Systematic NR fits to GW Peak Luminosity and Final States of BBH Mergers

Xisco Jiménez Forteza, Sascha Husa, David Keitel
Universitat de les Illes Balears
GR21. NY city. July 11, 2016
Session B2

Unió Europea
Fons Social Europeu

Govern de les Illes Balears
La consellera d'Educació, Cultura i Universitats

Motivation and goals

* Relevant **astrophysical information** can be obtained from **BBH merger and final states**.

** Spin distribution, maximal spin systems, radiated energy, luminosity…

* **Fits** are **used to calibrate phenomenological models**. Hannam+2014 , Husa+ 2015, Khan+2015

** Quasinormal ringdown frequency directly computed from final mass and spin.

* **Fits** can be **applied** to **PE posterior distributions**.

* We aim to build a **consistent hierarchical method** to get **non-precessing fits** (luminosity, final spin, energy radiated) based on:

** NR Data quality studies.

** Fits better constrained in the best covered 1D parameter regions (q=1, S=0).

** Constrained to extreme mass-ratio limit.

** Capture unequal-spin (χ_1-χ_2) effects as a perturbation of the 2D fits (η,S).

Final states. Build up the model.

1D non-spinning η fit

1D equal-mass equal-spin S fit

Padé approximants

1D rational fit

1D rational fit

Combine 1D best ansatze

$$\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$$

2D fit (η, S)

$$S = \frac{m_1^2 \chi_1 + m_2^2 \chi_2}{m_1^2 + m_2^2}$$

Extreme mass ratio limit

$$S_i = \frac{\chi_i}{m_i^2}$$

Constrained 2D fit (η, S) ← equal spin data

Unequal Spin Correction

3D fit (η, S, (χ_1 - χ_2)) ← all data

Final Spin. Parameter coverage

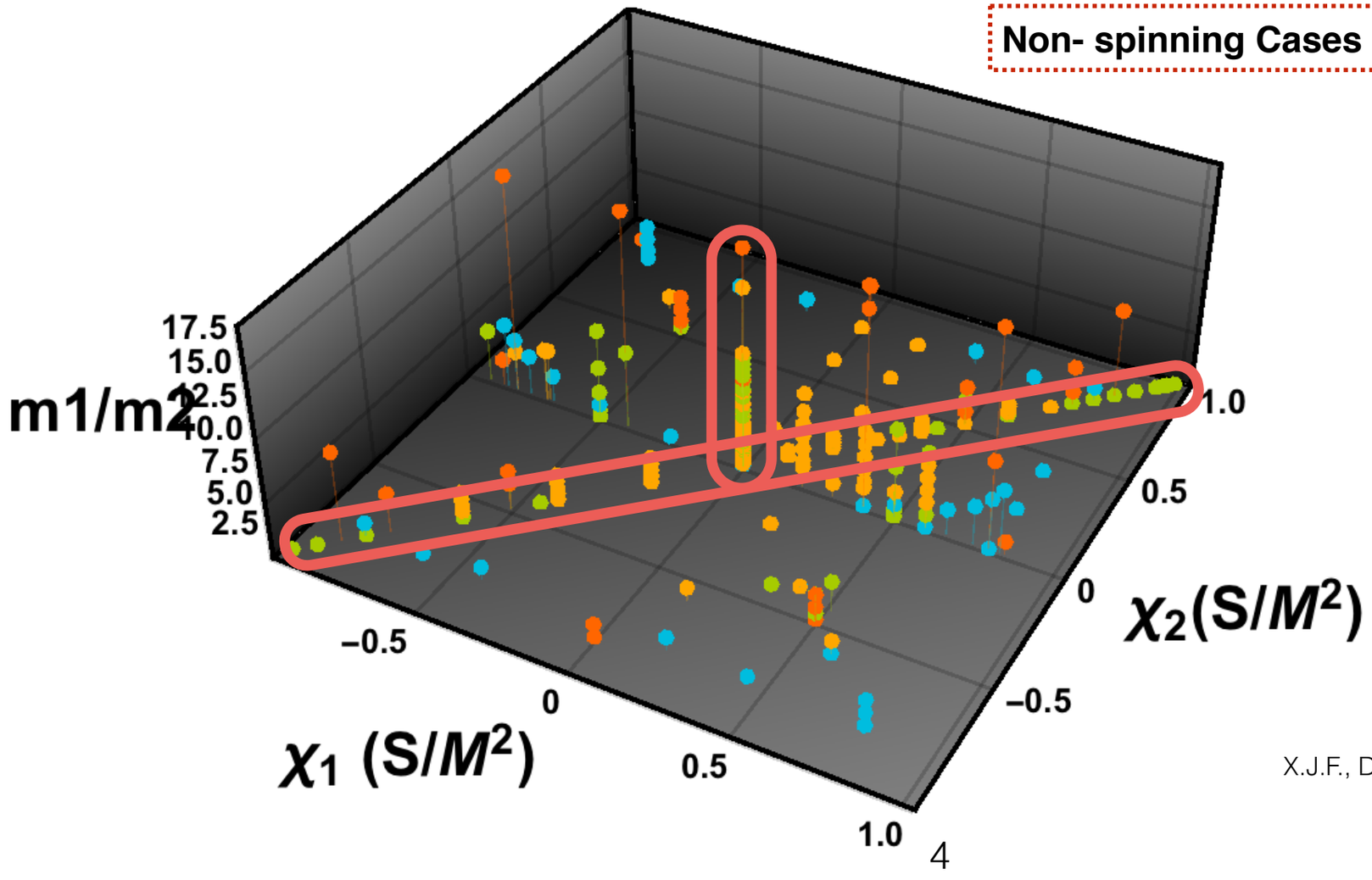
Data : 259 Cases → Outliers : 12 Cases → Total : 247 cases used for the fit

Unequal Spin Cases : 105

Equal Spin Cases : 142

Non- spinning Cases : 75

q=1 Eq. S. Cases: 67



- **BAM** UIB+Cardiff *
- **SXS** Mroue+ 2013. www.black-holes.org/
- **RIT** Healy+ 2014.
- **GaTech** Jani+ 2016.

X.J.F., D.K., S.H., M. Hannam, S. Khan, M. Pürrer

Final states. Build up the model.

- Combine the best 1D fits.

Non-Spinning fit :

$$\frac{4.73a_0\eta^2+0.98a_2\eta^3+2\sqrt{3}\eta}{2.7a_1\eta+1}$$

3 free parameters

Equal-mass equal-spin fit :

$$\frac{0.27b_0S^2+0.0064b_1S^3-0.69b_3S}{1-0.43b_2S}$$

4 free parameters

Combine + Solve 1D constrains

Final 2D Ansatz :

16 free parameters

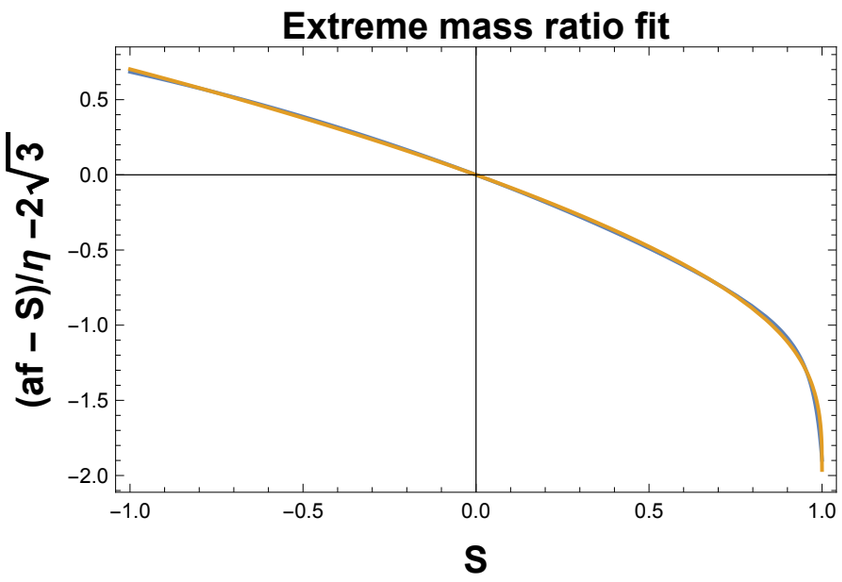
$$\frac{-10.1177\eta^3+16.7998\eta^2+2\sqrt{3}\eta}{6.24531\eta+1}+\frac{\left(0.075788S^2\left(\mathrm{f00}+\mathrm{f01}\eta+\mathrm{f02}\eta^2+\mathrm{f03}\eta^3\right)+0.007475S^3\left(\mathrm{f10}+\mathrm{f11}\eta+\mathrm{f12}\eta^2+\mathrm{f13}\eta^3\right)-0.194118S\left(\mathrm{f20}+\mathrm{f21}\eta+\mathrm{f22}\eta^2+\mathrm{f23}\eta^3\right)\right)}{1-0.529026S(\mathrm{f30}+\mathrm{f31}\eta+\mathrm{f32}\eta^2+\mathrm{f33}\eta^3)}$$

*** We know the final states in the extreme mass ratio limit case from unperturbed Kerr solution + the Kerr geodesic equation (Bardeen+ 1972).**

*** This provides an additional constraint equation.**

Final Spin. Build up the model.

- Extreme Mass Ratio Limit.



$$\lim_{\eta\to 0}\frac{\text{fit2D}(\eta,S)}{\eta}\approx\frac{S(S(-0.143f_{01}-0.0141f_{11}S)+0.367f_{21})}{f_{30}S-1.890}$$

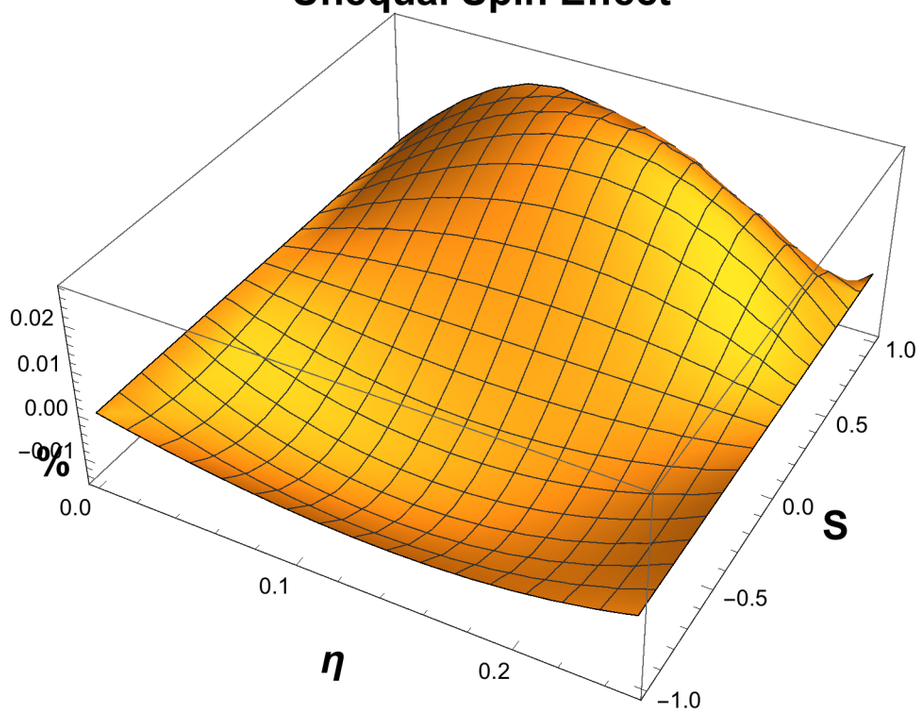
Number of Free parameters after applying the constrains for the 2D fit —> 3

- Unequal Spin effect.

* **Subdominant effect ~ 5%, treat as perturbation of 2D fit.**

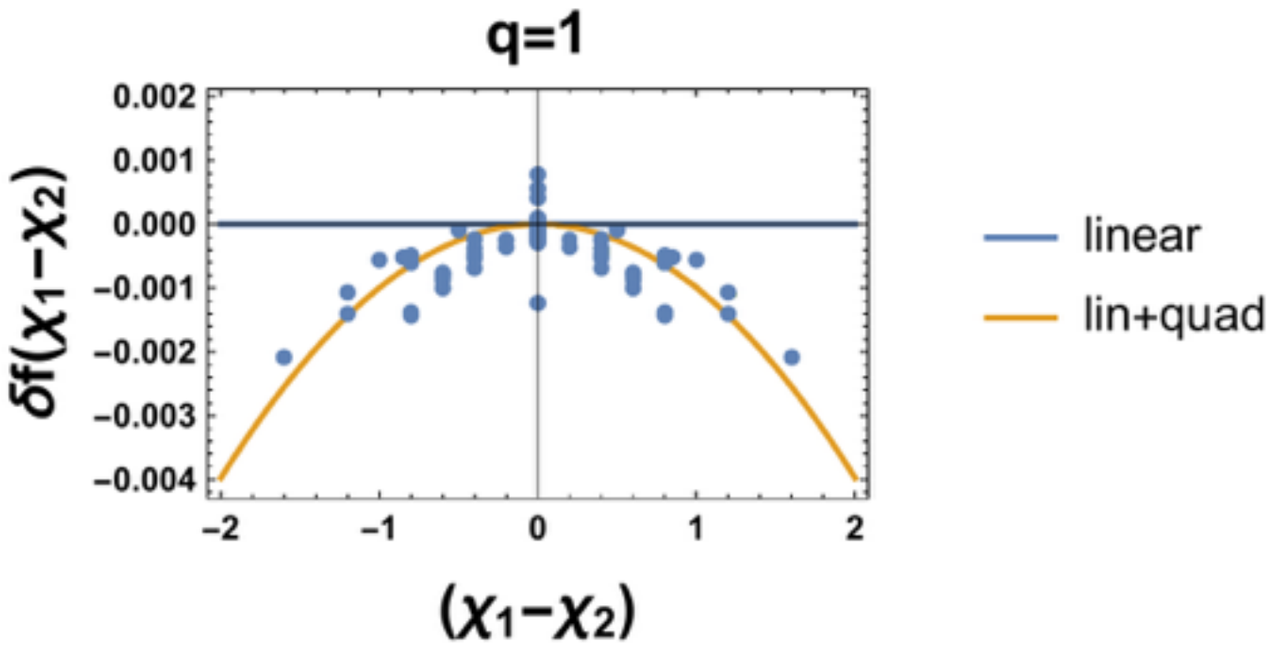
* **rms 2D fit. 0.00517 : rms 3D fit. 0.00062**

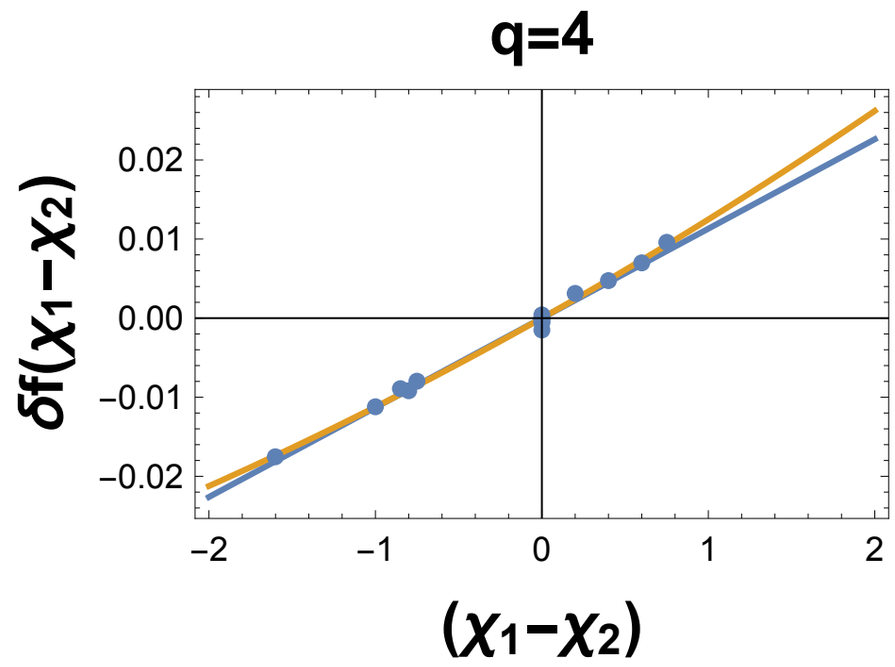
$$fit2D(\eta,S)+f_a(\eta)(\chi_1-\chi_2)+f_b(\eta)(\chi_1-\chi_2)^2$$



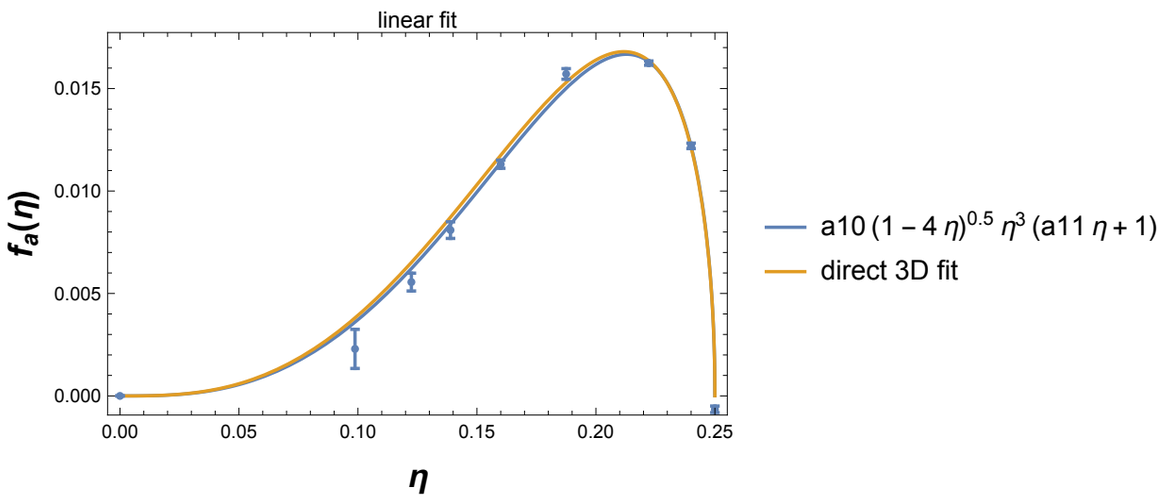
Final Spin. Build up the model.

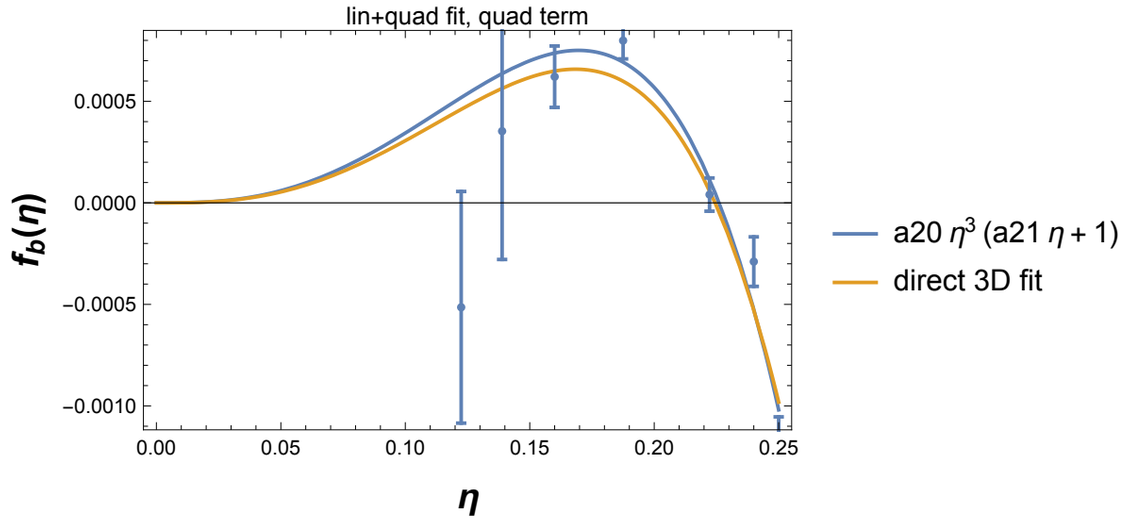
- Unequal Spin effect.





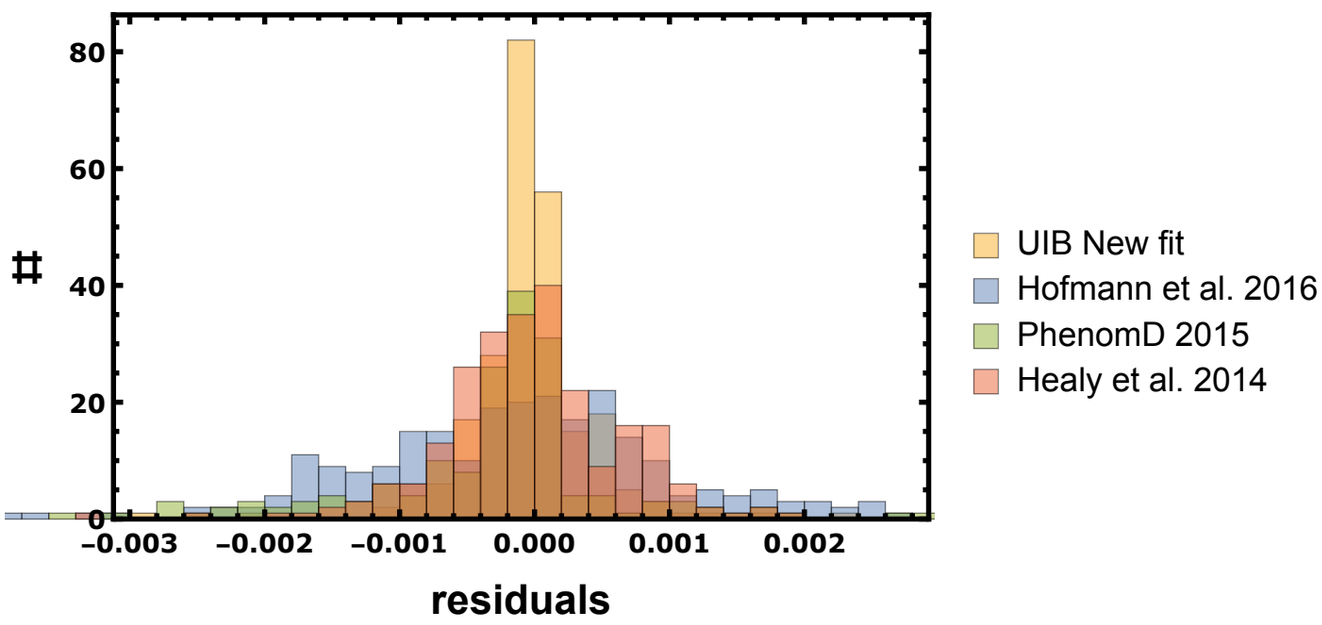
Doing an analysis per mass-ratio one finds evidence of both linear and quadratic dependence.





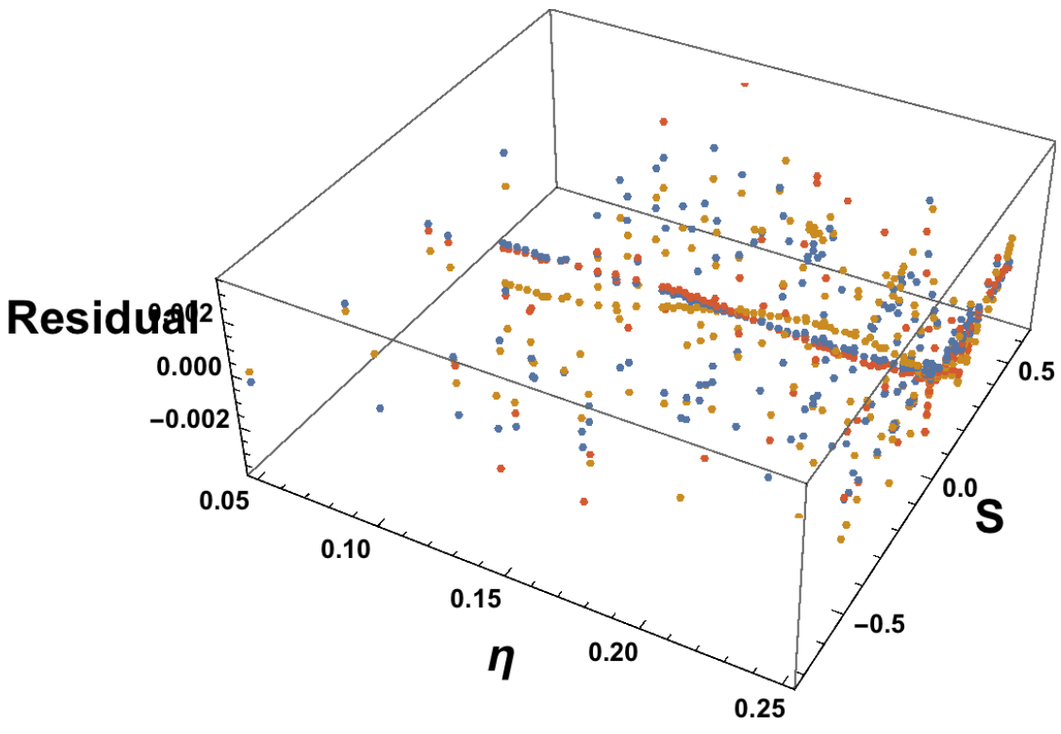
Final Spin. Test the model.

- Comparison with previous fits.



	Fits	μ	σ
3D Fit	Hofmann et al. 2016	-0.000132	0.00116
3D Fit	UIB New fit	-0.000023	0.00051
2D Fit	PhenD fit 2015	-0.000200	0.00566
3D Fit	Healy et al. 2014	0.000017	0.00079

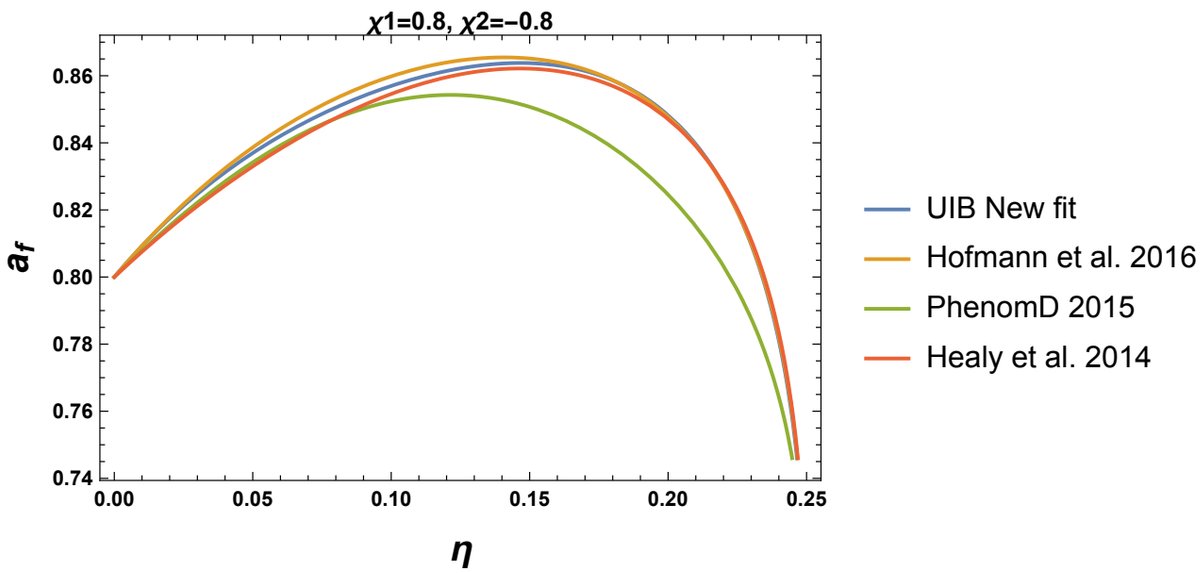
**** mean of residuals and root mean squared residuals**

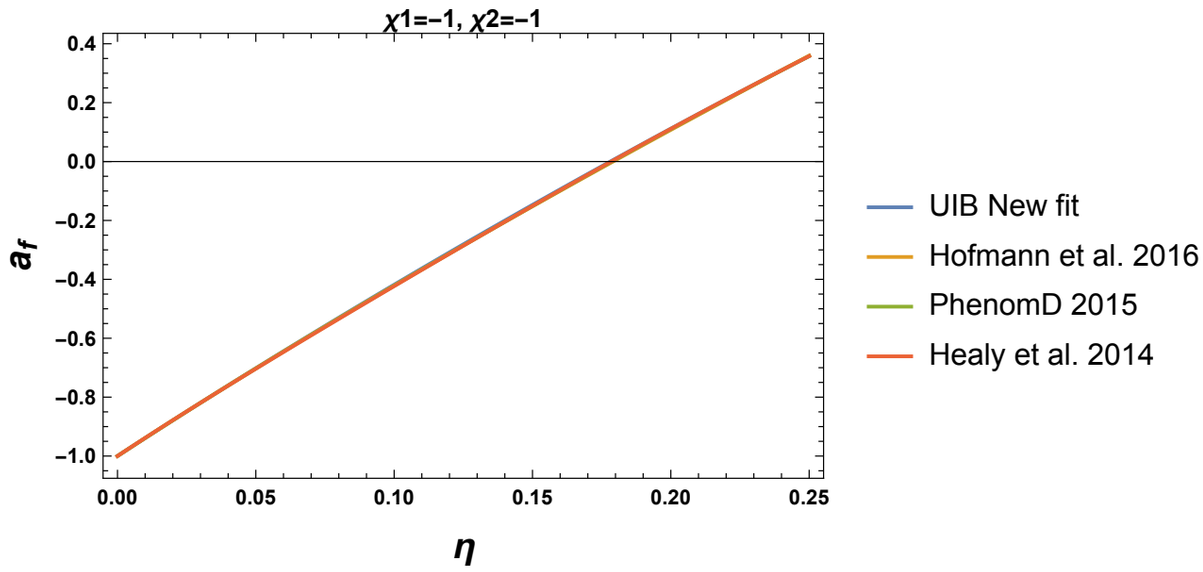


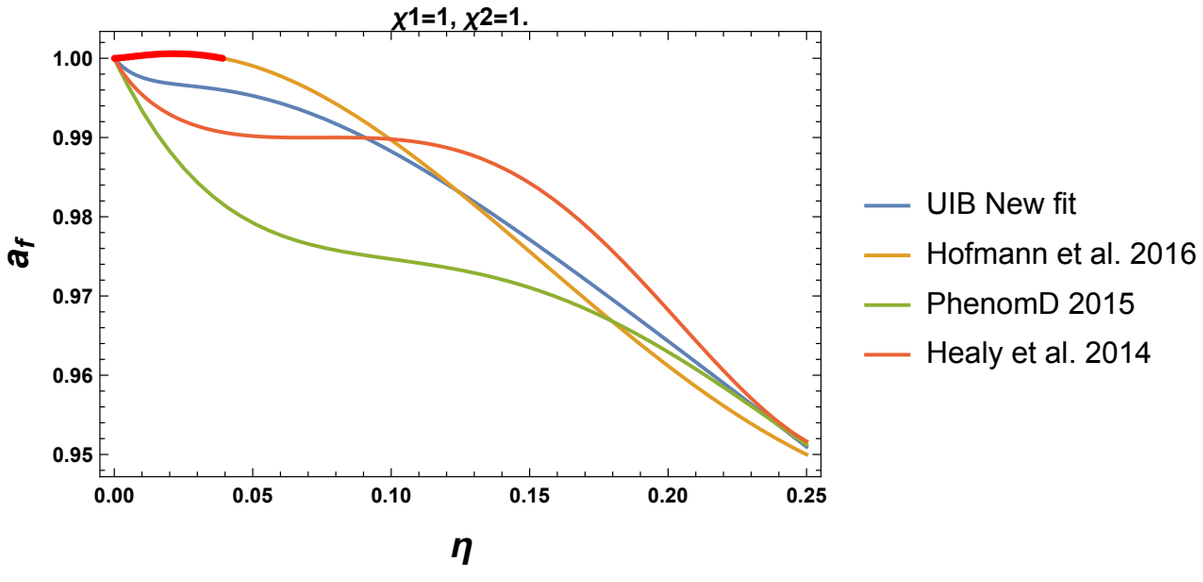
- **no bias between various fits**
- **compatible distributions of residuals**
- **However naive comparisons might be misleading since different fits have been calibrated to different data sets.**

Final states. Test the model.

- Comparison with previous fits. Some special cases.







* **The approach to the extreme limit is different for different fits.**

* **The actual extreme mass ratio limit is constrained.**

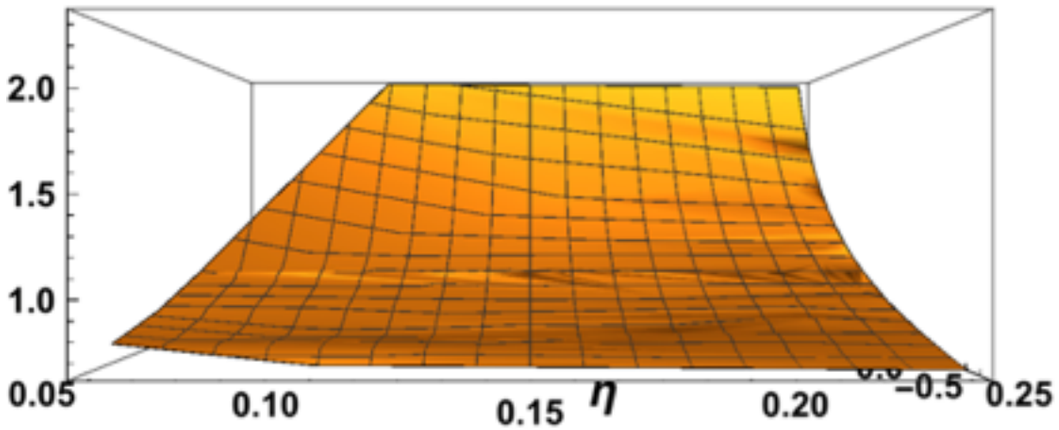
* **But no NR data below q=18. Differences are due to extrapolation.**

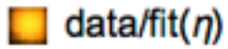
Final Mass

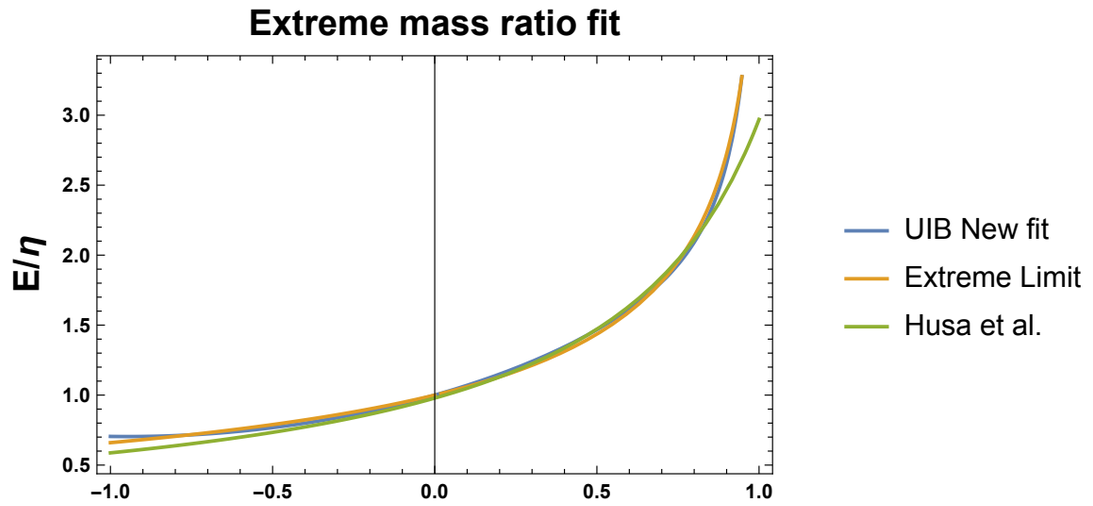
Preliminary!

- Same hierarchical procedure as for final spin.

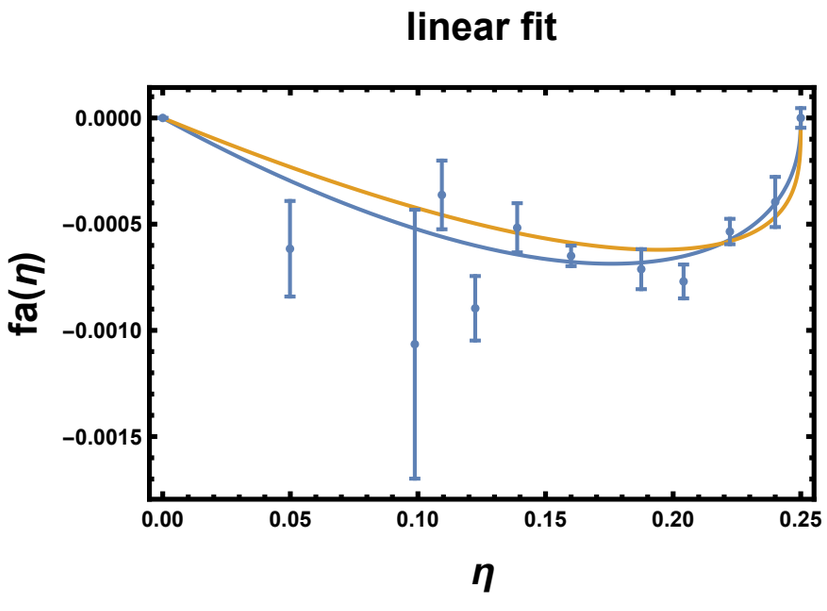
- 2D ansatz [η,S] is now a product (instead of sum).

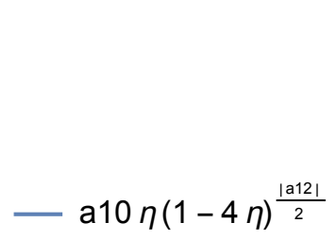


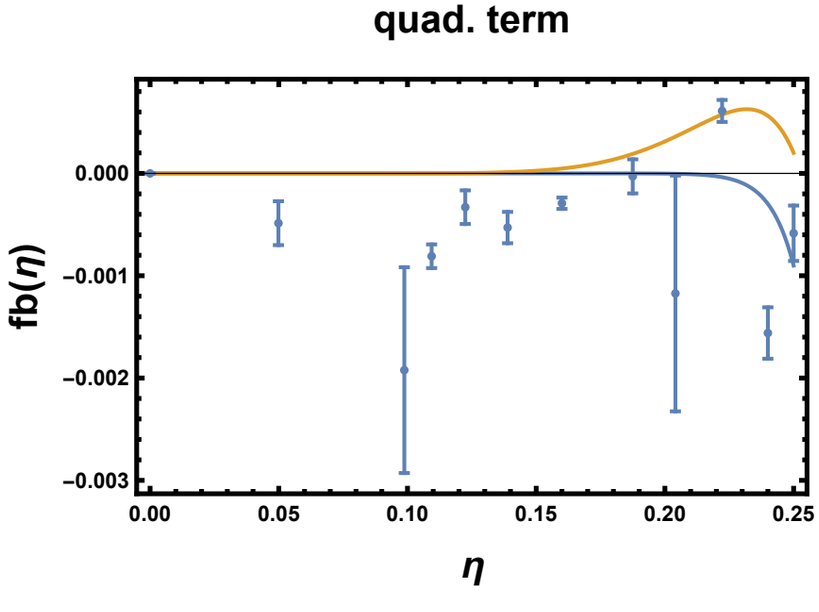


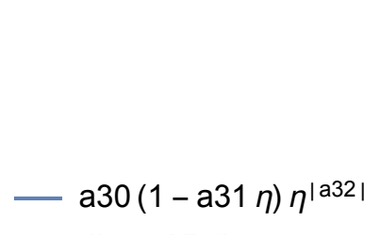


- Here we can currently only pull out the linear (χ1-χ2) term.









Luminosity

- An early version of this procedure has been already used for the peak luminosity.

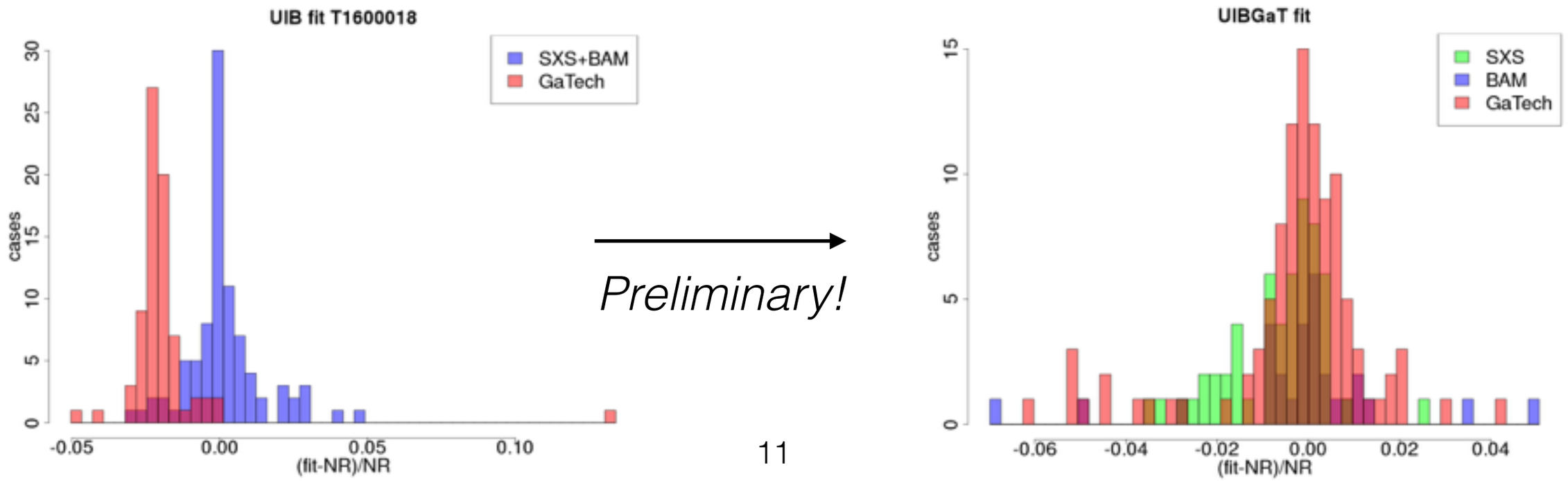
https://dcc.ligo.org/LIGO-T1600018/public

Xisco Jiménez-Forteza, David Keitel, Sascha Husa, Mark Hannam,
Sebastian Khan , Lionel London, Michael Pürrer

- Used in LVC publication on GW150914 and GW151226:

PRL **116**, 241103 (2016), *PRL* **116**, 061102 (2016), arXiv:1606.04856

- **Previously fitted to SXS and BAM data (89 cases).**
- **New version in preparation with modes up to ℓ = 6 and including GaTech data (arXiv:1605.03204 - processed for fit by L. London).**



Conclusions

* We aim to build a **consistent hierarchical method** to get **non-precessing fits** (luminosity, final spin, energy radiated) based on:

* Performing this **hierarchical study** provides a **better understanding** of the **3D parameter space** structure and control of **extrapolation behaviour.**

* **Improved final spin fit**. **Residuals compatible** with Healy et al., Hofmann et al.

* Same **approach** for **final mass** showing **similar results,** although **higher spin difference** effects **difficult** to **constrain.**

***** An early **version** of this procedure has **been** already **used for the peak luminosity.** New **version** in **preparation.**

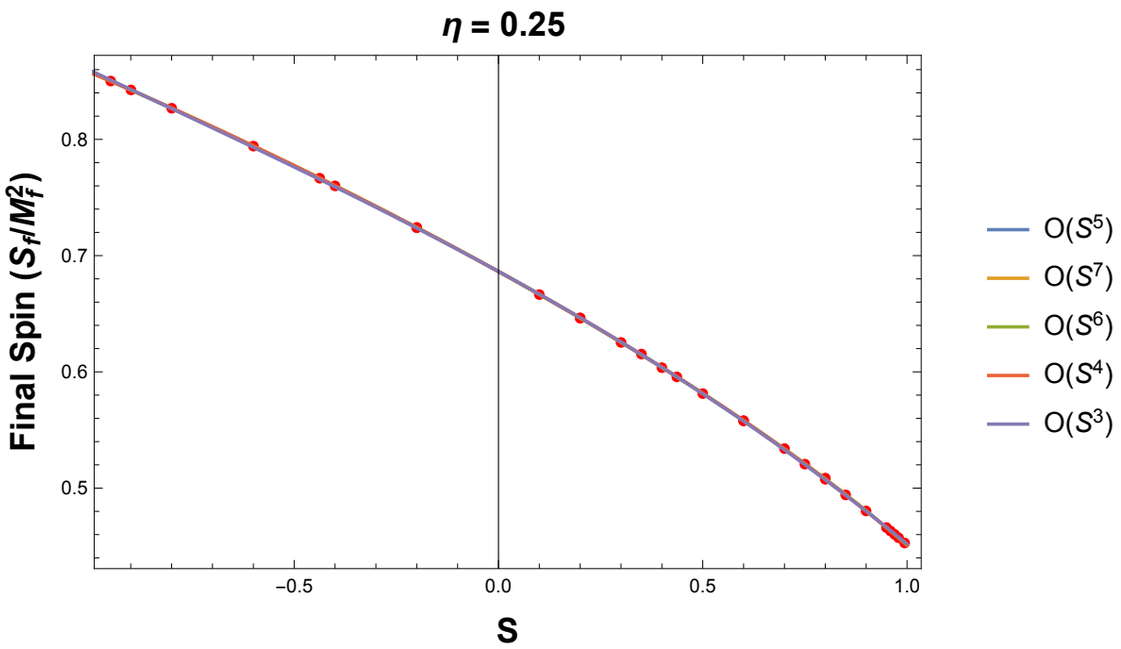
* When **combining NR results from several codes**/catalogues, it is important *to* ***carefully study*** *their* ***data quality.***

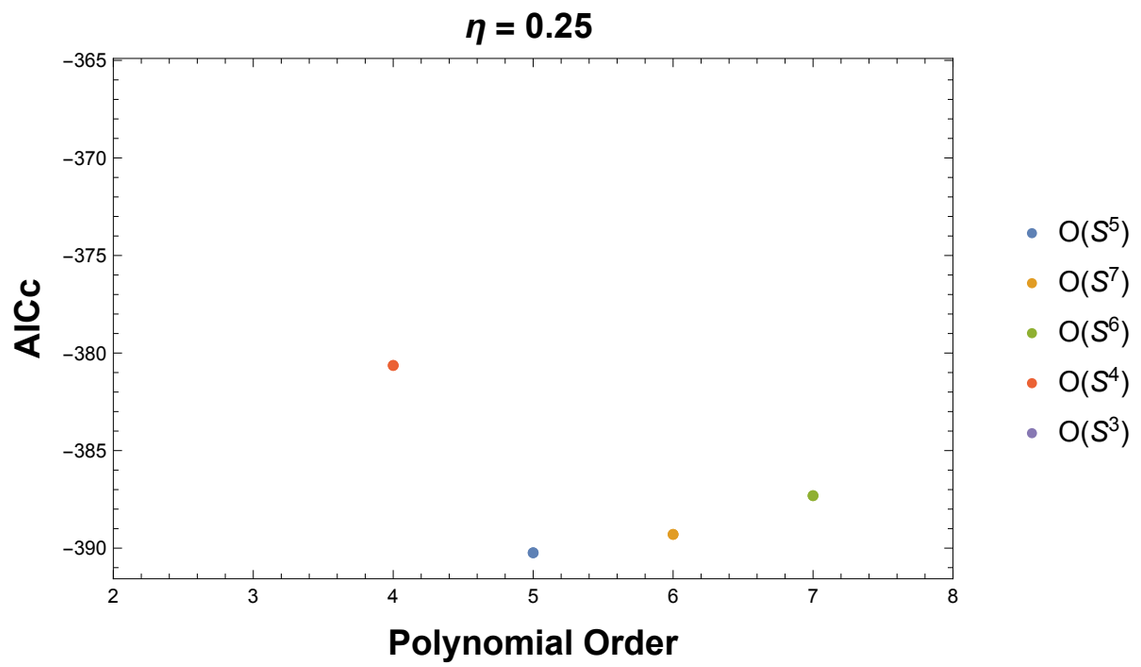
See also talk by Sascha Husa, Wednesday, Session C2.

Thanks!

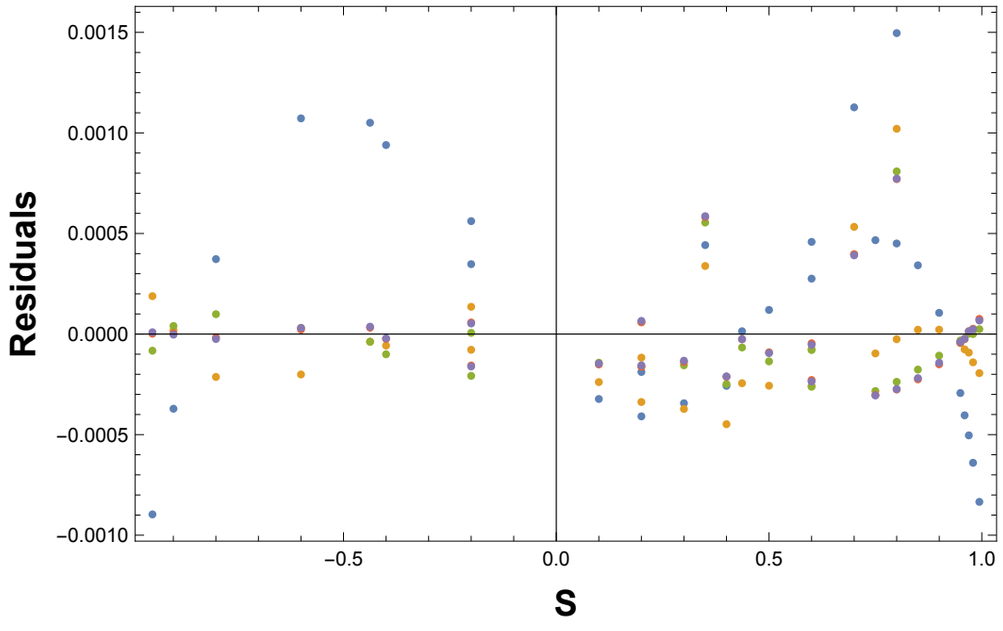
Final Spin. Build up the model.

- Get 1D fits from the most populated and NR most accurate regions: f(η=0.25,S) and f(η,0).





We **base** our **decision** on **A**kaike **I**nformation **C**riterion (**AICc**), **residuals** and the **t'statistics** of the free **parameters**.

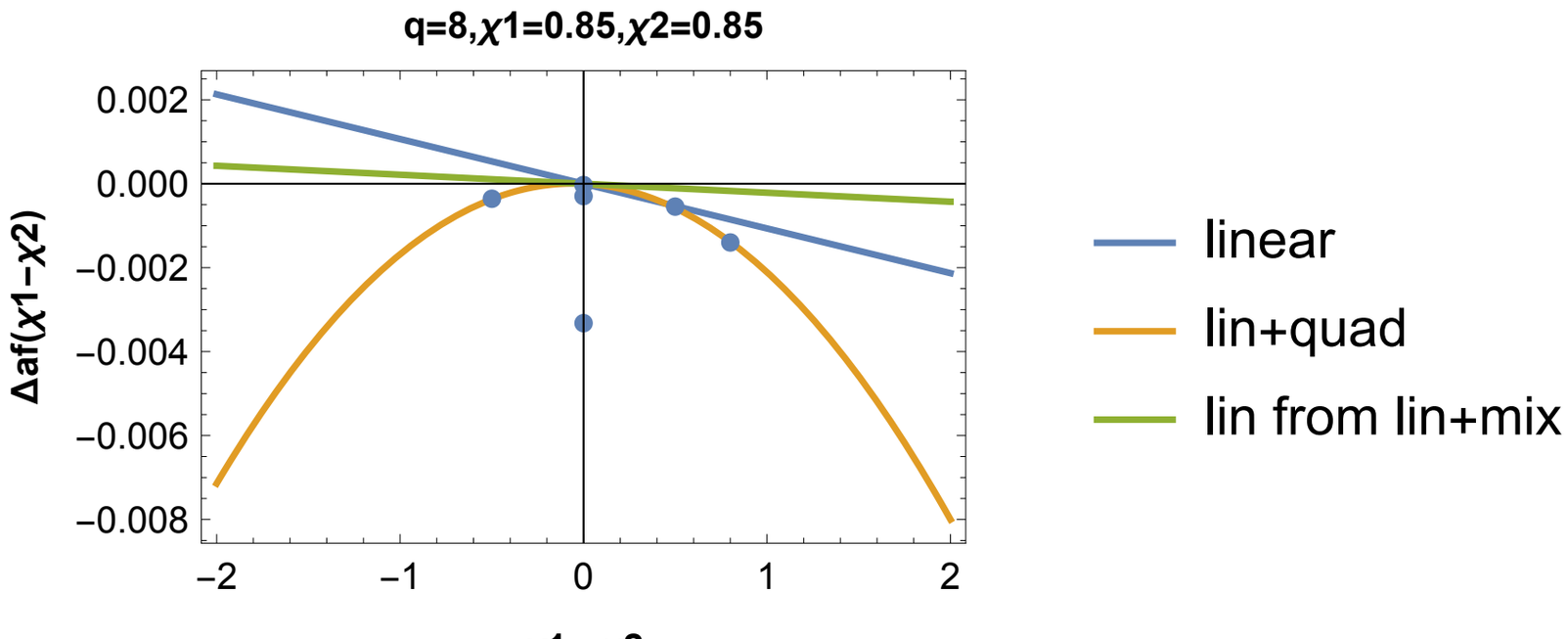


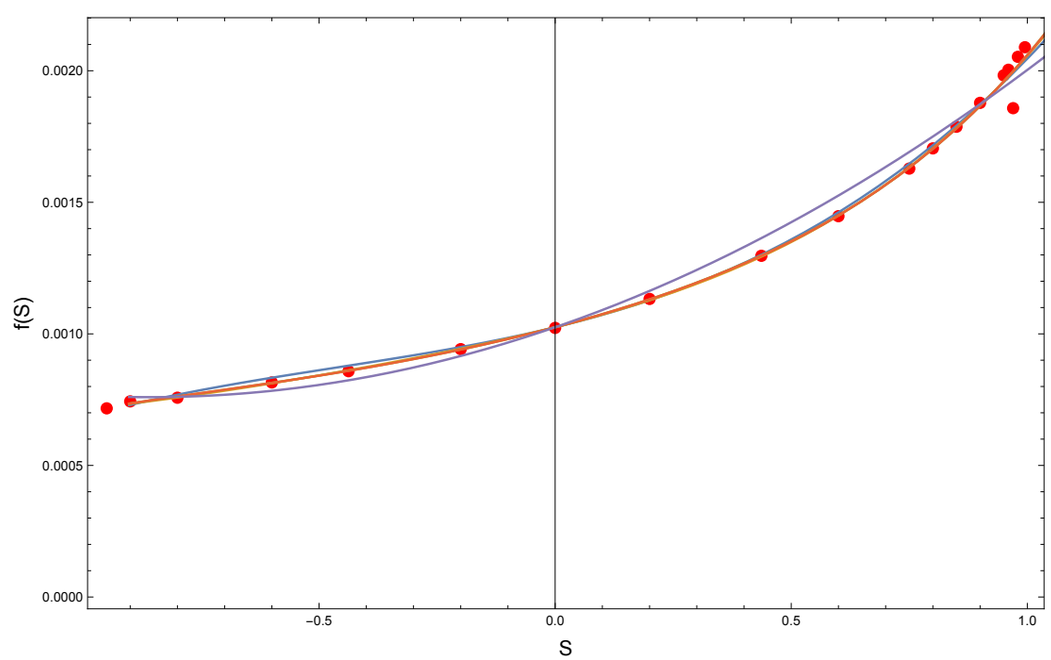
$$0.686355 + b_1 S + b_2 S^2 + b_3 S^3 + b_4 S^4 + b_5 S^5$$

	Estimate	Standard Error	t-Statistic	P-Value
b1	−0.194412	0.000363411	−534.964	1.94821×10^{-50}
b2	−0.0265515	0.000455693	−58.2663	2.31492×10^{-27}
b3	−0.00496448	0.00140788	−3.52621	0.00172663
b4	−0.00515274	0.000577171	−8.92758	4.29214×10^{-9}
b5	−0.00423716	0.00123315	−3.43605	0.00215744

**** First step before using Padé approximants.**

Bonus slide



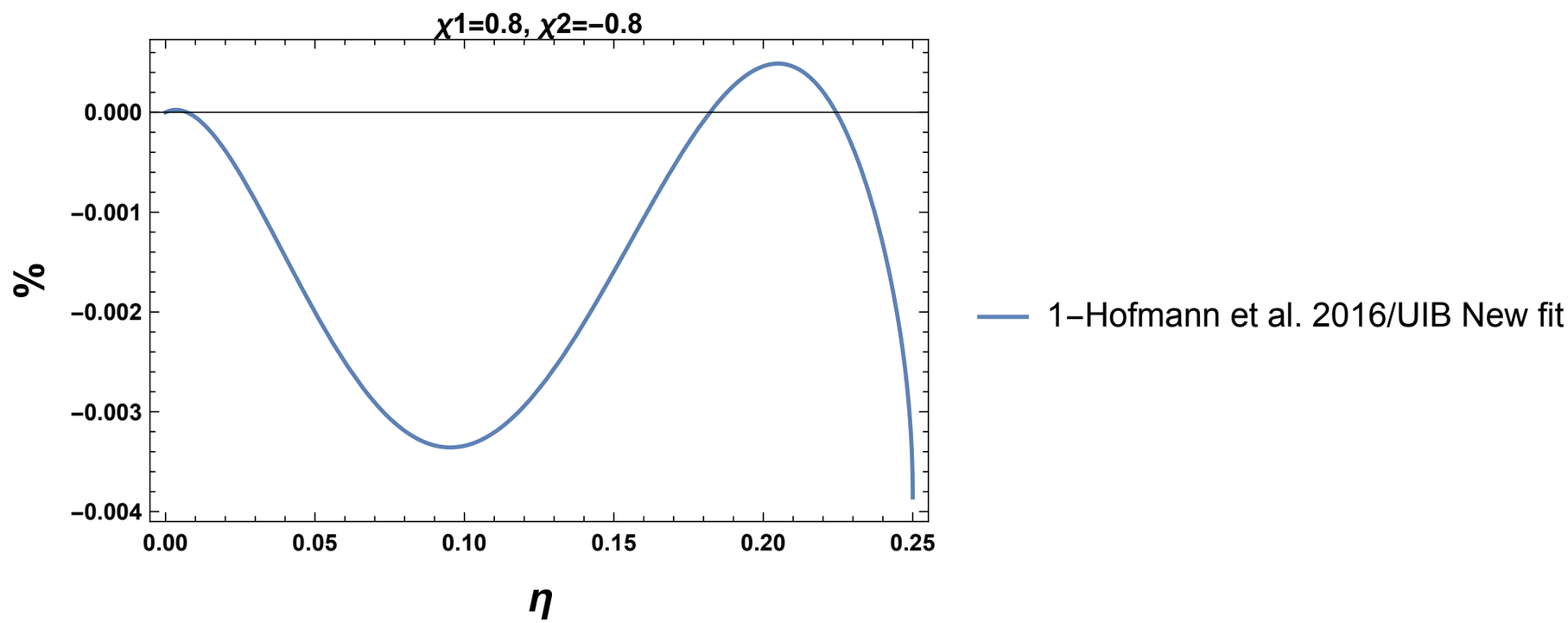


linear

lin+quad

lin from lin+mix

Bonus slide


χ1=0.8, χ2=−0.8
0.000
−0.001
−0.002
−0.003
−0.004
%
0.00
0.05
0.10
0.15
0.20
0.25
η
1−Hofmann et al. 2016/UIB New fit