1st TEONGRAV international workshop on the
Theory of Gravitational Waves

Modeling the full spectrum of Gravitational waves from BNS

Rossella Gamba
Rome, 20/09/2024

Outline

- **Gravitational waves from BNS Mergers**
    - Matter effects
    - Inspiral models
    - Post-merger models

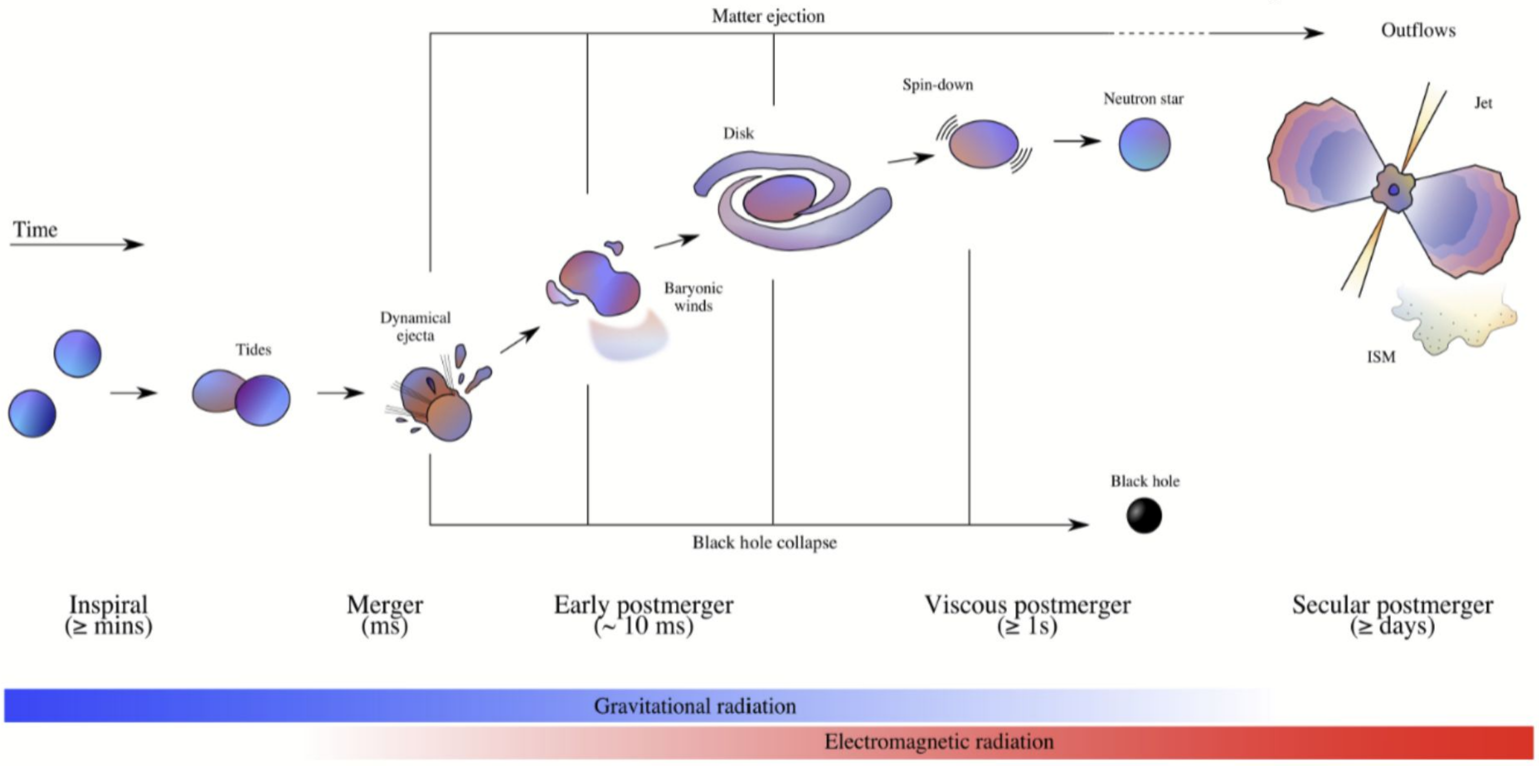
- **What’s next?**
    - Challenges
    - Developments

Part 1: Gravitational waves from BNSs

Matter effects, models and all that

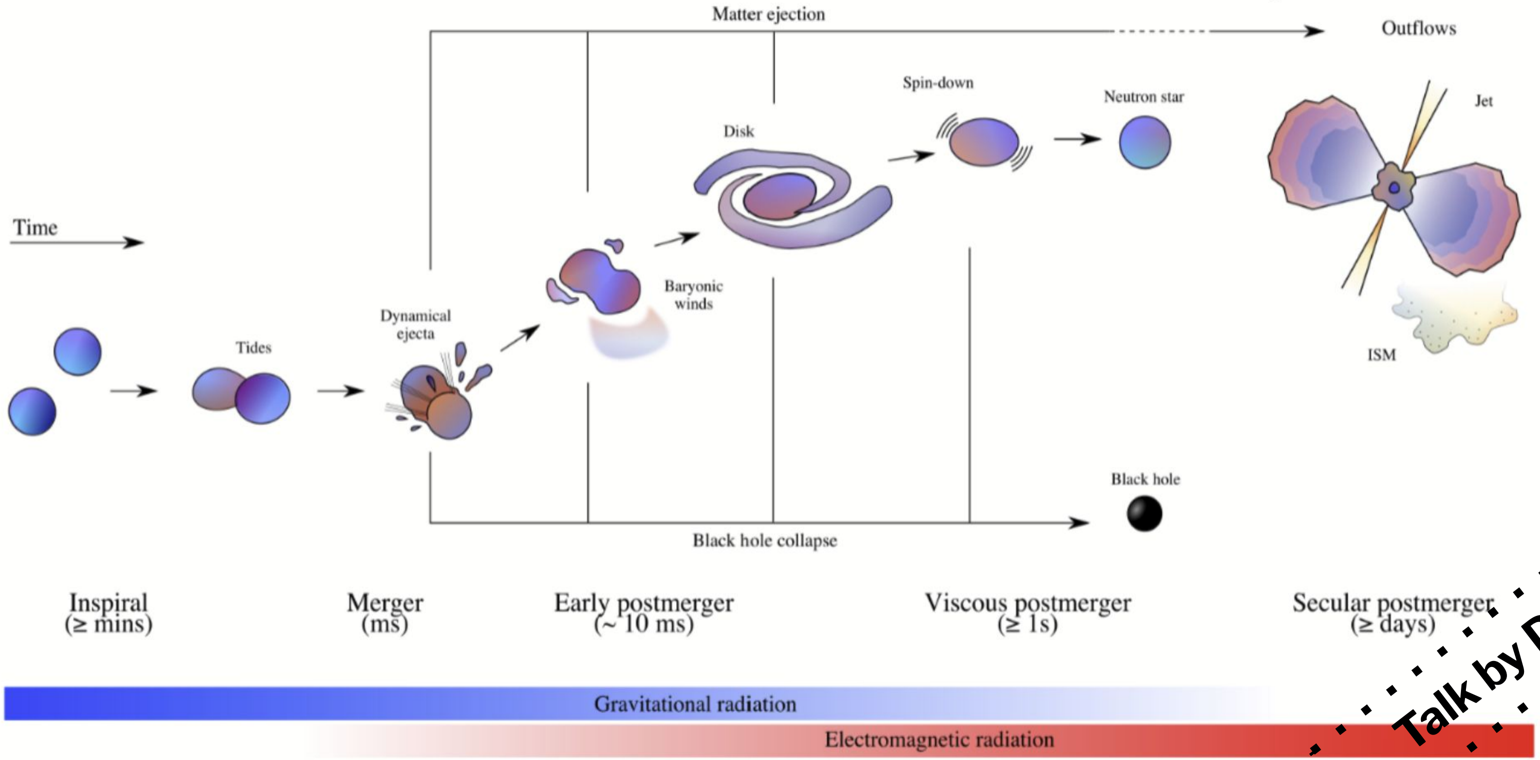
Phenomenology of a merger

Image Credits: Matteo Breschi



Phenomenology of a merger

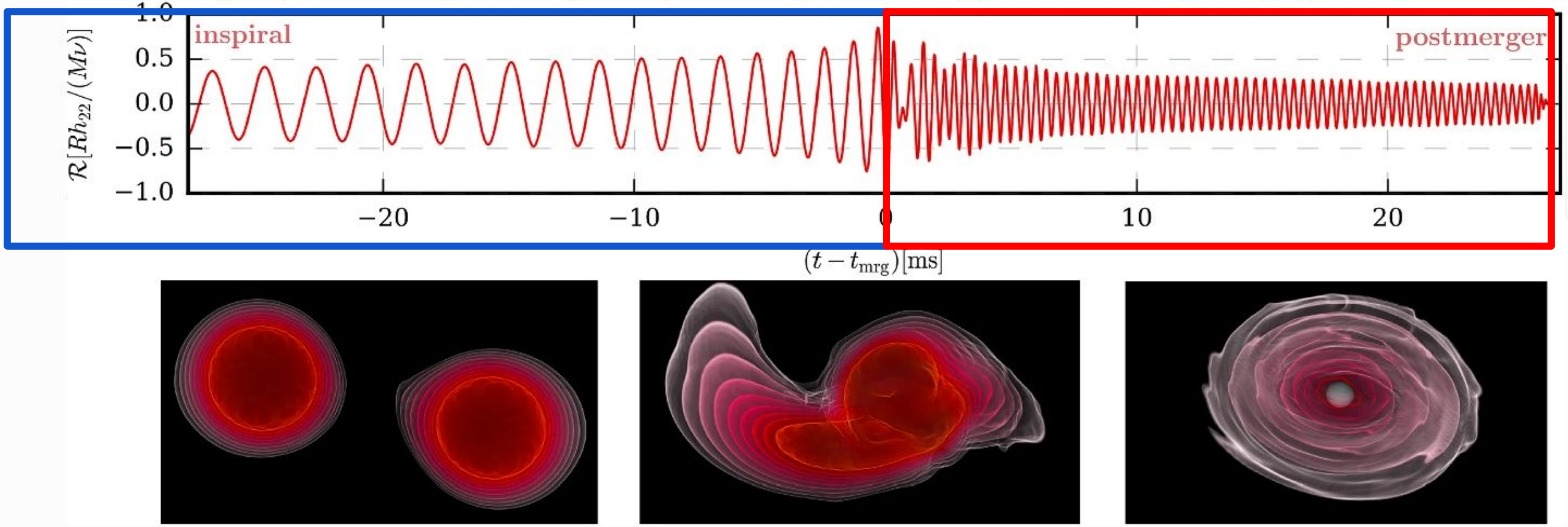
Image Credits: Matteo Breschi



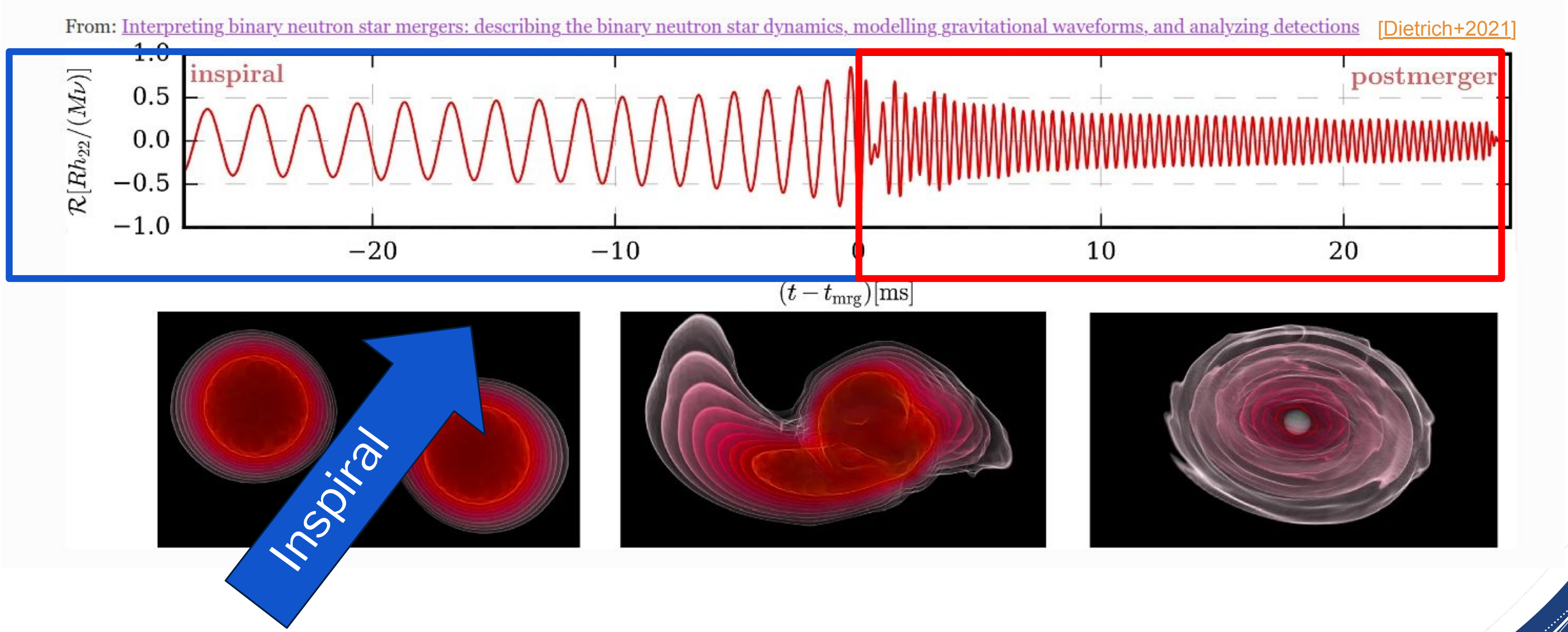
Talk by Daniel

Phenomenology of a merger: GWs

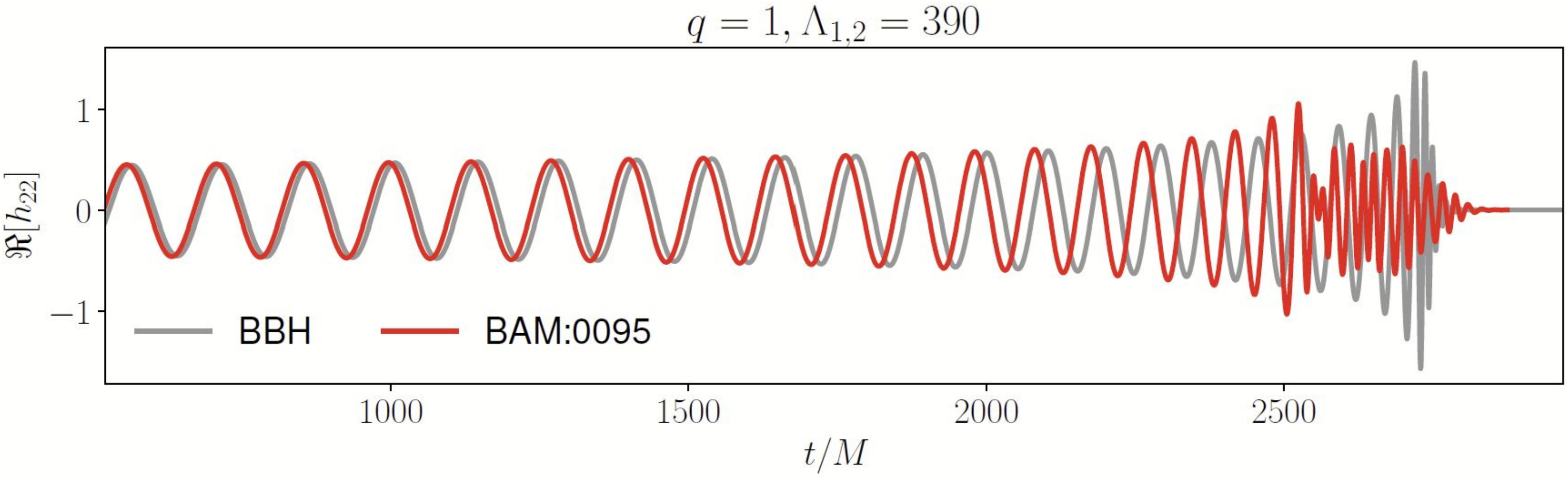
From: Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections [Dietrich+2021]



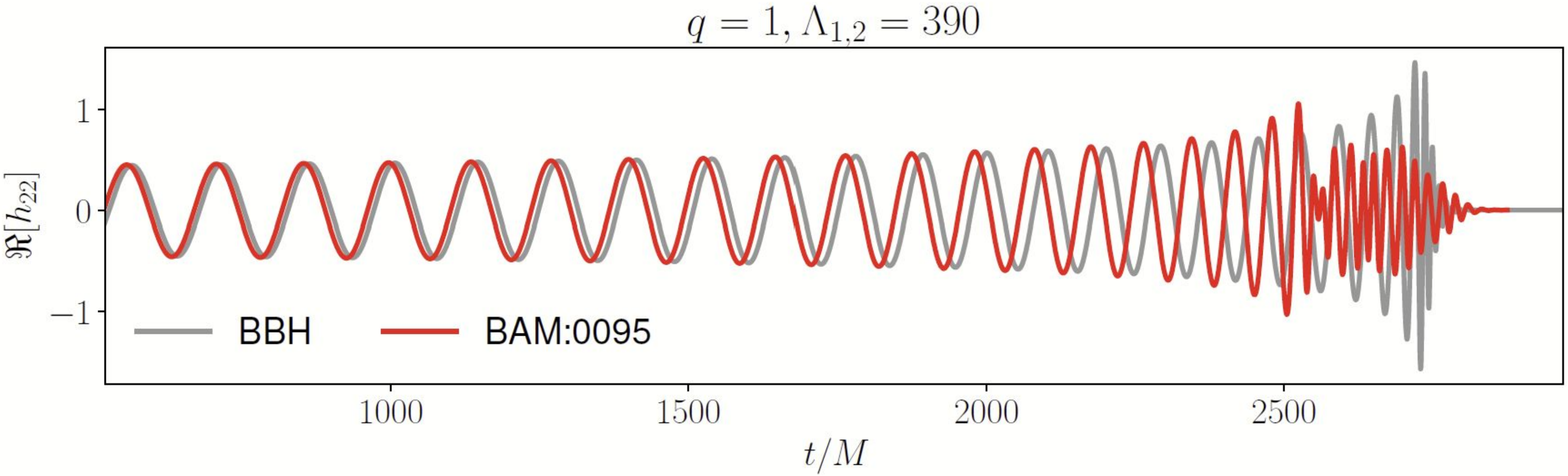
Phenomenology of a merger: GWs


From: Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections [Dietrich+2021]

Inspiral: matter effects



Inspiral: matter effects



BBH + **(some kind of correction)** = **BNS ?**

Inspiral: matter effects

Corrections = Matter effects. They are what distinguish NS from **point particles**.

- **Tidal effects:**
  - “**Adiabatic**” tidal effects $(\Lambda_\ell, \Sigma_\ell)$ [Damour1983,Flanagan+2007,Damour+2008,Vines+2010,Henry+2020,Mandal+24]
  - “**Dynamical**” tidal effects $(\bar{\omega}_f)$ [Lai+1994, Hinderer+2016, Steinhoff+2016, Steinhoff+2021]
- **Spin induced effects** $(C_{\rm q}, C_{\rm oct}, C_{\rm hex}, \dots)$ [Poisson1998, Krishnendu+2017]
- **Other effects**: nonlinear mode couplings, other modes resonances and excitations, crust shattering, dissipative effects … [Ho+1999, Tsang+2013, Andersson+2017, Ripley+24, …]

All of the above coefficients depend on the **Equation of State** (EOS):

$$(m, \mathrm{EOS}) \to (\Lambda_\ell, \Sigma_\ell, \dots)$$

Talk to Micaela

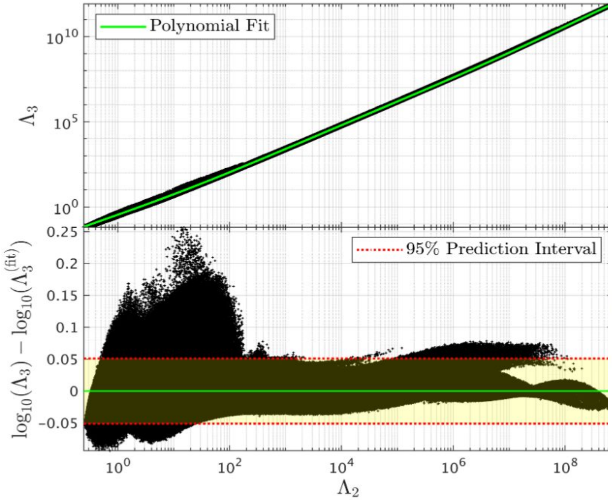
What we’d like: $$(m, \Lambda_\ell, \Sigma_\ell, \dots) \to \mathrm{EOS}$$

Inspiral: matter effects

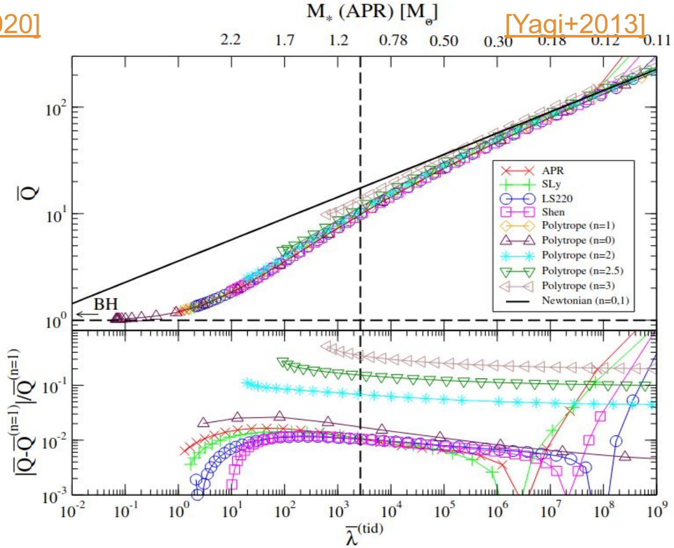
Various matter effects are not (entirely) independent from one-another: **quasi-universal relations**

$$\Lambda_2 \rightarrow (\Lambda_\ell, \Sigma_\ell, C_{\rm q}, C_{\rm oct}, \bar{\omega}_f, \dots)$$

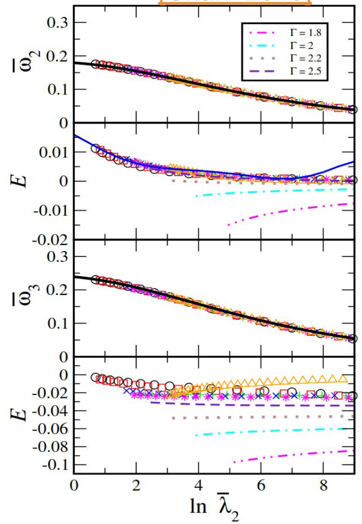
[Godzieba+2020]



[Yagi+2013]



[Chan+2015]



Inspiral: matter effects

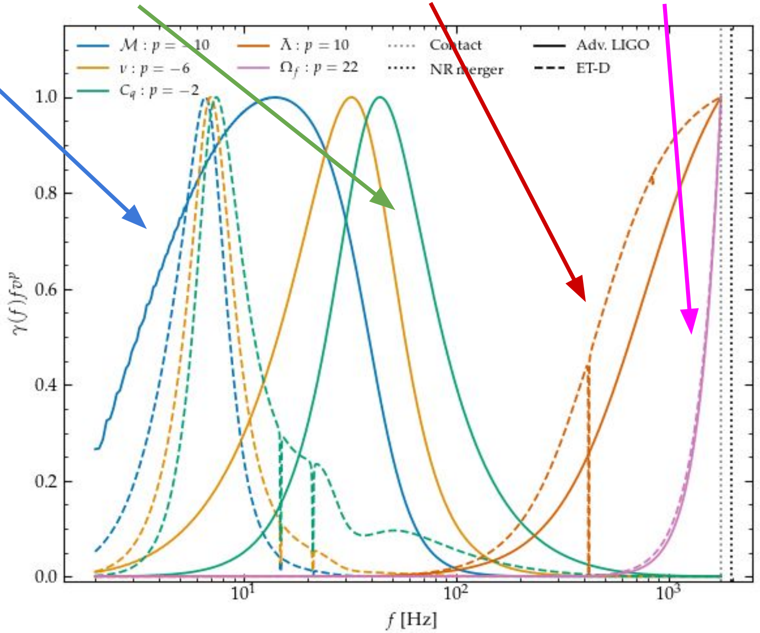
$$\Psi(x) = 2\pi f t_c - \phi_c - \pi/4 + \boxed{\frac{3}{128\nu}x^{-5/2}\Big[1} + \dots + \boxed{x^2 C_q c_{MQ}} + \dots + \boxed{x^5 \tilde{\Lambda} c_{\Lambda}} + \dots + \boxed{x^8 \frac{c_{dyn}}{\Omega^2_{\Lambda,f}}} + \dots \Big]$$

0 PN **2 PN** **5 PN**

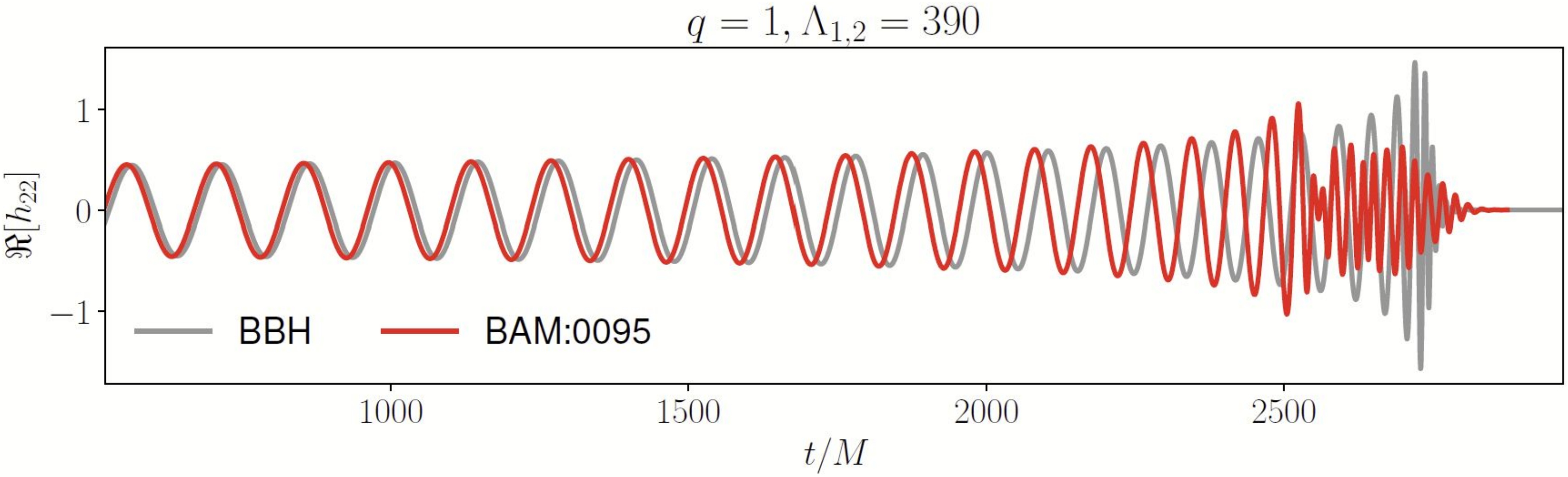
- Matter effects are a high-frequency correction:
  - Tidal effects are important above ~300 Hz
  - f-mode (most) relevant above 1kHz

- Current detectors are not very sensitive in those regions

→ **Hard to measure**

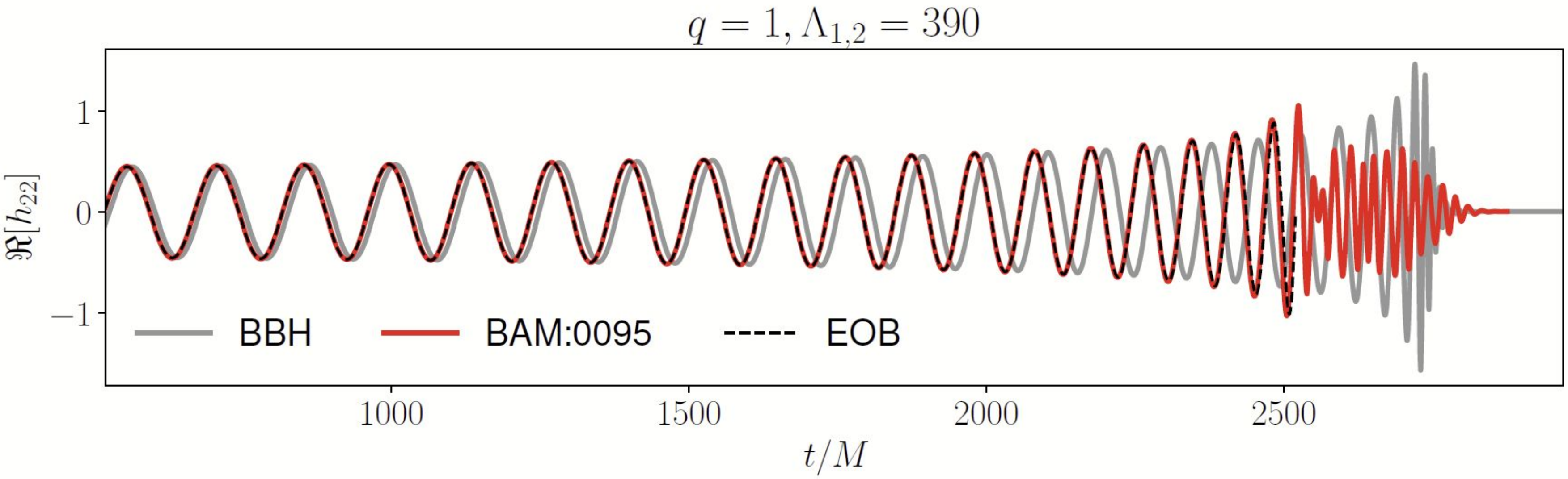


Inspiral: matter effects



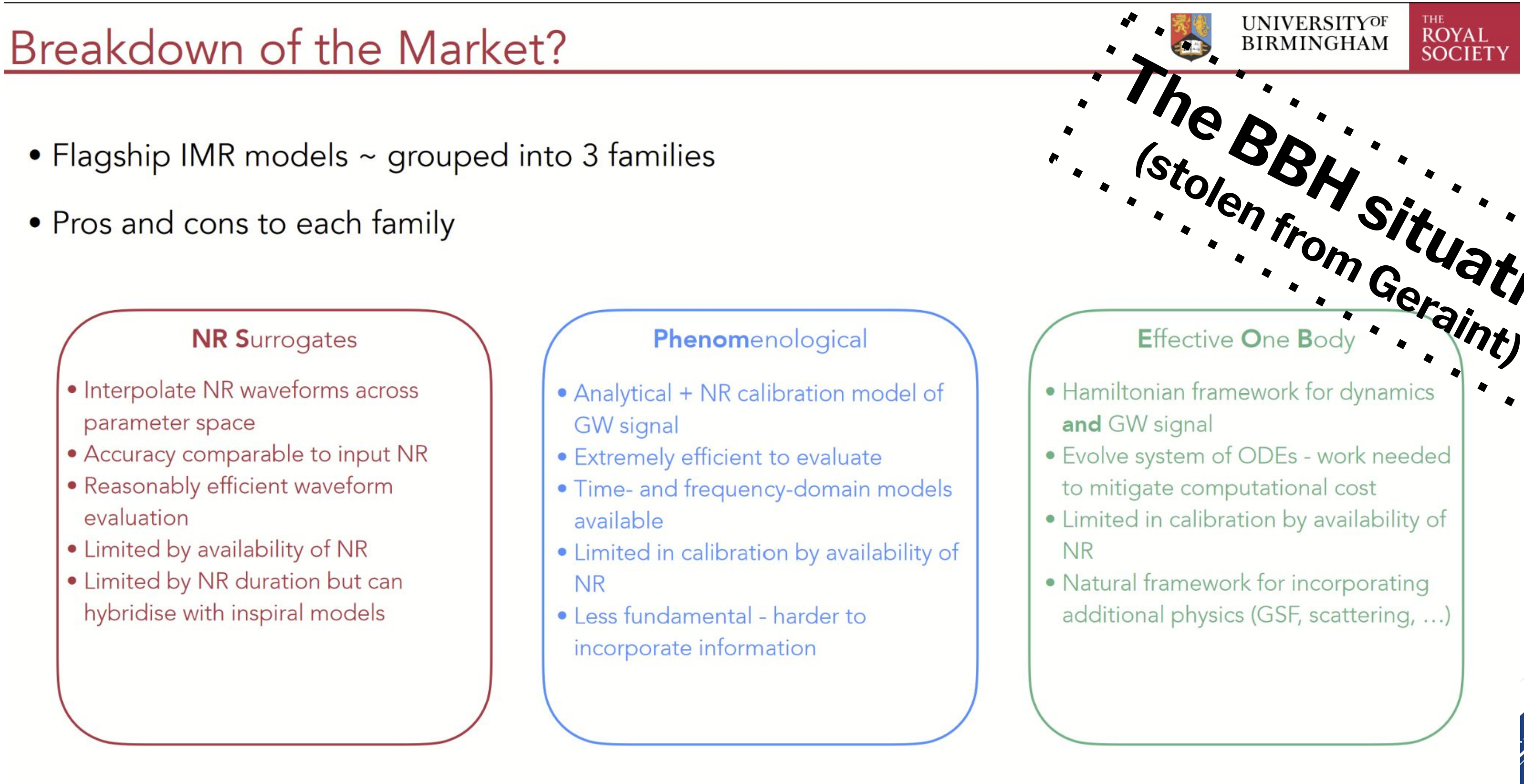
BBH + **(some kind of correction)** = **BNS ?**

Inspiral: matter effects



BBH + 2PN adiabatic conservative, 2PN adiabatic dissipative, Spin-induced moments = **BNS !**

Inspiral models



Breakdown of the Market?

UNIVERSITY OF BIRMINGHAM

THE ROYAL SOCIETY

- Flagship IMR models ~ grouped into 3 families
- Pros and cons to each family

NR Surrogates

- Interpolate NR waveforms across parameter space
- Accuracy comparable to input NR
- Reasonably efficient waveform evaluation
- Limited by availability of NR
- Limited by NR duration but can hybridise with inspiral models

Phenomenological

- Analytical + NR calibration model of GW signal
- Extremely efficient to evaluate
- Time- and frequency-domain models available
- Limited in calibration by availability of NR
- Less fundamental - harder to incorporate information

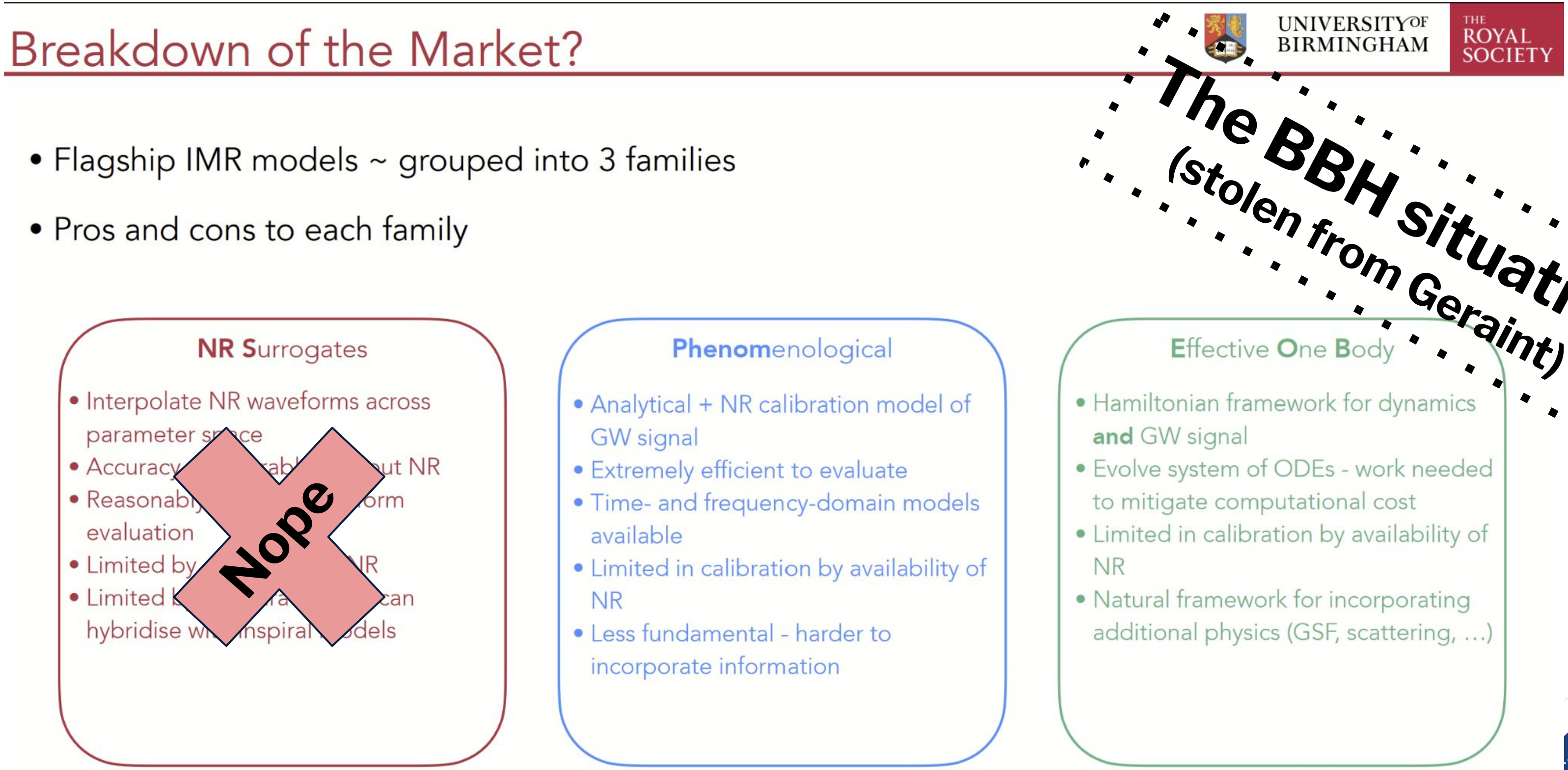
Effective **O**ne **B**ody

- Hamiltonian framework for dynamics **and** GW signal
- Evolve system of ODEs - work needed to mitigate computational cost
- Limited in calibration by availability of NR
- Natural framework for incorporating additional physics (GSF, scattering, …)

The BBH situation

(stolen from Geraint)

Inspiral models



The BBH situation
(stolen from Geraint)

Breakdown of the Market?

UNIVERSITY OF BIRMINGHAM
THE ROYAL SOCIETY

- Flagship IMR models ~ grouped into 3 families
- Pros and cons to each family

NR Surrogates

- Interpolate NR waveforms across parameter sp ce
- Accuracy abl ut NR
- Reasonabl orm evaluation
- Limited by IR
- Limited b a can hybridise wi nspiral odels

Nope

Phenomenological

- Analytical + NR calibration model of GW signal
- Extremely efficient to evaluate
- Time- and frequency-domain models available
- Limited in calibration by availability of NR
- Less fundamental - harder to incorporate information

Effective **O**ne **B**ody

- Hamiltonian framework for dynamics **and** GW signal
- Evolve system of ODEs - work needed to mitigate computational cost
- Limited in calibration by availability of NR
- Natural framework for incorporating additional physics (GSF, scattering, …)

Inspiral models

- **Post Newtonian** approximants (PN) [Krishnendu+2017,Henry+2020,Schmidt+2021]
  - Analytical and fast
  - Examples: TaylorF2, TaylorT4

- **Phenomenological** approximants (Phenom) [Dietrich+2017,Kawaguchi+2018,Dietrich+2019,Gamba+23,Williams+2024,Abac+2024]
  - Fits to EOB+NR hybrid waveforms
  - Fast
  - Examples: (any BBH inspiral model) + NRTidalv3, Kawaguchi+, PhenomGSF,...

- **Effective One Body** approximants (EOB) [Bini+2012, Akcay+2018, Lackey+2018, Tissino+22, Gamba+2023]
  - Semi-analytical, resummed PN + NR
  - Not-as-fast, generally, but there exist acceleration techniques (PA, SPA)
  - Examples: TEOBResumS, SEOBNRv4T (& related surrogates)

Inspiral models: Phenom

Simple idea:

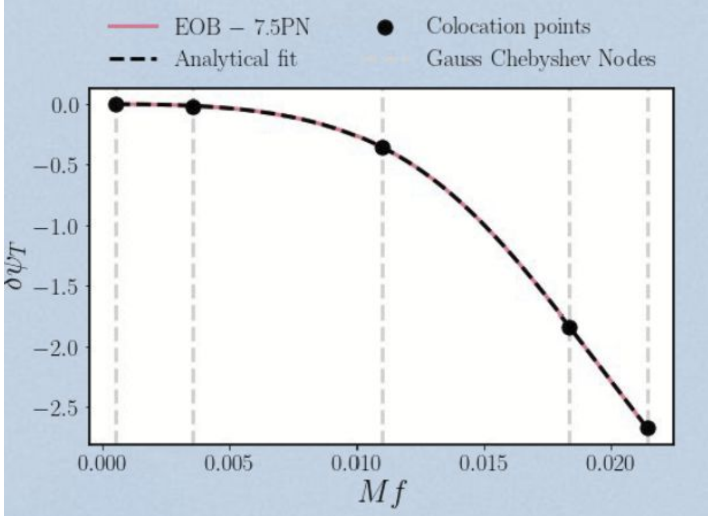
1. Choose your target BNS waveform (EOB + NR, pure EOB, …)
2. Choose your BBH baseline (EOB, NR, Phenom, NR surrogate, …)
3. Separate matter contributions from BBH baseline (both phase and amplitude):

$$\Psi_{\mathrm{BNS}} \sim \Psi_{\mathrm{BBH}} + \Delta\Psi_{\mathrm{matter}}$$
$$\Delta\Psi_{\mathrm{matter}} \sim \Psi_{\mathrm{BNS}} - \Psi_{\mathrm{BBH}}$$

4. Directly **fit** the matter contributions

$$\Delta\Psi_{\mathrm{matter}} \sim \Delta\Psi_{\mathrm{ad.tides}} + \Delta\Psi_{\mathrm{dyn.tides}} + \Delta\Psi_{MQ} + \ldots$$

[Williams+2024]



Example of tidal residual fitted to at discrete points

Talk to Natalie and Adrian

Inspiral models: EOB

Two body problem → test particle around (deformed) Kerr. Three ingredients:

- **Hamiltonian**

$$H_{\rm EOB} = M\sqrt{1+2\nu(\hat{H}_{\rm eff}-1)},$$

$$\hat{H}_{\rm eff} = \sqrt{\boxed{p_{r_*}^2}+\boxed{A(r)}\left(1+\frac{p_\varphi^2}{\boxed{r^2}}+2\nu(4-3\nu)\frac{p_{r_*}^4}{r^2}\right)}$$

- **Waveform**

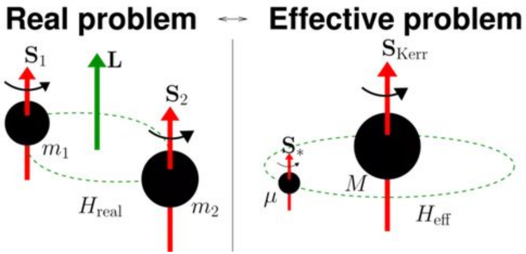
$$h_{\ell m} = h_{\ell m}^{(N,\epsilon)}\hat{S}_{\rm eff}^{(\epsilon)}\hat{h}_{\ell m}^{\rm tail}f_{\ell m}\boxed{\hat{h}_{\ell m}^{\rm NQC}}$$

$$h_{\ell m} = h_{\ell m}^0 + \boxed{h_{\ell m}^T} = h_{\ell m}^{\rm Newt}(\hat{h}_{\ell m}^0 + \hat{h}_{\ell m}^T)$$

- **Radiation Reaction**

$$\dot{p}_\varphi = \hat{\mathcal{F}}_\varphi\ ,$$

$$\dot{p}_{r_*} = \sqrt{\frac{A}{B}}\left(-\partial_r\hat{H}_{\rm EOB}\boxed{+\hat{\mathcal{F}}_r}\right)$$



The Hamiltonian can describe the dynamics along generic orbits

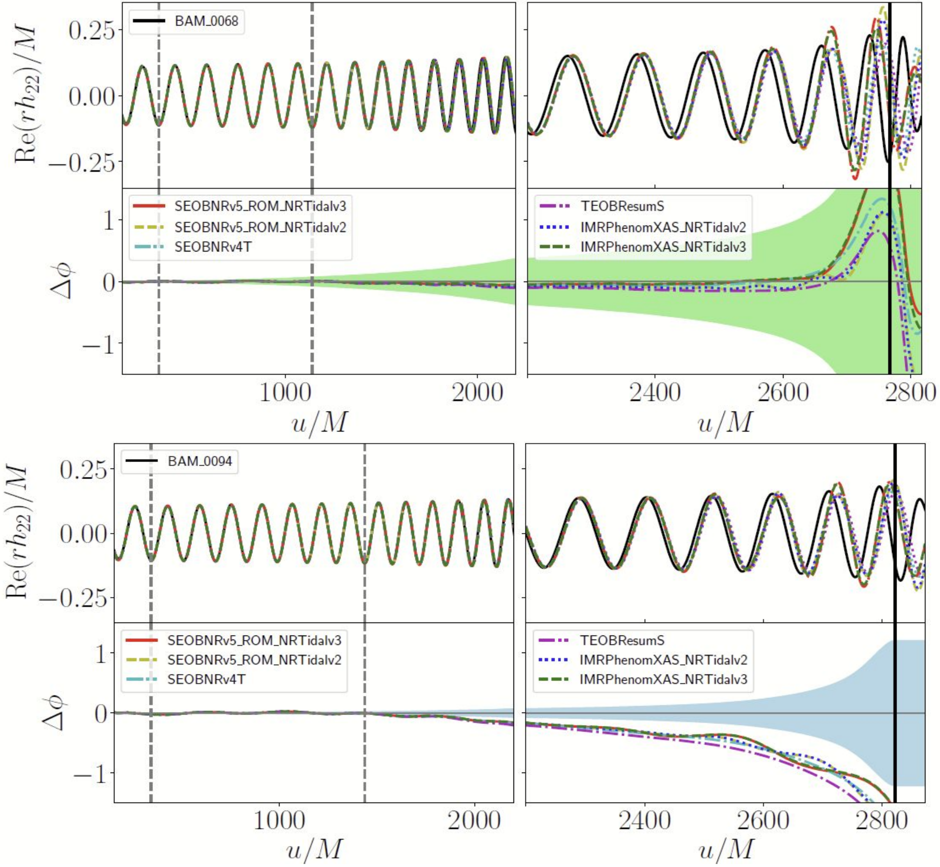
Tidal corrections added to waveform, metric potentials

For BNS systems on quasi-circular orbits, we may not have the terms in squares (depending on the model)

Inspiral models: in a nutshell

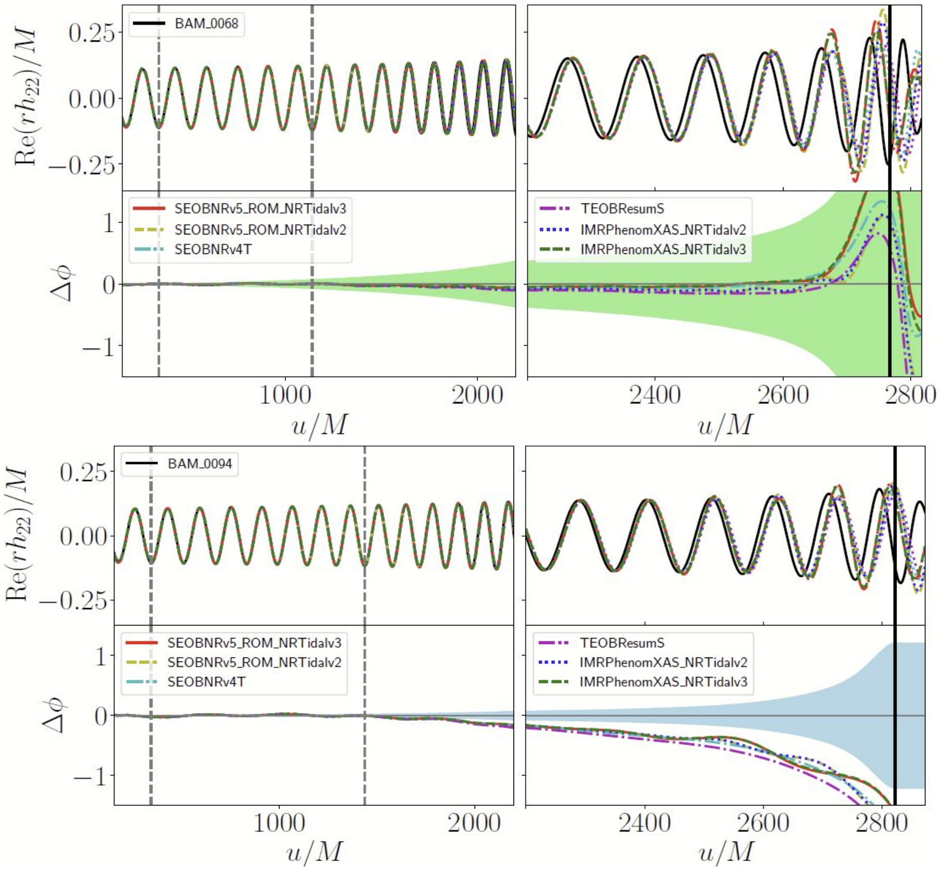
	PN	TEOBResumS	SEOBNRv4T	PhenomGSF	PhenomNRTv3
Adiabatic tides	Cons.3PN Diss. 2PN	Cons. 2.5 PN Diss. 2PN	Cons. 2.5 PN	2.5PN	2.5PN
Dynamic tides	Yes	yes	yes	no(t yet)	yes
self-spin	NNLO	NNLO (resummed)	NNLO (resummed)	no(t yet)	NNLO (PN)
Additional notes	Many more effects	GSF-resummation, ell=2,..,8 electric contributions; ell=2 magnetic contributions; Higher modes in wf; eccentricity; precession	BBH NQC corrections; ell=2,3 electric contributions;	Fits of phase calibrated to TEOBResumS, residual w.r.t. 7.5PN	Fits for phase and amplitude calibrated to EOBNR hybrids, Padé resummed, 55 simulations

Inspiral models: performance



Tides	Mass ratio	Spins	Error @ merger
Moderate (<1000)	equal mass	X	< 1 rad (0.2-0.5)
Large	equal mass	X	~ 1 rad
Moderate (<1000)	Unequal mass	X	~ 1 rad (0.5-1)
Large	Unequal mass	X	> 1 rad
Moderate	Equal mass	yes	> 1 rad, large for larger spins

Inspiral models: performance

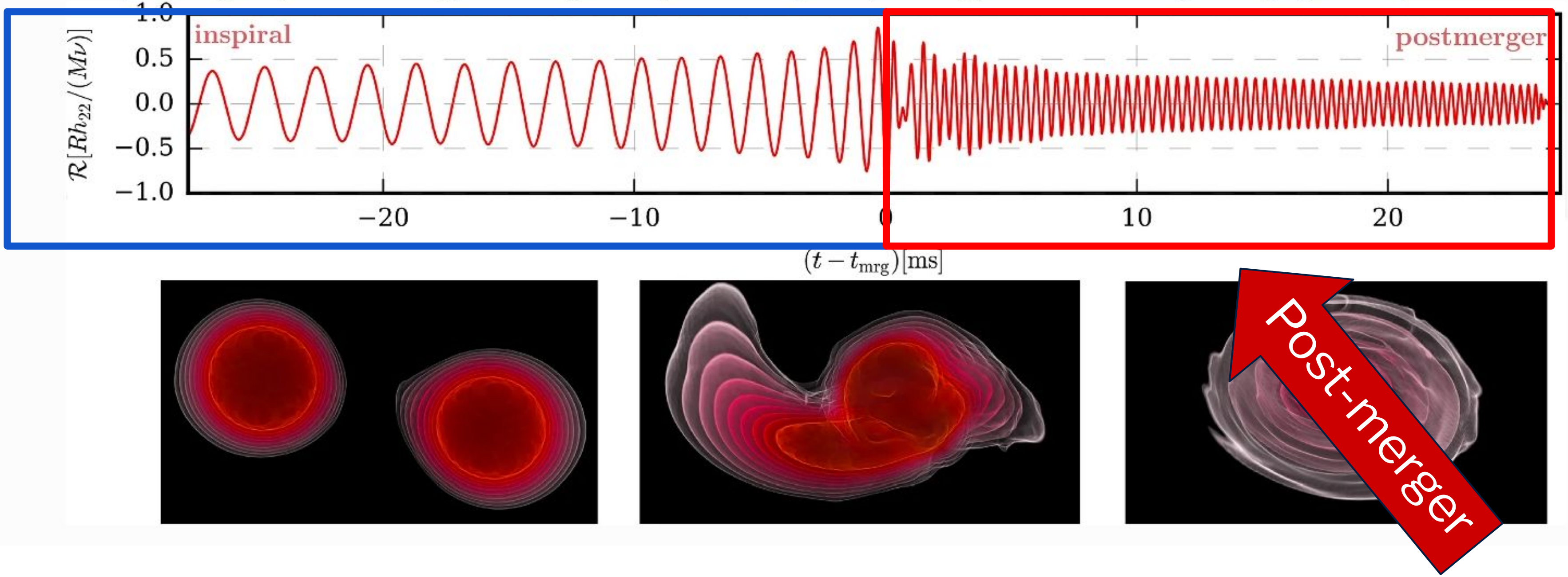


Tides	Mass ratio	Spins	Error @ merger
Moderate (<1000)	equal mass	X	< 1 rad (0.2-0.5)
Large	equal mass	X	~ 1 rad
Moderate (<1000)	Unequal mass	X	~ 1 rad (0.5-1)
Large	Unequal mass	X	> 1 rad
Moderate	Equal	yes	> 1 rad, large for

- Models perform the worst when for large tidal parameters/large spins
- Typical NR error ~1 rad at merger (large!)

Phenomenology of a merger: GWs

From: Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections [Dietrich+2021]

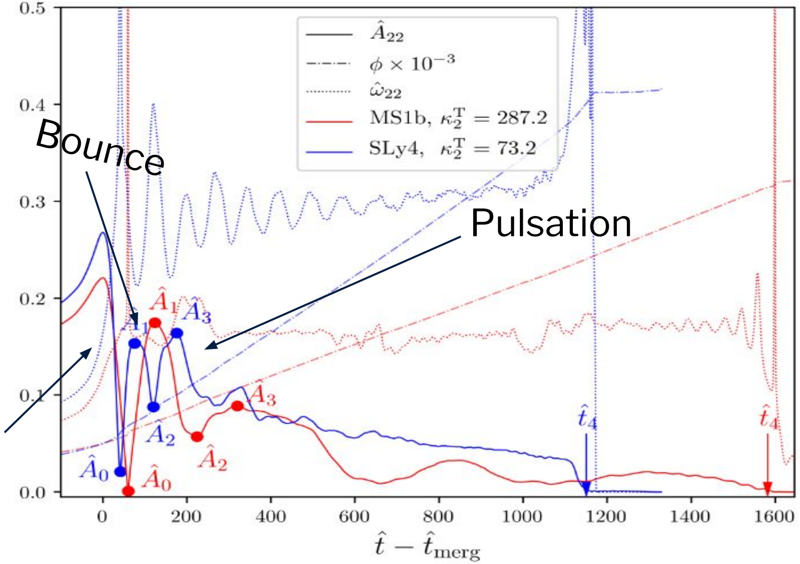


Post-merger: common features

Very high frequency emission (> 1kHz) → **Even harder to measure than inspiral!**
Additionally: complicated post-Merger (B fields, neutrinos, hydro, ...)

→ Look for robust, common features and model those

[Breschi+2019]

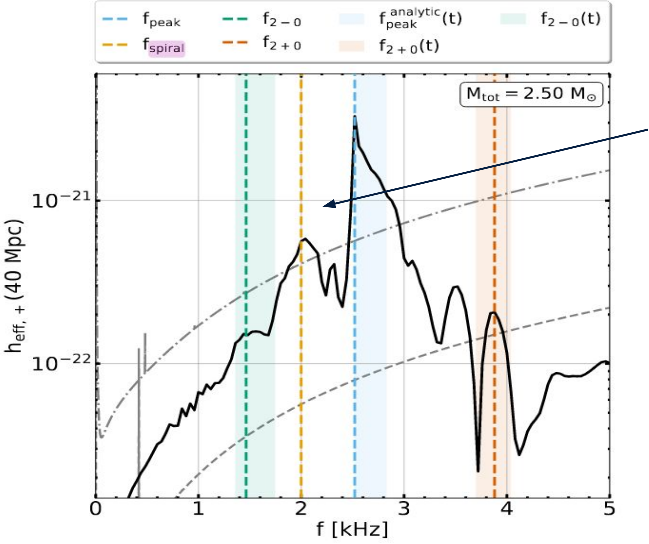


Bounce

Pulsation

Fusion

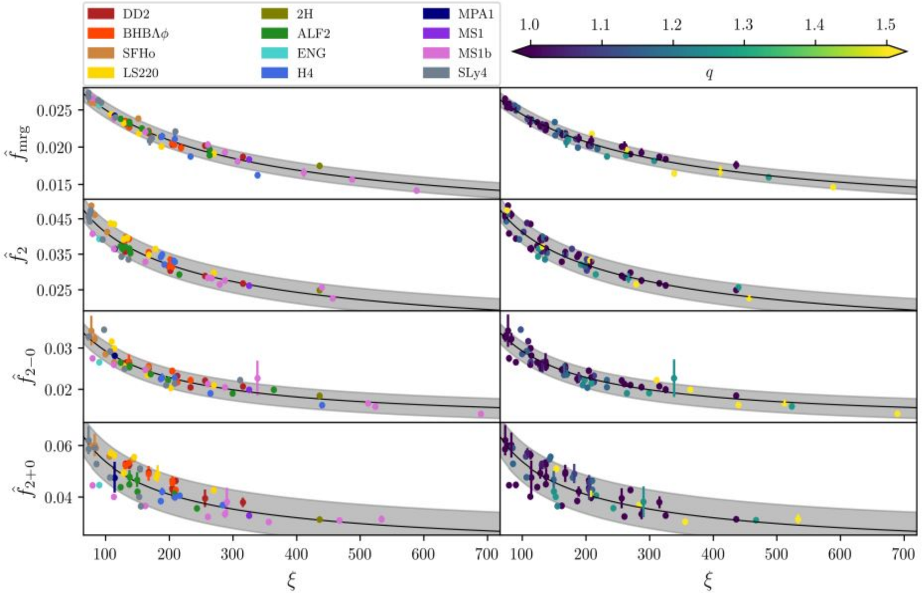
[Soultanis+2021]

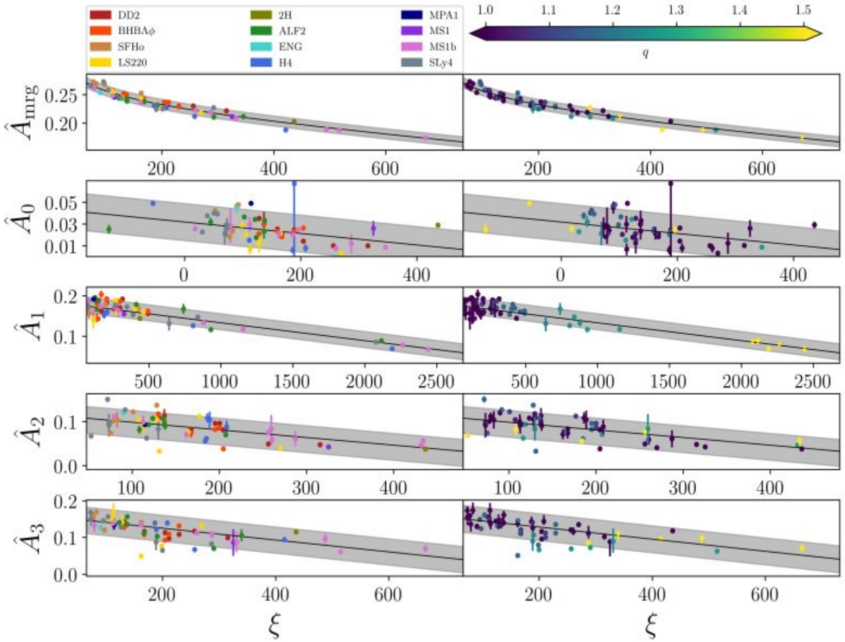


Tidal bulges

Post-merger: quasi-universality

$$\xi = \kappa_2^T + c(1 - 4\nu)$$





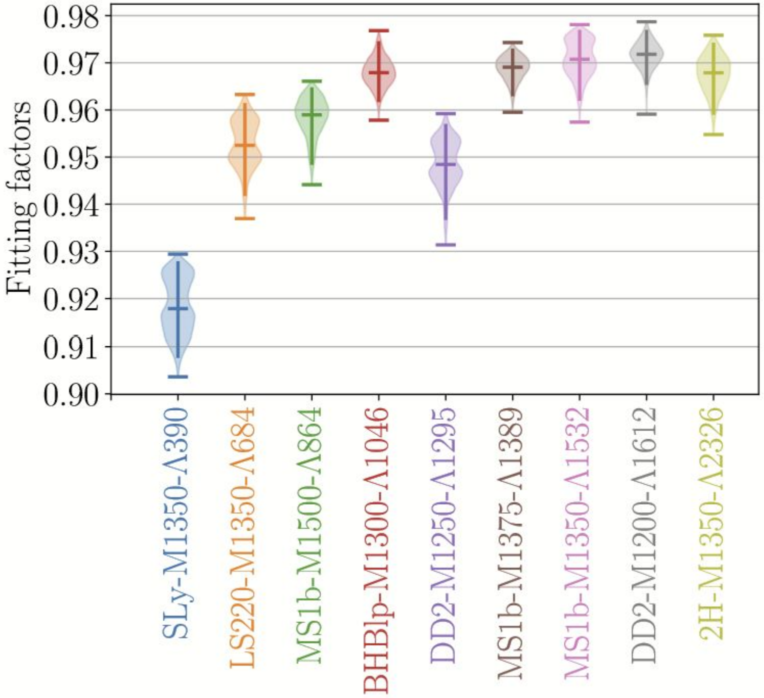
Post-merger: “models”

- **Unmodeled** [Chatziioannou+2017, Wijngaarden+22]
    - Detects PM even with (very) low SNRs
    - Identifies unexpected features in the waveform
    - Cannot directly be joined to inspiral WFs

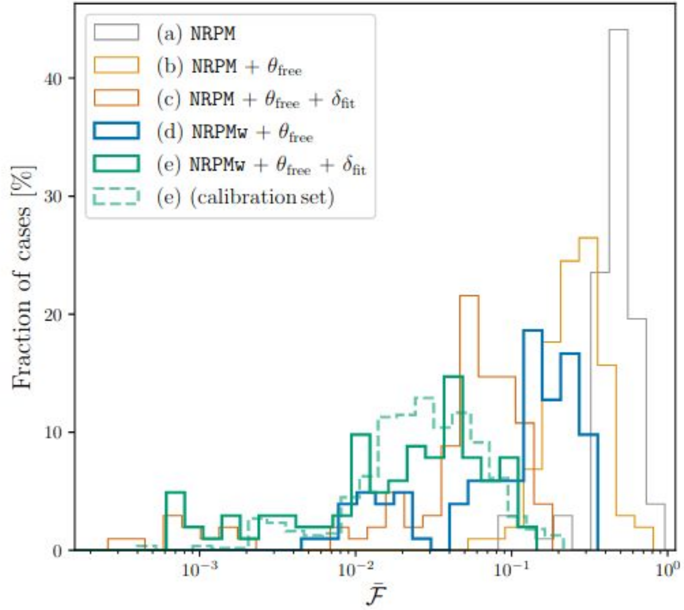
- **Phenomenological models** [Tsang+19, Breschi+19, Soultanis+2021, Breschi+22]
    - Models the most robust features of the PM (beyond f2)
    - Usually, lower fitting factors than unmodeled
    - Can be immediately joined to inspiral waveforms

- **NR-based** [Clark+2015 , Easter+2018]
    - Statistical representation of NR waveforms (reduced basis, PCA)...
    - Good fitting factors w/ NR
    - Retains all of NR uncertainty, less “flexible” than phenomenological wfs

Post-merger: performance

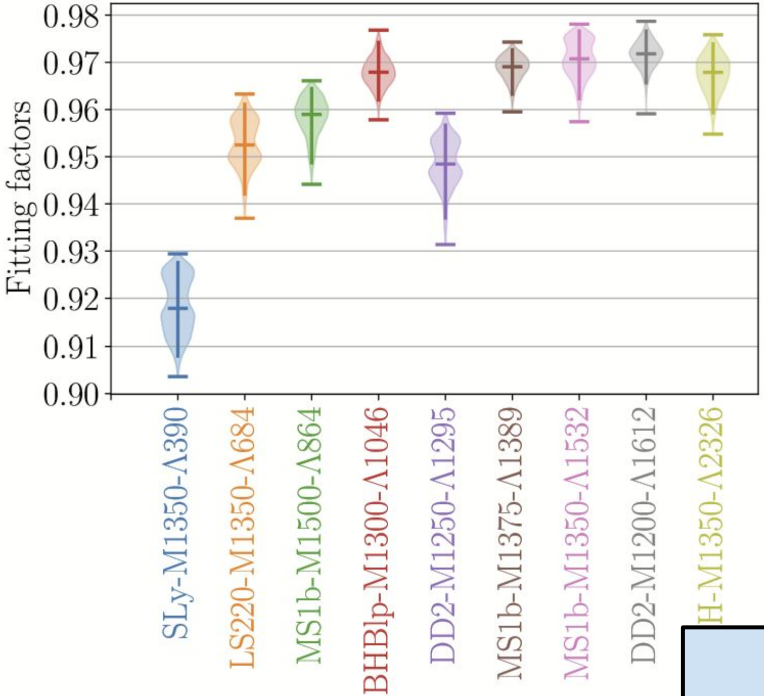


$$\mathcal{F} = \max_{t_c,\phi_c} \frac{(h|k)}{\sqrt{(h|h)(k|k)}} \qquad (h|k) = 4\Re \int \frac{\tilde{h}(f)\,\tilde{k}^*(f)}{S_n(f)}\,\mathrm{d}f$$

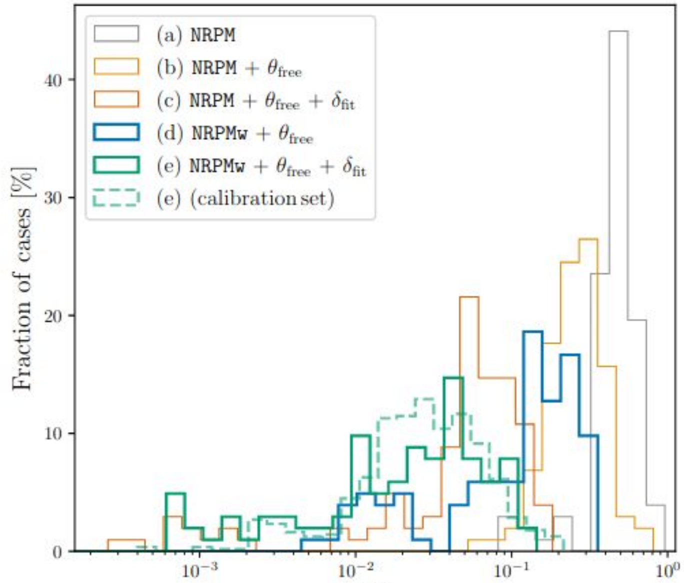


For more models see e.g. Hotokezaka+2011, Clark+2015, Chatziioannou+2017, Easter+2018, Bose+2017, Tsang+2019, Easter+2020, Soultanis+2021, Wijngaarden+2022

Post-merger: performance



$$\mathcal{F} = \max_{t_c,\phi_c} \frac{(h|k)}{\sqrt{(h|h)(k|k)}} \qquad (h|k) = 4\Re \int \frac{\tilde{h}(f)\,\tilde{k}^*(f)}{S_n(f)}\,\mathrm{d}f$$



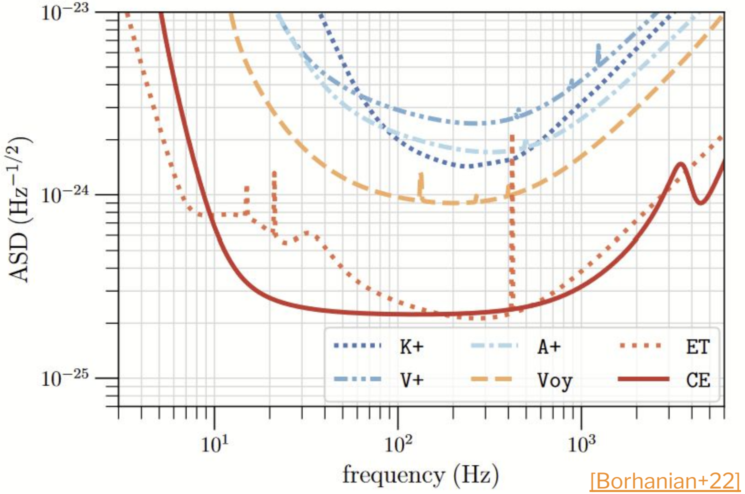
Worse than inspiral models

For more models see e.g. Hotokezaka+2011, Clark+2015, Chatziioannou+2017, Easter+2018, Bose+2017, Tsang+2019, Easter+2020, Soultanis+2021, Wijngaarden+2022

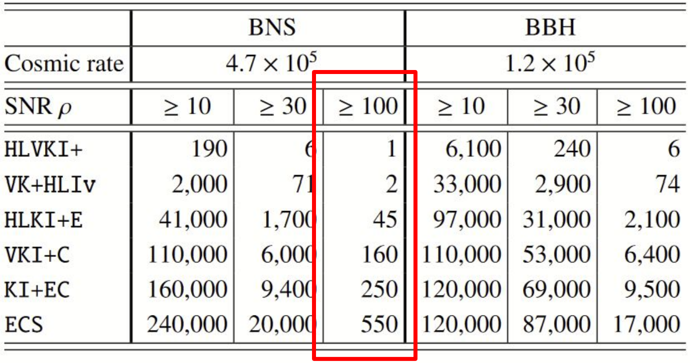
Part 2: What’s next?

Future developments and challenges

Future detectors



[Borhanian+22]



	BNS			BBH		
Cosmic rate	4.7×10^5			1.2×10^5		
SNR ρ	≥ 10	≥ 30	≥ 100	≥ 10	≥ 30	≥ 100
HLVKI+	190	6	1	6,100	240	6
VK+HLIv	2,000	71	2	33,000	2,900	74
HLKI+E	41,000	1,700	45	97,000	31,000	2,100
VKI+C	110,000	6,000	160	110,000	53,000	6,400
KI+EC	160,000	9,400	250	120,000	69,000	9,500
ECS	240,000	20,000	550	120,000	87,000	17,000

Next gen: large sensitivity improvement:

- Low frequency → improved masses measurement
- High frequency → improved matter effects measurement

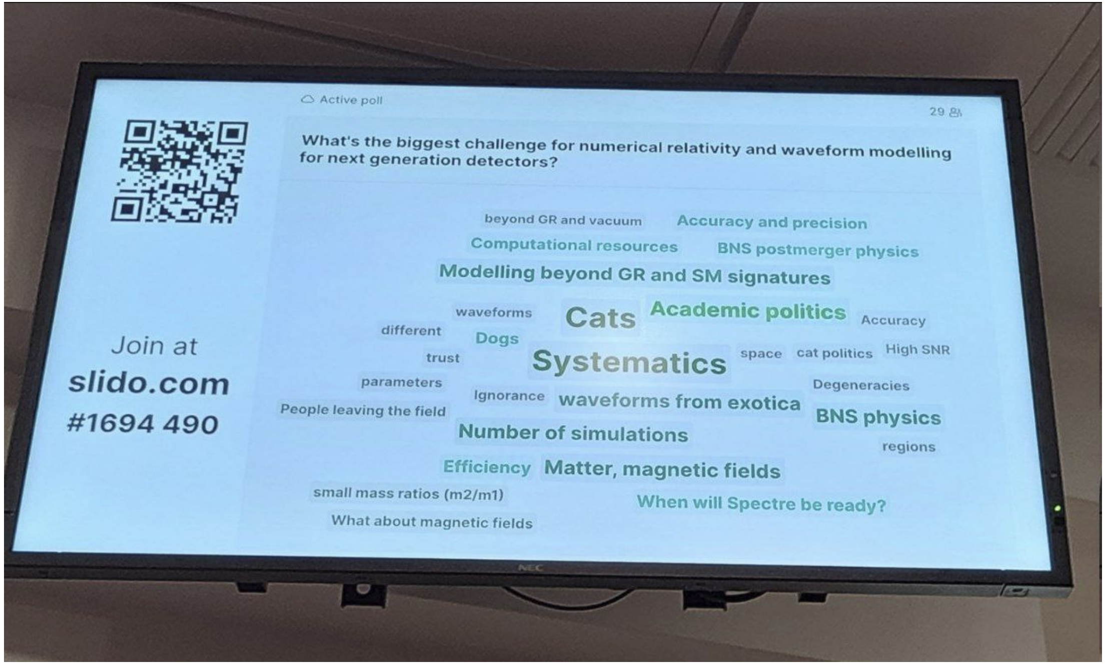
Few very loud signals (SNR > 100)

Some loud signals also with current gen!

→ What does this mean for our models?

Waveform systematics

"What's the biggest challenge for numerical relativity and waveform modeling for next generation detectors?"



Active poll

29

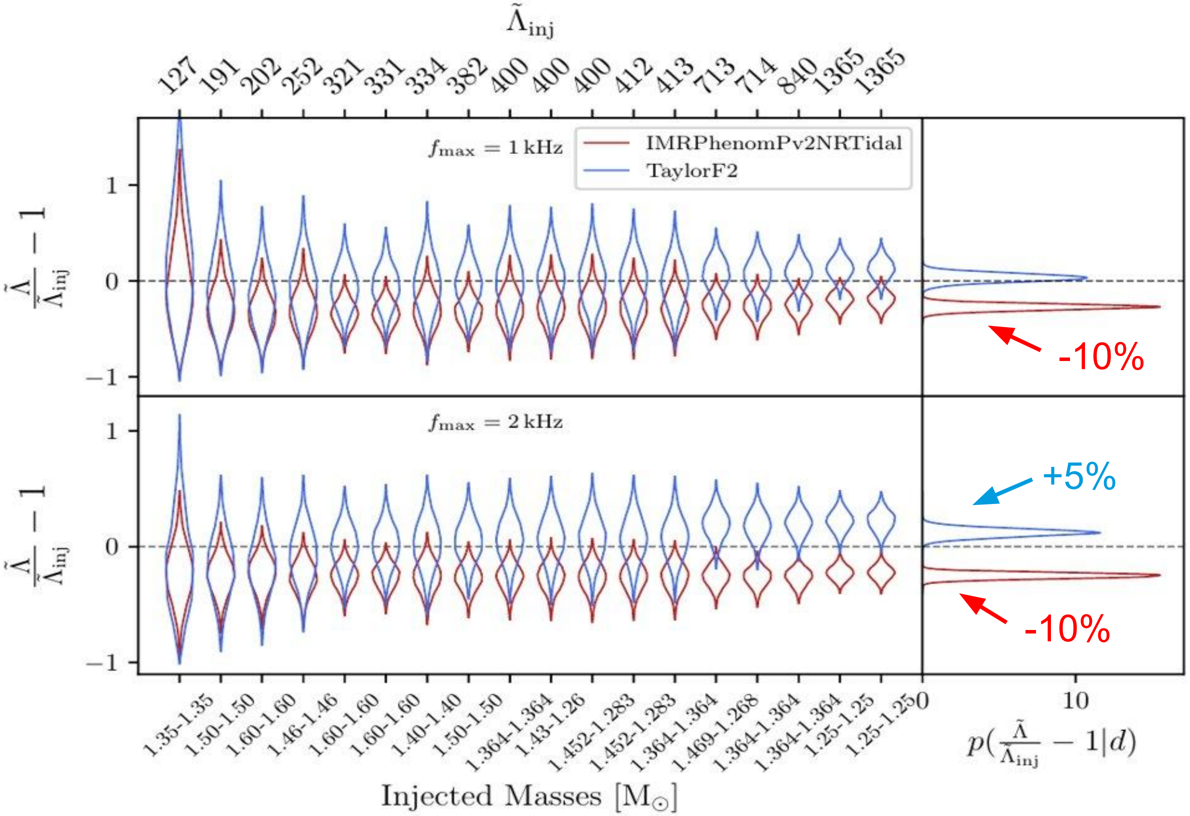
What's the biggest challenge for numerical relativity and waveform modelling for next generation detectors?

beyond GR and vacuum
Accuracy and precision
Computational resources
BNS postmerger physics
Modelling beyond GR and SM signatures
waveforms
Cats
Academic politics
Accuracy
different
Dogs
trust
Systematics
space
cat politics
High SNR
parameters
Degeneracies
Ignorance
waveforms from exotica
People leaving the field
BNS physics
Number of simulations
regions
Efficiency
Matter, magnetic fields
small mass ratios (m2/m1)
When will Spectre be ready?
What about magnetic fields

Join at
slido.com
#1694 490

Waveform systematics

Relative difference between recovered and injected Lambda



-10%

+5%

-10%

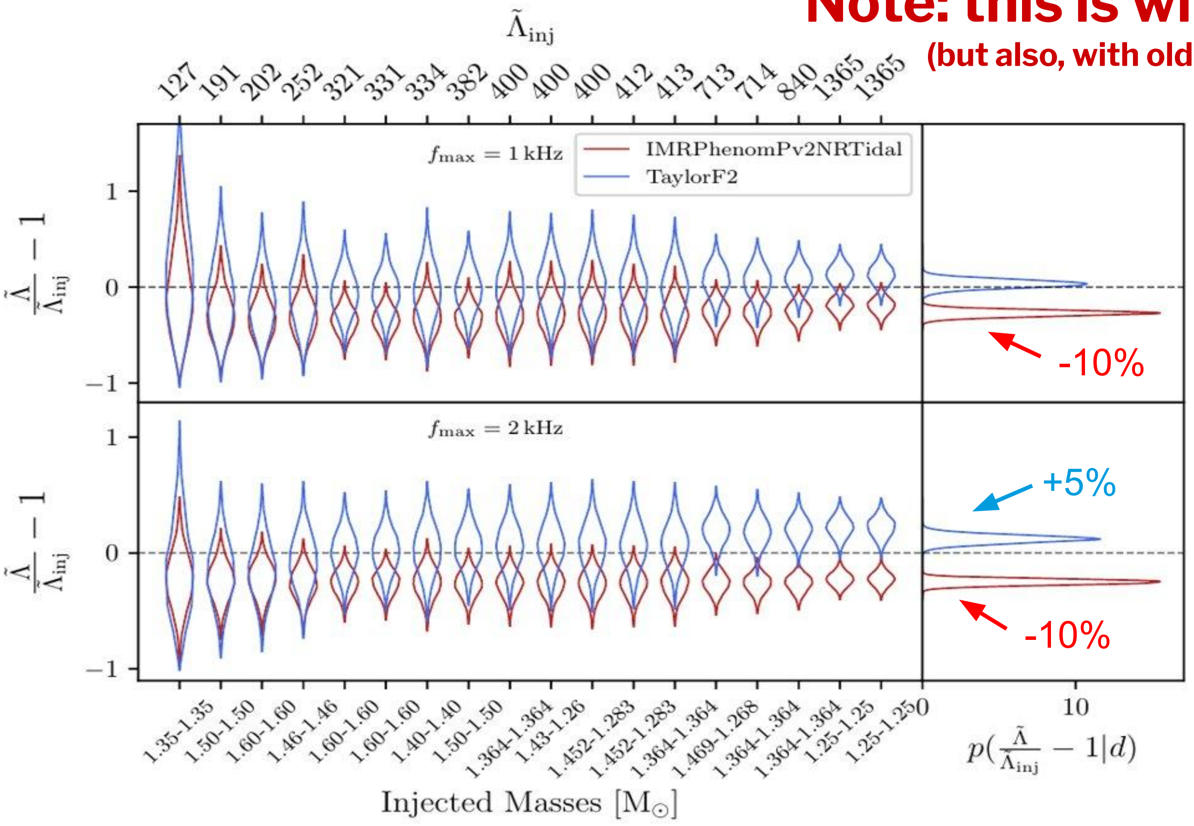
"Cumulative" difference between recovered and injected Lambdas

[Gamba+2020]

Waveform systematics

Note: this is with LVK PSD

(but also, with older models…)



-10%

+5%

-10%

Relative difference between recovered and injected Lambda

"Cumulative" difference between recovered and injected Lambdas

[Gamba+2020]

How do you beat systematics?

- “Marginalize” over model uncertainty, at the expense of measurement precision

How do you beat systematics?

- “Marginalize” over model uncertainty, at the expense of measurement precision [Read+23]
  - EOB and Phenom: sample over NR-fits error during PE
  - Do the same whenever quasi-universal relations are employed
  - Hypermodel approach [Puecher+24]

How do you beat systematics?

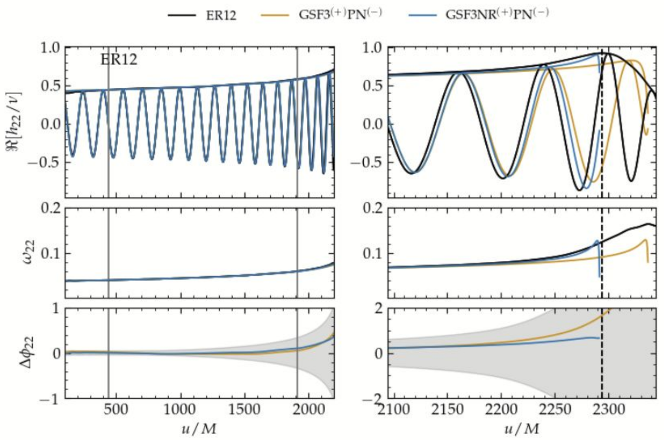
- “Marginalize” over model uncertainty, at the expense of measurement precision [Read+23]
    - EOB and Phenom: sample over NR-fits error during PE
    - Do the same whenever quasi-universal relations are employed
    - Hypermodel approach [Puecher+24]
- **“Just” build better models**

Developments

- Inspiral:

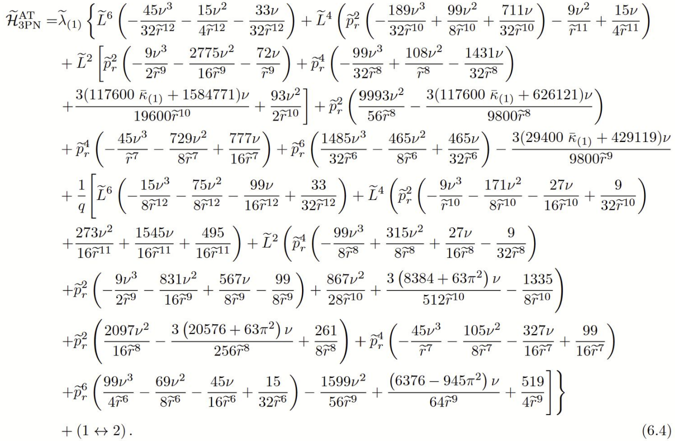
Developments

- Inspiral:
  - Folding in some information from NR in EOB models



Developments

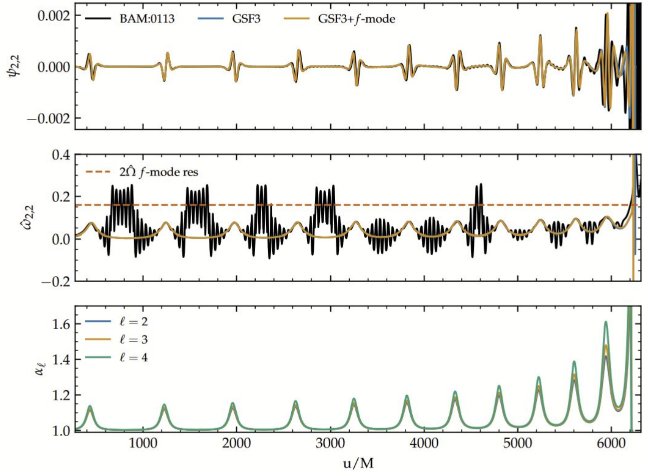
- Inspiral:
  - Folding in some information from NR in EOB models
  - Include some of the recent 3PN tidal effect terms, **not just circular**[Mandal+24]



$$
\begin{aligned}
\widetilde{\mathcal{H}}^{\mathrm{AT}}_{3\mathrm{PN}} =& \widetilde{\lambda}_{(1)} \Bigg\{ \widetilde{L}^6 \left(-\frac{45\nu^3}{32\widetilde{r}^{12}} - \frac{15\nu^2}{4\widetilde{r}^{12}} - \frac{33\nu}{32\widetilde{r}^{12}} \right) + \widetilde{L}^4 \left(\widetilde{p}_r^2 \left(-\frac{189\nu^3}{32\widetilde{r}^{10}} + \frac{99\nu^2}{8\widetilde{r}^{10}} + \frac{711\nu}{32\widetilde{r}^{10}} \right) - \frac{9\nu^2}{\widetilde{r}^{11}} + \frac{15\nu}{4\widetilde{r}^{11}} \right) \\
& + \widetilde{L}^2 \Bigg[\widetilde{p}_r^2 \left(-\frac{9\nu^3}{2\widetilde{r}^9} - \frac{2775\nu^2}{16\widetilde{r}^9} - \frac{72\nu}{\widetilde{r}^9} \right) + \widetilde{p}_r^4 \left(-\frac{99\nu^3}{32\widetilde{r}^8} + \frac{108\nu^2}{\widetilde{r}^8} - \frac{1431\nu}{32\widetilde{r}^8} \right) \\
& + \frac{3(117600\ \bar{\kappa}_{(1)} + 1584771)\nu}{19600\widetilde{r}^{10}} + \frac{93\nu^2}{2\widetilde{r}^{10}} \Bigg] + \widetilde{p}_r^2 \left(\frac{9993\nu^2}{56\widetilde{r}^8} - \frac{3(117600\ \bar{\kappa}_{(1)} + 626121)\nu}{9800\widetilde{r}^8} \right) \\
& + \widetilde{p}_r^4 \left(-\frac{45\nu^3}{\widetilde{r}^7} - \frac{729\nu^2}{8\widetilde{r}^7} + \frac{777\nu}{16\widetilde{r}^7} \right) + \widetilde{p}_r^6 \left(\frac{1485\nu^3}{32\widetilde{r}^6} - \frac{465\nu^2}{8\widetilde{r}^6} + \frac{465\nu}{32\widetilde{r}^6} \right) - \frac{3(29400\ \bar{\kappa}_{(1)} + 429119)\nu}{9800\widetilde{r}^9} \\
& + \frac{1}{q} \Bigg[\widetilde{L}^6 \left(-\frac{15\nu^3}{8\widetilde{r}^{12}} - \frac{75\nu^2}{8\widetilde{r}^{12}} - \frac{99\nu}{16\widetilde{r}^{12}} + \frac{33}{32\widetilde{r}^{12}} \right) + \widetilde{L}^4 \Bigg(\widetilde{p}_r^2 \left(-\frac{9\nu^3}{\widetilde{r}^{10}} - \frac{171\nu^2}{8\widetilde{r}^{10}} - \frac{27\nu}{16\widetilde{r}^{10}} + \frac{9}{32\widetilde{r}^{10}} \right) \\
& + \frac{273\nu^2}{16\widetilde{r}^{11}} + \frac{1545\nu}{16\widetilde{r}^{11}} + \frac{495}{16\widetilde{r}^{11}} \Bigg) + \widetilde{L}^2 \Bigg(\widetilde{p}_r^4 \left(-\frac{99\nu^3}{8\widetilde{r}^8} + \frac{315\nu^2}{8\widetilde{r}^8} + \frac{27\nu}{16\widetilde{r}^8} - \frac{9}{32\widetilde{r}^8} \right) \\
& + \widetilde{p}_r^2 \left(-\frac{9\nu^3}{2\widetilde{r}^9} - \frac{831\nu^2}{16\widetilde{r}^9} + \frac{567\nu}{8\widetilde{r}^9} - \frac{99}{8\widetilde{r}^9} \right) + \frac{867\nu^2}{28\widetilde{r}^{10}} + \frac{3\left(8384 + 63\pi^2\right)\nu}{512\widetilde{r}^{10}} - \frac{1335}{8\widetilde{r}^{10}} \Bigg) \\
& + \widetilde{p}_r^2 \left(\frac{2097\nu^2}{16\widetilde{r}^8} - \frac{3\left(20576 + 63\pi^2\right)\nu}{256\widetilde{r}^8} + \frac{261}{8\widetilde{r}^8} \right) + \widetilde{p}_r^4 \left(-\frac{45\nu^3}{\widetilde{r}^7} - \frac{105\nu^2}{8\widetilde{r}^7} - \frac{327\nu}{16\widetilde{r}^7} + \frac{99}{16\widetilde{r}^7} \right) \\
& + \widetilde{p}_r^6 \left(\frac{99\nu^3}{4\widetilde{r}^6} - \frac{69\nu^2}{8\widetilde{r}^6} - \frac{45\nu}{16\widetilde{r}^6} + \frac{15}{32\widetilde{r}^6} \right) - \frac{1599\nu^2}{56\widetilde{r}^9} + \frac{\left(6376 - 945\pi^2\right)\nu}{64\widetilde{r}^9} + \frac{519}{4\widetilde{r}^9} \Bigg] \Bigg\} \\
& + (1 \leftrightarrow 2)\,. \qquad (6.4)
\end{aligned}
$$

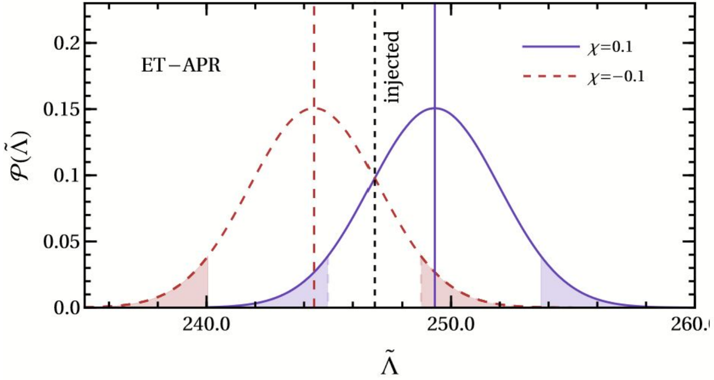
Developments

- Inspiral:
    - Folding in some information from NR in EOB models
    - Include some of the recent 3PN tidal effect terms, **not just circular** [Mandal+24]
    - Study the effect of eccentricity: dynamical tidal effects → excitations of the modes after close passages [Hang+24, Takatsi+24]



Developments

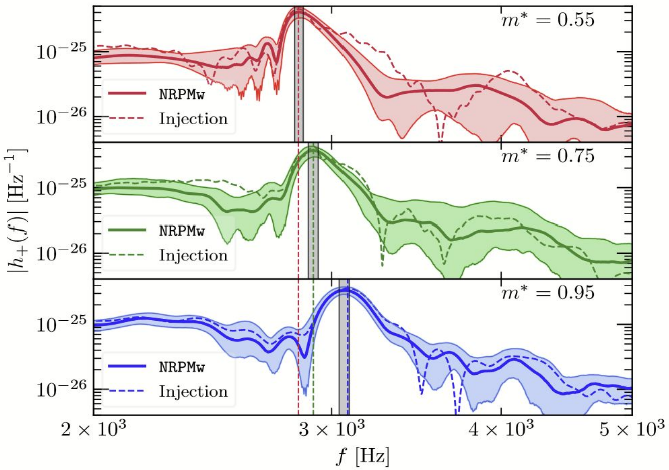
- Inspiral:
  - Folding in some information from NR in EOB models
  - Include some of the recent 3PN tidal effect terms, **not just circular**[Mandal+24]
  - Study the effect of eccentricity: dynamical tidal effects → excitations of the modes after close passages [Hang+24, Takatsi+24]
  - Spin-induced effects: spin-tidal couplings?[Abdelsahin+18,Castro+22]



Developments

- Inspiral:
  - Folding in some information from NR in EOB models
  - Include some of the recent 3PN tidal effect terms, **not just circular**[Mandal+24]
  - Study the effect of eccentricity: dynamical tidal effects → excitations of the modes after close passages [Hang+24, Takatsi+24]
  - Spin-induced effects: spin-tidal couplings?[Abdelsahin+18,Castro+22]
- Post-merger:
  - Numerical Relativity: understand muons, Pions,B-fields, neutrinos, thermal effectsresolution,.. [Gieg+24, Pajkos+24]

[Fields+23]



Conclusions

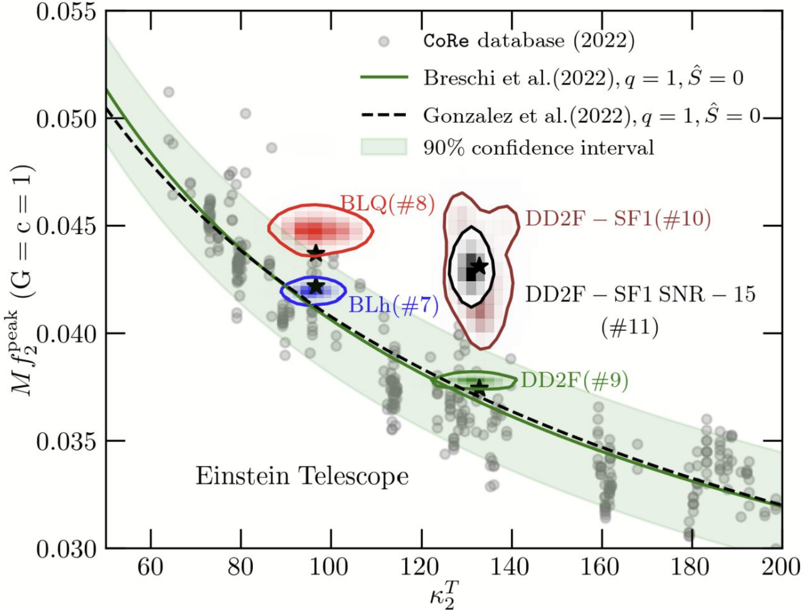
- Modeling the inspiral is “““easy”””, but we need to do it extremely well to avoid systematics
- Modeling the post-merger is harder, current models capture just few features
- NR is going to be fundamental to model the beyond-contact regime

Backup slides

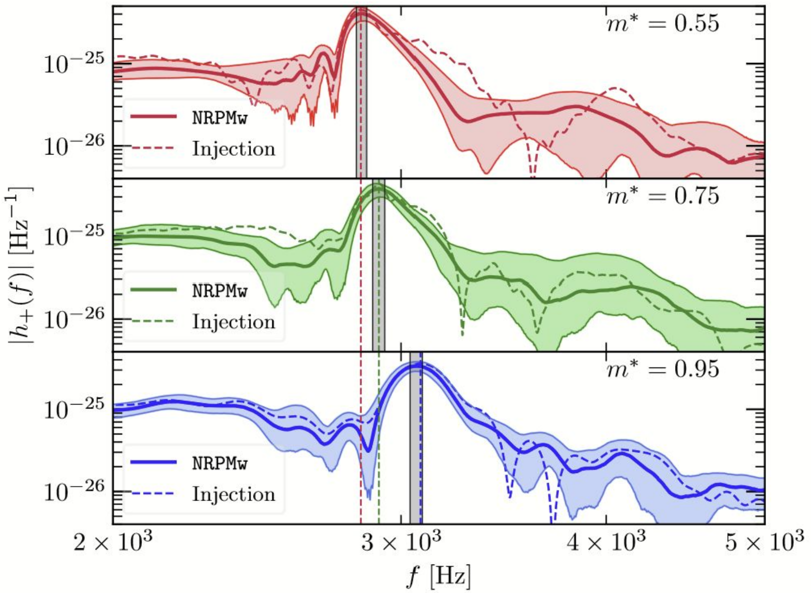
Next Gen detectors: post-merger

Quasi-universality breaking:
→ phase transitions, thermal effects, magnetic fields, muons, ...?

[Prakash+23]



[Fields+23]



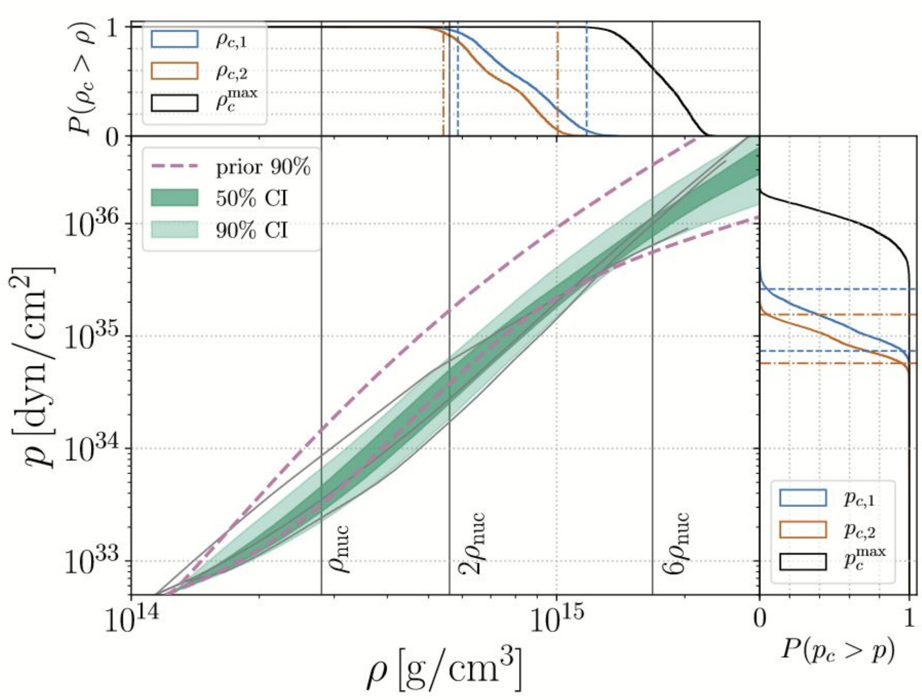
Current GW observations

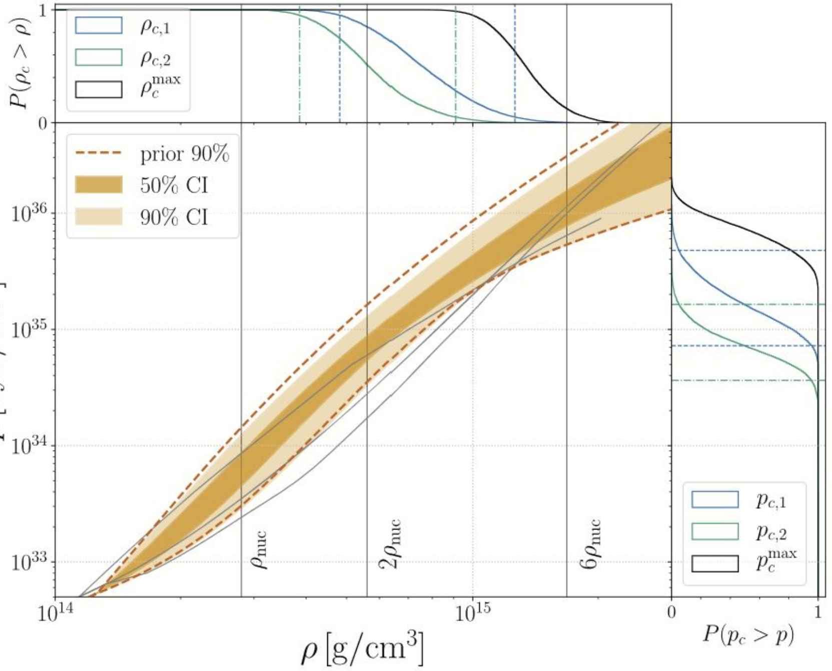
Confidently detected systems with at least one NS:

Name	Kind	SNR	Tides?	EM?
GW170817	BNS	~30	Upper limits	✅
GW190425	BNS	~14	(weak) upper limits	❌
GW200105	BHNS	~14	Uninformative	❌
GW200115	BHNS	~12	Uninformative	❌

Current GW observations

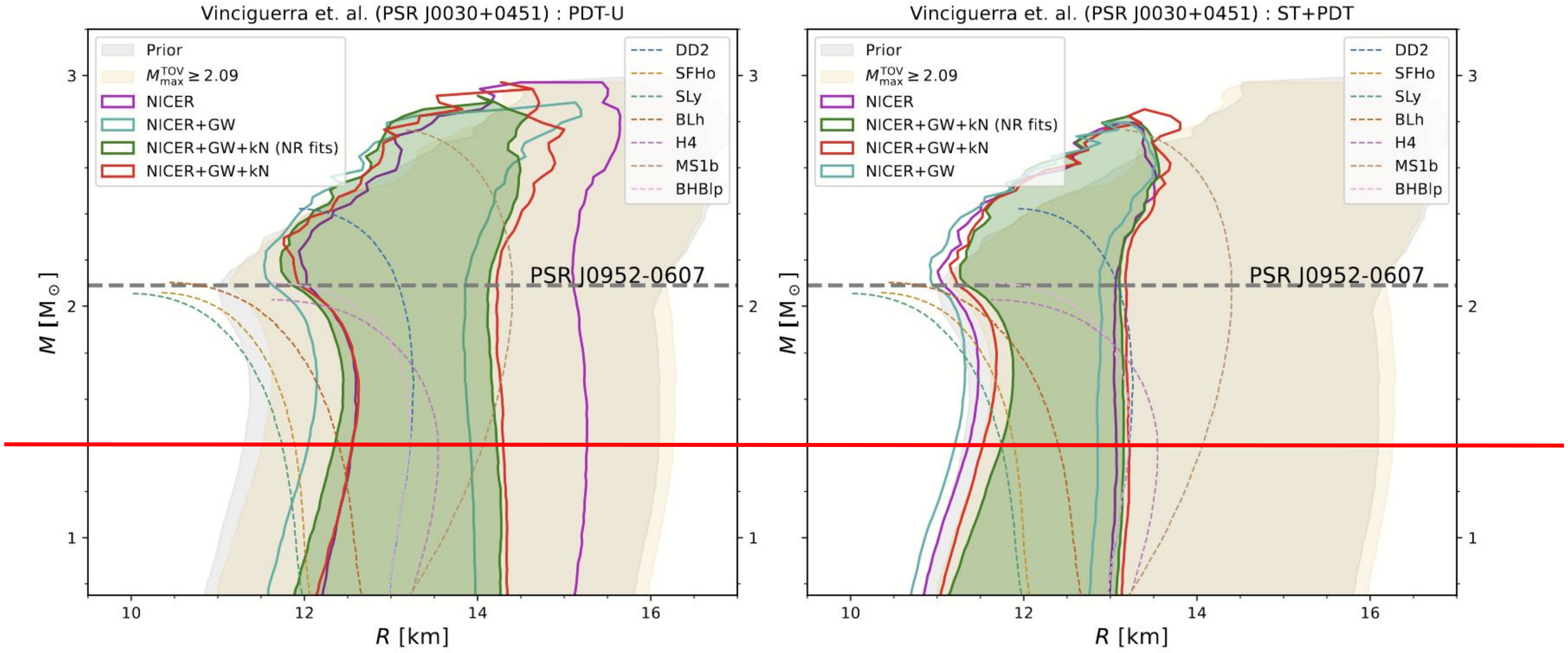
From GW alone (using a spectral parameterization of the EOS):





Current EOS constraints: GW + KN (+ NICER)

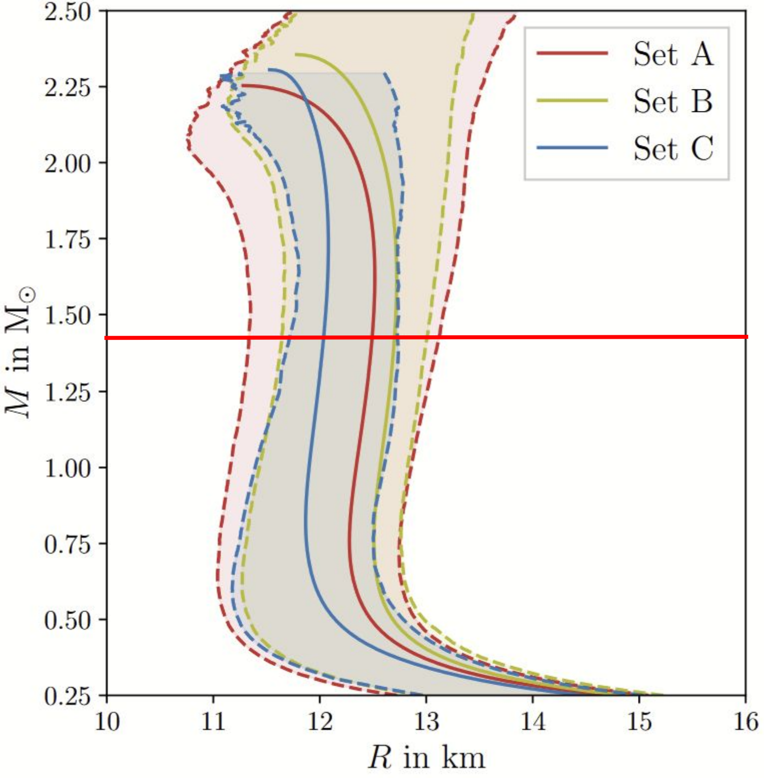
[Breschi+24]



$R_{1.4M_\odot}$ between 12-14 km or 11-13 km, depending on NICER

Current EOS constraints: GW + KN (+ NICER +...)

[Kohen+24]



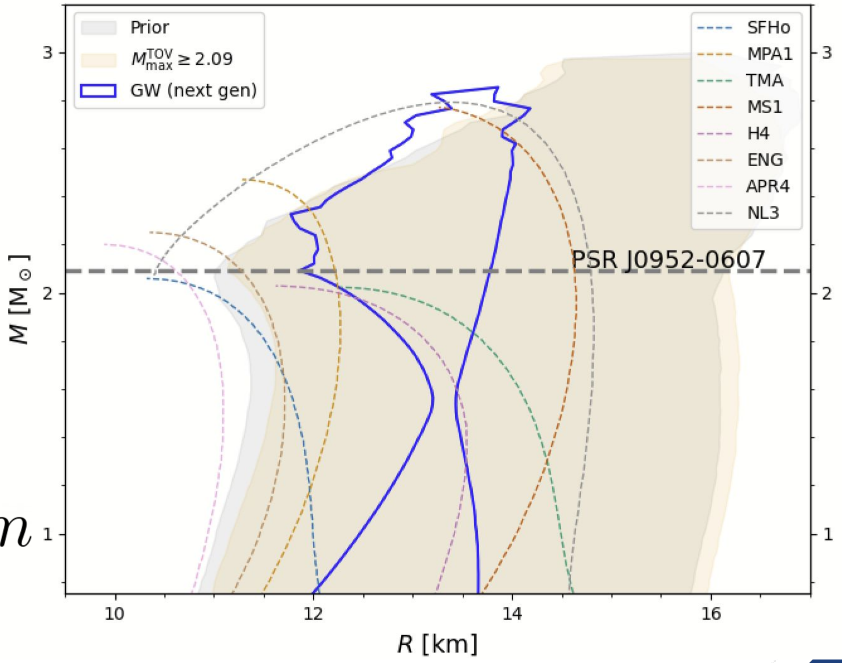
- Set A:
  Chiral EFT, pQCD, radio timing, NICER, GW170817

- Set B:
  Heavy-Ion collisions, qLMXBe, Black Widow, GW170817 + AT2017gfo + GRB170817A

- Set C:
  PREX, CREX, Burster, Hess, GW190425, GRB211211A, GW170817 (postmerger)

Next Gen detectors: inspiral

- Generate fake data: GW injection & recovery with ET
    - SNR ~ 540
    - q = 1.5, M = 2.8
    - Λ_1 = 600
    - Λ_2 = 1000
    - EOB model + ROQ

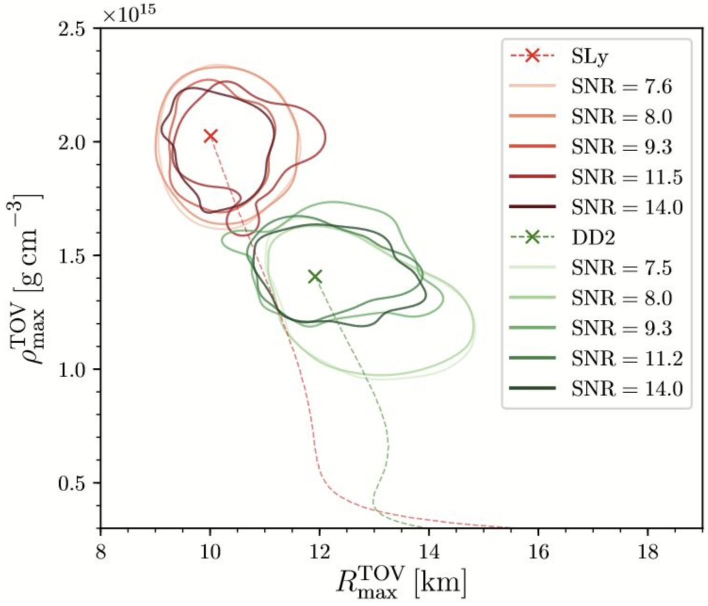


- Single tidal parameters meas
    - $\Lambda_1 = 600^{+130}_{-160}$
    - $\Lambda_2 = 970^{+730}_{-600}$

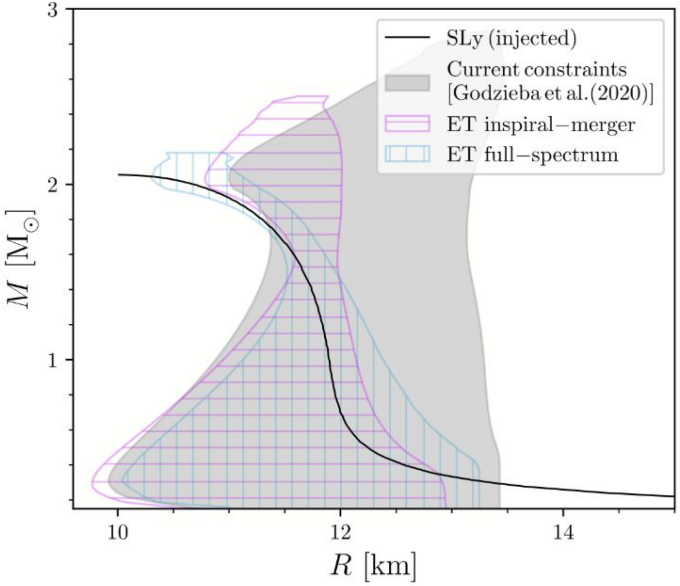
- Very tight constraints! $\pm 200m$

Next Gen detectors: post-merger

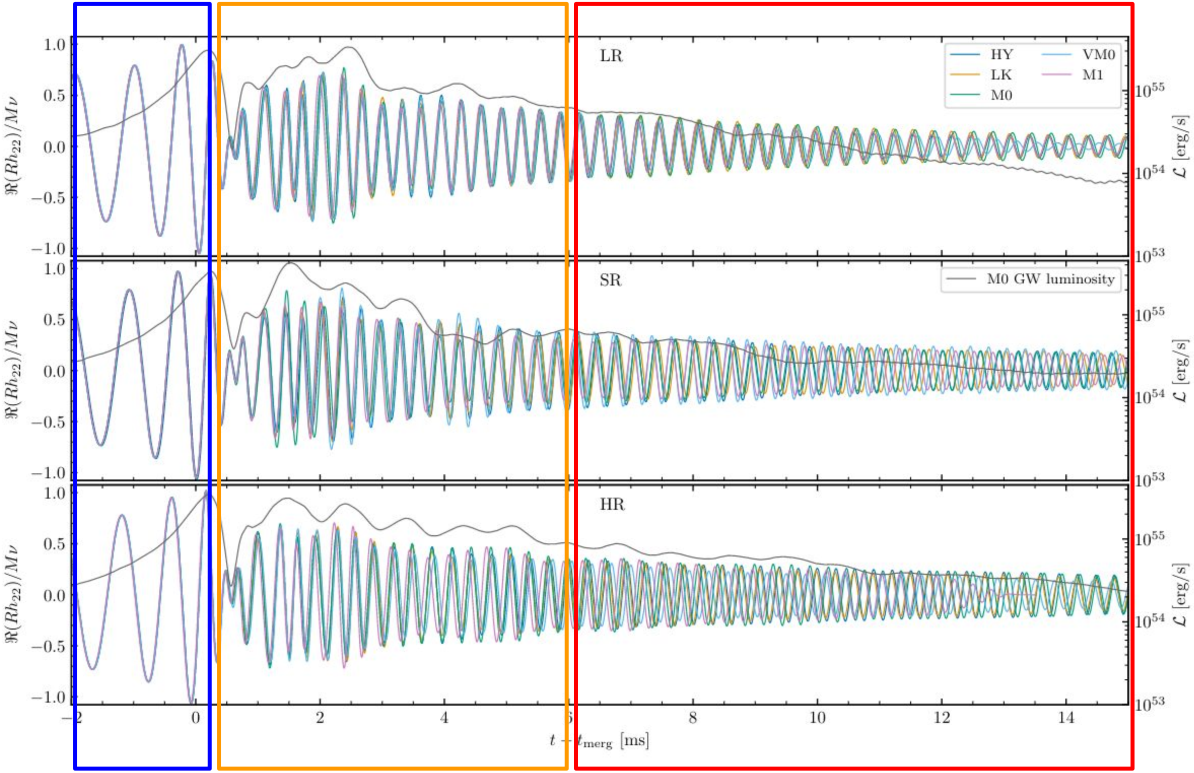
Post-merger detectable (on its own) if SNR(PM) > 8 → SNR(inspiral) O(100).
Constraints on the "max TOV" properties of the (cold) EOS



[Breschi+21]



NR simulations: physics & accuracy (PM)



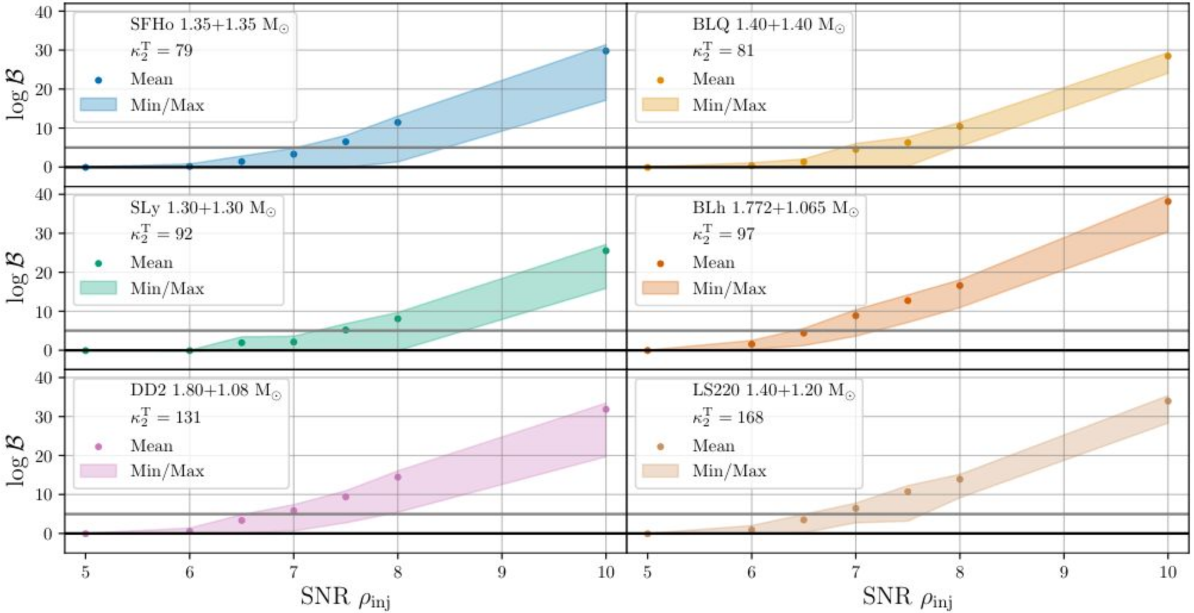
[Zappa+22]

HY = pure hydro
LK = Leakage
VM0 = Viscosity + M0

$\Delta x_{\rm LR} \approx 247$ m, $\Delta x_{\rm SR} \approx 185$ m, $\Delta x_{\rm HR} \approx 123$ m.

- Up to merger: little to no difference due to microphysics
- “Early” times: small differences
- “Late” times: large differences, especially for SR/HR simulations

Post-merger detectability



- Post-merger only
- Simulated ET signal, analyzed with NRPMw
- Locating the detector in Virgo's place (with typical triangular configuration)
- 10 different noise realizations

Current EOS constraints: GW + KN (+ NICER)

“Joint and coherent” analysis of GW170817 + AT2017gfo:

- Joint likelihood

$$p(\boldsymbol{d}_{\rm gw}, \boldsymbol{d}_{\rm kn}|\boldsymbol{\theta}_{\rm gw}, \boldsymbol{\theta}_{\rm kn}) = p(\boldsymbol{d}_{\rm gw}|\boldsymbol{\theta}_{\rm gw})\, p(\boldsymbol{d}_{\rm kn}|\boldsymbol{\theta}_{\rm kn})$$

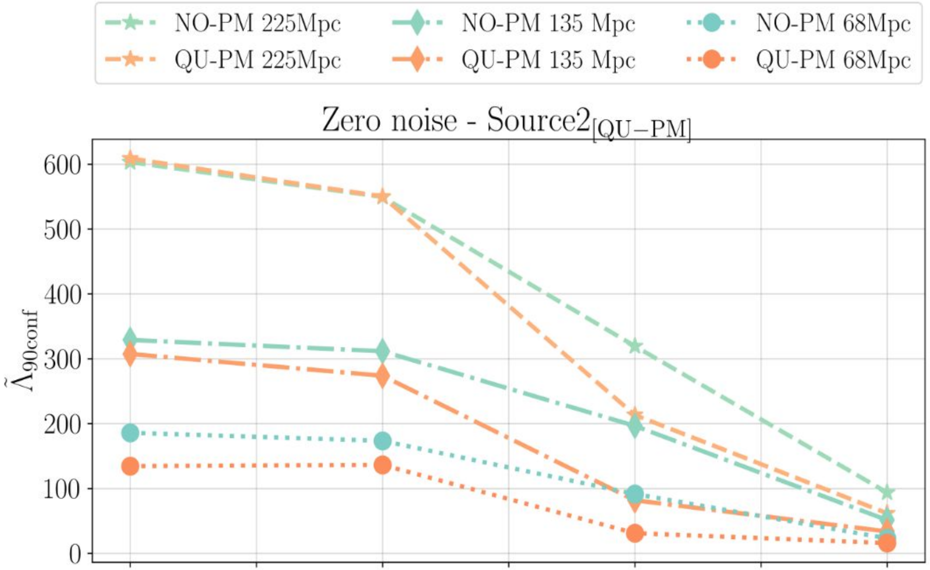
- Common parameters:
  - Luminosity distance
  - merger time
  - (inclination, if anisotropic model)
  - NR fits: link some KN parameters with GW ones

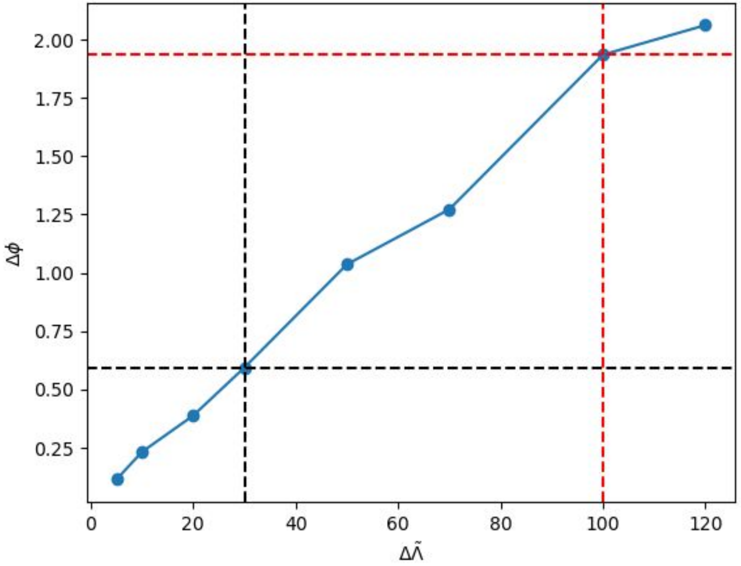
$$M_{\rm ej}^{d}, v^{d}, m_{\rm disk}$$

- Re-sampling of the posterior to determine EOS from a prior set of ~10M EOSs, adding also NICER results

Accuracy requirements (on the back of an envelope)

[Puecher+22]





$$\Delta\tilde{\Lambda} = 100 \rightarrow \Delta\phi \sim 2\mathrm{rad}$$

$$\Delta\tilde{\Lambda} = 25 \rightarrow \Delta\phi \sim 0.5\mathrm{rad}$$