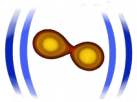


www.computational-relativity.org

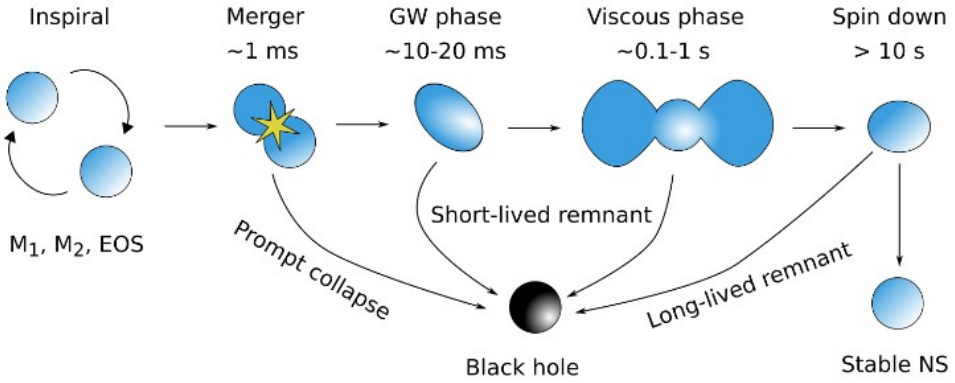
# Modeling the strong-field dynamics of binary neutron star mergers

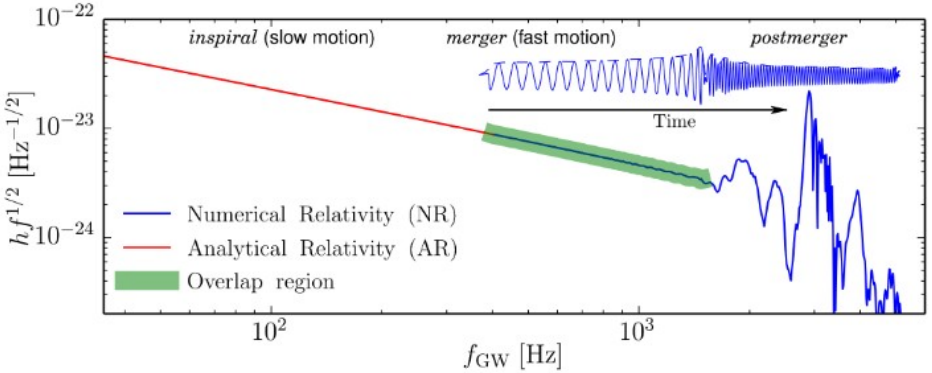
S.Bernuzzi

ETC* Neutron Stars as multi-messenger laboratories for Dense Matter

June 2021

# Where do we stand with the modeling?



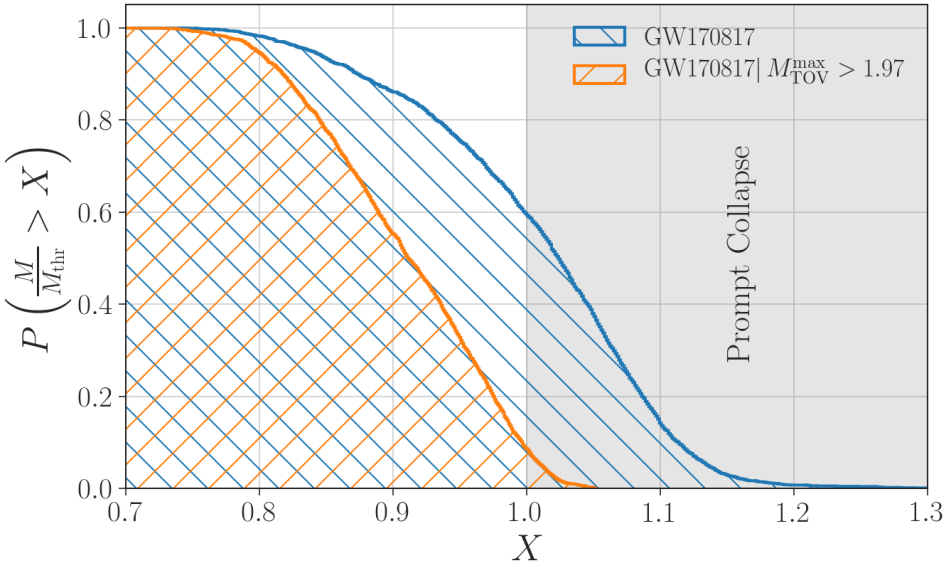




- Prompt collapse: GW-inference & NR EOS-insensitive relations
- GW-inference of tidal parameters & waveform systematics
- Info from kHz regime & complete spectrum model
- NR-informed kN-inference
- Next simulation targets for GW & counterpart modeling

Annual Reviews of Nuclear and Particle Science
Radice,SB,Perego [ https://arxiv.org/abs/2002.03863 ]

GERG Collection on Binary Neutron Star mergers
SB [ https://arxiv.org/abs/2002.03863 ]

# Inferring prompt collapse from inspiral GW




$P_{GW170817}$(prompt collapse|M>1.97) < 10%

- NR-based PC models (consistent results)
  - EOS inference + Threshold mass
    Hotokezaka+ [https://arxiv.org/abs/1105.4370]
    Bauswein+ [https://arxiv.org/abs/1307.5191]
  - Tidal parameter inference + $\overline{\Lambda}$-Threshold
    Zappa,SB+ [https://arxiv.org/abs/1712.04267]
- GW170817: quantitatively support the “no PC” interpretation from GW170817 counterparts, e.g. Margalit&Metzger (2017)
- GW190425 (M~3.4Mo):

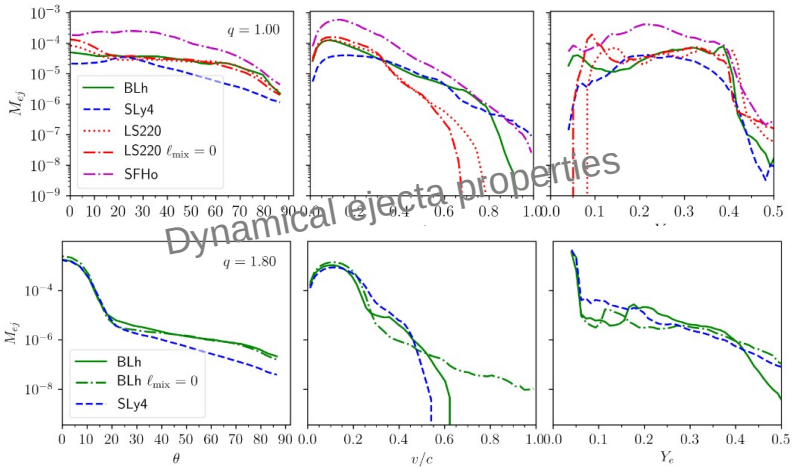
  $P_{GW190425}$(prompt collapse) ~ 97%

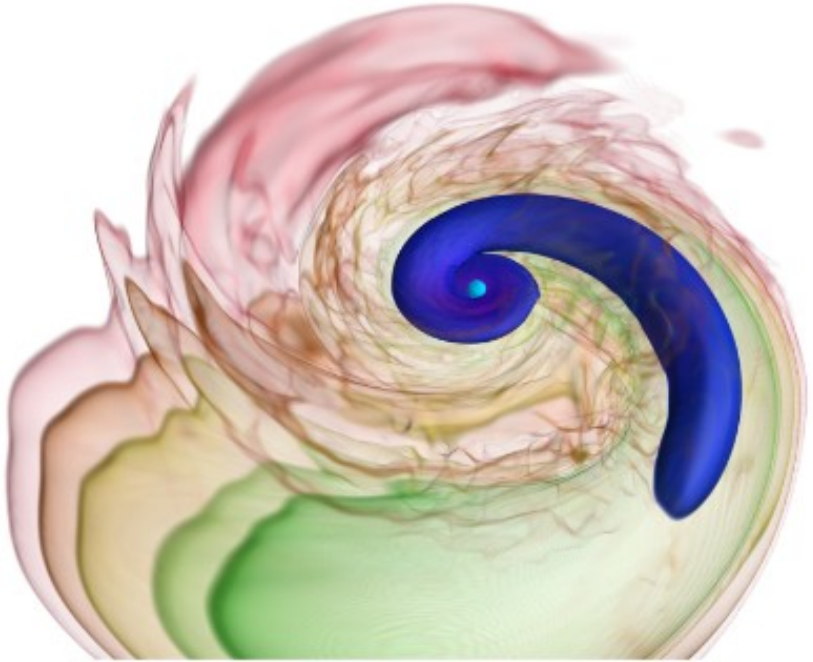
  LVC [https://arxiv.org/abs/2001.01761]

Agathos, Zappa, SB+ [https://arxiv.org/abs/1908.05442]

# Prompt collapse to BH: high-mass ratios

- Mass ratio q >~ 1.5 (Relevance: J1614-2230, J0348+0432, GW190425)
- Tidal disruption of the secondary
- No EOS-insensitive empirical relations for PC
- Mdisk ~ 0.1 Mo => EM loud !
- Bright, red and temporally extended kN



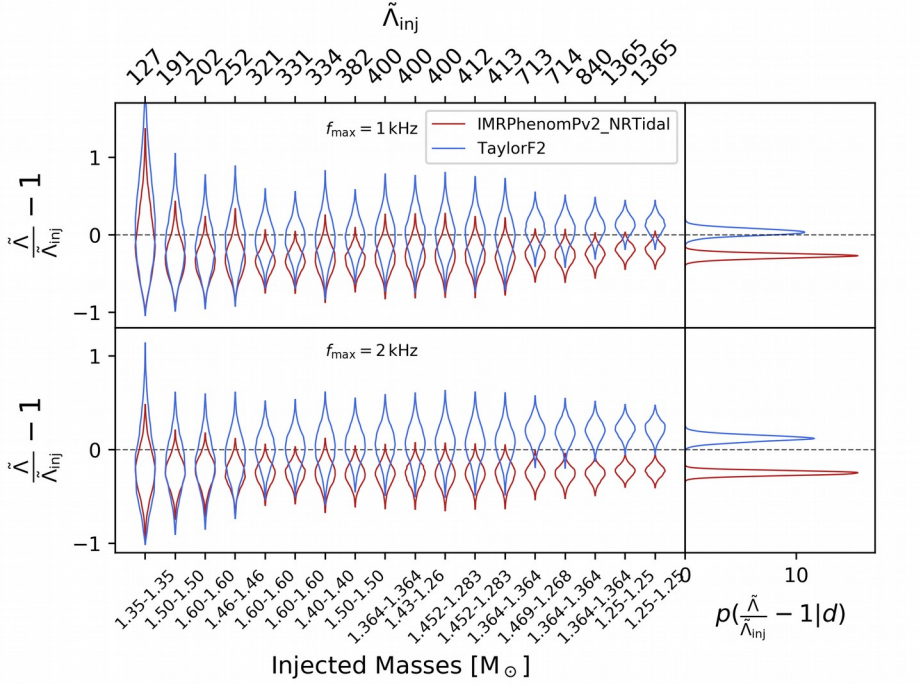



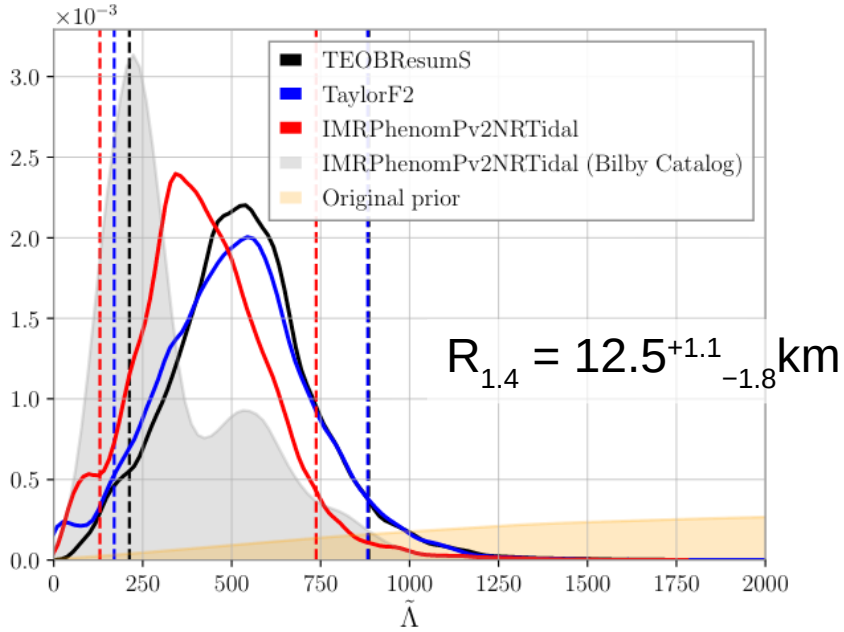
**Accretion-induced prompt collapse (q=1.8)**

SB+ [ https://arxiv.org/abs/2003.06015 ]

# Tidal parameters inference & wvf systematics

Gamba, Breschi, SB+ [https://arxiv.org/abs/2009.08467]

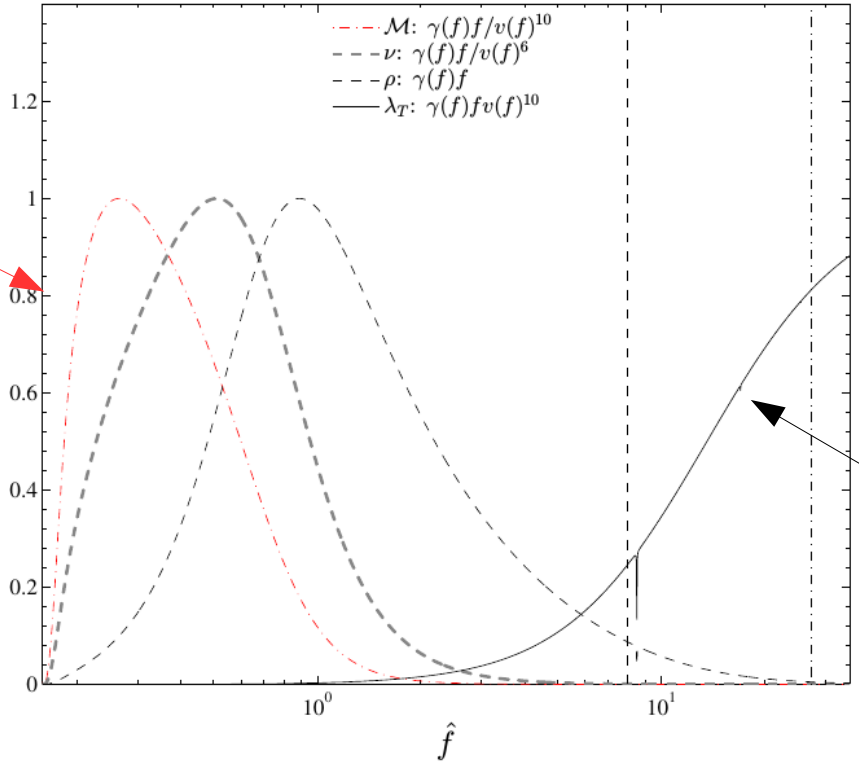



GW170817: no “strong” wvf systematics BUT $\bar{\Lambda}$ shift & “double peaked” posteriors
1kHz cut-off removes double peaks, less wvf baises and shifts to larger $\bar{\Lambda}$ (larger radii) for comparable log-like.
Estimated <10% SNR above f > 1kHz; high-frequencies issues in $\bar{\Lambda}$-inference? (Dai+ 2018, Narikawa+ 2019)

# Source’s parameters measurements from GWs

Chirp mass

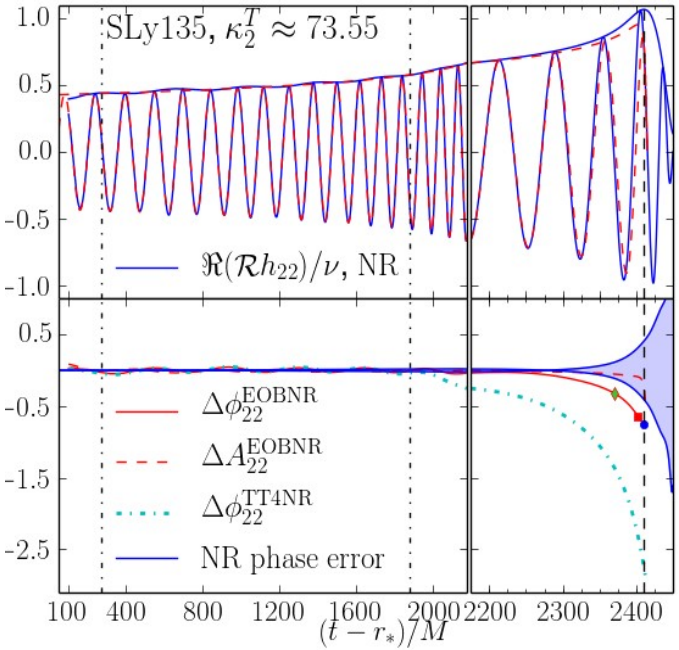


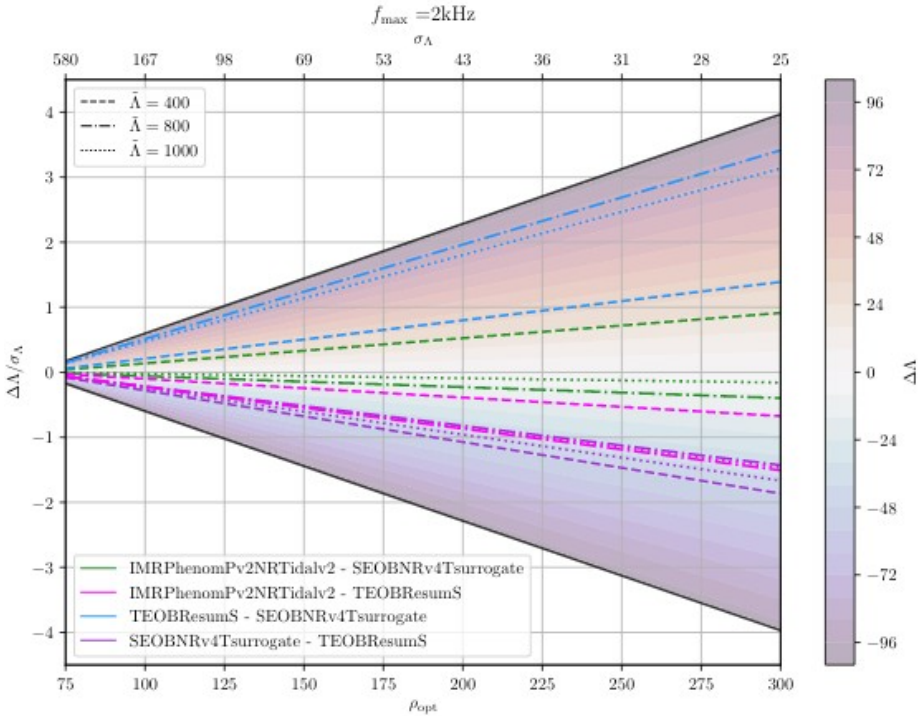

Tides

Damour+ [https://arxiv.org/abs/1203.4352]

# How well we do with waveforms?

SB+ [ https://arxiv.org/abs/1205.3403 ]
SB+ [ https://arxiv.org/abs/1412.4553 ]
Akcay, SB+ [ https://arxiv.org/abs/1812.02744]




Insufficient for SNR>80 [Gamba,Breschi,SB+ https://arxiv.org/abs/2009.08467]
Systematics will be a major issue for (high-precision) EOS measurements

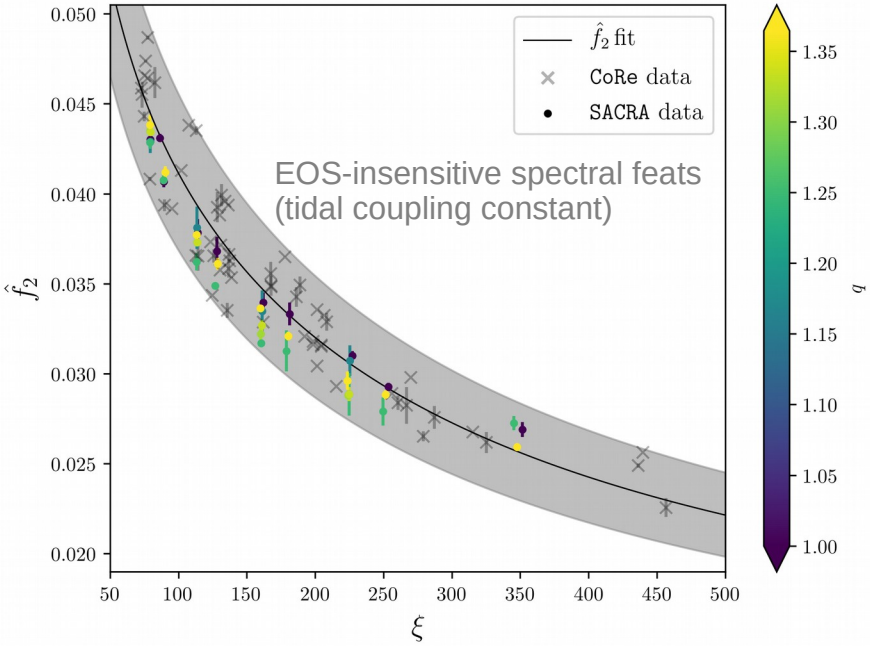
# Faithfulness of NR merger waveforms

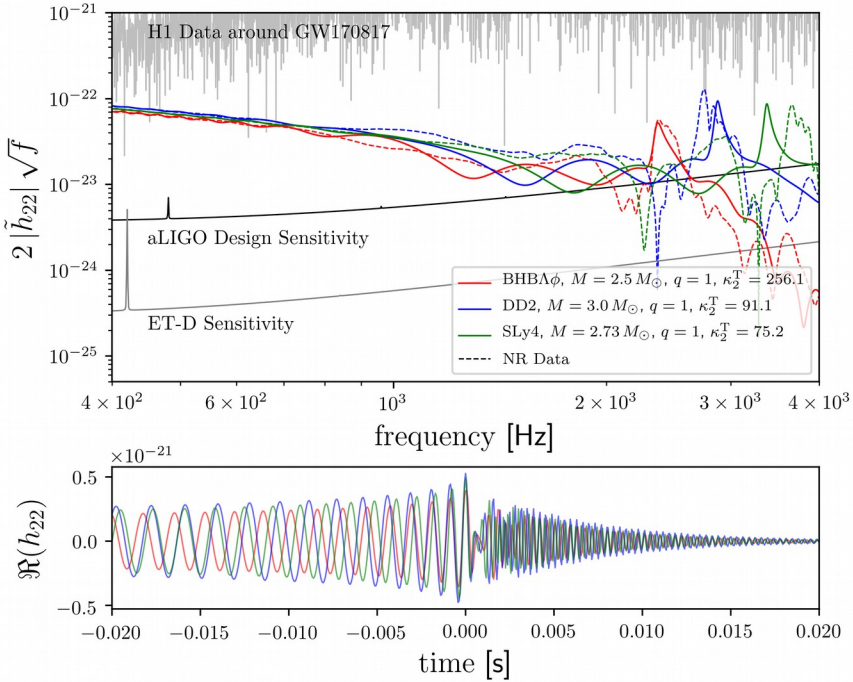
| Sim | npoints[a] | $\mathcal{F}$ | SNR | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 14 | | 30 | | 80 | |
| | | | $N=6$ | 1 | $N=6$ | 1 | $N=6$ | 1 |
| BAM:0011 | [96, 64] | 0.991298 | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ |
| BAM:0017 | [96, 64] | 0.985917 | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ |
| BAM:0021 | [96, 64] | 0.957098 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| BAM:0037 | [216, 144] | 0.998790 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| BAM:0048 | [108, 72] | 0.983724 | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| BAM:0058 | [64, 64] | 0.999127 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| BAM:0064 | [240, 160] | 0.997427 | ✓ | ✗ | ✓ | ✗ | ✗ | ✗ |
| BAM:0091 | [144, 108] | 0.997810 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |
| BAM:0094 | [144, 108] | 0.996804 | ✓ | ✗ | ✓ | ✗ | ✗ | ✗ |
| BAM:0095 | [256, 192] | 0.999550 | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| BAM:0107 | [128, 96] | 0.995219 | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ |
| BAM:0127 | [128, 96] | 0.999011 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |

[SB+ https://arxiv.org/abs/1109.3611 ; Gamba+ https://arxiv.org/abs/2009.08467]

# NRPM: Postmerger waveform (EOB-completion)

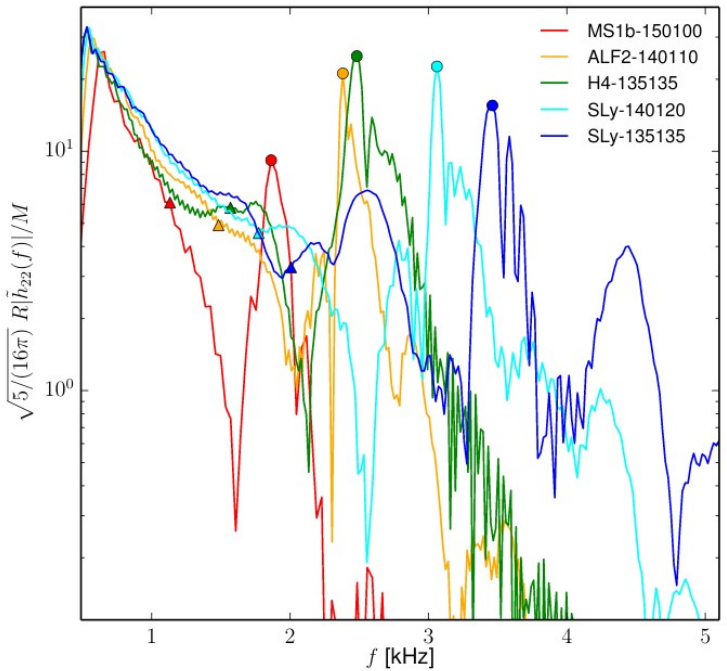
SB+ [https://arxiv.org/abs/1504.01764] Breschi+ [https://arxiv.org/abs/1908.11418]

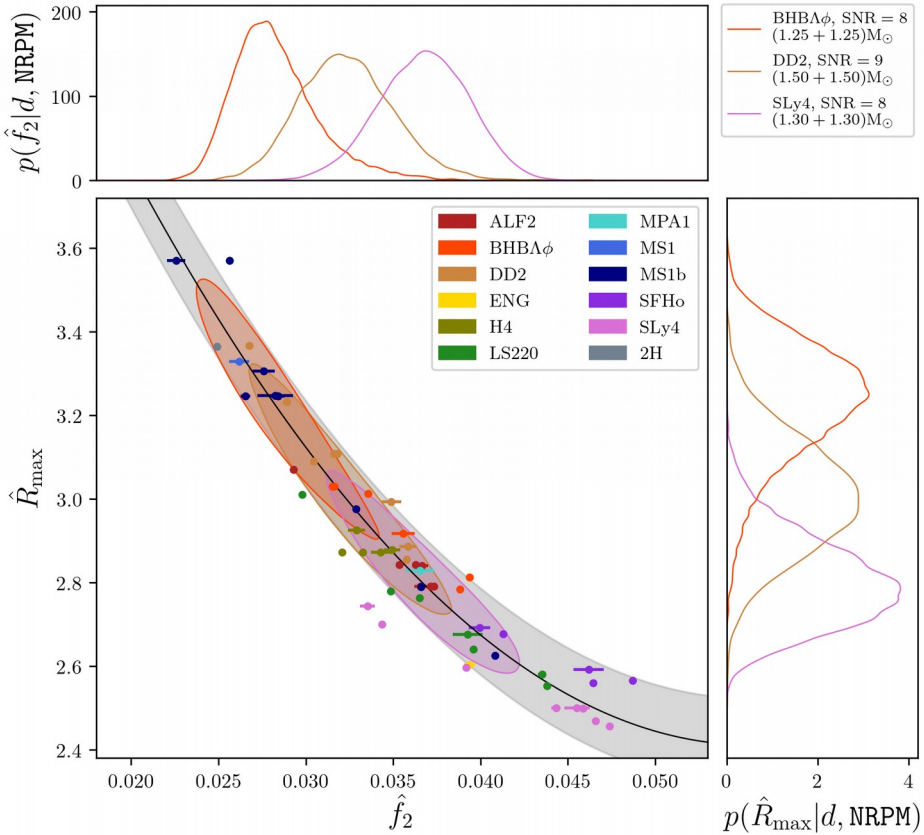



Hypothesis ranking to identify PC/PM signal: min PM SNR ~ 9-12 (GW170817-like events for 3G)
(cf. e.g. Torres-Rivas+ [https://arxiv.org/abs/1811.08931])

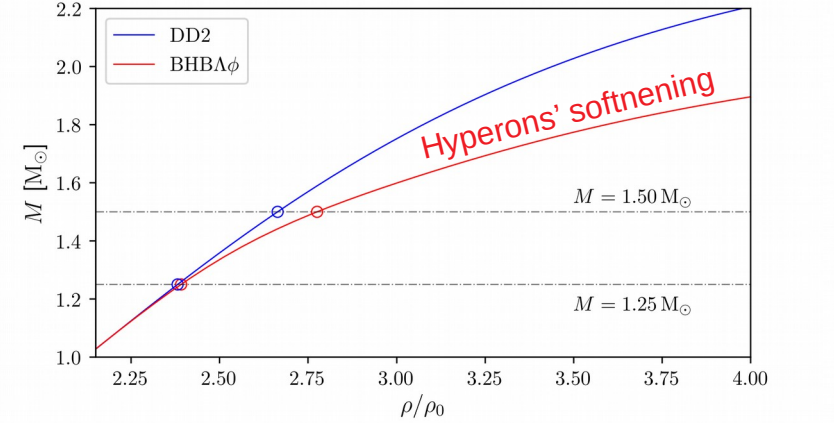
# Minimum radius from kiloHertz GWs

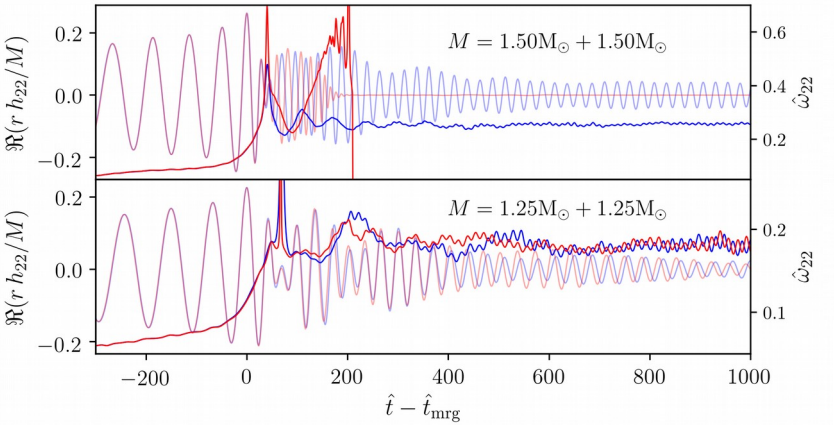


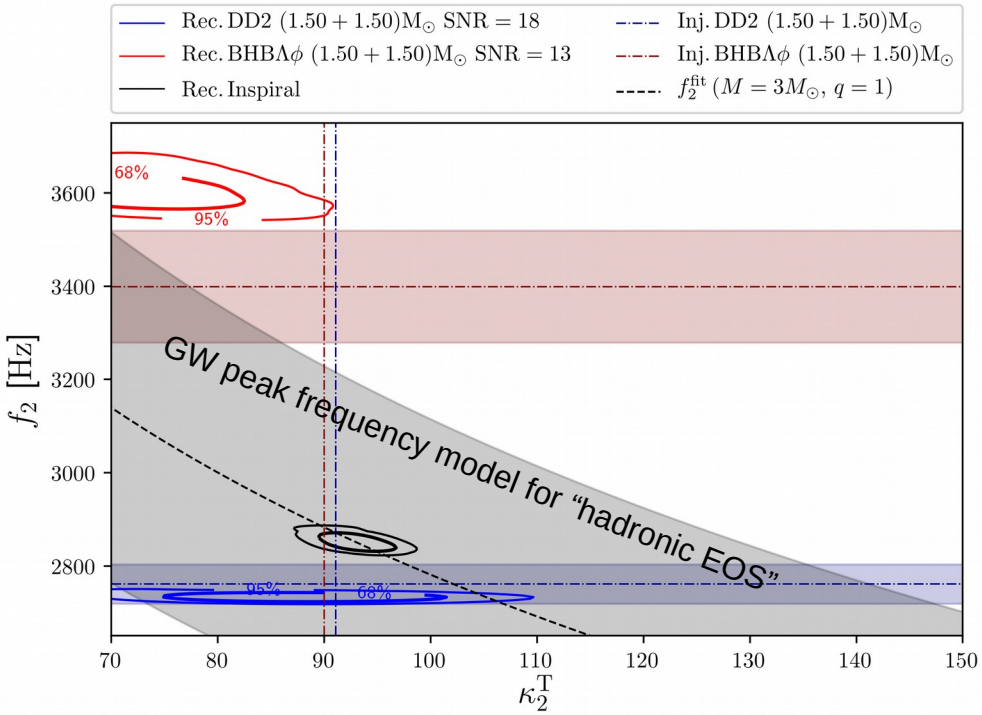




Breschi, SB+ [ https://arxiv.org/abs/1908.11418]

# EOS softness at extreme densities

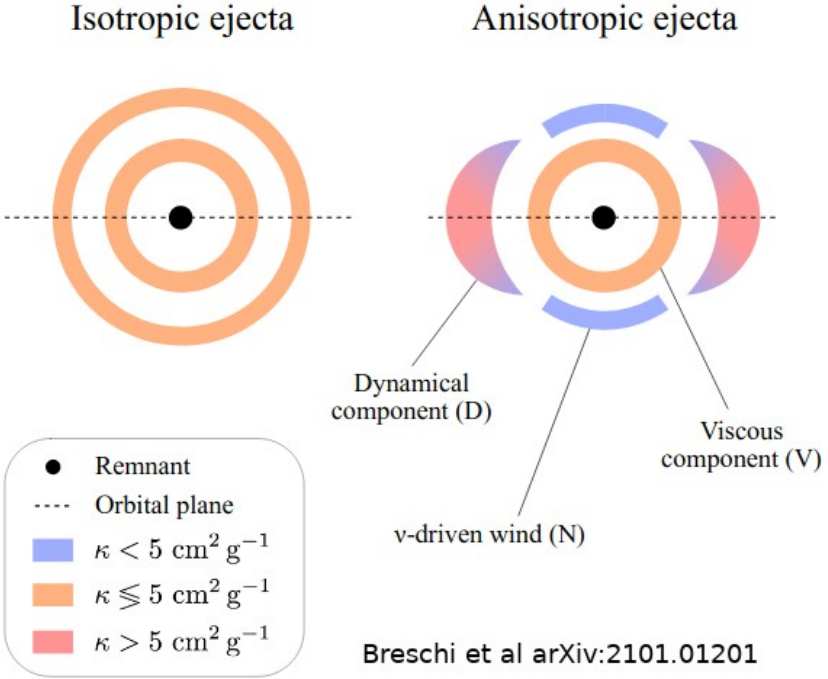


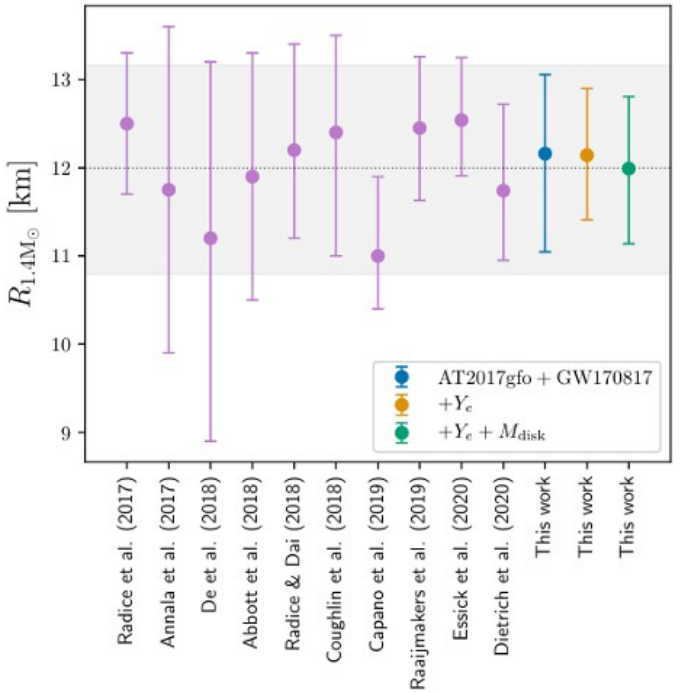




Breschi, SB+ [ https://arxiv.org/abs/1908.11418]
See also Radice, SB+ [ https://arxiv.org/abs/1612.06429 ]

# Bayesian analysis of AT2017gfo & NS radius constraints



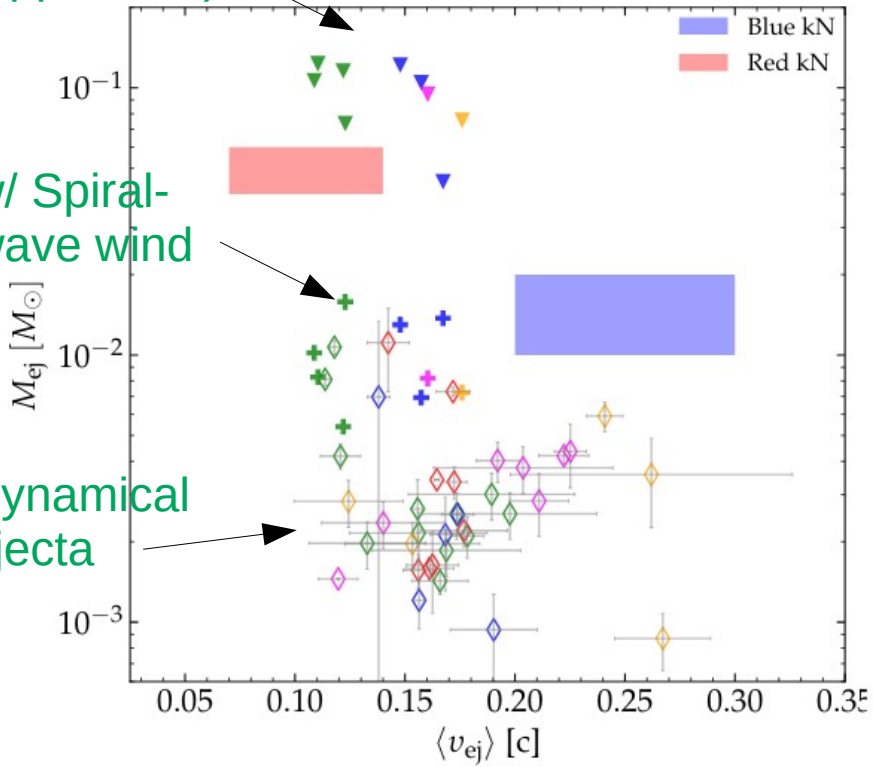

- NR-informed semi-analytical kN models (Perego+ [https://arxiv.org/abs/1711.03982] )
- Model selection: 3-component + anisotropic models preferred [https://arxiv.org/abs/2101.01201]

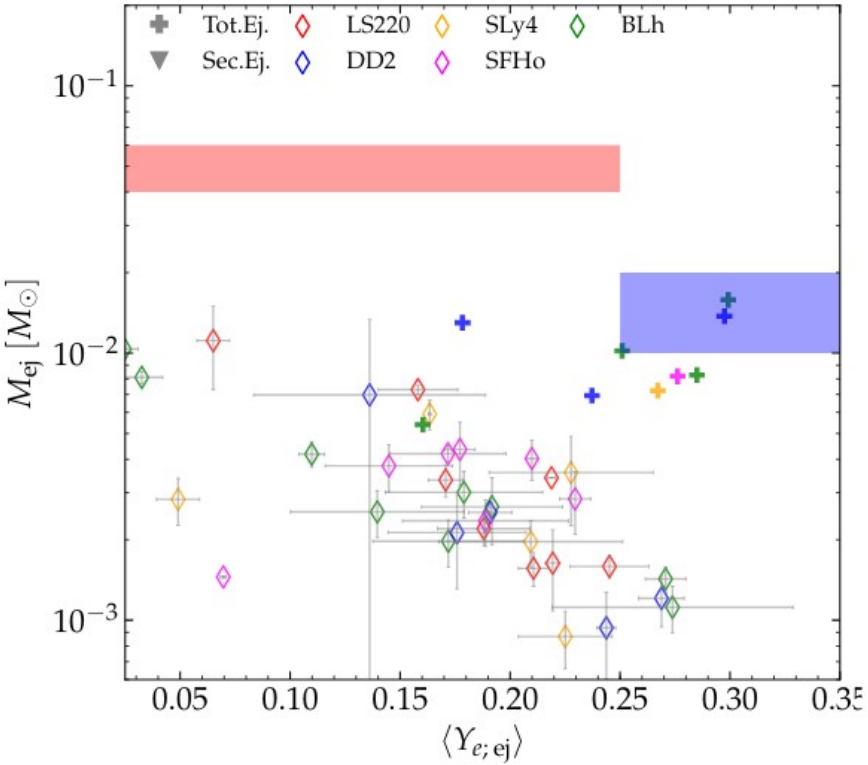
# AT2017gfo & targeted simulations

Disc wind
(upper limit)

w/ Spiral-
wave wind

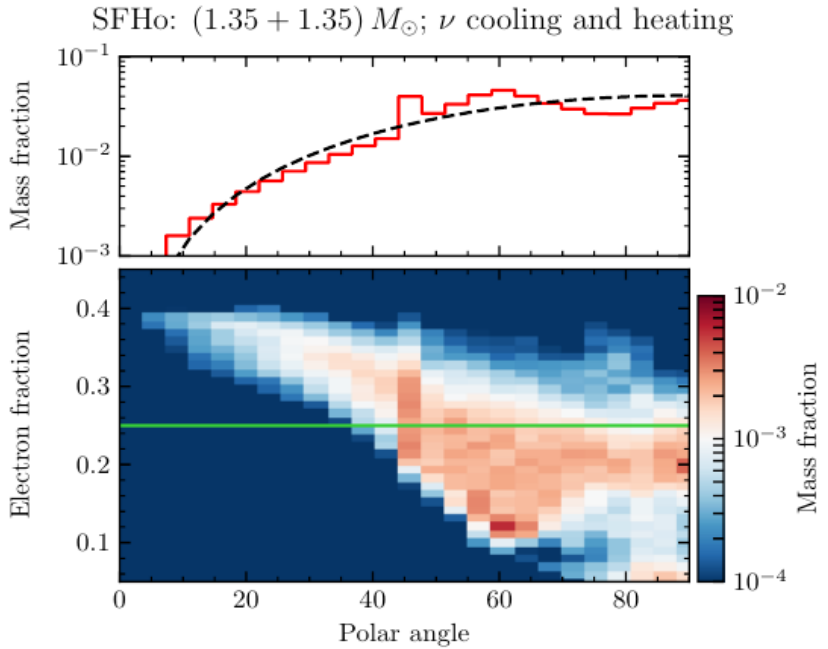
Dynamical
ejecta

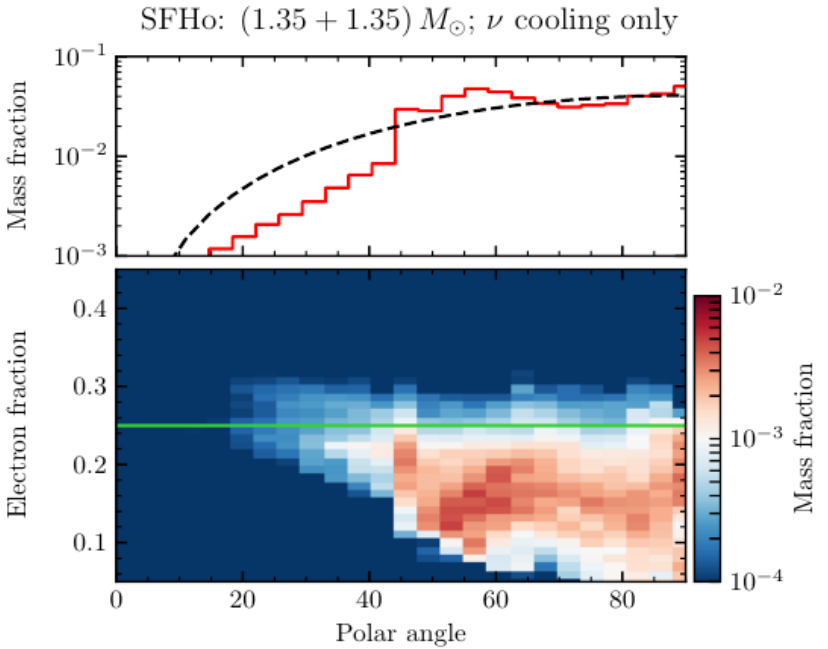



- Need at least two components high/low opacities (tentatively ~ dynamical ejecta+ winds ?)
- Spherical two-component models are incompatibile with NR ejecta

# Weak interactions in the dynamical ejecta

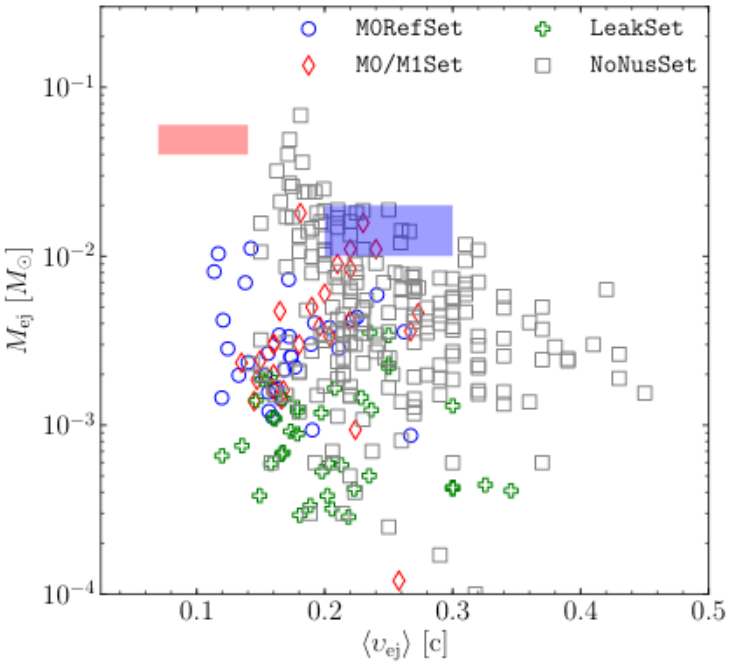



Neutrino absorption determines composition and kinetic properties

[Perego,Radice,SB ApJL 2017] See also [Wanajo+ 2014, Sekiguchi+ 2016, Foucart+ 2017/2018]

# Weak interactions in the dynamical ejecta




- Dynamical averaged properties are captured by the reduced tidal parameter* and the mass ratio

  (EOS-insensitive relations)

- => Application to astrophysical analyses

- Largest uncertainties are due to different neutrino transport schemes employed in simulations

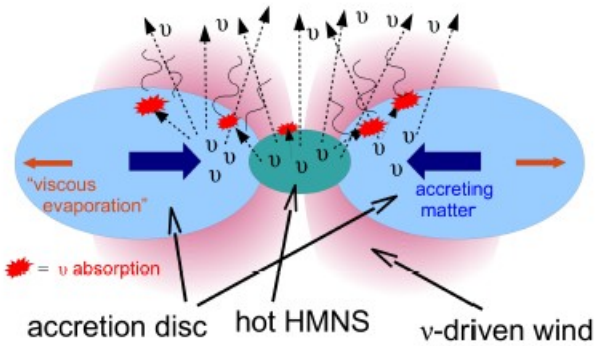
  [Nedora+ https://arxiv.org/abs/2011.11110]

* $\overline{\Lambda}$ (or $\kappa^T_2$ ) = coupling constant of tidal interactions at leading Newtonian order.
Measure of binary compactness

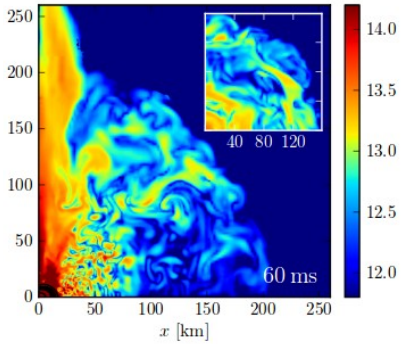
# Remnant evolution on viscous timescale

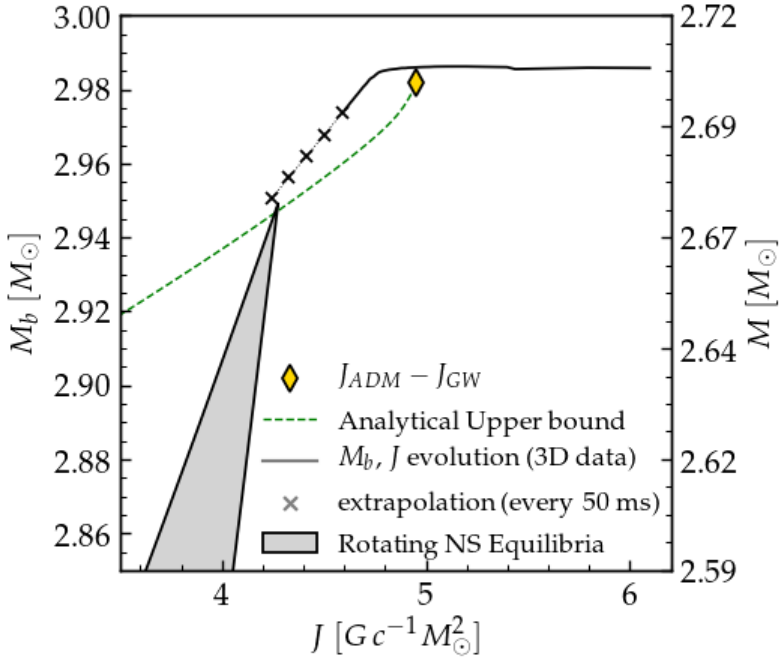
- Angular momentum (“super-Keplerian) and mass in excess
- Evolution dominated by neutrino cooling and viscous processes (magnetic turbulence & stresses, neutrino absorption, etc)
- Nuclear recombination → Massive winds

[Perego+ 2014]




[Siegel+ 2014]

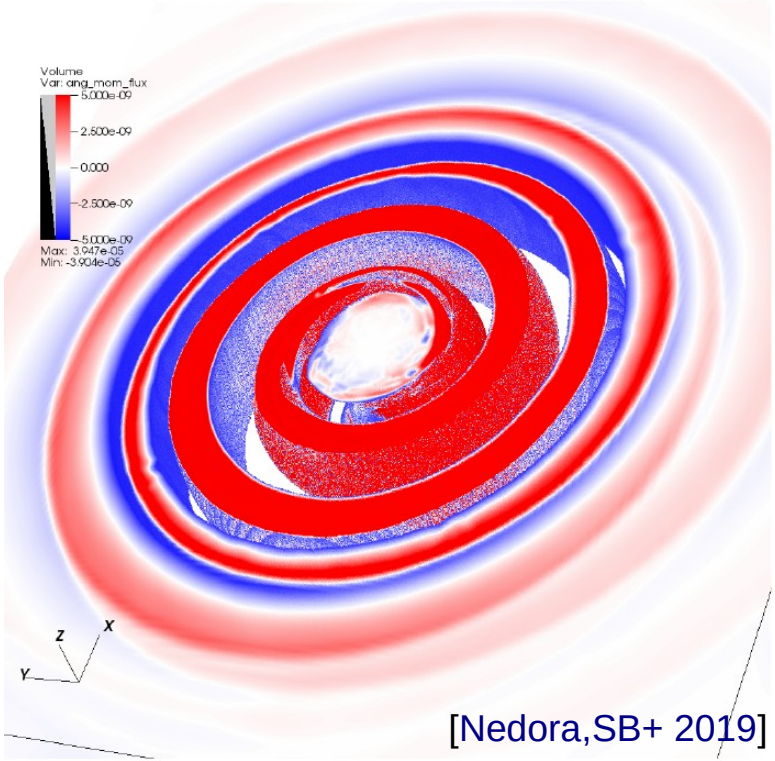



[Radice, Perego, SB, Zhang MNRAS 2018]
[Nedora, SB+ https://arxiv.org/pdf/2008.04333]

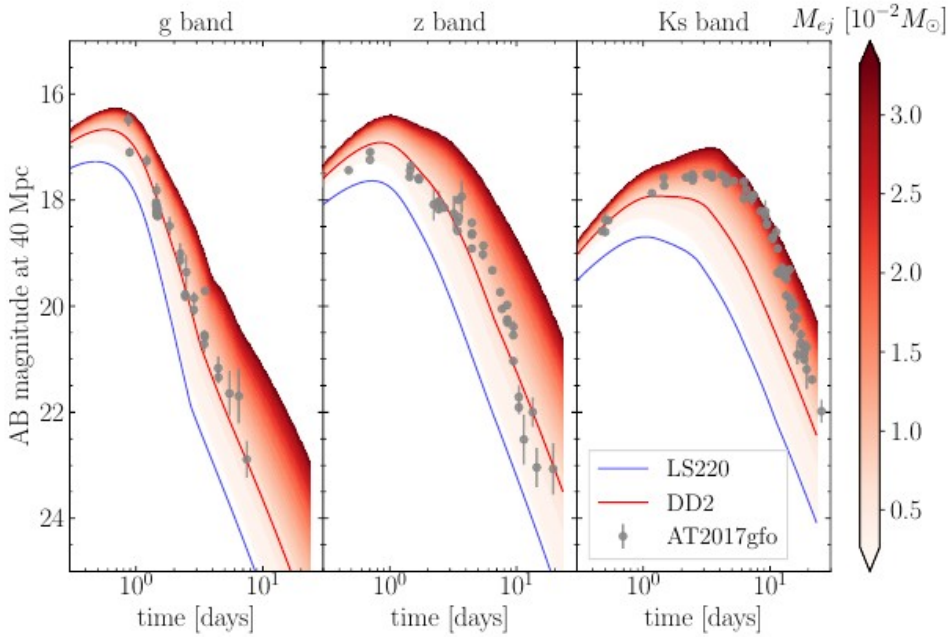
Need comprehensive approach !

# Spiral-wave wind



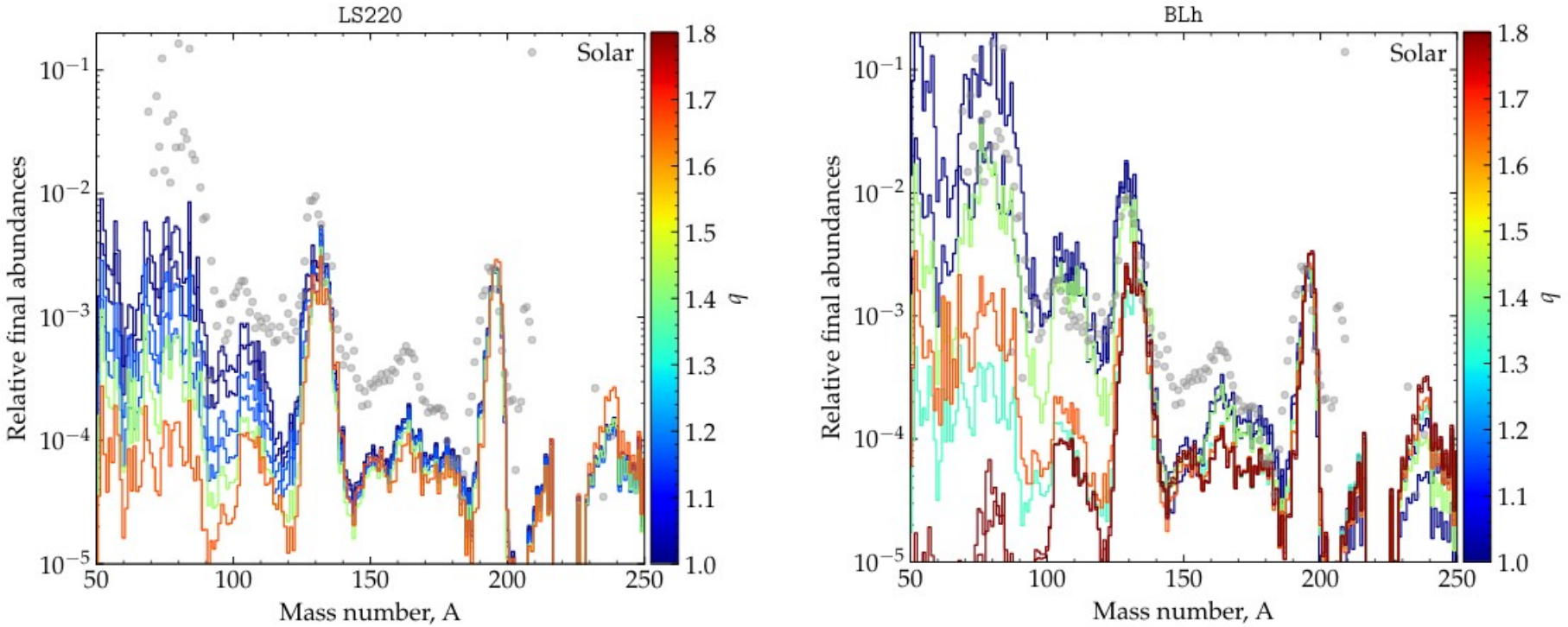

[Nedora,SB+ 2019]

Weak r-process nucleosynthesis and early kilonova emission (“blue”peak)



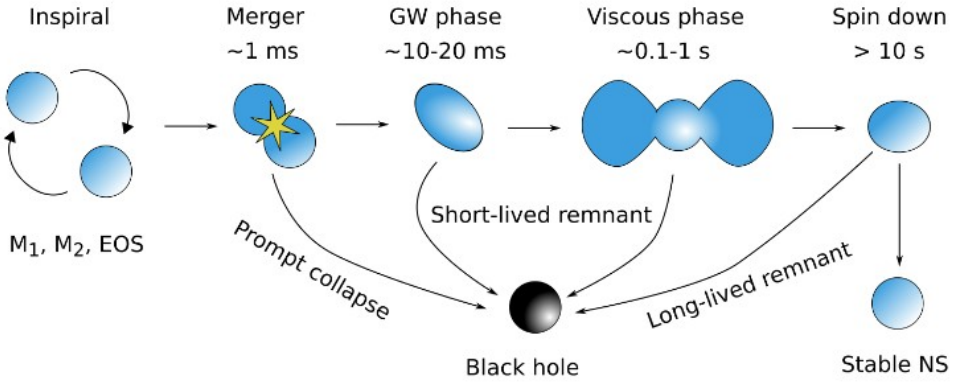

~100 ms 3D ab-inito evolutions with microphysics, neutrino transport and turbulent viscosity

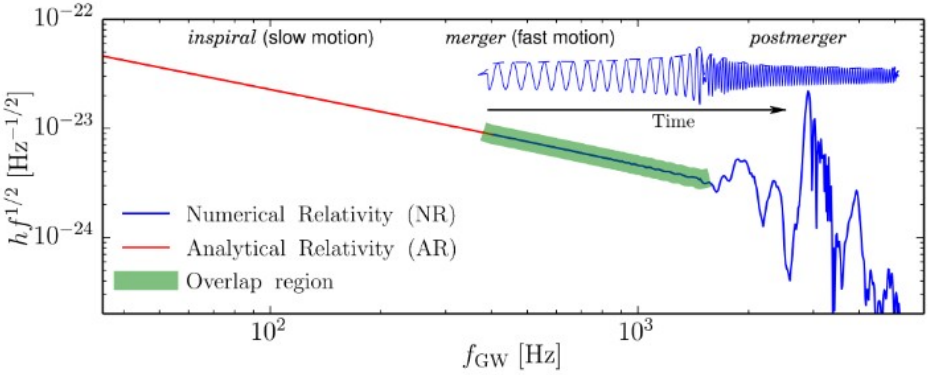
# r-process nucleosynthesis in dynamical ejecta and spiral-wave wind




[Nedora, SB+ https://arxiv.org/pdf/2008.04333]

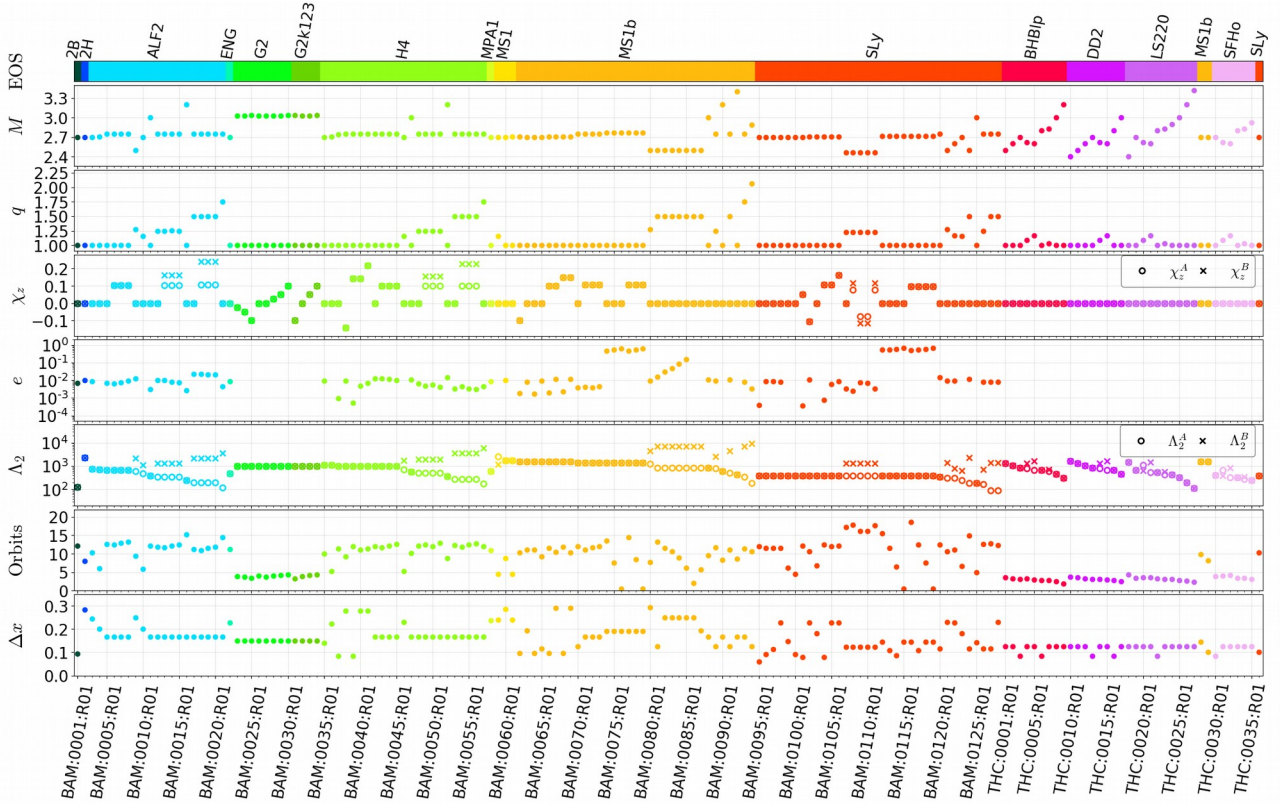
# Where do we stand with the modeling?

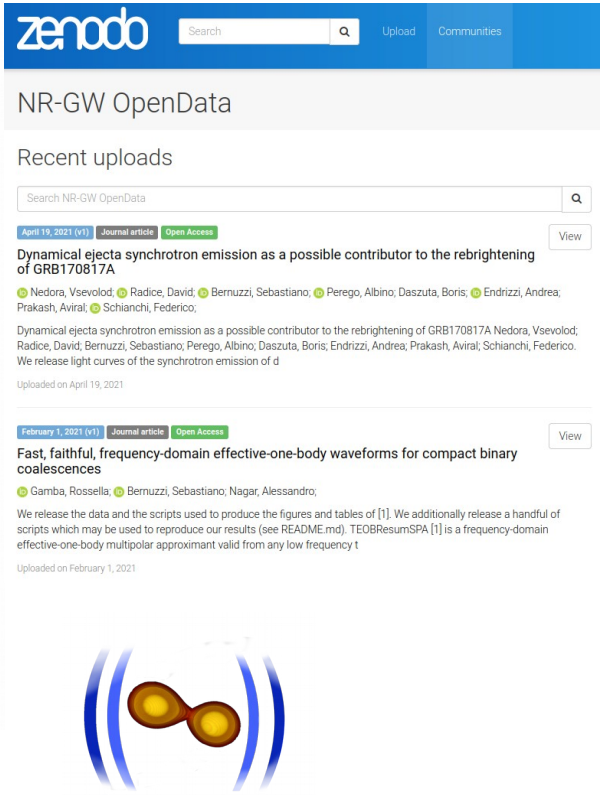



- Prompt collapse inference to be improved by precise NR EOS-insensitive relations
- Waveforms: NR not yet sufficient for high-SNR signals (and no alternatives)
- Waveforms: complete model exist now but accuracy to be improved
- Remnant & ejecta: Neutrino heating cannot be neglected (also for simple “MM applications”)
- Remnant & ejecta: Need comprehensive approach to attack viscous timescales

# Public data release






CoRe www.computational-relativity.org