Title: Hybrid waveforms for binary black holes with aligned spins: Matching errors and a phenomenological model in the frequency domain

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Abstract: We present a new construction of phenomenological templates for non-precessing spinning black hole binaries. This approach utilizes a frequency domain matching of post-Newtonian inspiral waveforms with numerical relativity based binary black hole coalescence waveforms. We quantify the various possible sources of systematic errors that could arise in matching post-Newtonian and numerical relativity waveforms and we use a matching criteria based on minimizing these errors. An analytical formula for the dominant mode of the gravitational radiation of non-precessing black-hole binaries is presented that captures the phenomenology of the hybrid waveforms. Its implementation in the current searches for gravitational waves should allow cross-checks of other inspiral-merger-ringdown waveform families as well as an improvement of the reach of the detection algorithms.

Hybrid waveforms for binary black holes with aligned spins

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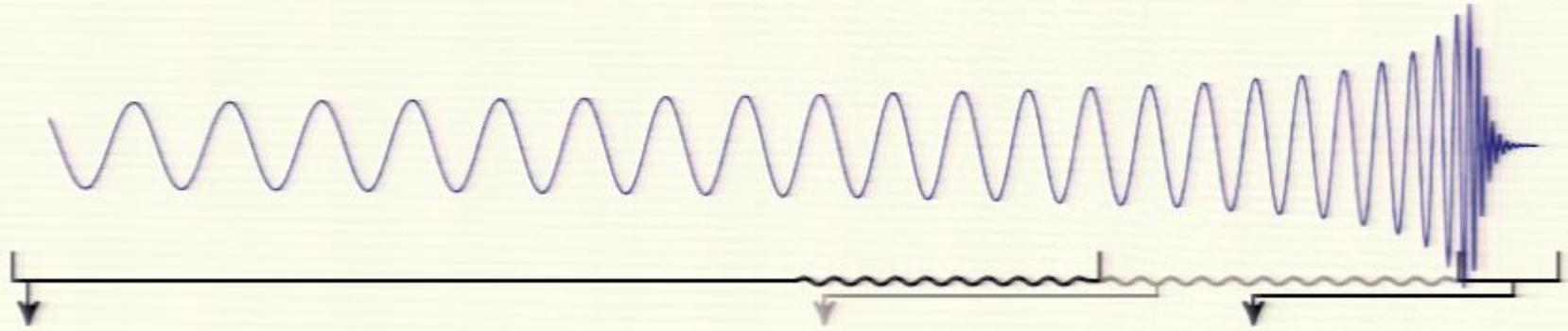
arXiv:1005.3306 [gr-qc]

in collaboration with L. Santamaría, P. Ajith, B. Brügmann, N. Dorband, M. Hannam, S. Husa, P. Mösta, D. Pollney, C. Reisswig, E. Robinson, J. Seiler and B. Krishnan

⇒ Detecting gravitational waves from compact binaries requires the knowledge of *accurate template signals*.



Focus on hybrid waveforms

- Used in NINJA 2
- Target signals to be modeled analytically

⇒ Natural limit of the accuracy of the final model

Assumptions

- Quasi-circular orbits
- No precession
- (Dominant spherical harmonic mode)

Fourier-domain hybrids

PN-NR hybrid waveforms

- 3.5 PN TaylorF2 phase + 3 PN amplitude
- `BAM, Llama, CCATIE, SpEC` waveforms.
  Mass-ratios $\leq 4/1$, spins aligned with orbital angular momentum

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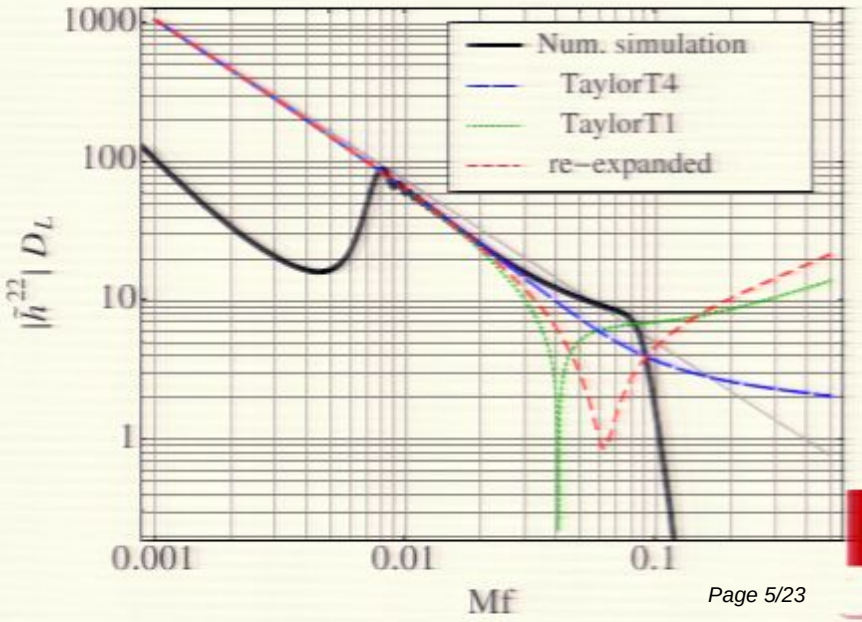
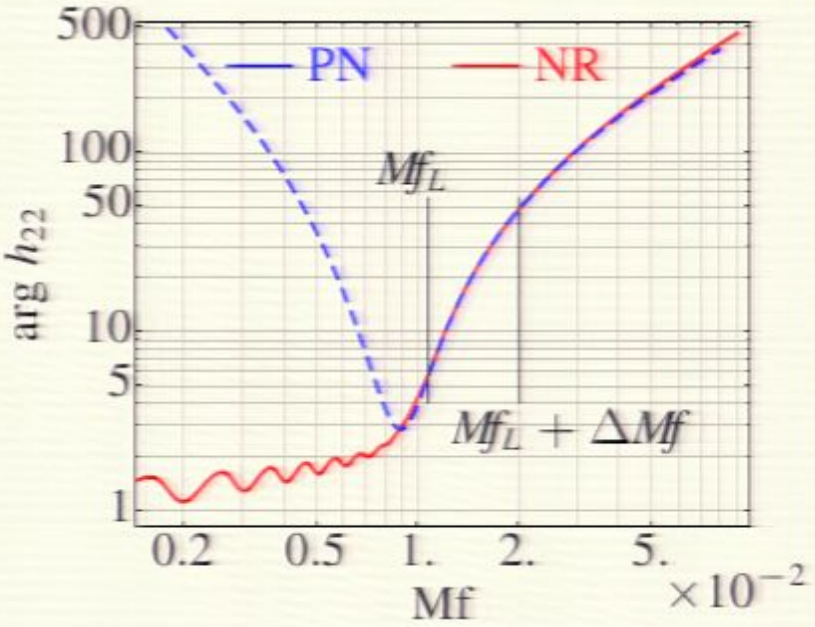
Stationary phase approx.

$$h(t) = Ae^{-i2\phi},\ \tilde{h}(f) = \tilde{A}e^{i\psi}$$

- $\psi = 2\pi f t_0 - \phi_0 + \sum_{k=0}^{7} \Psi_k f^{k/3}$
- $\tilde{A} \approx A(t_f)\sqrt{\frac{\pi}{\ddot{\phi}(t_f)}}$

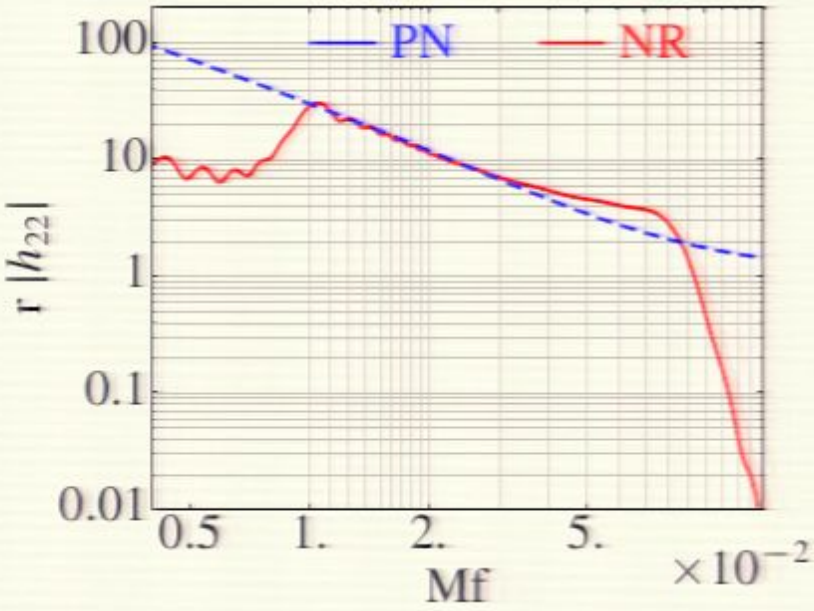


Phase



- t_0 and ϕ_0 fixed by least-square fitting

Amplitude



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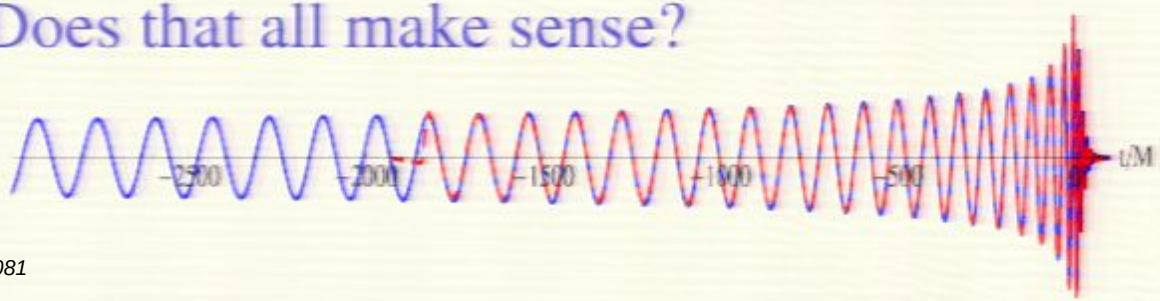
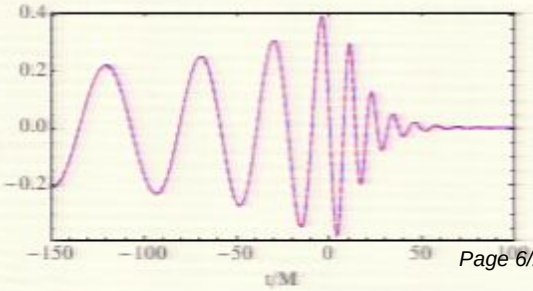


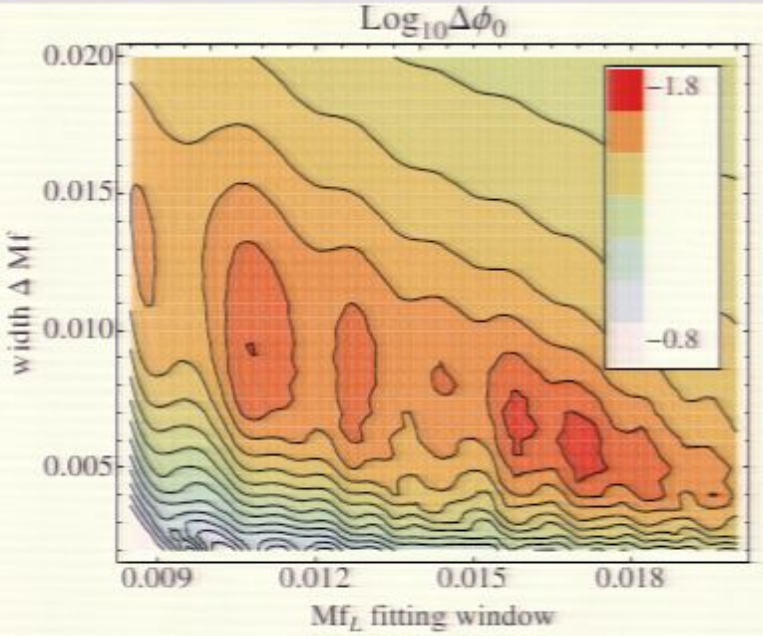


Choosing the fitting window

→ Analyzing the fitting error

Depending on:

- How long is the NR waveform?
- How much phase evolution is in the band?
- How well does PN resemble the NR phase?



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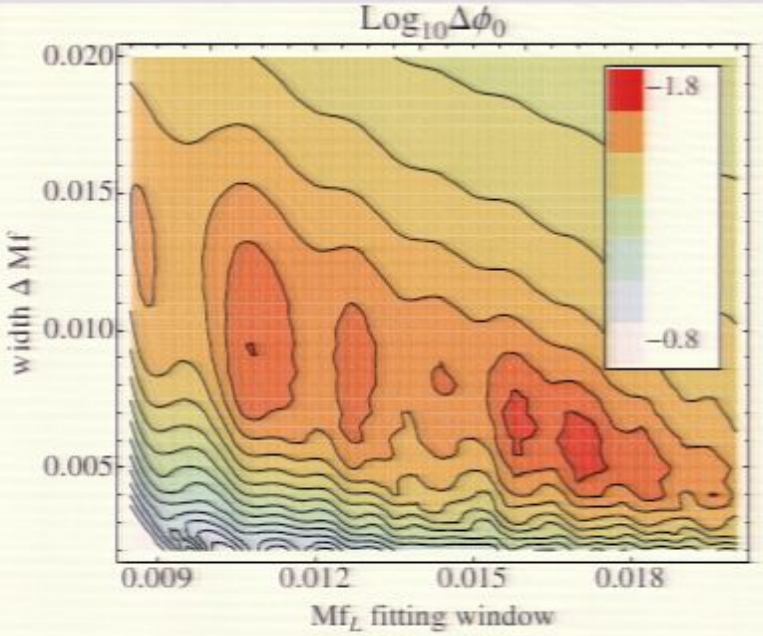
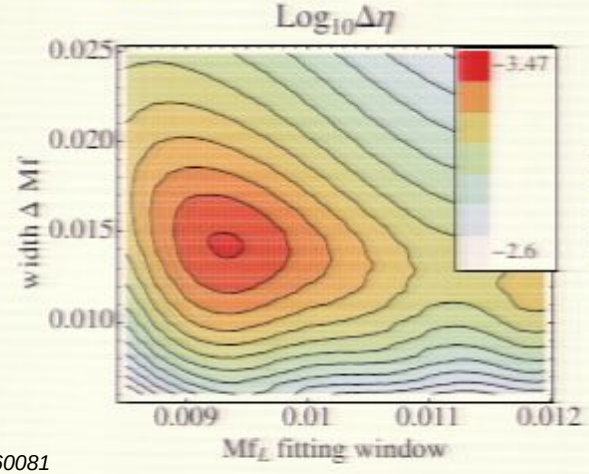
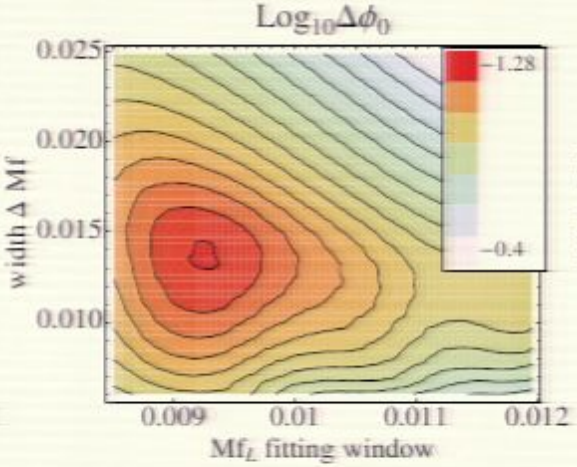
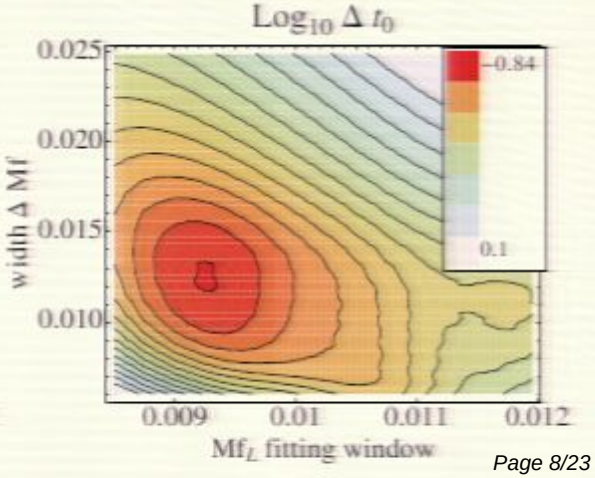


Fitting η as well

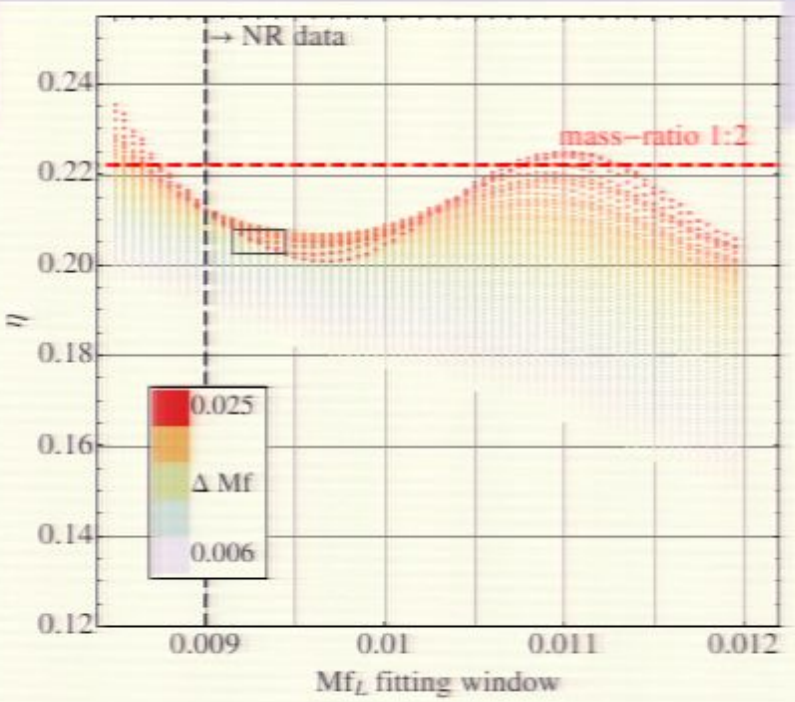






Choosing the fitting window

- PN and NR are formulated in different frameworks.
- The discrepancy in η is much larger than the numerical error.
- Bias of $\approx 10\%$ is not uncommon in PN-based searches
  [Buonanno *et al.* PRD 80, 084043 (2009)]



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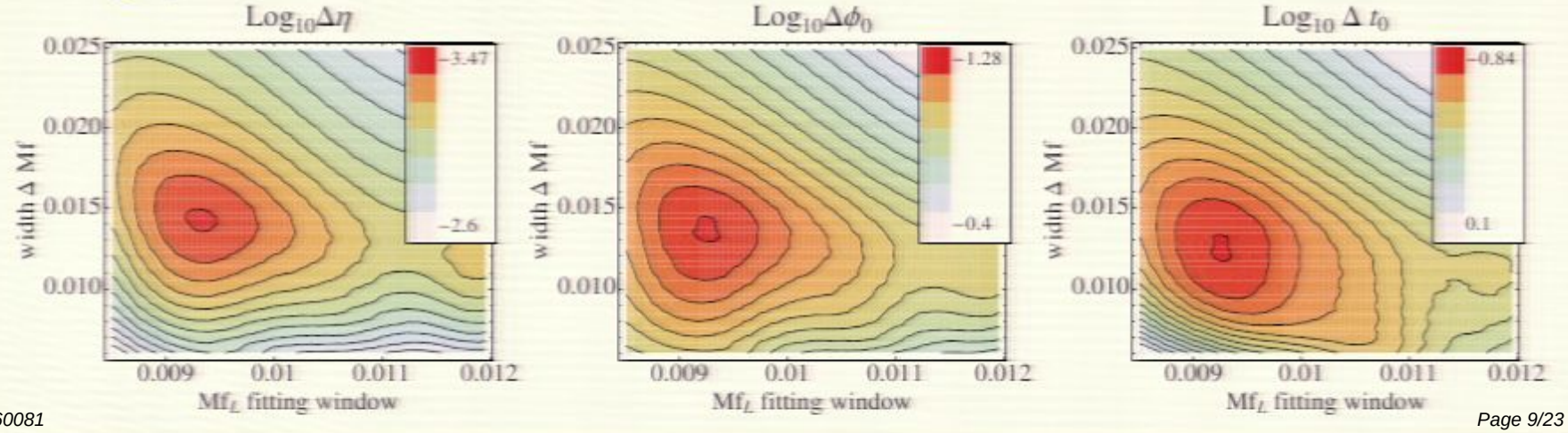

Ingredients I - NR

$$\|\Delta h\|^2 = \int_{f_{\text{low}}}^{f_{\text{high}}} \frac{|\tilde{h}_1 - \tilde{h}_2|^2}{S_n} df, \ \rho = \|h\|$$

- Indistinguishable: $\rho^{-2}\|\Delta h\|^2 \leq \rho^{-2}$
- Detection: $2m \approx \rho^{-2}\|\Delta h\|^2 \leq 2\epsilon$

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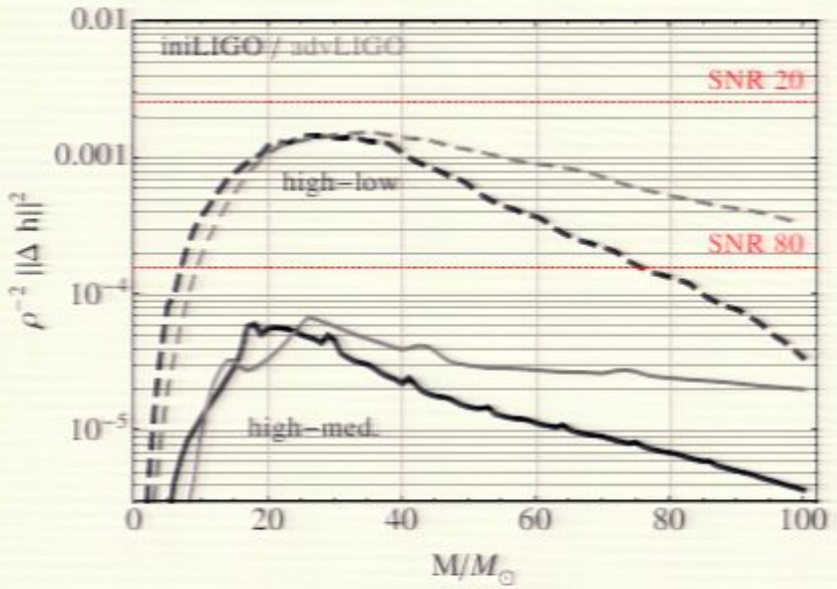
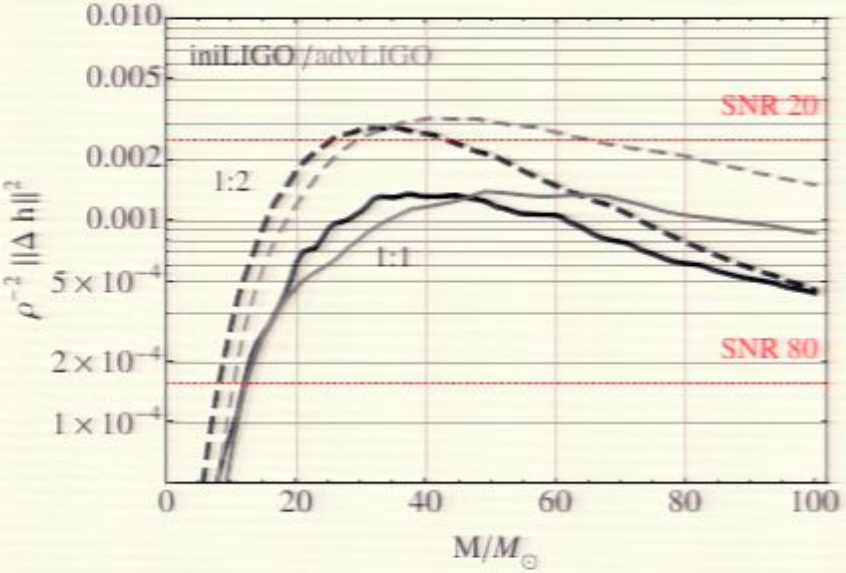
NR – Fixed matching window & PN part (F2)

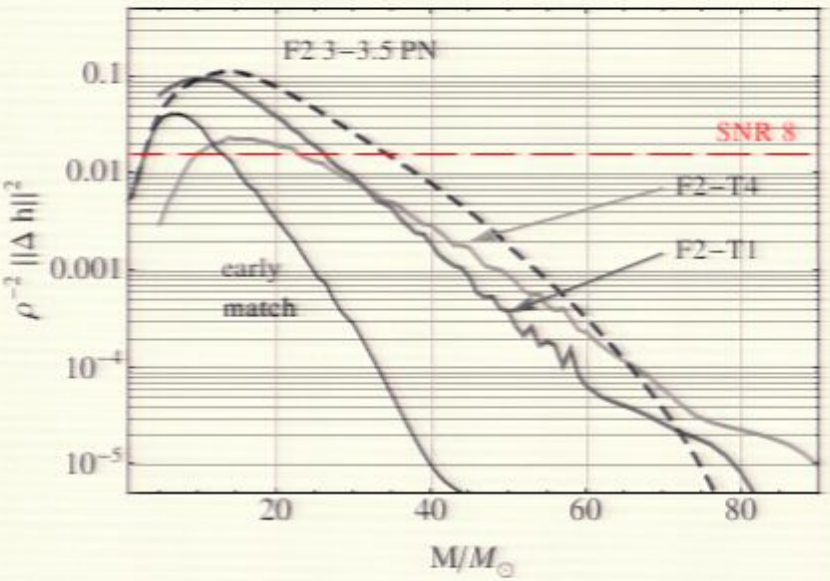




- Llama simulation with mass-ratio 1, non-spinning
- Resolution at wave extraction 0.64, 0.80, 0.96

- BAM and Llama simulations of non-spinning binaries with mass-ratio 1:1 and 1:2
- Differ at SNR 20 (advLIGO) for $30M_\odot \lesssim M \lesssim 65M_\odot$

PN – Fixed NR waveform



- SpEC equal-mass waveform
- Fixed matching window except *early match*

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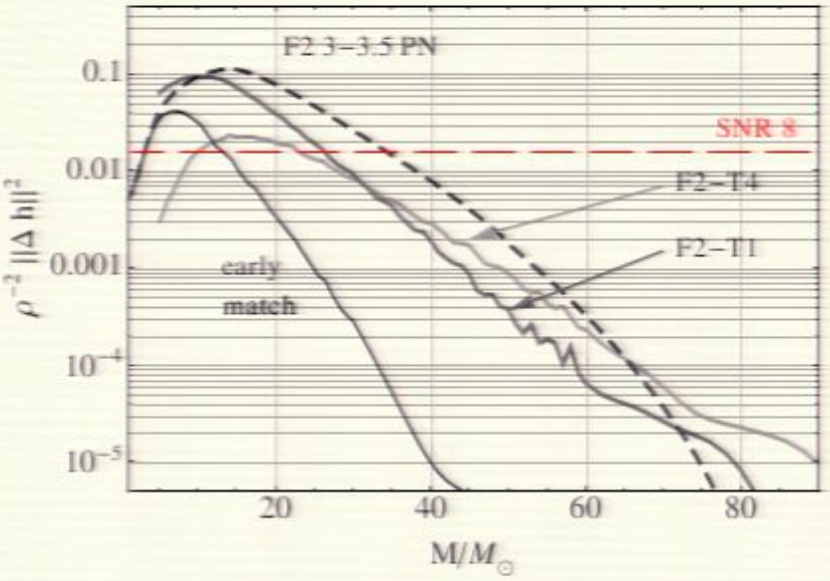

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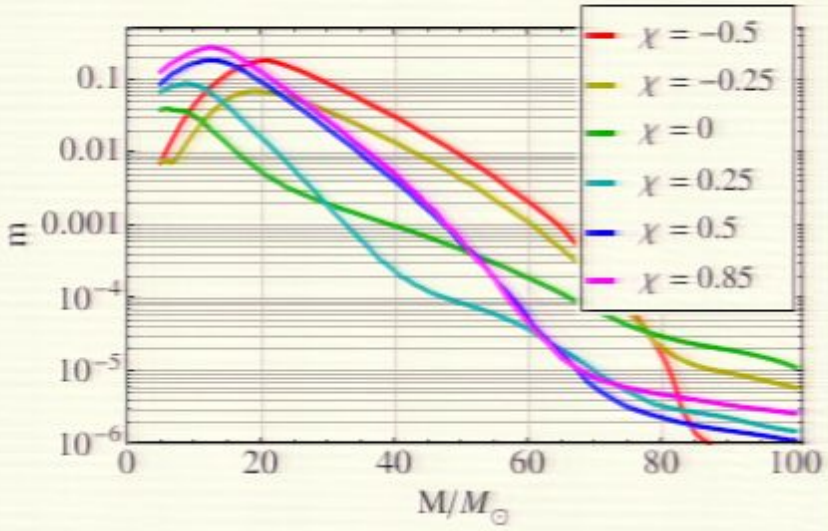
Time/frequency-domain matching



- Frequency-domain hybrids compared to time-domain hybrids (TaylorT1)
  [Ajith *et al.* 2007-2009]
- Equal mass BAM waveforms

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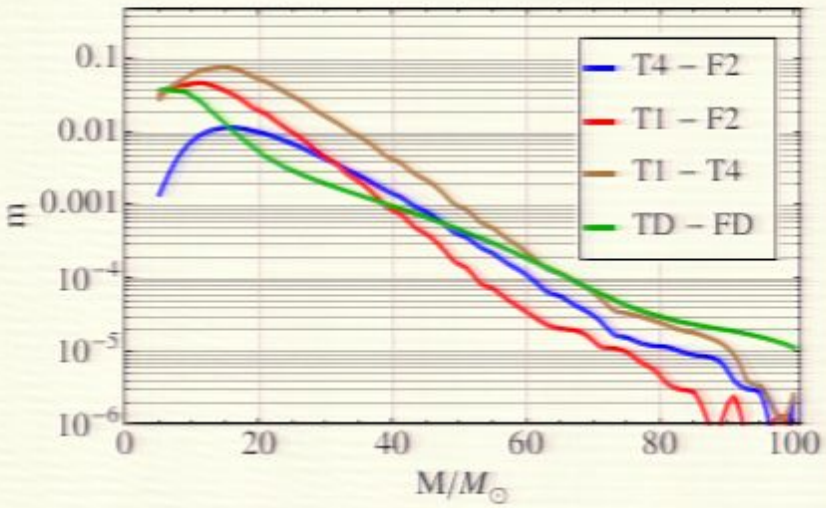

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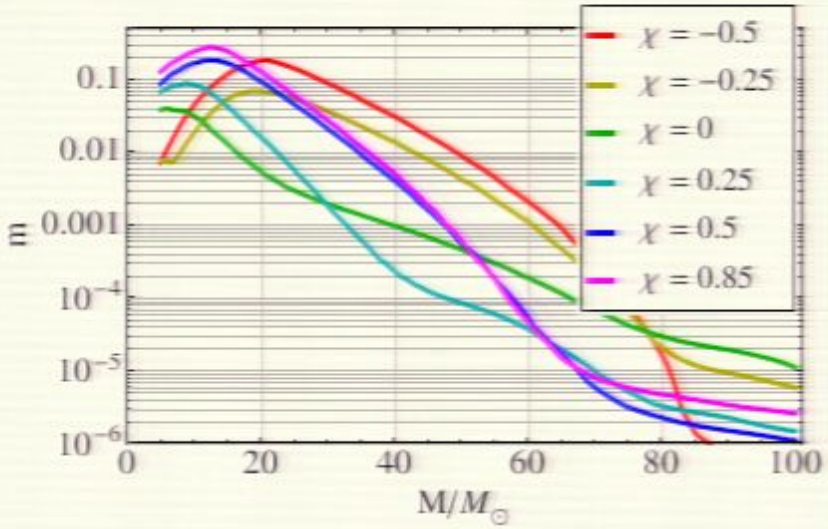

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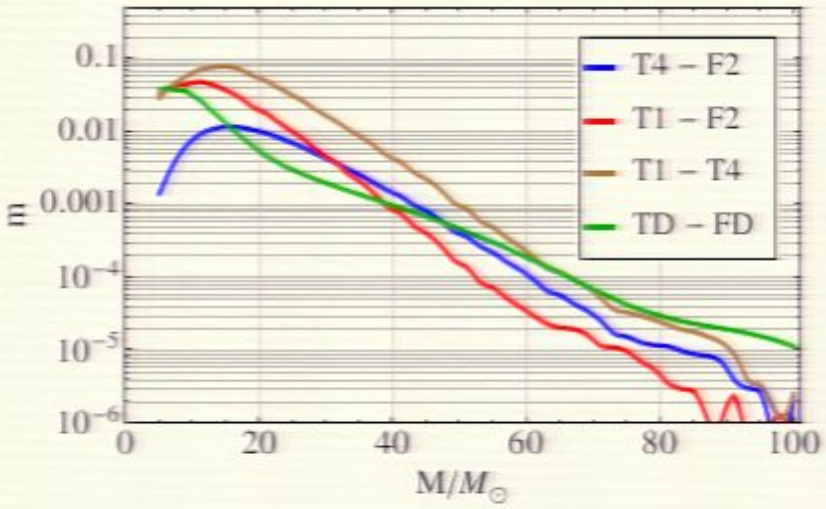

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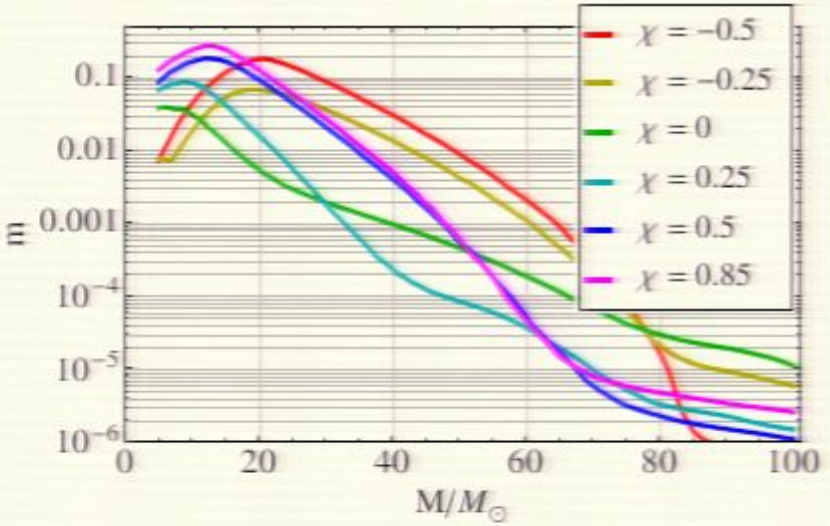

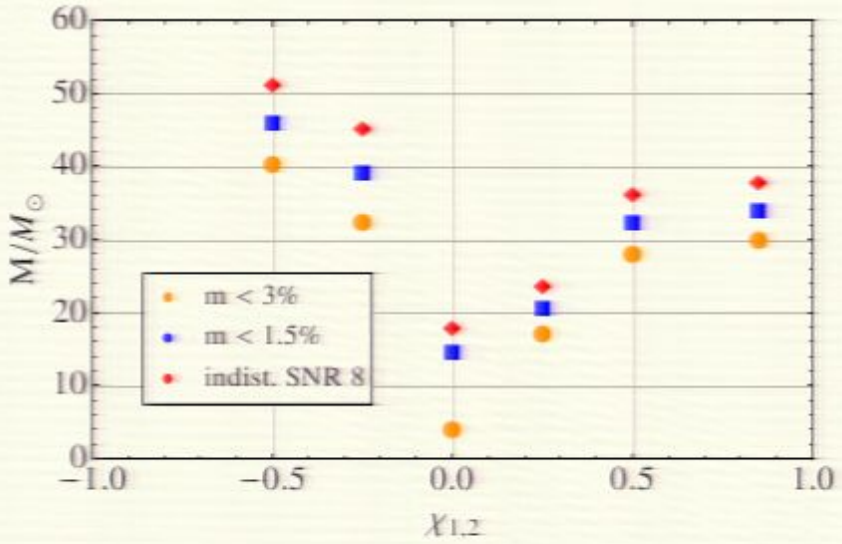

Conclusions

- Matching procedures well understood, time and frequency matching consistent
- Hybrids (and successive models) uncertain for lower masses ($\lesssim 20M_\odot..50M_\odot$)

$\Rightarrow$ Improvements needed at the interplay of NR/PN: *Slightly longer* NR waveforms, more PN (spin) contributions

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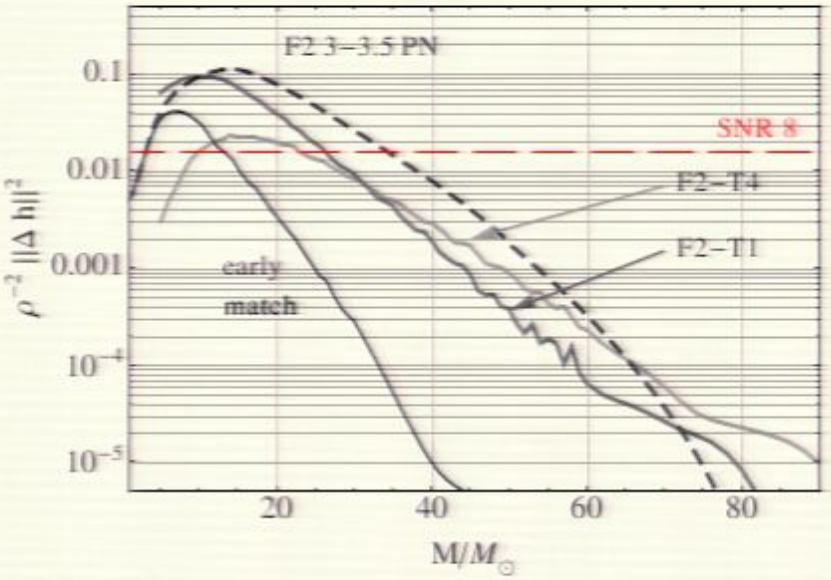
Much more to come

✓ Higher modes

? Precessing spins, higher mass-ratios, eccentricity

✓ Analytical models
Proposed: piecewise PN + PN like fit + ringdown model, smooth transitions, mapped to physical parameters η and χ (mass weighted total spin)

PN – Fixed NR waveform



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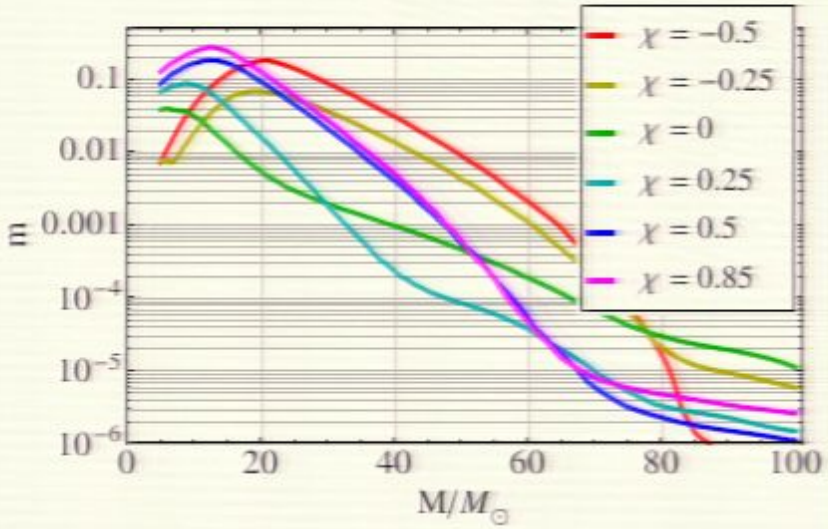

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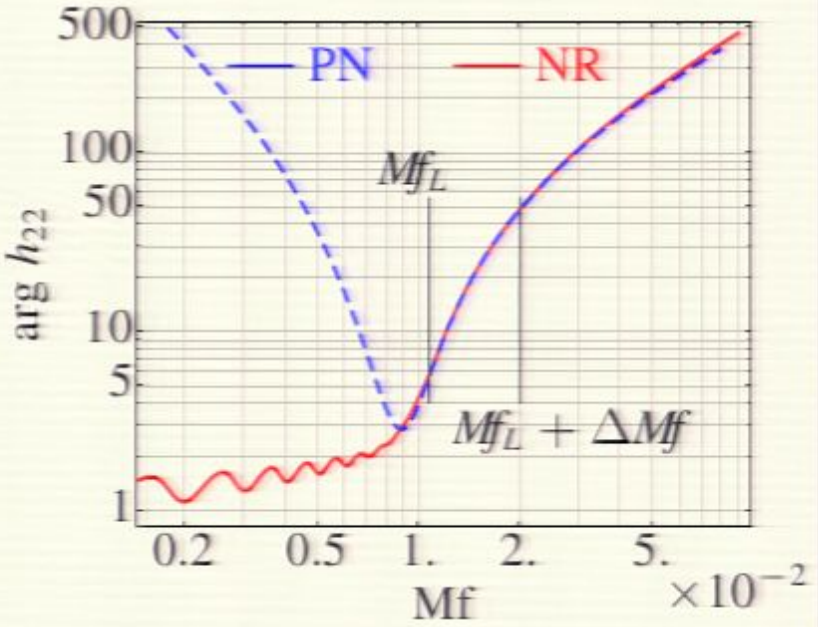

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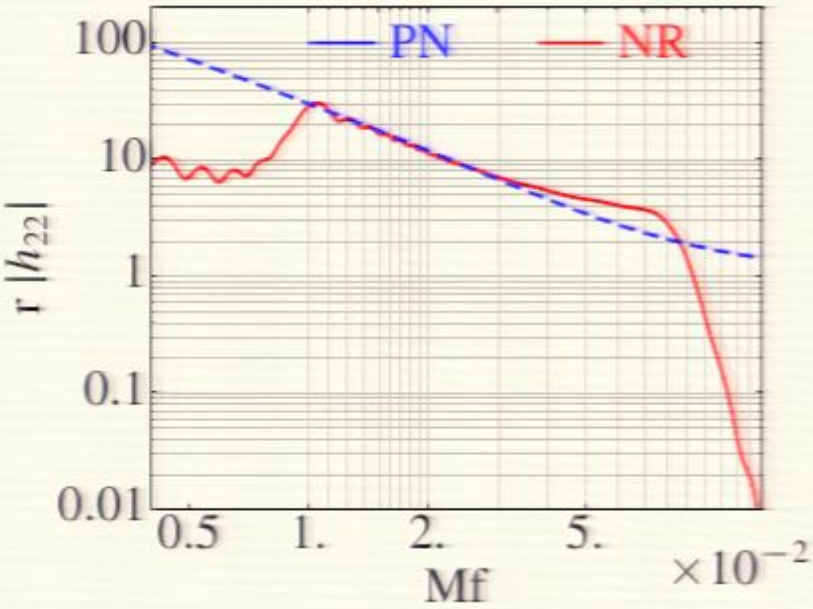

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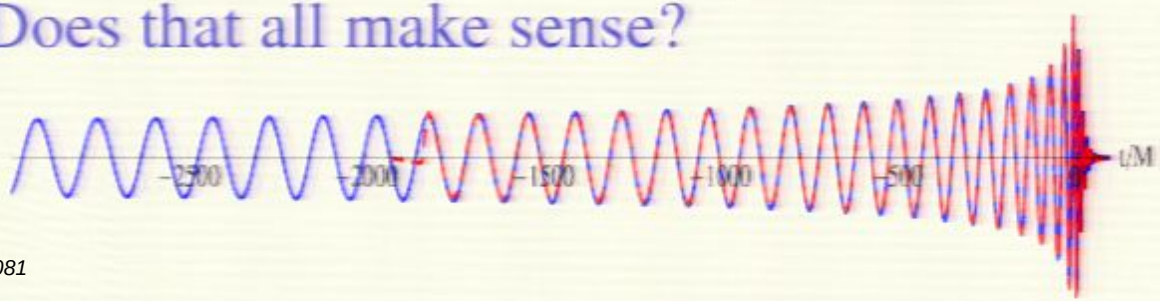

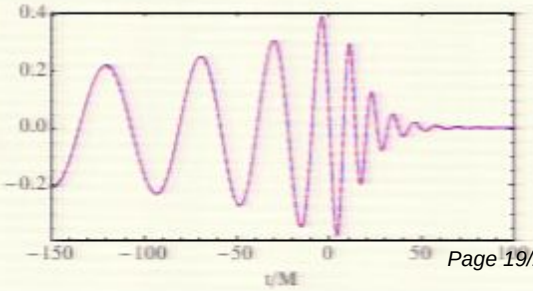

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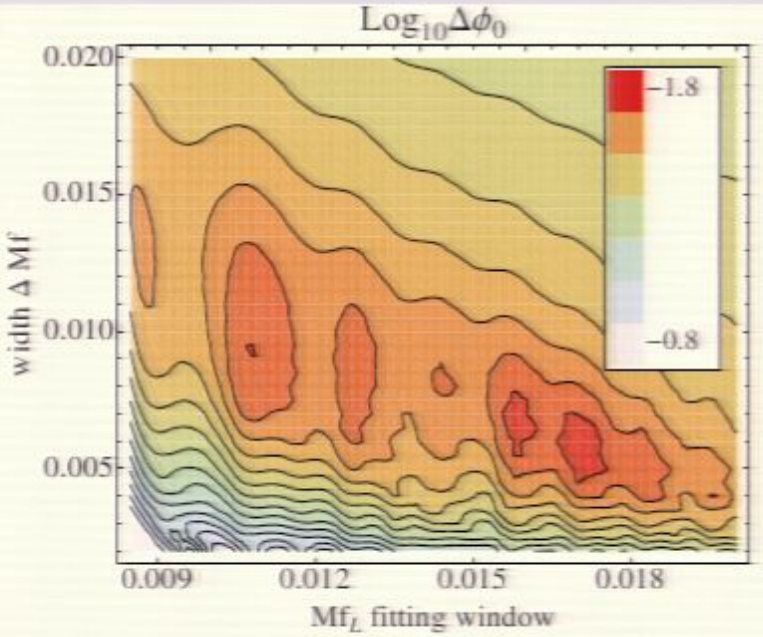

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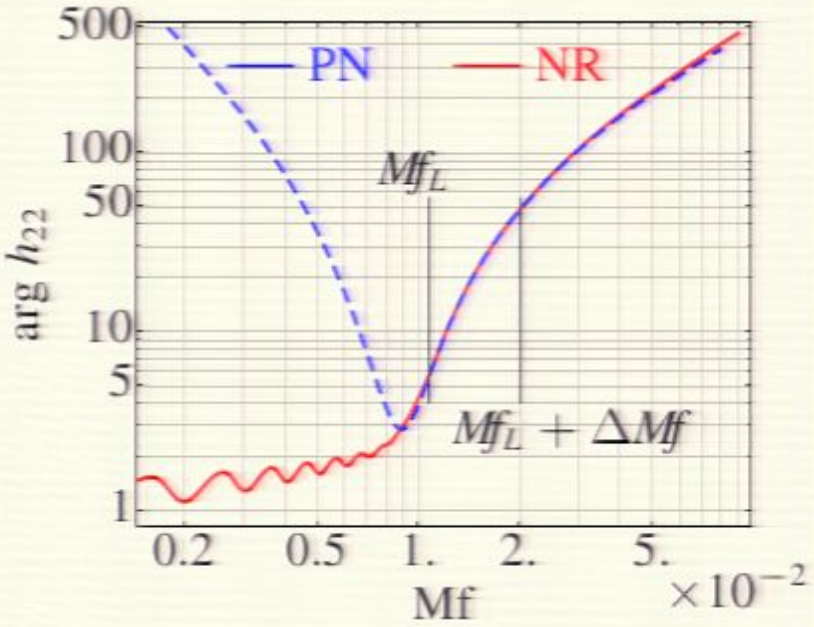

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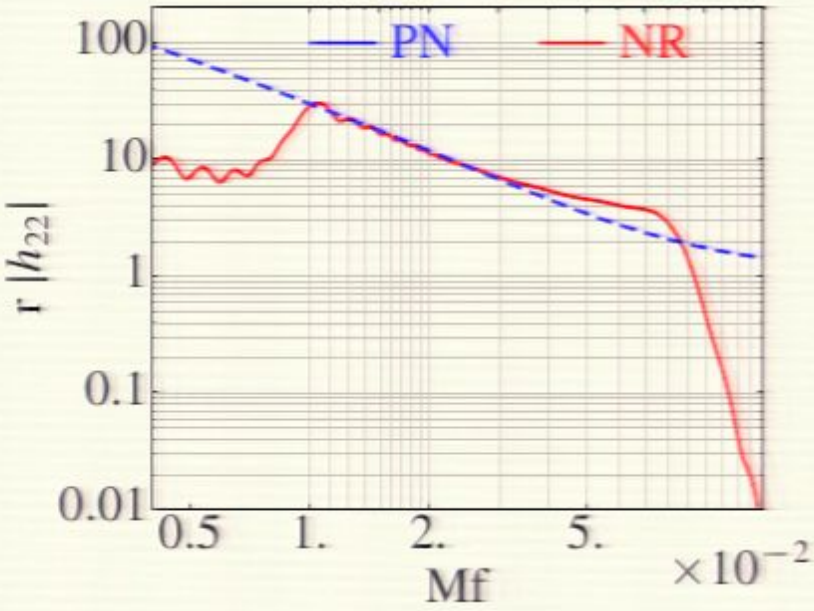

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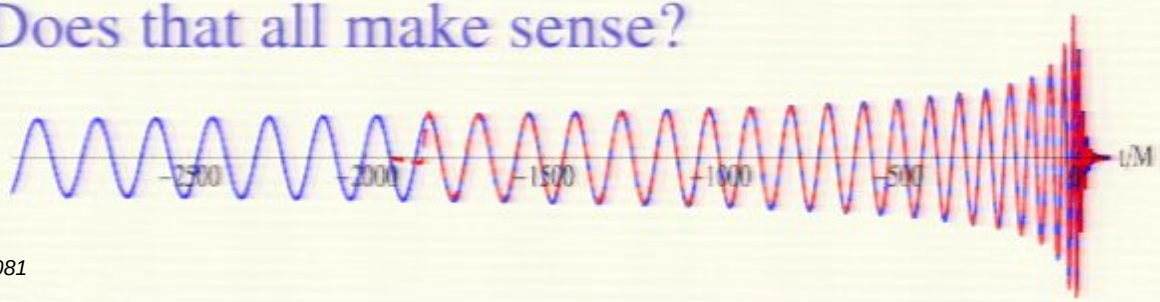

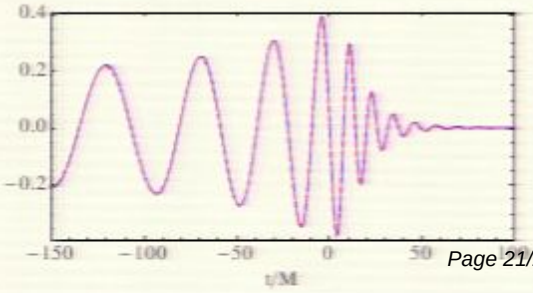

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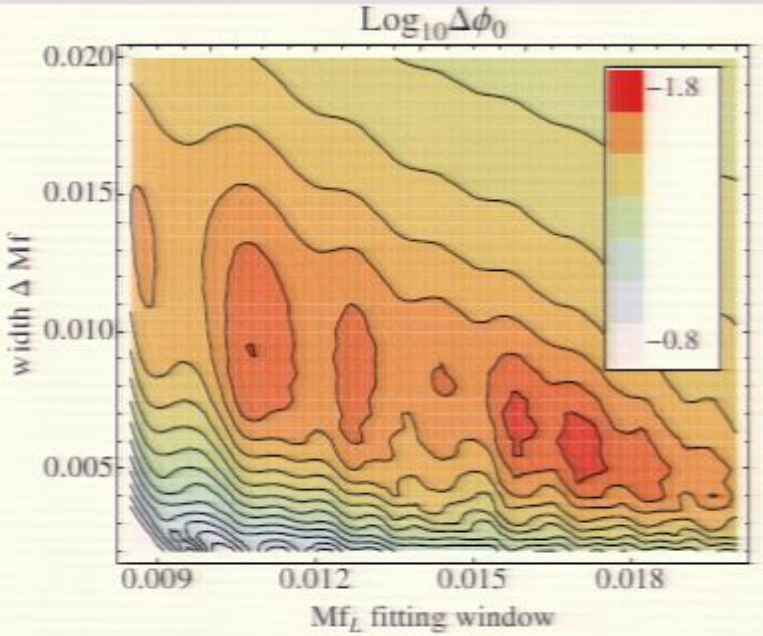

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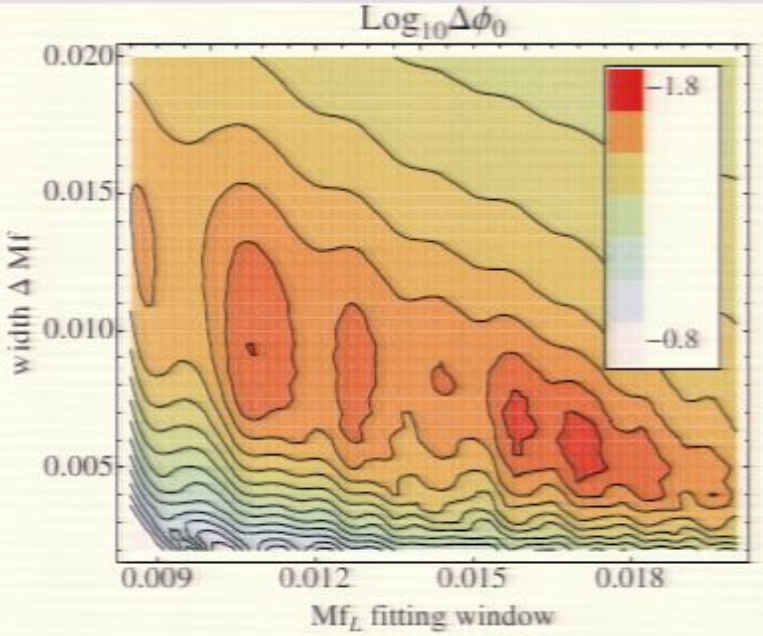

Fitting η as well