



**Universitat**  
de les Illes Balears

# IMRPHENOMXHM\_NSBH

A Fast and Accurate Gravitational-Wave Model for Neutron Star–Black Hole Coalescences

F. Ramis, M. Colleoni, A. Abac, T. Dietrich, A. Gonzalez, P. Mourier

# INTRODUCTION



# INTRODUCTION

## PHENOMENOLOGY AND DETECTIONS

### Non-Disruptive (ND)

- The NS is swallowed mostly whole by the BH
- The GW has subtle deviations from that of a BBH

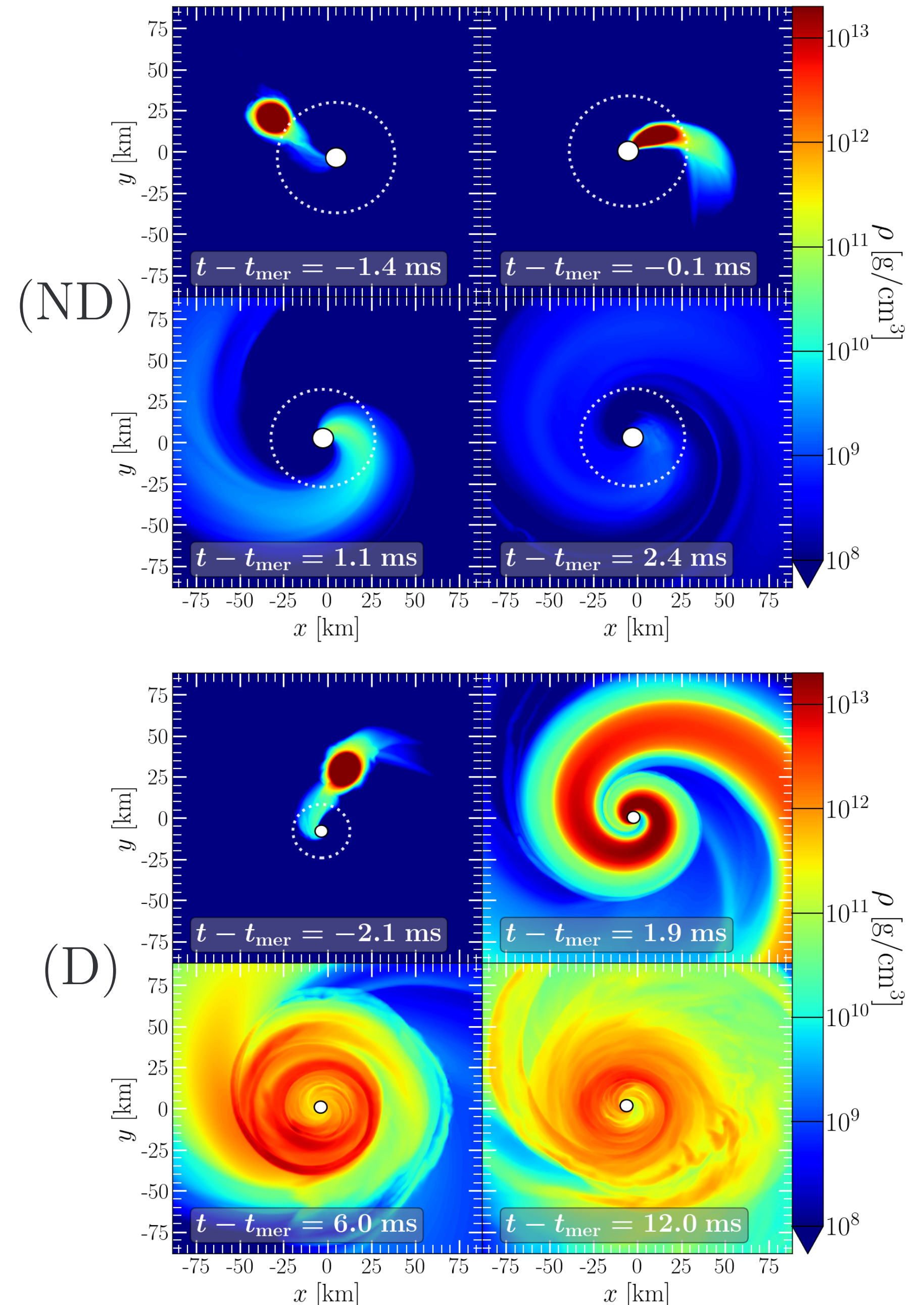
### Disruptive (D)

- The NS is torn apart before merging with the BH, resulting in mass ejecta and the formation of an accretion disk
- Sharp suppression of the GW signal after point of tidal disruption
- More likely to produce electromagnetic (EM) counterparts such as a kilonova or gamma-ray bursts

### Detections

- GW200105 & GW200115 (confident detections)
- GW230529 (very strong candidate with light BH)
- GW190814 (uncertain nature of the secondary object)

*No EM counterparts and unconstrained tidal deformabilitys*



# INTRODUCTION

## STATUS OF CURRENT MODELS

| Waveform Model                            | BBH Baseline               | Precession | Higher Multipoles | Tides | Disruption |
|-------------------------------------------|----------------------------|------------|-------------------|-------|------------|
| IMRPhenomNSBH <i>(2020)</i>               | IMRPhenomD <i>(2015)</i>   | —          | —                 | ✓     | ✓          |
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Neglecting higher-order multipoles, spin precession, or tidal disruption can reduce detection sensitivity and lead to significant biases in parameter estimation, especially at high SNRs or configurations highly sensitive to these effects [*Huang et al. (2020); Harry & Hoy (2025)*]



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| IMRPhenomXHM_NSBH (2025)           | IMRPhenomXHM (2020)    | —          | ✓                 | ✓     | ✓          |

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### Shortcomings of PhenomNSBH

- Piece-wise construction resulting in non-smooth transitions across the parameter space
- Unphysical amplitude dependence on the tidal deformability [*Brown et al. (2023)*]
- Lack of post-merger calibration

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# CONSTRUCTION OF THE MODEL



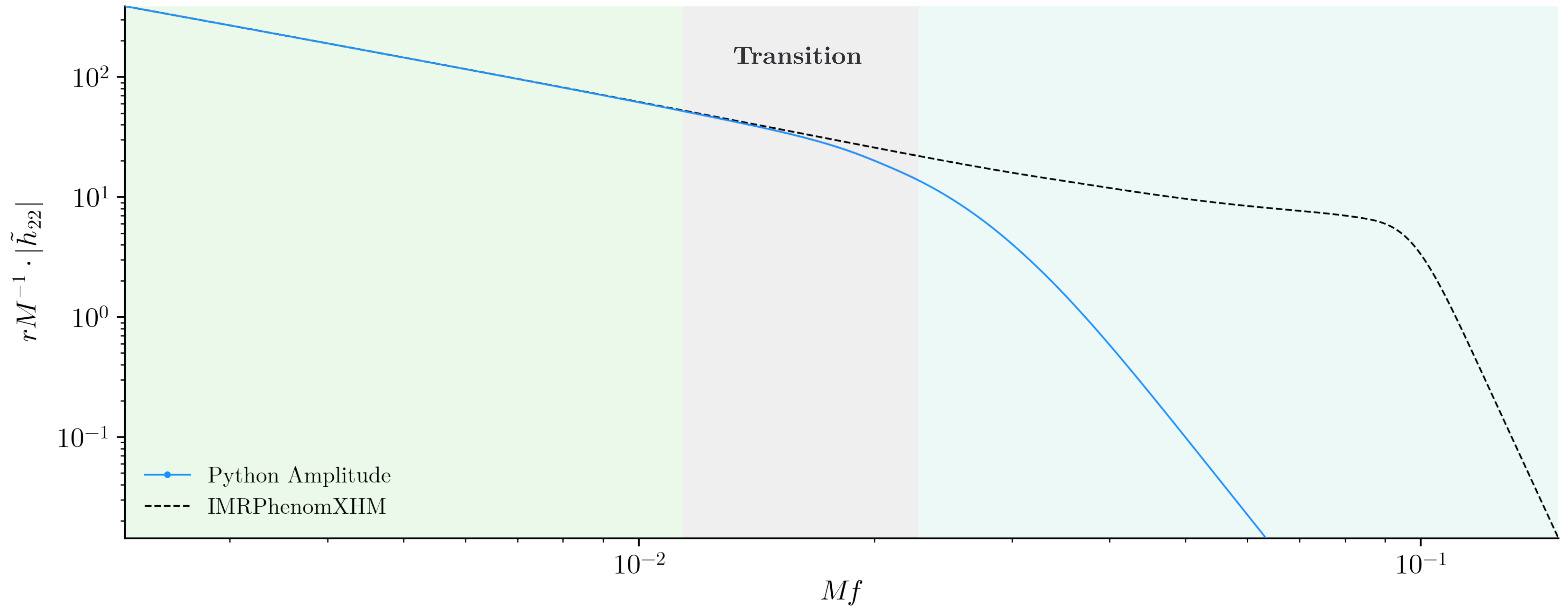
# AMPLITUDE MODEL

INSPIRAL - MERGER - RINGDOWN

Inspiral

$Q = 2, \quad M_{\text{NS}} = 1.35, \quad \chi_{\text{BH}}^z = 0.50, \quad \Lambda = 2000$

Merger-Ringdown





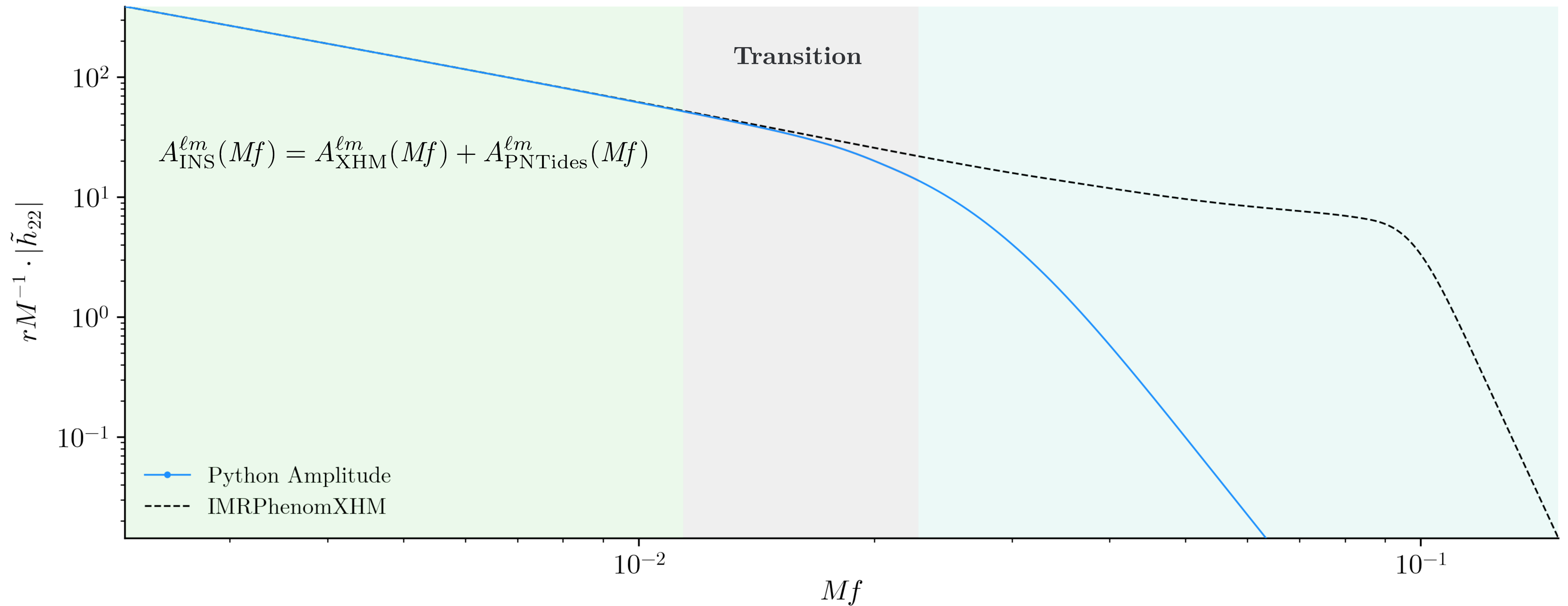
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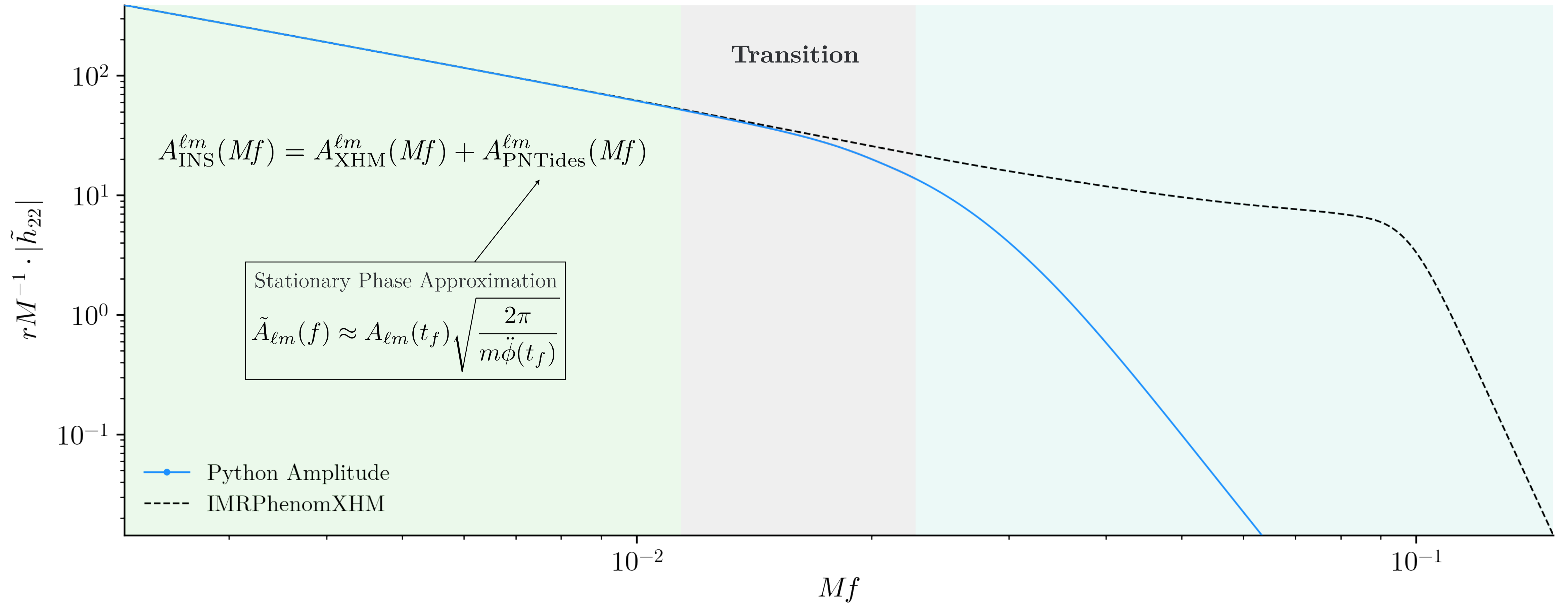
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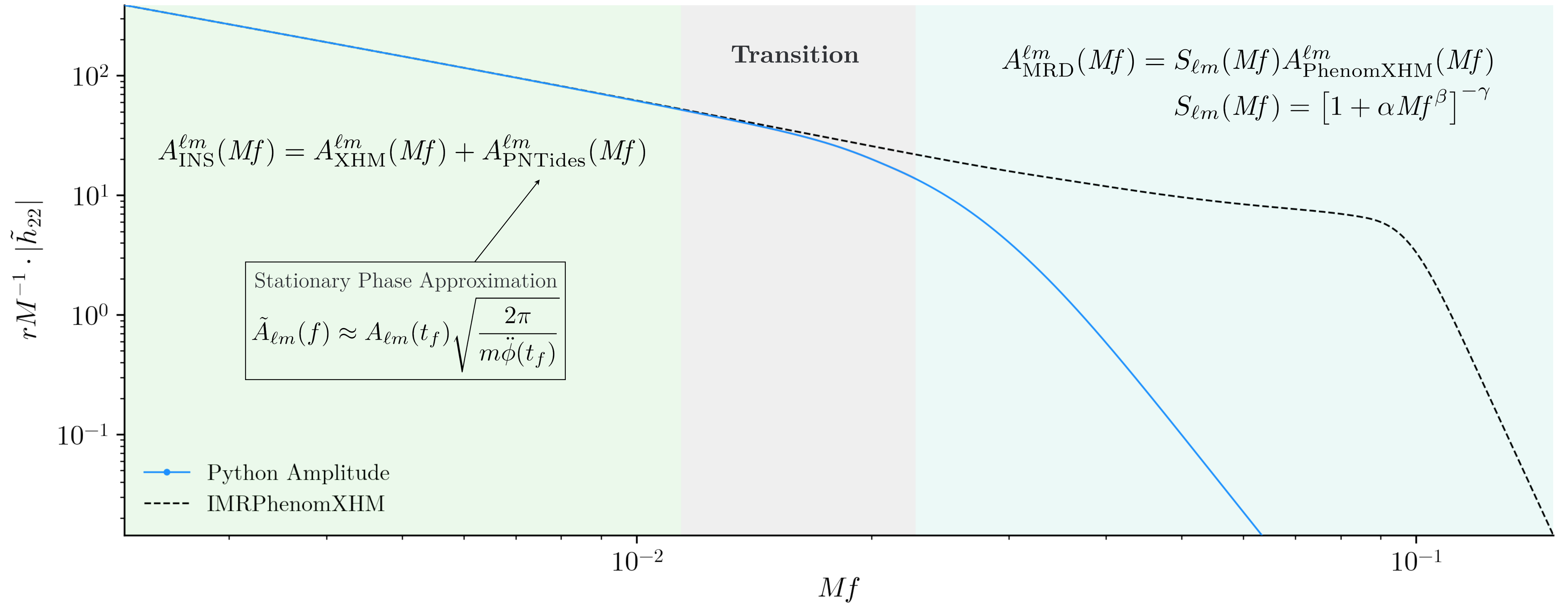
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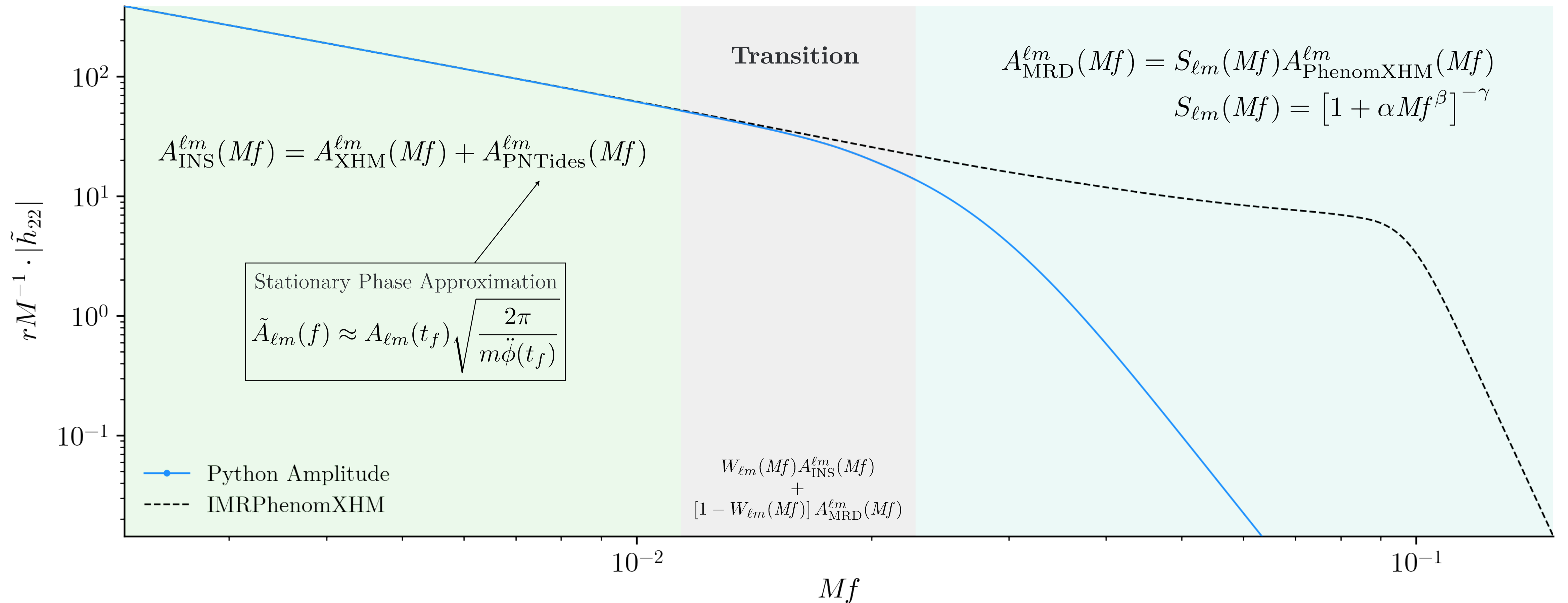
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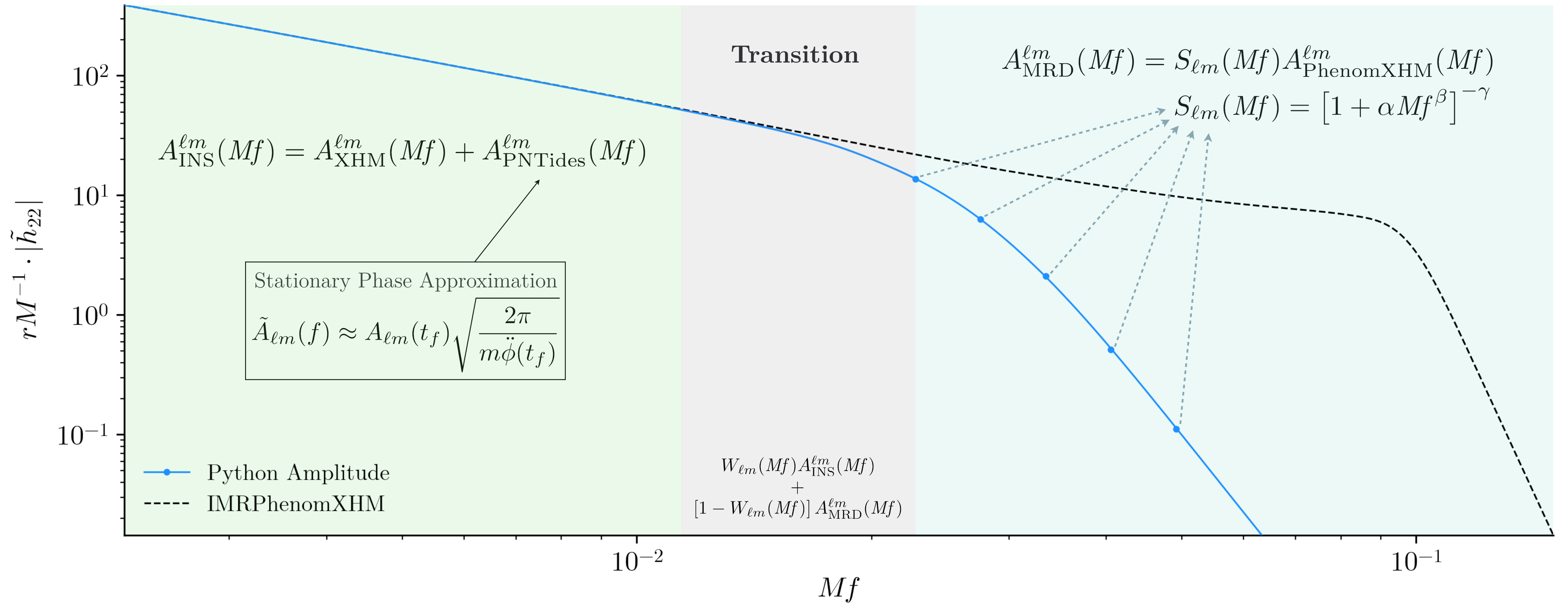
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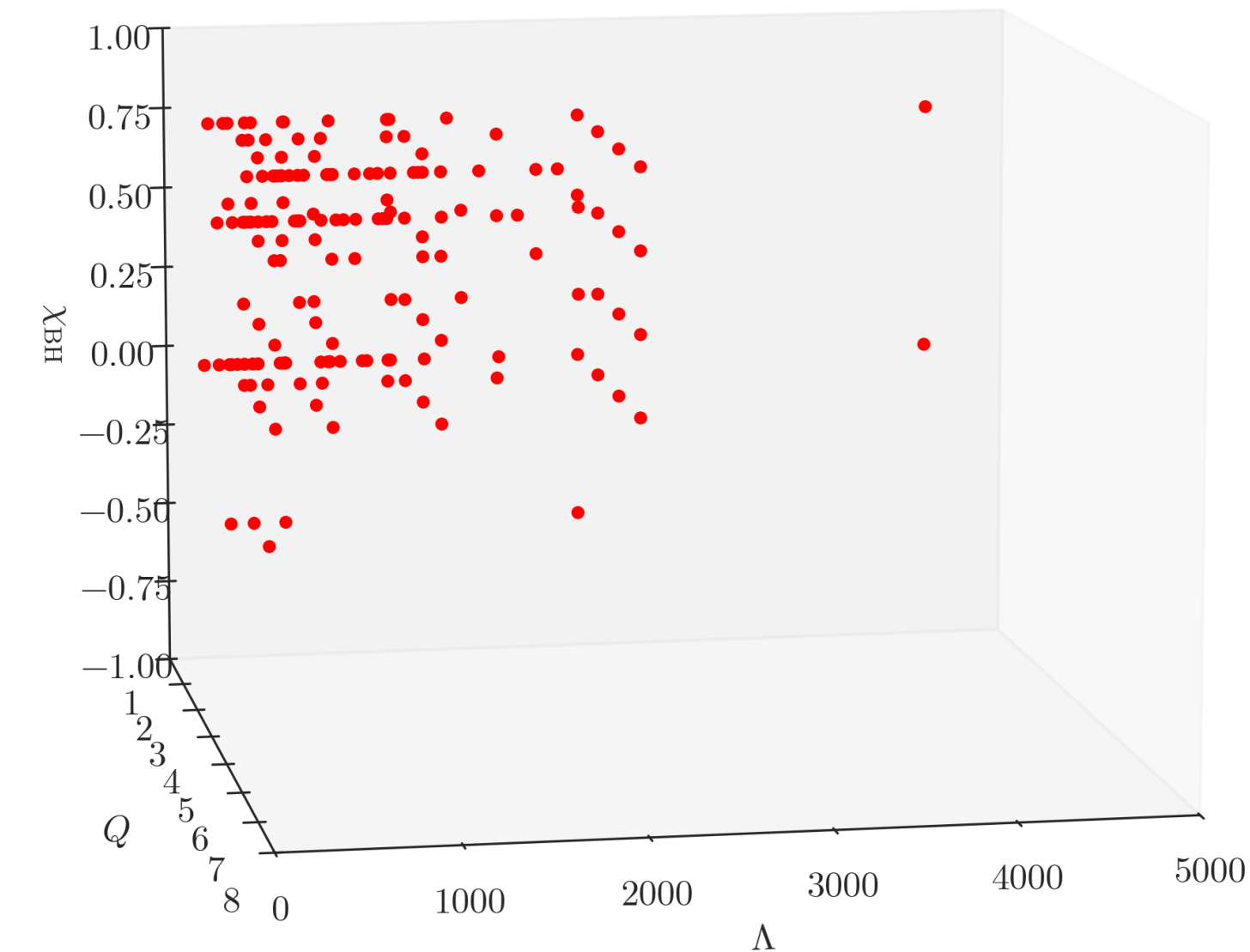
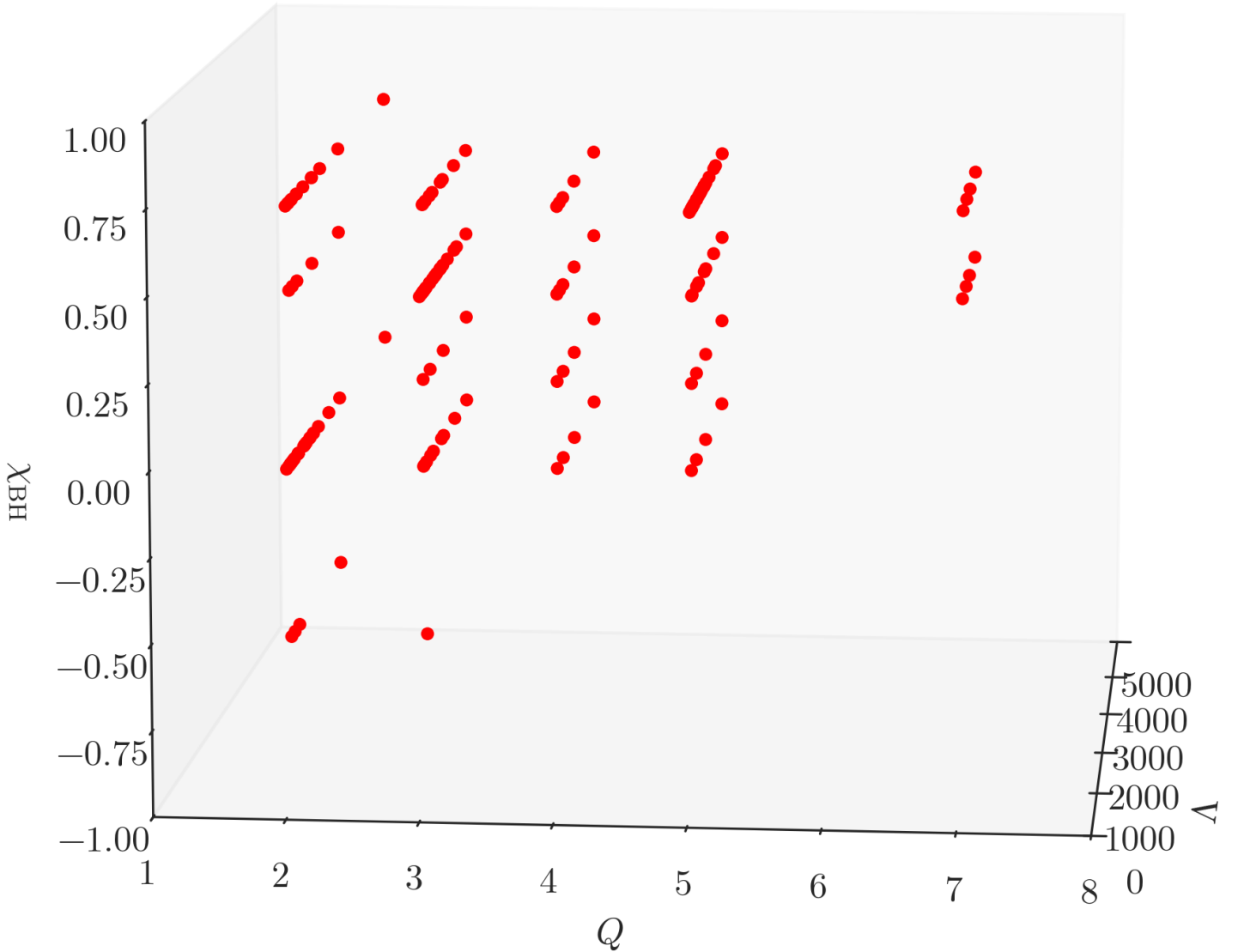
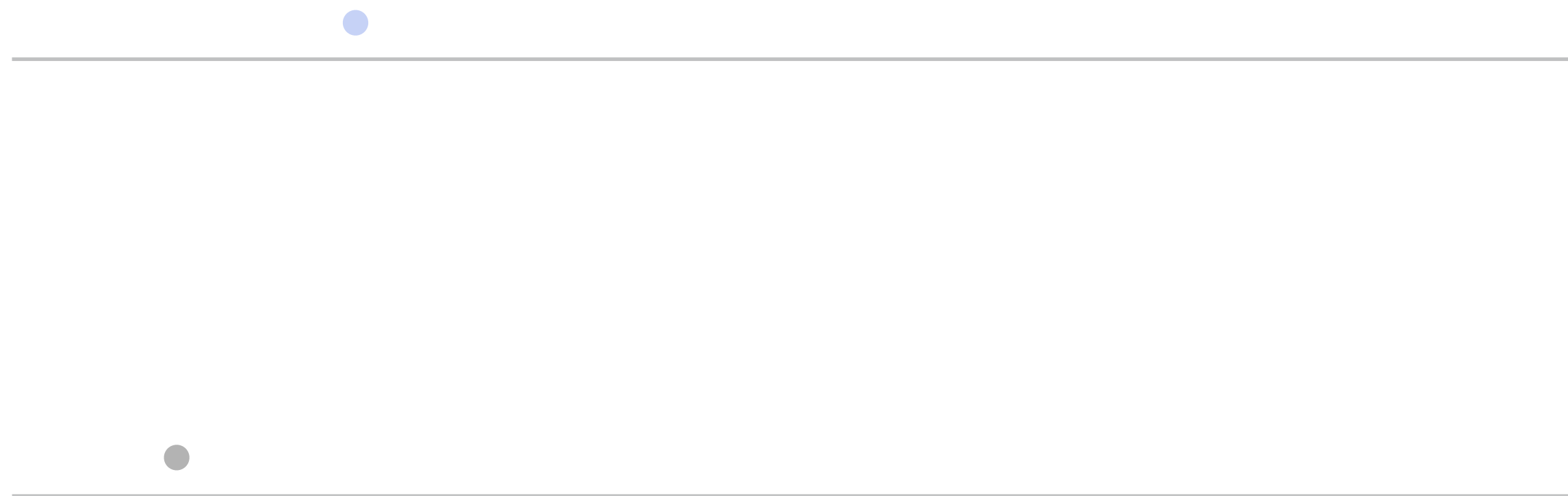


# AMPLITUDE MODEL

## CALIBRATION DATASET

### SACRA ●

- 162 simulations (*Kyutoku et al. 2011–2013*)
- Well distributed across a relevant region of parameter space
- Only provide the 22 mode



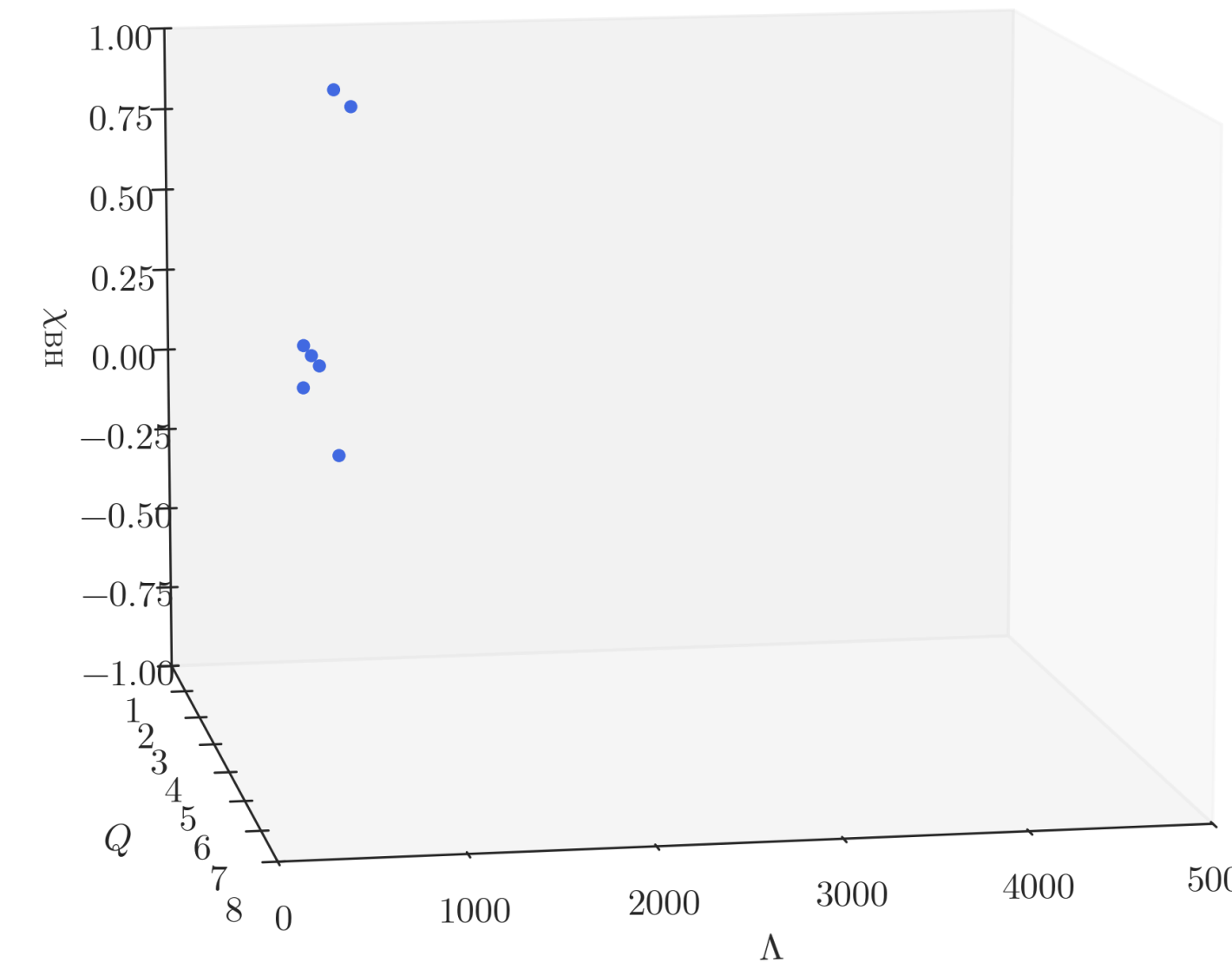
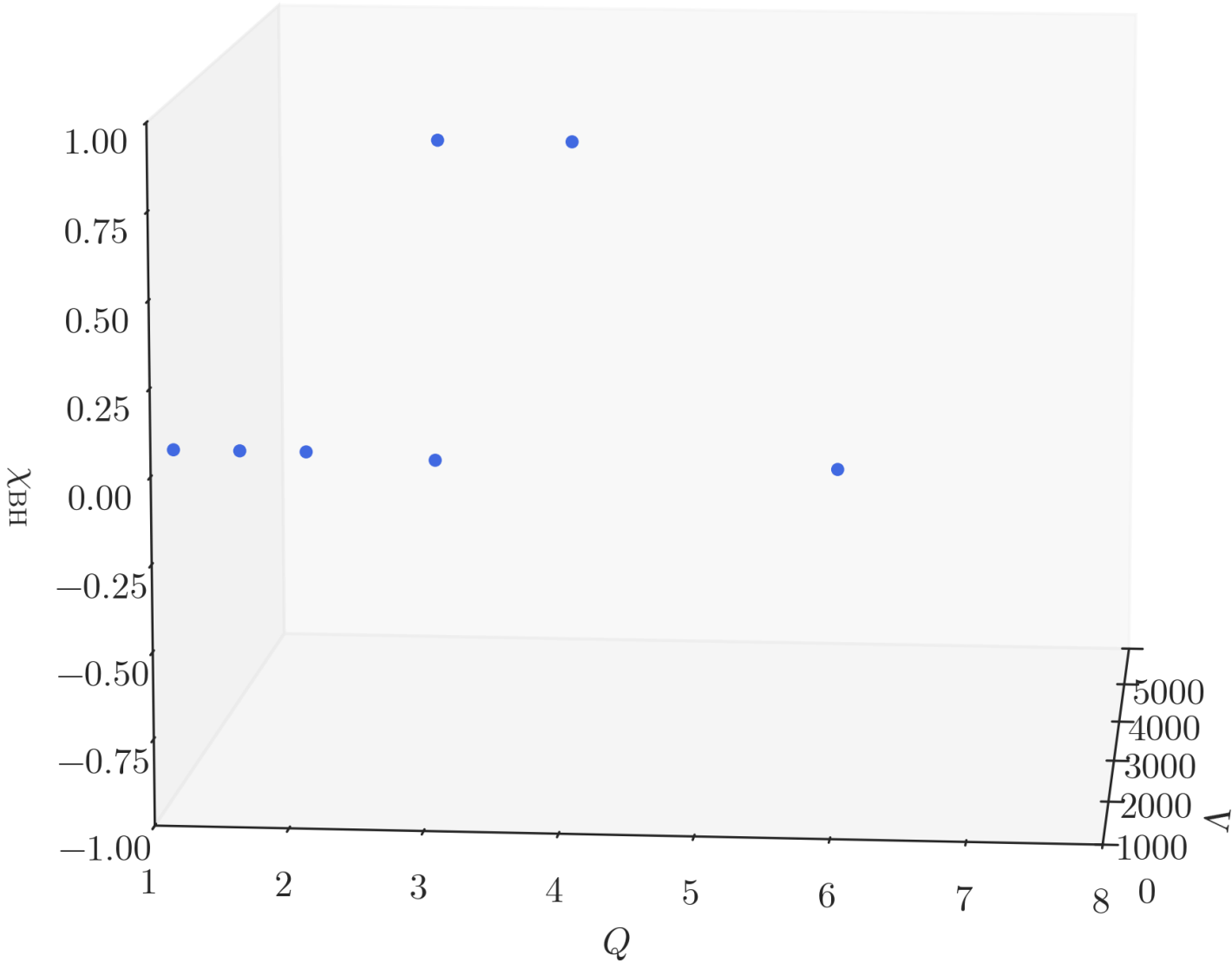
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## CALIBRATION DATASET



### SXS (SpEC) ●

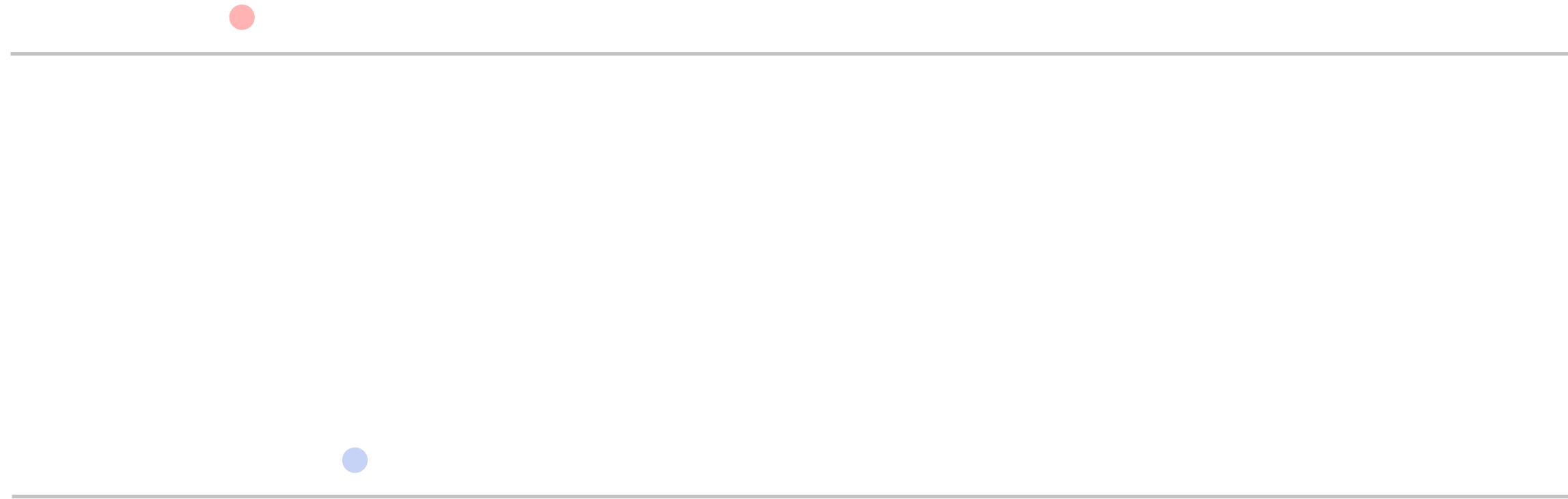
- 7 simulations (*Foucart et al. 2019–2021*)
- Key cases near equal-masses and highly spinning BHs
- Include higher-order modes





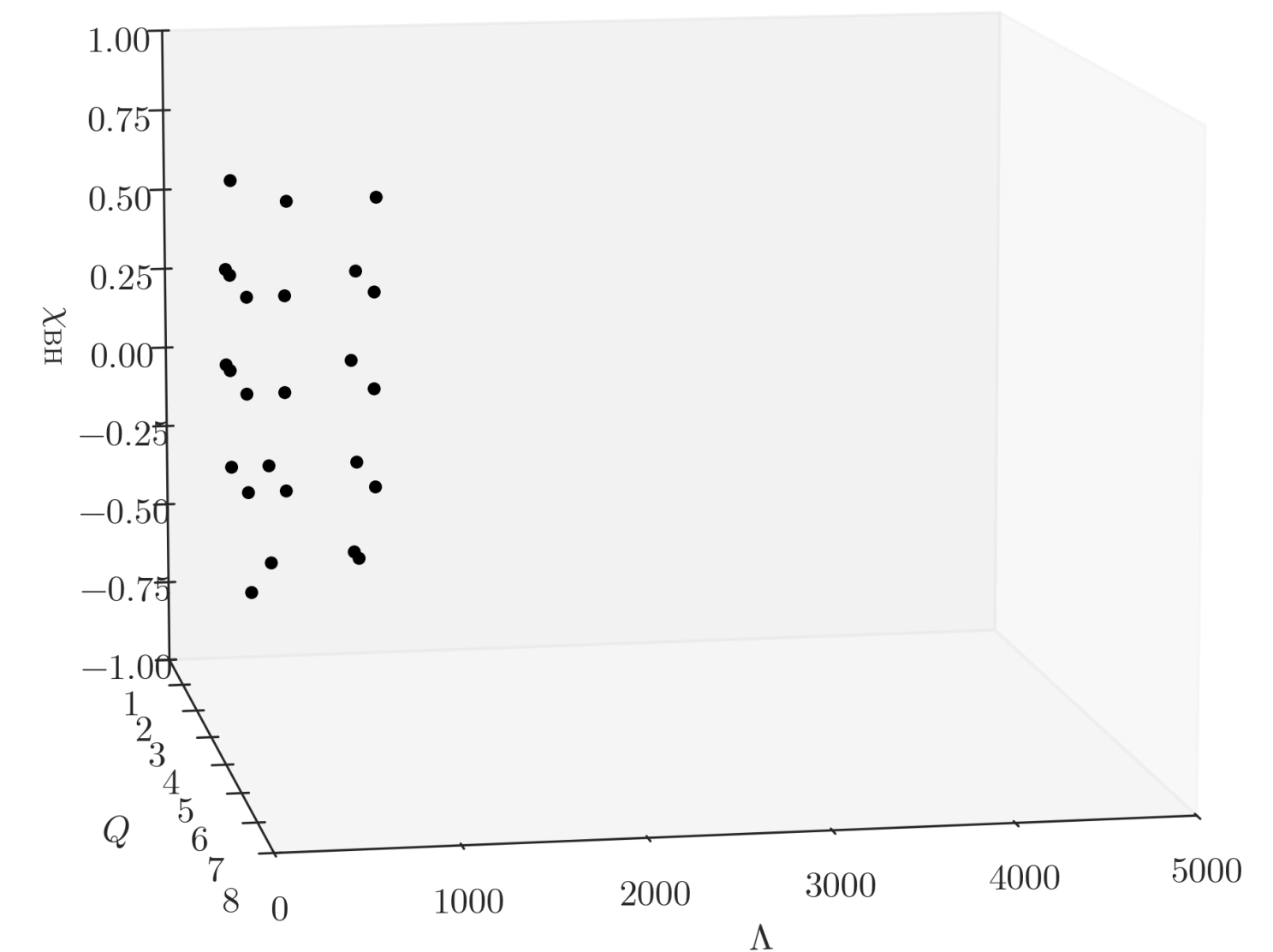
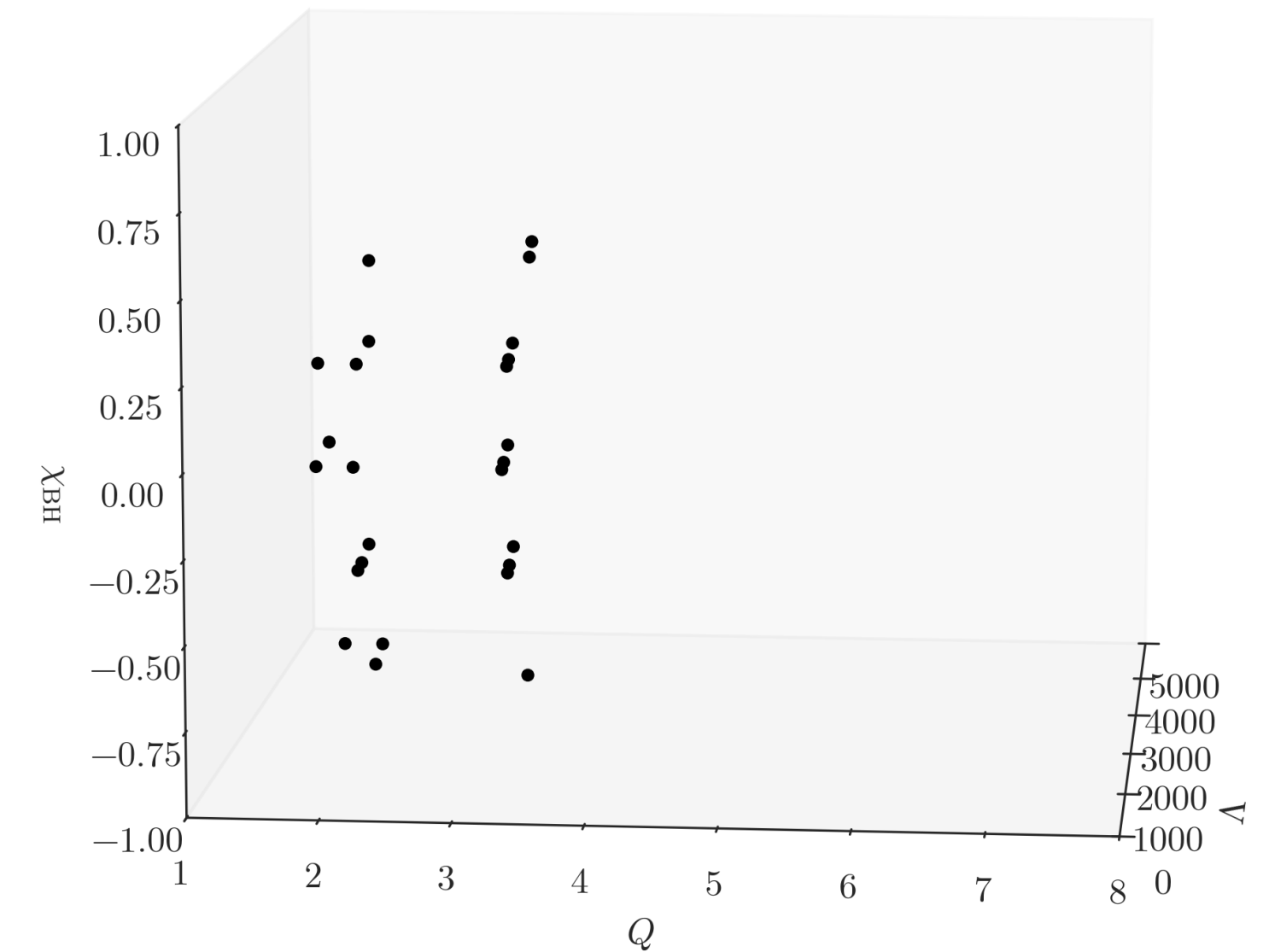
# AMPLITUDE MODEL

## CALIBRATION DATASET



### BAM ●

- 25 simulations (*Gonzalez et al. in prep.*)
- Localized around the transition to tidal disruption
- Make it possible to calibrate the HMs



● SACRA ● SXS ● BAM

# AMPLITUDE MODEL

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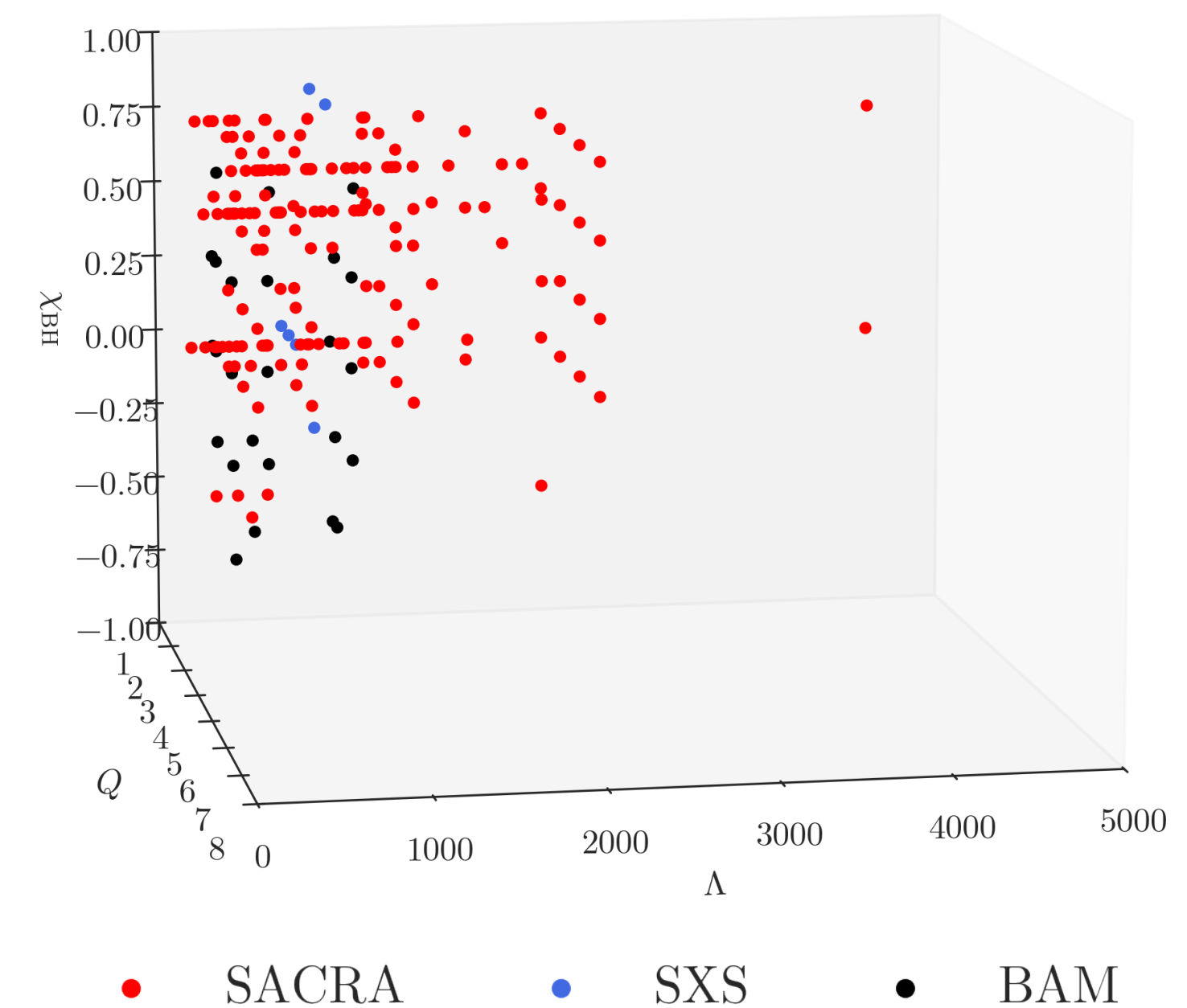
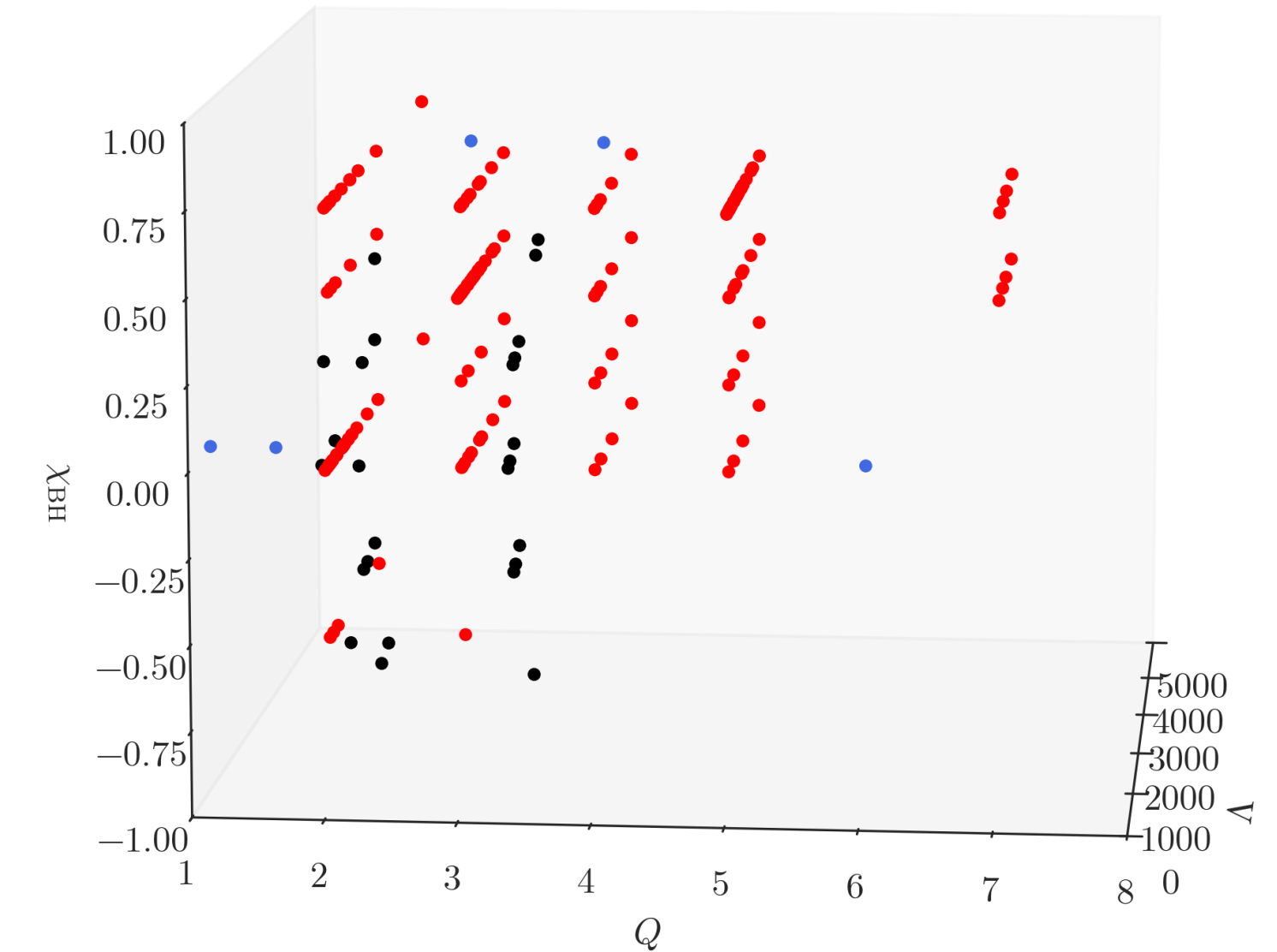
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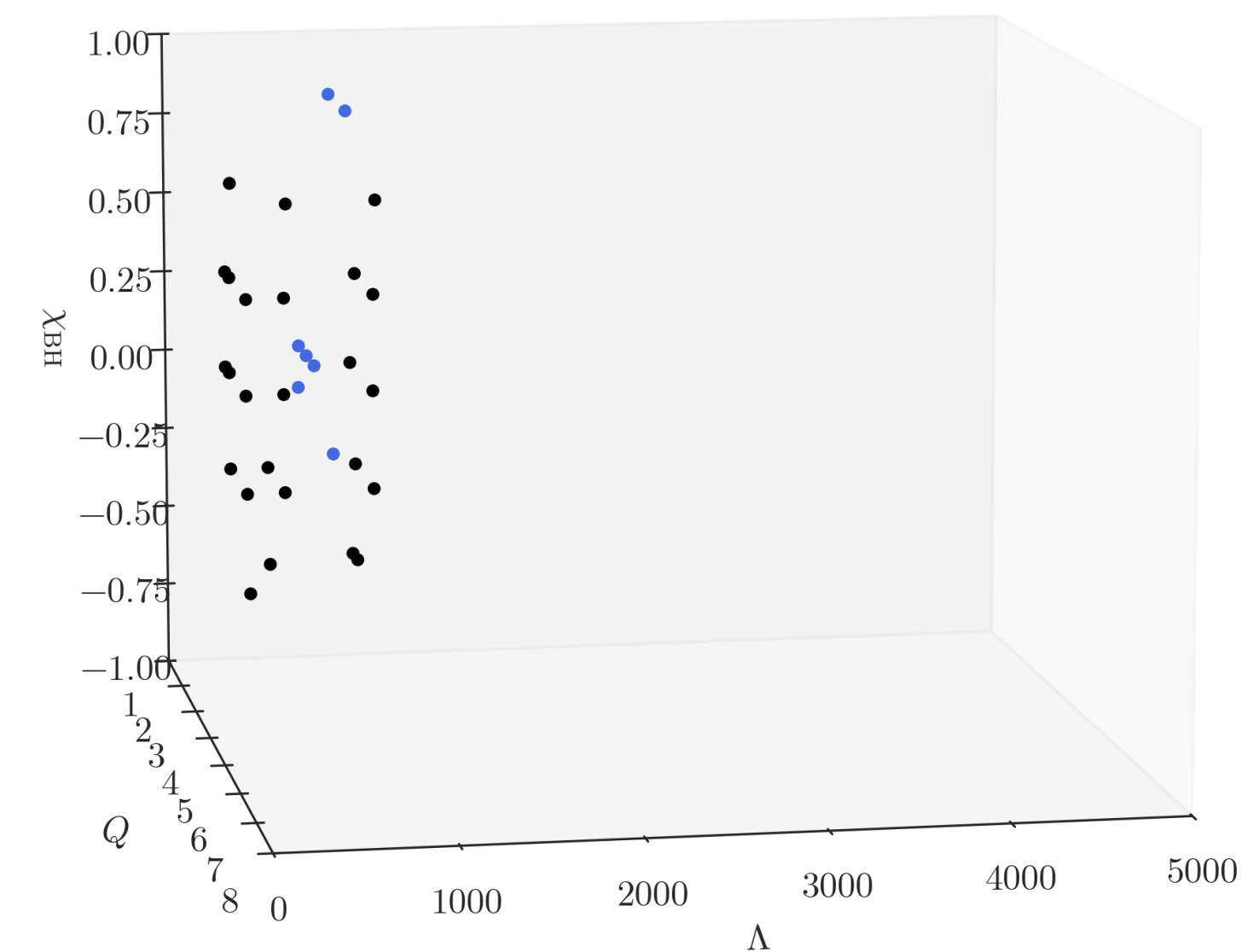
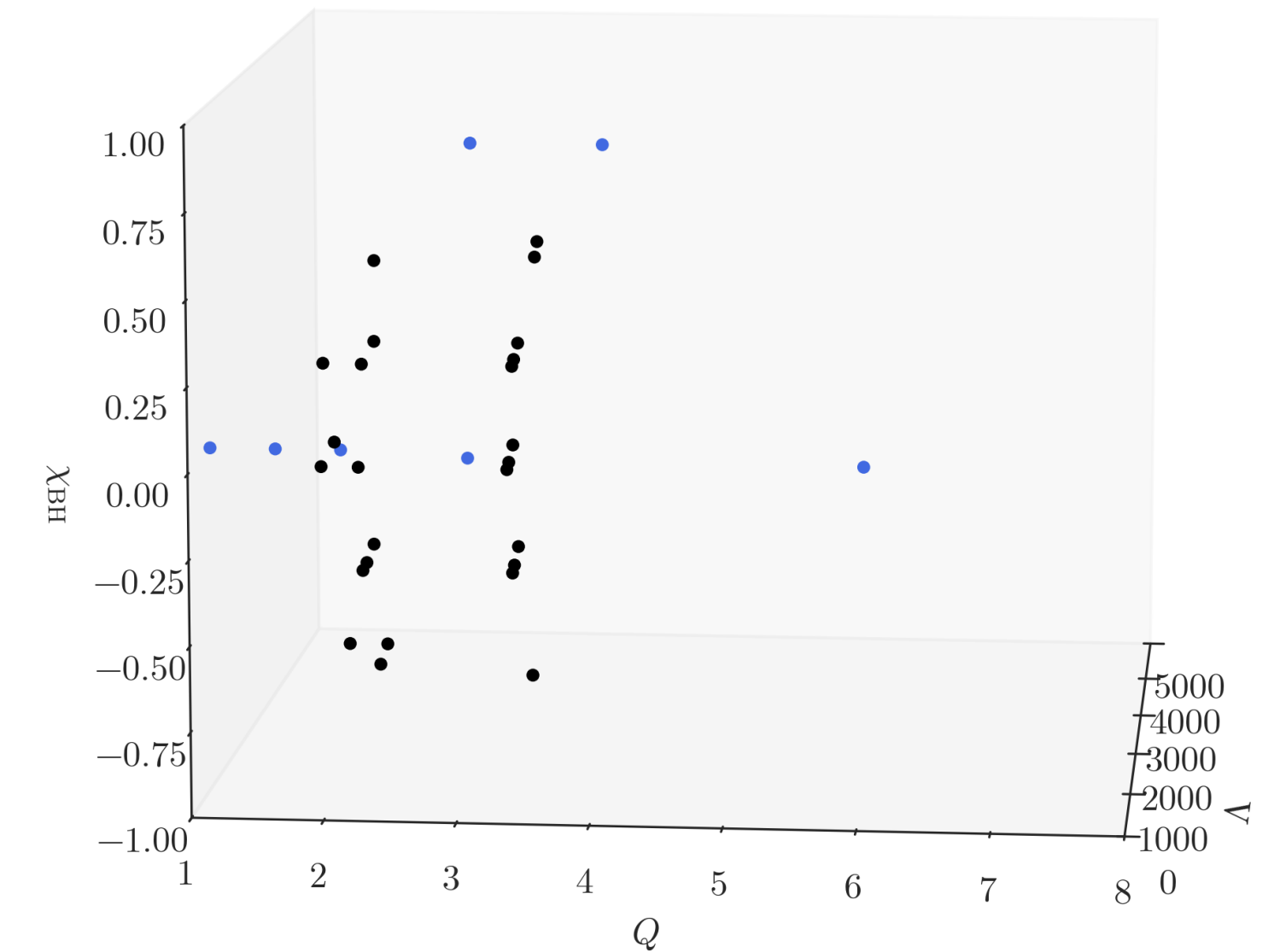


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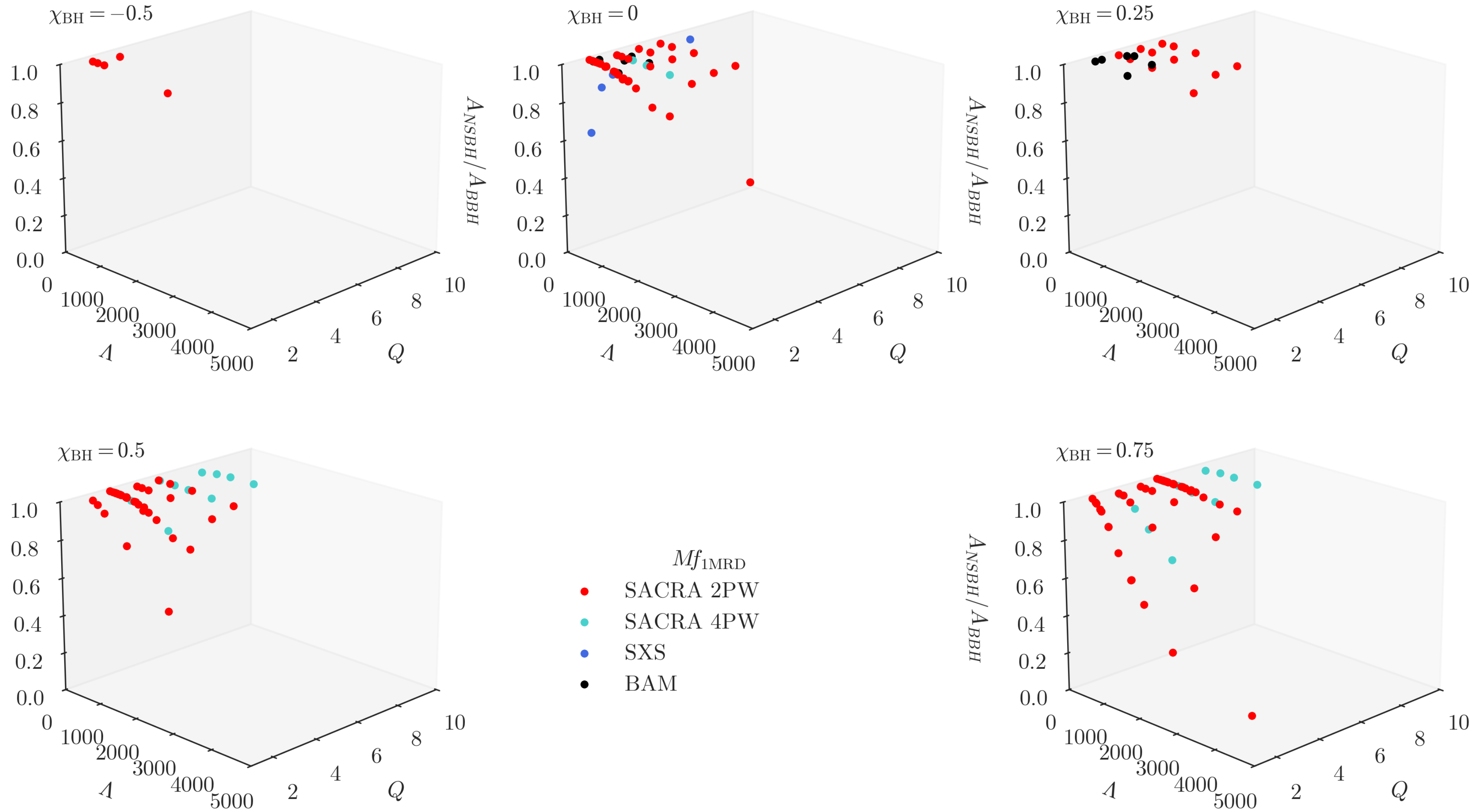


● SACRA ● SXS ● BAM

*Relatively unconstrained equal-mass and large tidal deformability limits (HMs)*

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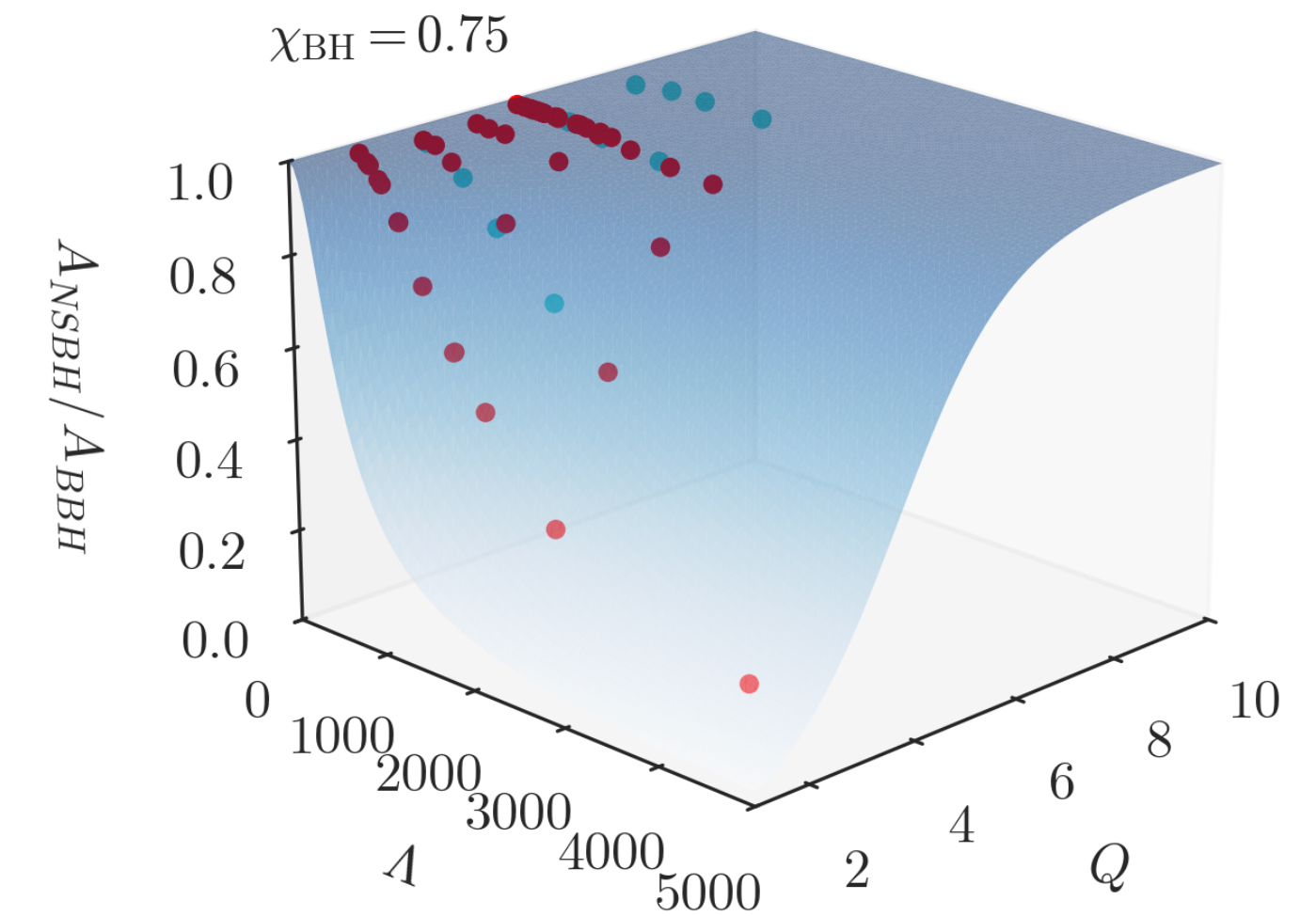
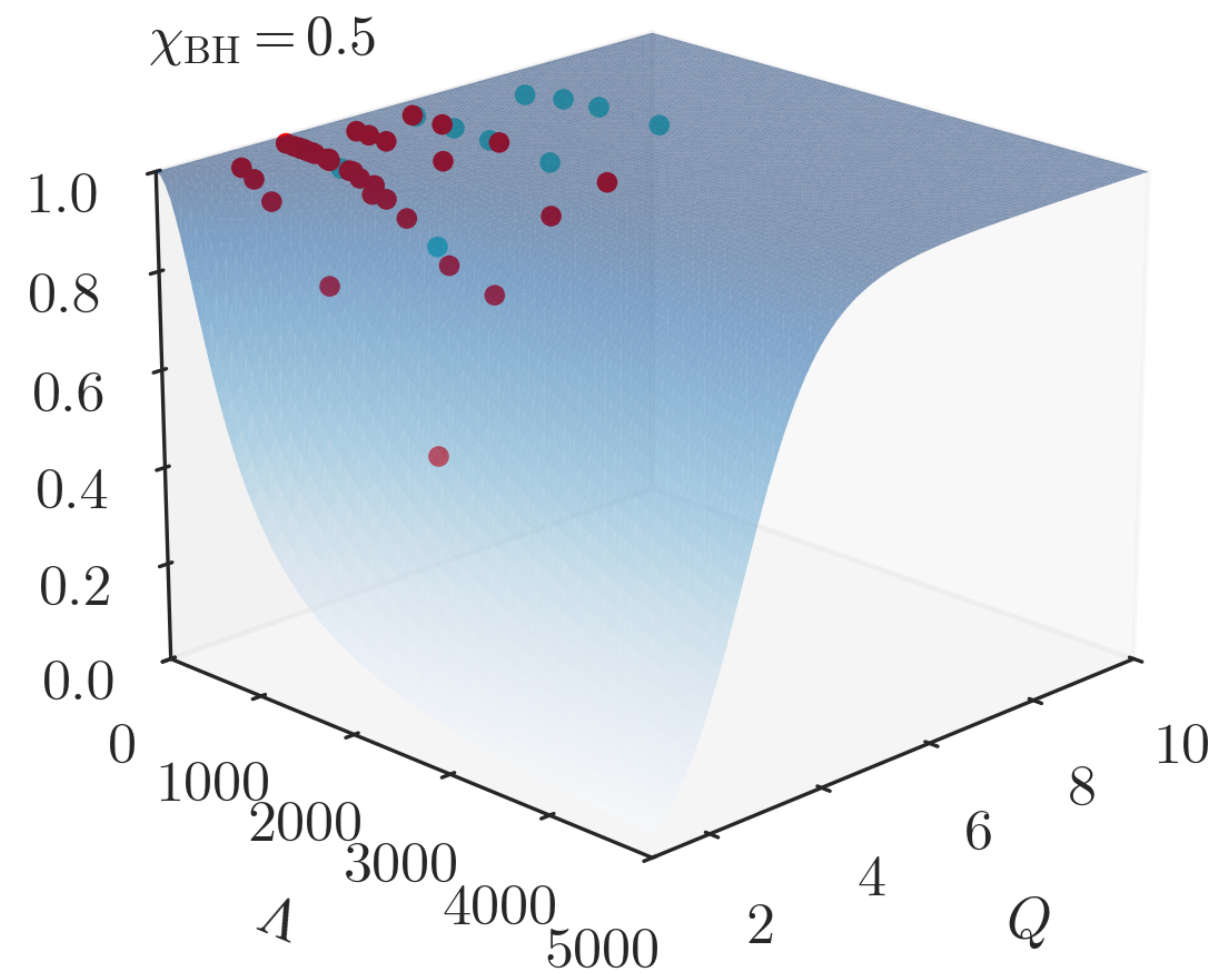
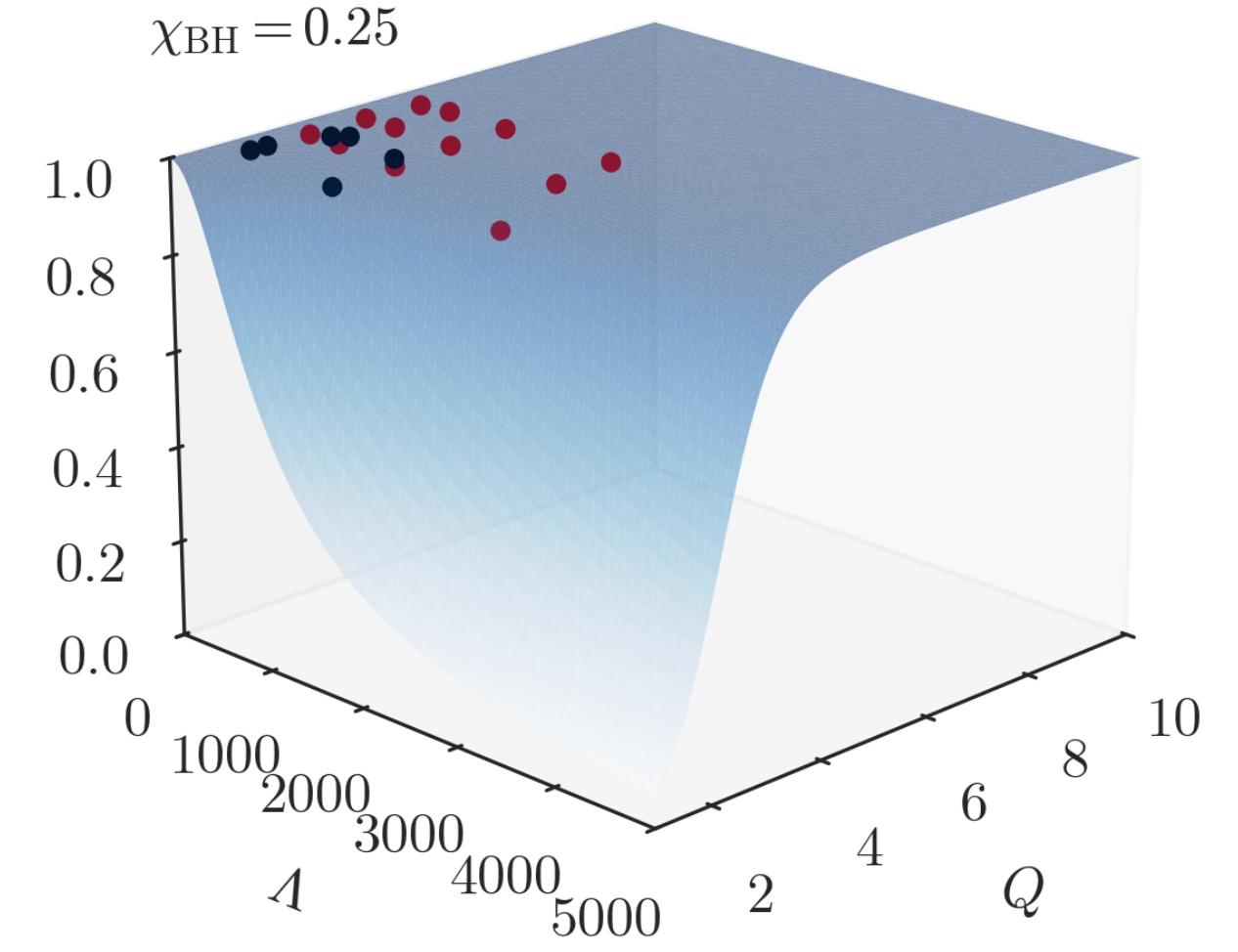
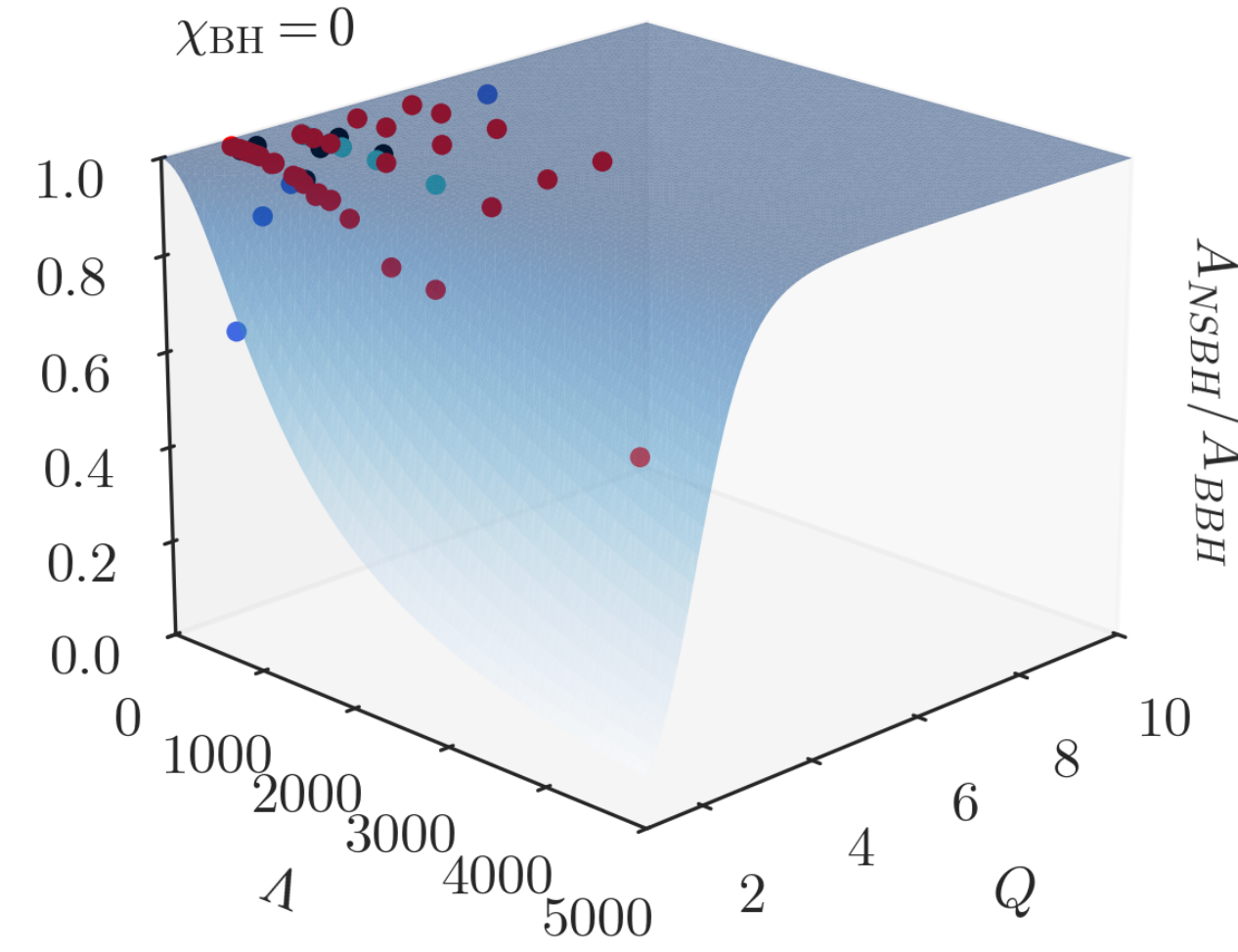
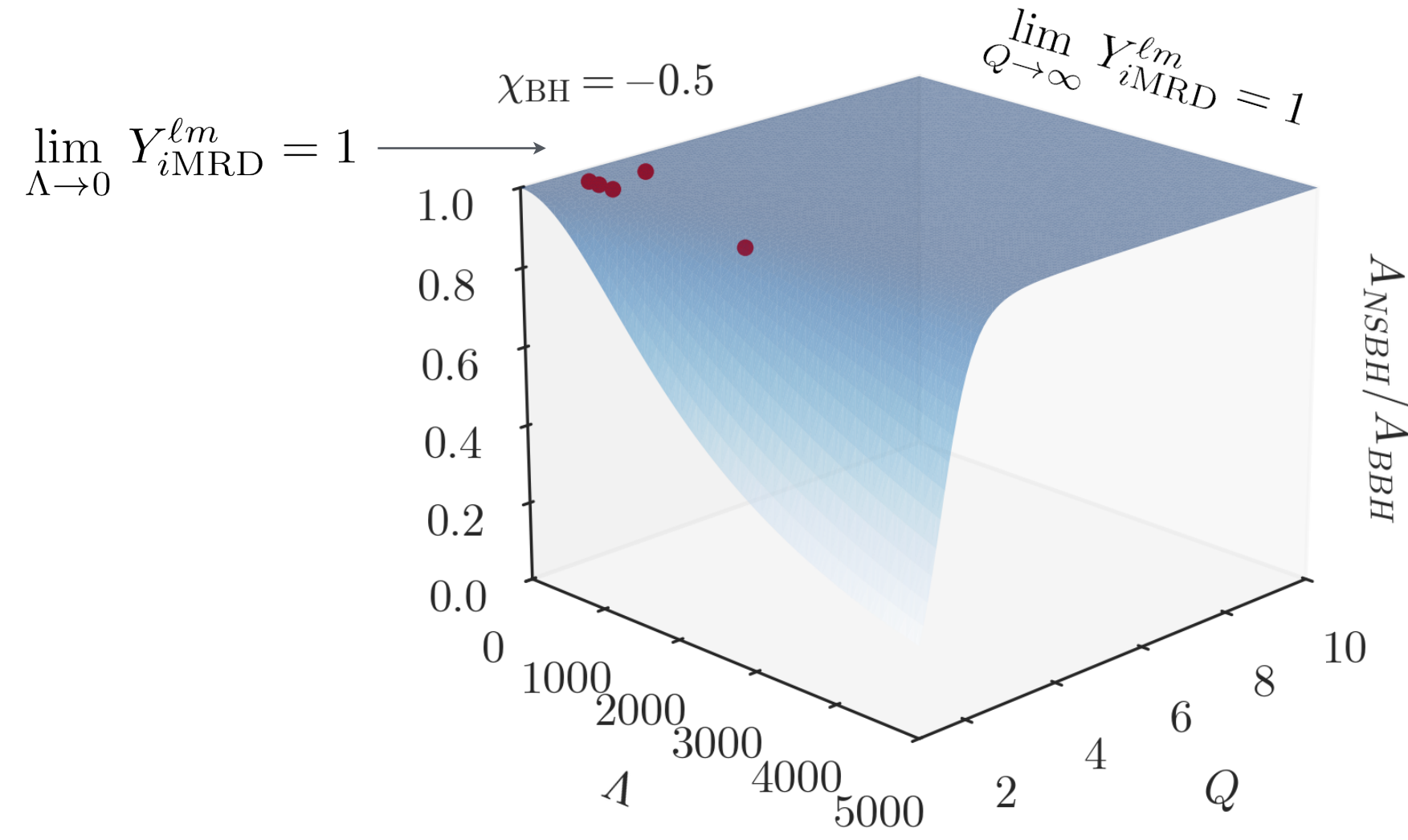




# AMPLITUDE MODEL

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$$Y_{i\text{FIT}}^{\ell m}(Q, \chi_{\text{BH}}, \Lambda) = \left[ 1 + \frac{\Lambda^{a_3}}{Q^{a_4}} \exp \left( -a_0 + a_1 \chi_{\text{BH}} + a_2 \left( \frac{1-Q}{1+Q} \right)^2 \chi_{\text{BH}} |\chi_{\text{BH}}| \right) \right]^{-a_6}$$



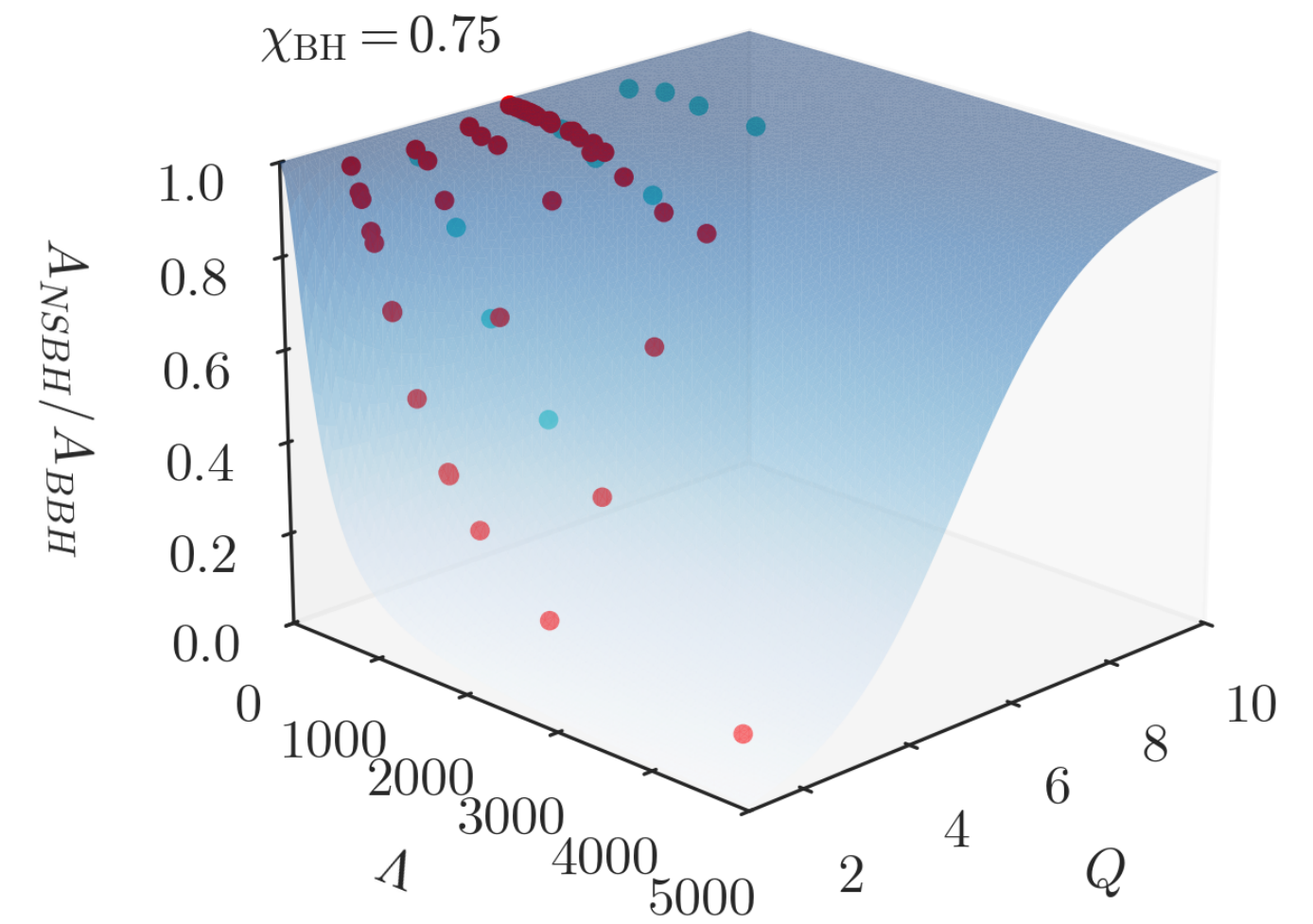
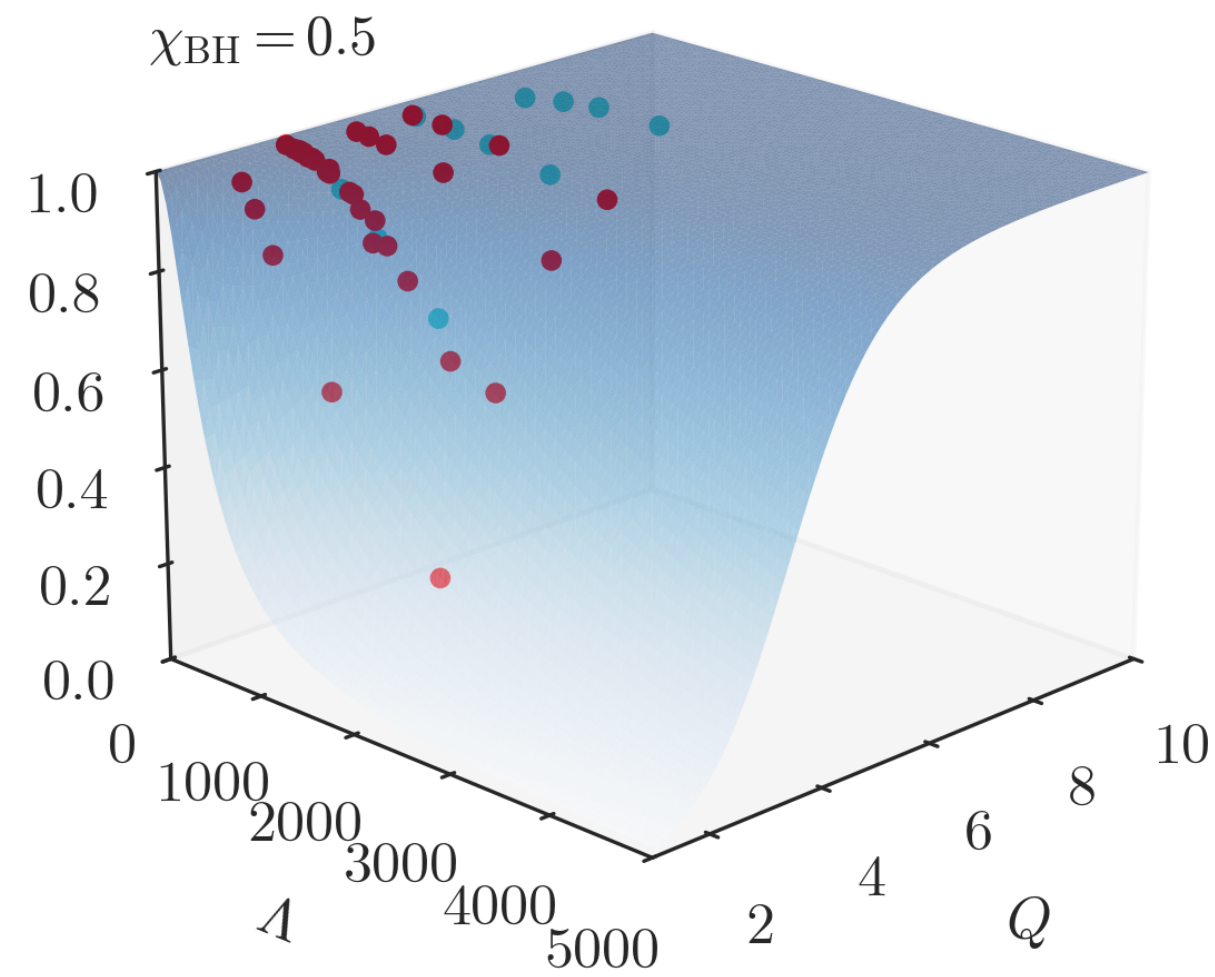
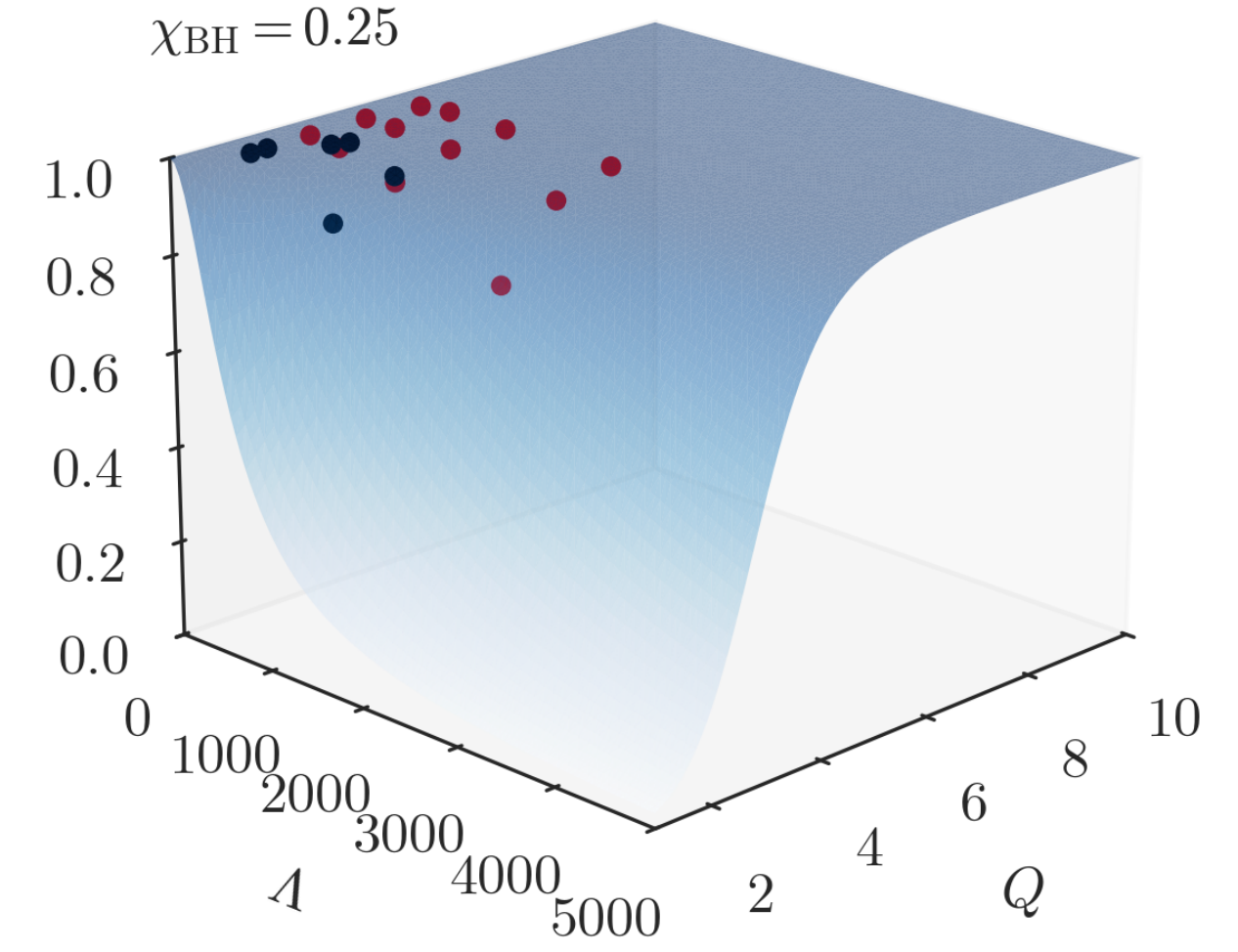
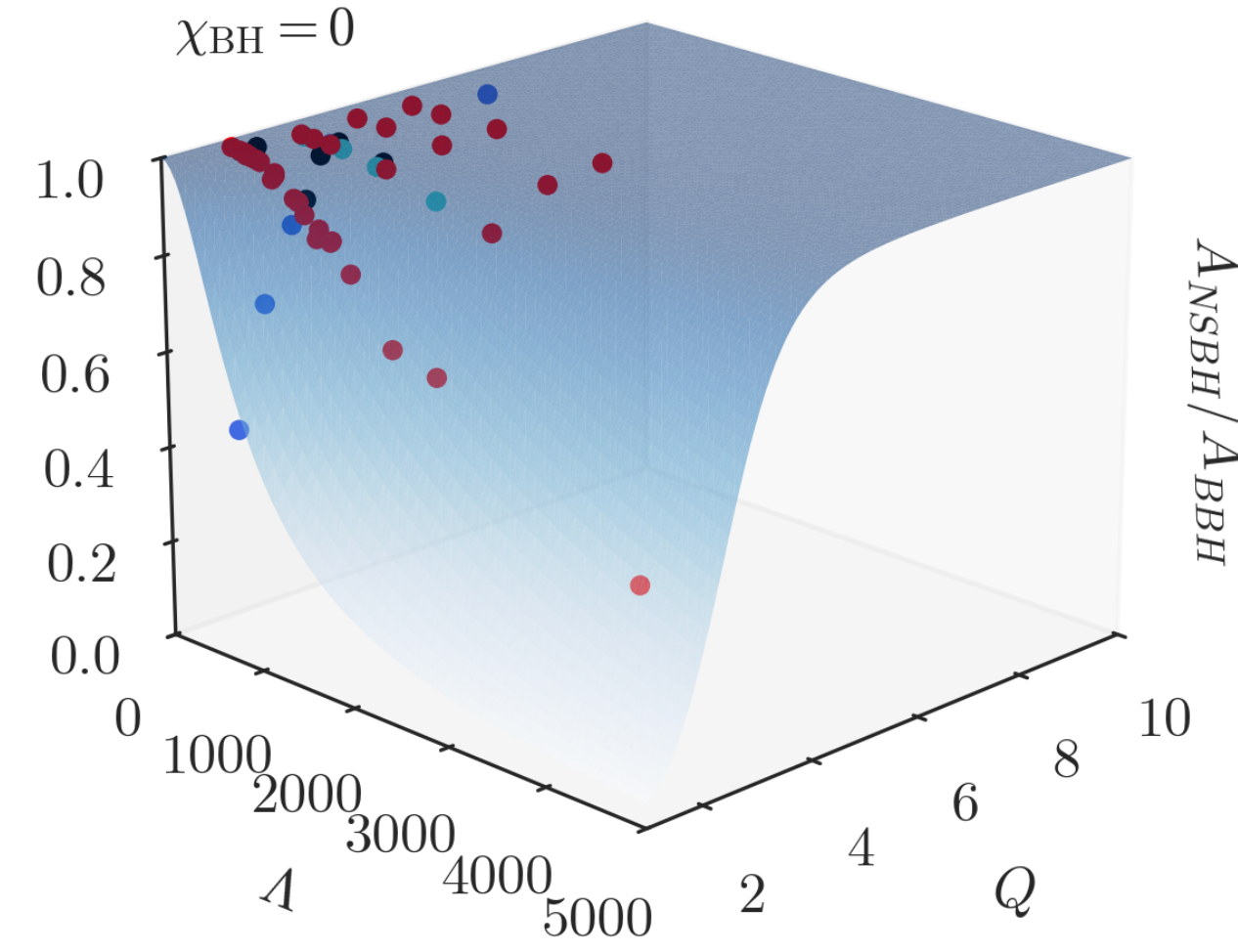
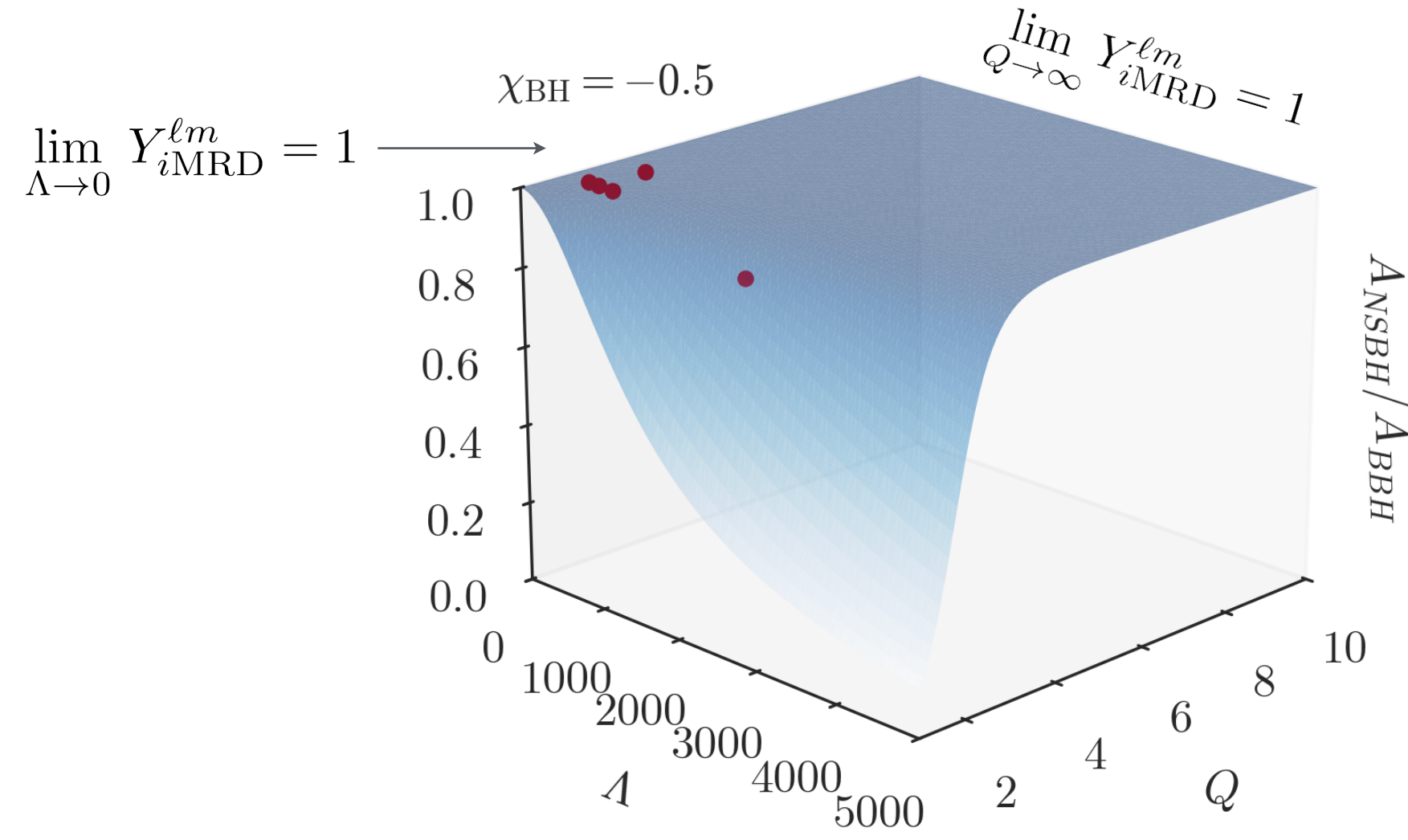
- $Mf_{1\text{MRD}}$
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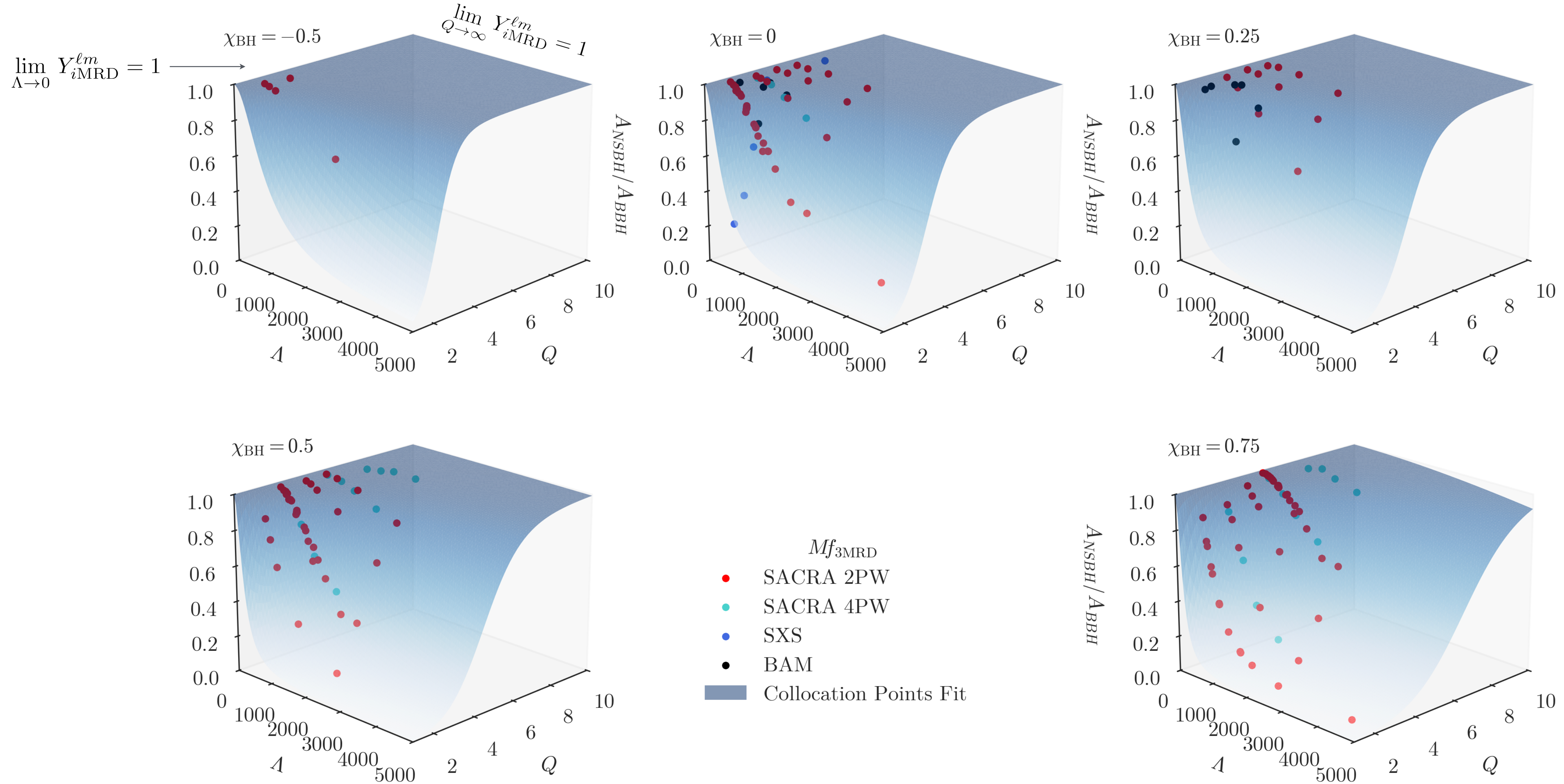
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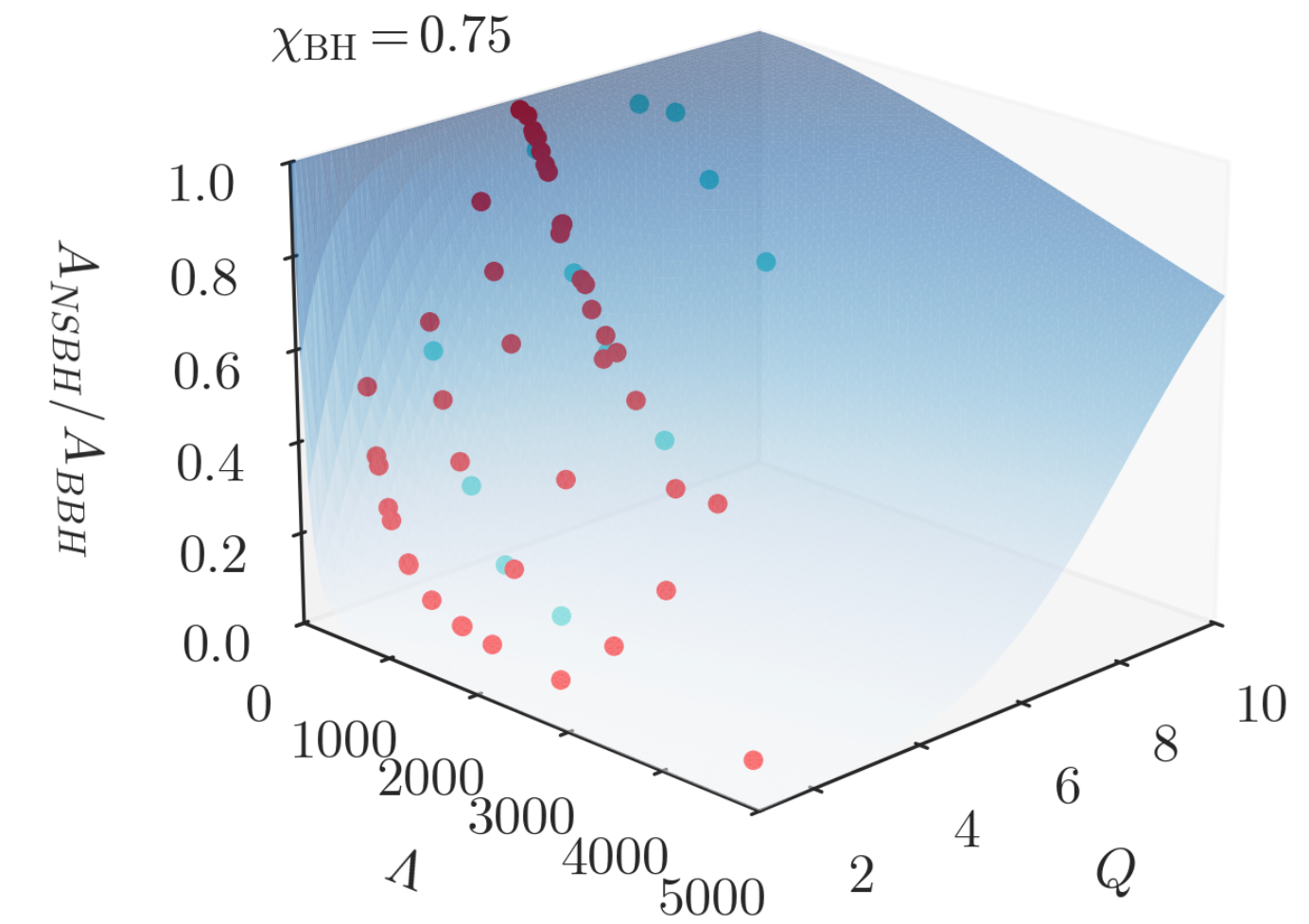
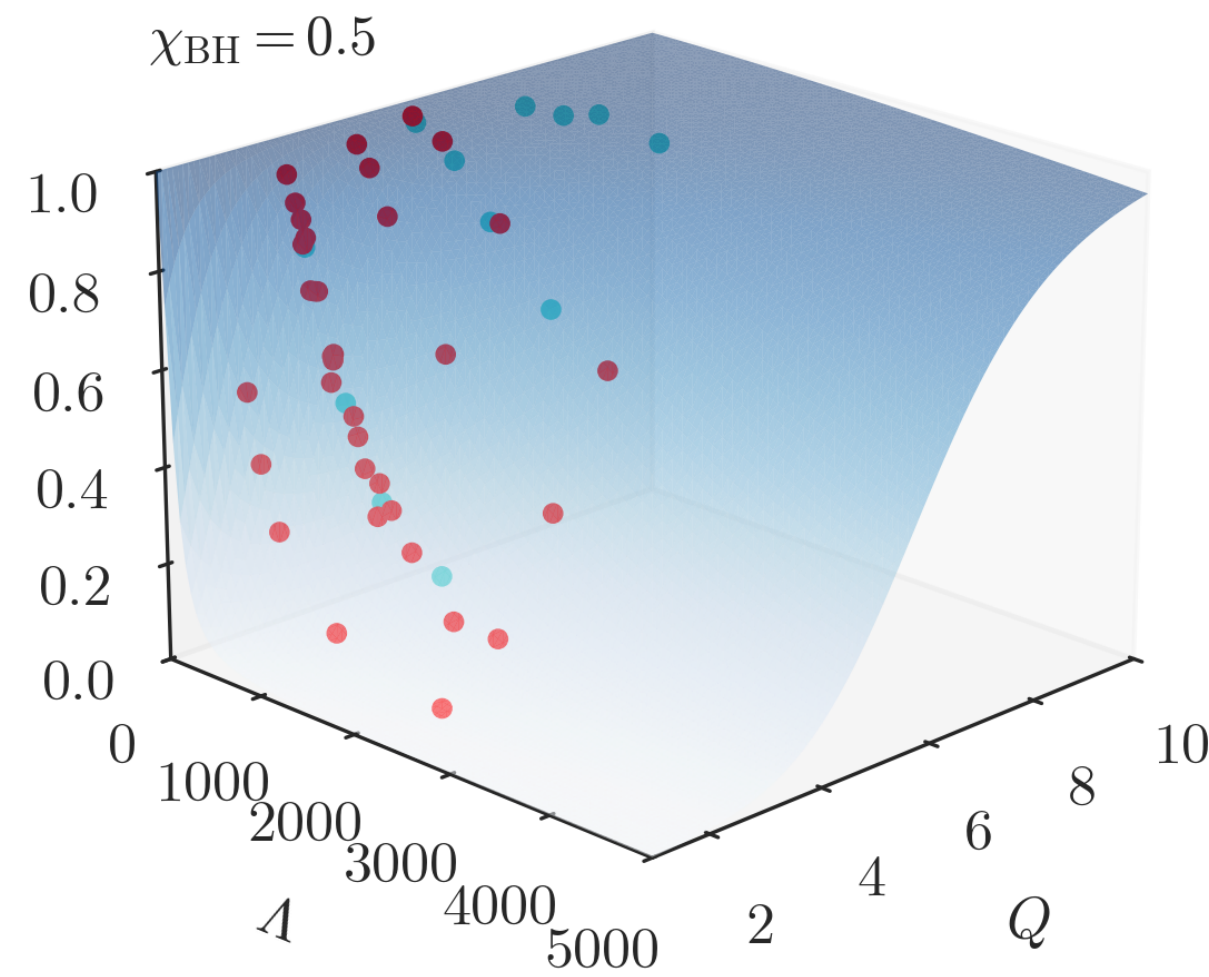
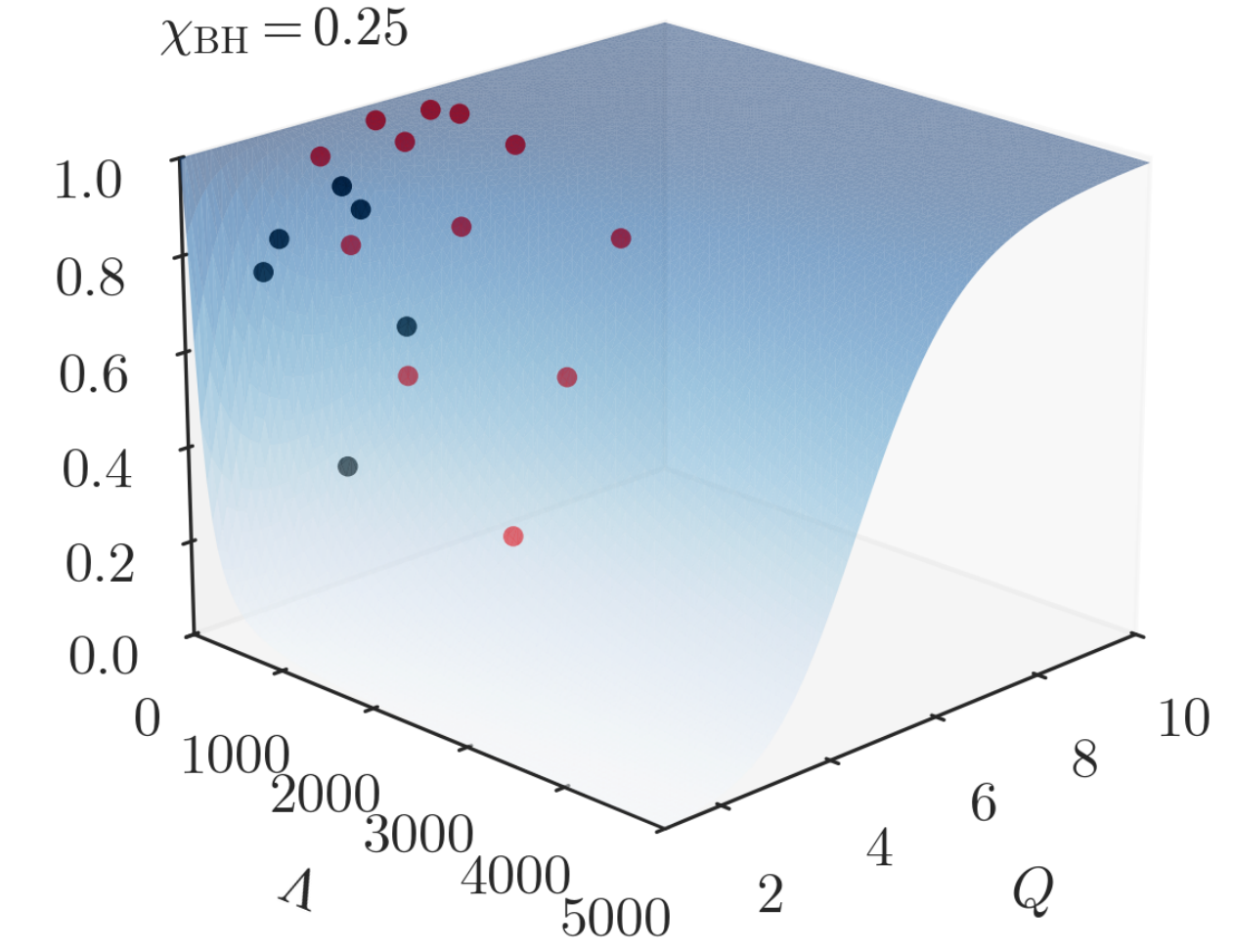
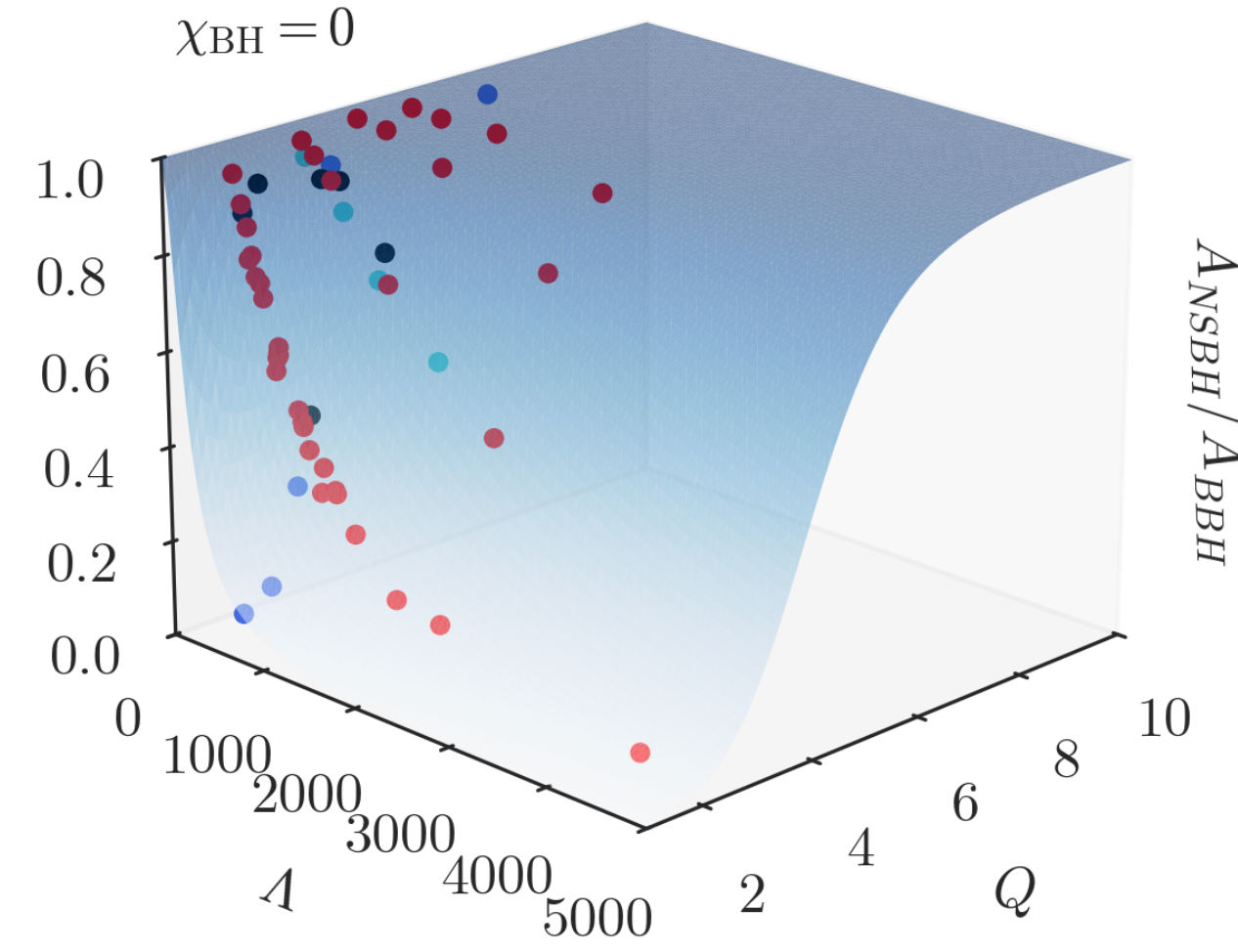
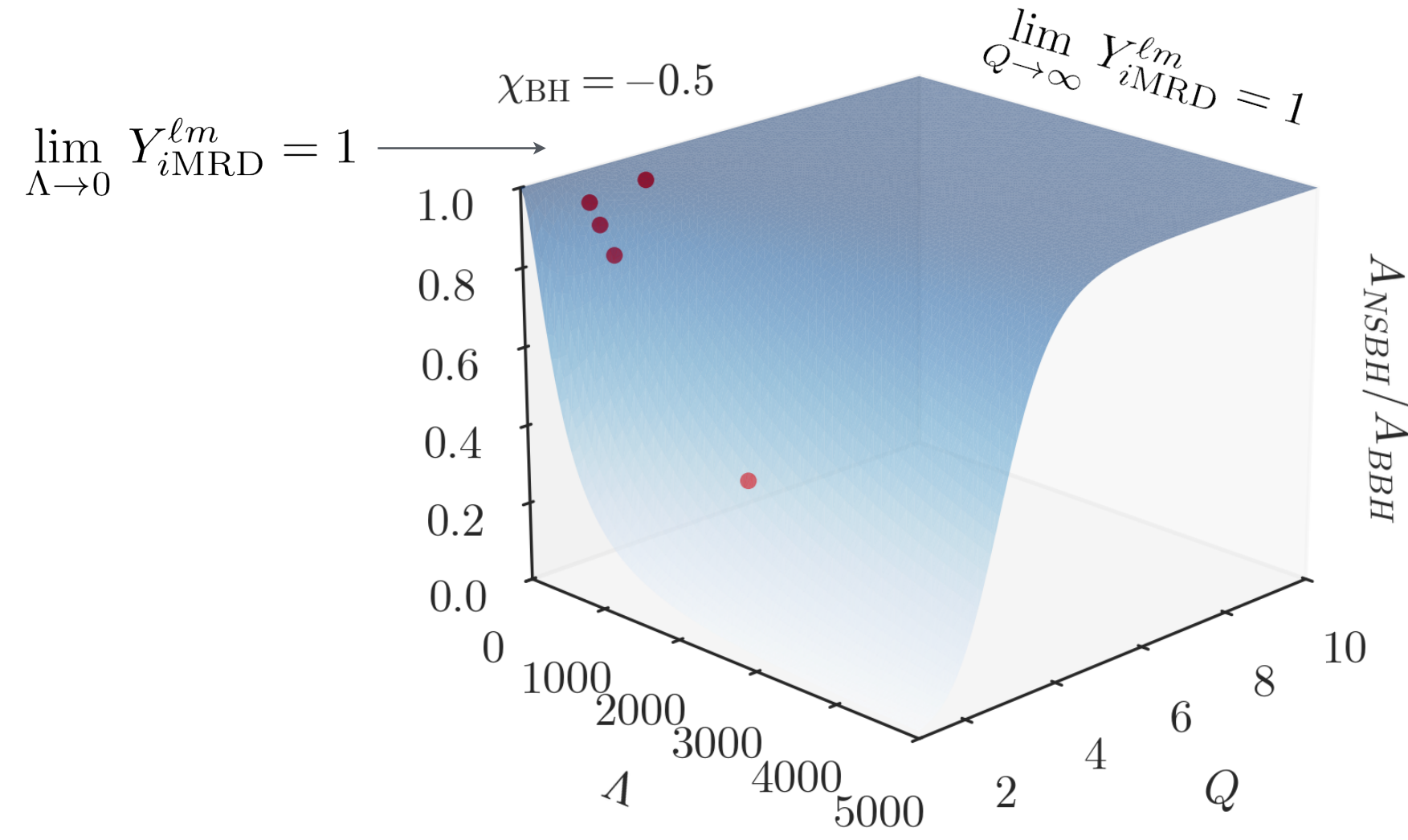




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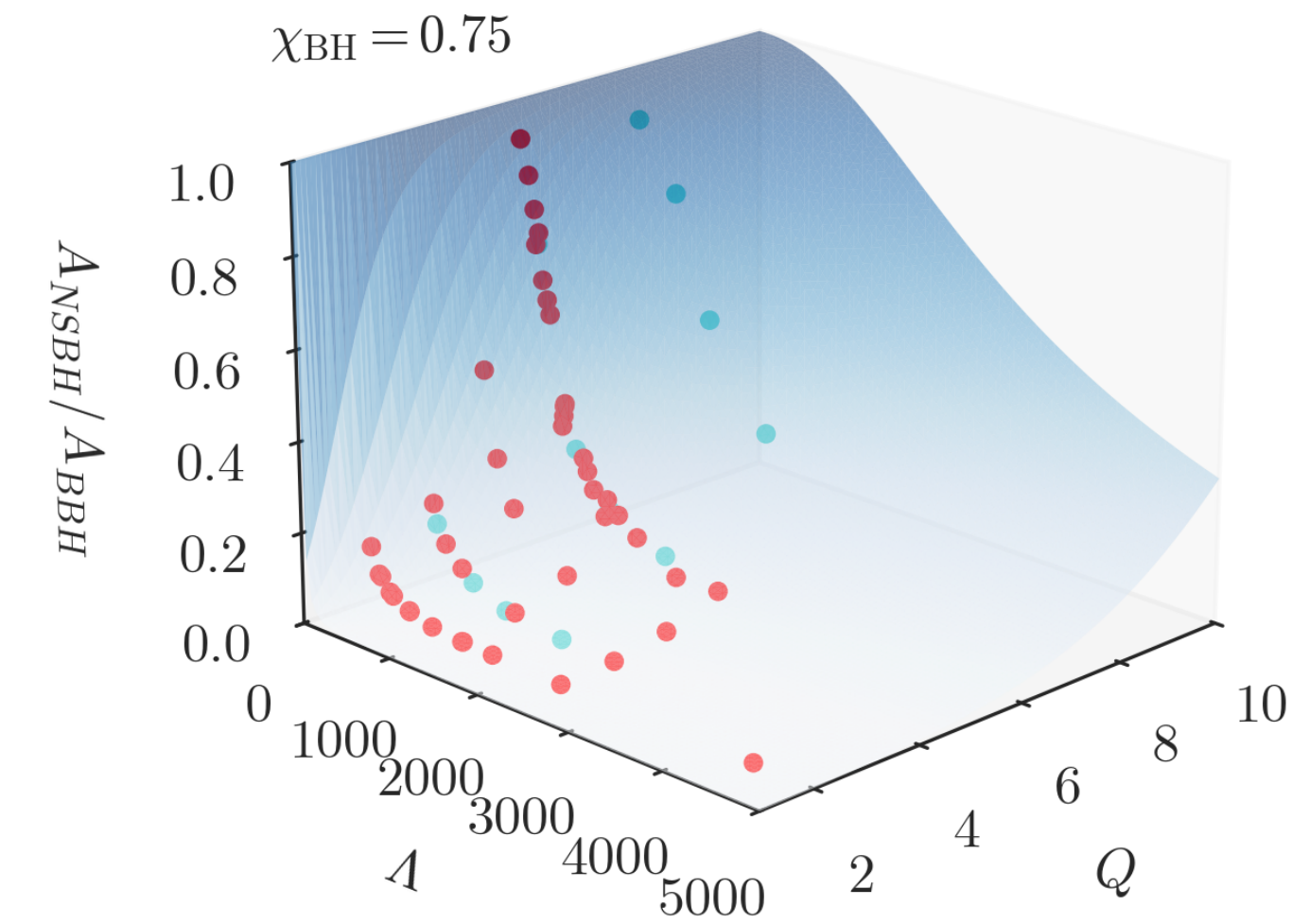
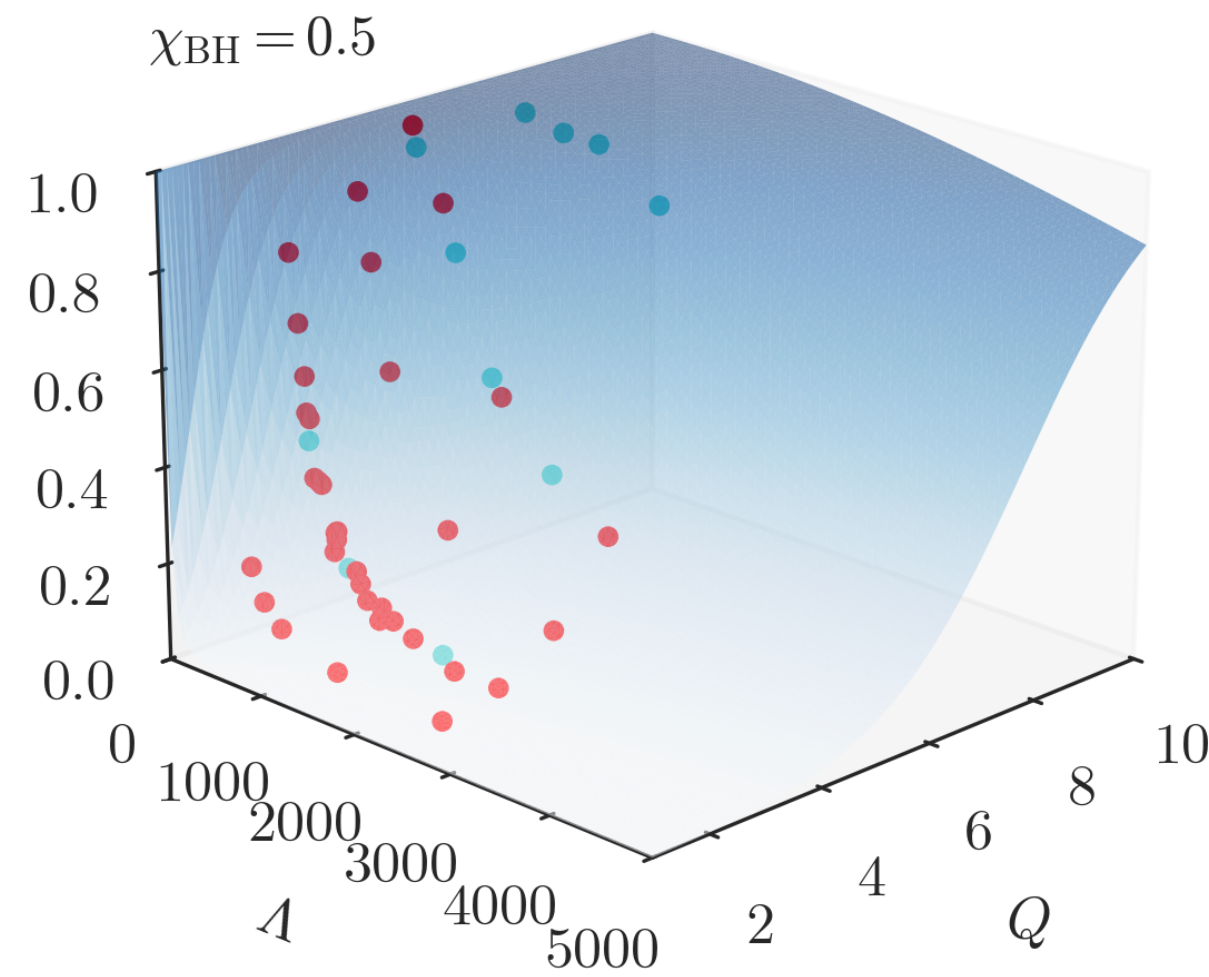
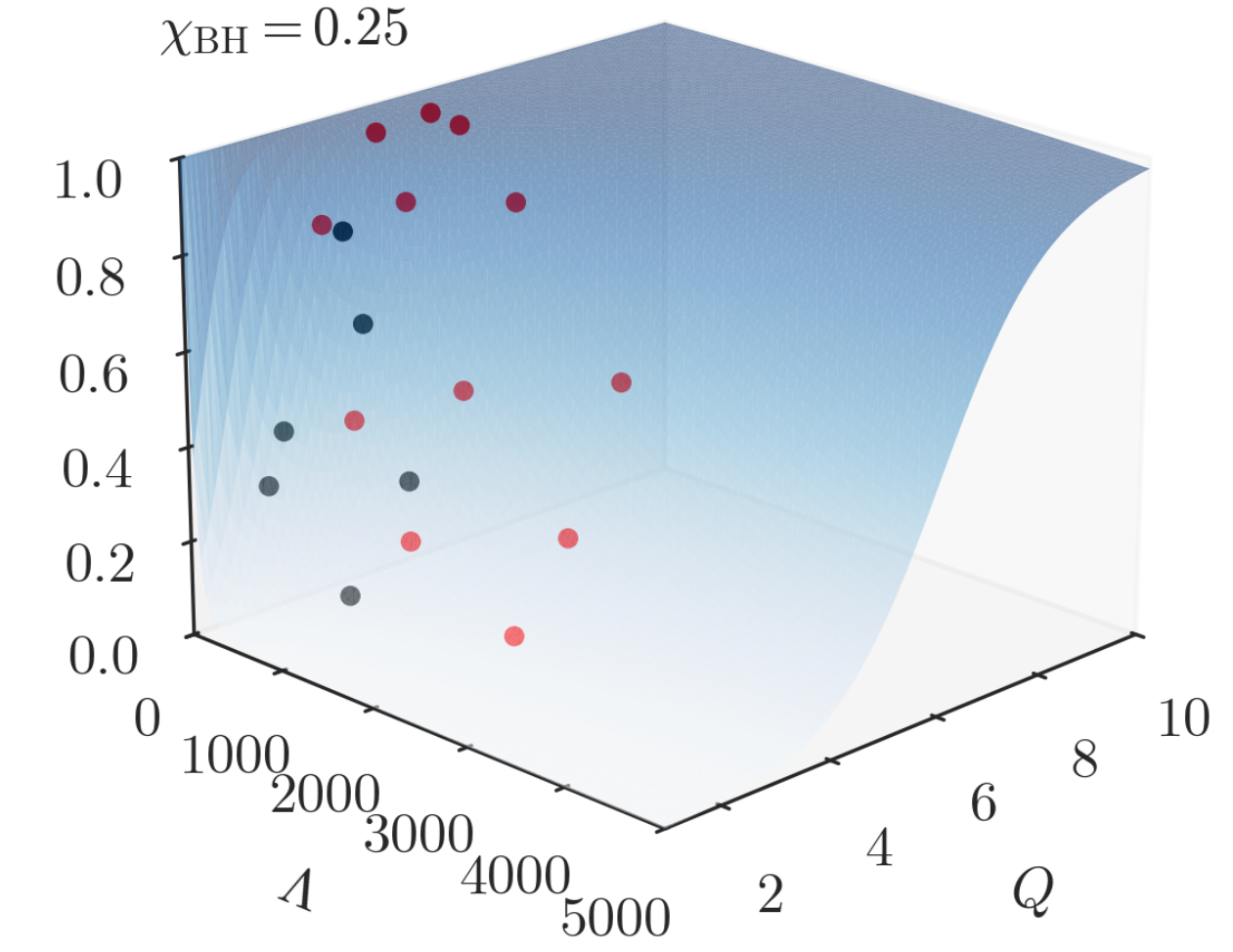
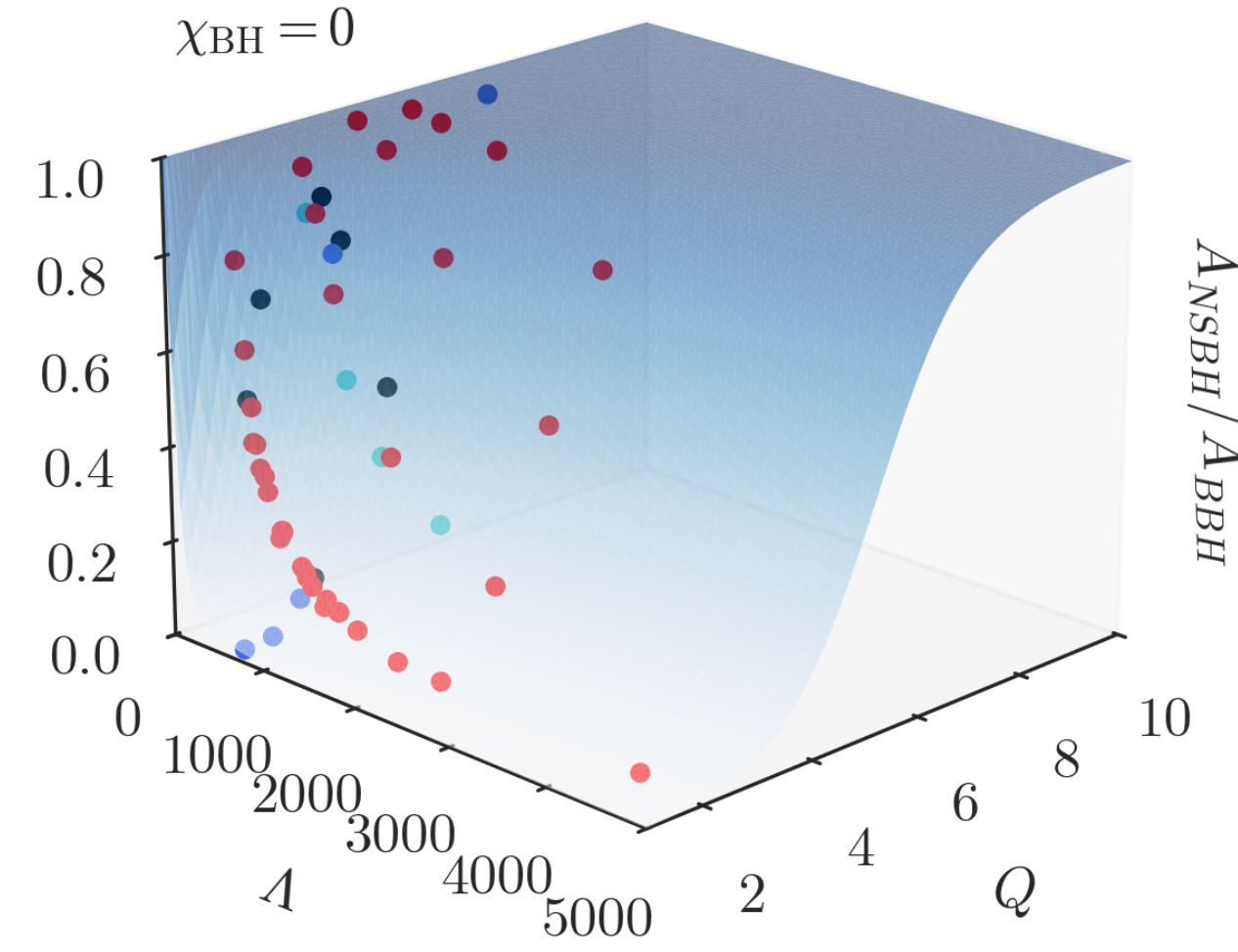
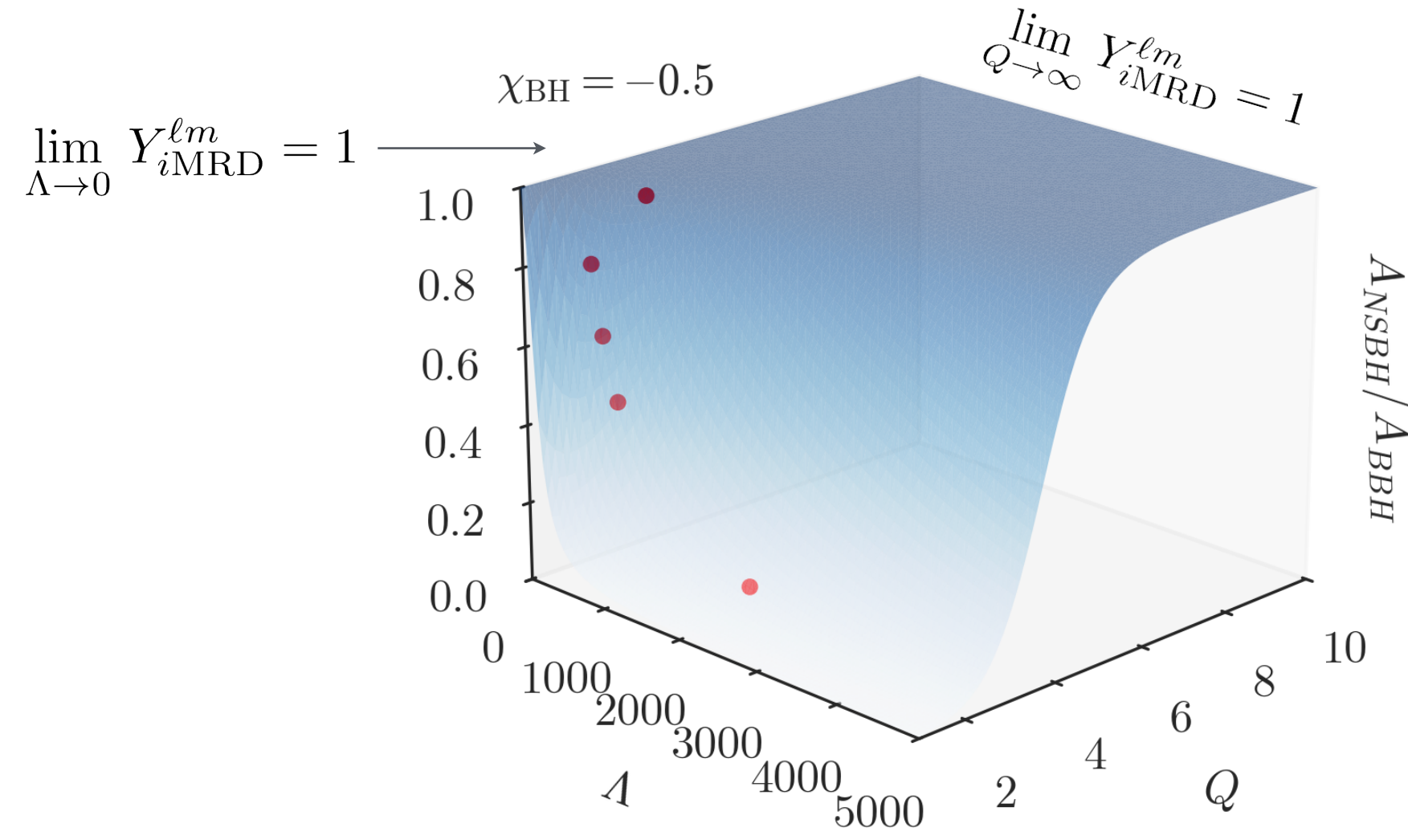
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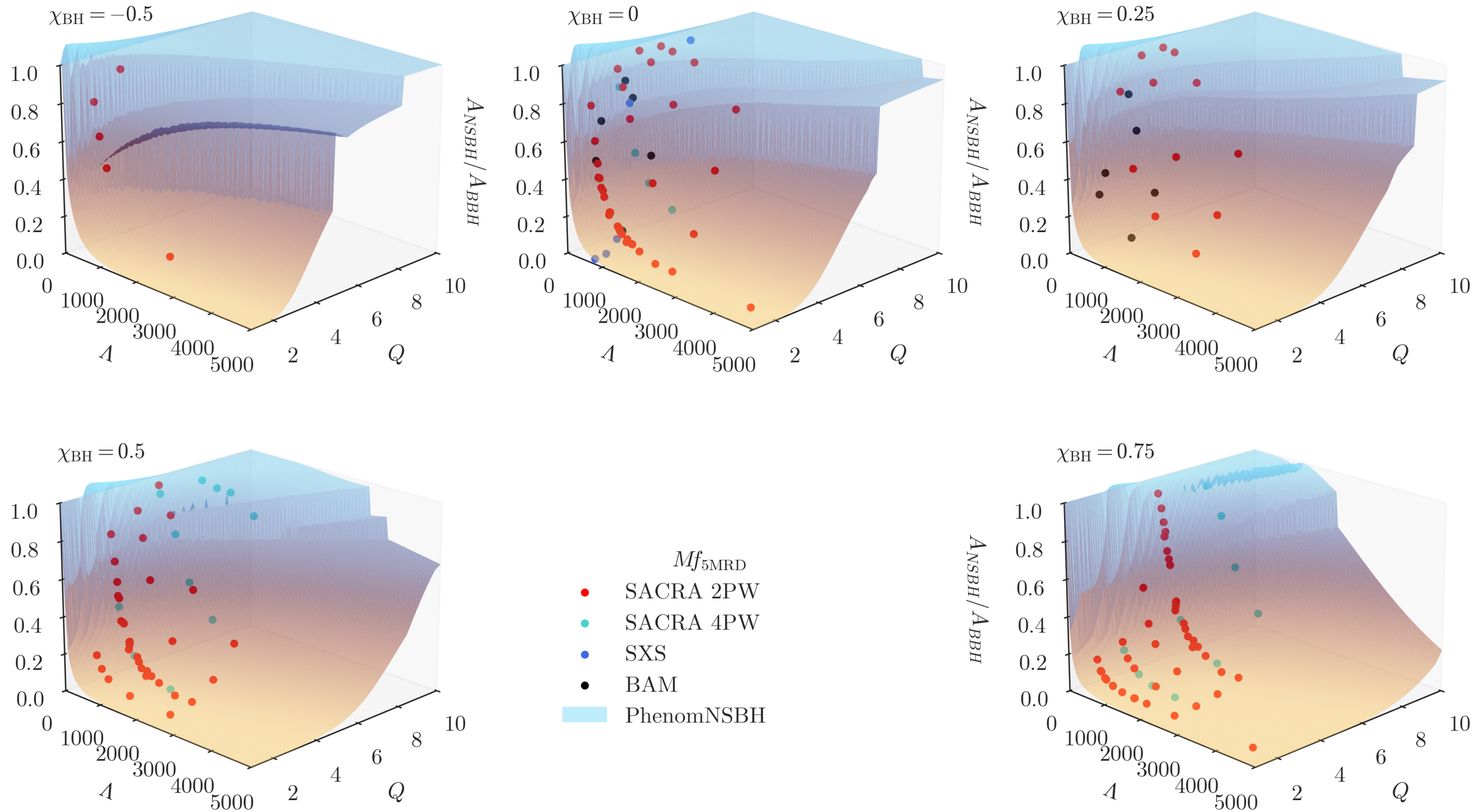


- $Mf_{5\text{MRD}}$
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# AMPLITUDE MODEL

## CALIBRATION



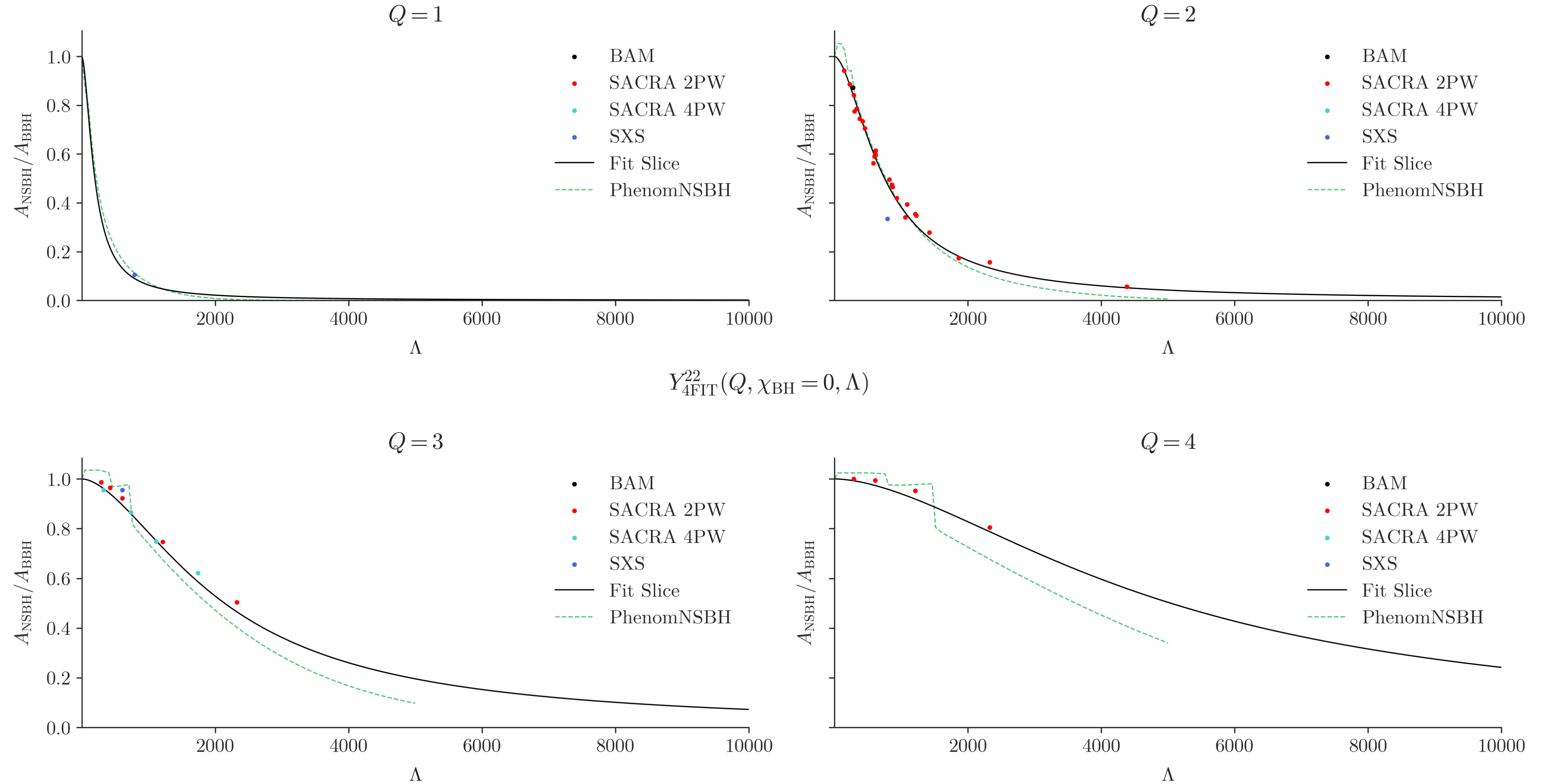
*We can see pronounced jumps in the parameter space for PhenomNSBH!*



# AMPLITUDE MODEL

## CALIBRATION

$$Y_{4\text{FIT}}^{22}(Q, \chi_{\text{BH}} = 0, \Lambda)$$

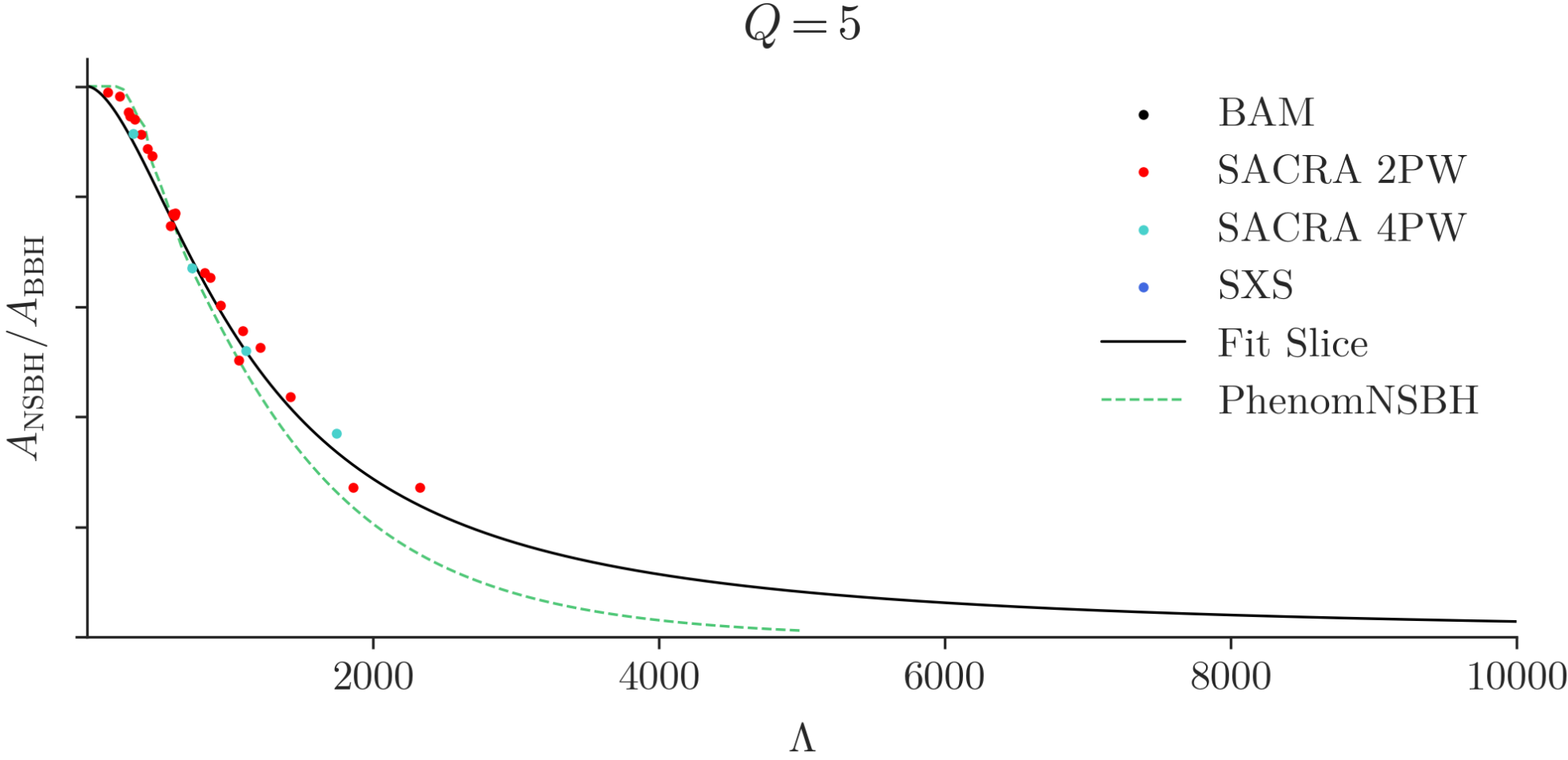
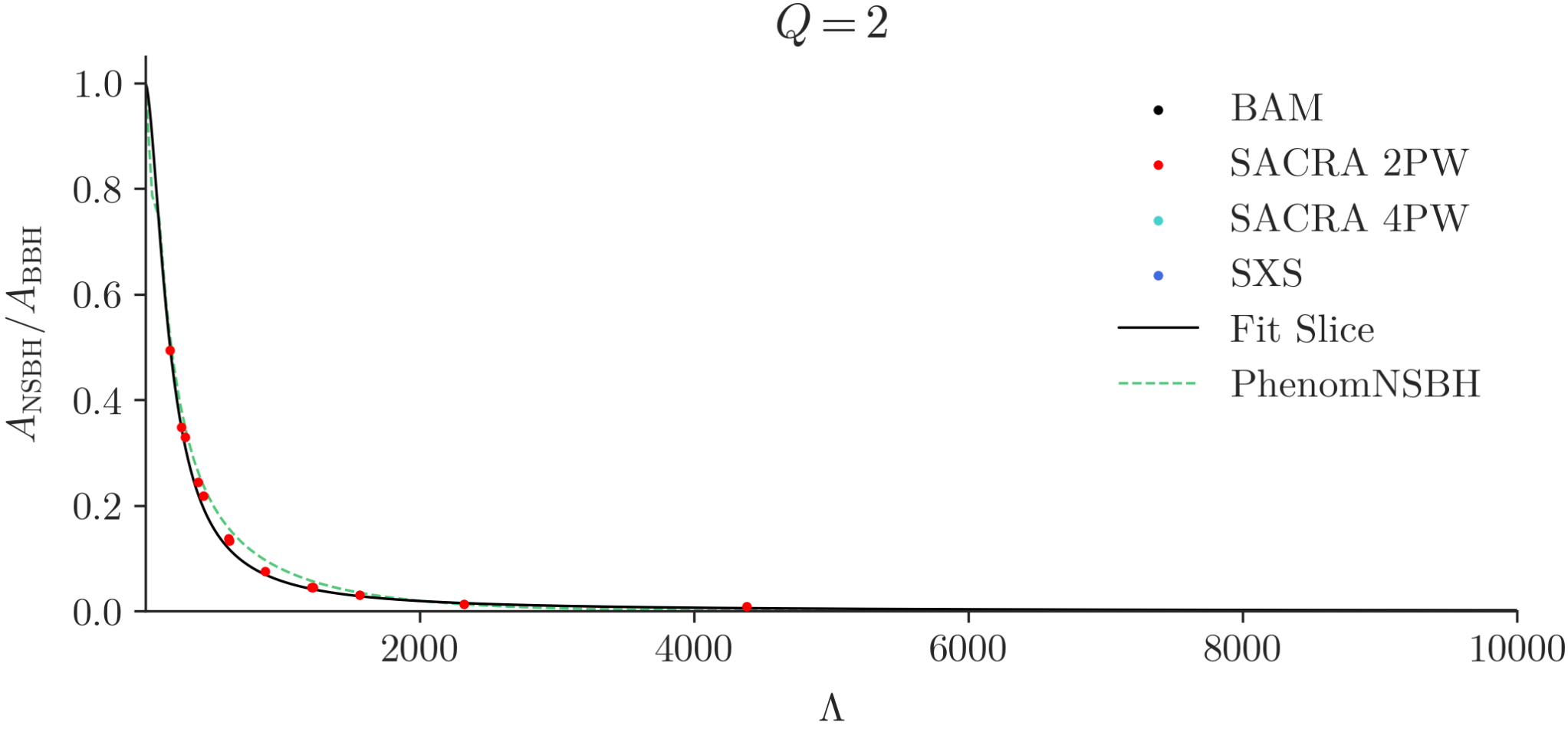




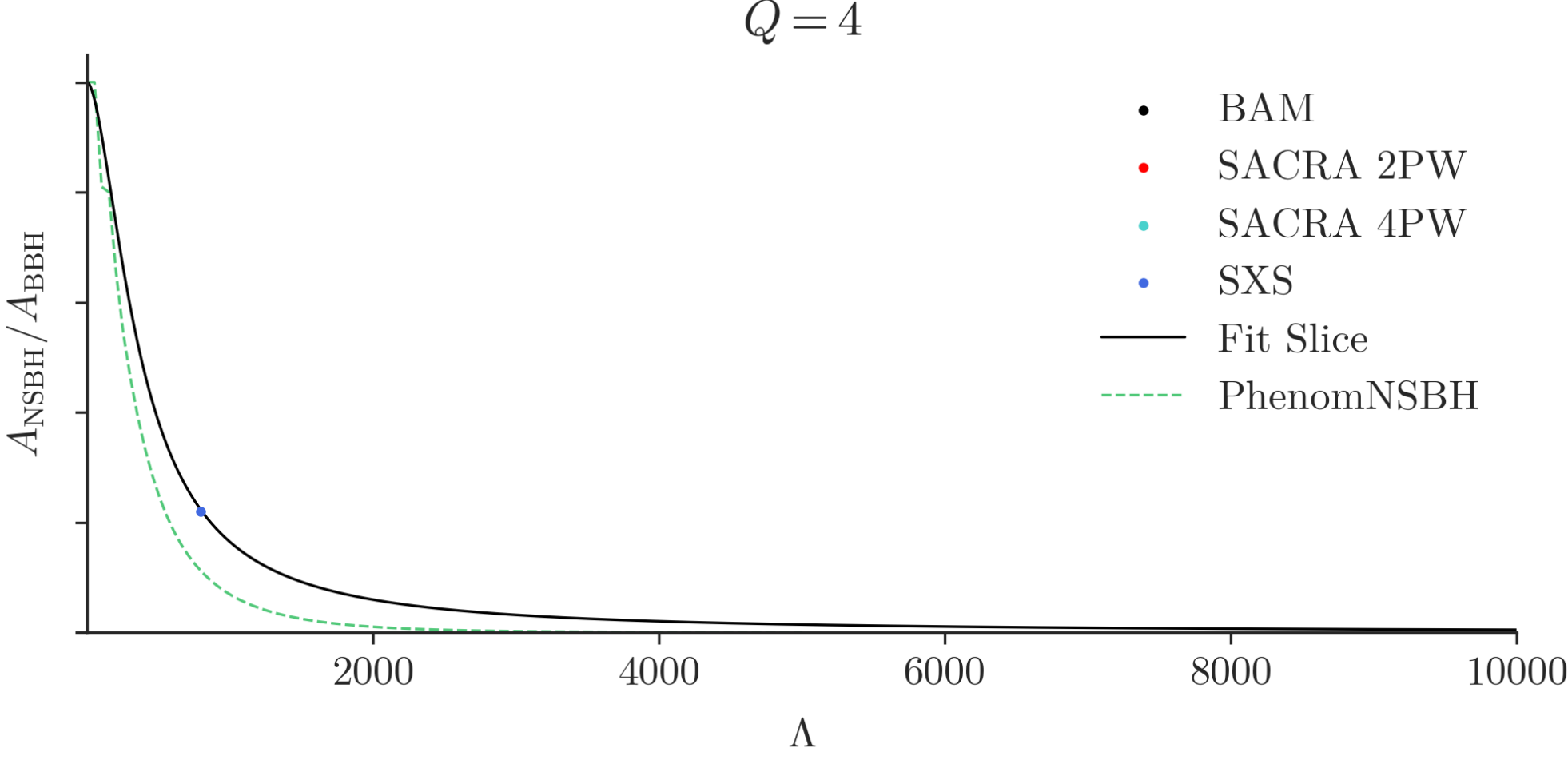
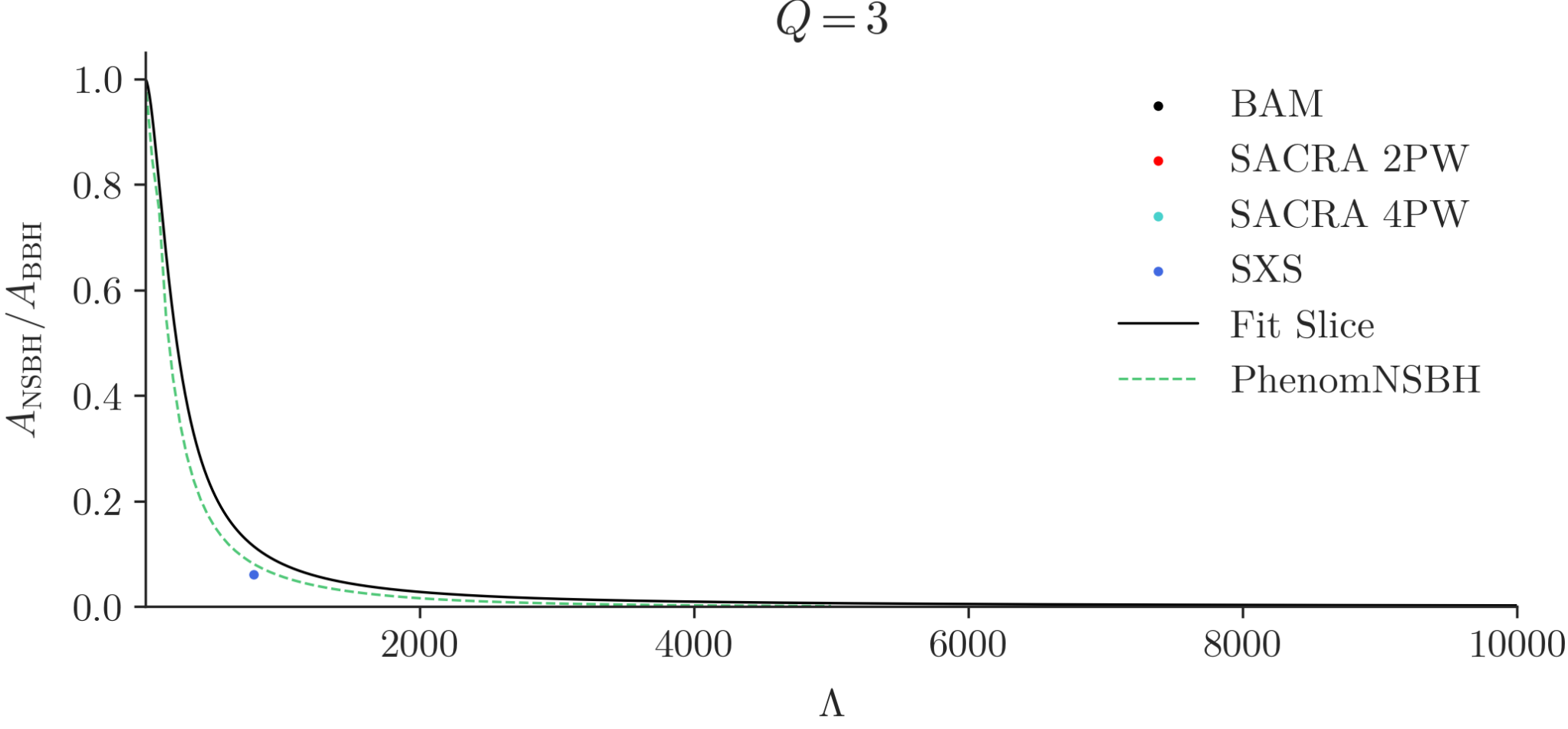
# AMPLITUDE MODEL

## CALIBRATION

$$Y_{4\text{FIT}}^{22}(Q, \chi_{\text{BH}} = 0.75, \Lambda)$$



$$Y_{4\text{FIT}}^{22}(Q, \chi_{\text{BH}} = 0.9, \Lambda)$$



# PHASE MODEL

NRTIDALV3

Summary of NRTidalv3 [*Abac et al.*]

---

- Dynamical Tides
- Mass-Ratio Dependence
- Spin-Spin and Cubic-in-Spin Corrections
- Calibrated to BNS simulations with 10 different EOS and  $Q \in [1, 2]$   
*Insufficient high-accuracy simulations to robustly calibrate to NSBHs*

# PHASE MODEL

NRTIDALV3 EXTENDED TO HMs

## Summary of NRTidalv3 [*Abac et al.*]

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- Mass-Ratio Dependence
- Spin-Spin and Cubic-in-Spin Corrections
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## Higher-order Modes

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$$\psi_{\ell m}(f) = \psi_{\ell m}^{\text{BBH}}(f) + \frac{m}{2} \psi_{22}^{\text{NRT3}} \left( \frac{2f}{m} \right)$$

*The phase of the higher-order multipoles can be well approximated by a rescaling of the 22 phase*  
[*London et al. 2018, Ujevic et al. 2022*]

*Higher modes implemented for:*

|                           |  |                           |  |                      |
|---------------------------|--|---------------------------|--|----------------------|
| IMRPhenomX(P)HM_NRTidalv2 |  | IMRPhenomX(P)HM_NRTidalv3 |  | IMRPhenomX(P)HM_NSBH |
|---------------------------|--|---------------------------|--|----------------------|

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[*Abac et al., in prep.*]

*Calibrated remnant properties*

---

*This Work*

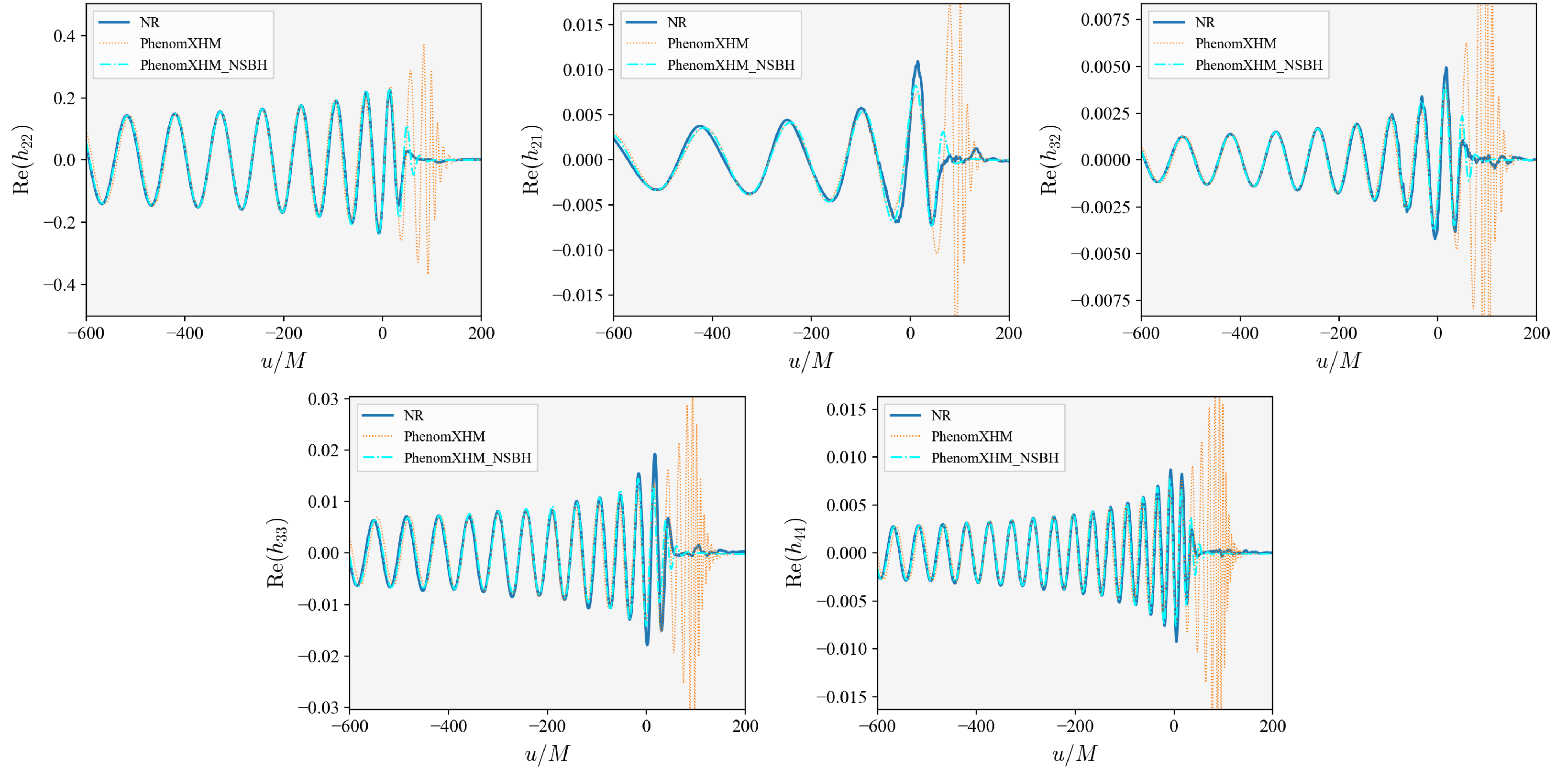


# RESULTS

# RESULTS

## TIME DOMAIN COMPARISONS

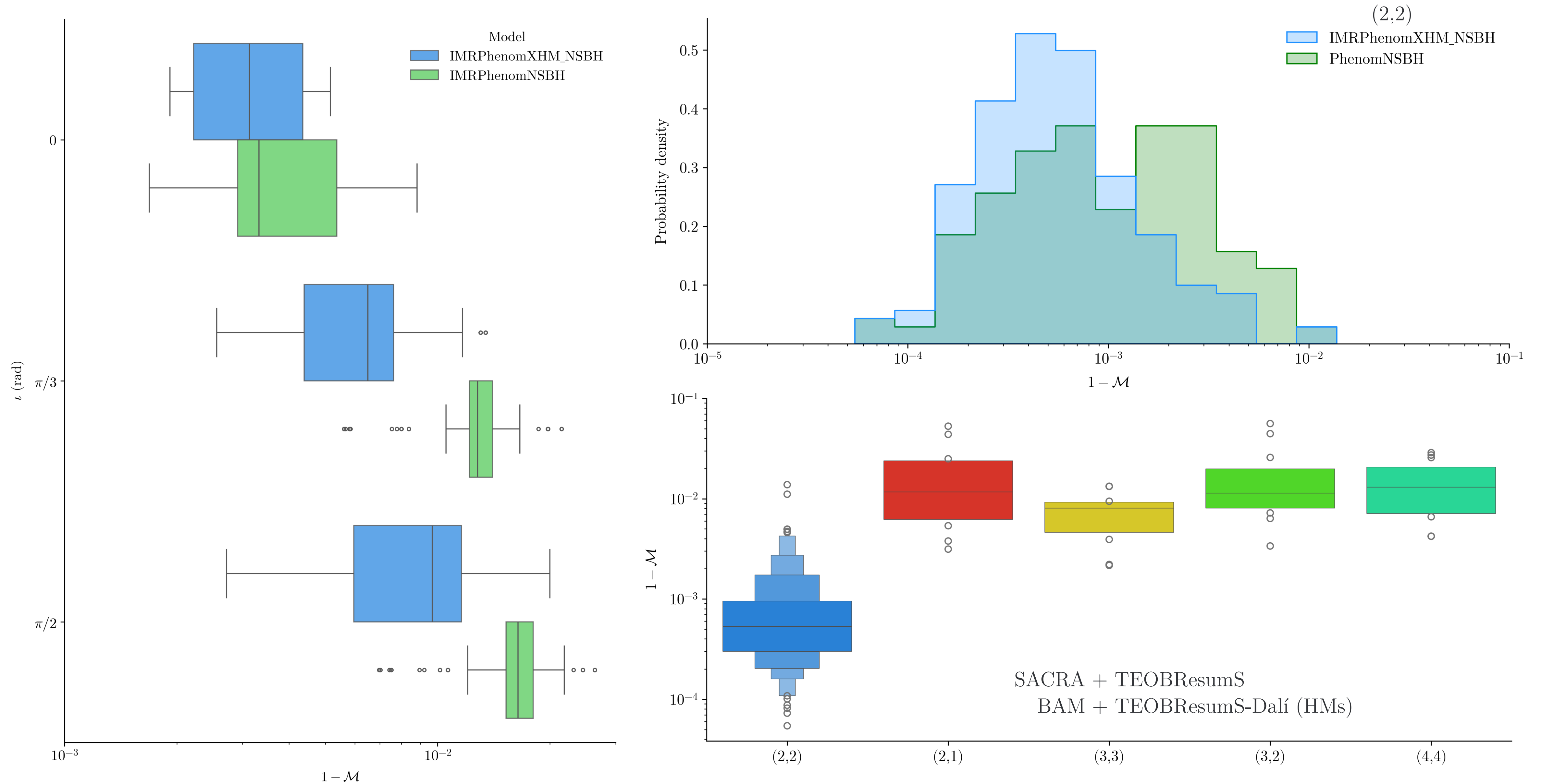
SXS:BHNS:0006



# RESULTS

MATCHES

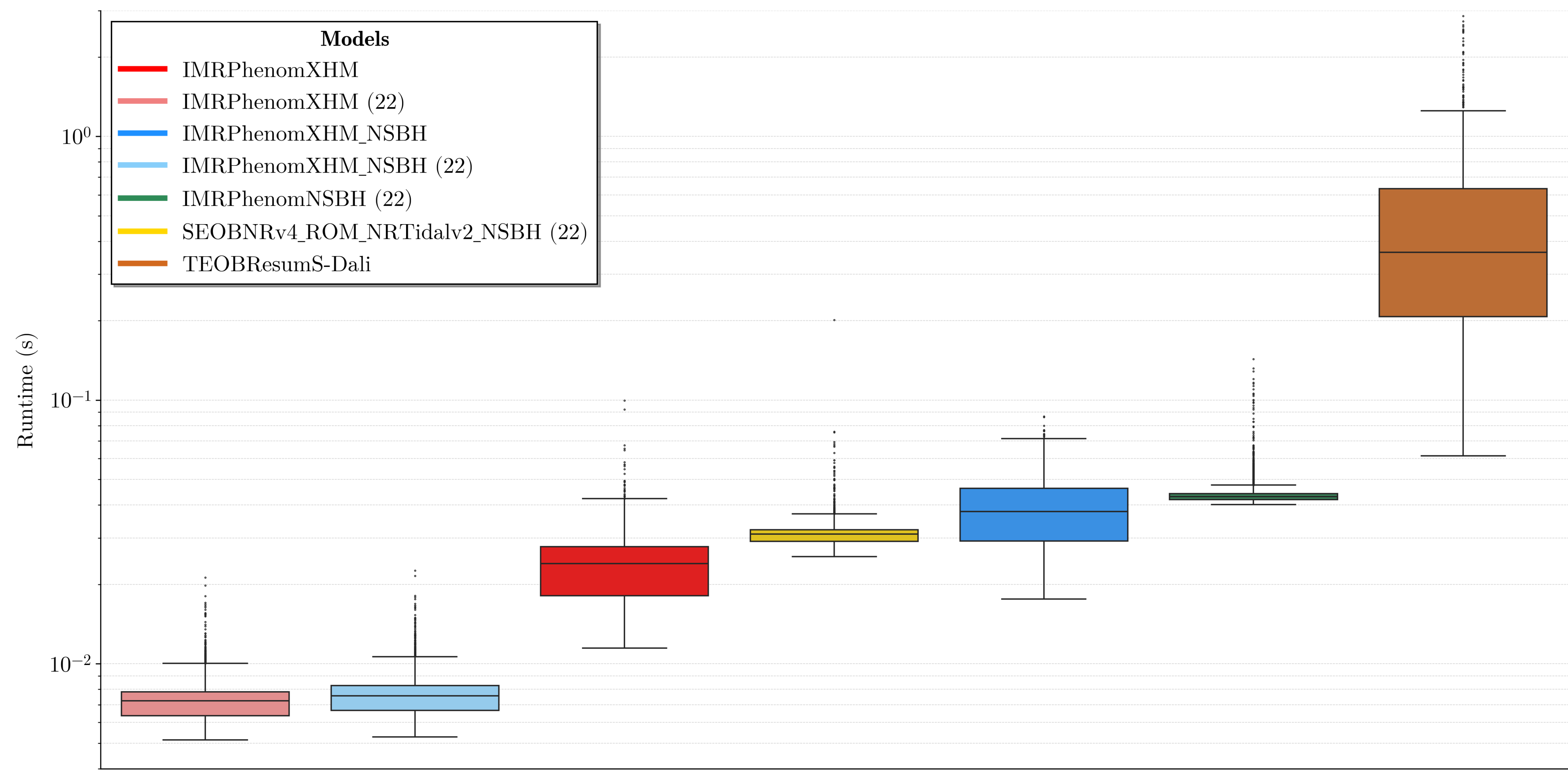
IMRPhenomXHM\_NSBH vs NR Hybrids





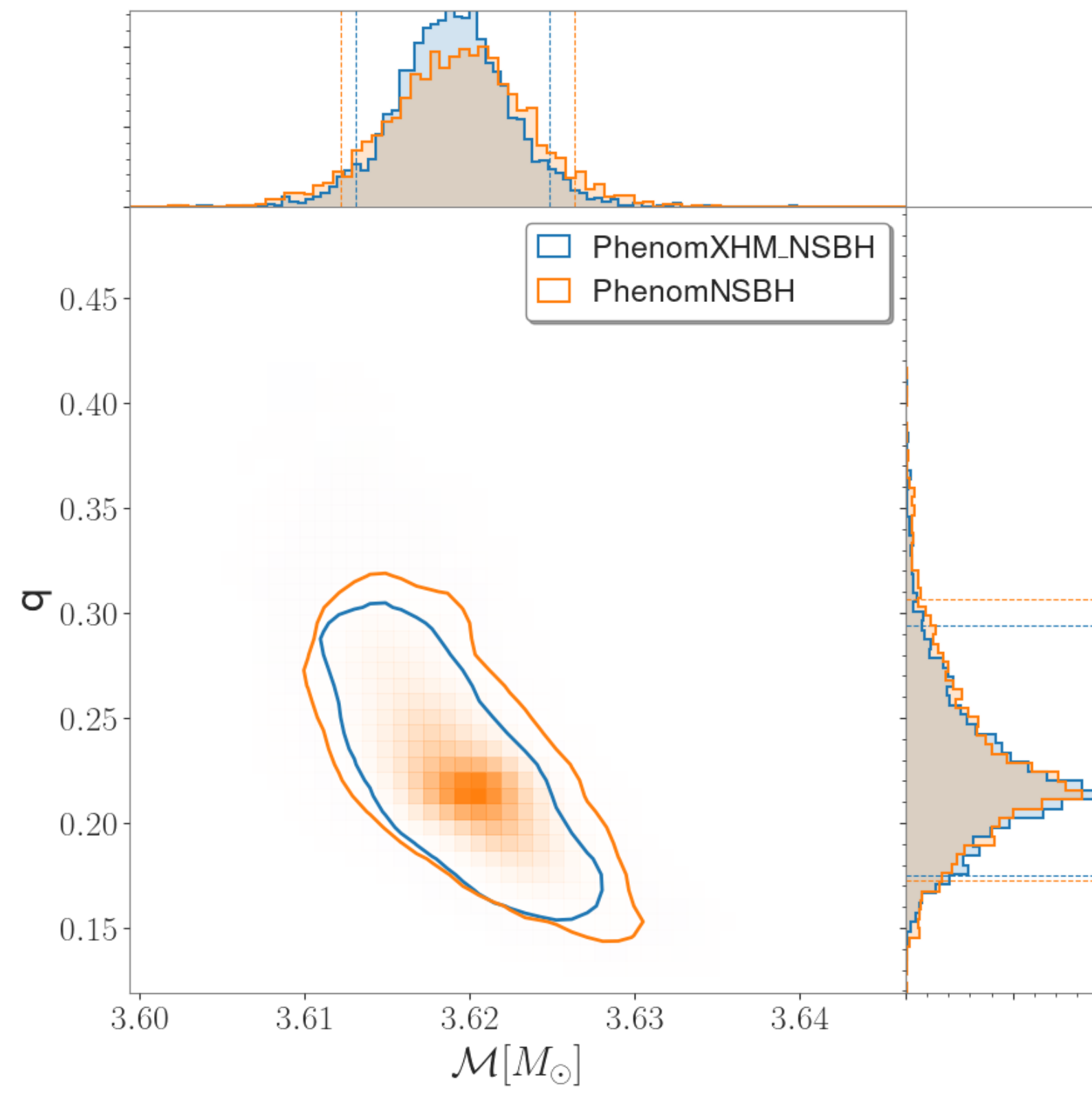
# RESULTS

## TIMINGS

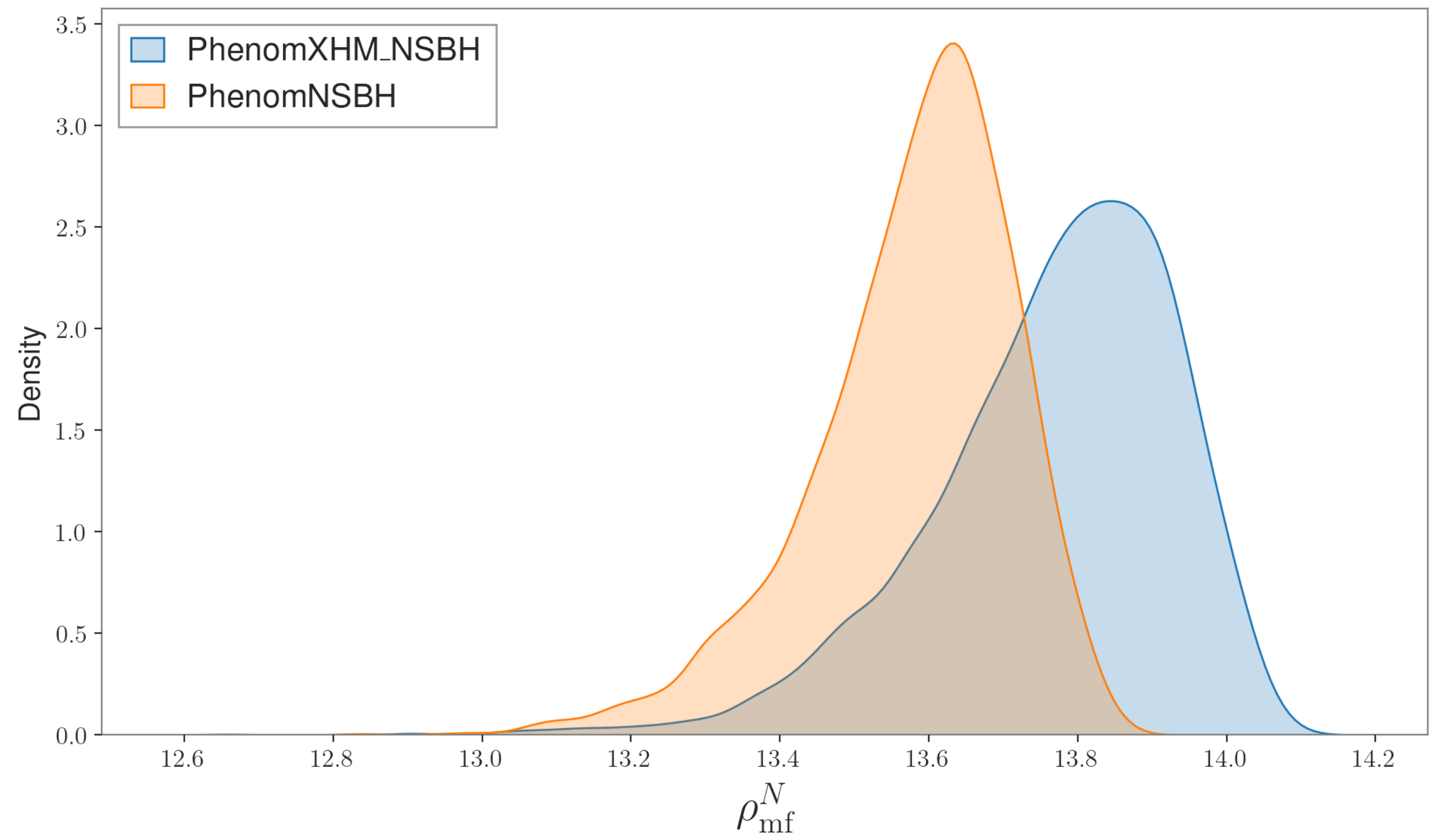


# RESULTS

## PARAMETER ESTIMATION



GW200105



# CONCLUSIONS



# CURRENT STATUS & FUTURE WORK

*Where are we standing?*

## **Summary**

New waveform model for NSBH coalescences which:

- Incorporates more BBH and tidal physics ✓
- Ensures smooth, well-behaved behavior across parameter space ✓
- Computationally efficient LALSuite implementation ✓
- Expected to enable more reliable analyses for current and future detectors ✓

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- Finish implementation of the precessing model ⚠️🔨

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## Future Work

- Parameter estimation of real events 📡
- Systematics studies and 3G detector forecasts 🤖
- Population-level inference studies 🌌
- NSBH-specific calibration of tidal phase 🌊
- Possible combination with eccentricity and/or memory in a future model 🌀  
[*Lluc Planas et al., Rosselló-Sastre et al.*]



# Acknowledgements

Felip Antoni Ramis Vidal is supported through the Conselleria d'Educació i Universitats via an FPI-CAIB doctoral grant (FPI\_092\_2022). This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigación grants PID2022-138626NB-I00, RED2022-134204-E, RED2022-134411-T, funded by MICIU/AEI/10.13039/501100011033 and the ERDF/EU; and the Comunitat Autònoma de les Illes Balears through the Conselleria d'Educació i Universitats with funds from the European Union - NextGenerationEU/PRTR-C17.I1 (SINCO2022/6719) and from the European Union - European Regional Development Fund (ERDF) (SINCO2022/18146). The authors thankfully acknowledge the computer resources at Picasso and the technical support provided by Barcelona Supercomputing Center (BSC) through grant No. AECT-2025-1-0035 from the Red Española Supercomputación (RES). The authors thank the Supercomputing and Bioinnovation Center (SCBI) of the University of Malaga for their provision of computational resources and technical support ([www.scbi.uma.es/site](http://www.scbi.uma.es/site)).



Q&A

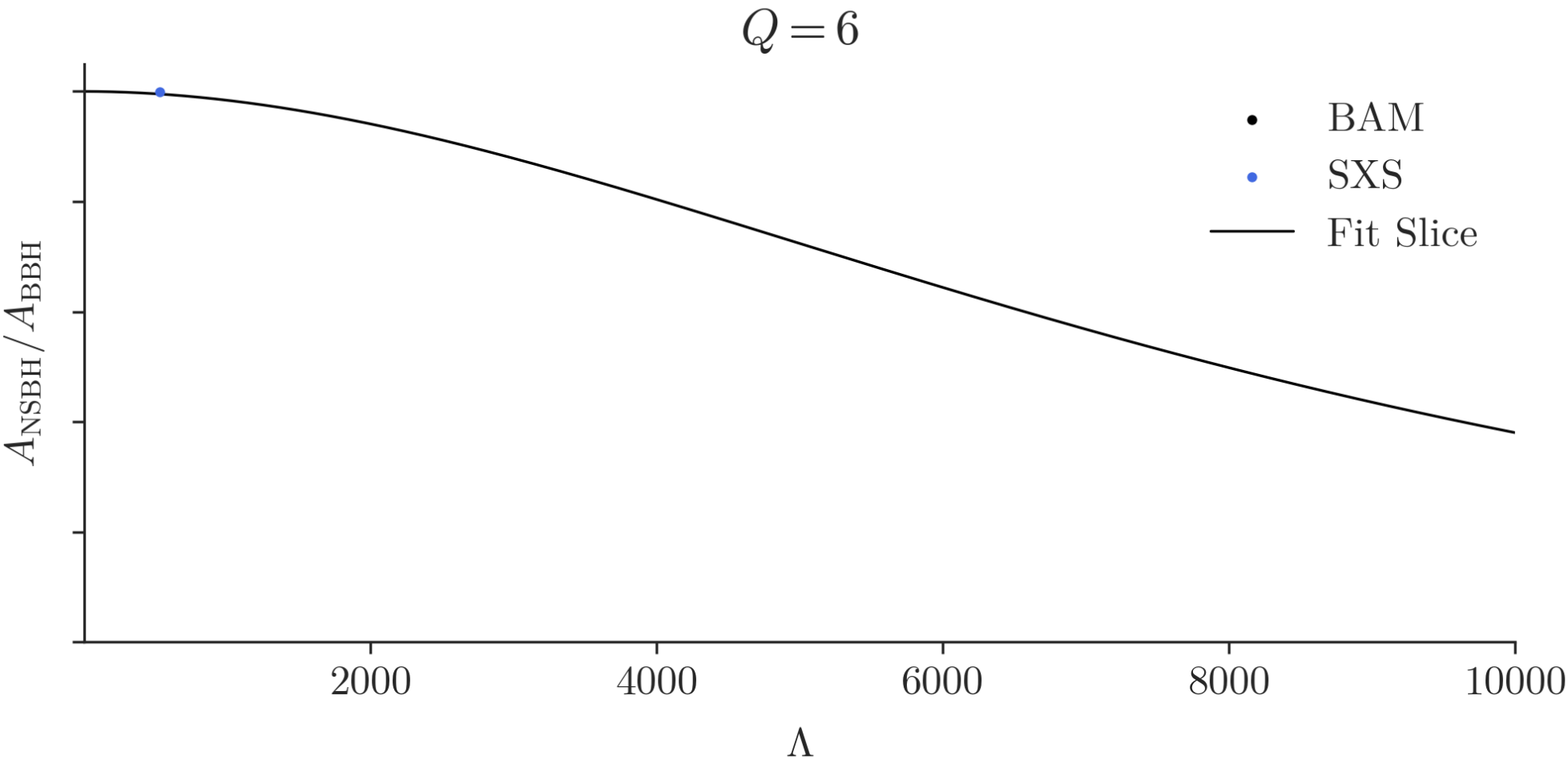
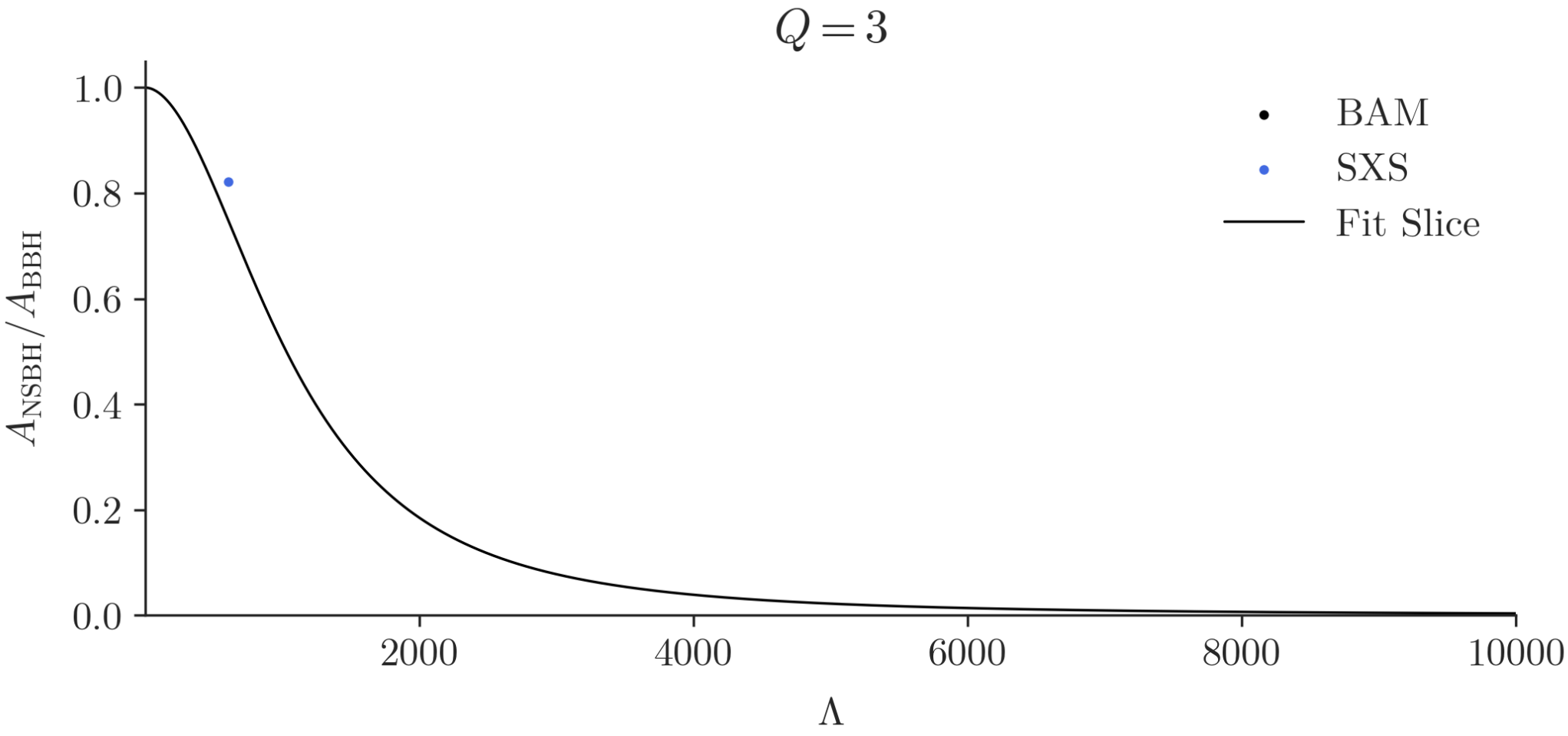
# BACKUP SLIDES



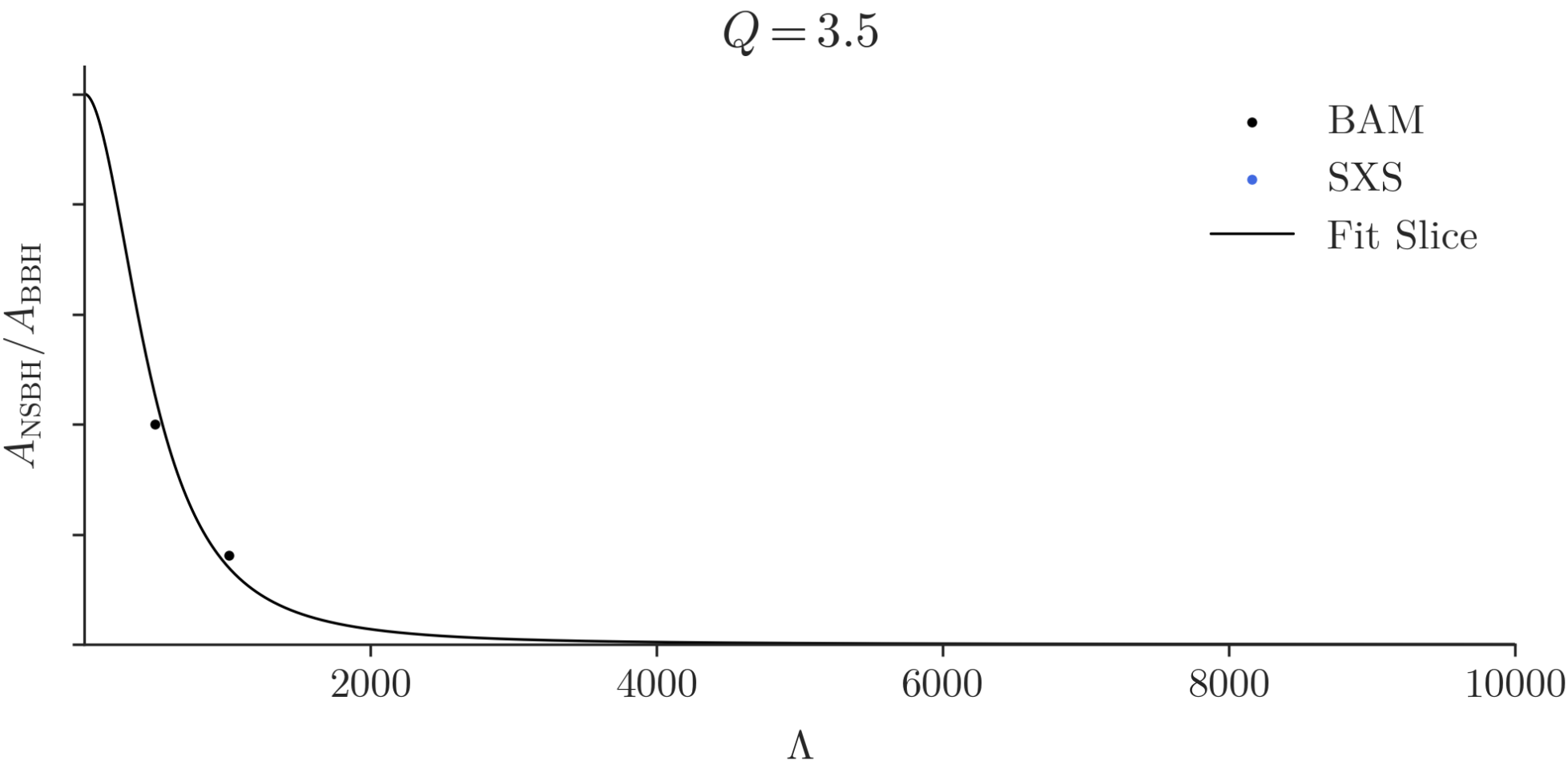
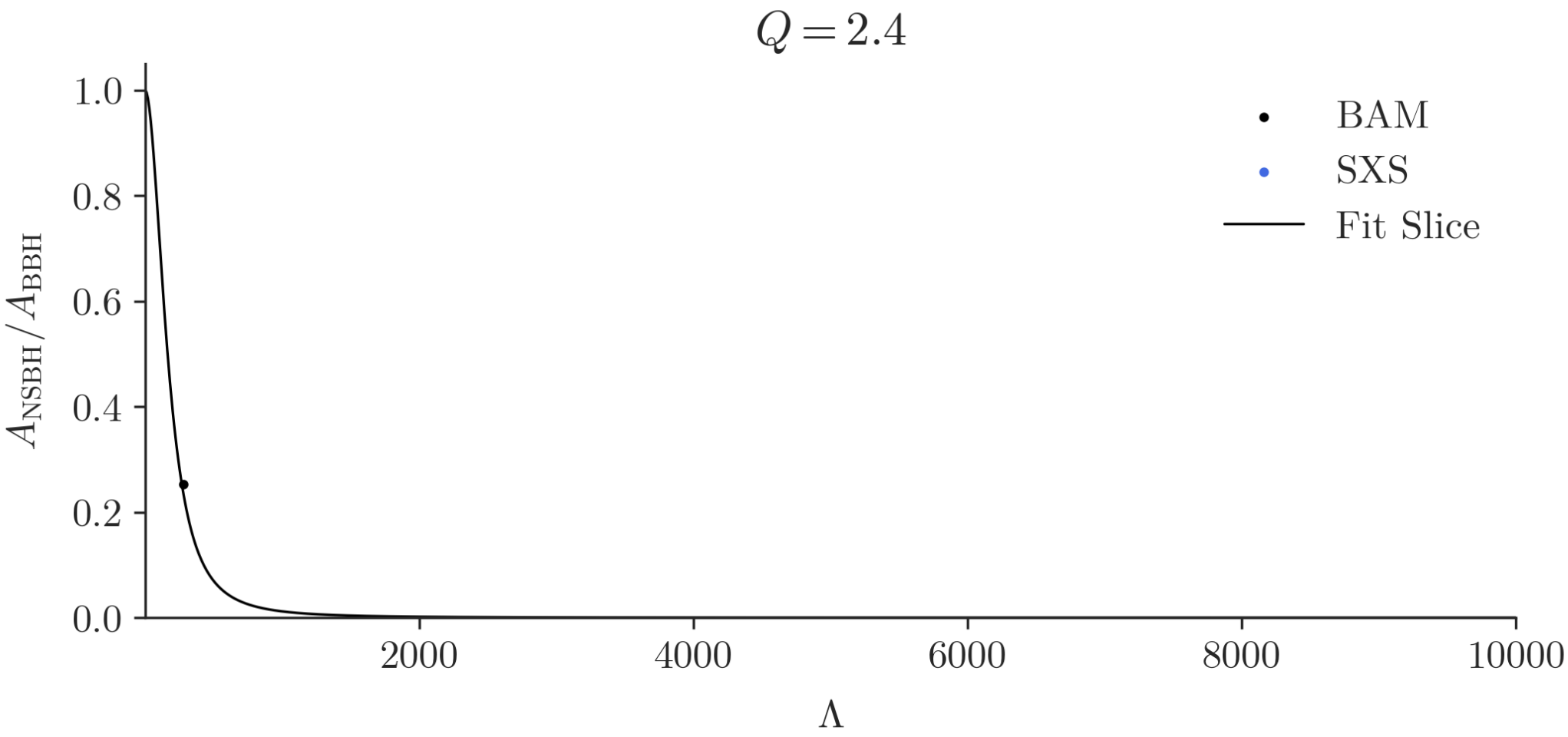
# CALIBRATION OF THE MODEL

## PARAMETER SPACE FITS - MODE 33

$$Y_{4\text{FIT}}^{33}(Q, \chi_{\text{BH}} = 0, \Lambda)$$

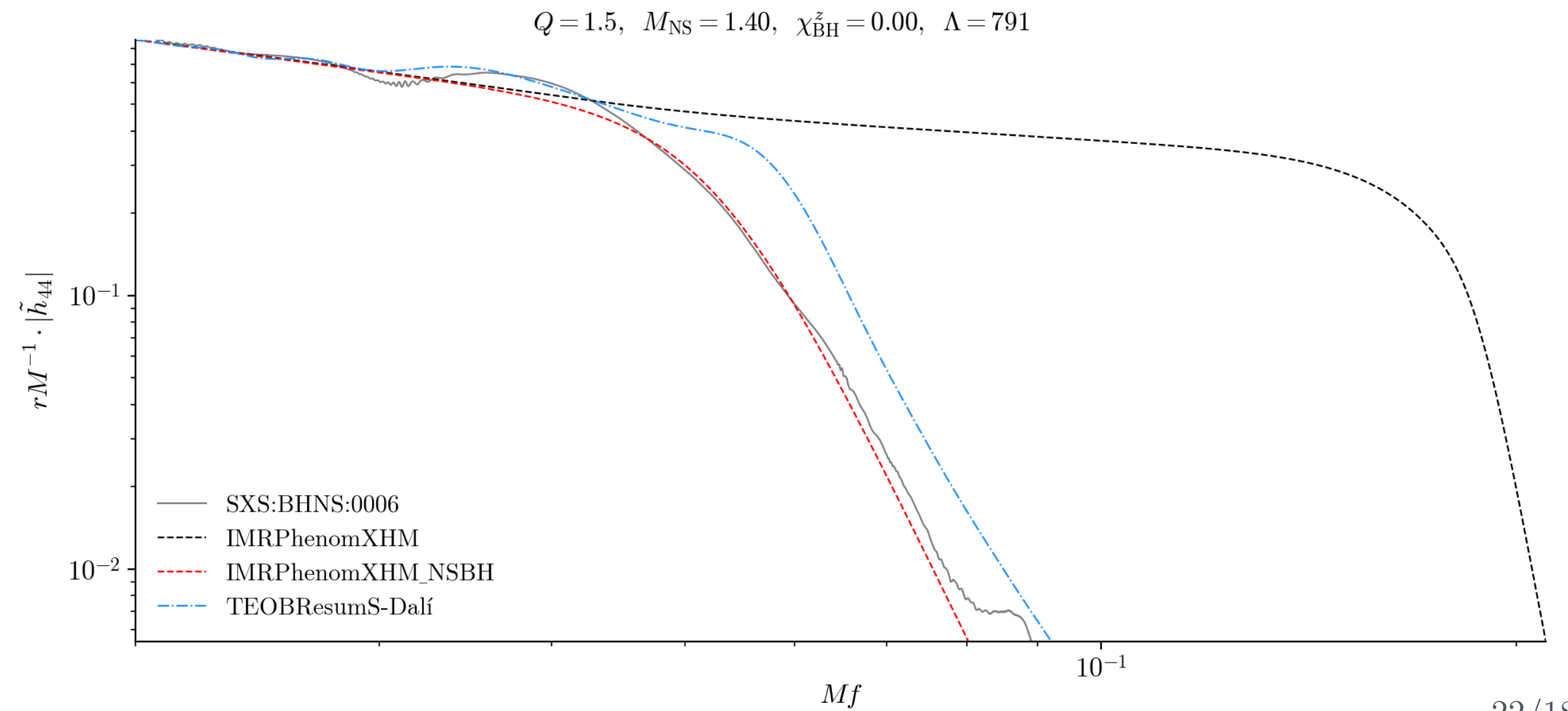
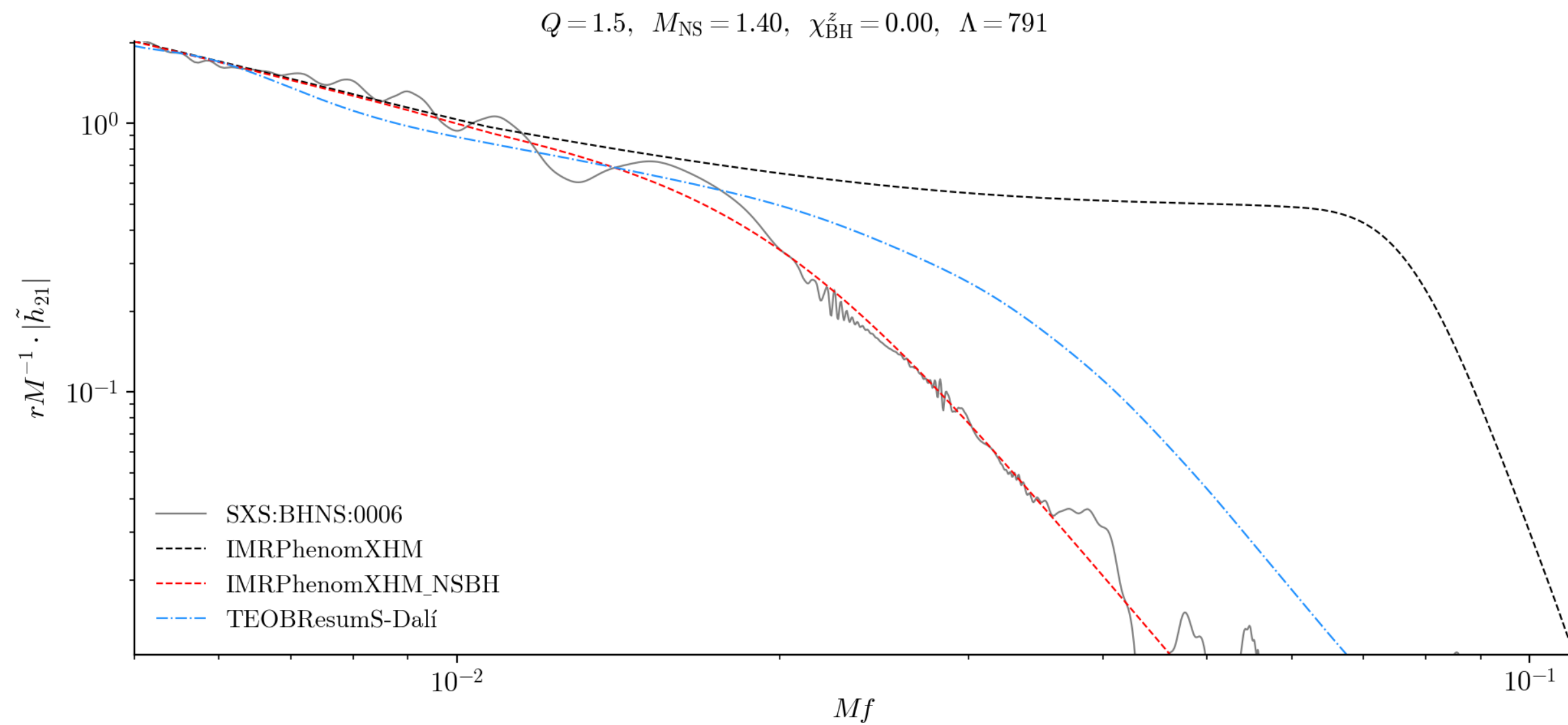
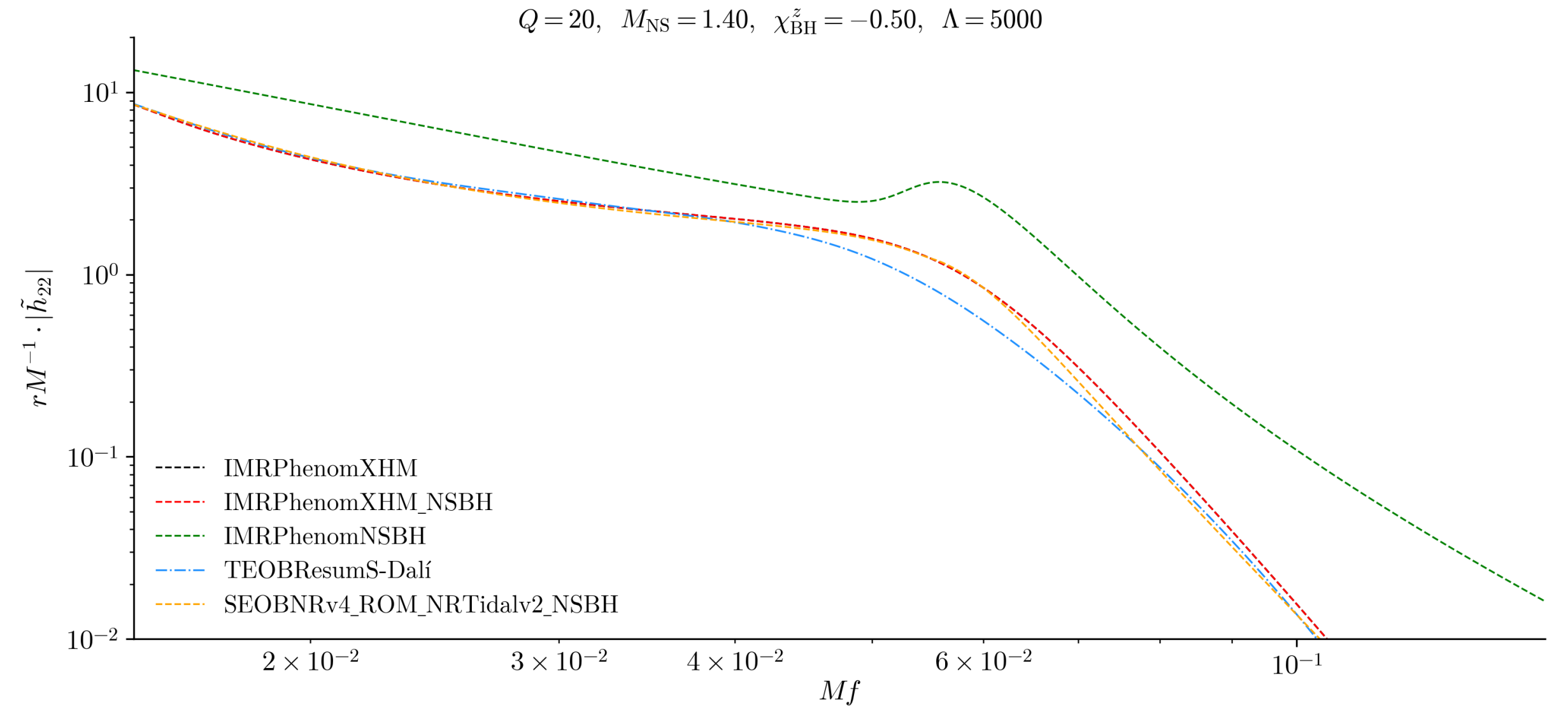
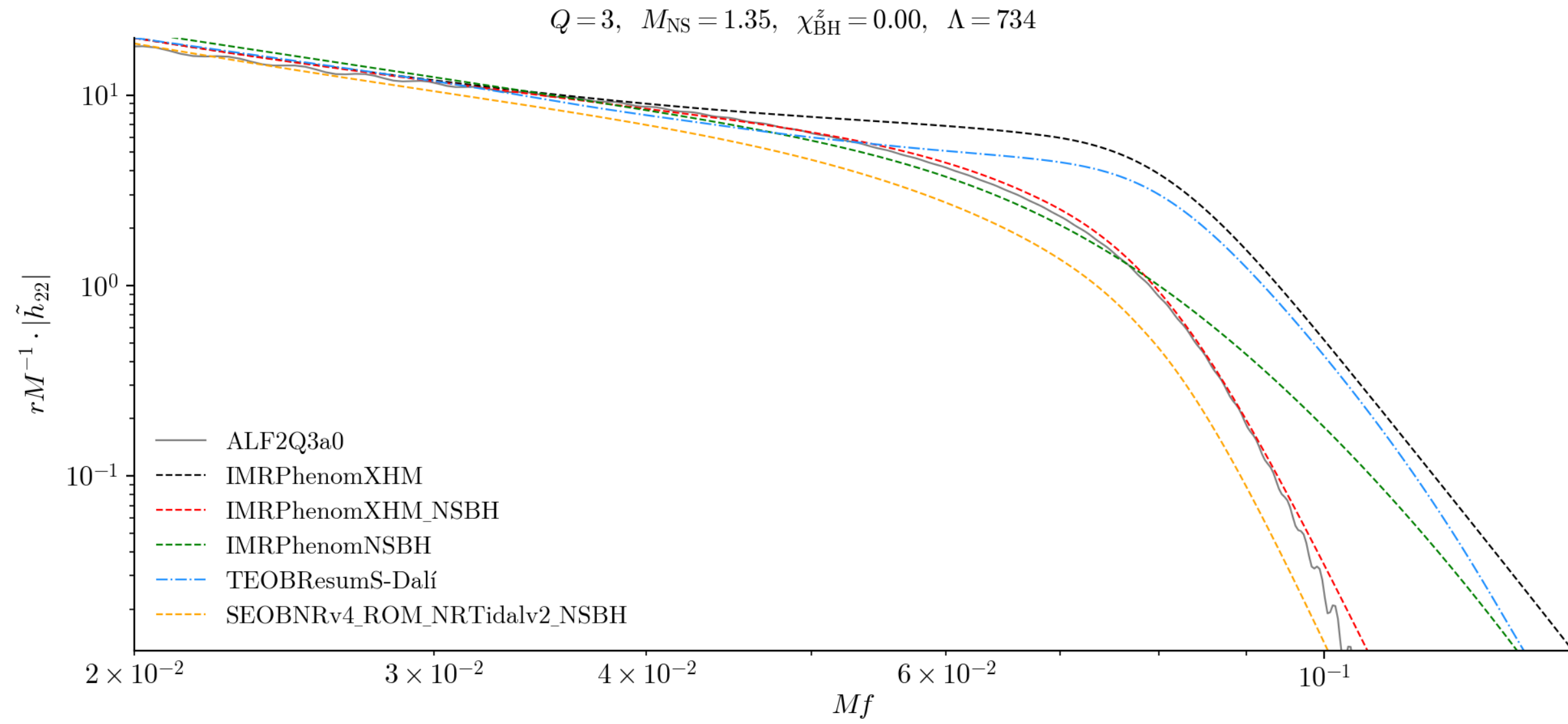


$$Y_{4\text{FIT}}^{33}(Q, \chi_{\text{BH}} = 0.6, \Lambda)$$



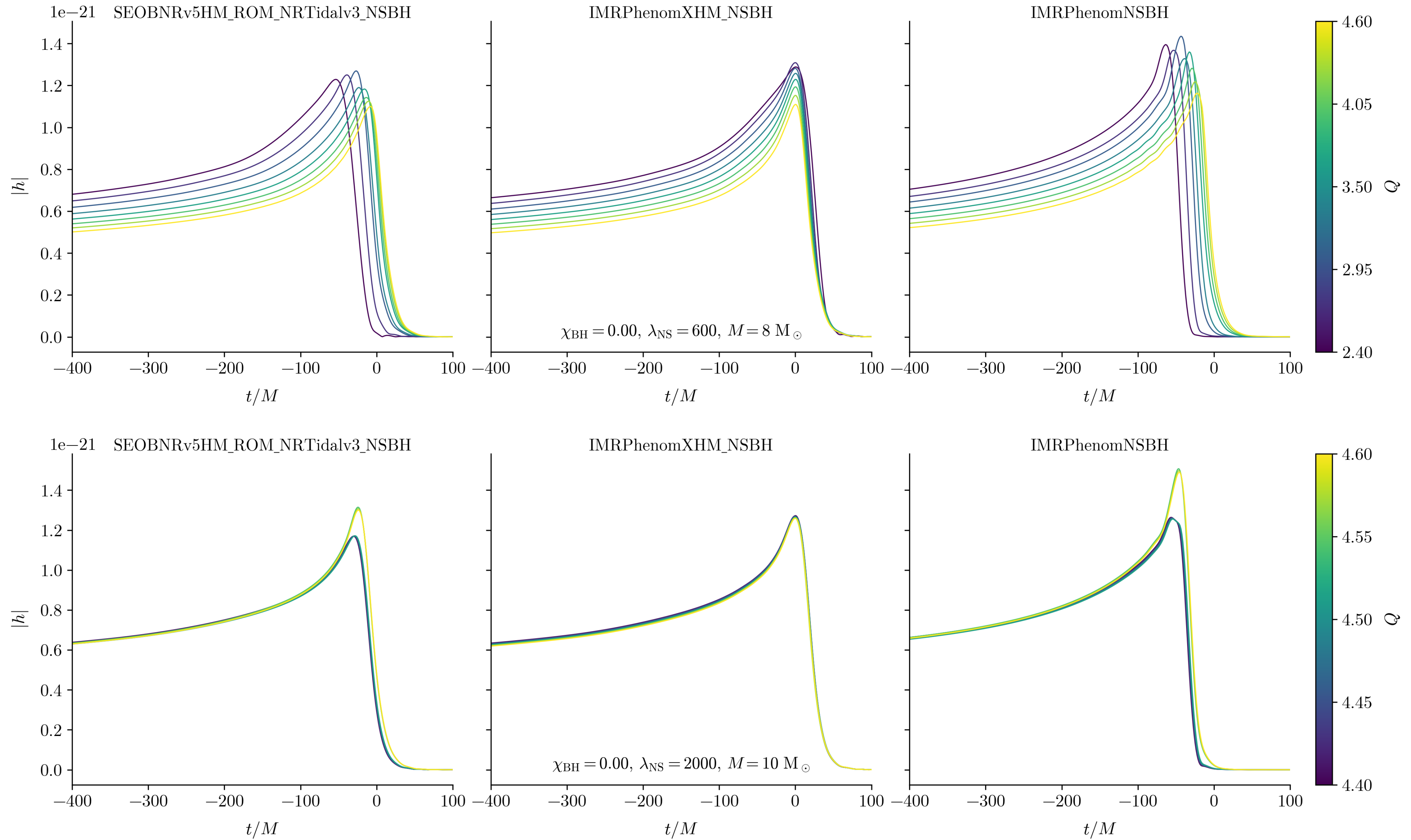
# AMPLITUDE MODEL

## FREQUENCY DOMAIN COMPARISONS



# RESULTS

## SMOOTHNESS TESTS





# RESULTS

## TIMINGS

