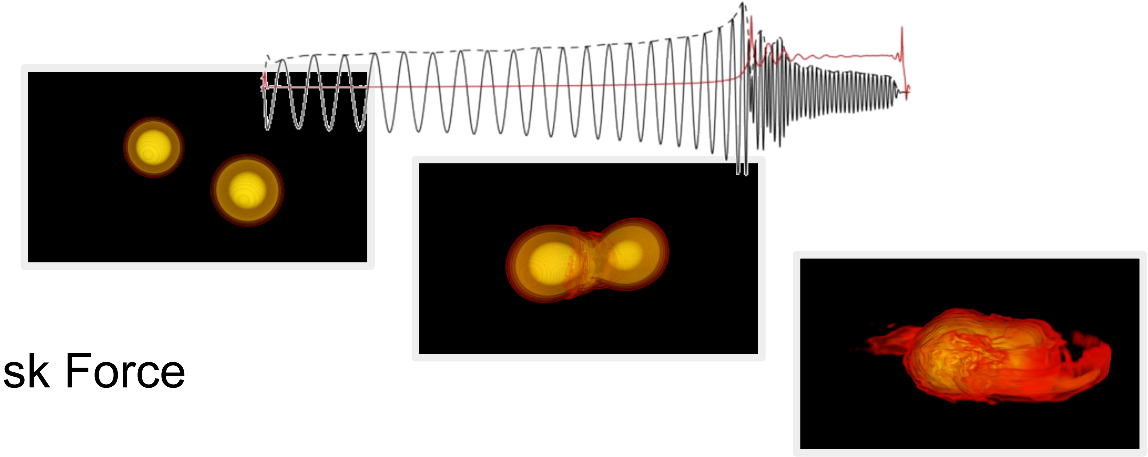
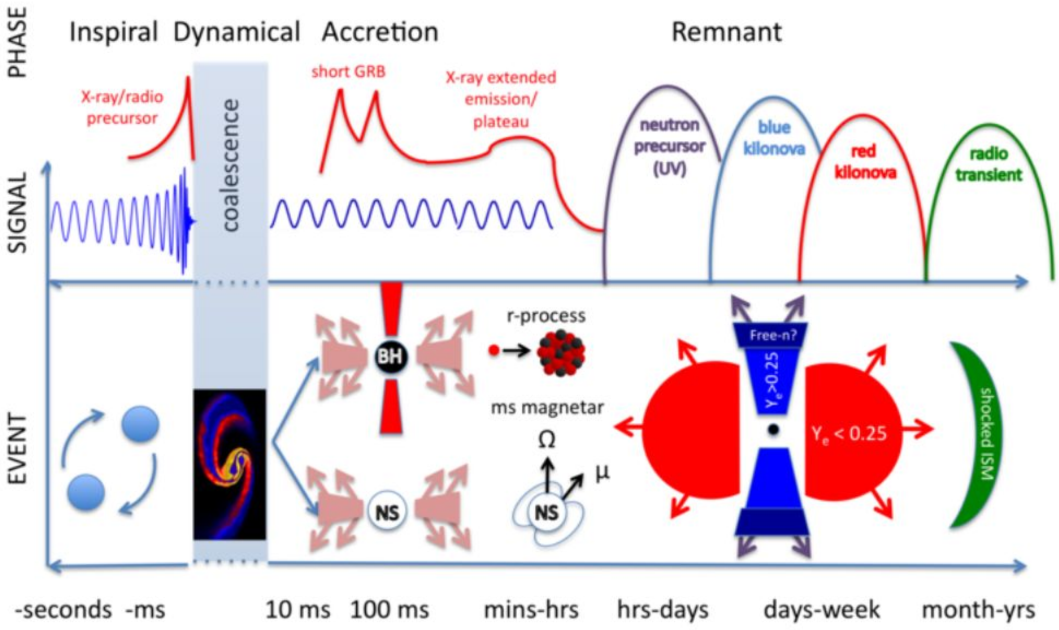
Modeling neutron star mergers with numerical relativity



EMMI Rapid Reaction Task Force
Darmstadt 12.06.2018

S.Bernuzzi

Some questions



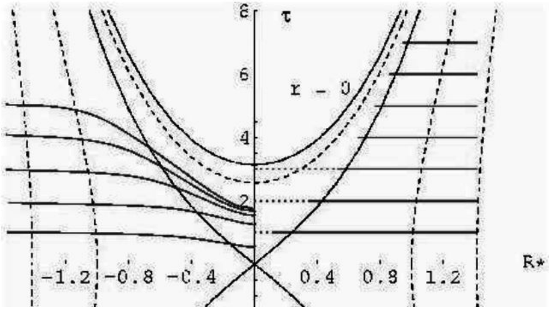
[Fernandez&Metzger 2015]

- What can we learn about the EOS from GW observations?
- What are the implication for NS properties from observations (both GW and EM)?
- How can we improve current simulations? (What we need)
- Physics (and timescale) for the description of the remnant

What is the interplay between rotational and thermal support in the hyper-massive or supermassive neutron star remnant, and how does it depend on the properties of the finite-temperature equation of state? What controls the "viscosity" inside the remnant?

$$
\begin{aligned}
\partial_t \tilde{\Gamma}^i &= -2\,\tilde{A}^{ij}\,\partial_j\alpha + 2\,\alpha\left[\tilde{\Gamma}^i{}_{jk}\,\tilde{A}^{jk} - \frac{3}{2}\,\tilde{A}^{ij}\,\partial_j\ln(\chi)\right.\\
&\quad\left. -\frac{1}{3}\,\tilde{\gamma}^{ij}\,\partial_j(2\,\hat{K}+\Theta) - 8\,\pi\,\tilde{\gamma}^{ij}\,S_j\right] + \tilde{\gamma}^{jk}\,\partial_j\partial_k\beta\\
&\quad + \frac{1}{3}\,\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\,\partial_j\tilde{\Gamma}^i - (\tilde{\Gamma}_d)^j\,\partial_j\beta^i\\
&\quad + \frac{2}{3}\,(\tilde{\Gamma}_d)^i\,\partial_j\beta^j - 2\,\alpha\,\kappa_1\,[\tilde{\Gamma}^i - (\tilde{\Gamma}_d)^i]\,,\\
\partial_t\Theta &= \frac{1}{2}\,\alpha\,[R - \tilde{A}_{ij}\,\tilde{A}^{ij} + \frac{2}{3}\,(\hat{K}+2\,\Theta)^2]\\
&\quad - \alpha\,[8\,\pi\,\rho + \kappa_1\,(2+\kappa_2)\,\Theta] + \beta^i\partial_i\Theta\,,
\end{aligned}
$$

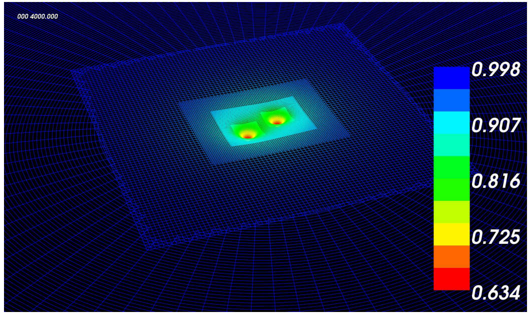
GR Formulation and Cauchy problem
+ GR hydrodynamics



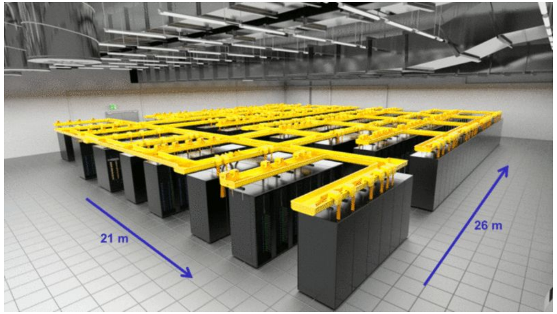
Coordinates and Singularities

Numerical relativity in a nutshell

Numerical methods for PDEs on adaptive grids



High-performance-computing (HPC)



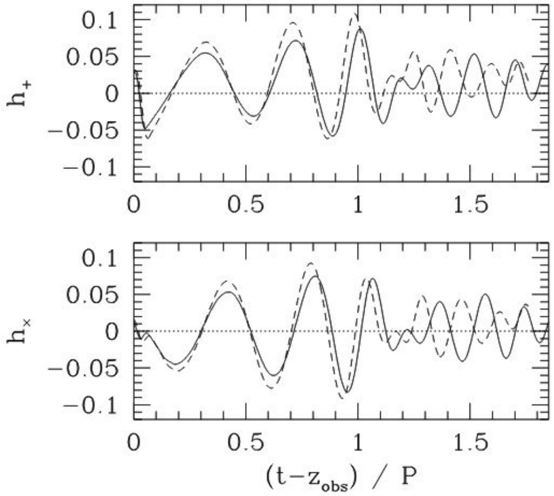
PHYSICAL REVIEW D, VOLUME 61, 064001

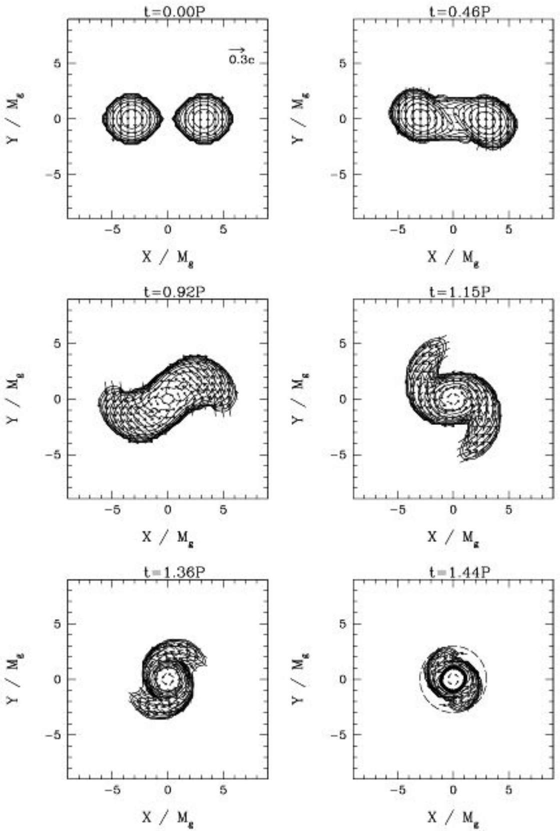
Simulation of merging binary neutron stars in full general relativity: Γ = 2 case

Masaru Shibata
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
and Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

Kōji Uryū
SISSA, Via Beirut 2/4, 34013 Trieste, Italy
(Received 11 October 1999; published 10 February 2000)

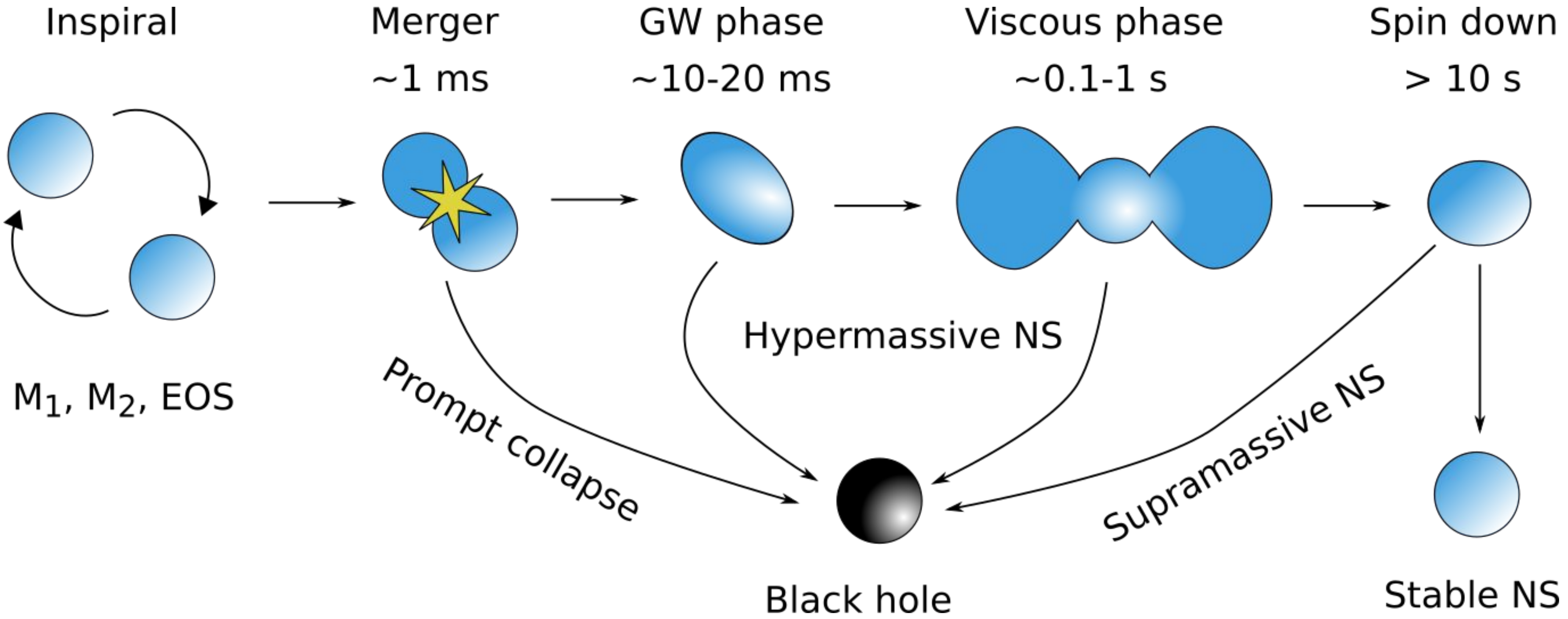
We perform 3D numerical simulations for the merger of equal mass binary neutron stars in full general relativity. We adopt a Γ-law equation of state in the form $P=(\Gamma-1)\rho\varepsilon$ where P, ρ, ε and Γ are the pressure, rest mass density, specific internal energy, and the adiabatic constant with $\Gamma=2$. As initial conditions, we adopt models of corotational and irrotational binary neutron stars in a quasiequilibrium state which are obtained using the conformal flatness approximation for the three geometry as well as the assumption that a helicoidal Killing vector exists. In this paper, we pay particular attention to the final product of the coalescence. We find that the final product depends sensitively on the initial compactness parameter of the neutron stars: In a merger between sufficiently compact neutron stars, a black hole is formed in a dynamical time scale. As the compactness is decreased, the formation time scale becomes longer and longer. It is also found that a differentially rotating massive neutron star is formed instead of a black hole for less compact binary cases, in which the rest mass of each star is less than 70–80 % of the maximum allowed mass of a spherical star. In the case of black hole formation, we roughly evaluate the mass of the disk around the black hole. For the merger of corotational binaries, a disk of mass $\sim 0.05-0.1 M_*$ may be formed, where M_* is the total rest mass of the system. On the other hand, for the merger of irrotational binaries, the disk mass appears to be very small: $<0.01 M$





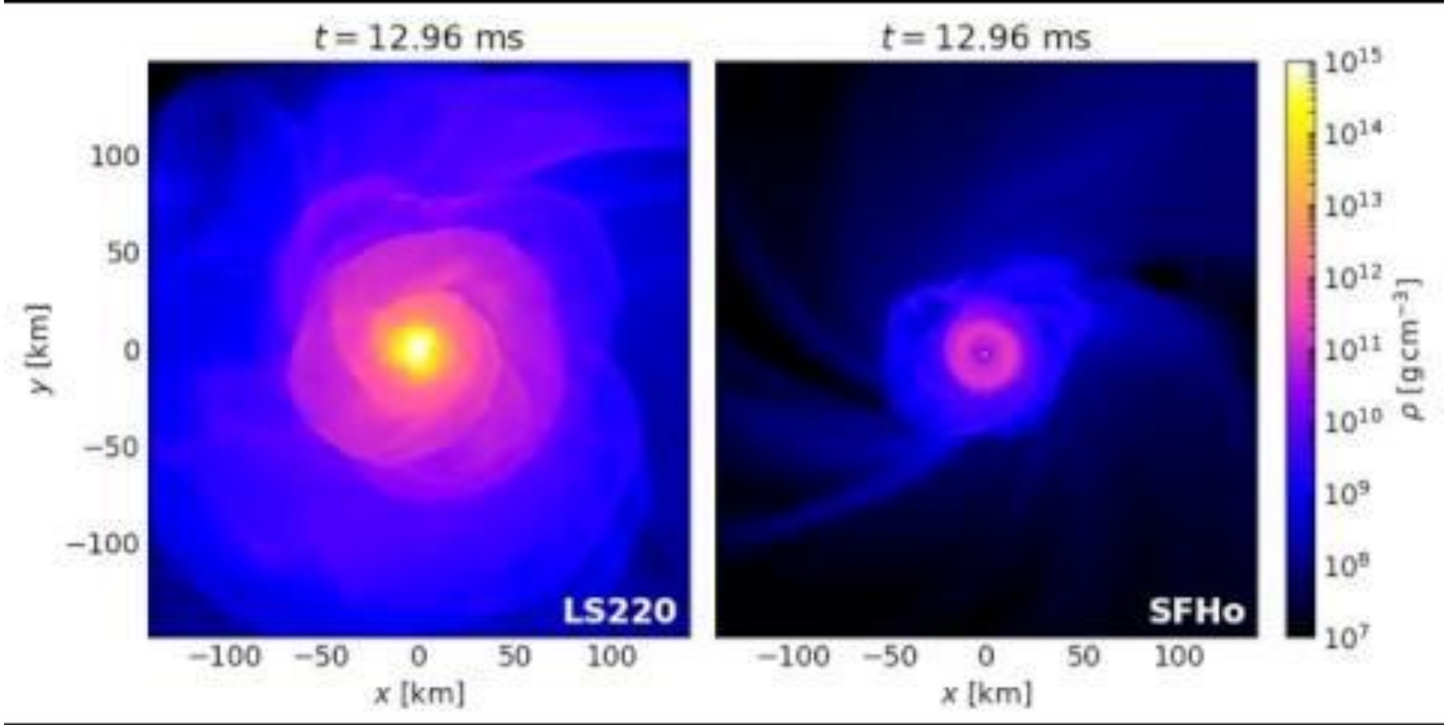
Irrotational BNS

Merger dynamics and remnant



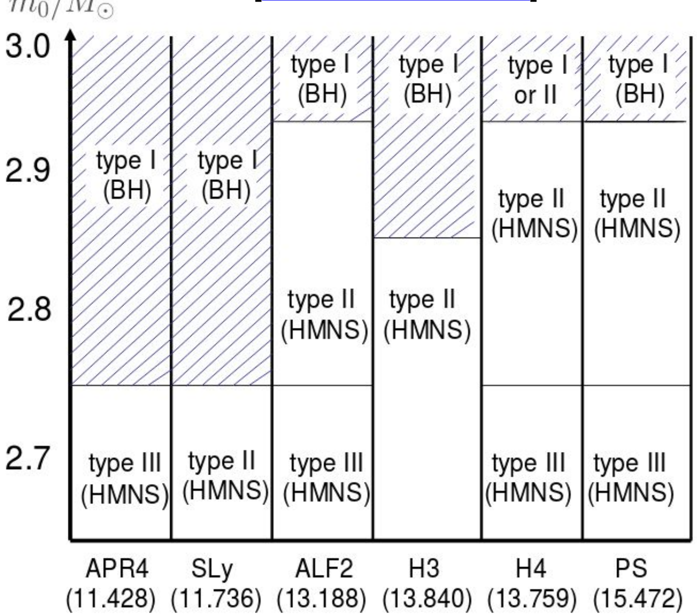
Credit: D.Radice

Viz. By D.Radice



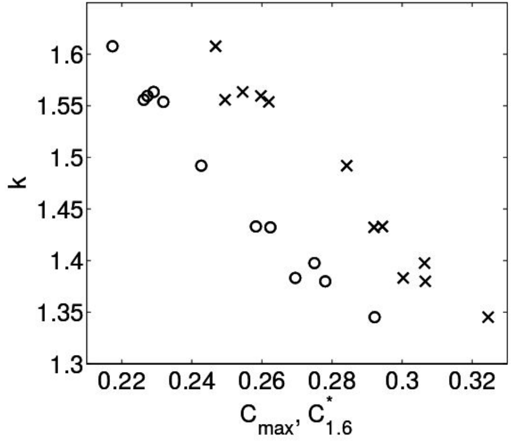
Prompt collapse to BH

[Hotokezaka+ 2011]



EoS	$M_{\max}$ $[M_\odot]$	$R_{\max}$ [km]	$C_{\max}$	$R_{1.6}$ [km]	$M_{\rm thres}$ $[M_\odot]$	ρ_c/ρ_0	$f_{\rm peak}^{\rm stab}$ [kHz]
NL3 [40, 41]	2.79	13.43	0.307	14.81	3.85	5.6	2.78
GS1 [42]	2.75	13.27	0.306	14.79	3.85	5.7	2.81
LS375 [43]	2.71	12.34	0.325	13.71	3.65	6.5	3.05
DD2 [41, 44]	2.42	11.90	0.300	13.26	3.35	7.2	3.06
Shen [45]	2.22	13.12	0.250	14.46	3.45	6.7	2.85
TM1 [46, 47]	2.21	12.57	0.260	14.36	3.45	6.7	2.91
SFHX [48]	2.13	10.76	0.292	11.98	3.05	8.9	3.52
GS2 [49]	2.09	11.78	0.262	13.31	3.25	7.6	3.19
SFHO [48]	2.06	10.32	0.294	11.76	2.95	9.8	3.67
LS220 [43]	2.04	10.62	0.284	12.43	3.05	9.4	3.52
TMA [47, 50]	2.02	12.09	0.247	13.73	3.25	7.2	2.96
IUF [41, 51]	1.95	11.31	0.255	12.57	3.05	8.1	3.31

[Bauswein+ 2013]

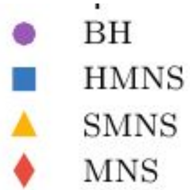


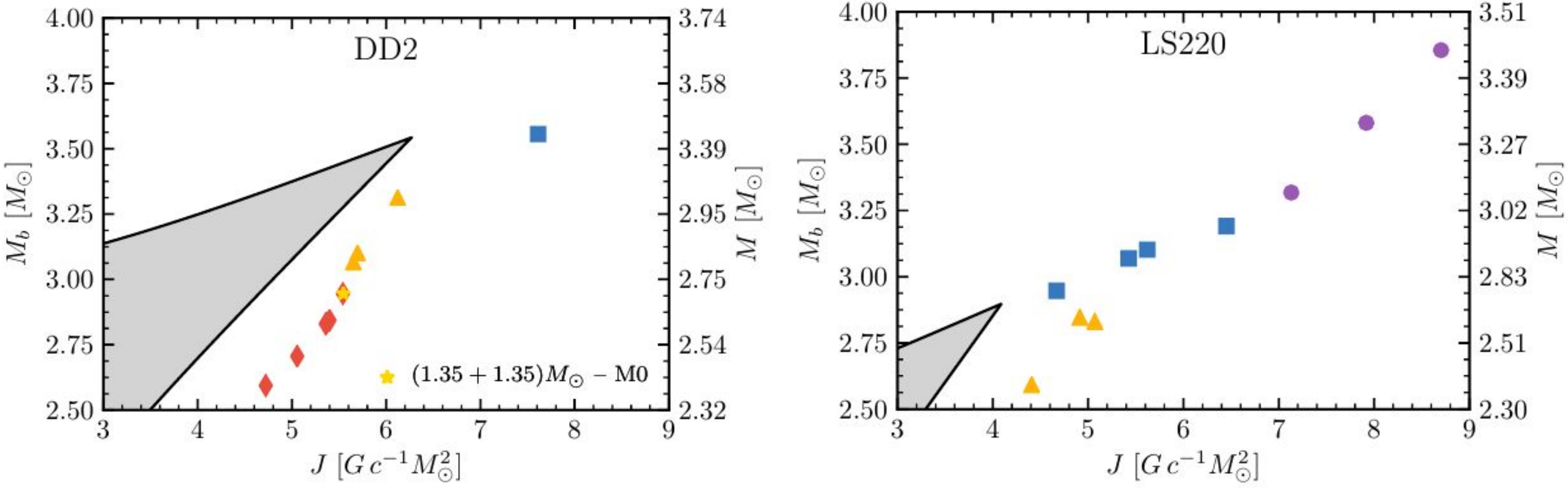
$$M_{\rm collapse} = k M_{\rm max}^{\rm TOV}$$

$$1.3 \lesssim k(EOS, C) \lesssim 1.7$$

Merger remnant angular momentum

- BH: 0.6 <~ J/M^2 <~ 0.8 (HMNS → 0.6-0.7, Prompt BH → 0.7-0.8)
  [Kiuchi+ 2009, Kastaun+ 2013, Bernuzzi+ 2016, Zappa+ 2018]
- NS: “super Keplerian” and grav. mass excess
  [Zappa+ 2018, Radice+ 2018]

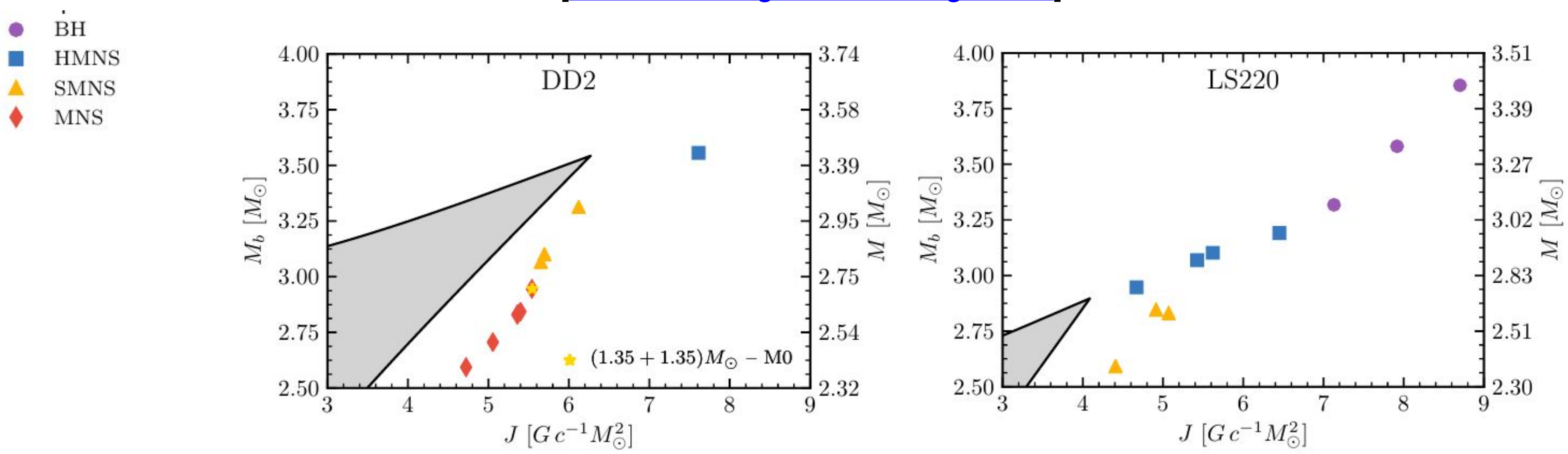


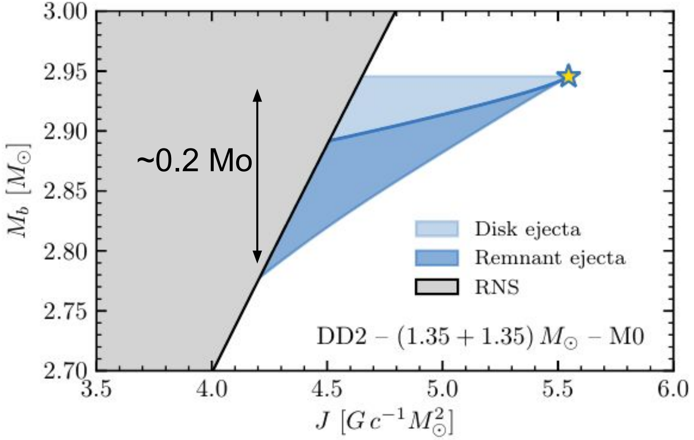


[Radice, Perego, SB, Zhang 2018]

NS remnant evolution on viscous timescale

[Radice, Perego, SB, Zhang 2018]

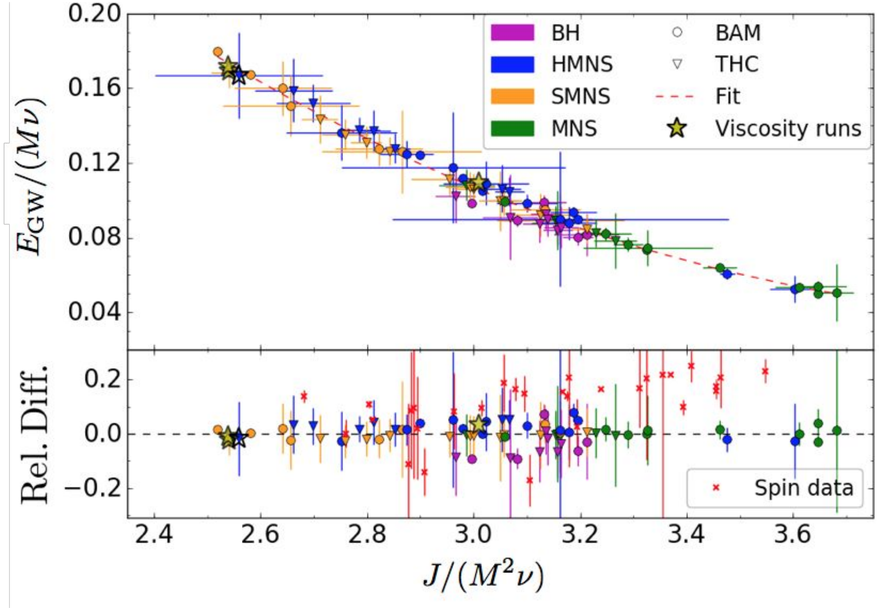




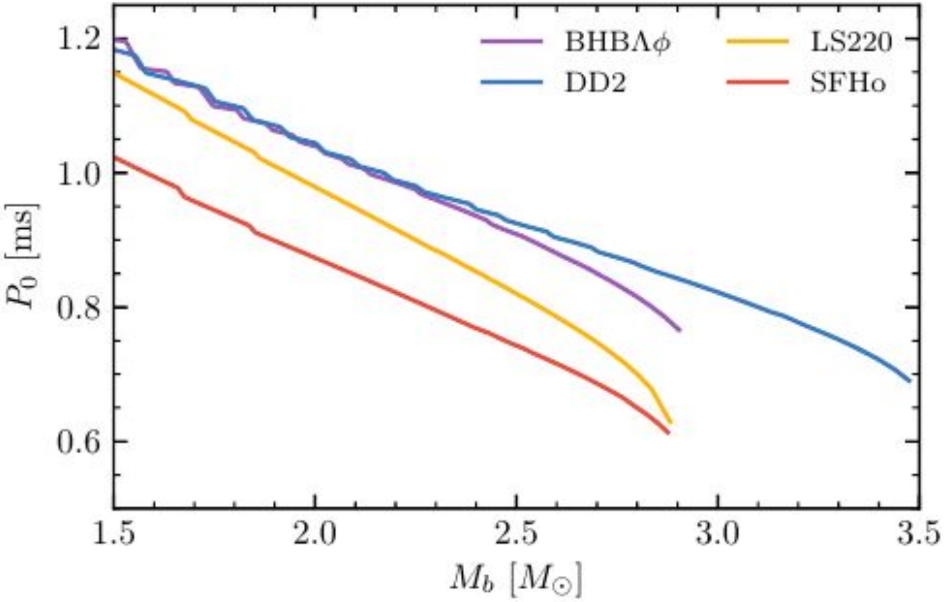
- After an initial transient (see later), GW dissipate ang.mom. on timescales >~ sec
- T_{visc} ~ O(100 ms) → ang.mom. redistribution might be dominated by “viscous” effects
  → mass outflows
- Finite T, neutrino effects → NS remnant stability (?)
- Remark: BH+disk is sub-Kerr

NS remnant spin

Angular momentum after GW transient (end of simulations)



Spin after viscous phase O(100) ms (estimate)

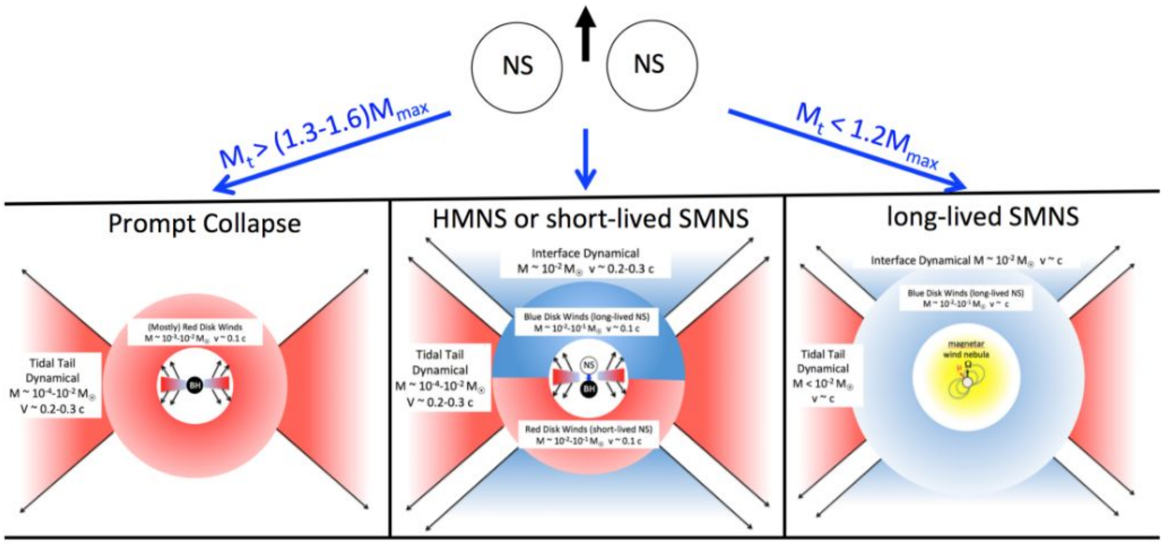


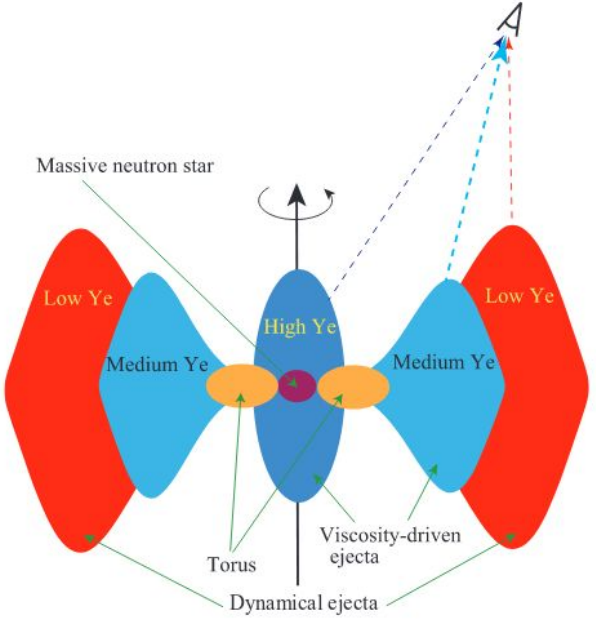
[Zappa+ 2018]

[Radice, Perego, SB, Zhang 2018]

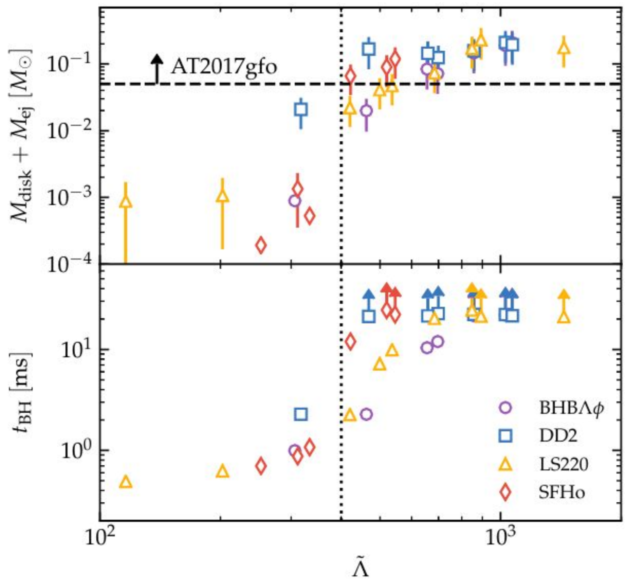
Applications to GW170817

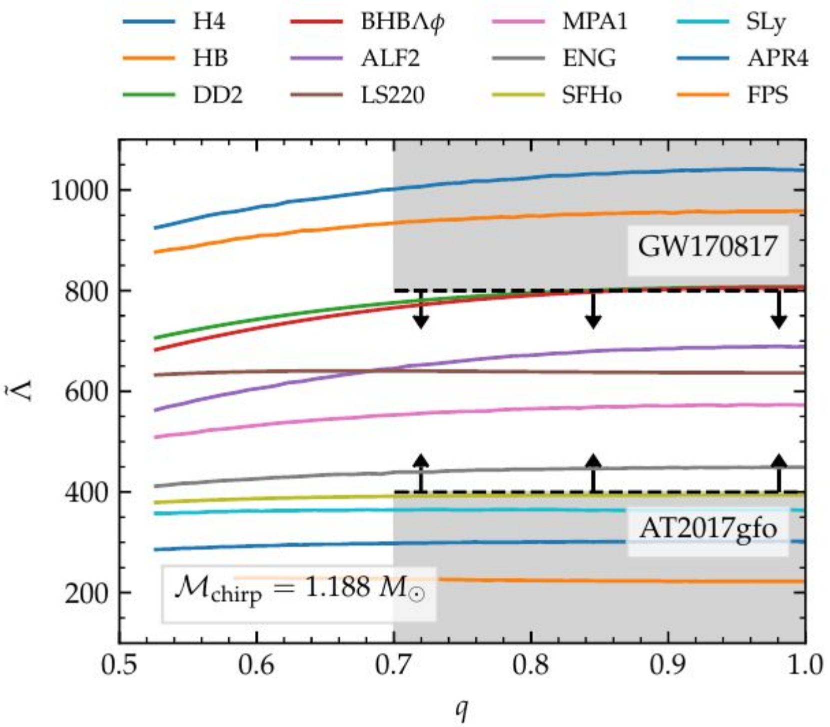
- Merger product → HMNS/SMNS (chirp mass + blue kN 1 day peak)
- Mmax ~ 2.1-2.3 [Margalit&Metzger 2017, Shibata+ 2017, Rezzola+ 2017, Ruiz+ 2017, ...]
- Radii R<13 [Bauswein+ 2017, Fattoyev+2018, Annala+2018, Raithel+2018,De+ 2018, Abbott+ 2018(LV)]
- Tidal parameter Lambda [Abbott+ 2017(LV), Radice+2017, Annala+2017, De+ 2018, Abbott 2018 (LV)]
- EOS parameters [Malik+2018]





Joint constraint on the neutron star equation of state from multimessenger observations

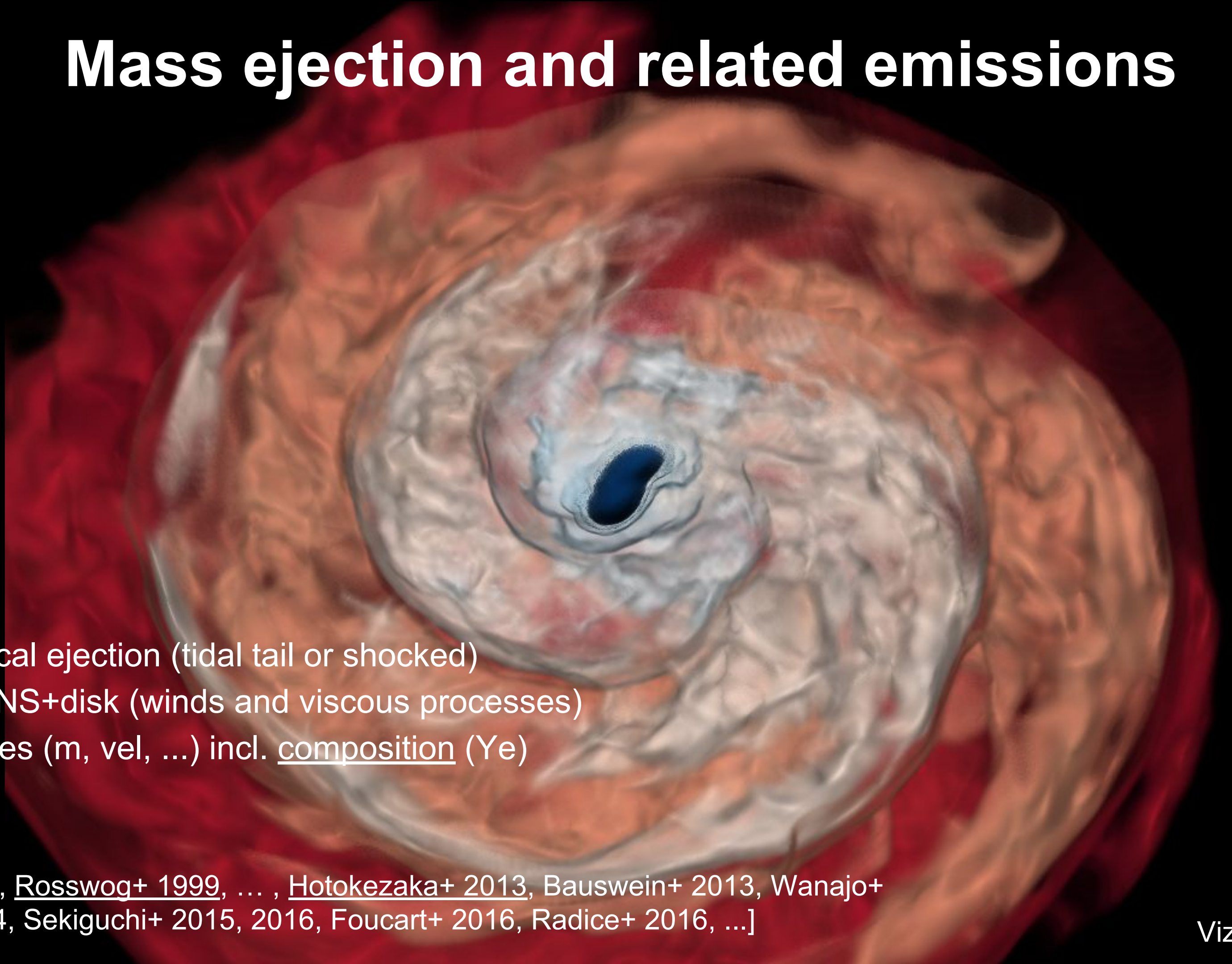




- kN model → lower bound on Mdisk
- Numerical relativity → Mdisk(Lambda)
- EM+NR analysis → lower bound on Lambda
- GW analysis → upper bound on Lambda

[Radice, Perego, Zappa, SB ApJL (2018)]

Mass ejection and related emissions



- Dynamical ejection (tidal tail or shocked)
- Disk or NS+disk (winds and viscous processes)
- Properties (m, vel, ...) incl. composition (Ye)

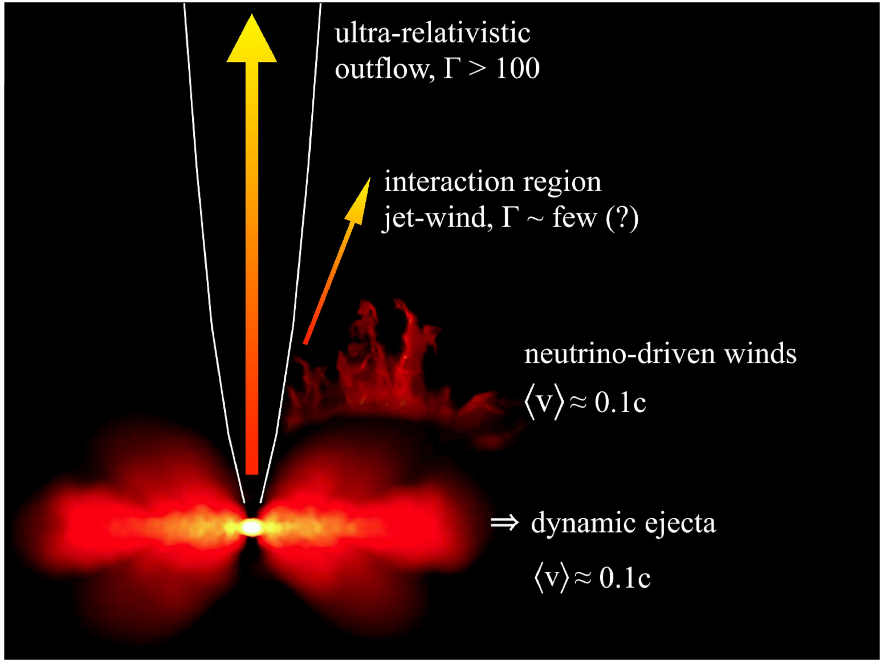
[Davies+ 1994, Rosswog+ 1999, ... , Hotokezaka+ 2013, Bauswein+ 2013, Wanajo+ 2014, Sekiguchi+ 2015, 2016, Foucart+ 2016, Radice+ 2016, ...]

Viz. By D.Radice

Ejecta from BNS mergers

- Different ejection channels:
  mechanisms, time scales, merger remnant, etc…
  - Dynamic ejecta
  - Wind ejecta (neutrino or magnetic)
  - Viscous ejecta

- Different ejecta properties:
  - Mass, velocity
  - angular distributions
  - composition → nucleosynthesis → opacity

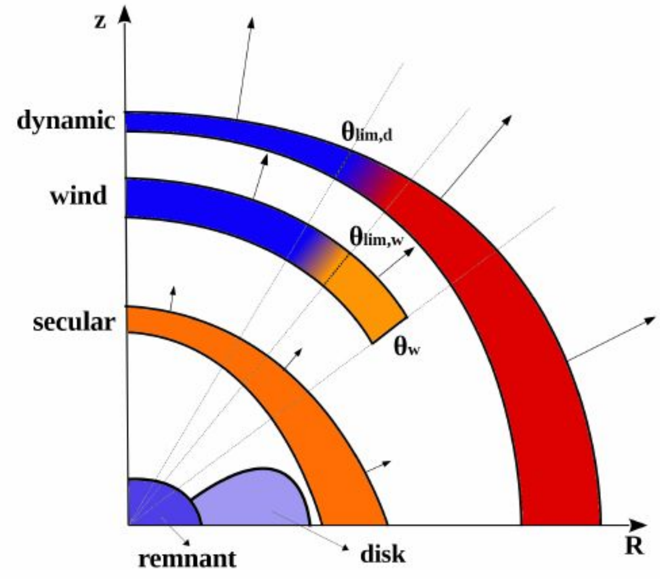


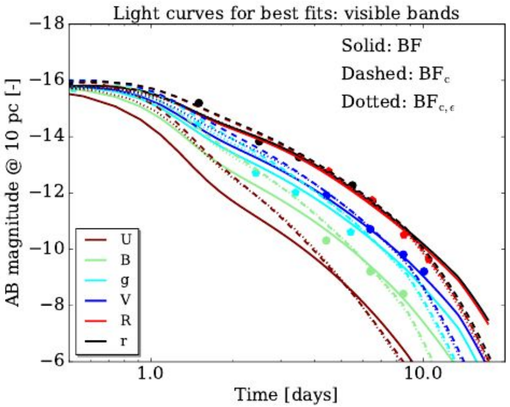
[Rosswog 2012]

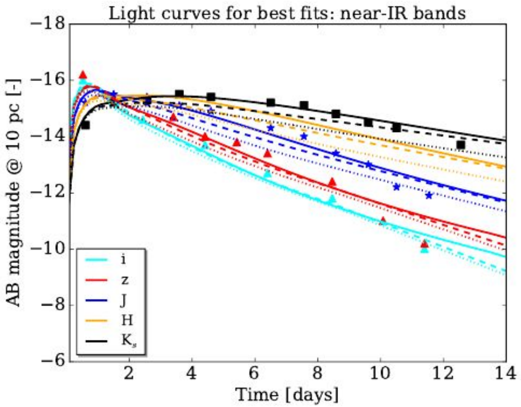
An anisotropic and three-components kilonova counterpart of GW170817

[Perego+ ApJL (2017)]

- Kilonova model containing all the ejecta information
- Several components with different contributions
- Can we reproduce AT2017gfo, KN of GW170817?





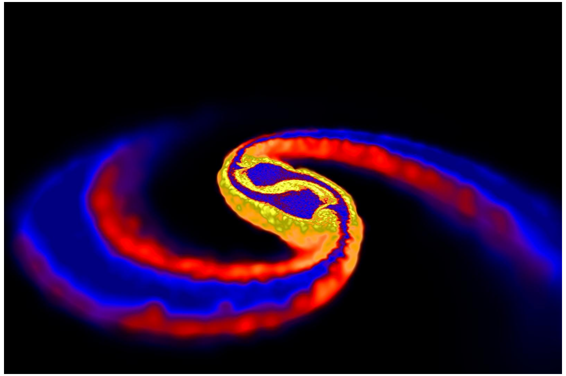


Dynamical ejecta

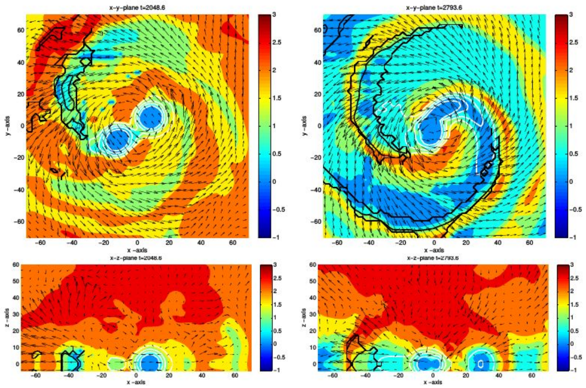
[Davies+ 1994, Rosswog+ 1999, … (Newtonian SPH, Stiff EOS)
Hotokezaka+ 2013, Bauswein+ 2013, Wanajo+ 2014, Sekiguchi+ 2015, 2016, Foucart+ 2016, Radice+ 2016]

- Tidal (cold, mainly equatorial) Vs shocked (hot, 4*pi ejection)
- Mass ~10^-4 - 10^-3 Msun
- <v> ~ 0.2 - 0.3 *c*, with possible high speed tail (< 0.8 *c*)

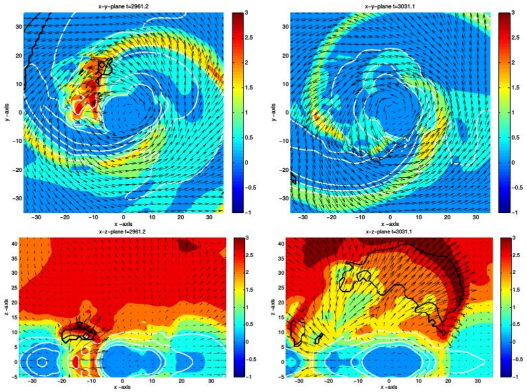
[Price & Rosswog 2007]



Tidal tail (Newt.+Stiff EOS)



Tidal tail (NR)



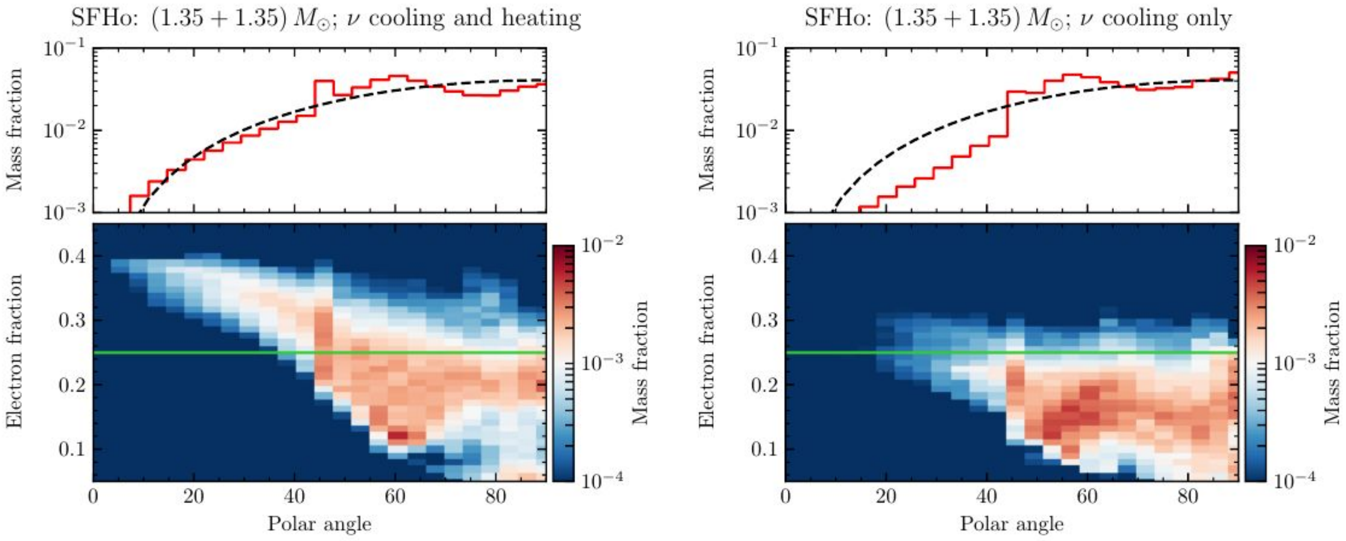
Shock driven (NR, soft EOS)

[Dietrich+ 2015]

Dynamical ejecta: composition

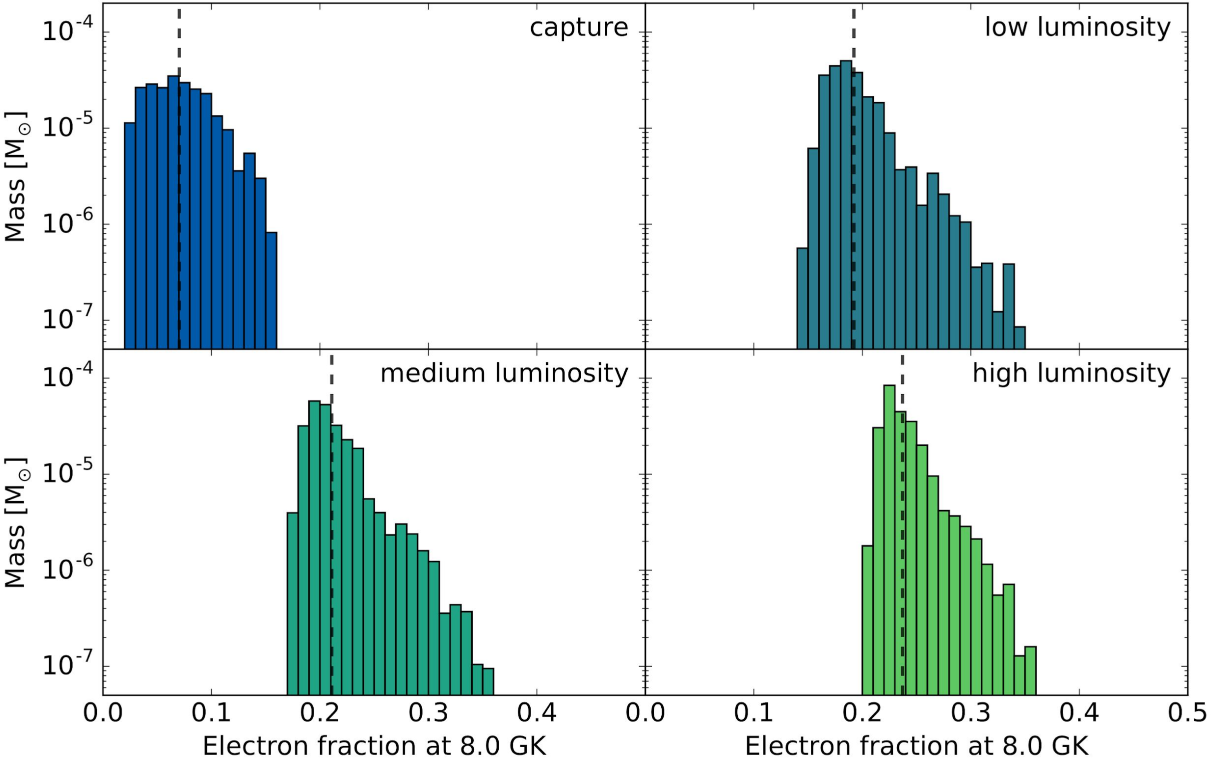
- Ejecta initially composed of free neutrons and protons (T > 10 GK)
- Ejecta composition → neutron richness of the ejecta
- Only when T < 4 GK nuclear recombination occurs
- NS matter: initially very neutron rich and low entropy
- Weak interactions can change neutron richness

$$p + e^- \leftrightarrow n + \nu_e \text{ (EC)}$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e \text{ (PC)}$$



Impact of electron neutrino absorption on ejecta composition. Simulations by D.Radice [Perego+2017 ApJL]
See also [Wanajo et al. (2014); Sekiguchi et al. (2015); Foucart et al. (2015), (2016)]

Dynamical ejecta: yields

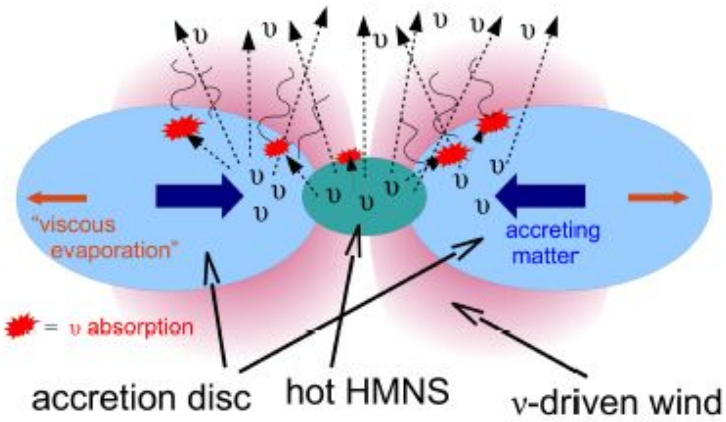


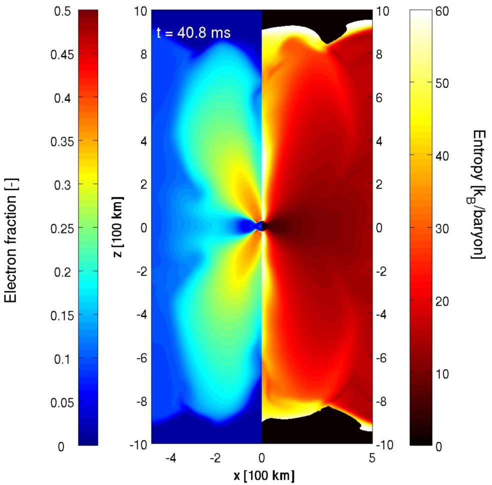
- larger neutrino luminosities lead to larger <Ye> due to electron neutrino absorption
- too higher Ye distribution prevent production of third r-process peak

[Martin, Perego, Kastaun, Arcones 2018, Goriely+2015]

Disk & secular ejecta

- If T < 5 GK inside the accretion disk, nuclear recombination energy (+ 8 MeV/baryon) can unbind matter from the disk itself
- temperature drop due to disk cooling and matter expansion
- causes of remnant expansion:
  - Neutrino absorption (t ~ 10s ms) [Dessart+2011,Perego+2014,Martin+2015, Metzger&Fernandez 2014]
  - Magnetic processes (t ~ 10s ms) [Siegel+2014]
  - Viscous processes (t ~ 100s ms) [Metzger+2010,Fernandez & Metzger 2013, Just+2015, Siegel&Metzger 2017,Fujibayashi+2017]

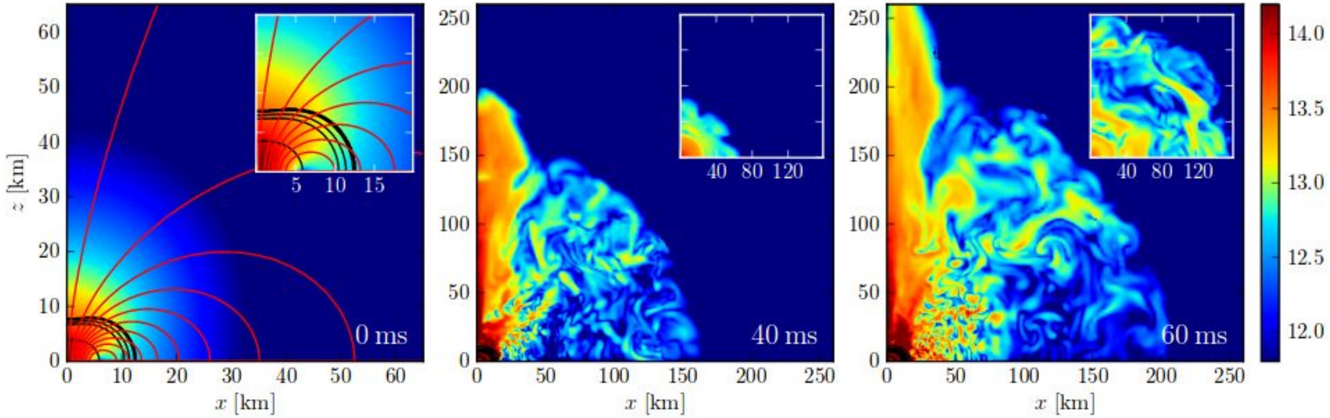




[Perego+ 2014]

Disk & secular ejecta

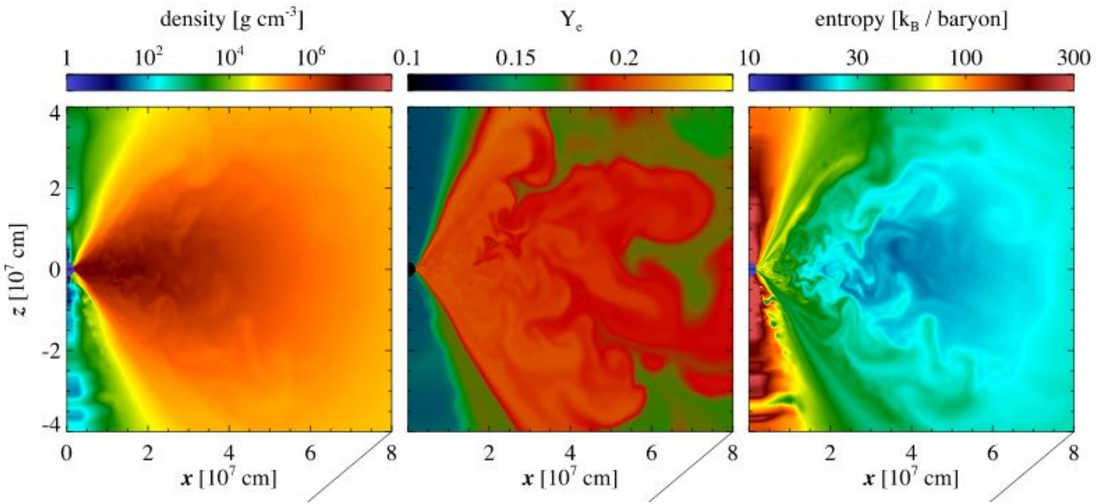
- If T < 5 GK inside the accretion disk, nuclear recombination energy (+ 8 MeV/baryon) can unbind matter from the disk itself
- temperature drop due to disk cooling and matter expansion
- causes of remnant expansion:
  - Neutrino absorption (t ~ 10s ms) [Dessart+2011,Perego+2014,Martin+2015, Metzger&Fernandez 2014]
  - Magnetic processes (t ~ 10s ms) [Siegel+2014]
  - Viscous processes (t ~ 100s ms) [Metzger+2010,Fernandez & Metzger 2013, Just+2015, Siegel&Metzger 2017,Fujibayashi+2017]



[Siegel+ 2014]

Disk & secular ejecta

- If $T < 5$ GK inside the accretion disk, nuclear recombination energy (+ 8 MeV/baryon) can unbind matter from the disk itself
- temperature drop due to disk cooling and matter expansion
- causes of remnant expansion:
  - Neutrino absorption (t ~ 10s ms) [Dessart+2011,Perego+2014,Martin+2015, Metzger&Fernandez 2014]
  - Magnetic processes (t ~ 10s ms) [Siegel+2014]
  - Viscous processes (t ~ 100s ms) [Metzger+2010,Fernandez & Metzger 2013, Just+2015, Siegel&Metzger 2017,Fujibayashi+2017]

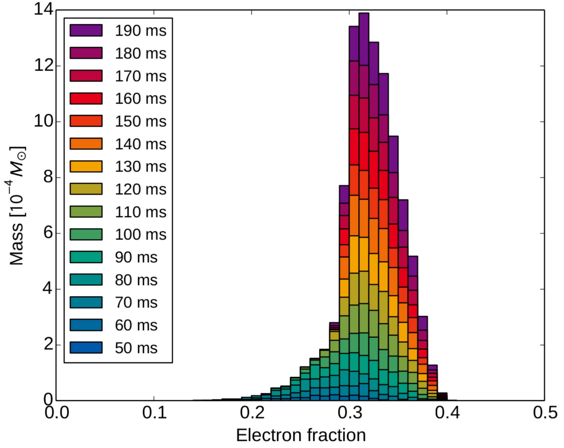


[Fernandez & Metzger 2013]

Properties of disk and viscous ejecta

Neutrino-driven wind

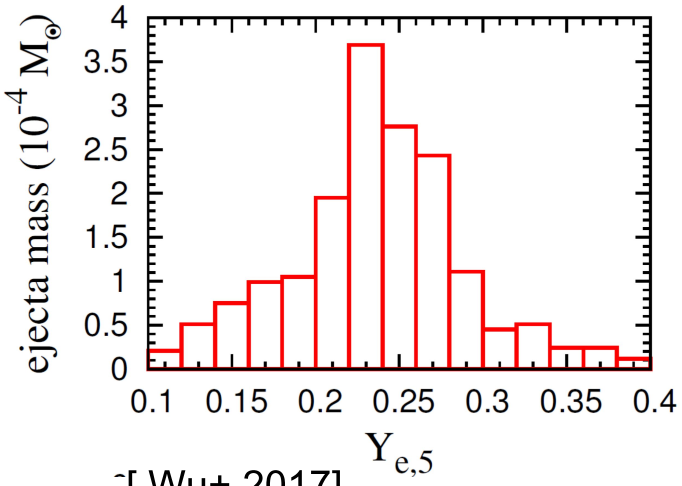
- Ye >~ 0.3
- Mwind <~ 5% disk
- (m_disk ~ 0.01 - 0.2Msun)
- <v> ~ 0.1 c



[Martin+ 2015]

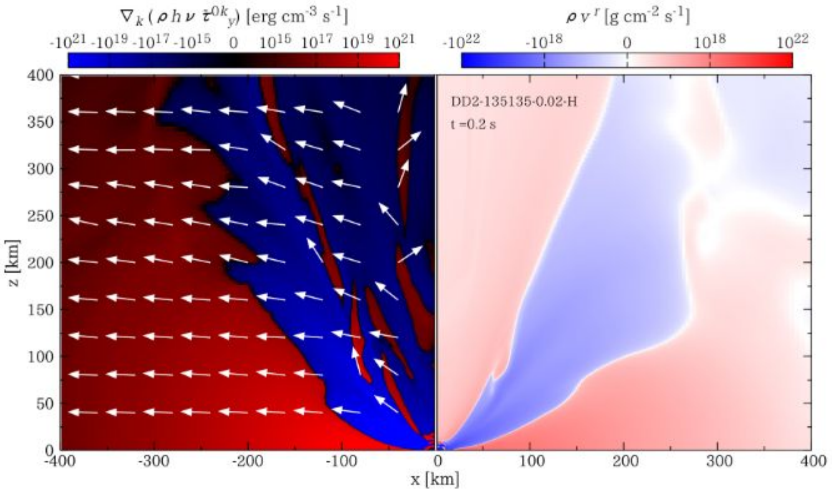
Viscous ejecta

- 0.15 < Ye < 0.35
- 20 - 40% disk
- <v> <~ 0.1 c



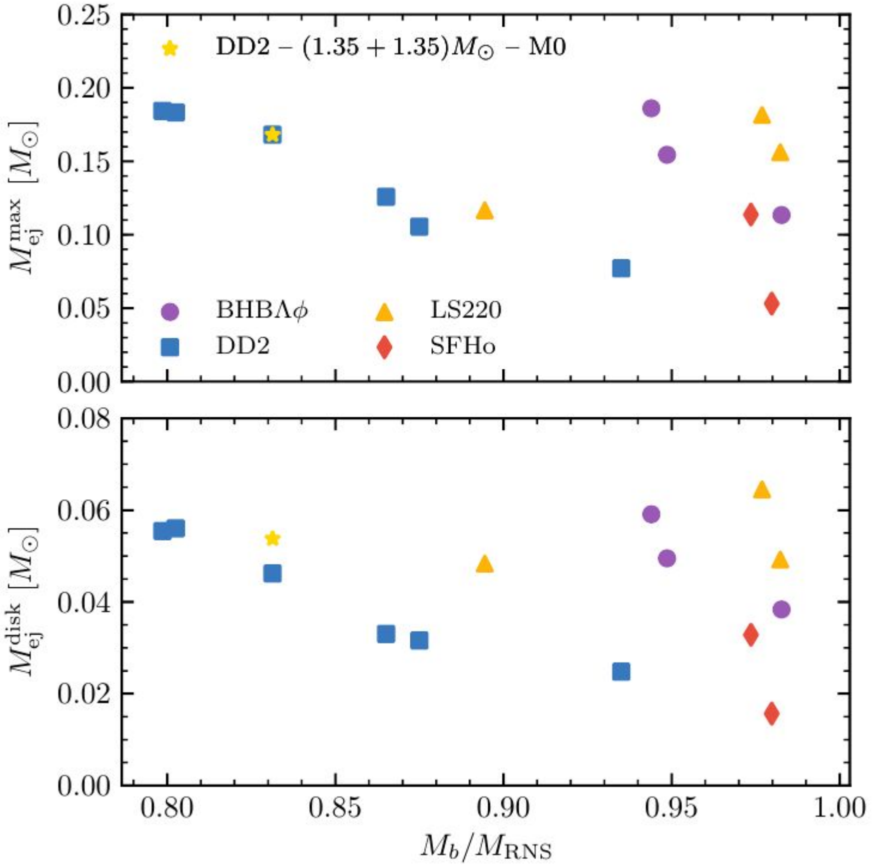
[Wu+ 2017]

Mass outflow from NS + disk remnant



Viscous-radiation simulation in 2D

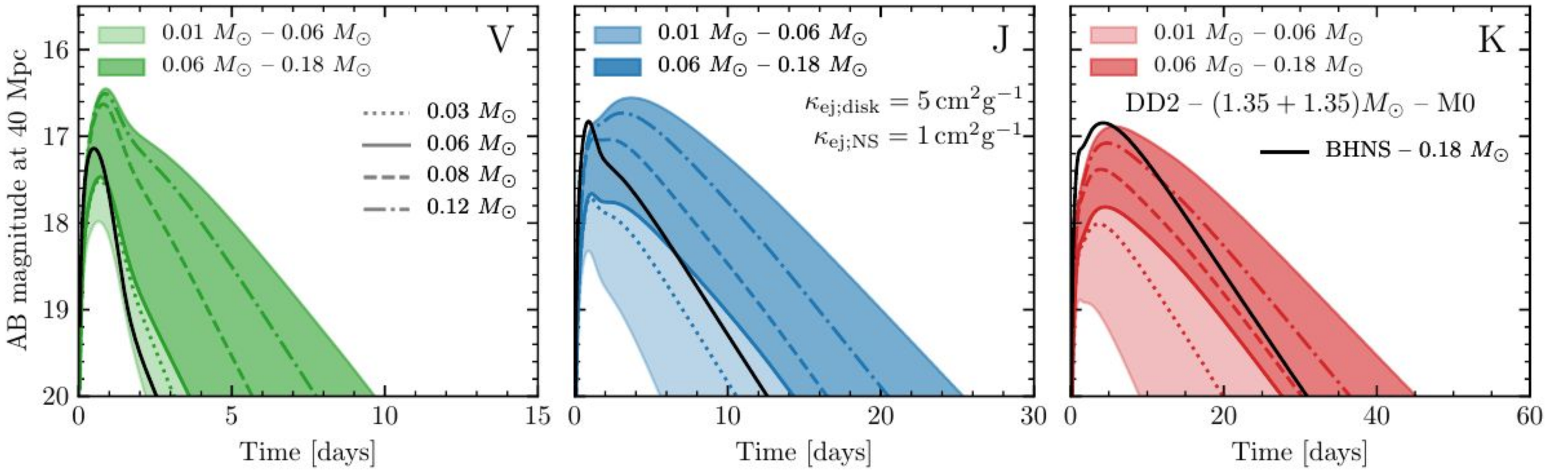
[Fujibayashi+ 2017]



Upper limits from 3D hydro+M0 simulations → [Radice, Perego, SB, Zhang 2018]

Blue+red kN signature from massive outflows

[Radice, Perego, SB, Zhang 2018]



- Fiducial NR model + Multicomponent kN model [Perego+ ApJL (2017)]
- Dyn. ejecta, winds, + **2 viscous ejecta** components:
  - Disk (nuclear recombination) M <~ 0.06 Mo
  - Remnant M <~ 0.18 Mo

Potentially observable signatures, and distinguishable from BHNS

Viscous hydrodynamics in GR

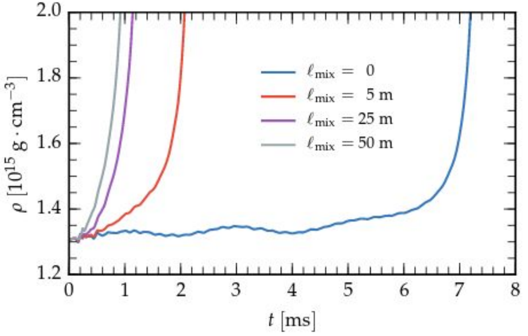
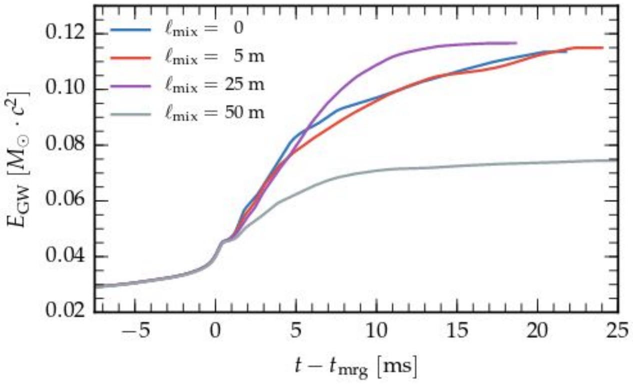


Figure 1. Maximum density in the collapse of a differentially rotating equilibrium configuration. Turbulent transport of angular momentum leads to an accelerated collapse.

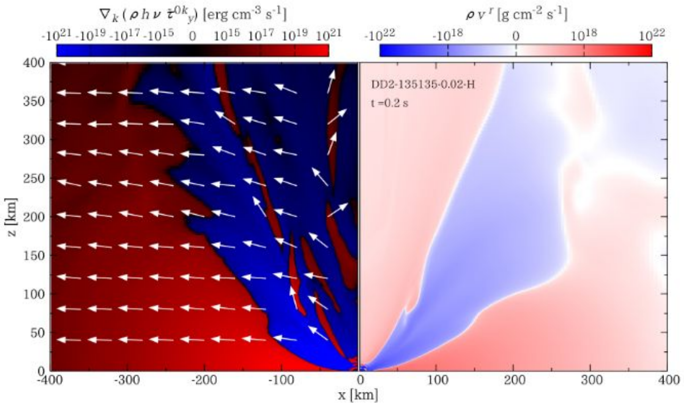


[Radice 2017]

- Accelerated collapse
- Massive winds → brighter kN
- Effect on post-merger GW amplitude
- GR-LES [Radice 2017]
- Israel-Stewart [Shibata&Kiuchi 2017]
- Results strongly depend on phenomenological parameter !

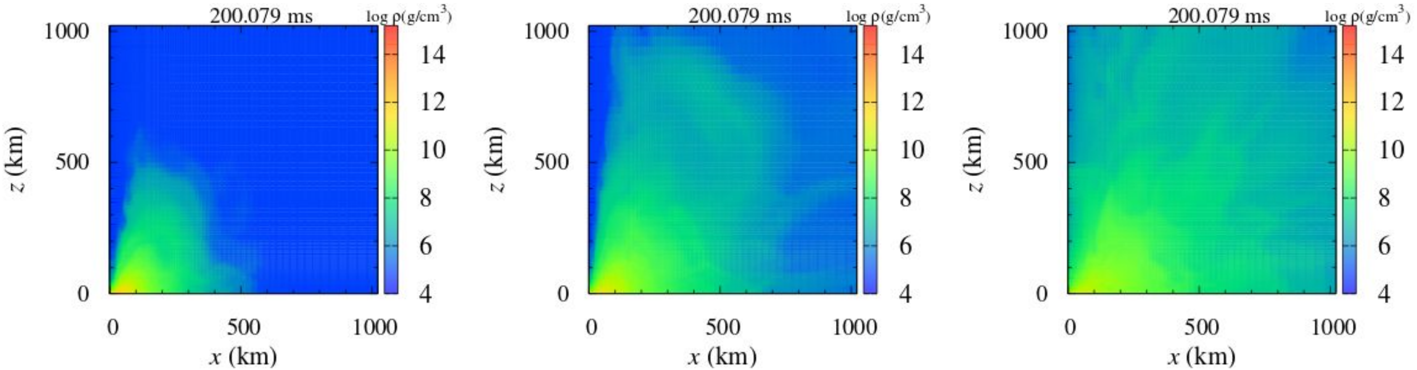
Viscous hydrodynamics in GR

[Fujibayashi+ 2017]



Viscous-radiation simulation in 2D

- Accelerated collapse
- Massive winds → brighter kN
- Effect on post-merger GW amplitude
- GR-LES [Radice 2017]
- Israel-Stewart [Shibata&Kiuchi 2017]
- Results strongly depend on phenomenological parameter !



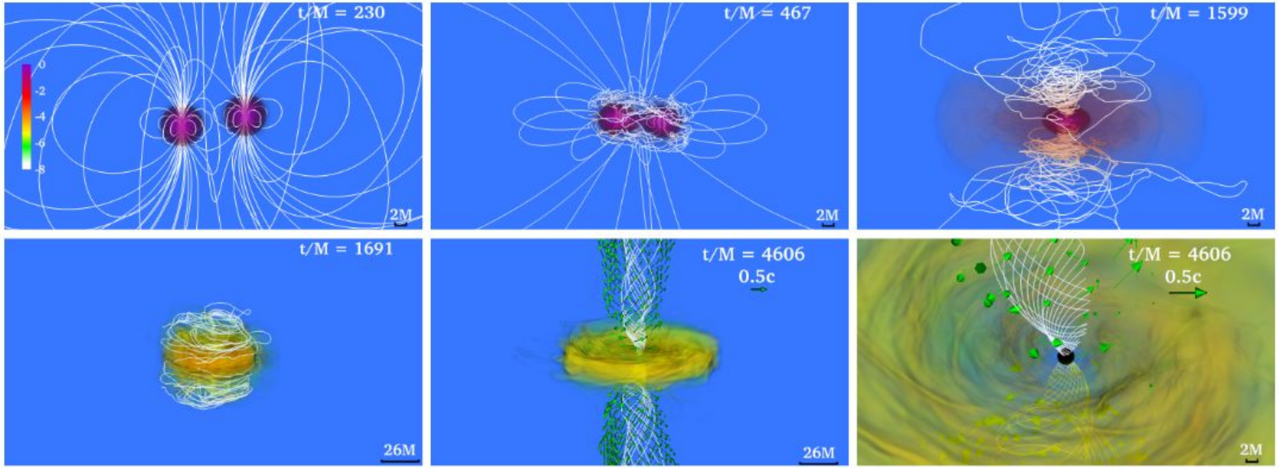
[Shibata&Kiuchi 2017]

Increasing alpha-parameter

Magnetic fields

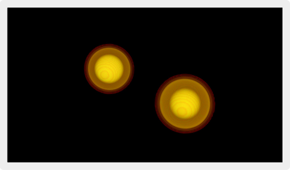
- No significant effect on inspiral-to-merge dynamics and GWs
- Magnetospheres interaction → $L_{EM} \sim 10^{40\text{-}43}$ $(B/10^{11}$ G$)^2$ erg/s
- KH instability at contact
- Delayed HMNS collapse
- Jet formation (?)
- MRI, turbulence and viscosity → $T_{visc} \sim O(100$ ms$)$ [alpha-viscosity model]

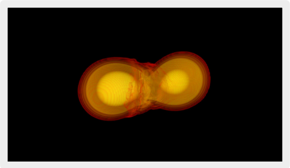
Caveat: simulations employ artificially large B and poorly (if at all) resolve these effects

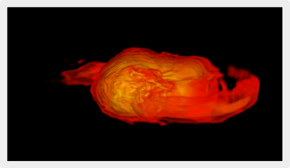


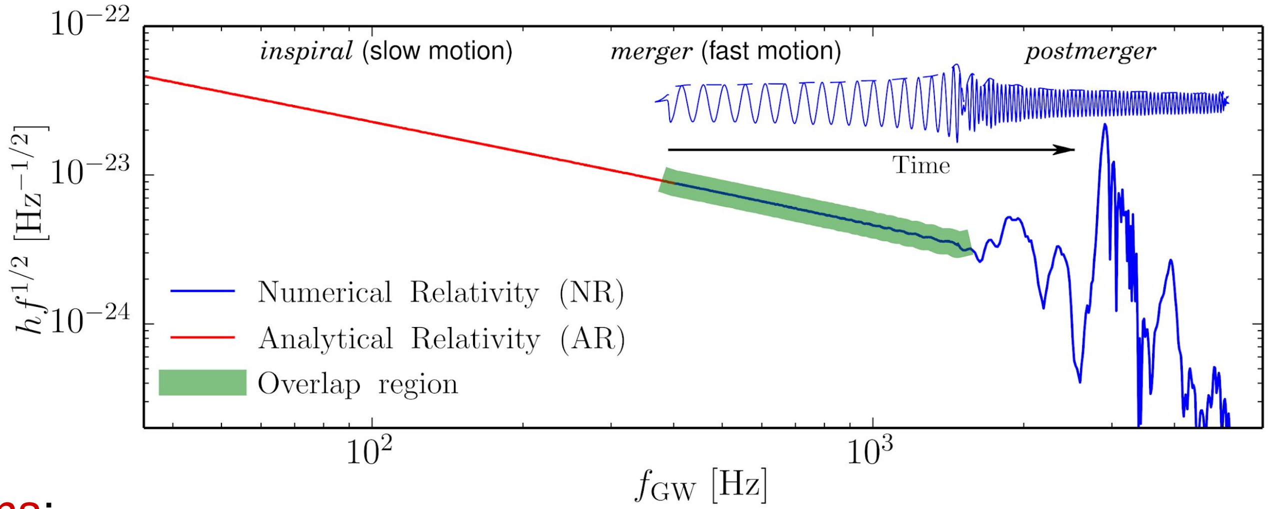
[Andersson+ 2008,Liu+ 2008,Giacomazzo+ 2009,Rezzolla+ 2011,Palenzuela+ 2013,Kiuchi+ 2014, Kiuchi+ 2015, Ruiz+ 2016,2017,Endrizzi+ 2016, Kiuchi+ 2017]

The GW spectrum of binary neutron stars





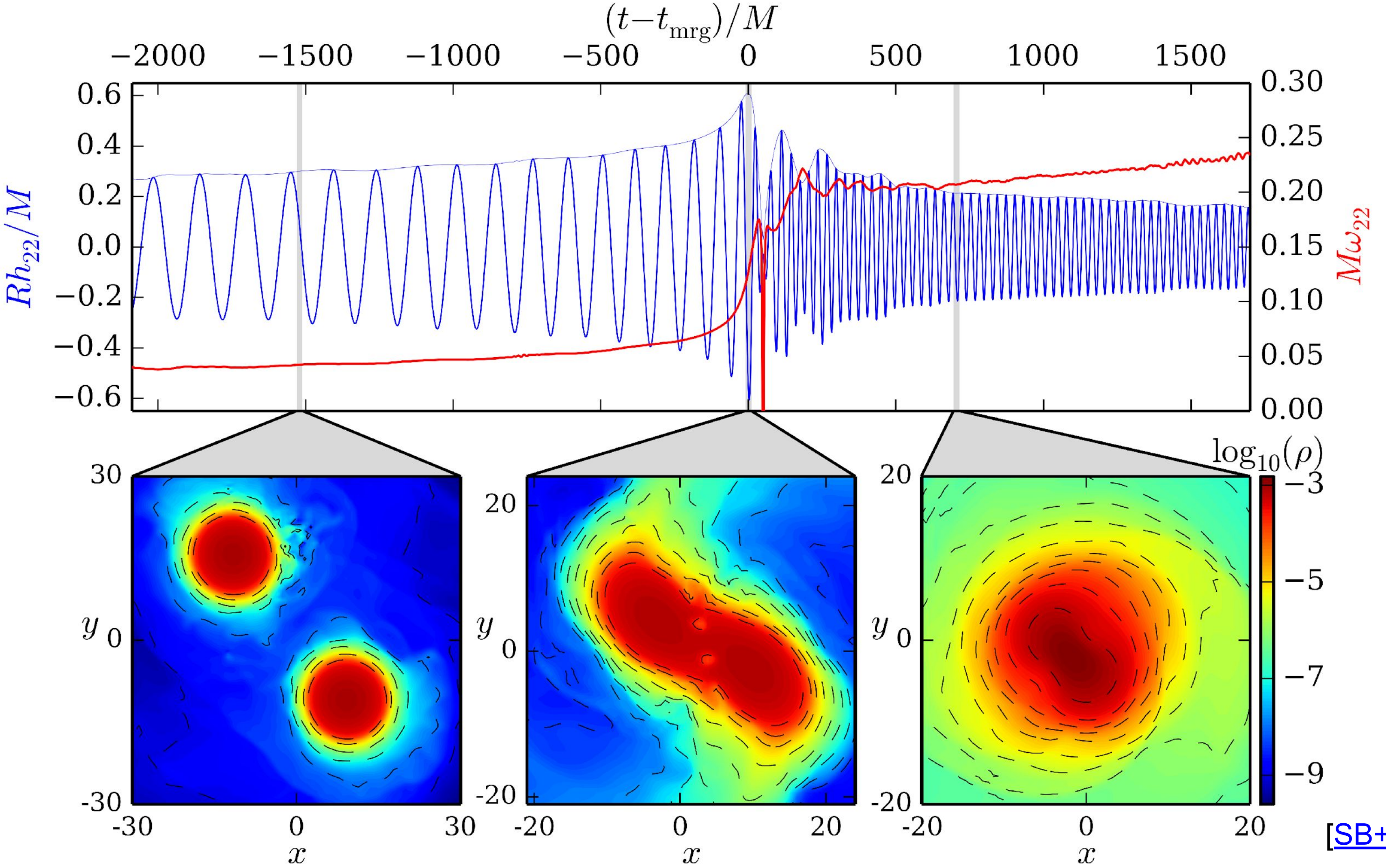




Open problems:

- Faithful and **complete waveform model** (*inspiral*+*merger*+*postmerger*)
- Coverage of the **parameter space** (mass, spins, EOS, …)
- Exploration of input physics

Dynamics and waveform



[SB+ 2015]

PHYSICAL REVIEW D, VOLUME 61, 064001

Simulation of merging binary neutron stars in full general relativity: $\Gamma=2$ case

Masaru Shibata
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
and Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

Kōji Uryū
SISSA, Via Beirut 2/4, 34013 Trieste, Italy
(Received 11 October 1999; published 10 February 2000)

We perform 3D numerical simulations for the merger of equal mass binary neutron stars in full general relativity. We adopt a Γ-law equation of state in the form $P=(\Gamma-1)\rho\varepsilon$ where P, ρ, ε and Γ are the pressure, rest mass density, specific internal energy, and the adiabatic constant with $\Gamma=2$. As initial conditions, we adopt models of corotational and irrotational binary neutron stars in a quasiequilibrium state which are obtained using the conformal flatness approximation for the three geometry as well as the assumption that a helicoidal Killing vector exists. In this paper, we pay particular attention to the final product of the coalescence. We find that the final product depends sensitively on the initial compactness parameter of the neutron stars: In a merger between sufficiently compact neutron stars, a black hole is formed in a dynamical time scale. As the compactness is decreased, the formation time scale becomes longer and longer. It is also found that a differentially rotating massive neutron star is formed instead of a black hole for less compact binary cases, in which the rest mass of each star is less than 70–80 % of the maximum allowed mass of a spherical star. In the case of black hole formation, we roughly evaluate the mass of the disk around the black hole. For the merger of corotational binaries, a disk of mass $\sim 0.05-0.1 M_*$ may be formed, where M_* is the total rest mass of the system. On the other hand, for the merger of irrotational binaries, the disk mass appears to be very small: $<0.01 M_*$.

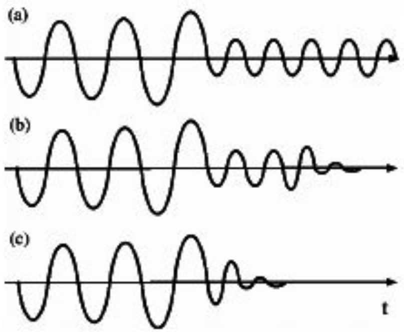
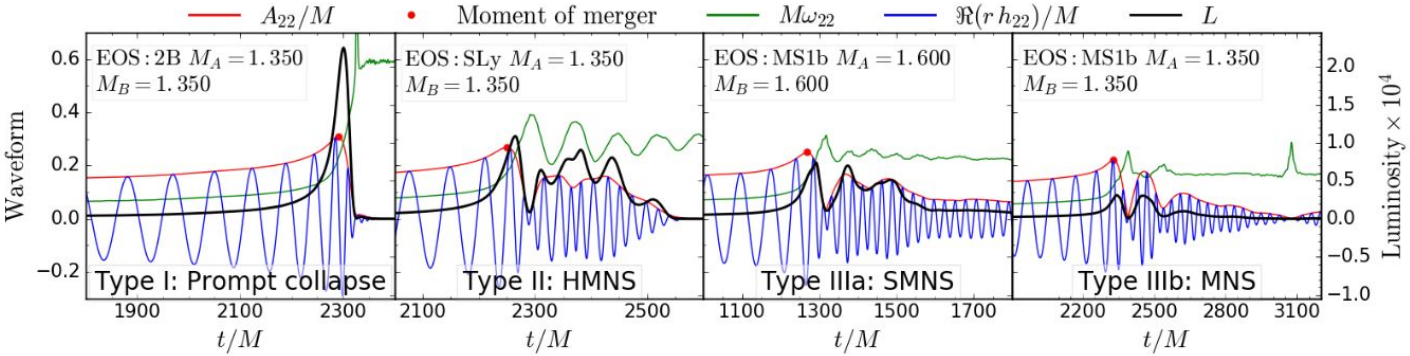
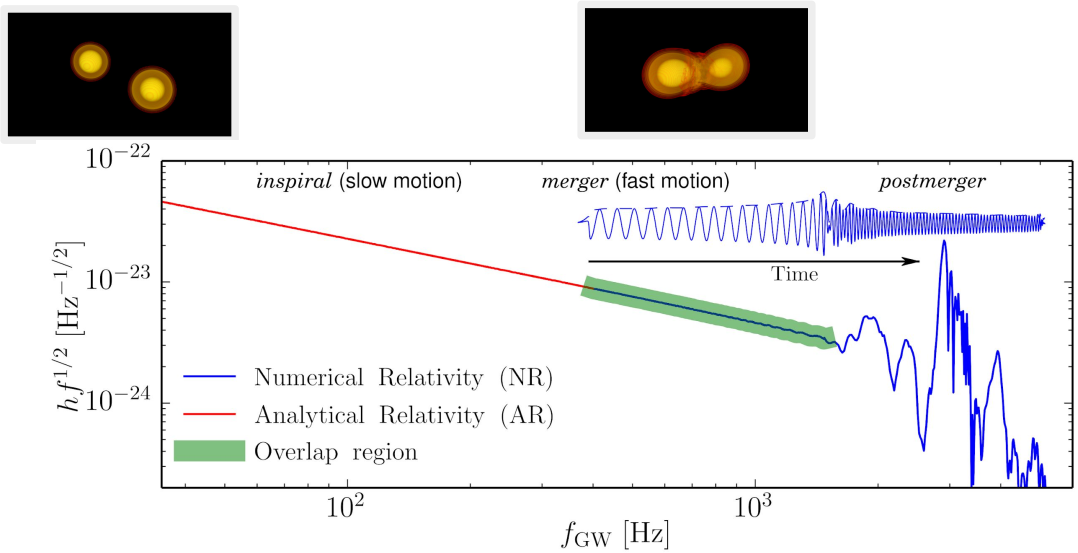


FIG. 19. Schematic pictures for expected gravitational wave forms during and after the merger for (a) the neutron star formation case; (b) the black hole formation case in which the compactness of the neutron stars before the merger is not very large and the formation time scale is fairly long; (c) the black hole formation case in which the compactness of the neutron stars before the merger is large enough that the formation time scale is short.

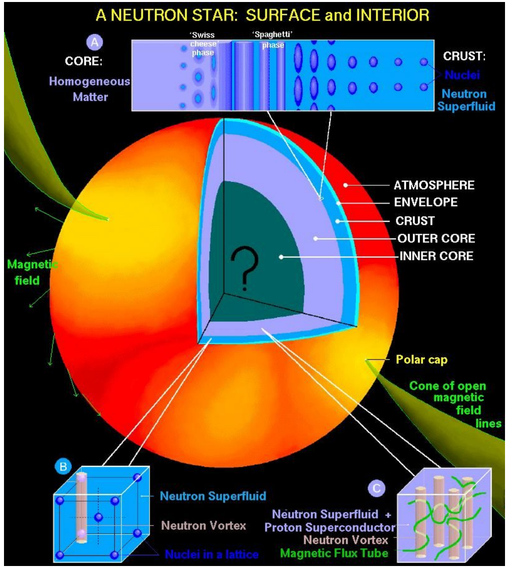
Picture confirmed by several groups by 2011-18, e.g.

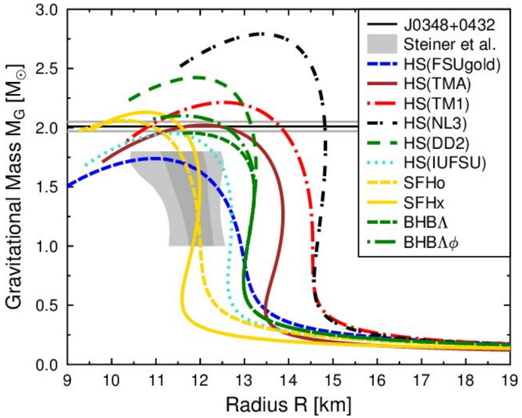


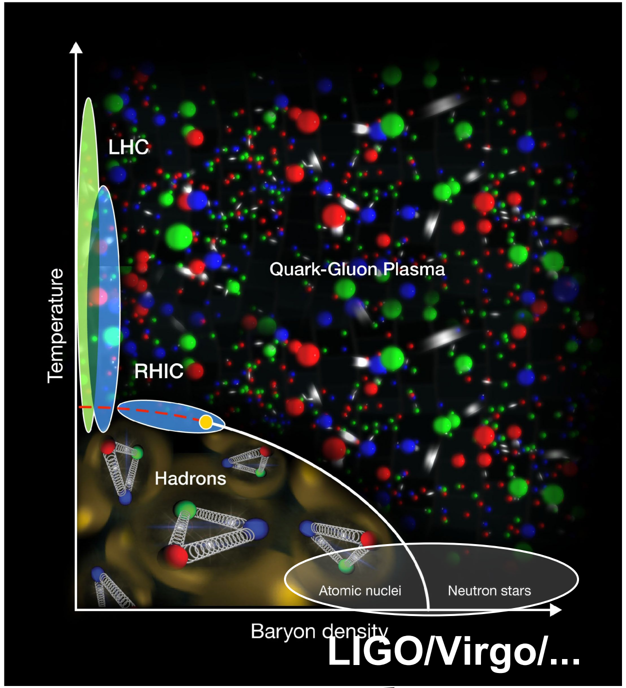
inspiral → merger - postmerger



What can we say about neutron star matter?



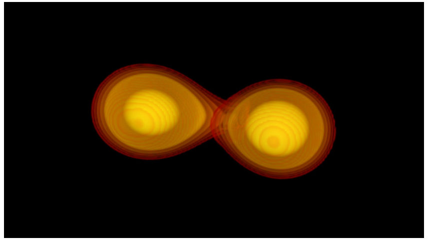


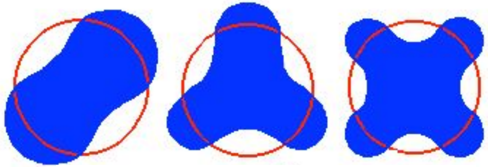


Different EOS → different star's structure

Binary neutron star mergers

Observing tidal effects in GWs tells us about the neutron star matter

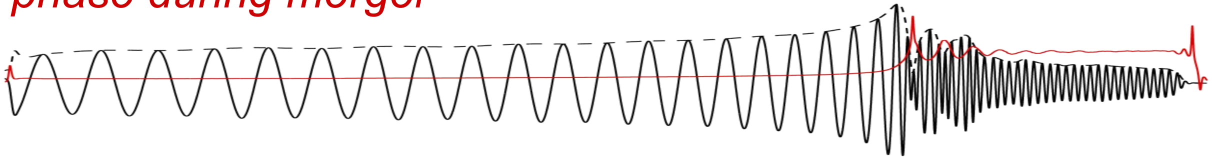




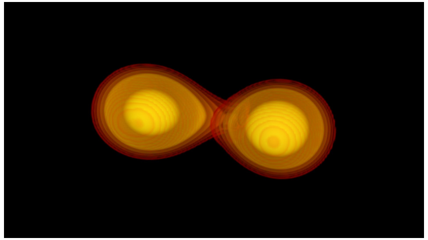
$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$

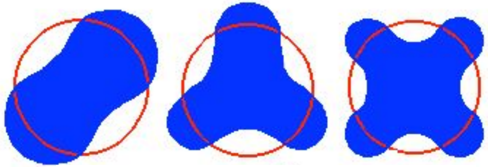
Tides depend critically on EOS

Tides determine the wave's phase during merger



Observing tidal effects in GWs tells us about the neutron star matter

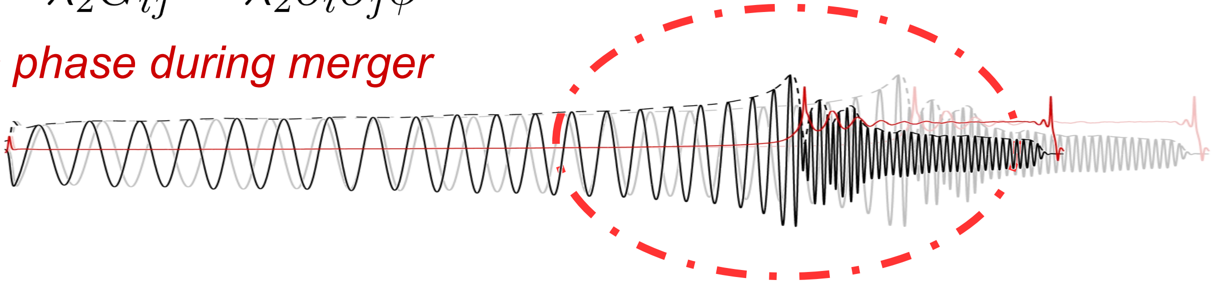




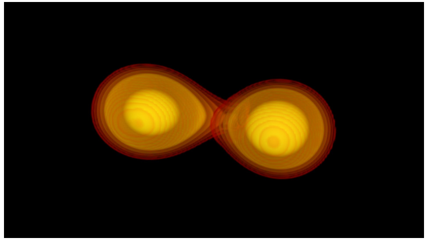
$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$

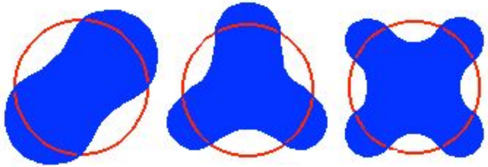
Tides depend critically on EOS

Tides determine the wave's phase during merger



Observing tidal effects in GWs tells us about the neutron star matter

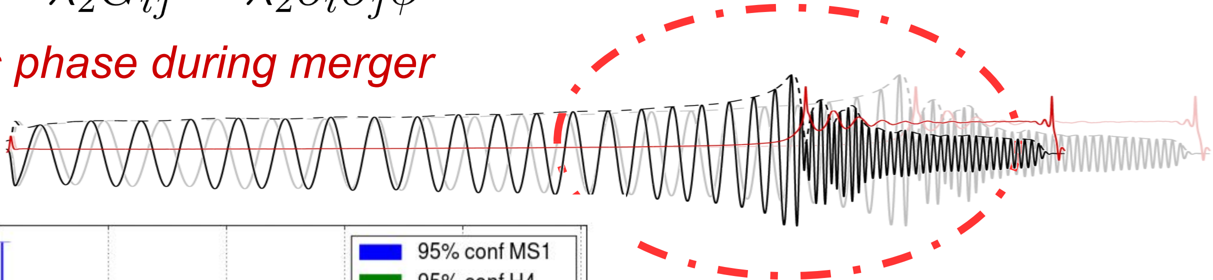


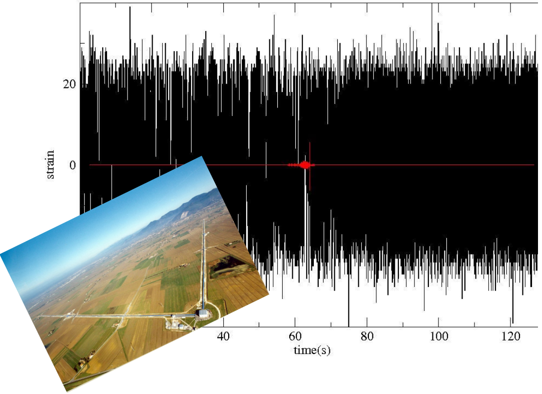


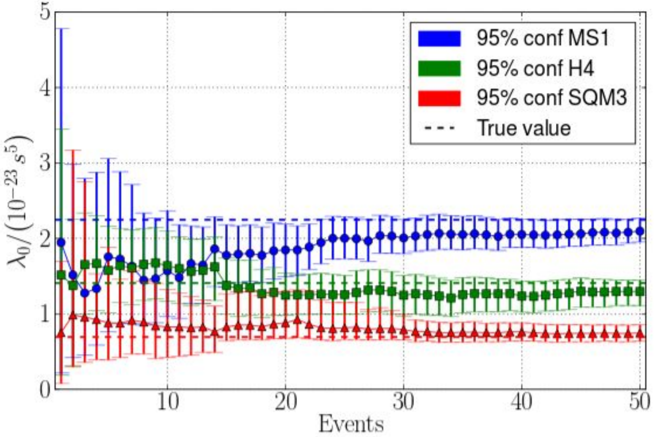
$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$

Tides depend critically on EOS

Tides determine the wave's phase during merger

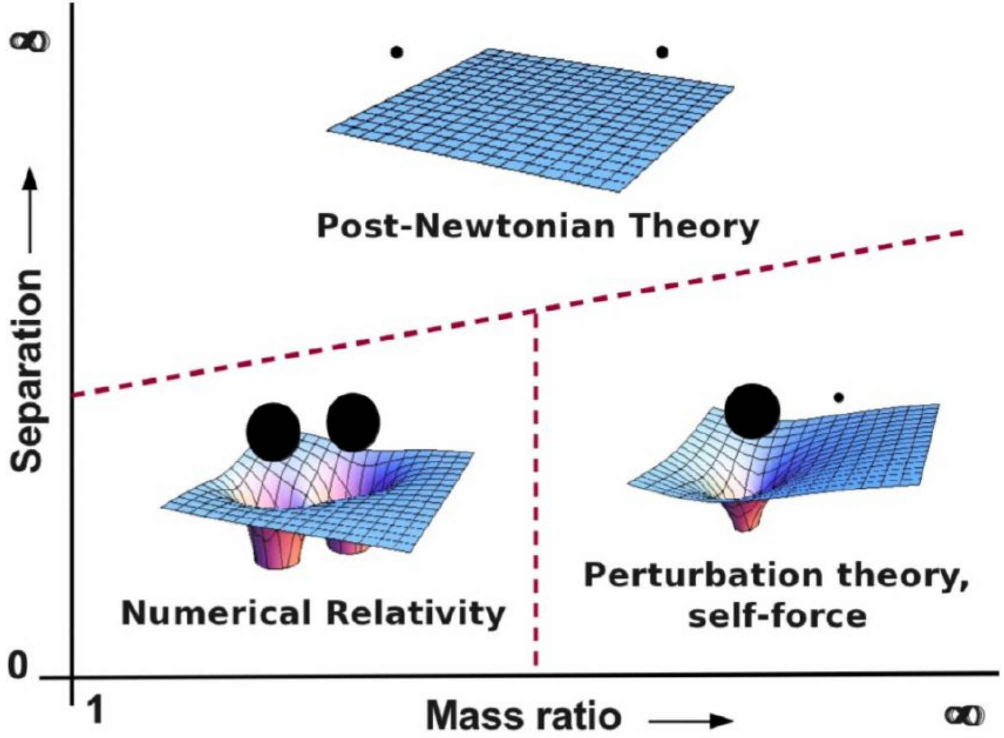






[Del Pozzo+ PRL 111 (2013)]

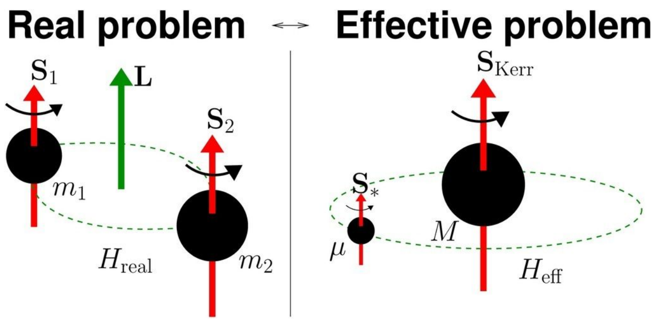
Methods for the GR 2-body problem



Credit: L.Barak

Effective-one-body framework in a nutshell

[Buonanno&Damour 2000a, 2000b]



Credit: A.Taracchini/AEI

$$H_{\rm eff} \sim \mu\sqrt{A(u)(1+p_\phi^2 u^2) + p_{r*}^2}$$

$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

$$A^0(u;\nu) = 1 - 2u + \nu(\ldots$$

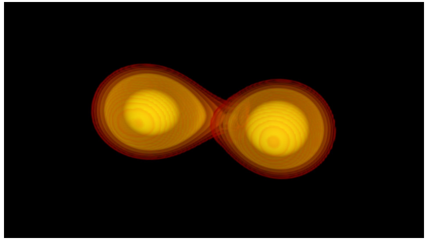
Factorized (resummed) PN waveform
[Damour,Iyer,Nagar 2008]

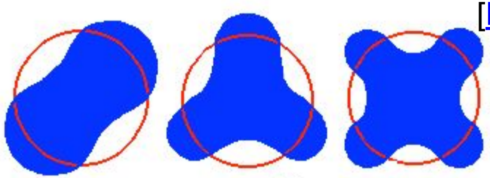
- Includes test-mass limit (i.e. particle on Schwarzschild)
- Includes post-Newtonian and self-force results
- Uses resummation techniques → predictive strong-field regime
- Includes tidal interactions (→ BNS) [Damour&Nagar PRD 2010]
- Flexible framework, can include NR results ("NR-informed")
- Most accurate framework to describe compact binary waveforms

See e.g. [Taracchini+ 2013,SB+ 2015,Nagar+ 2015,Hinderer+ 2016]

Relativistic Tides

[Hinderer 2007, Damour&Nagar 2009a,Binnington&Poisson 2009]





$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$

$$\kappa_2^T = 2\left[\frac{X_A}{X_B}\left(\frac{X_A}{C_A}\right)^5 k_2^A + \frac{X_B}{X_A}\left(\frac{X_B}{C_B}\right)^5 k_2^B\right]$$

[Damour&Nagar 2009b]

Tidal contribution to (post-) Newtonian dynamics and waveform:

Hamiltonian (Newtonian limit):

$$H_{\rm EOB} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$

$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

Tides are attractive and “act” at small separations

Tidal coupling constant

Waveform:

$$h \sim Af^{-7/6}e^{-i\Psi(f)} \approx Af^{-7/6}e^{-i\Psi_{PP}(f) + i39/4\kappa_2^T x(f)^{5/2}}$$

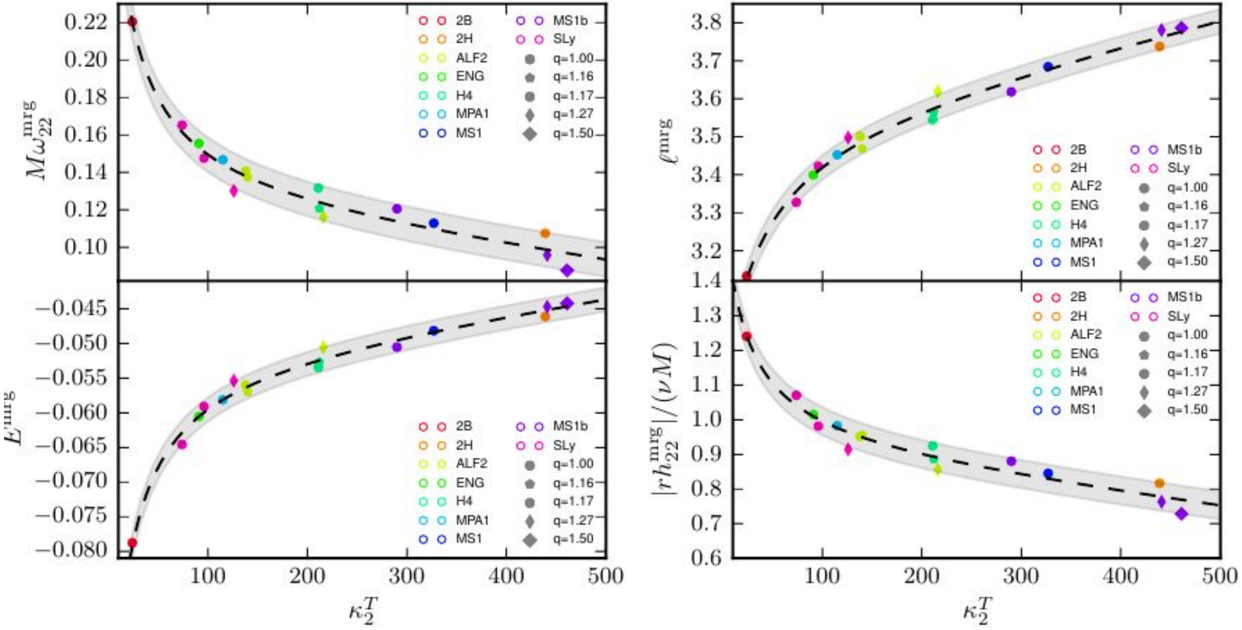
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism

One parameter to characterize merger dynamics

[SB,Nagar,Balmelli,Dietrich,Ujevic PRL 112 (2014)]

GW frequency

Binding energy



Ang. Mom.

GW amplitude

Tidal polarizability coef. (l=2)

One parameter to characterize merger dynamics

[SB,Nagar,Balmelli,Dietrich,Ujevic PRL 112 (2014)]

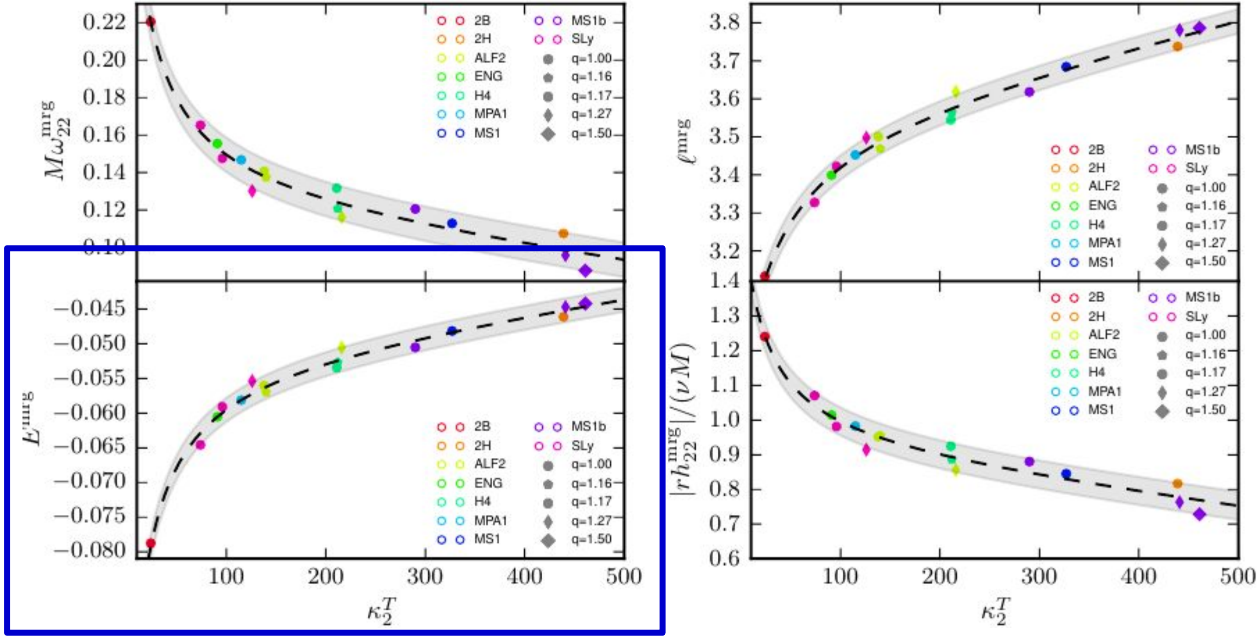
Predict energy emitted in GW for all binaries, range 1-2% M
(all possible EOS, masses, mas-ratios)

GW frequency

Binding energy

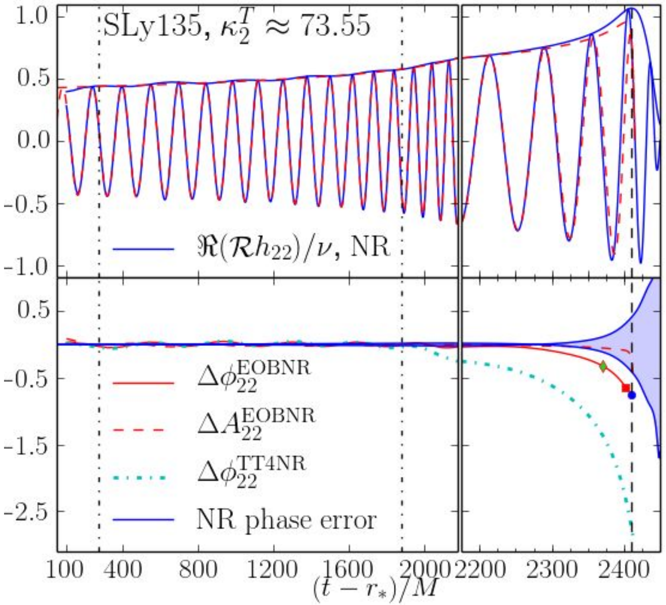
Ang. Mom.

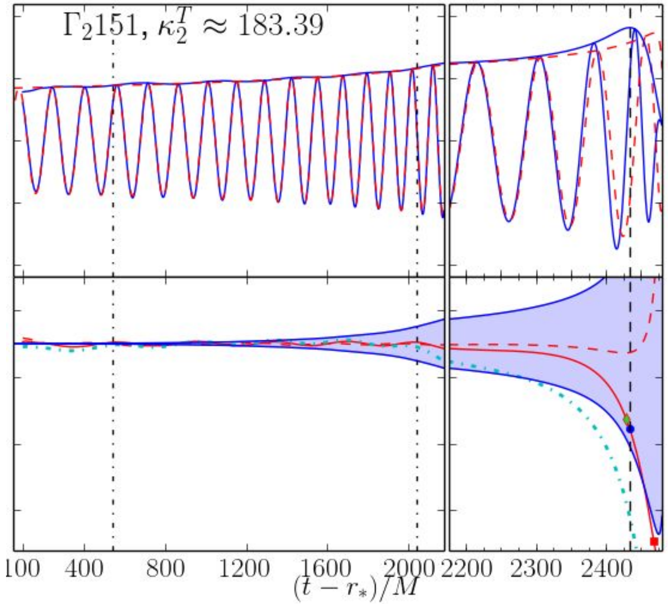
GW amplitude



Tidal polarizability coef. (l=2)

Developing analytical waveform models



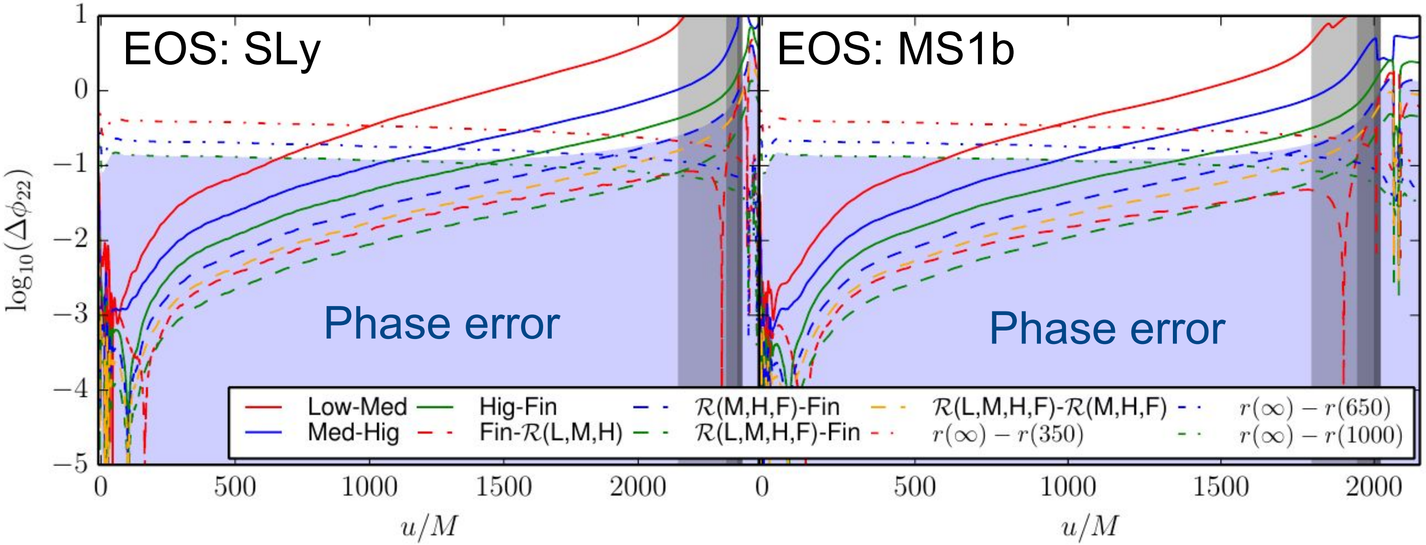


- Effective-one-body model (TEOBResumS) and PN Taylor T4
- Align waveforms at low frequencies and measure accumulated phase diff.
- Accuracy: uncertainties of the numerical data (improve simulations!)

[SB,Nagar,Dietrich,Damour PRL 114 (2015), Nagar+ (2018)]

Improved NR GW with high-order WENO schemes

[SB&Dietrich (2016)]

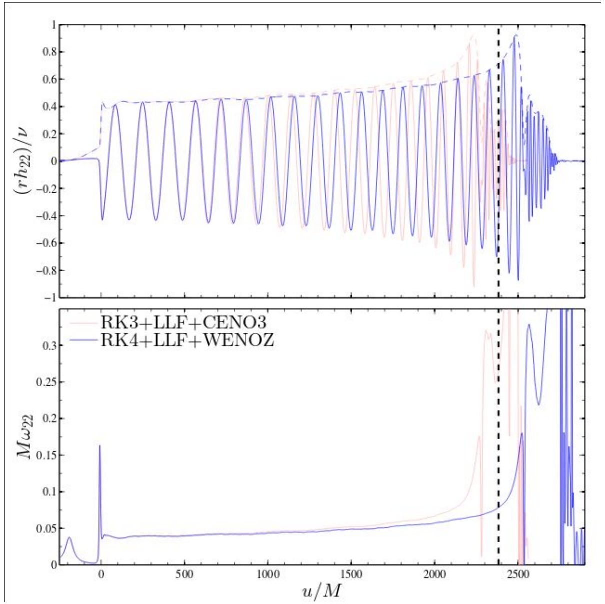


- Robust convergence assessment (although not 5th order)
- Large resolution span (64^3 -192^3), no alignment
- Error budget: significant improvement wrt FV schemes
- Truncation error dominates at high frequencies
- Finite radius extraction dominates at low frequencies

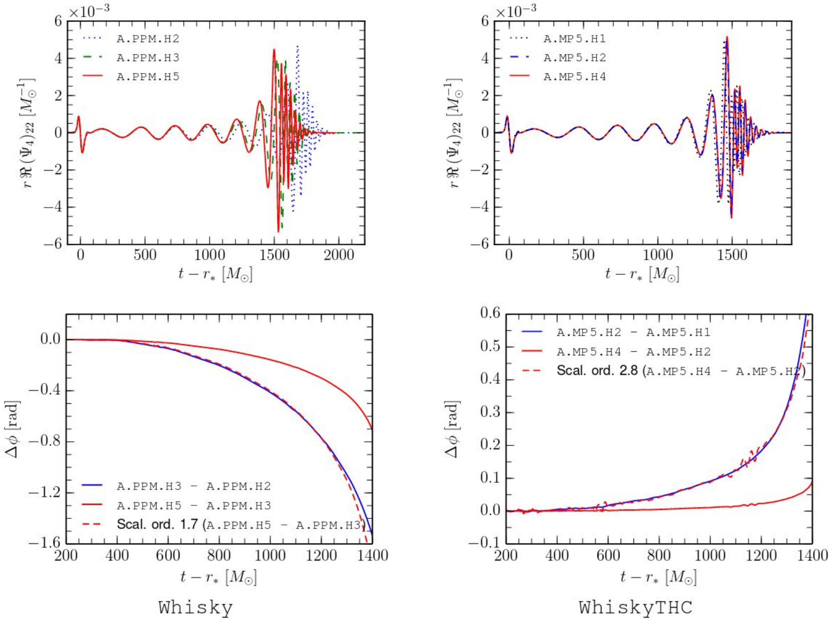
See also [SB+ 2011,2012, Radice+ 2013, 2013b]

Error analysis and systematics

[SB+ 2012]



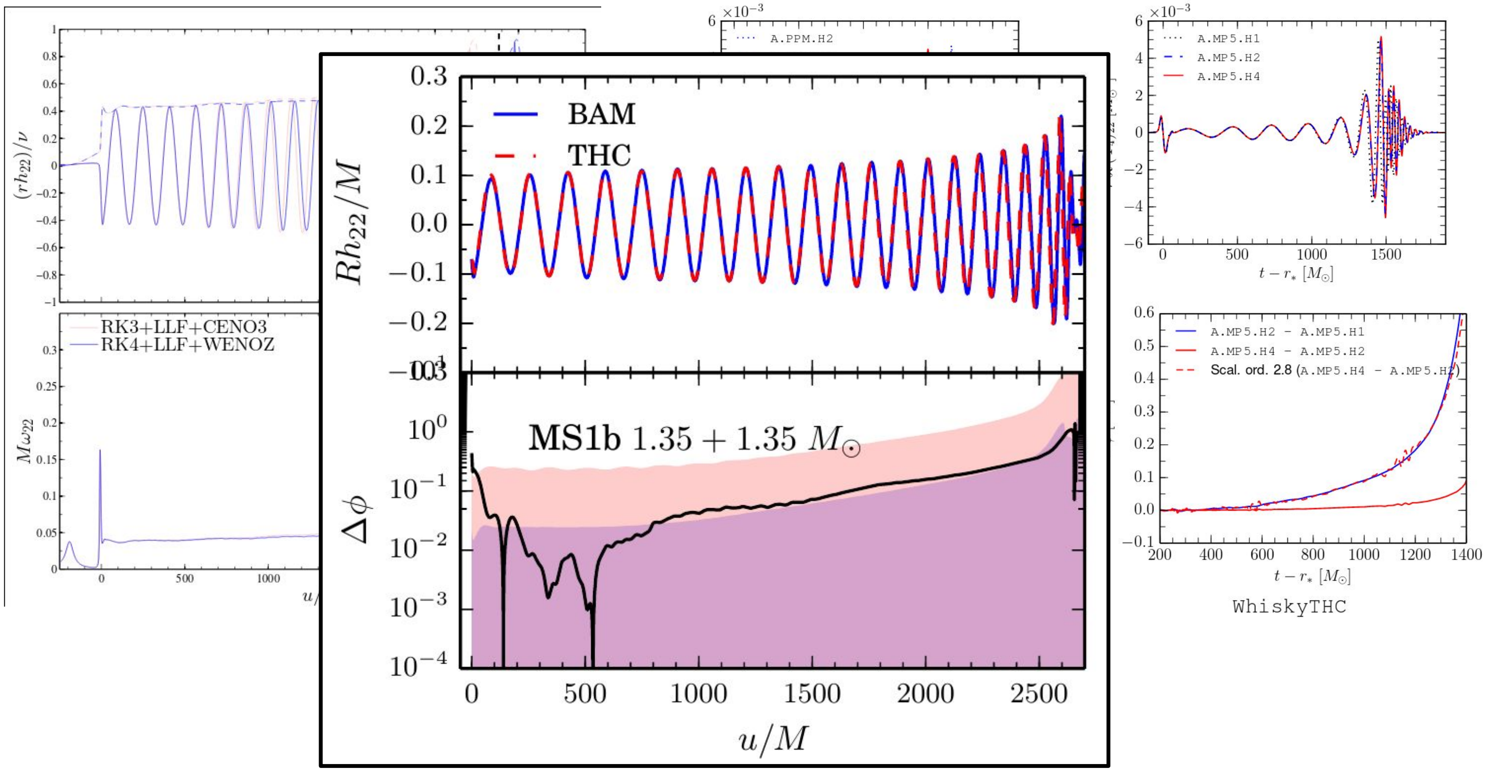
[Radice+2013b]



Numerical dissipation of hydro schemes can be a significant source of systematic error

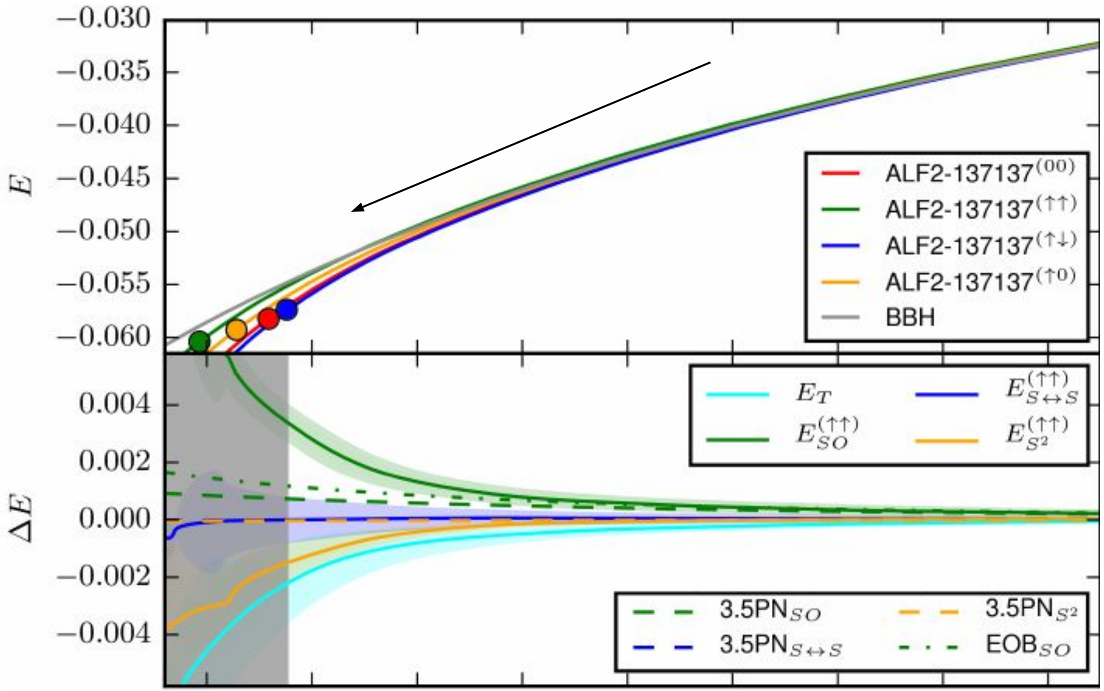
Error analysis and systematics

[SB+ 2012] [Radice+2013b]



Spins & tides during merger: energetics

[SB+ 2013, Dietrich+ 2017]



Binding energy

Angular momentum

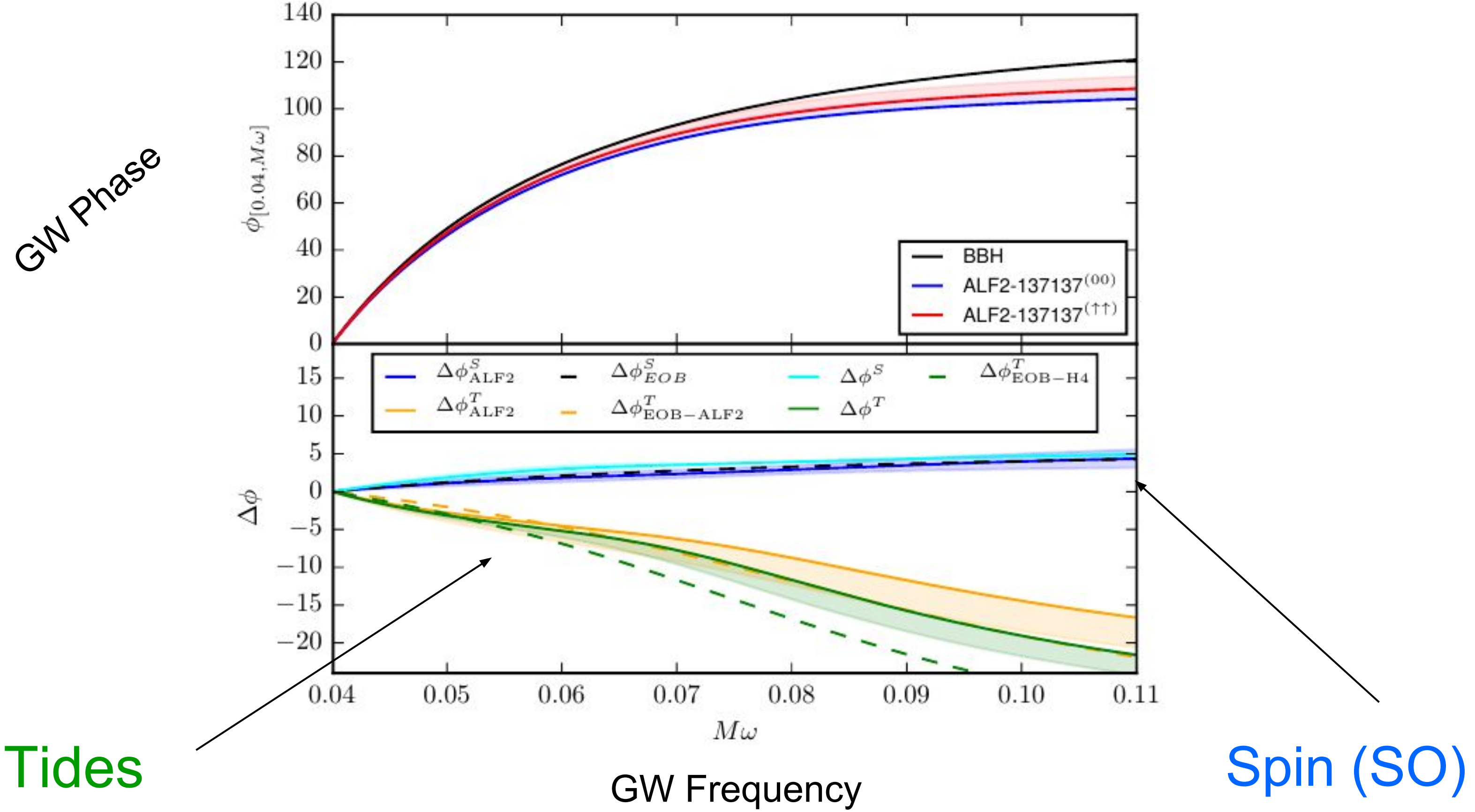
See also

[Damour 2001] for strong-field behaviour of spherical orbits

[Campanelli+ 2006] for binary black hole simulations “hang-up” effect

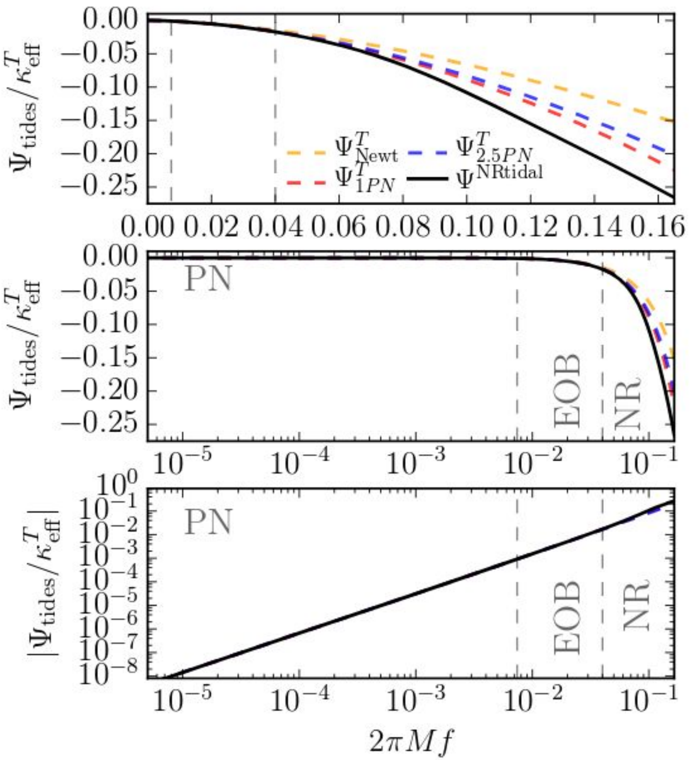
Spins & tides during merger: phasing

[Dietrich, SB, Ujevic, Tichy PRD 95 (2017)]



Closed-form tidal approximants: NRtidal

[Dietrich,SB,Tichy 2017]



NR-based tidal approximant
3F: *fast, flexible,faithful*

Build:
PN + TEOBResum + NR

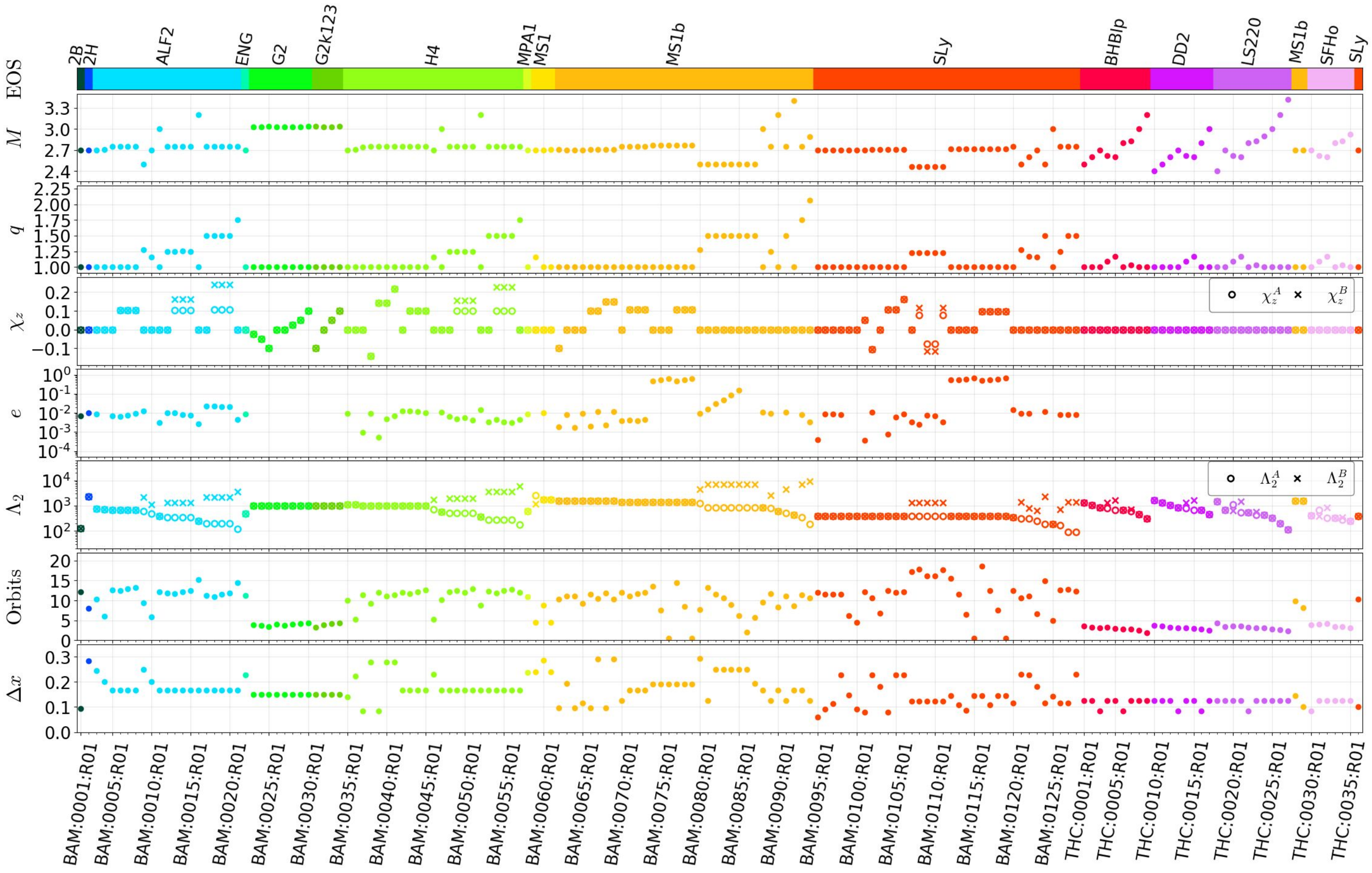
Use:
Add to any BBH waveform

Used for GW170817 analysis

Further developments [Kawaguchi+ 2018,Dietrich+ 2018]

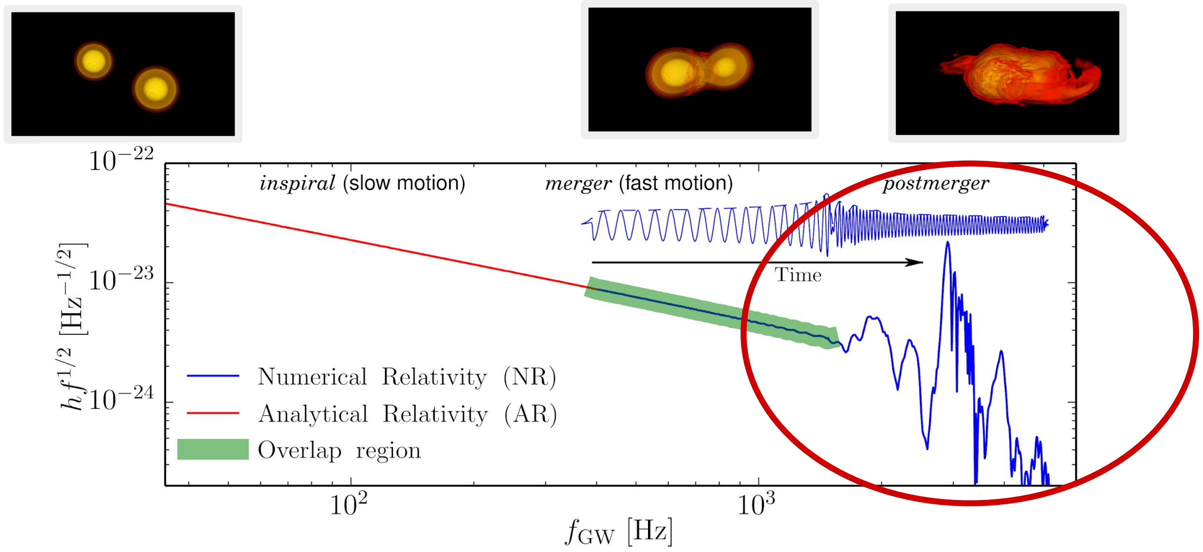
CoRe project: Exploring the BNS parameters

www.computational-relativity.org

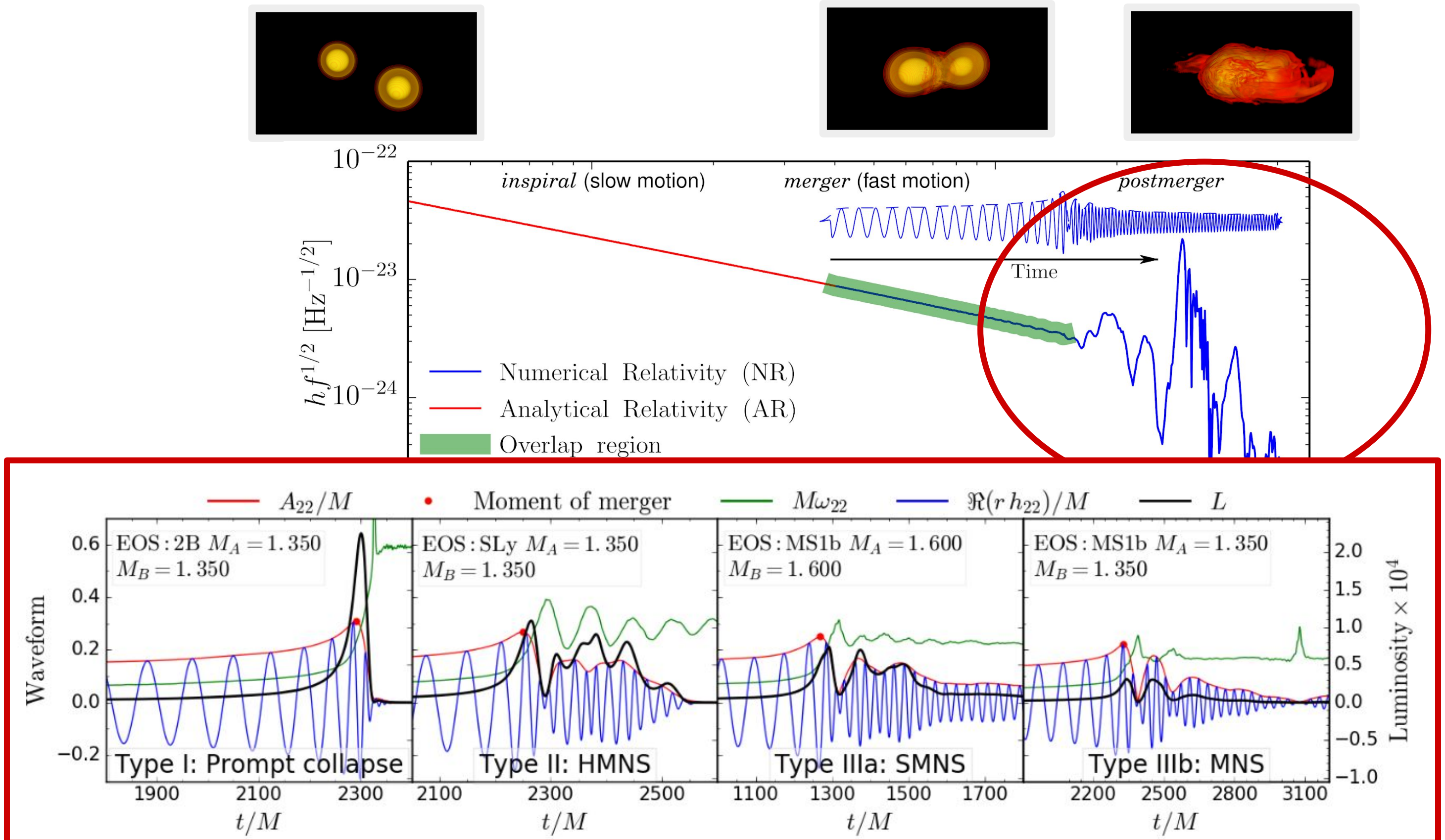


[Bernuzzi+ PRL (2015), Dietrich+ PRD91 (2015), SB+ PRD94 (2016), Radice+ PRD94 (2016), SB&Dietrich PRD94 (2016), Dietrich+ PRD95 024029 (2017), Radice+ ApJL 842 (2017), ….] Picture: F.Zappa

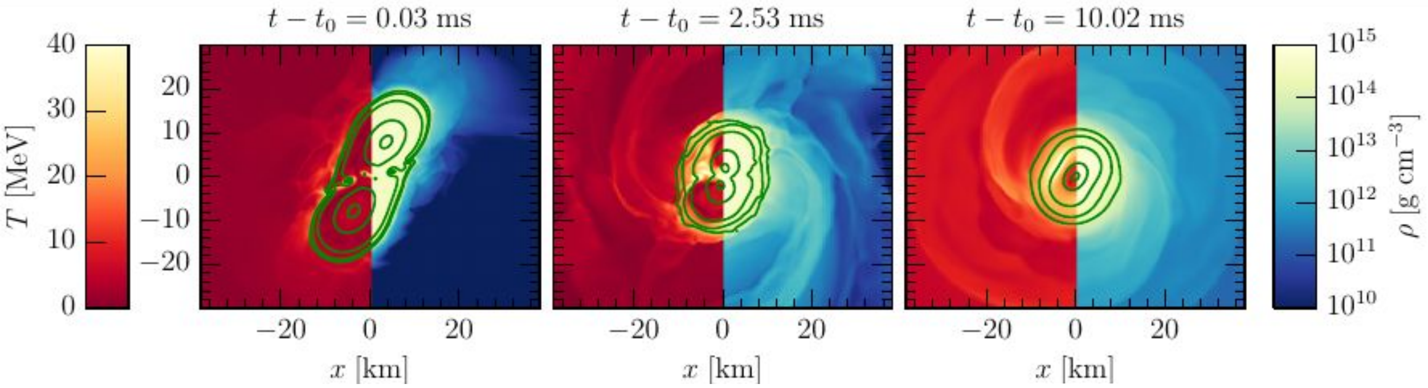
Inspiral - merger → postmerger



Inspiral - merger → postmerger



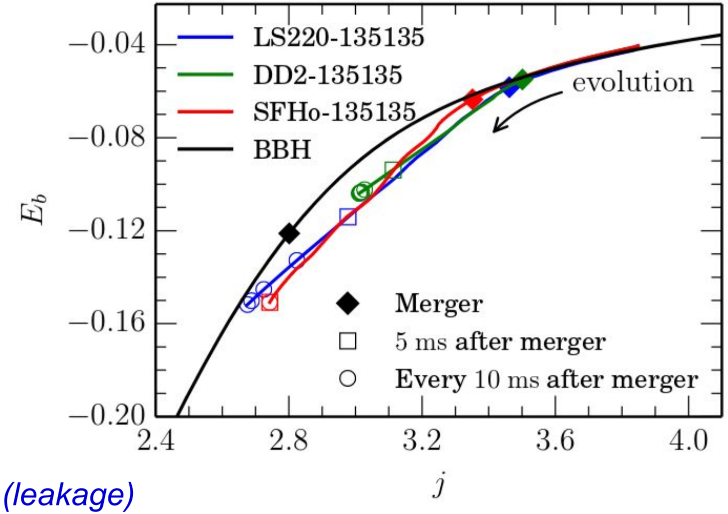
Remnant HMNS is the loudest GW phase



- Emission is FAST(*post-merger initial transient*)
  τ_{GW}~ 20 ms

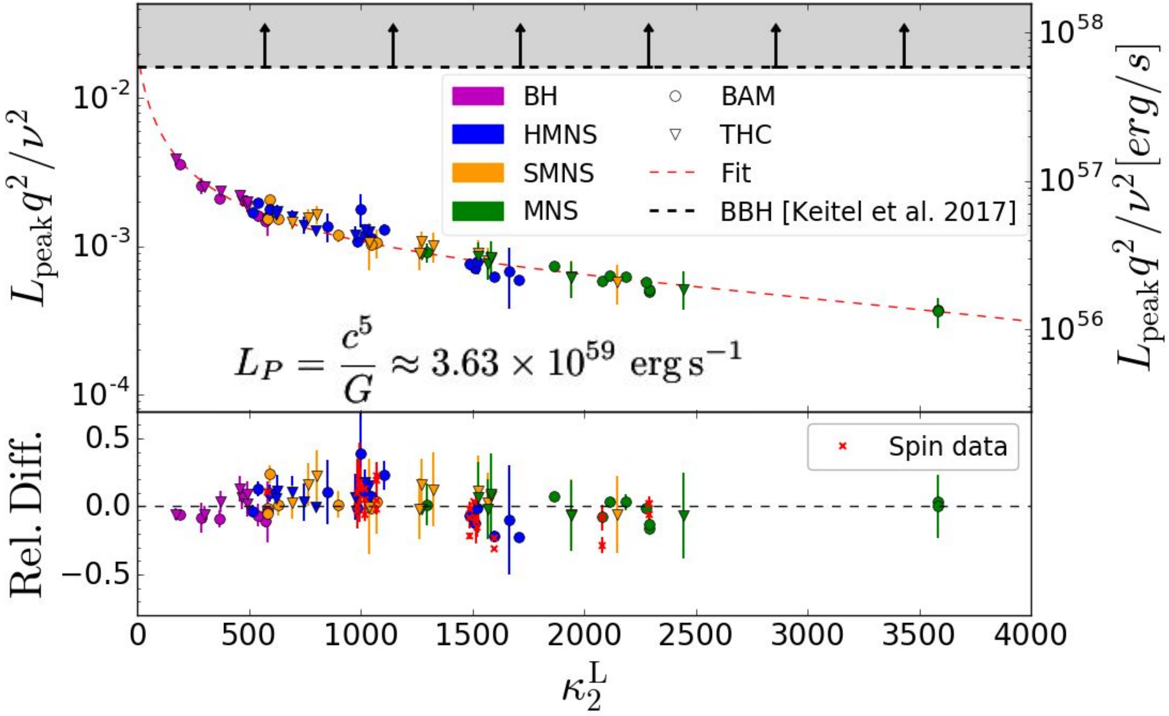
- Emission is LOUD:
  E(HMNS) ~ 2x E(merger)

- Most of the power is emitted at frequency
  ~ 2 x (Rotational frequency @ formation)



[SB+ 2016] *Simulations w/ microphysical EOS and neutrino cooling effects (leakage)*

Compact binaries are the most luminous events

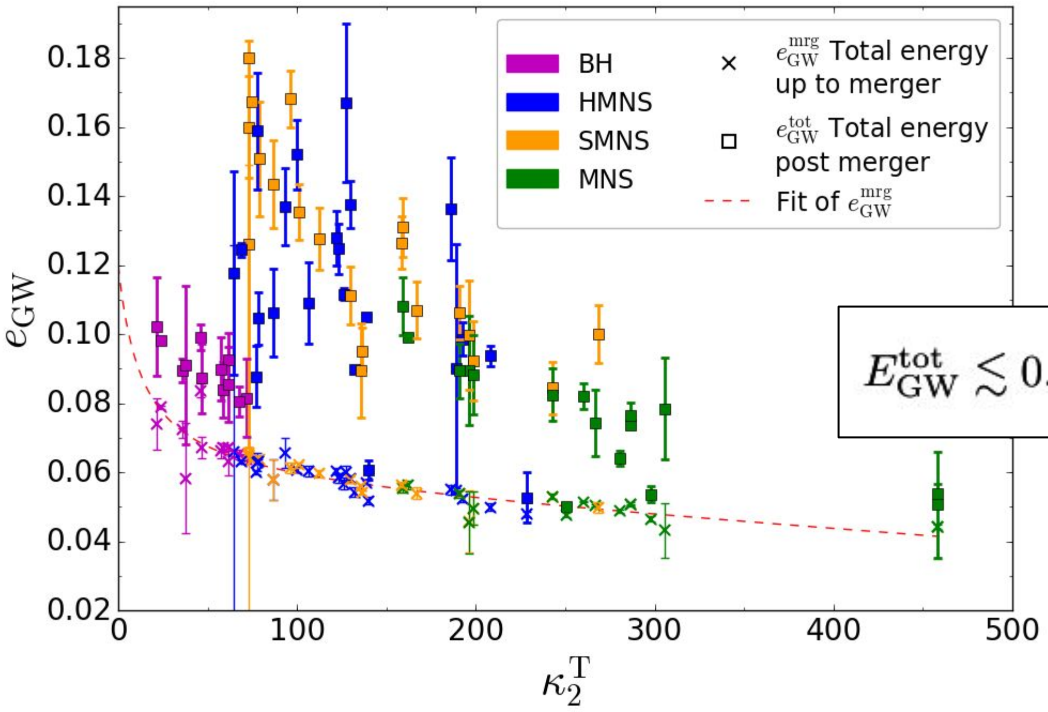


- Simple description of all simulated BNS based on tidal parameter
- Estimate for GW170817:

[Zappa+ 2018]

$$9.896 \times 10^{54} \text{erg/s} \lesssim L_{\rm peak} \lesssim 4.940 \times 10^{56}\ \text{erg/s}$$

Upper limit on total energy emitted



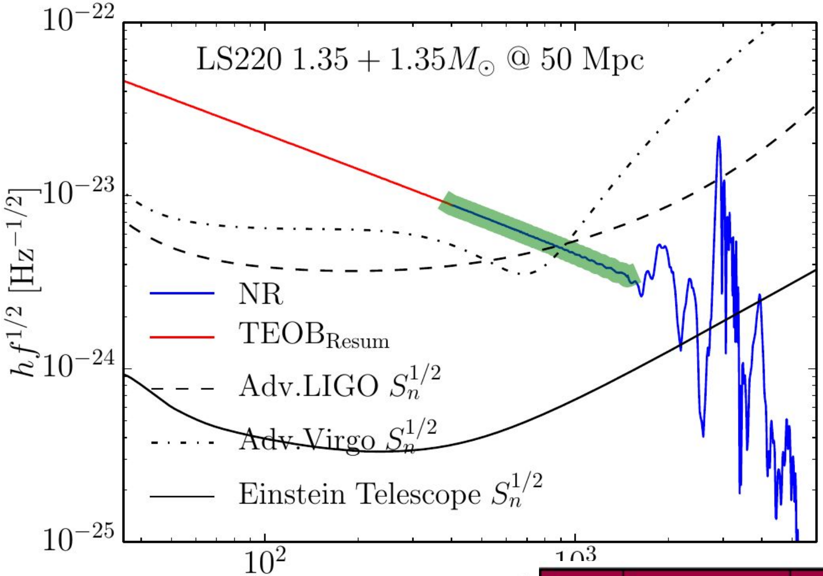
[Zappa+ 2018]

$$E_{GW}^{tot} \lesssim 0.126 \frac{M}{2.8} \, M_\odot c^2$$

- Energy up to merger simple description based on tidal parameter [SB+ 2014]
- Post-merger energy requires more complex description, but tidal par. captures a behaviour
- Upper limit on total energy → postmerger unlikely to be detected by LIGO/Virgo
- BBH events ~ 1-3 Msun c^2

Frequency content

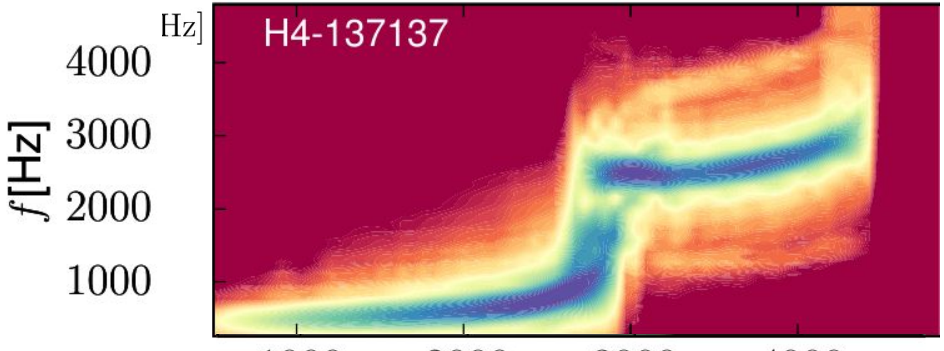
[Bauswein+ 2011,Hotokezaka+ 2013,Takami+ 2014,SB+ 2015, Clark+ 2015, ...]



Rich frequency content

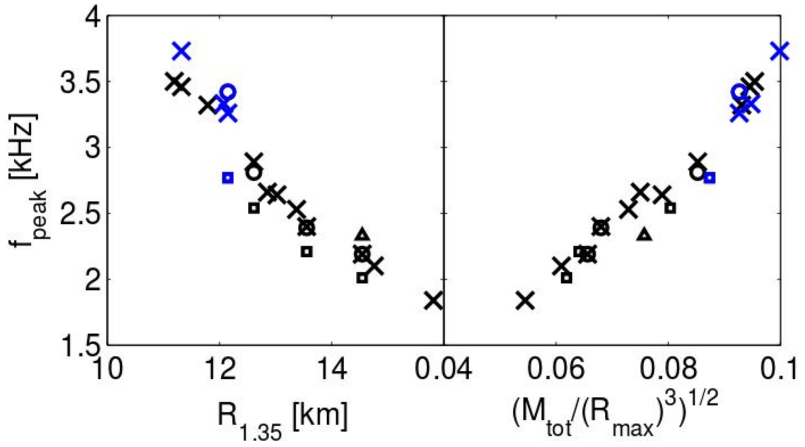
Main peak f_2 (m=2)
HMNS rot. freq at ~ peak luminosity

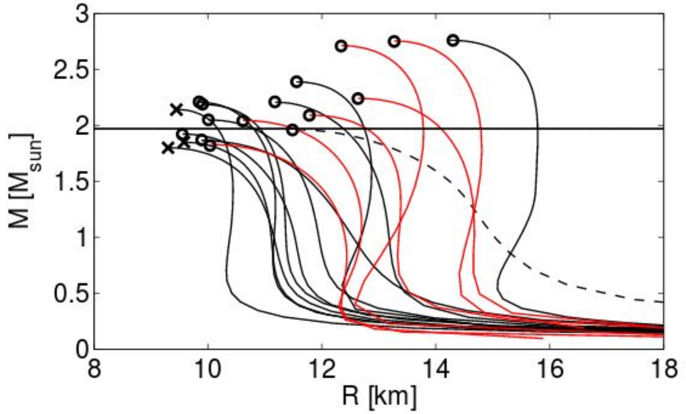
HMNS → collapse

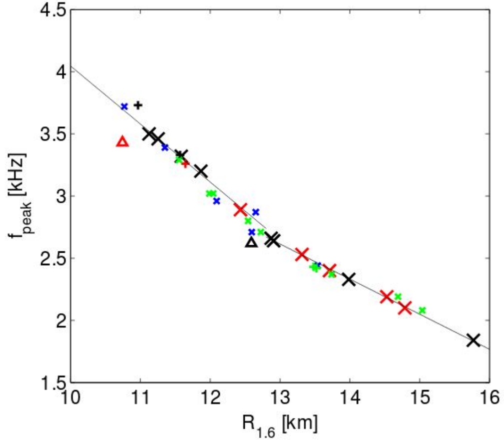


Time

Peak frequency correlates to TOV radius

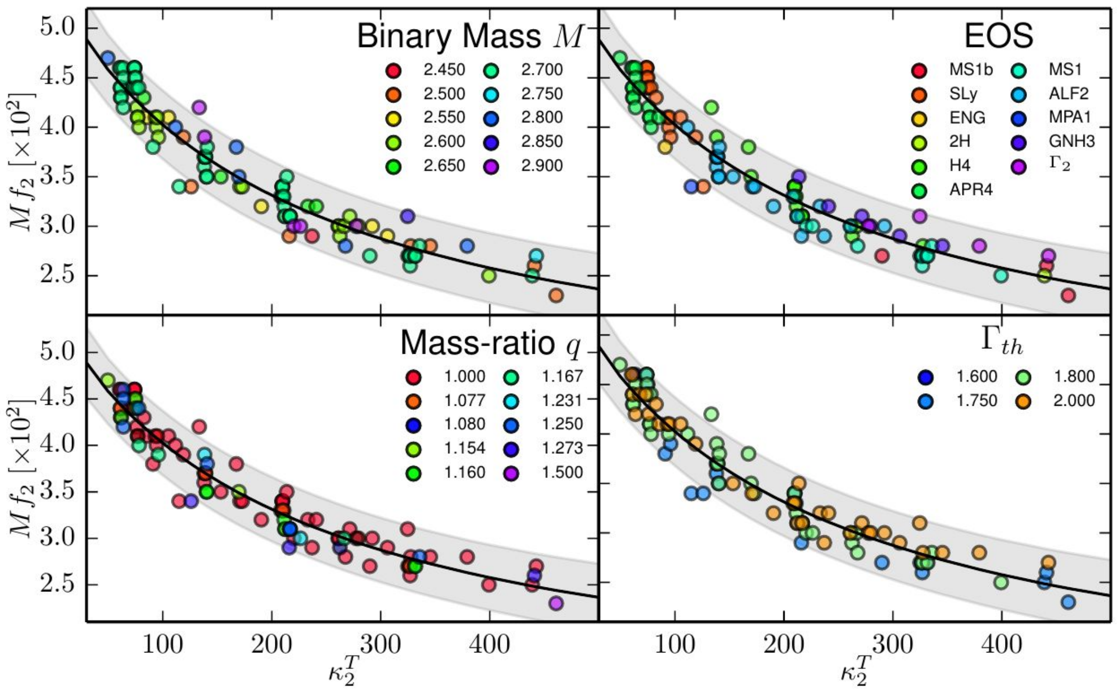






[Bauswein+ 2011,2012]

Peak frequencies correlate to tidal parameter

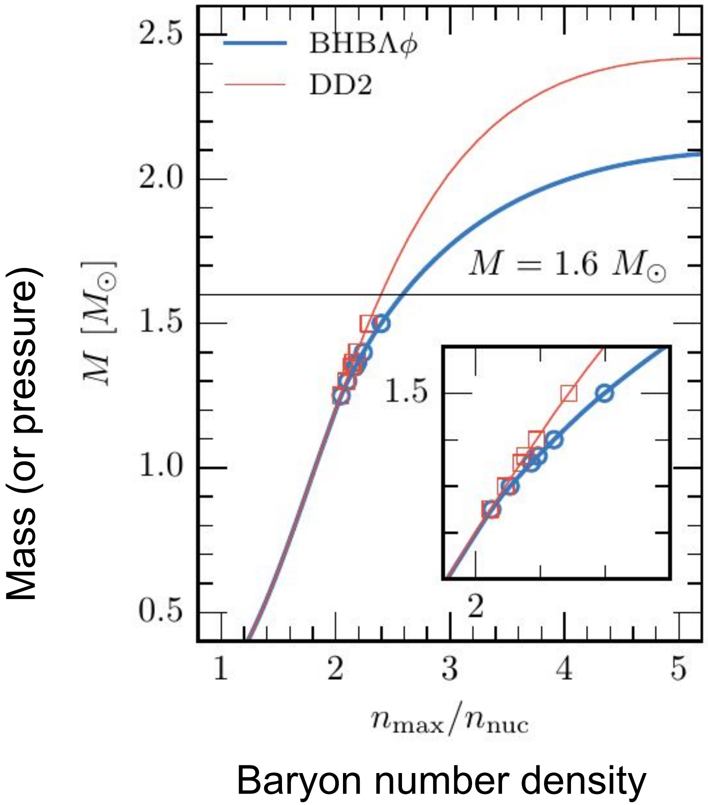


- Large NR dataset (~100, 3 codes) [SB+,Hotokezaka+ 2013,Takami+ 2014]
- Postmerger frequencies essentially determined by *merger* physics
- Conceptually “compatible” with inspiral-merger → Unified model !

[SB+ 2015]

Merger remnant reaches extreme densities

Can GW observations inform us about EOS changes at those densities?



- Baryon number density **n ~ 3-5 n_{nuc}**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons

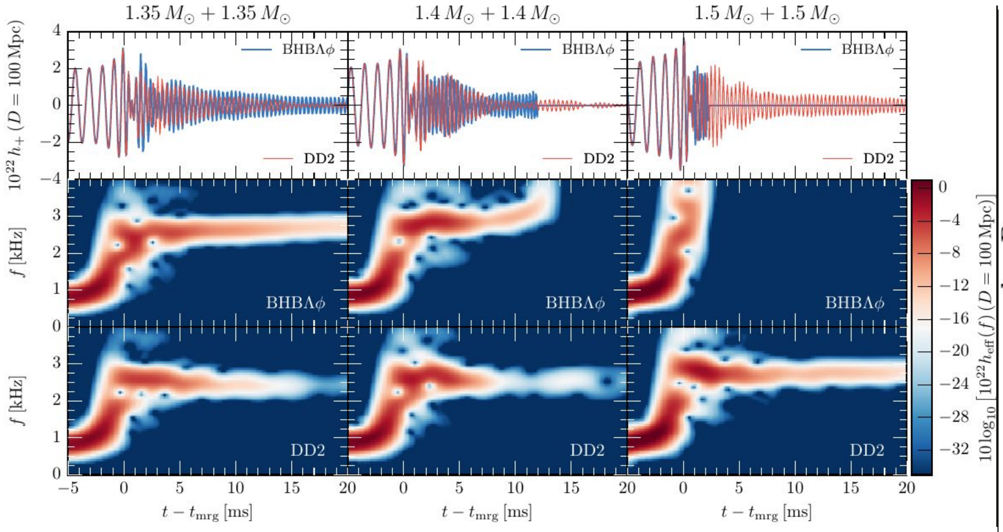
  [Banik+ arxiv:1404.6173]

Microphysical EOS compatible with astro and nuclear phys constraints

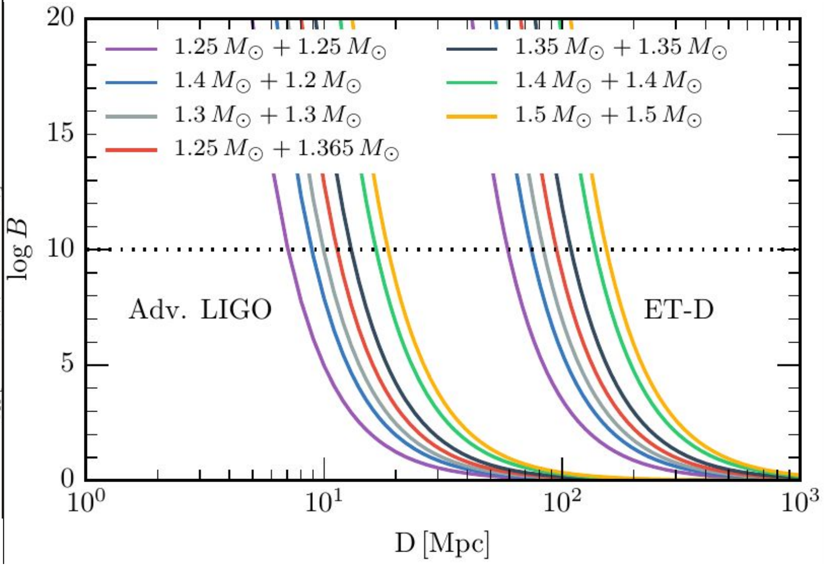
- In general: probe "softness" effects

[Radice+ 2016]

GWs could probe such “softness effects”



Data-analysis study: distinguishablity



log(Bayes factor) vs. Source distance

- Postmerger GW morfology contains unique info
- Detailed and generic models are necessary for DA studies
- High-freq. GW challenging to detect (→ Einstein telescope)

[Radice+ 2016]