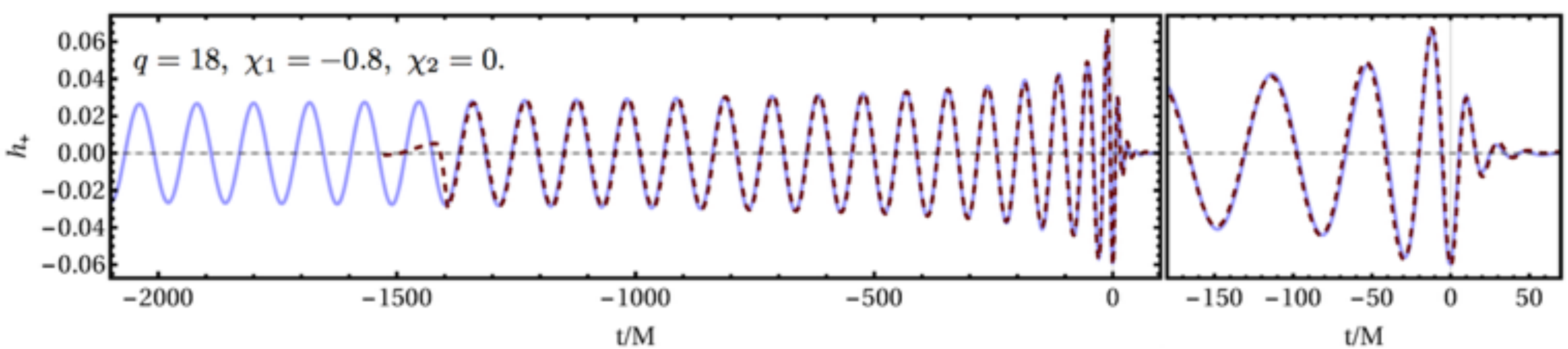
Phenomenological waveform models for the advanced detector era

Phenom* models have been used to analyse first detections - what are these models, and how are we improving them.

Goal: synthesize **inspiral-merger-ringdown** models of the complete WF of Compact Binary Coalescence from pN/EOB, NR, BH perturbation theory, Kerr geodesics, self-force.



S. Husa, Universitat de les Illes Balears
GR21, 13/7/2016

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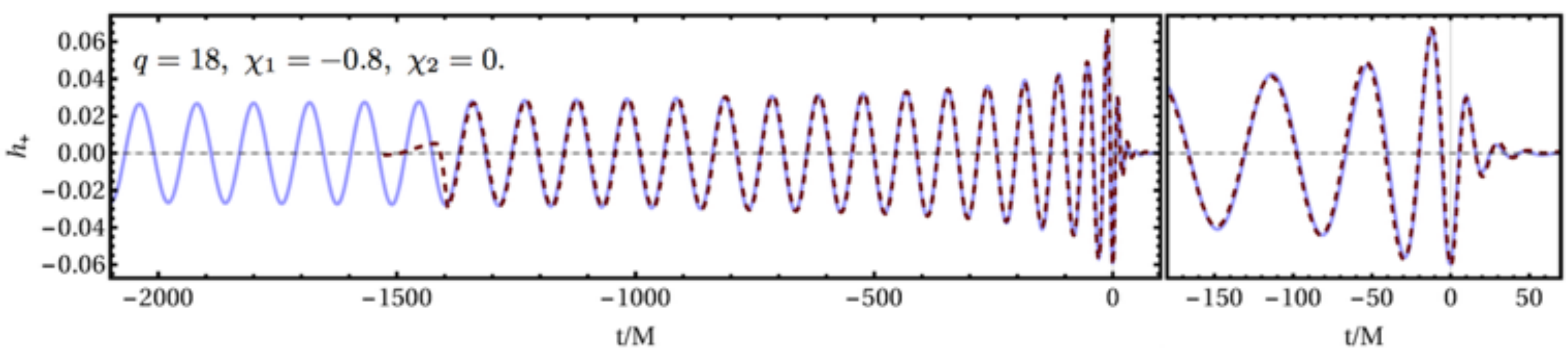
open source in LAL



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Contributors: M. Hannam, M. Pürrer, S. Khan, F. Ohme, A. Bohé, X. Jiménez, P. Schmidt, D. Keitel

PhenomD: non-precessing models

Frequency-domain gravitational waves from non-precessing black-hole binaries -
I. New numerical waveforms and anatomy of the signal
II. A phenomenological model for the advanced detector era

SH, S Khan, M Hannam, M Pürrer, F Ohme, X Jiménez Forteza, A Bohé, PRD 2016
S Khan, SH, M Hannam, F Ohme, M Pürrer, X Jiménez Forteza, A Bohé, PRD 2016

PhenomP: precessing models
M Hannam, P Schmidt, A Bohé, L Haegel, S Husa, F Ohme, G Pratten, M Pürrer. Phys. Rev. Lett. 113, 151101 (2014), detailed PhenomP (version 2) paper coming up

Systematic model building and double spin upgrades:
New work with X Jiménez Forteza & D Keitel

Phenomenological modelling of IMR waveforms

- Key design ideas [alternative: **E**ffective **O**ne **B**ody -> A Bohé’s talk]
  - “phenomenological”: look at waveforms and describe what we see.
  - Frequency domain: matched filter calculations in Freq. domain.
  - Explicit expression in terms of elementary functions -> fast, simple. [fast without ROM acceleration]
- Start with l=|m|=2 spherical harmonic mode (in co-rotating frame)
- Model directions in parameter space in order of importance.
  - Non-spinning (PhenomA)
  - Single effective spin, neglect spin difference effects (PhenomB/C/D).
  - Leading precession effects via PN, no NR calibration (PhenomP)
  - In progress: full double spin model
    - systematic model building procedure ✅
    - final state and peak amplitude -> Xisco’s talk Monday ✅

A simple model for precession: PhenomP

- **Orbital time scale << precession time scale**

 => Co-rotating frame: radiated $\vec{L}$, energy & phasing essentially unaffected by precession

=> dominated by $\vec{S}_i \cdot \vec{L}$

- Spherical harmonic mode structure in standard frame corresponds to non-precessing case

 -> "twisting up" aligned spin model with "post-Newtonian" Euler angles works well

Fourier domain PhenomP construction:

[Schmidt+ PRD 2012, Hannam+ PRL 2014]

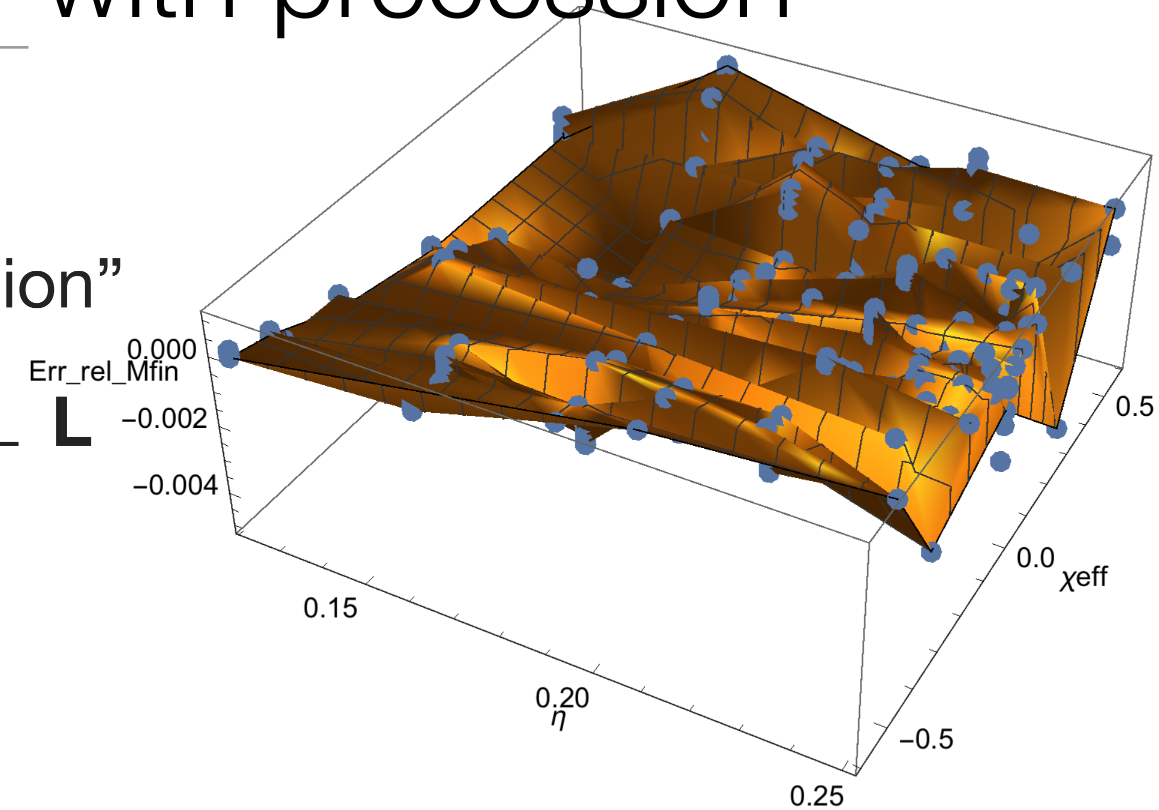
Time domain EOB version: Pan+ PRD 89, 2014]

PhenomP shortcomings:

- Not tuned to actual precessing NR waveforms.
- Incomplete:
  - Does not handle aligned/anit-aligned instability [Gerosa+ PRL (2015)]
  - Does not include symmetry-breaking "superkick recoil" effect

Final spin and radiated energy with precession

- Based on PhenomP approximation:
  - emission in comoving frame ~ “no precession”
  - ~ preserve total spin projections unto || & ⊥ **L**
  - => radiated energy should depend only weakly on precession. ✅



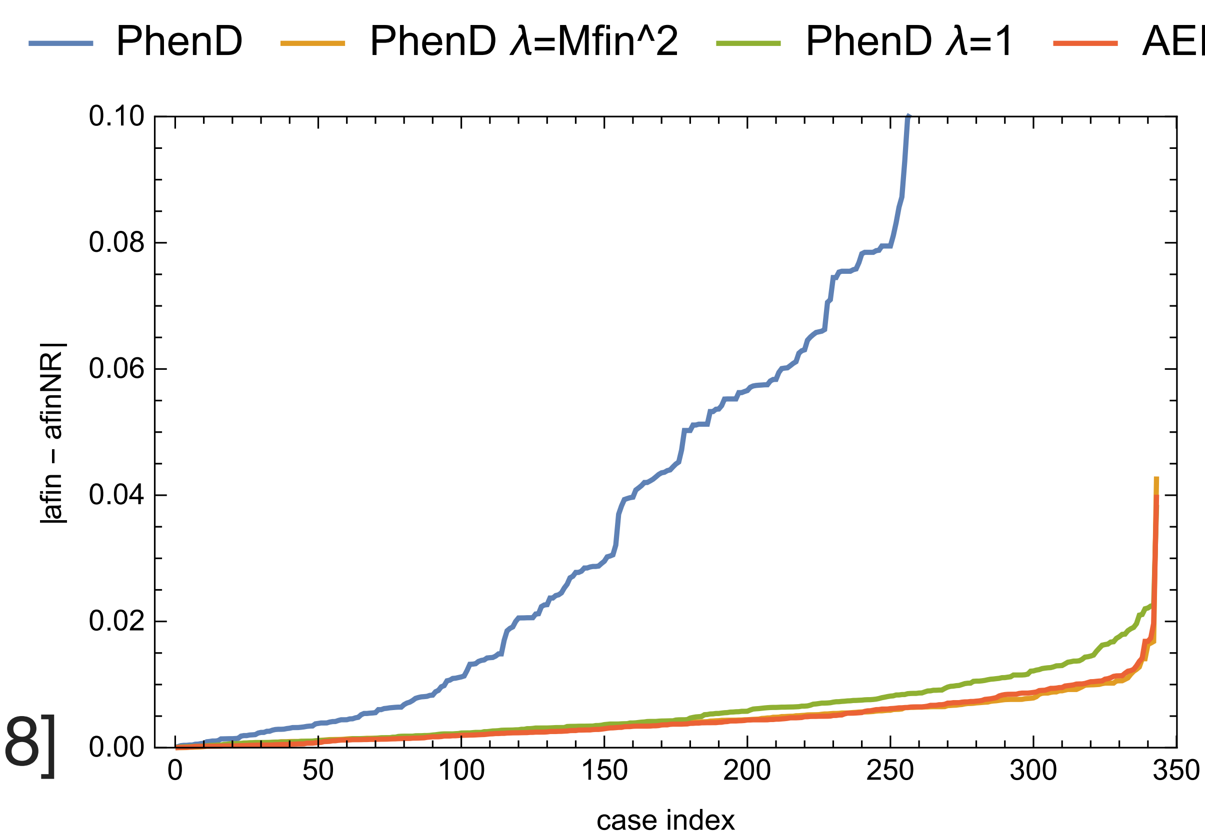
- Final spin:

$$|a_{fin}| = \sqrt{S_\perp^2 \frac{\lambda}{M_{fin}^2}^2 + a_{fin}^{||}{}^2}$$

  - choose “fudge parameter”

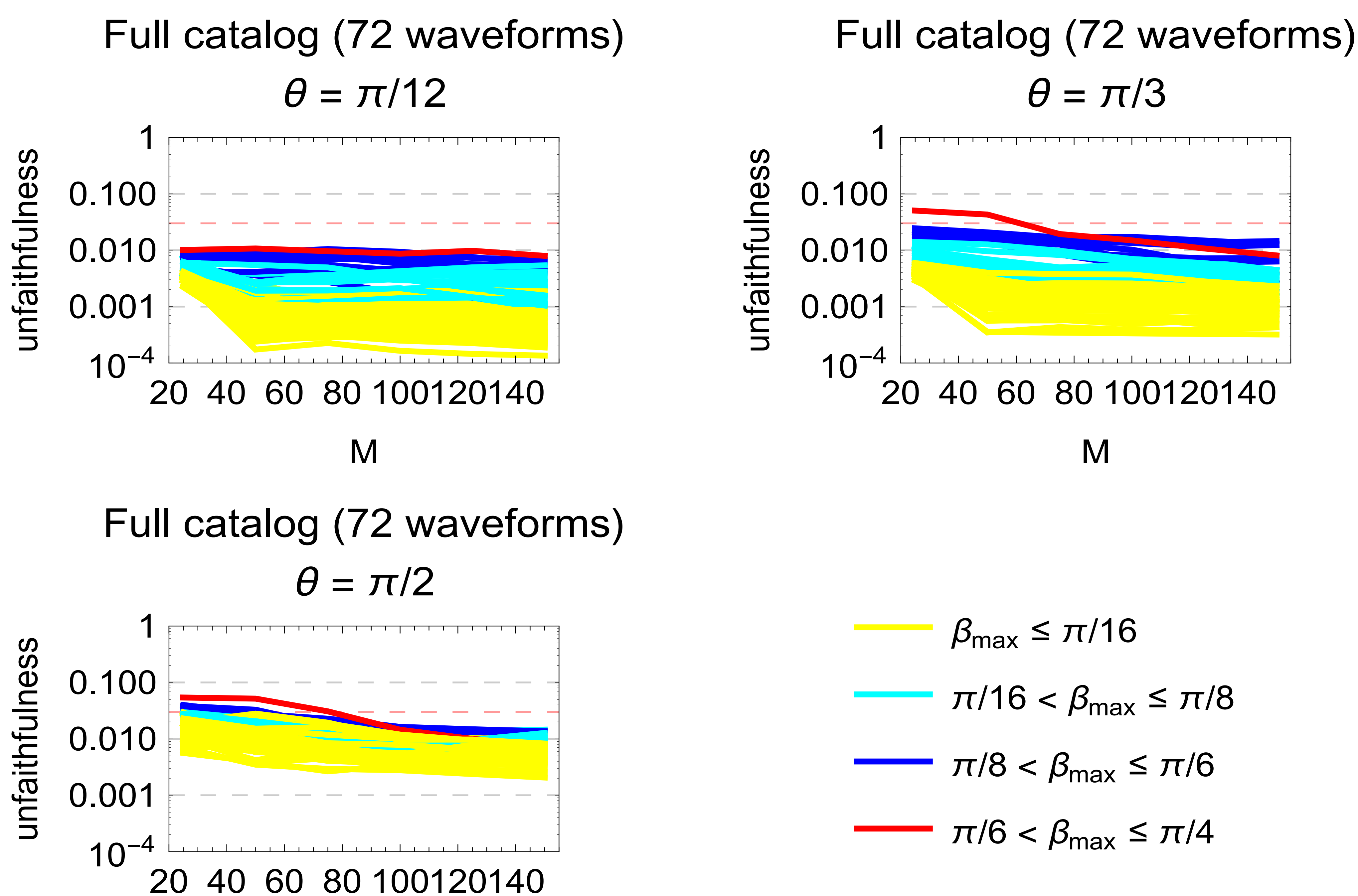
$$\lambda = M_{fin}^2$$

  - as in 2007 AEI fit [Rezzolla+,PRD78,2008]



PhenomPv2 used in O1 BBH parameter estimation

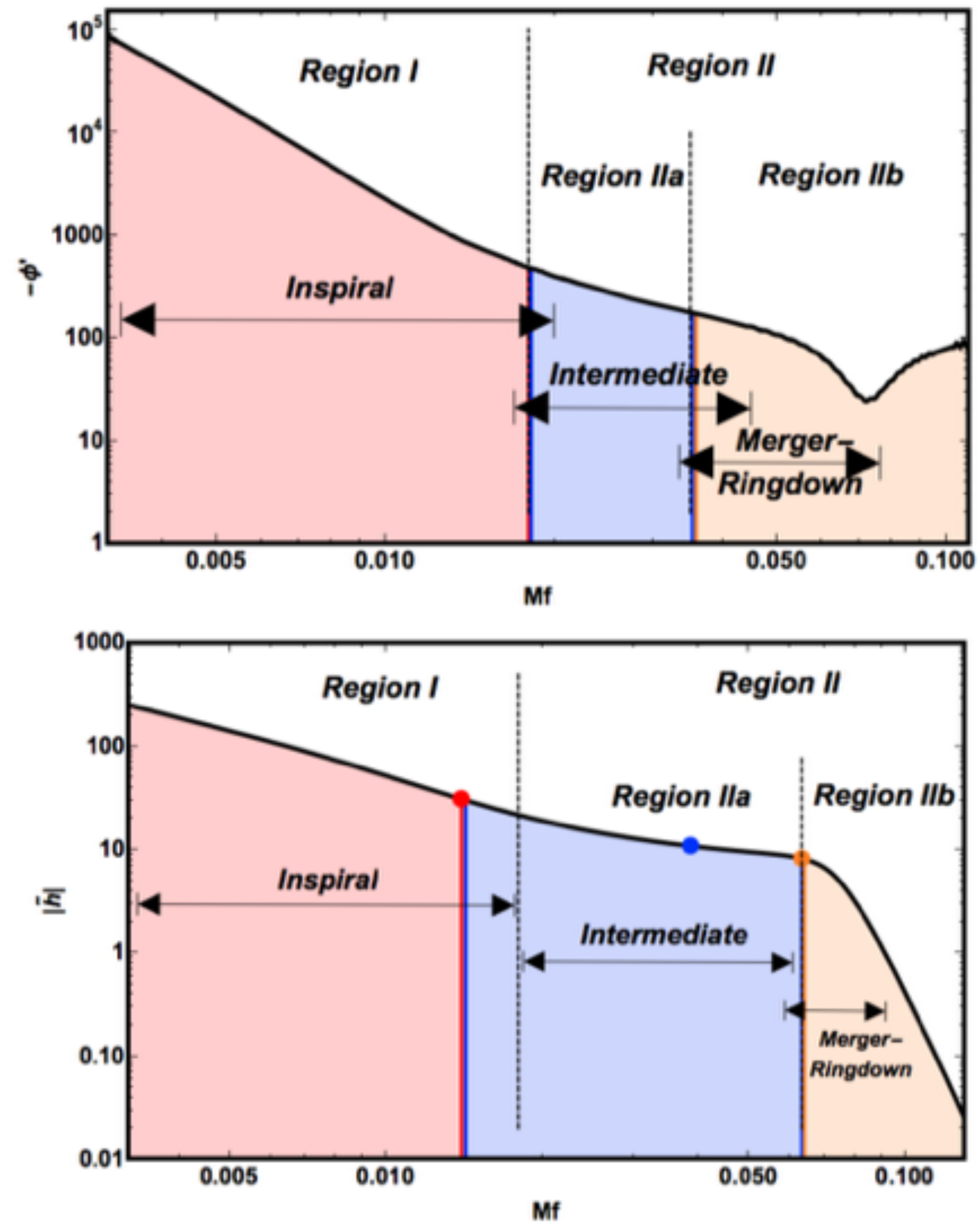
- relies on accurate non-precessing model!
- 2010 PhenomC replaced by 2015 PhenomD model
- twisted up with 2PN PN+SPA Euler angles (detailed paper in prep.)



Splitting into amplitude/phase & frequency regions

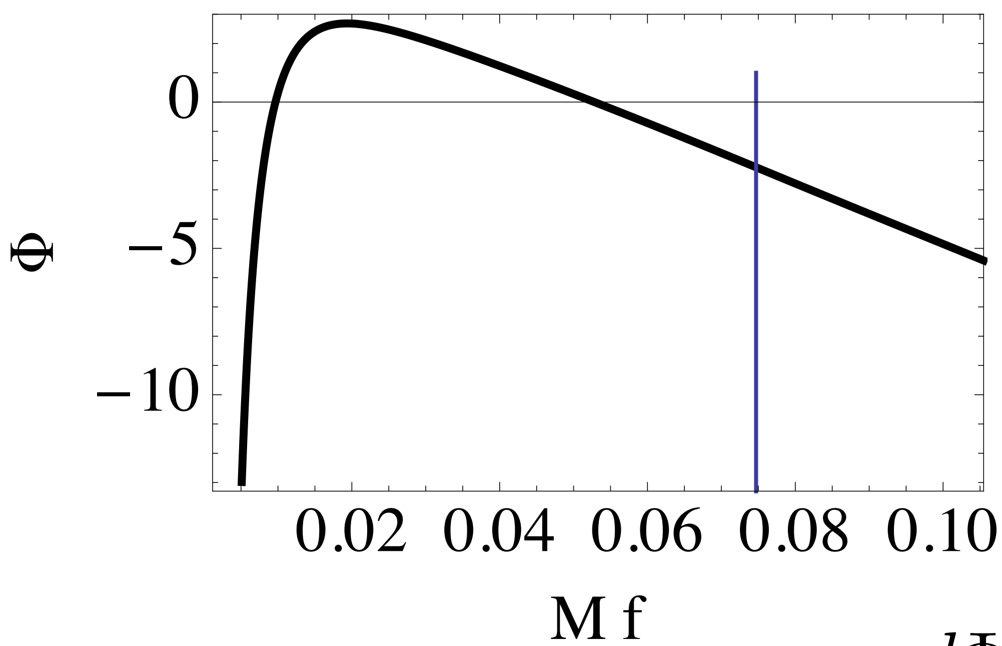
Divide and conquer:

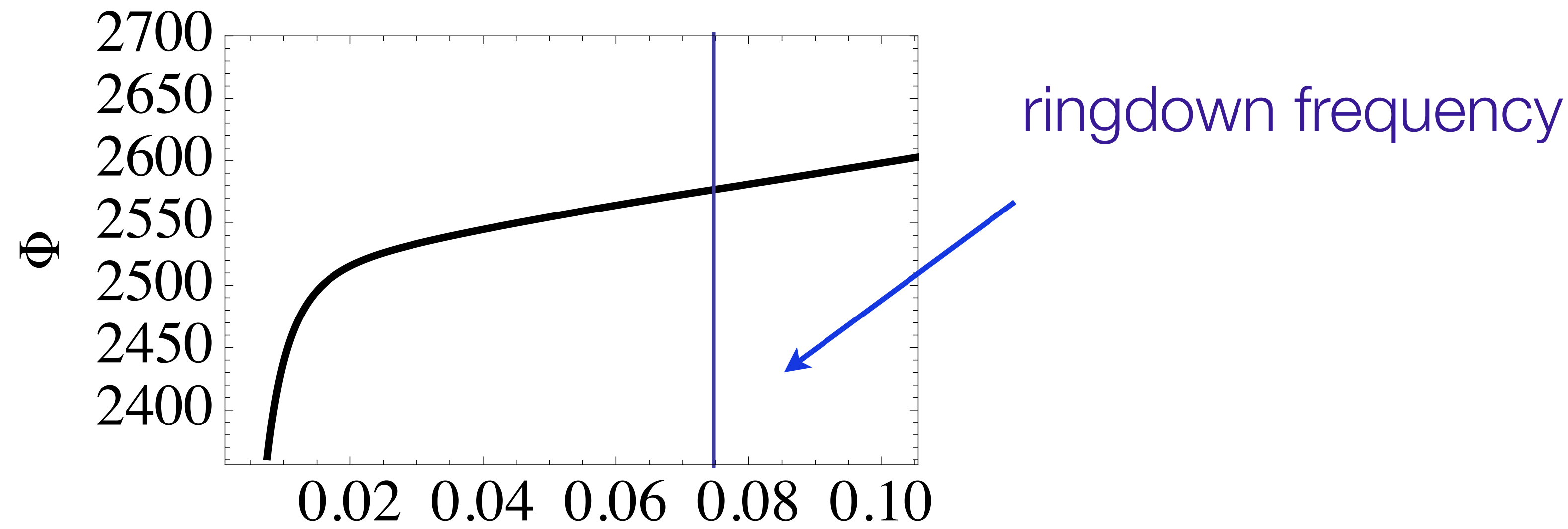
- Split waveform into amplitude and phase, model simple non-oscillatory functions.
- Simplicity of modelling increases with the number of frequency-regions.
- Simplest: tens of points, cubic spline.
- Our choice - 3 regions:
  - inspiral (use PN intuition)
  - merger-ringdown (use QNM intuition)
  - intermediate



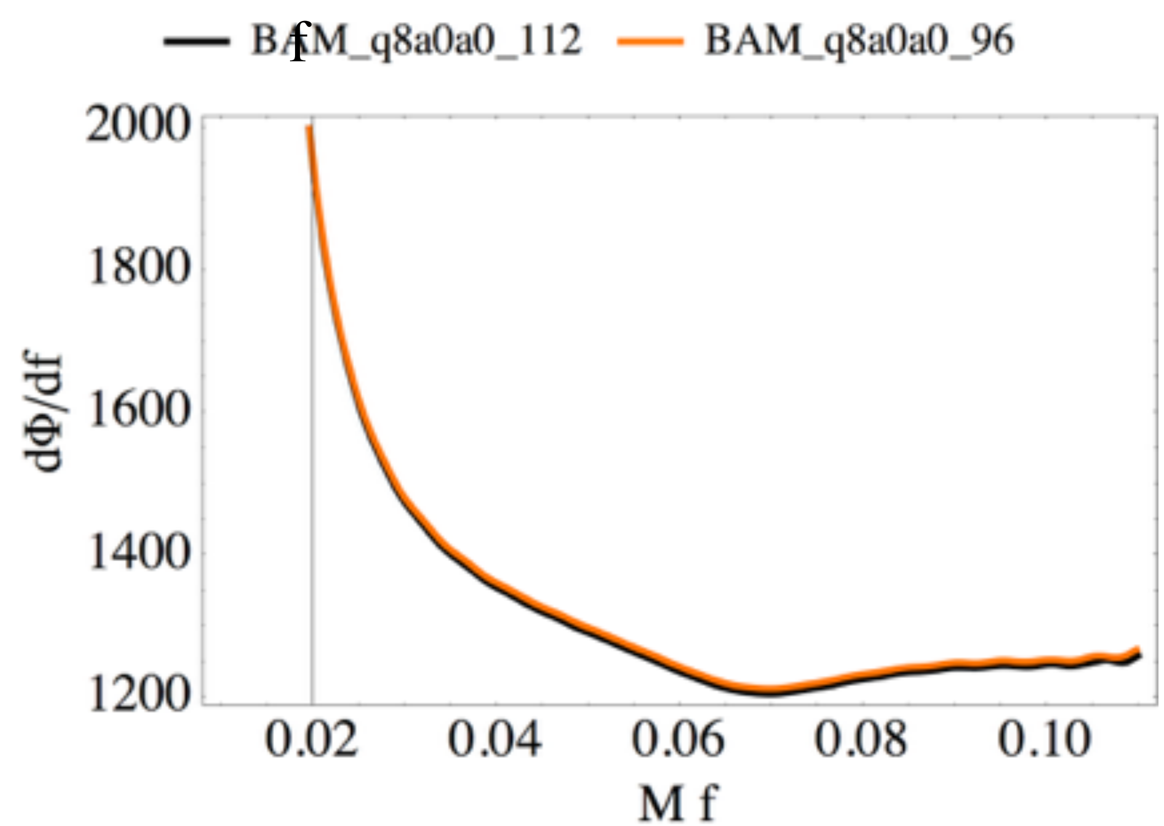
Example: Modelling the Fourier domain phase

- Freedom in initial phase & time shift: $\Phi(f) \rightarrow \Phi(f) + \Phi_0 + 2\pi t$





- Look at first derivative: $\dfrac{d\Phi(f)}{df}$
  - 2nd derivative often too noisy.
- Can you spot the ringdown frequency?



- MRD-Ansatz:

$$\phi'_{\mathrm{MR}} = \alpha_1 + \sum_{i=2}^{n} \alpha_n f^{-p_n} + \frac{a}{f_{damp}^2 + (f - f_{RD})^2}$$

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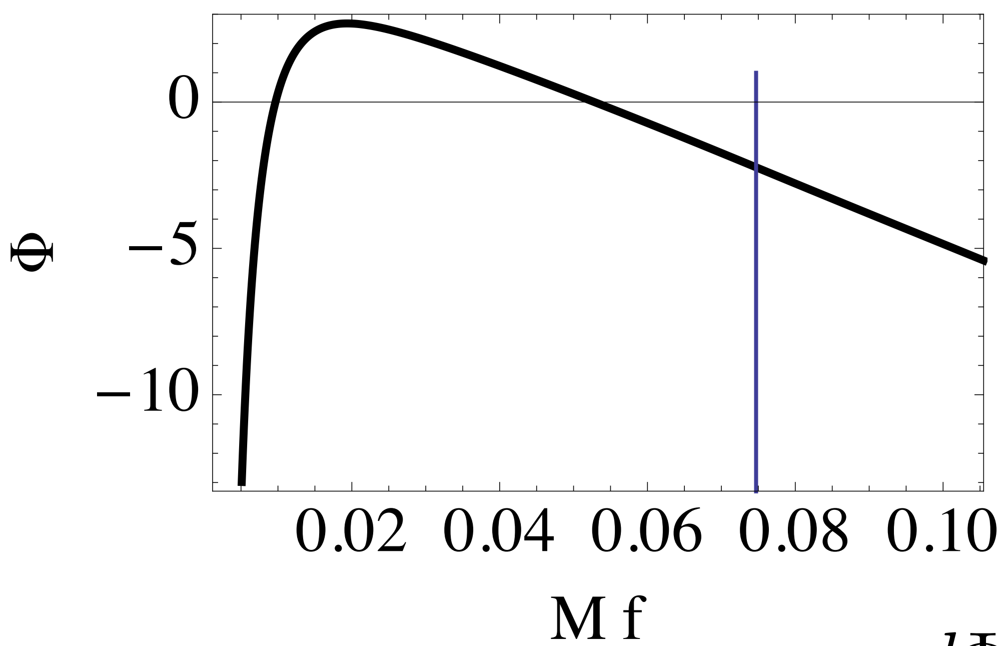

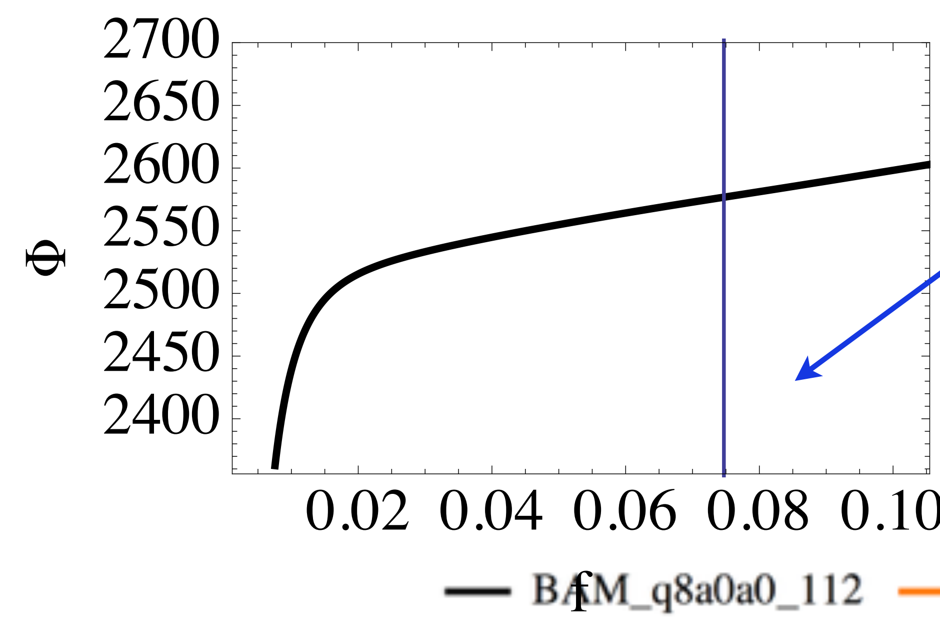

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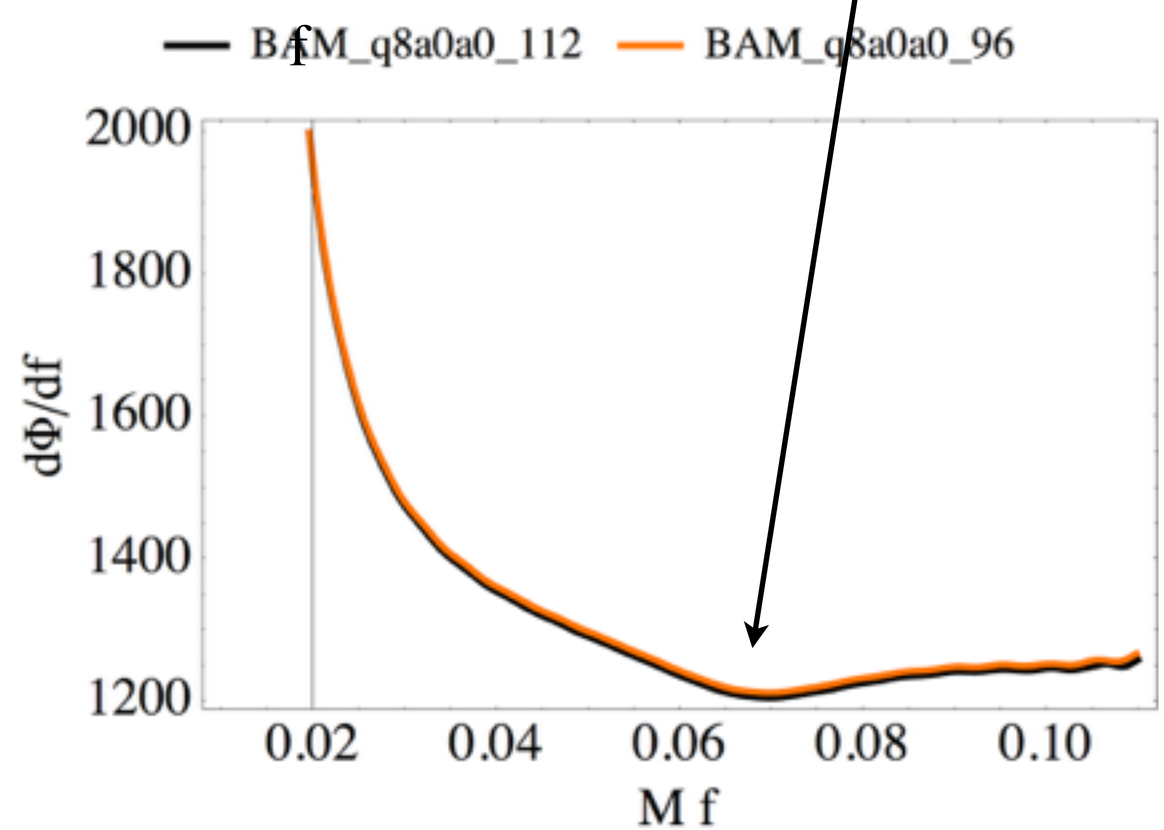

$$\phi'_{\mathrm{MR}} = \alpha_1 + \sum_{i=2}^{n} \alpha_n f^{-p_n} + \frac{a}{f_{damp}^2 + (f - f_{RD})^2}$$

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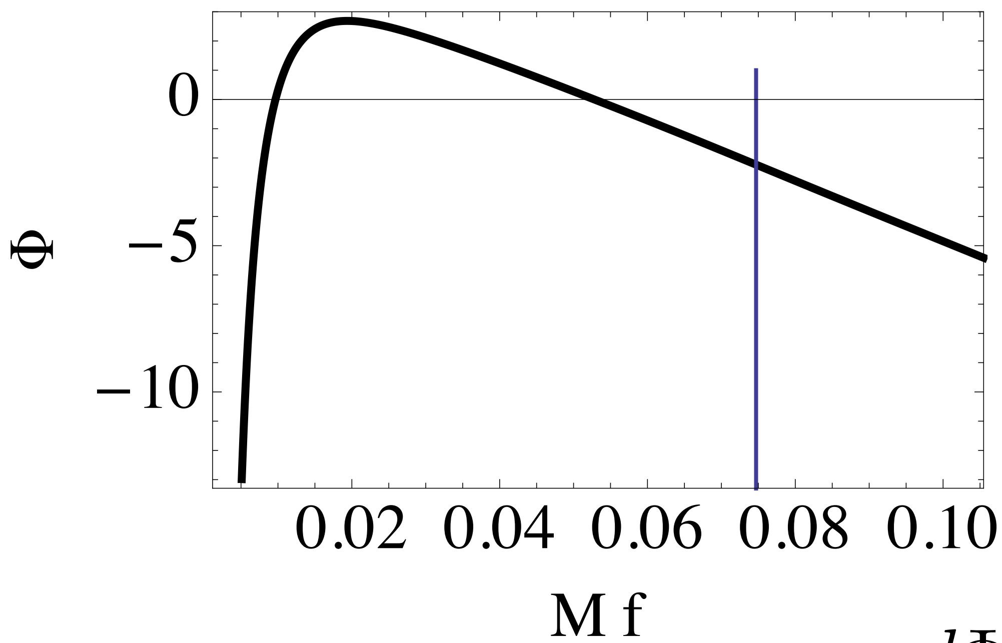

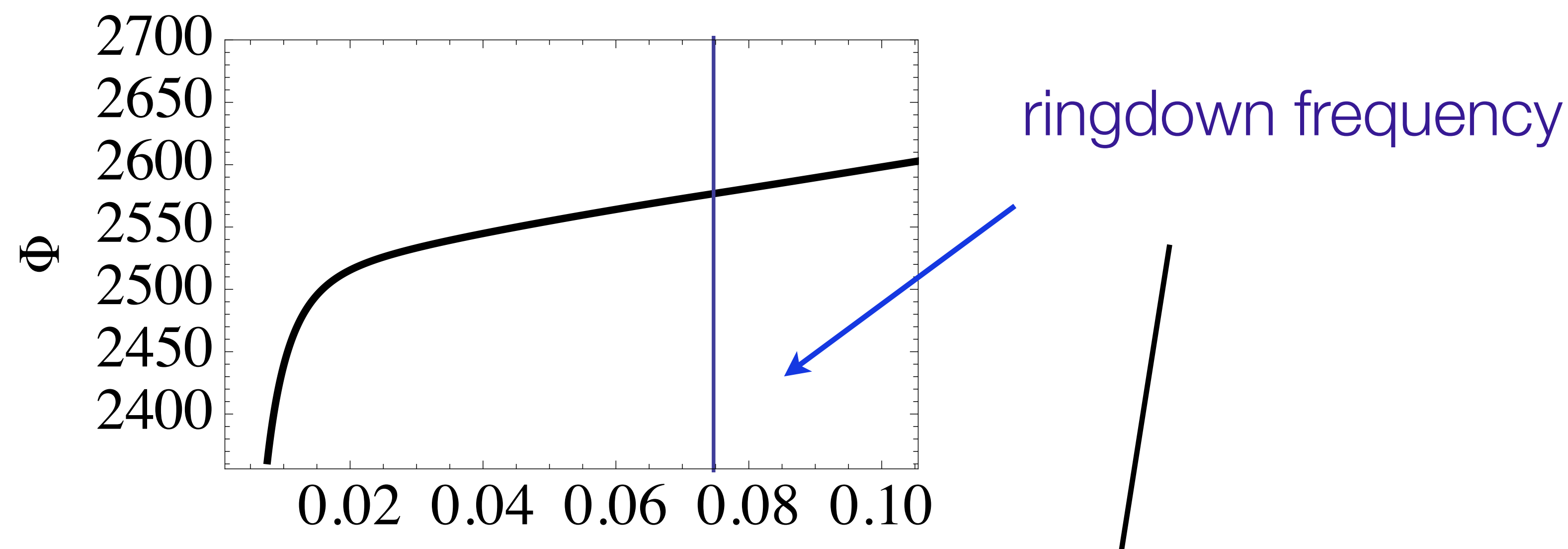

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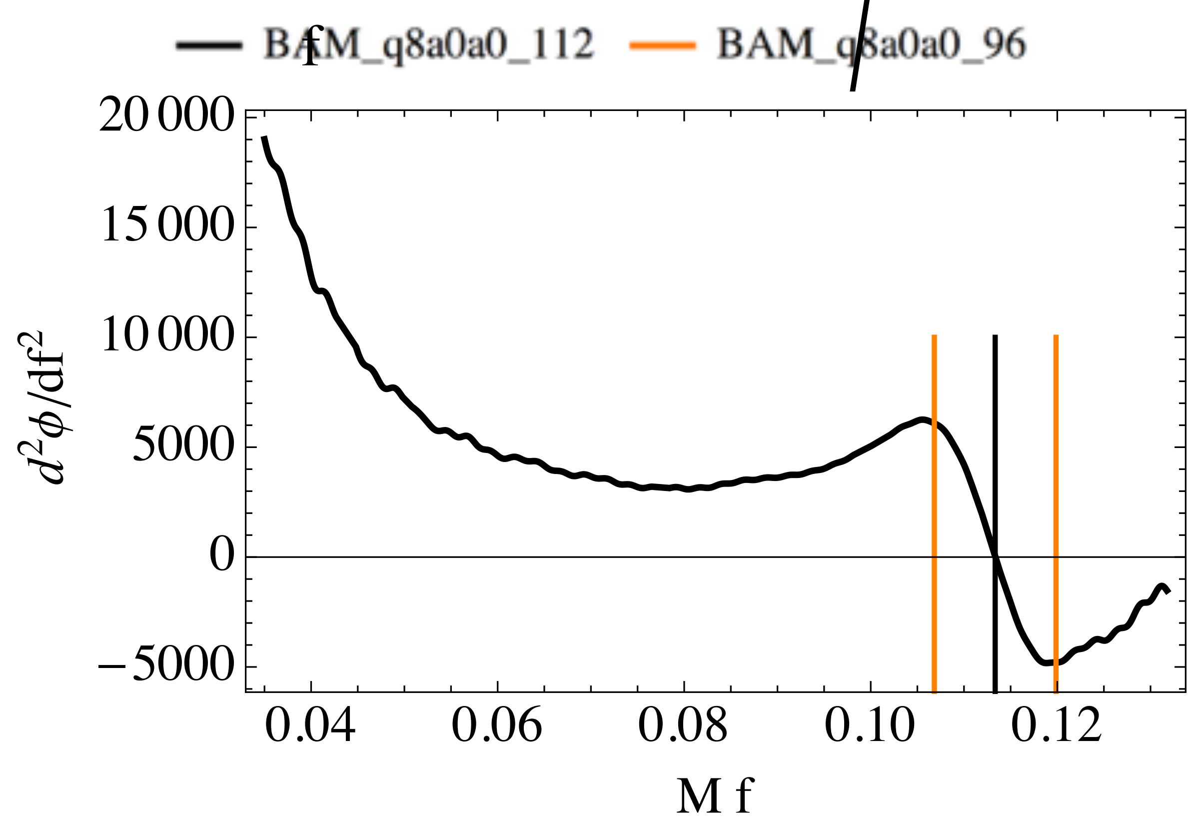

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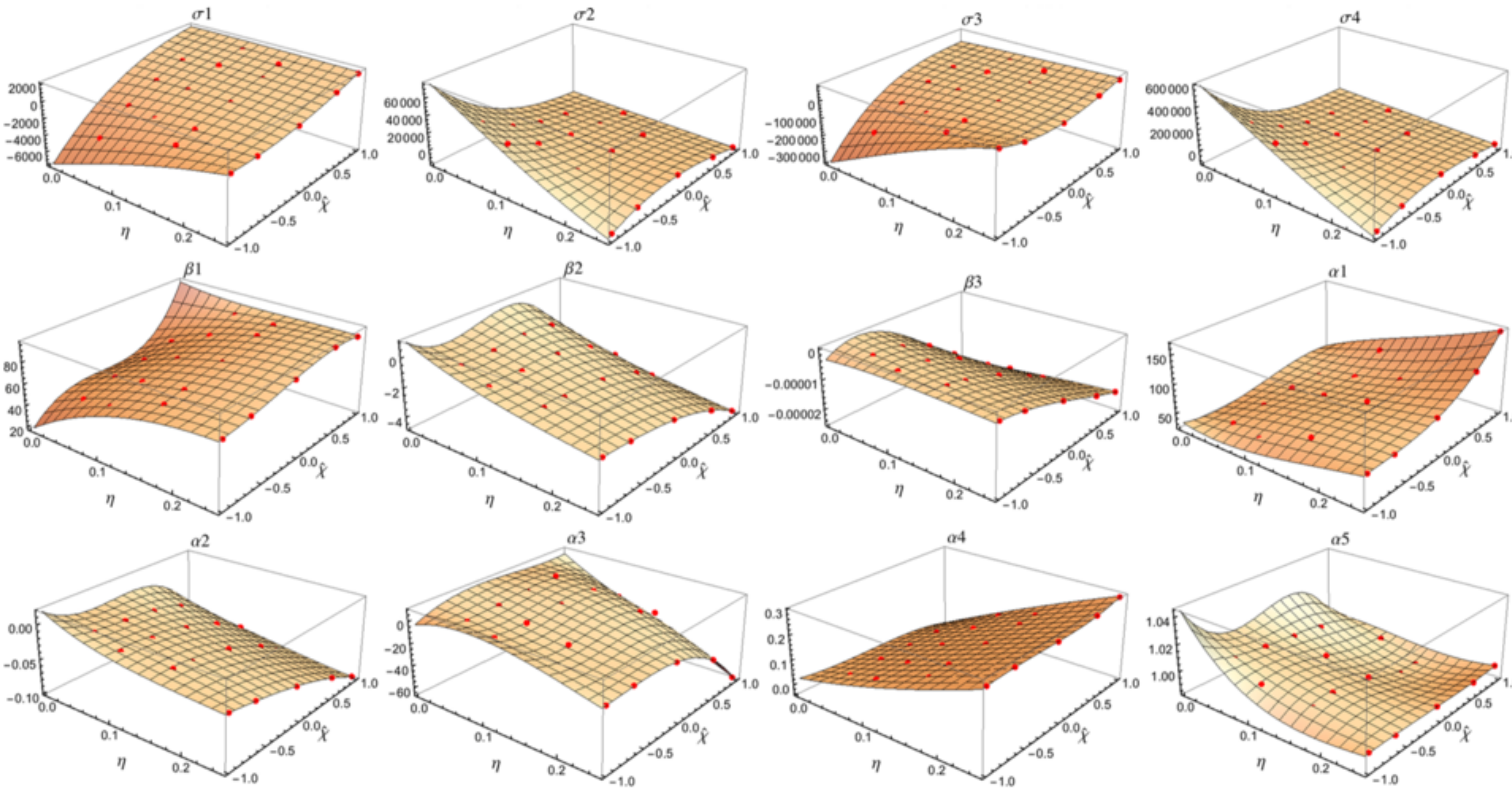
Phase coefficients as functions of $\eta, \hat{\chi}$

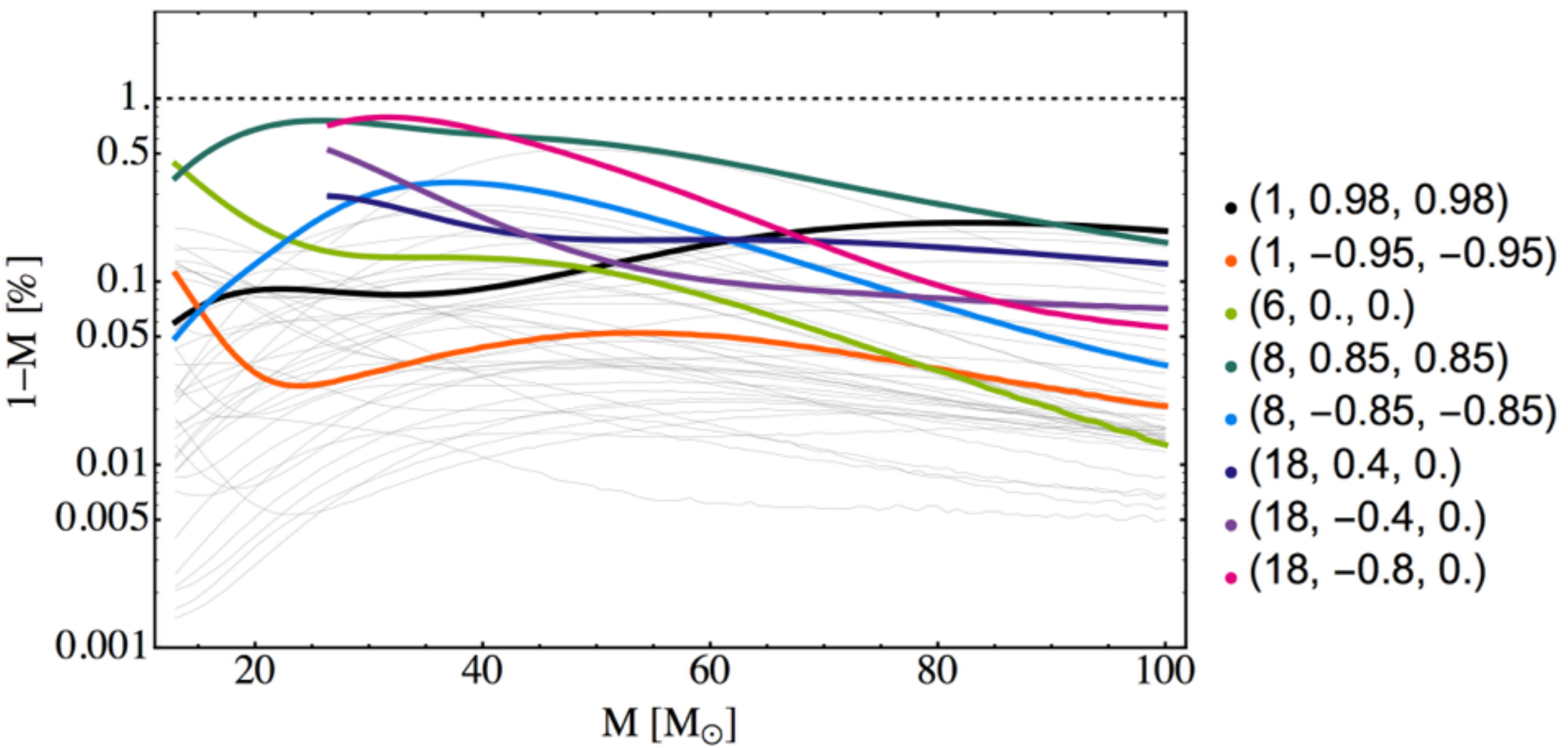


New:

- more WFs: 19 -> 80+, include m_1/m_2=18, spins 0.8,0
- use all available WFs with weights depending on error bars.

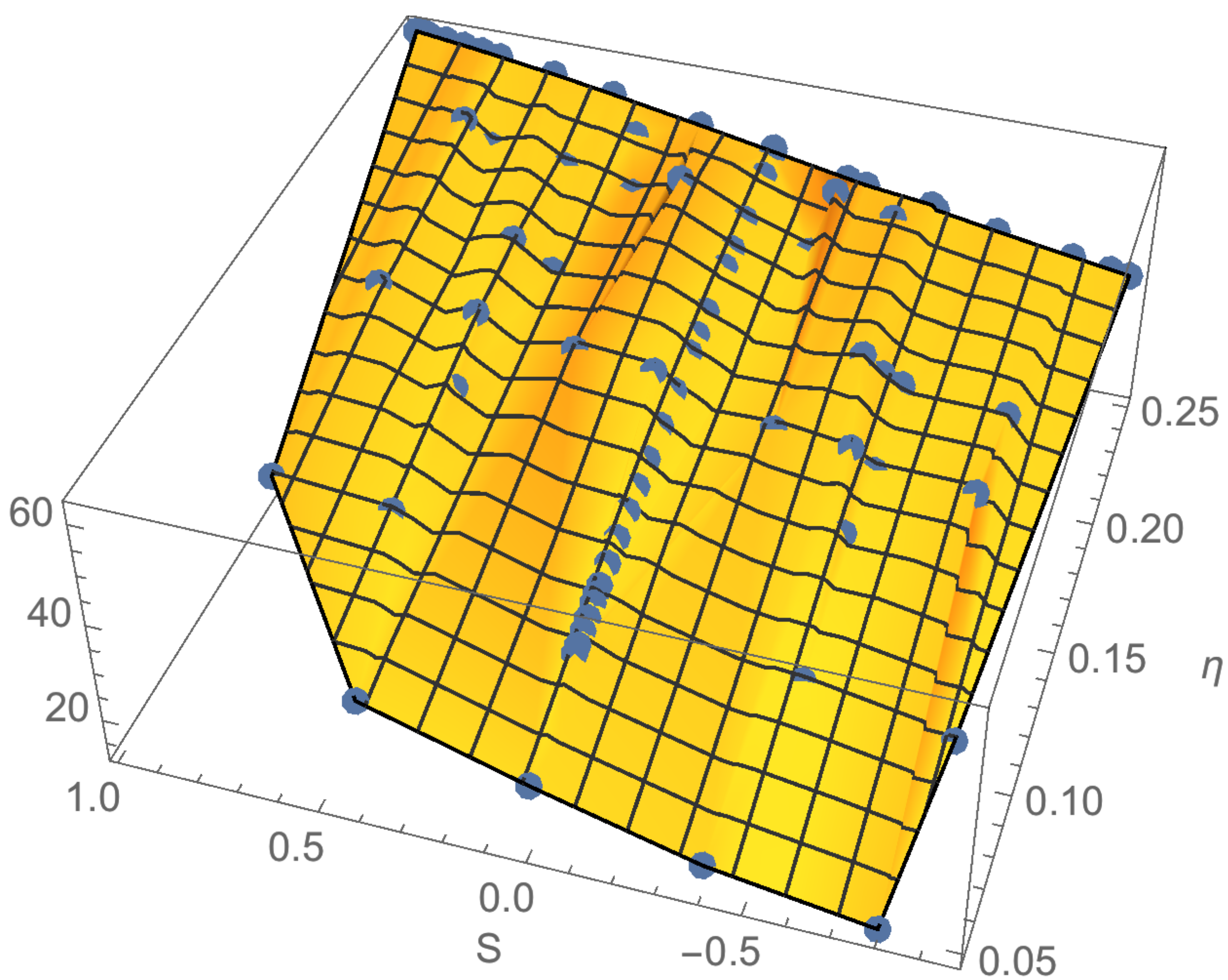
PhenomD mismatches against all (48) hybrids

early aLIGO noise curve, low freq. cutoff @ 30 Hz



Systematic fitting example: control point difference in merger regime

Better conditioned than basis coefficients: fit values of value at fixed frequencies, and differences between values.

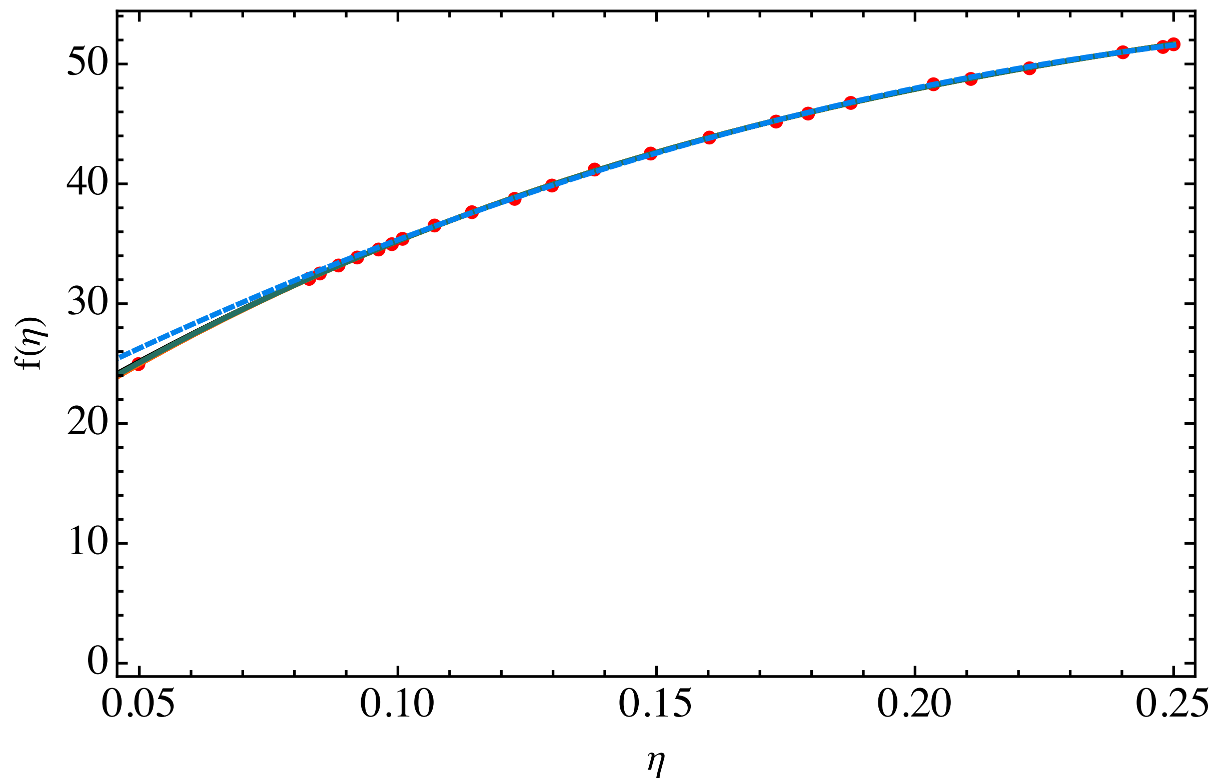


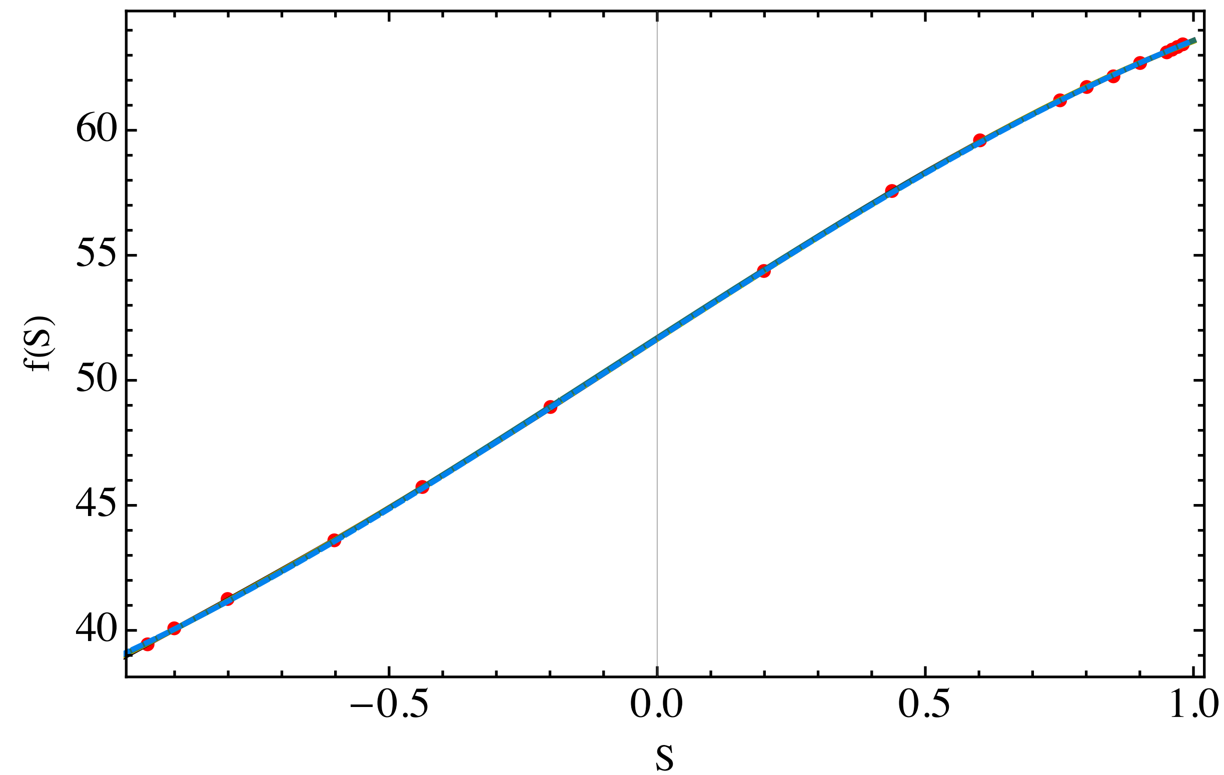
- eff. spin parameter S works reasonably well
- spin diff. can not be neglected for good fit.
- accurate polynomial fits may require high order.
- a good ansatz may only require very few coefficients in some direction.
- To avoid confusion with further subdom. effects (higher modes, precession), want accurate representation of spin difference effect.

Systematic fitting example: control point difference in merger regime

Start with selecting best fits to 1D problems with dense data:

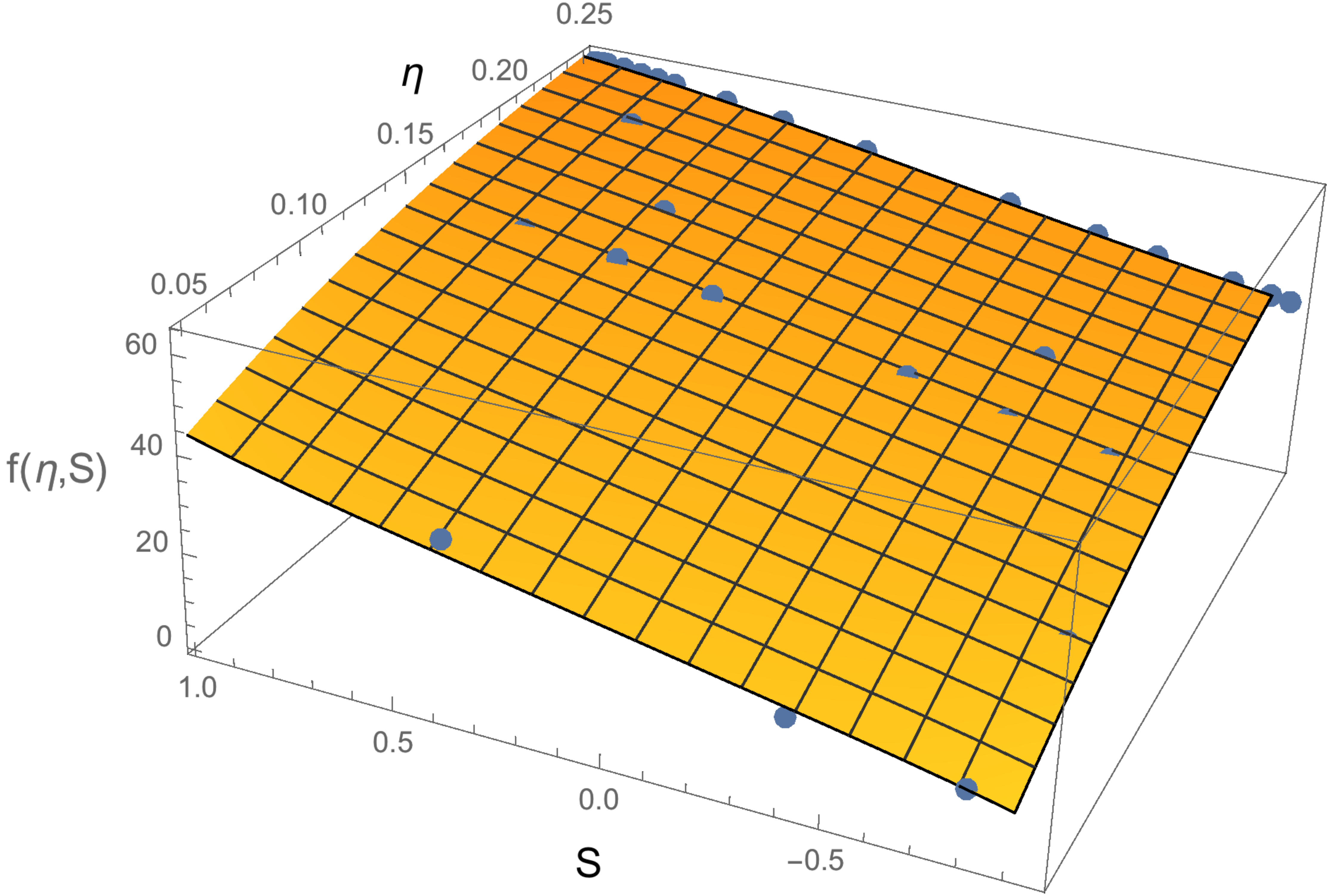
- non-spinning
- equal mass equal spin





Use BIC, AIC, AICc together with residuals to find best fit.

Equal-spin 2D fit.



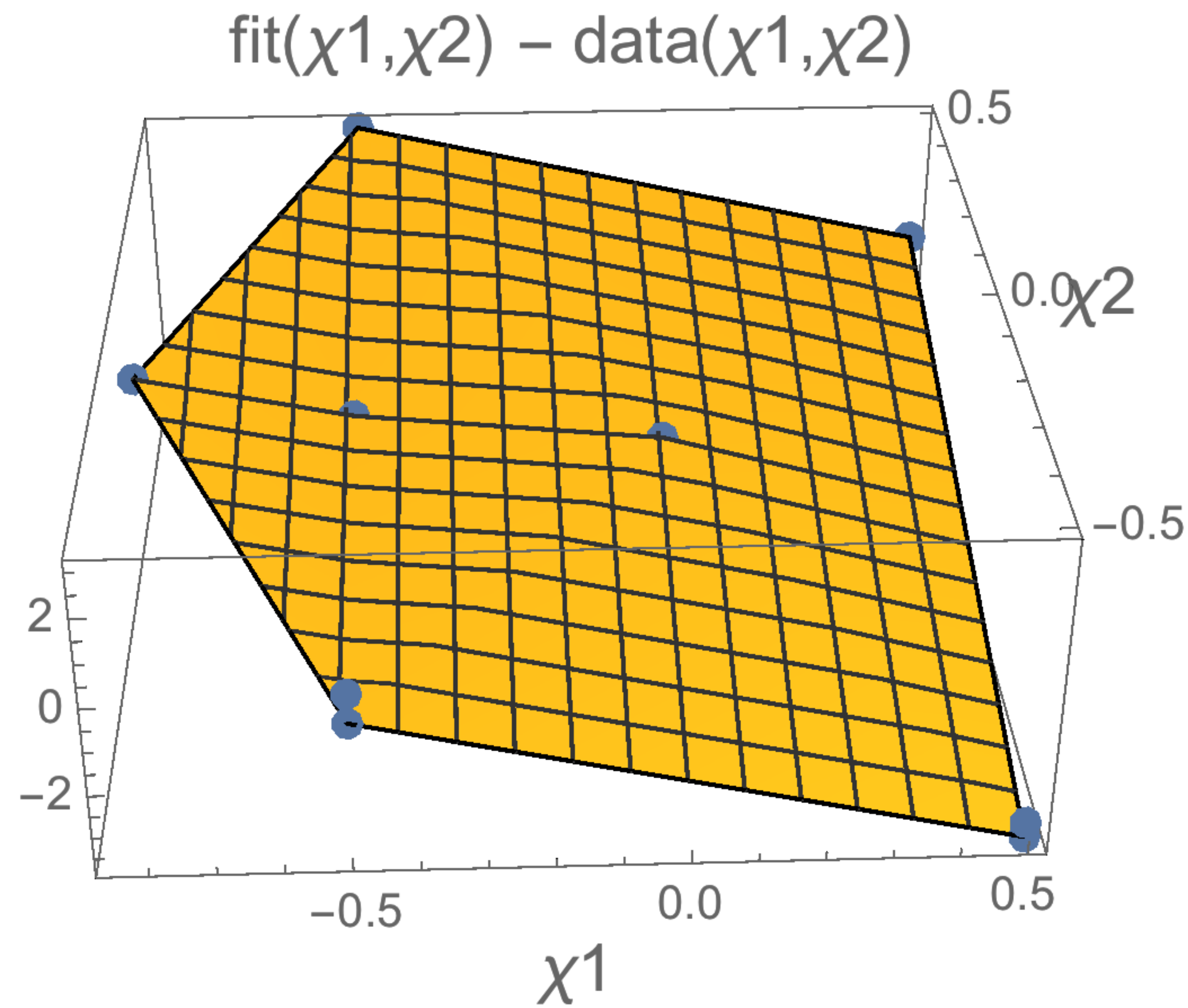
Unequal spin fit

- Fit unequal spins term of the form:

$$X = X_{Eq} + f(\eta)\,(\chi_1 - \chi_2) + \ldots$$

- Guess ansatz for f(η) from inspecting data:

$$f(\eta) = a_0\,\eta^p (1-4\eta)^q$$



- Consistency check:
  - 1D fit vs.
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  - to be completed:

    tune unequal spin fits
    for ~ 30 PhenomD coefficients

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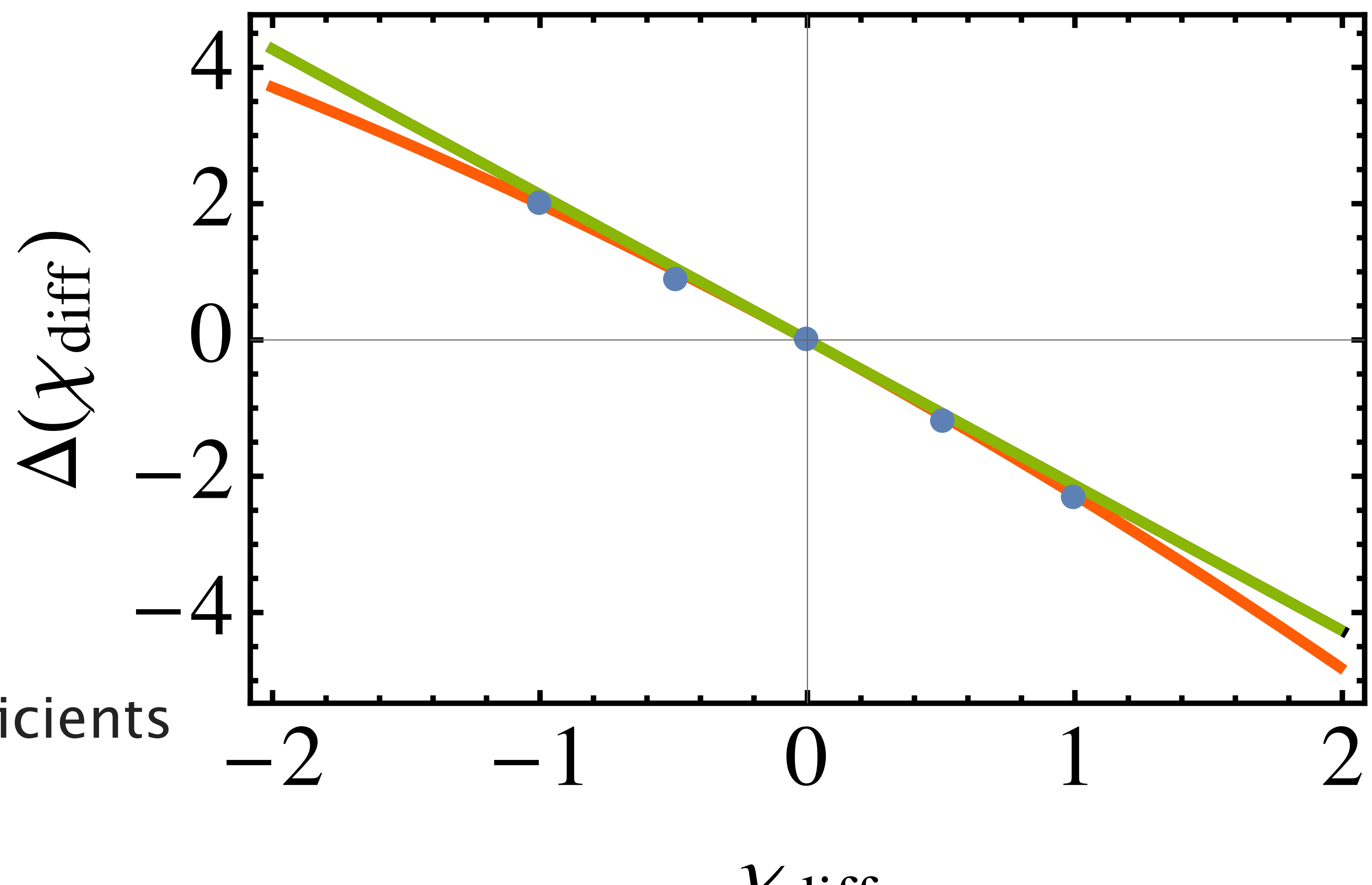

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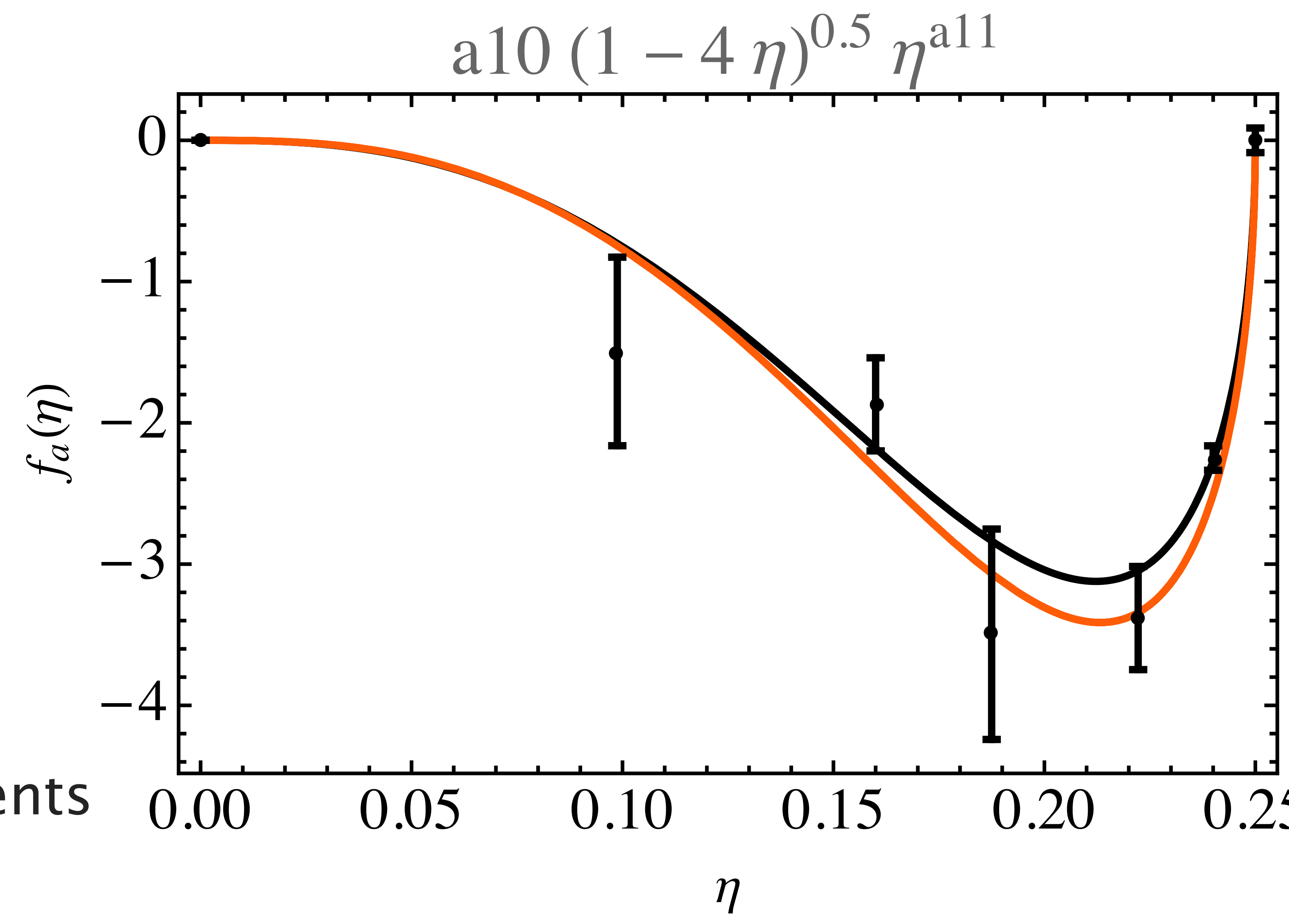

Summary

- PhenomD: very accurate WFs in time & frequency domain.
  - Builds upon EOB inspiral description & detailed study of WF anatomy.
- PhenomD is modular, e.g. inspiral and MRD can be tuned from different waveform sets, variations of Phen* models easy to generate.
  - Did not talk about modifications for modGR, eccentricity …
- IMRPhenomP: precessing IMR model that is fast enough for general applications in Bayesian inference.
- In progress: unequal spin extension of PhenomD
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Interested in helping?
We have an open postdoc position!