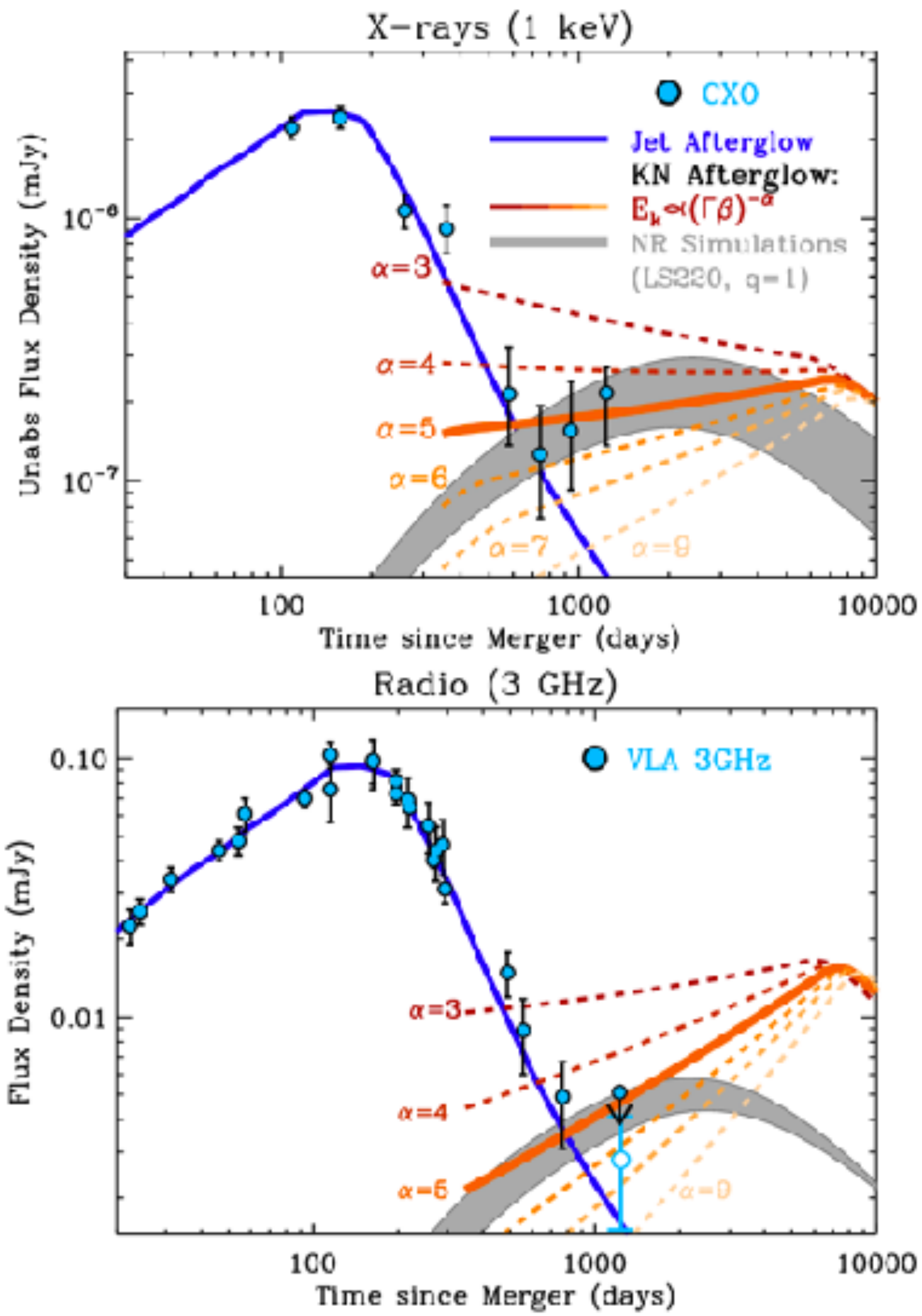




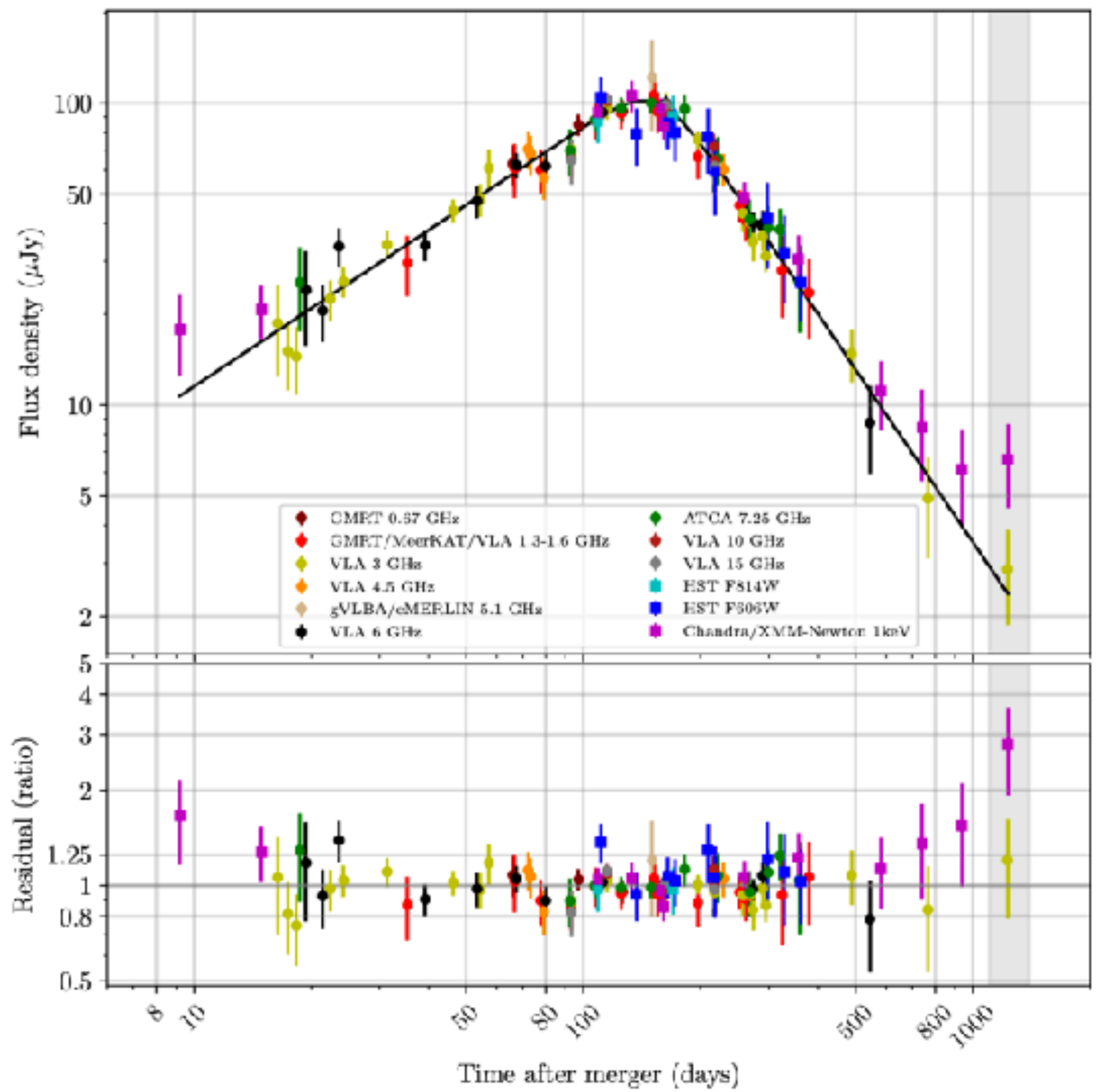
See also Nakar & Piran 2011, Hotokezaka & Piran 2015, Hotokezaka+ 2018, Radice+ 2018, …

Nedora, **DR**+ 2021, 2104.04537

A possible detection?

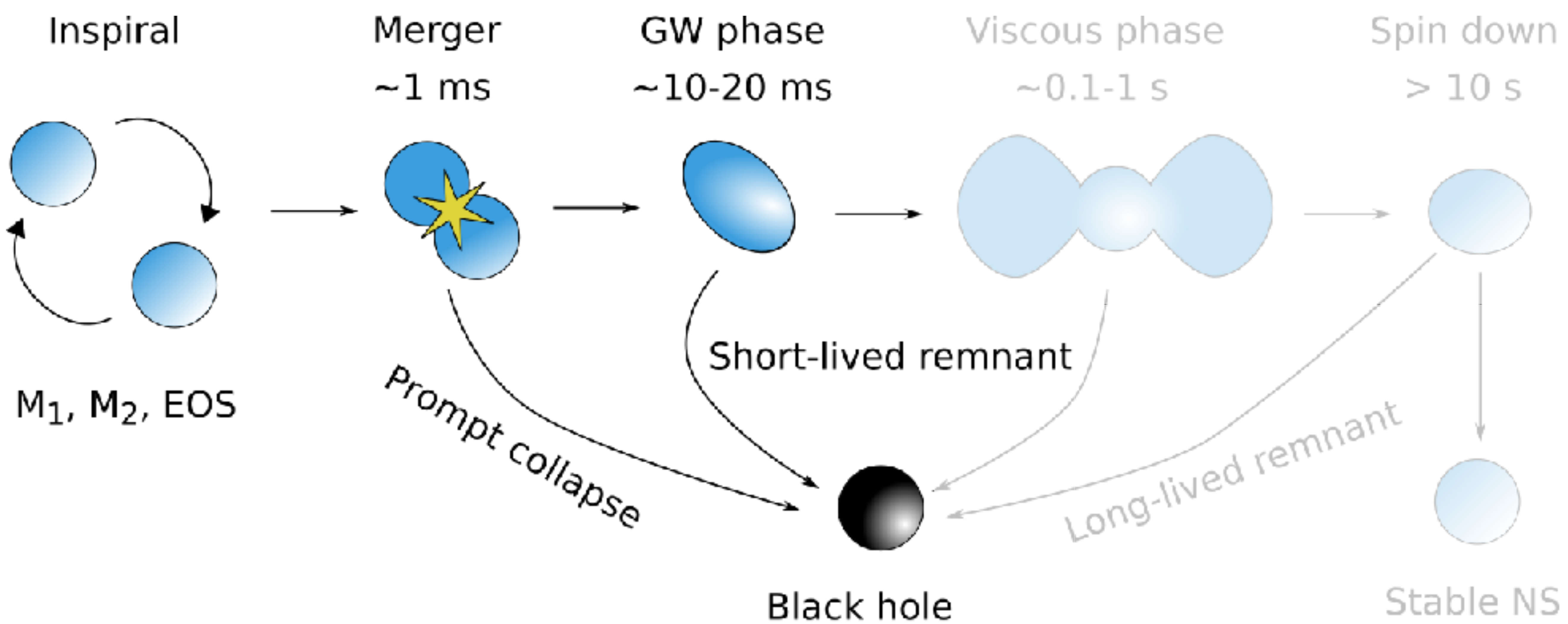


From Hajela+ 2021

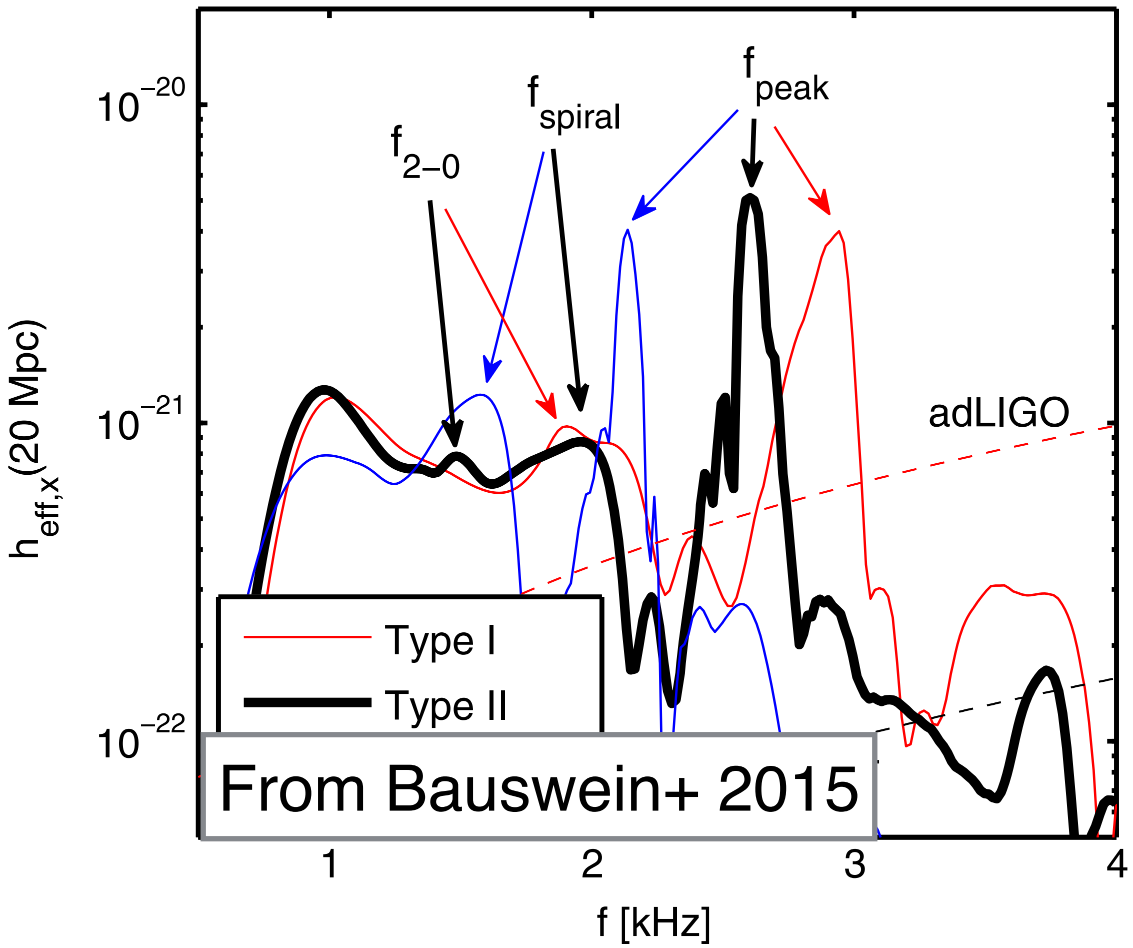


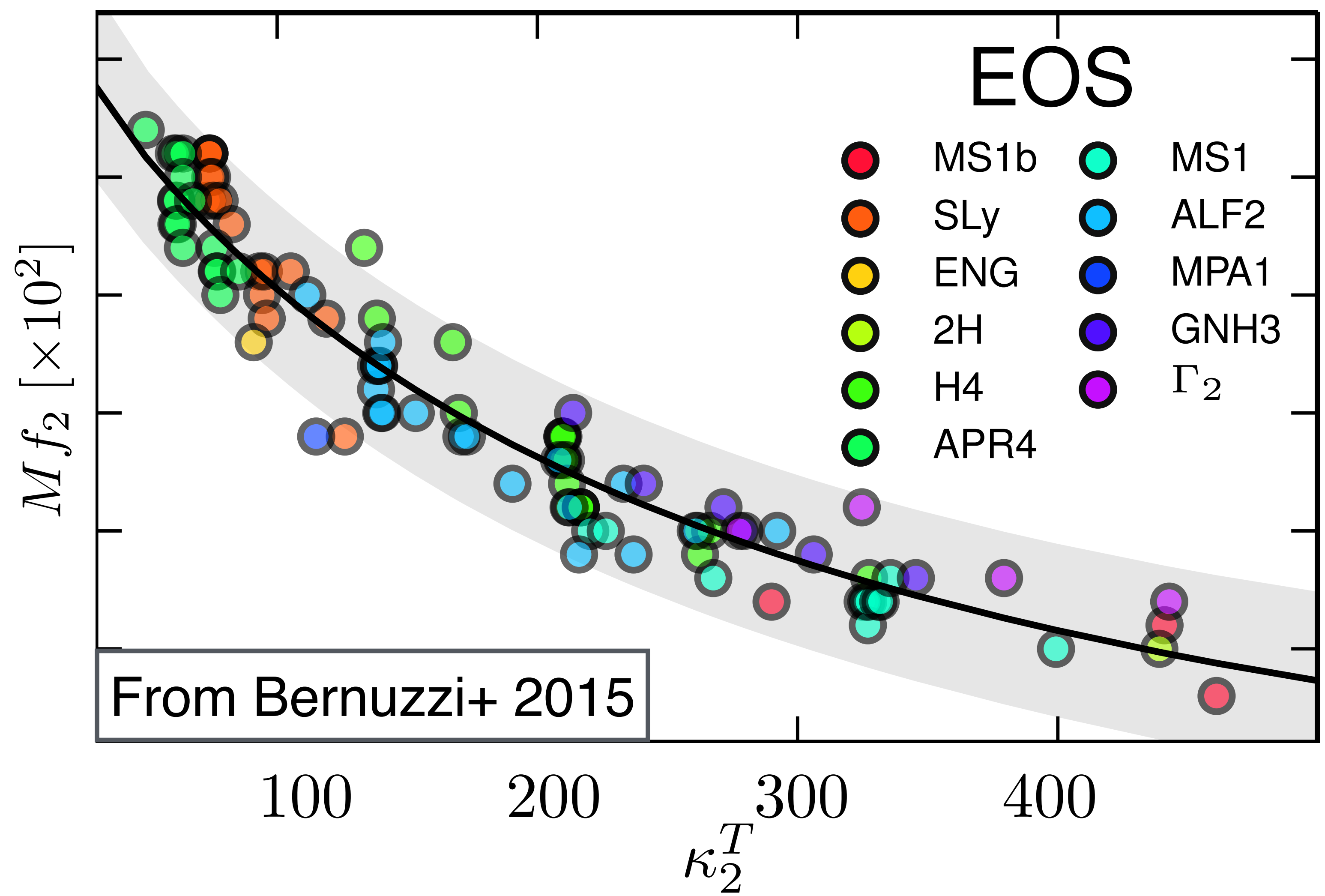
From Balasubramanian, Corsi+ 2021

Early postmerger evolution



Postmerger peak frequency

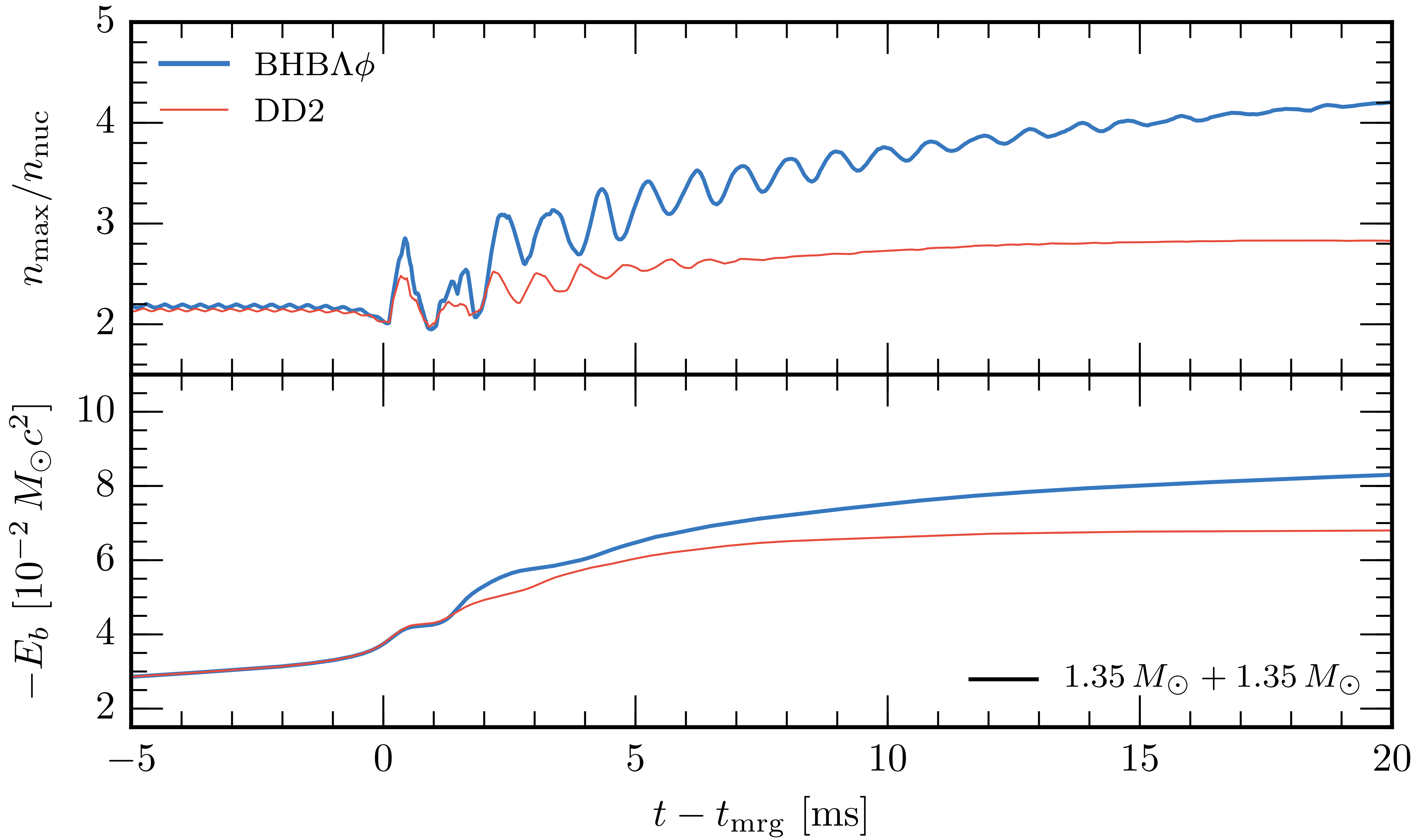




- Post-merger signal has a characteristic peak frequency
- f_{peak} correlates with the NS radius and tidal deformability
- Systematics not fully understood (e.g., turbulence [Radice+ 2017], bulk viscosity [Alford+ 2018], pions [Fore+ 2019])

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bauswein+ 2019; …

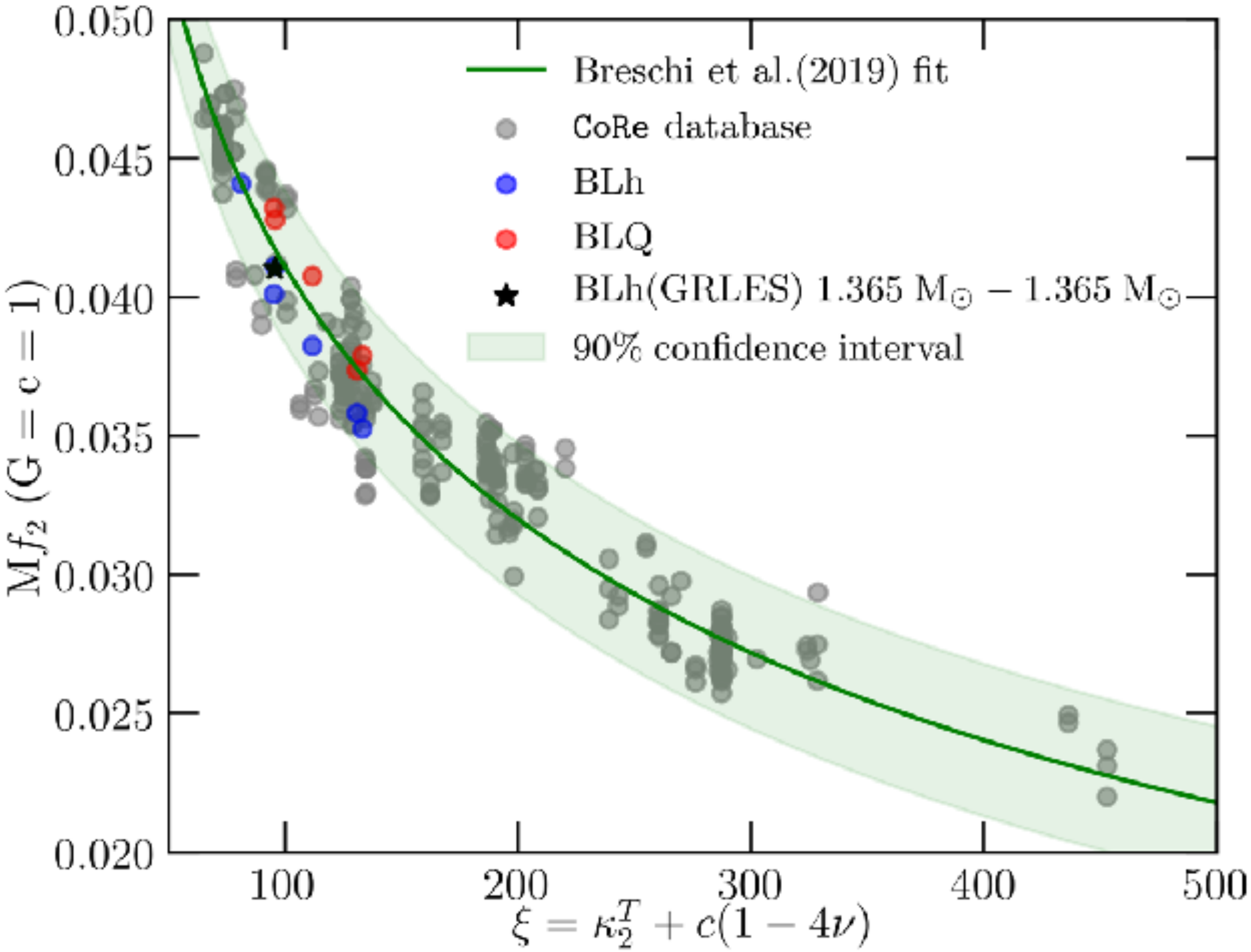
Postmerger amplitude



High-density EOS encoded in the binding energy

DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

QCD phase transitions

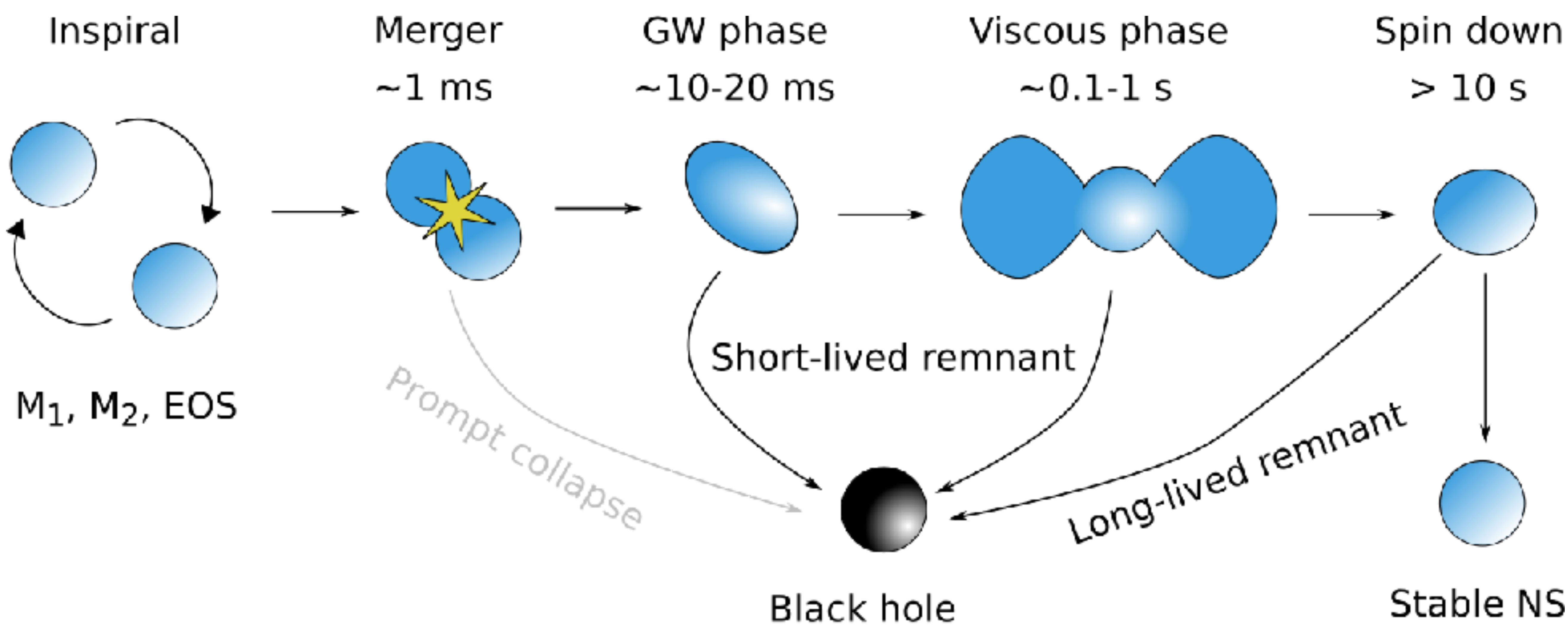


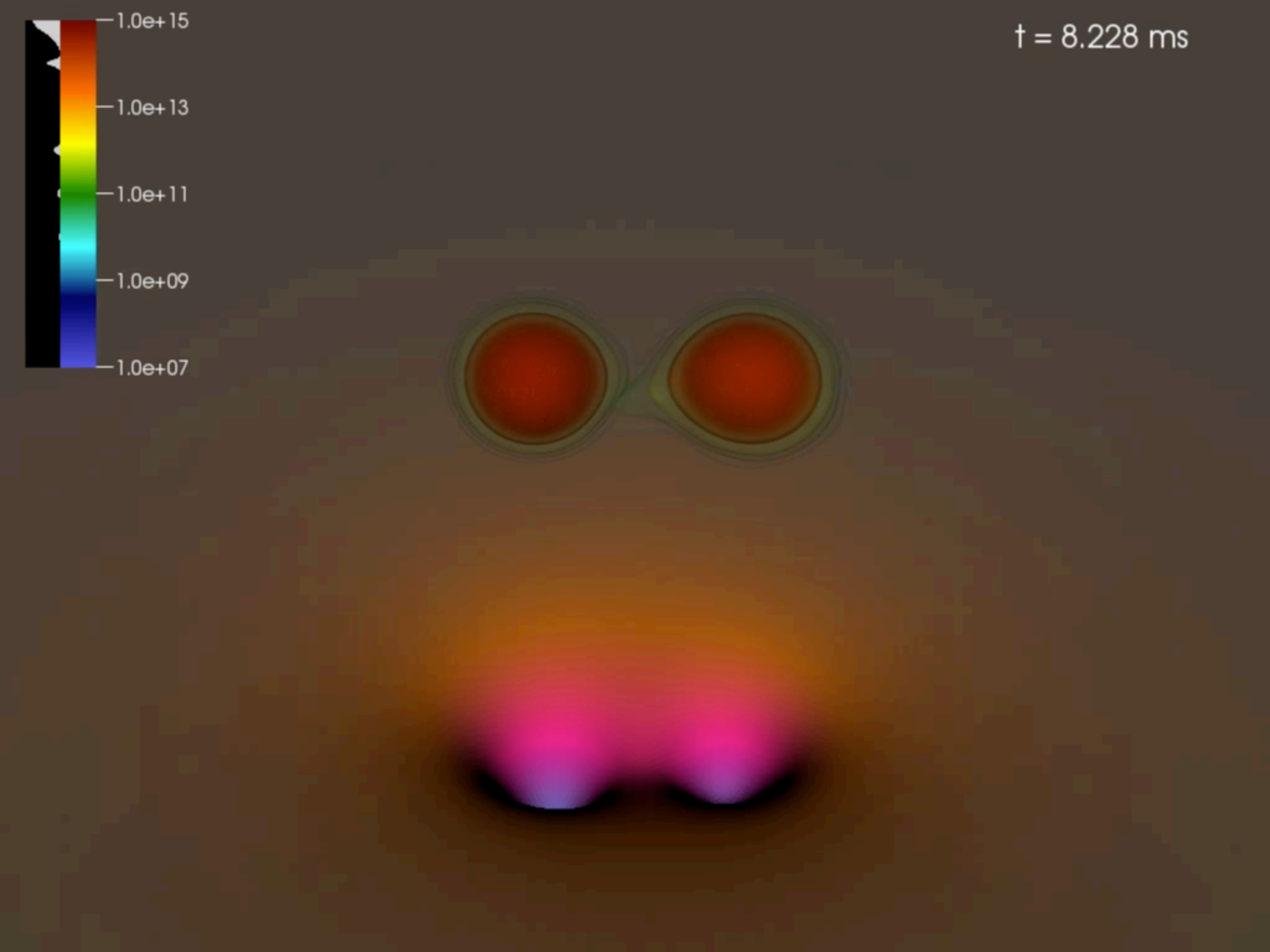
- QCD transition can lead to early collapse
- Increase GW luminosity
- First order phase transitions can lead to shifts in f_{peak}
- The effect can be subtle, degenerate with other physics… more work is needed

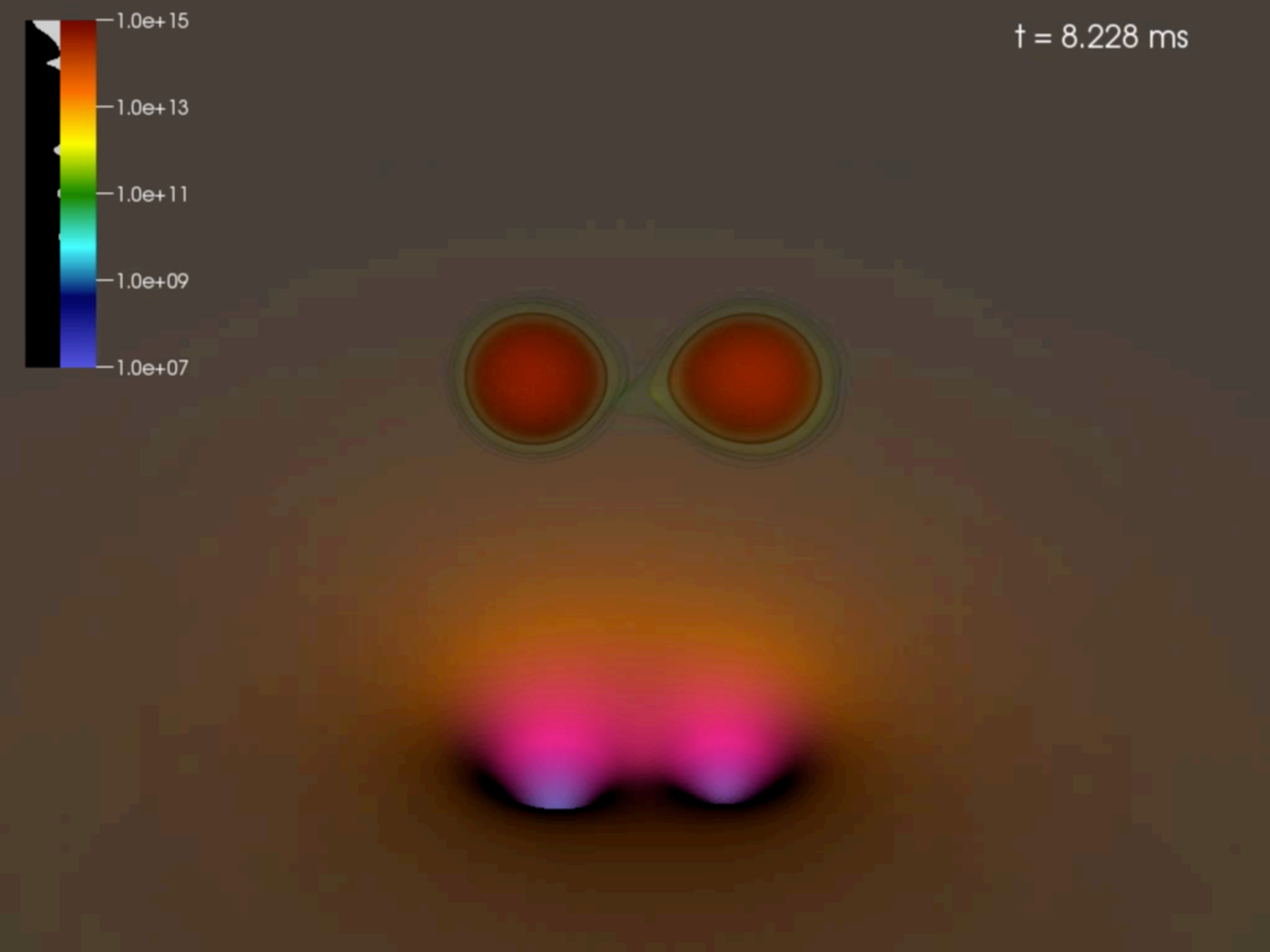
See also Most+ 2018; Bauswein+ 2018; Weih+ 2019; Blacker+ 2020

Prakash, **DR**+, 2106.07885

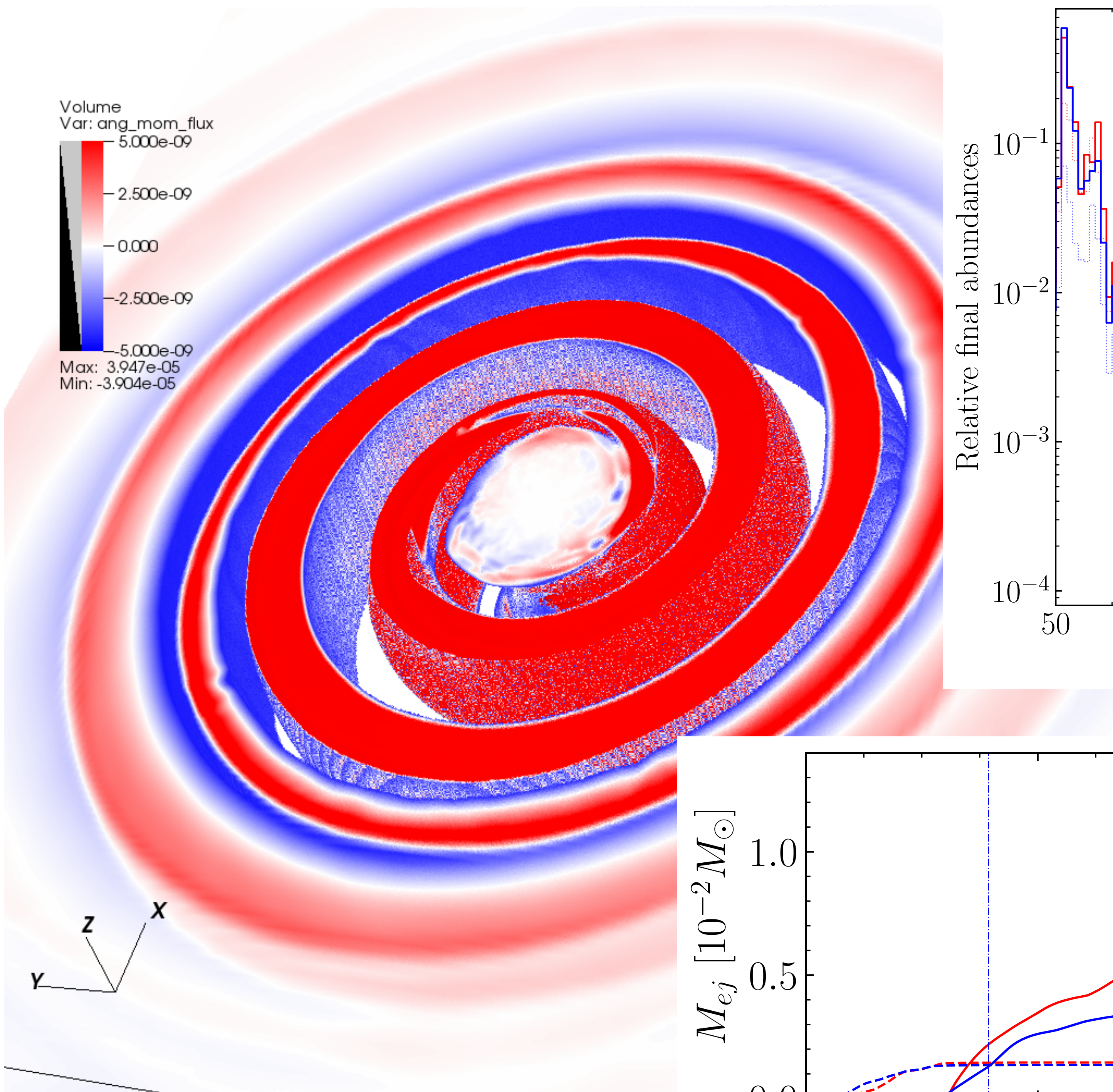
Long-term evolution

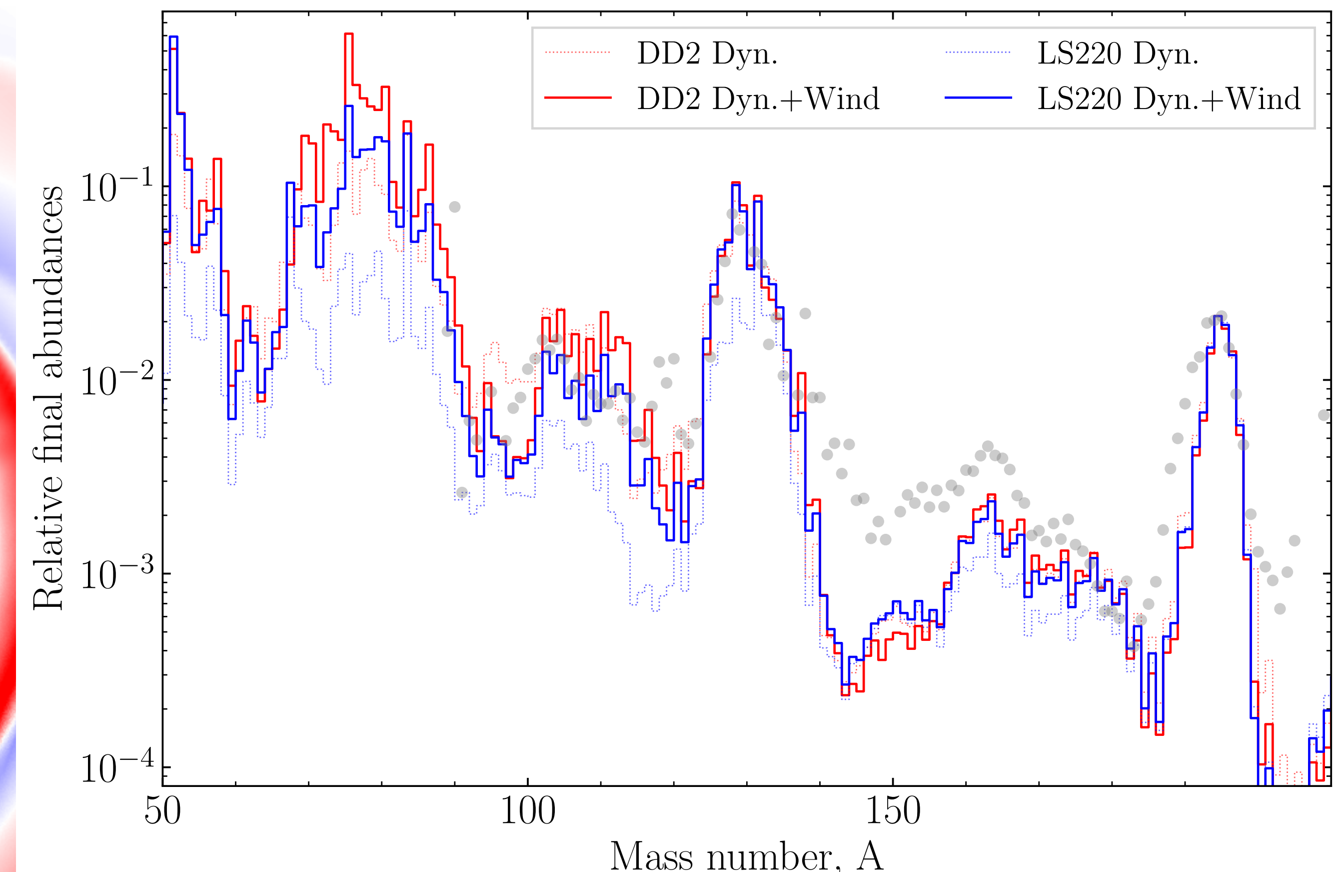


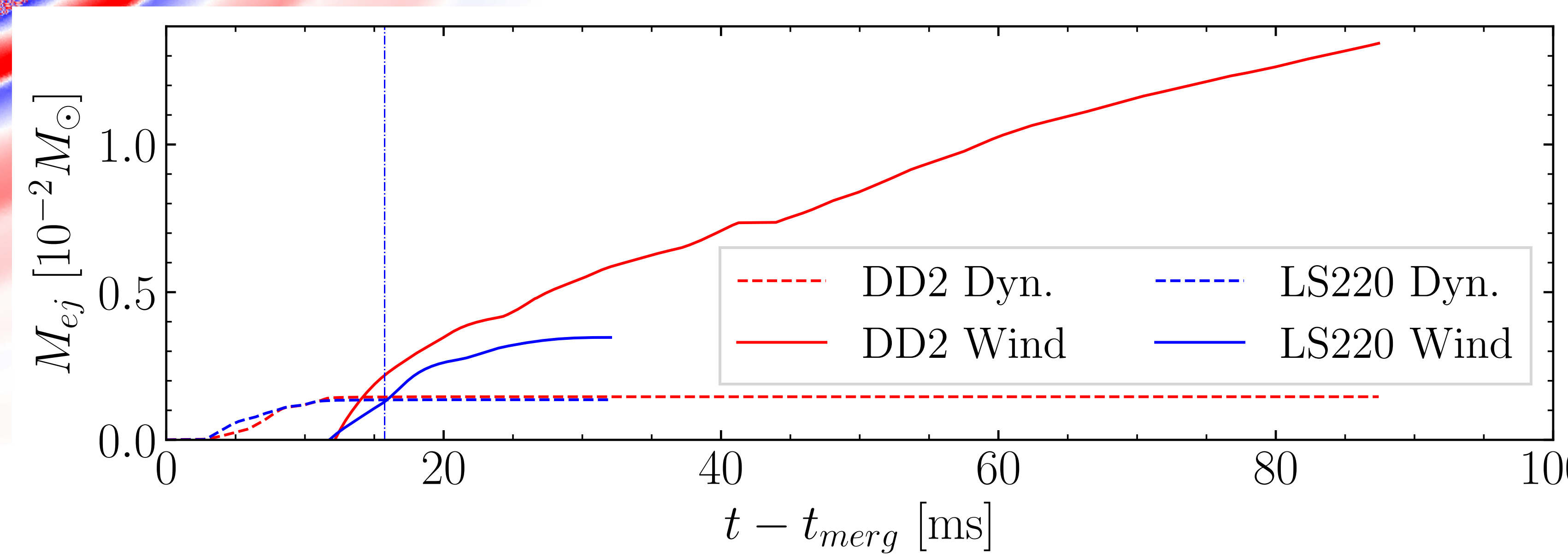

1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 8.228 ms


1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 8.228 ms

Spiral-wave wind (I)

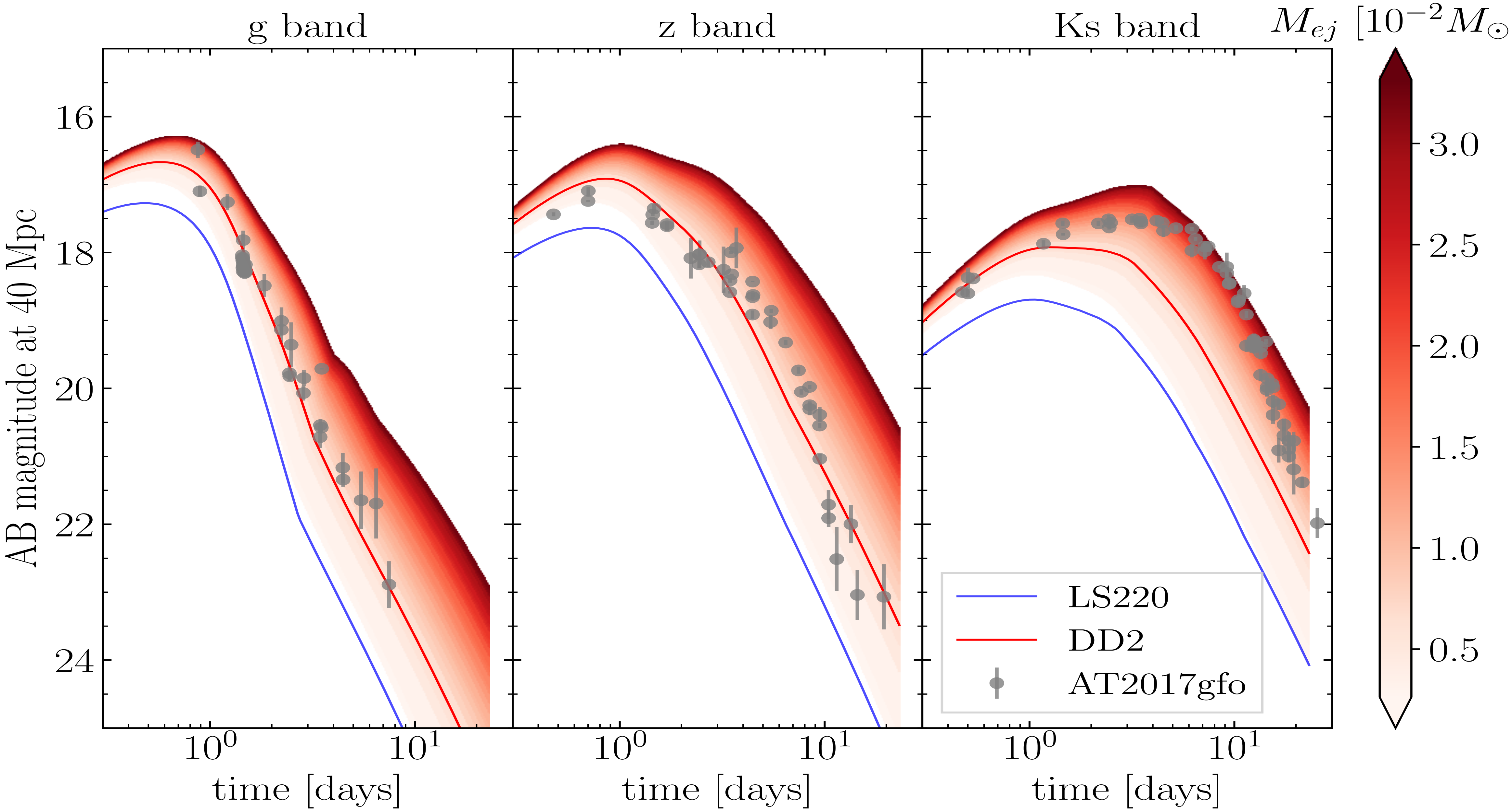






From Nedora, Bernuzzi, **DR**+, ApJL 886:L30 (2019)

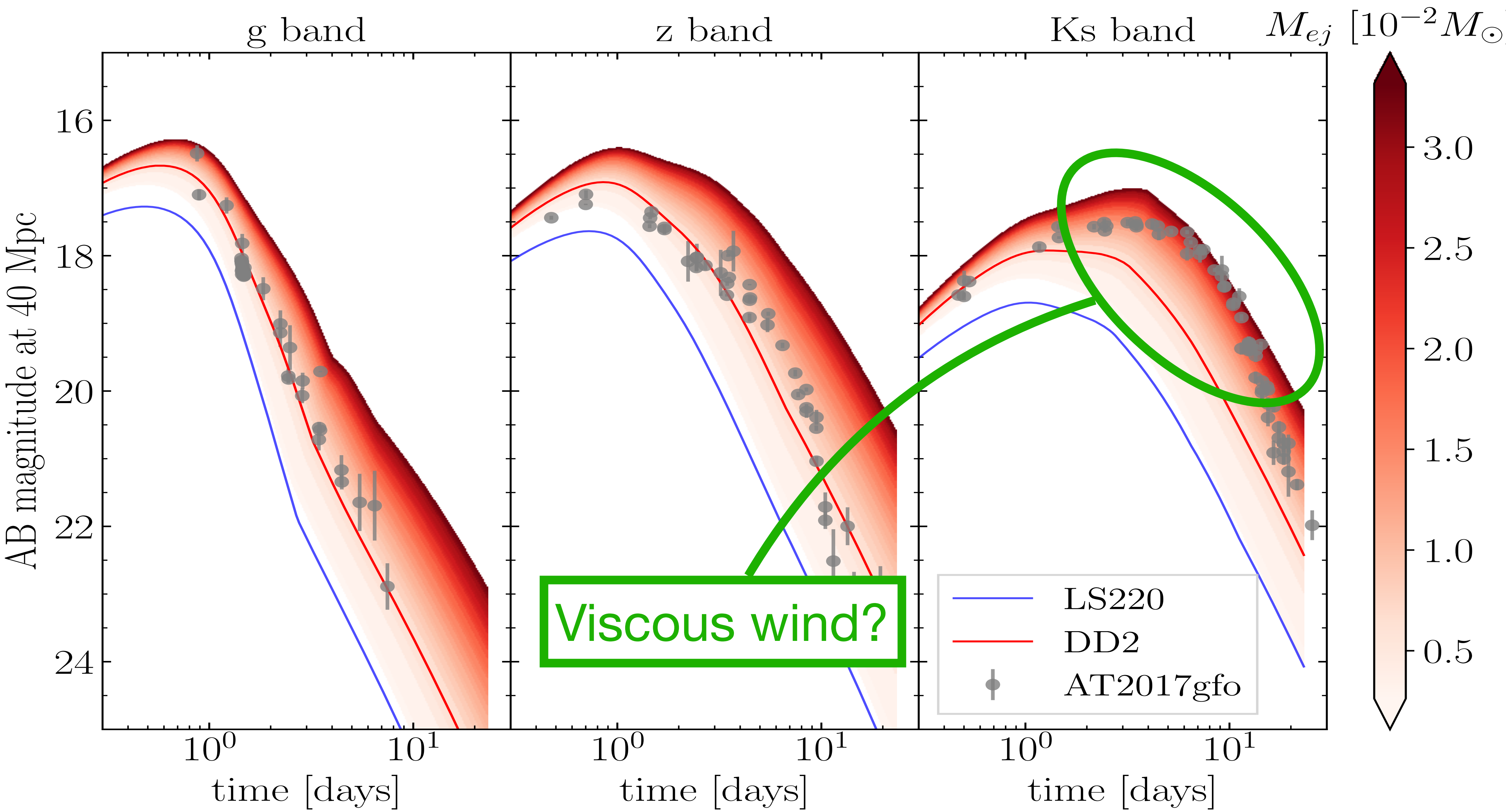
Spiral-wave wind (II)



Promising, but incomplete, and not the only possible explanation

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

Spiral-wave wind (II)

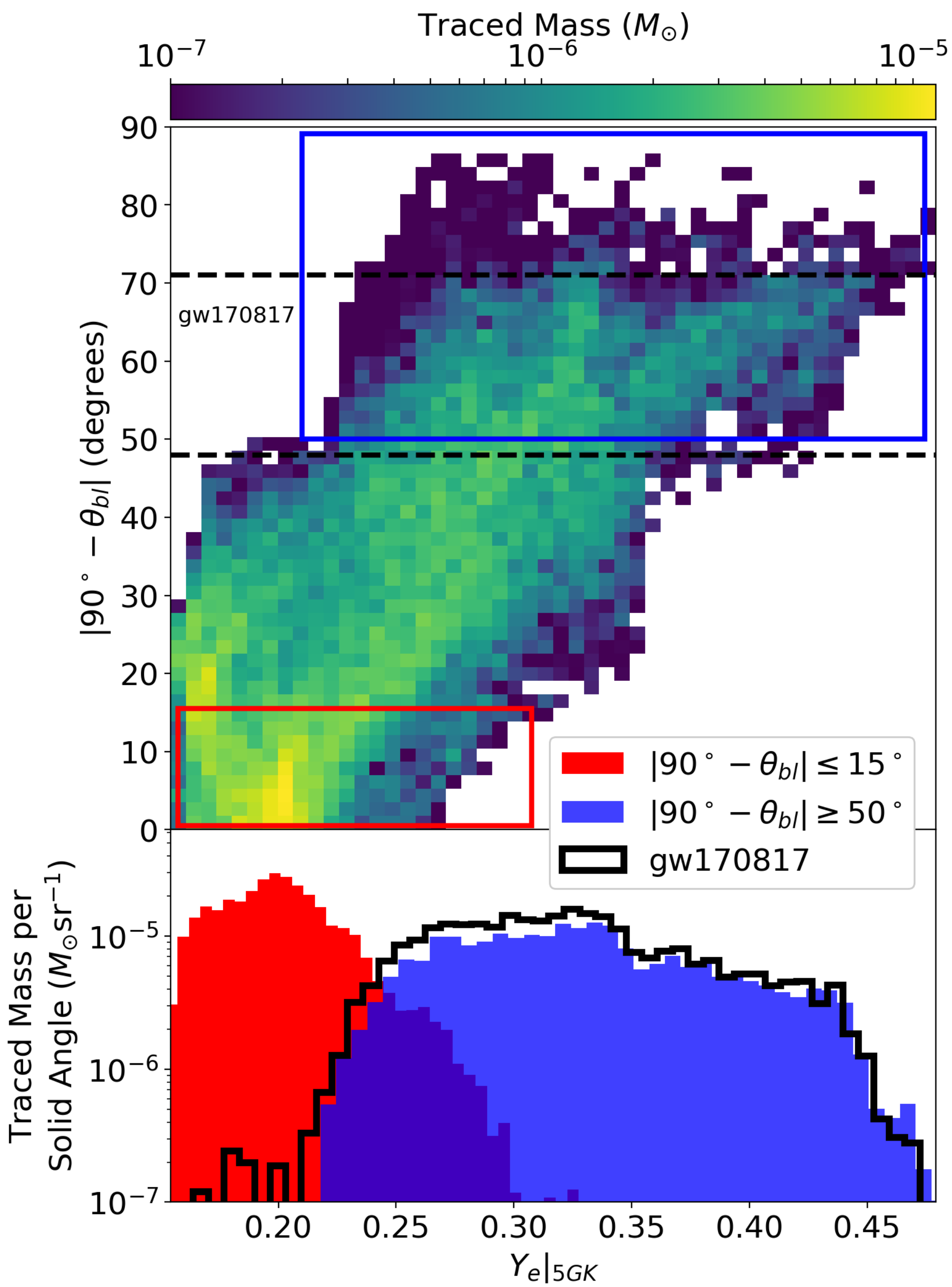


Promising, but incomplete, and not the only possible explanation

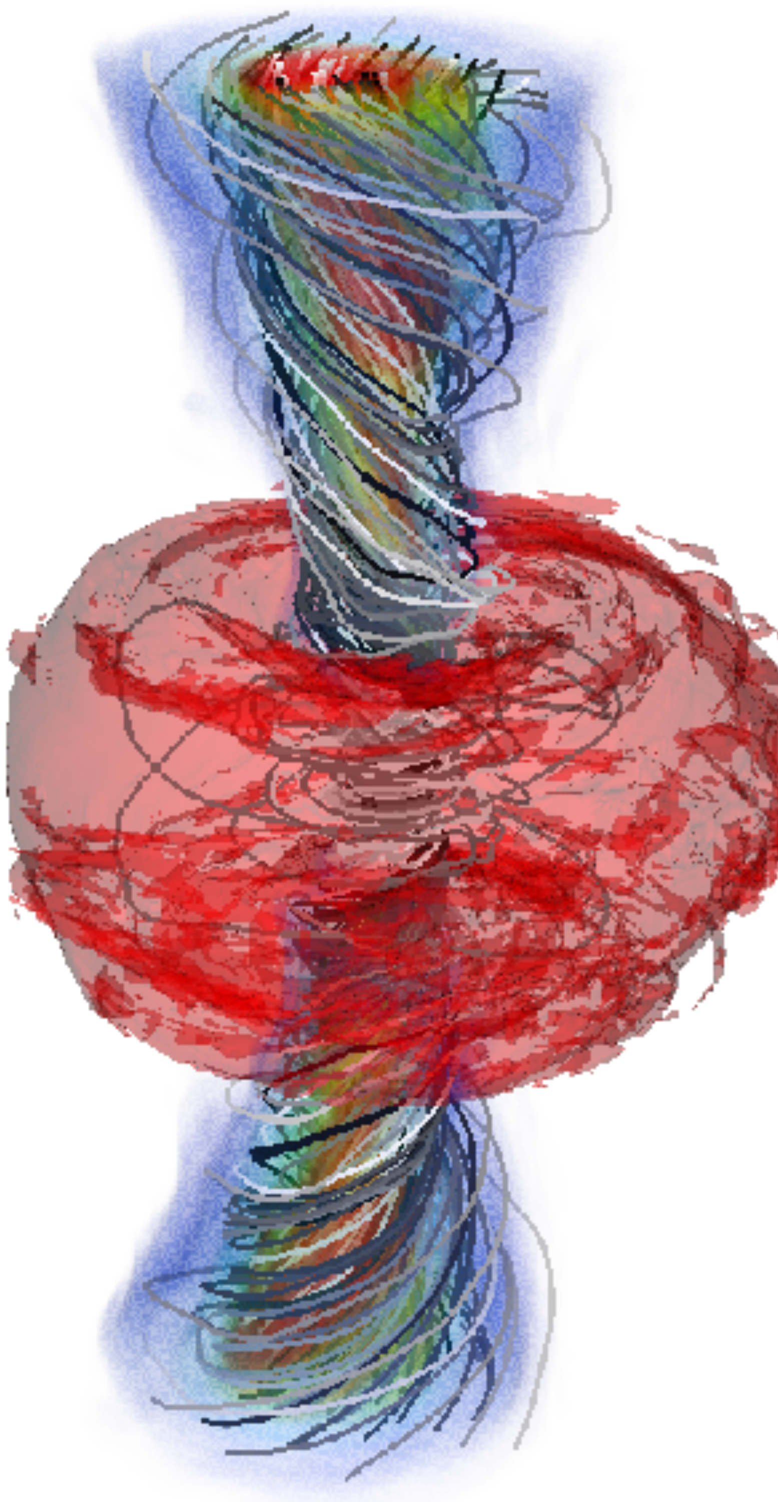
From Nedora, Bernuzzi, **DR**+, ApJL 886:L30 (2019)

Challenges

- Disk winds dominate EM counterpart and nucleosynthesis
- Neutrino transport
- MHD turbulence
- Nuclear burning
- 3D effects

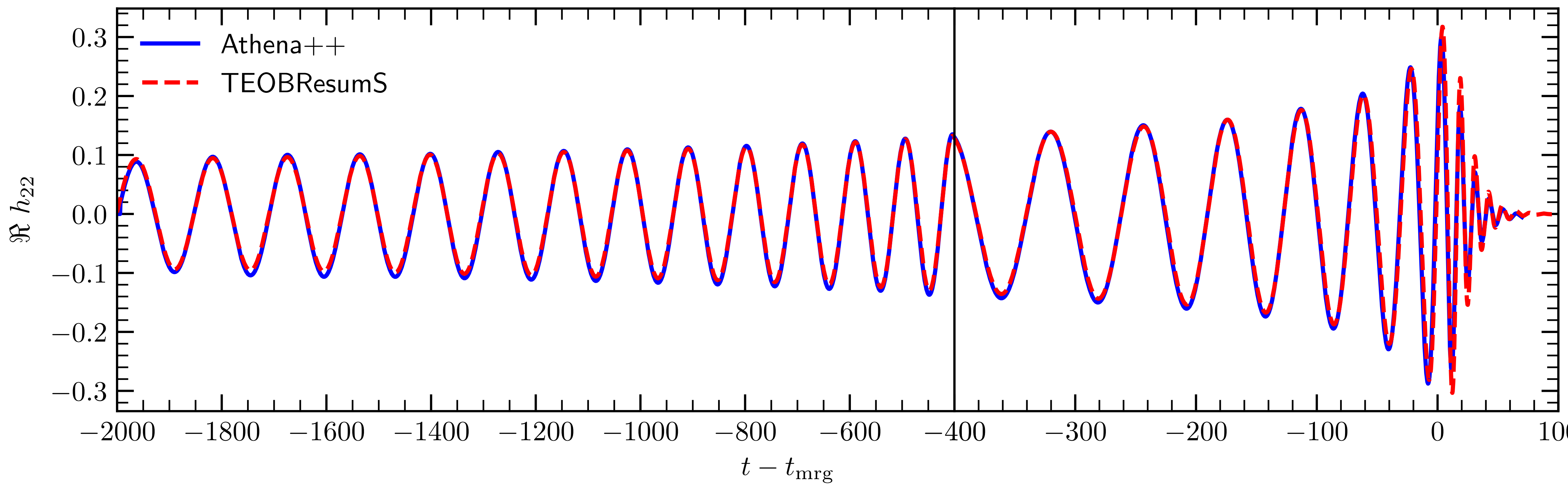


From Miller+ 2019



Mösta, **DR**+ 2020

GRAthena++



GRAthena++

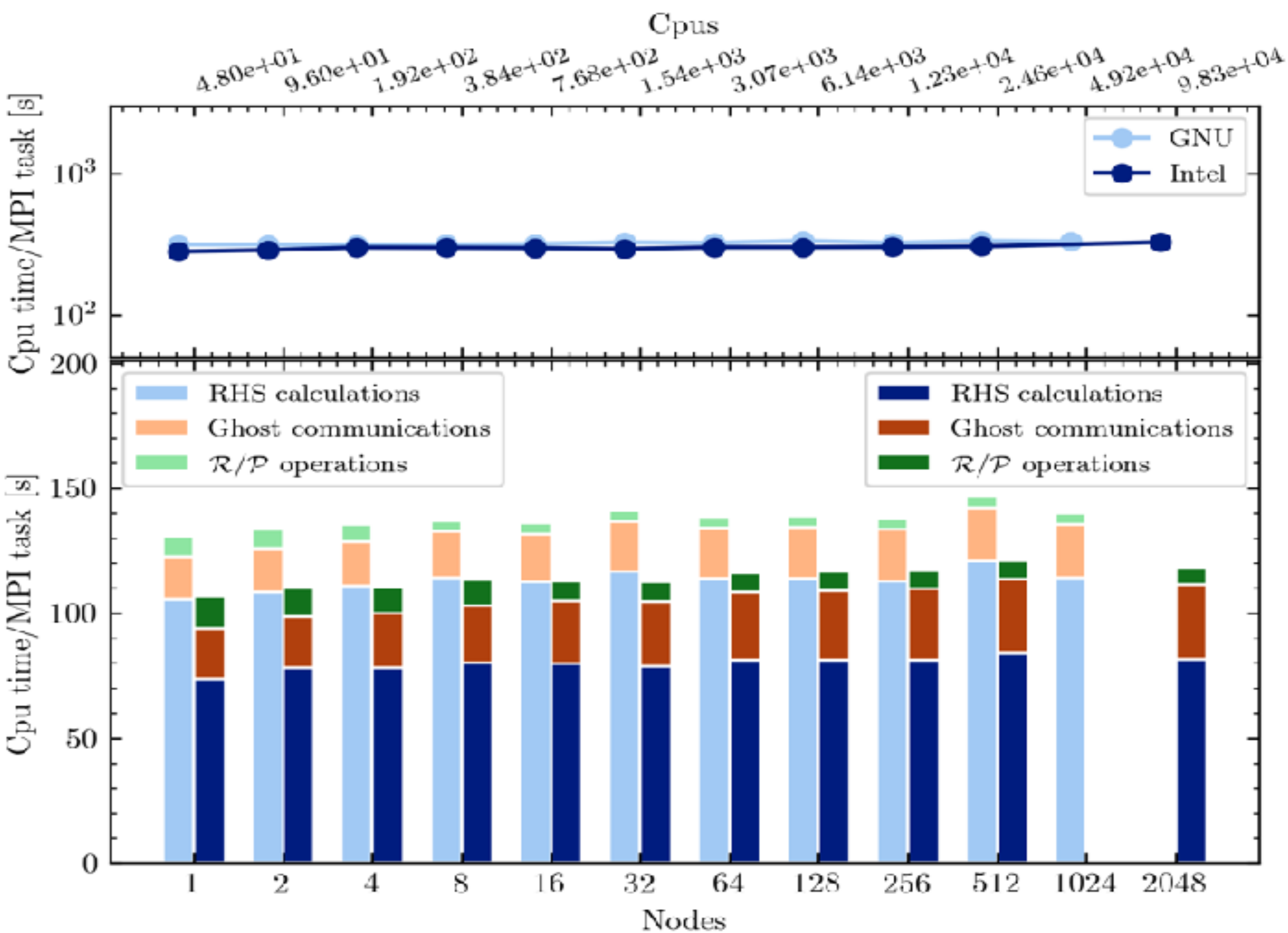
- Vertex centered octree AMR
- High order FD and low-storage Runge-Kutta time integration
- Hybrid MPI/OpenMP, SIMD vectorized

Coming soon

- GRMHD (already working, but needs testing)
- GPU acceleration (with Kokkos)
- Spectral-like compact FD

Daszuta+ 2021, 2101.08289

GRAthena++



Daszuta+ 2021, 2101.08289

Conclusions

- We can already do multimessenger astrophysics!
- Postmerger GWs can reveal the physics of matter at extreme densities
- The physics becomes increasingly complex on longer timescales in the postmerger. Higher resolution, longer, and more sophisticated simulations are needed