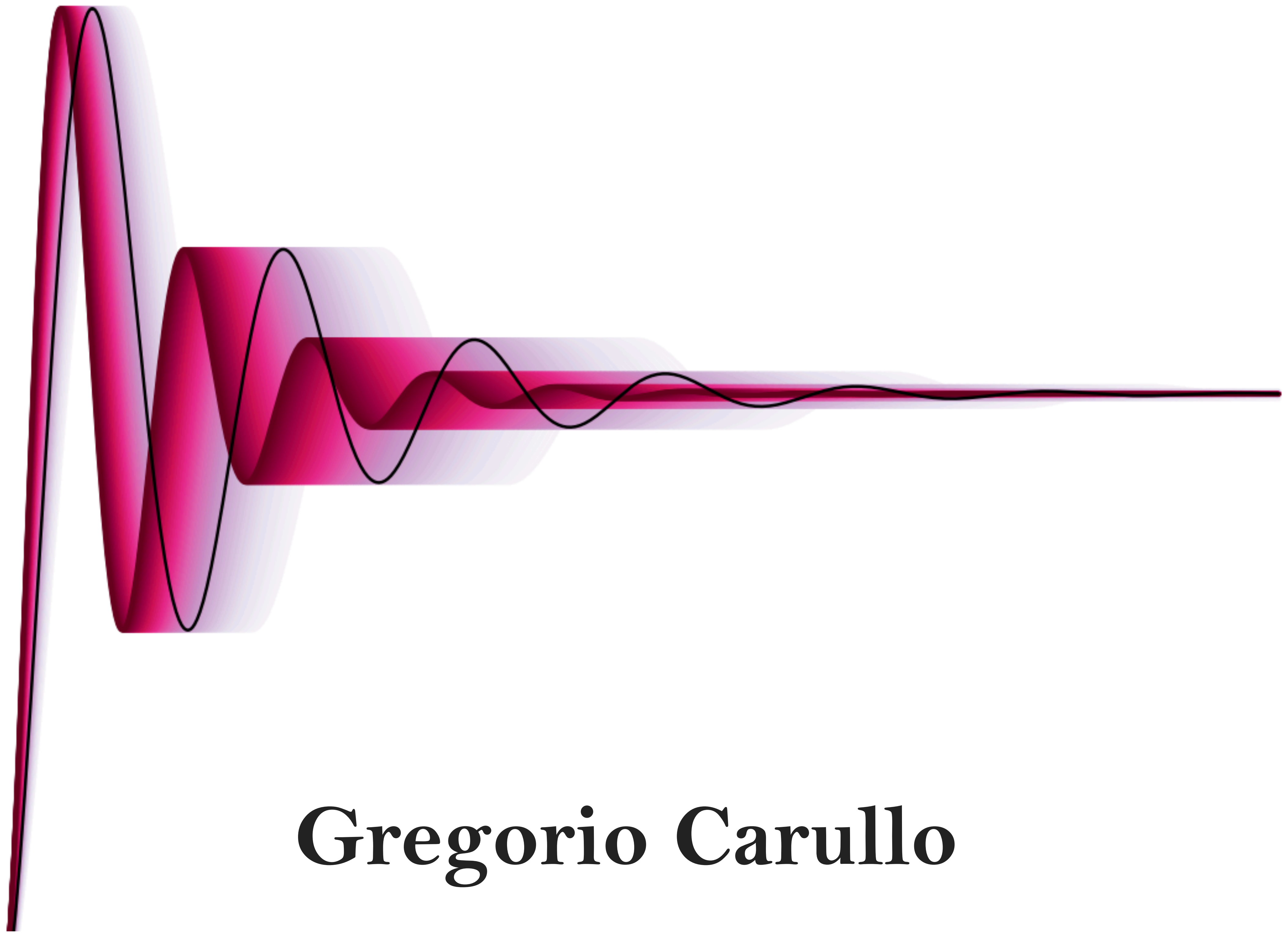
MODELING AND OBSERVATIONAL STATUS OF BLACK HOLE VIBRATIONAL SPECTRA



Gregorio Carullo

TEONGRAV I

18/09/2024

Sapienza Università di Roma

UNIVERSITY OF BIRMINGHAM

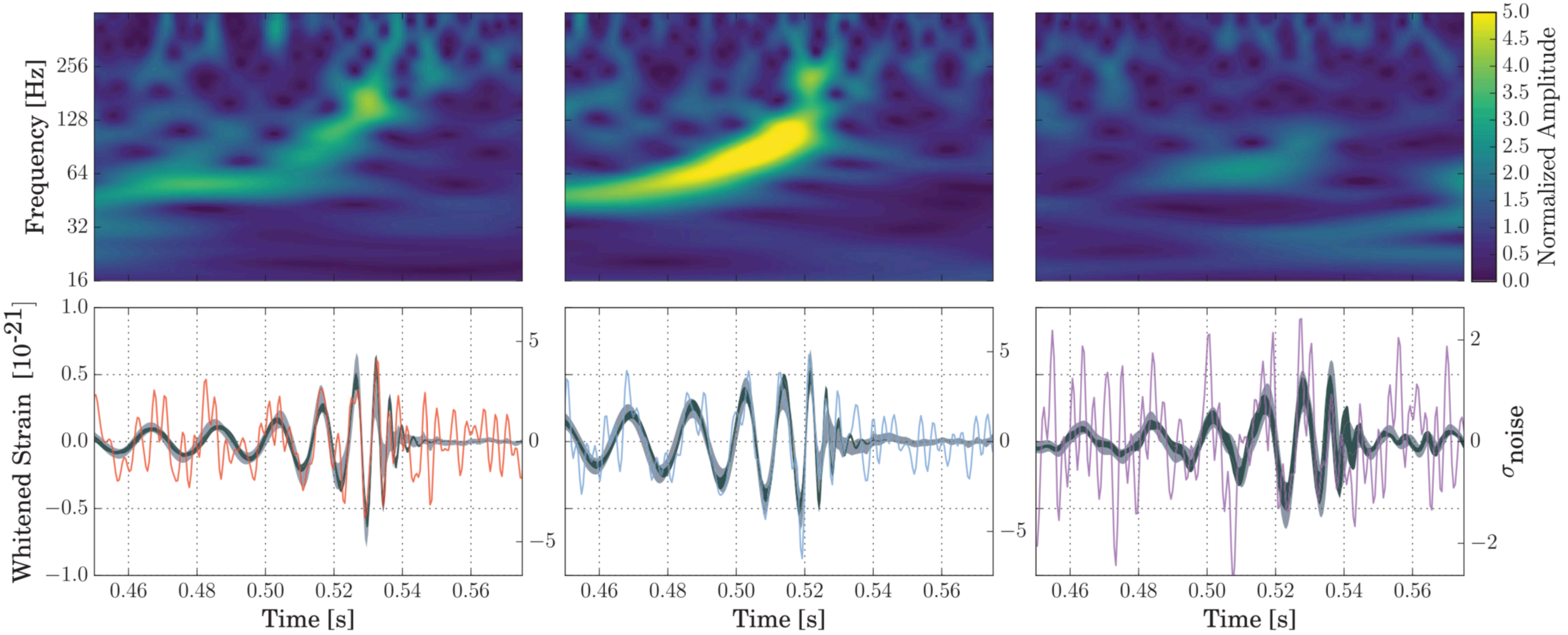
VIRGO

CONTENT

- **Black holes coalescences** and what can we learn from them
- Black hole **ringdown:** perturbative picture, nonlinear picture, their merger
- Observational black hole **spectroscopy:** the LVK search
- Recent modeling **developments** (non-linear, non-circular, …)
- Prospects with **future** gravitational-wave **detectors**

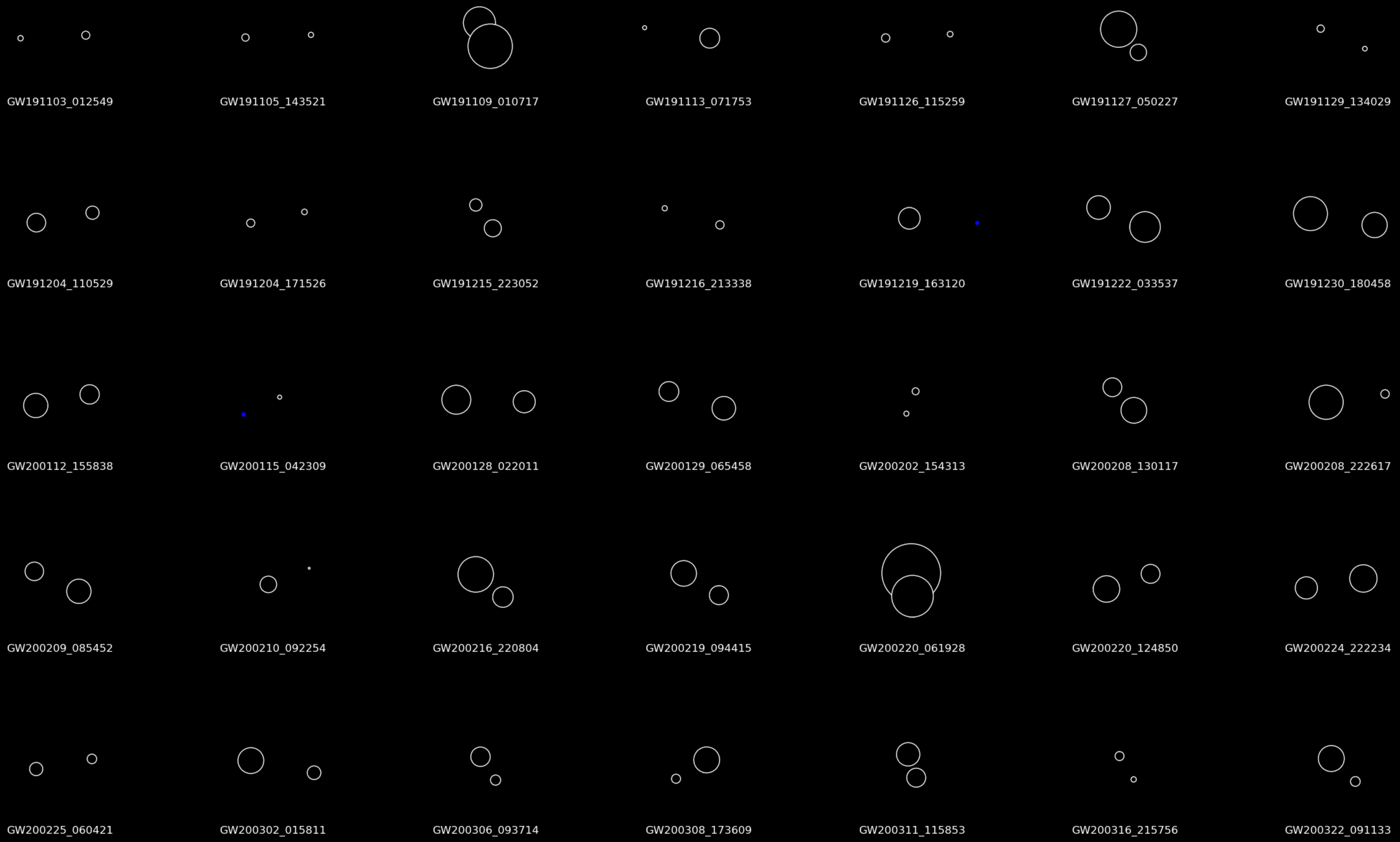
What have we observed?

GRAVITATIONAL WAVE SIGNALS



LVC, PRL 119, 141101 (2017)

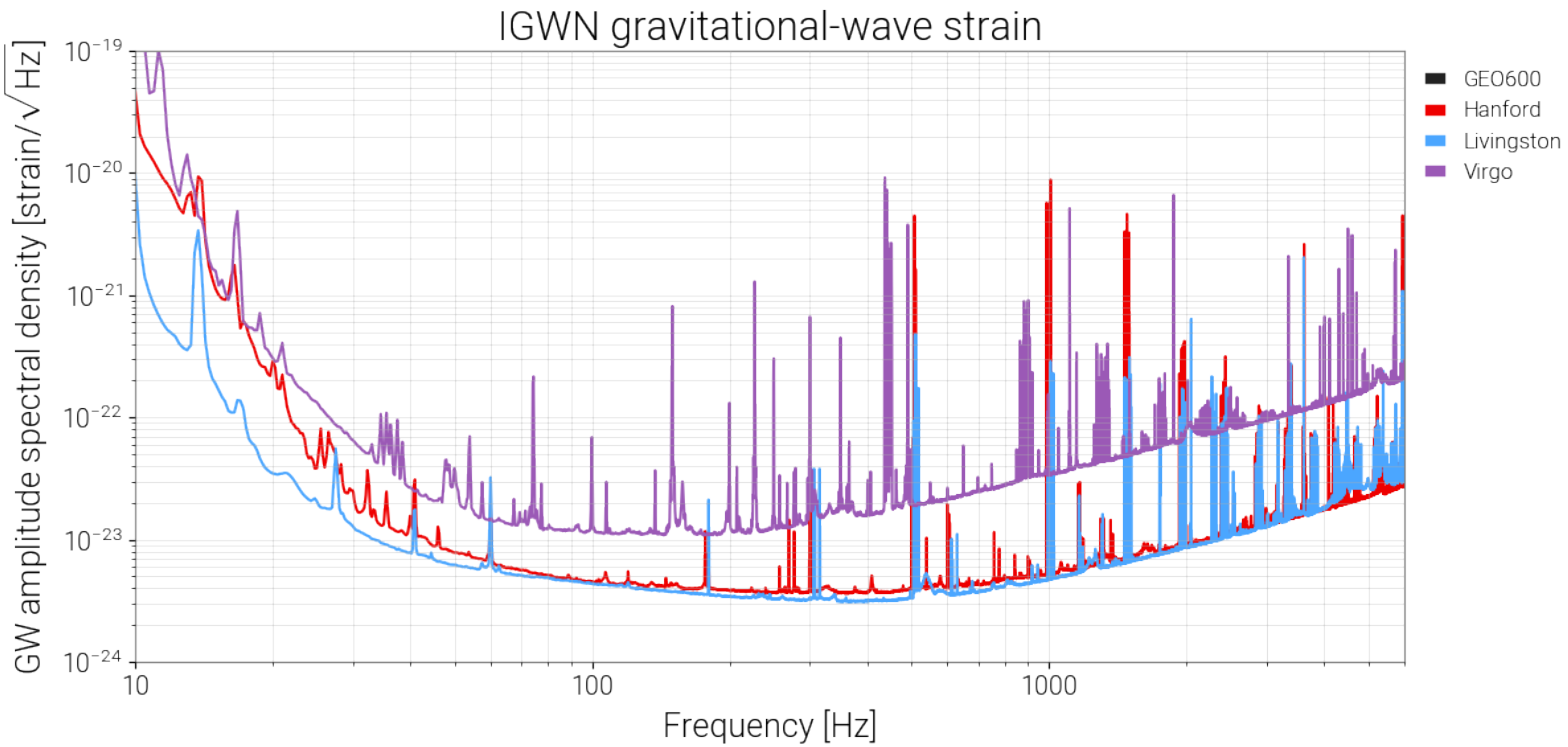
What have we inferred?



Zoheyr Doctor / CIERA / LIGO-Virgo Collaboration

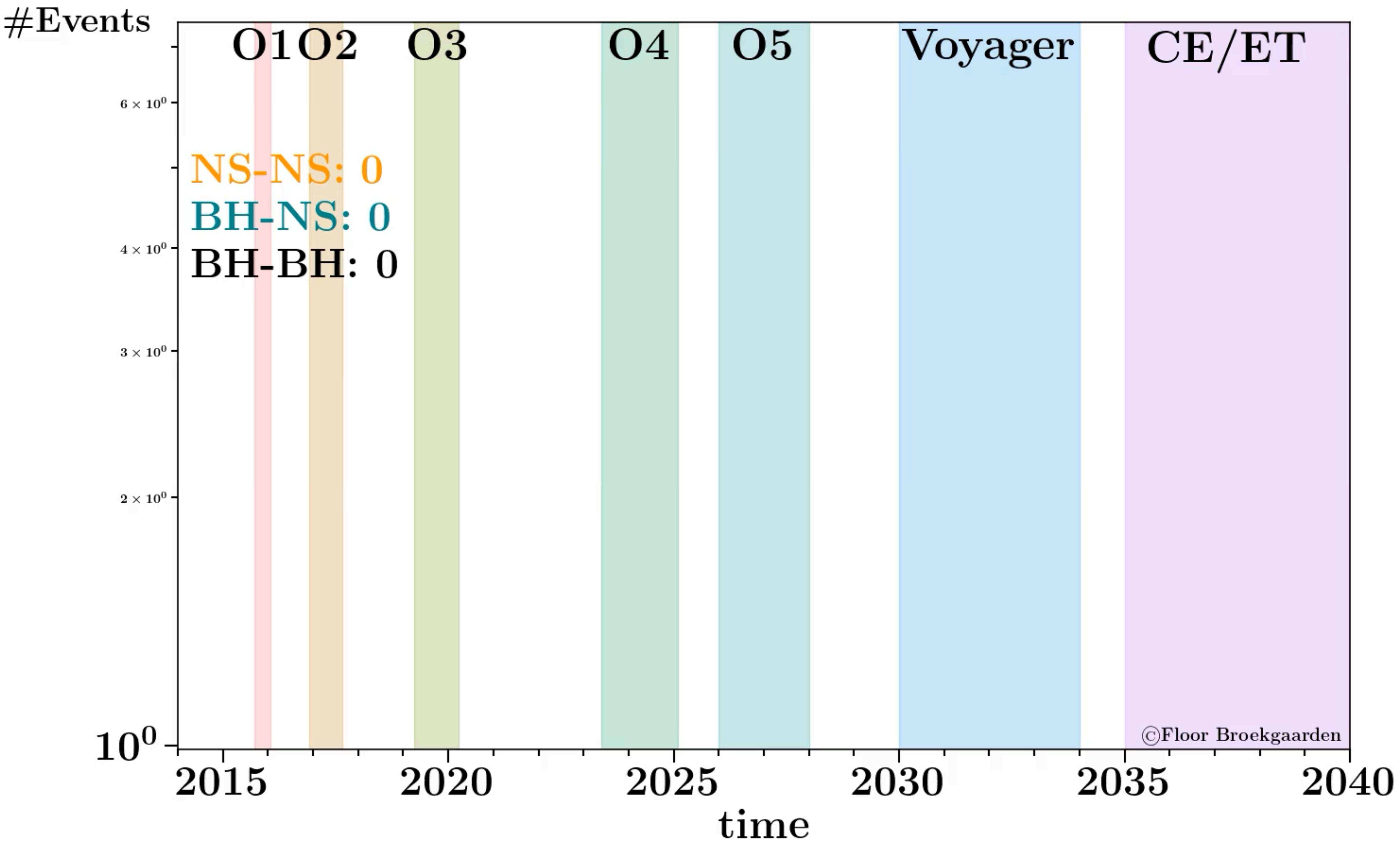
FOURTH OBSERVING RUN

- Instruments are online again:



observing.docs.ligo.org/plan

A CROWDED FUTURE



Credits: Broekgaarden

What do we want to learn from these signals?

SCIENCE GOALS

- **Searching** for new physics:

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    Do observed black holes have additional hairs, apart from (M,a)?

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    Do observed black holes have additional hairs, apart from (M,a)?
  - General Relativity predictions for **spectral emission**
    Is General Relativity a correct description of gravity at high curvatures?

MISSING PHYSICS?

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Barausse, Cardoso, Pani, PRD 89 (2014) 104059

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  - ~~**Cosmological expansion, dark matter**~~
  - ~~**Accretion, magnetic fields, electric charge**~~
- Ringdown **searches for new physics** in the LVK band *expected* to be **clean**

Inspiral (EMRIs especially) likely less so:

Kavanagh+, 1805.09034, Speri+, 2207.10086,
Bamber+, 2210.09254, Bertone+, 2404.08731
Garg+, 2402.14058, Aurrekoetxea+, 2409.01937
…

Barausse, Cardoso, Pani, PRD 89 (2014) 104059

Cannizzaro+, 2405.05315 (charged+plasma)
Leong+, 2308.03250 (scalar field bubble),
Aurrekoetxea+, 2409.01937 (DM spikes)

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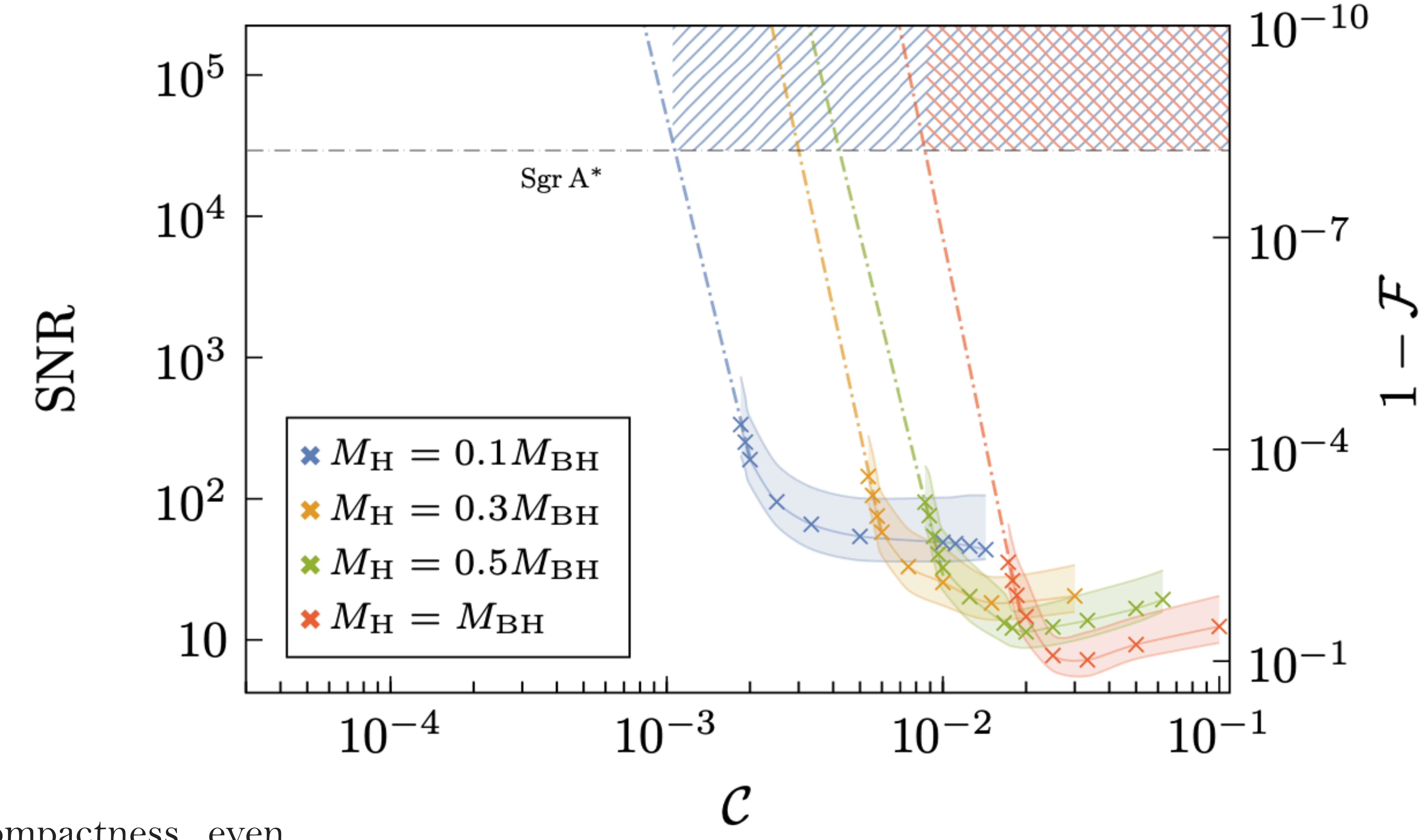
Spieksma, Cardoso, Carullo, Duque, Della Rocca, 2409.05950



For astro values of DM compactness, even EMRI ringdown in Sgr A* with LISA clean

Full NR? DM model dependence?

KERR BLACK HOLE PROPERTIES

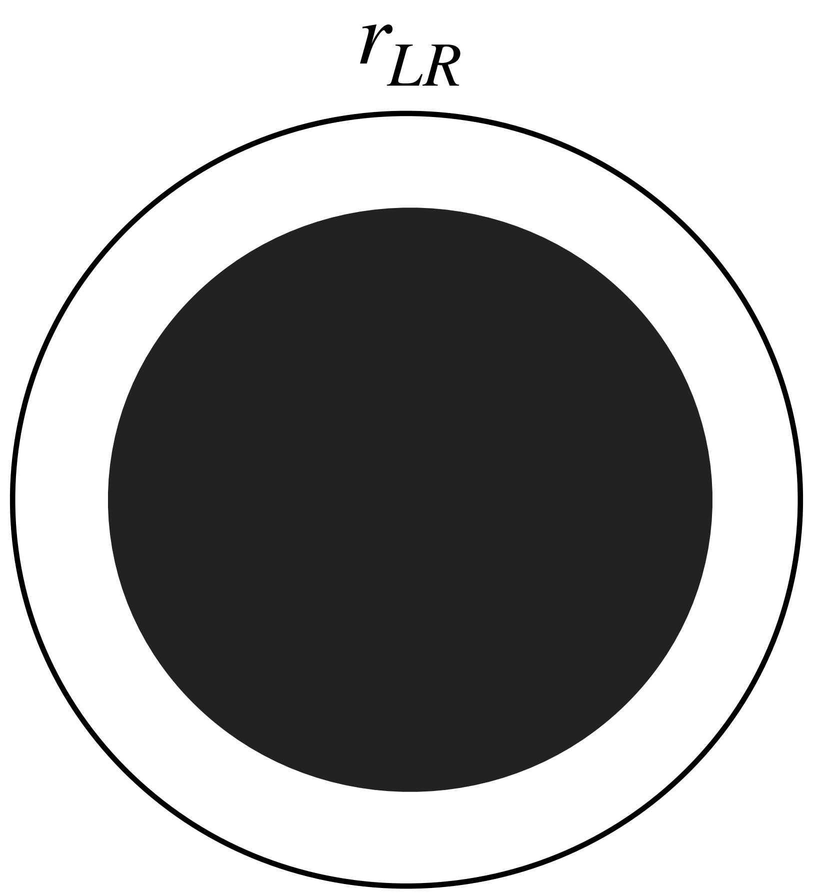
This workshop: Cannizzaro, Chakraborty

Tidal deformations

$$\Lambda = 0$$

Multipole moments

$$M_{2n} = M(-a^2)^n \, , S_{2n+1} = Ma(-a^2)^n$$



$$\{\omega_{lmn}(M,a), \tau_{lmn}(M,a)\}$$

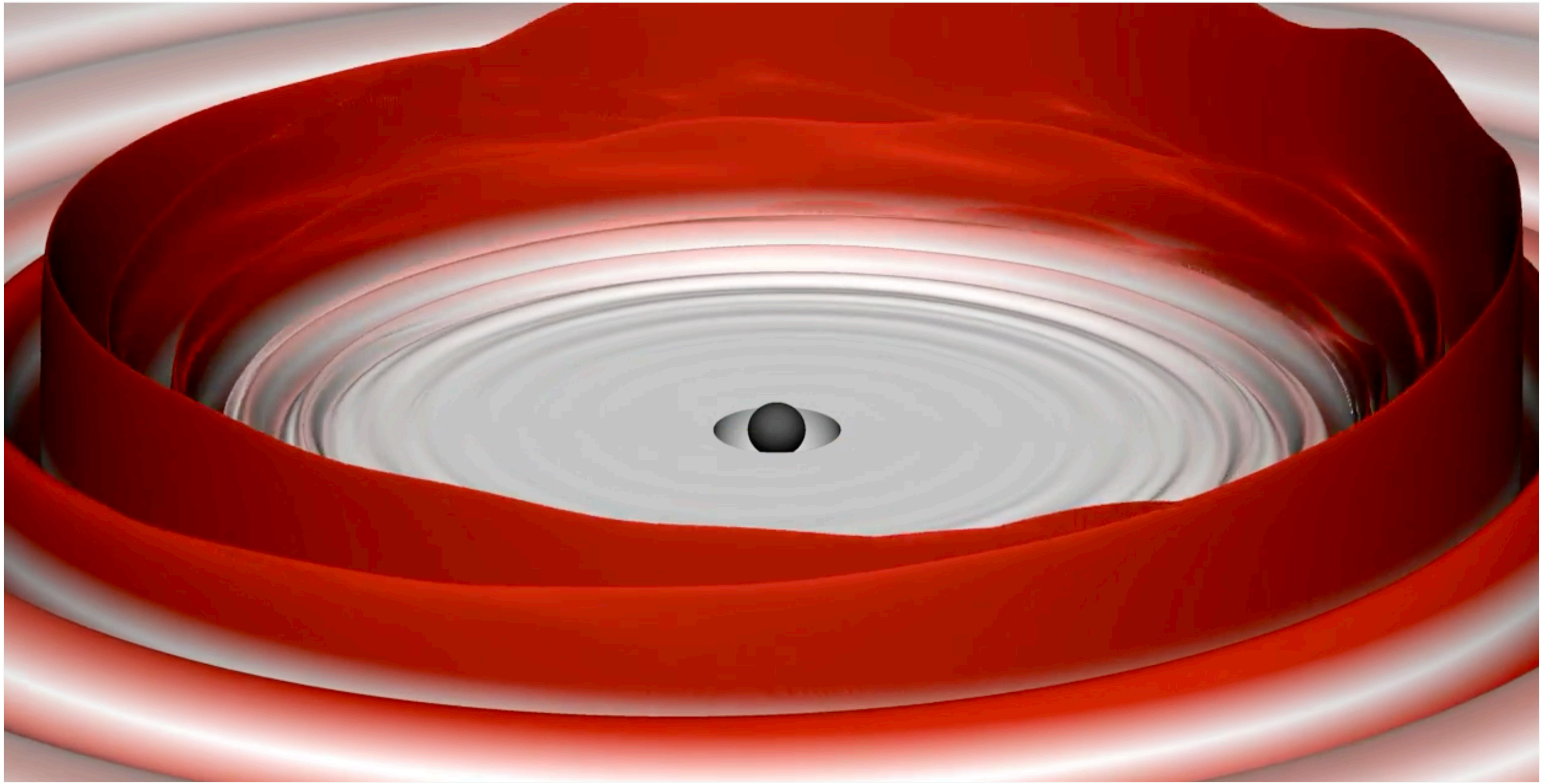
Quasi-normal spectrum

$$\epsilon = 0$$

Horizon absorption

This workshop: Datta, Chiaramello-Gamba

BLACK HOLE SPECTROSCOPY



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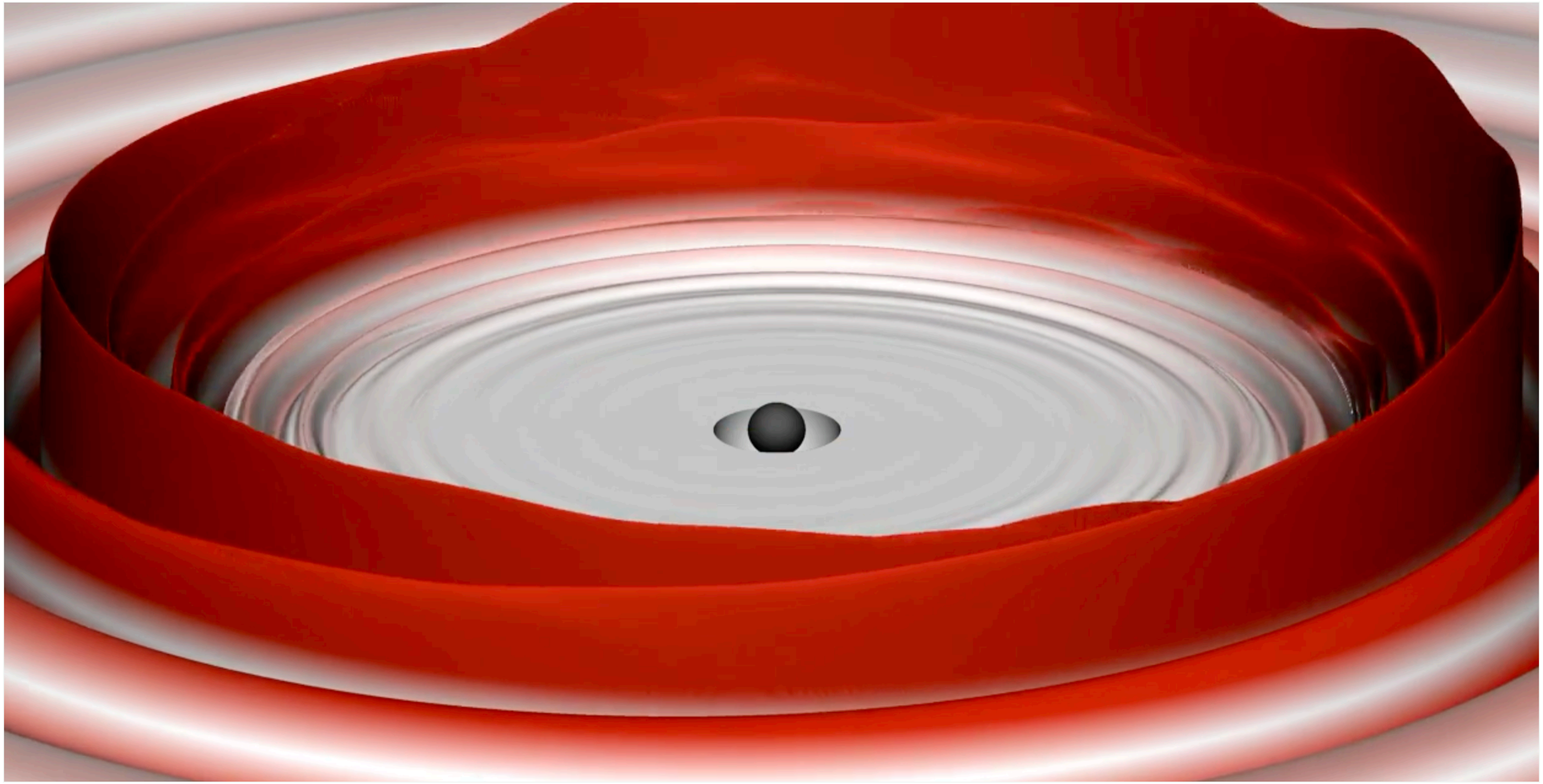

3.1 Physics near the black hole horizon: from tests of GR to quantum gravity

Arun+, LLR (2022) **New Horizons for Fundamental Physics with LISA** Maggiore+, JCAP (2020)


Max Planck Institute
for Gravitational Physics


Nonlinear dynamics


Nonlinear dynamics
Dynamical horizon


Quasinormal ringing
Max Planck Institute
for Gravitational Physics


The "sound" of a black hole

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave multipoles:

Berti-Cardoso-Starinets, 0905.2975

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$$h_+ - i\,h_\times = -\frac{M}{r}\sum_{l,m,n}\mathcal{A}_{lmn}\,S(\theta,\phi)\,e^{i\omega_{lmn}t}\,e^{-t/\tau_{lmn}}$$

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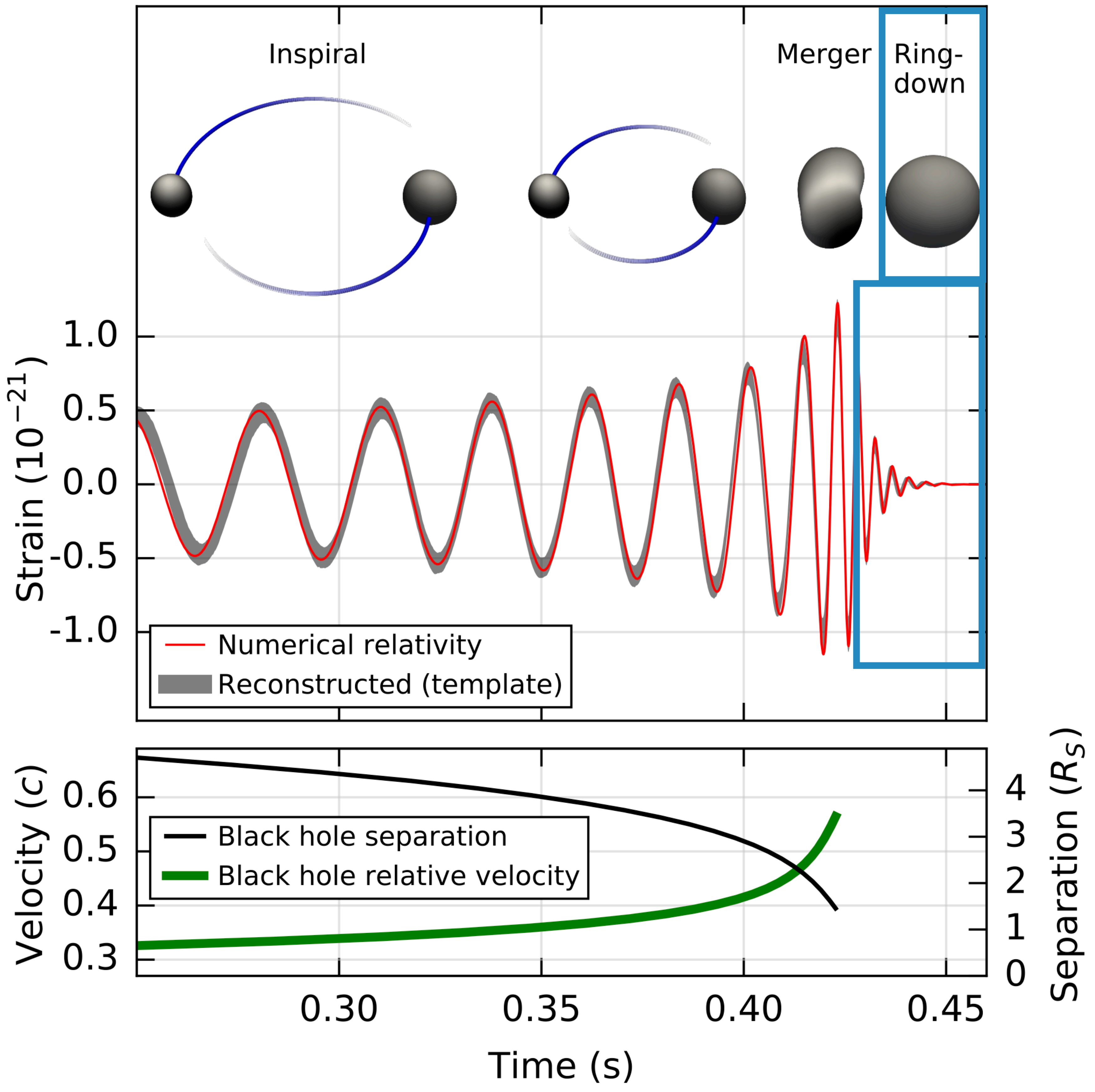

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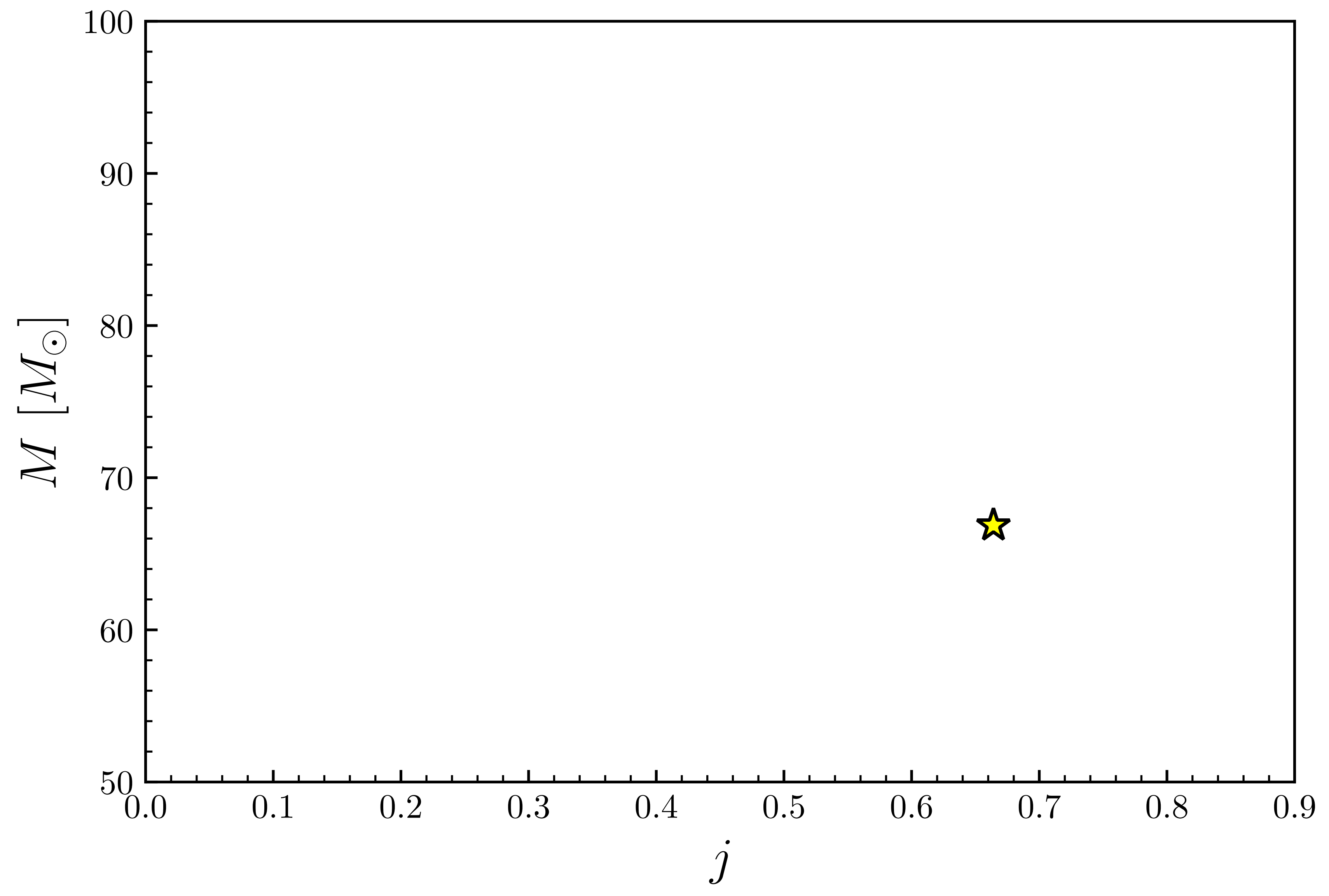
Brito (credits), Buonanno, Reymond, PRD (2018)



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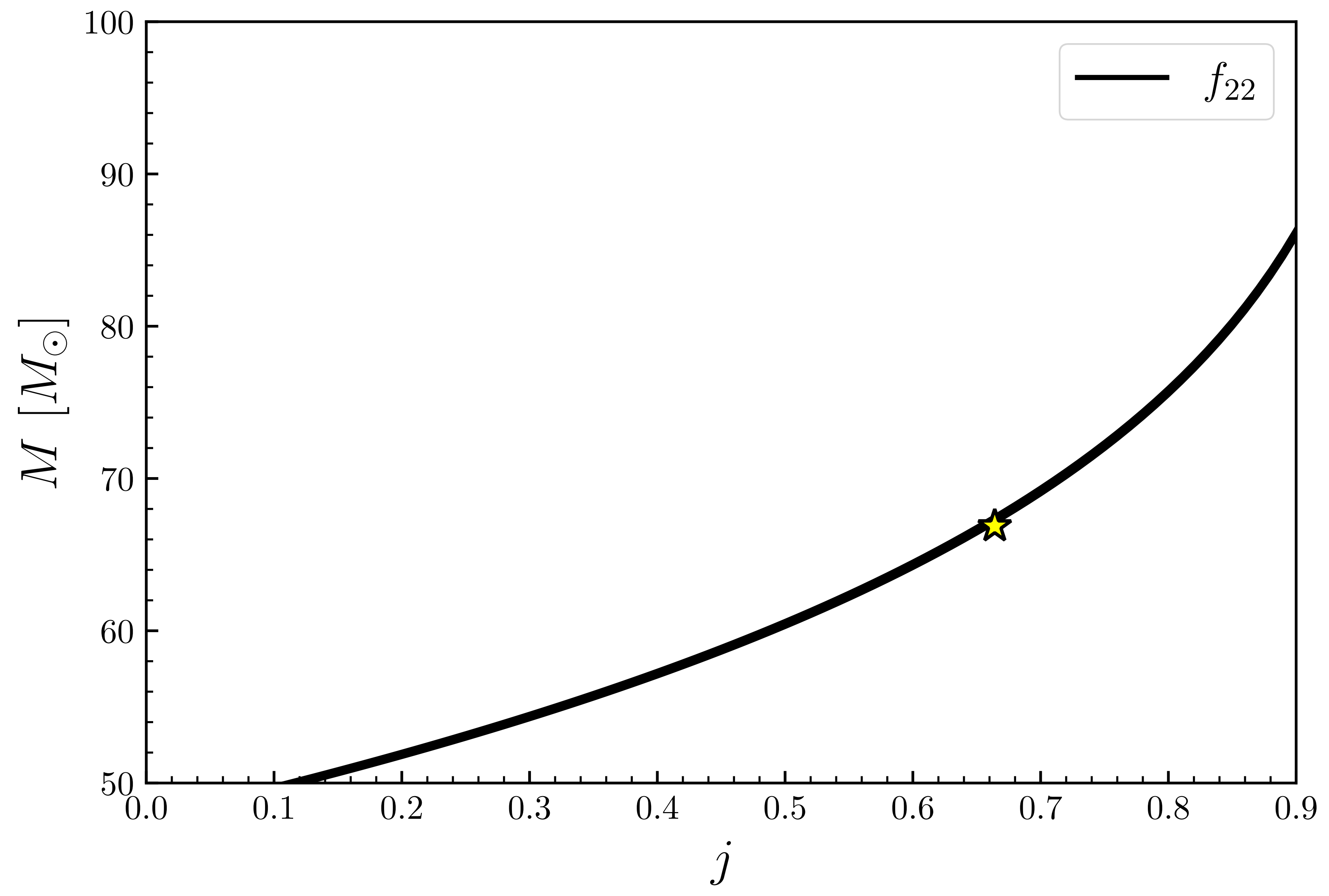

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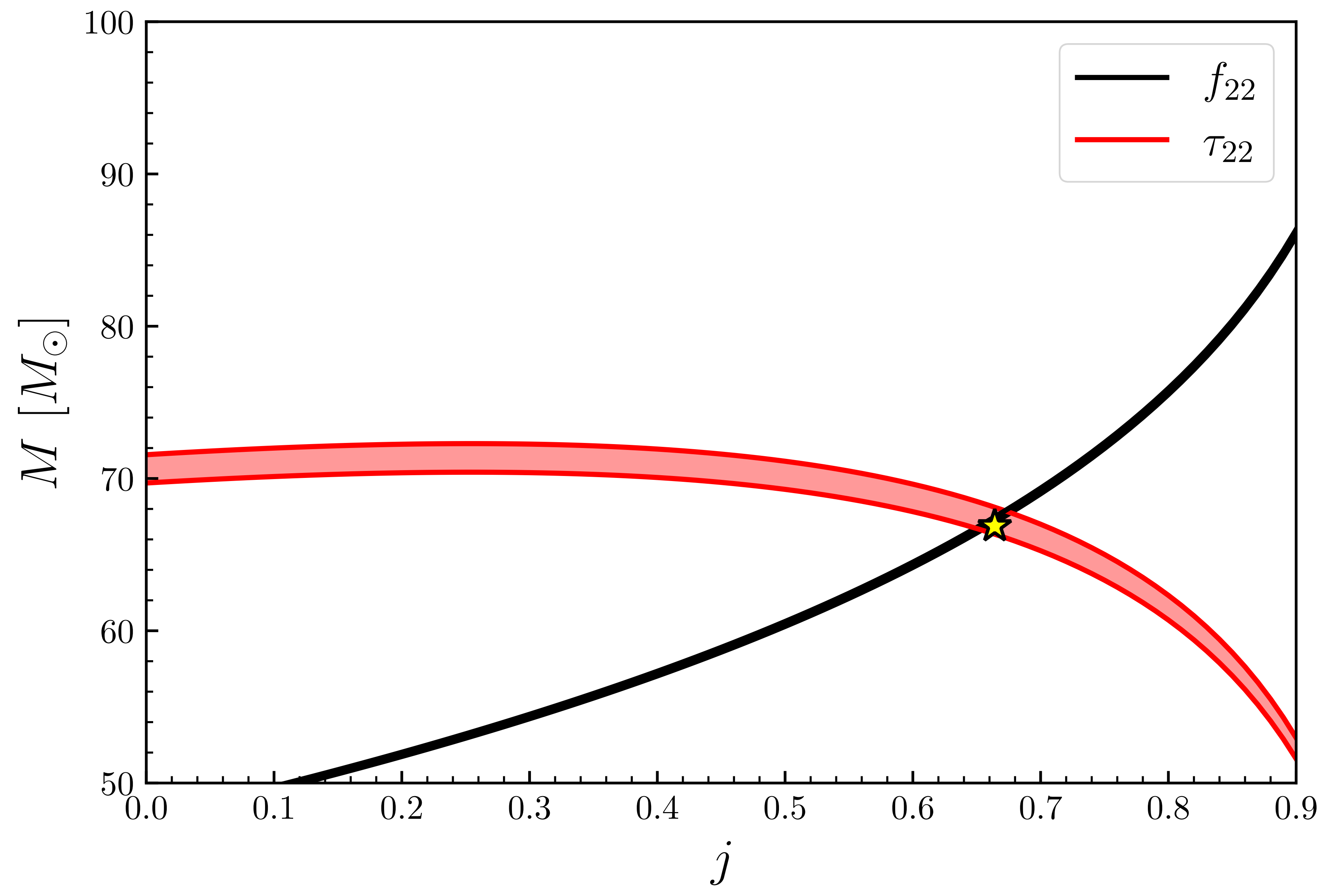

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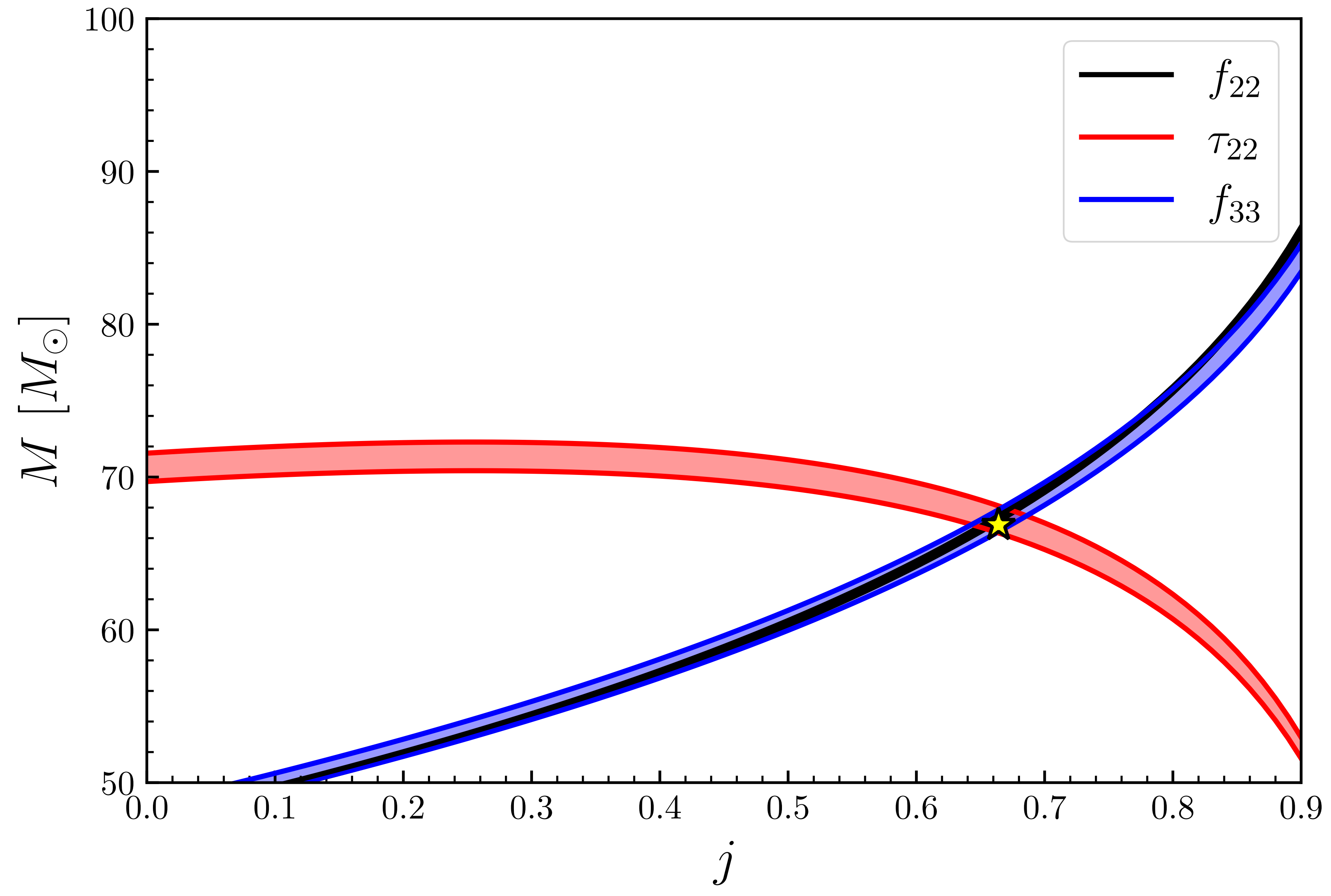

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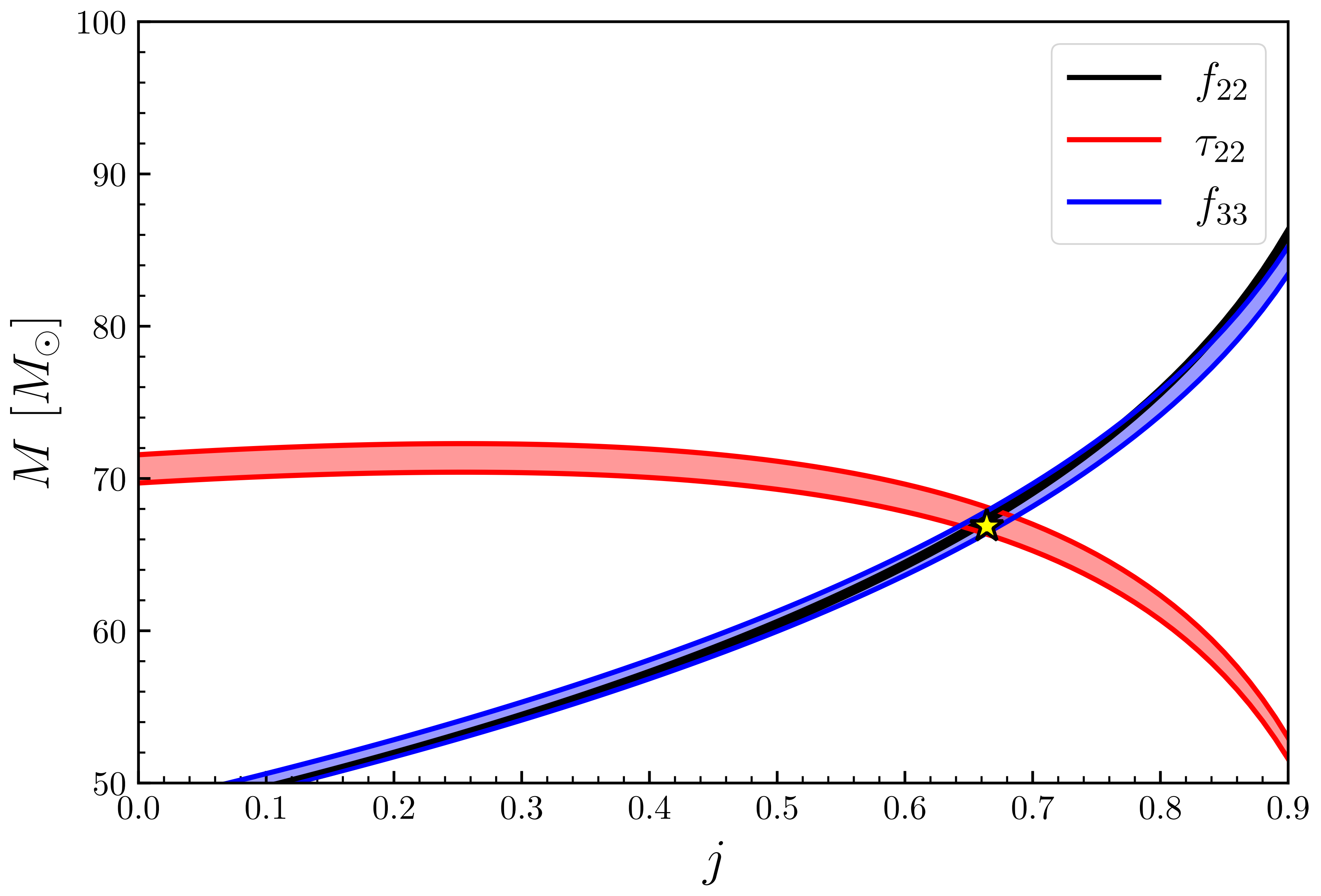

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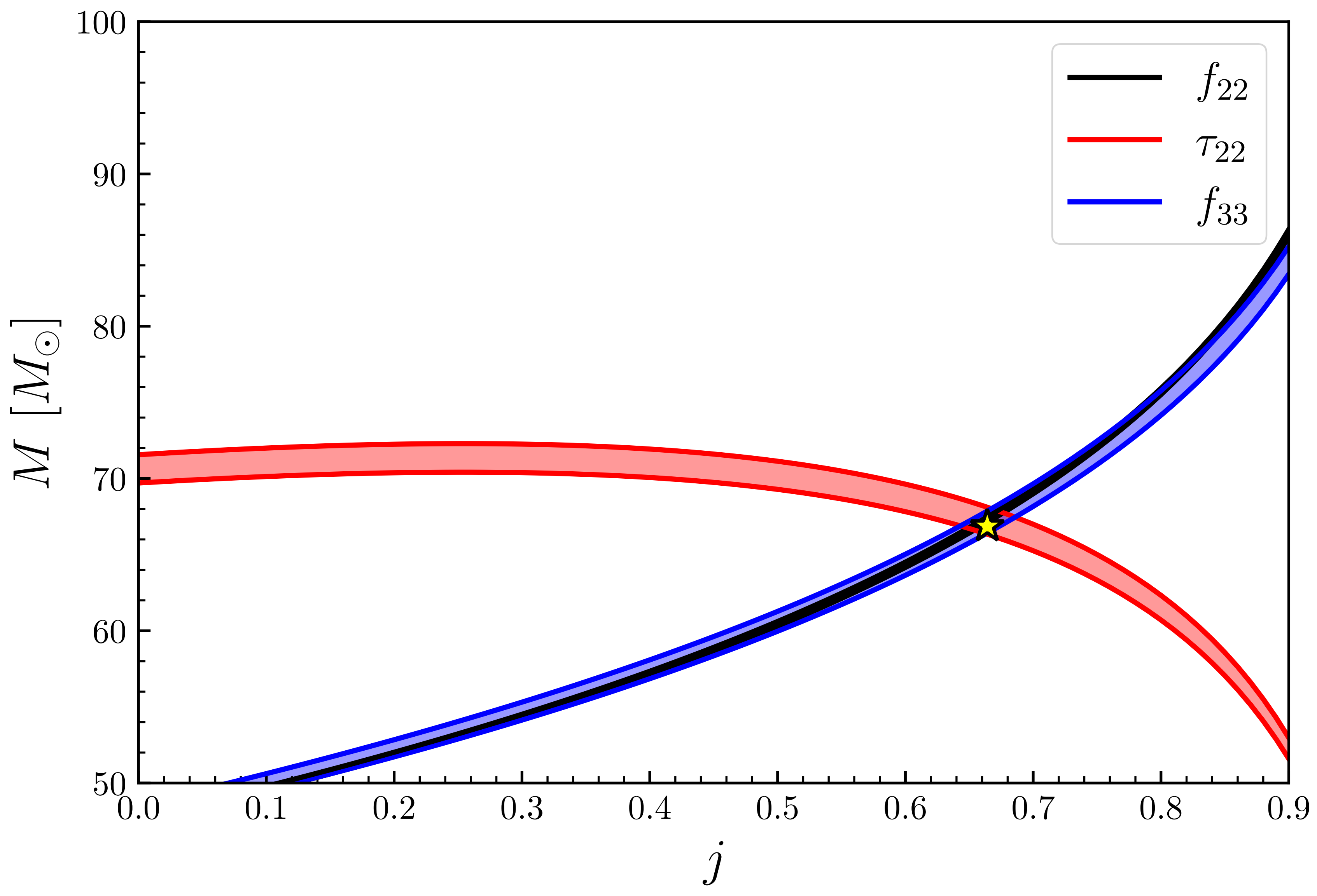

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- "Universal" prediction: "easy" to add **beyond-GR** effects

Berti-Cardoso-Starinets, 0905.2975

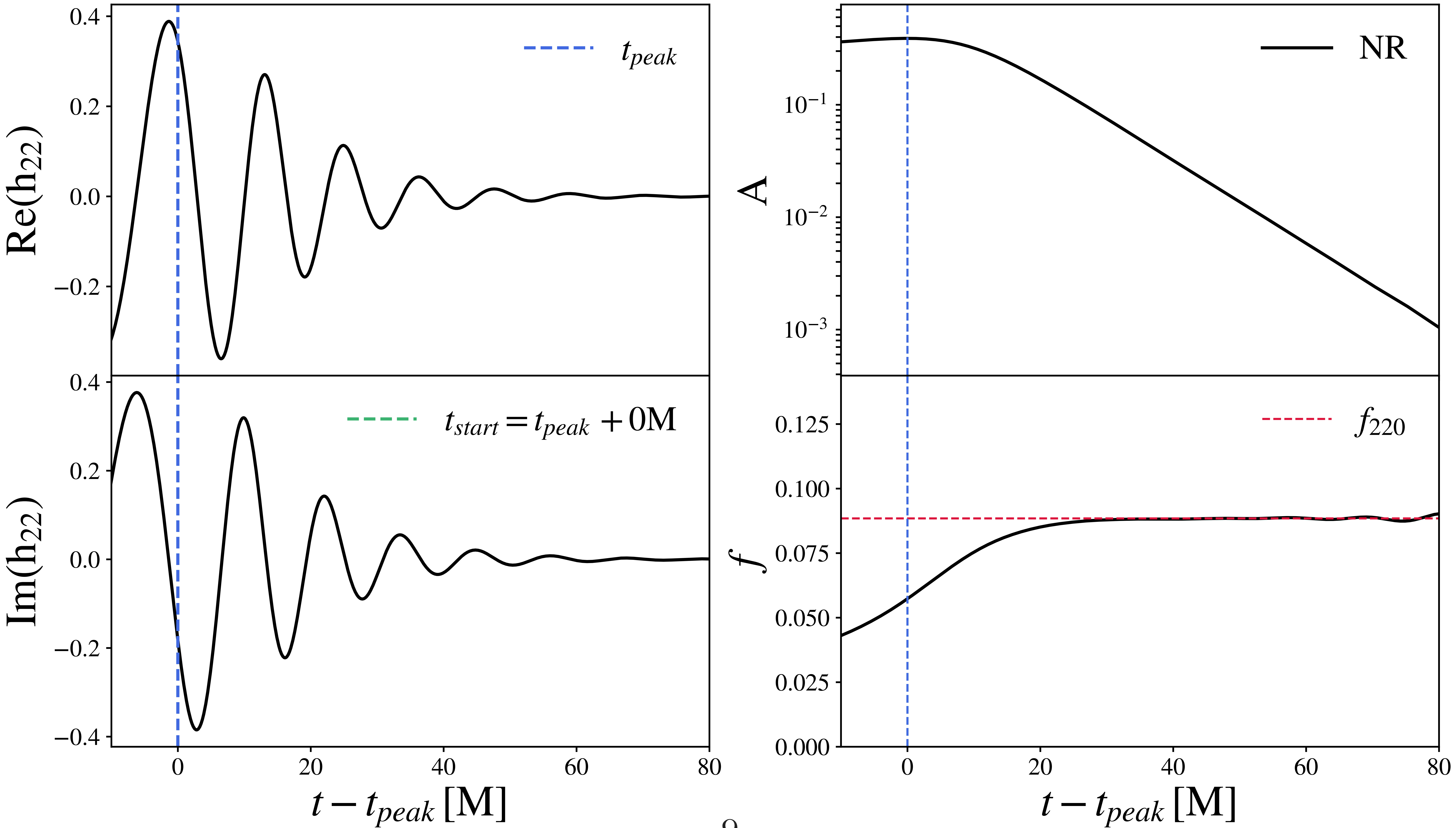
Is this picture applicable to comparable-masses binary coalescences?

Buonanno, Damour, gr-qc/0001013
Buonanno, Cook, Pretorius, gr-qc/0610122,
Berti+, gr-qc/0703053, …

SXS-0305

$h = A(t)\, e^{i\phi(t)}$

$f(t) = \dot{\phi}(t)$



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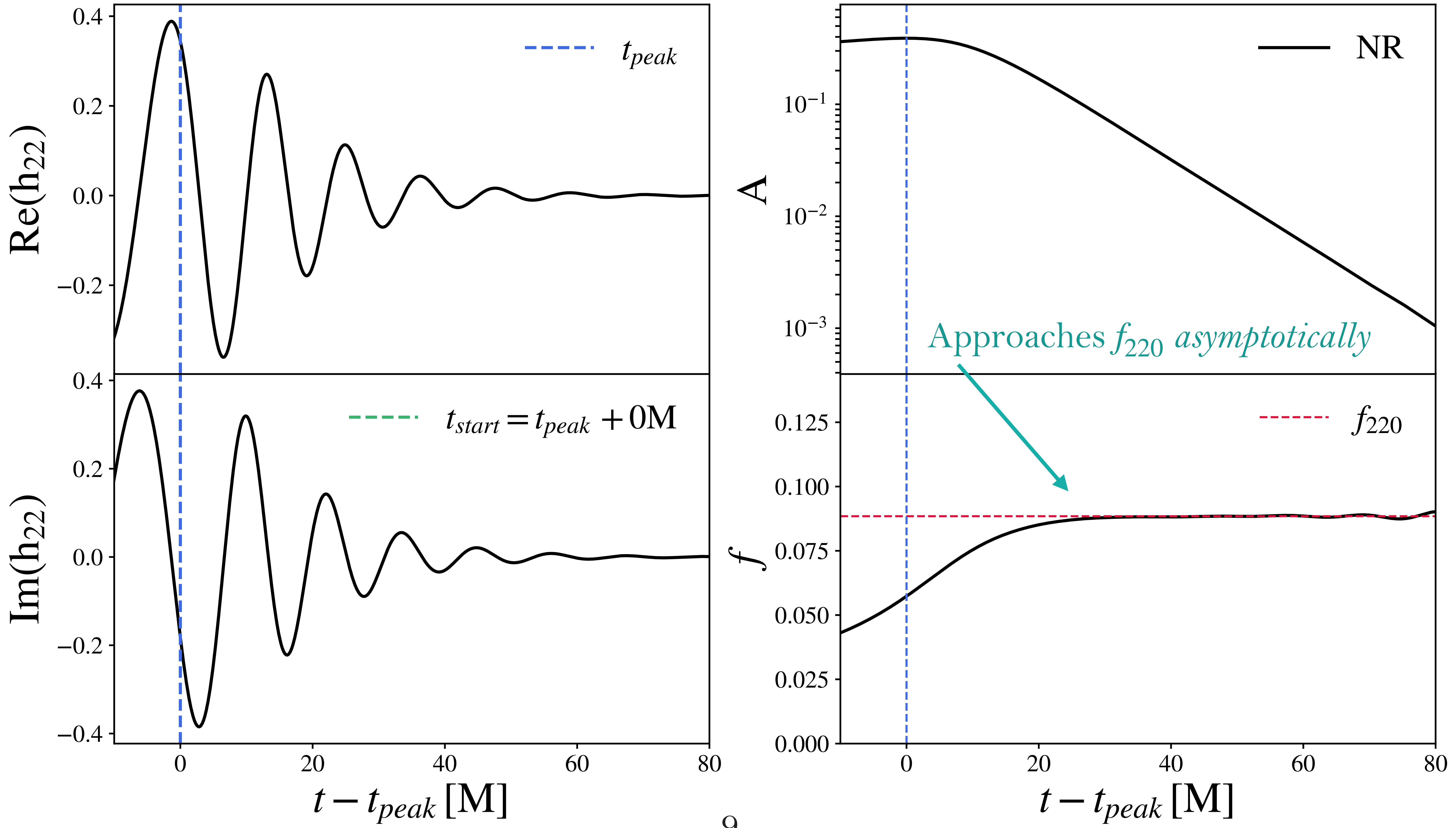
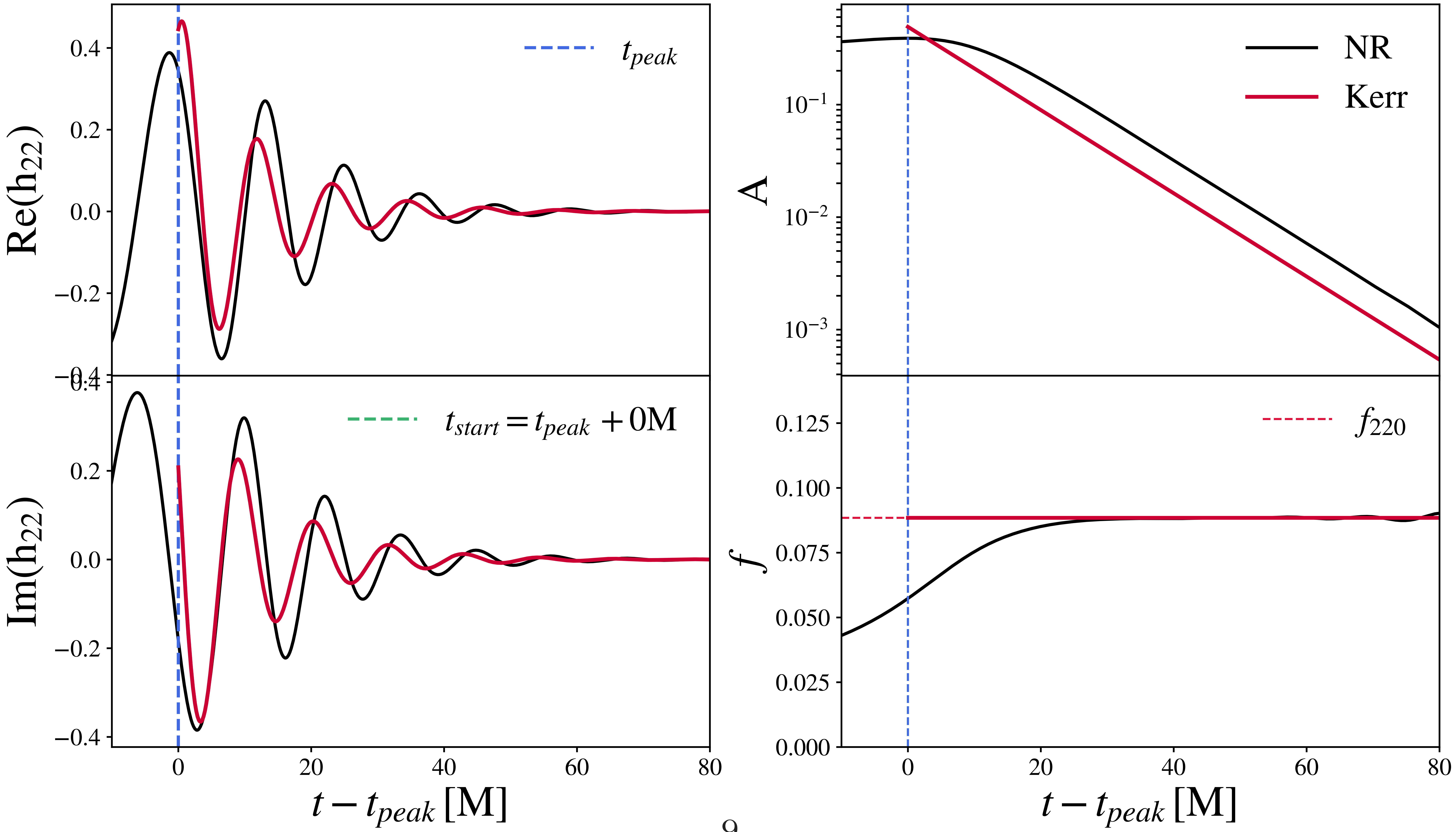


SXS-0305

$$h_{22} = A\, e^{i(\omega_{220} t + \phi)}\, e^{-t/\tau_{220}}$$

$$(A, \phi) = \,?$$



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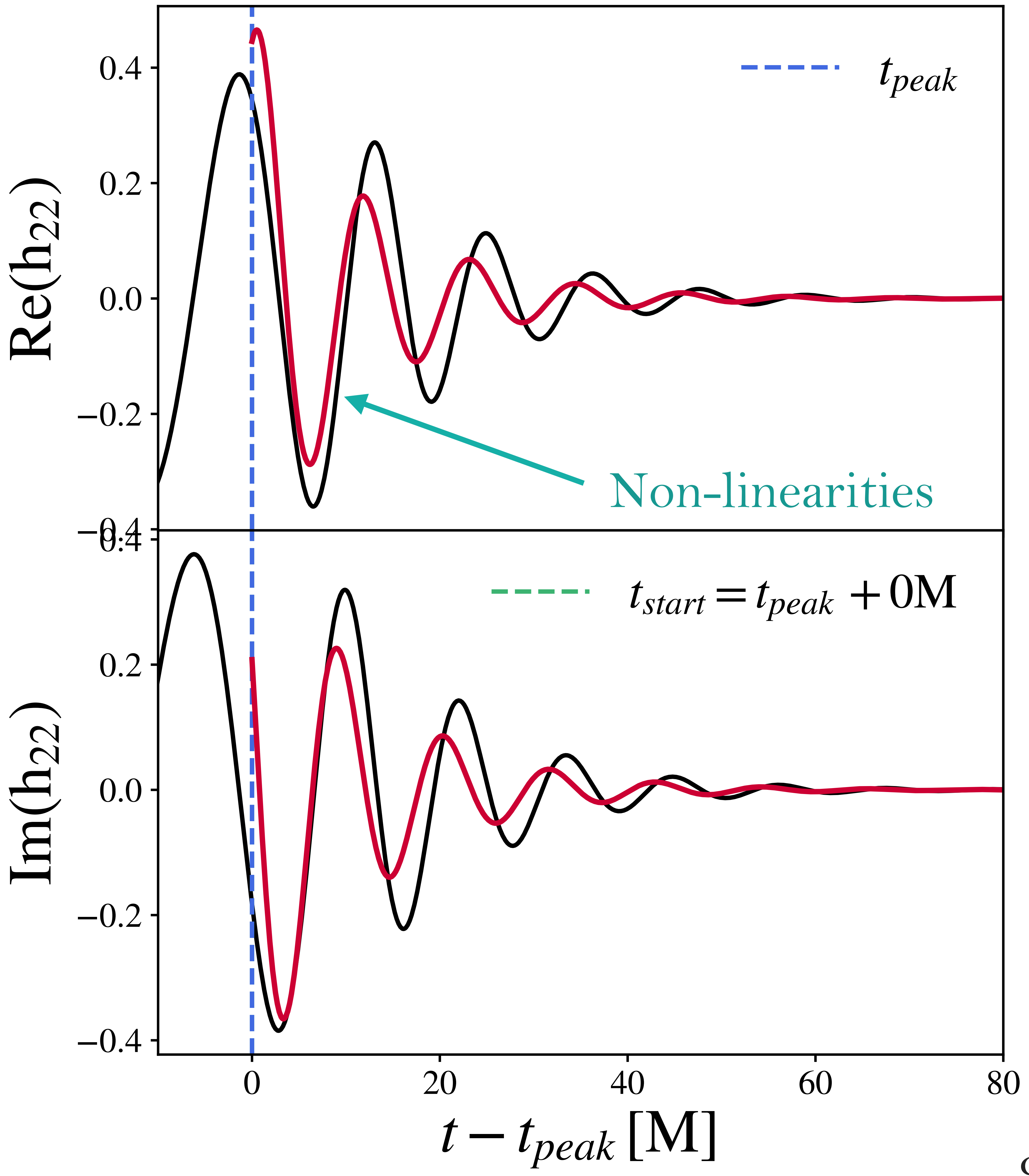

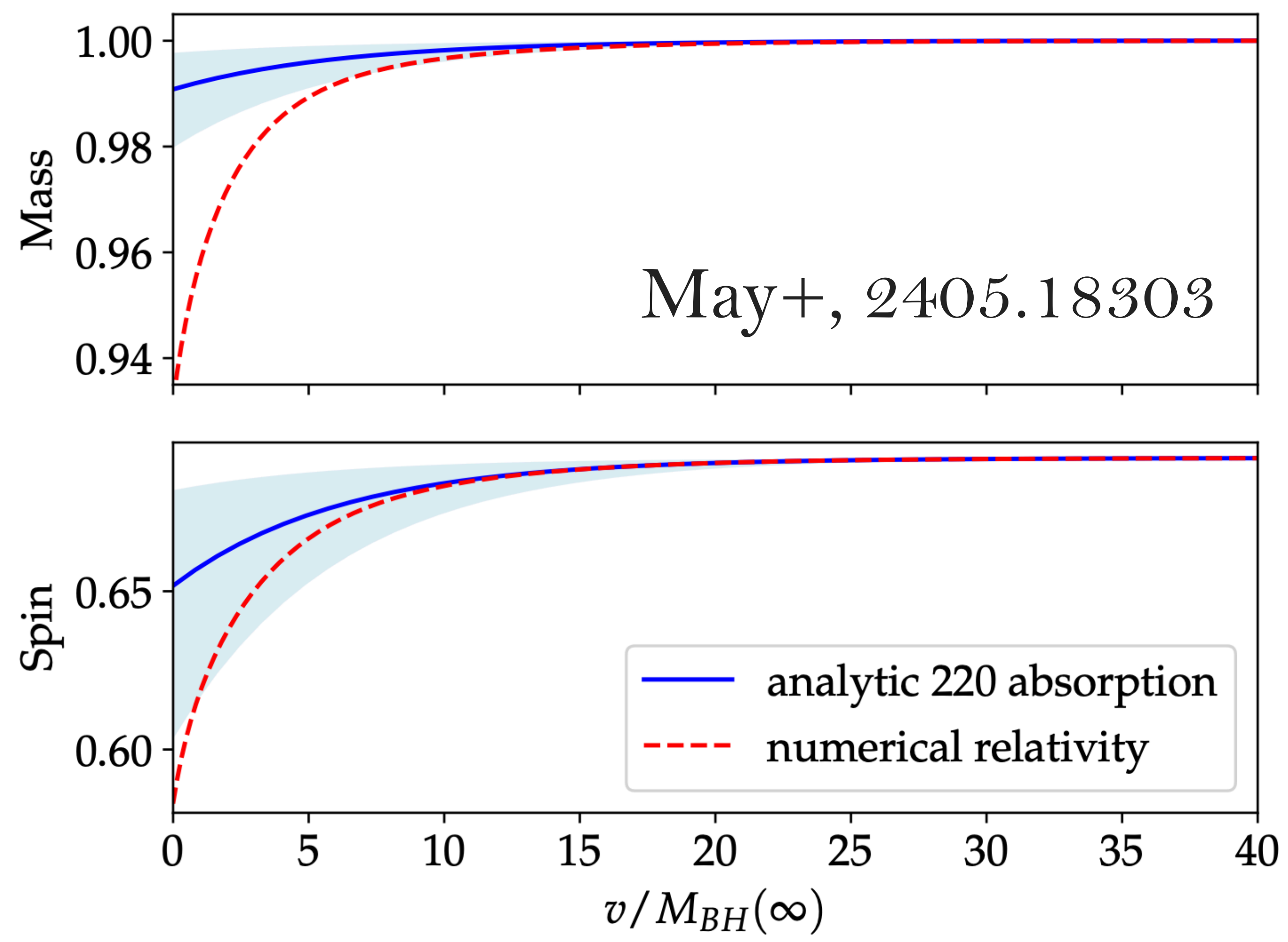

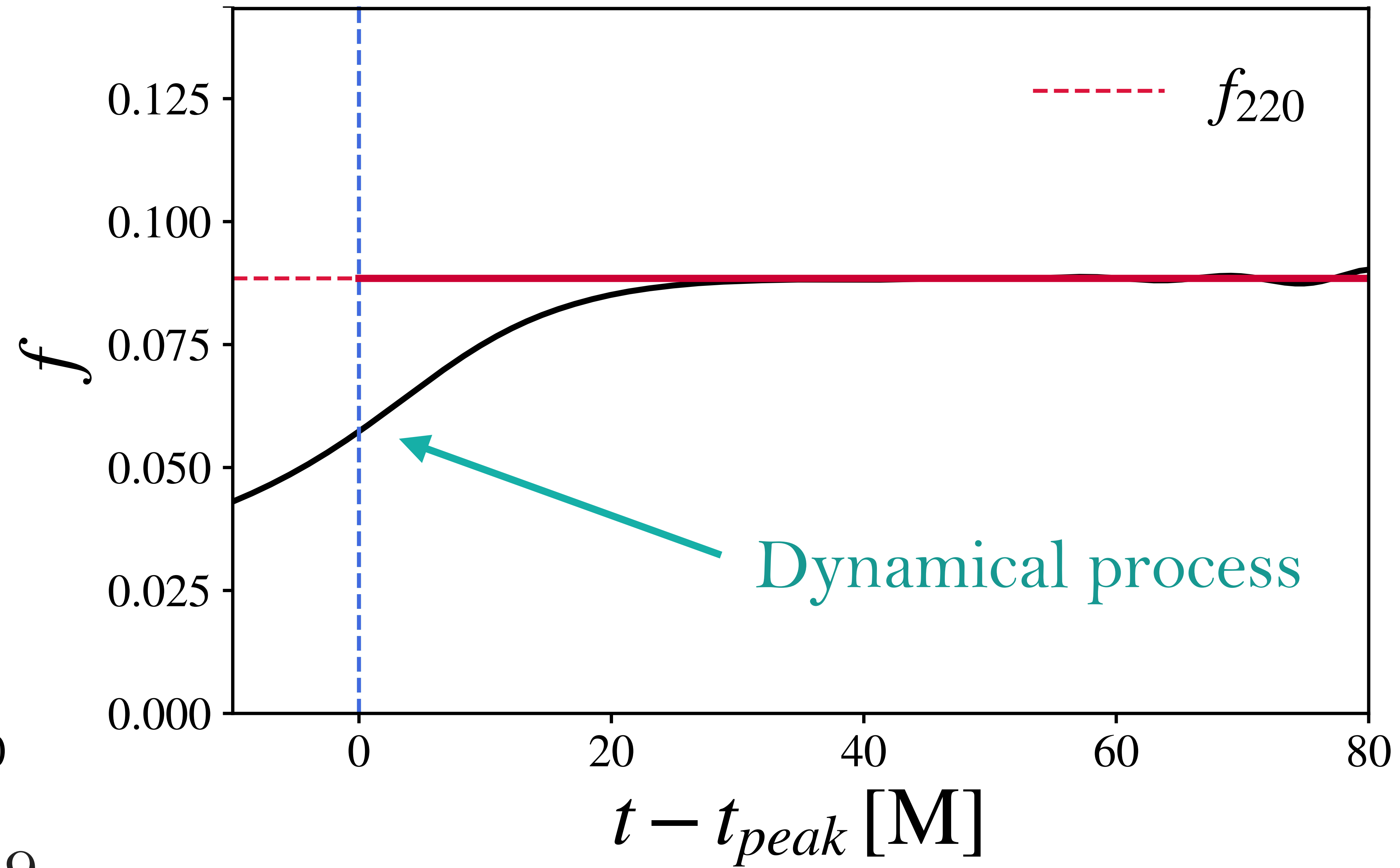

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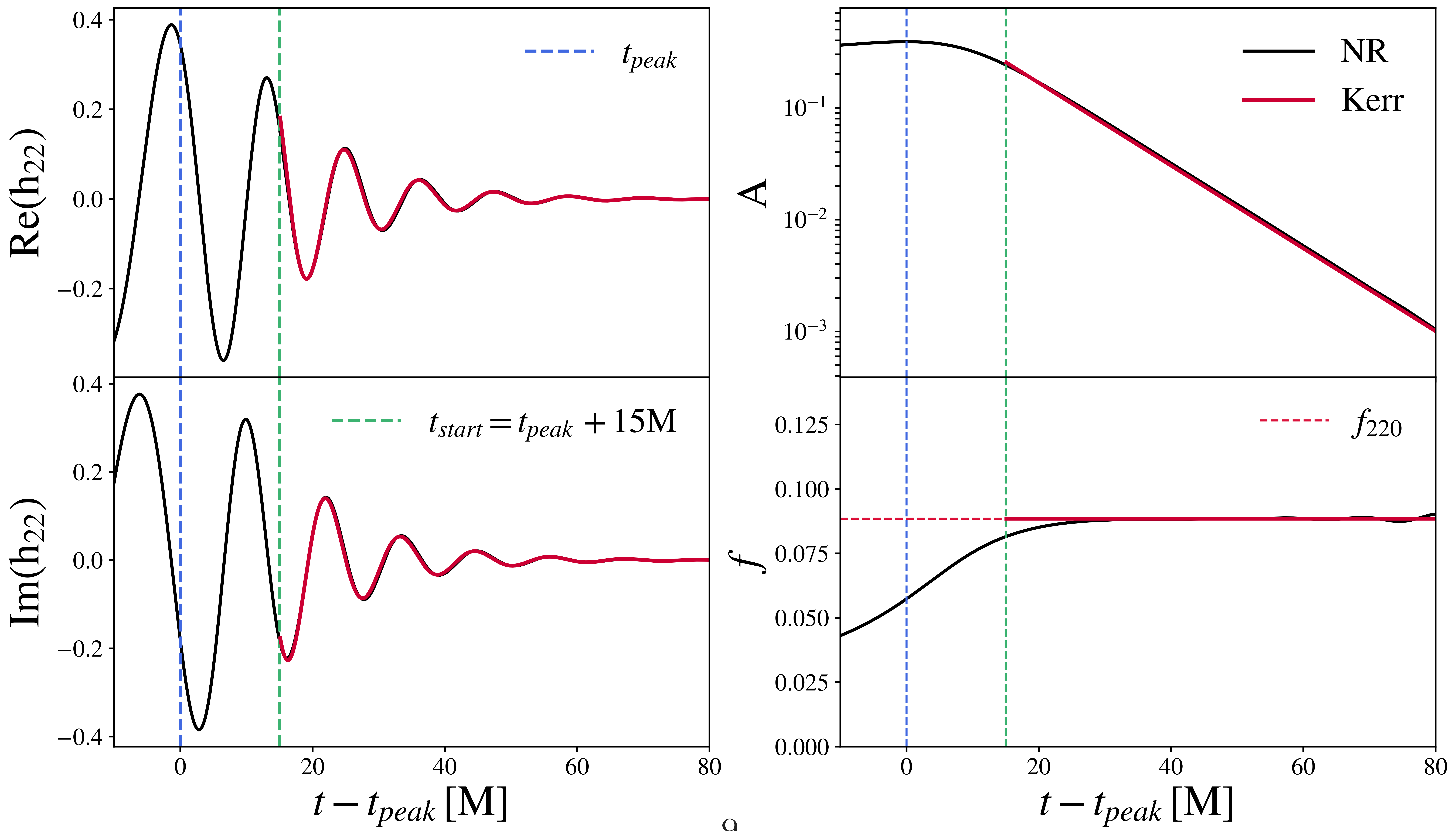

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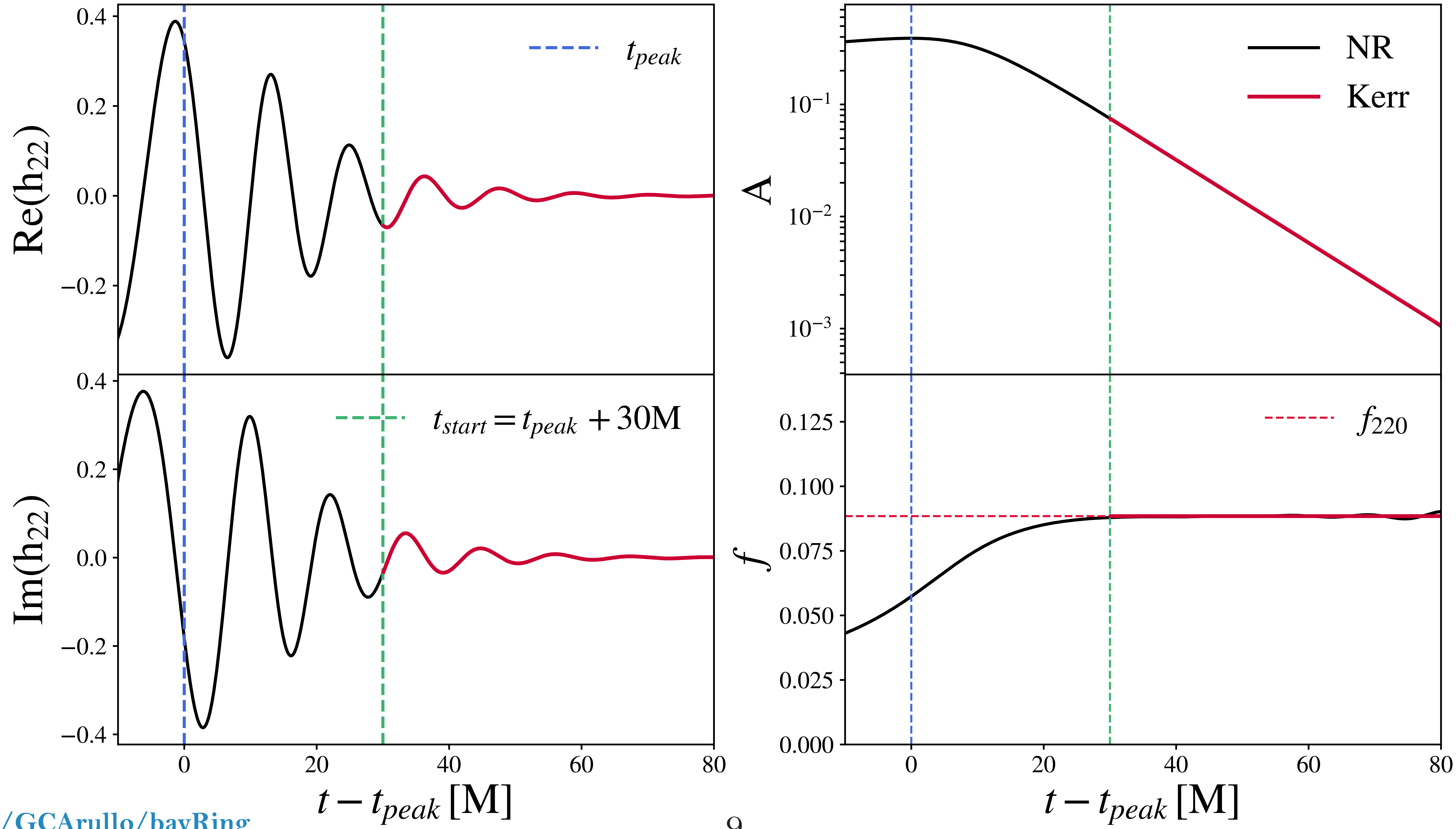

github.com/GCArullo/bayRing

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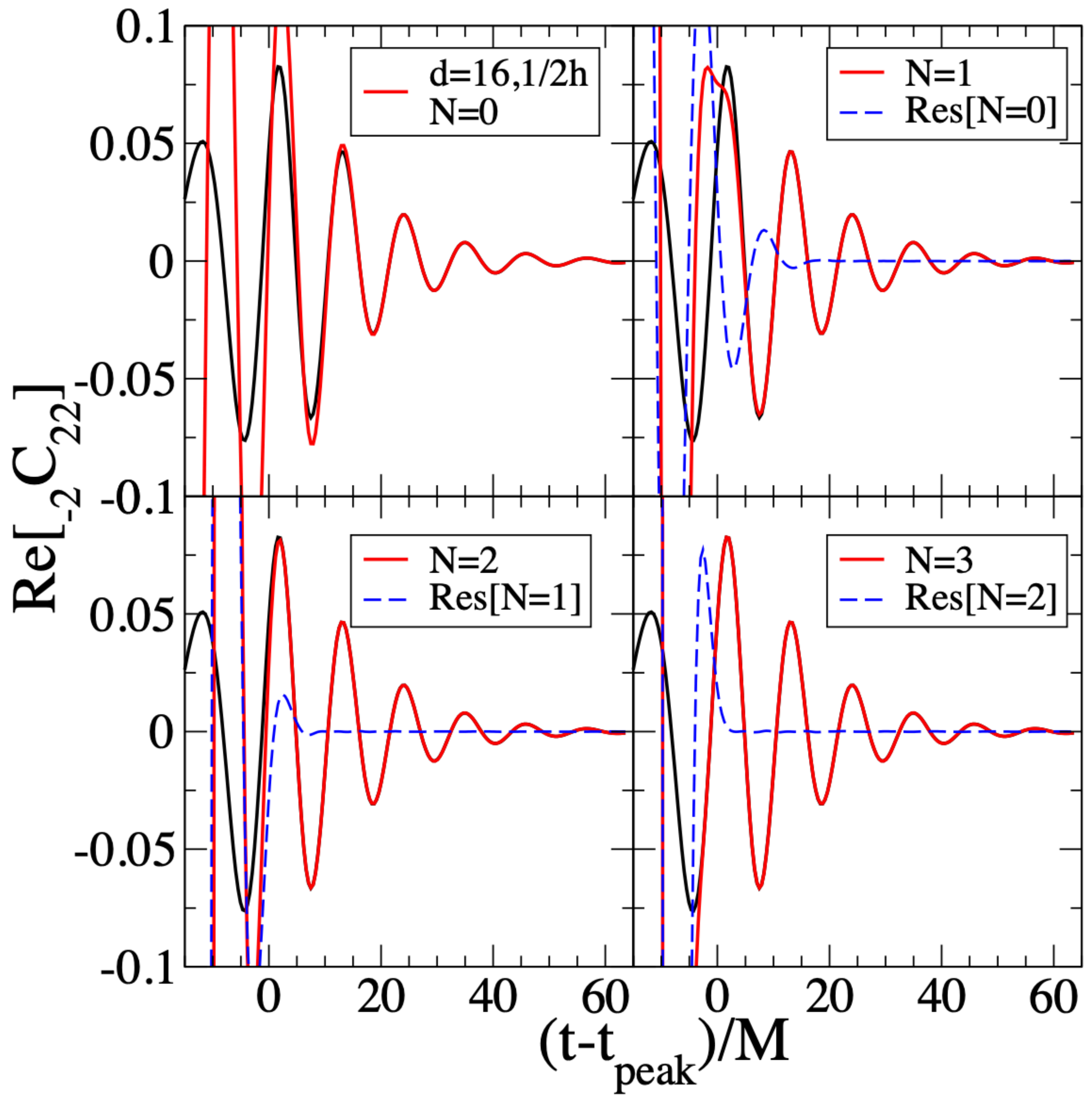

Buonanno-Cook-Pretorius, gr-qc/0610122
Berti+, gr-qc/0703053

Baker+, 0805.1428, Damour-Nagar, 1406.0401

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  - But "price to pay" when gaining SNR analysing early times

WARNING AND GOAL

- Spectroscopy from binary mergers, **systematics**-plagued measurements:
  - "**Ringdown start time**" uncertainty (ill-defined)
  - **Dynamical evolution** of the system

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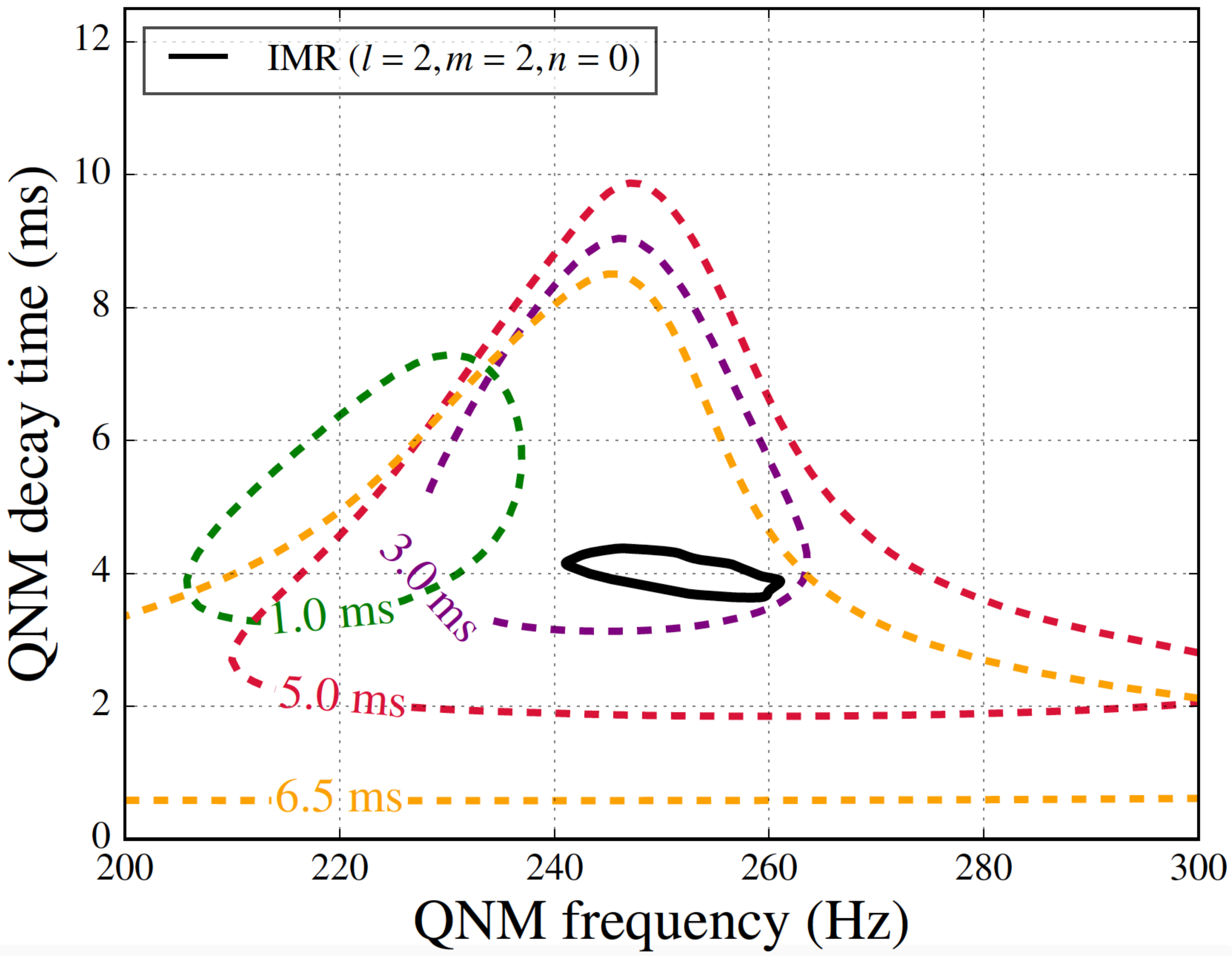
  - Affect **measurement precision**, but also **physical interpretability** (*extract true QNM vs fit with a bunch of damped sinusoids*)

London+, 1404.3197, Forteza+, 2005.03260, **Baibhav+, 2302.03050,** Nee+, 2302.06634**,** Cheung+, 2310.04489

Observational black hole spectroscopy

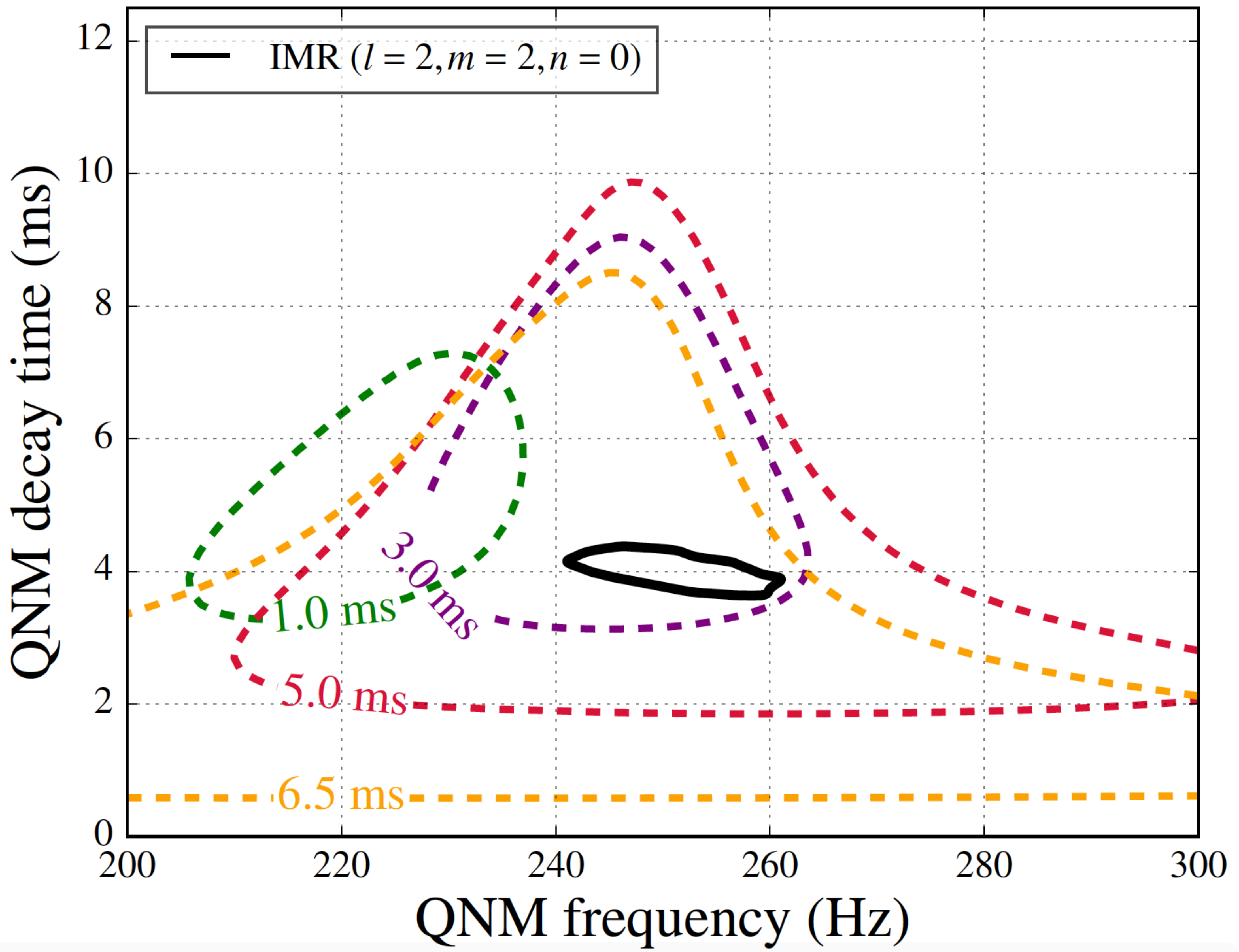
GW150914: THE DAY WE SAW A BLACK HOLE RINGING



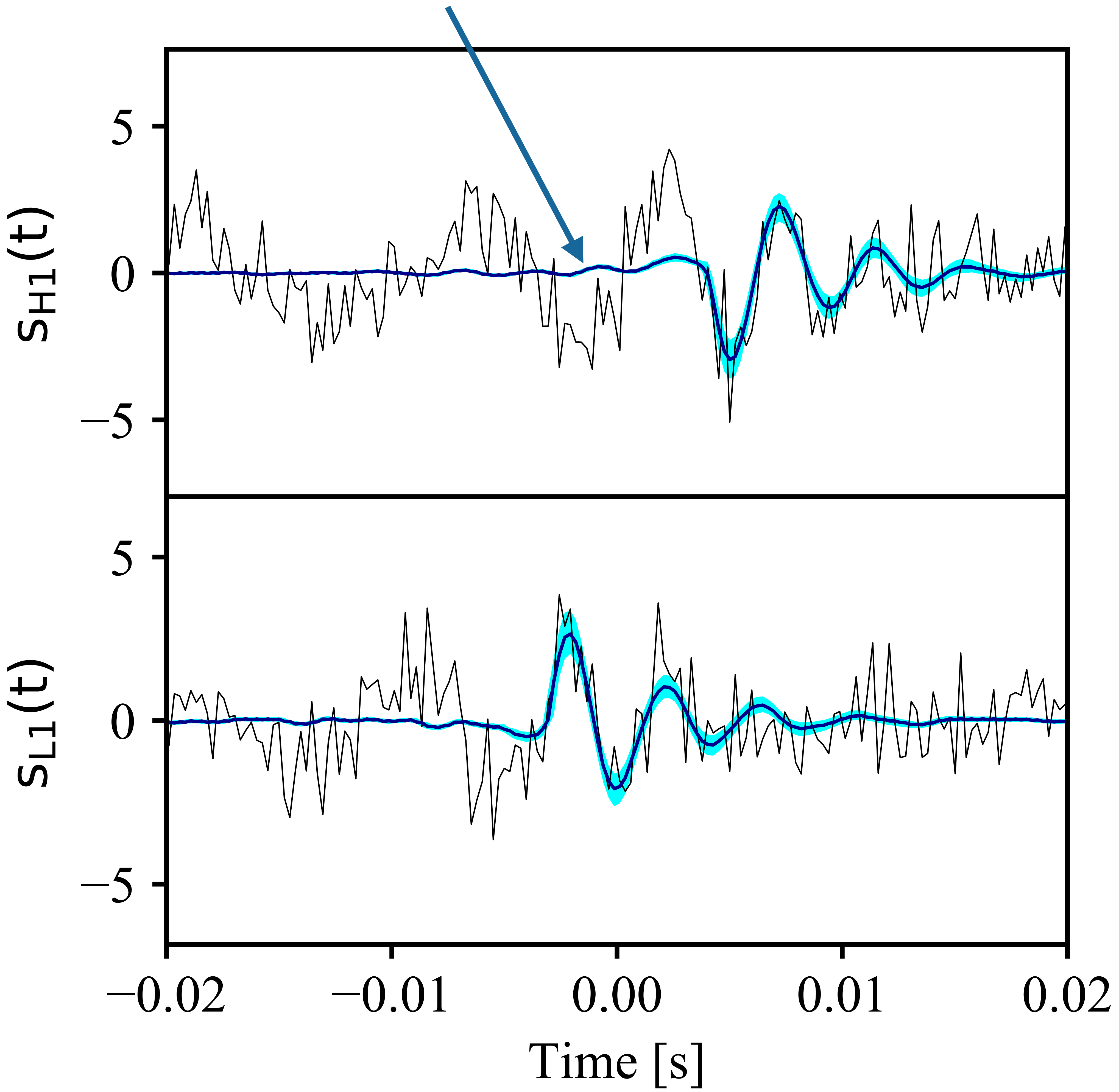
LVC, Phys. Rev. Lett. 116, 221101 (2016)

Yunes, Yagi, Pretorius, 1603.08955

GW150914: THE DAY WE SAW A BLACK HOLE RINGING



Analysis needed some refinement

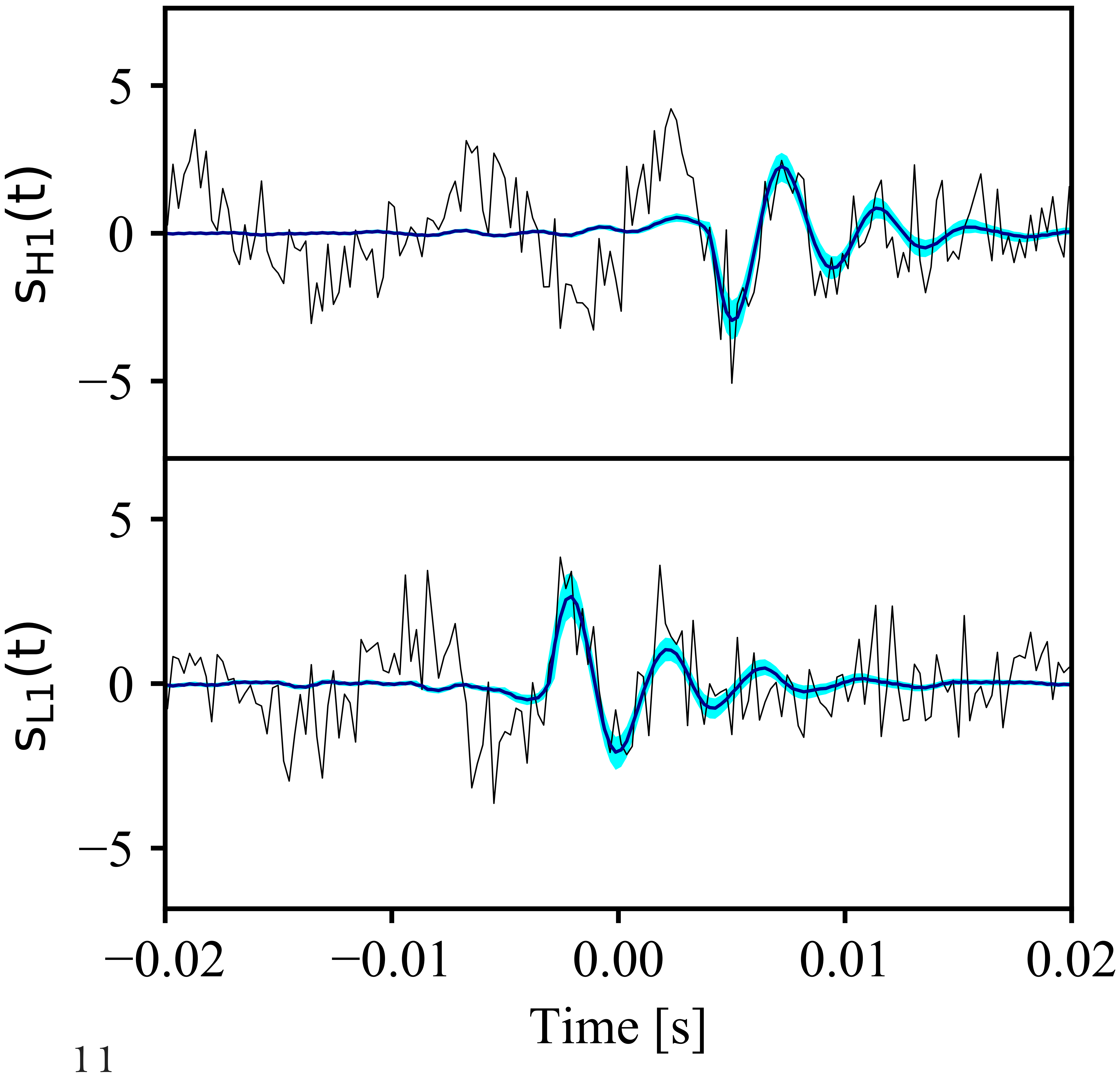


LVC, Phys. Rev. Lett. 116, 221101 (2016)

Carullo, Del Pozzo, Veitch, 1902.07527

BLACK HOLE SPECTROSCOPY

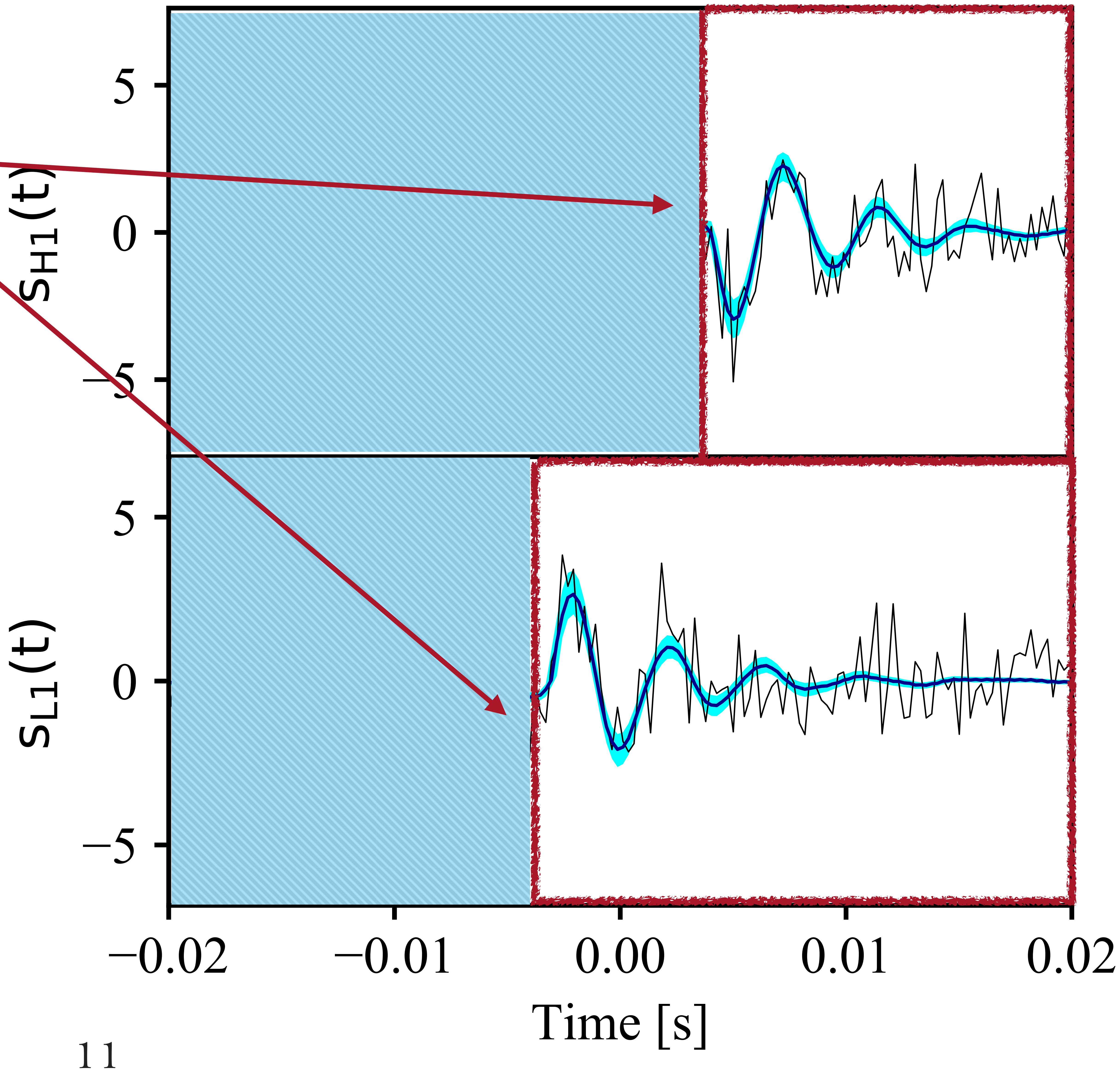
- Time-domain approach:



White noise, no-merger: Del Pozzo, Nagar, 1606.03952
Coloured noise: Carullo, Del Pozzo, Veitch, 1902.07527
Full solution: Isi, Farr, 2107.05609
Also: Capano+, 2105.05238 | Finch-Moore, 2108.09344
Crisostomi+, 2305.18528 | Pacilio+, 2404.11373

BLACK HOLE SPECTROSCOPY

- Time-domain approach:
  - **Isolate** ringdown portion
  - **Avoid** spurious frequencies from abrupt t_{start} (**Gibbs phenomena**)

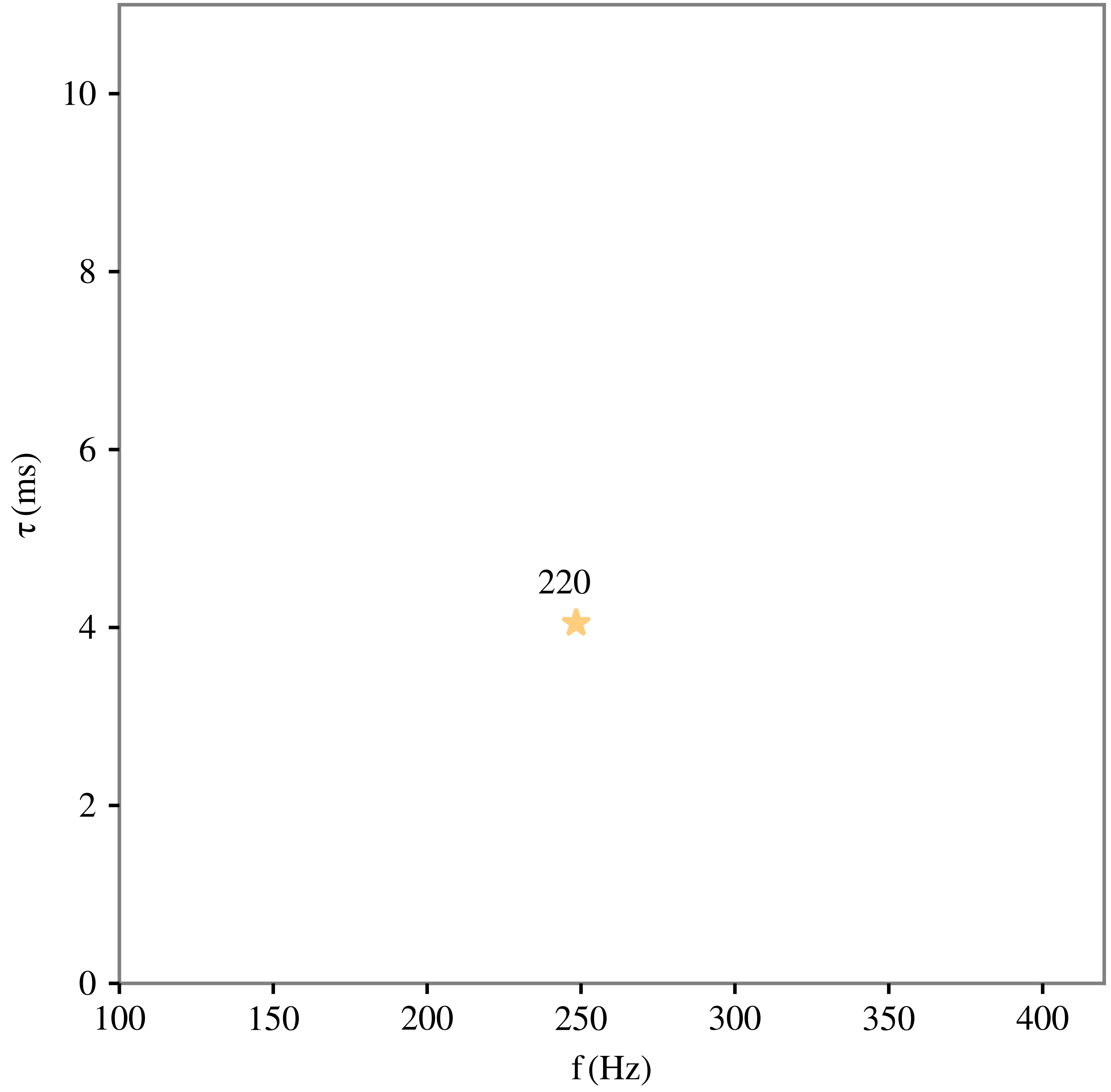


White noise, no-merger: Del Pozzo, Nagar, 1606.03952
Coloured noise: Carullo, Del Pozzo, Veitch, 1902.07527
Full solution: Isi, Farr, 2107.05609
Also: Capano+, 2105.05238 | Finch-Moore, 2108.09344
Crisostomi+, 2305.18528 | Pacilio+, 2404.11373

BLACK HOLE SPECTROSCOPY: GW150914

- Inspiral predicts GR **spectrum**

(Uncertainty collapsed for visualisation)



Carullo, Del Pozzo, Veitch, 1902.07527

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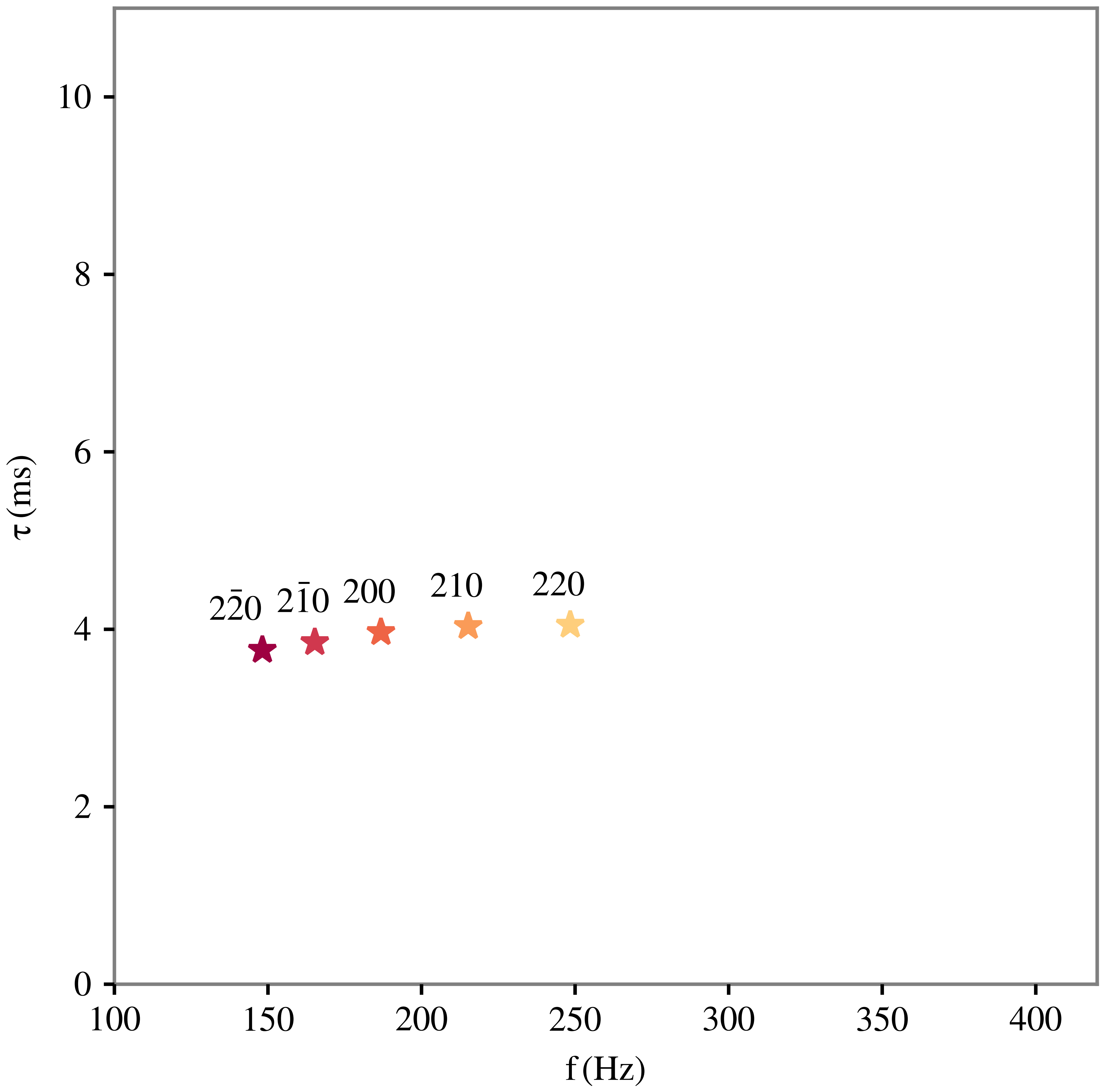

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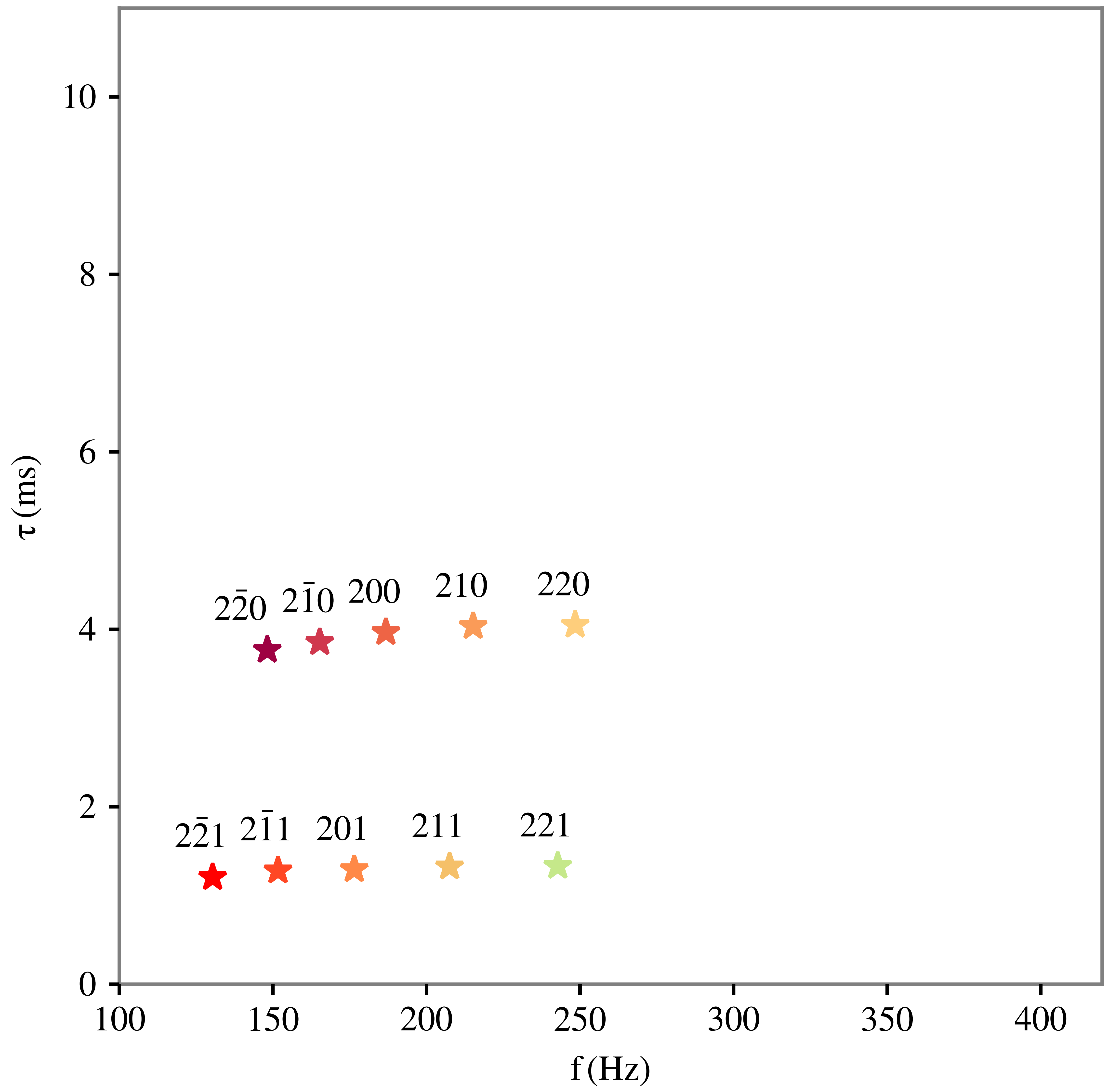

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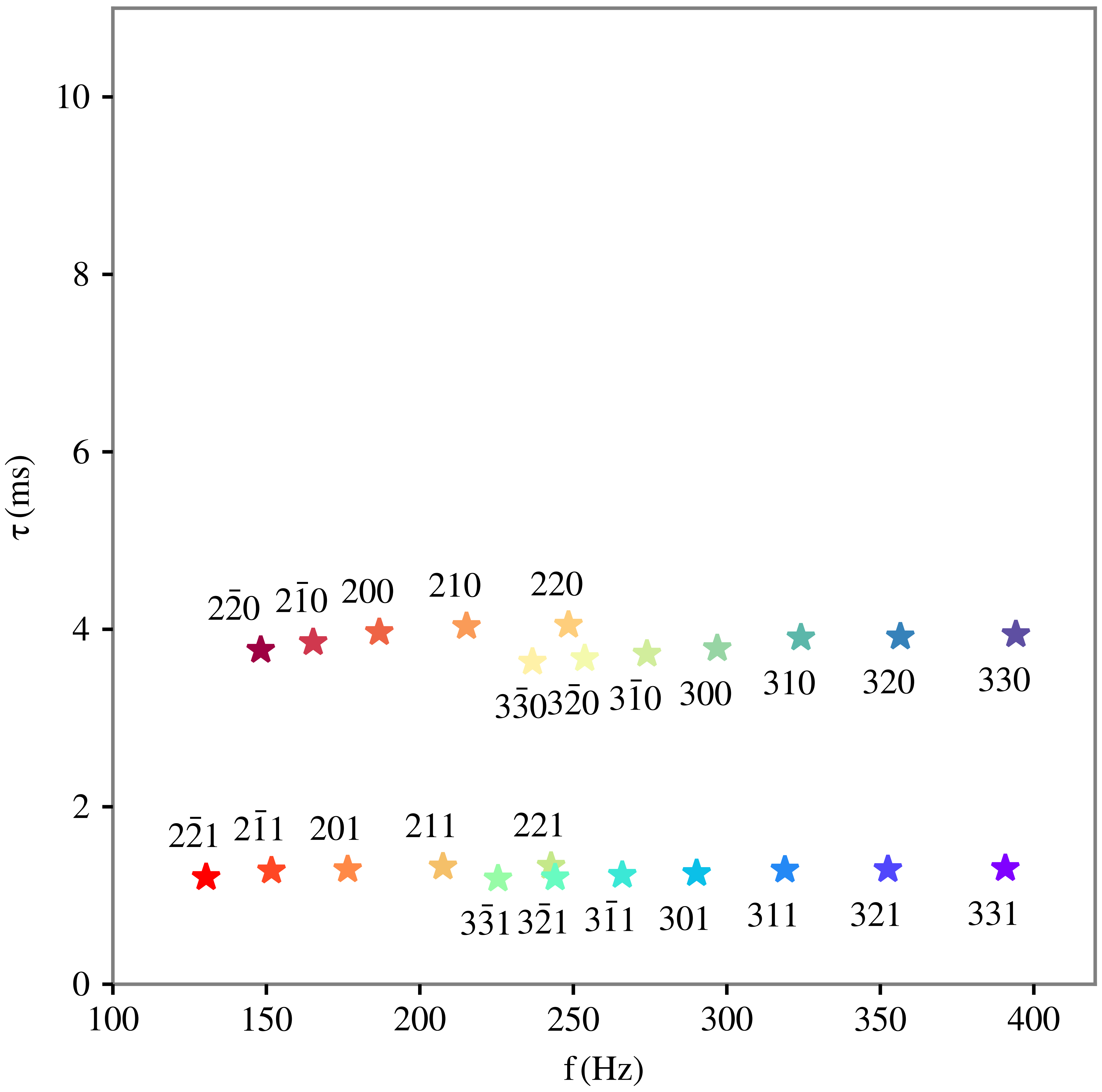

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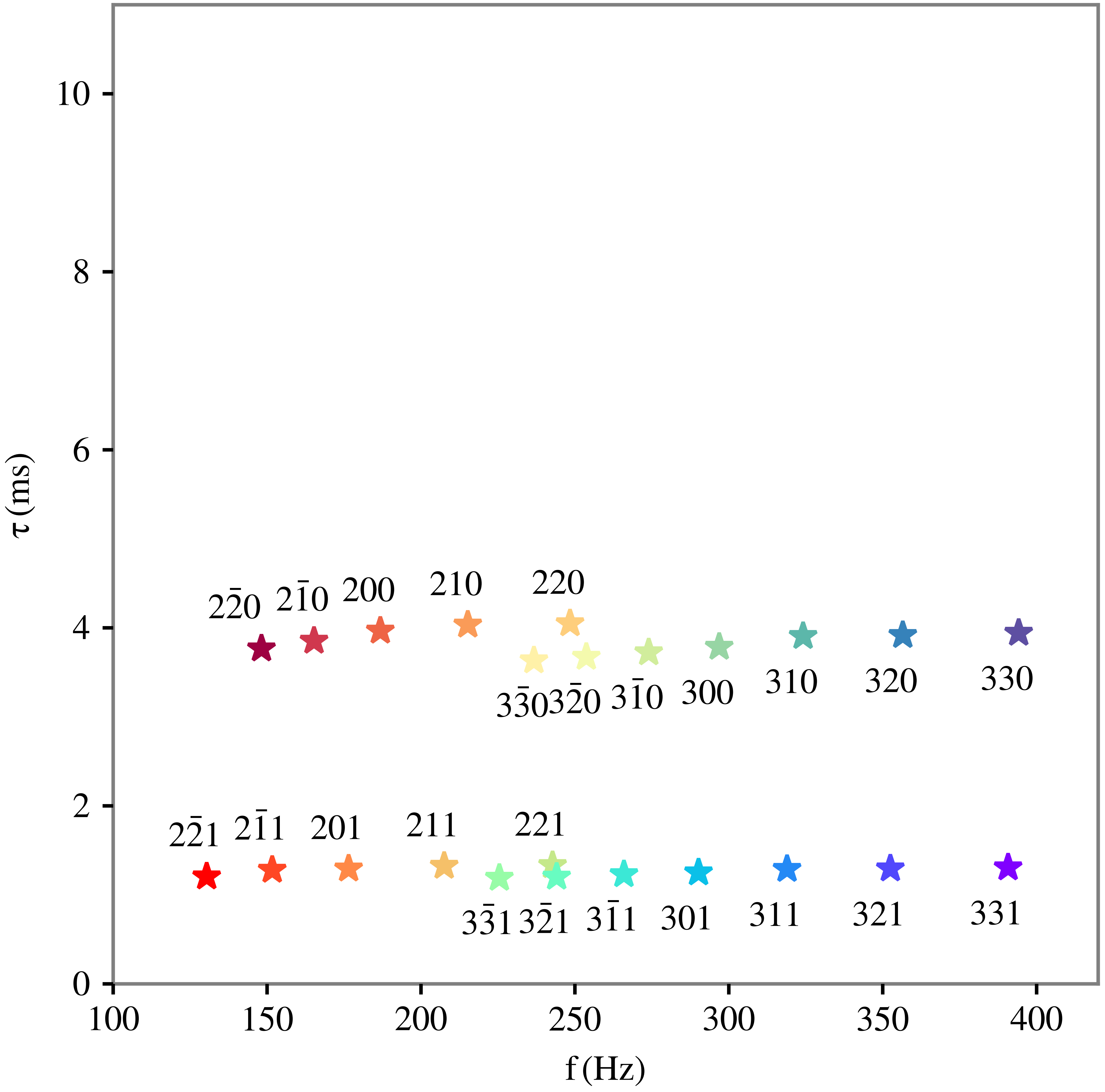

Carullo, Del Pozzo, Veitch, 1902.07527

BLACK HOLE SPECTROSCOPY: GW150914

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- **Agnostic** frequency reconstruction
- **Probability** agnostic mode agrees with GR

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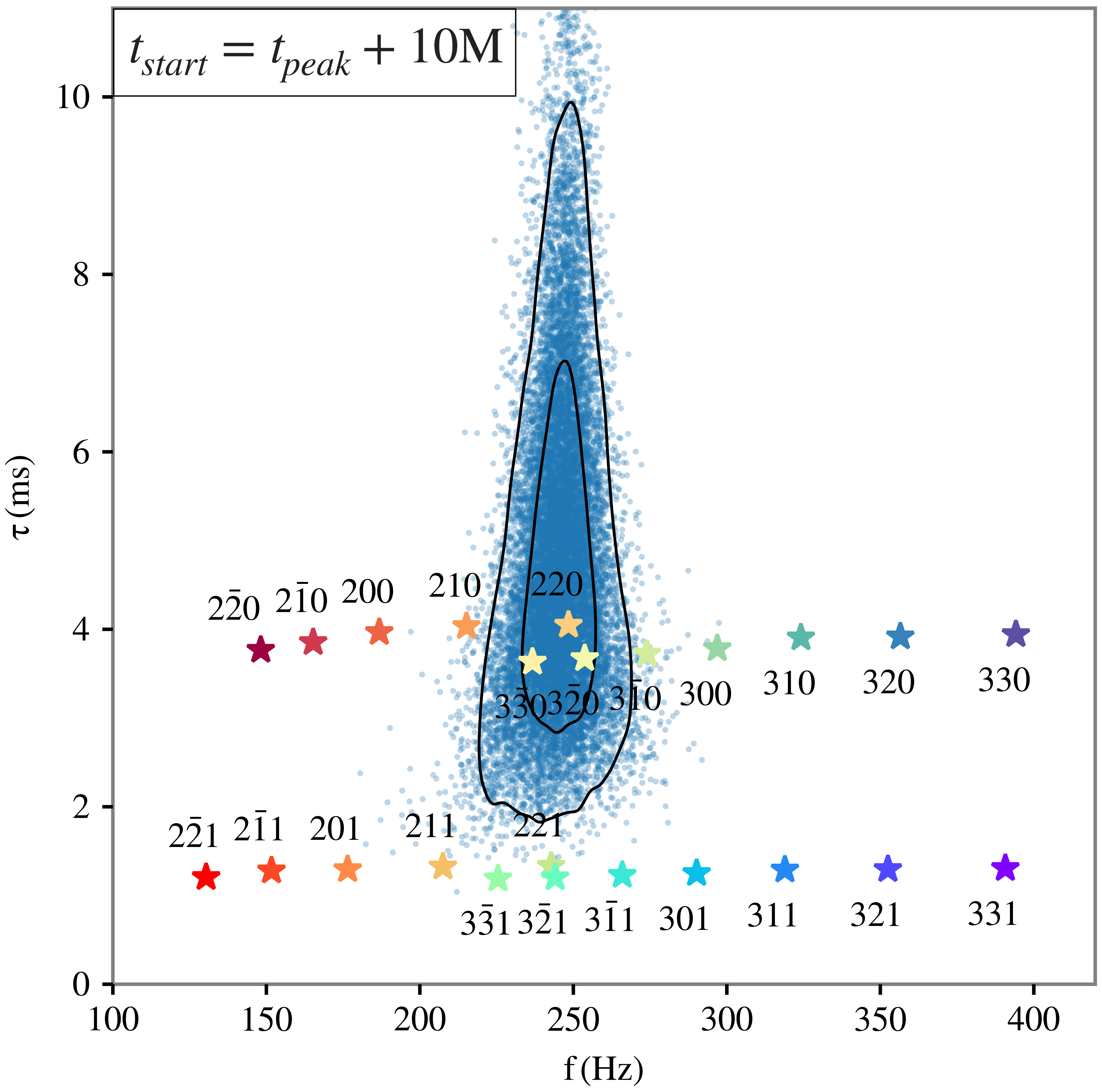

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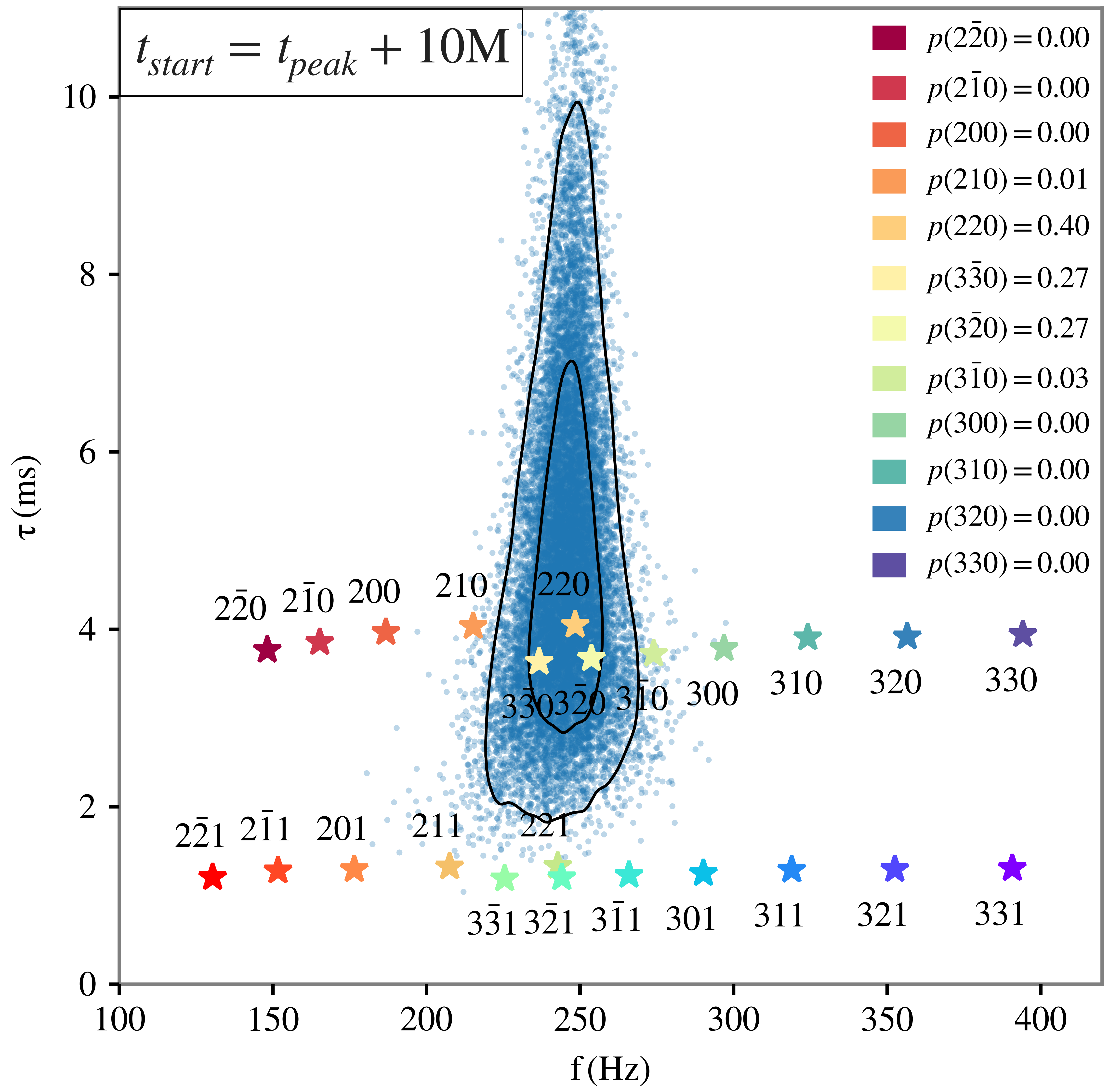

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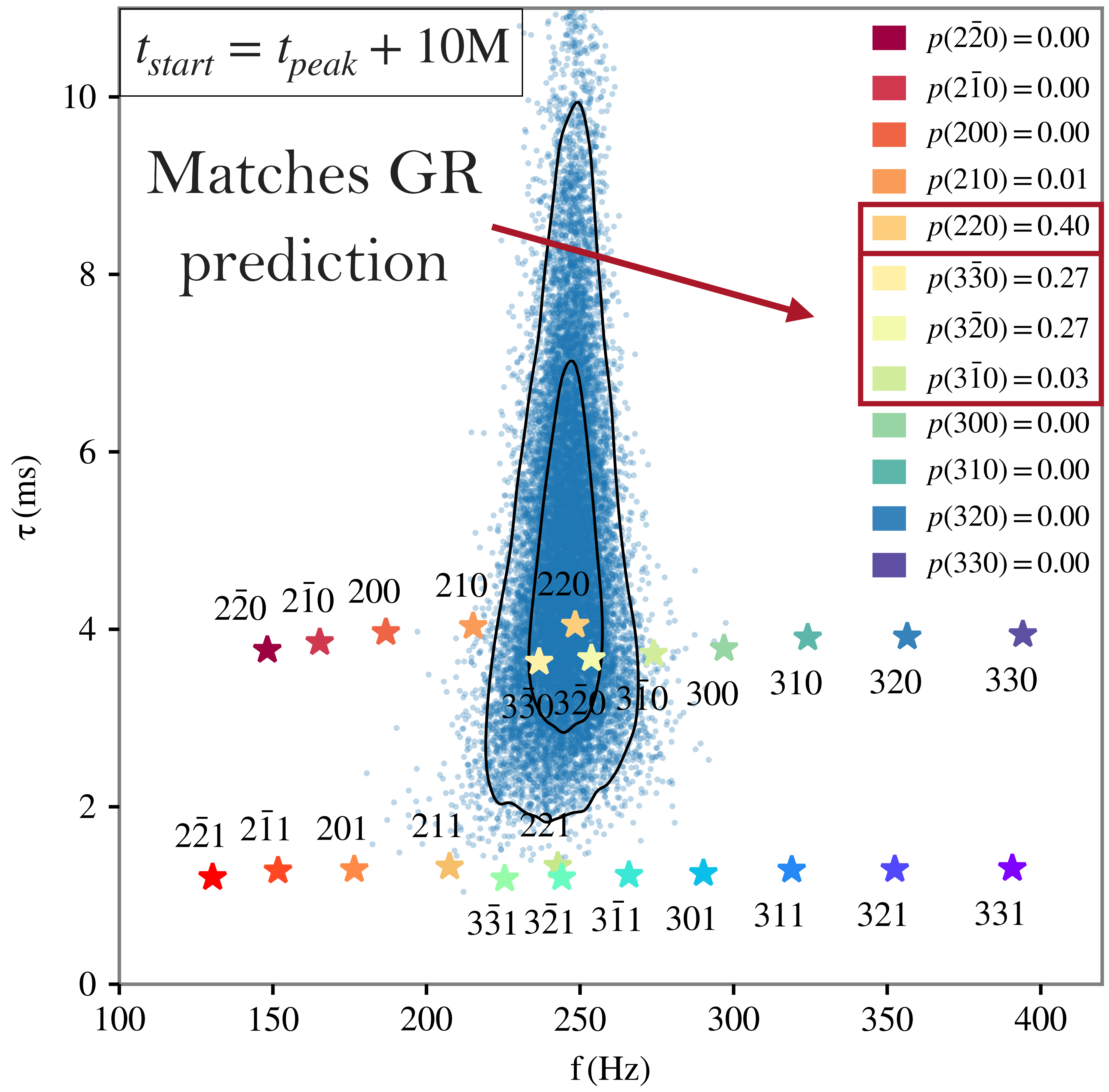
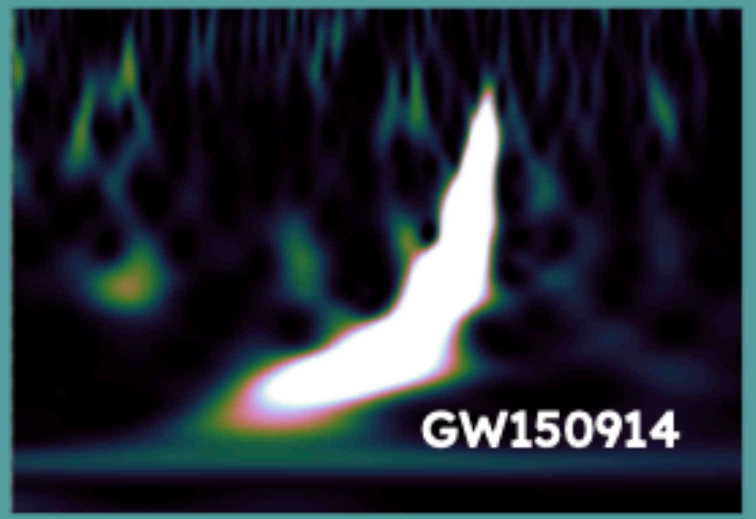
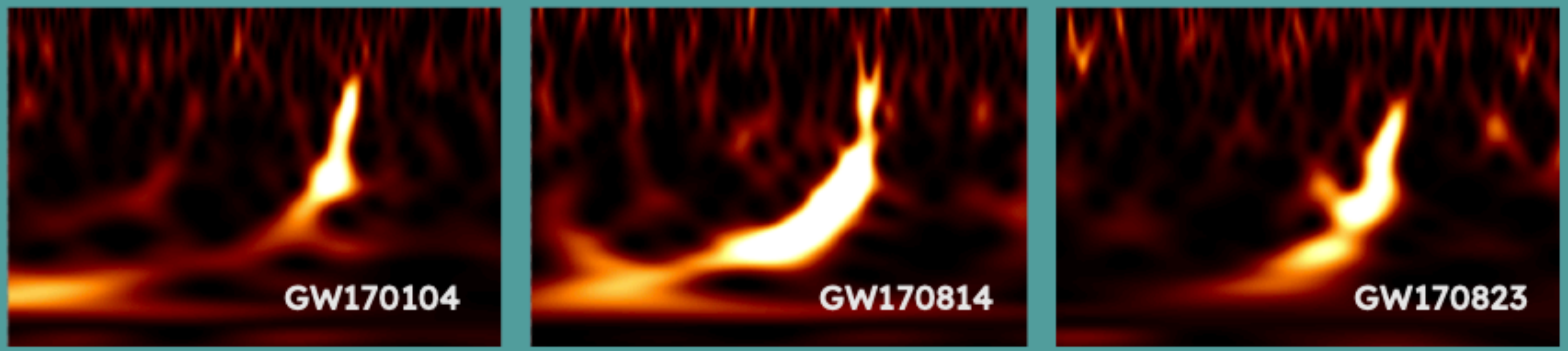


The LVK search

Ringdown Gravitational Wave Catalog

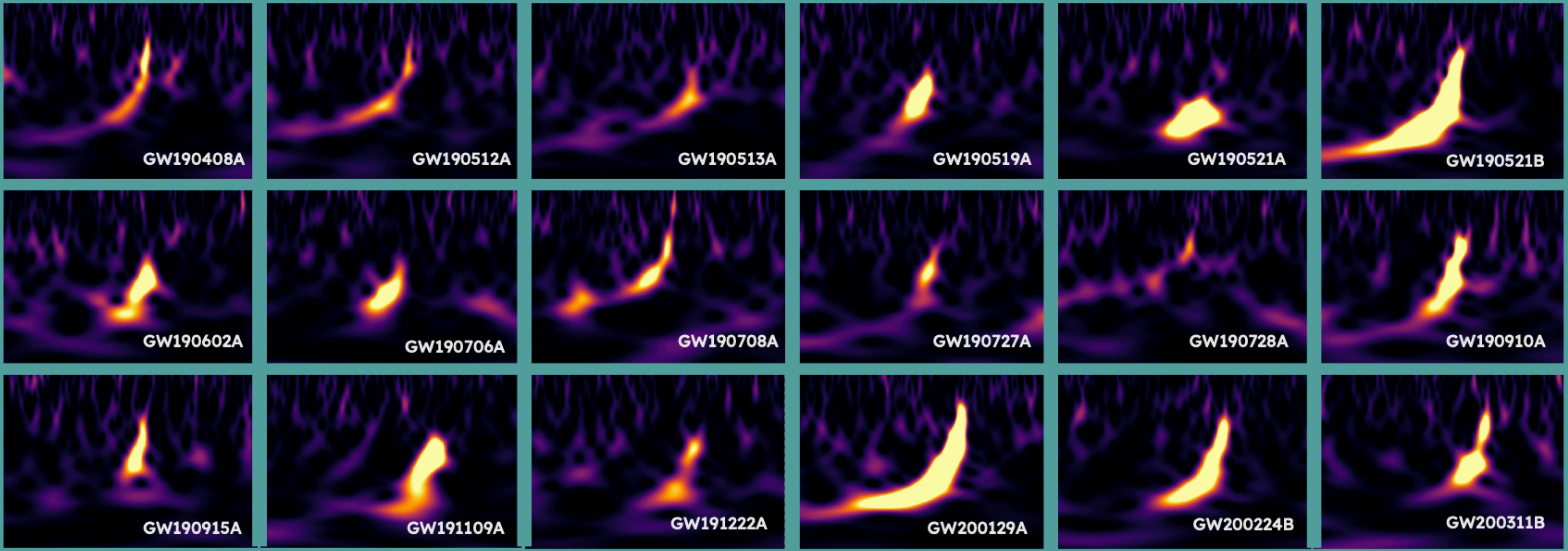




Detections from 2015-2020
passing the ringdown selection criteria

LVK, 2021

Giada Caneva



MODELS

- "*Ringdown dissection*": start **agnostic**, add increasingly **more information**, reflecting additional effects, e.g. **symmetries**

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Kamaretsos+, London+, Baibhav+, Forteza+, Cheung+, Carullo+, Zertuche+, Pacilio+

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"Weak no-hair tests" with a single mode

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Pacilio, Wed 15:20, Amaldi

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Baker+, 0805.1428, Damour-Nagar, 1406.0401, Pompili+, 2303.18039

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Brito+, 1805.00293

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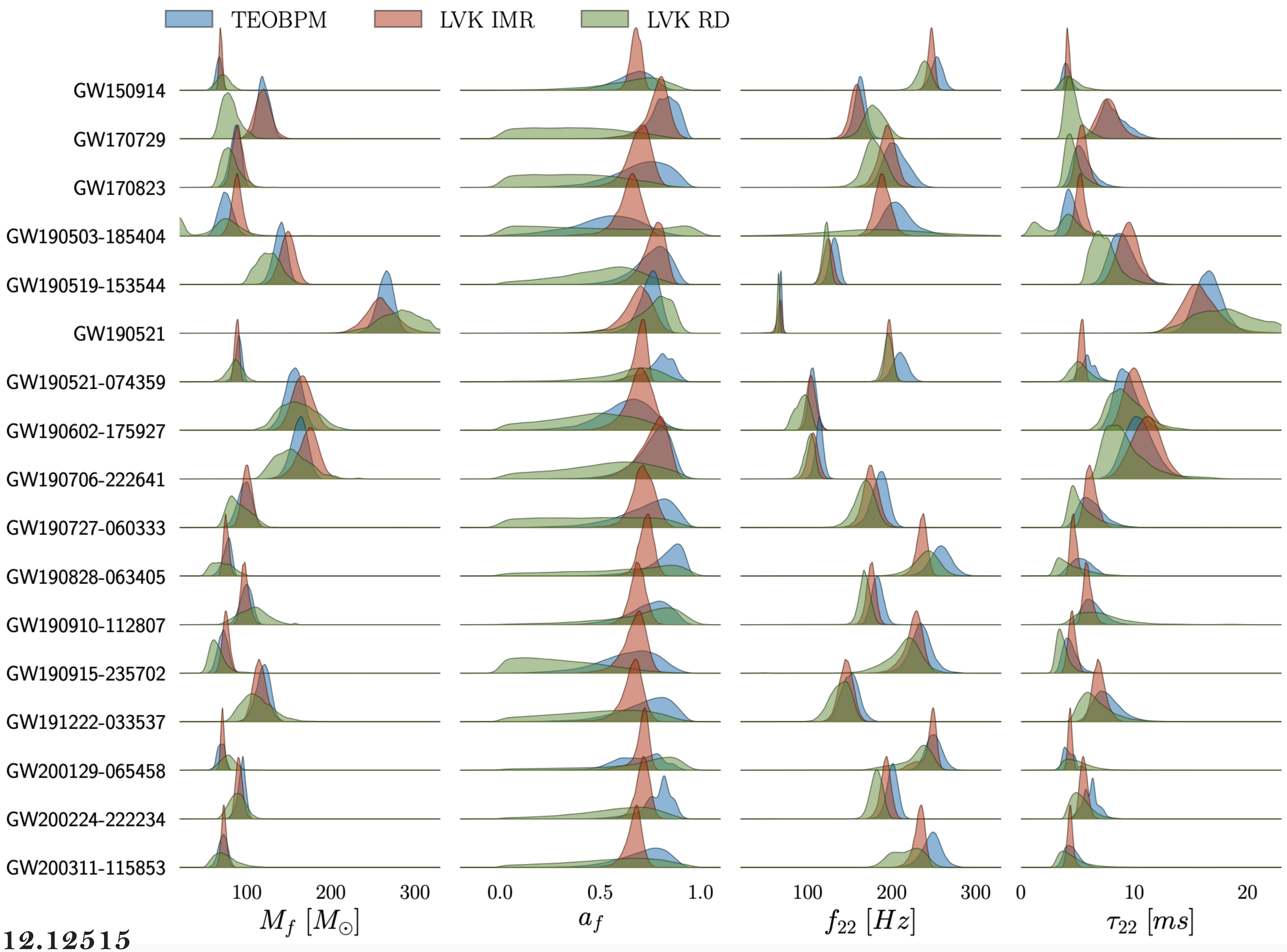
pSEOB = last + inspiral information

BLACK HOLE SPECTROSCOPY: RESULTS

- **Ringdown catalog:**
  - Searches for multiple ("higher") modes
  - Searches for GR deviations
  - Data characterisation
  - …
- All events **consistent** with remnant **Kerr black hole**.

LVC, 2010.14529, 2112.06861



Damour-Nagar, 1406.0401, London+, 1801.08208
Brito+, 1805.00293, **Gennari, Carullo, Del Pozzo, 2312.12515**

TESTS OF GENERAL RELATIVITY WITH GWTC-3

- **Bounds on deviations** from the GR spectrum.

- **Deviations** parameterized as:

$$\omega = \omega^{Kerr} \cdot (1 + \delta\omega)$$
$$\tau = \tau^{Kerr} \cdot (1 + \delta\tau)$$

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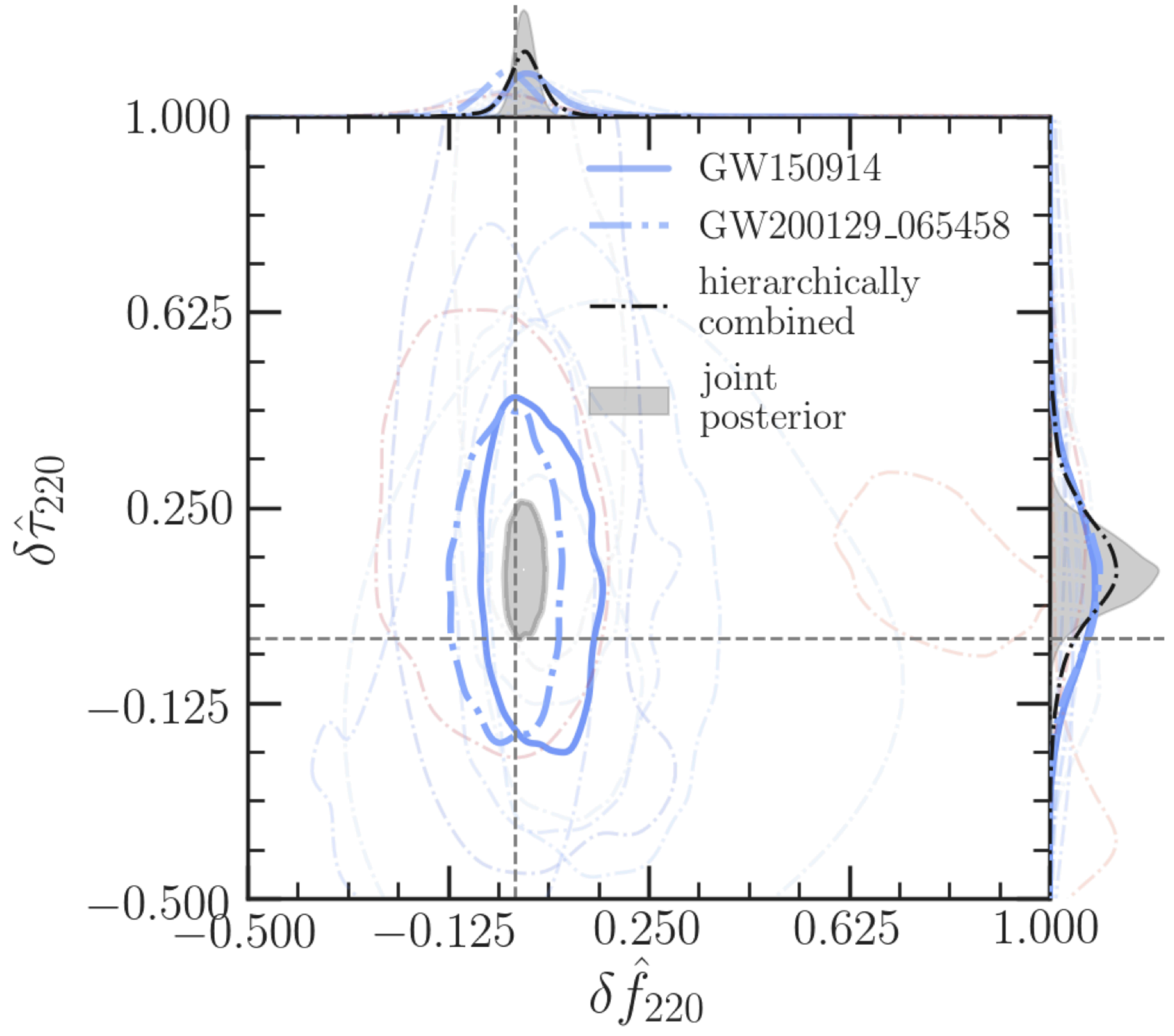

pyRing $\log B^{\rm modGR}_{\rm GR} = -0.9$

Carullo, Del Pozzo, Veitch, 1902.07527, Isi, Farr, 2107.05609.

pSEOB

Brito, Buonanno, Ghosh, Maggio, Silva+
1805.00293, 2104.01906, 2212.09655

What about multiple modes?

allowing to perform "clean no-hair" tests with Kerr templates?

Have we measured multiple quasinormal modes?

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Not yet.

SYSTEMATIC/STATISTICAL UNCERTAINTIES

- Extensive debate on multiple QNMs detection claims

Isi+, 1905.00869 | Cotesta+ 2201.00822
Isi, Farr, 2202.02941 | Finch-Moore, 2205.07809
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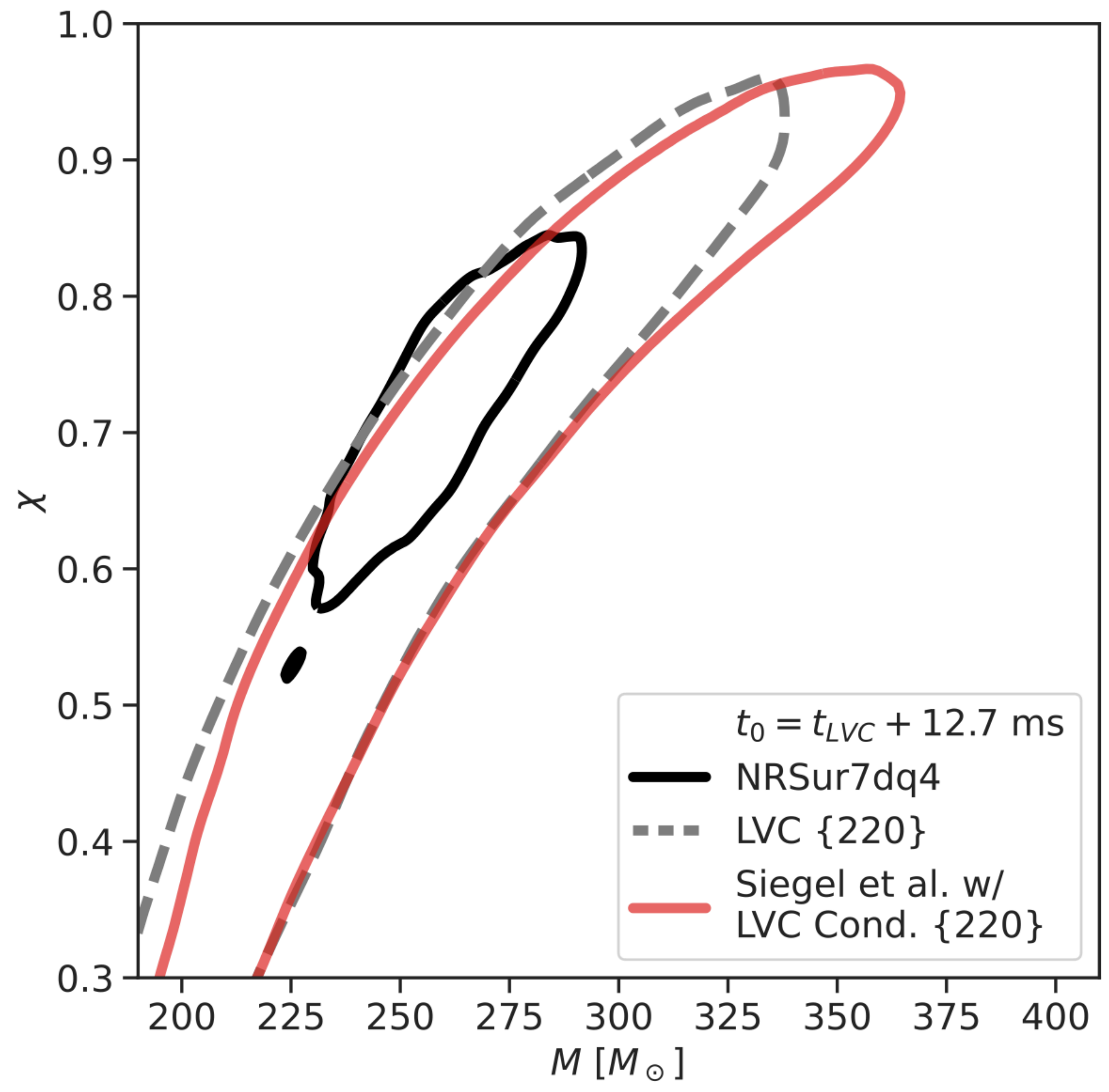
- **Analysis**
  - Initially discrepancies (incomplete analyses, noise estimation, sampling rate, …)
  - **Agreement** among different analysis setup with **same inputs** (overtones $\lesssim 2\sigma$)

Srinivasan, Thu 16:40, Conversi



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- **Modeling systematics** (interpretation)
  - Claimed detections **close to merger**: not a spectroscopy measurement
  - **Coupling** of statistical and systematic uncertainties (often ignored on t_{start})
  - **No** inclusion of **eccentric** or (often) **precessing** configurations

Way forward?

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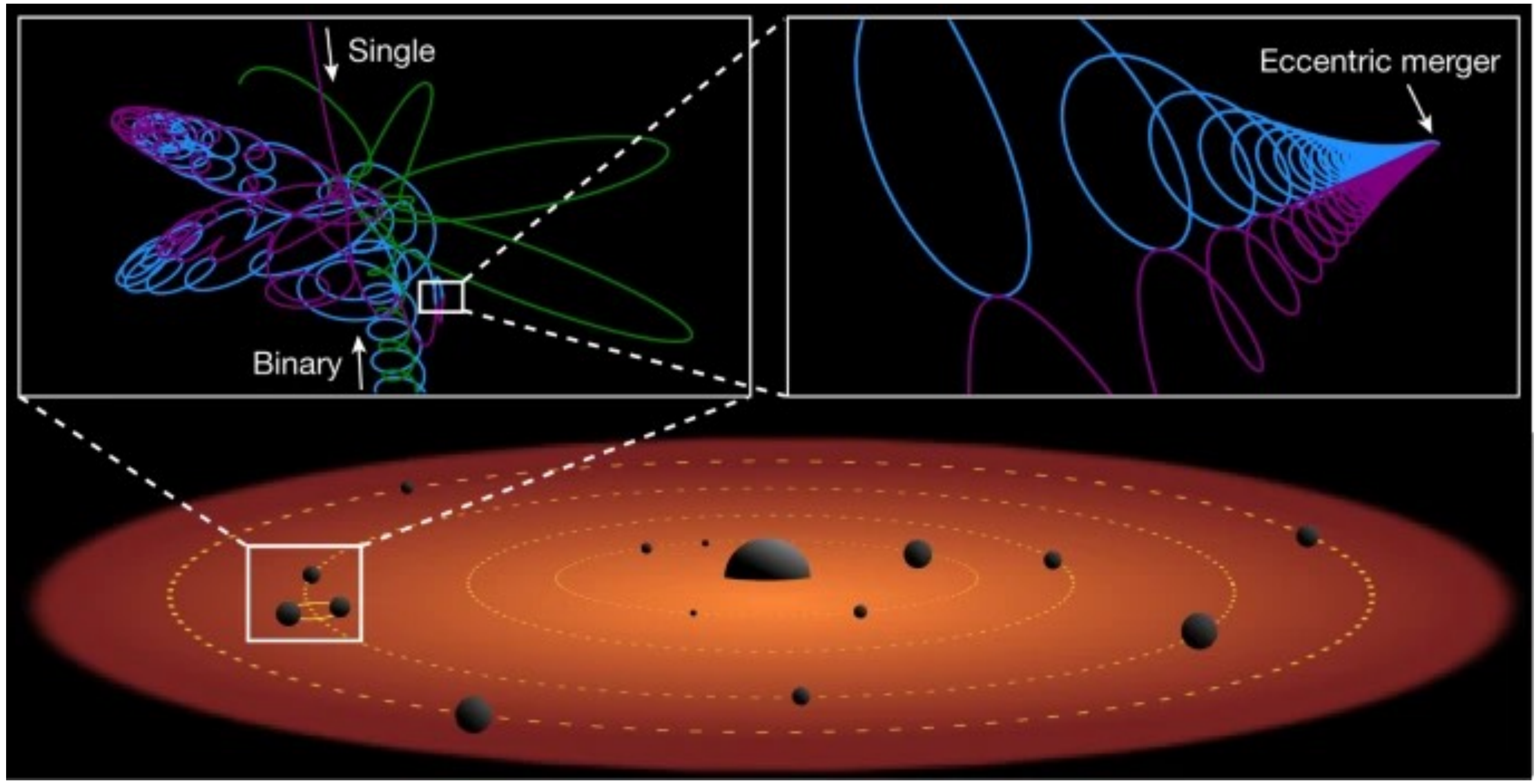
Stat: marginalise

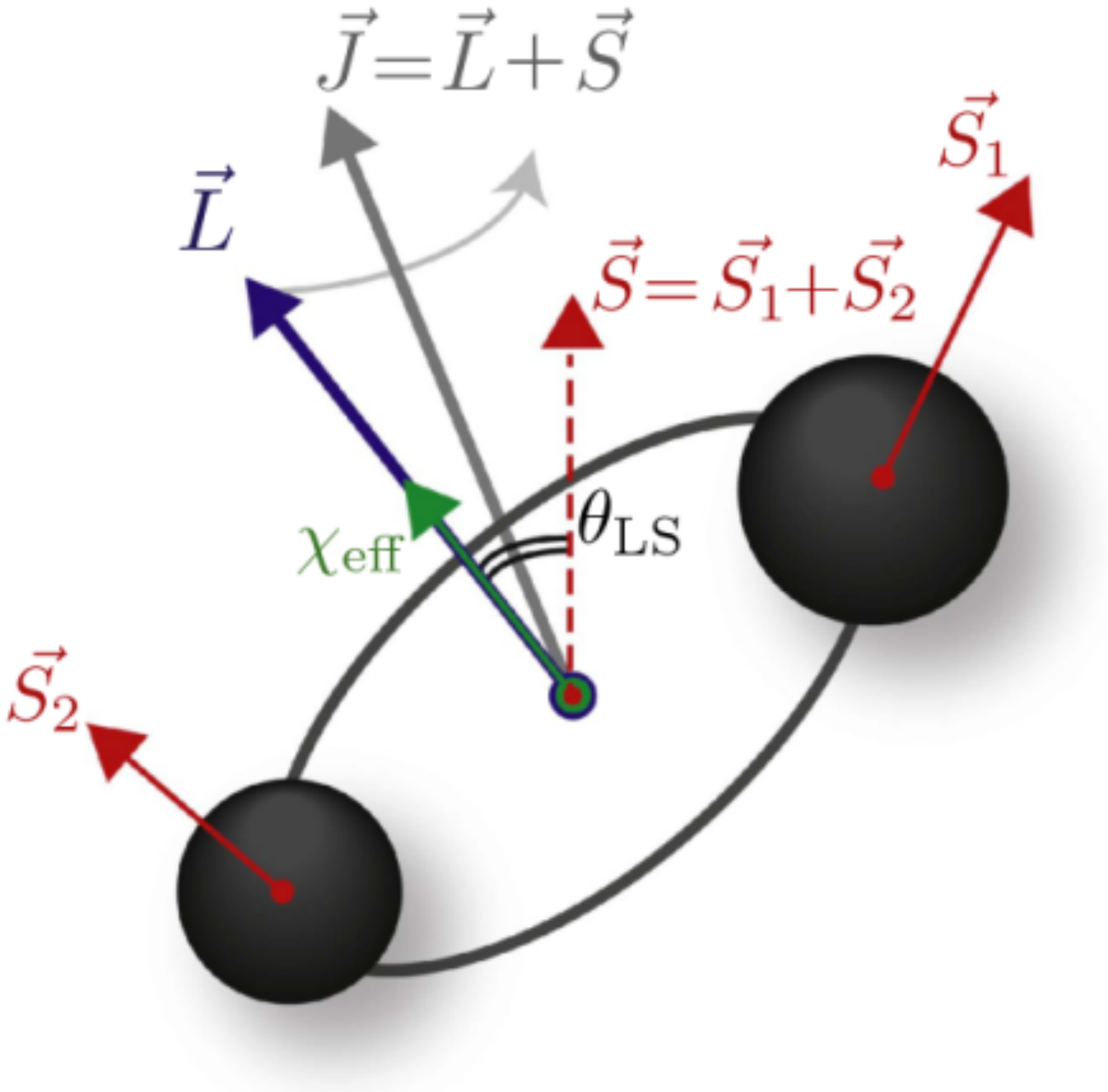
Sys: model!

BEYOND THE CIRCULAR PICTURE

- To overcome these issues, need to take into account: **noncircular and spin-precession effects**

Samsing+, Nature 603, 237–240 (2022)





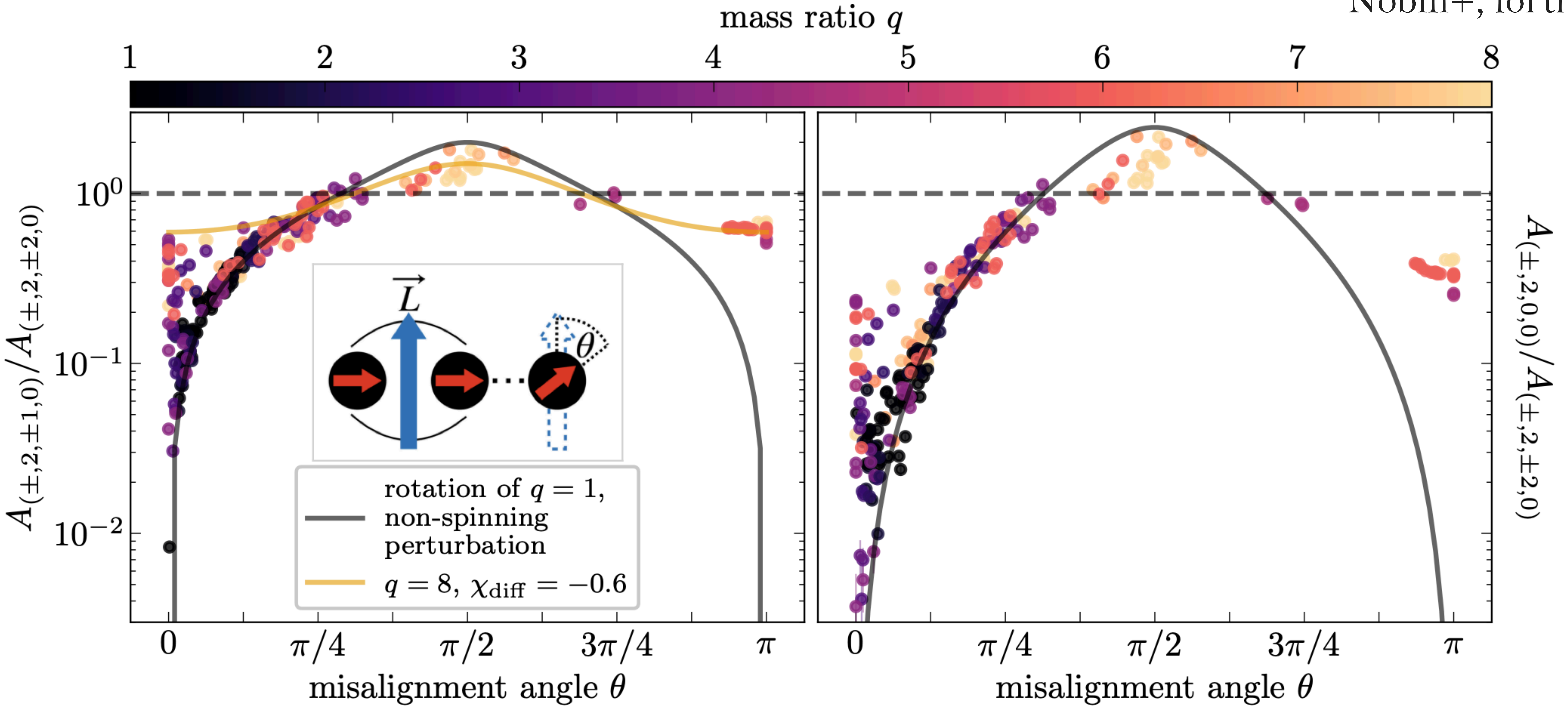
Ecc. signatures claimed in:

Gamba+, Nat. Astro. (2022), Gayathri+, Nat. Astro. (2022)
Romero-Shaw, APJ (2022) , Gupte+, 2404.14286

BEYOND THE SPHERICAL PICTURE

- Precessional impact on QNM amplitudes:

Finch-Moore, 2102.07794
Hamilton-London-Hannam, 2301.06558
Zhu, Siegel+, 2312.08588
Nobili+, forthcoming.



Captured by static rotation of non-prececessing system, follows PT

Lim+, 1901.05902

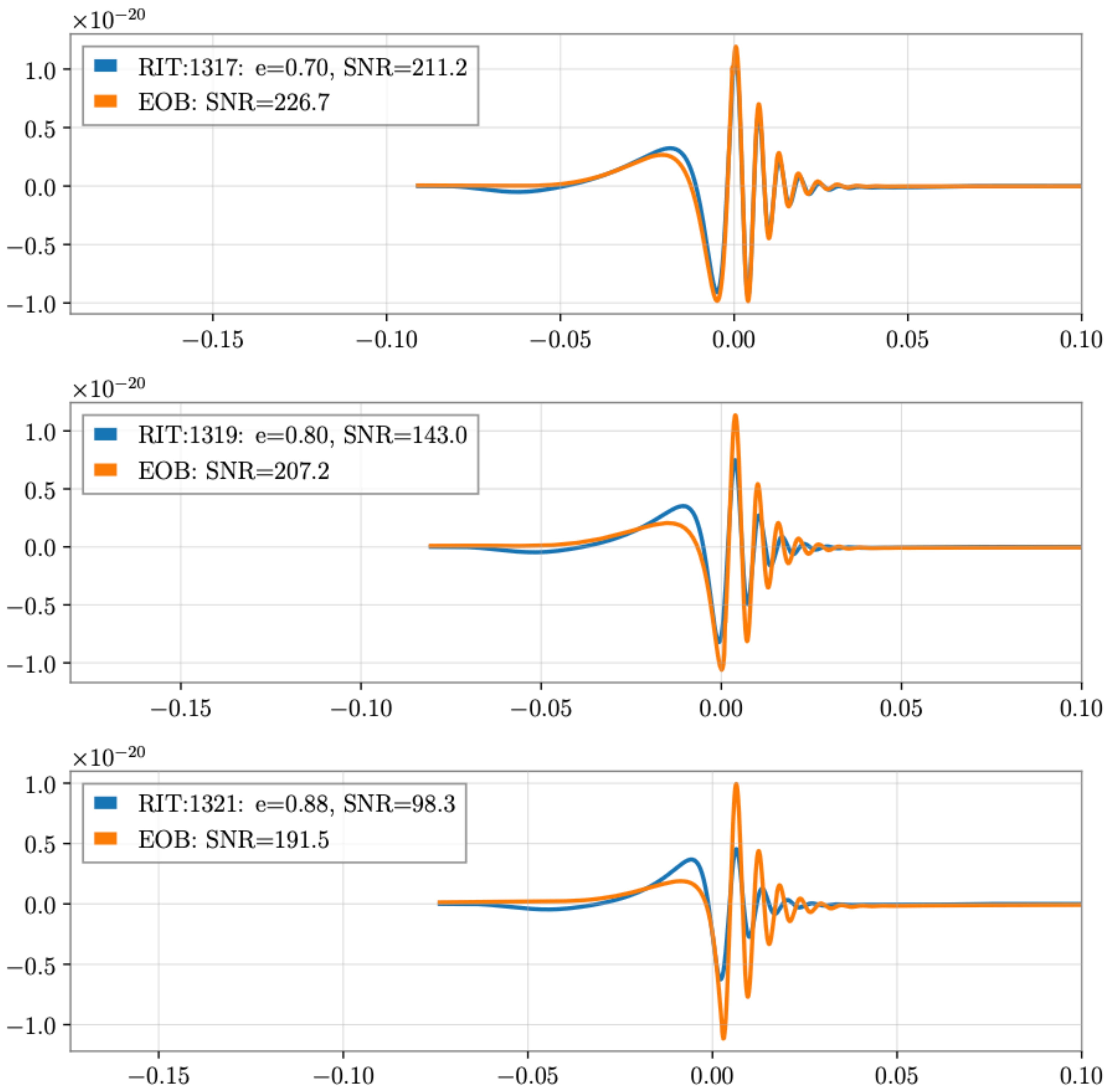
Focusing on QNM modeling. For IMR see: O'Shaughnessy, 1109.5224, Schmidt+, 1408.1810, Gamba+, 2111.03675, Thompson+, 2312.10025, Ramos-Buades+, 2303.18046, …

NONCIRCULAR MERGER MODEL

- To overcome these issues, need to take into account: noncircular effects

NONCIRCULAR MERGER MODEL

- To overcome these issues, need to take into account: noncircular effects
  - No IMR template currently includes eccentricity corrections to merger-ringdown
  - Decreased search sensitivity for medium/high eccentricity



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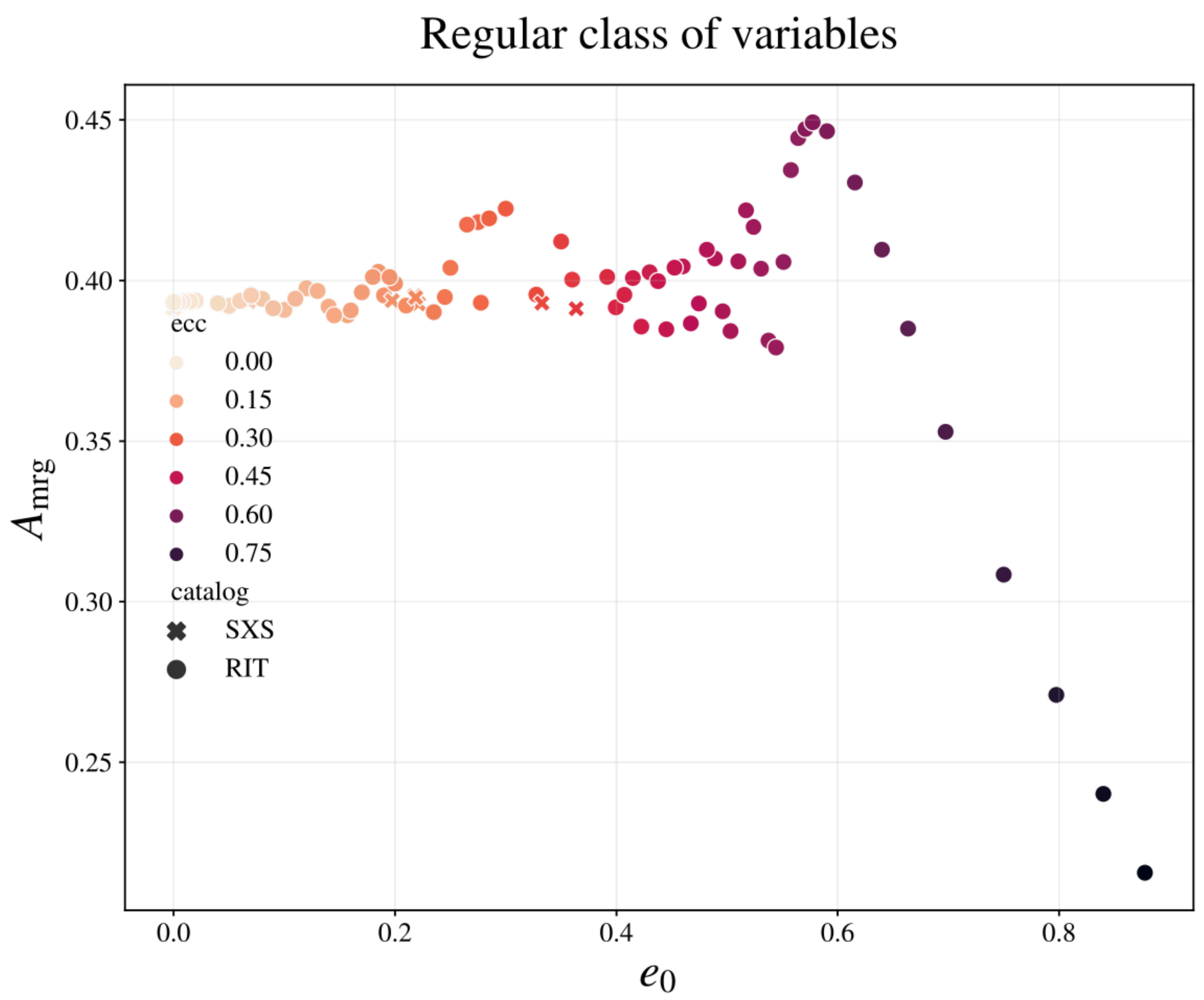

Not surprising: Radia+, 2101.11015

NONCIRCULAR MERGER MODEL

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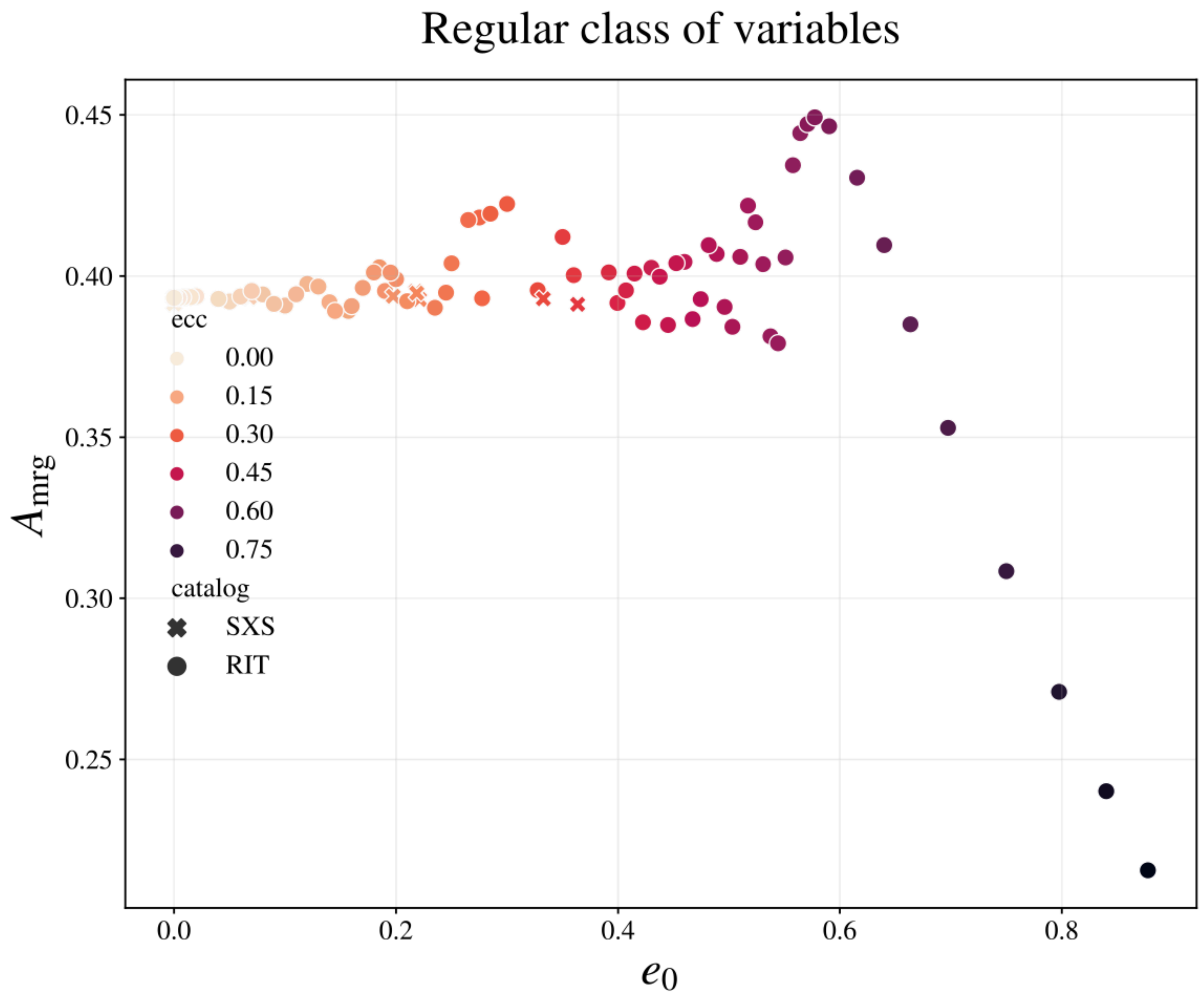

- To describe generic orbits, switch to (E, J)

$$E(t) = E_0^{\rm ADM} - \int_{t_0}^{t} \dot{E}(t')dt'$$

$$J(t) = J_0^{\rm ADM} - \int_{t_0}^{t} \dot{J}(t')dt' \,,$$

$$h := E/M \qquad j = J/(\nu M^2)$$

$$\hat{E}_{\rm eff}(h, \nu) = 1 + (h^2 - 1)/(2\nu),$$

$$\hat{b}_{\rm mrg} \equiv \frac{j_{\rm mrg}\, h(\hat{E}_{\rm eff}^{\rm mrg}, \nu)}{\hat{E}_{\rm eff}^{\rm mrg}}$$

Albanesi+, 2305.19336

Carullo+, 2309.07228

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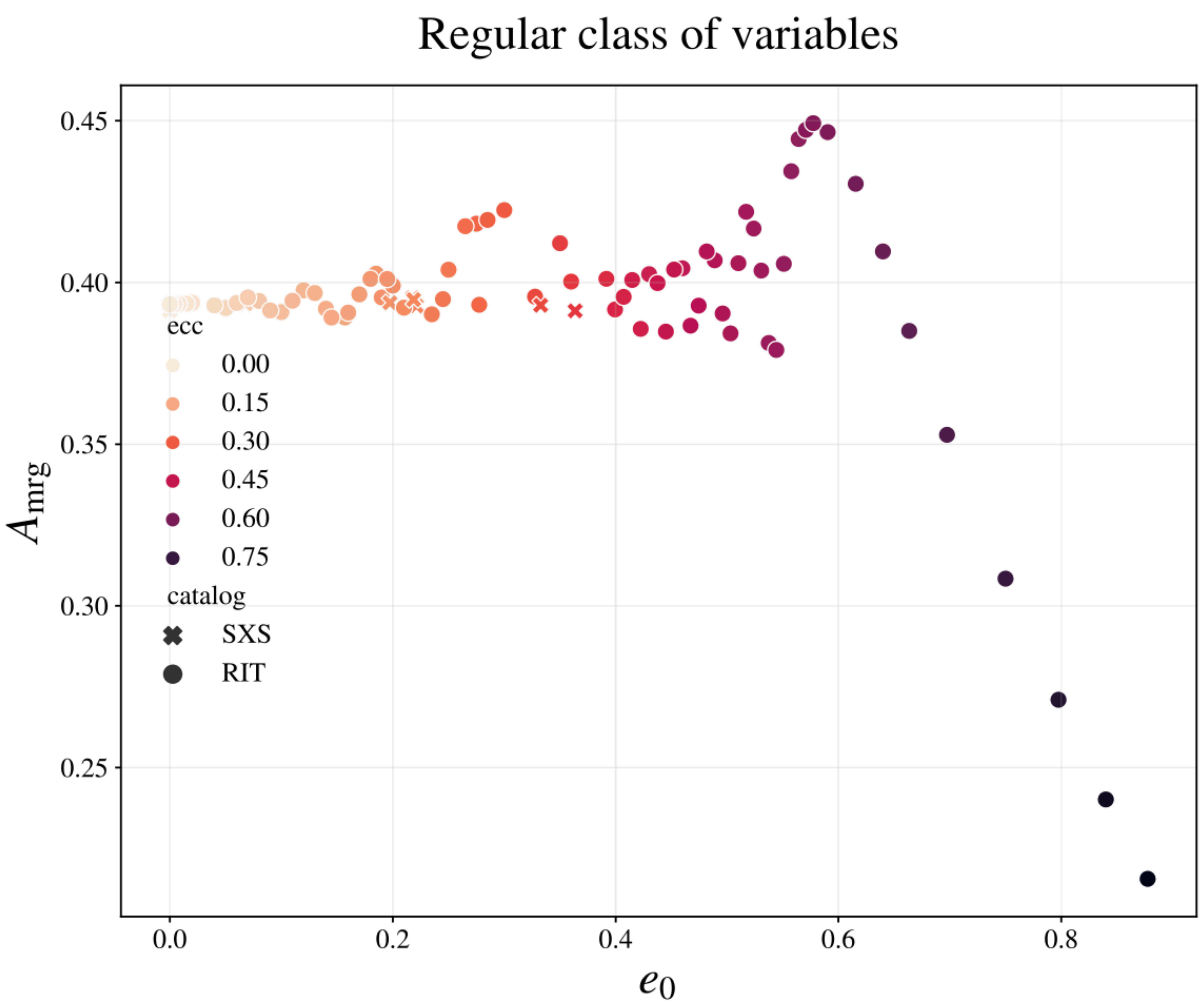

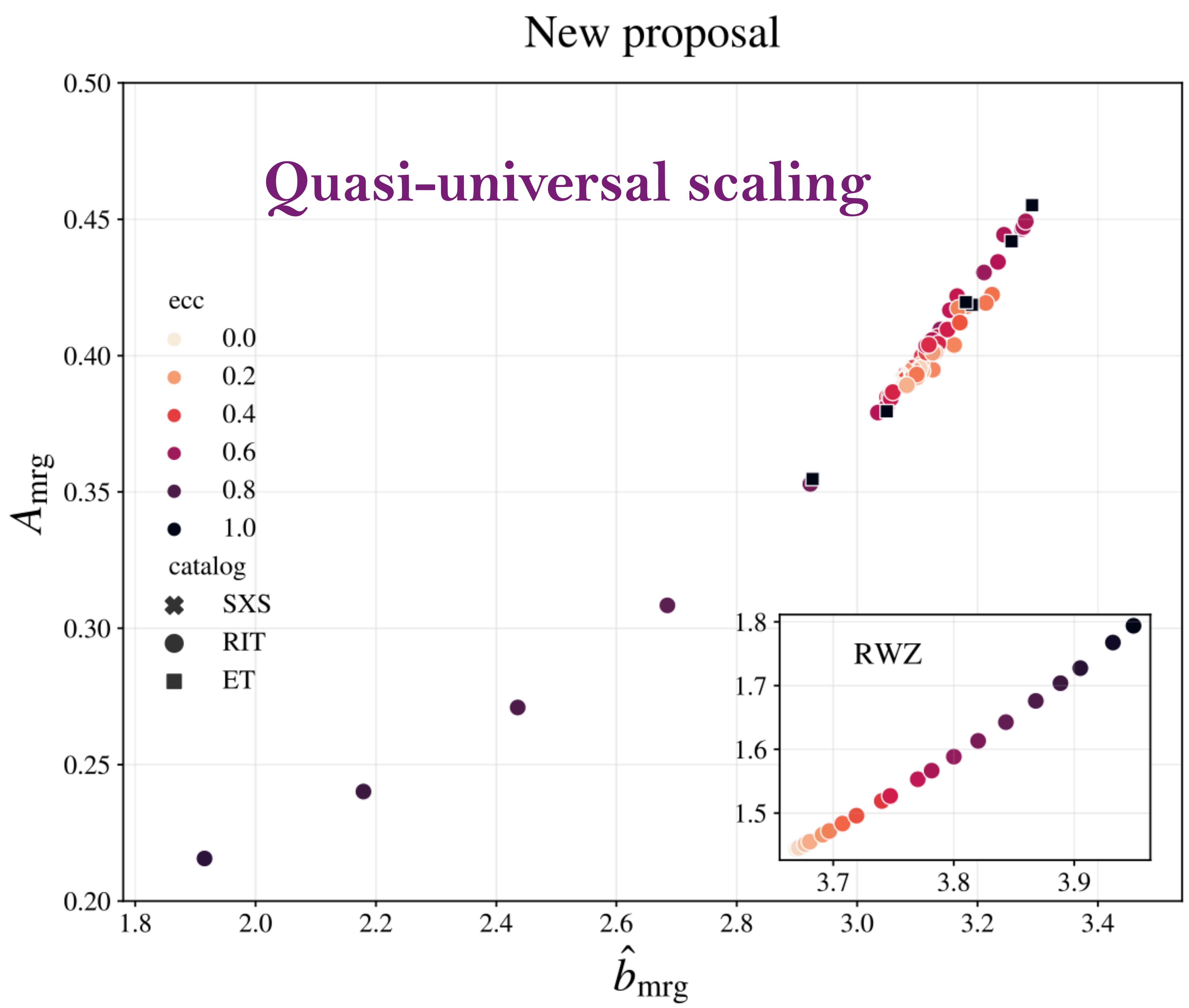

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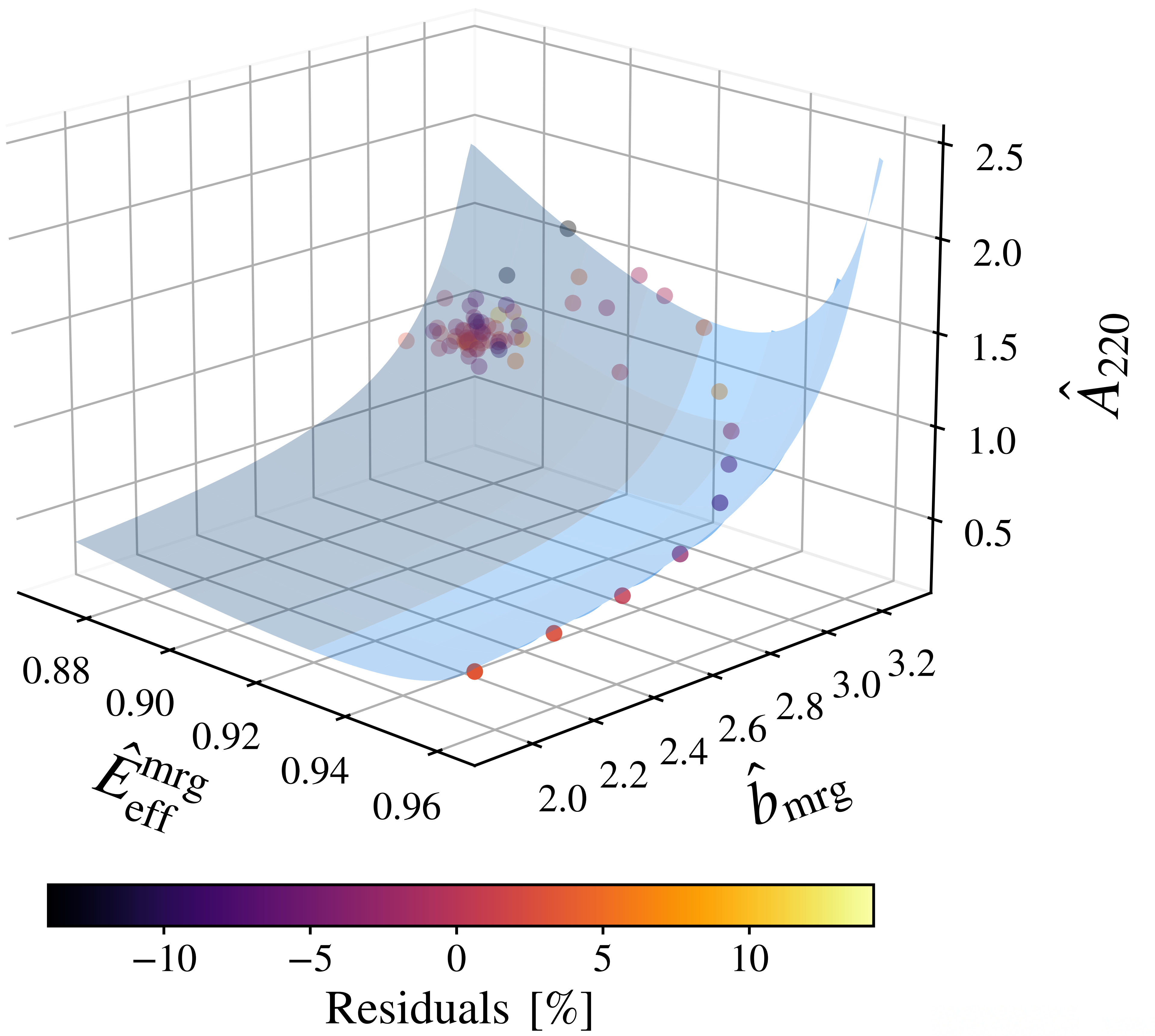
NONCIRCULAR RINGDOWN MODEL

- Similar results hold for QNM amplitudes:

Currently, all eccentric IMR models assume circularisation before merger



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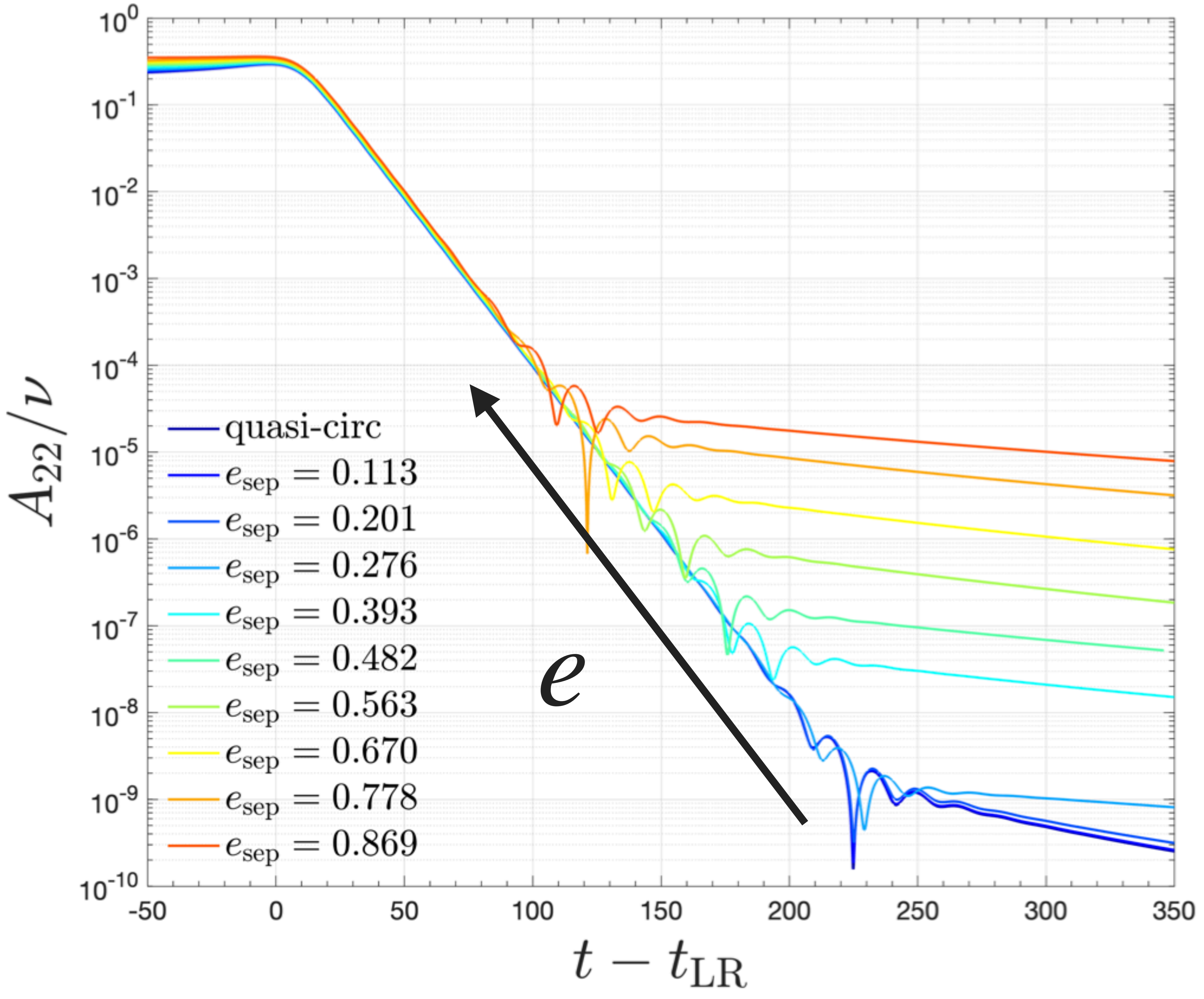
Carullo, 2406.19442

LATE-TIME TAILS

- For highly eccentric systems, tails might play an important role as well!



De Amicis, Wed 17:00, Amaldi

Albanesi, Fri 09:50, Amaldi

Albanesi+, 2305.19336
Carullo-De Amicis, 2310.12968
Cardoso+,
De Amicis-Albanesi-Carullo, 2406.17018
Islam+, 2407.04682

BEYOND THE LINEAR PICTURE

- To overcome these issues, need to take into account: **nonlinear effects**

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    - Dynamical background
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Sberna+, 2112.11168 (AdS)
Redondo-Pereniguez+, 2312.04633,
Capuano+, 2407.06009 (Vaidya)
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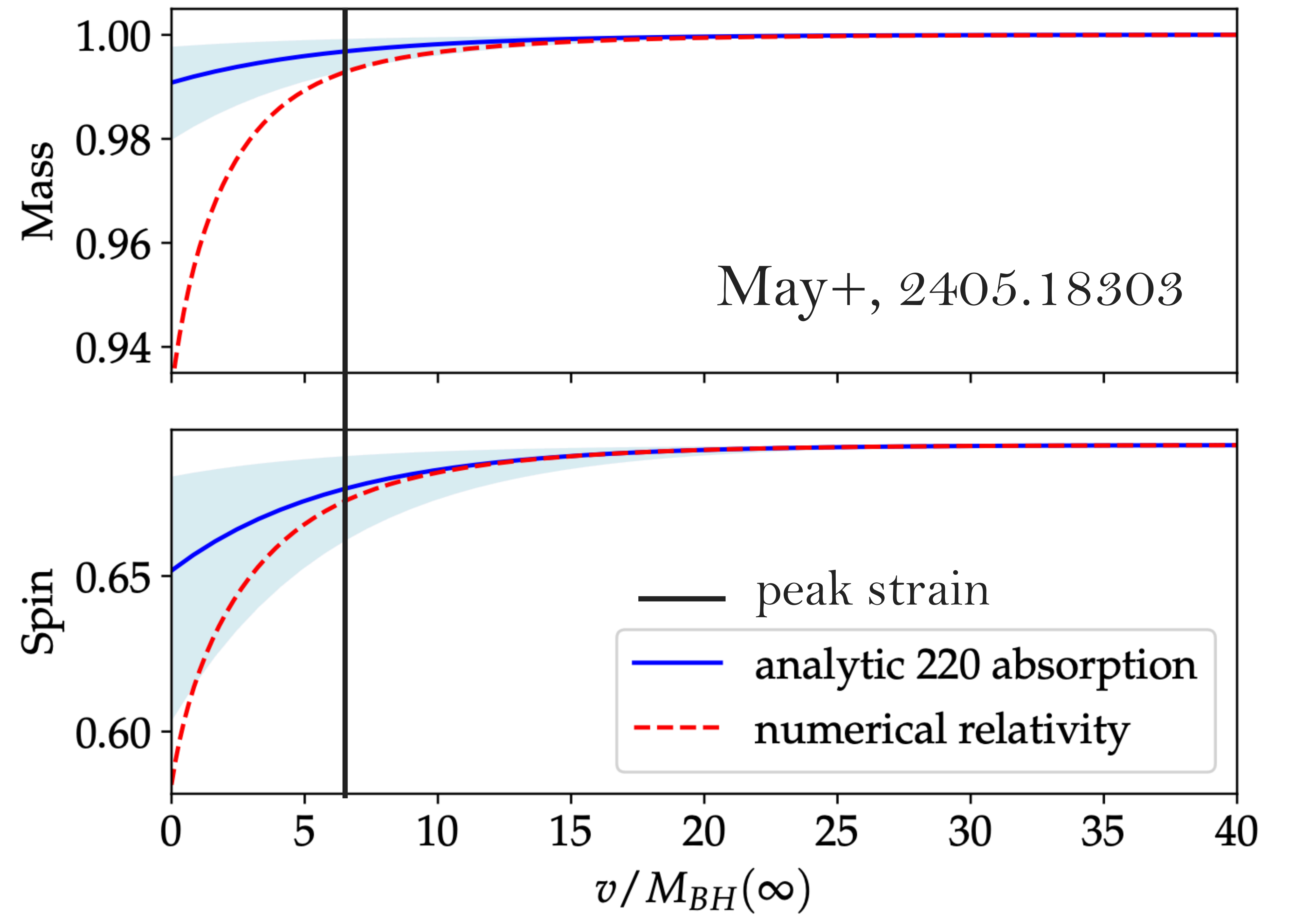

Mode-spreading, frequency drift, …

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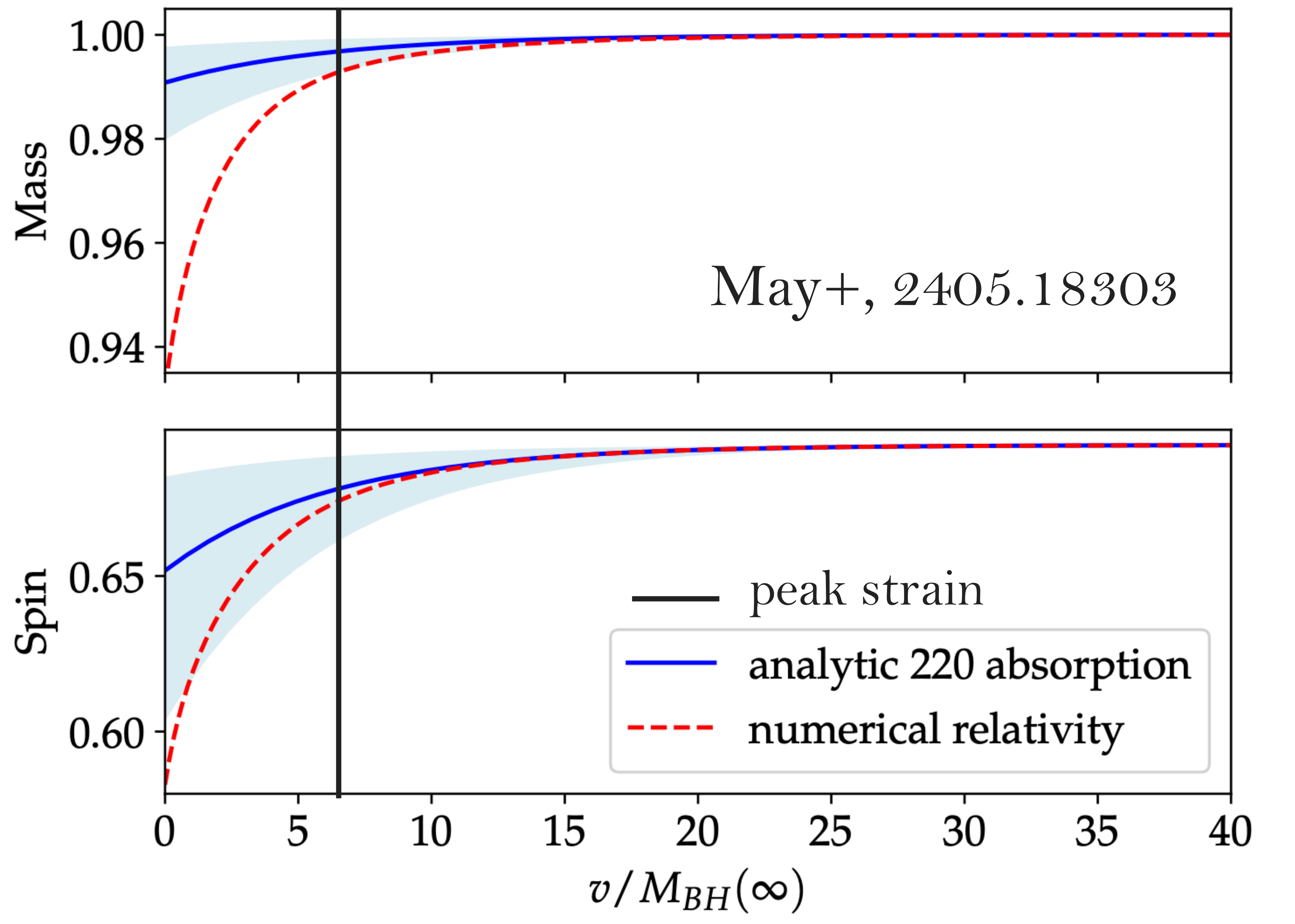

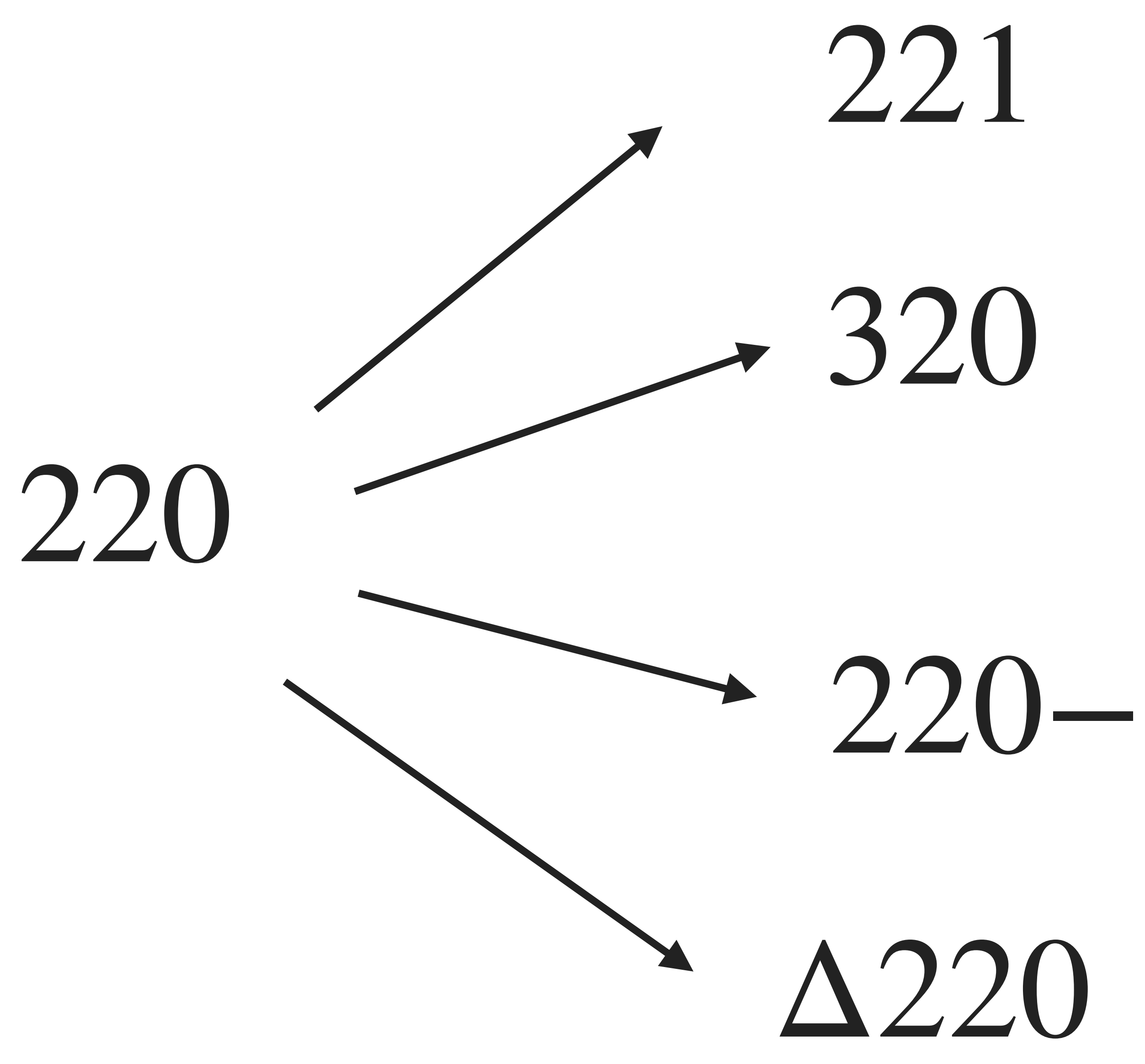

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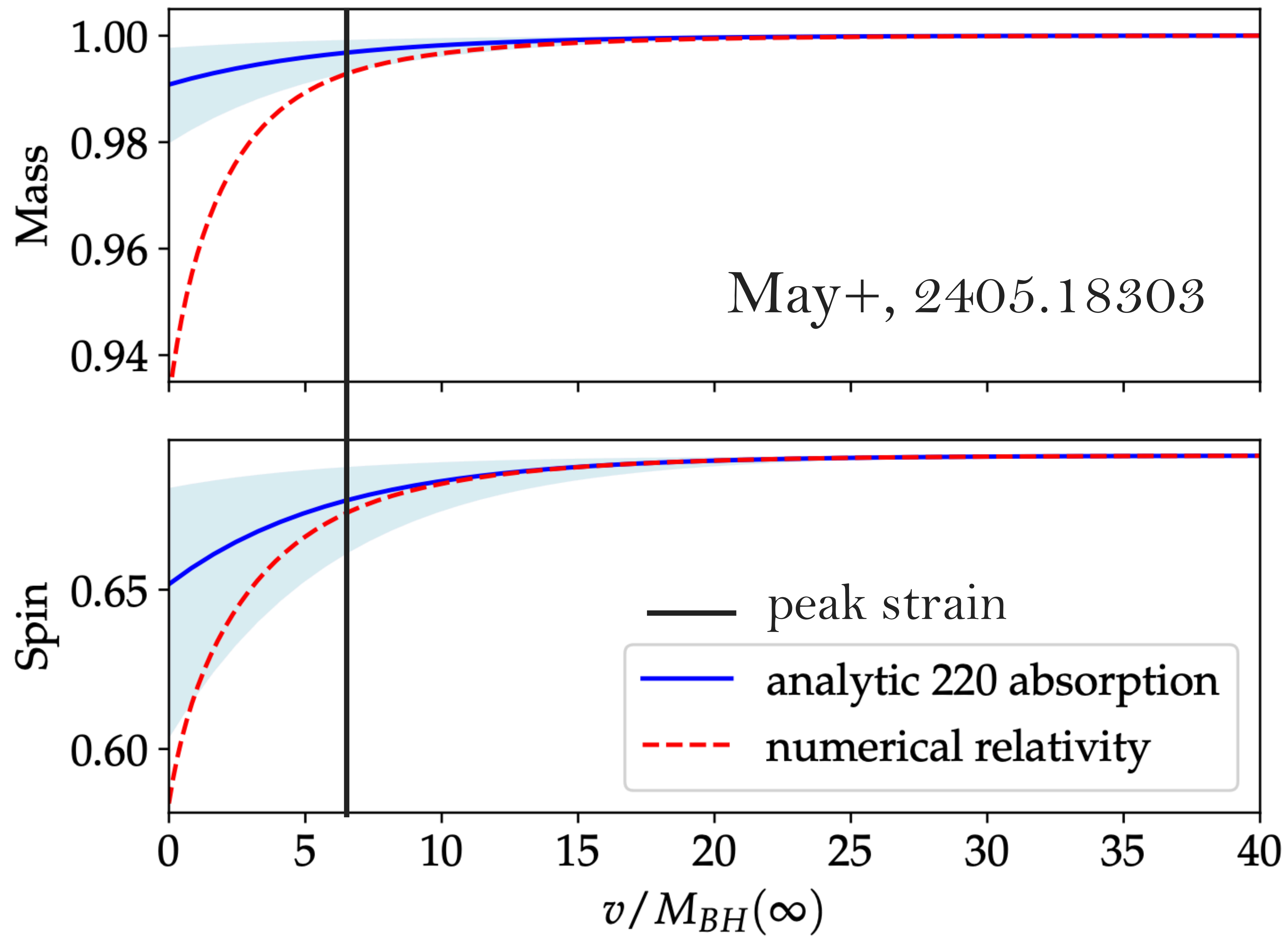

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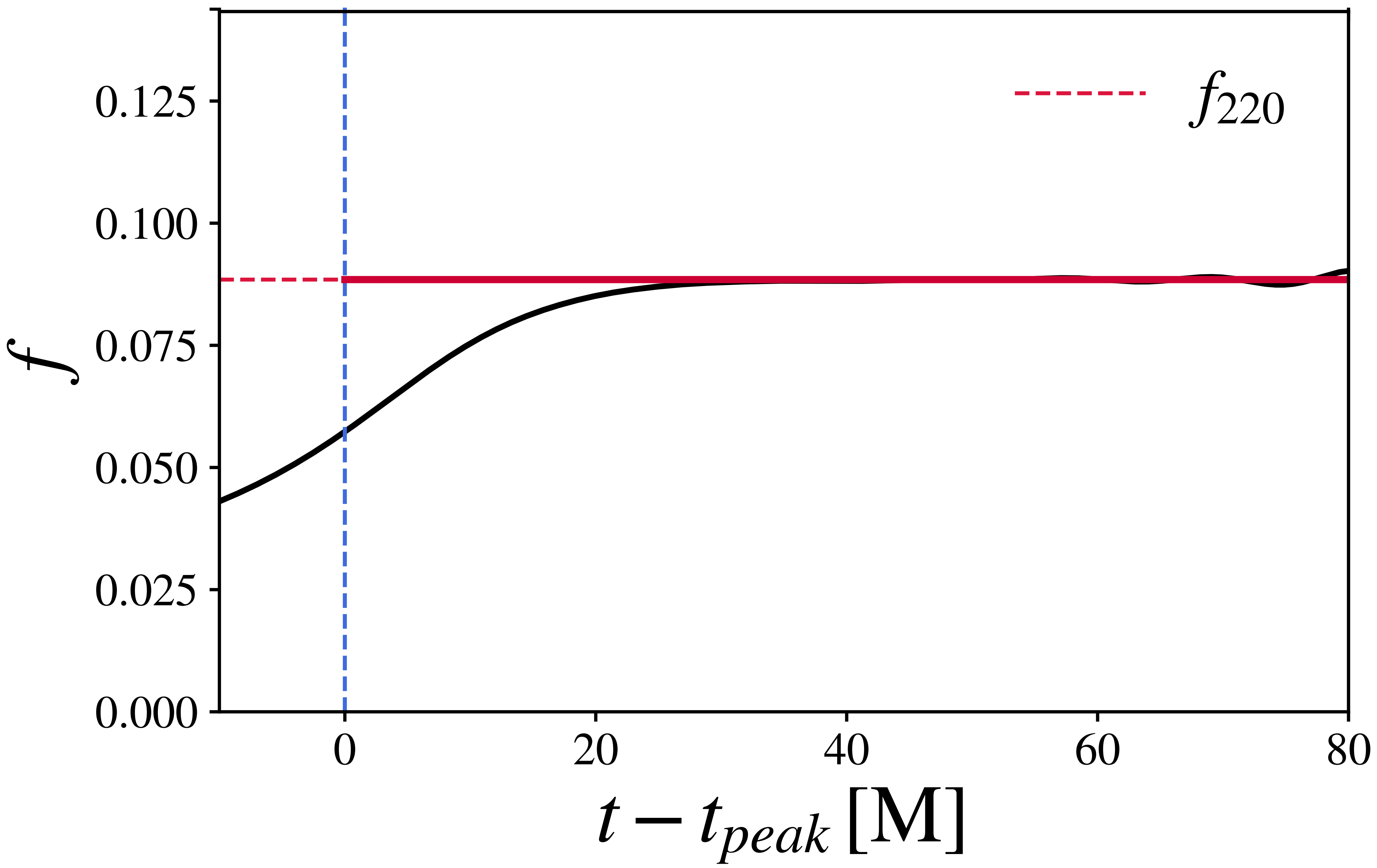

Cannot reproduce frequency increase with $\omega_{\ell mn}(M(t), a(t))$
(both using ADM and horizon quantities)

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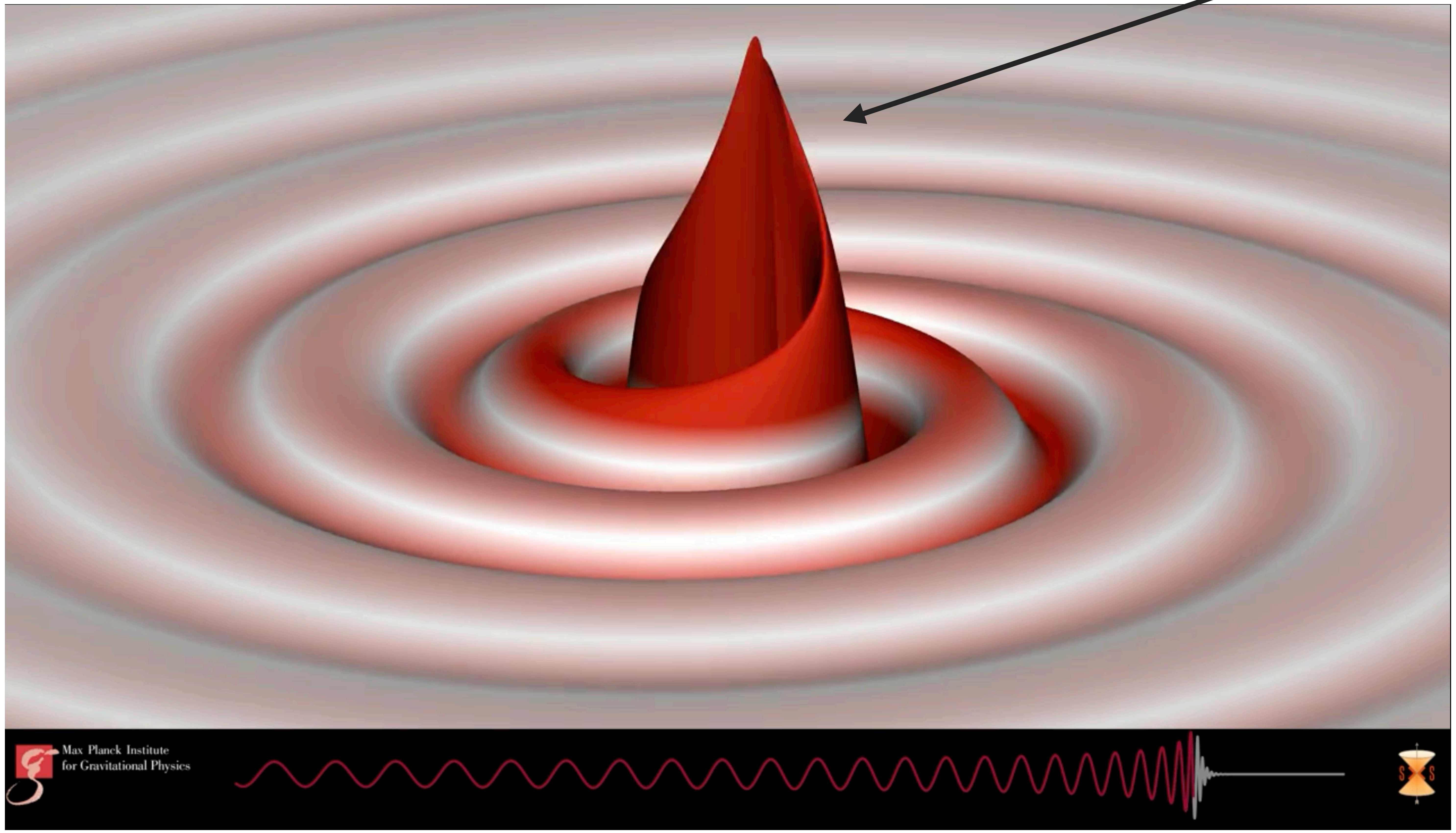
$$(\ell, m) \times (\ell', m') \rightarrow (\ell'', m + m')$$

Nonlinear dynamics



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  - **Mode coupling**

$$(\ell, m) \times (\ell', m') \to (\ell'', m + m')$$

$$g_{ab} = g_{ab}^{\rm Kerr} + \epsilon h_{ab}^{(1)} + \epsilon^2 h_{ab}^{(2)}$$

Gleiser, Nicasio, Price, Pullin, Ioka, Nakano, Brizuela, Martin-Garcia, Marugan …

$$\mathcal{O}_s \mathcal{T}[h_{ab}^{(1)}] = 0\,,$$

$$\mathcal{O}_s \mathcal{T}[h_{ab}^{(2)}] = \mathcal{S}_s[h_{ab}^{(1)}, h_{ab}^{(1)}]$$

Credits: Redondo-Yuste

Campanelli&Lousto (1998)
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- Most-studied coupling: $(2,2) \times (2,2) \rightarrow (4,4)$

$$\Psi_4^{\ell=4,m=4} = A_{440} e^{i\omega_{440} t + \phi_{440}} + A_{220\times 220} e^{i\omega_{220\times 220} t + \phi_{220\times 220}}$$

Fundamental mode

QQNM

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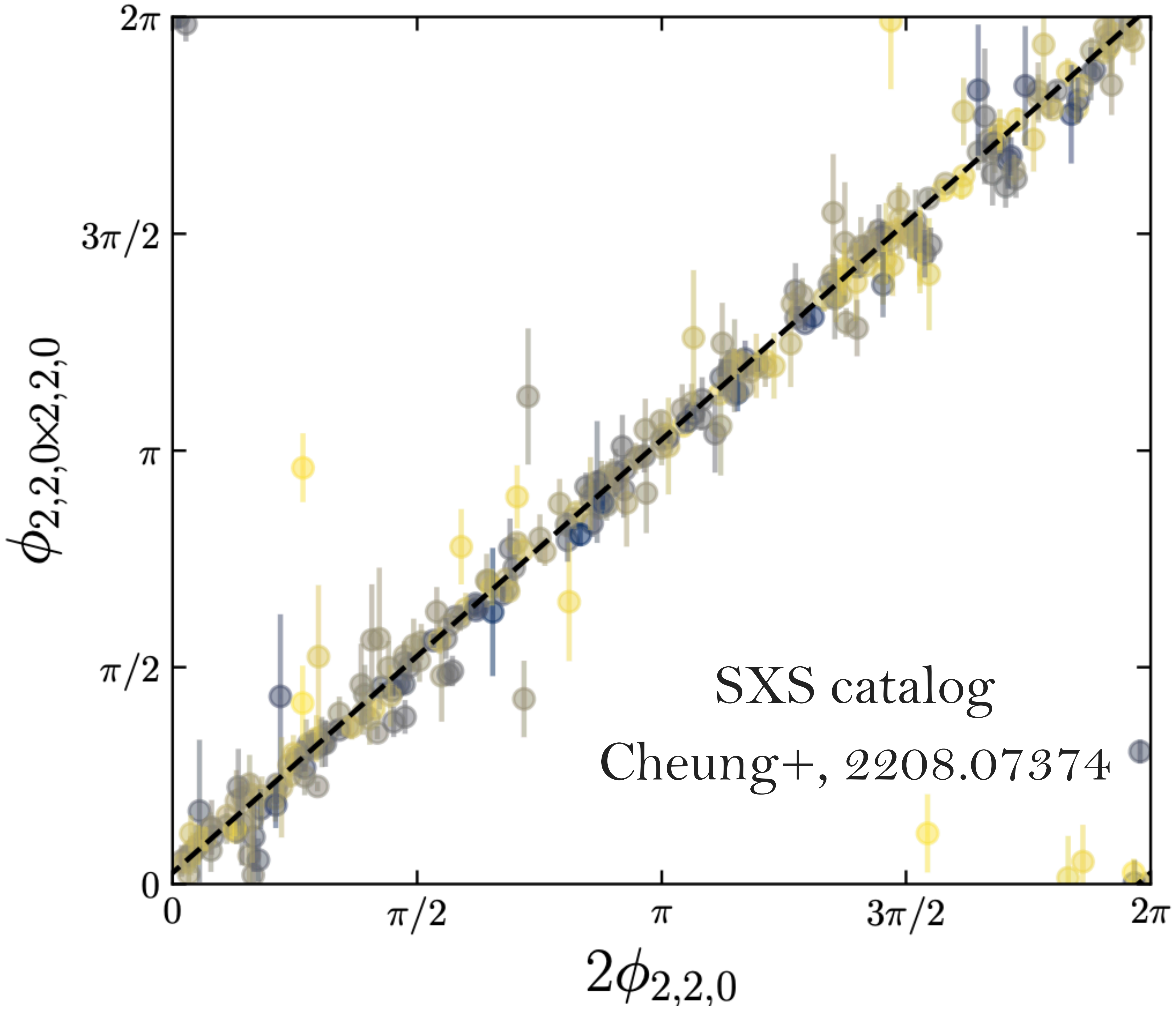

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Fundamental mode QQNM

Comparable or larger than linear 440!

Kehagias+, 2301.09345
(Kerr/CFT correspondence)
Universality?

$$\mathcal{R} = \frac{A_{220\times220}}{A_{220}^2}$$

Loutrel+, 2008.11770, Ripley+, 2010.00162
London+, 1404.3197, **Cheung+, 2208.07374**
Mitman+, 2208.07380, Khera+, 2306.11142
Cheung+, 2310.04489

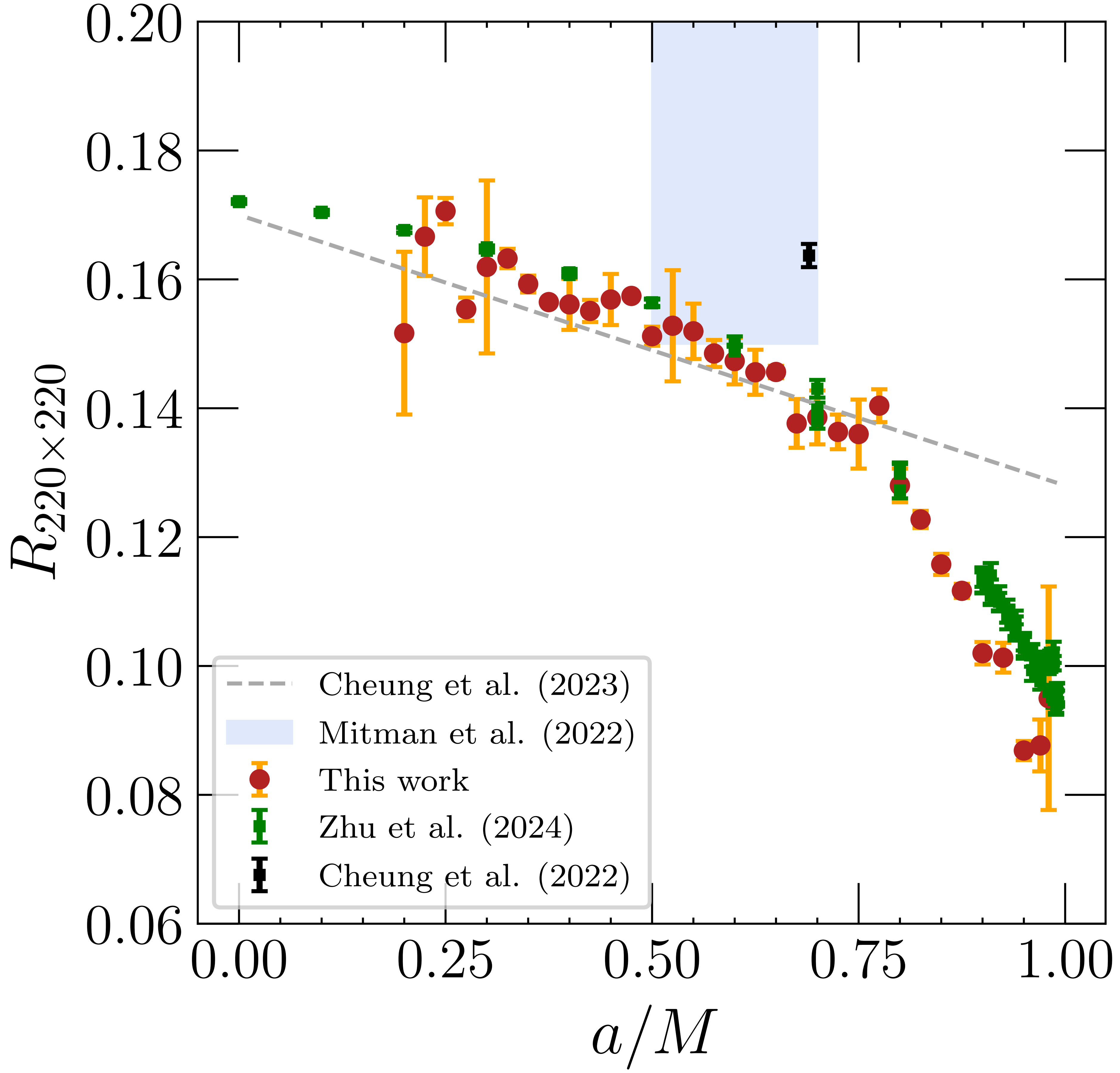
BEYOND THE LINEAR PICTURE

- **Properties**:
  - Dependence on parity initial data Bourg+, 2405.10270
  - Significant dependence on the spin

$$\mathcal{R} = \frac{A_{220\times 220}}{A_{220}^2}$$

Redondo-Yuste, GC+, 2308.14796

Zhu+, 2401.00805



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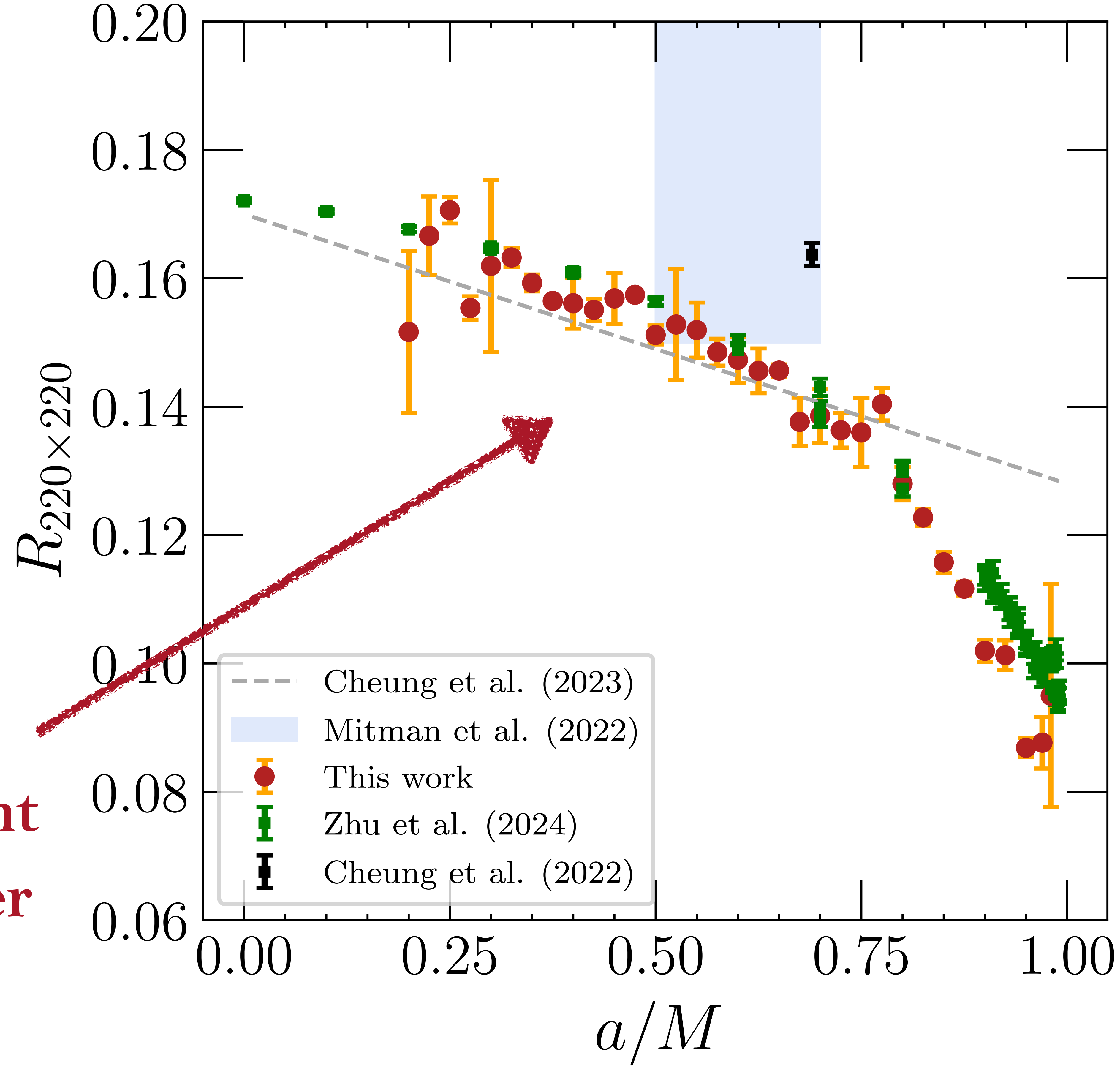

Remarkable agreement nonlinear vs 2nd order

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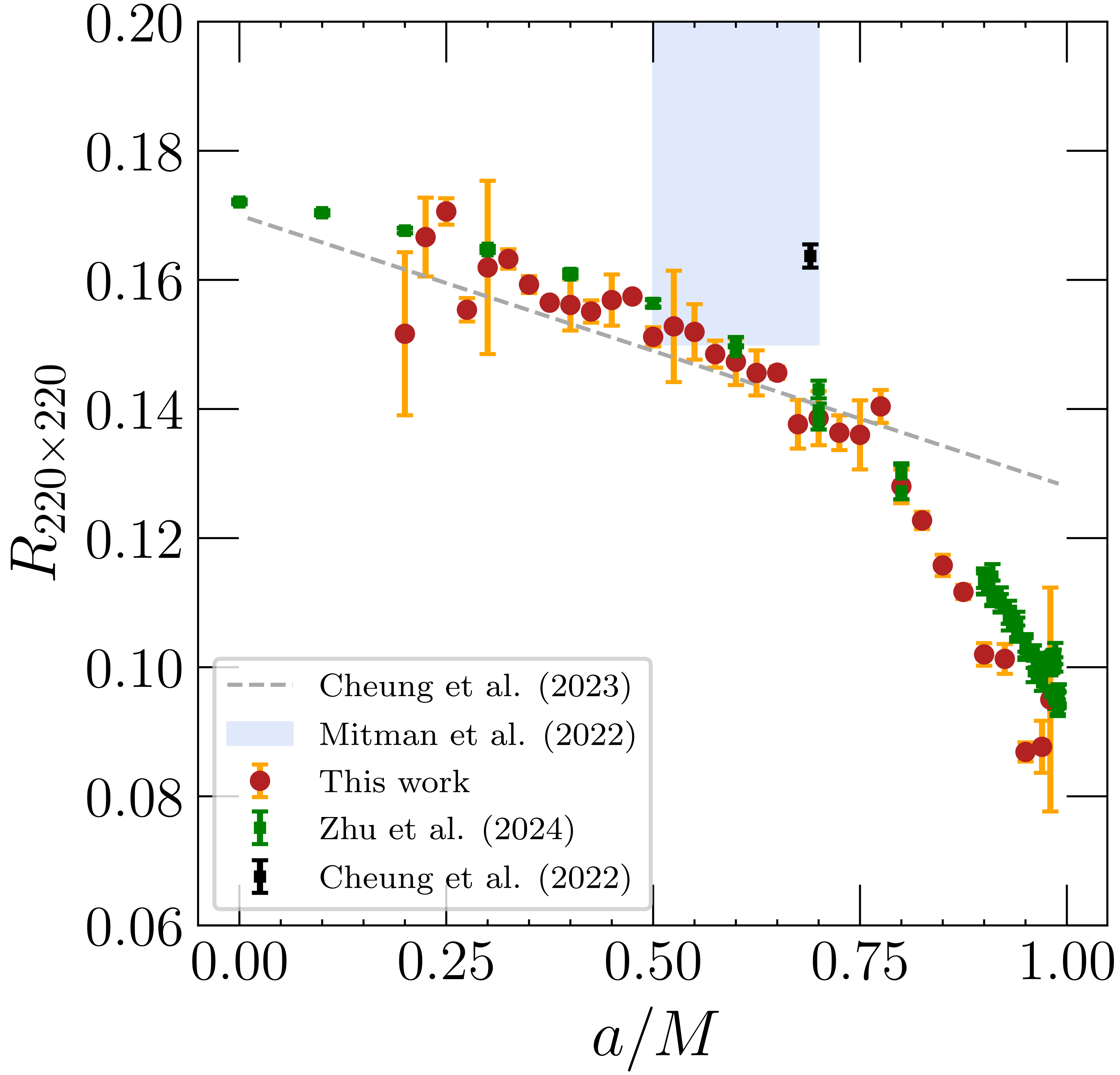

- **Analytical computations**:

Kuntz, today 16:40, Amaldi

  - Schw: Bucciotti+, 2309.08501, 2405.06012, 2405.0601, 2406.14611, Perrone+, 2308.15886

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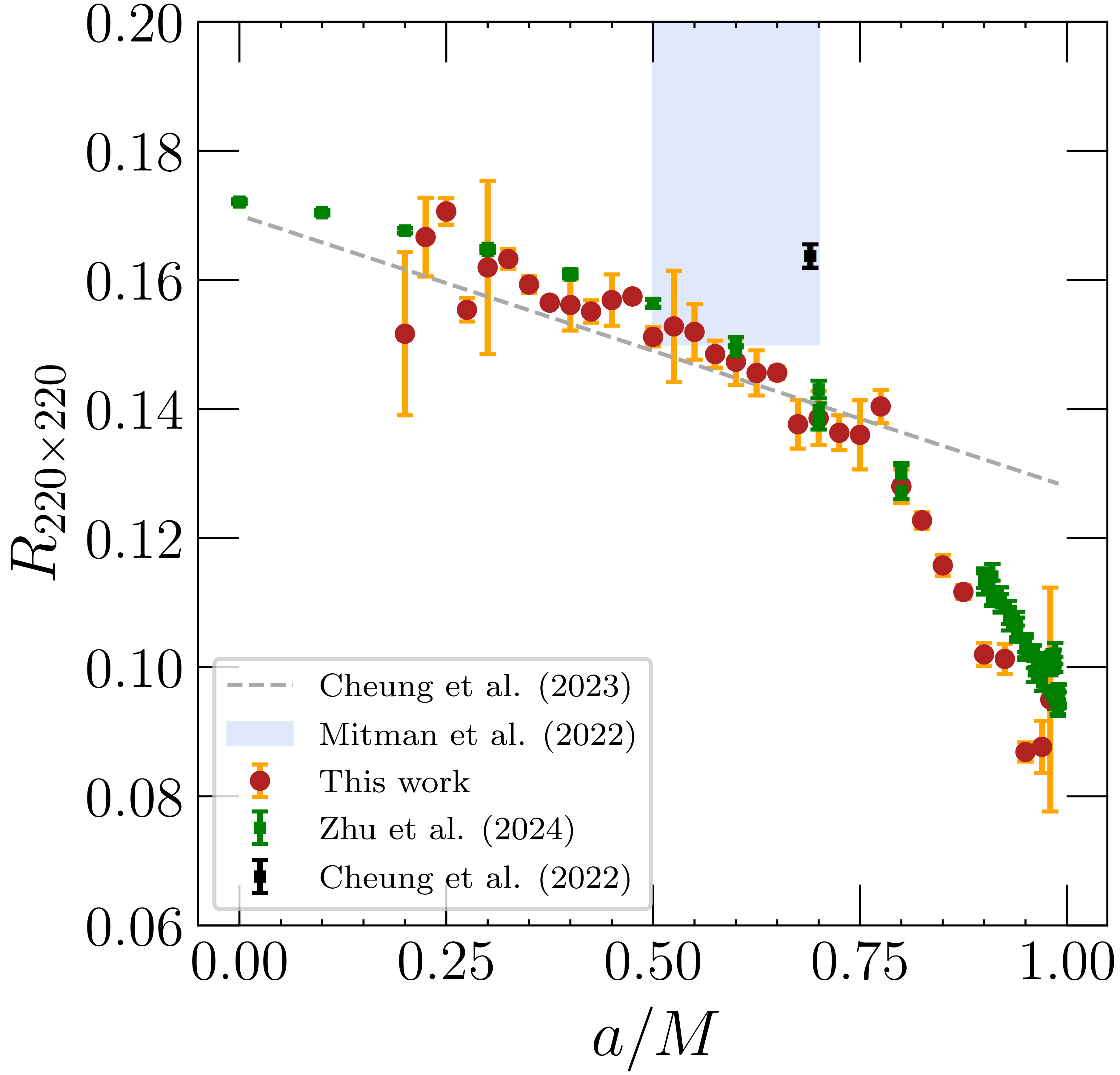
  - Kerr: Ma, Yang, 2401.15516,

Well-captured by angular structure

$$\mathcal{R} = \frac{A_{220\times 220}}{A_{220}^2}$$

Redondo-Yuste, GC+, 2308.14796

Zhu+, 2401.00805



$$(2,2) \times (2,2) \rightarrow (4,4)$$

Nonlinear couplings in (2,2) mode?

Third-order couplings or counter-rotating/radial modes, expect them to be suppressed:

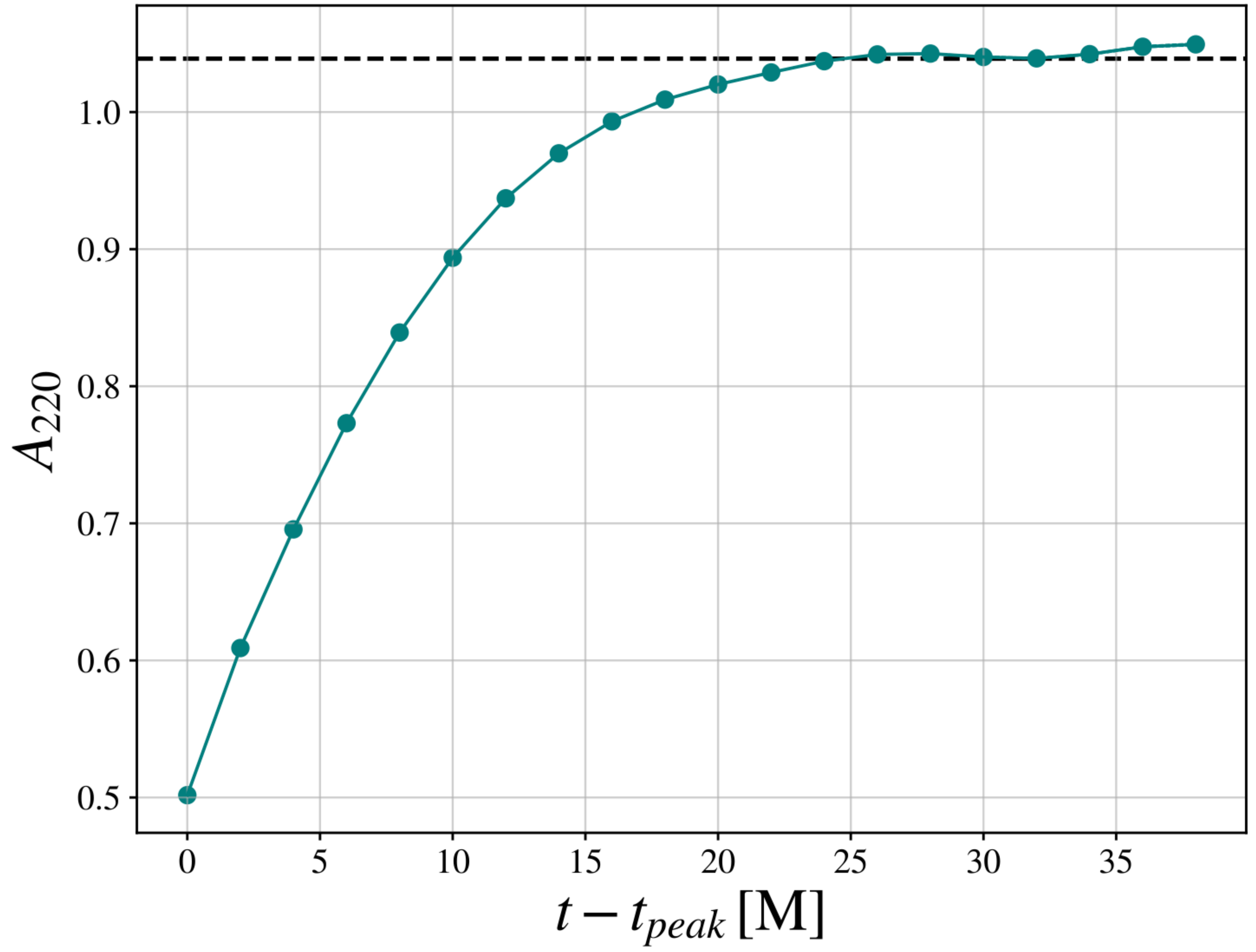
$$(\ell, 0) \times (\ell'', 2) \rightarrow (\ell''', 2)$$

$$\dots$$

Beyond coupling contributions

BEYOND THE LINEAR PICTURE

- To overcome validity regime issues with QNM superpositions, need to take into account "nonlinear" effects
  - **Amplitude growth**



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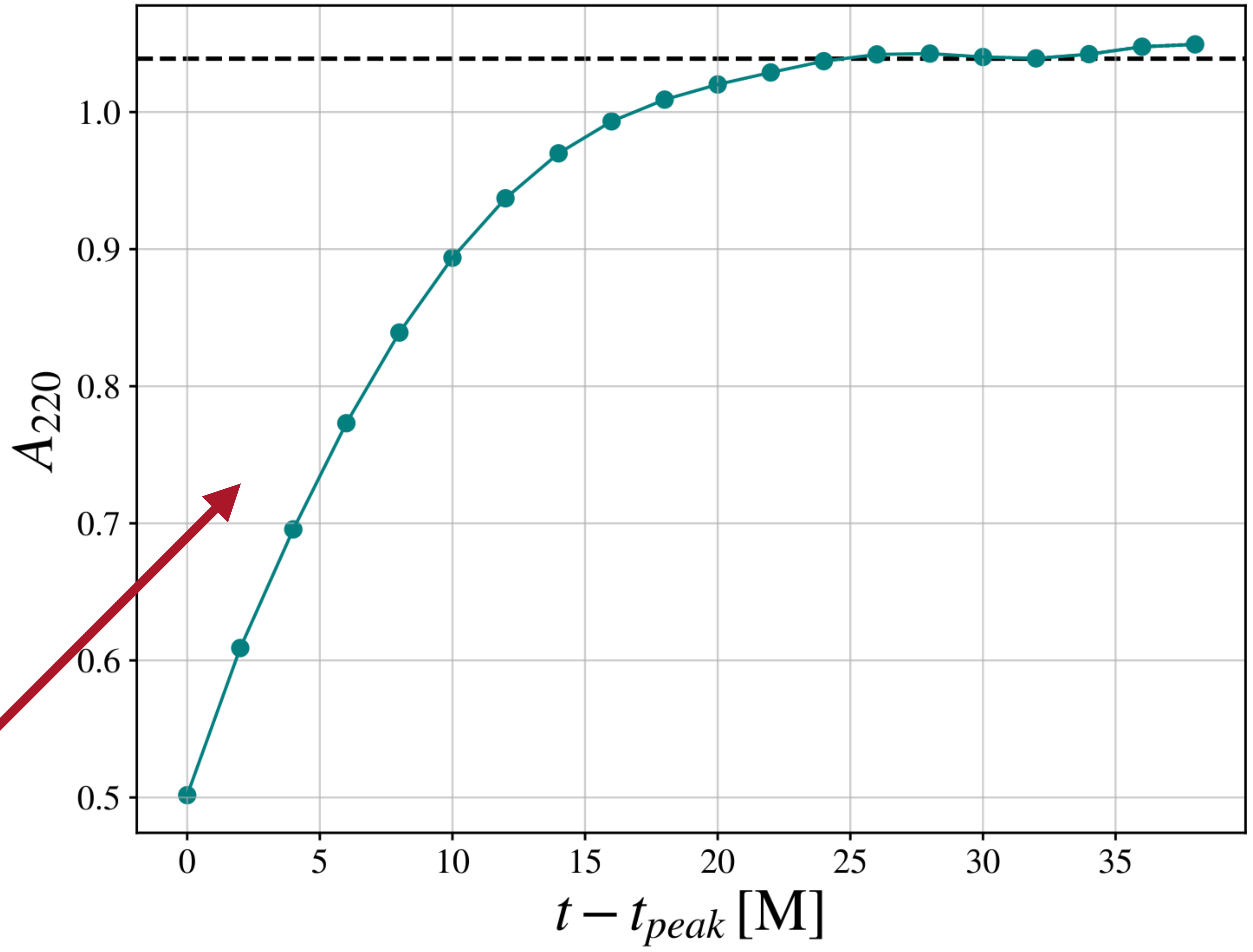
QNM shifts, quantum-mech PT?
(poster by Jacopo Lestingi)



Transient due to "initial data" (binary multipoles-driven)

Bohranian+, 1901.08516

OPEN PROBLEM!

- Many complications in current spectroscopy analyses derive from lack of **understanding of early ringdown**
- Need *physical* and *interpretable* model to move forward

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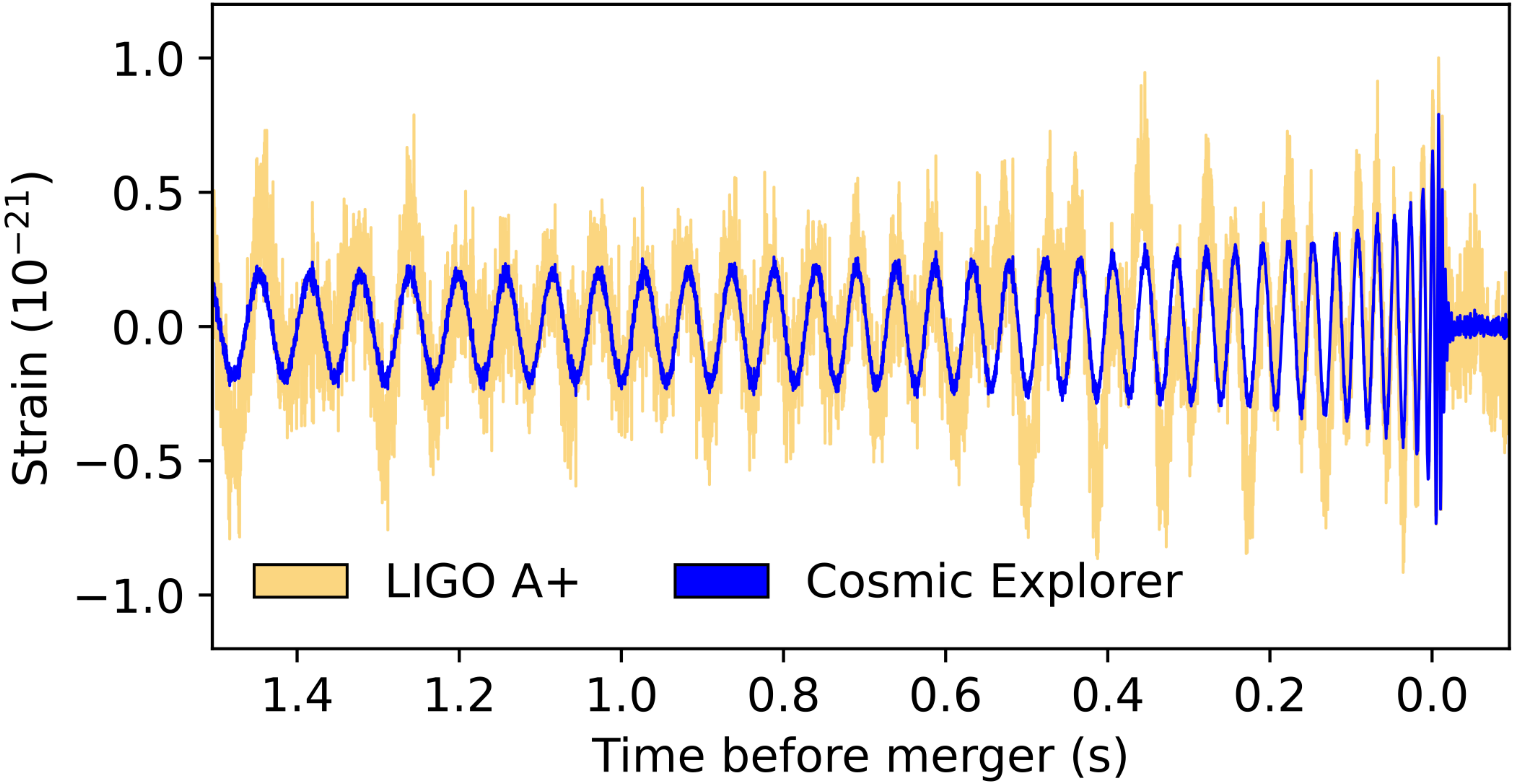
- Many complications in current spectroscopy analyses derive from lack of **understanding of early ringdown**
- Need *physical* and *interpretable* model to move forward
- This is still an open issue: strong-field two-body problem *numerically solved*, but not yet *analytically understood*
  - Important for **next gen**. and to **extend** the model (environmental corrections, beyond GR, …)
  - Unavoidably tied to "*When does the ringdown start?*"

Future detection prospects

A LOUD FUTURE



Evans+, arXiv:2109.09882

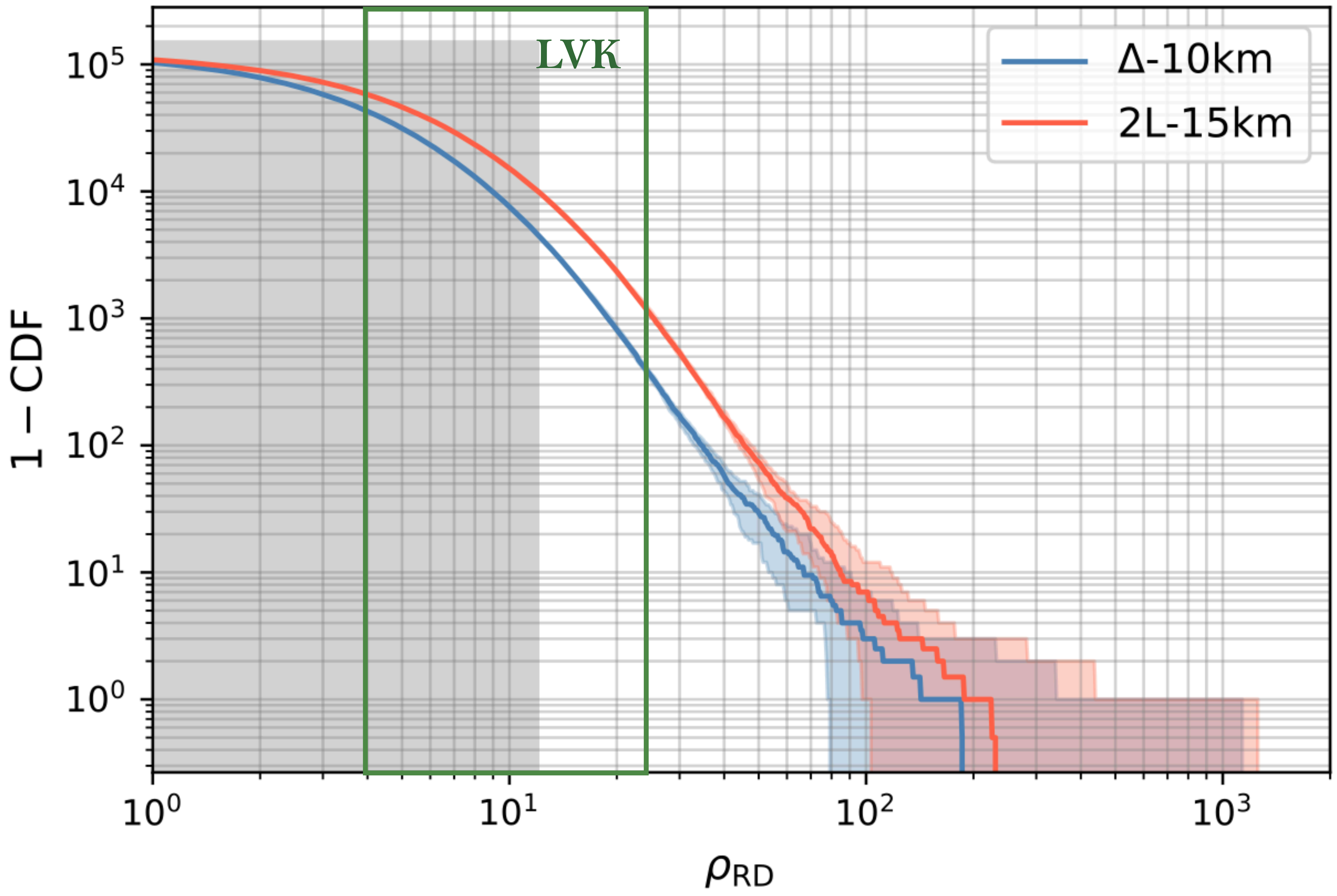
BACK TO THE FUTURE

- Future **large SNR** will present many complications:

- Significant **data analysis challenges**

- Reward: unprecedented **opportunities** for **signs of new physics** (dark matter, new "charges" modified gravity, …)

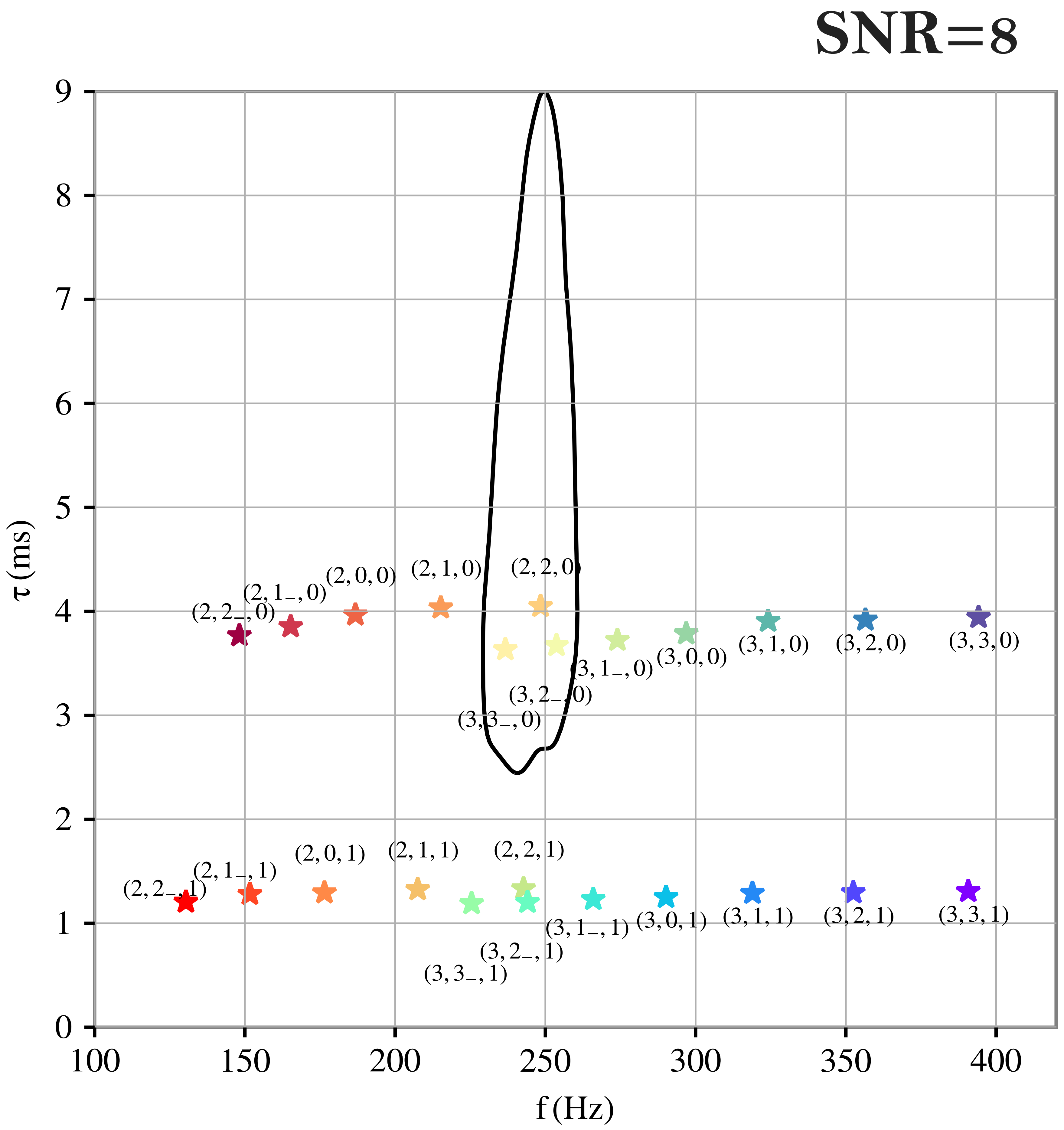
Toubiana+, 2307.15086
Pitte+, 2406.14552



Bhagwat+, arXiv:2304.02283

BACK TO THE FUTURE

- Transitioning to **high-precision** measurements:



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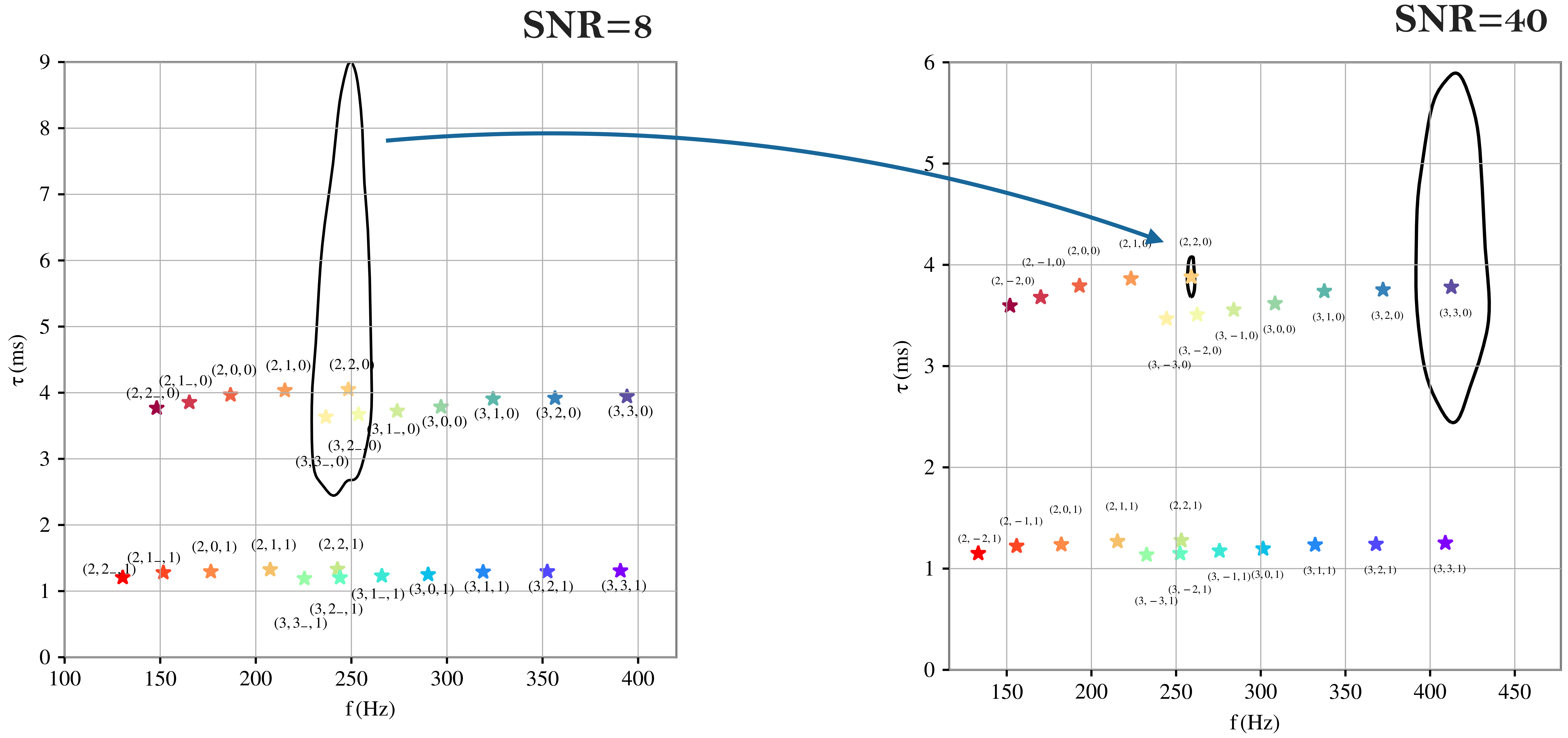
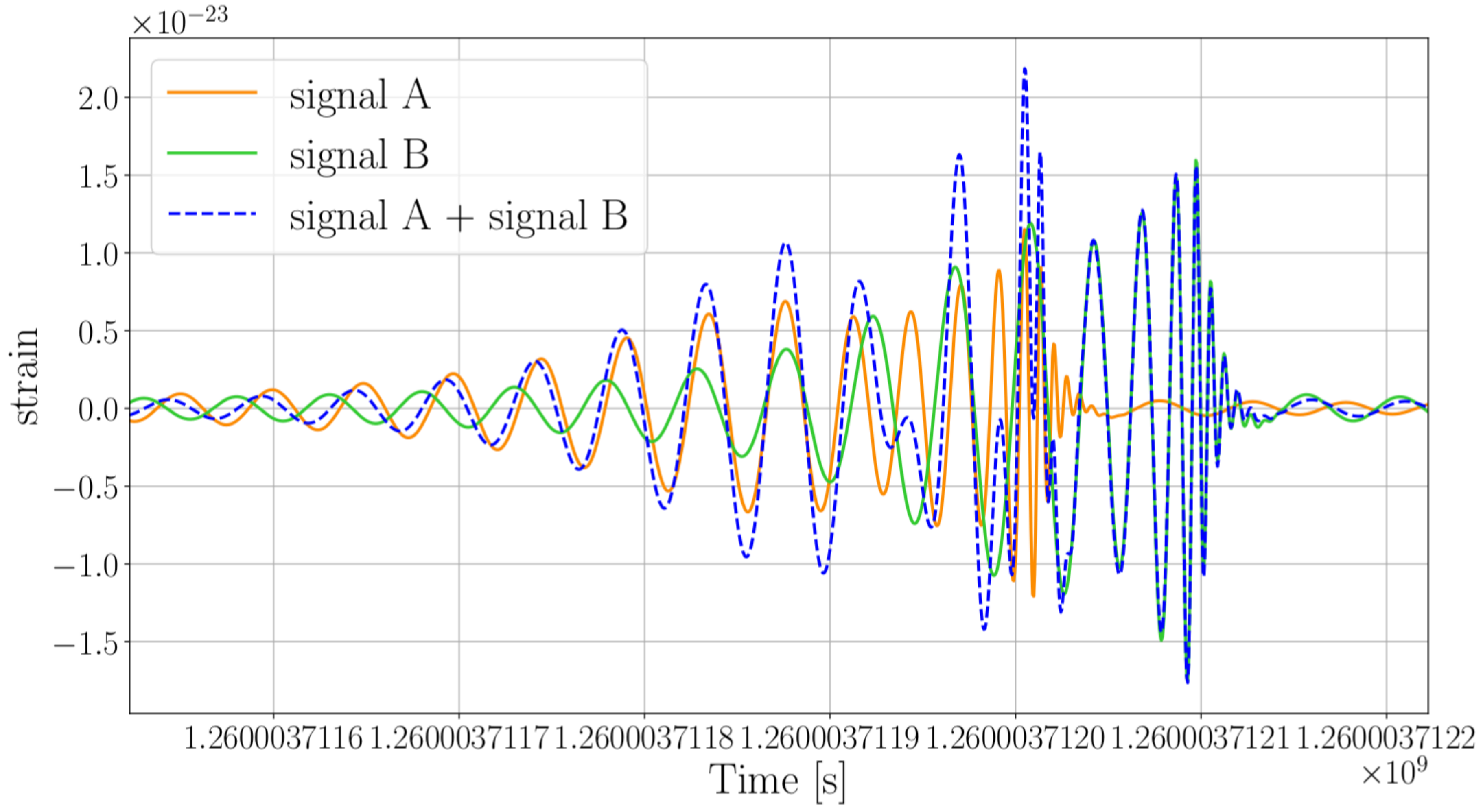


q=3, $\chi_1 = \chi_2 = 0$ **vanilla** case

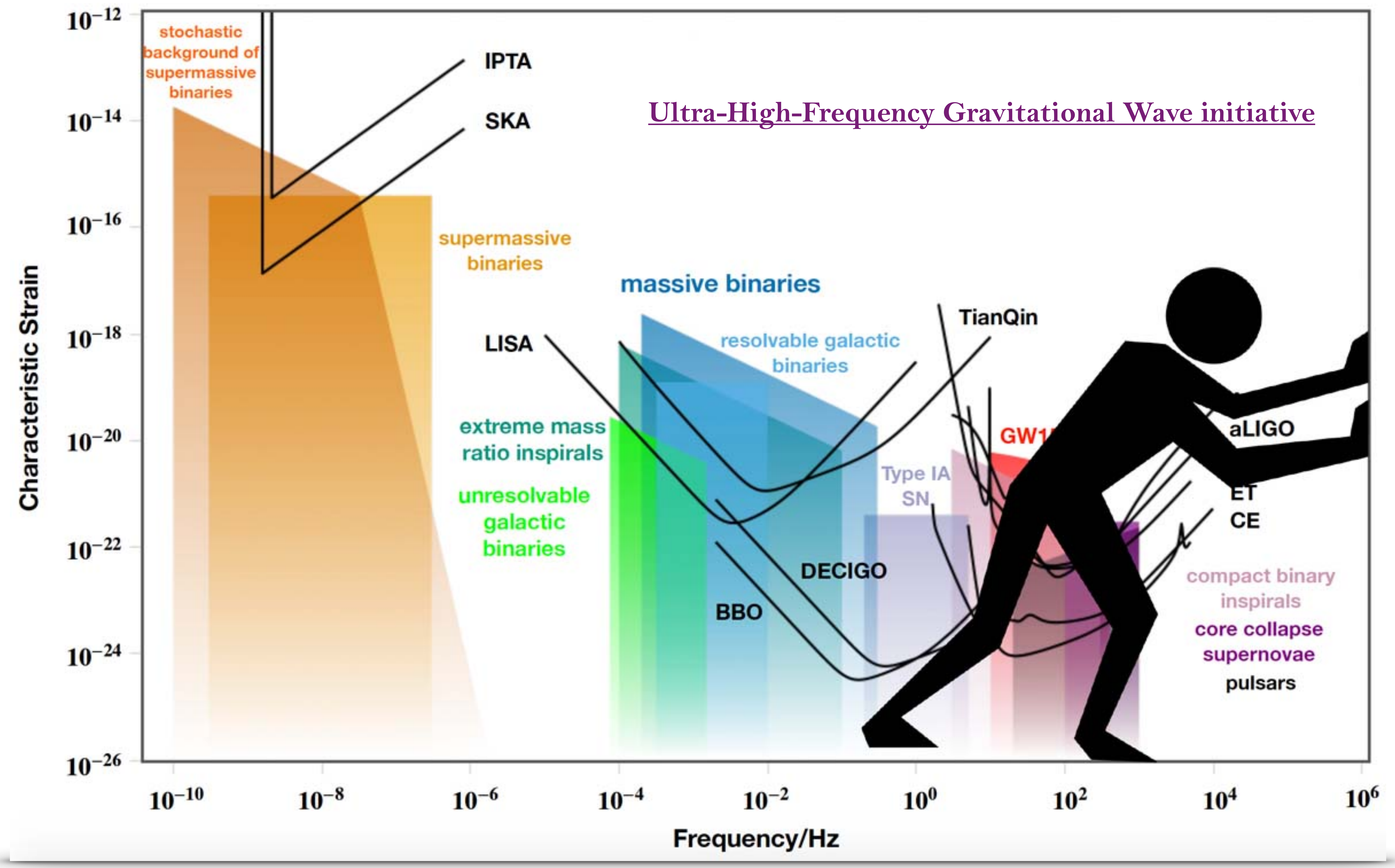
CONSTRUCTING THE HIGH-ACCURACY TOOLBOX

- **Extend** standard GW likelihood, strategy: **Bayesian global fit**
  - Marginalisation over **theoretical uncertainties**
  - **On-source** and **joint** noise-estimation
  - Inclusion of **time-varying background** $S_n(f;t)$
  - Excision of **data gaps**
  - Overlapping signals (**confusion** noise)
- **High rates** (SNR) will require **highly efficient** (**accurate**) models.

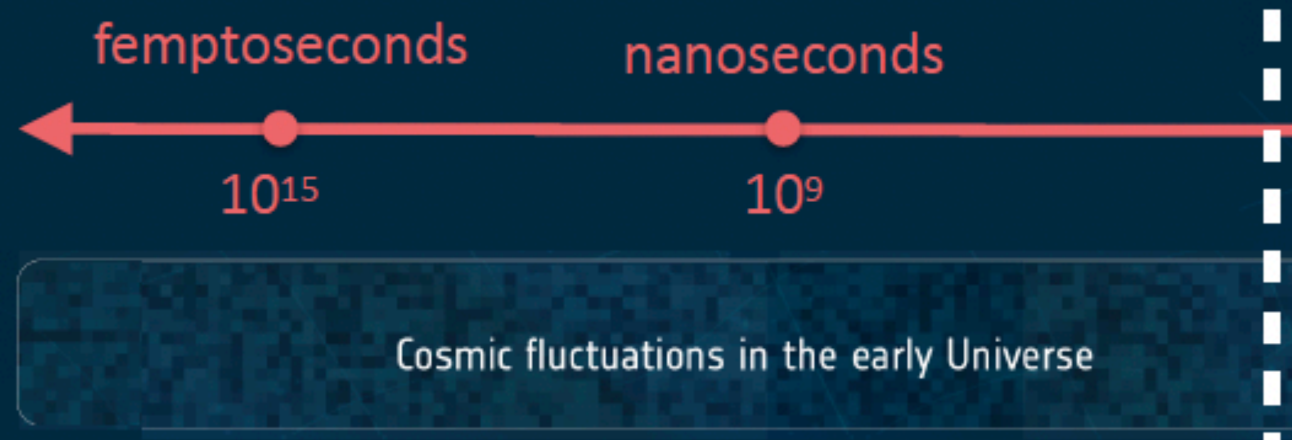


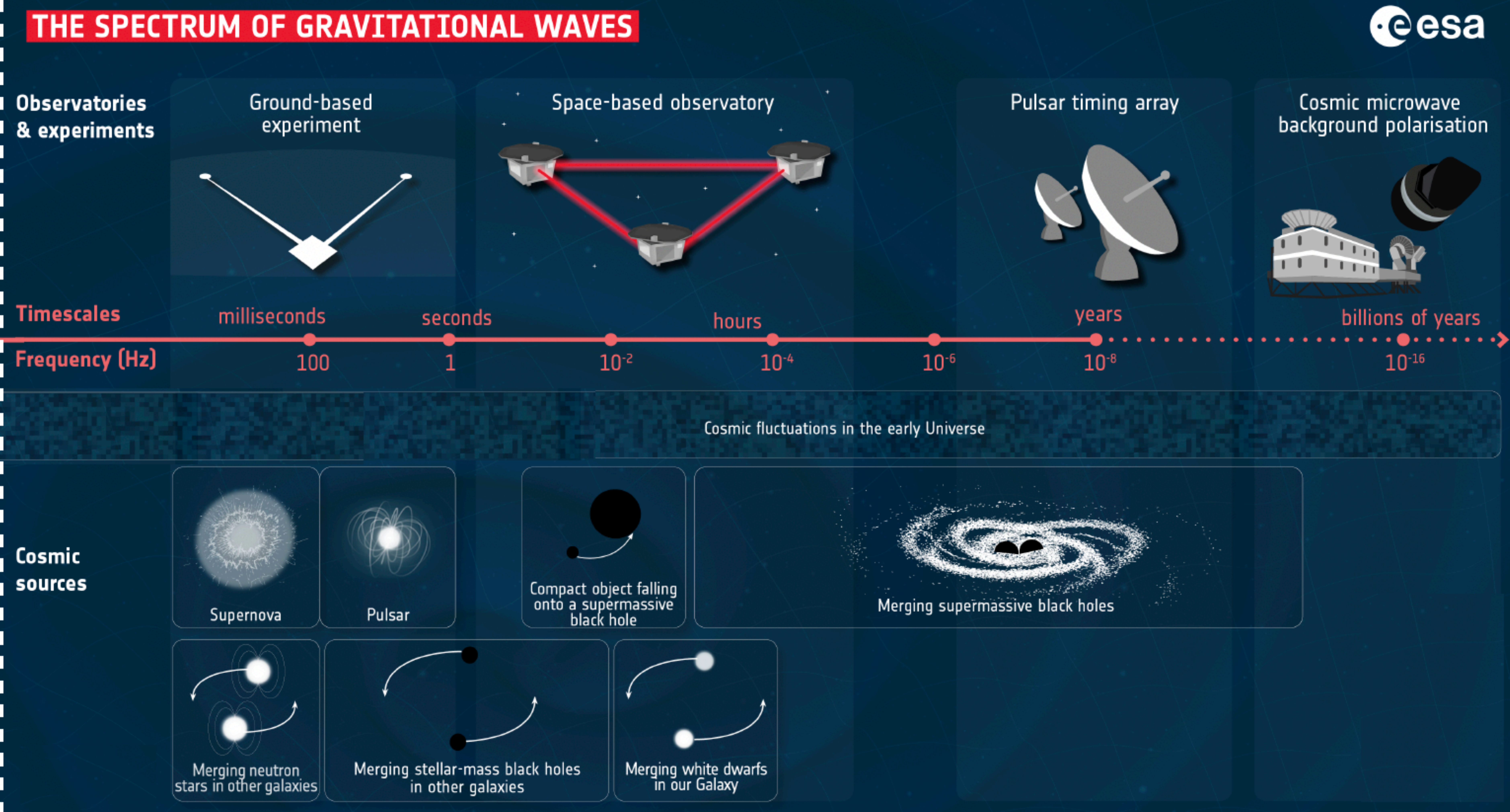
Janquart+, arXiv:2211.01304

CONCLUSIONS



Ultra-high frequency GW experiments





Exotic subsolar compact objects

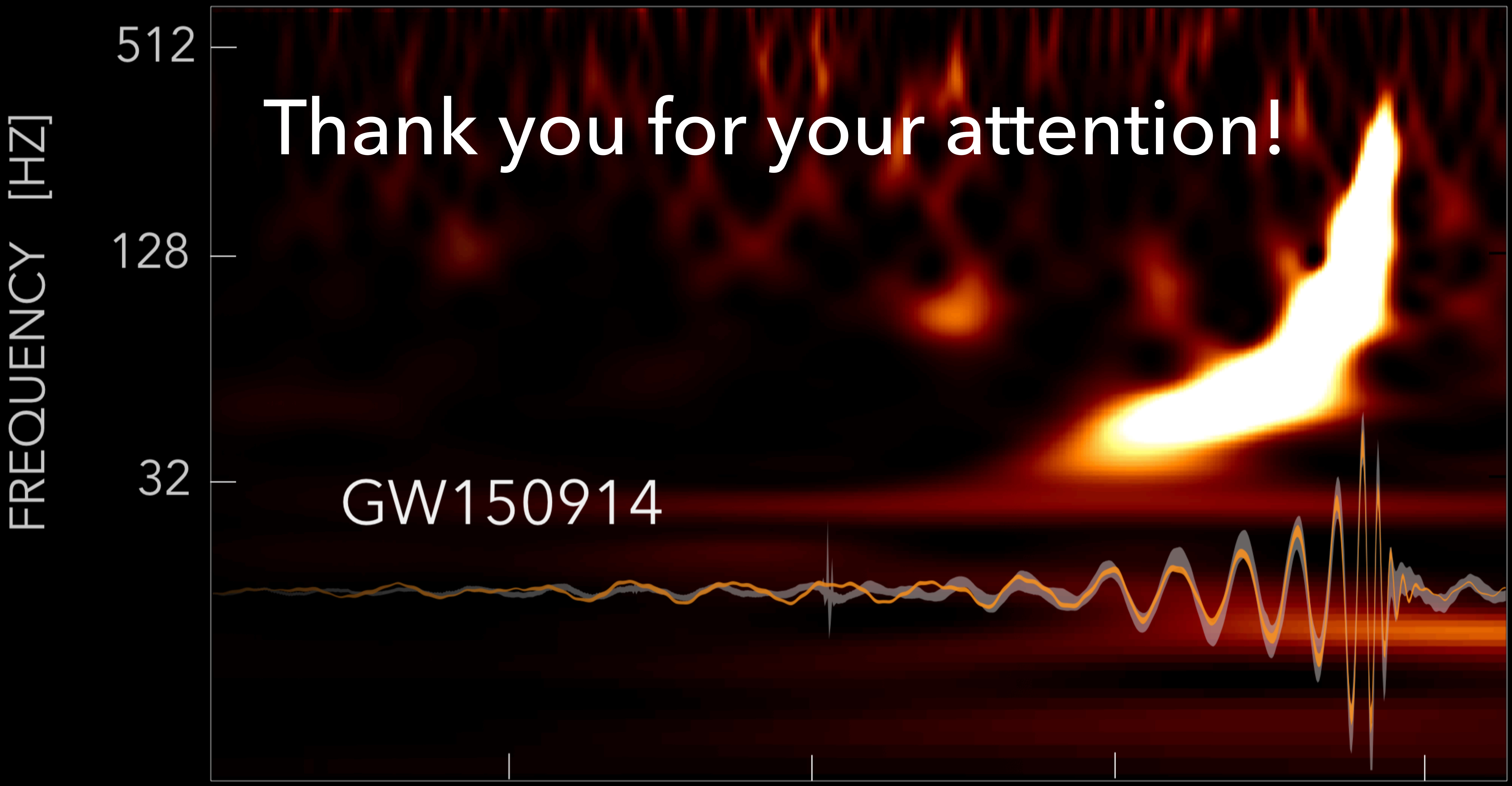
Axions

Phase trans. @ GHz:
~ GUT/String scale

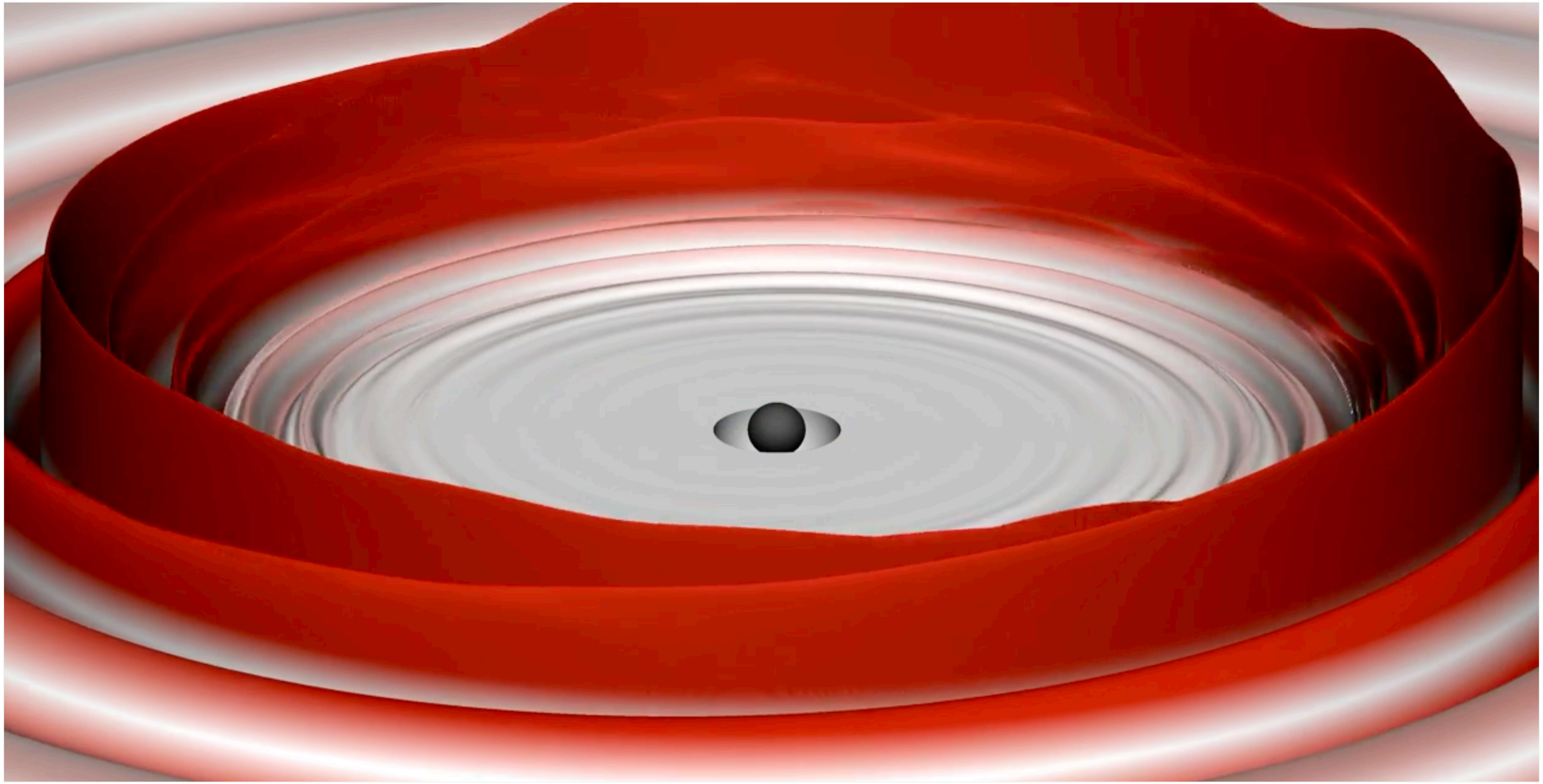
CONCLUSIONS AND PROSPECTS

- The analysis of **black hole ringdown** signals is far richer than initially expected, and a powerful tool to:
  - Test our current **gravity paradigm**
  - Investigate the **nature** of dark **compact objects**
  - Search for signs of **new physics**
  - … infer **horizon** properties?

Credits: Jani, Ghonge



BLACK HOLE “STRUCTURE”



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- Rotating BHs acquire:

$$Q = -\kappa \chi^2 m^3$$

BH: $\kappa = 1$
NS: $\kappa \in [2,14]$
BS: $\kappa \in [10,150]$

GWTC-3 Testing GR, LVC (2021), 2112.06861

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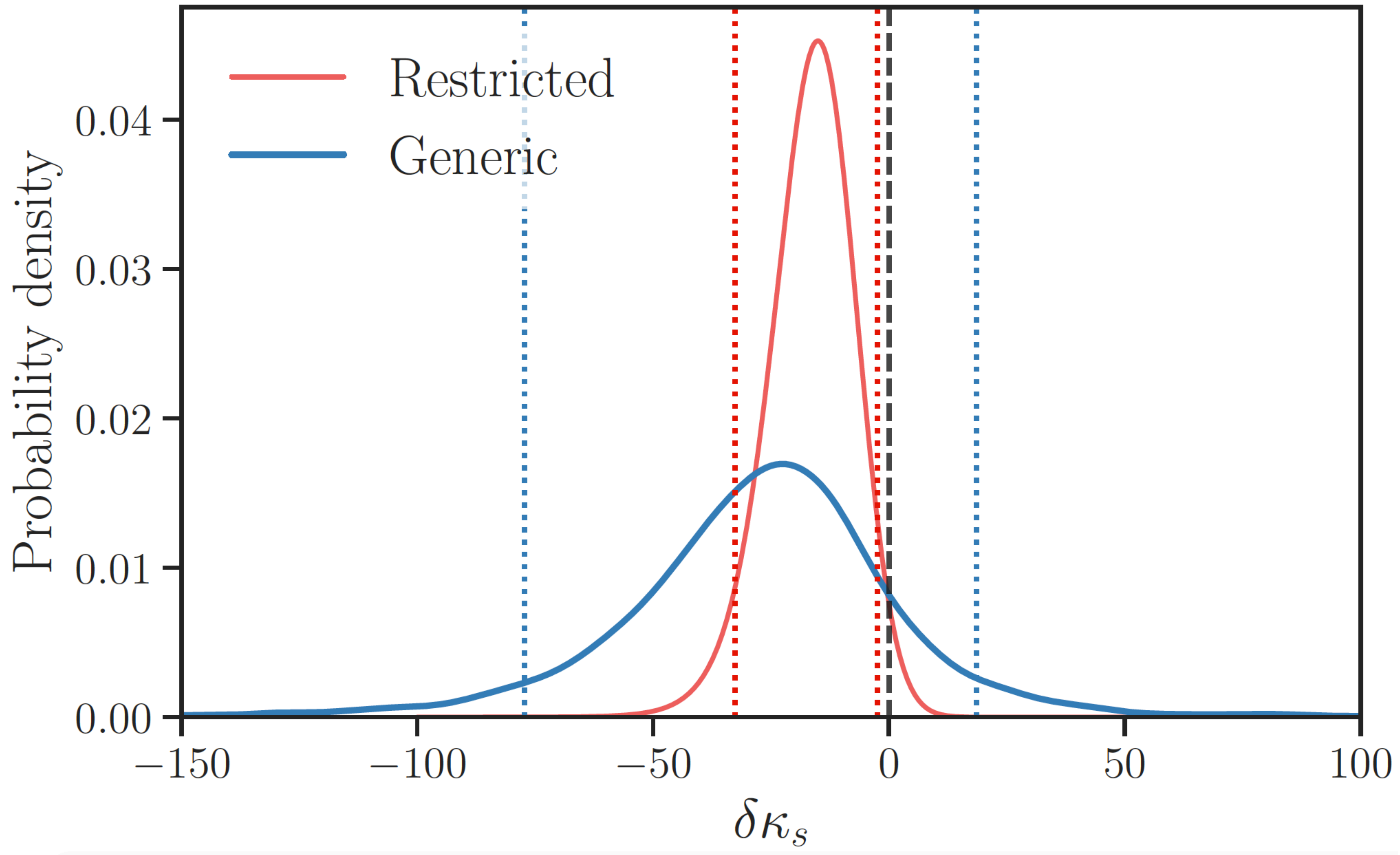

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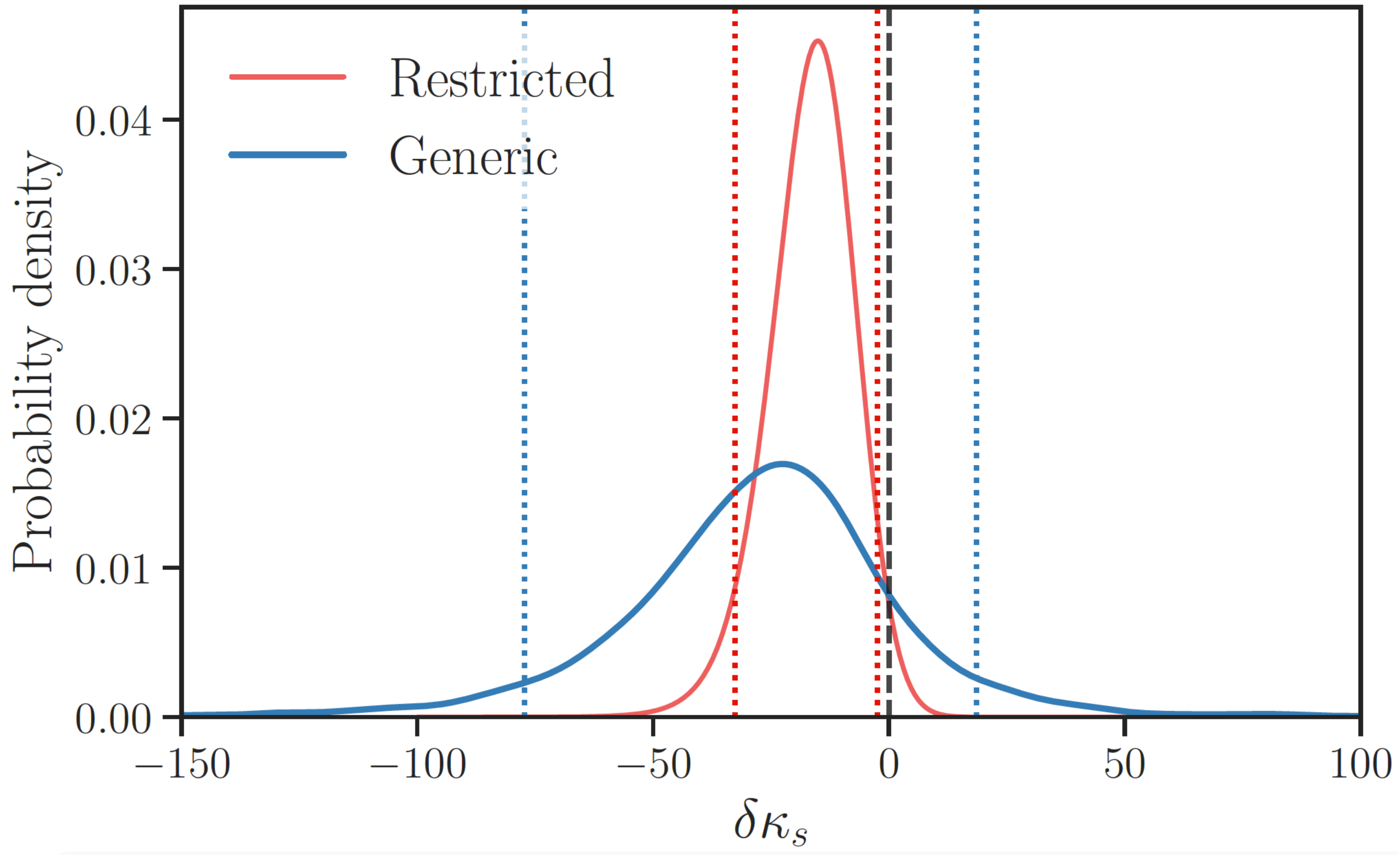

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- Lacks inclusion of: higher-modes, tidal polarizability, inspiral QNM low-f resonances, tidal-heating (more later)

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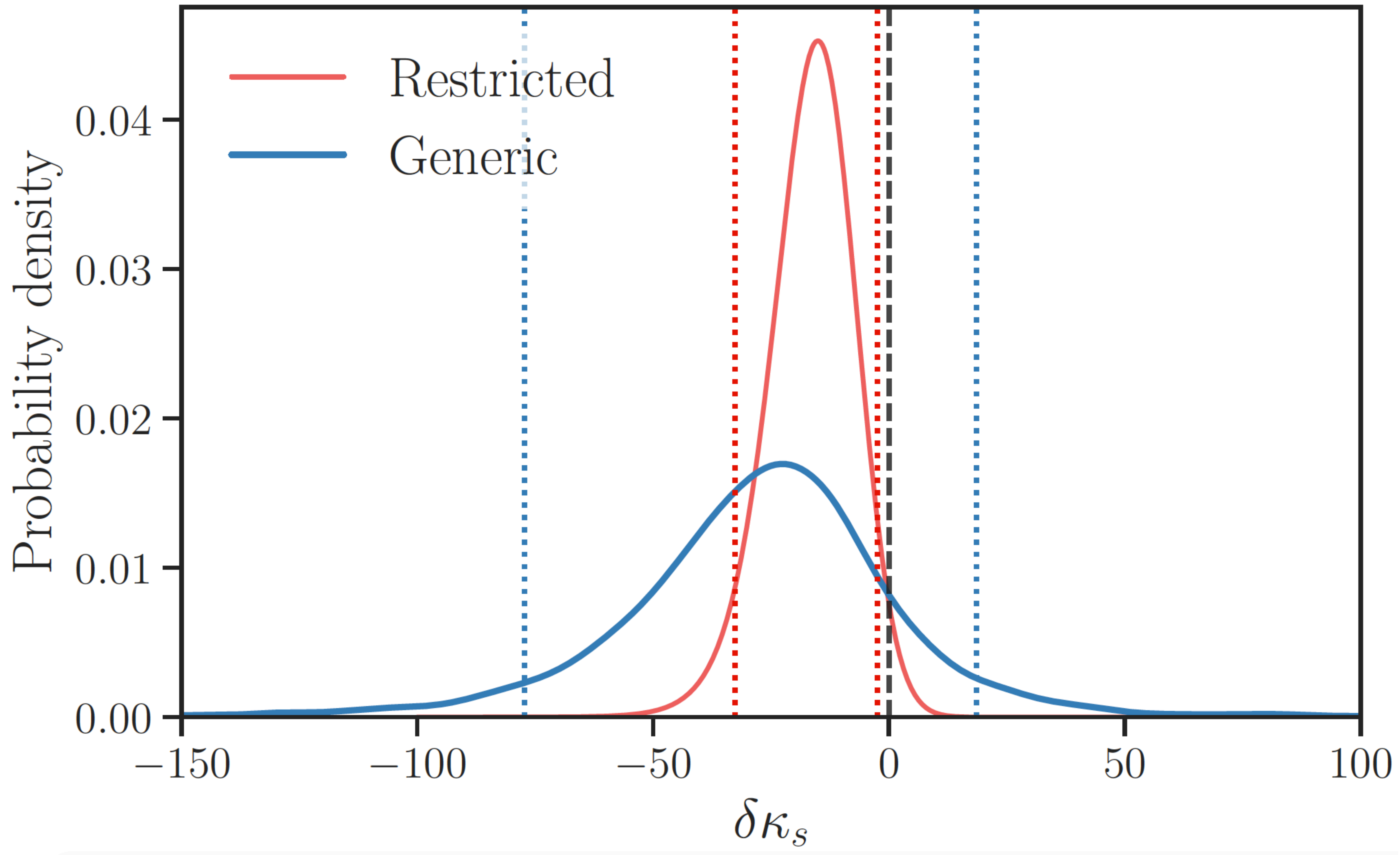
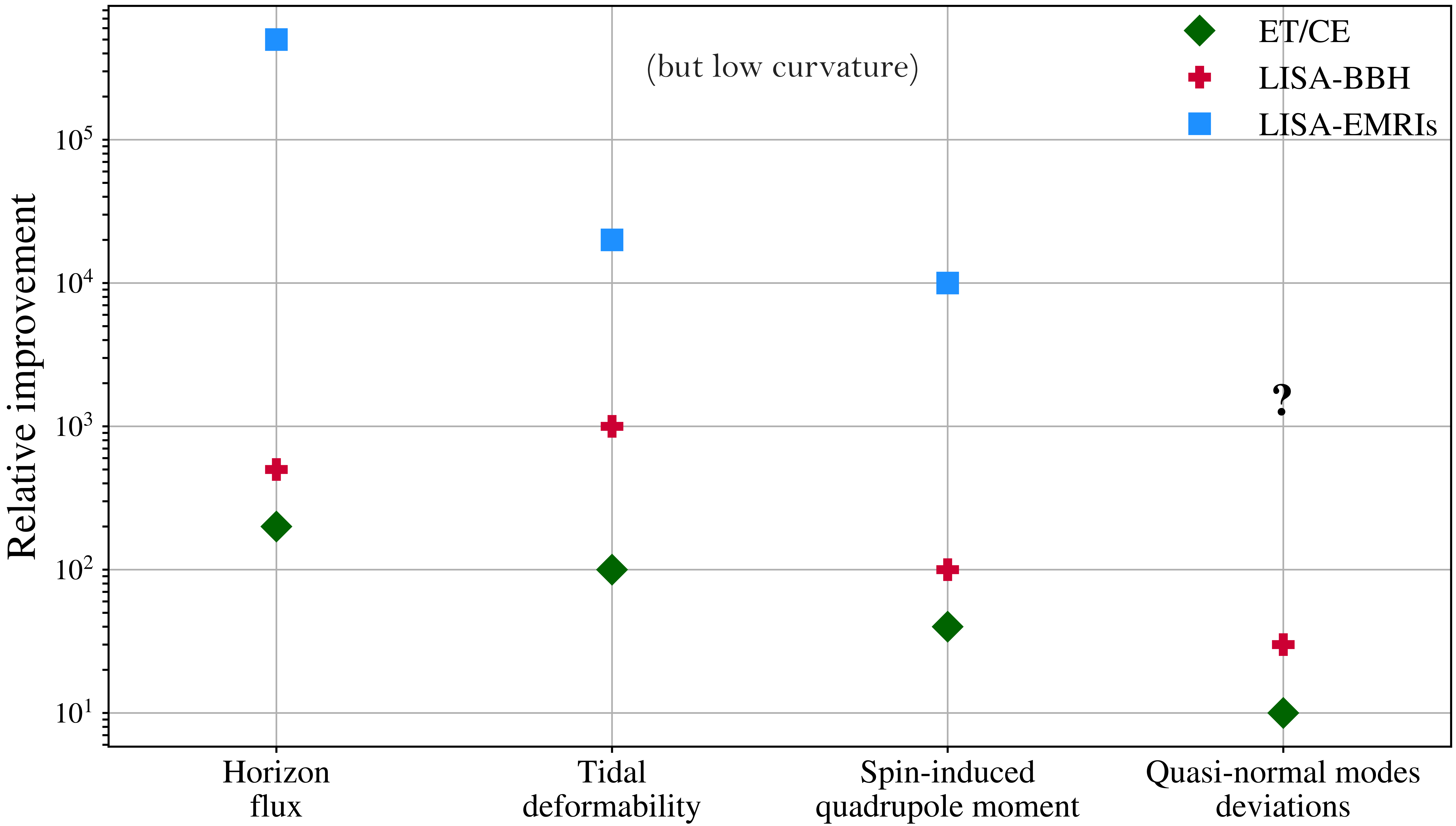


GWTC-3 Testing GR, LVC (2021), 2112.06861

Can we say something on horizon physics from ringdown?

SPACE SUPREMACY



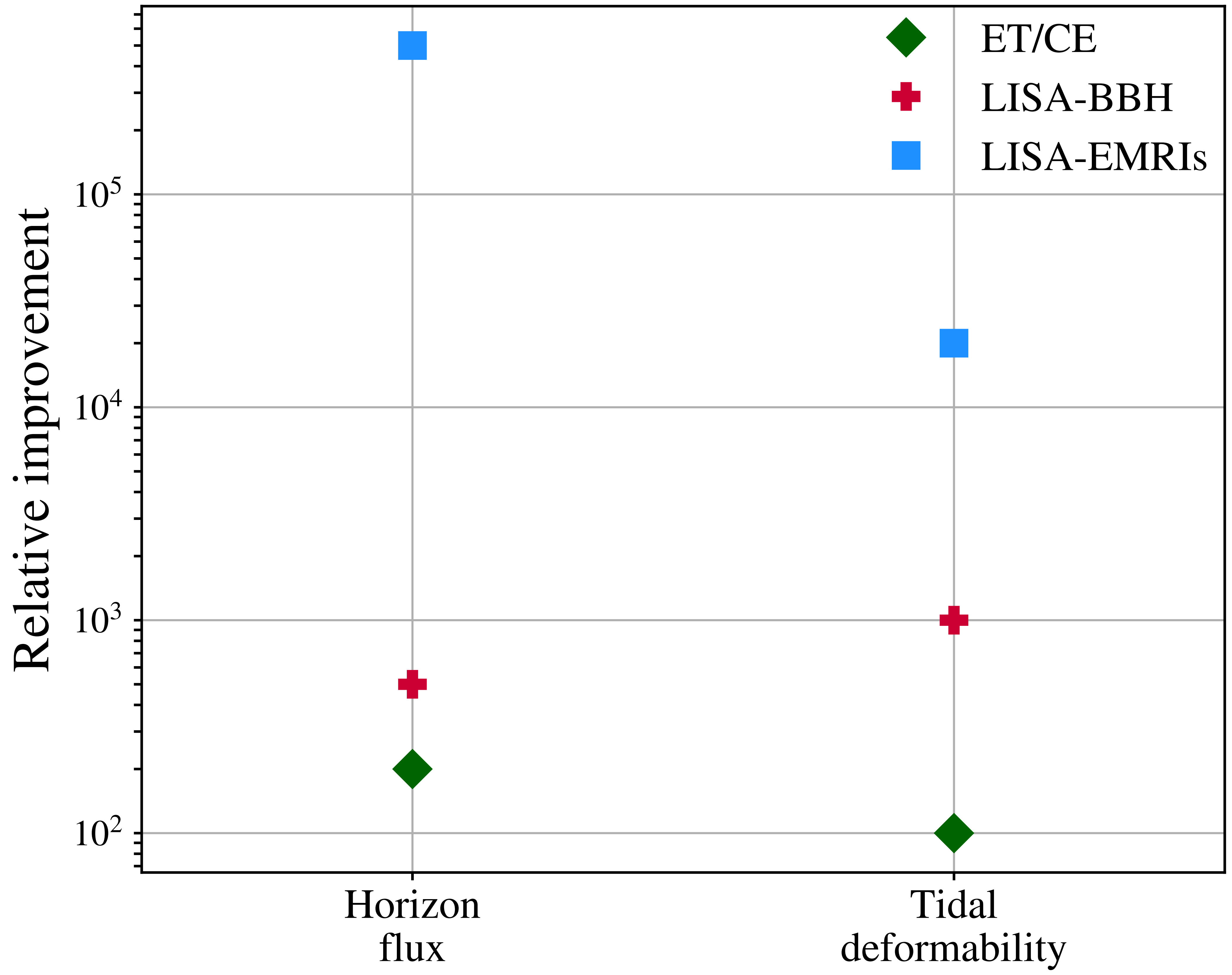
Babak+, arXiv:1703.09722 Cardoso-Pani, arXiv:1904.05363 Datta+, arXiv:1910.07841 Maselli+, arXiv:1910.12893

HORIZON FLUX (TIDAL HEATING)

- Will start to be meaningfully **measurable** only by **3G** or **LISA**.

Lai-Li, 1807.01840

Current precision 1 ± 20



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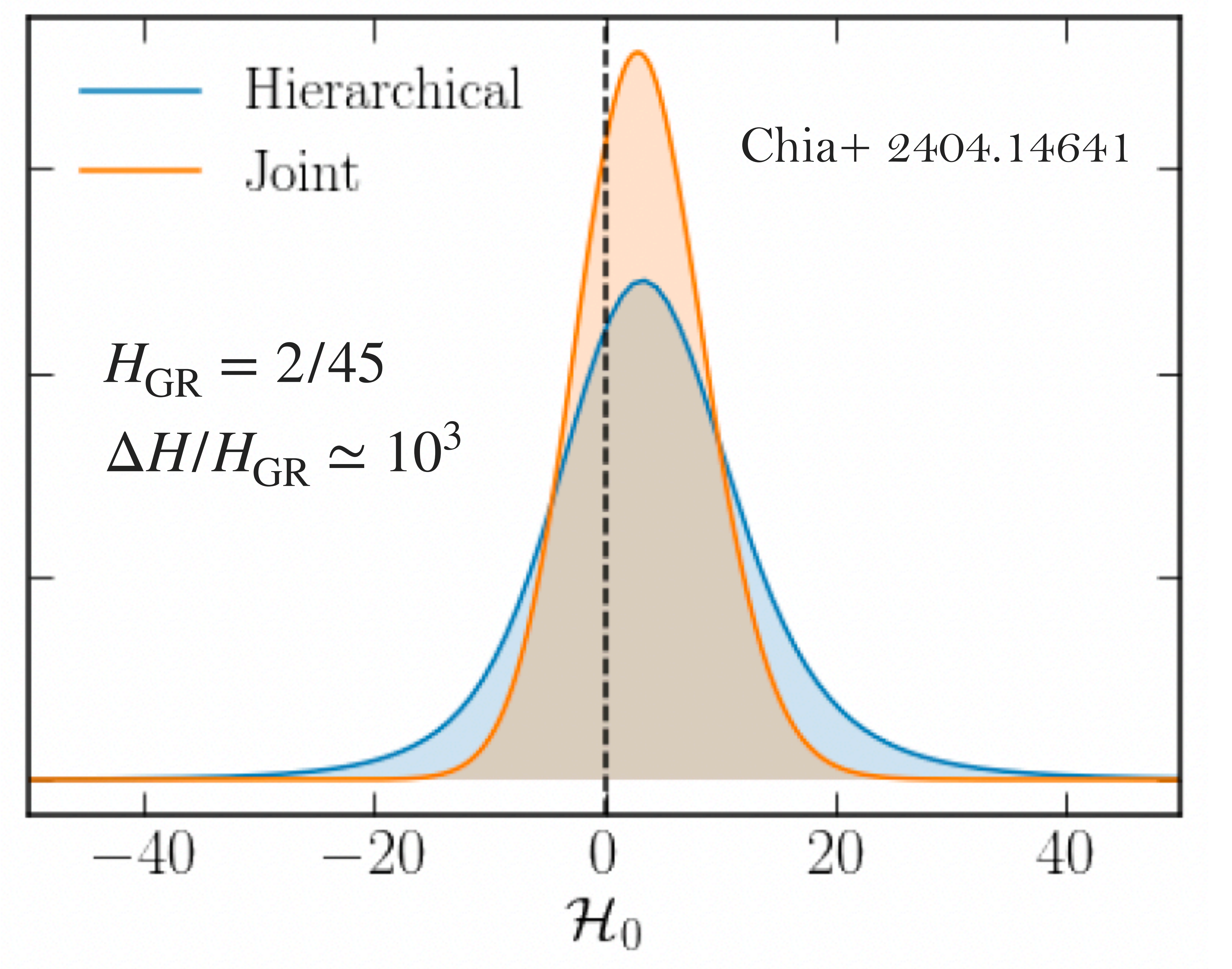

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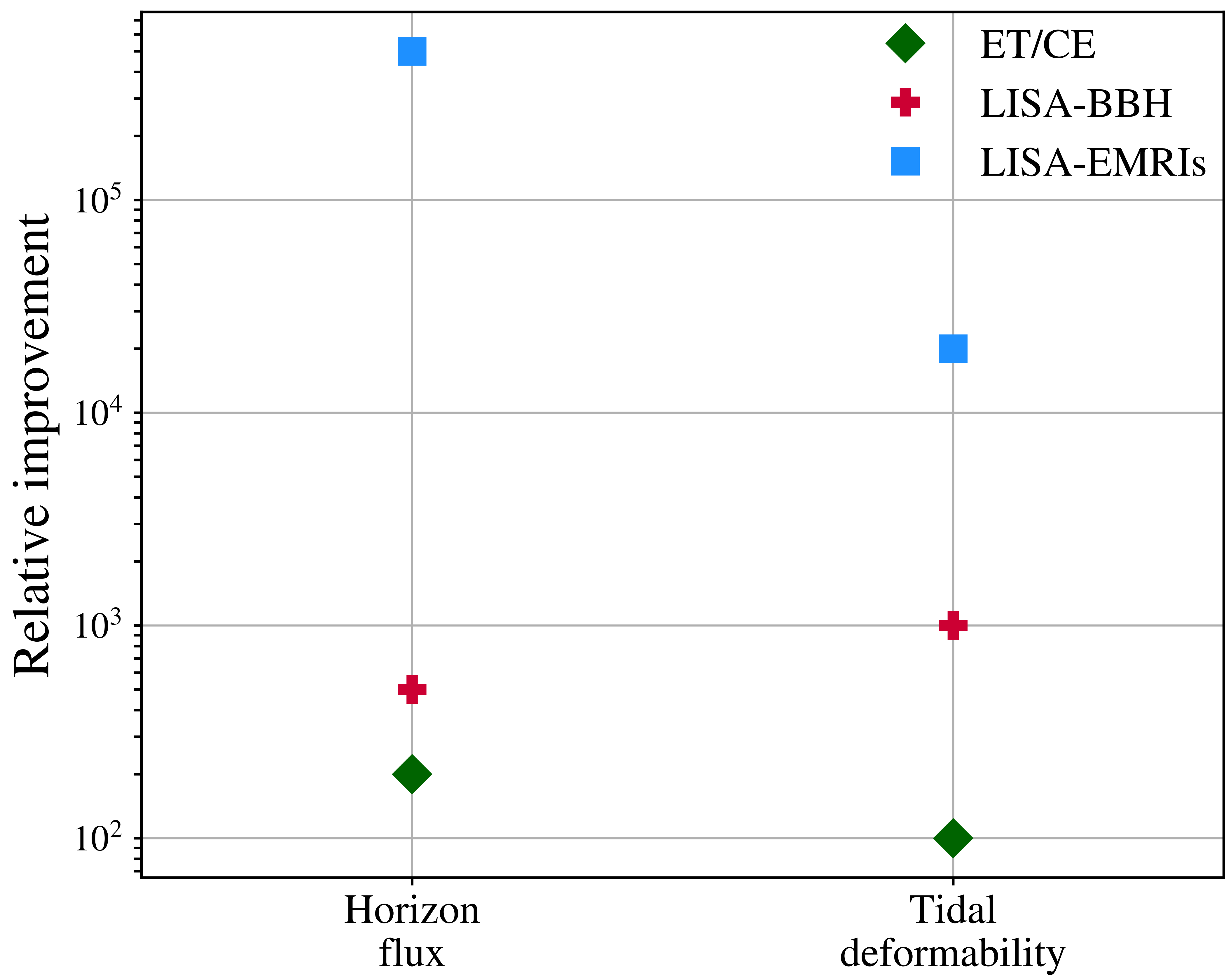

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- **Eccentricity** boost to this measurement? Datta+, 2404.04013, Chiaramello-Gamba, 2408.15322

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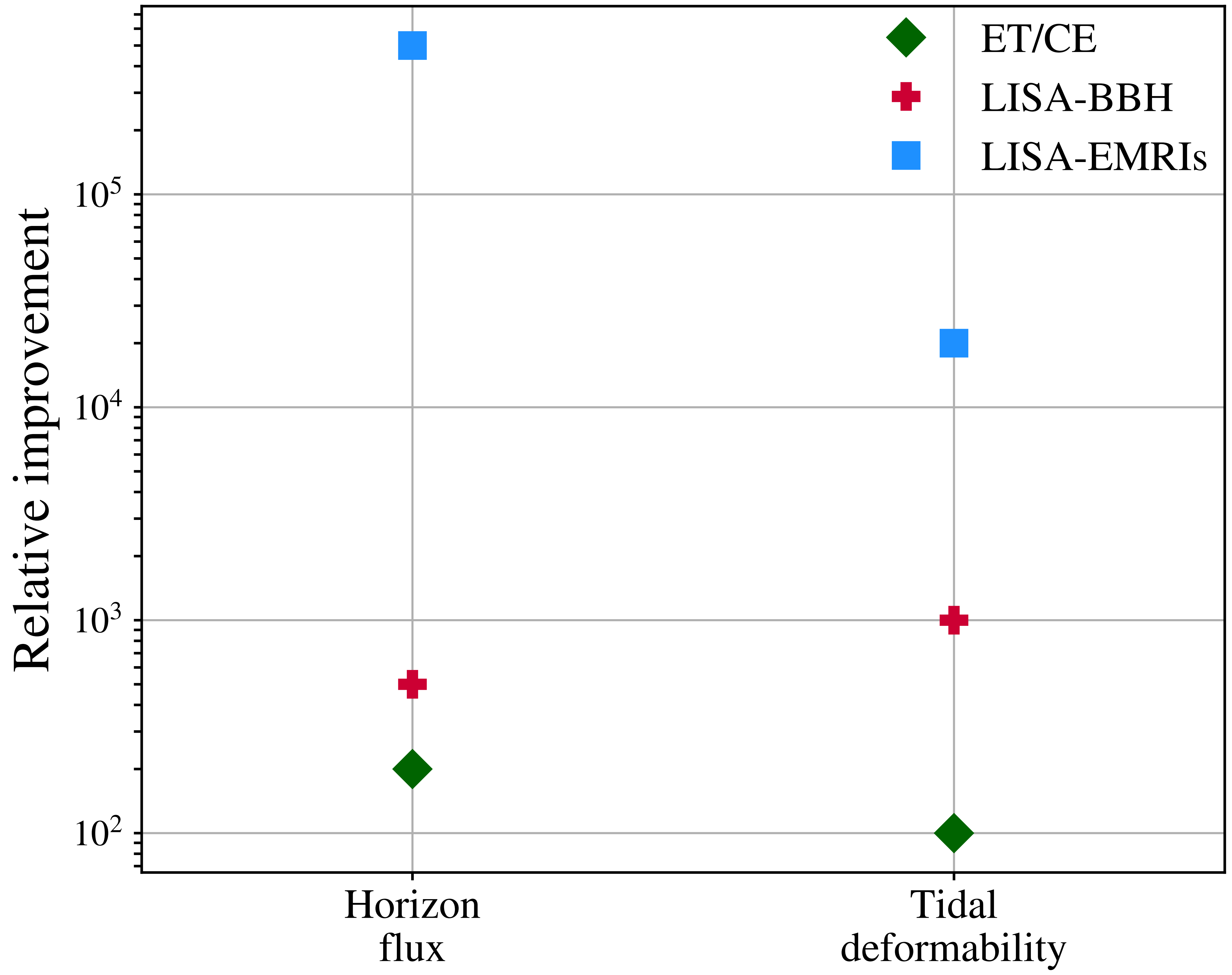

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.

Ferrari, Kokkotas, Mashoon, ….

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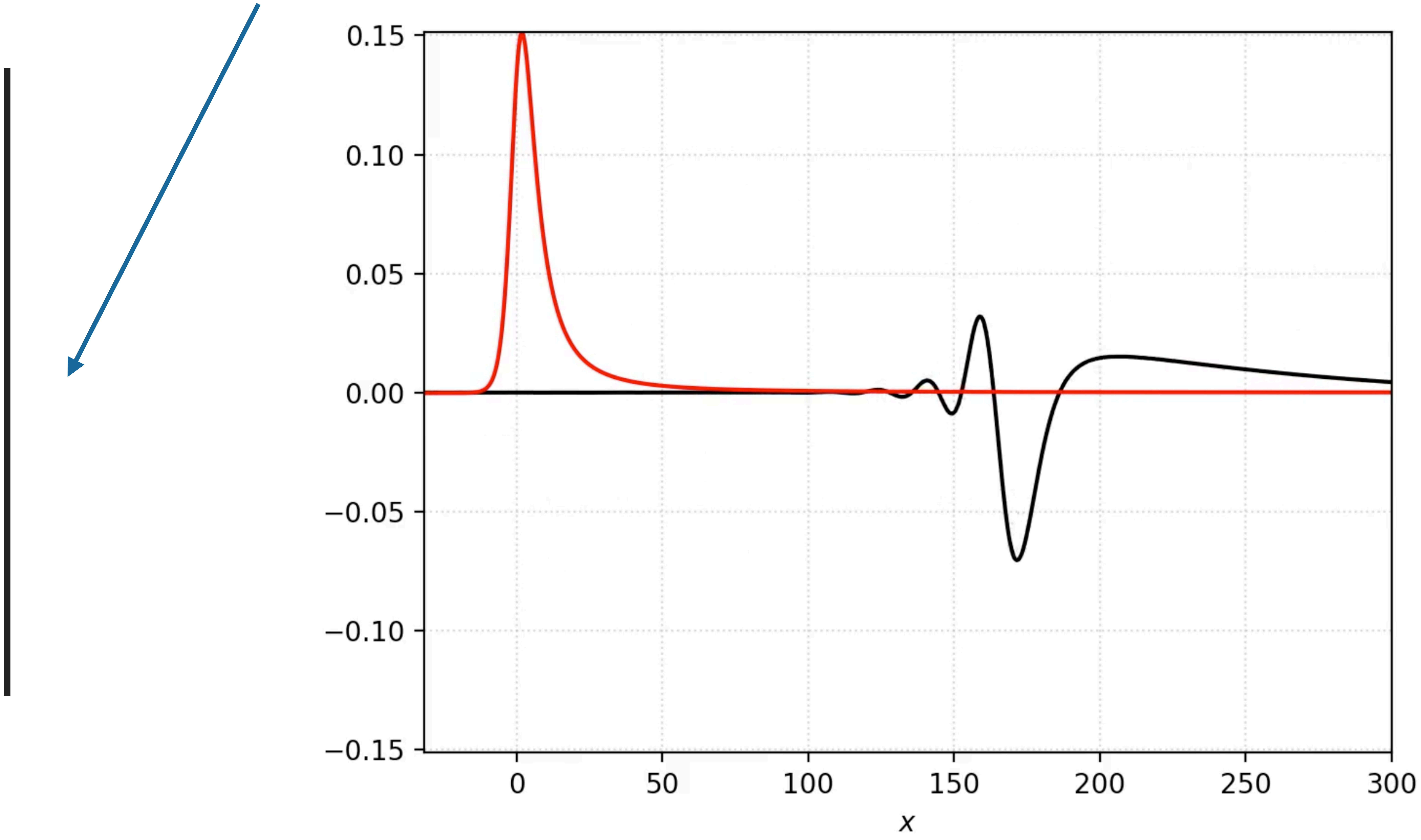
- Standard ringdown emission dominated by light-ring physics.

Ferrari, Kokkotas, Mashoon, ….

- Might probe the horizon through some “exotic” physics

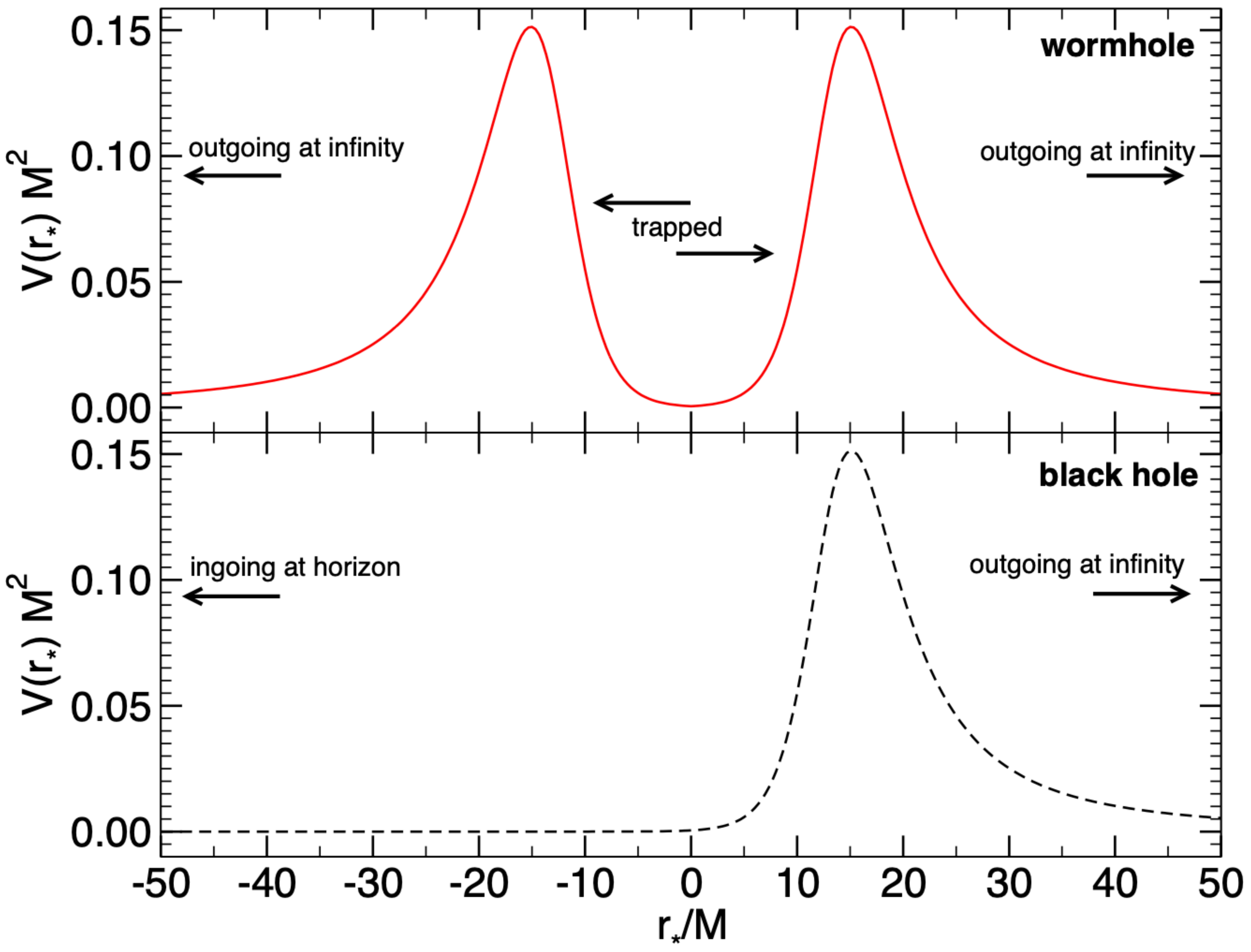
Cardoso, Franzin, Pani, 1602.07309

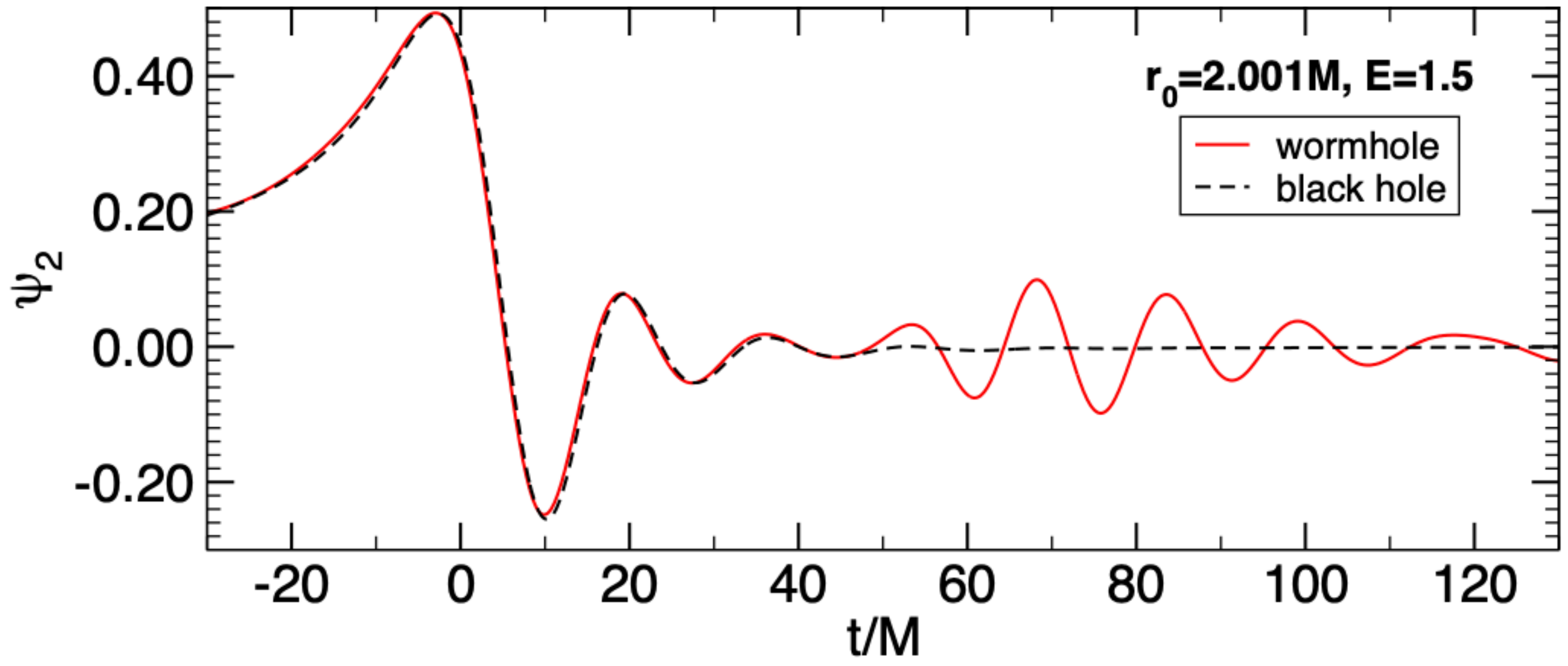
What if there's no complete absorption here?



What if there's no complete absorption?

- Identical ringdown
- Cavity sets late-time response



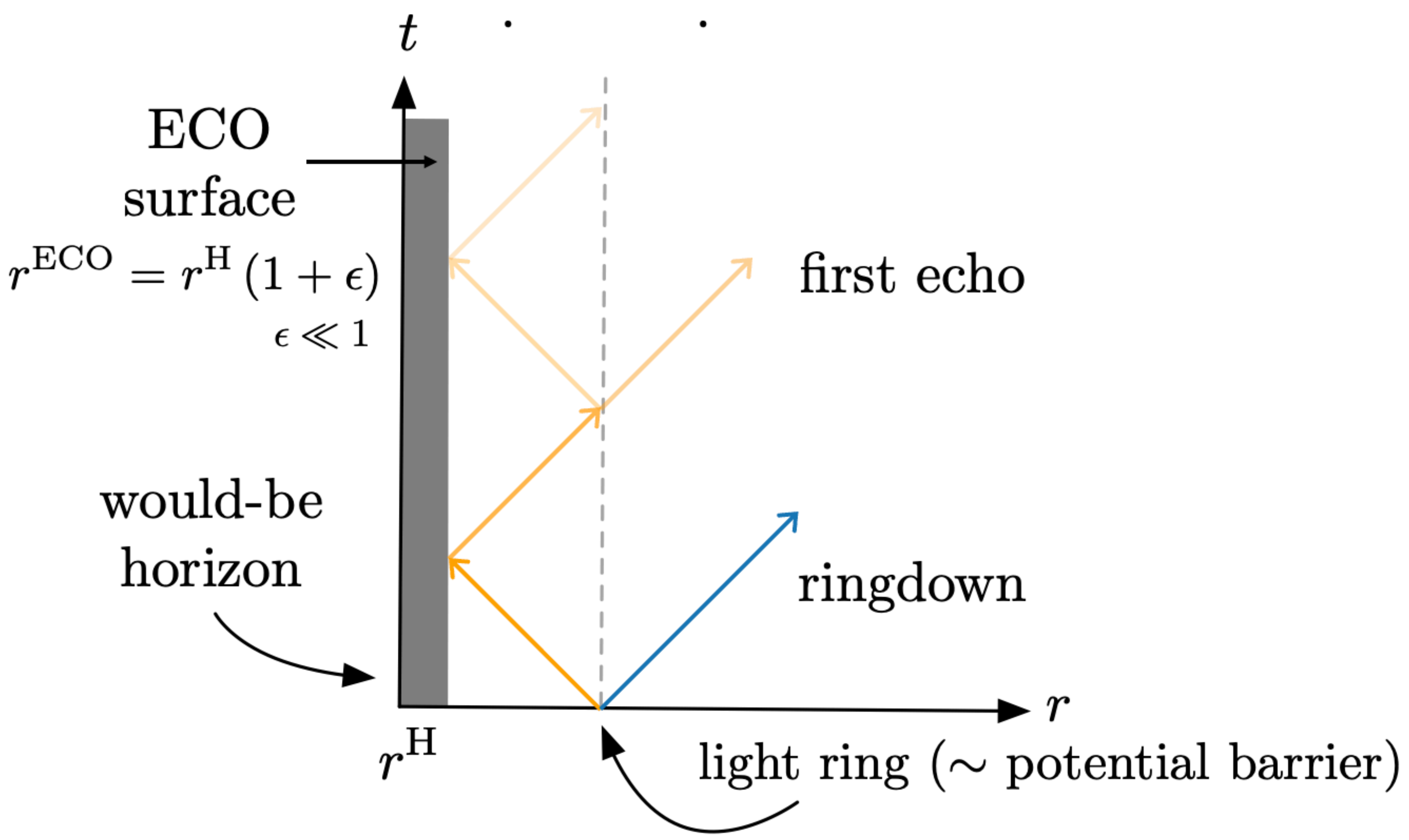


Cardoso, Franzin, Pani, 1602.07309

ECHOS OF ECOS

- Exotic compact objects (**ECOs**) are **BHs mimickers** candidates
- Instead of simple ringdown produce **echos:** **multiple reflections** between **potential barrier** and **would-be-horizon**

$$\tilde{\Psi} \to e^{-i\omega(x-x_0)} + \mathcal{R}(\omega)e^{i\omega(x-x_0)}$$



Cardoso, Pani, LRR (2019)
Maggio, 2211.16900

Credits: Rico Ka Lok Lo

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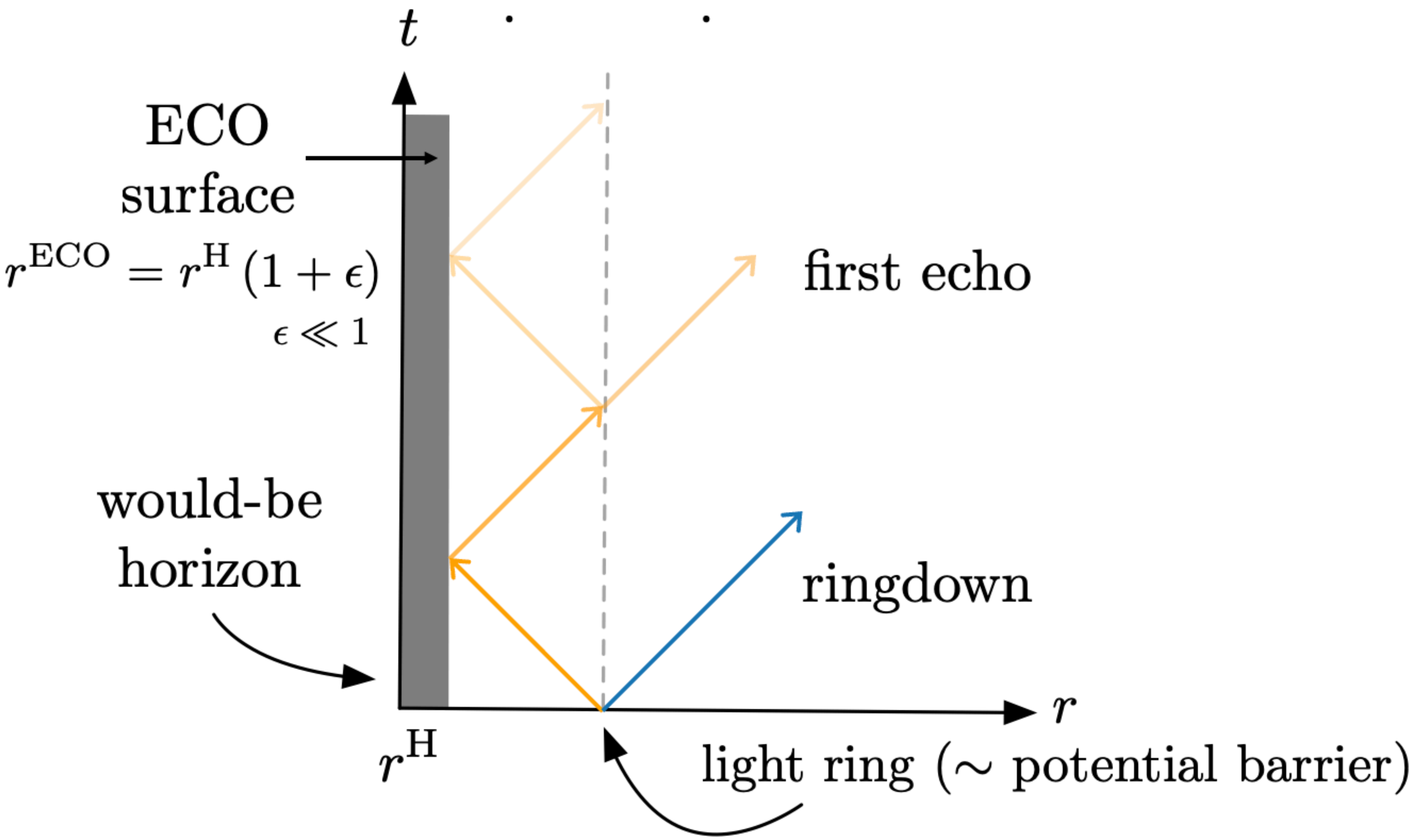

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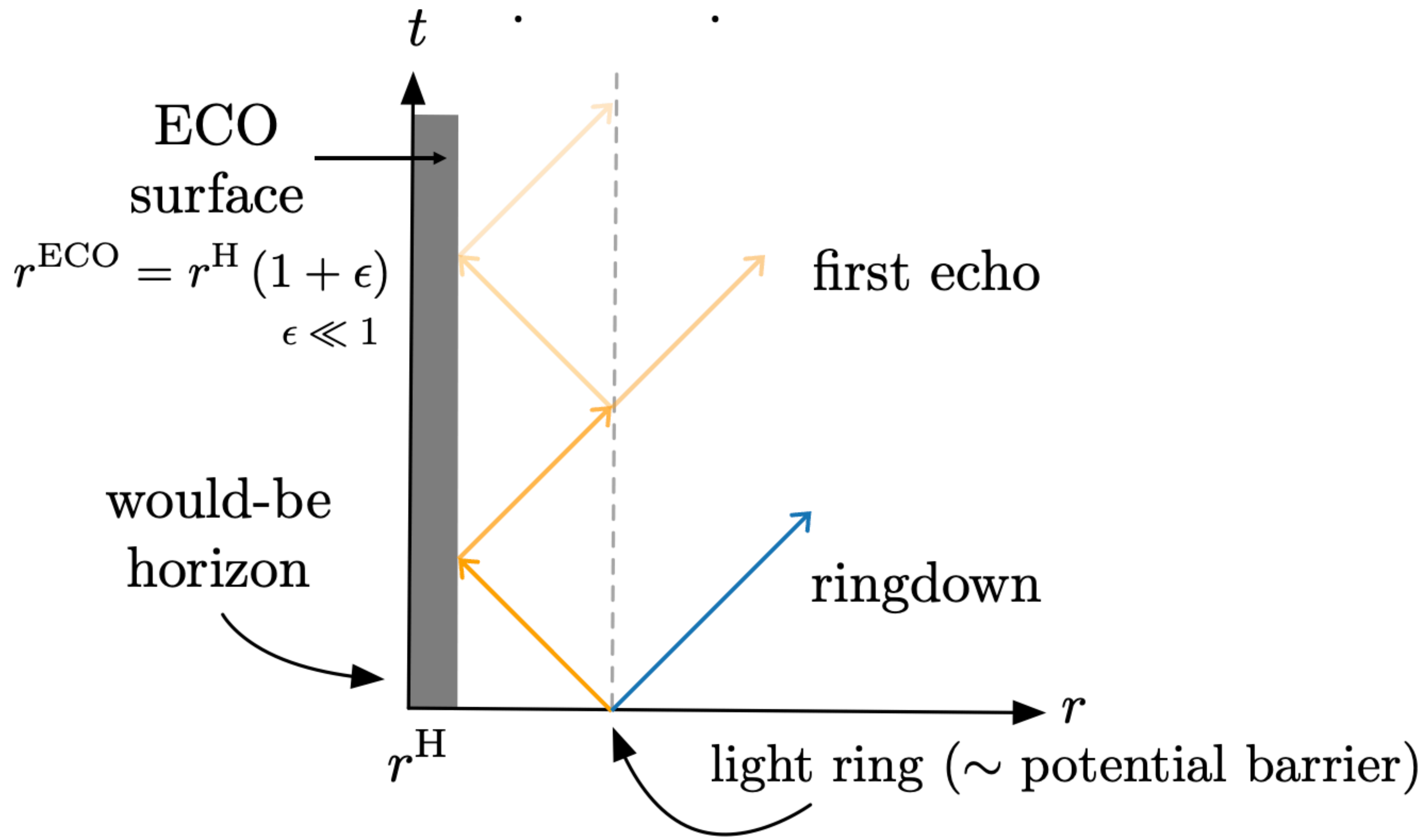

Simplified picture, more complictated in full NR

Siemonsen 2404.14536

Cardoso, Pani, LRR (2019)

Maggio, 2211.16900

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SEARCHES

Abedi, Afshordi et al.: 1612.00266, 1803.10454, 2301.00025

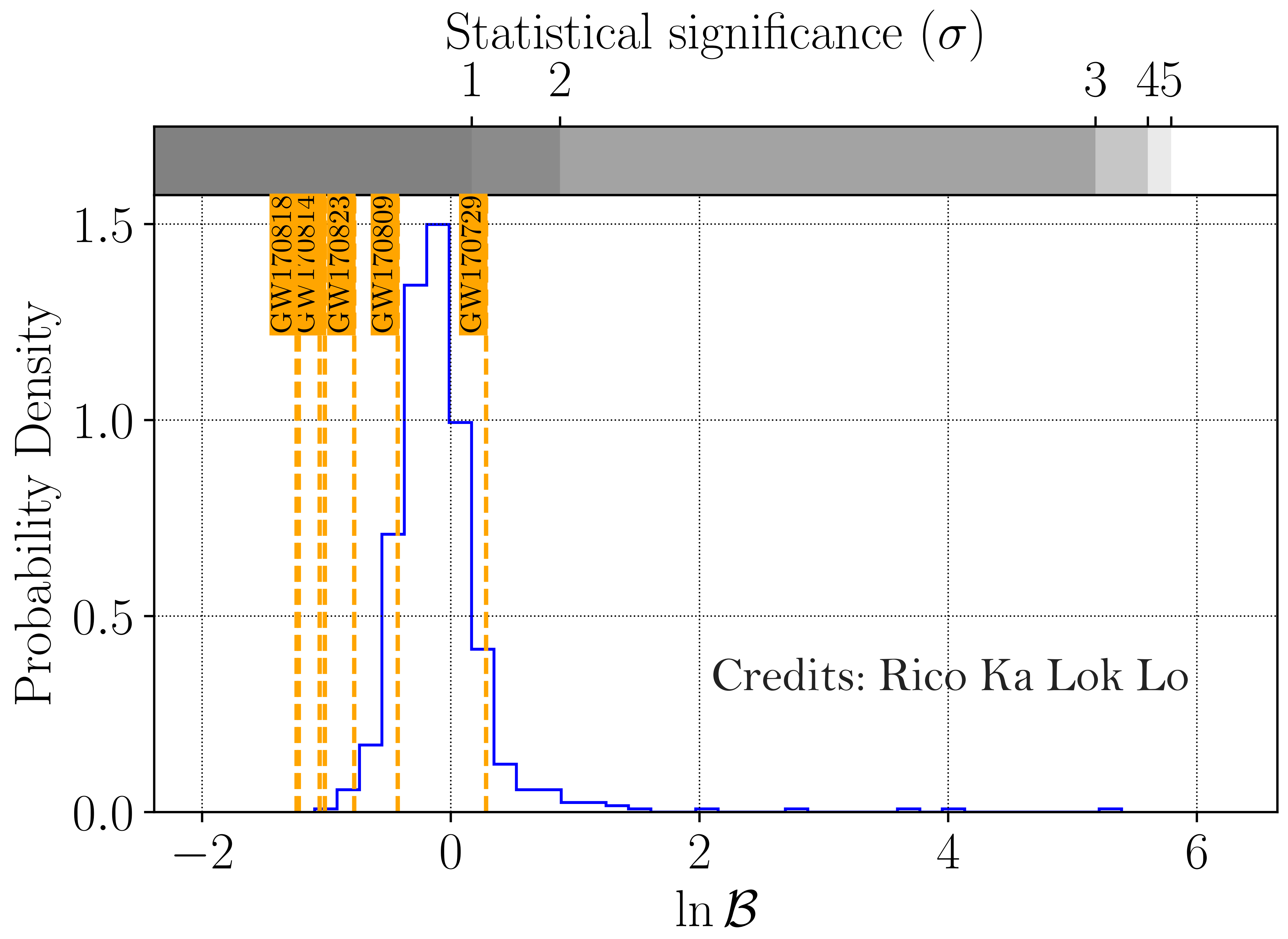
Westerweck+,1712.09966, Nielsen+,1811.04904, Uchikata+, 2309.01894

LVK SEARCHES

Modelled

based on: Lo-Li-Weinstein+, 1811.07431

Abedi+, arXiv:1612.00266



GWTC-2 Testing GR, LVC, 2010.14529

GWTC-3 Testing GR, LVC, 2112.06861

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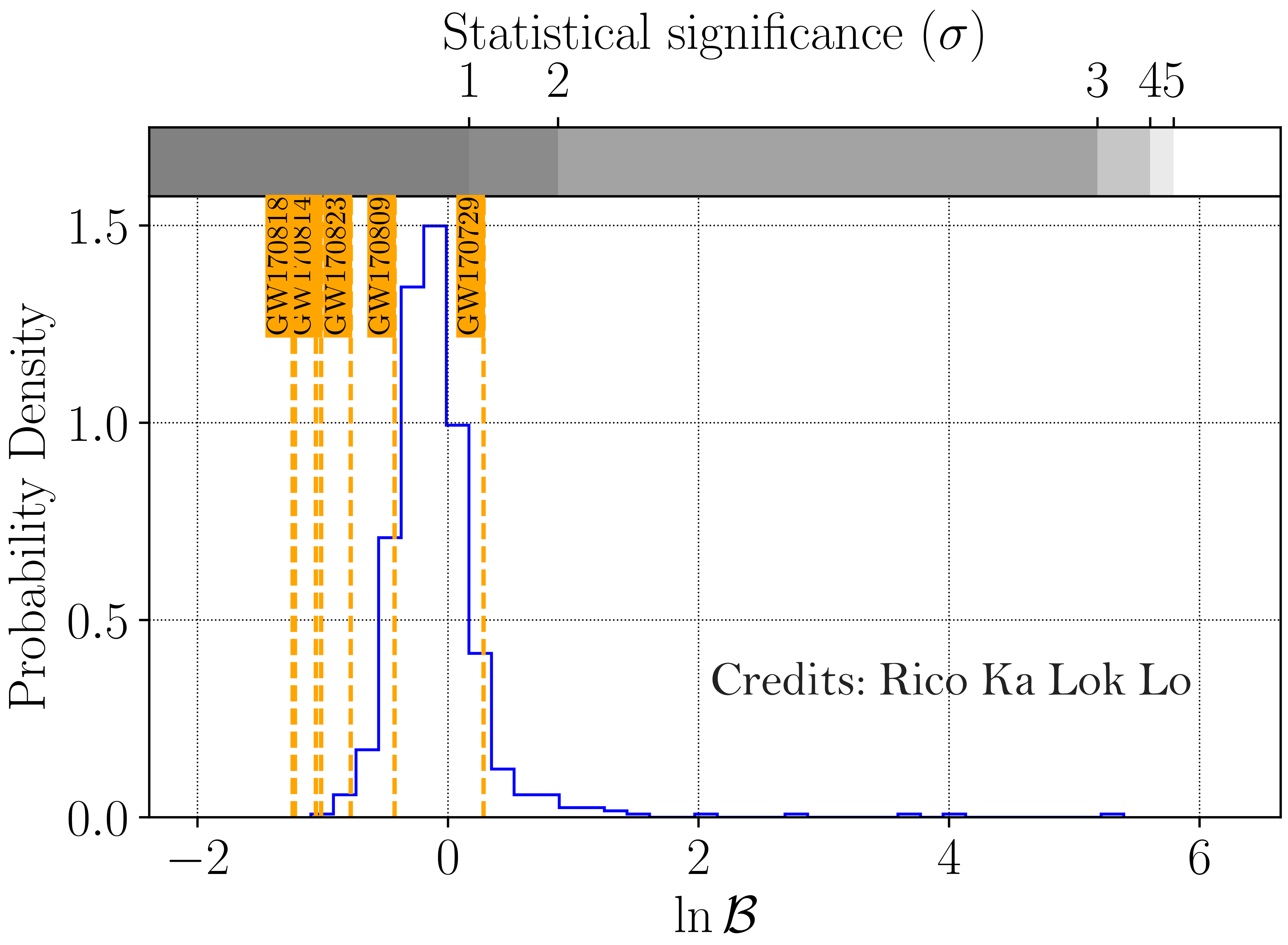

GWTC-2 Testing GR, LVC, 2010.14529

GWTC-3 Testing GR, LVC, 2112.06861

Caveat: Simplified model and phenomenology.

Can have no echoes at all, or long-lived emission, see e.g. 2108.08823, 2306.11166

Abedi, Afshordi et al.: 1612.00266, 1803.10454, 2301.00025

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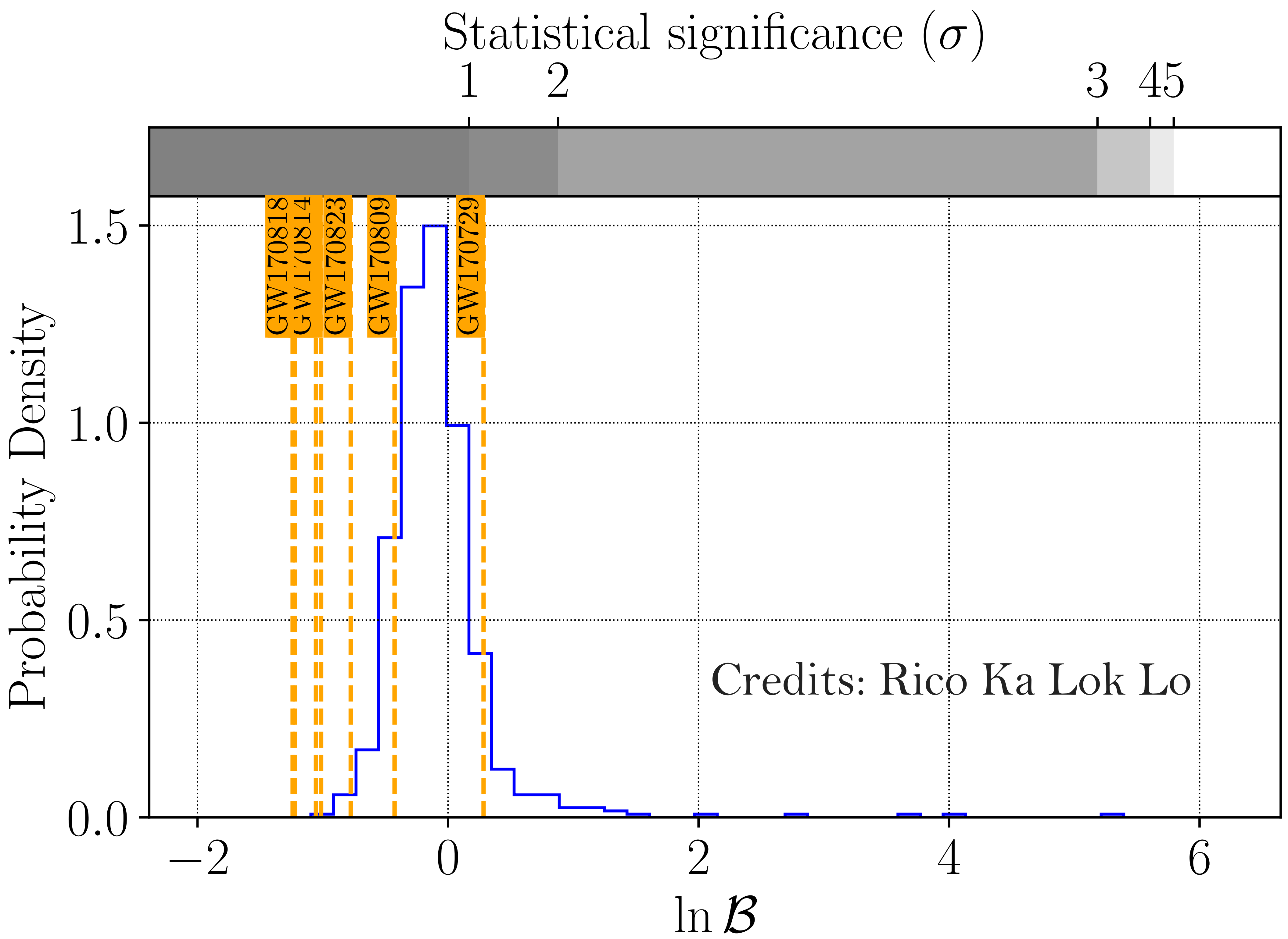


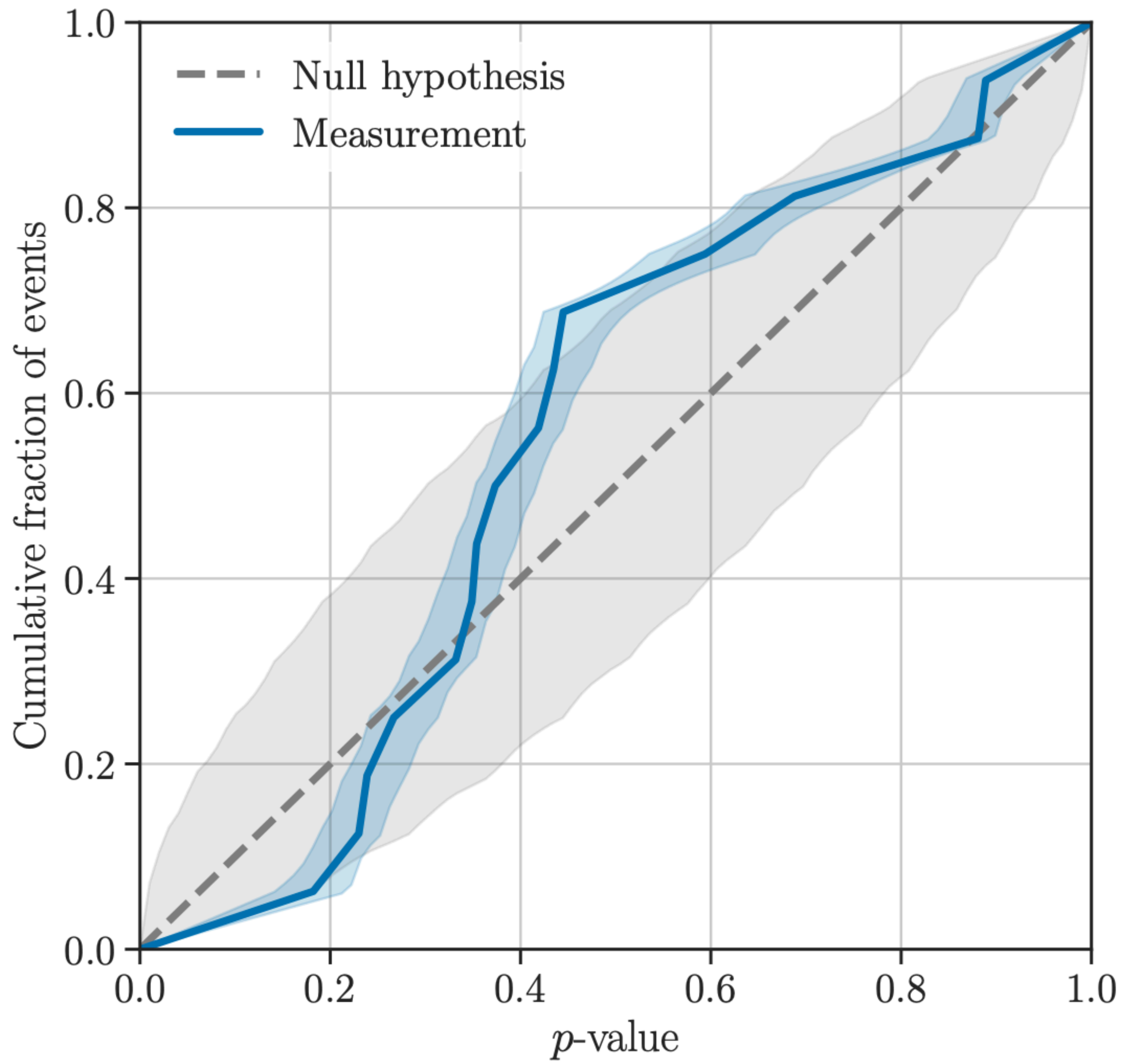
GWTC-2 Testing GR, LVC, 2010.14529

GWTC-3 Testing GR, LVC, 2112.06861

Unmodelled

(BayesWave: Cornish-Littenberg 1410.3835)

based on: Tsang+, 1804.04877, 1906.11168



Abedi, Afshordi et al.: 1612.00266, 1803.10454, 2301.00025

Westerweck+,1712.09966, Nielsen+,1811.04904, Uchikata+, 2309.01894

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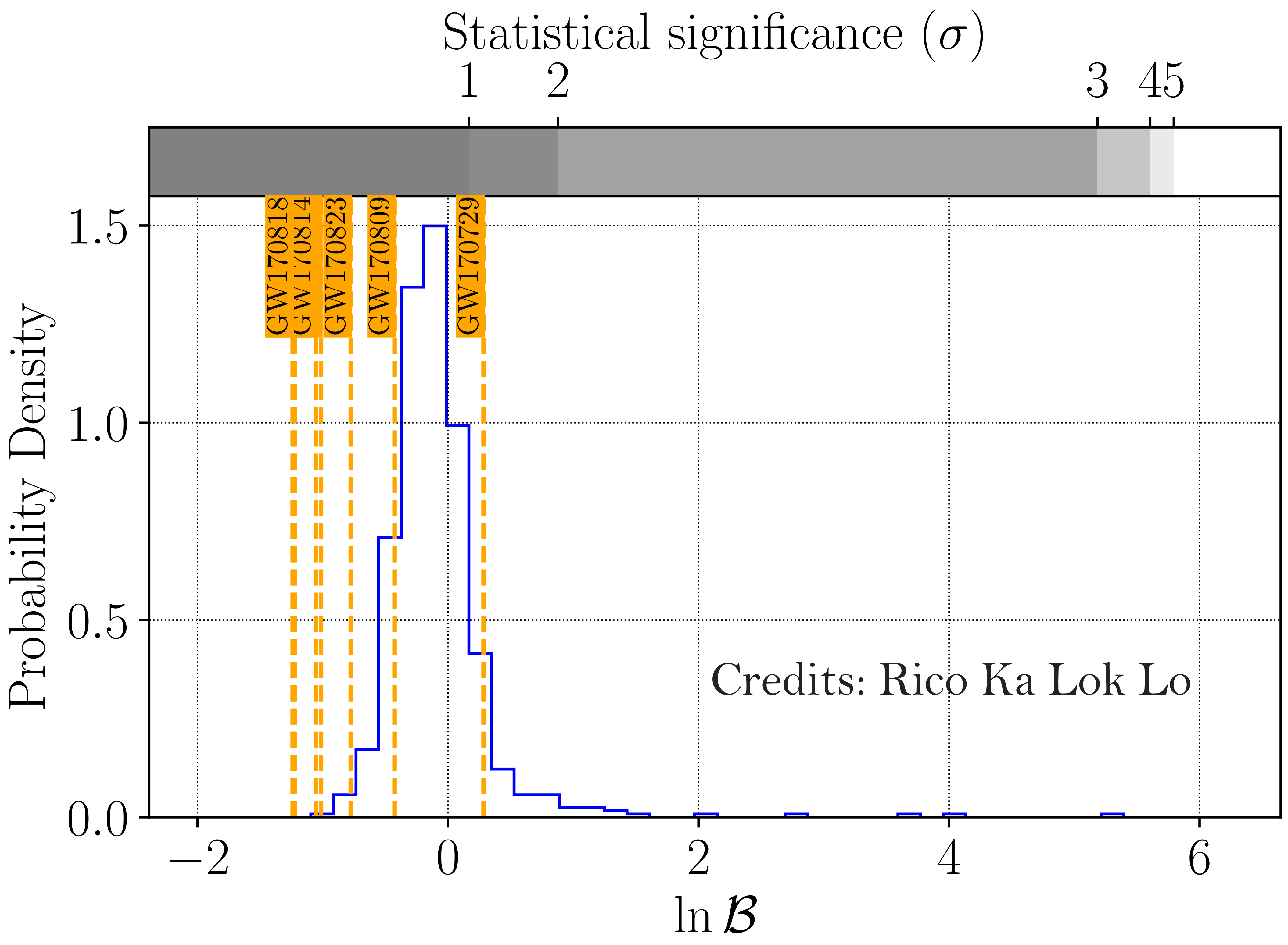
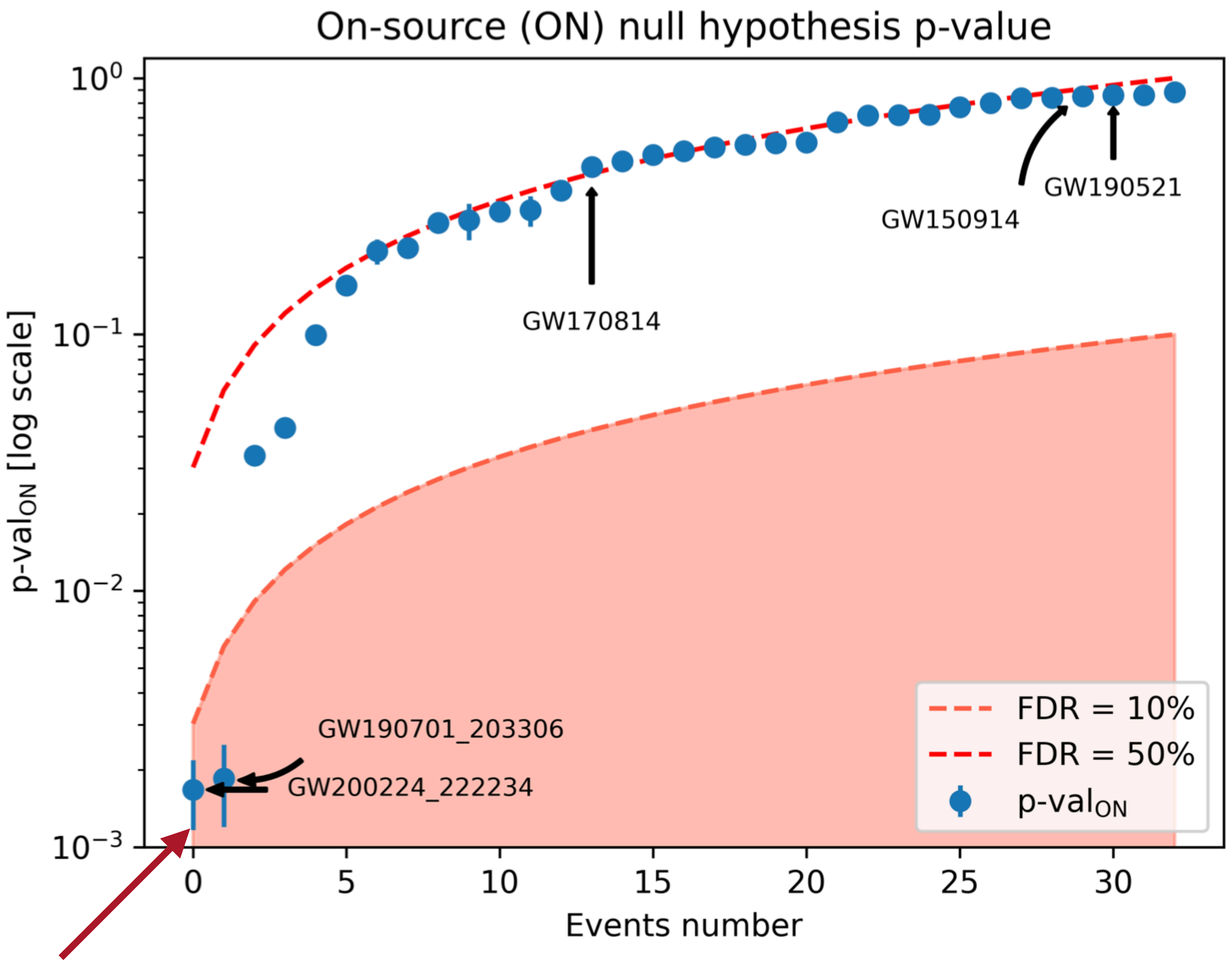
Abedi+, arXiv:1612.00266



GWTC-2 Testing GR, LVC, 2010.14529
GWTC-3 Testing GR, LVC, 2112.06861

Unmodelled

(Coherent Wave Burst: Klimenko+, 0802.3232)
based on: Miani+, 2302.12158



Instrumental artifacts

Abedi, Afshordi et al.: 1612.00266, 1803.10454, 2301.00025

Westerweck+,1712.09966, Nielsen+,1811.04904, Uchikata+, 2309.01894

Beyond the Kerr spectrum

LOST IN TRANSLATION

- **Implications** of **LVC** results to specific **alternative theories** of gravity?

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- **Large amount of possibilities** and of effects to take into account (isospectrality breaking, modes induced by extra-fields dynamics…)

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- **Implications** of **LVC** results to specific **alternative theories** of gravity?
- **Large amount of possibilities** and of effects to take into account (isospectrality breaking, modes induced by extra-fields dynamics…)
- Previous (global) parameterisation not very suited:
  - Event-dependent (requires hierarchical analysis)
  - No dependence on spin
  - No dependence on extra-couplings

THEORY-SEMIAGNOSTIC RESULTS

THEORY-SEMIAGNOSTIC RESULTS

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)} \, (1 + \gamma \, \delta\omega_K^{(j)})$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)} \, (1 + \gamma \, \delta\tau_K^{(j)})$$

Proportional to action coupling(s):

$$\gamma := \left(\frac{\ell \, c^2 \, (1+z)}{G \, M} \right)^p$$

Add deviations at each given order.

Numerical constants predicted by new theory.
Independent of specific signal.

Maselli+, PRD (2020)

THEORY LANDSCAPE

- **p=0** (e.g. certain **scalar-tensor** or **Lorentz-violating**)

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g}\; (R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu)\; d^4x$$

- **p=2** (e.g. **Kerr-Newman** or charged dark matter)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + 4\pi e j^\mu_{\rm em} A_\mu + 4\pi e_h j^\mu_h B_\mu + 4\pi \epsilon e j^\mu_h A_\mu\right)$$

- **p=4** (e.g. **Einstein-scalar-Gauss-Bonnet** or **dynamical Chern-Simons**)

$$S \equiv \int \frac{m_{\rm pl}^2}{2} d^4x \sqrt{-g}\left[R - \frac{1}{2}(\partial\vartheta)^2 + 2\alpha_{\rm GB} f(\vartheta)\mathcal{R}_{\rm GB}\right], \quad S \equiv \int d^4x \sqrt{-g}\left(\frac{m_{\rm pl}^2}{2} R - \frac{1}{2}(\partial\vartheta)^2 - \frac{m_{\rm pl}}{8}\ell^2 \vartheta\, {}^*RR\right)$$

- **p=6** (e.g. **Effective Field Theories**)

Symmetries + short distance experiments (assuming causality, locality, diff. inv., unitarity)

$$S_{\rm eff} = \int d^4x \sqrt{-g}\, 2M_{\rm pl}^2 \left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6}\right)$$

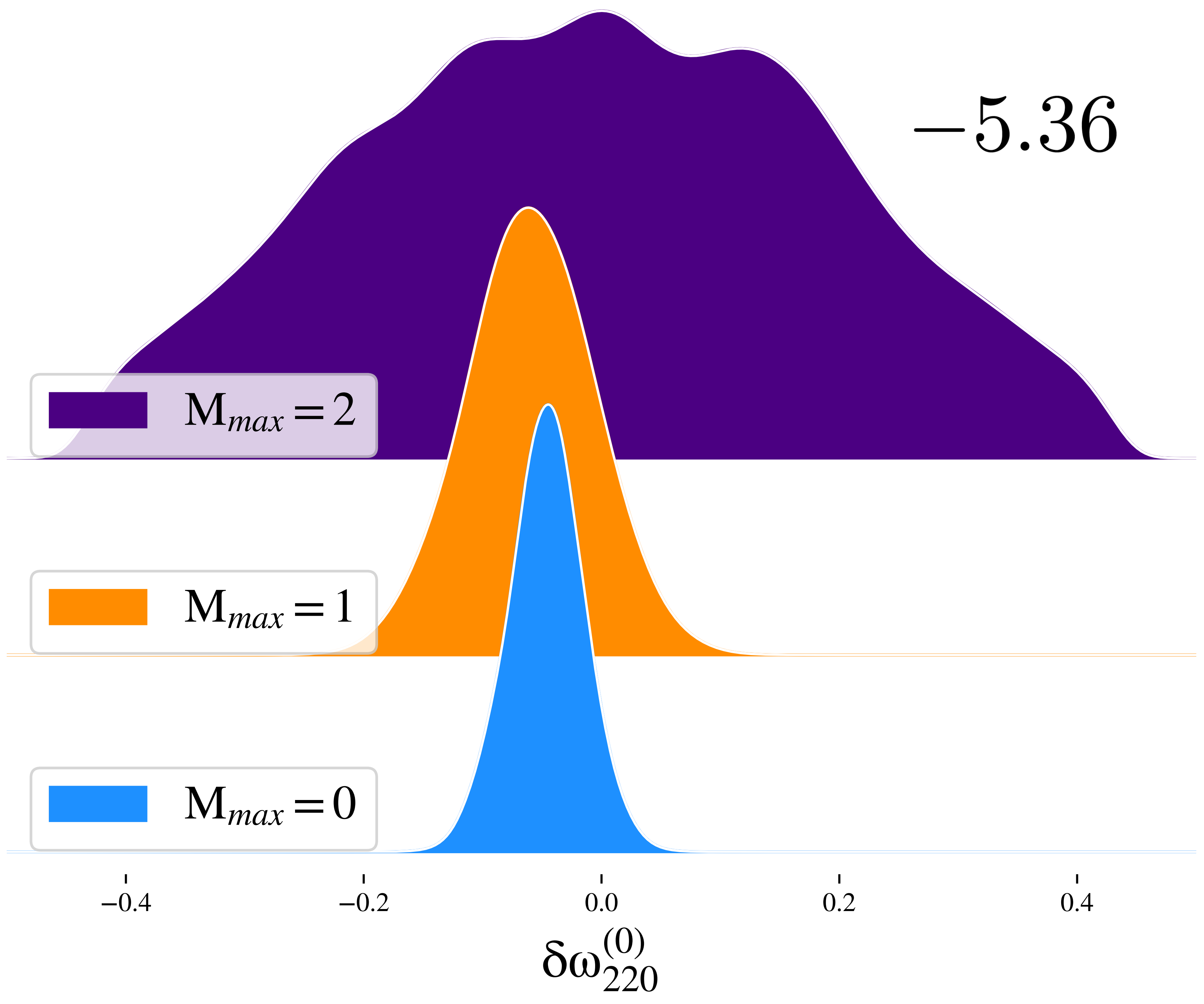
$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \qquad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}$$

Endlich+, arXiv:1704.01590 Cardoso+, arXiv:1604.07845 Berti+, arXiv:1501.07274

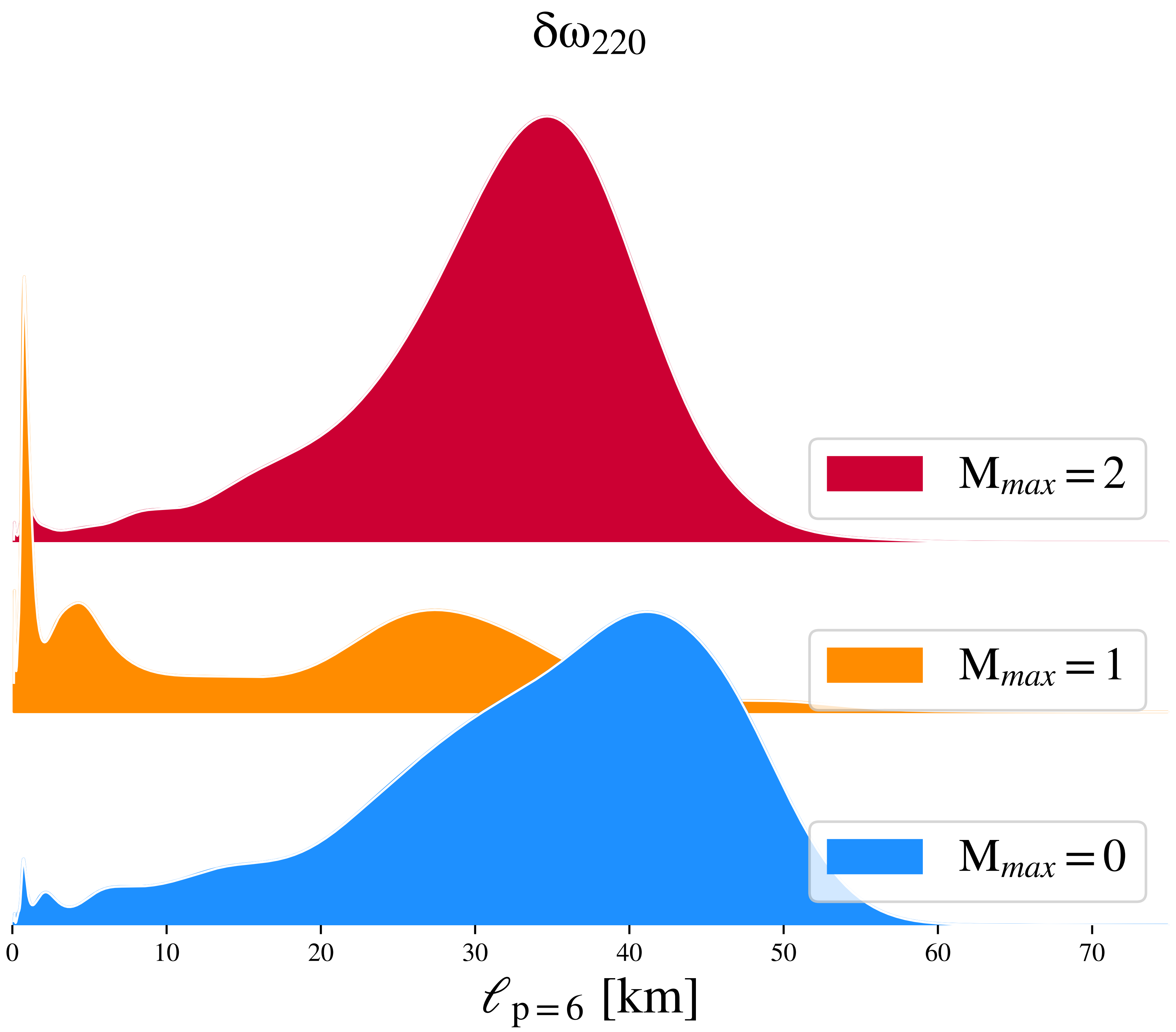
THEORY-SEMIAGNOSTIC RESULTS

- Input **mass-scaling** from beyond-GR actions and **QNM spin-dependence**: improve constraints

$$\delta\omega^{0}_{220} = -0.05^{+0.05}_{-0.05}$$



$$\ell_{\mathrm{p}=6} \lesssim 42\ \mathrm{km}$$



Carullo, 2102.05939

Maselli+, 1910.12893

THEORY-DEPENDENT RESULTS

THEORY-DEPENDENT RESULTS

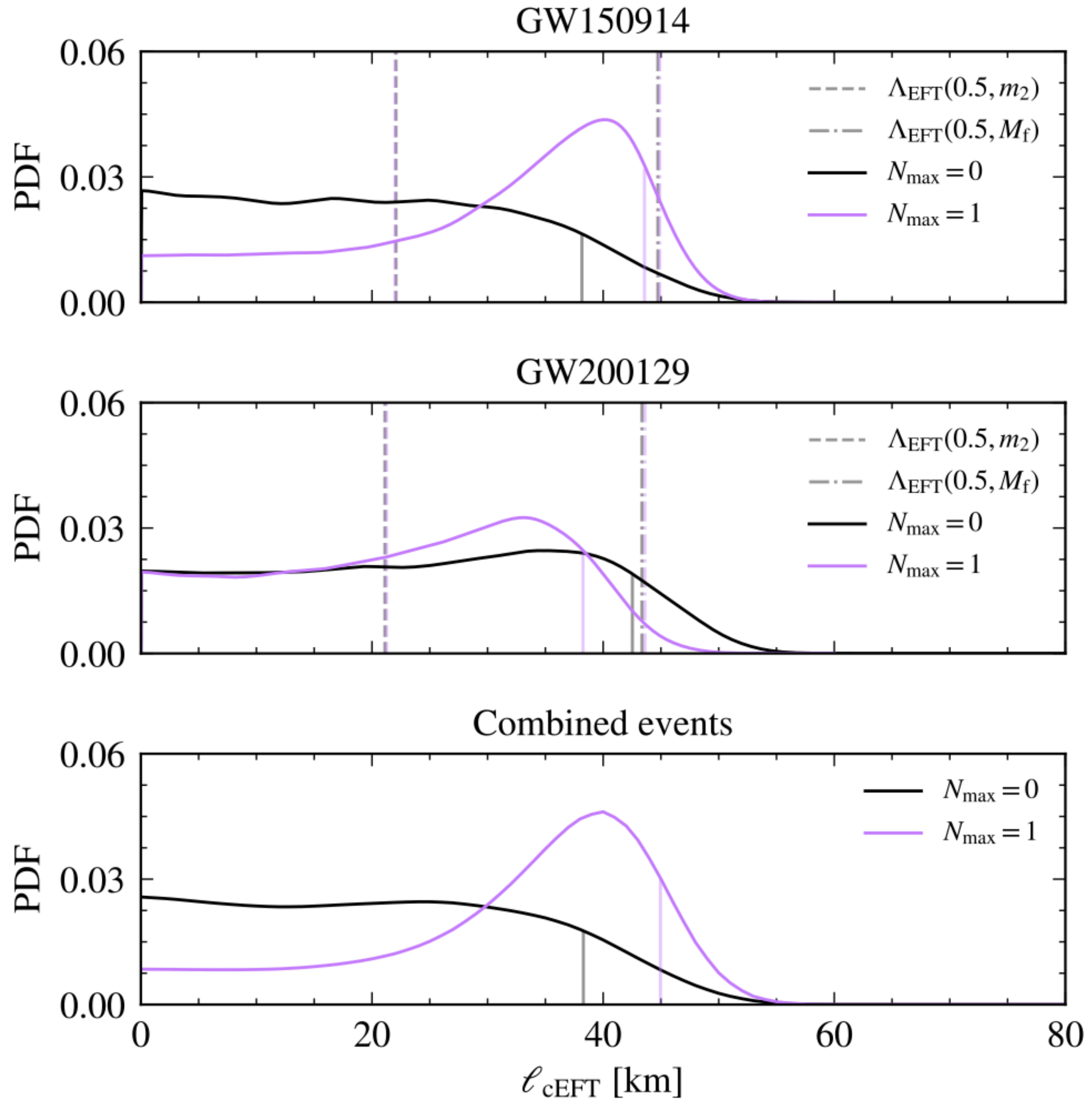
- Linear order corrections in QNM of EOB models:

$$S_{\mathrm{EFT}} = \frac{1}{16\pi}\int \mathrm{d}^4x\sqrt{-g}\left[R + \sum_{n\geqslant 2}\ell_{\mathrm{EFT}}^{2n-2}L^{(2n)}\right],$$

$$L^{(6)} = \lambda_{\mathrm{e}}R_{\mu\nu}{}^{\rho\sigma}R_{\rho\sigma}{}^{\gamma\delta}R_{\gamma\delta}{}^{\mu\nu} + \lambda_{\mathrm{o}}R_{\mu\nu}{}^{\rho\sigma}R_{\rho\sigma}{}^{\gamma\delta}\tilde{R}_{\gamma\delta}{}^{\mu\nu},$$

Regularisation at high spins?

Franciolini+, Salcedo+, Pierini-Gualtieri, Srivastava+, Wagle+, Cano+, …



Silva+, arXiv:2205.05132

THEORY-DEPENDENT RESULTS

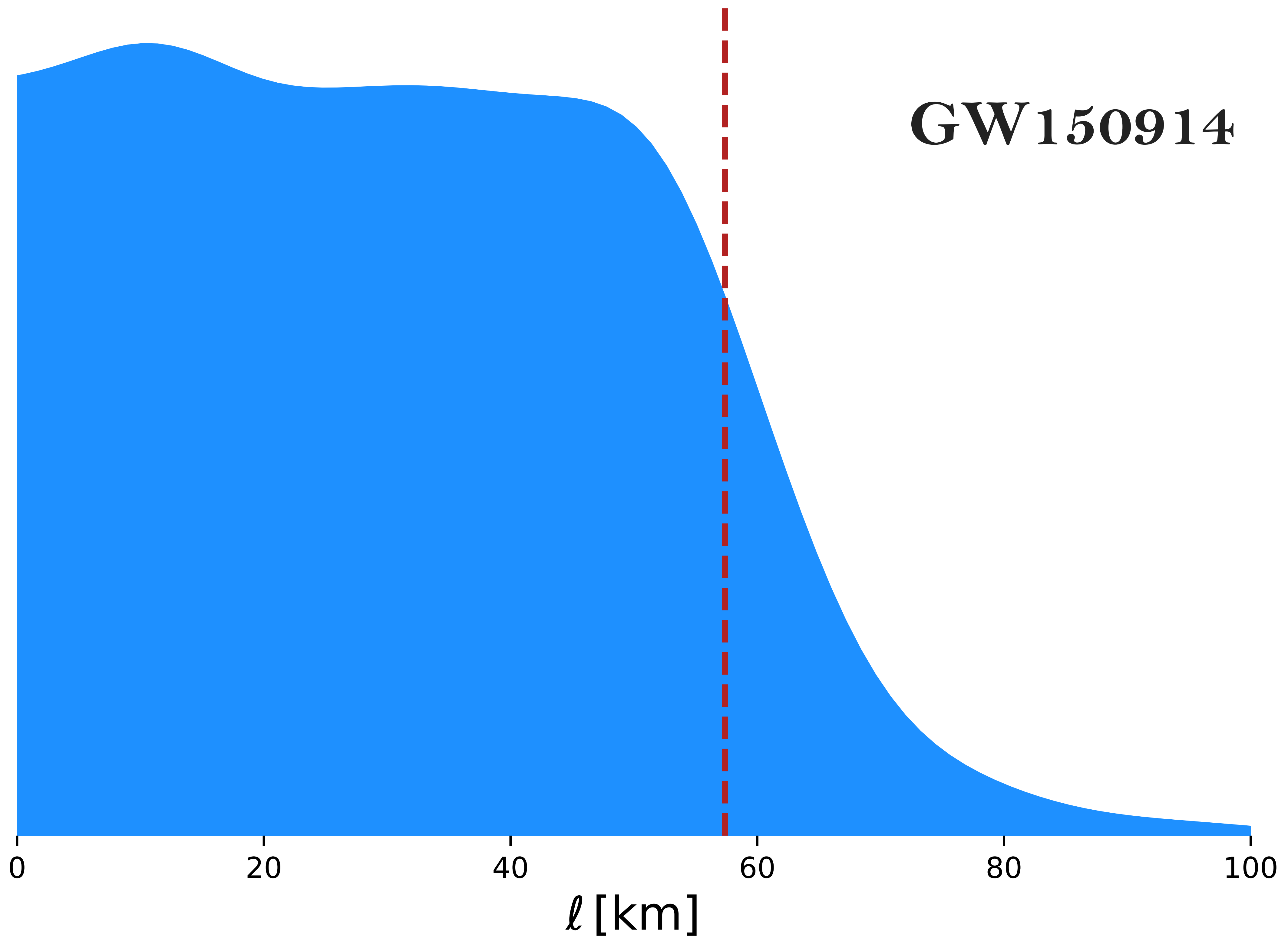
- Predictions for arbitrary spins in **beyond-GR EFTs**
  - Refining it with theory-dependent predictions

Cano, Capuano, Franchini, Fransen, Hertog, Maenaut, Ruiperez, Volkel

1901.01315, 2005.03671, 2110.11378, 2304.02663, **2307.07431**, 2407.15947

$$S_{\text{eff}} = \int d^4x\sqrt{-g}2M_{\text{pl}}^2\left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6}\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \qquad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}$$

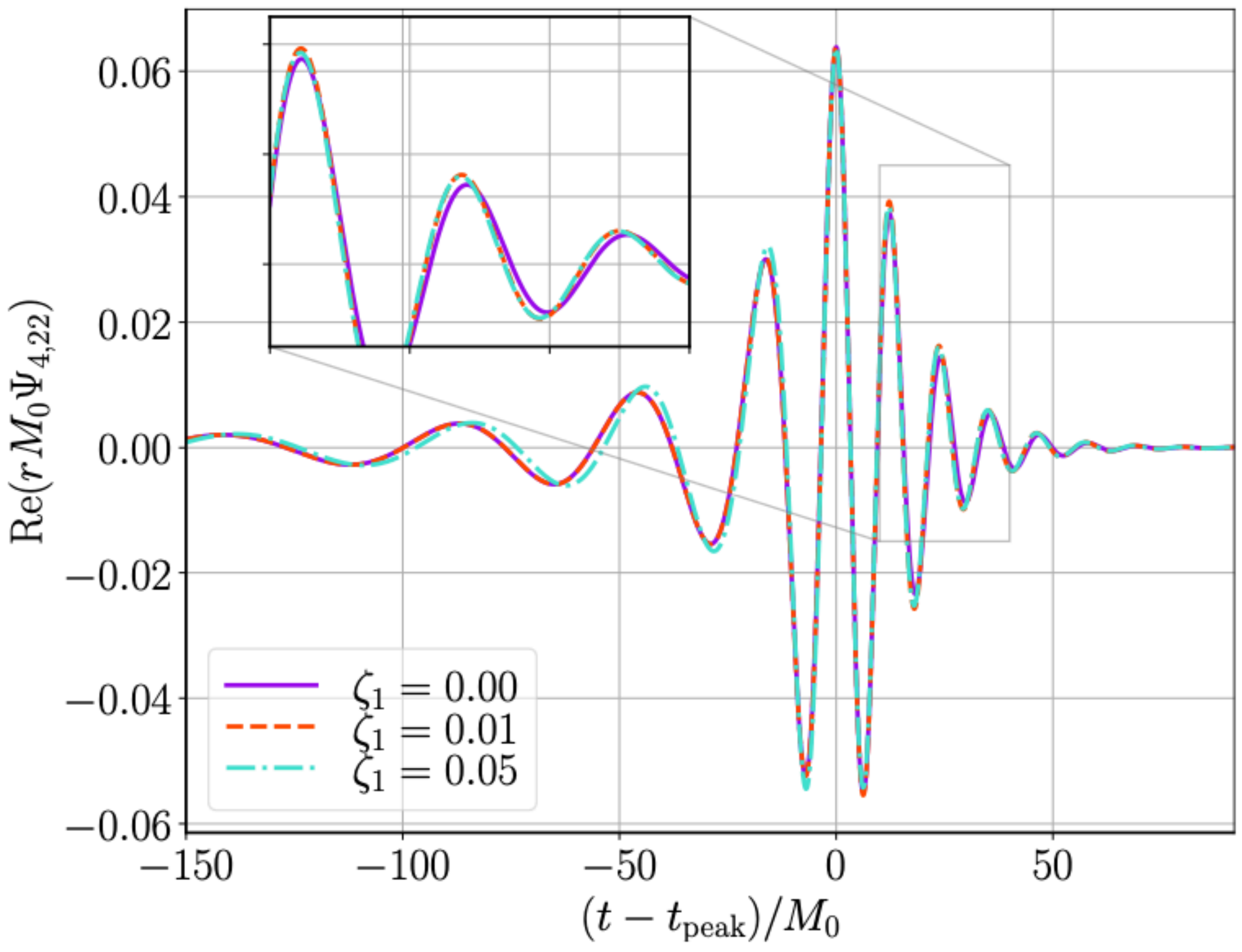


Menaut, Carullo, Cano+ (forthcoming)

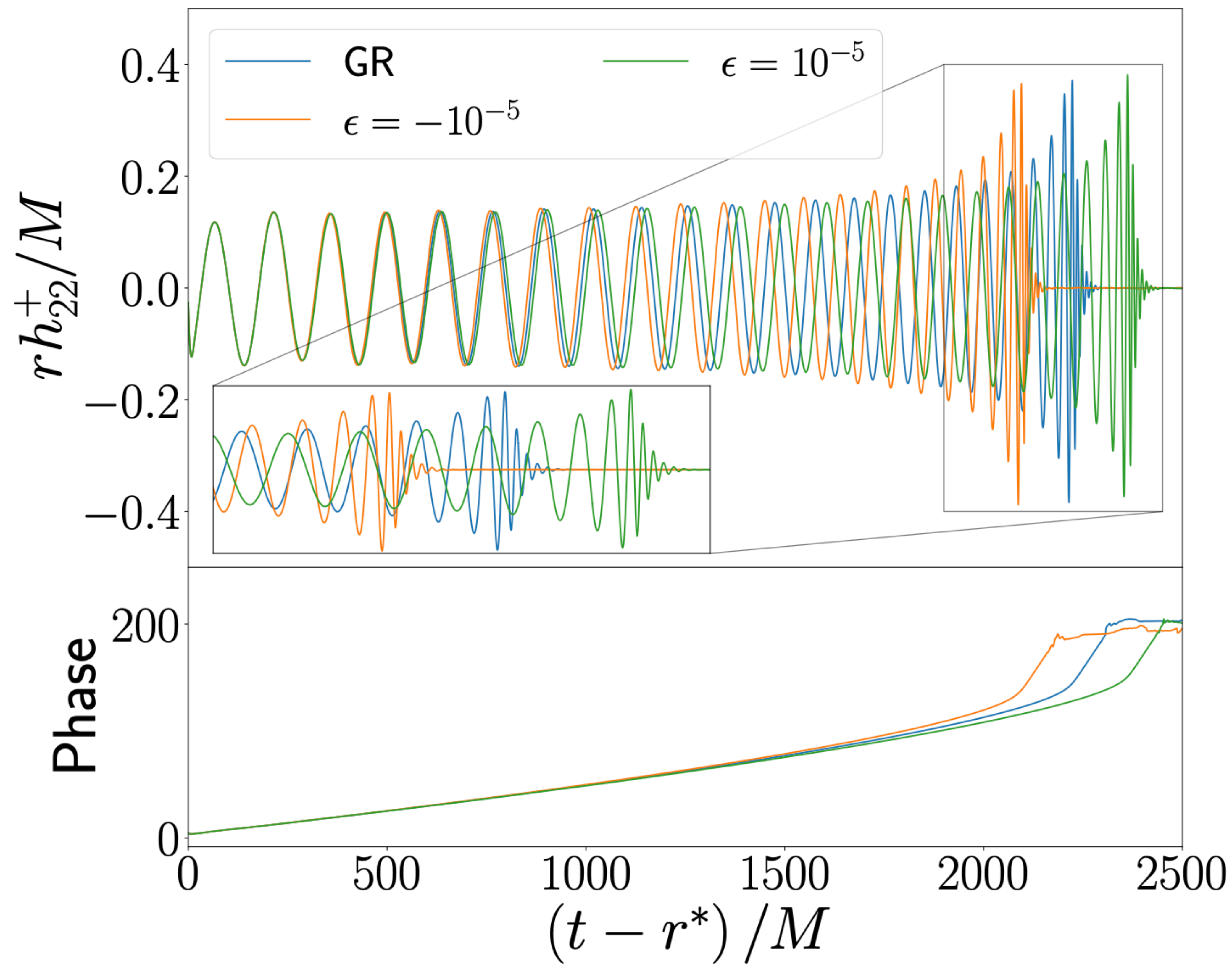
RECENT DEVELOPMENTS

- The final aim is to use predictions from full numerical simulations to search for beyond-Kerr signatures:

Corman, Ripley, East, 2210.09235



Cayuso, Figueras, Franca, Lehner, 2303.07246



Many other efforts: Okounkova+, 1911.02588, Silva+, 2012.10436 , Ripley, 2207.13074, Corman+, 2405.15581-2405.18496

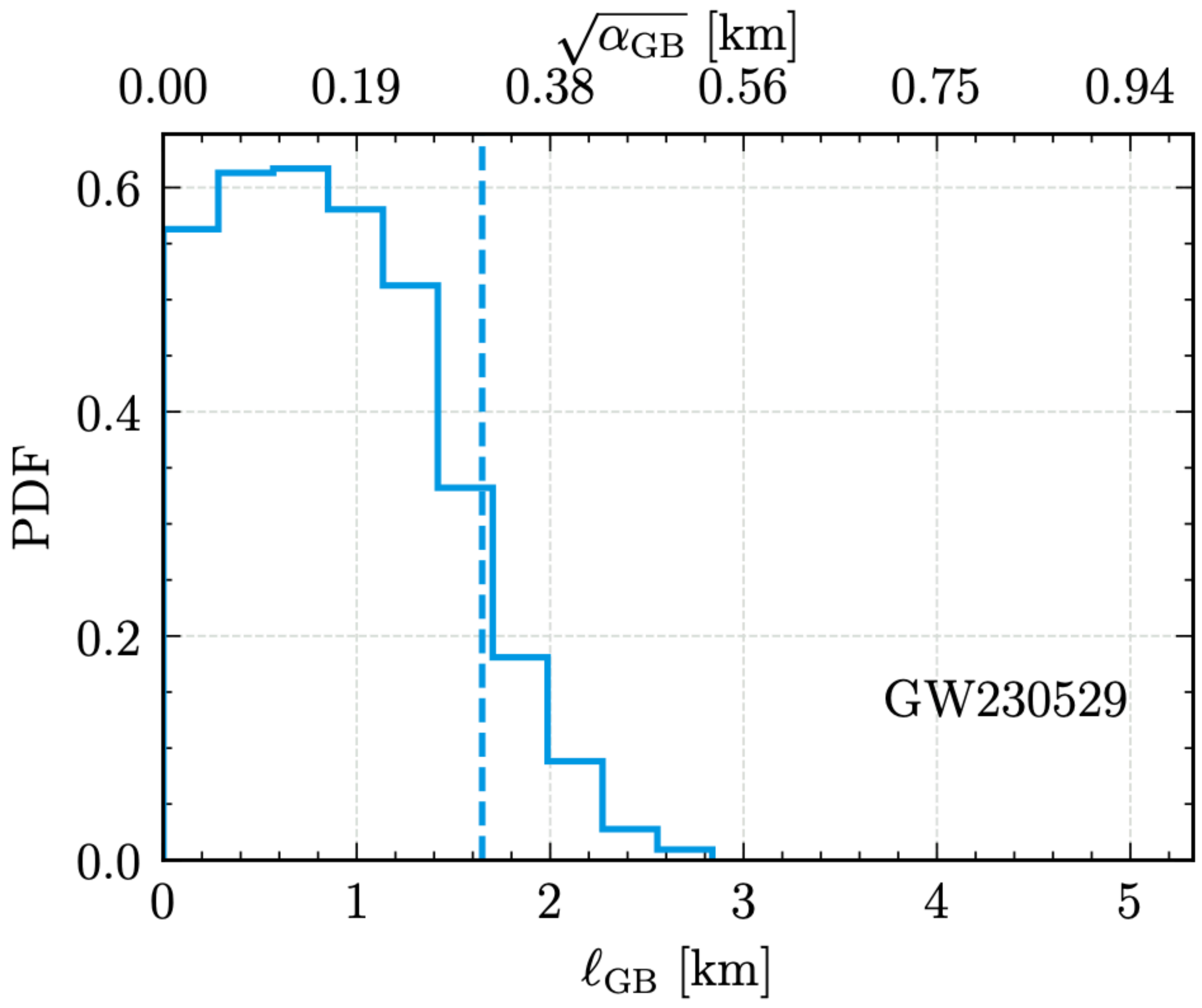
RECENT DEVELOPMENTS

- The final aim is to use predictions from full numerical simulations to search for beyond-Kerr signatures:

- Recent advancements in EsGB:

  Chung, Yunes, 2406.11986

- Leading to first complete IMR EOB model



Julie, Pompili, Buonanno, 2406.13654

KERR-NEWMAN RINGDOWN

- Final state conjecture (*No-hair* theorems+): black hole solutions belong to the Kerr-Newman family, and are determined by mass, spin and **charge**
    - **Astrophysical charge** expected to be **negligible (polarised vacuum**, **neutralisation,** …). Can it be observationally confirmed?

Cardoso+, arXiv:1604.07845

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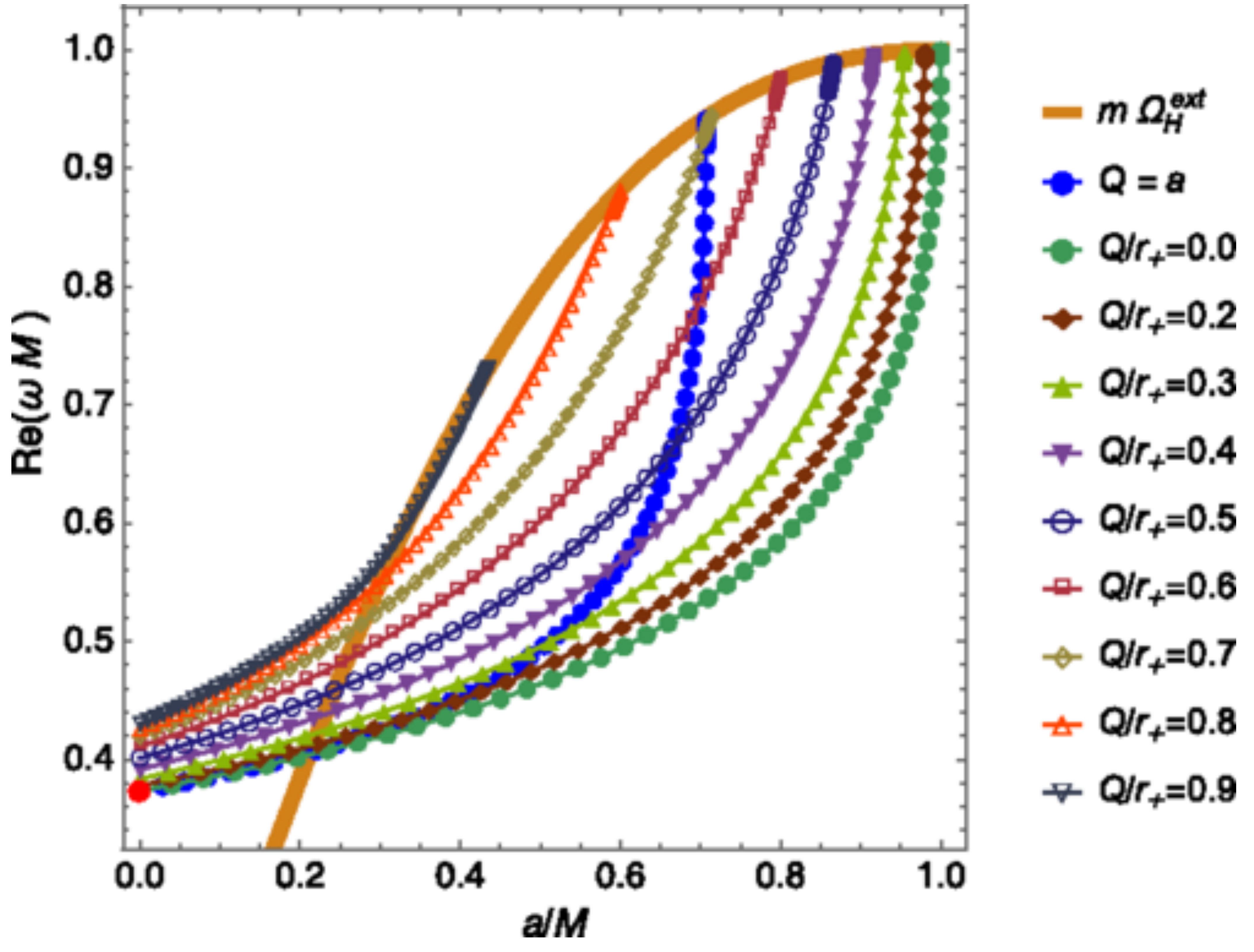
  - **Astrophysical charge** expected to be **negligible (polarised vacuum, neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:
  - Minicharged **dark matter, magnetic charge** (primordial magnetic monopoles)
  - Scalar-**vector**-tensor gravity, **topologically** induced charge
  - Valuable **test-bed** for **beyond-Kerr** effects.

Cardoso+, arXiv:1604.07845

QNM SPECTRUM PREDICTIONS

- Long-standing problem (Einstein-Maxwell equations **non-separable**)
- **Dias, Godazgar, Santos: Linear stability** of Kerr-Newman up to 99.999% of extemality
- Modes **connected to Schwarzschild** dominate the spectrum



Dias, Godazgar, Santos, arXiv:1501.04625

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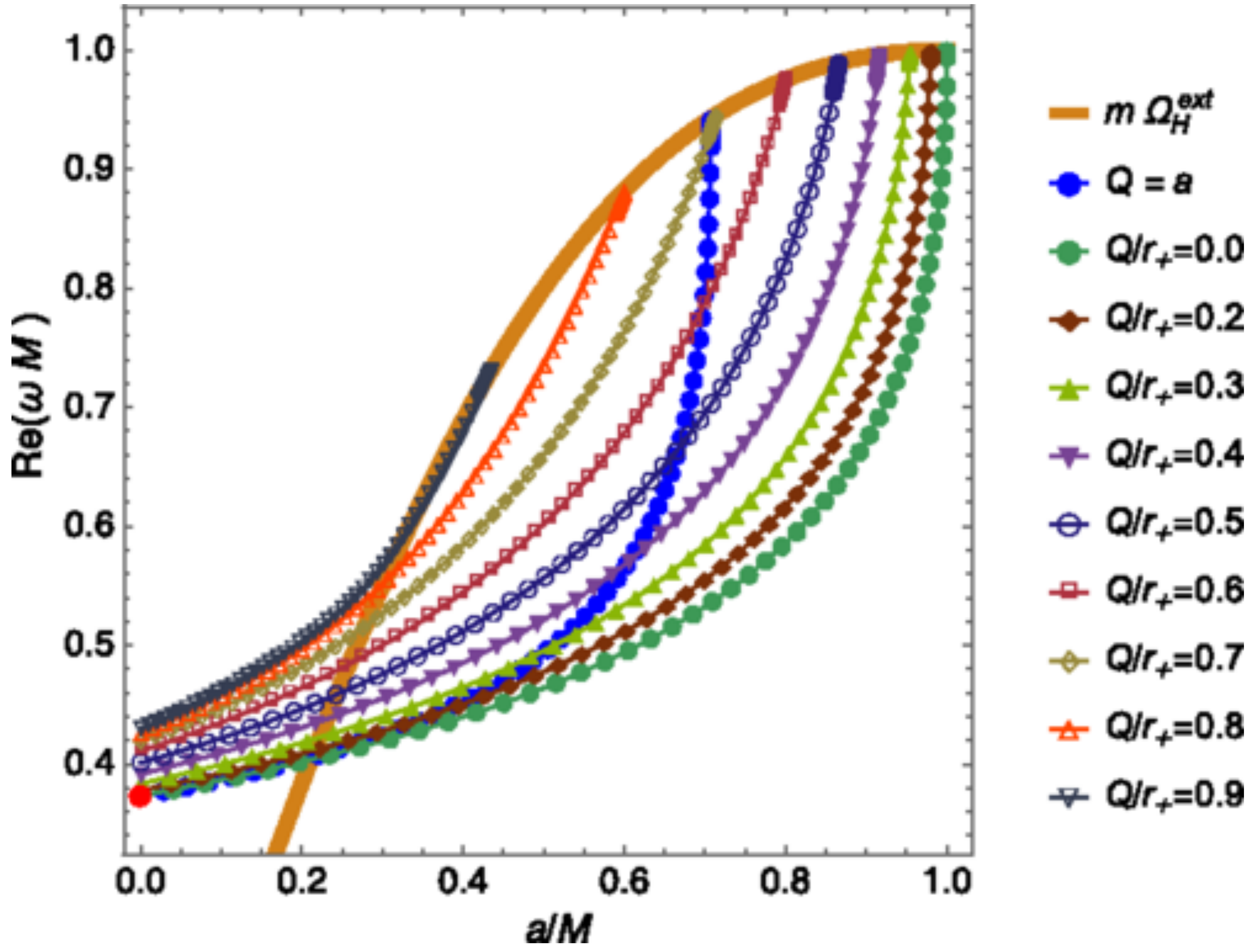
- Performed extensive tabulation
- Built a corresponding GW template

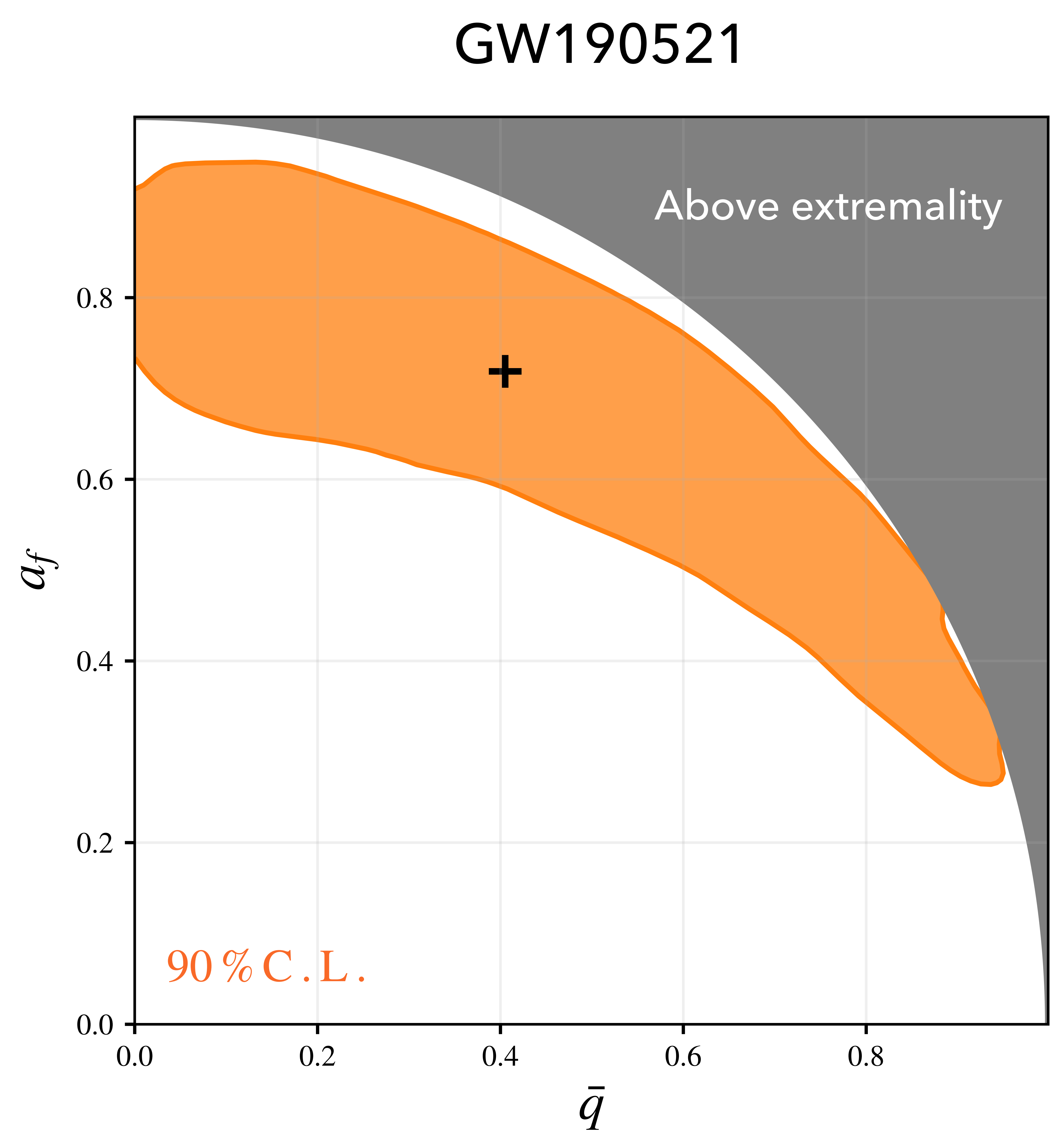


Carullo+, Phys. Rev. D (2022)

Dias, Godazgar, Santos, arXiv:1501.04625

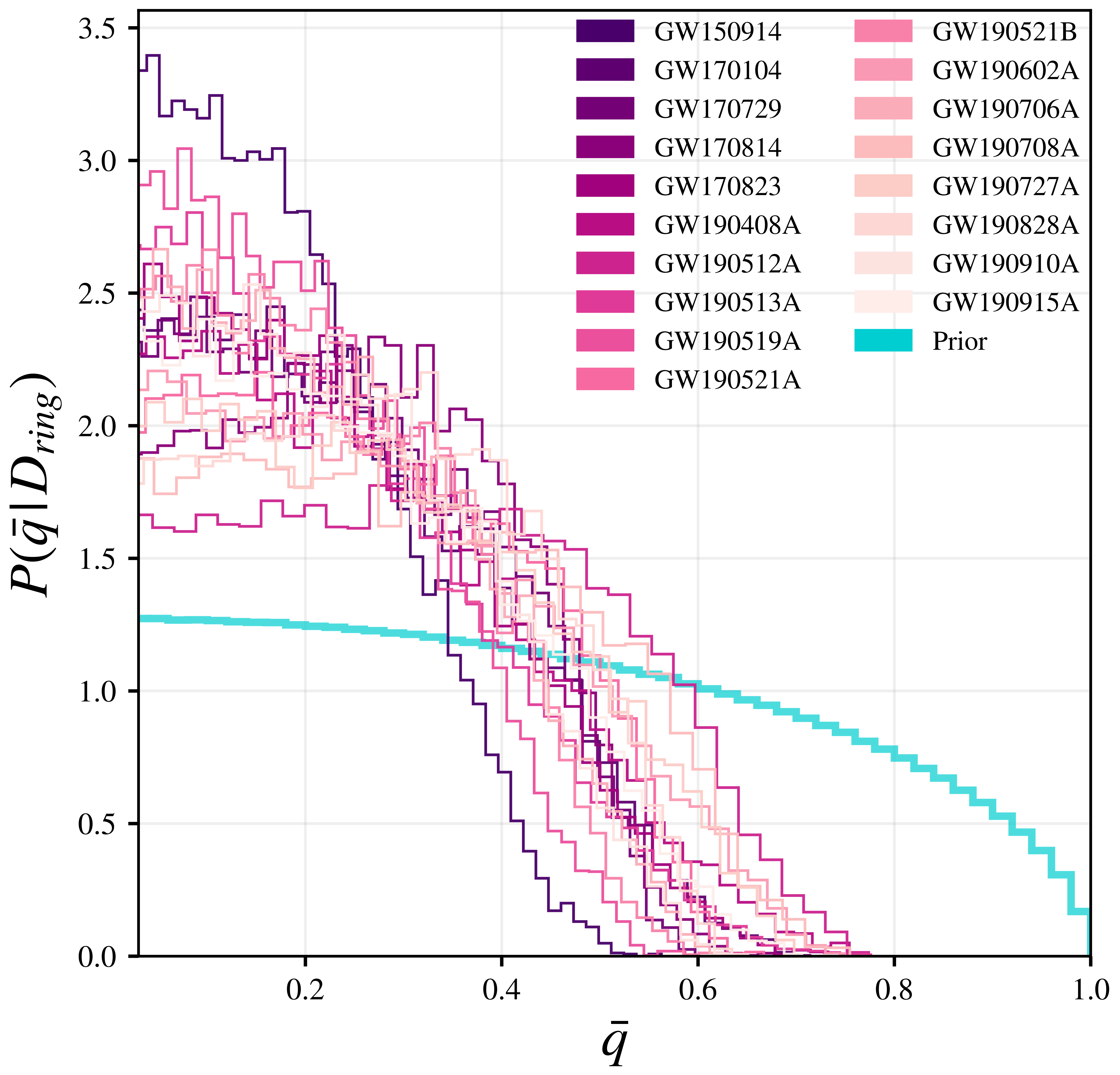
KERR-NEWMAN CONSTRAINTS

- Apply to **LIGO-Virgo detections**
- **Strong** spin-charge correlation
- **No direct measurement** possible: posterior is equal to the prior for Q (conditioned on $\bar{q}^2 + a^2 < 1$)



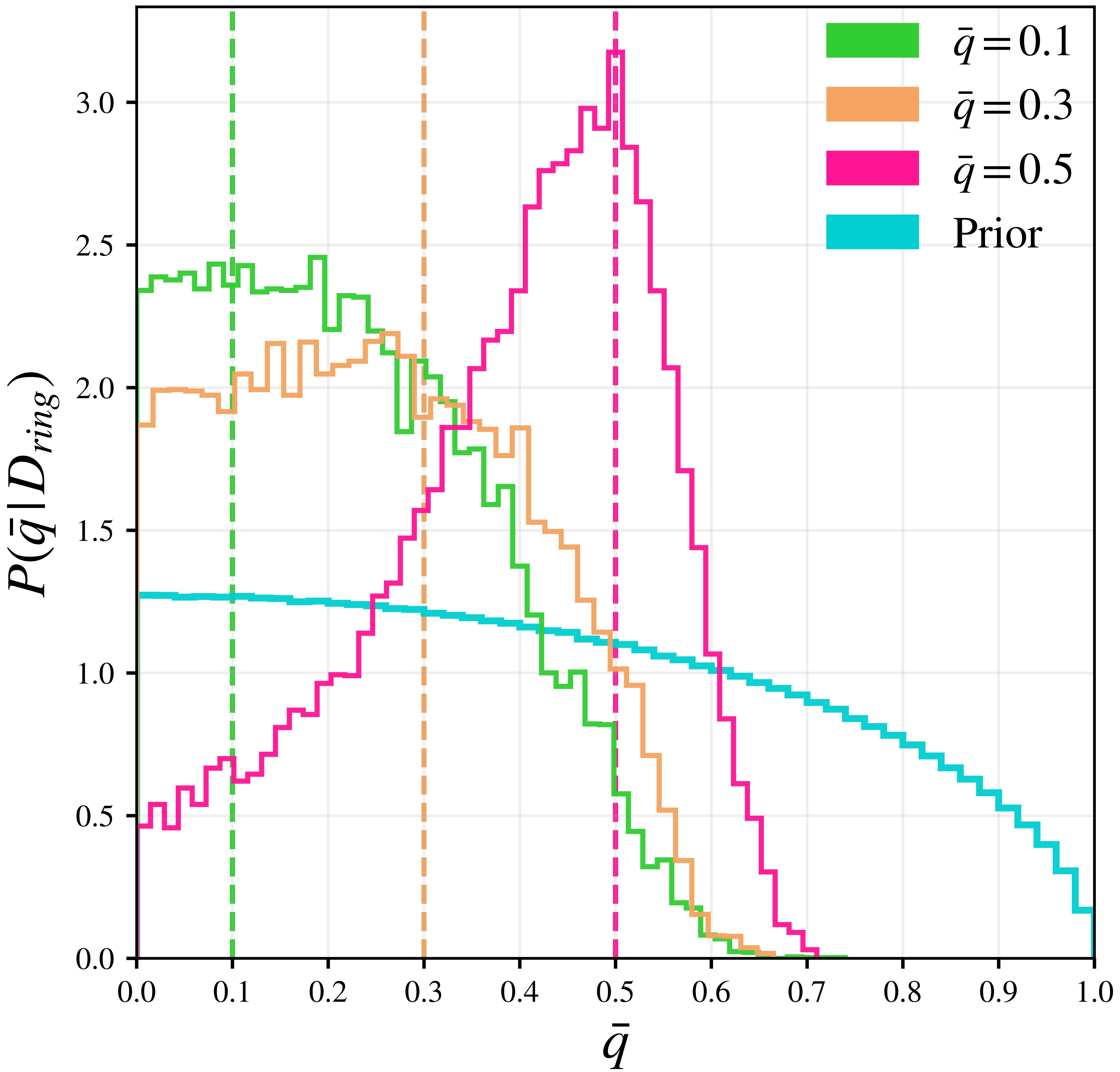
KERR-NEWMAN OBSERVATIONAL CONSTRAINTS

- **Restrict mass-spin** around LIGO-Virgo values: "mimick" information from inspiral-merger
- **Null** test: maximum amount of charge compatible with current observations
- Best event (GW150914) gives: $\bar{q} < 0.33$



KERR-NEWMAN FUTURE CONSTRAINTS

- Can future observations from current detector network **discriminate** the presence of a **charge**?
- Simulate observations of KN signals with LIGO-Virgo at design sensitivity
- Need more info to break **spin-charge correlations**

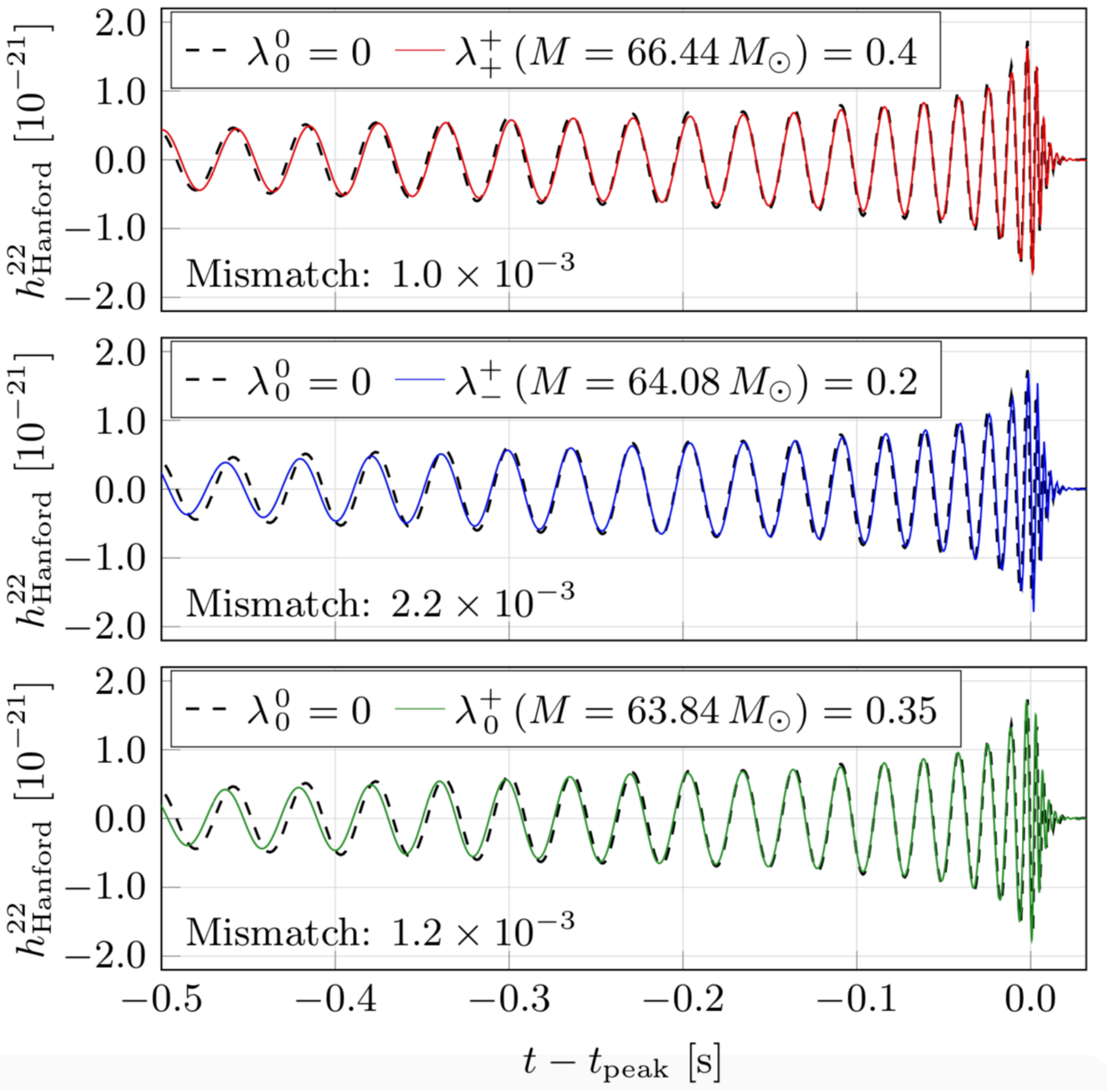


Khalil+, arXiv:1809.03109 Gupta+, arXiv:2107.12111

KERR-NEWMAN TEMPLATE

- Next:
  - Compare against fully relativistic numerical simulations
  - Predict amplitudes
  - Search for additional modes
  - Combine with inspiral model

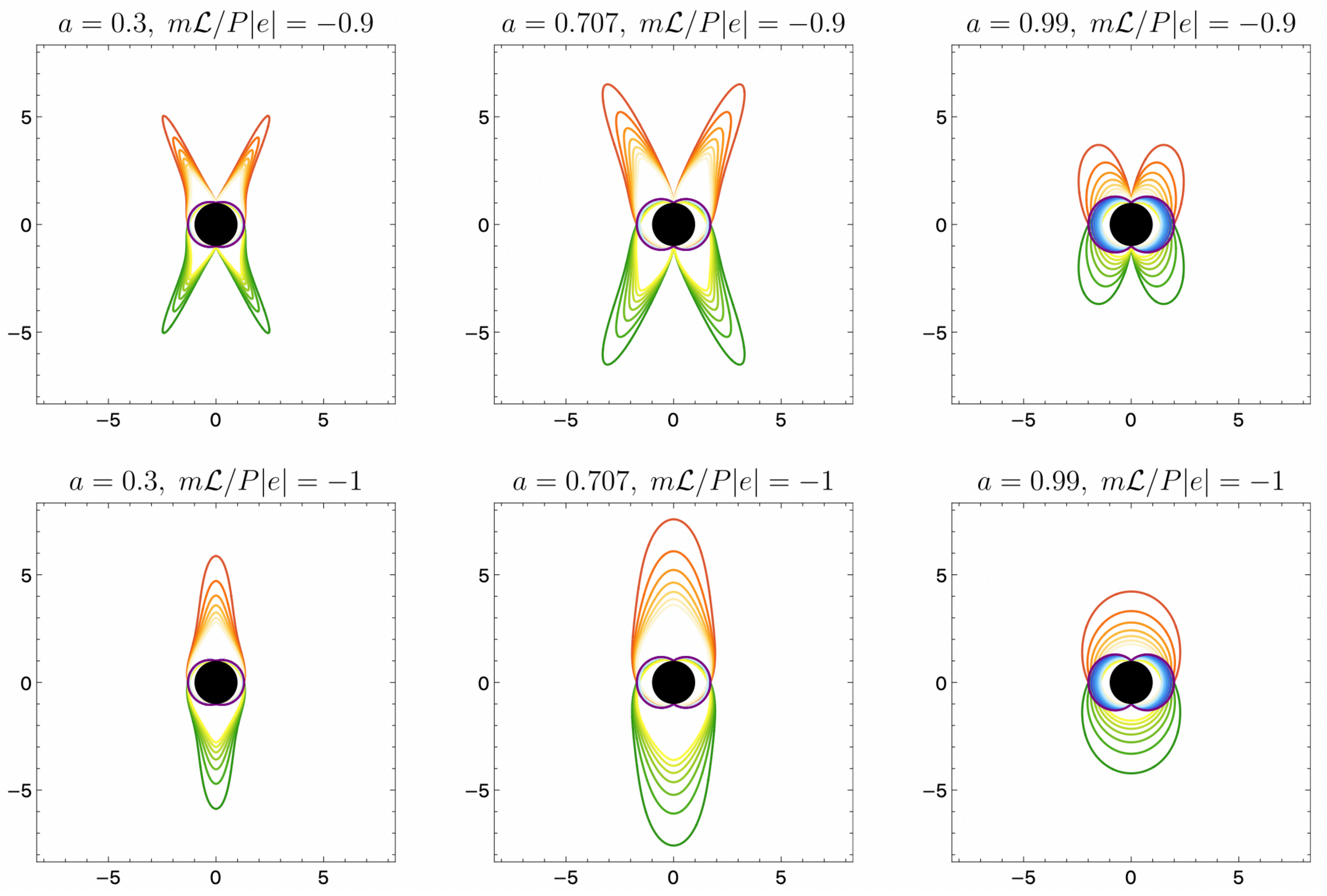
Bozzola, Paschalidis, arXiv:2006.15764



De Amicis, Bozzola, Cardoso, Carullo, - In prep.

KERR-NEWMAN TEMPLATE

- Beyond pure electric/magnetic charge: unlock a **much richer phenomenology**



Regions of negative energy states of an electric particle in the field of a rotating magnetic BH

Dyson, Pereñiguez - arXiv:2306.15751