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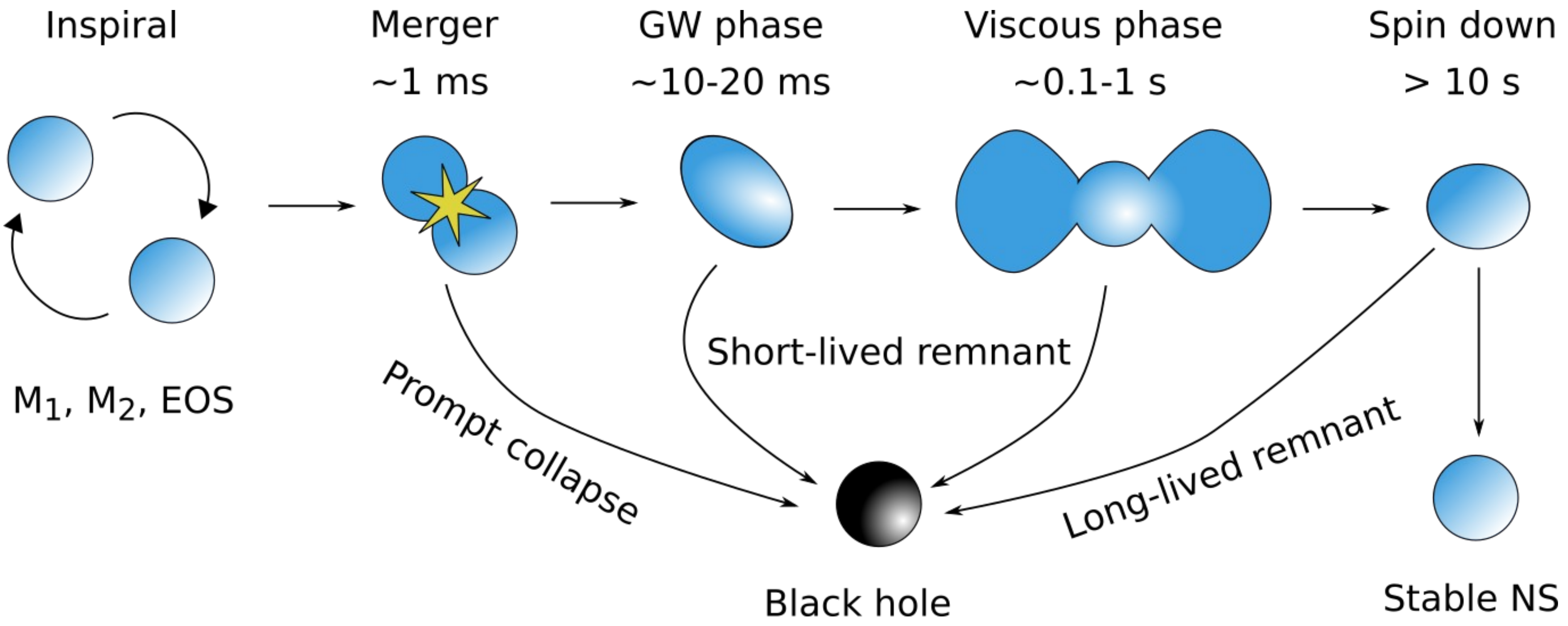
Binary Neutron Star Mergers: Dynamics and Multimessenger Aspects

David Radice – Oct. 13, 2022

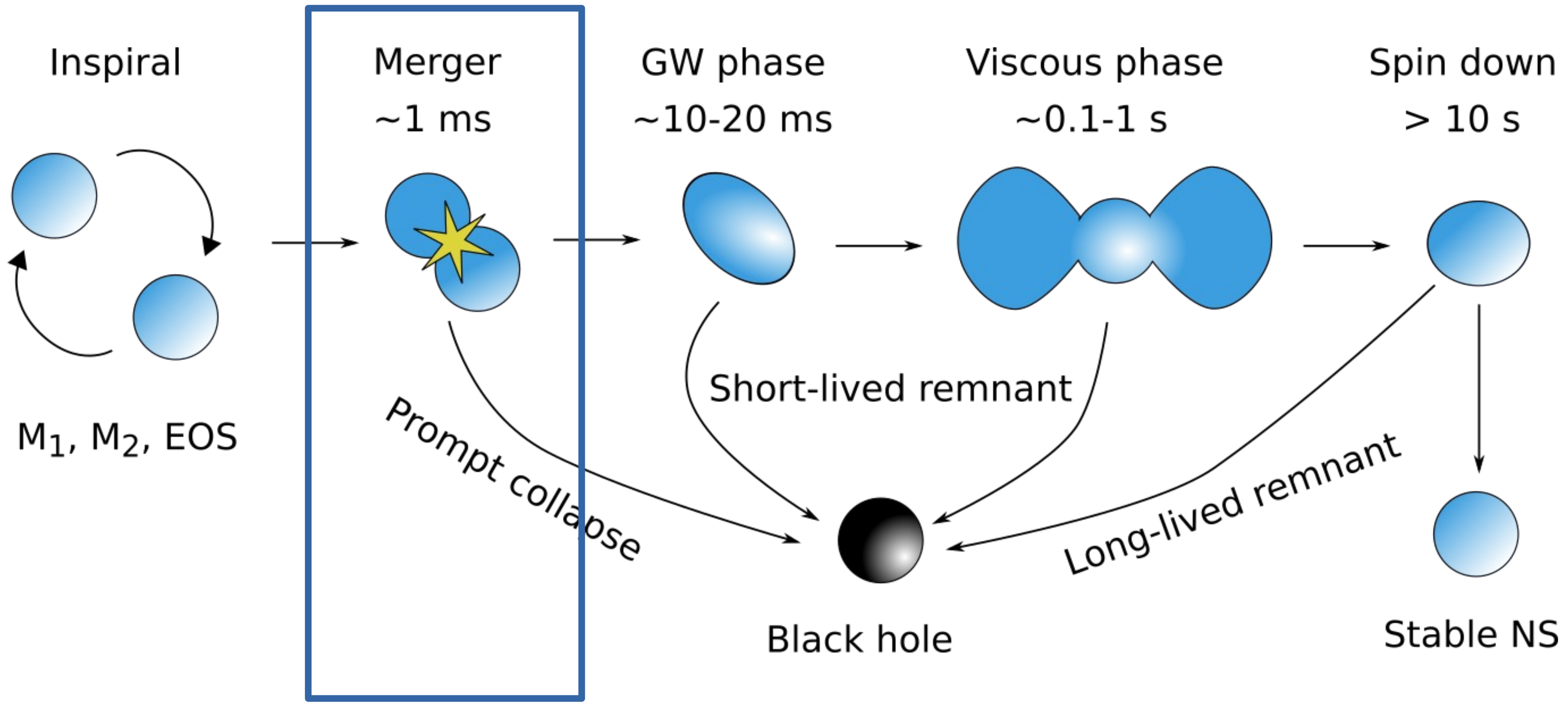
NP3M
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER
NSF
NASA

NS mergers roadmap



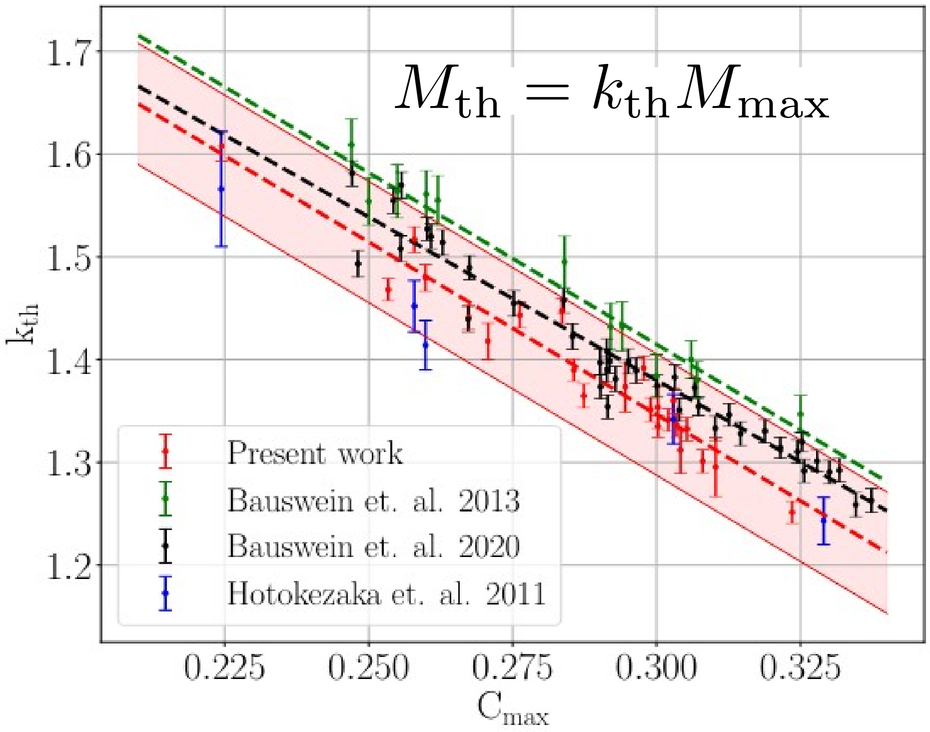
From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)

NS mergers roadmap



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

Prompt collapse: q ≈ 1

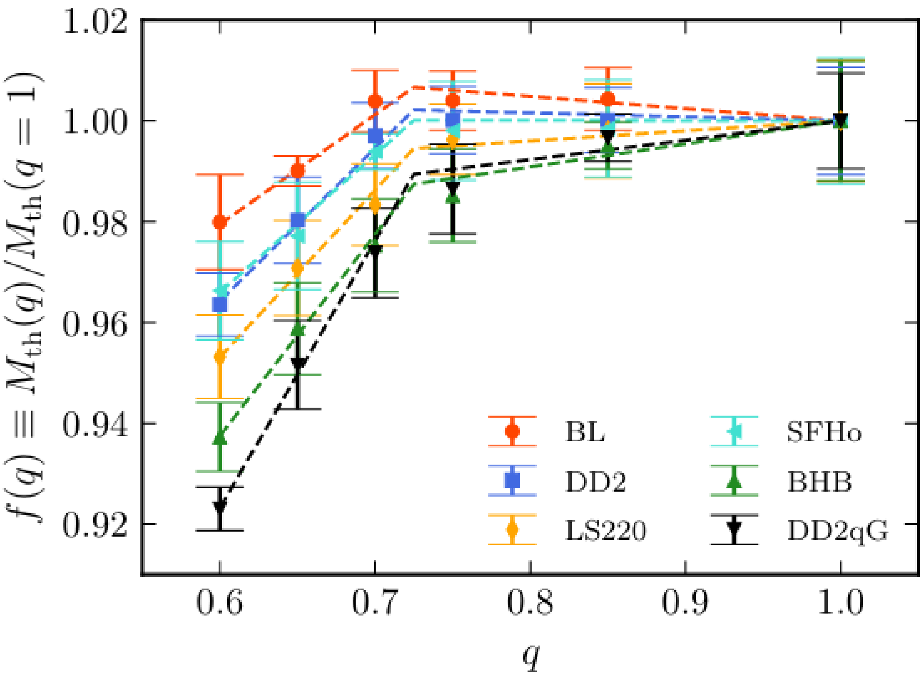


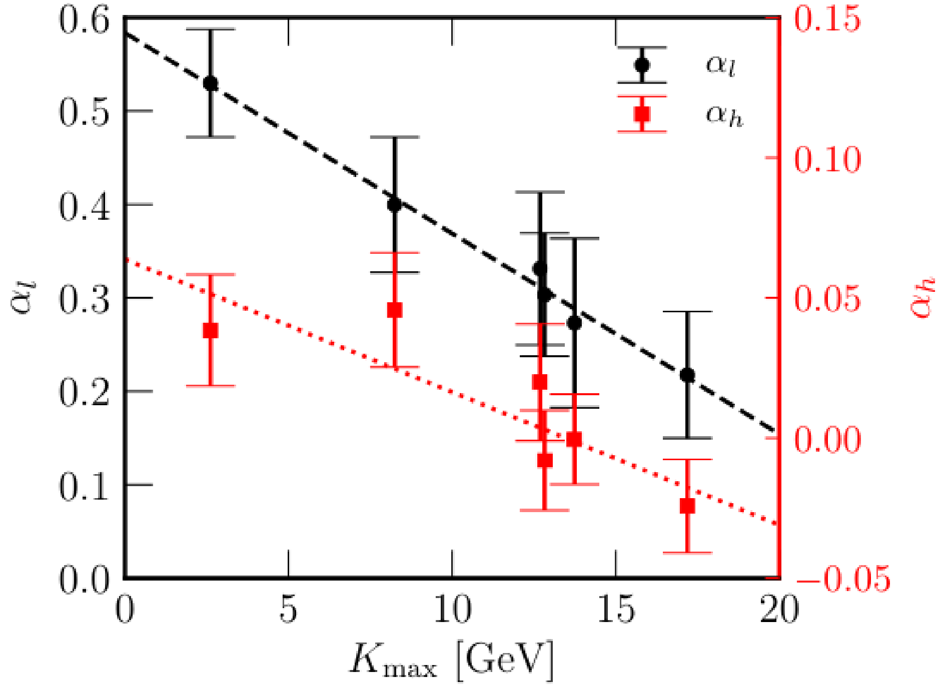
- Prompt collapse: no bounce after merger, direct BH formation
- EOS has a qualitative impact
- If $q \simeq 1$ expected to be EM quiet
- Alternative: use postmerger GWs (likely with 3G)
- Needs of high-quality NR data

See also Hotokezaka+ 11, Bauswein 2013, 2020, Koeppel 2019, ...

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

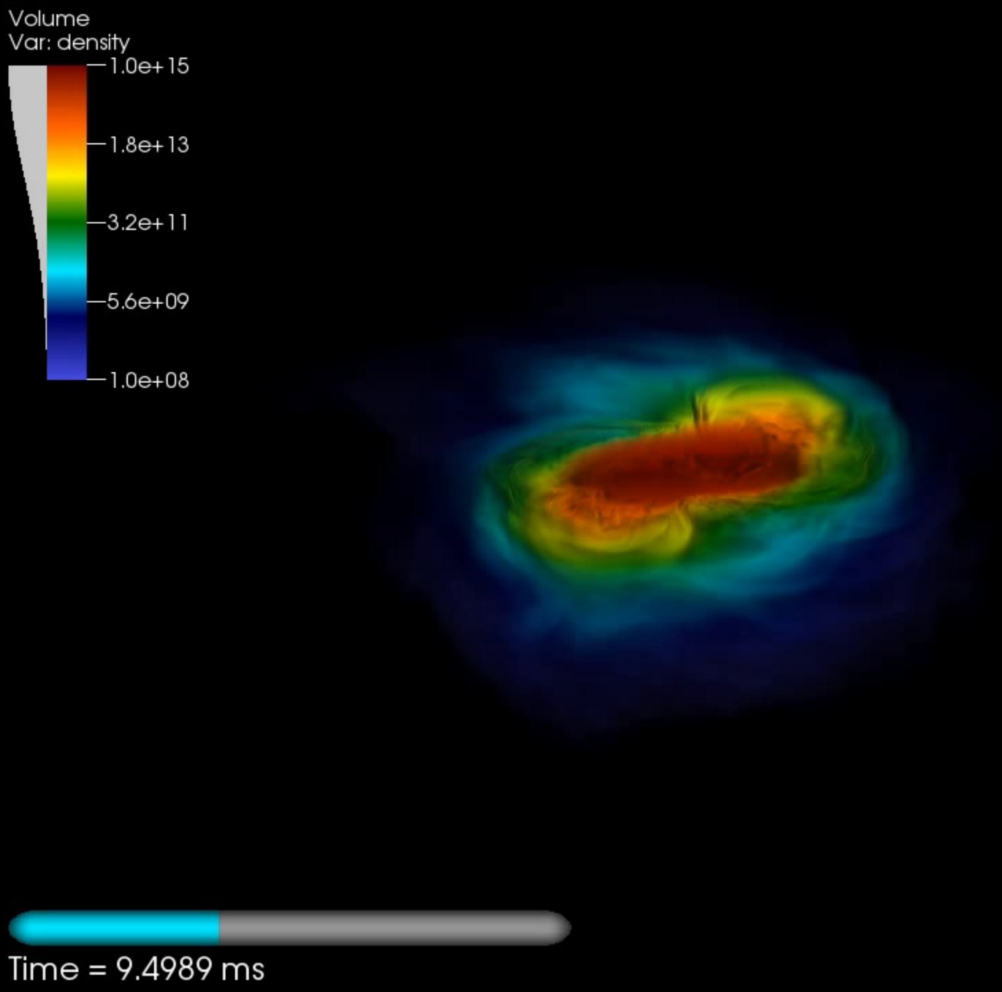
Prompt collapse: q ≠ 1



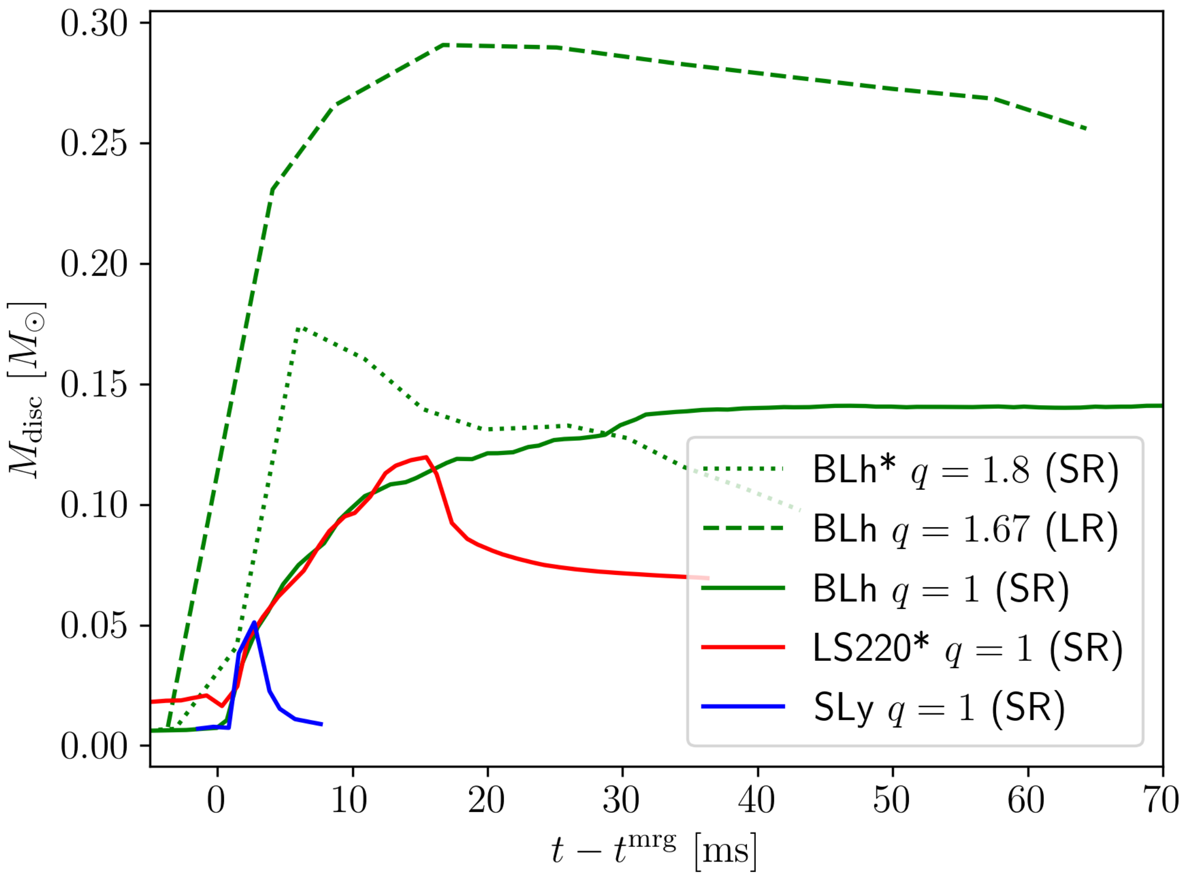


Can constrain the incompressibility at the highest density achieved in NSs!

From Perego, Logoteta, DR+, PRL 129:032701

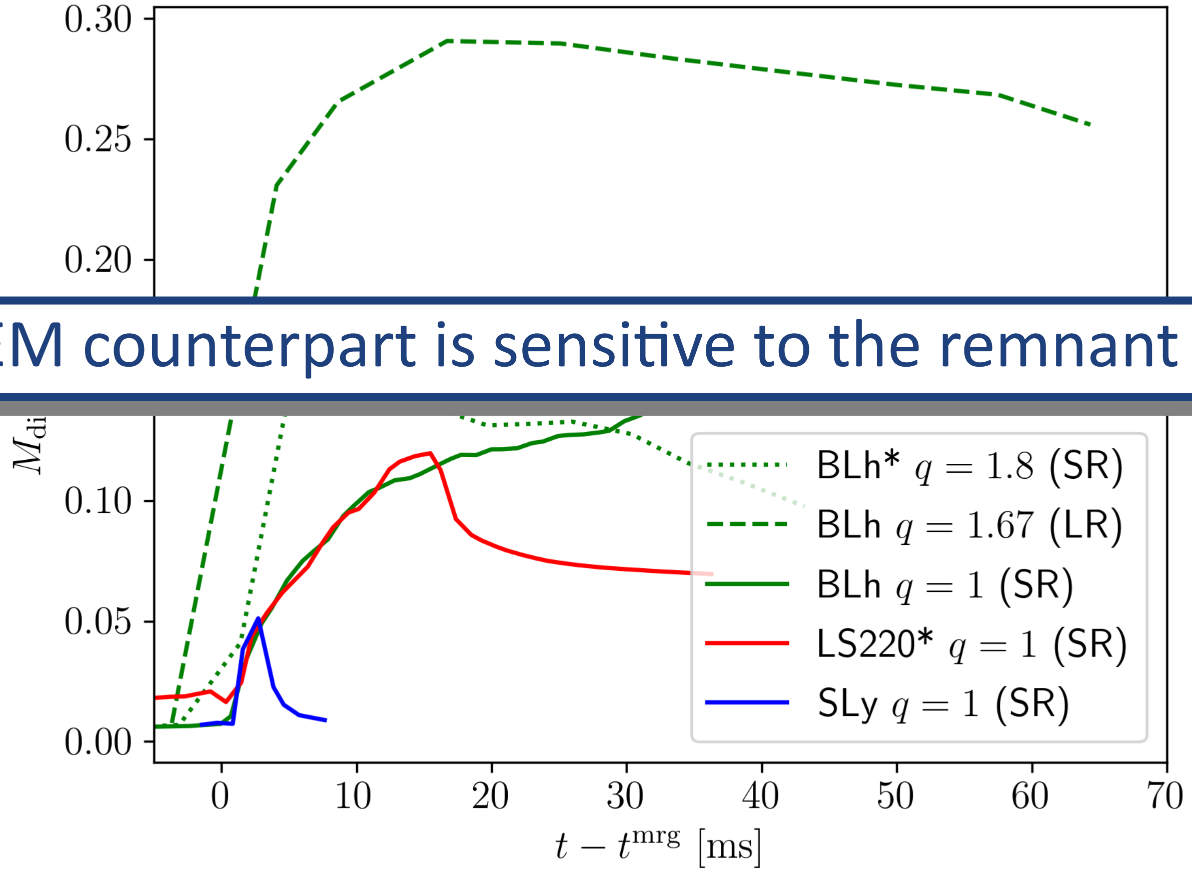

Volume
Var: density
1.0e+15
1.8e+13
3.2e+11
5.6e+09
1.0e+08
Time = 9.4989 ms

Impact of BH formation



From Bernuzzi+, MNRAS 497:1488 (2020)

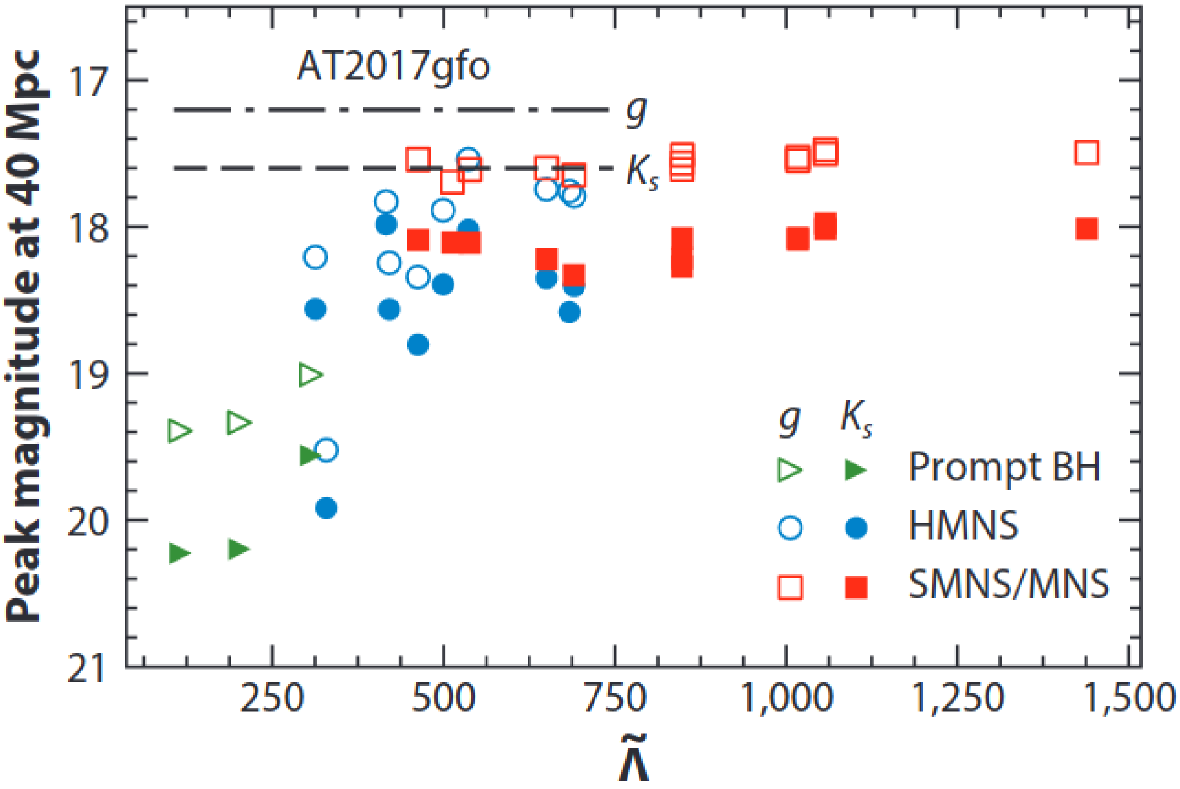
Impact of BH formation



The EM counterpart is sensitive to the remnant lifetime!

From Bernuzzi+, MNRAS 497:1488 (2020)

EM constraints on Λ



- Simulations connect GW parameters to EM observables
- Small Λ binaries form BHs quickly: EM faint
- Large Λ binaries form MNSs: EM bright
- Use this to place joint constraints on Λ

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

Multi-messenger constraints

$$P[\theta|d]$$

Multi-messenger constraints

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

Multi-messenger constraints

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

Multi-messenger constraints

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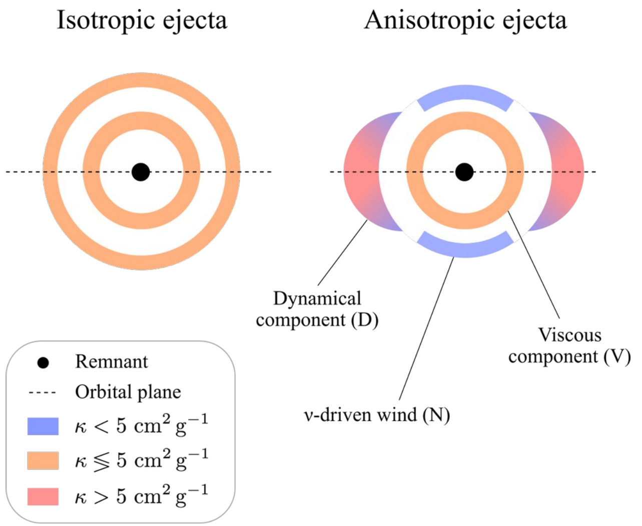
GW modeling and data analysis

Multi-messenger constraints

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

GW modeling and data analysis



kilonova modeling

Perego+, ApJL 850:L37 (2017)

Multi-messenger constraints

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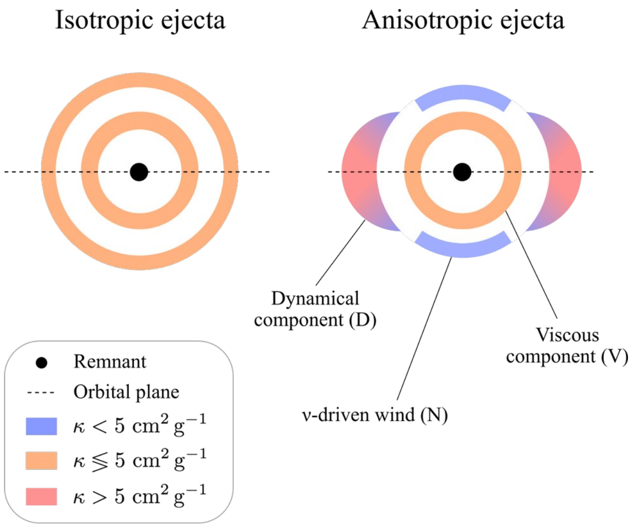
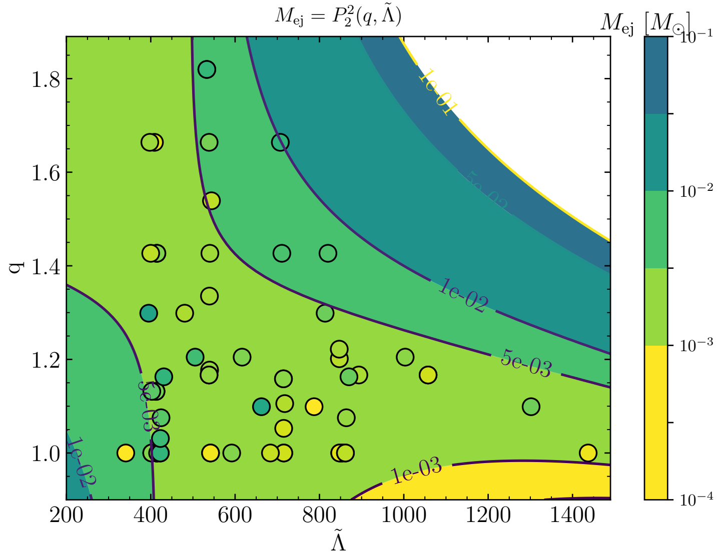
GW modeling and data analysis



kilonova modeling

NR simulations



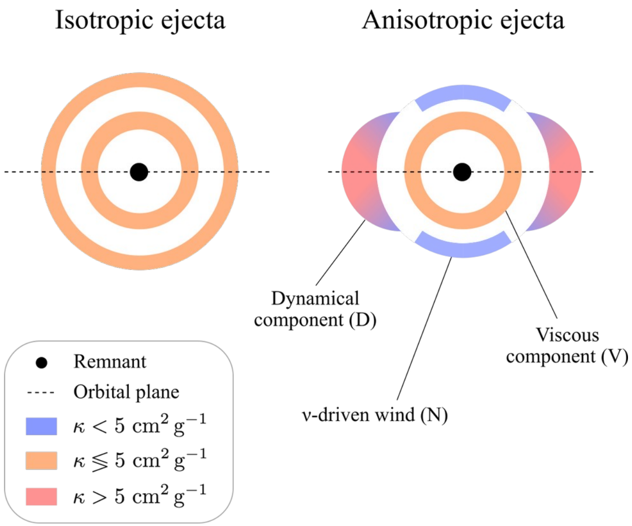
Perego+, ApJL 850:L37 (2017)

Nedora+, CQG 39:015008 (2022)

Multi-messenger constraints

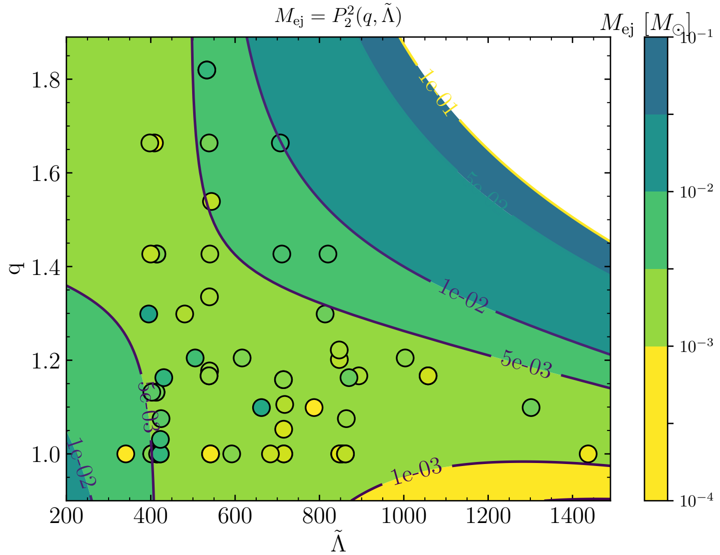
$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]P[d_{\rm EM}|\theta]$$

GW modeling and data analysis



kilonova modeling

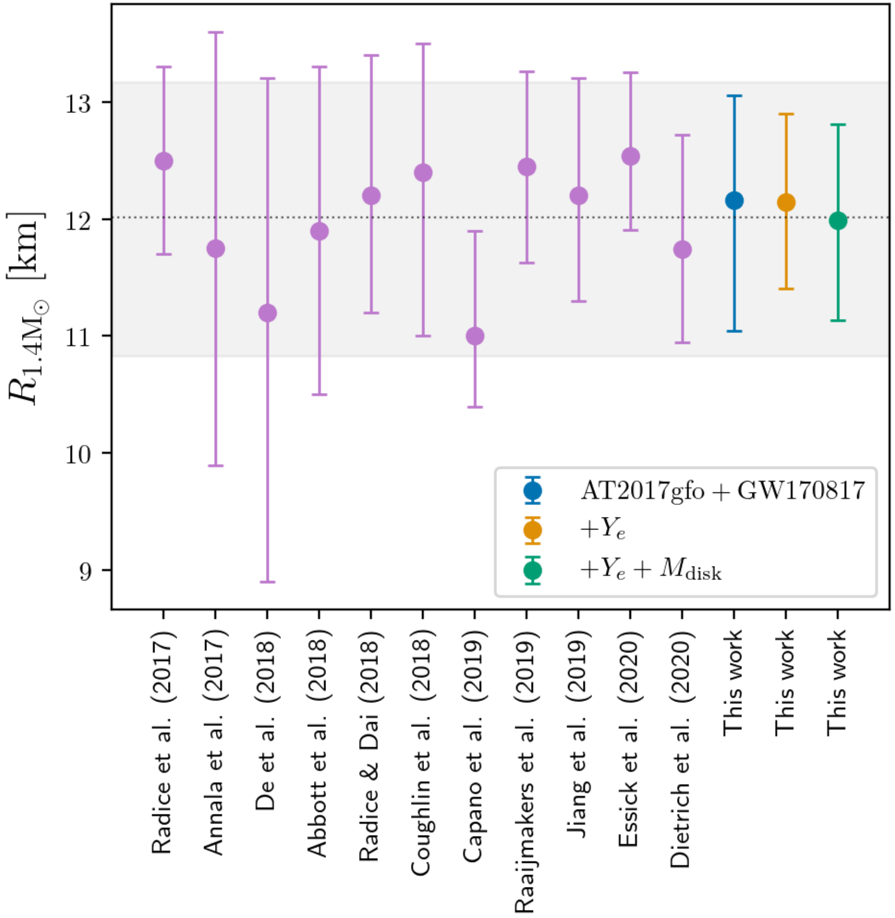
NR simulations



Perego+, ApJL 850:L37 (2017)

Nedora+, CQG 39:015008 (2022)

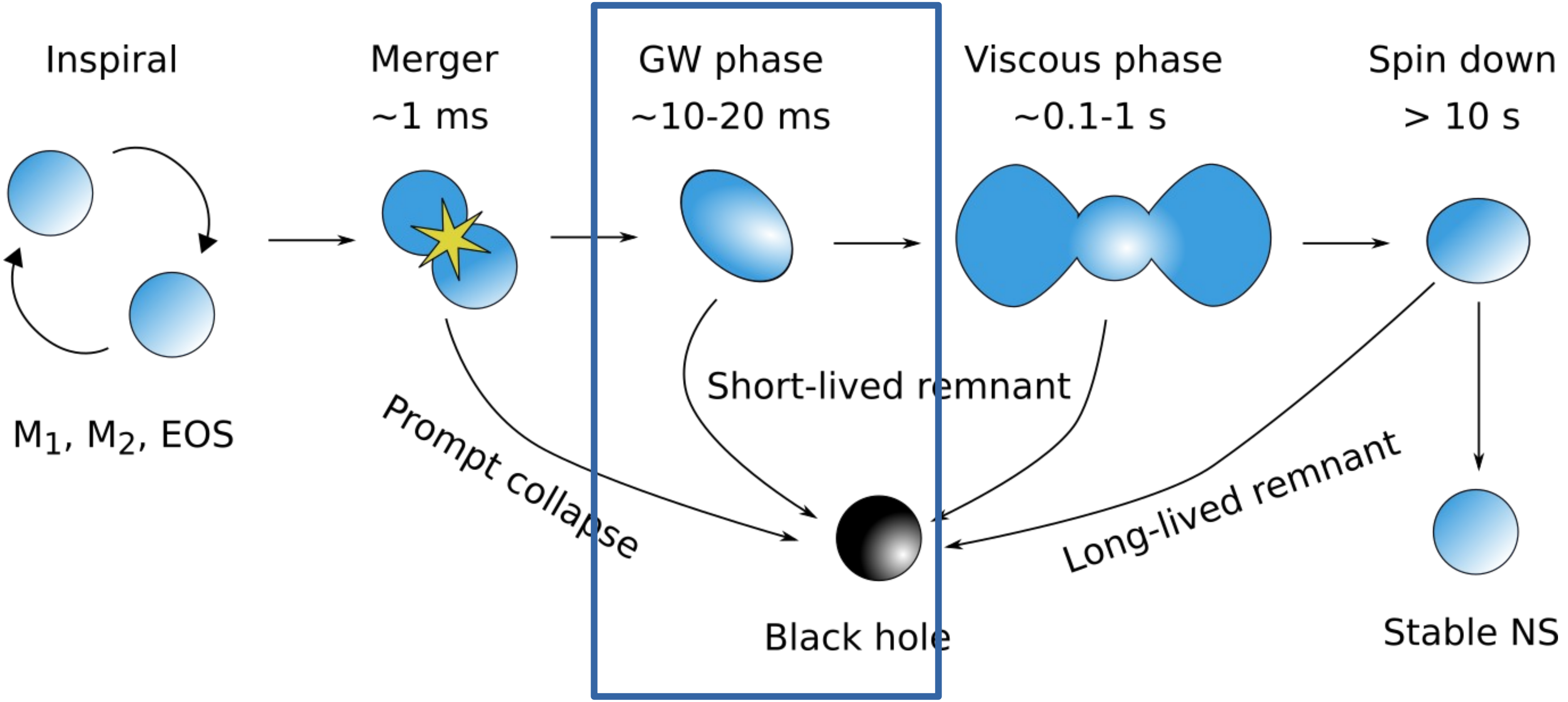
Multi-messenger EOS constraints



- Potential to also constrain the mass ratio
- Error dominated by modeling uncertainty, but well understood
- Constraints set by the merger and early post-merger dynamics
- Parameter exploration and inclusion of long-term disk winds from remnant needed

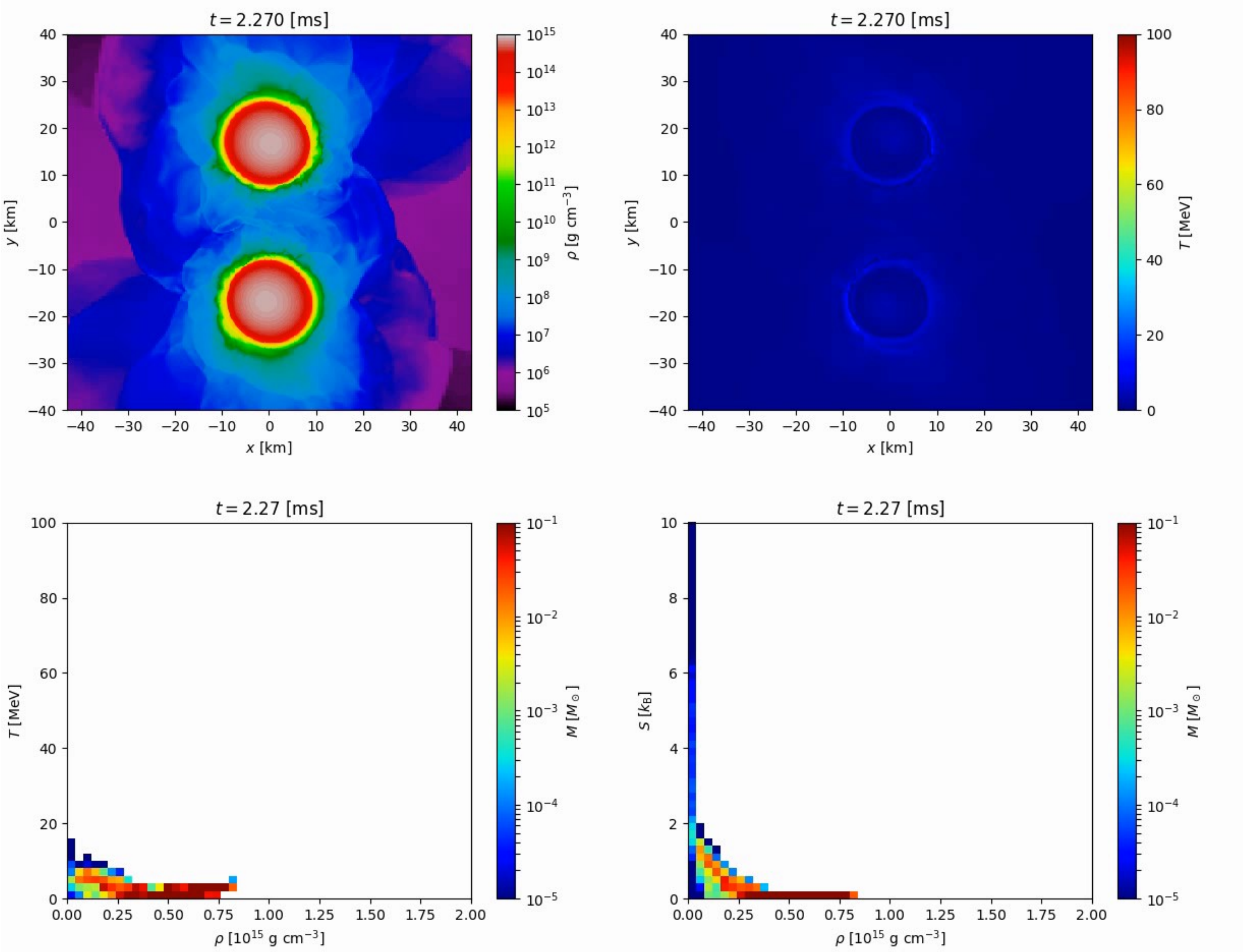
From Breschi+ MNRAS 505:1661 (2021)

NS mergers roadmap

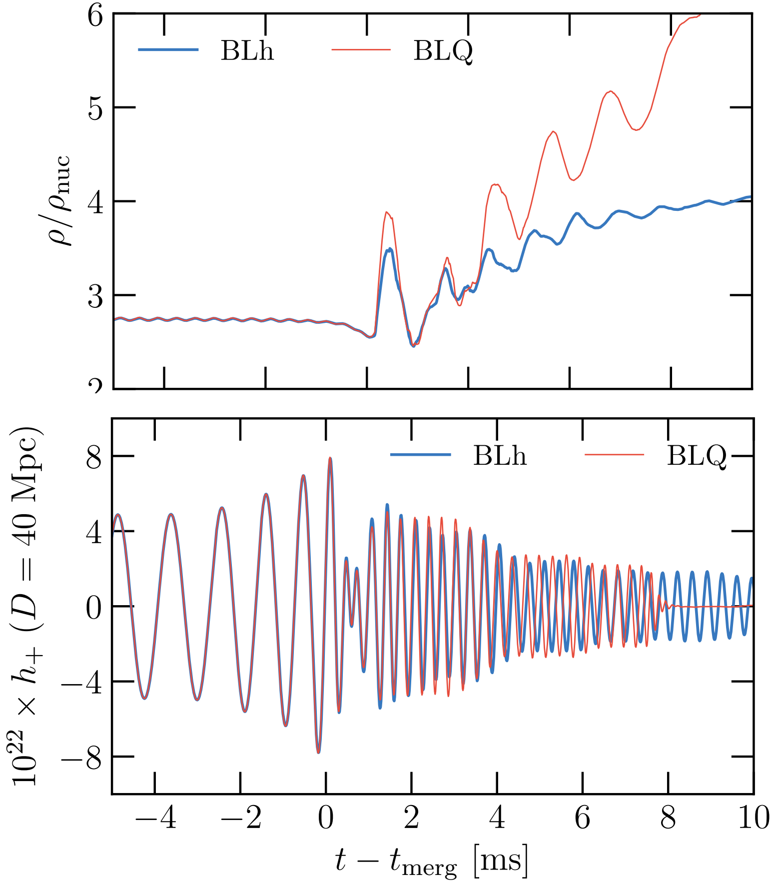


From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)

Perego+, EPJA 55:124 (2019)



High-density physics



Prakash+, PRD 104:083029 (2021)

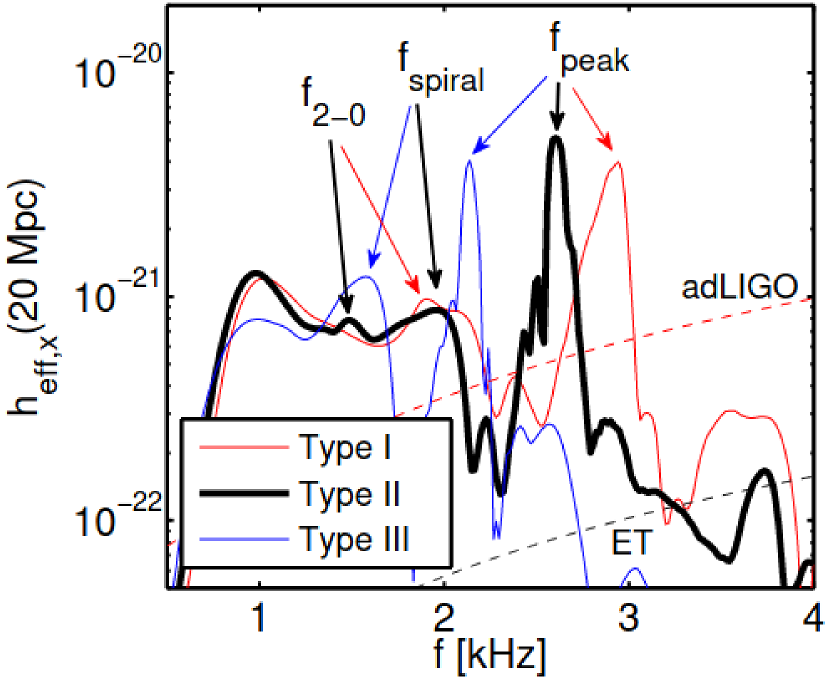
Blh: hadrons only
BLQ: deconfined quarks

- Phase transitions impact the life time of the remnant and the GWs
- Phase transition also cause more violent centrifugal bounce
- These effects are difficult to disentangle from other physics (eg., turbulence)

See also: Bauswein+ 2019, 2020; Most+ 2019, Weigh+ 2019; Blacker+ 2020; Liebling+ 2021; ...

Postmerger GW signal

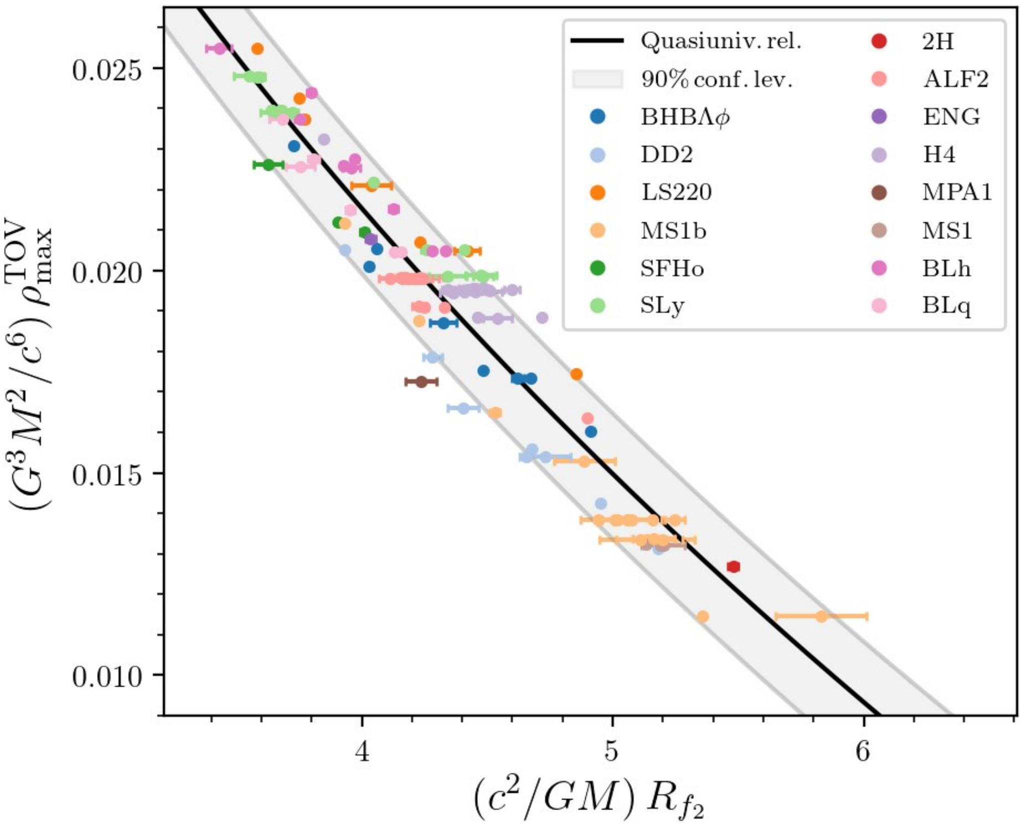
From Bauswein+ 2015

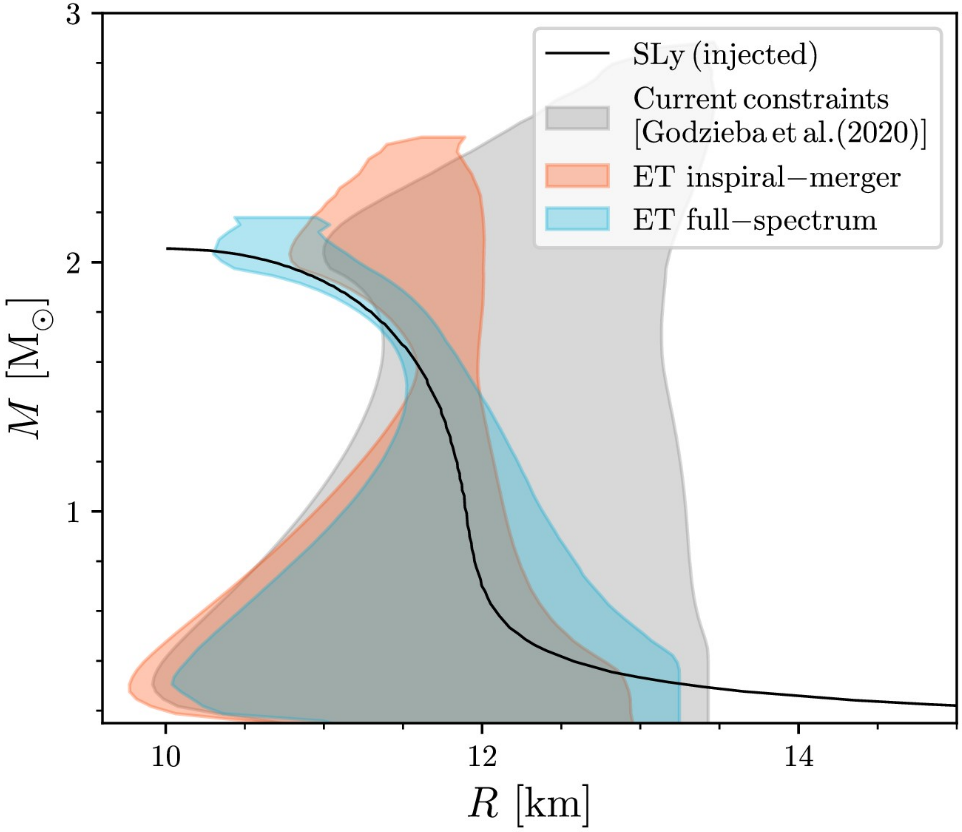


- Postmerger signal characterized by dominant frequency f_{peak}
- Need next gen. GW experiments, or very close (rare) events
- What can we learn from f_{peak}?
- Many ideas in the literature

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

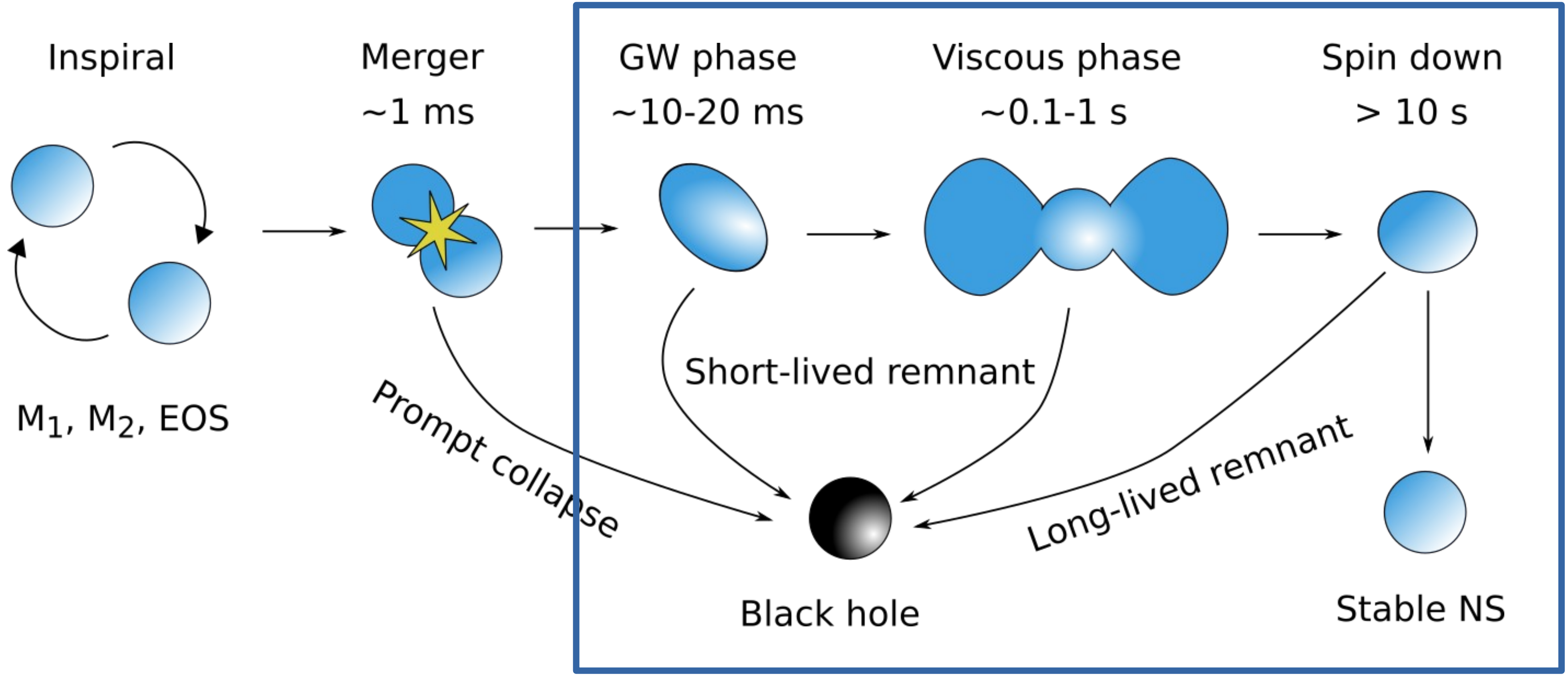
Universal relations





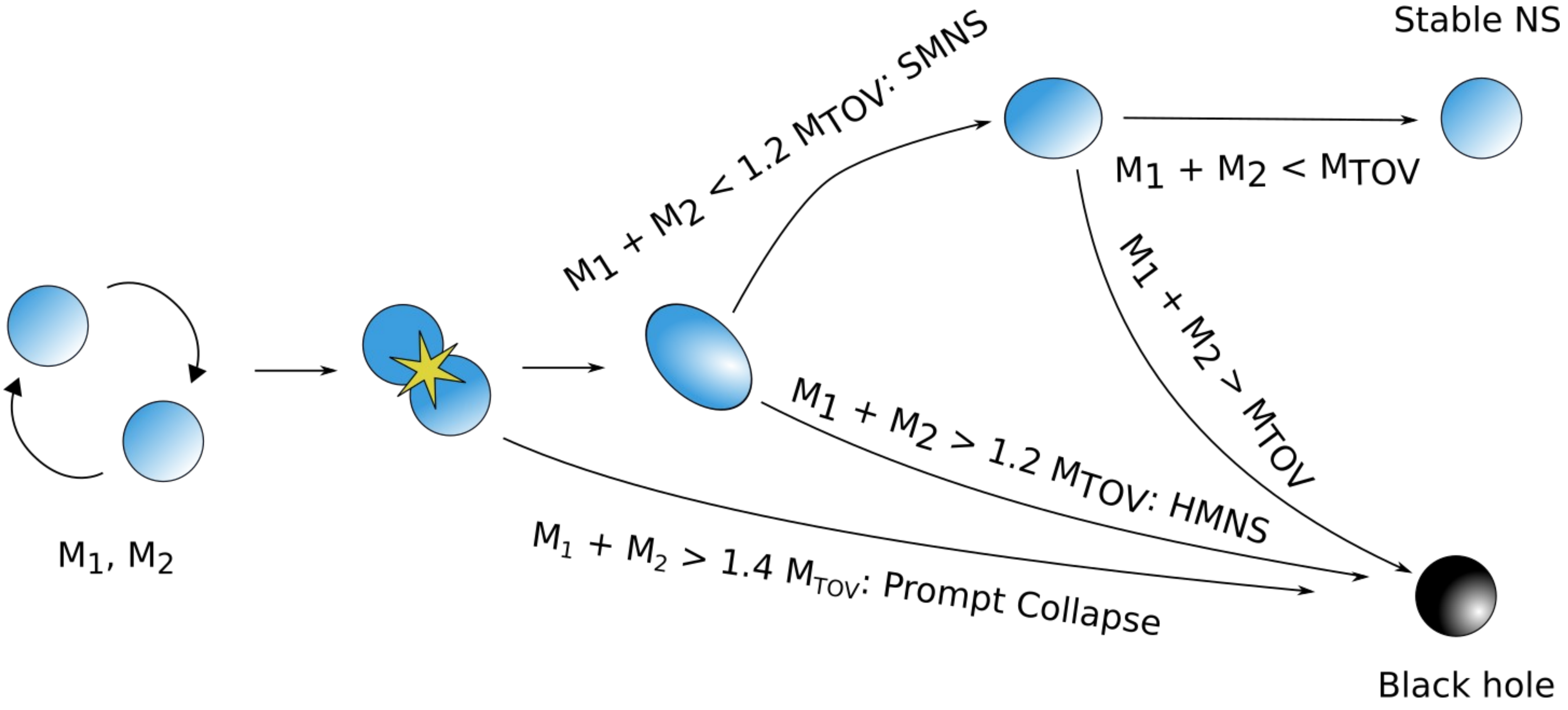
From Breschi+ PRL **128**:161102 (2022)

NS mergers roadmap

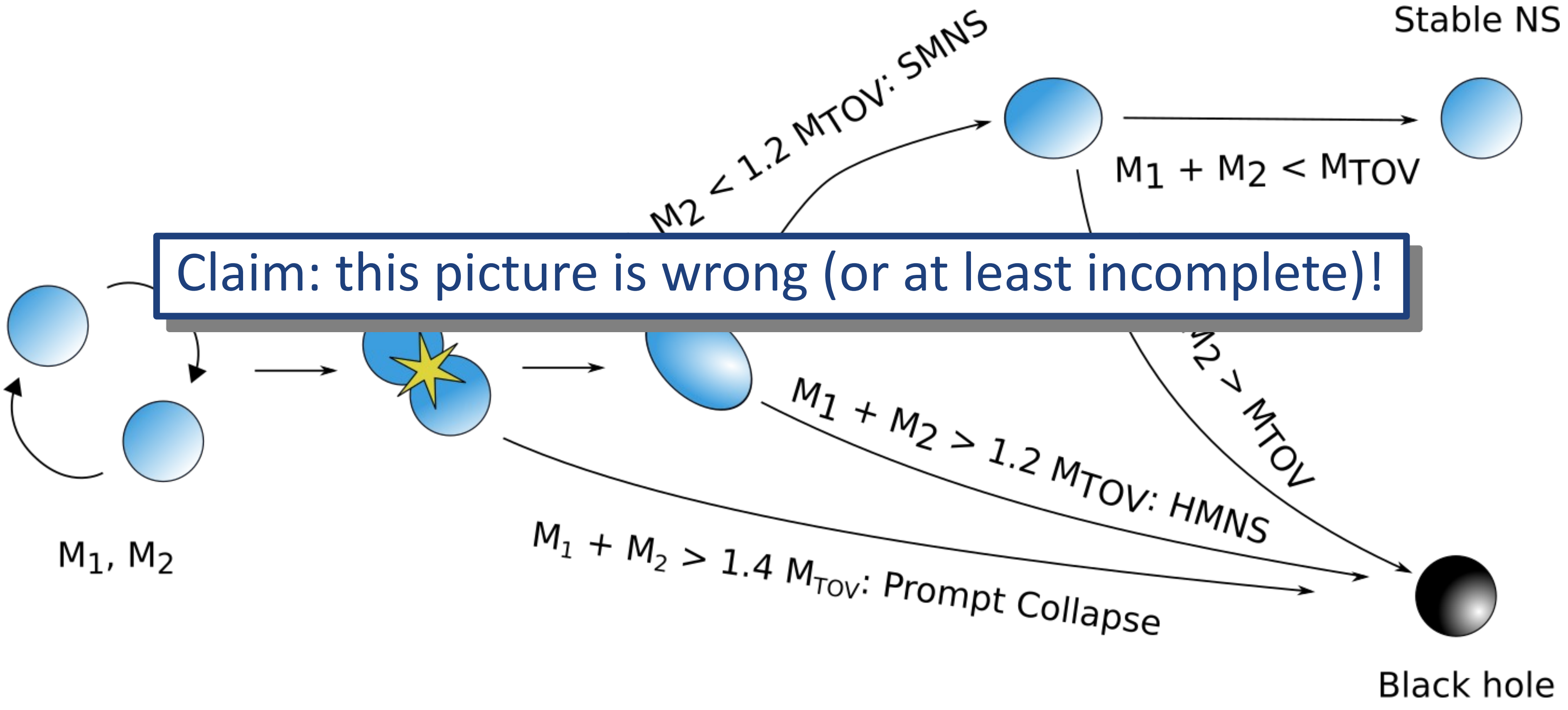


From Radice+, Ann. Rev. Nucl. Part. Sci. 70:95 (2020)

Common wisdom



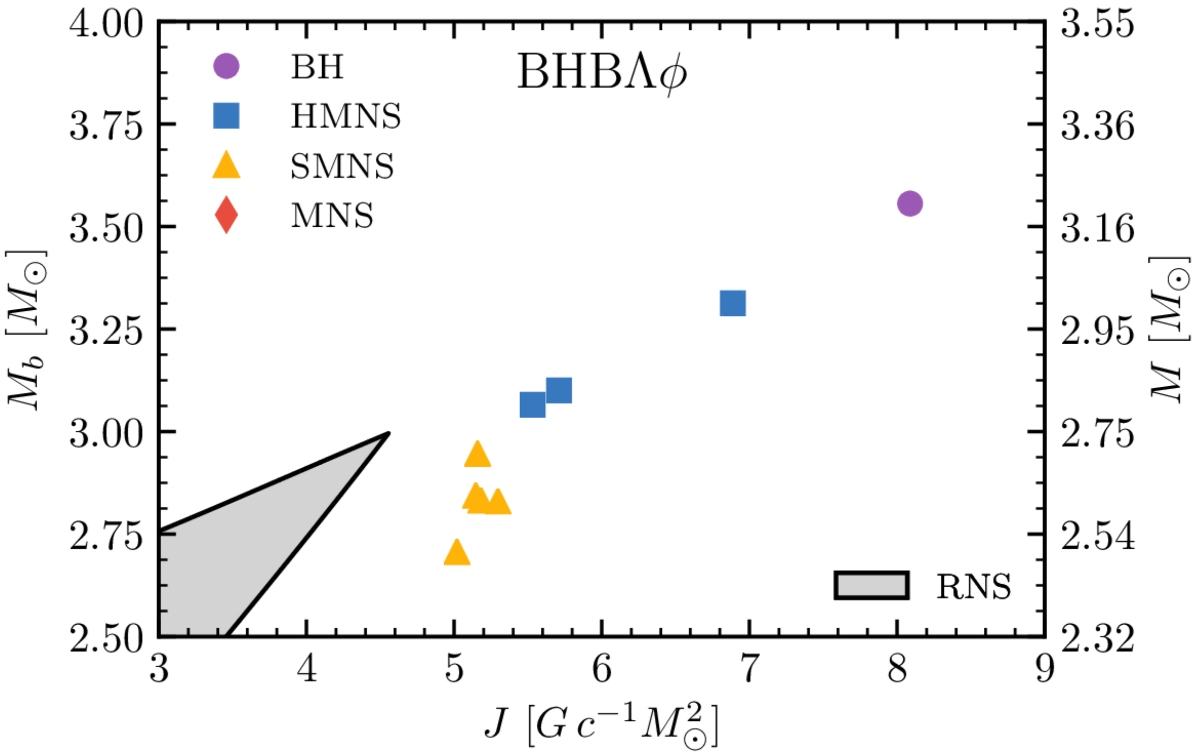
Common wisdom



Claim: this picture is wrong (or at least incomplete)!

Angular momentum transport

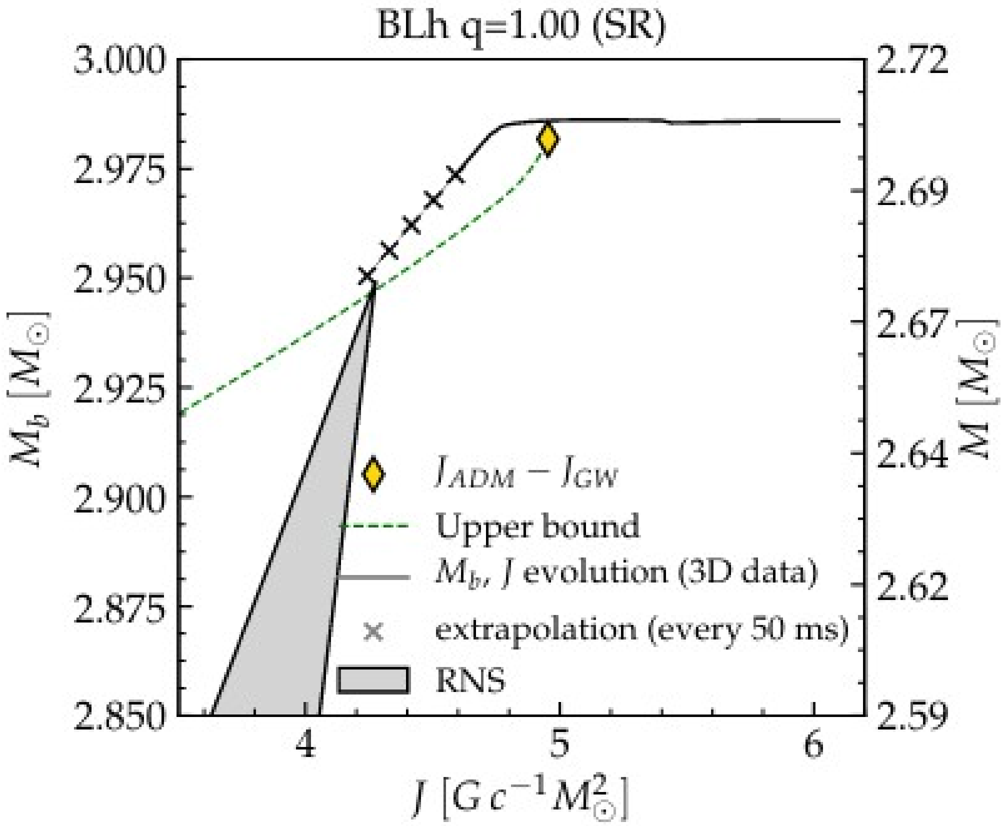
- SMNS are born with significant excess of angular momentum
- Thermal effects could facilitate the collapse
- Outcome depends on competition between viscous effects and cooling



See also Beniamini & Lu 2021; Margalit+ 2022

Radice+, MNRAS 481:3670 (2018)

A stable HMNS?

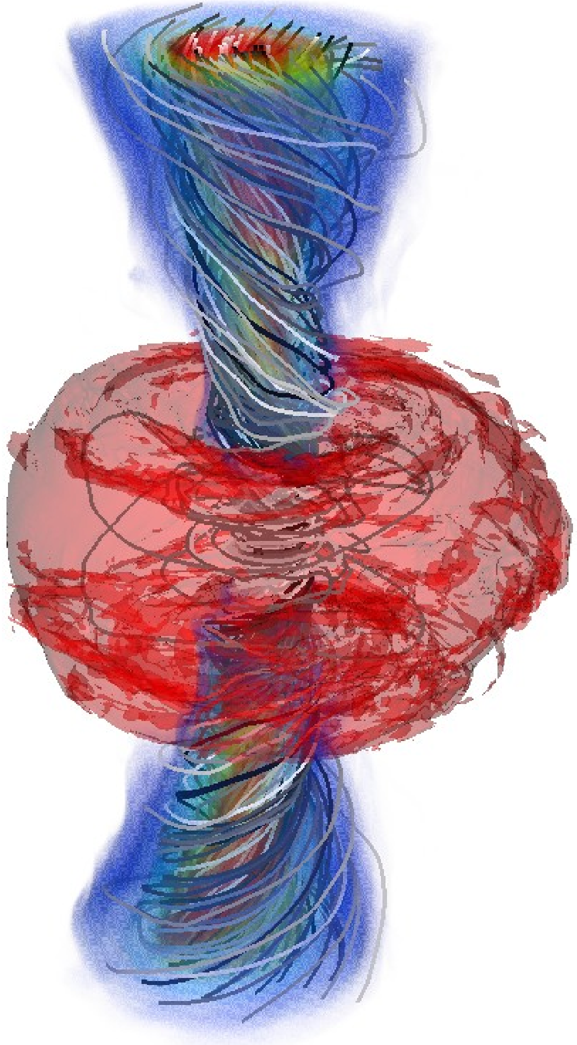


- Targeted simulations to GW170817 reveal cases in which the spiral-wave wind could be sufficiently intense to stabilize the remnant
- Need longer simulations with MHD and real neutrino transport

Nedora+, ApJ 906:98 (2021)

Challenges

- Need O(few seconds) full physics simulations
- Capture MHD turbulence and dynamo processes in the remnant
- Neutrino interactions in dense matter
- Non-LTE radiation-hydrodynamics effect
- Neutrino flavor conversion



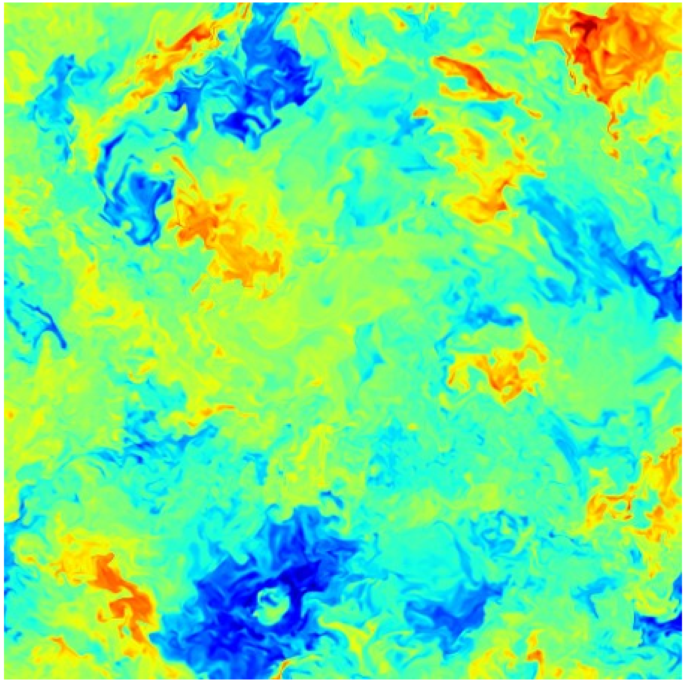
From Moesta+ ApJL, 901:L37 (2020)

Summary

- Many avenues to constrain the physics of dense matter from mergers
- Systematic uncertainties increase in the postmerger
  1) Inspiral: well understood, but need higher precision models
  2) Early merger dynamics: physics understood, but large portions of parameter space to explore
  3) Late postmerger: large systematic uncertainties
- Post-merger GW signal would constrain the EOS at the highest densities

WhiskyTHC

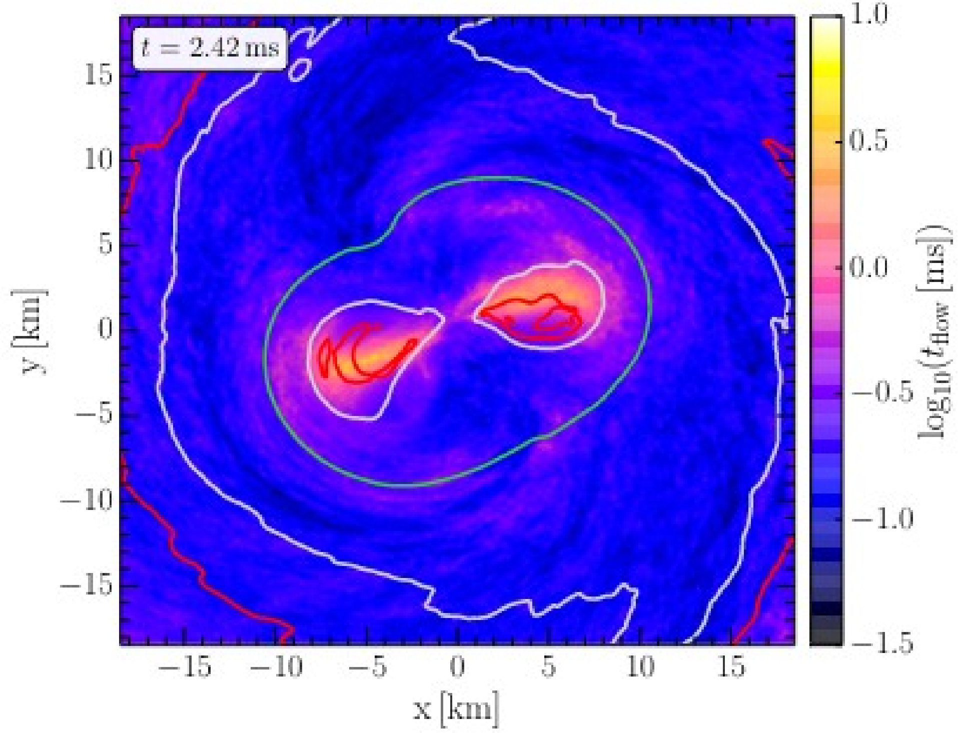
http://personal.psu.edu/~dur566/whiskythc.html



- Full-GR dynamical spacetime
- Nuclear EOS
- M0 & M1 neutrino transport
- Subgrid turbulence modeling
- Builds on top of the Einstein Toolkit and open source

THC: Templated Hydrodynamics Code

Bulk viscosity?



From Alford+ 2017

- When dense matter is compressed it undergoes strong and weak reactions
- $t_{strong} << t_{hydro}$, so strong reactions are always in equilibrium
- $t_{weak} \approx 10^{-3}$ ms $\approx t_{hydro}$: potentially out of equilibrium
- Analogous to ε-mechanism in stars
- First simulations with trapped neutrinos in Radice+ 2021 do not reveal strong bulk viscosity

See also Most+ 2021, Hammond+ 2021, Radice+ 2021