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# Extreme Matter Constraints from Binary Neutron Star Mergers (BNSMs) and Gravitational Waves (GWs)

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VIRGO

FRIEDRICH-SCHILLER-
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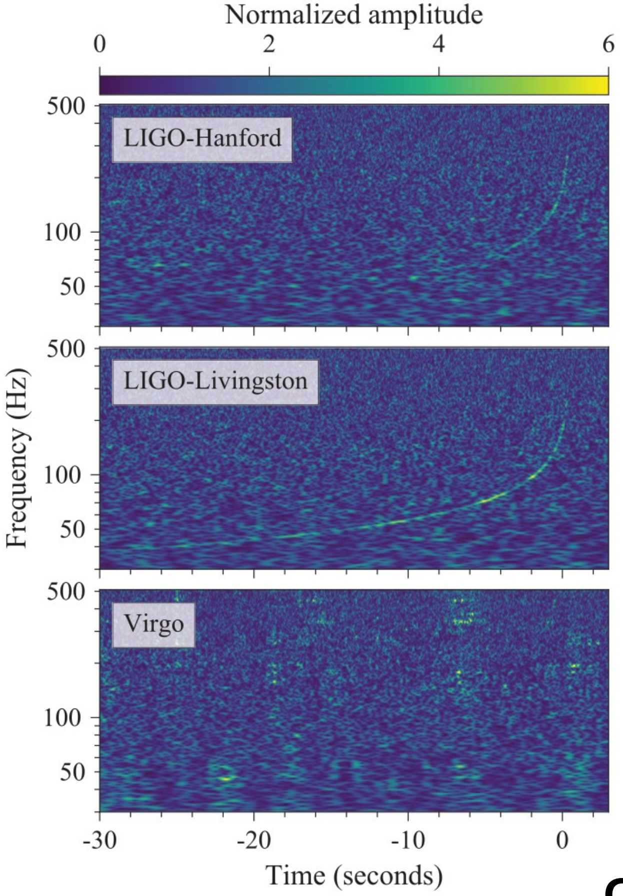
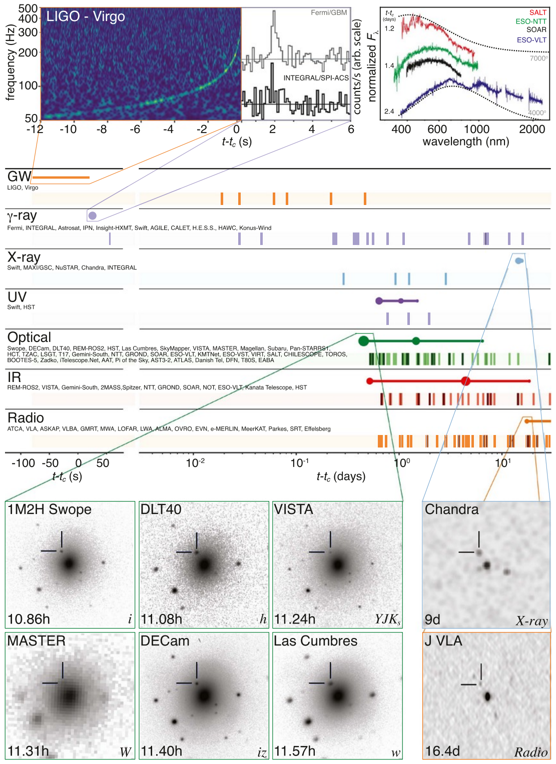
JENA

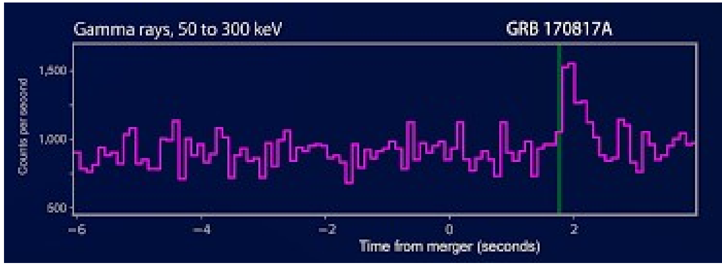
www.computational-relativity.org

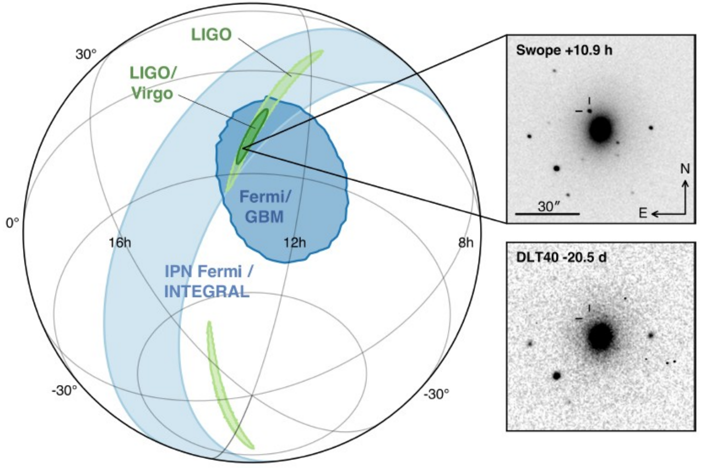
63. Cracow School of Theoretical Physics – Sept 2023

# BNSMs messengers: rare, but bright & loud



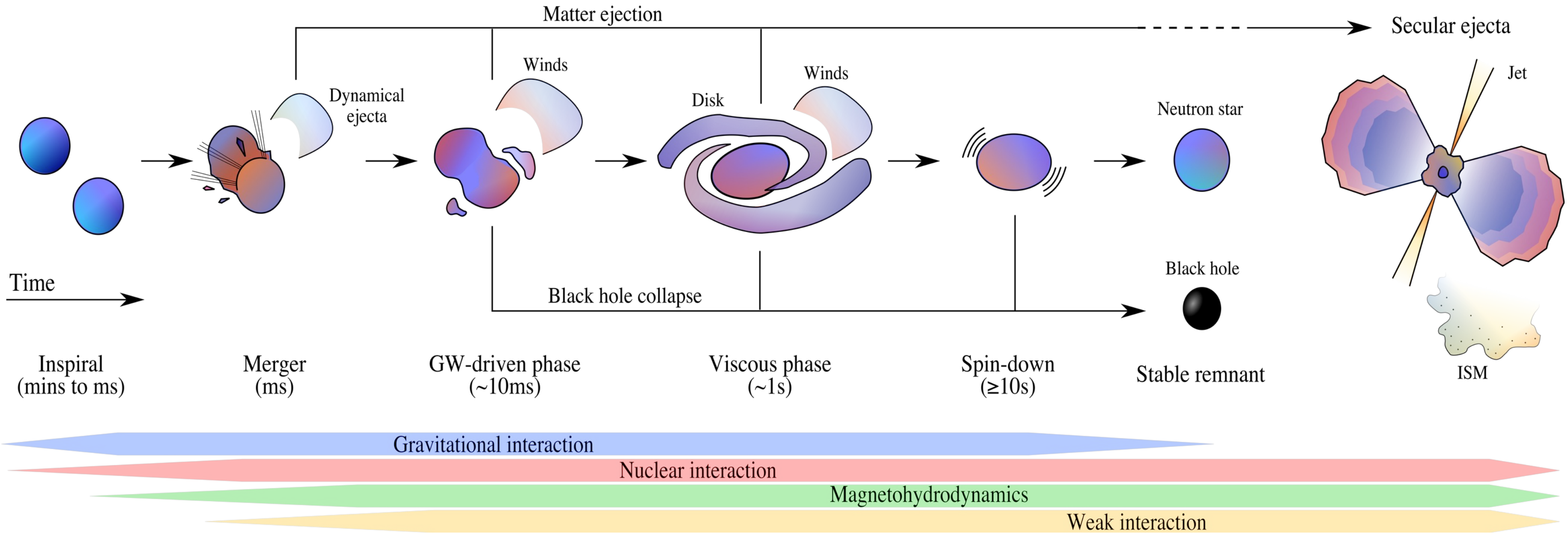






**GW170817 August, 17th 2017, 12:41:01 UTC**

# The picture emerging from theory



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

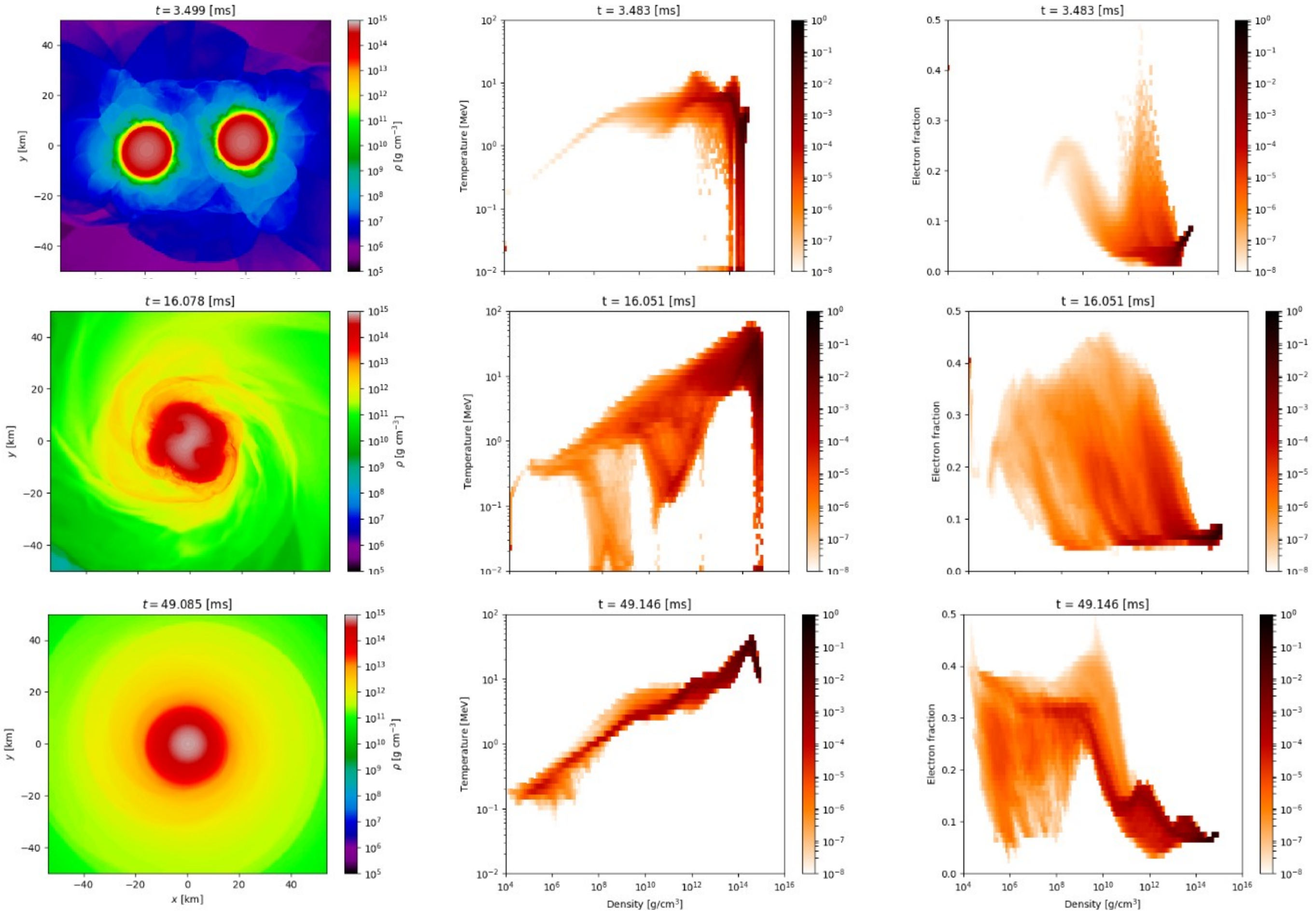
GERG Collection on Binary Neutron Star mergers
SB [ https://arxiv.org/abs/2002.03863 ]

# Extreme Matter in BNSMs

Inspiral phase

GW-driven phase

Viscous phase



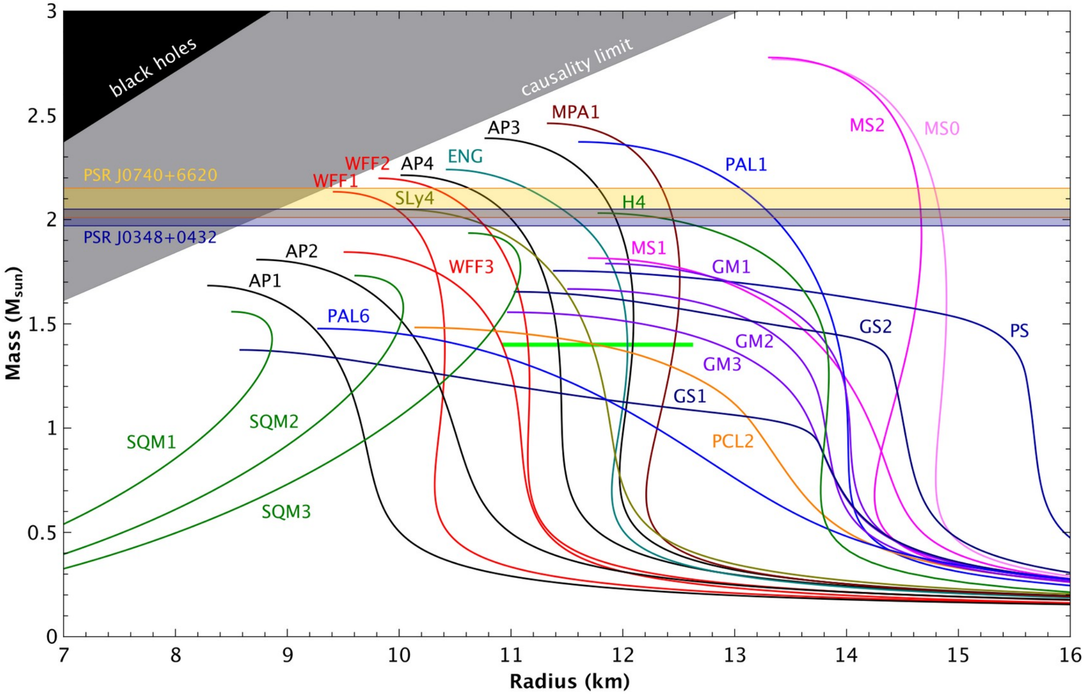
[ https://arxiv.org/abs/1903.07898 ]

# Plan of the talks/lectures

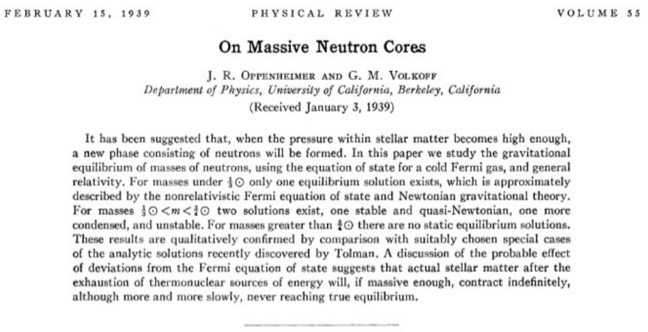
1. What can we learn from GWs?

2. What can we learn from remnants and EMs signalt?

# Neutron stars and the mass-radius diagram



From: https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html



FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

On Massive Neutron Cores

J. R. Oppenheimer and G. M. Volkoff
*Department of Physics, University of California, Berkeley, California*
(Received January 3, 1939)

It has been suggested that, when the pressure within stellar matter becomes high enough, a new phase consisting of neutrons will be formed. In this paper we study the gravitational equilibrium of masses of neutrons, using the equation of state for a cold Fermi gas, and general relativity. For masses under $\frac{1}{3}\odot$ only one equilibrium solution exists, which is approximately described by the nonrelativistic Fermi equation of state and Newtonian gravitational theory. For masses $\frac{1}{3}\odot < m < \frac{3}{4}\odot$ two solutions exist, one stable and quasi-Newtonian, one more condensed, and unstable. For masses greater than $\frac{3}{4}\odot$ there are no static equilibrium solutions. These results are qualitatively confirmed by comparison with suitably chosen special cases of the analytic solutions recently discovered by Tolman. A discussion of the probable effect of deviations from the Fermi equation of state suggests that actual stellar matter after the exhaustion of thermonuclear sources of energy will, if massive enough, contract indefinitely, although more and more slowly, never reaching true equilibrium.

Tolmann-Oppenheimer-Volkoff (TOV) equations

$$\frac{dm}{dr} = 4\pi\rho r^2$$

$$\frac{d\alpha}{dr} = \frac{m + 4\pi r^3 p}{r(r-2m)} \approx \frac{m}{r^2}$$

$$\frac{dP}{dr} = -(p+\rho)\frac{m + 4\pi r^3 p}{r(r-2m)} \approx -\frac{\rho m}{r^2} \; .$$

# Maximum mass (under minimal assumptions)

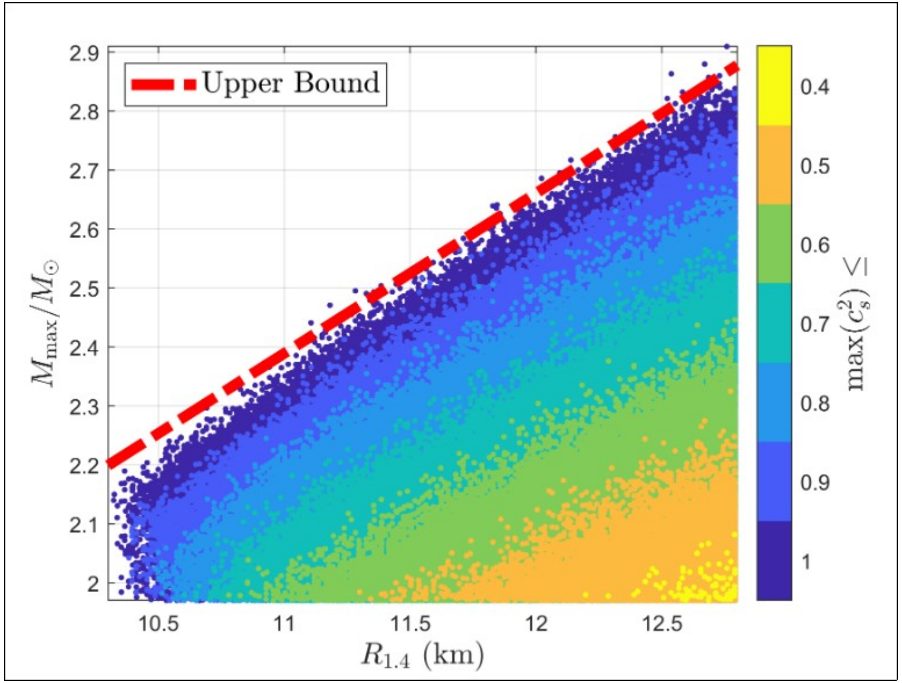
- GR & Causality
- No EOS assumptions
- ~2M phenomenological EOS

In general, we find that the upper bound on $M_{\max}$ can be very well approximated as

$$M_{\max} \leq \alpha(M) + \beta(M) R_M , \qquad (2)$$

where $R_M$ is the radius in km of a NS of gravitational mass $M$ and

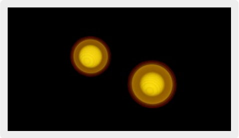
$$\alpha = 0.45\,\mathrm{M}_\odot - 1.22\,M ,$$
$$\beta = -0.051\,\mathrm{M}_\odot\,\mathrm{km}^{-1} + 0.34\,M\,\mathrm{km}^{-1} . \qquad (3)$$



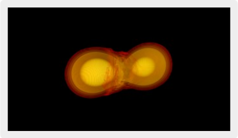
Rhoades & Ruffini Phys. Rev. Lett. 32, 324 – 1974   Mmax<~ 3.2Mo

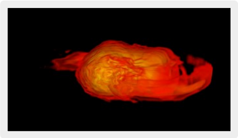
[Godzieba+ 2020]

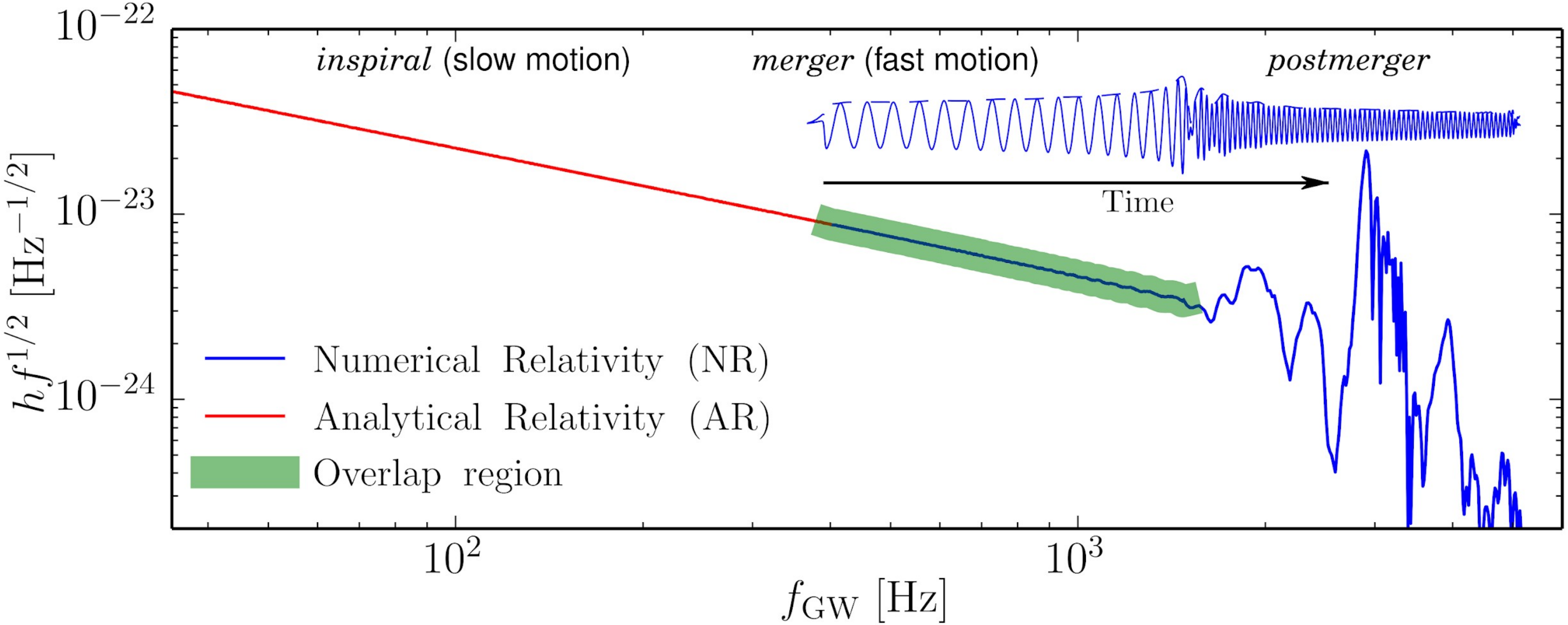
# The BNSM GW spectrum



SB+ [https://arxiv.org/abs/1504.01764]
Breschi,SB+ [https://arxiv.org/abs/1908.11418]
Breschi,SB+ [https://arxiv.org/abs/2205.09112]







# GW170817: Measurements of Neutron Star Radii and Equation of State

The LIGO Scientific Collaboration and The Virgo Collaboration

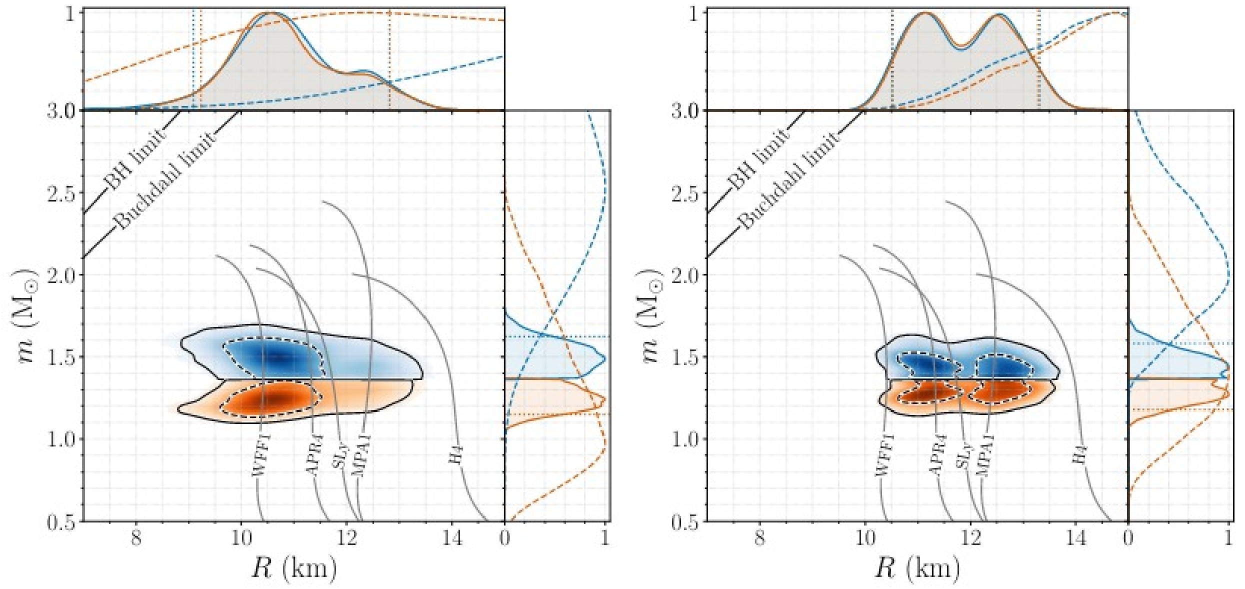
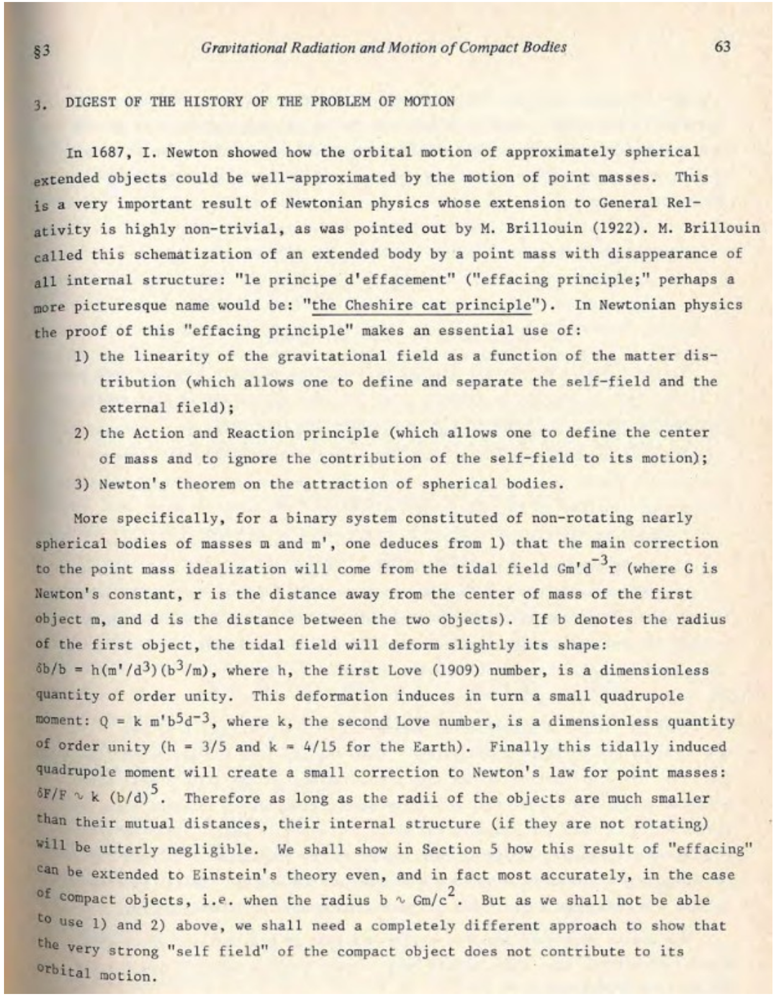


FIG. 3. Marginalized posterior for the mass $m$ and areal radius $R$ of each binary component using EOS-insensitive relations (left panel) and a parametrized EOS where we impose a lower limit on the maximum mass of $1.97\ \mathrm{M}_\odot$ (right panel). The top blue (bottom orange) posterior corresponds to the heavier (lighter) NS. Example mass-radius curves for selected EOSs are overplotted in gray. The lines in the top left denote the Schwarzschild BH ($R = 2m$) and Buchdahl ($R = 9m/4$) limits. In the one-dimensional plots, solid lines are used for the posteriors, while dashed lines are used for the corresponding parameter priors. Dotted vertical lines are used for the bounds of the 90% credible intervals.



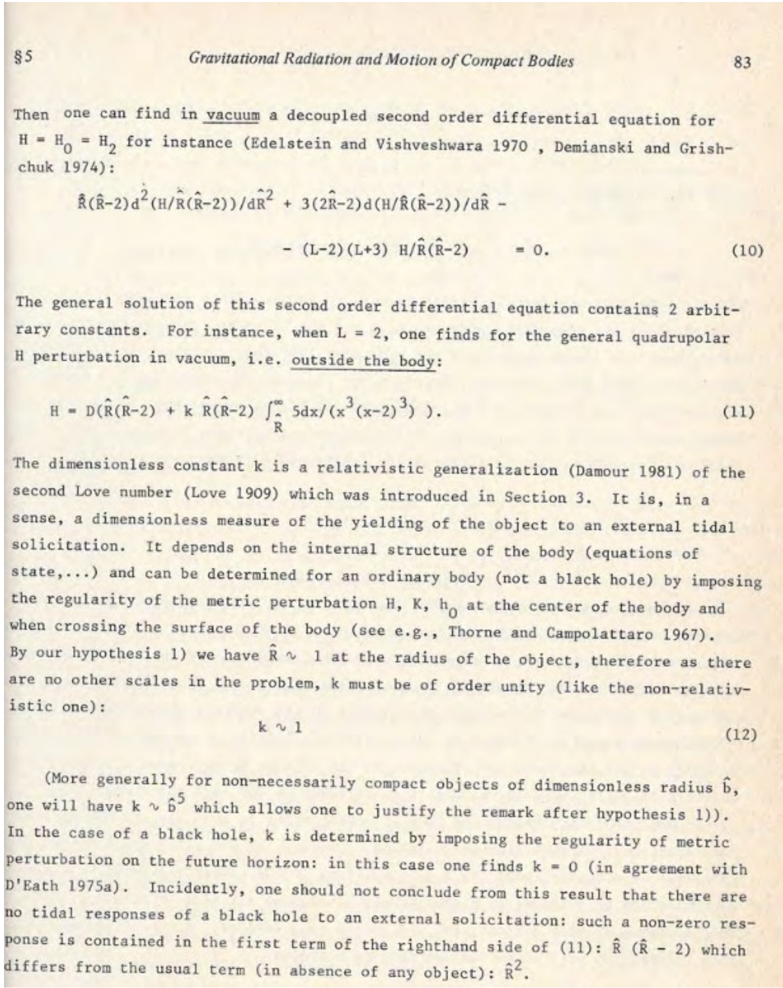
§3 *Gravitational Radiation and Motion of Compact Bodies* 63

## 3. DIGEST OF THE HISTORY OF THE PROBLEM OF MOTION

In 1687, I. Newton showed how the orbital motion of approximately spherical extended objects could be well-approximated by the motion of point masses. This is a very important result of Newtonian physics whose extension to General Relativity is highly non-trivial, as was pointed out by M. Brillouin (1922). M. Brillouin called this schematization of an extended body by a point mass with disappearance of all internal structure: "le principe d'effacement" ("effacing principle;" perhaps a more picturesque name would be: "the Cheshire cat principle"). In Newtonian physics the proof of this "effacing principle" makes an essential use of:

1) the linearity of the gravitational field as a function of the matter distribution (which allows one to define and separate the self-field and the external field);
2) the Action and Reaction principle (which allows one to define the center of mass and to ignore the contribution of the self-field to its motion);
3) Newton's theorem on the attraction of spherical bodies.

More specifically, for a binary system constituted of non-rotating nearly spherical bodies of masses m and m', one deduces from 1) that the main correction to the point mass idealization will come from the tidal field $Gm'd^{-3}r$ (where G is Newton's constant, r is the distance away from the center of mass of the first object m, and d is the distance between the two objects). If b denotes the radius of the first object, the tidal field will deform slightly its shape: $\delta b/b = h(m'/d^3)(b^3/m)$, where h, the first Love (1909) number, is a dimensionless quantity of order unity. This deformation induces in turn a small quadrupole moment: $Q = k\, m'b^5d^{-3}$, where k, the second Love number, is a dimensionless quantity of order unity ($h = 3/5$ and $k = 4/15$ for the Earth). Finally this tidally induced quadrupole moment will create a small correction to Newton's law for point masses: $\delta F/F \sim k\,(b/d)^5$. Therefore as long as the radii of the objects are much smaller than their mutual distances, their internal structure (if they are not rotating) will be utterly negligible. We shall show in Section 5 how this result of "effacing" can be extended to Einstein's theory even, and in fact most accurately, in the case of compact objects, i.e. when the radius $b \sim Gm/c^2$. But as we shall not be able to use 1) and 2) above, we shall need a completely different approach to show that the very strong "self field" of the compact object does not contribute to its orbital motion.



§5 *Gravitational Radiation and Motion of Compact Bodies* 83

Then one can find in vacuum a decoupled second order differential equation for $H = H_0 = H_2$ for instance (Edelstein and Vishveshwara 1970 , Demianski and Grishchuk 1974):

$$\hat{R}(\hat{R}-2)d^2(H/\hat{R}(\hat{R}-2))/d\hat{R}^2 + 3(2\hat{R}-2)d(H/\hat{R}(\hat{R}-2))/d\hat{R} - \\ - (L-2)(L+3)\ H/\hat{R}(\hat{R}-2) = 0. \tag{10}$$

The general solution of this second order differential equation contains 2 arbitrary constants. For instance, when L = 2, one finds for the general quadrupolar H perturbation in vacuum, i.e. outside the body:

$$H = D(\hat{R}(\hat{R}-2) + k\ \hat{R}(\hat{R}-2)\int_{\hat{R}}^{\infty} 5dx/(x^3(x-2)^3)\ ). \tag{11}$$

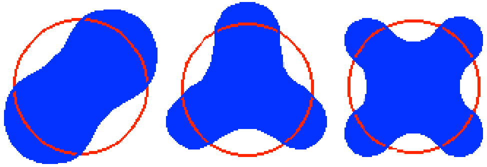
The dimensionless constant k is a relativistic generalization (Damour 1981) of the second Love number (Love 1909) which was introduced in Section 3. It is, in a sense, a dimensionless measure of the yielding of the object to an external tidal solicitation. It depends on the internal structure of the body (equations of state,...) and can be determined for an ordinary body (not a black hole) by imposing the regularity of the metric perturbation H, K, $h_0$ at the center of the body and when crossing the surface of the body (see e.g., Thorne and Campolattaro 1967). By our hypothesis 1) we have $\hat{R} \sim 1$ at the radius of the object, therefore as there are no other scales in the problem, k must be of order unity (like the non-relativistic one):

$$k \sim 1 \tag{12}$$

(More generally for non-necessarily compact objects of dimensionless radius $\hat{b}$, one will have $k \sim \hat{b}^5$ which allows one to justify the remark after hypothesis 1)). In the case of a black hole, k is determined by imposing the regularity of metric perturbation on the future horizon: in this case one finds k = 0 (in agreement with D'Eath 1975a). Incidently, one should not conclude from this result that there are no tidal responses of a black hole to an external solicitation: such a non-zero response is contained in the first term of the righthand side of (11): $\hat{R}\ (\hat{R} - 2)$ which differs from the usual term (in absence of any object): $\hat{R}^2$.

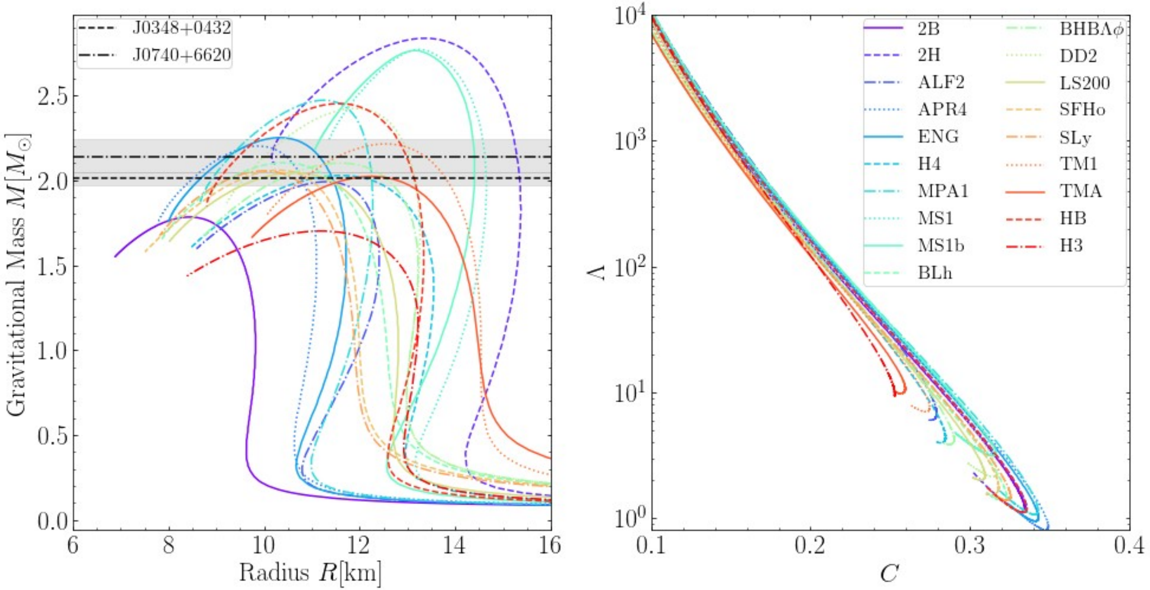
T.Damour 1981

# Tidal polarizability coefficients

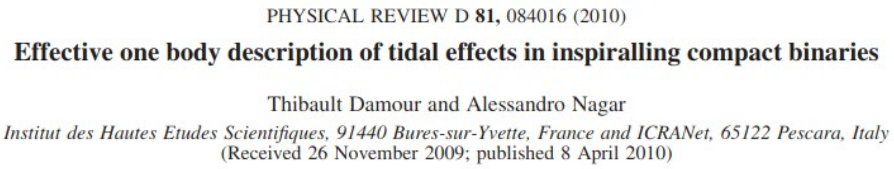


$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$

$$\Lambda_2 = \frac{2}{3} \lambda_2 \left( \frac{M}{R} \right)^5$$



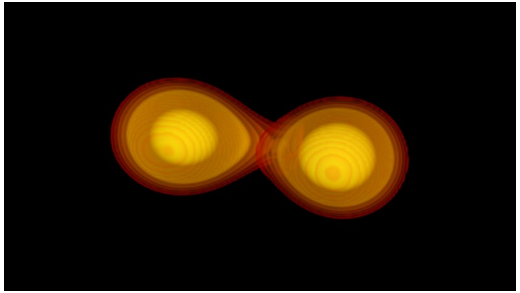
[Hinderer 2007, Damour&Nagar 2009a, Binnington&Poisson 2009]


PHYSICAL REVIEW D **81,** 084016 (2010)

**Effective one body description of tidal effects in inspiralling compact binaries**

Thibault Damour and Alessandro Nagar

*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France and ICRANet, 65122 Pescara, Italy*
(Received 26 November 2009; published 8 April 2010)



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

**Tidal coupling constant** (Analogous to the reduced tidal parameter $\bar{\Lambda}$ [Favata 2013])

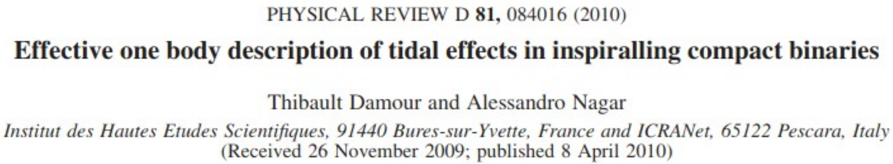
Hamiltonian
(Newtonian limit):

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

$$A(r) = 1 - \frac{2}{r} - \frac{\kappa_2^T(k_2)}{r^6}$$

Waveform:

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



PHYSICAL REVIEW D **81,** 084016 (2010)

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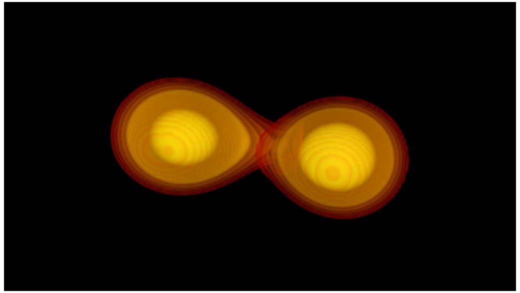

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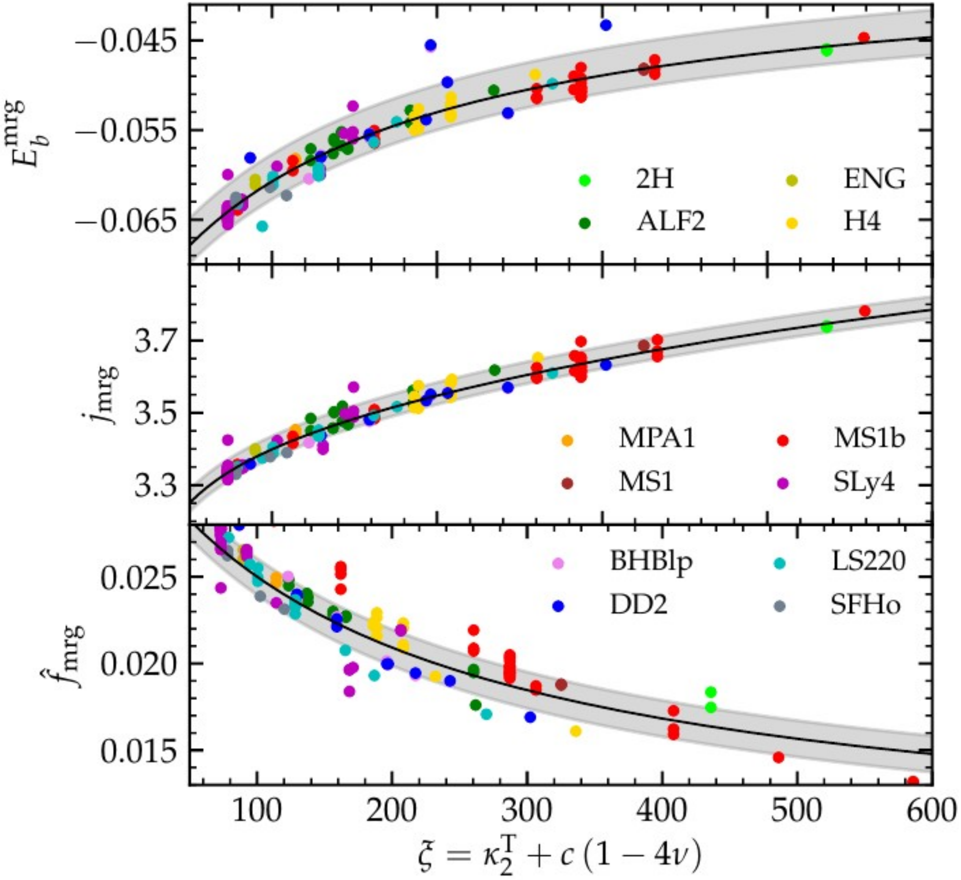
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism at LO

# Merger parametrization (aka quasiuniversality)



- How to interpret numerical-relativity (NR) data?
- *Y-axis:* simulation results from multi-orbit NR simulations with different EOS, masses, mass-ratio, spins, etc.
- *X-axis:* tidal coupling constant (plus effective correction for very asymmetric binaries)

- Tidal coupling constant captures strong-field features to high precision!
  SB+ (2014) [https://arxiv.org/abs/1402.6244]

- Why useful?
  - Lower bounds for energy, angular momentum, radiated to merger (at the end of chirp)
  - GW merger frequency/amplitude (not predicted by post-Newtonian methods)
  - Peak luminosity and upper bounds for remnant's energy, ang.momentum, etc. [Zappa,SB+ (2017)]

PHYSICAL REVIEW D **85,** 123007 (2012)

# Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals

Thibault Damour and Alessandro Nagar
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Loïc Villain
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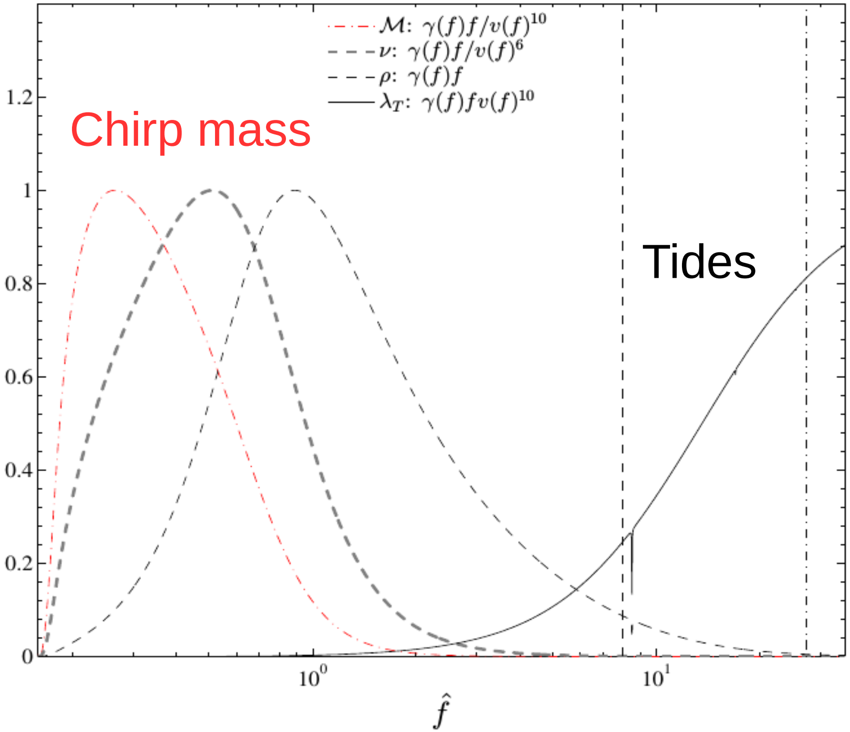
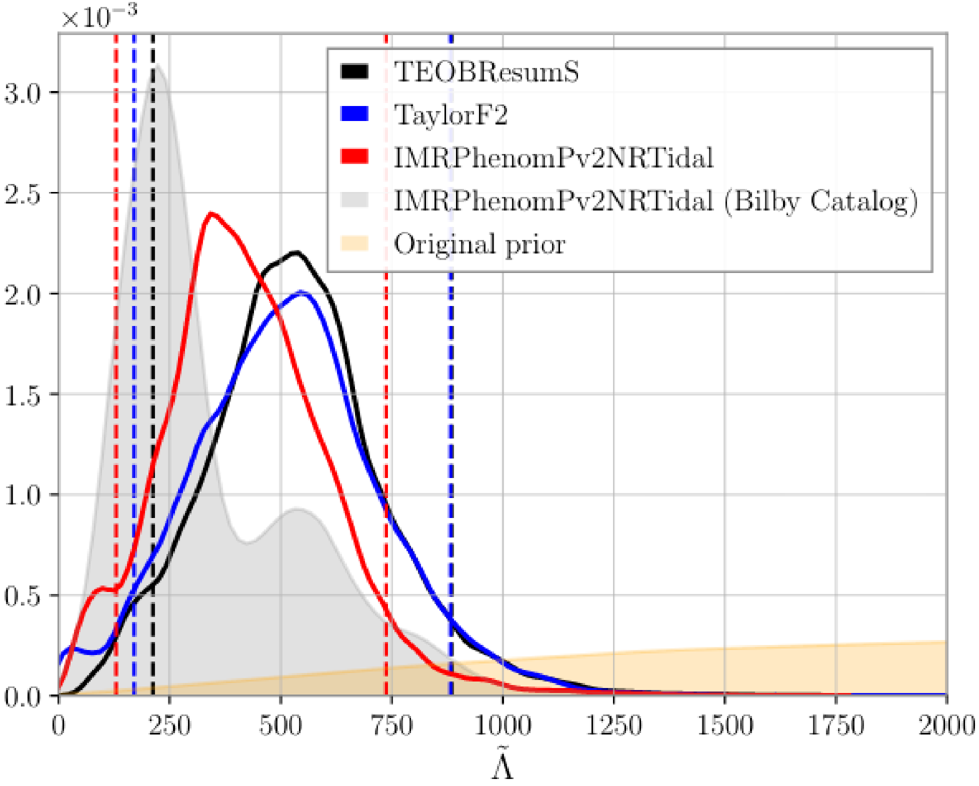
*Féd. Denis Poisson, 37200 Tours, France*
(Received 20 March 2012; published 15 June 2012)



Chirp mass

Tides

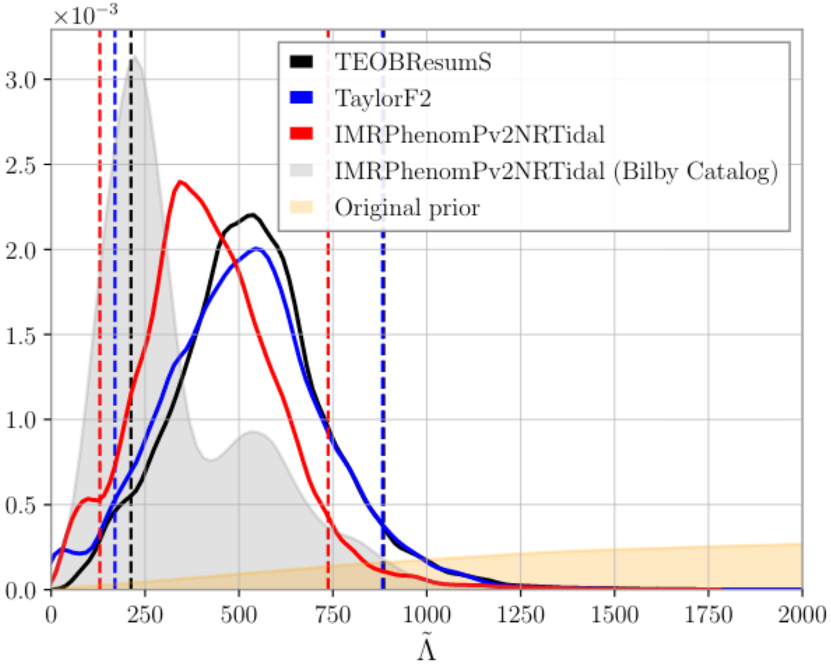
# GW170817 inference of tidal parameters



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

# GW170817 inference of tidal parameters

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



NB Tidal effects are **the** signature of matter in the inspiral GWs. The tidal polarizability parameters (a multipolar set of each star) are **the** physical quantities that can be inferred from these GW observations.

Other parameters can be constrained by further assuming specific EOS, various EOS parametrizations, etc. and computing them as functions of tidal polarizability parameters (either from actual EOS data or via EOS-insensive/quasi universal relations*). This is extensively studied in literature with several variations on the main theme.

For example, the use of a EOS-insensitive relations built with ~2M parametrized EOS with minimal assumptions (and allowinf 1st order EOS with phase transitions) leads to

GW NS radius measurement:
$R_{1.4} = 12.5^{+1.1}_{-1.8}$ km

# Summary /1

- Circularized BNS coalescences differ from black holes because of tidal effects
- Matter (cold EOS) effects are encoded in the tidal polarizability parameters
- Tidal interactions are short range → high-frequency effect on the GWs
- Tidal polarizability parameters can be measured using standard matched filtering techniques and waveform templates
- Any other parameter can be inferred using EOS parametrizations and/or NS equilibra in GR
- Current constraints not much constraining … but more observations to come!
- Watch out: waveform systematics

# Post-merger detection with 3G

Breschi,SB+ [https://arxiv.org/abs/2205.09112]

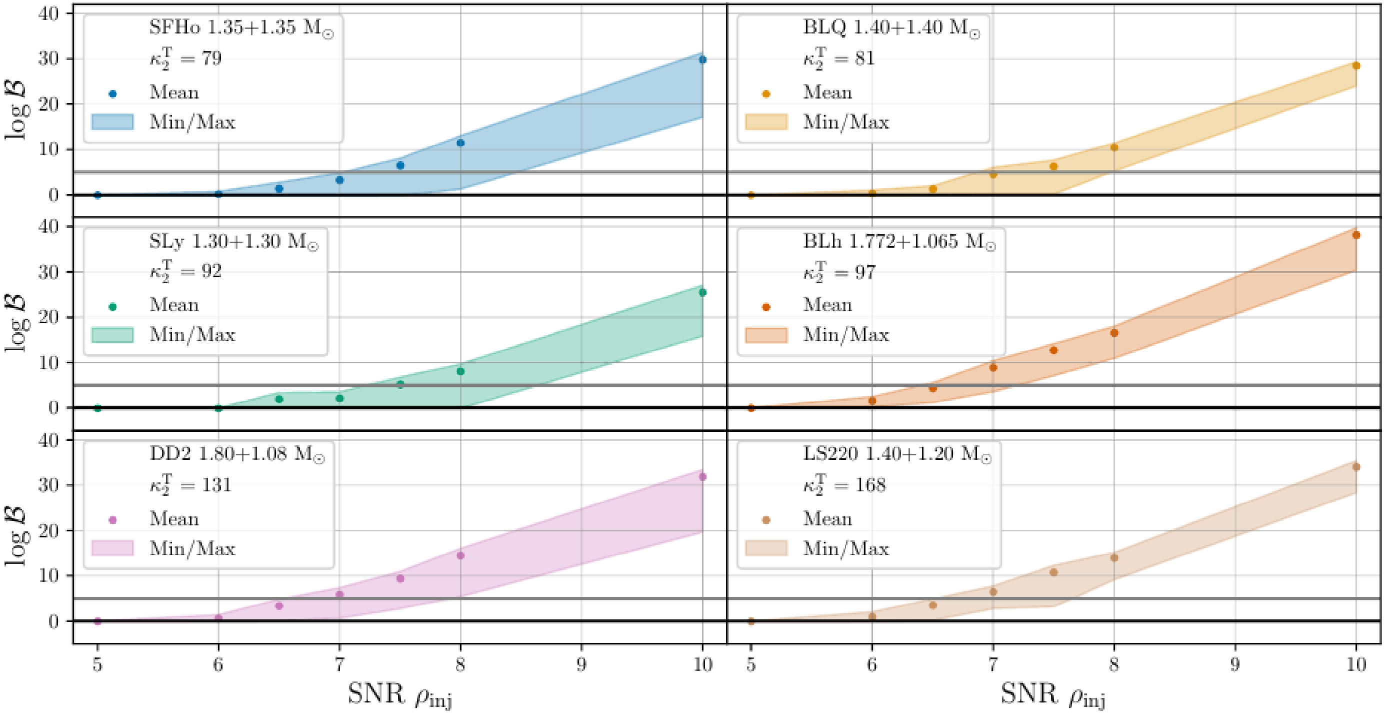
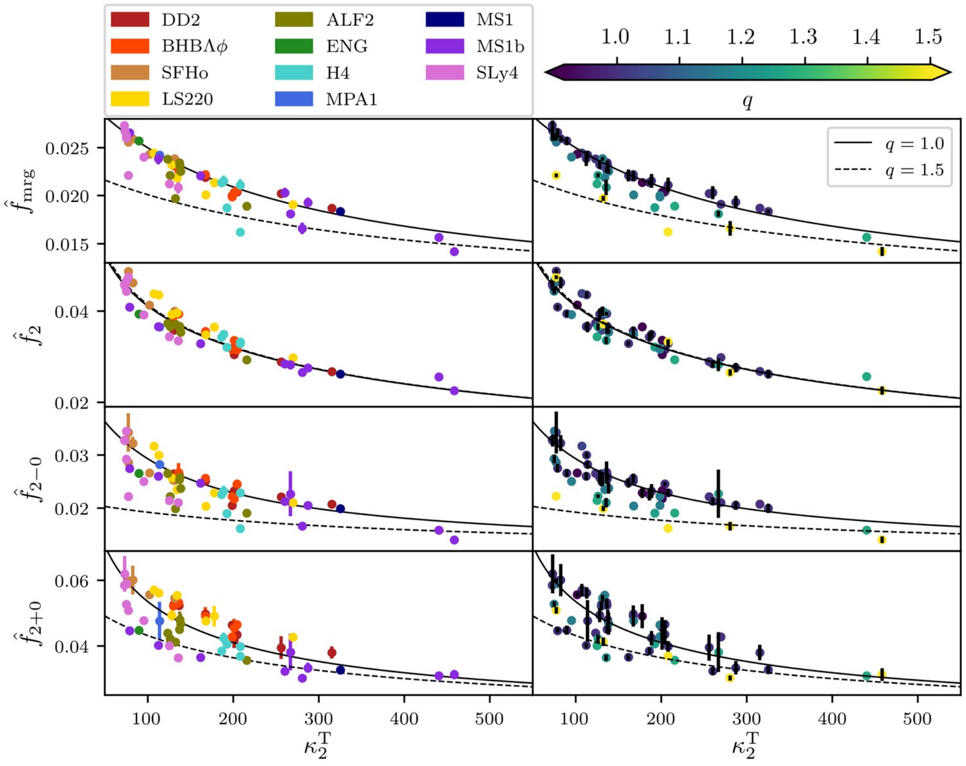


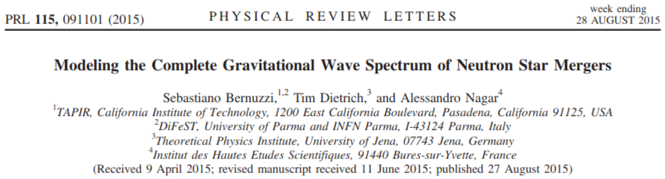
FIG. 5. Logarithmic BFs $\log \mathcal{B}$ as functions of the PM SNR $\rho_{\rm inj}$ of the injected NR template from Table I. The dots refer to the mean values averaged over the different noise realizations and the shadowed areas correspond to the minimum and maximum values recovered in the survey. Two horizontal lines identify $\log \mathcal{B} = 0$ (black) and $\log \mathcal{B} = 5$ (gray).

# Post-merger parametrization



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

- Merger parametrization can be extended to postmerger frequencies


PRL **115,** 091101 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

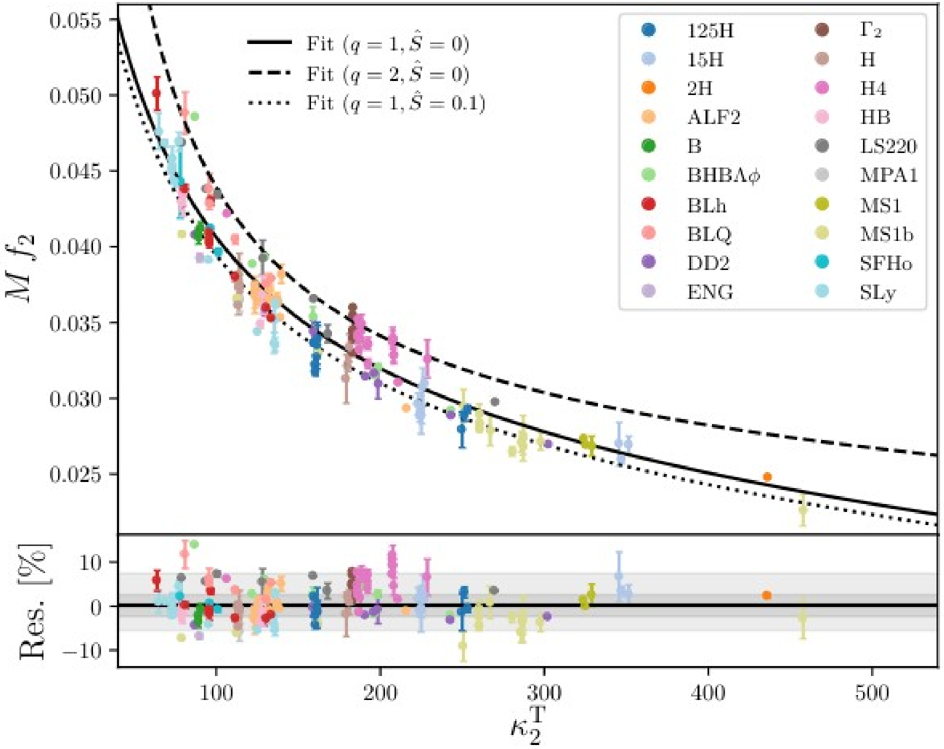
**Modeling the Complete Gravitational Wave Spectrum of Neutron Star Mergers**

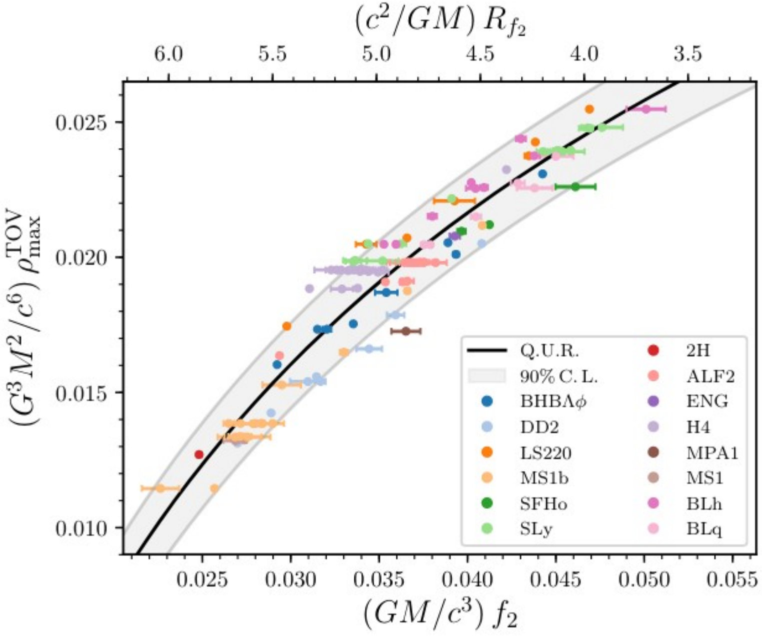
Sebastiano Bernuzzi,[1,2] Tim Dietrich,[3] and Alessandro Nagar[4]
[1]*TAPIR, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA*
[2]*DiFeST, University of Parma and INFN Parma, I-43124 Parma, Italy*
[3]*Theoretical Physics Institute, University of Jena, 07743 Jena, Germany*
[4]*Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France*
(Received 9 April 2015; revised manuscript received 11 June 2015; published 27 August 2015)

- Basic reason: efficiency of early postmerger GW emission. GW energy emitted in short time at f ~ const = 2x rotation (No discrete freqs!) SB+ [https://arxiv.org/abs/1512.06397]

- Other, similar proposals, see work by Bauswein+, Hotokezaka+, Stergioulas+, Takami+, ...

# EOS-insensitive/“quasi-universal” relations





Breschi, SB+ [https://arxiv.org/abs/2205.09112 ]

# NB The choice of parametrization matters!

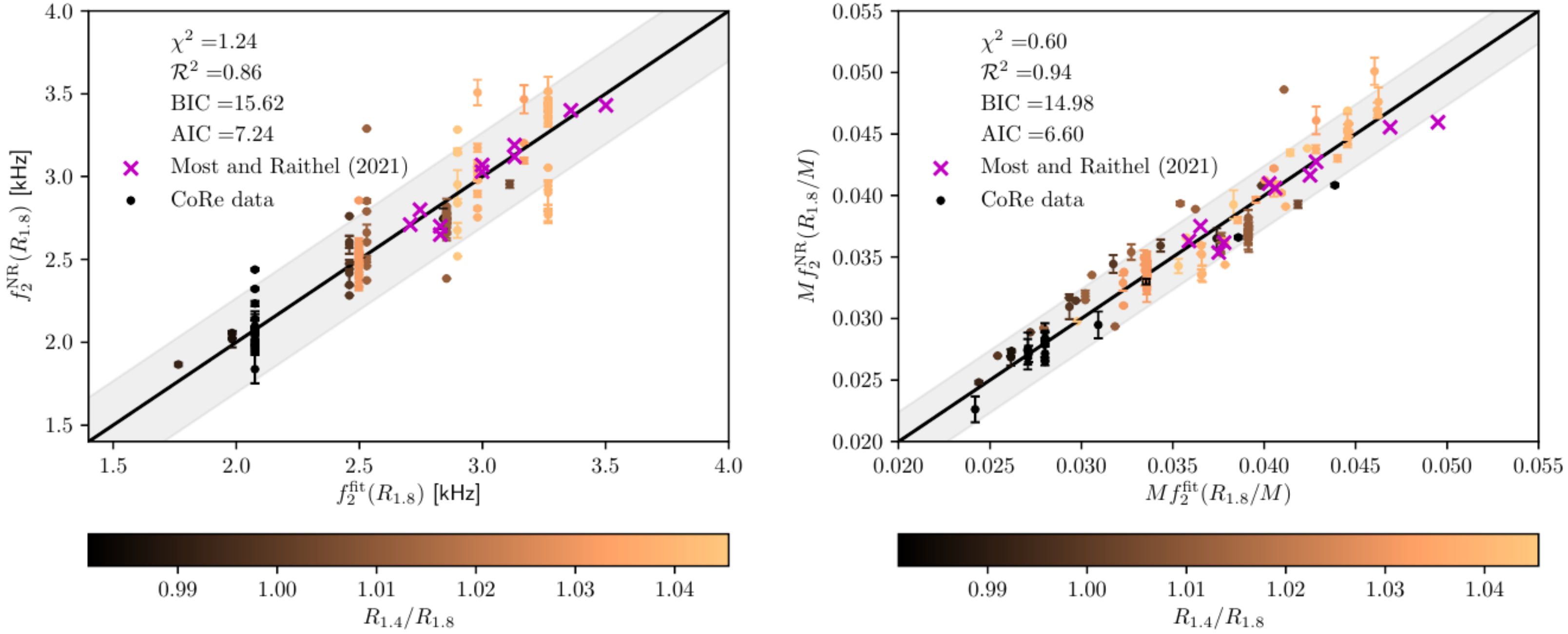


FIG. 8. Predicted values from the calibrated relations Eq. (F1) compared to the respective NR observed quantities. Top panels show $X = 1.4$ and bottom panels show $X = 1.8$. Left panels show non-mass-scaled $f_2$ and right panels show mass-scaled dimensionless $M f_2$. The diagonal (black line) represents the case in which predictions and observations match and the gray area is the 90% credibility level. The CoRe data are reported with circles colored according to $R_{1.4}/R_{1.8}$ and magenta crosses are the data extracted from [27].

# Full-spectrum constraints on M-R diagram

- Full-spectrum (mock) analysis using ET @ minimum SNR threshold for a PM detection

- NS maximum density to 15% and maximum mass to 12% (90% conf. Lev.) using direct quasiuniversal relation

- Hits theoretical uncertainty, i.e. not possible to do better

- Recalibration parameters: account for theoretical uncertainties in EOS-insensitive rel.

Breschi, SB+ [https://arxiv.org/abs/2110.06957]

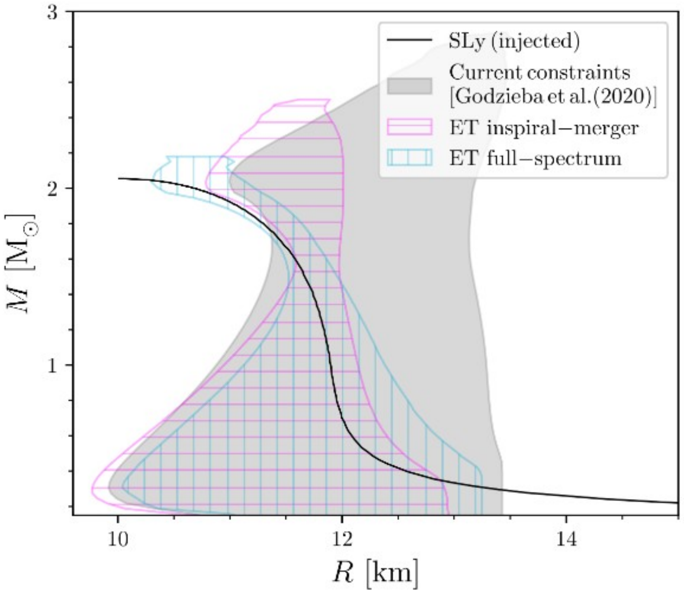
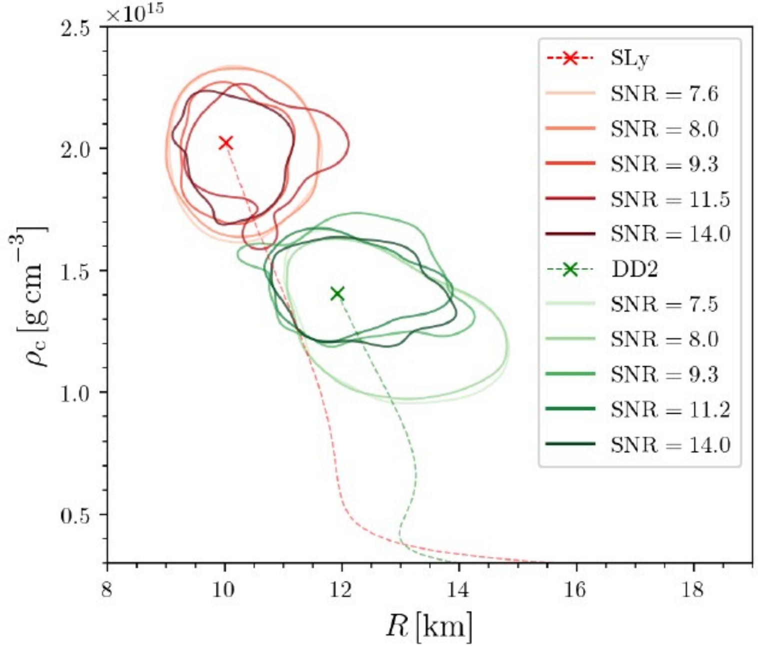
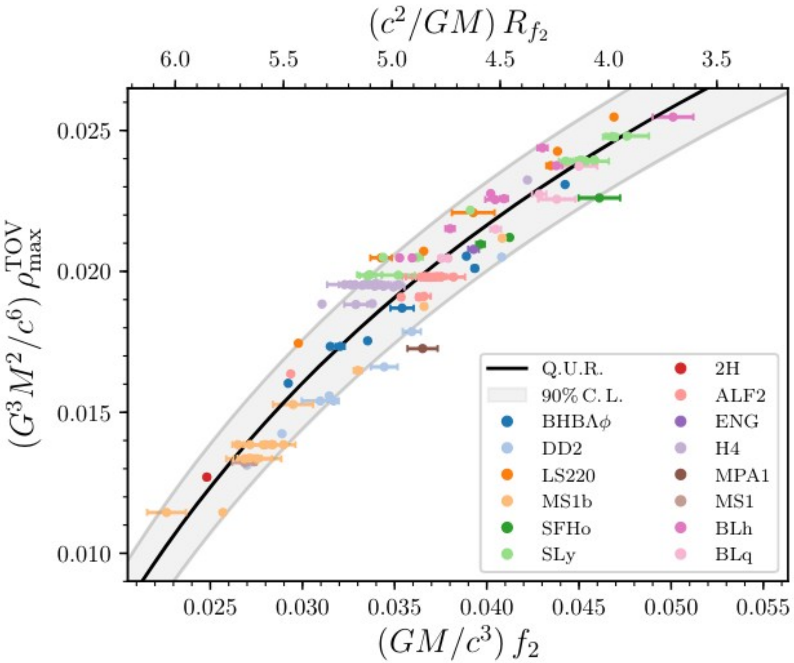


FIG. 4. Mass-radius diagram constraints from a single full-spectrum Einstein Telescope (ET) BNS observation with PM SNR 10 (total SNR 180). The gray area (prior) corresponds to the two-million EOS sample of Ref. [69]. The magenta and cyan areas are the 90% credibility regions given by inspiral-merger and inspiral-merger-PM inferences respectively. The full-spectrum (cyan) posterior agrees with the injected EOS (black).

# GW constraints on NS’s extreme matter

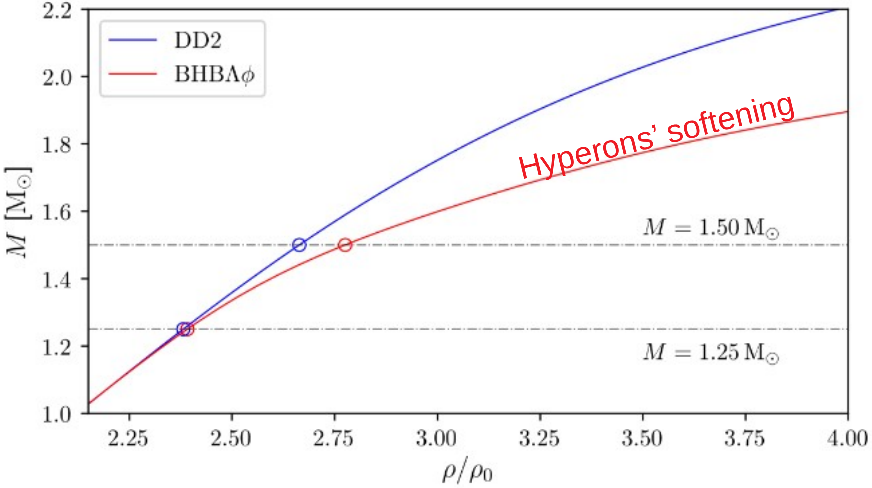




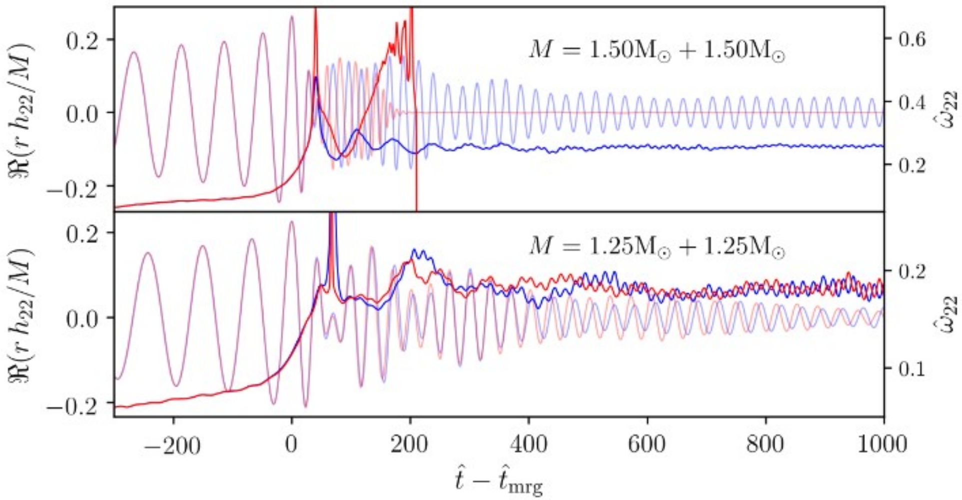
Full-spectrum (mock) analysis using Einstein Telescope sligthly above the minimum SNR threshold for a PM detection
New quasi-universal (EOS-insensitive) relation for the maximum density of an equilibrium NS
NS maximum density to 15% and maximum mass to 12% (90% confidence level)

Breschi,SB+ [https://arxiv.org/abs/2205.09112]

# EOS softness at extreme densities



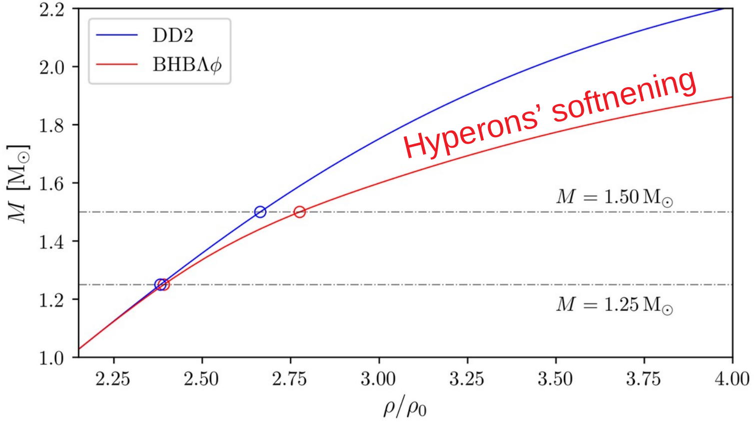
Hyperons’ softening



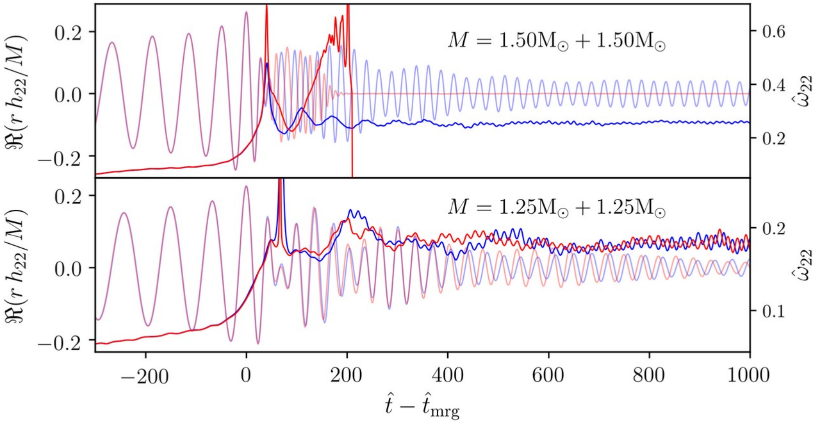
Radice, SB+ [ https://arxiv.org/abs/1612.06429 ]

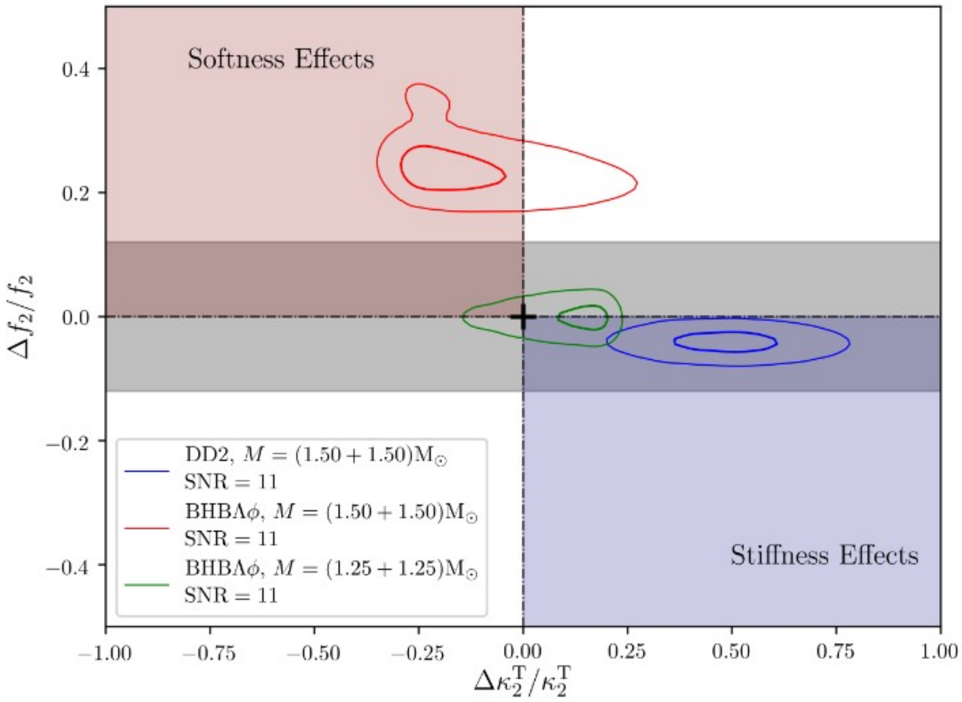
NB There are several other examples in the literature:
the specific mechanism (phase transitions, etc) is not relevant, the effect is conceptually analogous (EOS softening/stiffening with impact on the remnant’s compactness and stability)

# EOS softness at extreme densities



Hyperons’ softnening



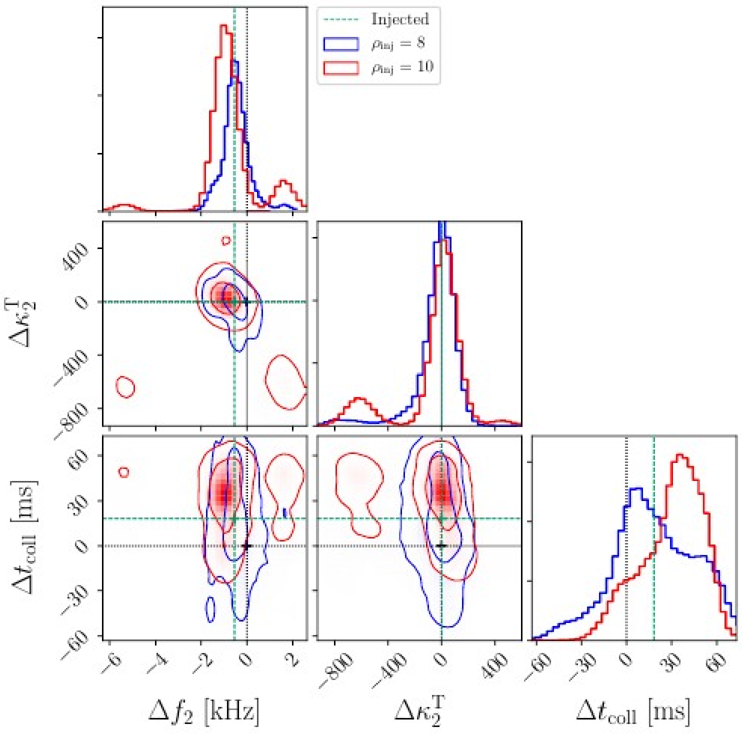


Breschi, SB+ [ https://arxiv.org/abs/1908.11418]
See also Radice, SB+ [ https://arxiv.org/abs/1612.06429 ]

# Caveats...

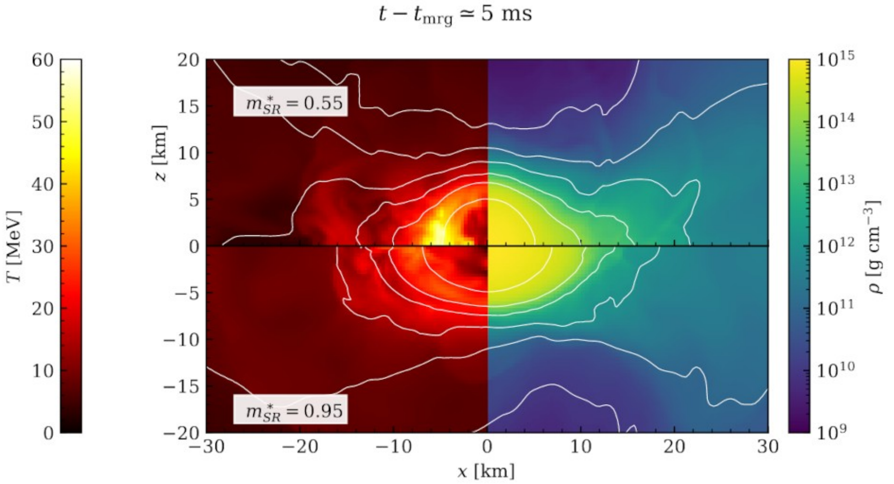
- Usually small “window” of binary parameters (EOS dependent)
- f2 or collapse time? Morphology! The specific parameter is not relevant
- Uncertainties in quasi-universal relations must be incorporated in the analysis (e.g. recalibration parameters)
- A practical procedure to unambiguously **detect** these effects is NOT know (and difficult to establish). At best one can detect a deviation from the assumed model (no proof of a physical effect).

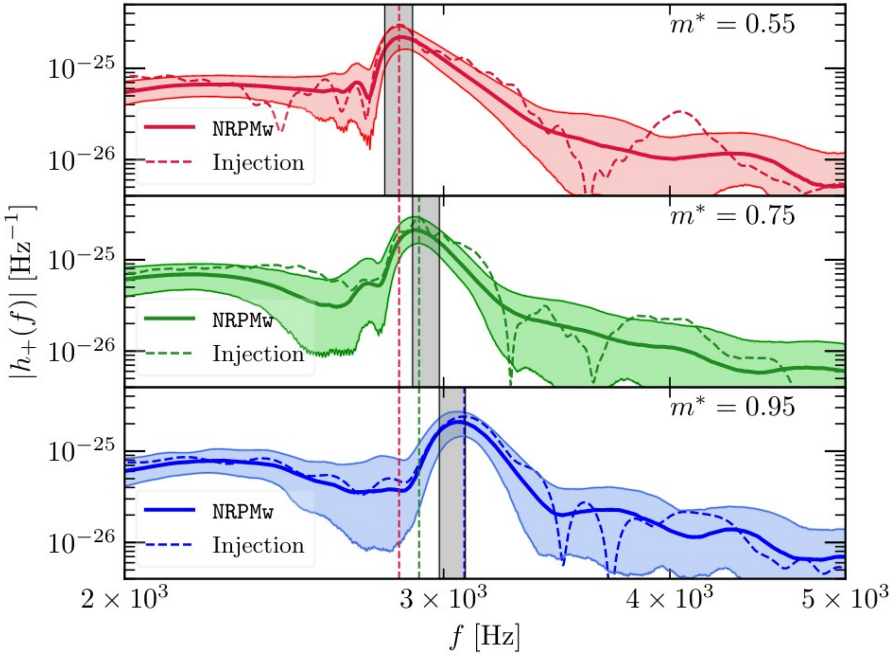
All these type of experiments are proofs of principle, establishing only the **sensitivity** of the instruments to these physical effects.



Breschi+ [https://arxiv.org/abs/1908.11418]
Breschi+ [https://arxiv.org/abs/2205.09979]
Breschi+ [https://arxiv.org/abs/2301.09672]

# 3G (ET) sensitivity to thermal EOS effects





Microphysical EOS w/ different effective nucleon masses
→ specific heat increases, thermal pressure support reduces
→ the remnants become colder and more compact

How to actually detect this?

Fields+ [ https://arxiv.org/abs/2302.11359 ]

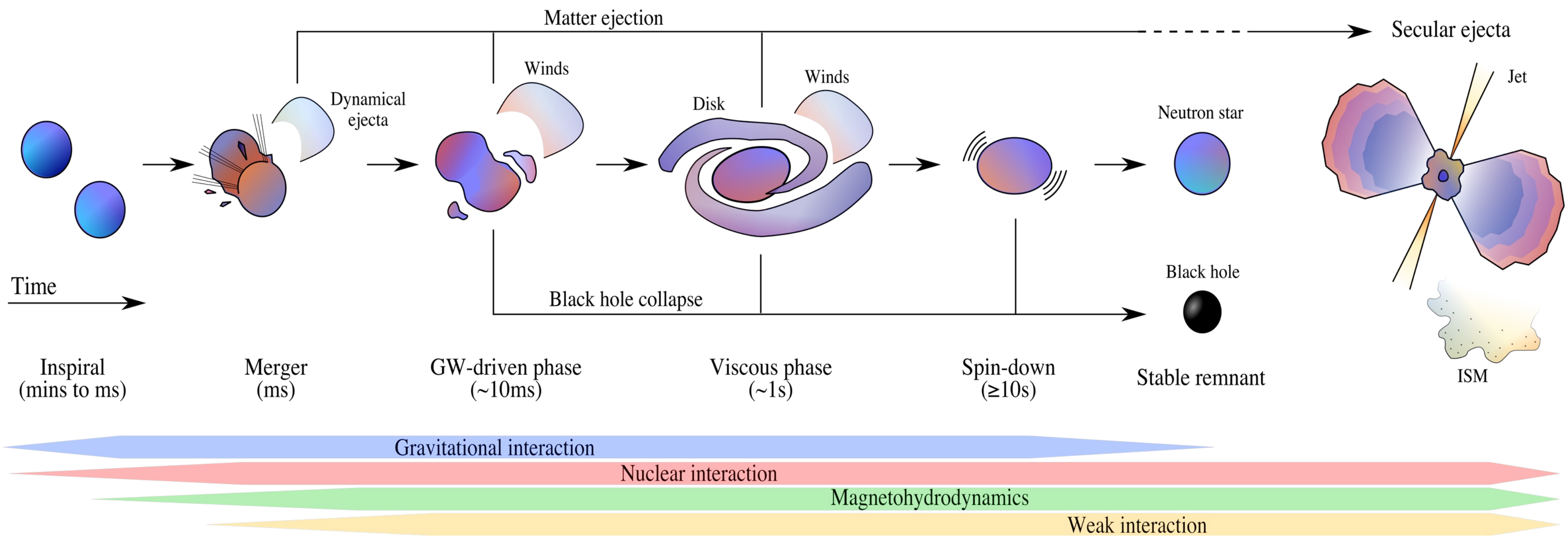
# Summary /2

- NS remnants emit GW in the kiloHertz (postmerger Gws)
- Full-spectrum analyses can increase the constraints on the mass-radius diagram
- Postmerger GWs are influenced by the hot matter and high(er than original binary stars) densities …
- … in principle different EOS aspects can be probed: new d.o.f., (various) phase transitions, thermal effects, etc.
- 3G detectors are sensitive to these effects! (for high SNR events)
- However:

  1) observations need modeling (use quasi-universal relations)

  2) no unambiguous procedure to actually measure and identify the effect
- No detection so far
- Watch out: use & abuse of quasi-universal relations

# The picture emerging from theory



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 ]

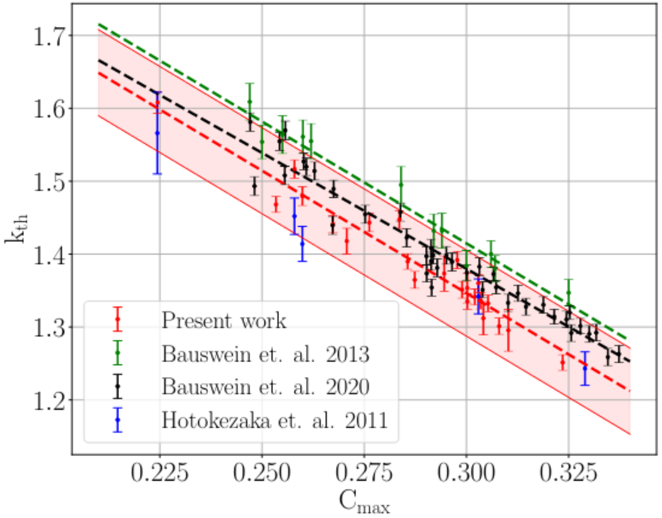
# Black-hole prompt collapse, equal-mass BNSMs

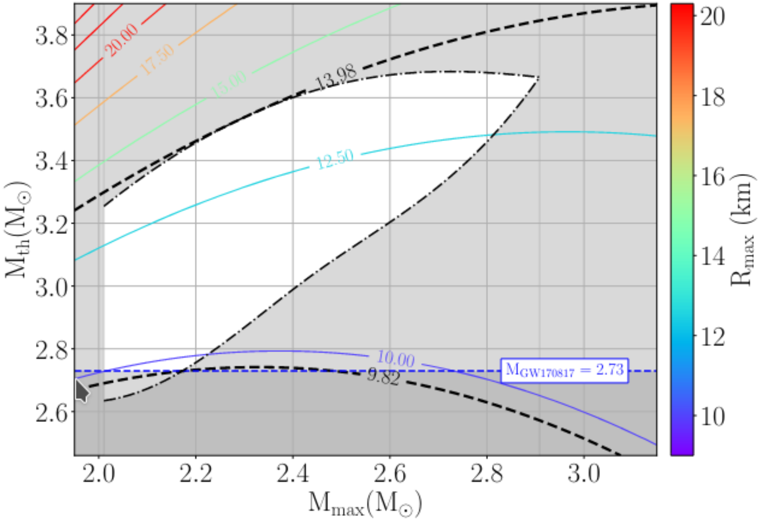
$$M_{\rm collapse} = k M_{\rm max}^{\rm TOV}$$

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

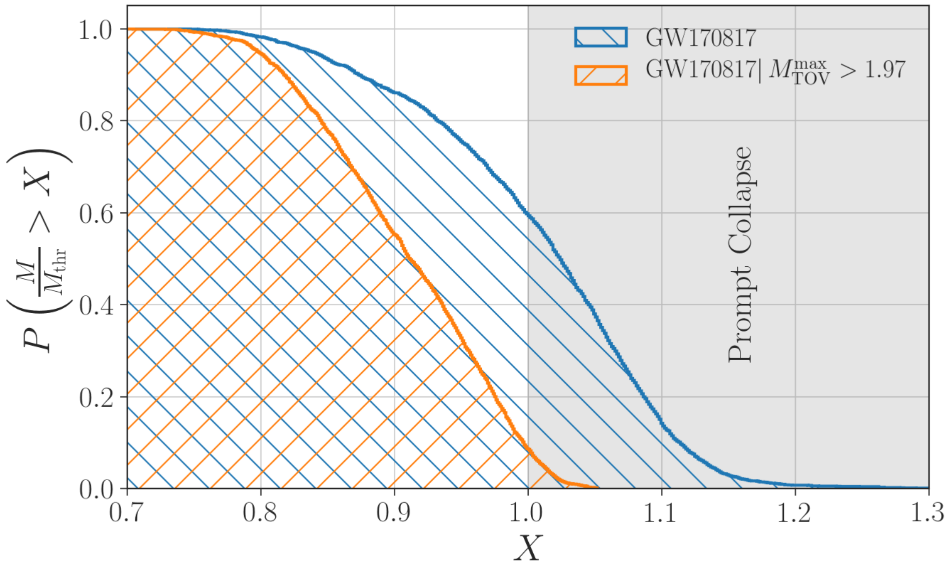
Hotokezaka+ [https://arxiv.org/abs/1105.4370]
Bauswein+ [https://arxiv.org/abs/1307.5191]

Kashyap+ [https://arxiv.org/abs/2111.05183]





# Inferring prompt collapse from inspiral GW



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

- Two methods, w/ NR-based PC criteria (consistent results)
  - EOS inference + Threshold mass
  - Tidal parameter + $\bar{\Lambda}$-Threshold
- GW170817: quantitatively support the “mainstream” interpretation of counterparts

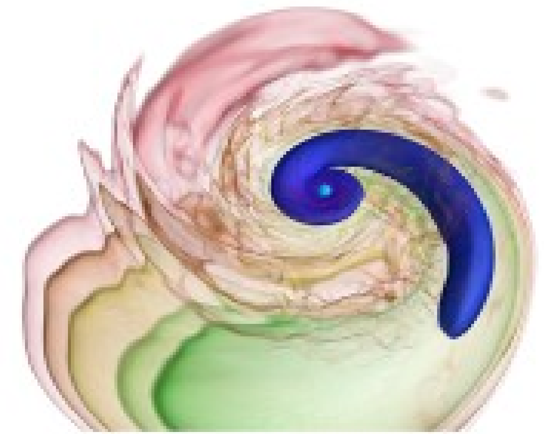
  Margalit&Metzger [https://arxiv.org/abs/1710.05938]
- GW190425 (M~3.4Mo):

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

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

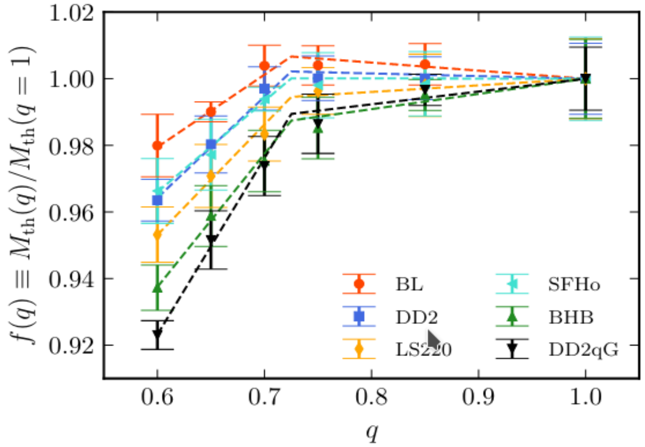
Agathos, Zappa, SB+ [https://arxiv.org/abs/1908.05442]

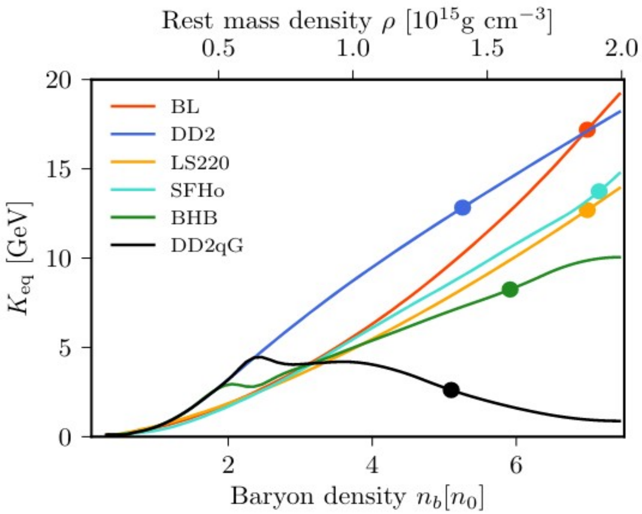
# Black-hole prompt collapse, unequal masses



Accretion-induced prompt collapse : tidal disruption and massive disks → EM loud!
SB+ [ https://arxiv.org/abs/2003.06015 ]

Collapse threshold depends Nuclear incompressibility of matter at max densities
Perego+ [https://arxiv.org/abs/2112.05864]

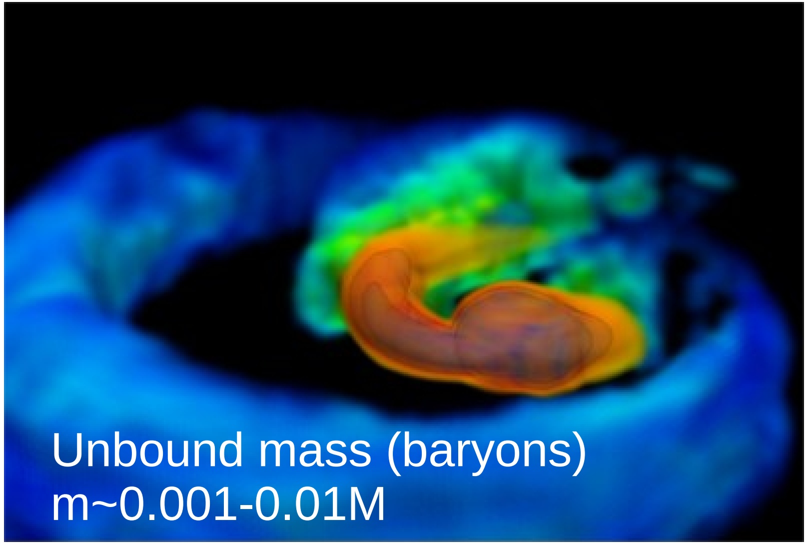




# Summary /3

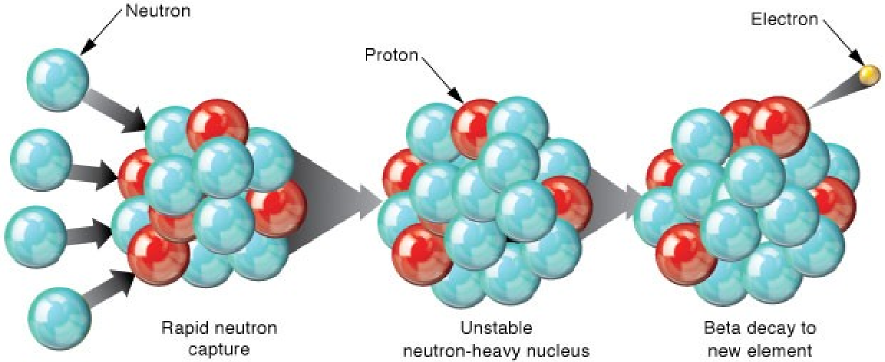
- Prompt BH collapse can inform on the maximum TOV mass, Mmax
    - Indirectly: from inspiral GWs and theory (simulation) results
    - Directly: from a non-detection of postmerger GWs (model selection)
- Note: current astrophysics constraints from Mmax (pulsars) are strong constraints for the nuclear EOS; GW might add/improve over those.
- Watch out: unequal masses binaries and tidal disruption cases; interesting physics to be explored ...

# Mass ejecta & nucleosynthesis


Unbound mass (baryons)
m~0.001-0.01M

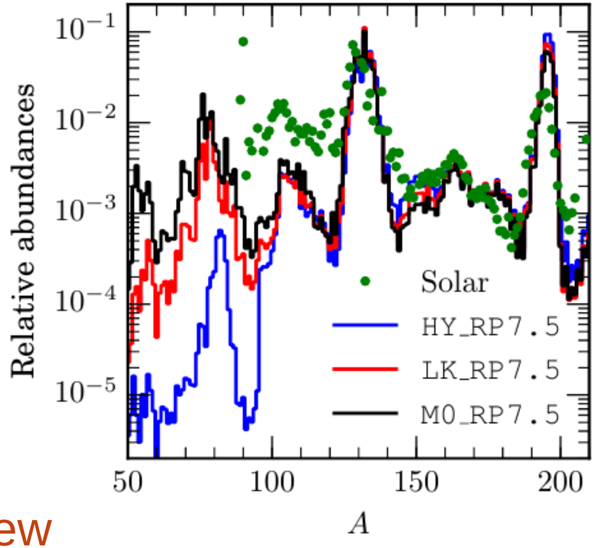
NS-BH collisions (1974) Decompression of cold neutron star matter

D. Schramm, J. Lattimer, D. Eichler, T. Piran, F. Thielemann, S. Rosswog and many others



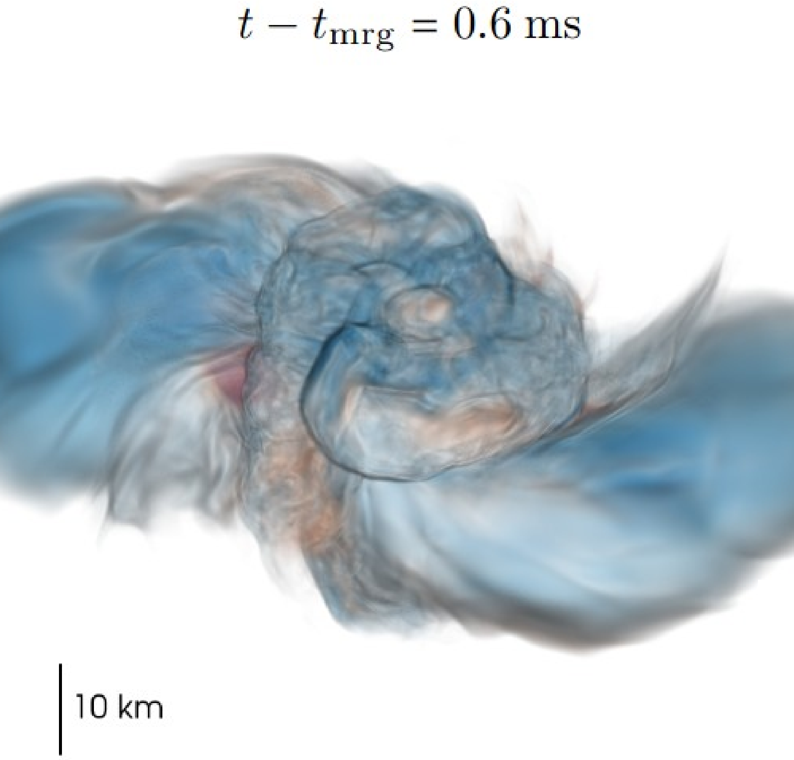
**KILONOVA**

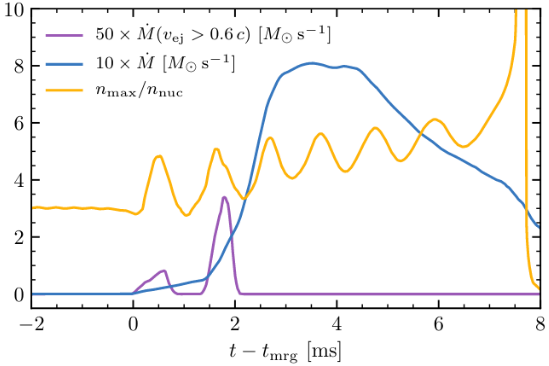
Radioactive heating & thermalization ($\beta$-decays, $\alpha$-decays, fission)



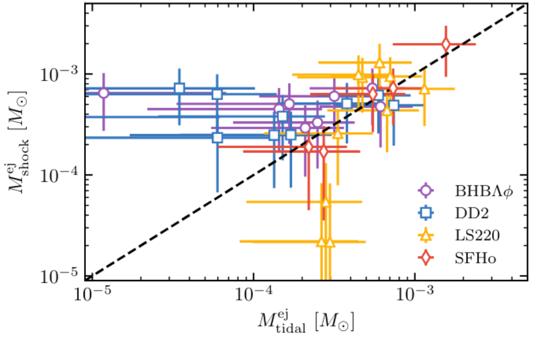
See Metzger Review

# Dynamical ejecta

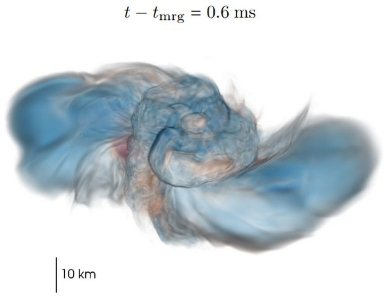


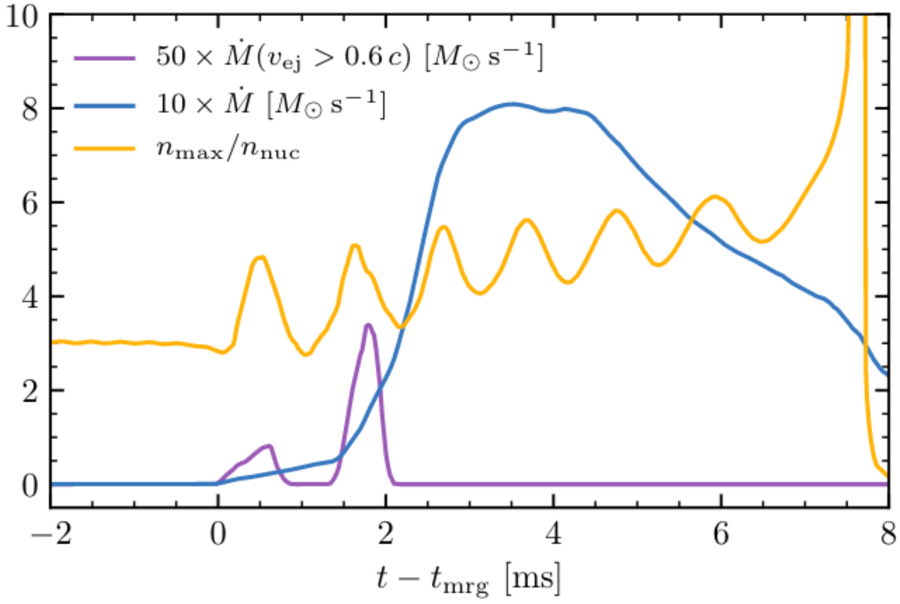


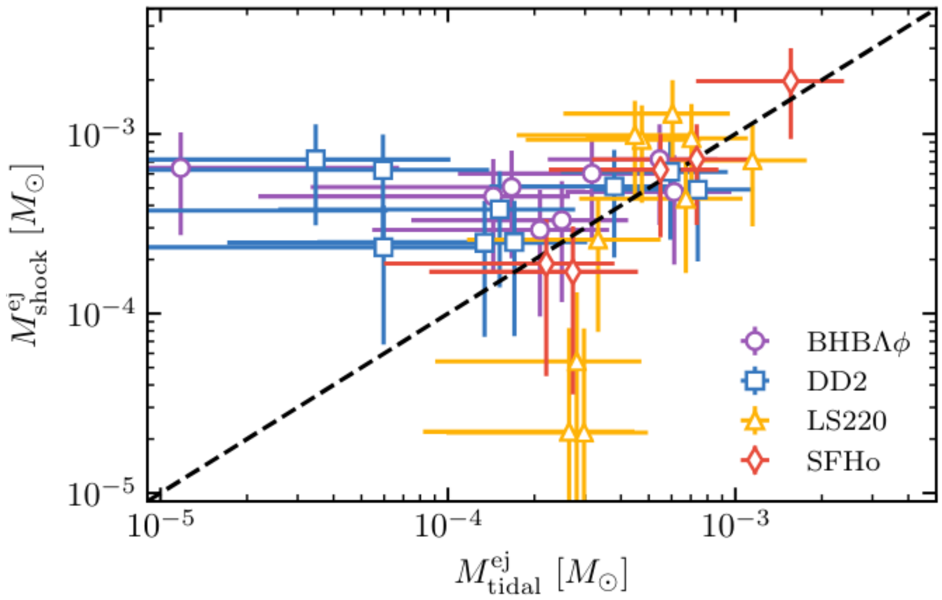
Radice+ [https://arxiv.org/abs/1809.11161]



# Dynamical ejecta

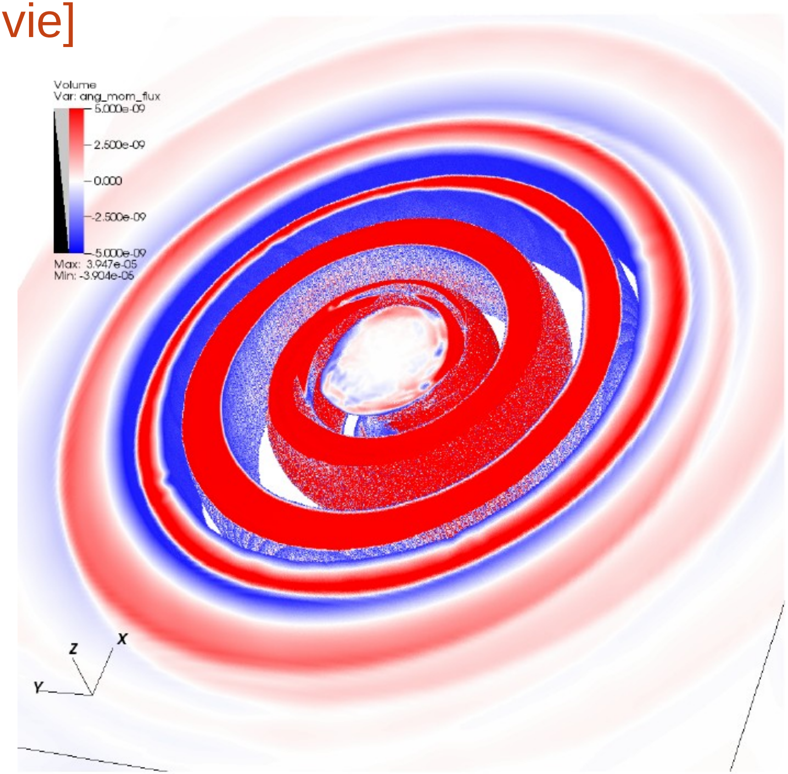




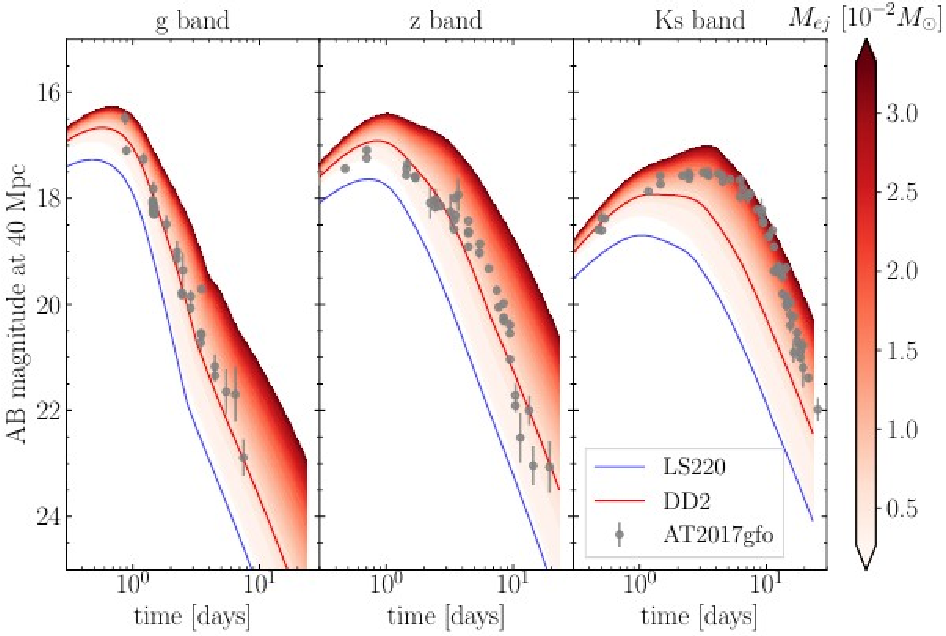


# Spiral-wave wind

[Movie]



Timescale > 10s postmerger
Mass ~ 0.005 - 0.01Mo



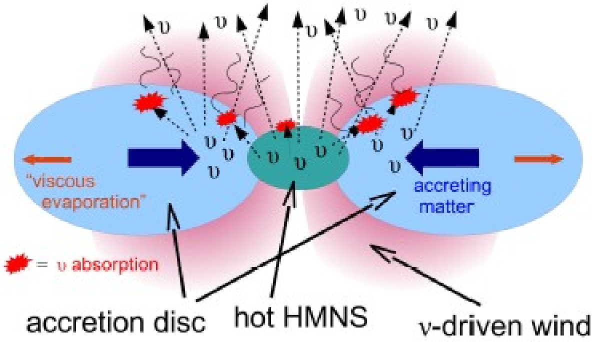
[Nedora, SB+ https://arxiv.org/abs/1907.04872 ]

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

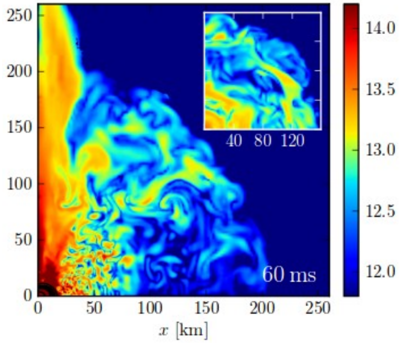
# Remnant evolution on viscous timescale

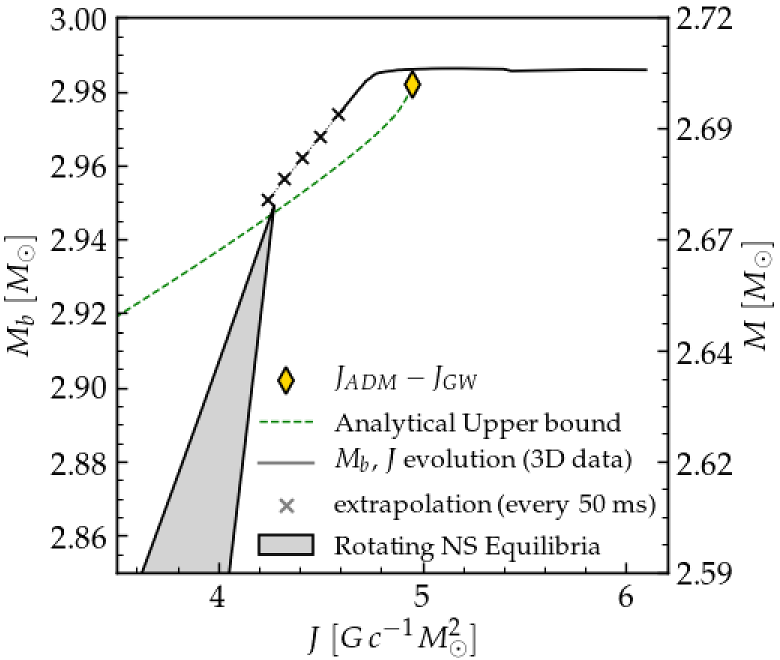
- Angular momentum (“super-Keplerian) and mass in excess
- Evolution governed by neutrino cooling and viscous processes (magnetic turbulence & stresses, neutrino heating, etc)
- Nuclear recombination → Massive winds

[Perego+ 2014]



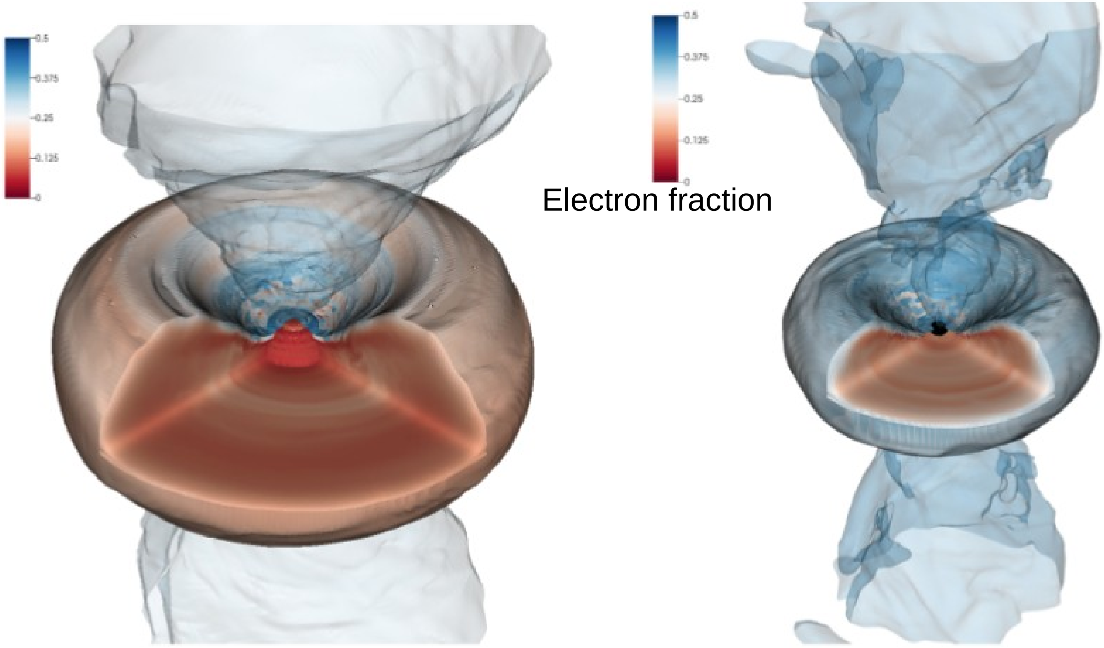
[Siegel+ 2014]



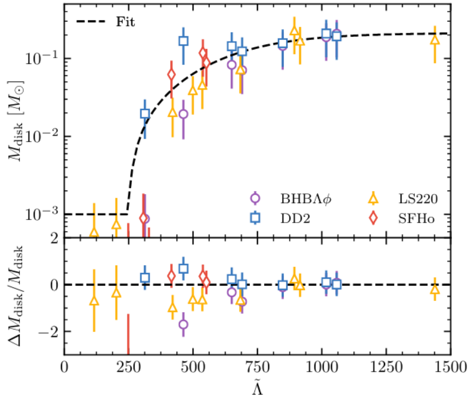


[Radice, Perego, SB, Zhang MNRAS 2018]
[Nedora, SB+ https://arxiv.org/pdf/2008.04333]

# Discs around NS and BH remnants



Perego, SB, Radice [ https://arxiv.org/abs/1903.07898 ]



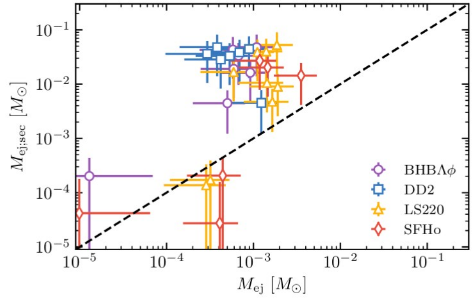
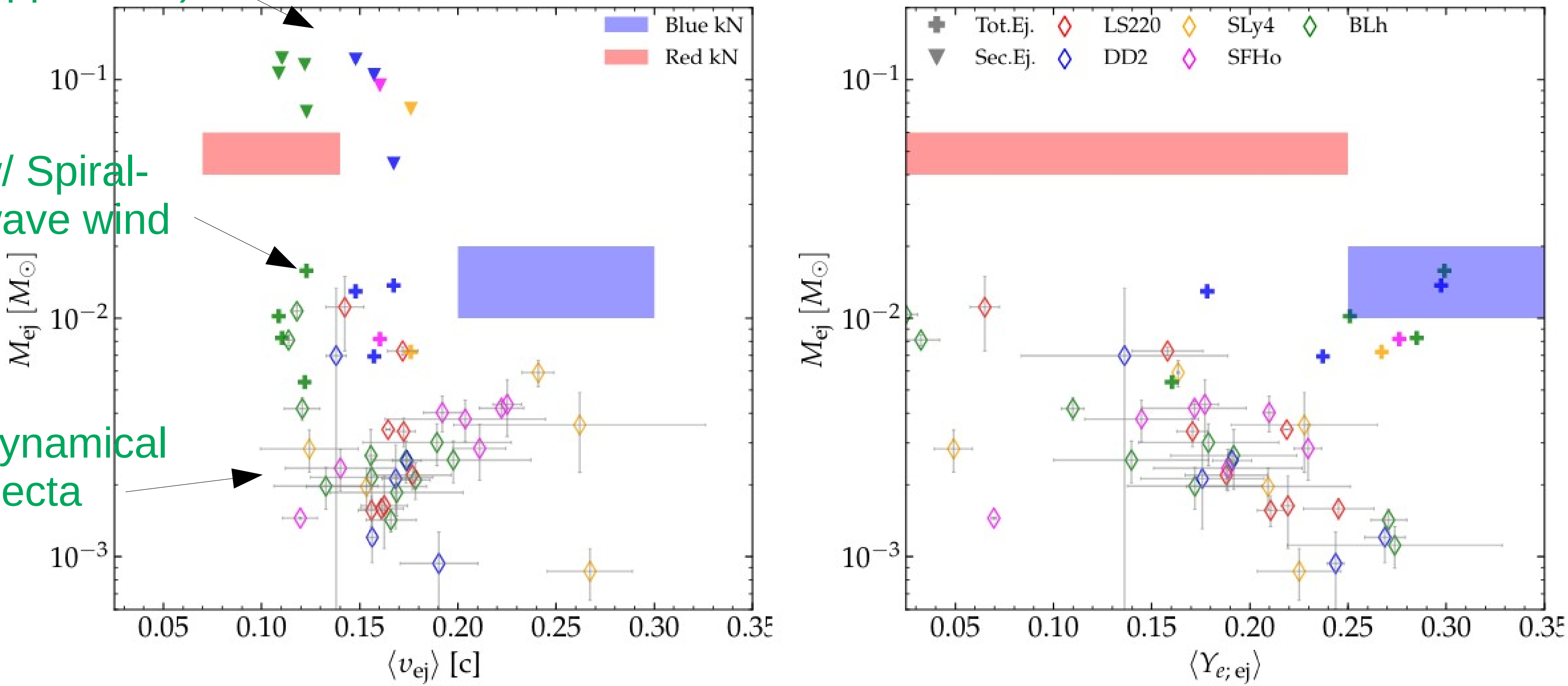


**Figure 16.** Dynamical ejecta $M_{\rm ej;dyn}$ versus secular ejecta masses $M_{\rm ej;sec}$. With the exception of the prompt BH formation cases that are able to expel at least a few $10^{-4}\,M_\odot$ in dynamical ejecta, the secular ejecta dominate over the dynamical ejecta.

- Winds from discs: Lee+ 2009, Fernandez+ 2013, Metzger+ 2014, Siegel+ 2014, ... , Fujibaiashi+, Kiuchi+ 2020
- Disc masses can be estimated from the reduced tidal parameter Λ (EOS-insensitive relation) [Radice,Perego+ 2018]

# AT2017gfo & targeted simulations



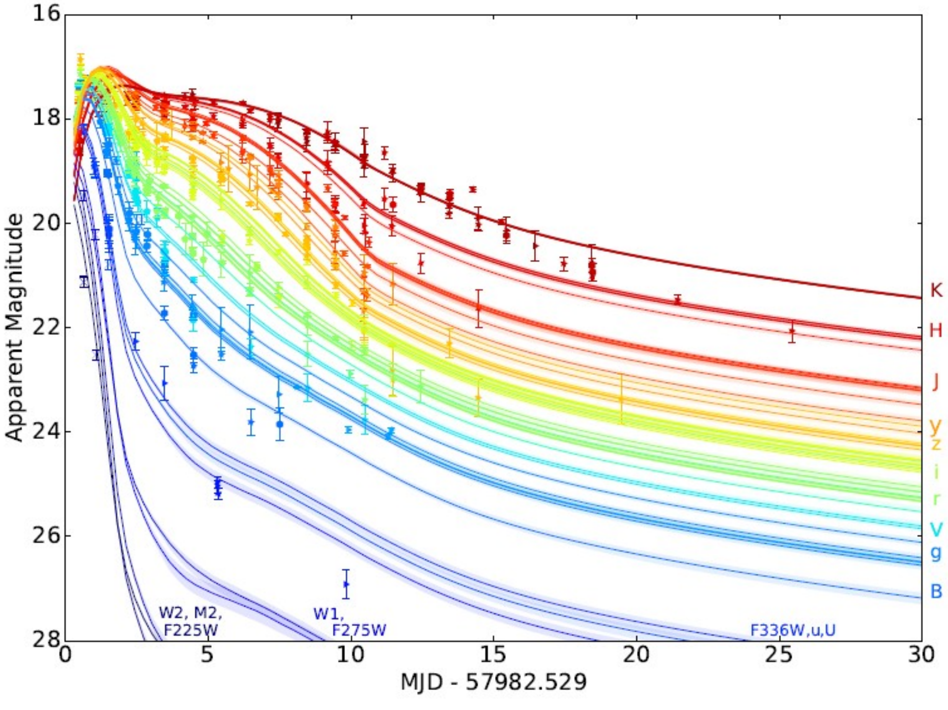
Disc wind
(upper limit)

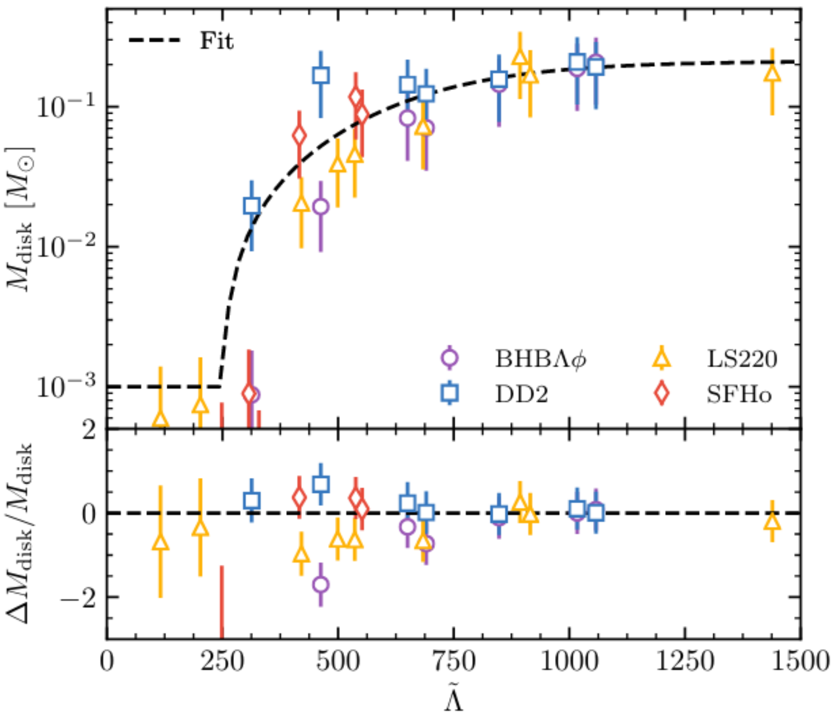
w/ Spiral-wave wind

Dynamical ejecta

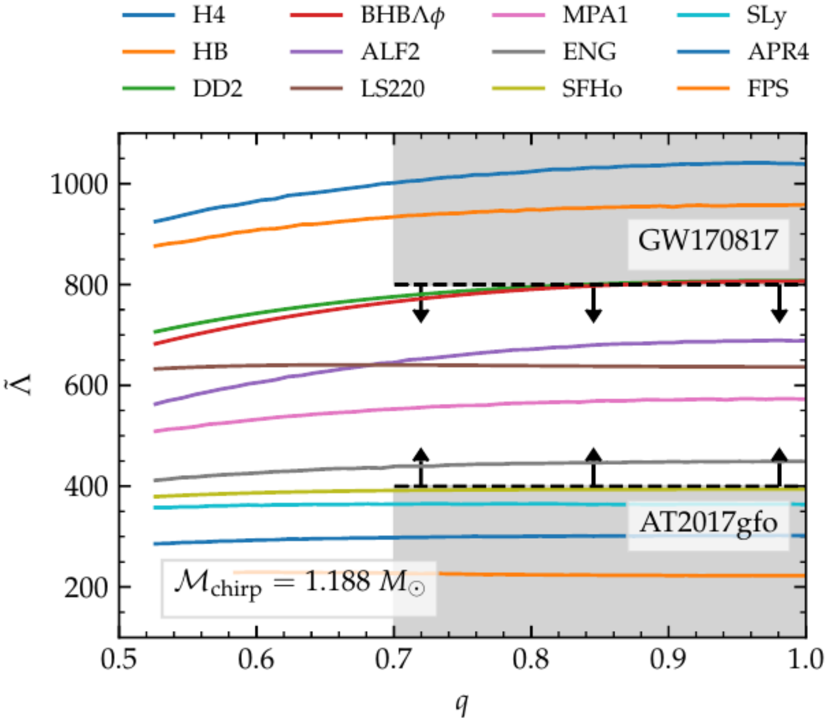
Need at least two components high/low opacities (tentatively ~ dynamical ejecta+ winds ?)
Spherical two-component models are incompatibile with NR ejecta

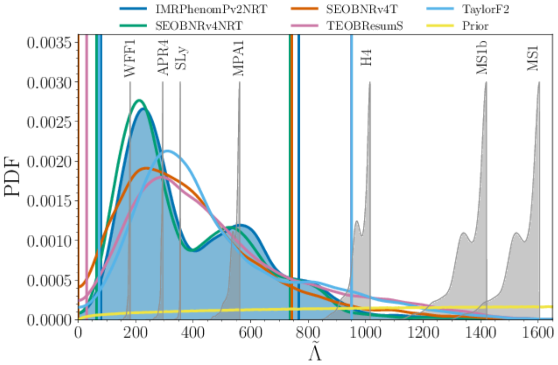
# AT2017gfo requires disk formation, and thus constrains the reduced tidal parameter



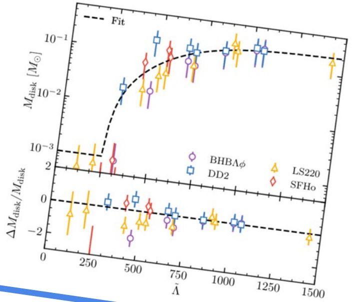


# Joint analyses to maximize science output

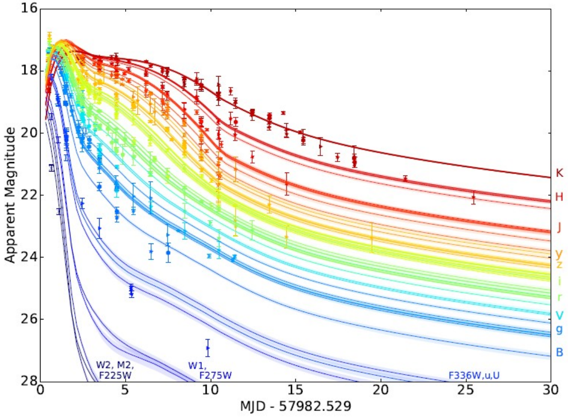




waveform modeling

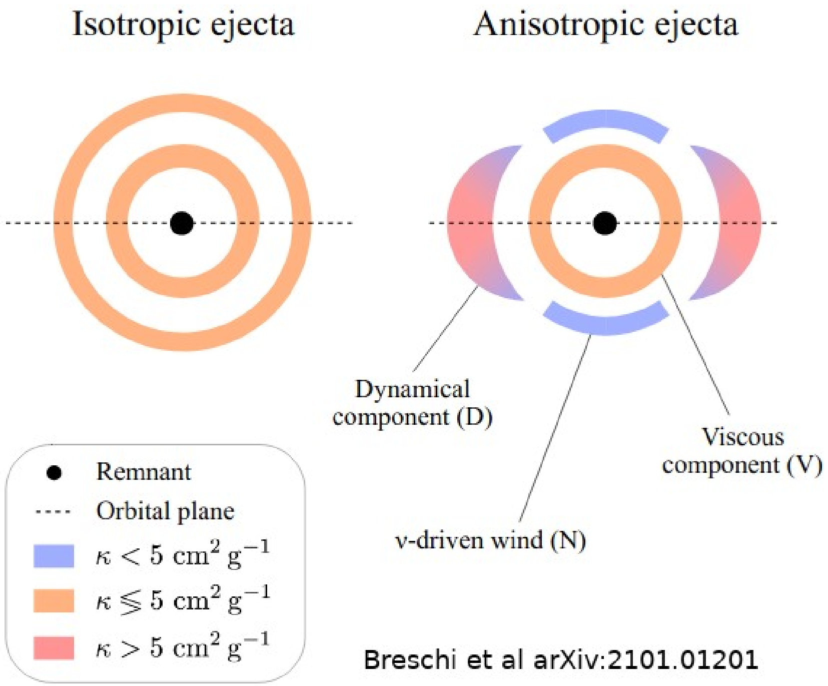


simulations

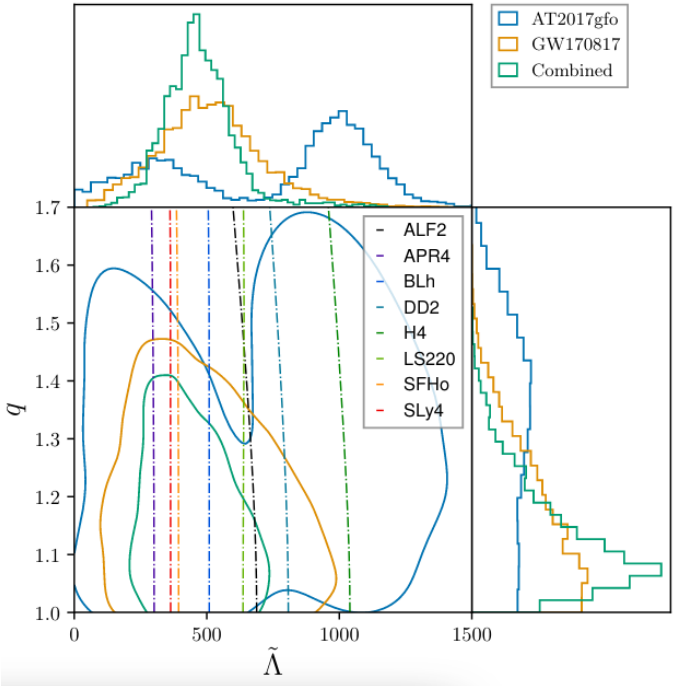


Radice,Perego,Zappa,SB [ https://arxiv.org/abs/1711.03647 ]

# AT2017gfo Bayesian inference



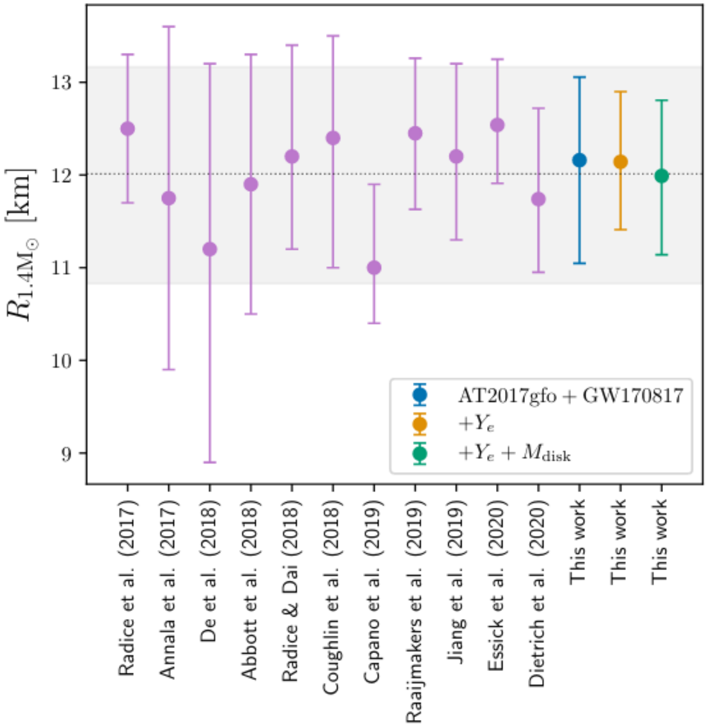
Breschi et al arXiv:2101.01201



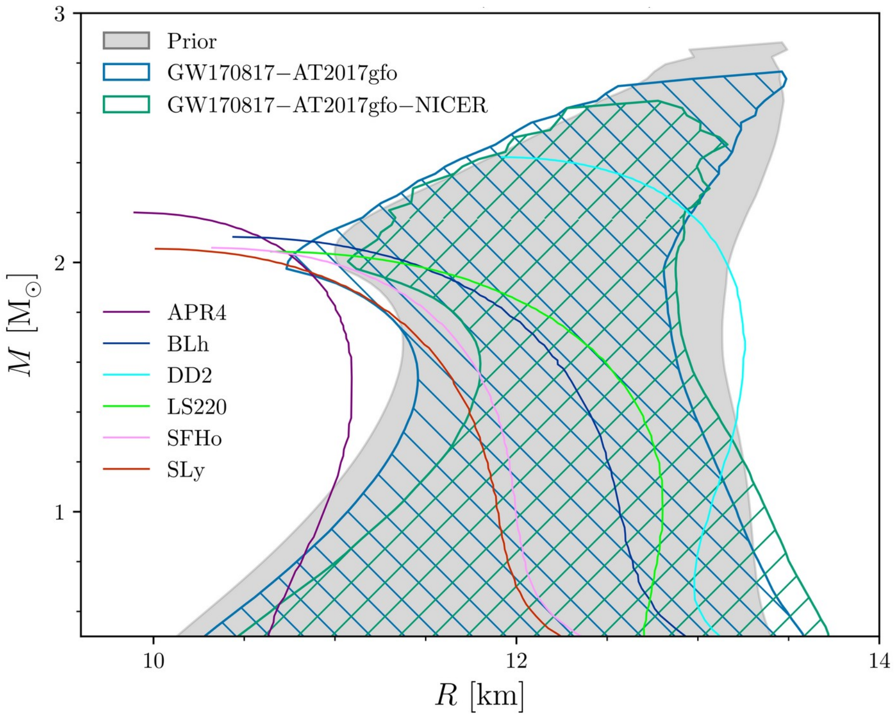
Bayesian model selection: 3-components + anisotropic models preferred
Breschi+ [https://arxiv.org/abs/2101.01201]

# Constraints on EOS after GW170817

NS radius GW170817+AT2017gfo
$R_{1.4} = 12.2^{+0.5}_{-0.5}$km



Breschi+ [https://arxiv.org/abs/2101.01201]



NS radius measurement w/ NICER
$R_{1.4} = 12.3^{+0.7}_{-0.7}$km

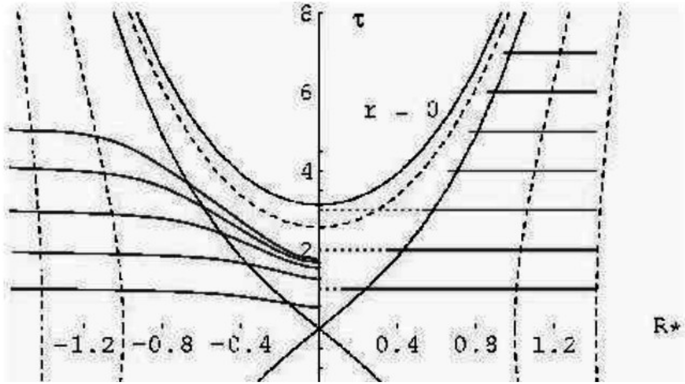
# Summary /4

- Multi-messenger (joint) observations of GW+EM can improve EOS constraints
- Example: kilonova
  - Produced by neutron-rich mass ejection (notably remnant winds)
  - Light curves and spectra can (to some extend) be connected to binary parameters (= GWs parameters) →
  - Joint inference and complementary information
- Current constraints not much constraining … but more observations to come!
- Watch out: this program requires detailed understanding of multi-scale ad multi-physics processes→ simulations, atomic/nuclear input and observations should progress together

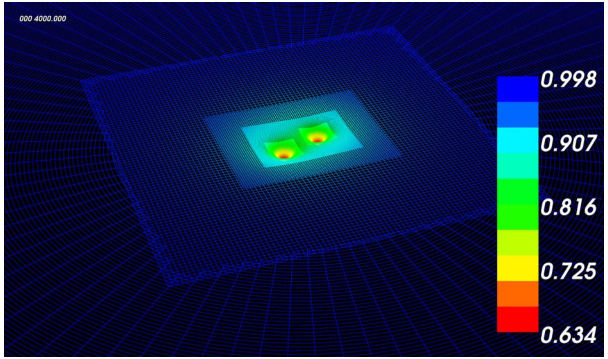
multi-messenger relativistic astrophysics is multi-disciplinary !

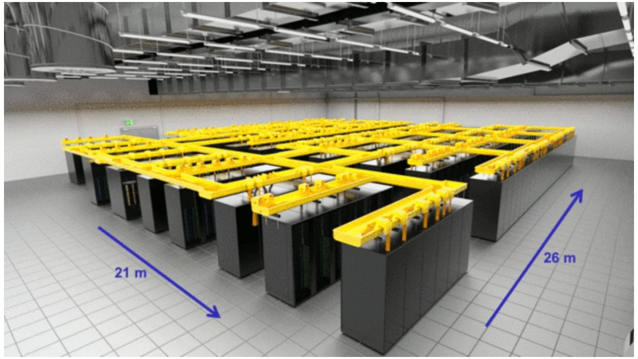
# Backup slides

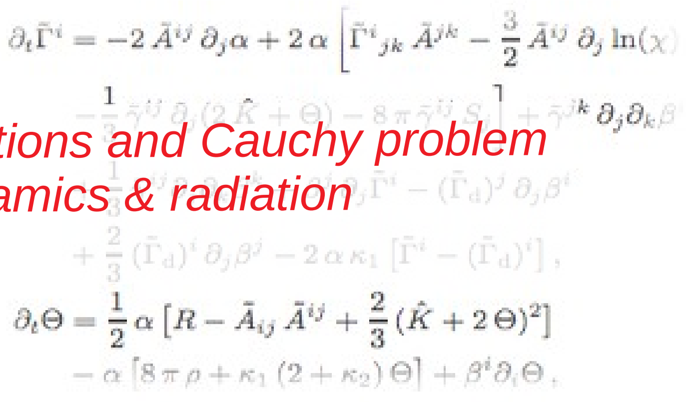
$$
\begin{aligned}
\partial_t \tilde{\Gamma}^i = & -2\,\tilde{A}^{ij}\,\partial_j\alpha + 2\,\alpha\left[\tilde{\Gamma}^i{}_{jk}\,\tilde{A}^{jk} - \frac{3}{2}\,\tilde{A}^{ij}\,\partial_j \ln(\chi)\right.\\
& \left. - \frac{1}{3}\,\tilde{\gamma}^{ij}\,\partial_j(2\,\hat{K} + \Theta) - 8\,\pi\,\tilde{\gamma}^{ij}\,S_j\right]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



# Numerical relativity in a nutshell







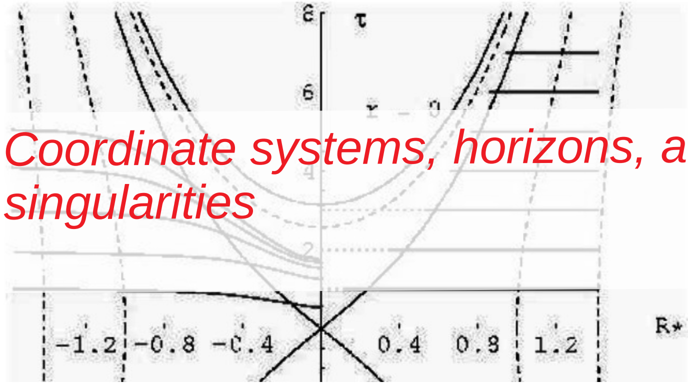
$$\partial_t\tilde\Gamma^i = -2\,\tilde A^{ij}\,\partial_j\alpha + 2\,\alpha\left[\tilde\Gamma^i{}_{jk}\,\tilde A^{jk} - \frac{3}{2}\,\tilde A^{ij}\,\partial_j\ln(\chi\right.$$

$$\left.-\frac{1}{3}\,\tilde\gamma^{ij}\,\partial_j(2\,\hat K + \Theta) - 8\,\pi\,\tilde\gamma^{ij}\,S_j\right] + \tilde\gamma^{jk}\,\partial_j\partial_k\beta$$

$$+\frac{2}{3}\,(\tilde\Gamma_d)^i\,\partial_j\beta^j - 2\,\alpha\,\kappa_1\left[\tilde\Gamma^i - (\tilde\Gamma_d)^i\right],$$

$$\partial_t\Theta = \frac{1}{2}\,\alpha\left[R - \tilde A_{ij}\,\tilde A^{ij} + \frac{2}{3}\,(\hat K + 2\,\Theta)^2\right] - \alpha\left[8\,\pi\,\rho + \kappa_1\,(2+\kappa_2)\,\Theta\right] + \beta^i\partial_i\Theta\,.$$

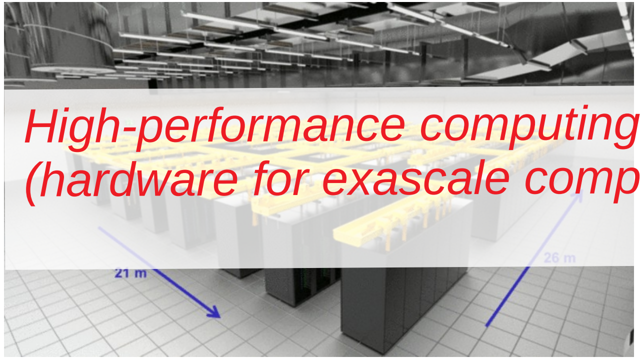
*GR formulations and Cauchy problem*
*+ hydrodynamics & radiation*



*Coordinate systems, horizons, and*
*singularities*

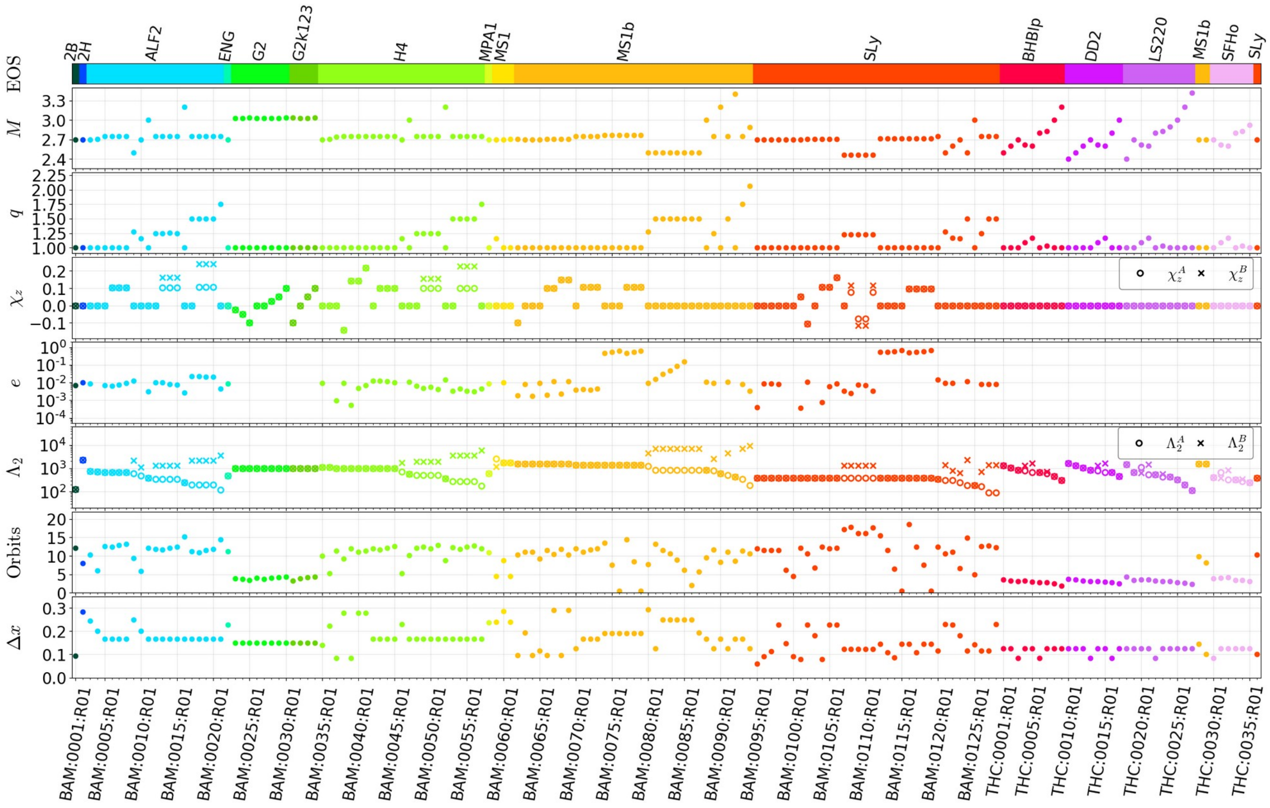
# Numerical relativity in a nutshell

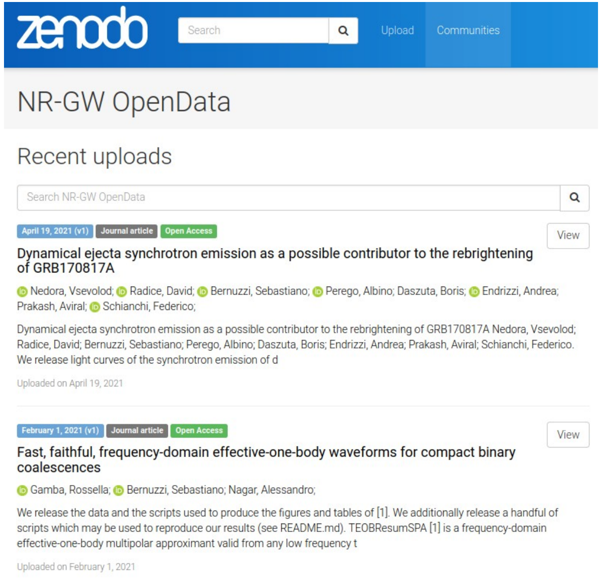
*Numerics for nonlinear PDEs*
*Adaptive mesh for multiscale simulations*



*High-performance computing*
*(hardware for exascale computing)*

# Public data release





NR-GW OpenData

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