# Waveform systematics in the gravitational-wave inference of tidal parameters from binary neutron star signals

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# Outline

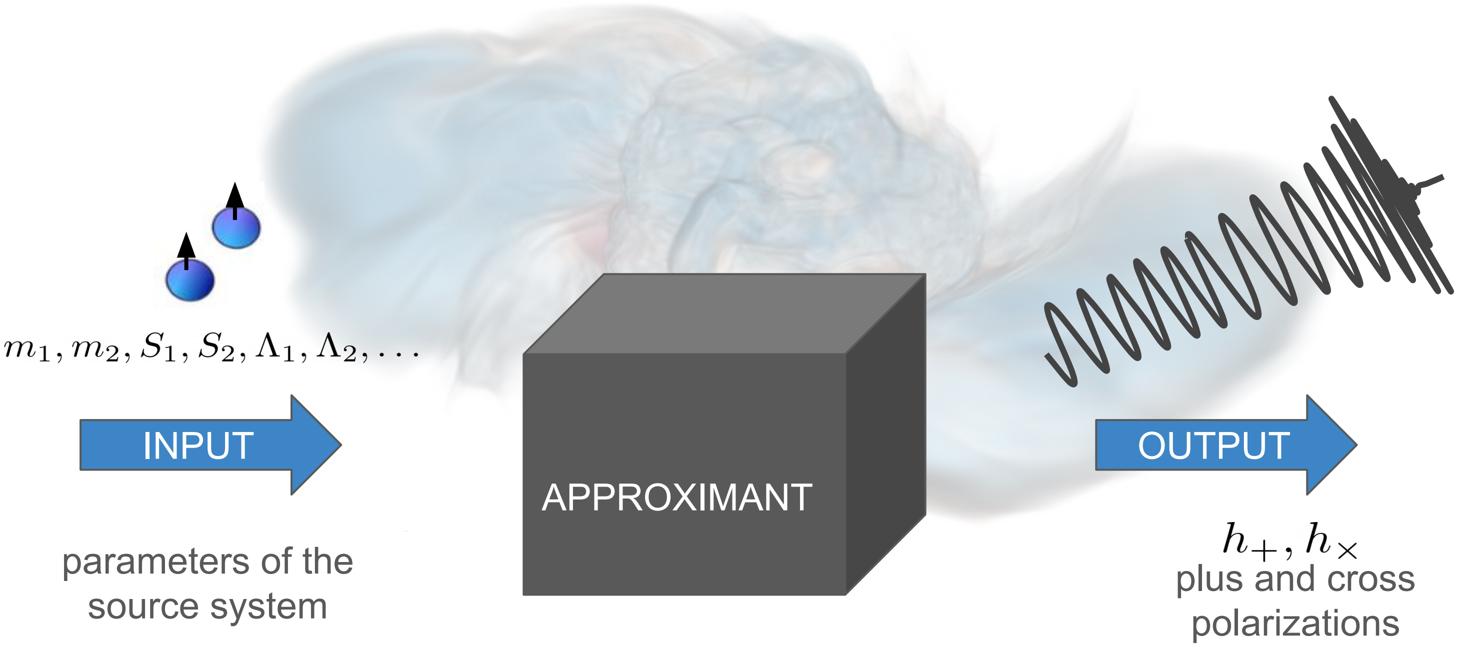
Previous talks:

- Q: Why should we care about neutron stars? A: because they are cool (pun intended)
- Q: What can we do with GW data from binary neutron star signals? A: EOS, Cosmology, ...

In the next ~40 minutes:

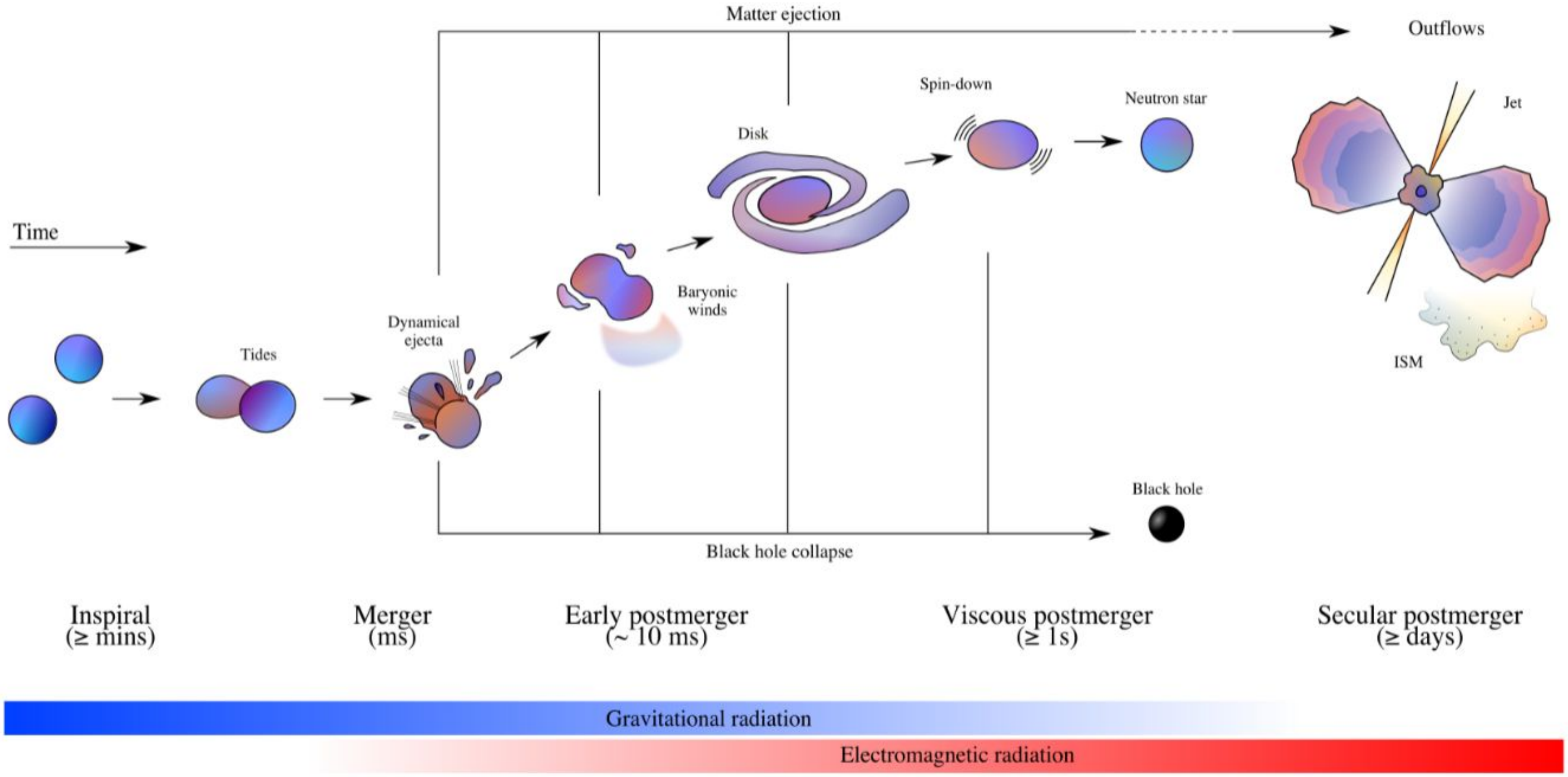
- **Q1: How can we model the GW signal from BNS?**
- **Q2: How do modelling differences affect GW parameter estimation?**

# 1. Modelling of GWs from binary Neutron star systems



# Phenomenology of a merger

Image Credits: Matteo Breschi



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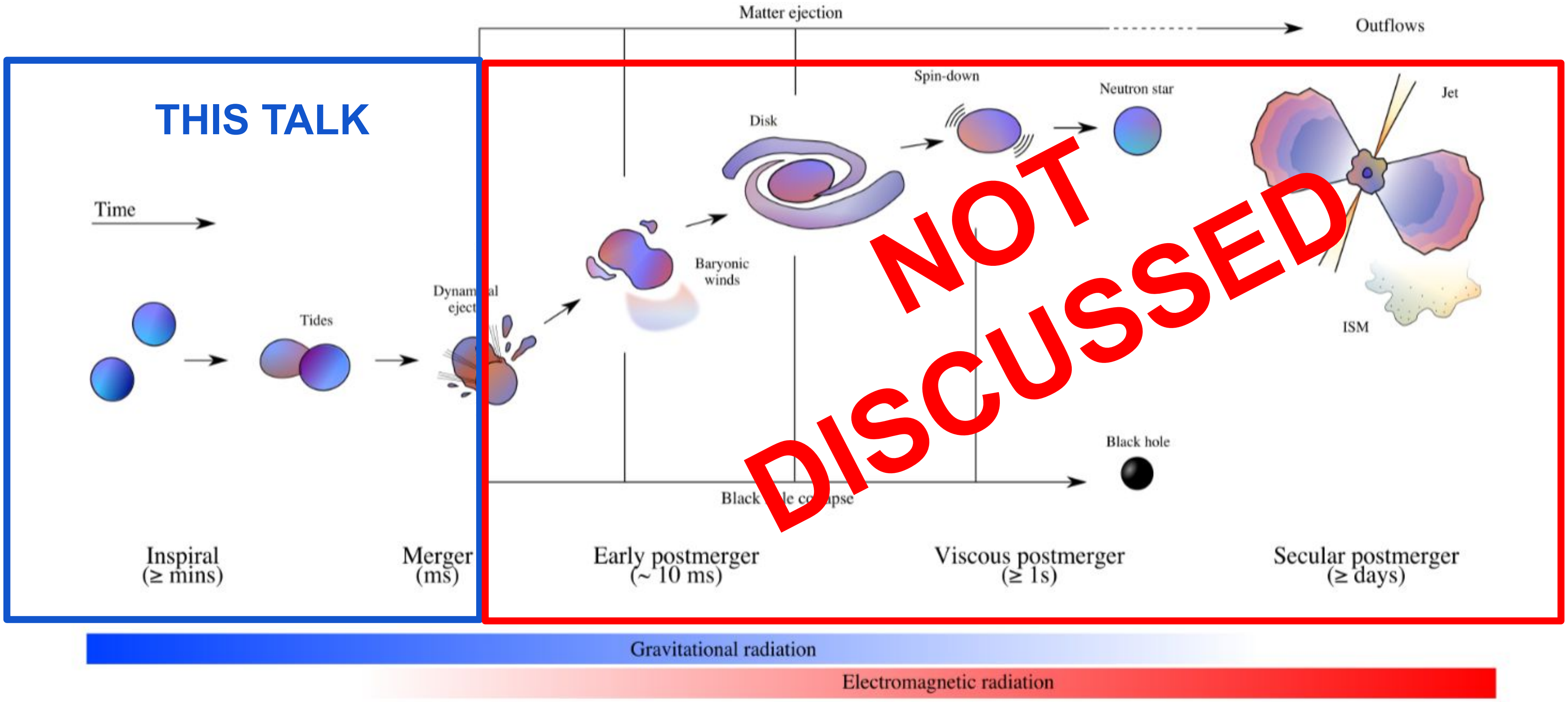

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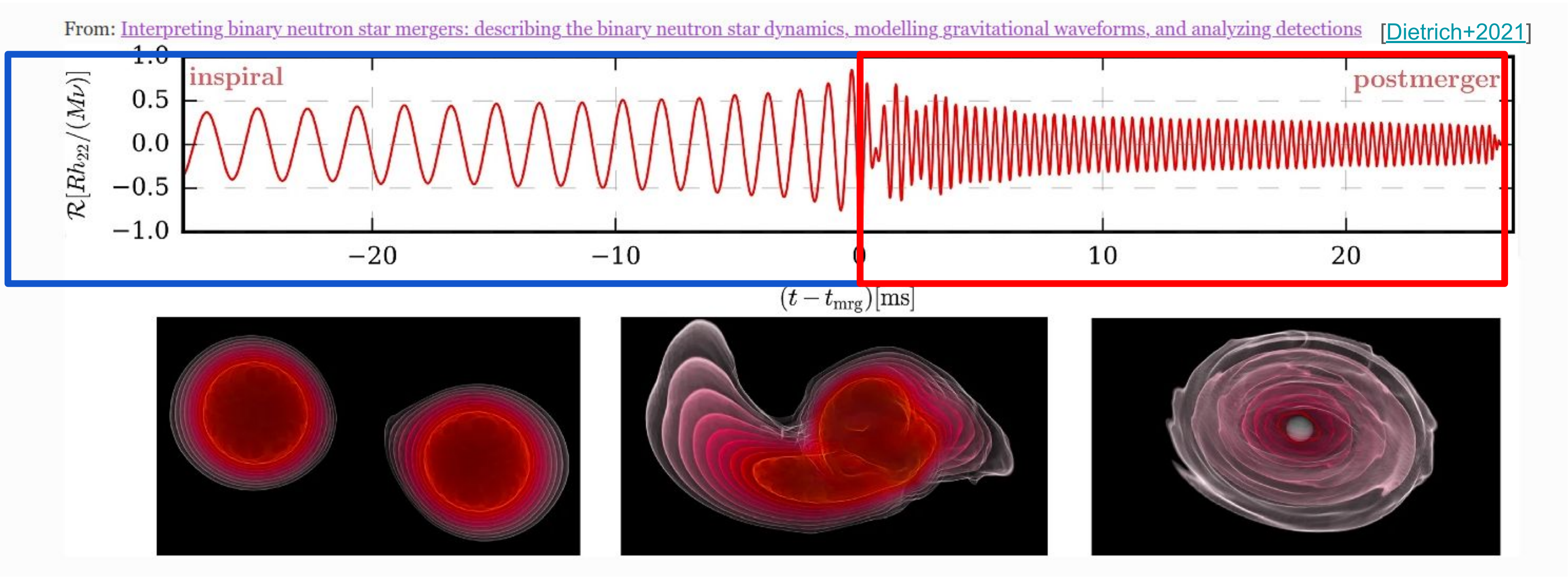



Inspiral up to merger: "similar" to a BBH waveform for slowly spinning bodies and q~1 [See Geraint's talk]

→ We can model this as BBH + corrections! Should be easy right?

# Matter effects

**Matter effects** are what distinguish NS from point particles (=black holes, BH)

For GW modelling of BNS, the more important ones are:

- **Tidal effects**
  - “adiabatic” tidal effects [Damour1983, Flanagan+2007,Damour+2008,Vines+2010,...,Henry+2020]
  - “dynamical” tidal effects [Lai+1994, Hinderer+2016, Steinhoff+2016, Steinhoff+2021]
- **Spin induced effects** [Poisson1998,Krishnendu+2017]

Additional effects due to resonant modes of neutron stars can be considered (but will not be discussed here)

# Adiabatic tides

- When a NS is subject to the gravitational field of another object, it gets deformed → Tidal effects
- Proportionality constant between external field and quadrupolar deformation → tidal parameter

$$Q_{ij} = -\lambda E_{ij} \qquad \lambda_i = \frac{\text{Quadrupole deformation of the star}}{\text{External tidal field}} \to \Lambda_i = \frac{\lambda_i}{m_i^5}$$

$$\boxed{\rho(p)} + \boxed{\begin{aligned} \frac{1-g_{tt}}{2} &= -\frac{m}{r} - \frac{3Q_{ij}}{2r^3}\left(n^i n^j - \frac{1}{3}\delta^{ij}\right) + O\left(r^{-3}\right) \\ &+ \frac{1}{2}\mathcal{E}_{ij}x^i x^j + O\left(r^3\right) \end{aligned}} = \boxed{\lambda_2}$$

EOS

Perturbed static spherically symm. metric

Tidal deformability

# Adiabatic tides

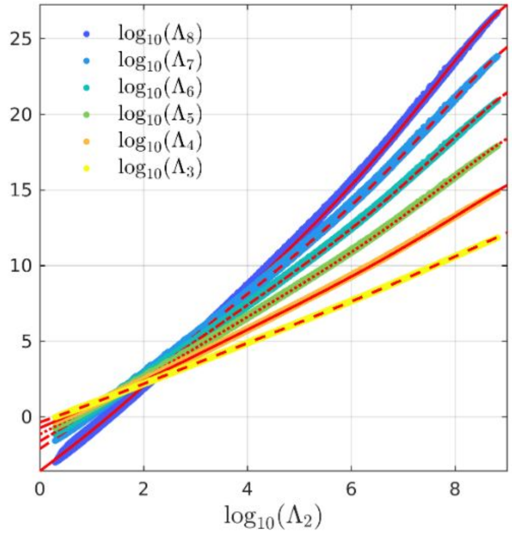
Generalization to higher multipoles (Otcupole, Hexadecupole, …)

$$\Lambda_l \equiv \frac{2}{(2l-1)!!}\frac{k_l}{C^{2l+1}}$$

Love number

compactness, M/R

Godzieba+2021




There exist quasi-universal (=EOS independent) relations between the quadrupolar tidal parameter and the “higher order” ones [Yagi+2016, Carson+2019,Godzieba+2021]

# Dynamical tides

- **Dynamical** Tidal effects (f-mode resonance):

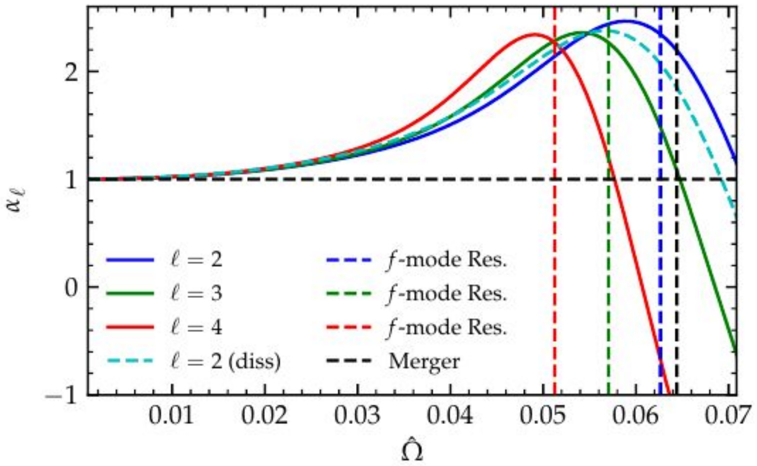
$$L_{\rm DT} = \frac{1}{4\lambda\omega_f^2}\left[\dot{Q}^{ij}\dot{Q}^{ij} - \omega_f^2 Q^{ij}Q^{ij}\right] - \frac{1}{2}E_{ij}Q^{ij},$$

Harmonic Osc.

- **“Dressing factor”** for love numbers:

$$k_\ell \mapsto k_\ell^{\rm eff} := \alpha_{\ell m}(\nu, \Omega, \bar{\omega}_f^{(\ell)}, X_{\rm A})k_\ell$$

$$\alpha_{\ell m} = a_\ell + b_\ell\left\{\underbrace{\frac{x^2}{x^2-1} + \frac{5}{6}\frac{x^2}{1-x^{5/3}}}_{\text{Resonant part}} + \frac{x^2}{\sqrt{\epsilon}}\left[\underbrace{\cos\left(\Omega'\hat{t}^2\right)\int_{-\infty}^{\hat{t}}\sin\left(\Omega' s^2\right){\rm d}s - \sin\left(\Omega'\hat{t}^2\right)\int_{-\infty}^{\hat{t}}\cos\left(\Omega' s^2\right){\rm d}s}_{\text{Fresnel Part}}\right]\right\}$$



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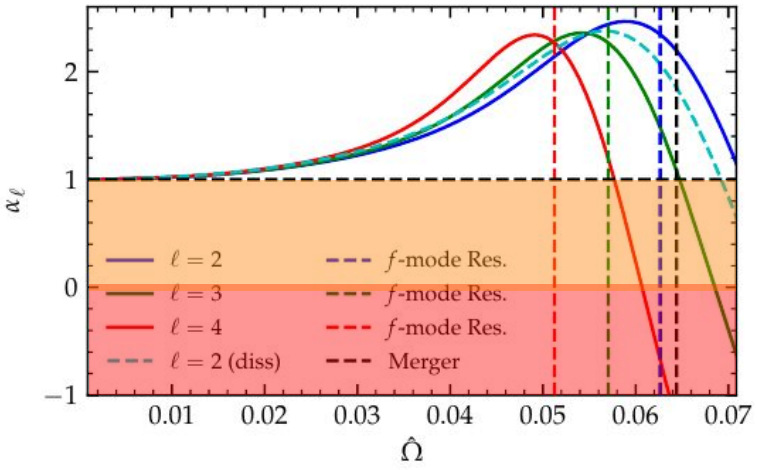


# Spin-induced effects

- The spinning motion of companion A creates a distortion in its mass distribution
- In turn, this distorts the gravitational field outside the star
- Clearly, this impacts the orbital motion and the emission of GWs

$$Q_A \simeq -a {\chi_A}^2 {m_A}^3$$

EOS dependent coefficient, can
be related to Λ

# “State of the art” BNS Waveform models

Current “state of the art” models include most of the effects previously discussed

Three families:

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

- **Effective One Body** approximants **(EOB)** [Bini+2012, Akcay+2018,Lackey+2018]
  - Semi-analytical, resummed PN + NR
  - Not-as-fast, generally
  - **Examples**: **TEOBResumS**, SEOBNRv4T (& related surrogate)

- **Phenomenological** approximants **(Phenom)** [Dietrich+2017,Kawaguchi+2018,Dietrich+2019]
  - Fits to PN+EOB+NR
  - Fast
  - **Examples**: (any BBH inspiral model) + NRTidal, NRTidalv2, Kawaguchi+ model

# PN Waveform models (TaylorF2)

$$\tilde{h}^{\rm spa}(f) = \frac{a(t_f)}{\sqrt{\dot{F}(t_f)}} e^{i[\psi_f(t_f)-\pi/4]}, \quad \psi_f(t) \equiv 2\pi f t - 2\,\phi(t).$$

$$t_f = t_{\rm ref} + M \int_{v_f}^{v_{\rm ref}} \frac{E'(v)}{\mathcal{F}(v)} dv,$$

$$\psi_f(t_f) = 2\pi f t_{\rm ref} - \phi_{\rm ref} + 2 \int_{v_f}^{v_{\rm ref}} (v_f^3 - v^3) \frac{E'(v)}{\mathcal{F}(v)} dv$$

**PN phase**: orbital + tides + spin +quadrupole-monupole

$$\boxed{\Psi(f) = \Psi_{\rm O} + \Psi_{\Lambda} + \Psi_{S} + \Psi_{\rm MQ}\,.}$$

**Matter contributions**

$$\boxed{\Delta\Psi(f) = \Psi^{\rm BNS}(f) - \Psi^{\rm BBH}(f) \approx \Psi_{\Lambda} + \Psi_{\rm MQ}}$$

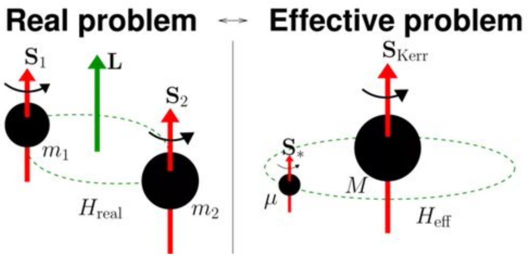
$$\boxed{\Psi_{\rm MQ} = \frac{3}{128\nu} c_{\rm LO}^{\rm MQ} x^{-1/2} (1 + c_1^{\rm MQ,NLO} x + c_{3/2}^{\rm MQ,tail} x^{3/2})}$$

$$\boxed{\Psi_{\Lambda} = c_{\rm LO}^{\Lambda} x^{5/2} (1 + c_1^{\Lambda} x + c_{3/2}^{\Lambda} x^{3/2} + c_2^{\Lambda} x^2 + c_{5/2}^{\Lambda} x^{5/2})}$$

**Quadrupole-Monupole** (or spin-spin)

**Tides**

# EOB Waveform models




Three ingredients:

- **Hamiltonian**

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

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

The Hamiltonian can describe the dynamics along generic orbits

- **Waveform**

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

- **Radiation Reaction**

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

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

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

# EOB Waveform models

- In the metric and hamiltonian:

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

$$\boxed{A = A_0 + A_T}$$

$$\boxed{B = D/A = B_0 + B_T}$$

[Nagar+2018]

$$\boxed{r_c^2(r, \tilde{a}_A, \tilde{a}_B)^{\rm NNLO} = r^2 + \tilde{a}_Q^2\left(1 + \frac{2}{r}\right) + \frac{\delta a^2_{\rm NLO}}{r} + \frac{\delta a^2_{\rm NNLO}}{r^2}}$$

On **circular orbits** pr = 0 → main contribution through **A(r)**
**B(r) → non-circular correction**
**If the system is spinning, r→ rc = centrifugal radius (TEOBResumS)**

- In the waveform:

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

Currently, corrections available to (2,2), (2,1), (3,3), (3,2), (3,1), (4,4), (4,2)

# EOB: Enhancing tidal effects close to merger

EOB models which employ “just” PN, adiabatic tides are known to underestimate tidal effects w.r.t NR

→ SEOBNRv4T: dynamical tides [Hinderer+2016, Steinhoff+2016, Steinhoff+2021]

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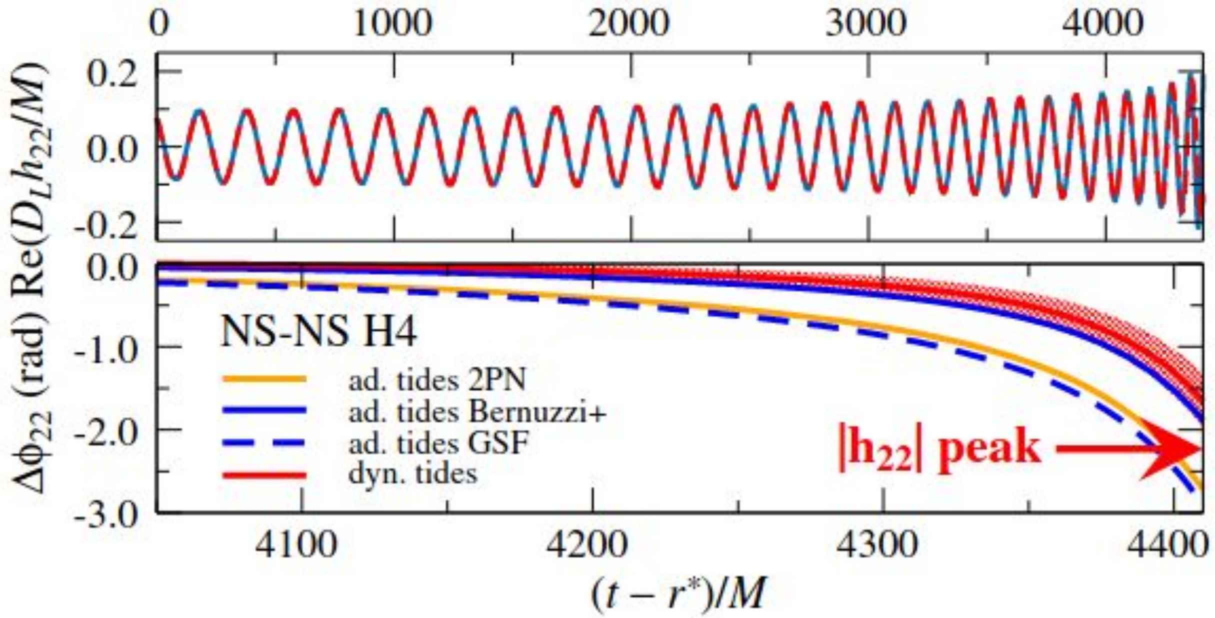
→ SEOBNRv4T: **dynamical tides** [Hinderer+2016, Steinhoff+2016, Steinhoff+2021]



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→ TEOBResumS: GSF resummation [Akcay+2018]

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$$A_{\mathrm{T}}(u) = \sum_{l\geq 2} A_A^{(\ell+)\mathrm{LO}}(u)\hat{A}_A^{(\ell+)}(u) + A_A^{(\ell-)\mathrm{LO}}(u)\hat{A}_A^{(\ell-)}(u) + (A \leftrightarrow B)$$

$$\boxed{\hat{A}_A^{(\ell+)}(u) = 1 + \alpha_{1A}^{(\ell+)}u + \alpha_{2A}^{(\ell+)}u^2 \ .}$$

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PN

$$\cancel{\hat{A}_A^{(\ell+)}(u) = 1 + \alpha_{1A}^{(\ell+)} u + \alpha_{2A}^{(\ell+)} u^2 \ .}$$

GSF

$$\boxed{\hat{A}_A^{(\ell\pm)}(u) = \hat{A}^{(\ell\pm)0\mathrm{GSF}} + X_A \underline{\hat{A}^{(\ell\pm)1\mathrm{GSF}}} + X_A^2 \hat{A}^{(\ell\pm)2\mathrm{GSF}}}$$

For +2,+3,-2 this term is resummed

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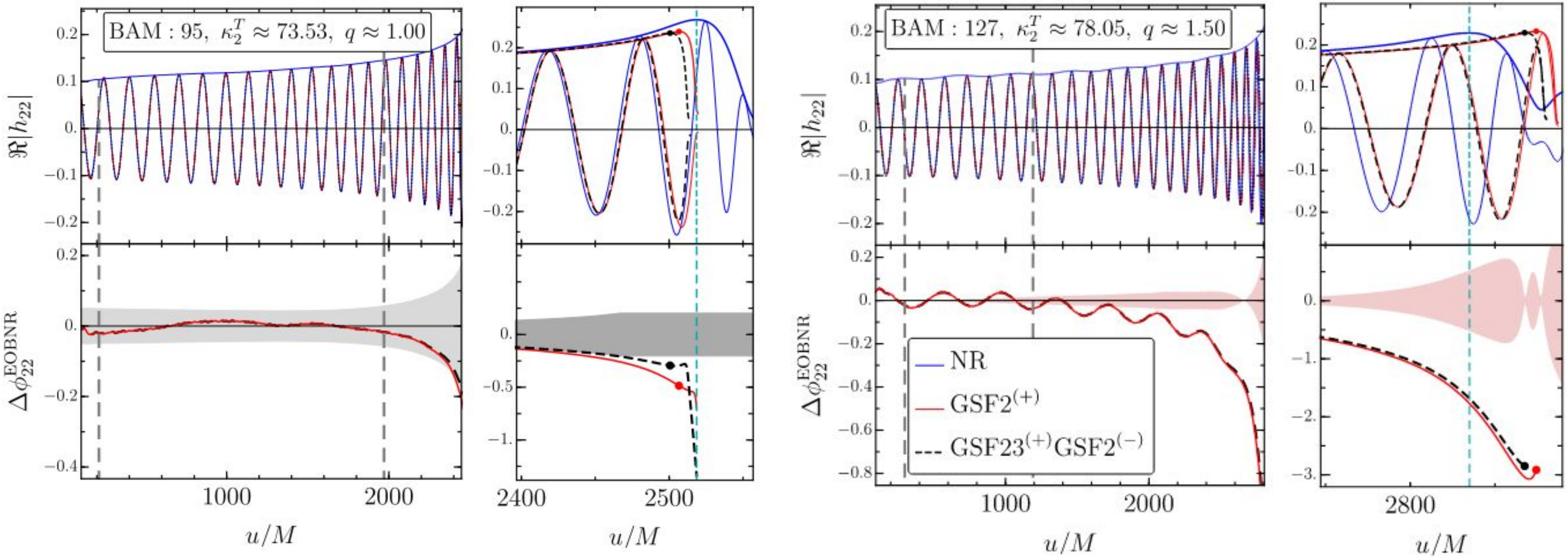


# Phenom Waveform models (NRTidalv2)

Dietrich+2019

## Phase

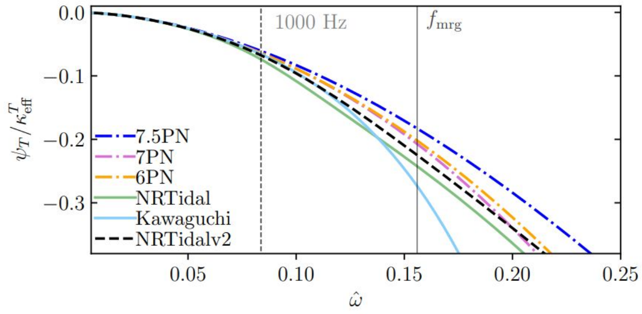
$$\psi_T(x) = -\kappa^T_{\rm eff}\frac{39}{16\nu}x^{5/2}\tilde{P}_{\rm NRTidalv2}(x) \qquad \psi_{\rm SS} = \frac{3x^{-5/2}}{128\nu}\left(\hat{\psi}^{(A)}_{\rm SS,\,2PN}x^2 + \hat{\psi}^{(A)}_{\rm SS,\,3PN}x^3 + \hat{\psi}^{(A)}_{\rm SS,\,3.5PN}x^{7/2}\right) + [A \leftrightarrow B]$$

$$\tilde{P}_{\rm NRTidalv2}(x) = \frac{1 + \tilde{n}_1 x + \tilde{n}_{3/2}x^{3/2} + \tilde{n}_2 x^2 + \tilde{n}_{5/2}x^{5/2} + \tilde{n}_3 x^3}{1 + \tilde{d}_1 x + \tilde{d}_{3/2}x^{3/2} + \tilde{d}_2 x^2}$$

## Amplitude

$$\tilde{A}_T^{\rm NRTidalv2} = -\sqrt{\frac{5\pi\nu}{24}}\frac{9M^2}{D_L}\kappa^T_{\rm eff}x^{13/4}\frac{1 + \frac{449}{108}x + \frac{22672}{9}x^{2.89}}{1 + d\,x^4}$$

Dashed circles: coefficients fit to NR simulations + hybrids



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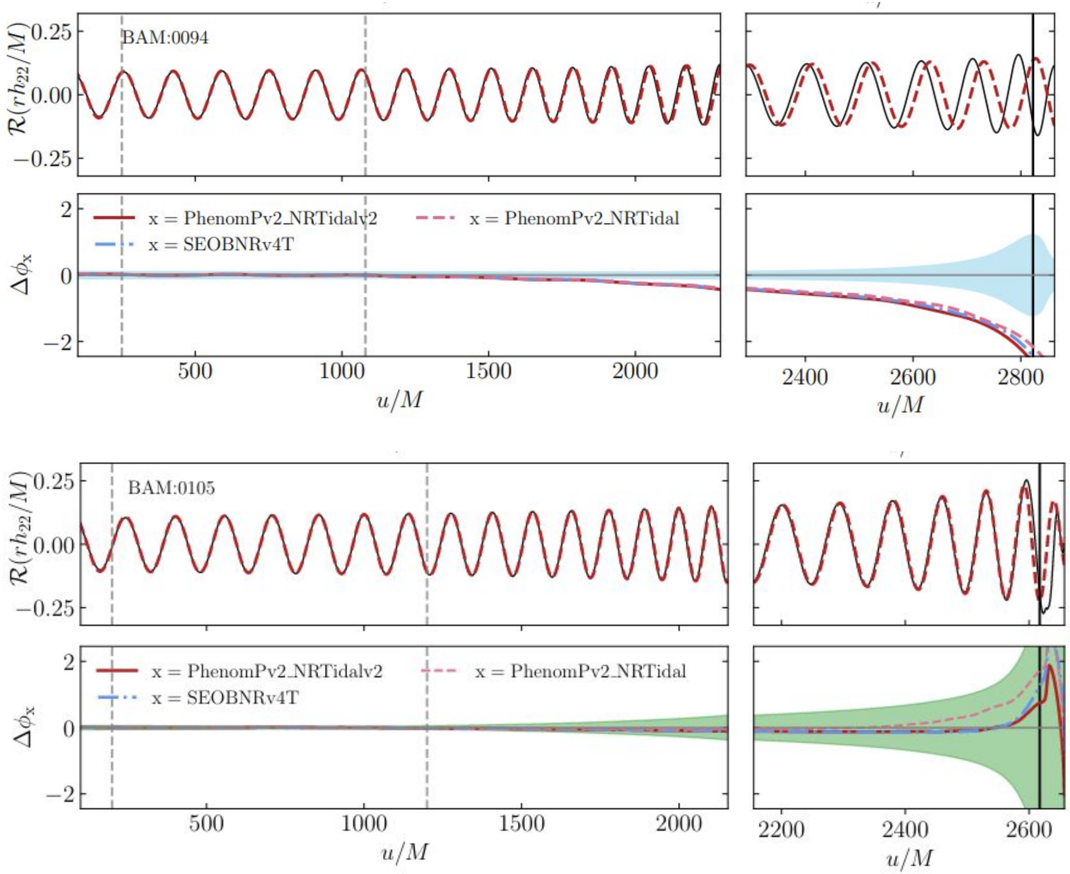
Dietrich+2019



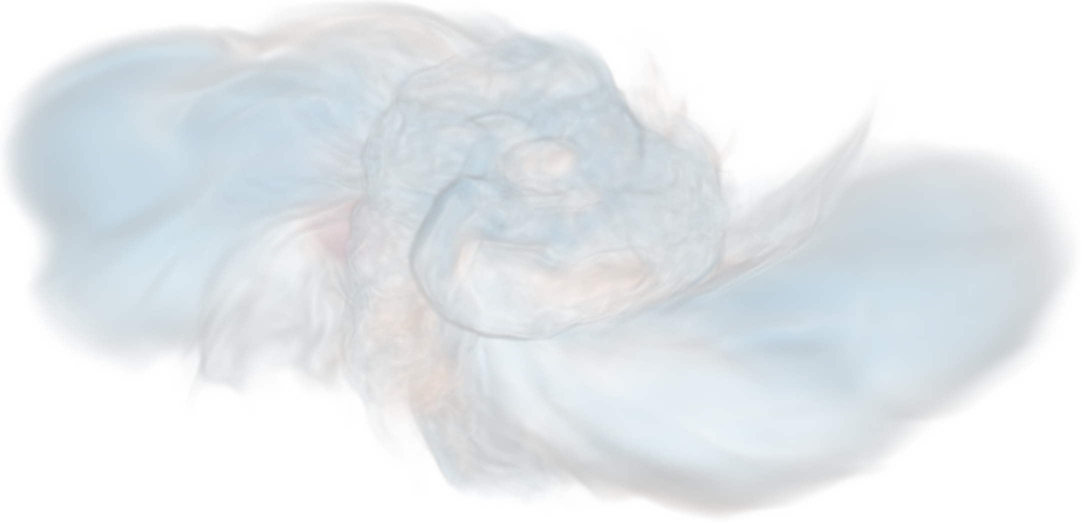

Much like EOB, while the inspiral is modelled well, the merger description is still not entirely satisfactory for some configurations

# Summary Table

| | TaylorF2 | TEOBResumS | SEOBNRv4T | PhenomDNRT | PhenomPNRTv2 |
|---|---|---|---|---|---|
| **Adiabatic tides** | 2.5 PN | 2.5 PN in Hamiltonian | 2.5 PN in Hamiltonian | 1PN | 2.5PN |
| **Dynamic tides** | yes | no* | yes | no | no |
| **spin-spin** | NNLO | NNLO (resummed) | NNLO (resummed) | no | NNLO (PN) |
| **Additional notes** | ---- | GSF-resummation, ell=2,..,8 electric contributions; ell=2 magnetic contributions; Higher modes in wf | BBH NQC corrections; ell=2,3 electric contributions; | NR fits for phase and amplitude, padé resummed | NR fits for phase and amplitude, padé resummed |

*yes as of last week :)

# 2. Waveform systematics and effect on the NS radius



# The problem of PE

In modelled analyses waveform templates are necessary to extract the signal

Different waveform models may recover different source parameters → waveform systematics

- How large is the effect of waveform systematics on tidal parameters/R
- How will this affect future detectors?

# How should we study systematics?

Many waveform models, very different between each other → systematics are expected!

To study them, we should:

- Compare the approximants in a meaningful way and understand the general behavior of the models w.r.t. one another
- Test our understanding via injection-recovery studies

Note: **both** are needed! We are not really understanding systematics if we don’t understand the structural differences between the models.

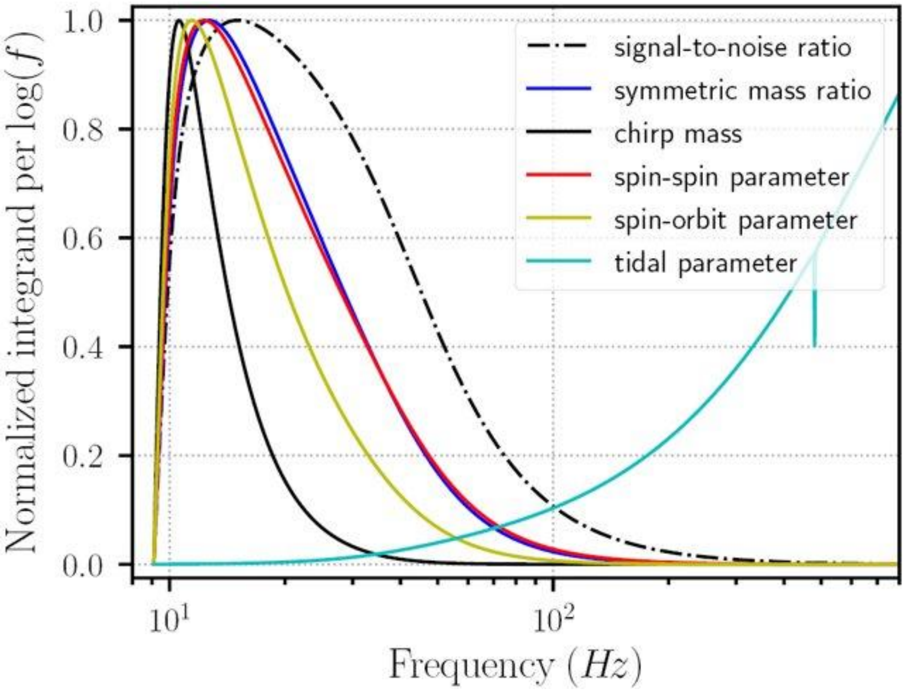
# Measurability of Tidal parameters

[Damour+2012,Harry+2018]

**Fisher matrix**: estimate of the statistical error on a parameter "i" in the high signal to noise ratio regime

$$\sigma_i^2 = (F^{-1})_{ii}$$

$$F_{ij} = (\partial_i h|\partial_j h) \simeq 4\Re \int \boxed{\frac{\tilde{A}_h^2}{S_n} (\partial_i \Psi_h \partial_j \Psi_h)} \mathrm{d}f,$$




The integrand indicates at which frequencies most of the information on a certain parameter is located

**Tidal effects** are measured at **high (> 100 Hz ) frequencies**, where the noise of the detector is large

# Comparison of approximants

[Gamba+2020]

Direct comparisons of the GW phase are tricky due to alignment issues

To overcome the problem, one can use a “gauge invariant” quantity:

$$Q_{\hat\omega} = \frac{\hat\omega^2}{\dot{\hat\omega}} = \frac{\mathrm{d}\phi(t)}{\mathrm{d}\ln\hat\omega}$$

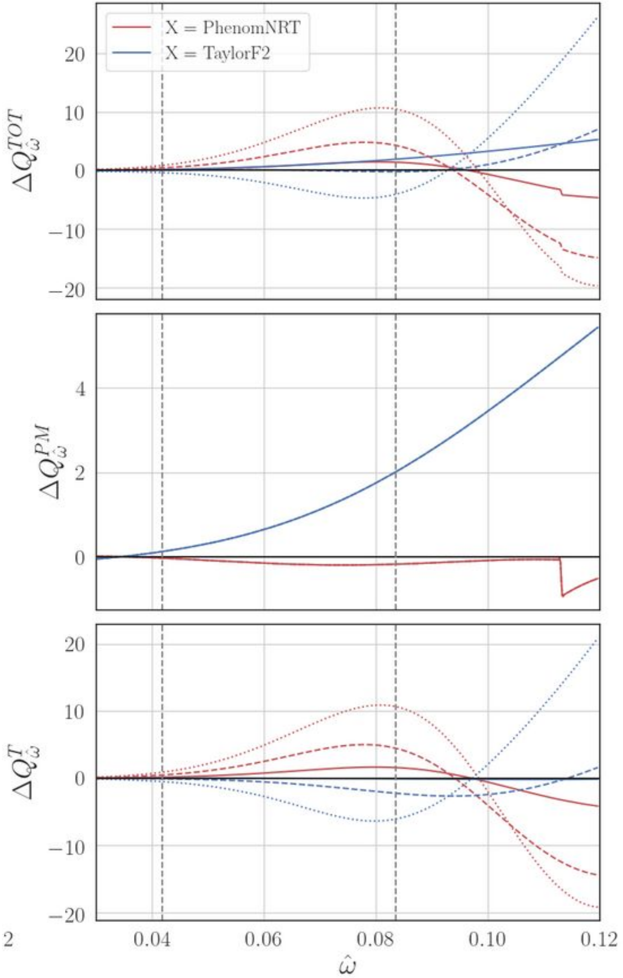
And compute

$$\Delta Q_{\hat\omega} = Q^Y_{\hat\omega} - Q^X_{\hat\omega}$$

Then, for a fixed value of omega, if the difference is positive:

$$\begin{aligned} Q^Y_{\hat\omega} &> Q^X_{\hat\omega} \\ 1/\dot{\hat\omega}^Y &> 1/\dot{\hat\omega}^X \\ \dot{\hat\omega}^X &> \dot{\hat\omega}^Y \end{aligned}$$

X is more attractive (faster omega evolution) than Y at that frequency



# Comparison of approximants

We observe that:

- **Phenom**'s tidal effects are **more attractive** (stronger) than TEOB's and its point mass description is close to TEOB's
  $\longrightarrow$ <u>smaller $\Lambda$ than TEOB</u>

- **TF2**'s tidal effects are **more repulsive** (weaker) than TEOB's and the difference between TF2's point mass and TEOB's is large and positive. It partially compensates for the negative
  $\longrightarrow$ <u>larger $\Lambda$ than TEOB</u>

# Injection study

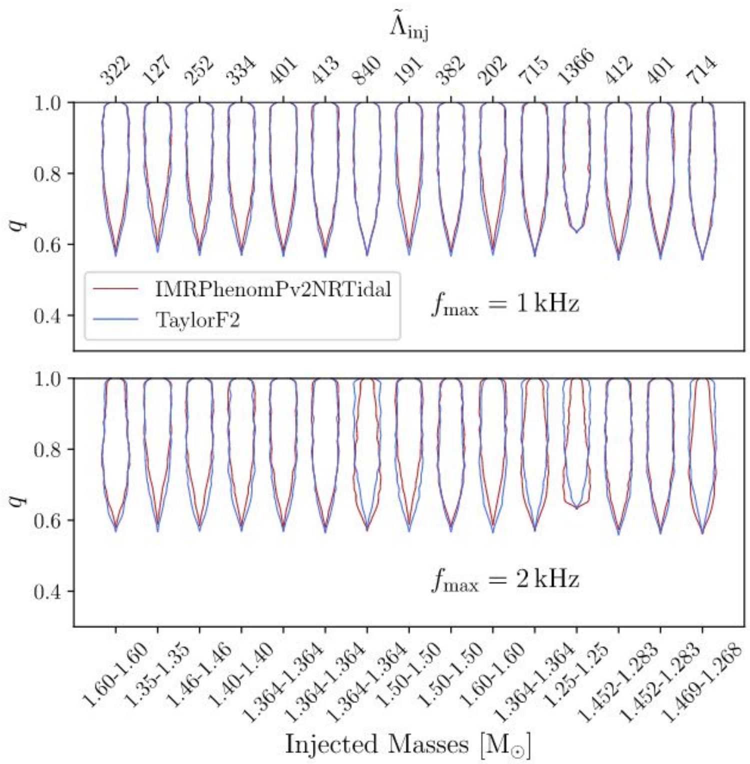
Injection-recoveries with LALInference:

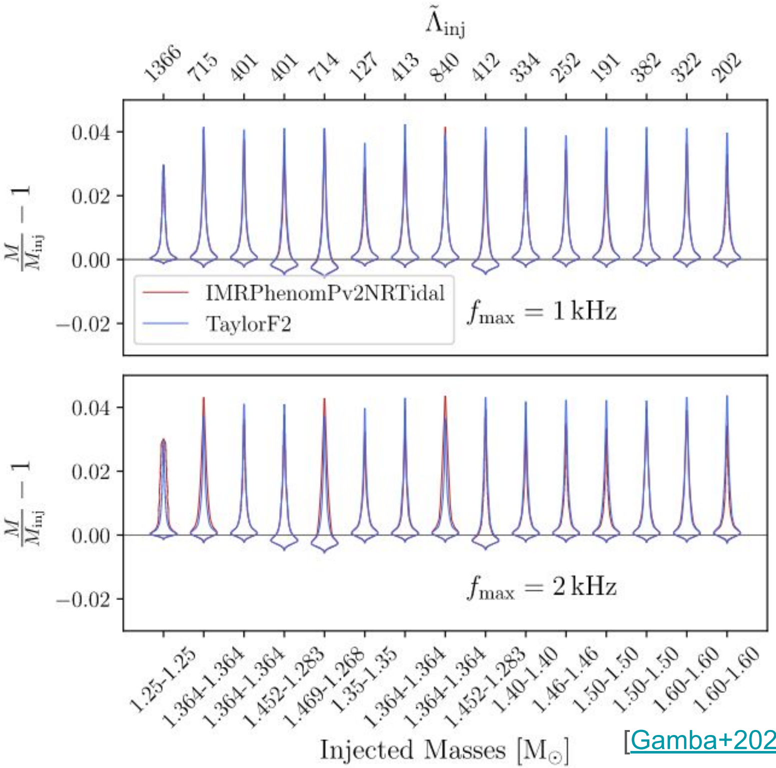
- 15 **TEOBResumS** waveforms with varying $\tilde{\Lambda}$ and masses;
- GW170817's sky location;
- Advanced LIGO and Virgo design PSD;
- Zero-noise configuration;
- Two cutoffs: 1024 Hz and 2048 Hz
- Recovery with **IMRPhenomPv2NRTidal** (Phenom) and **TaylorF2** (TF2)
- SNR > 80

| EOS | $M_{\rm inj}$ | $q_{\rm inj}$ | $\tilde{\Lambda}_{\rm inj}$ |
|---|---|---|---|
| 2B | 2.70 | 1.00 | 127 |
| SLy | 3.00 | 1.00 | 191 |
| LS220 | 3.20 | 1.00 | 202 |
| SFHo | 2.92 | 1.00 | 252 |
| DD2 | 3.18 | 1.00 | 332 |
| SFHo | 2.80 | 1.00 | 334 |
| ALF2 | 3.00 | 1.00 | 382 |
| SLy | 2.68 | 1.00 | 401 |
| SLy | 2.69 | 0.88 | 401 |
| SFHo | 2.72 | 0.88 | 412 |
| SFHo | 2.71 | 1.00 | 413 |
| LS220 | 2.69 | 0.86 | 714 |
| LS220 | 2.68 | 1.00 | 715 |
| DD2 | 2.71 | 1.00 | 840 |
| DD2 | 2.48 | 1.00 | 1366 |

# Injections: early inspiral parameters

Total mass and mass ratio are (usually) recovered quite well!



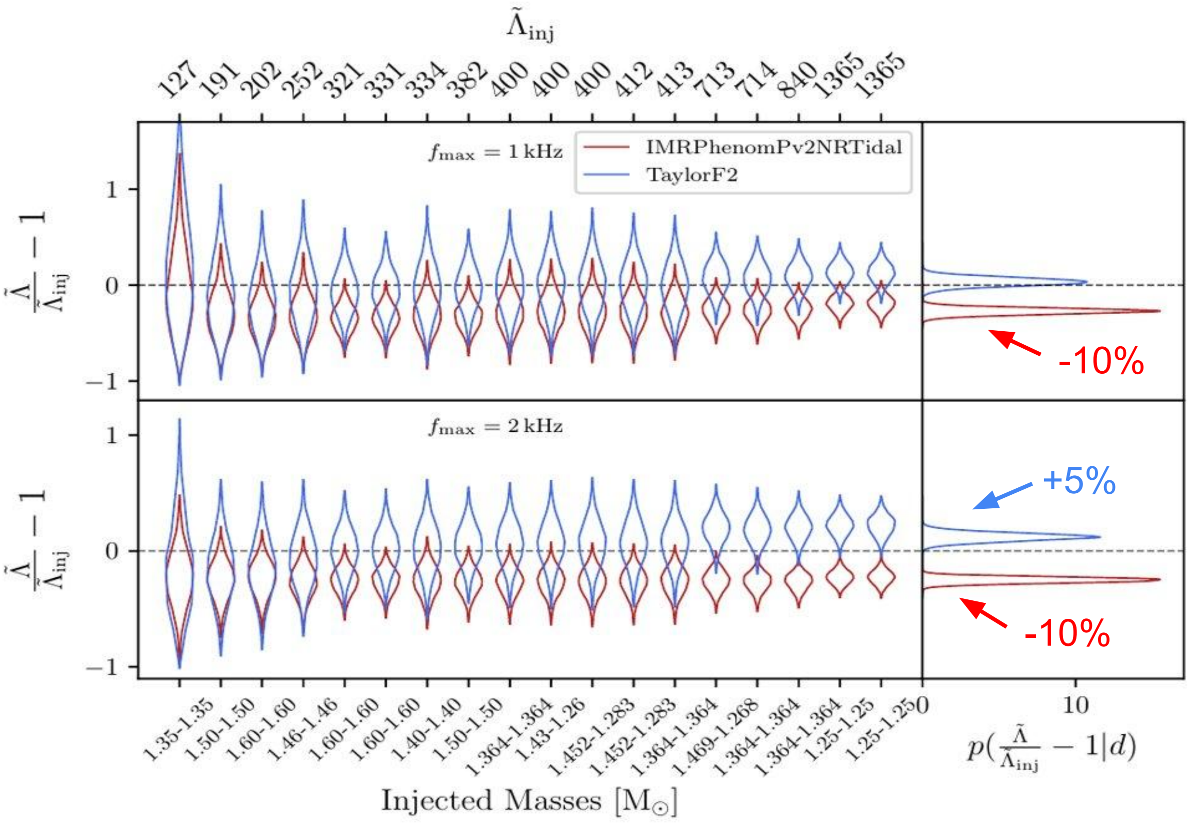




[Gamba+2020]

# Injections: $\tilde{\Lambda}$ recovery

**Our qualitative expectations are roughly confirmed!**

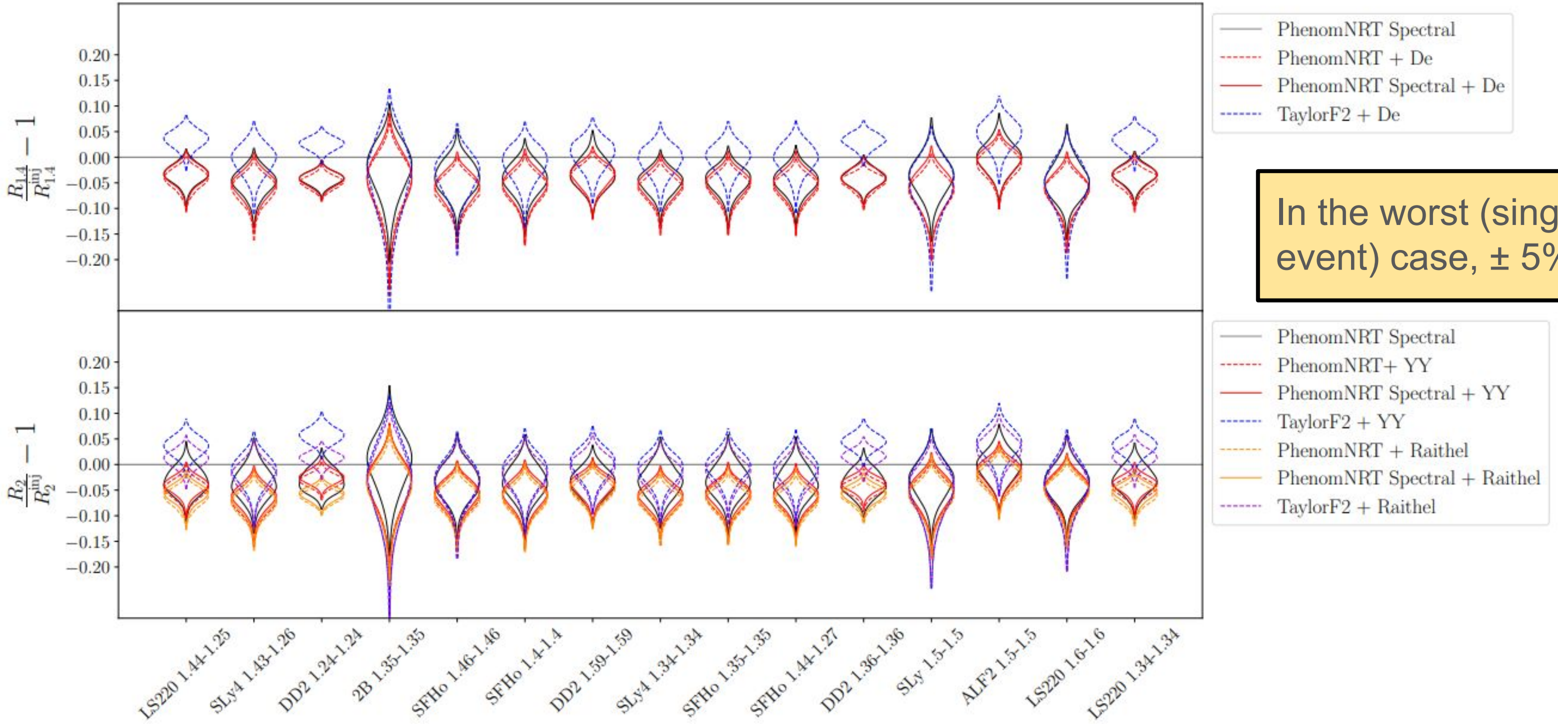
Relative difference between recovered and injected Lambda




"Cumulative" difference between recovered and injected Lambdas

[Gamba+2020]

# Injections: $\tilde{\Lambda}$ recovery



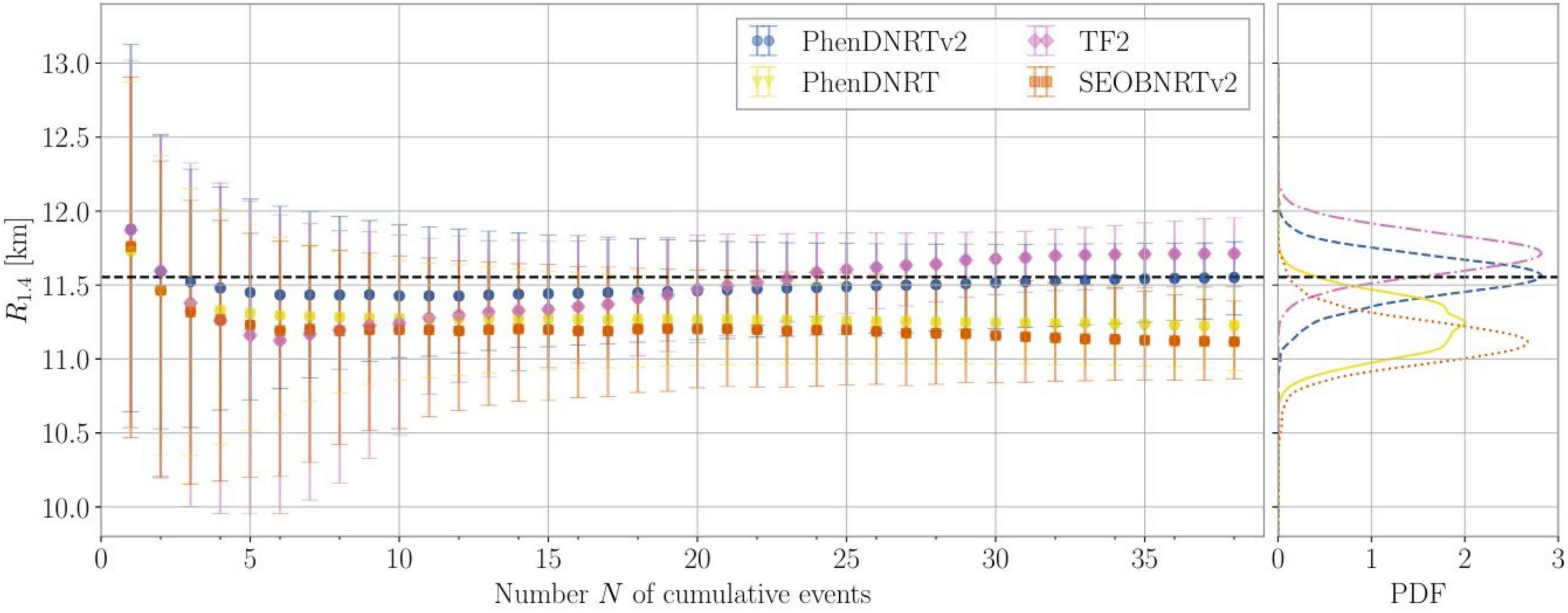

In the worst (single event) case, ± 5%

[Gamba+2020]

# Injections: R

~ 5% error on the radius, the qualitative picture we observed is the same

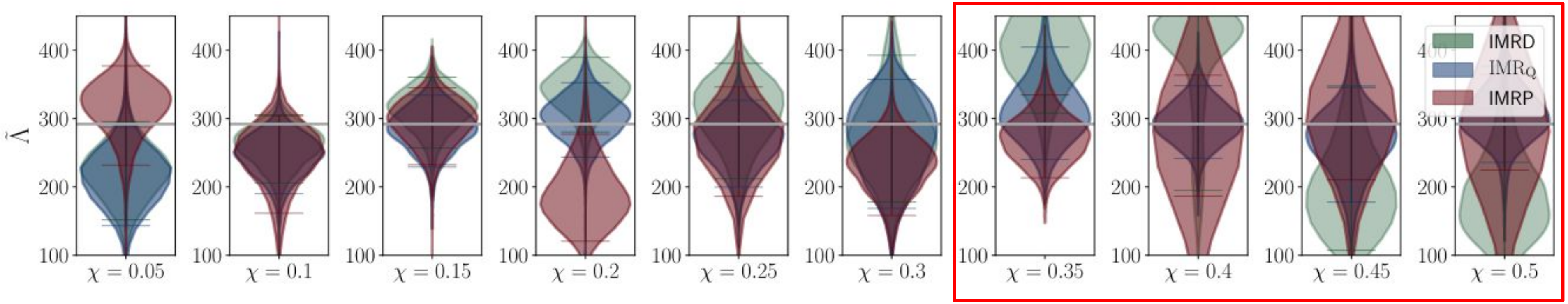
[Kunert+2021]



# Injections: importance of spin-induced effects

Quadrupole-monupole terms too can bias the inference of tidal parameters for highly spinning NS

Samajdar+2019

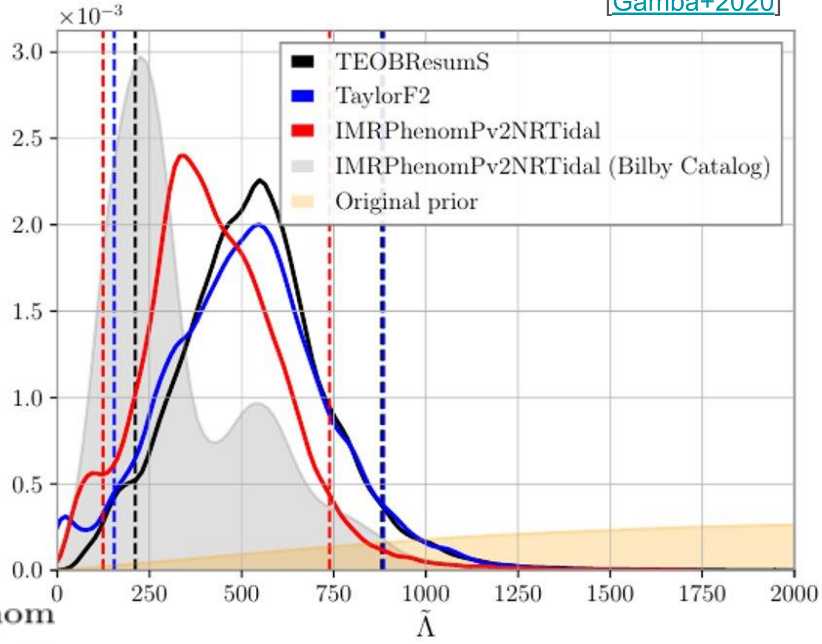


# Real data: GW170817

[Gamba+2020]

Analysis setup:

- Parallel bilby;
- Very smilar priors/config as bilby catalog, but...
  - **1 kHz frequency cutoff**
  - Small aligned spins (< 0.05)
- Waveform systematics are smaller than statistical error, but $\tilde{\Lambda}^{\mathrm{TF2,TEOB}} > \tilde{\Lambda}^{\mathrm{Phenom}}$
- We find $R = 12.5^{+1.1}_{-1.8}$ km




| Approximant | $\ln p(d\|\mathrm{Approx.})$ |
|---|---|
| TaylorF2 | $523.078 \pm 0.102$ |
| TEOBResumS | $522.585 \pm 0.102$ |
| IMRPhenomPv2NRTidal | $522.261 \pm 0.103$ |

# Real data: GW170817 (again!)

To account for uncertainties in the approximants, one can:

1. combine samples...
2. ...and/or reweight based on the model evidence

Along the second line, new paper yesterday! [Dietrich+2021]

Main idea: sample not only binary parameters but also waveform models

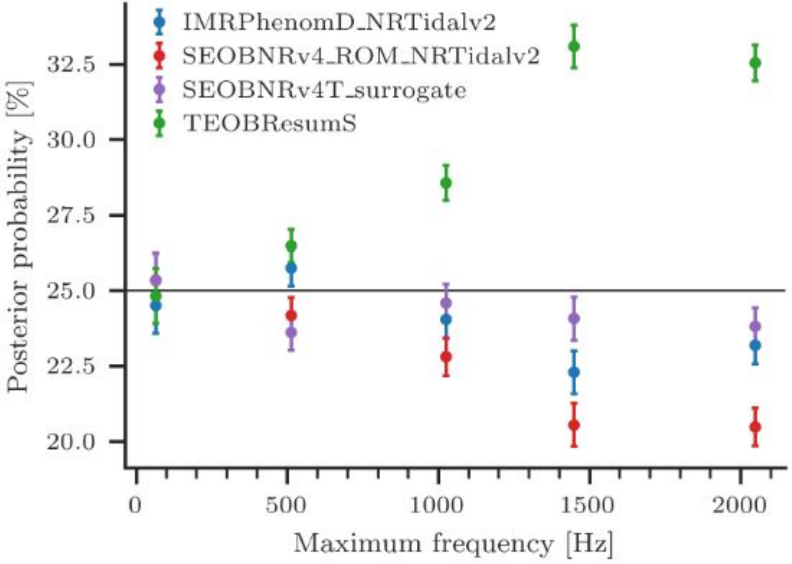
$$p(\boldsymbol{\theta}|\mathbf{d},\Omega) \propto \mathcal{L}(\mathbf{d}|\boldsymbol{\theta},\Omega)\pi(\boldsymbol{\theta}|\Omega)\,,$$

$$\Omega = \{\Omega_0, \Omega_1, \ldots \Omega_{n-1}\}$$

Bayesian odds between two models

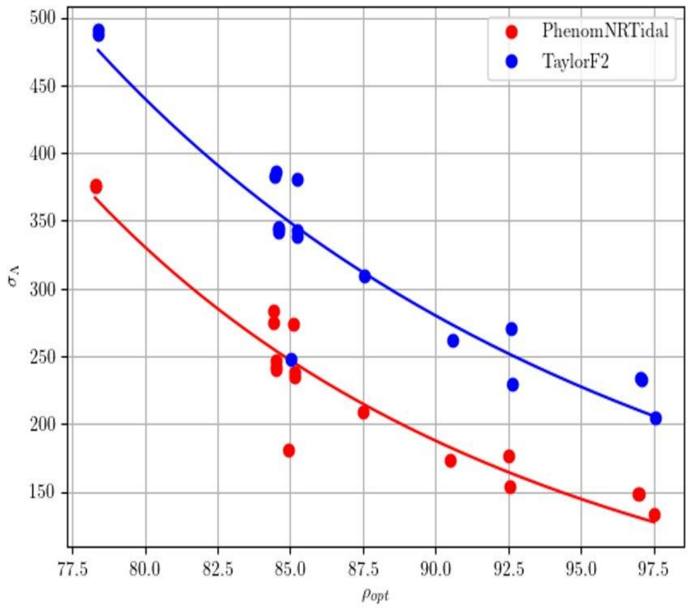
$$\mathcal{O}_{A/B} = \frac{p_A}{p_B}$$

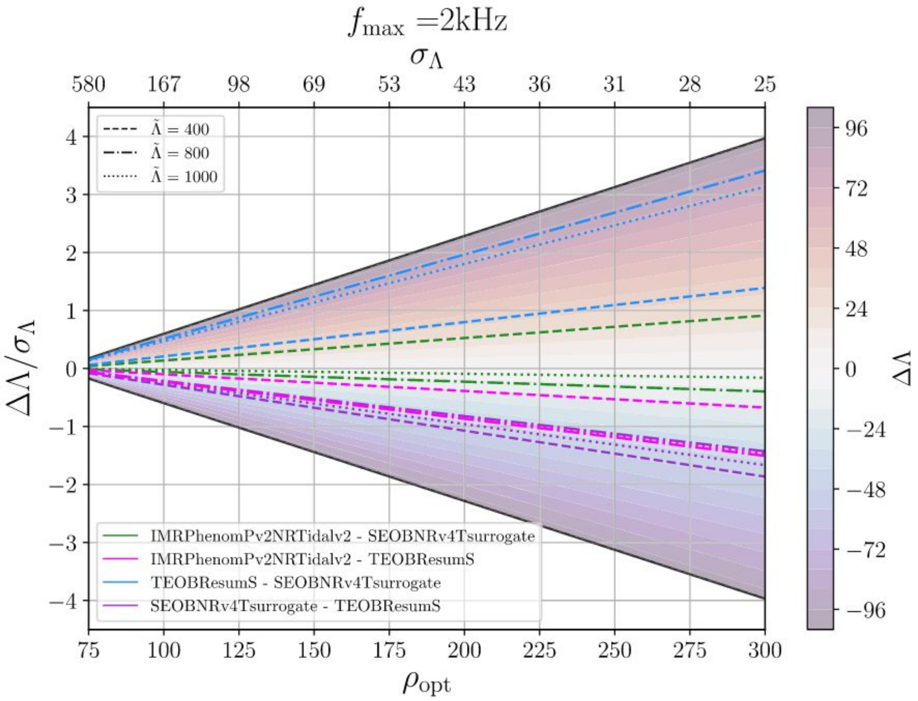
Way to “marginalize” over approximants uncertainty



# Future data: 3G, high SNR events

- Estimate of the error on $\tilde{\Lambda}$ by fitting the width of the injections of slide 34
- Comparison between expected difference and error for state of the art approximants



# Future data: 3G, high SNR events

- Higher order effects will become measurable, and give different estimates based on their inclusion (or not)

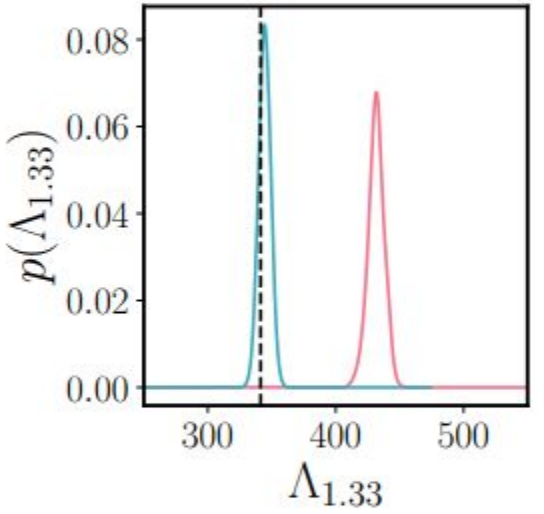
- Proof of principle:

  **TaylorF2+adiabatic tides+dynamical tides**

  vs

  **TaylorF2+adiabatic tides**

[Pratten+2021]




Comments: 6 pages, 3 figures, comments and feedback welcome!
Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE);**

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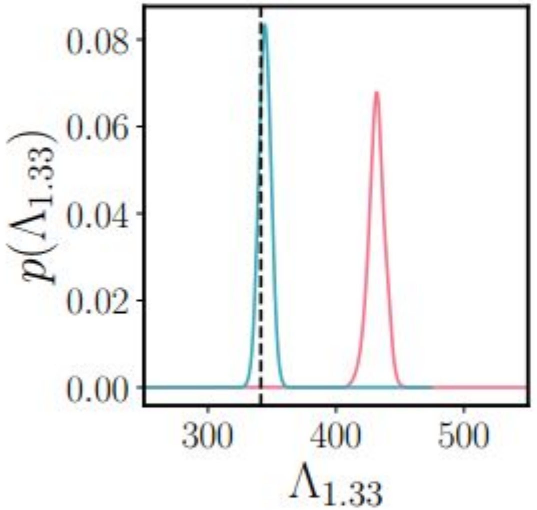


Comments: 6 pages, 3 figures, comments and feedback welcome!
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My **personal** opinion: I don't believe in dynamical tides more than I believe in GSF resummation (=would not do PE on dyn. tides parameters), but it is an interesting study showing that even high order PN uncertainty can bias our inference for 3G detectors

# Numerical Relativity

- Need of better NR simulations to understand the strong field behavior
- However, NR too is flawed!
- We consider a handful of BAM simulations taken from the CoRe database ([GW database](GW database))
- Faithfulness threshold:

$$\mathcal{F} > 1 - \frac{\epsilon^2}{2\,\rho^2} \qquad \mathcal{F} = \max_{t_c,\phi_c} \frac{(h|k)}{\sqrt{(h|h)(k|k)}}$$

- For SNR > 80 no simulation exceeds the theoretical faithfulness threshold
- **Current NR simulations might not be faithful enough to inform waveform models**

TABLE V. Faithfulness values $\mathcal{F}$ computed considering frequencies from $f_{\rm low}$ to $f_{\rm mrg}$ between simulations with the same intrinsic parameters and two different resolutions, extracted at $r/M = 1000$. The source is situated in the same sky location as GW170817, and the waveform polarizations $h_+$ and $h_\times$ are computed and projected on the Livingston detector. We employ the `aLIGODesignSensitivityP1200087` [23] PSD from `pycbc` [115] to compute the matches and compare the values obtained to the thresholds $\mathcal{F}_{\rm thr}$ calculated with Eq. (19) with $\epsilon^2 = 1$ or $\epsilon^2 = 6$. A tick ✓ indicates that $\mathcal{F} > \mathcal{F}_{\rm thr}$. Conversely, a cross ✗ indicates that $\mathcal{F} < \mathcal{F}_{\rm thr}$.

| | | | SNR | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 14 | | 30 | | 80 | |
| Sim | n[a] | $\mathcal{F}$ | 6 | 1 | 6 | 1 | 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 | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ |

[a]Number of grid point (linear resolution) of the finest grid refinement, roughly covering the diameter of one NS.

# Conclusions

- To **understand** waveform systematics, it necessary to compare the models and not “just” rely on injection-recovery studies
- Waveform systematics relevant already at design sensitivity…
- ...And dominant for 3G detectors!
- Waveform models **must** improve
- Numerical relativity simulations, too, must improve (higher resolutions, more physics)