PennState
Eberly College of Science

NR Simulations of NS Mergers: Status and Future

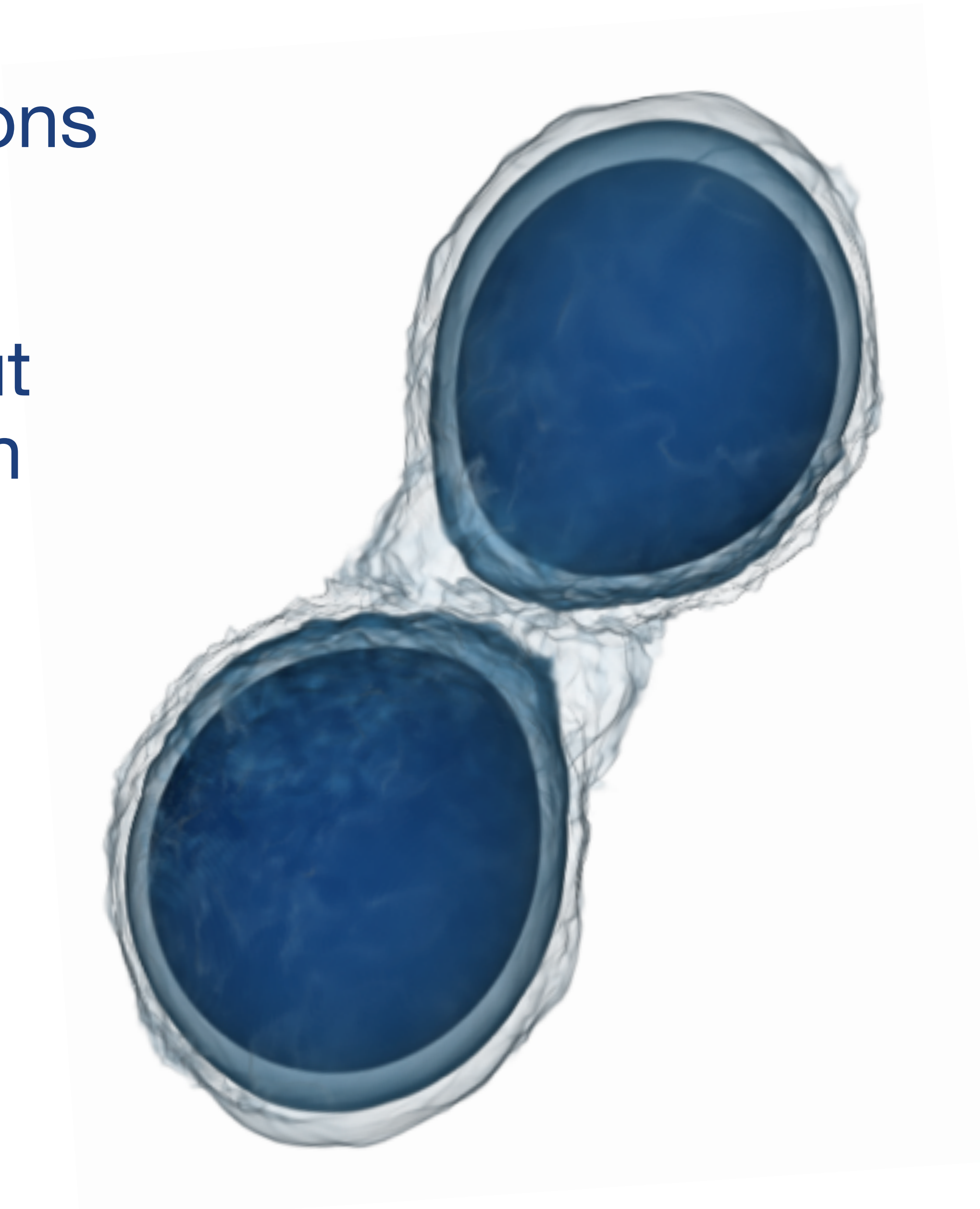
www.computational-relativity.org

arXiv:2002.03863

David Radice — August 21, 2020

Neutron Star Merger Simulations

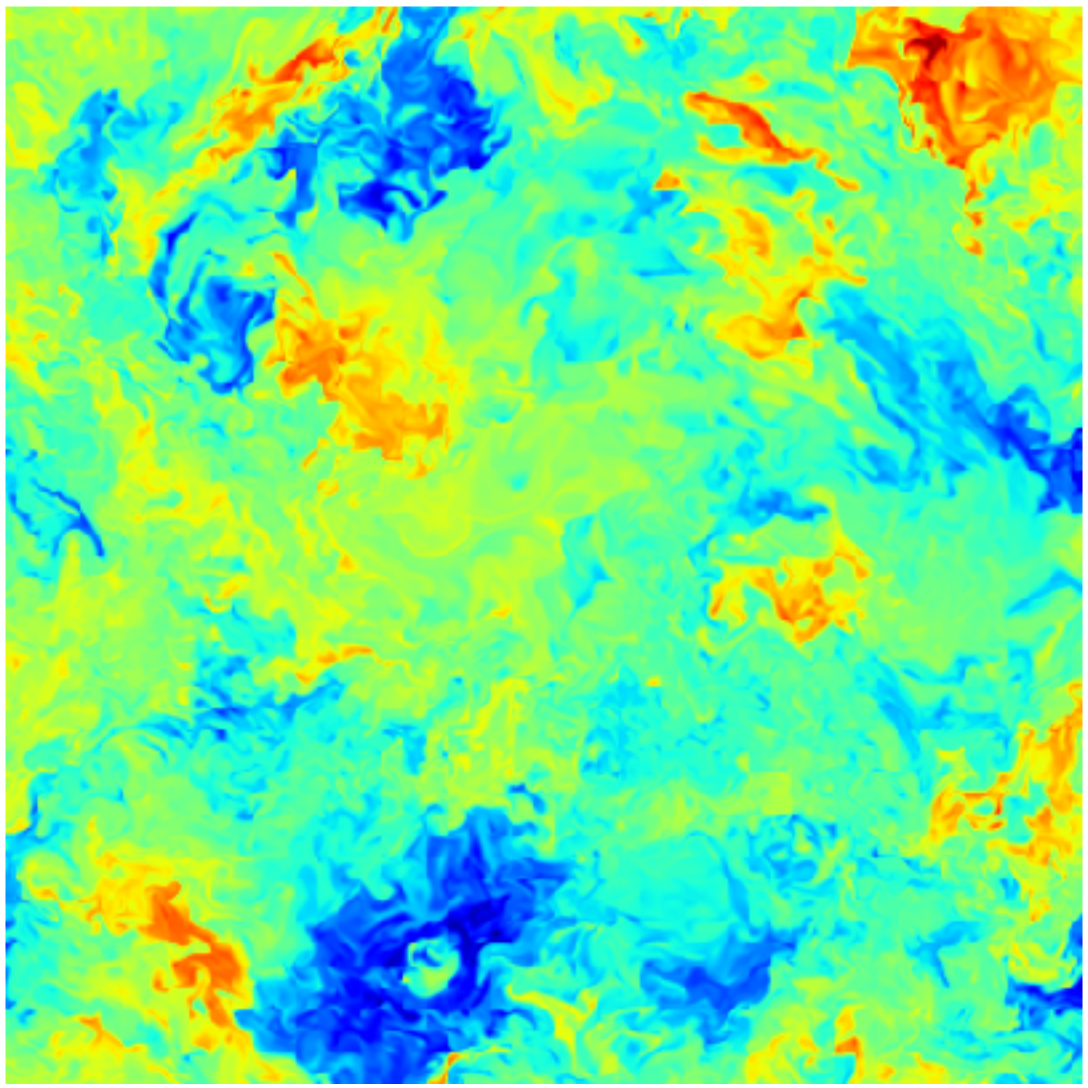
- Gravity. Full numerical relativity simulations available in the last ~20 years.
- Dense matter. Finite temperature and out of beta-equilibrium EOS in simulations in the last ~10 years.
- Neutrino transport. GR simulations with approximate neutrinos: ~5 years ago.
- Magnetic fields. GRMHD merger simulations ~10 years ago.



No simulation includes everything!

WhiskyTHC

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



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

* using the Einstein Toolkit metric solvers

THC: Templated Hydrodynamics Code

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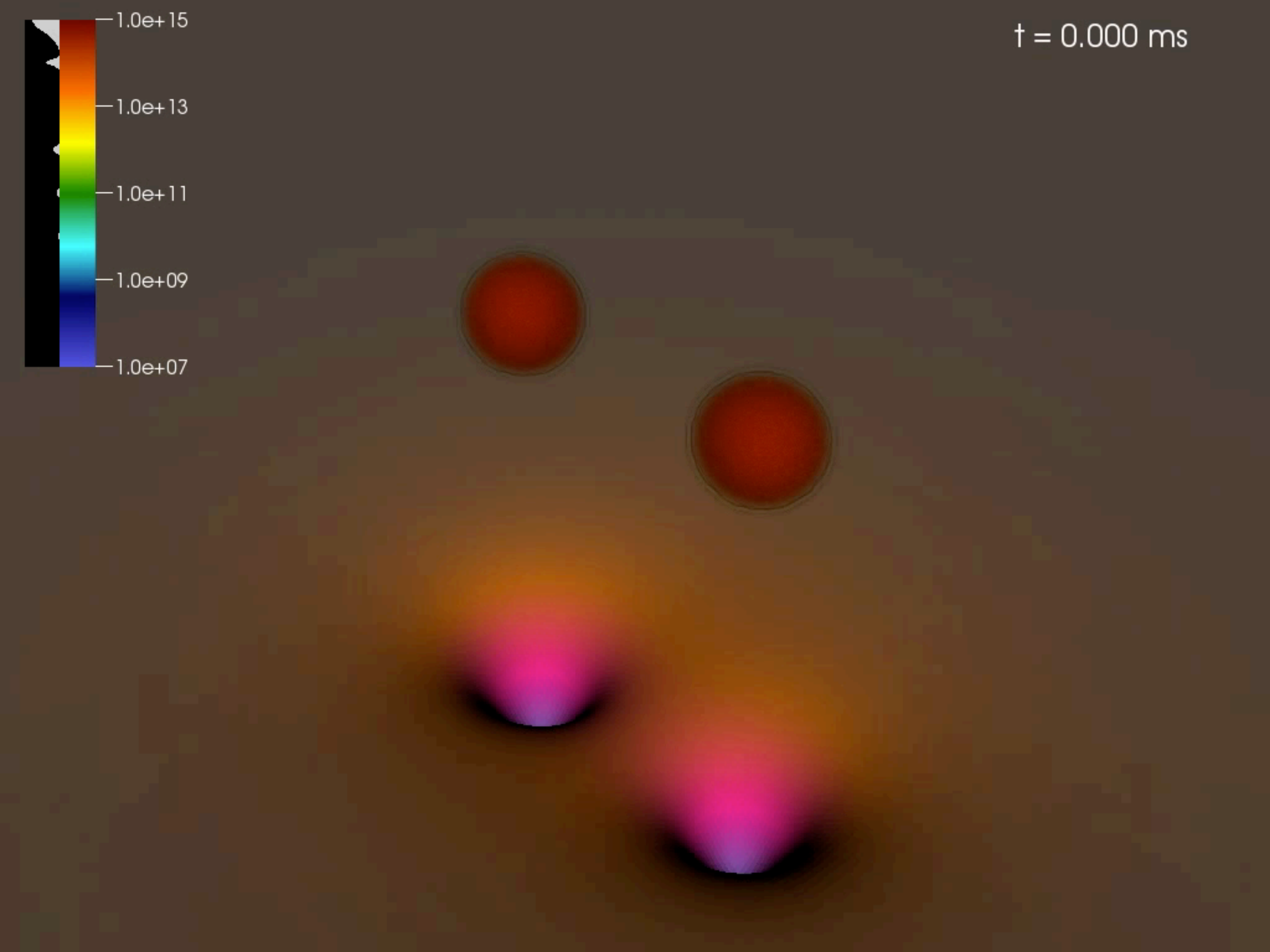
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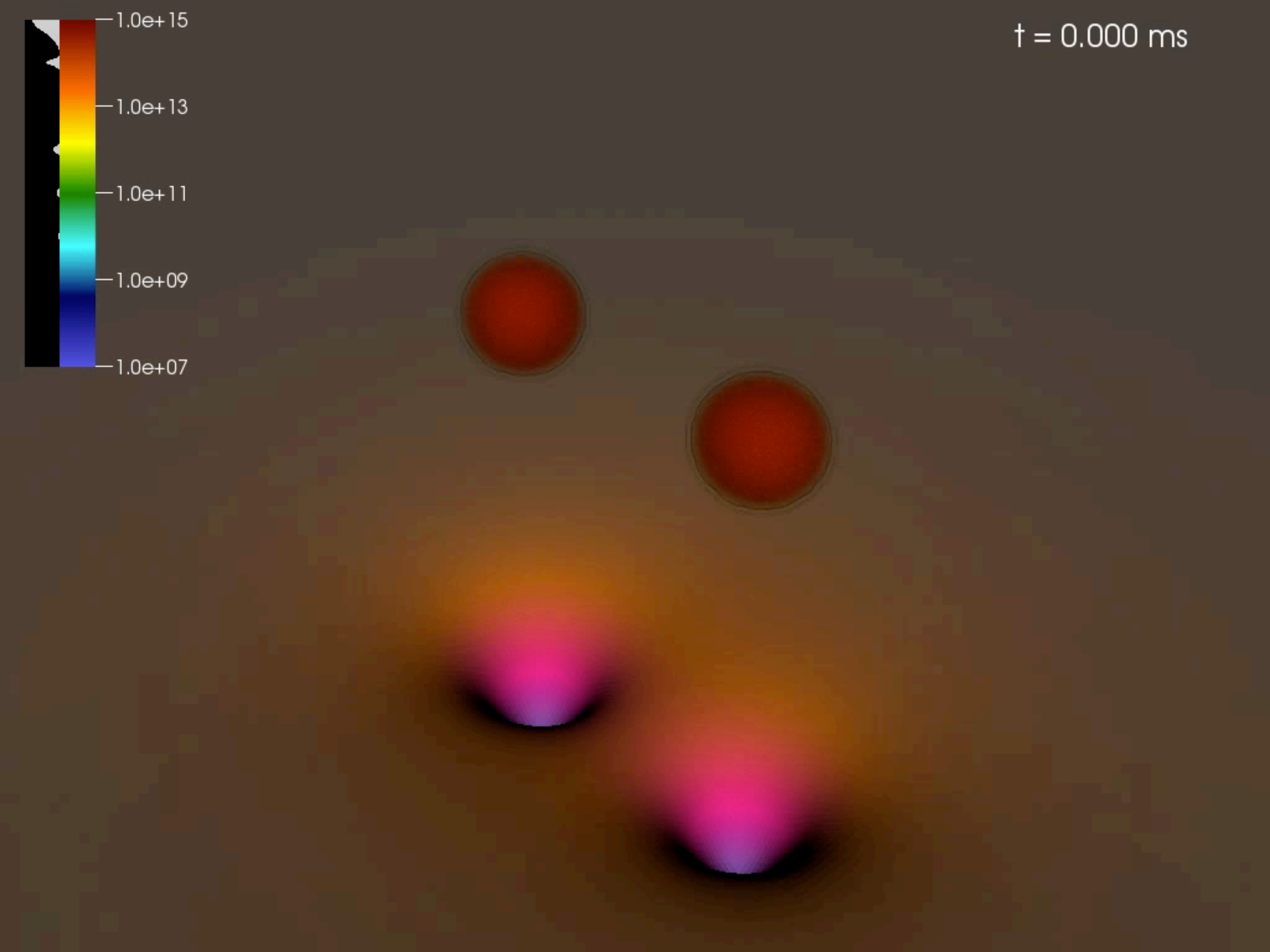
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 0.000 ms



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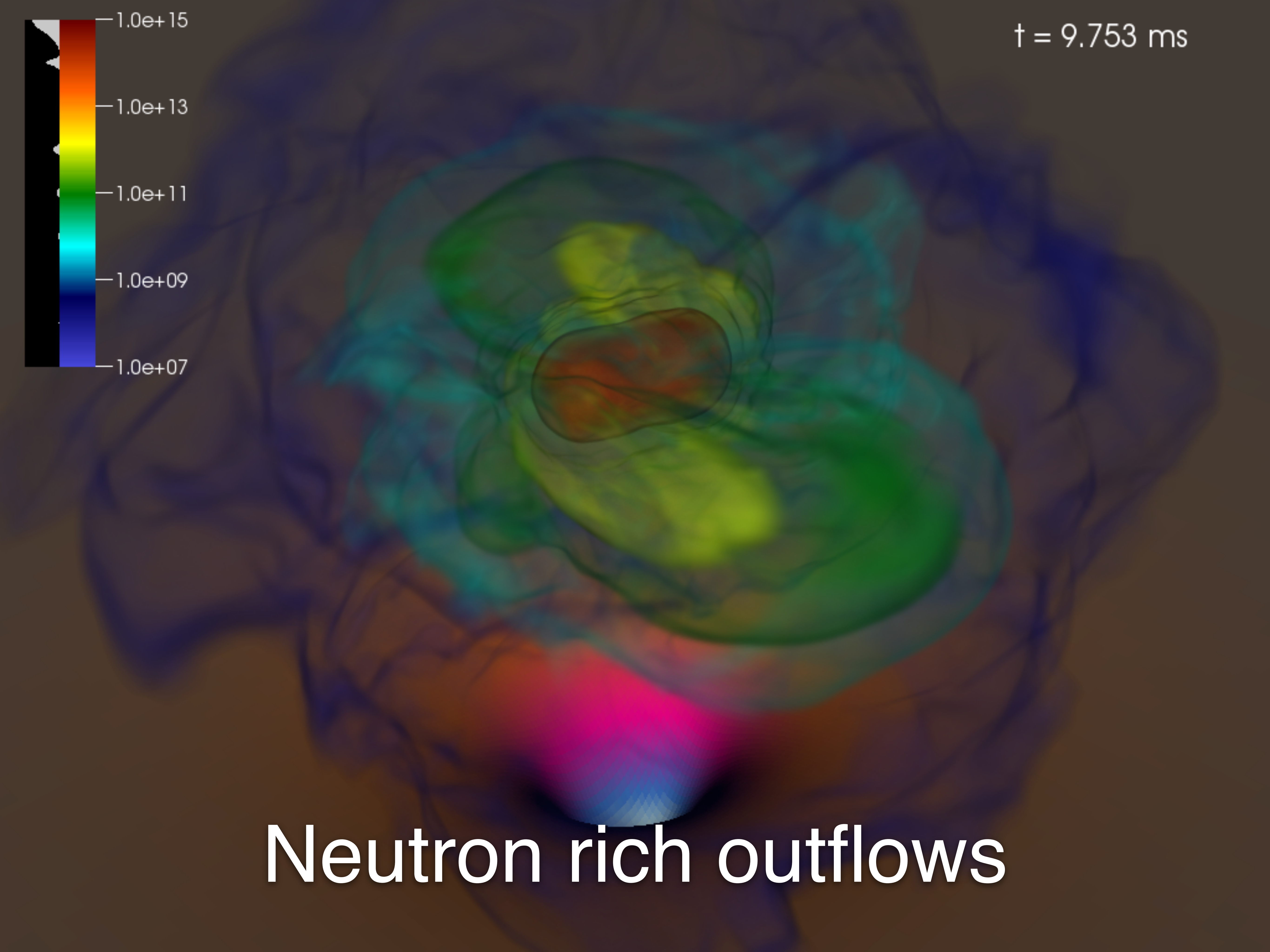
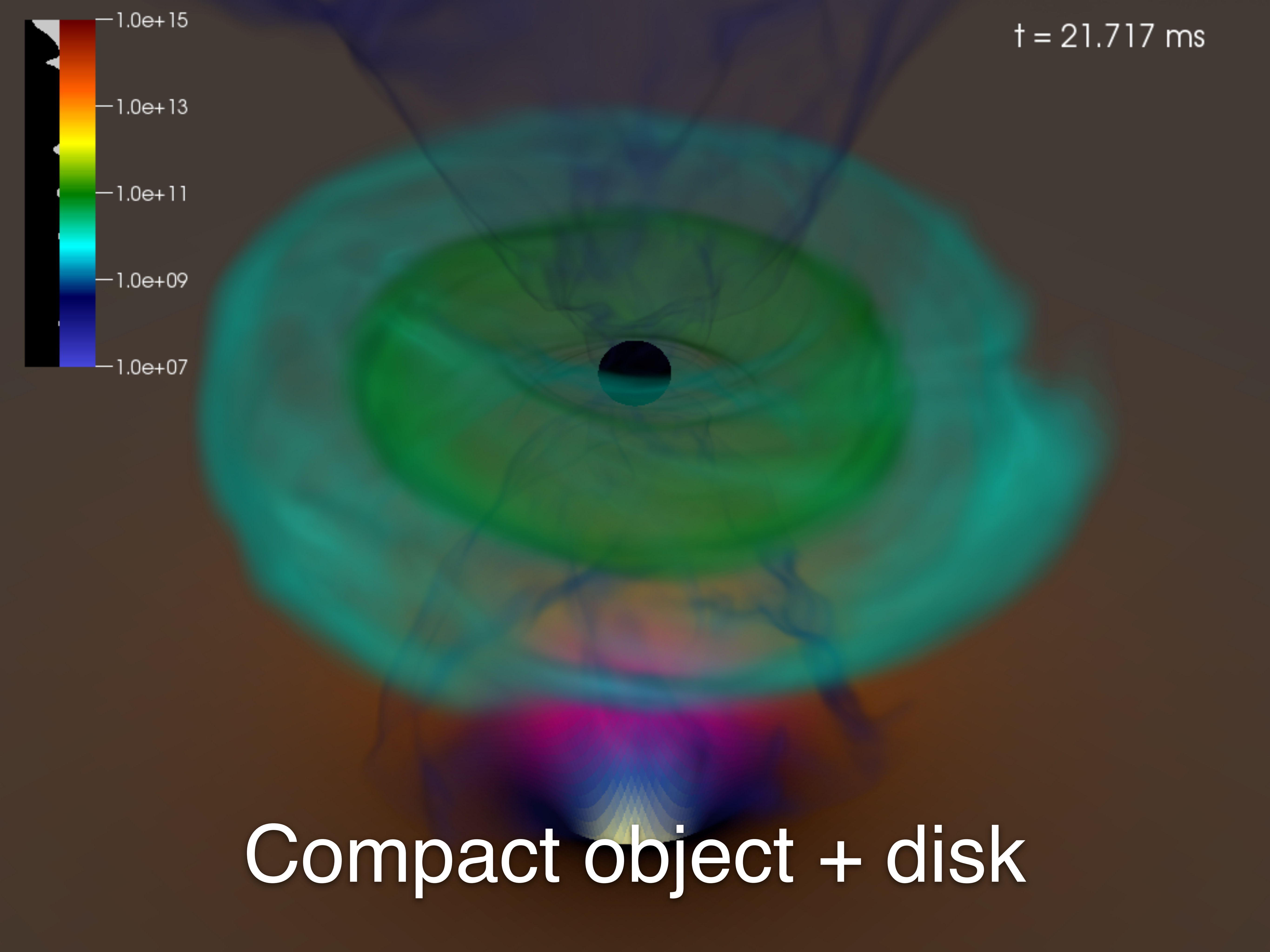
t = 0.000 ms

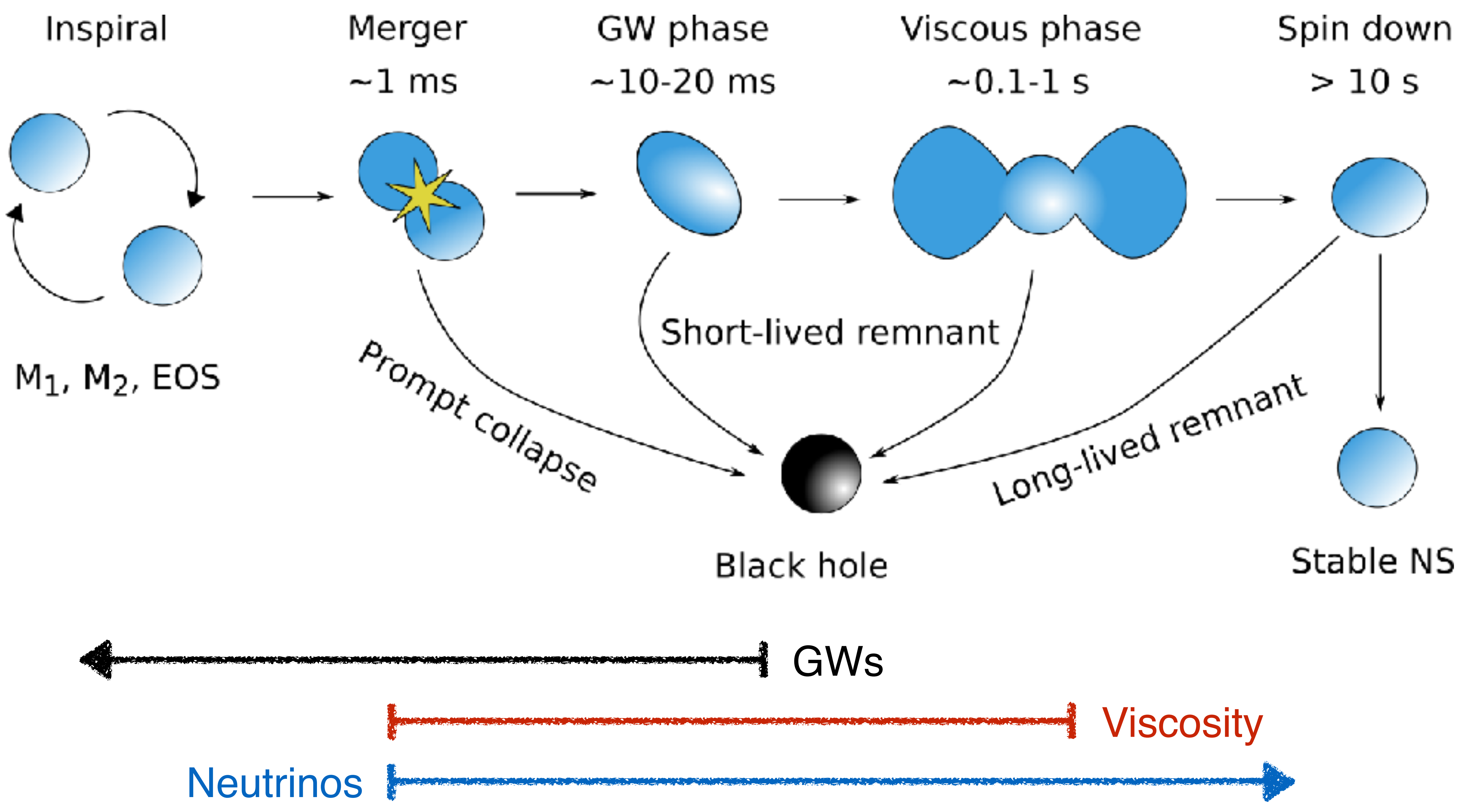


Neutron rich outflows

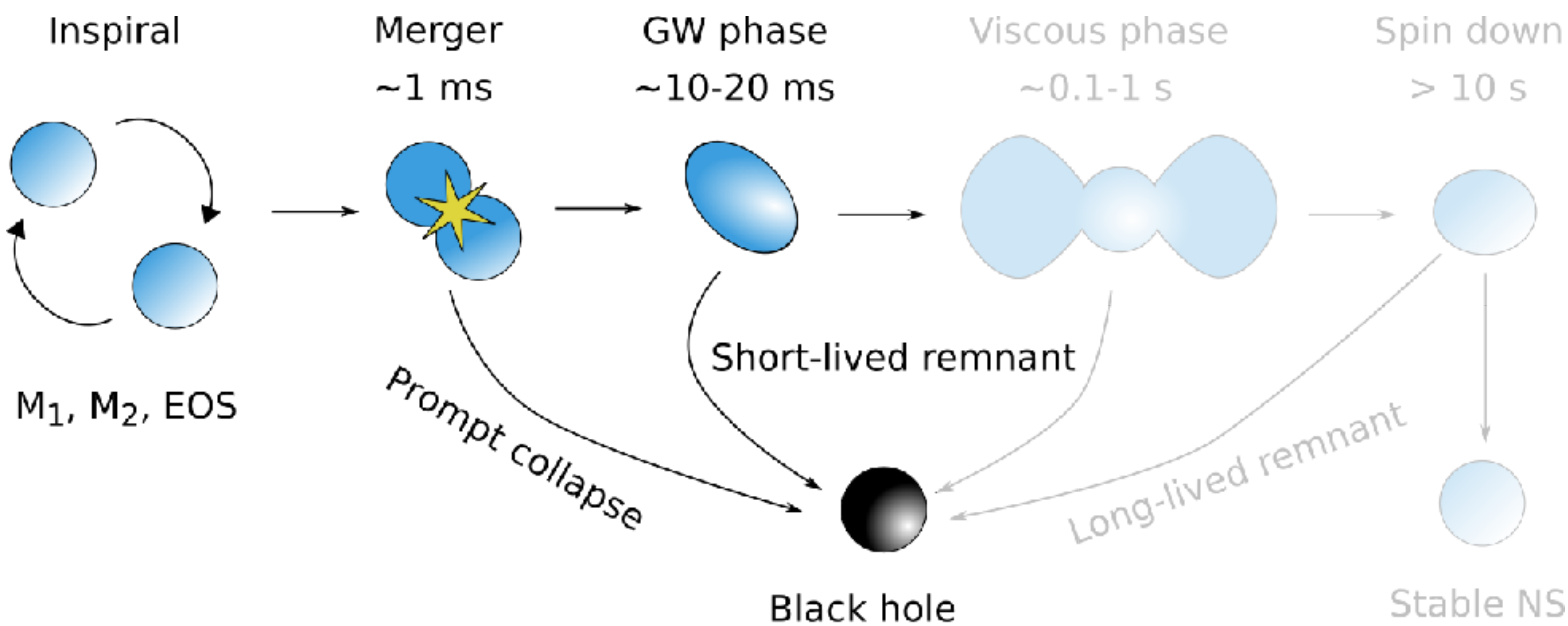


Compact object + disk

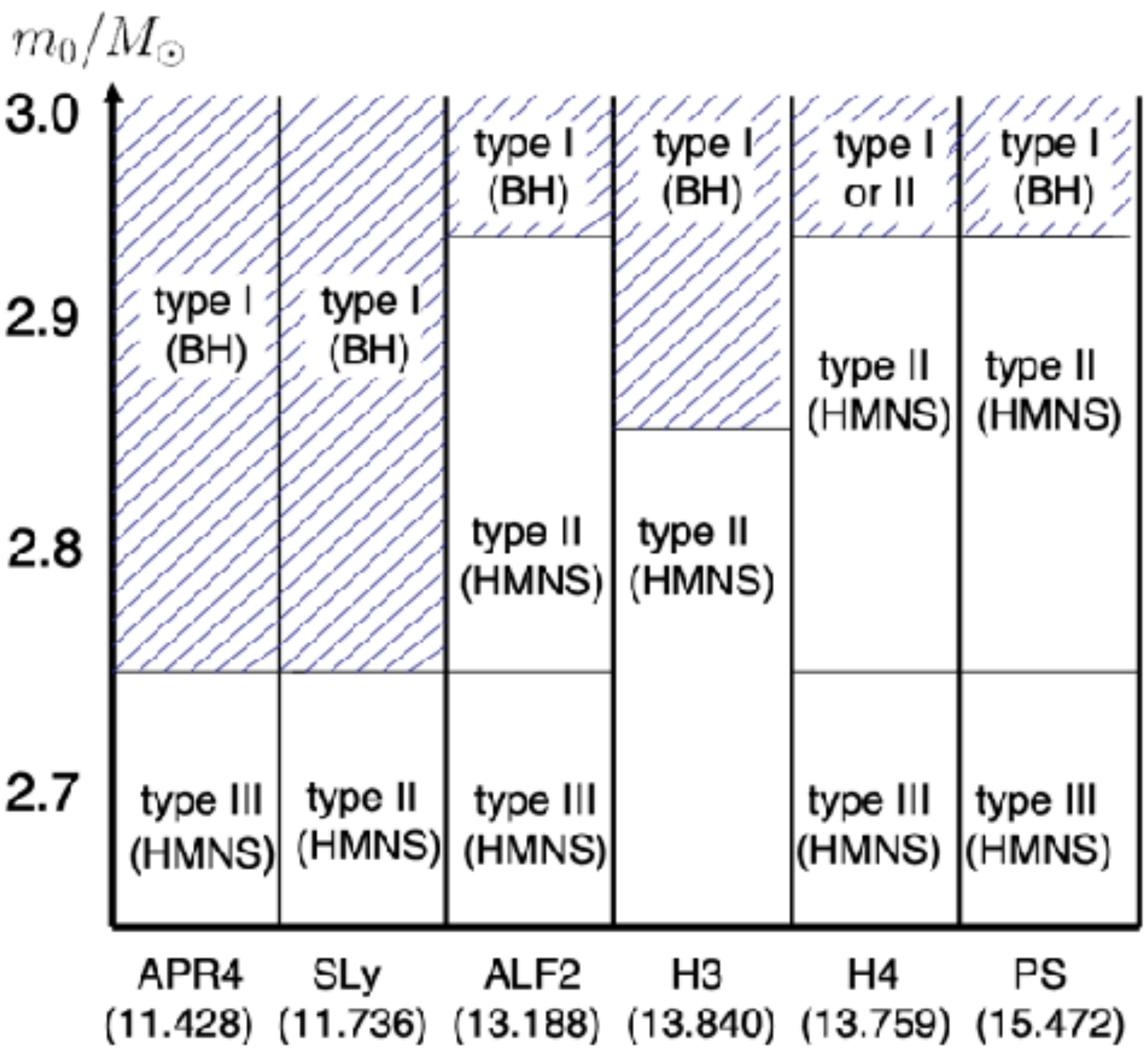
Neutron star merger evolution

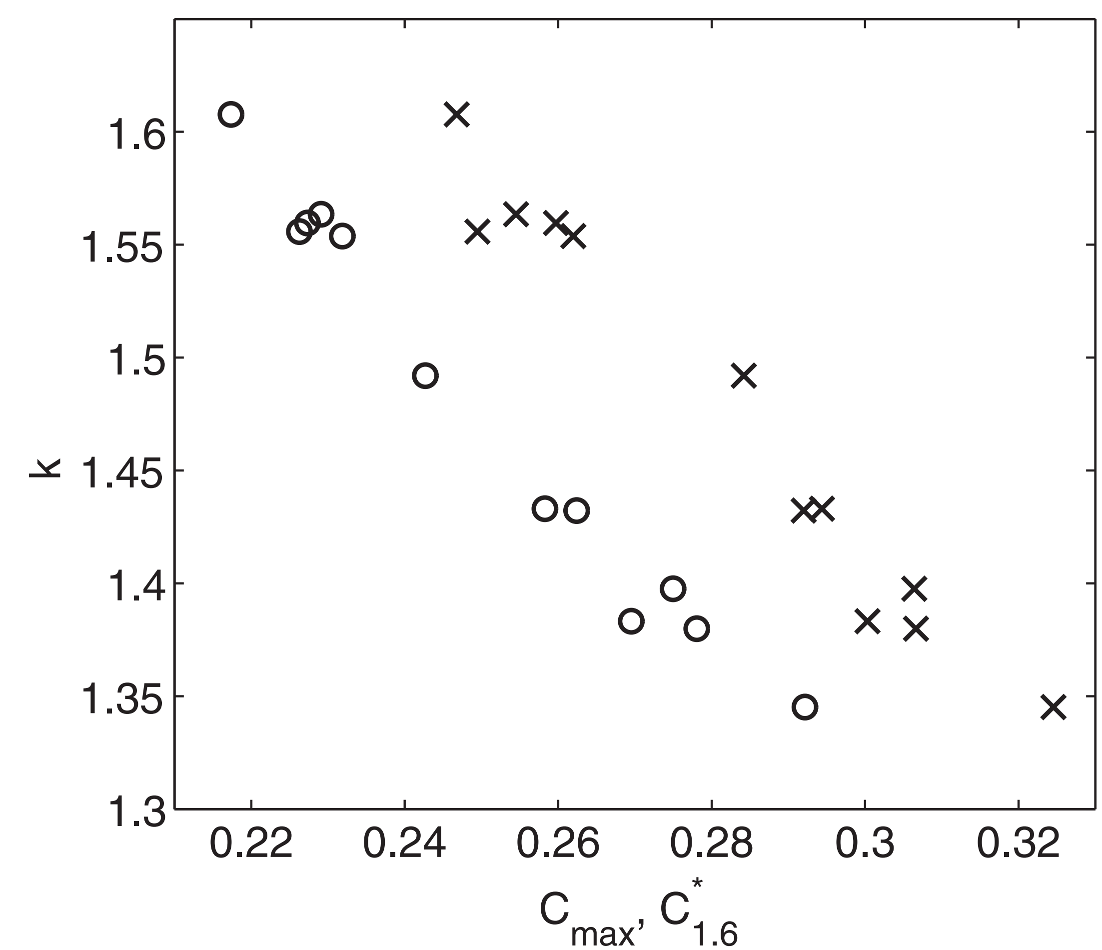


Early postmerger evolution



Prompt BH formation: $q \simeq 1$





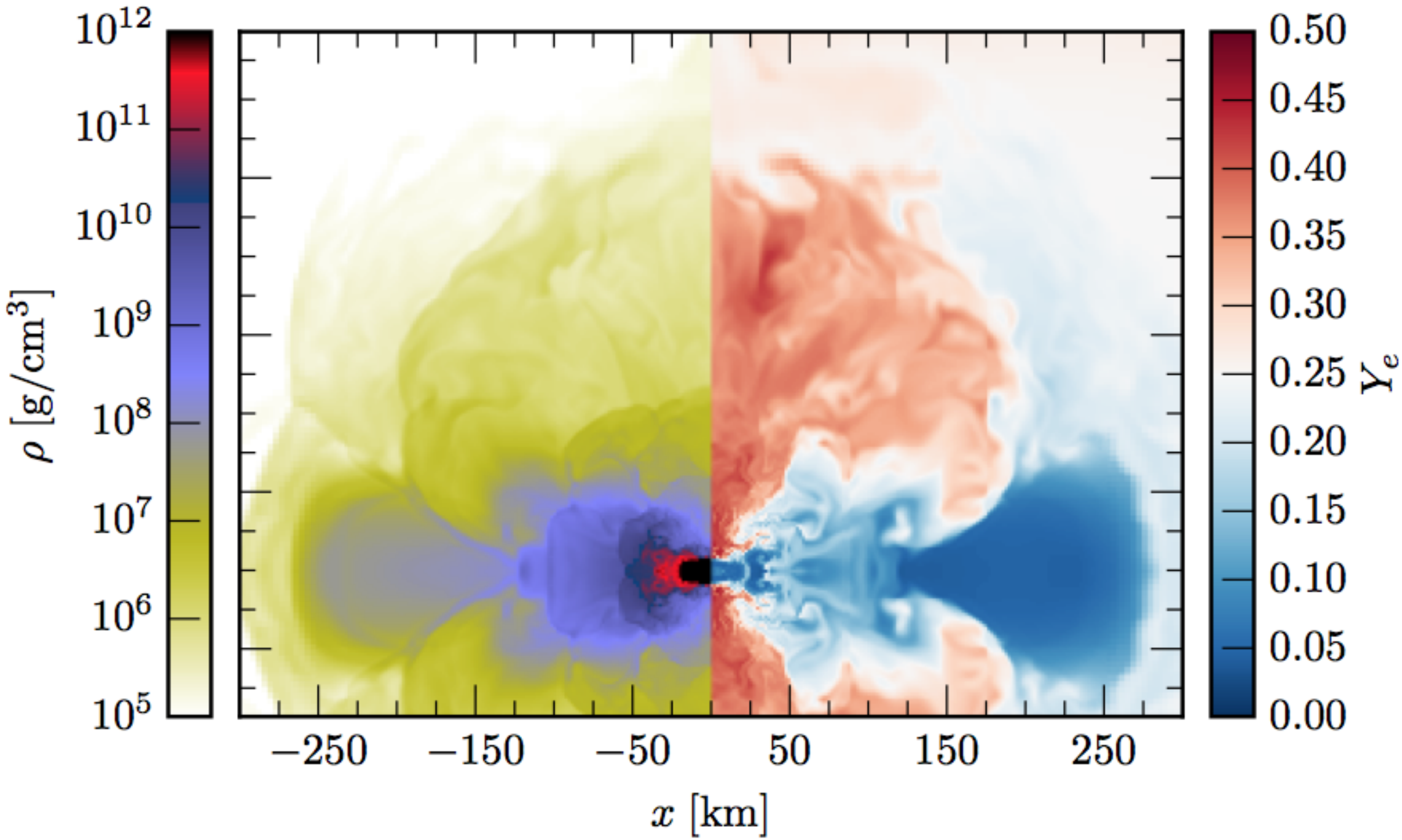
$$M_{\rm thr} = k_{\rm thr} M_{\rm max}$$

From Hotokezaka+ 2011

From Bauswein+ 2013

See also Bauswein+ 2017, Köppel+ 2019, Agathos+ 2019, Bernuzzi+ 2020

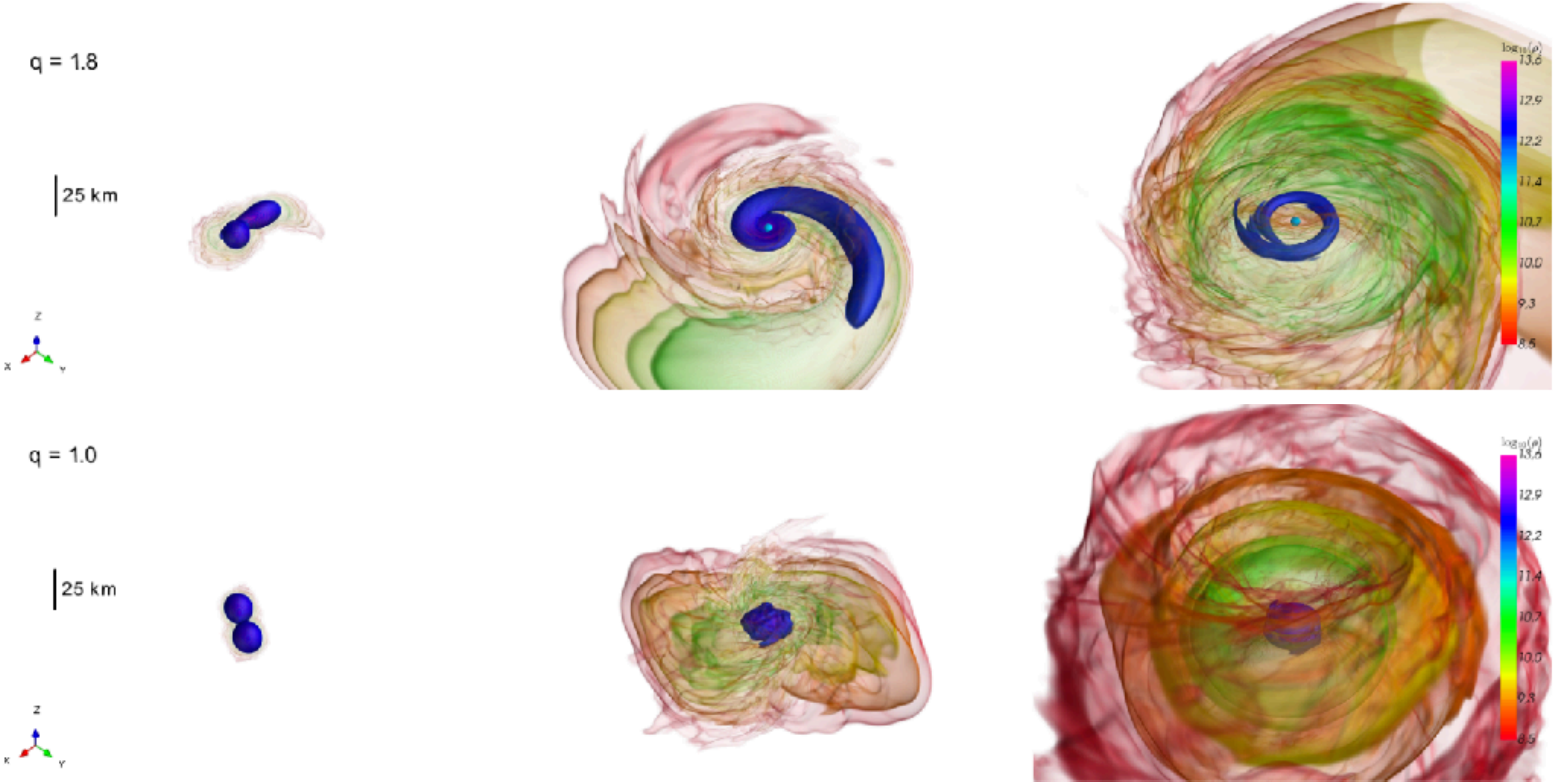
Dynamical mass ejection



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)

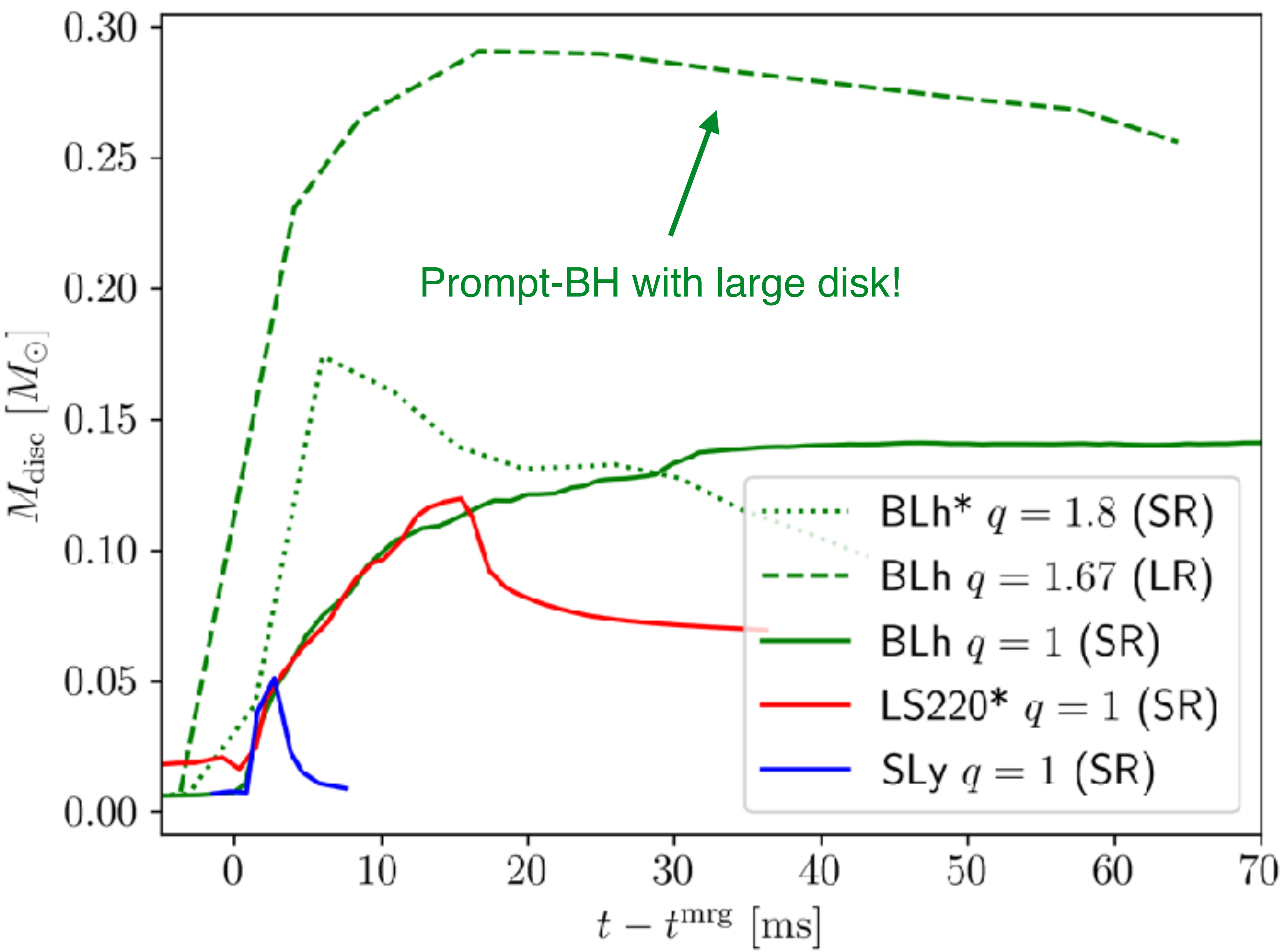
Disk formation I



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

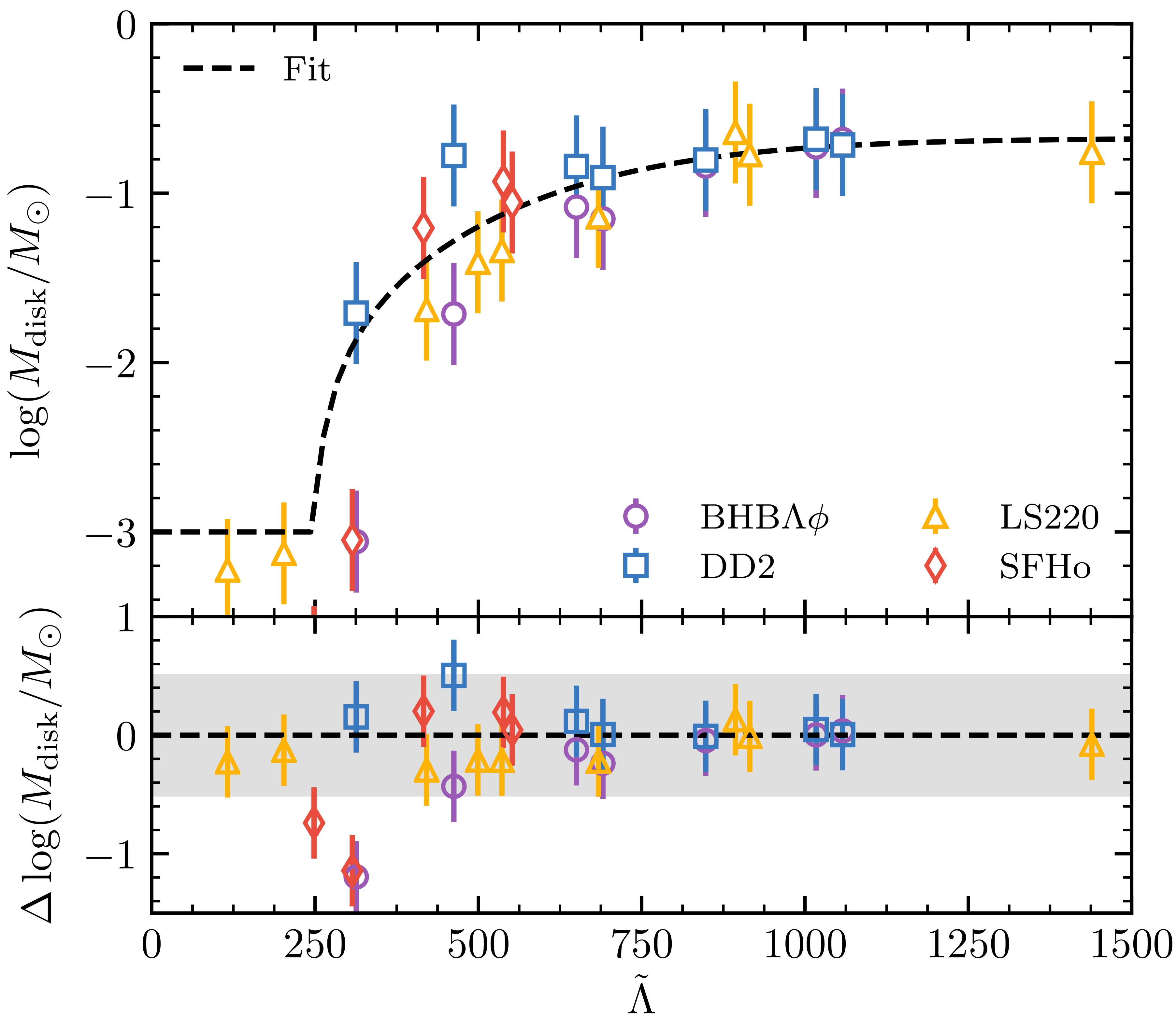
Bernuzzi, …, **DR**+, MNRAS 497:1488 (2020)

Disk formation II



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

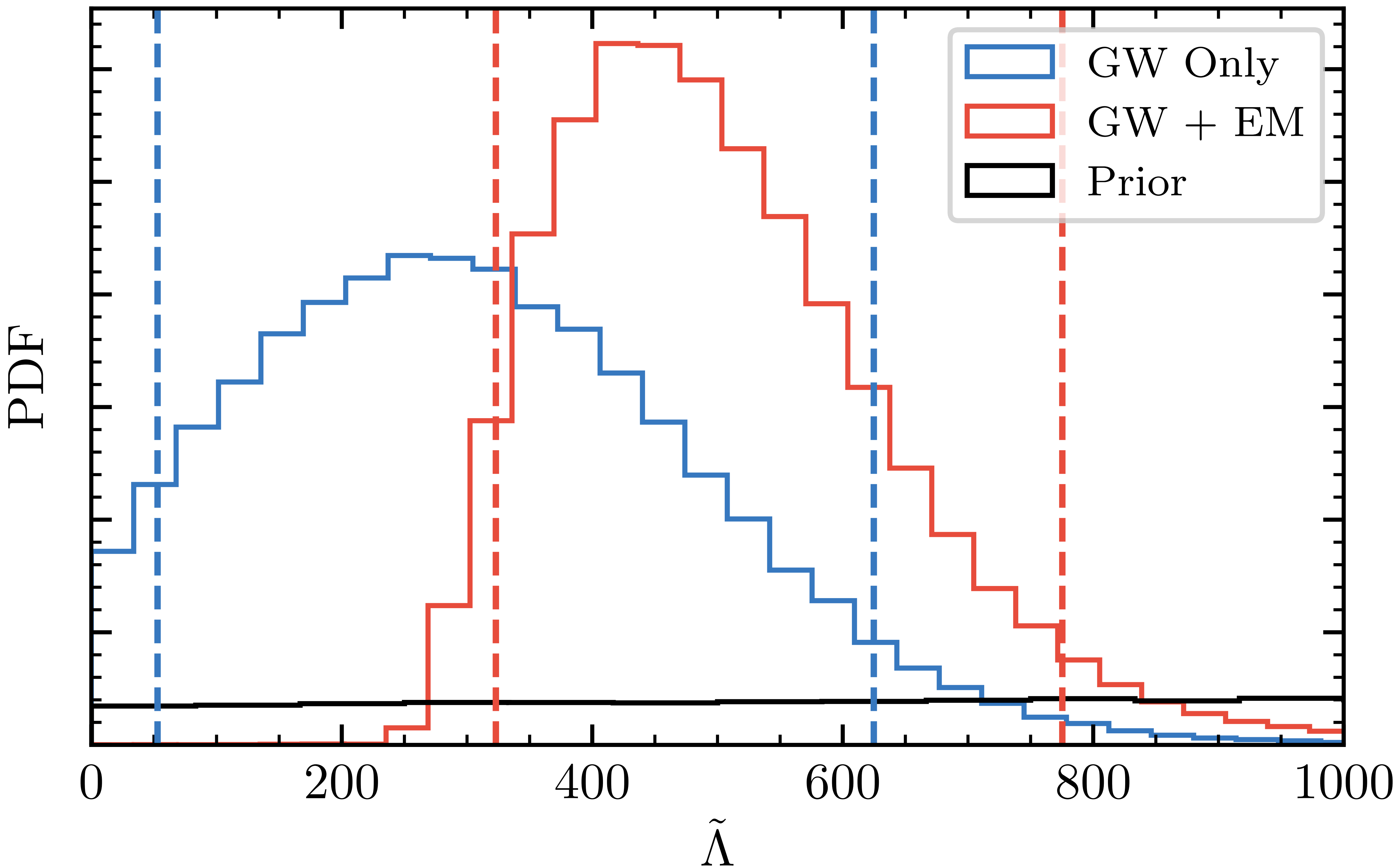
Disk masses



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



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

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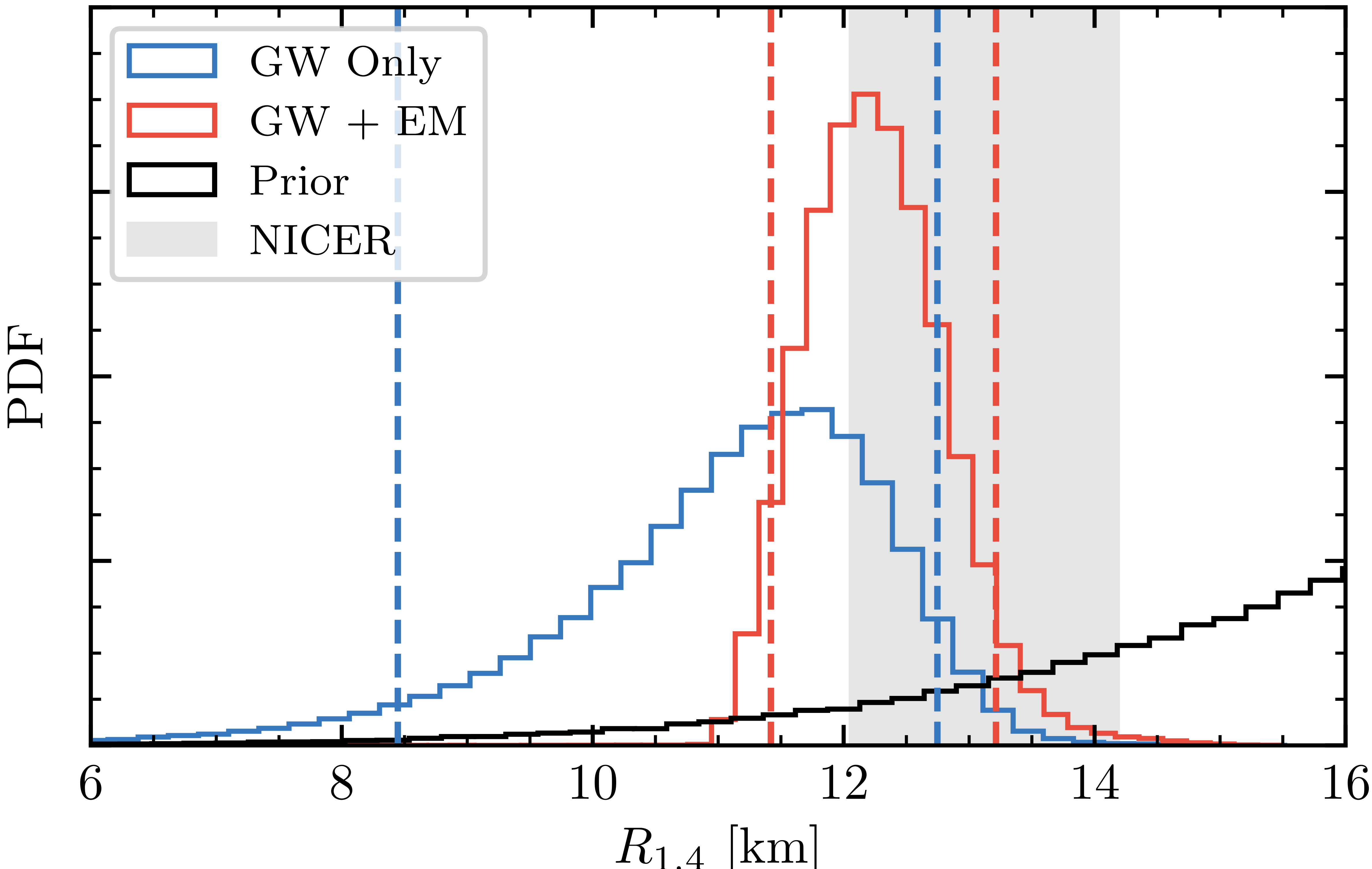

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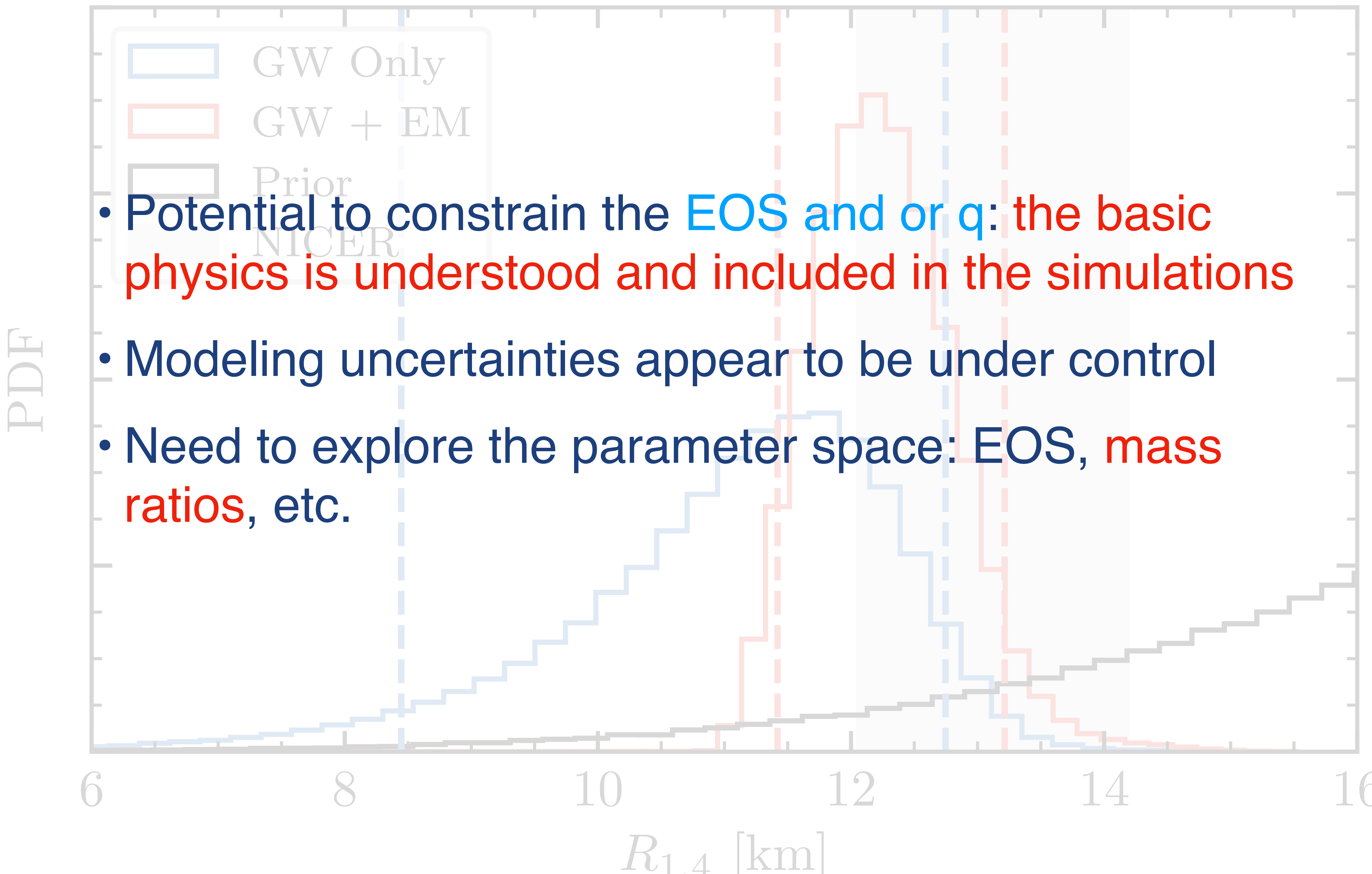
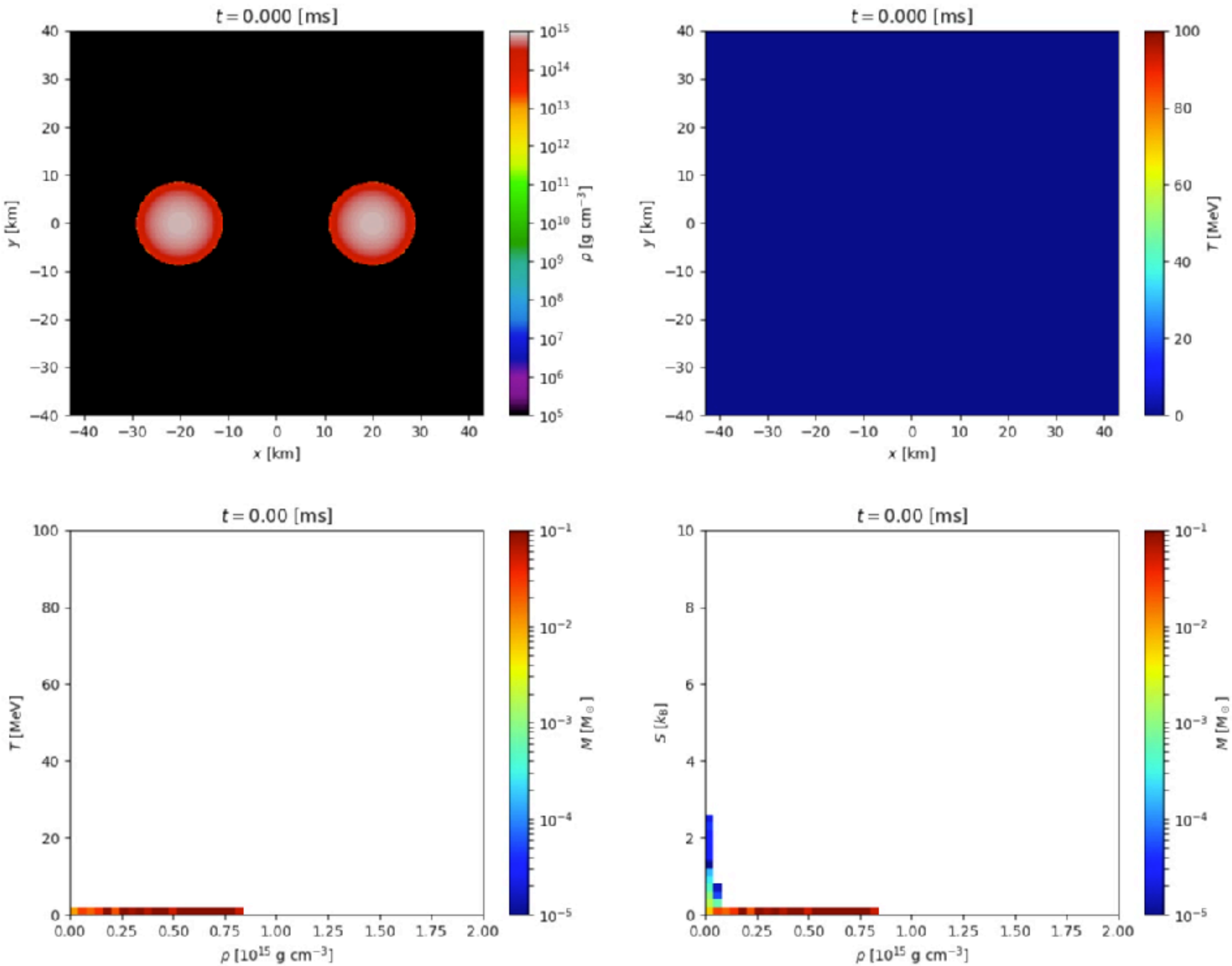
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

Equation of state constraints

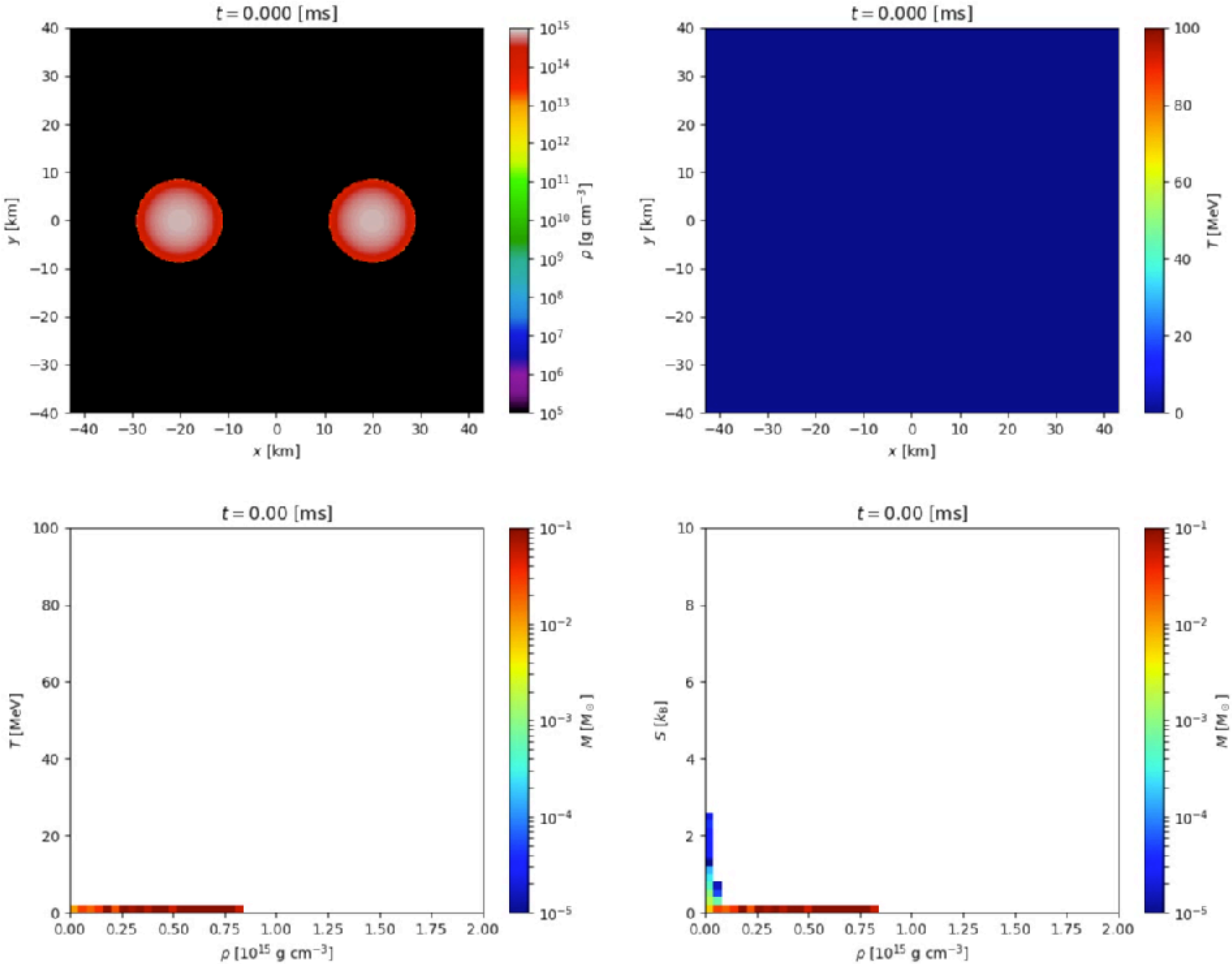


- Potential to constrain the EOS and or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Need to explore the parameter space: EOS, mass ratios, etc.

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



$t = 0.000$ [ms]
y [km]
x [km]
ρ [g cm^{-3}]
$t = 0.000$ [ms]
y [km]
x [km]
T [MeV]
$t = 0.00$ [ms]
T [MeV]
ρ [10^{15} g cm^{-3}]
M [$M_\odot$]
$t = 0.00$ [ms]
S [k_B]
ρ [10^{15} g cm^{-3}]
M [$M_\odot$]



$t = 0.000$ [ms]
y [km]
x [km]
ρ [g cm^{-3}]
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x [km]
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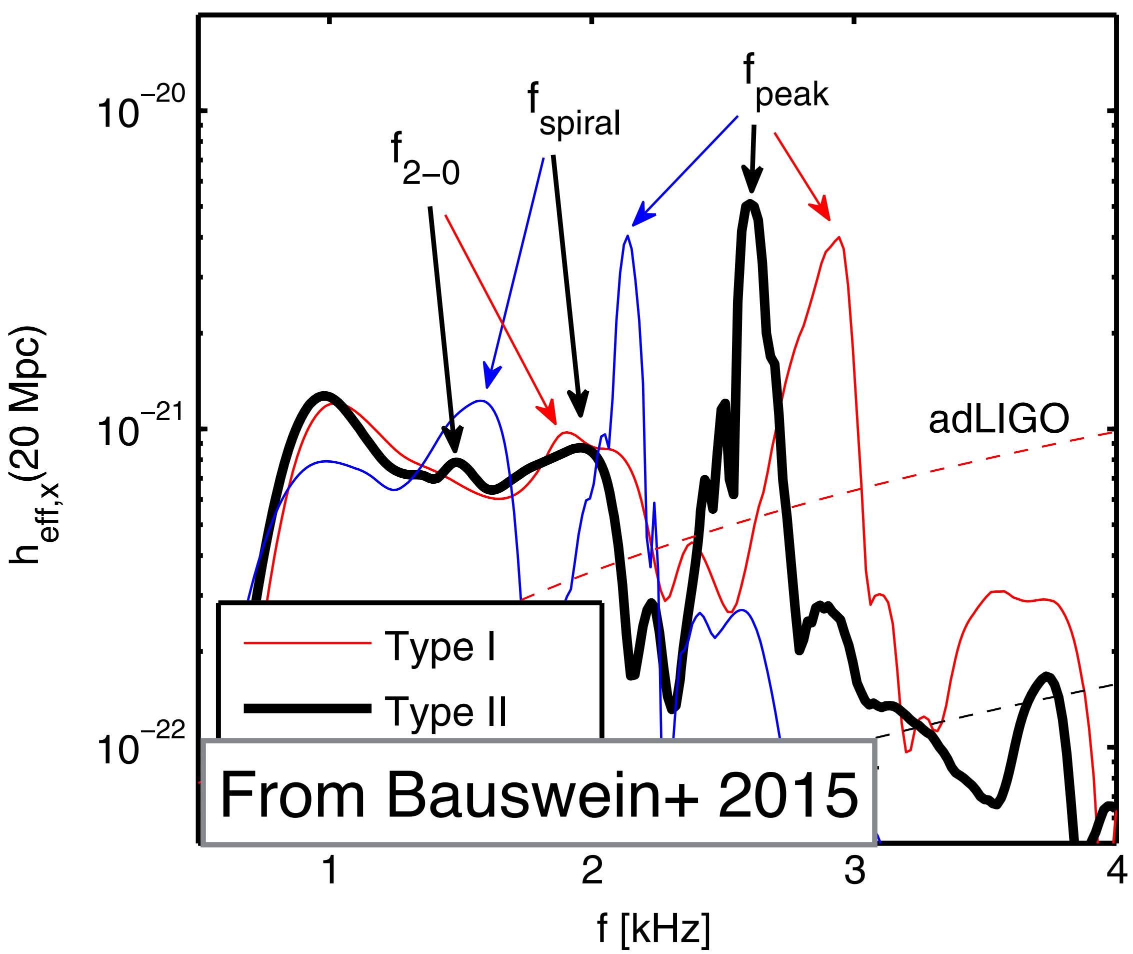
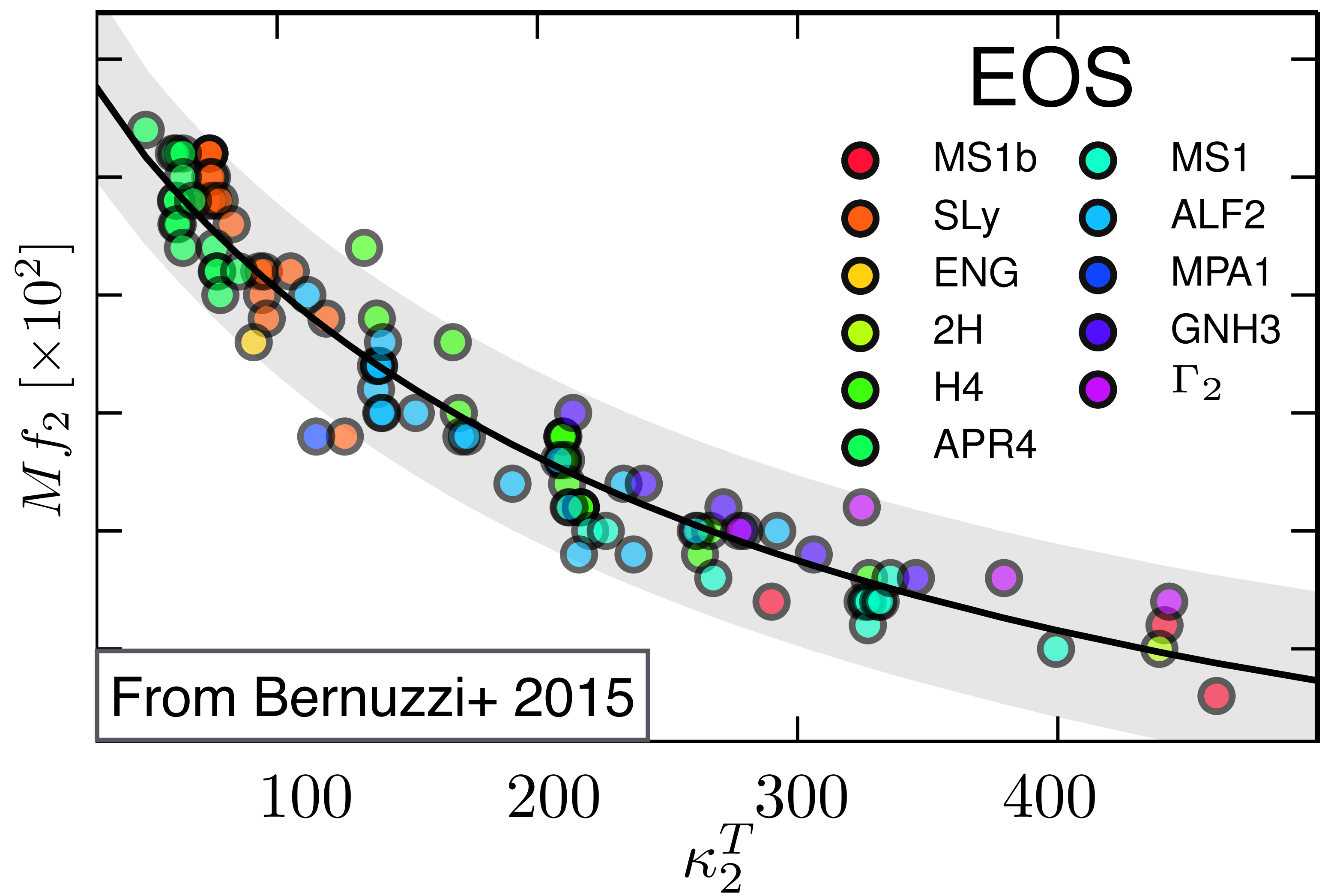
T [MeV]
ρ [10^{15} g cm^{-3}]
M [$M_\odot$]
$t = 0.00$ [ms]
S [k_B]
ρ [10^{15} g cm^{-3}]
M [$M_\odot$]

Postmerger GW signal

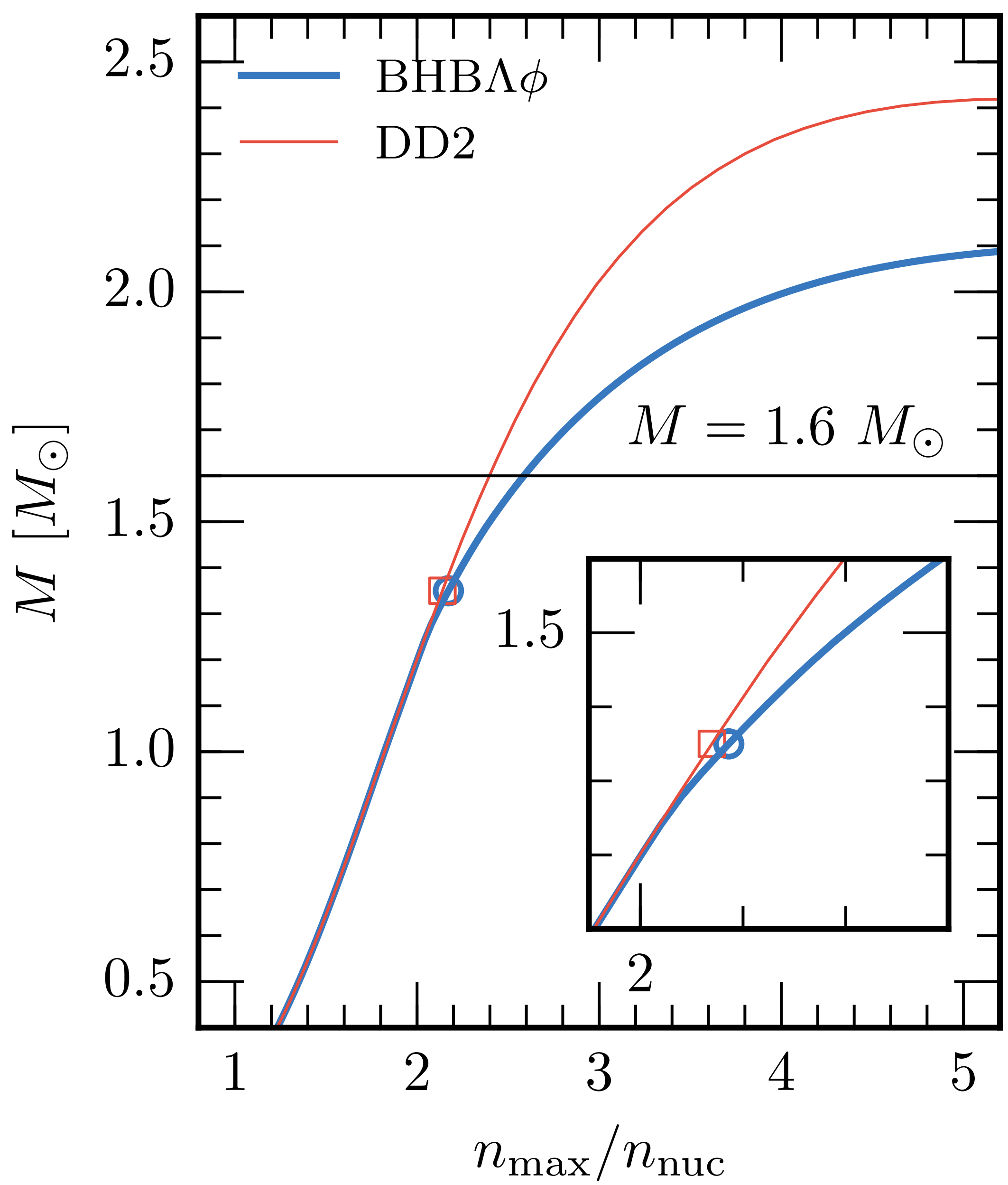


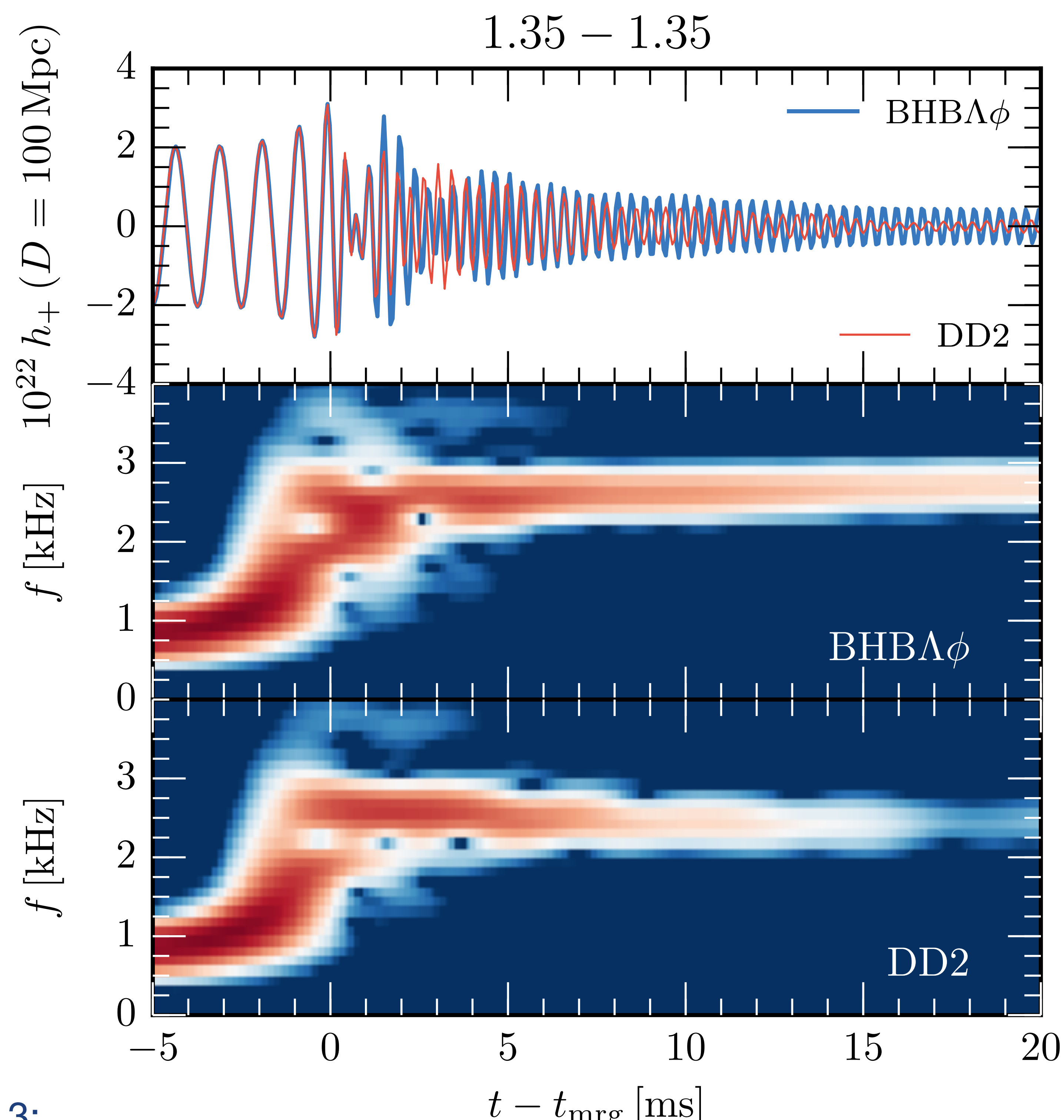


- Post-merger signal has a characteristic peak frequency
- f_{peak} correlates with the NS radius and tidal deformability
- Small statistical uncertainty, systematics not understood yet

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bose+ 2017; …

High density EOS (I)

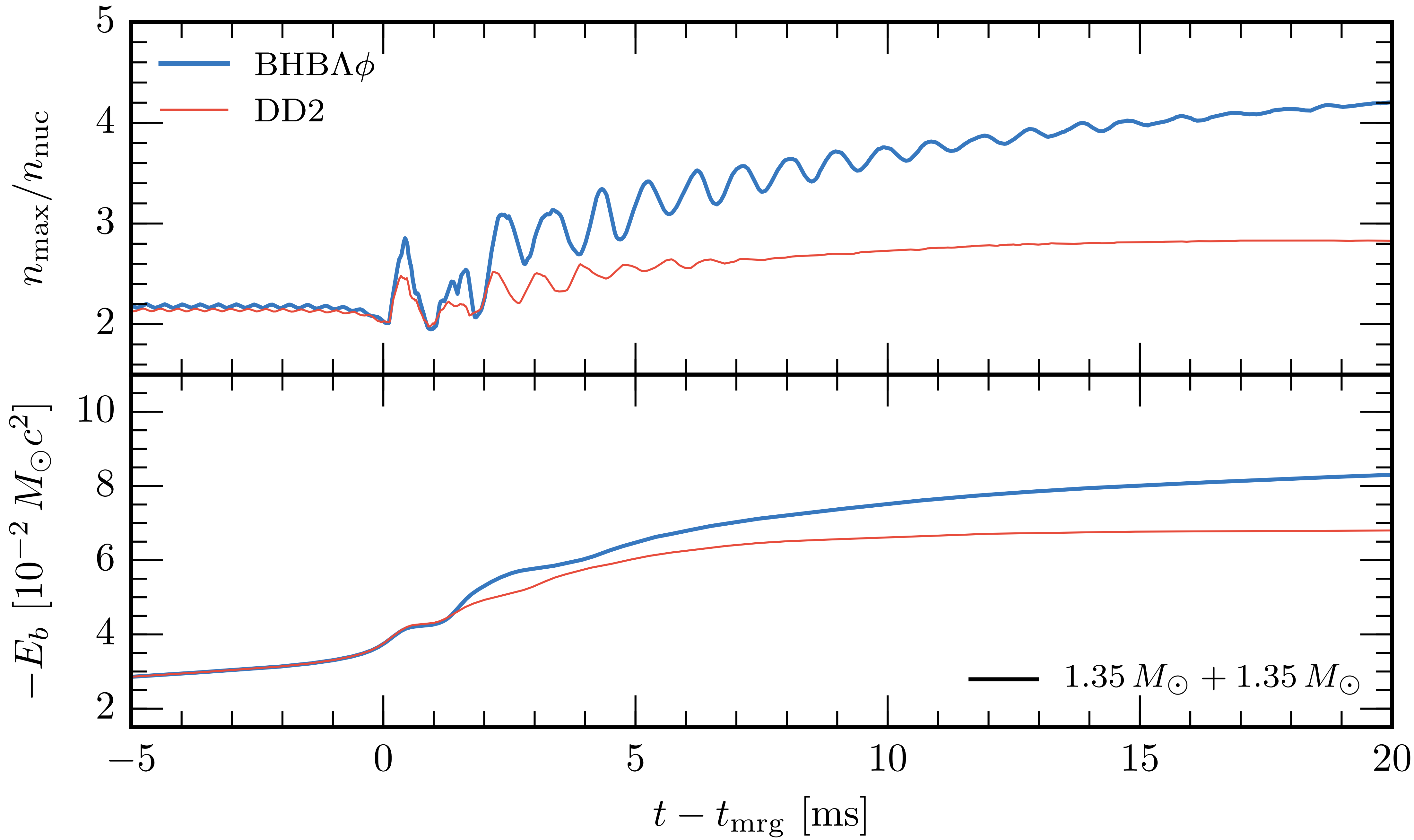




See also Bauswein+ 2011, 2013; 2015, Read+ 2013; Hotokezaka+ 2013, Takami+ 2014, Bernuzzi+ 2015; Clark+ 2014, 2016; Bose+ 2017; Chatziioannou 2017; Most+ 2019; Bausswein+ 2019…

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

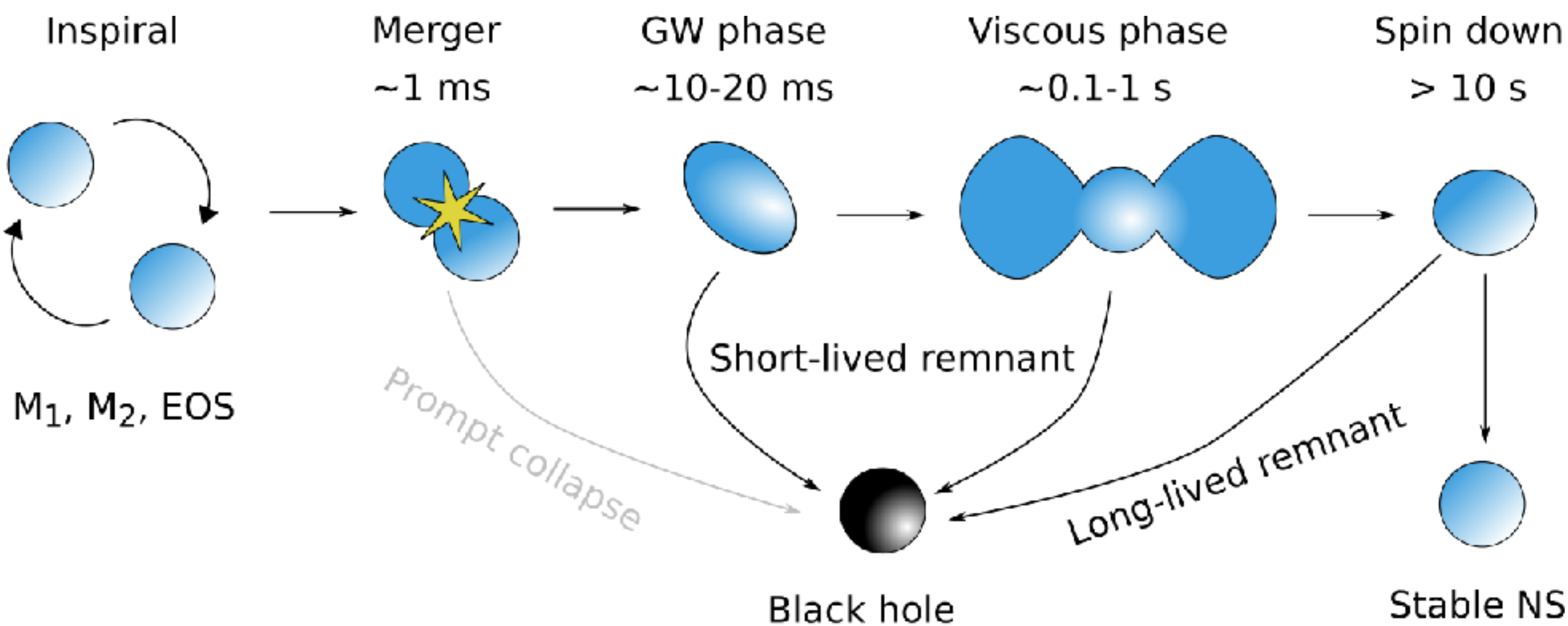
High density EOS (II)



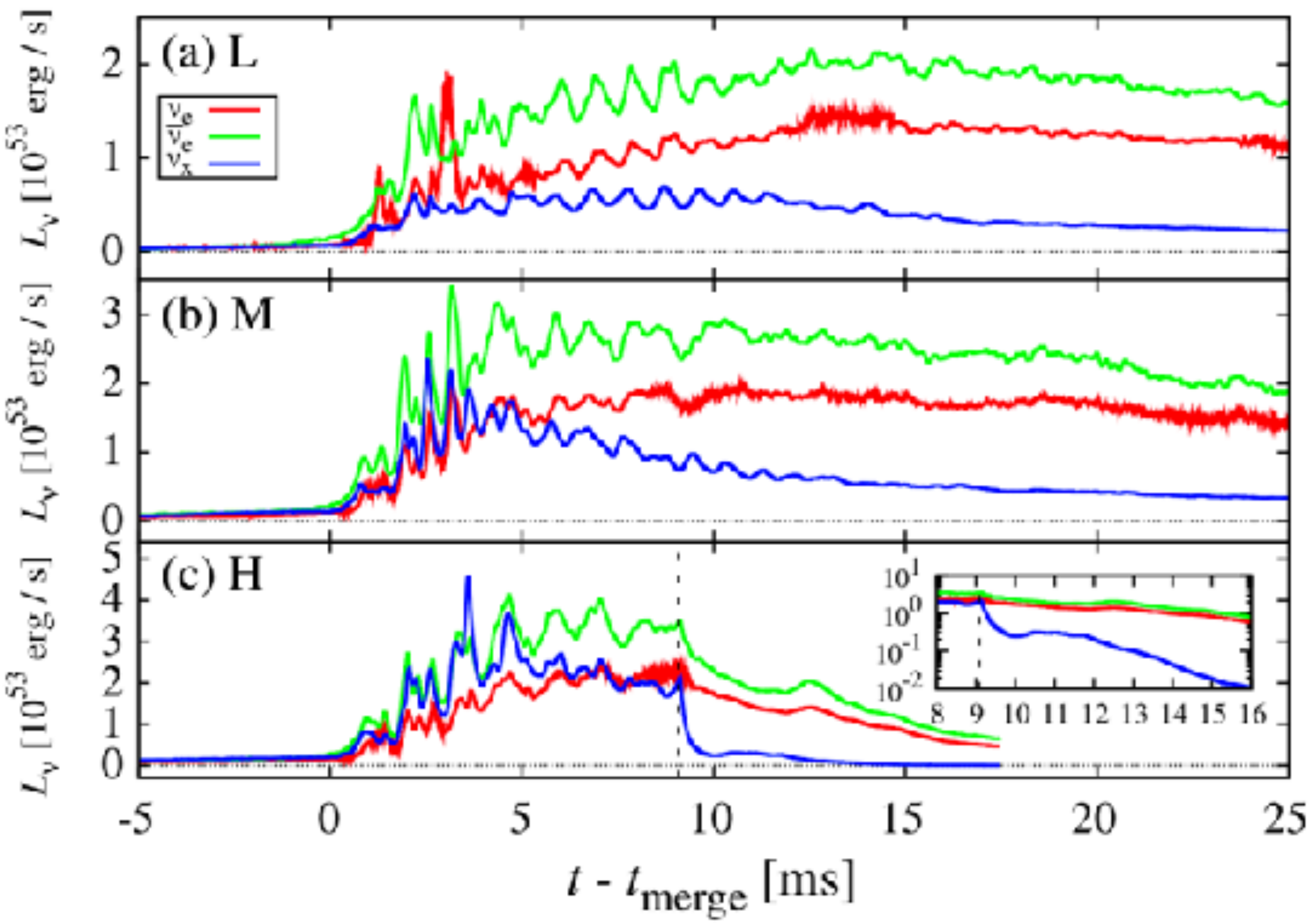
High-density EOS encoded in the binding energy

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

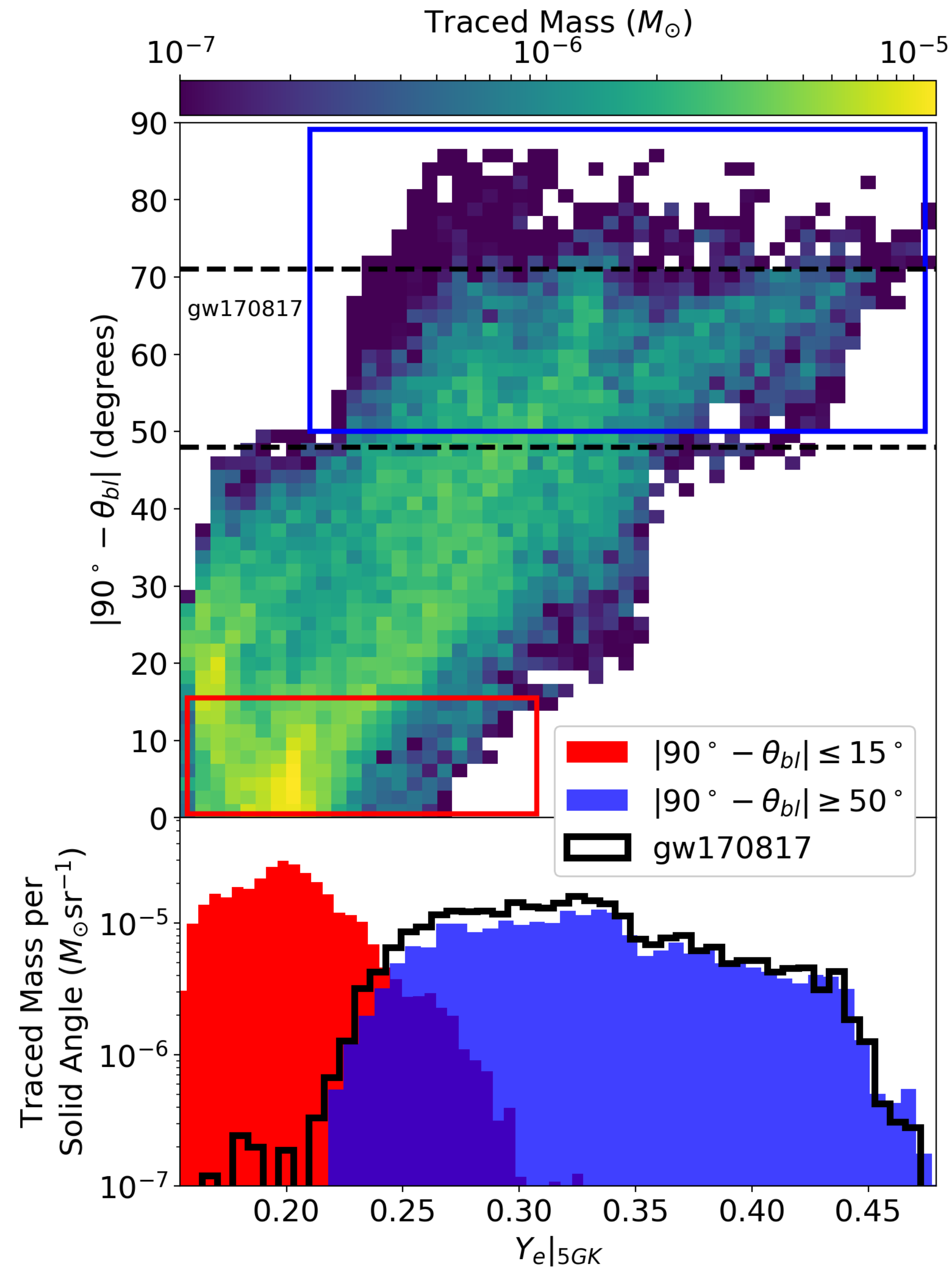
Long-term evolution



Neutrino physics



From Sekiguchi+ 2011

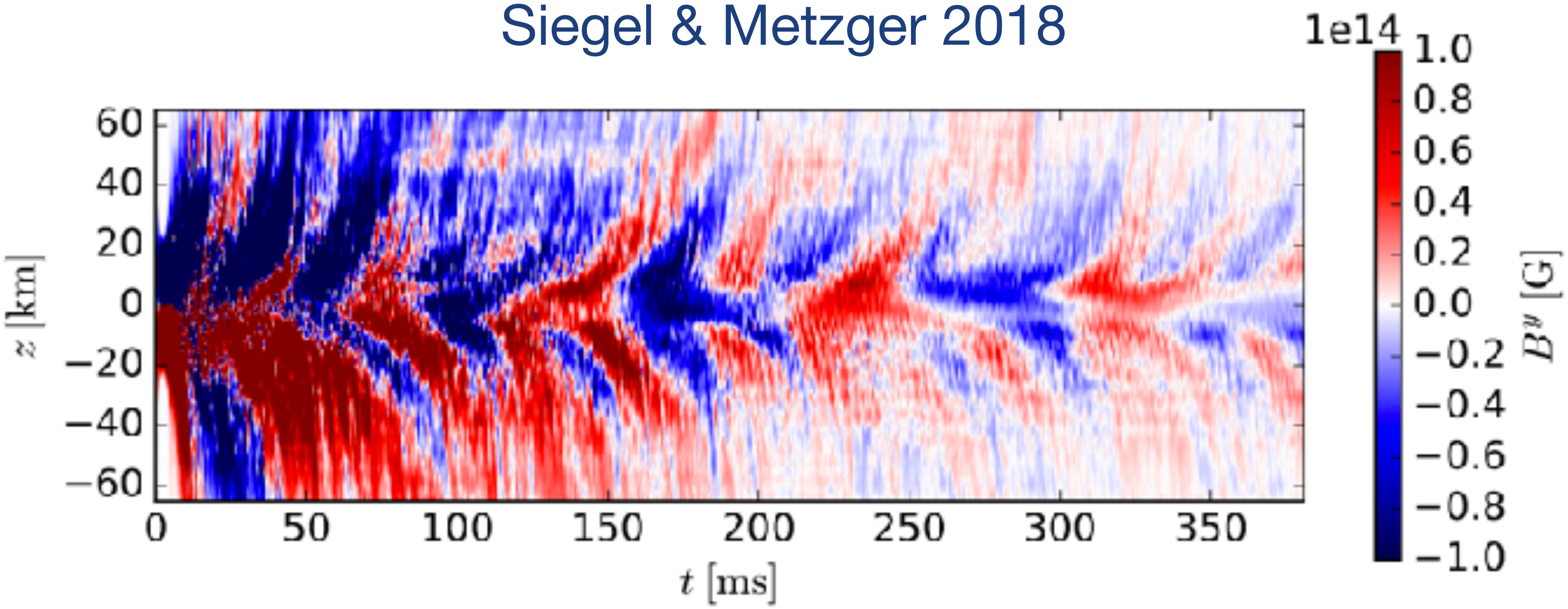


From Miller+ 2019

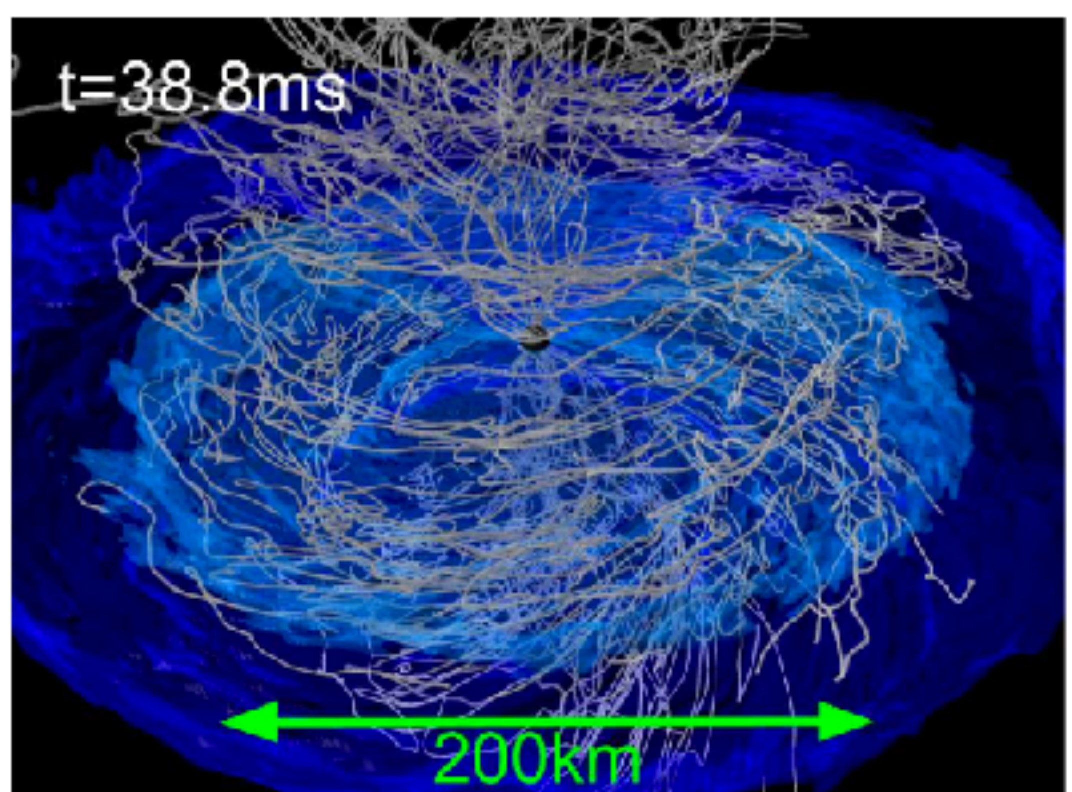
See also: Dessart+ 2008, Perego+ 2014, Just+ 2015, Metzger+ 2014, Foucart+ 2016, Siegel & Metzger 2018, Foucart+ 2020, …

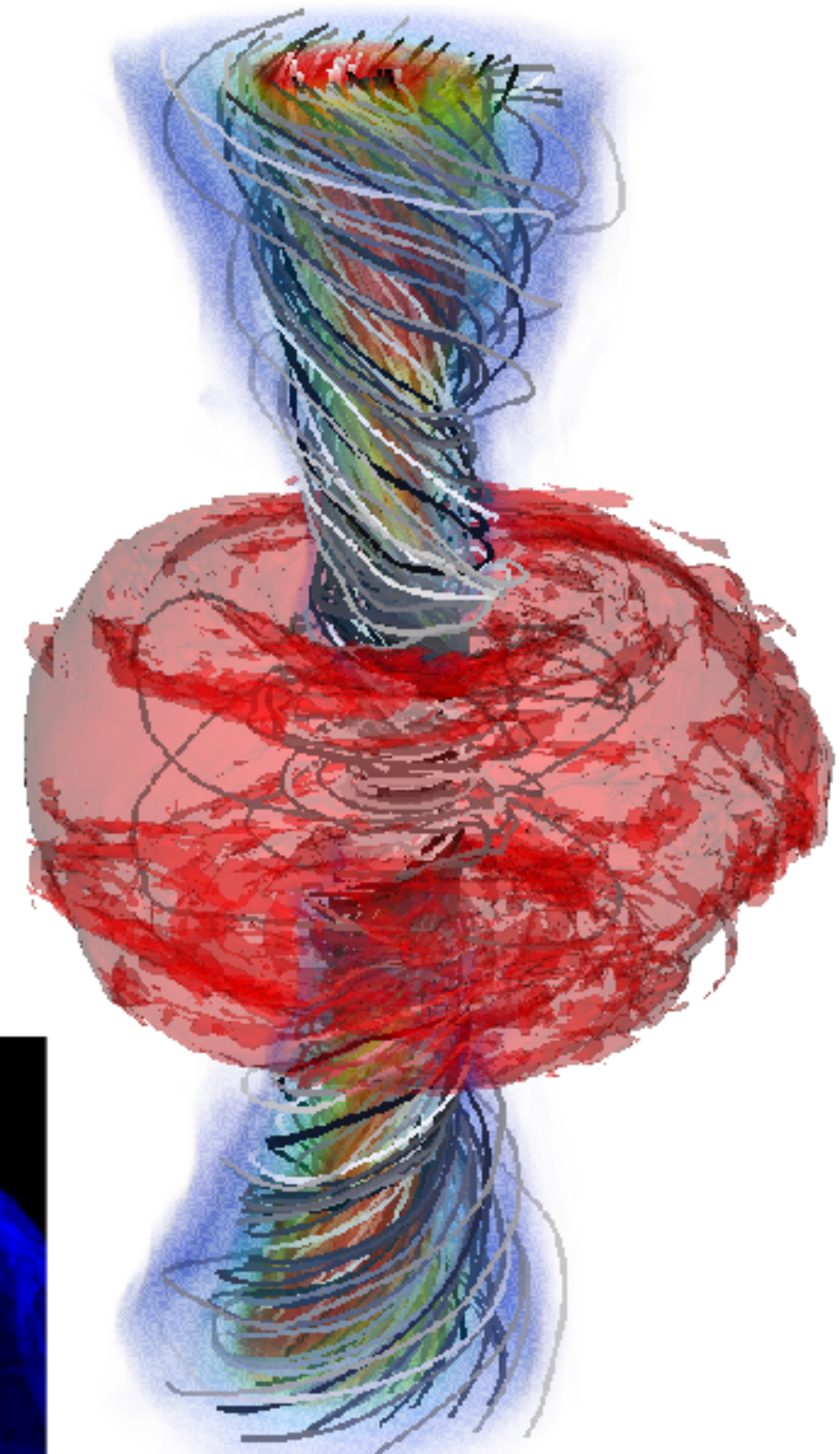
MHD turbulence

Siegel & Metzger 2018



Kiuchi+ 2014



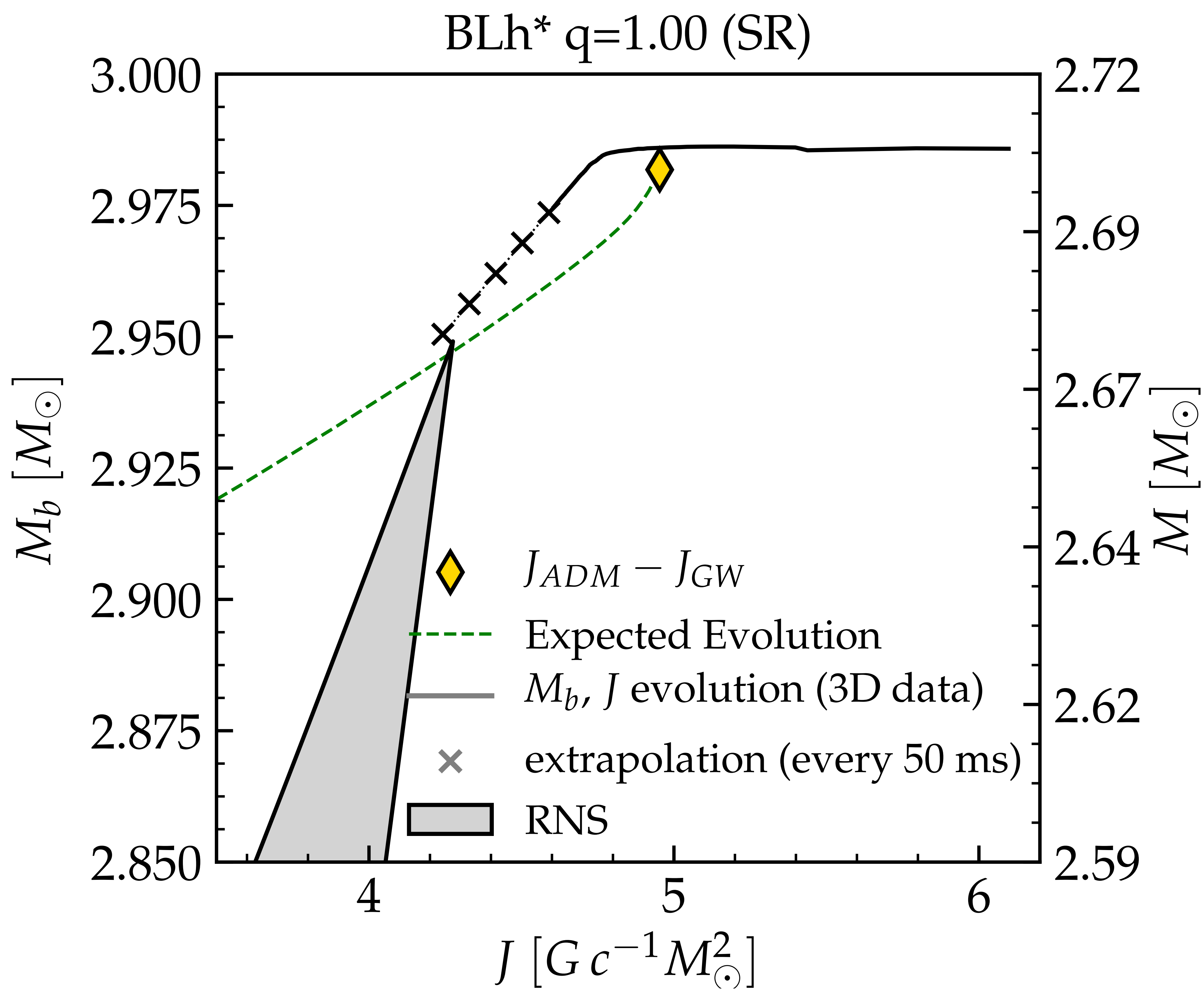


Mösta, **DR**+ 2020

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**+, arXiv: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.