TESTS OF GENERAL RELATIVITY: SEARCHES FOR NEW GRAVITATIONAL PHYSICS

Extended slides on the topic are available at:

https://drive.google.com/drive/folders/1zvEFm6sK9Mi6X3RYSKNYBf21wVzsKtrh

EOB@Work

University of Turin, Oct.2023

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European Commission

Horizon 2020
European Union funding
for Research & Innovation

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niels bohr
institute

Danmarks
Grundforskningsfond
Danish National
Research Foundation

USEFUL MATERIAL

Will - The Confrontation between General Relativity and Experiment, Living Reviews in Relativity (2014)

Berti et al. - Testing General Relativity with Present and Future Astrophysical Observations, CQG (2015)

Yunes, Pretorius - Fundamental Theoretical Bias in Gravitational Wave Astrophysics and the Parameterized Post-Einsteinian Framework, PRD (2009)

LVK, Tests of general relativity with GW150914, PRL (2016)

Yunes, Yagi, Pretorius - Theoretical Physics Implications of the Binary Black-Hole Mergers GW150914 and GW151226, PRD (2016)

LVK, Tests of General Relativity with Binary Black Holes from the second LIGO-Virgo Gravitational-Wave Transient Catalog, PRD (2021)

Gair et al. - Testing General Relativity with Low-Frequency, Space-Based Gravitational-Wave Detectors, Living Reviews in Relativity (2013)

Arun et al. - New horizons for fundamental physics with LISA, Living Reviews in Relativity (2022)

WHY TESTING GENERAL RELATIVITY?

- Non-renormalizability
- Dark matter
- Dark energy
- Singularities
- Information paradox, thermodynamical interpretation
- …
- **Agnostic approach**: exploring new observations in the strong-field and dynamical regime

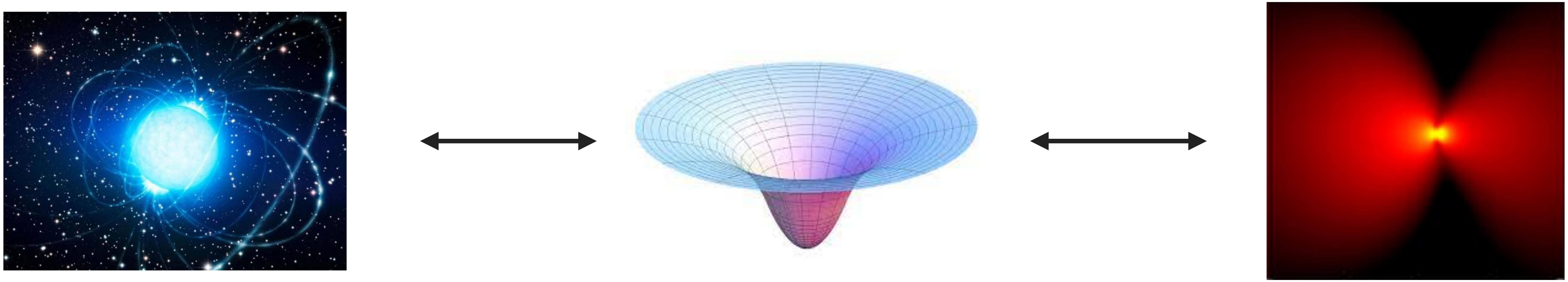
NEW GRAVITATIONAL FIELDS

- Beyond GR, new fields: $g \to (g, \varphi)$

- No direct coupling of φ to matter (EEP). Can couple to g though.

- Matter M sees "effective coupling" to φ, mediated by g:

$$M \longleftrightarrow g \longleftrightarrow \varphi$$



NEW GRAVITATIONAL FIELDS

$$M \longleftrightarrow g \longleftrightarrow \varphi$$

- "Effective coupling" non-negligible for strong grav. fields
- Rate of "free fall" depend on $\varphi(\vec{x}, t)$
- Violation of "free fall" universality, i.e position dependence of *local* experiments (e.g. close to neutron stars)

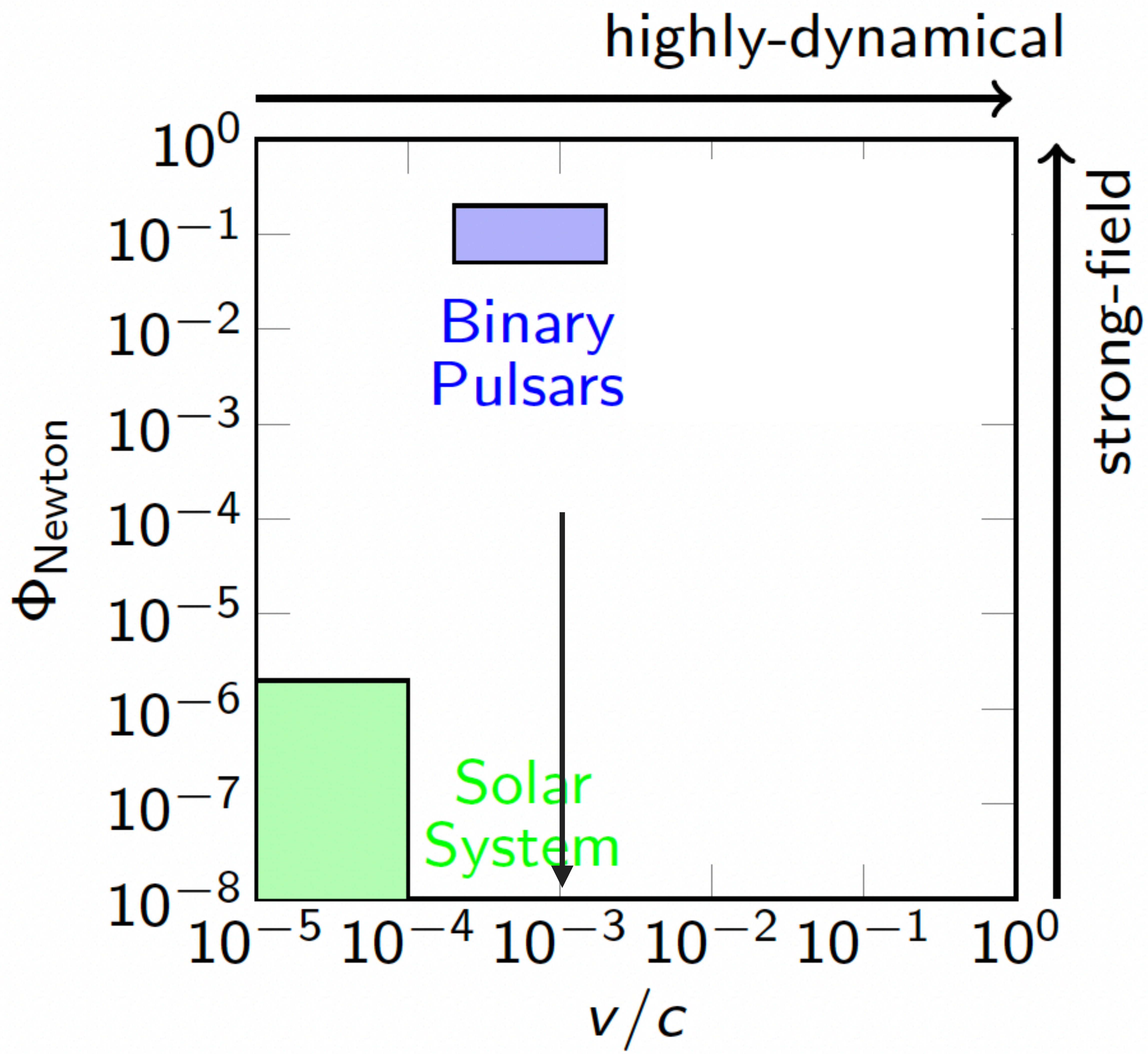
Will, arXiv:1403.7377, Toubiana+, arXiv:2004.03626

STRONG EQUIVALENCE PRINCIPLE

- Metric theories respect EEP (e.g. gravitational redshift), i.e. EEP consequence of matter-gravity universal coupling
- GR only known theory respecting SEP in agreement with observations
- *"The unsatisfactory fact that the equivalence principle maintains the absolute character of the coupling constants of physics, while general relativity and its generalizations suggest that all absolute structures should be replaced by dynamical entities."*

WHAT WAS NOT YET PROBED

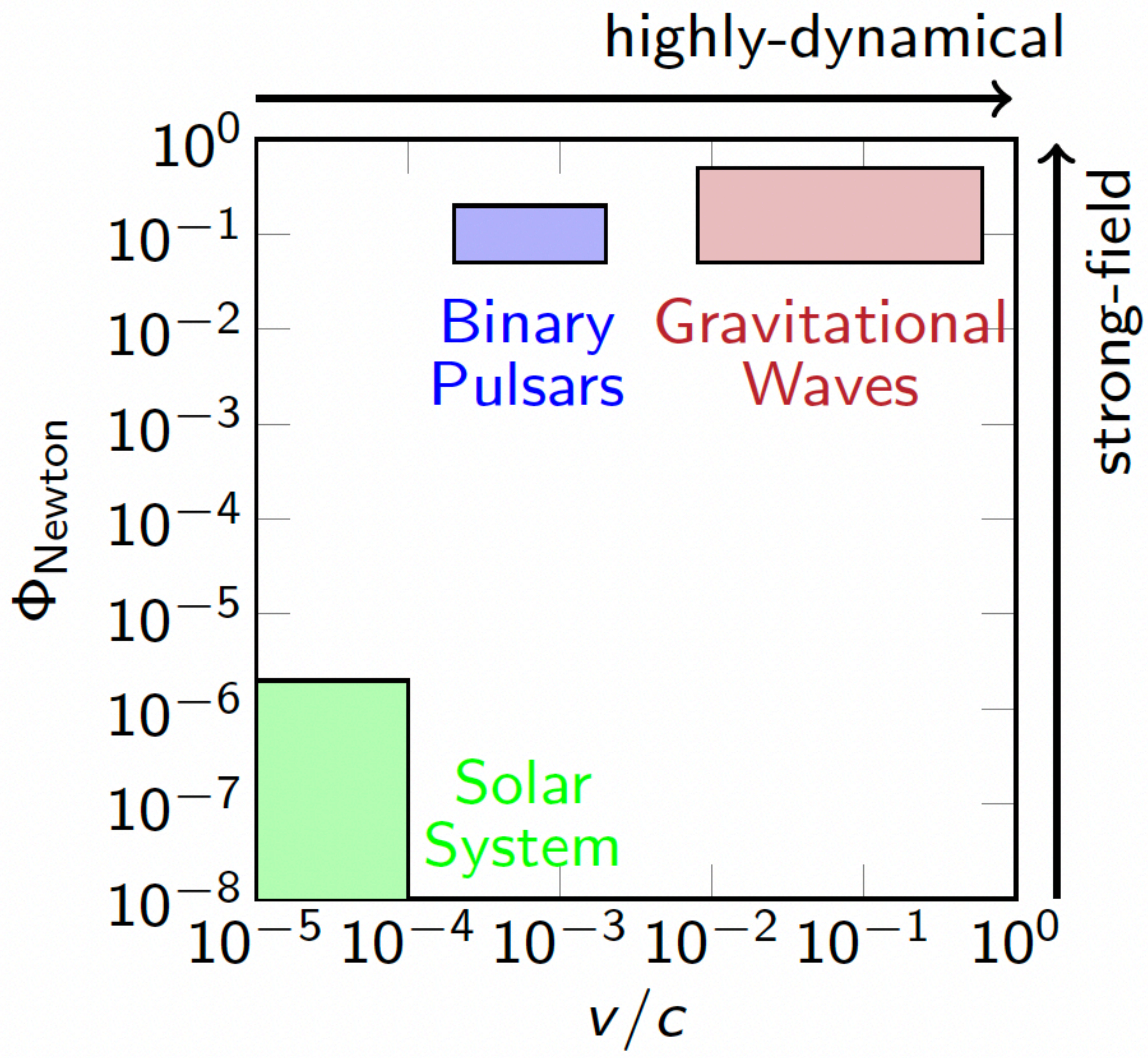
- All these restricted to regime with:
  - Low-velocity: $v/c \ll 1$
  - Wide orbits: $M_{tot}/R_{orb} \ll 1$ (tidal effects small)
  - Compactness close to BHs (BHs only ~5 times more compact)



Credits: Sennett, Buonanno

WHAT WAS NOT YET PROBED

- Graviational waves are instead in the strong-field and dynamical regime



Credits: Sennett, Buonanno


Max Planck Institute
for Gravitational Physics


High PN-order terms
Max Planck Institute
for Gravitational Physics


Wave backscattering (“tails”)
High PN-order terms


Wave backscattering (“tails”)
Spin effects
High PN-order terms


Nonlinear dynamics


Nonlinear dynamics
Horizon absorption


Quasinormal ringing

Masses in the Stellar Graveyard

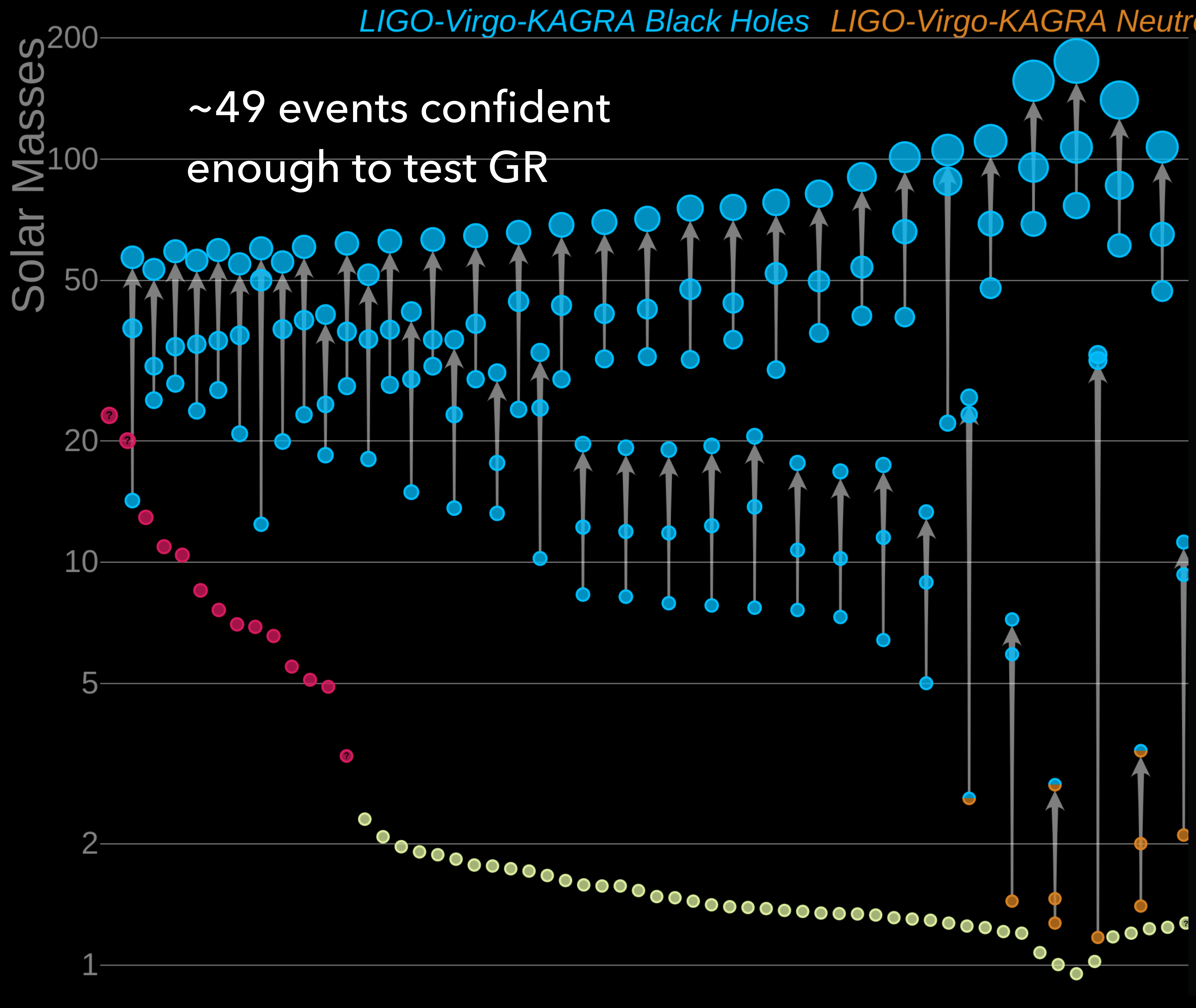
GWTC-3

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard

GWTC-3

~49 events confident
enough to test GR



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

SCIENCE GOALS

1. Theory of gravity

   Is General Relativity a correct description of gravity at high velocities and curvatures?

2. Nature of compact objects

   Are we really observing black holes?

3. New fundamental fields

   Are there additional "forces" or "particles" influencing GW signals?

SYNERGIES

- Searching for new physics requires control of all analysis ingredients

Data conditioning and characterisation

Model assumptions, construction and systematics,

$$\log p(d|\theta, I) \propto - \sum_j \frac{|d(f_j) - h(f_j;\theta)|^2}{S(f_j)}$$

Noise estimation

Beyond-GR models

HOW DO WE MOVE FORWARD?

- More sensitive when assuming a specific theory.
  Model selection vs GR. Note:
  - GR no free couplings
  - Most theories: $S = S_{\rm GR} + \alpha\, S_{\rm new}$
  - "Disconnected theories" easier to falsify, e.g. Laghi+, 2011.03816
- Focus on "natural extensions" or well-motivated theories:
  - Terms/fields predicted by fundamental physics
  - With well-posed evolution

THEORY LANDSCAPE

- **Scalar-tensor** (e.g. Bergmann and Wagoner, at most quadratic in field derivatives)

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - U(\phi)\right] + S_M[\Psi, g_{\mu\nu}]$$

- **Lorentz-violating** (e.g. Einstein-Aether)

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

- **Einstein-scalar-Gauss-Bonnet** or **dynamical Chern-Simons**

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

- **Effective Field Theories**

Short distance experiments +
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

Berti+, arXiv:1501.07274

BEYOND-GR BINARY MODELING

- Need BH binary model. Numerical interpolant or semi-analytic.
- Numerical interpolant:
    - Pros: built from exact solutions

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- Semi-analytical. Building blocks:
  - Inspiral: PN theory;

Yagi+, 1110.5950
Julie, Berti, 1909.05258
Sennet+, 1912.09917
Shiralilou+, 2012.09162
Bernard+, 2201.10924
Higashino, Tsujikawa, 2209.13749,
…

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Julie, Derouelle, 1703.05360
Julie, 1709.09742
Jain+, 2211.15580
Julie+, 2212.13802
Jain, 2301.01070
…

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  - Ringdown: QNM (frequencies) + NR (amplitudes)
- Con: approximate

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- Semi-analytical. Building blocks:
  - Inspiral: PN theory;
  - Plunge-merger: NR and EOB (extend PN);
  - Ringdown: QNM (frequencies) + NR (amplitudes)
- Pro: Can be extended using *little* and *controlled* input

Chiaramello, Nagar, arXiv:2001.11736

BEYOND-GR BINARY MODELING

- Easier said than done…
  - Computations are hard
  - Many new effects to account for
- Which theory should receive attention?
- Ideally develop general methods or parameterisations…

Example: ringdown

CURRENT DEVELOPMENTS

- Incorporate **predictions** available up to a **given order** for specific theories

$$\omega = \omega^{\mathrm{GR}} + \gamma\left(\omega_0^{\mathrm{nGR}} + a\,\omega_1^{\mathrm{nGR}} + a^2\,\omega_2^{\mathrm{nGR}}\right)$$

Schwarzschild prediction

Slow rotation

Things start to get interesting (resummation)

CURRENT DEVELOPMENTS

- Incorporate **predictions** available up to a **given order** for specific theories

$$\omega = \omega^{\mathrm{GR}} + \gamma\left(\boxed{\omega_0^{\mathrm{nGR}}} + a\,\boxed{\omega_1^{\mathrm{nGR}}} + a^2\,\boxed{\omega_2^{\mathrm{nGR}}}\right)$$

- **Marginalise** over unknown terms

$$\omega = \omega^{\mathrm{GR}} + \gamma\left(\omega_0^{\mathrm{nGR}} + a\,\omega_1^{\mathrm{nGR}} + a^2\,\omega_2^{\mathrm{nGR}} + a^3\,\boxed{\omega_3^{\mathrm{nGR}}}\right)$$

Extract from data

CURRENT DEVELOPMENTS

- Quadratic spin corrections (and higher-order): work in progress

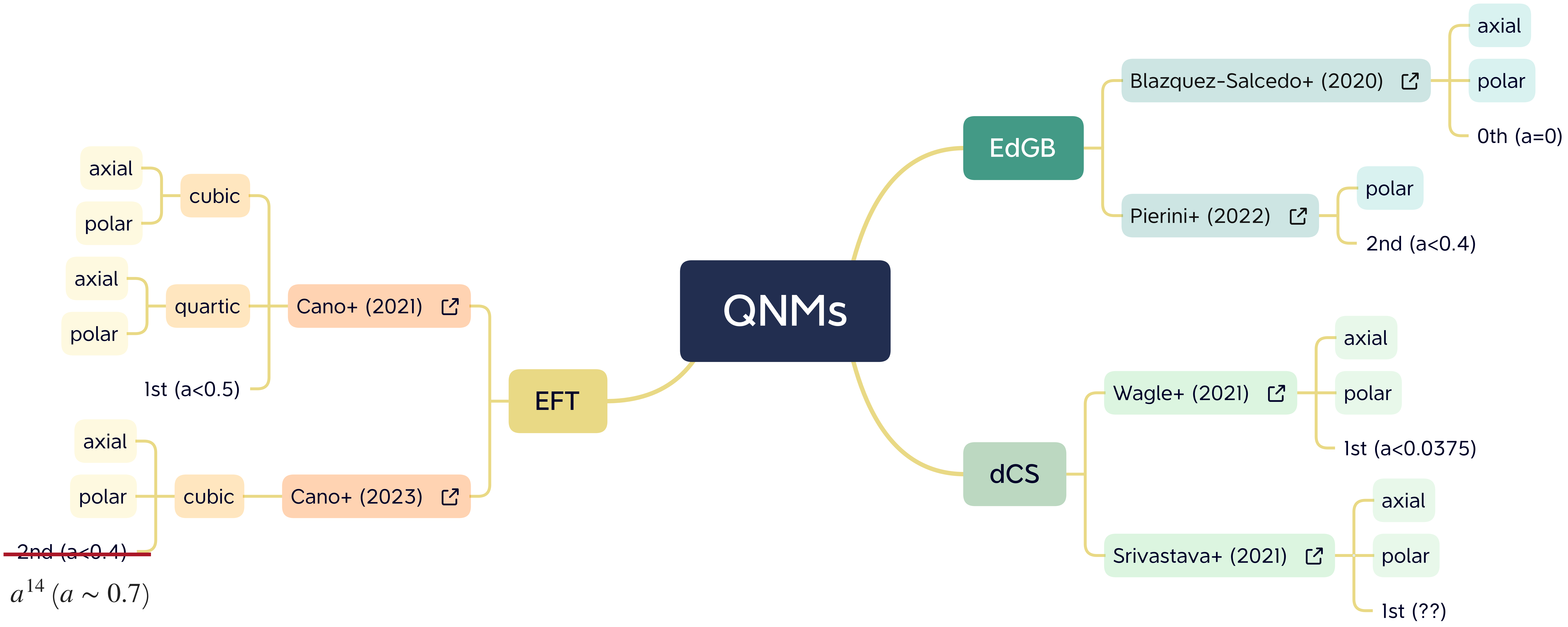
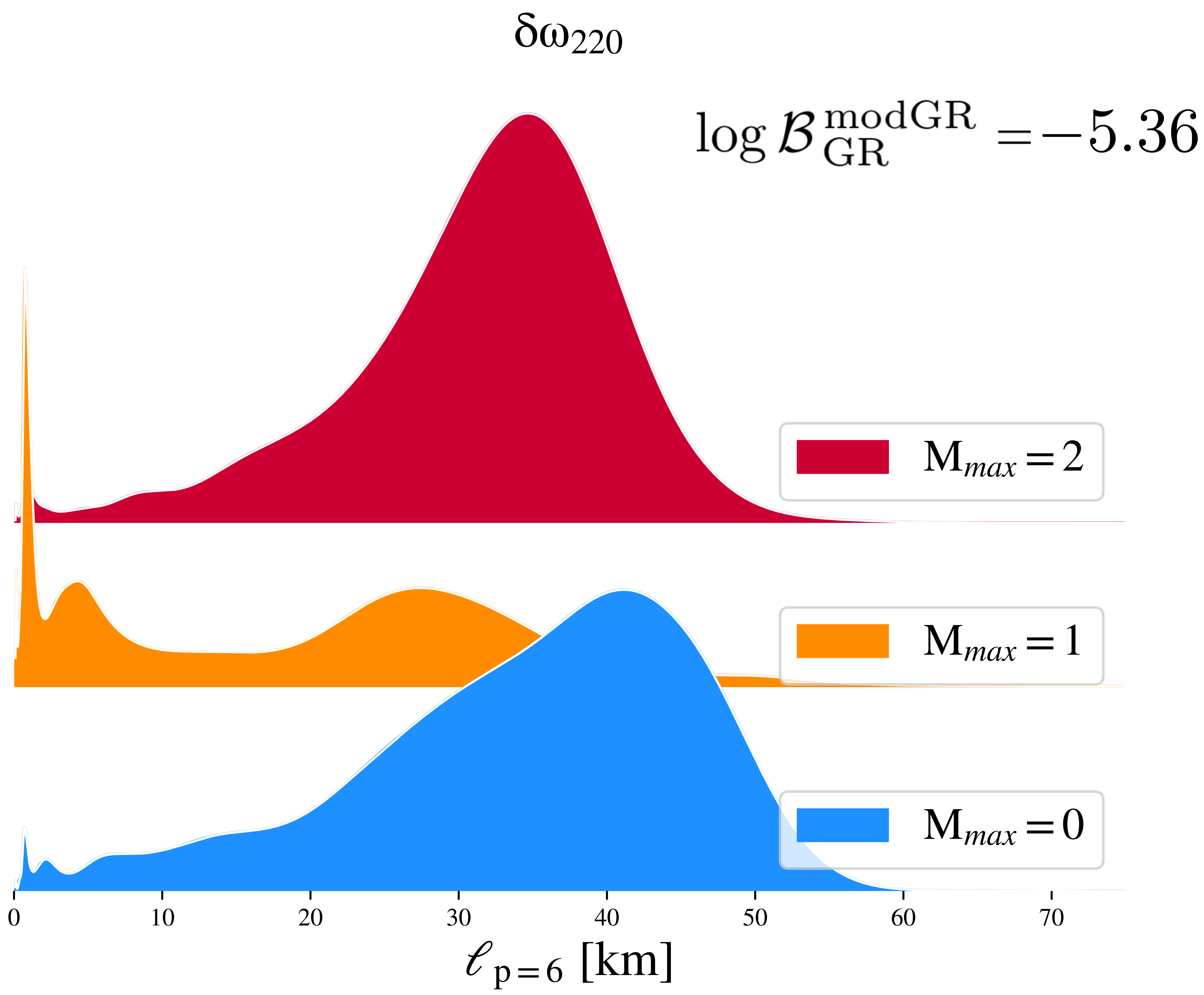


Image credits: Vasco Gennari

EFFECTIVE FIELD THEORIES P-SCALING

- Constraints on theories with beyond-GR EFTs scaling:



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

Carullo, 2102.05939

From GW inspiral:

$$\ell \lesssim 150\,\rm km$$

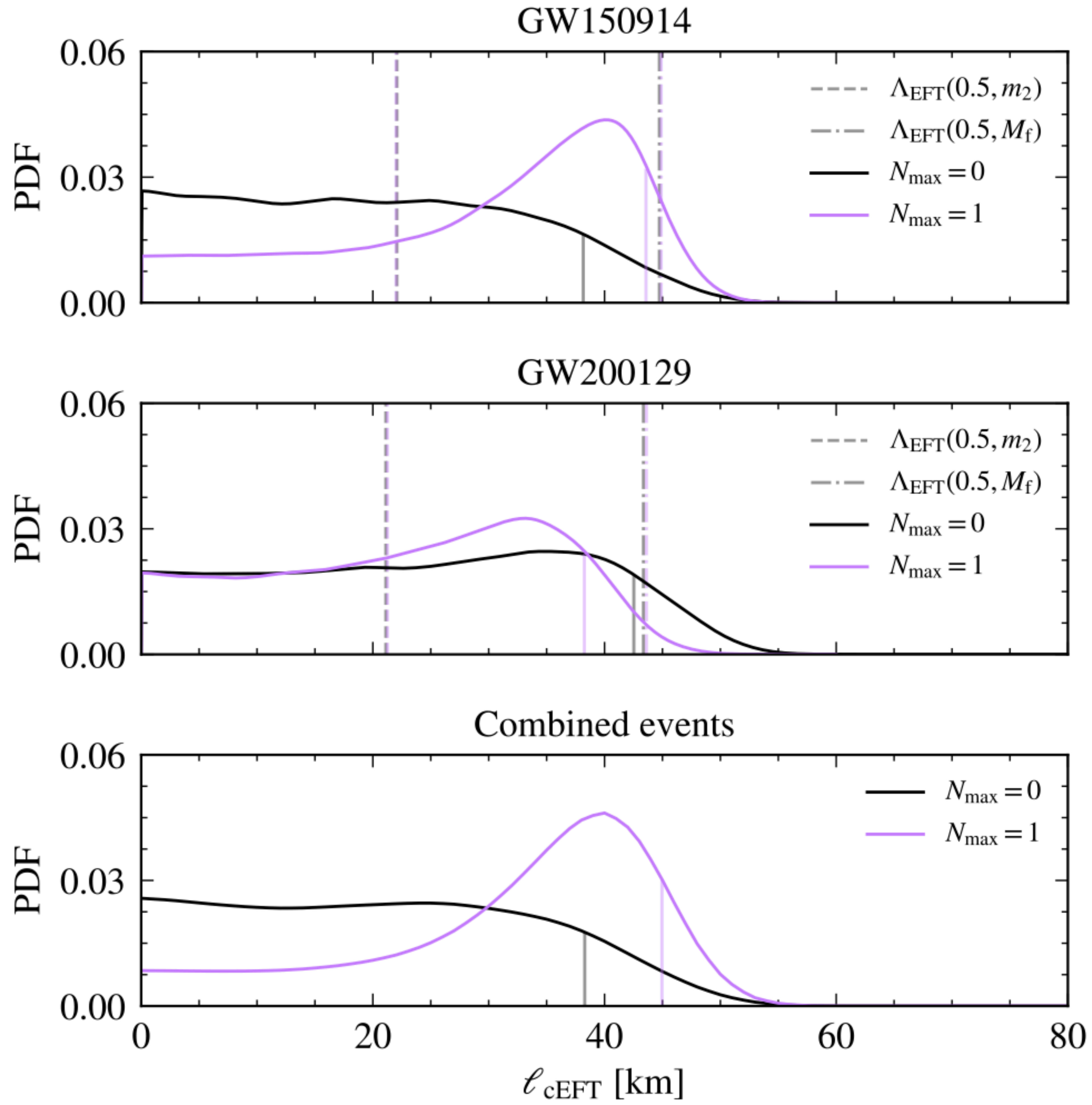
Sennett+, 1912.09917

CURRENT DEVELOPMENTS

- Linear order corrections:

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

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



No regularisation at high spins.

Silva+, arXiv:2205.05132

FUTURE DEVELOPMENTS

- Final aim: use full NR predictions, construct beyond-GR templates and search for new physics.
- Many efforts, including:

East, Ripley, 2105.08571
Ripley, 2207.13074
Corman+, 2210.09235
Evstafyeva+, 2212.11359
Cayuso+, 2303.07246

Okounkova+, 1906.08789, 1911.02588
Silva+, 2012.10436

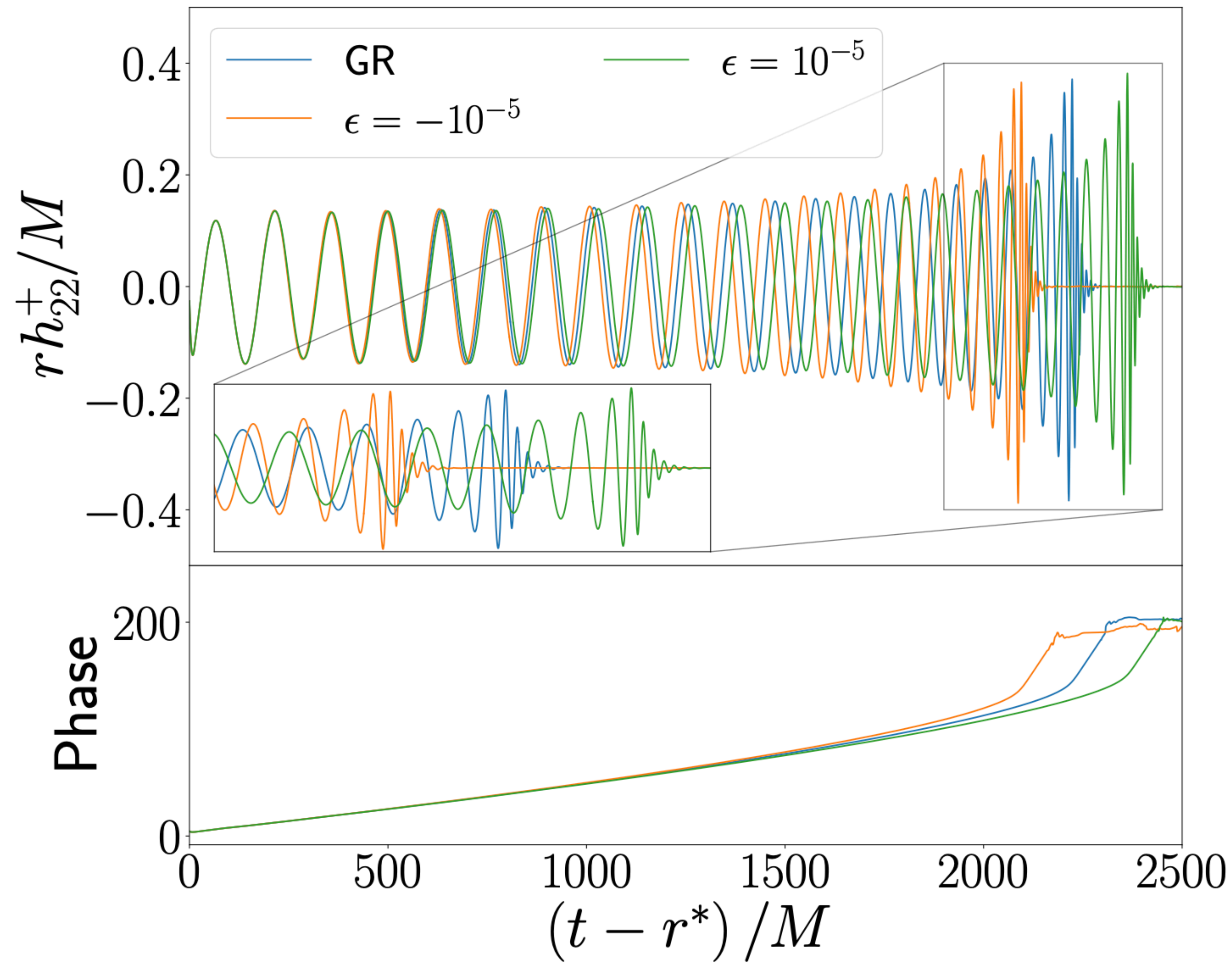
FUTURE DEVELOPMENTS

- Final aim: use full NR predictions, construct beyond-GR templates and search for new physics.

- Effects in the waveform:
  - Non-zero tidal effects
  - Shifts in QNM frequencies
  - New modes
  - ...

$$I_{\text{eff}} = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left(R - \frac{1}{\Lambda^6}\,\mathcal{C}^2 + \cdots\right)$$

Cayuso+, 2303.07246



$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$, $\epsilon = \Lambda^{-6}$

Black hole charges

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

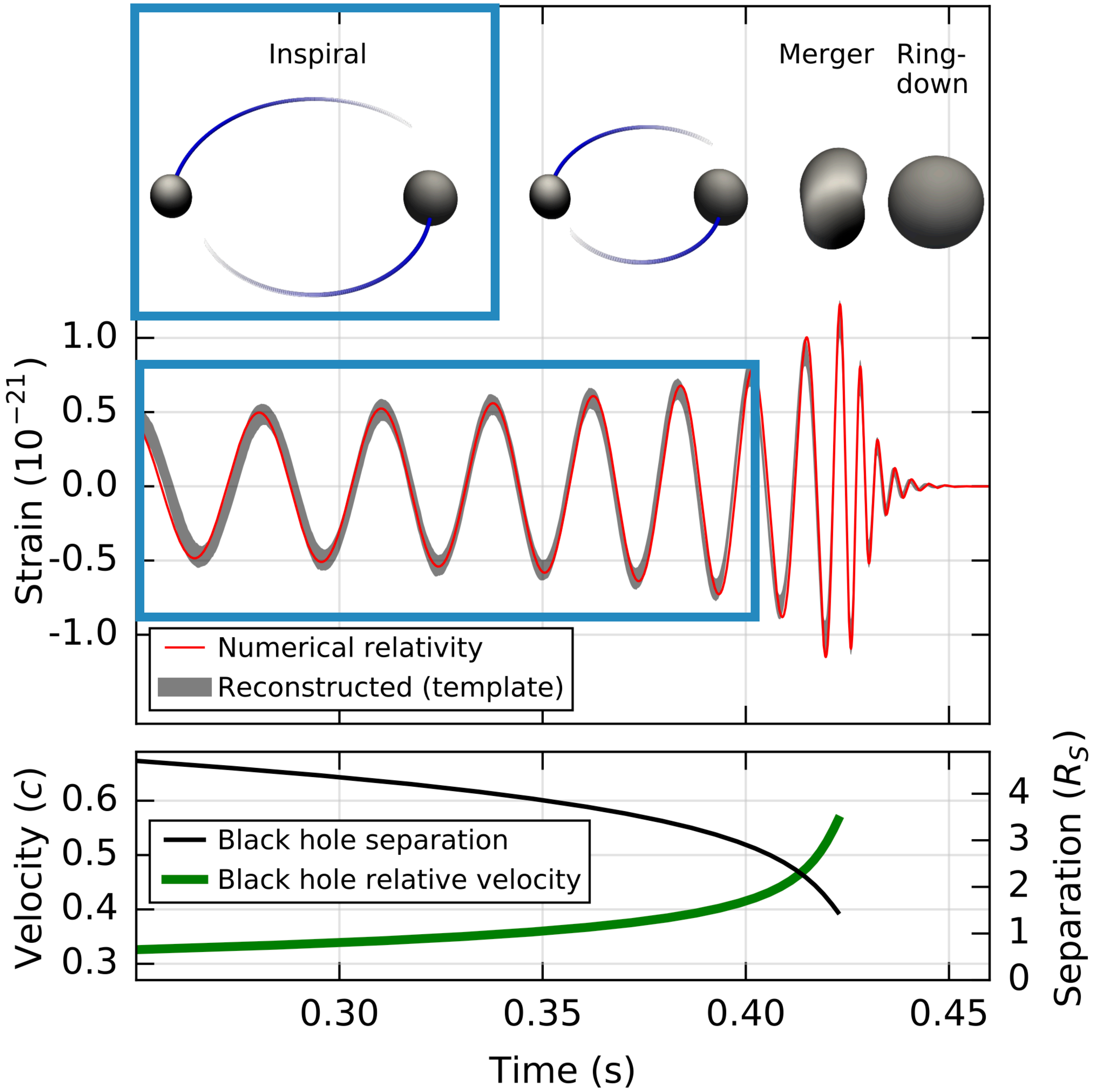
- *No-hair* conjecture: Kerr-Newman family (M, a, Q)
  - **Astrophysical charge** expected to be **negligible (polarised vacuum, neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:
  - Minicharged **dark matter, magnetic charge** (primordial magnetic monopoles), **exotic** compact objects, …
  - Scalar-**vector**-tensor gravity, **topologically** induced charge
  - Valuable **test-bed** for **beyond-Kerr** effects.

Cardoso+, arXiv:1604.07845

Inspiral

BINARY BLACK HOLES COALESCENCES

- Three main phases of the coalescence:
  - **Inspiral**: quasi-adiabatic evolution (PN theory + resummation)



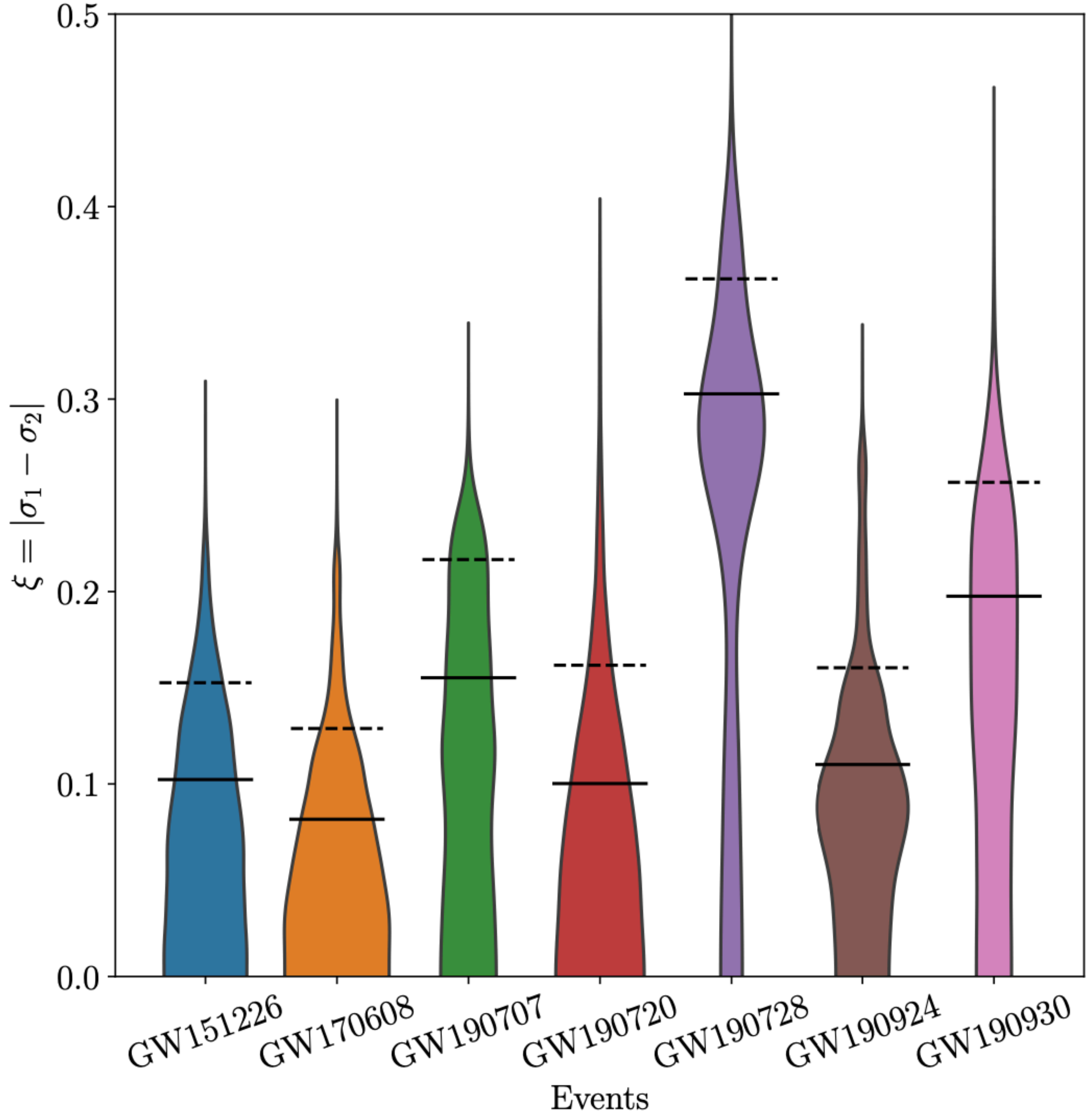
LVC, Phys. Rev. Lett. 116, 221101 (2016)

DIPOLAR CONSTRAINTS

- Charge difference can be bounded through dipolar emission
- Pros: Long accumulation
- Cons:
  - Not sensitive to single charges
  - Low-PN order.

Complementary to ringdown

Refs:
arXiv:1711.10769
arXiv:1809.03109
arxiv:1809.05041
arxiv:2205.11591
arXiv:2209.00874
arXiv:2303.17536

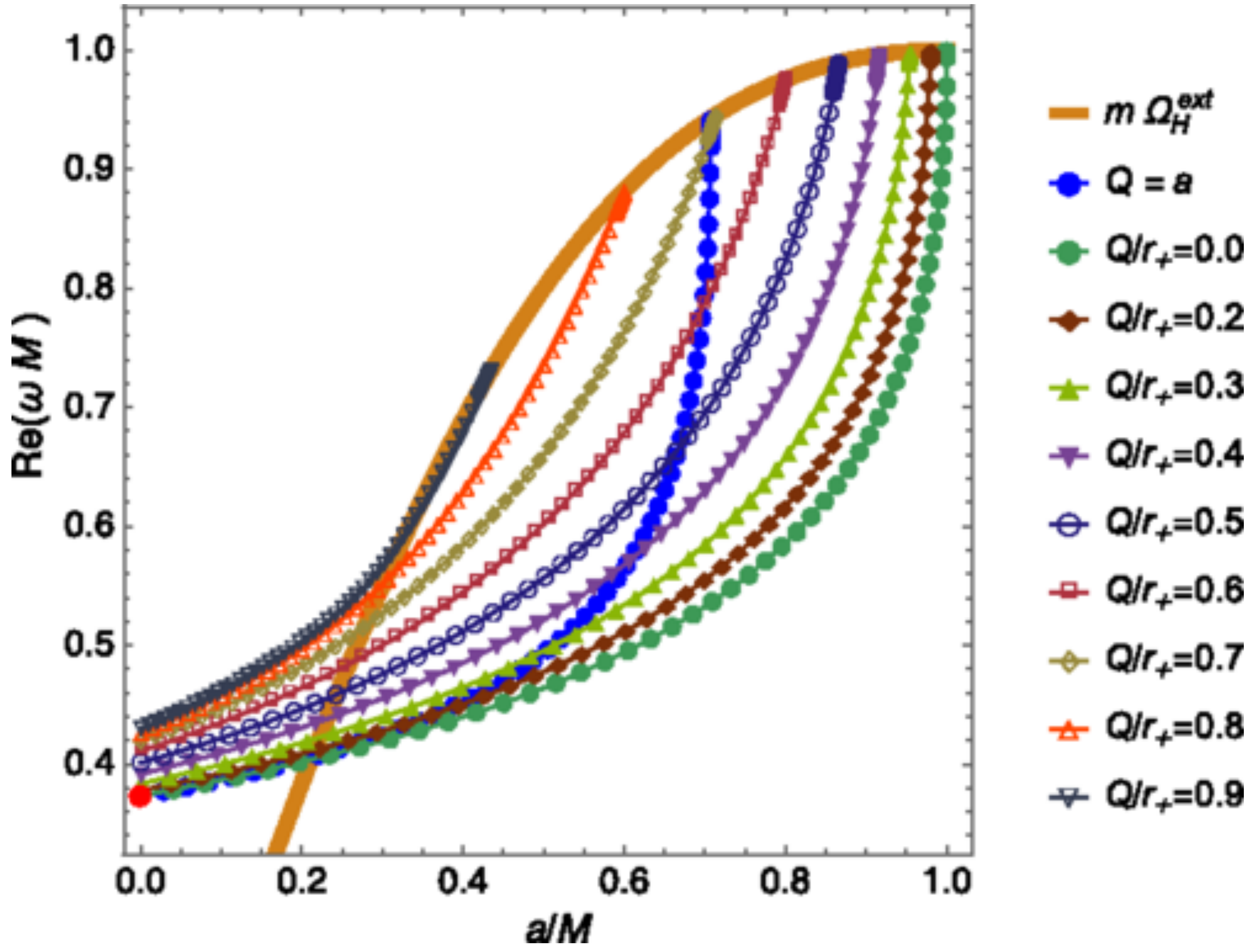


arXiv:2107.12111

Ringdown

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
- Missing extensive tabulation



Berti+. arXiv:gr-qc/0502065
Pani+, arXiv:1304.1160
Mark+, arXiv:1409.5800
Zimmerman+, arXiv:1512.02247

Dias, Godazgar, Santos, arXiv:1501.04625

KERR-NEWMAN TEMPLATE

- Build a **template** by using KN complex frequencies
- Free complex amplitudes, ignore **EM modes**

$$h_+ - i h_\times = \frac{M_f}{D_L} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} \sum_{n=0}^{\infty} \left(h^+_{\ell mn} + h^-_{\ell mn}\right) \tag{7}$$

with:

$$h^+_{\ell mn} = \mathcal{A}^+_{\ell mn}\, S_{\ell mn}(\iota, \varphi)\, e^{-i(t-t_{\ell mn})\tilde{\omega}_{\ell mn} + i\phi^+_{\ell mn}} \tag{8a}$$

$$h^-_{\ell mn} = \mathcal{A}^-_{\ell mn}\, S^*_{\ell mn}(\pi - \iota, \varphi)\, e^{+i(t-t_{\ell mn})\tilde{\omega}^*_{\ell mn} + i\phi^-_{\ell mn}} \tag{8b}$$

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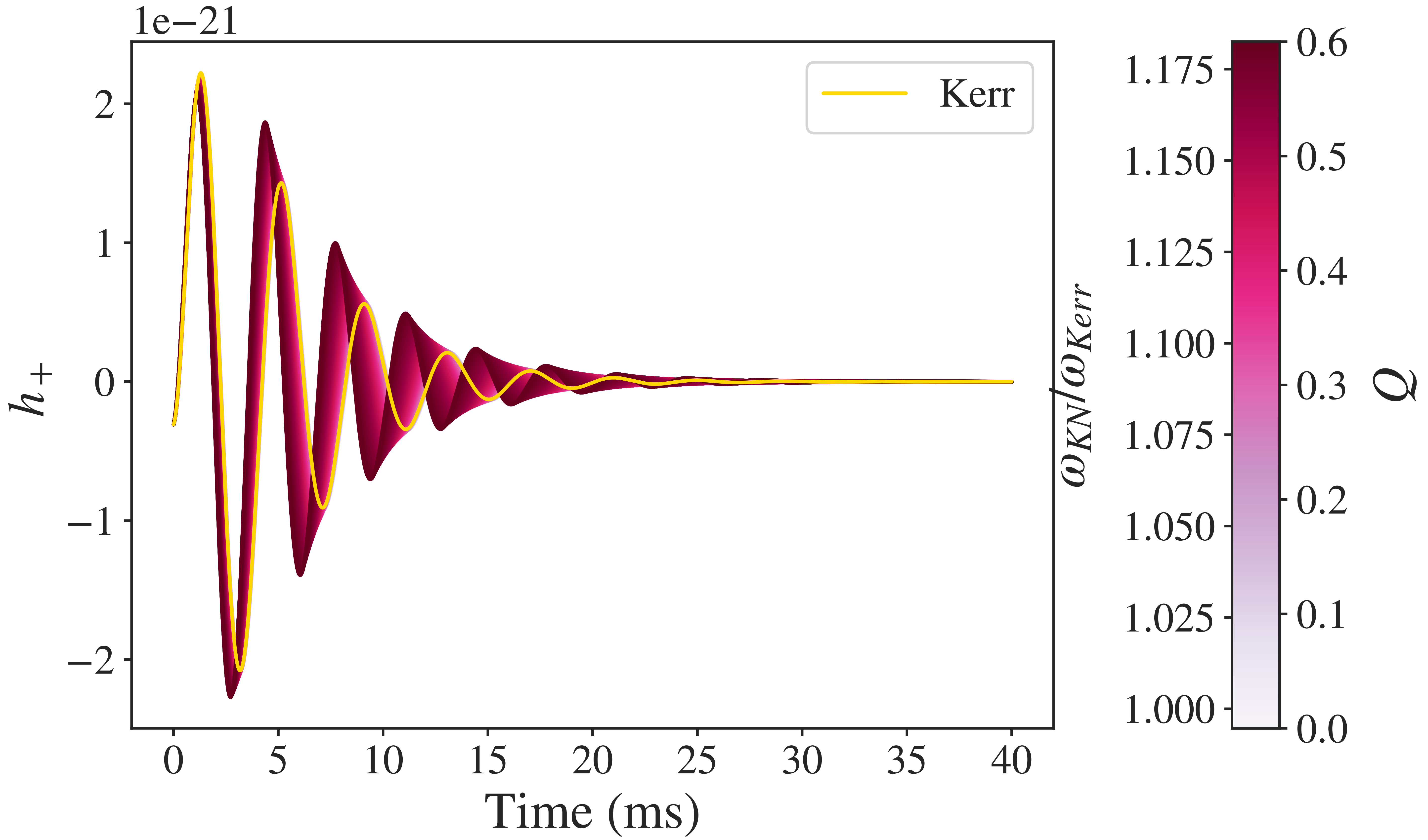
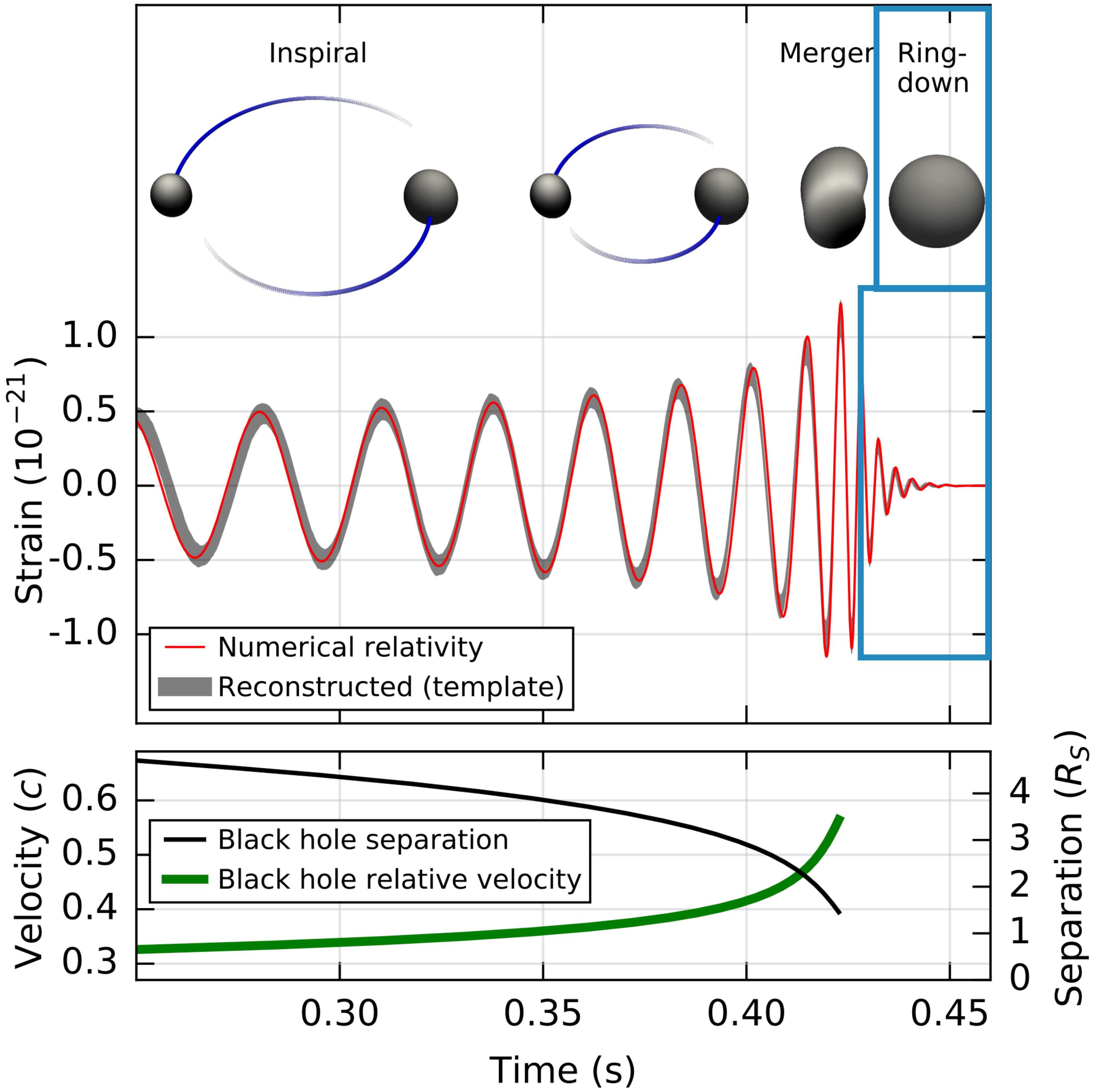


Carullo+, arXiv:2109.13961

BINARY BLACK HOLES COALESCENCES

- Three main phases of the coalescence:
  - **Inspiral**: quasi-adiabatic evolution (PN theory + resummation)
  - **Plunge-merger**: highly dynamical (NR)
  - **Ringdown**: **remnant** approaches equilibrium. Damped **normal-modes** emission **(perturbation theory + NR)**

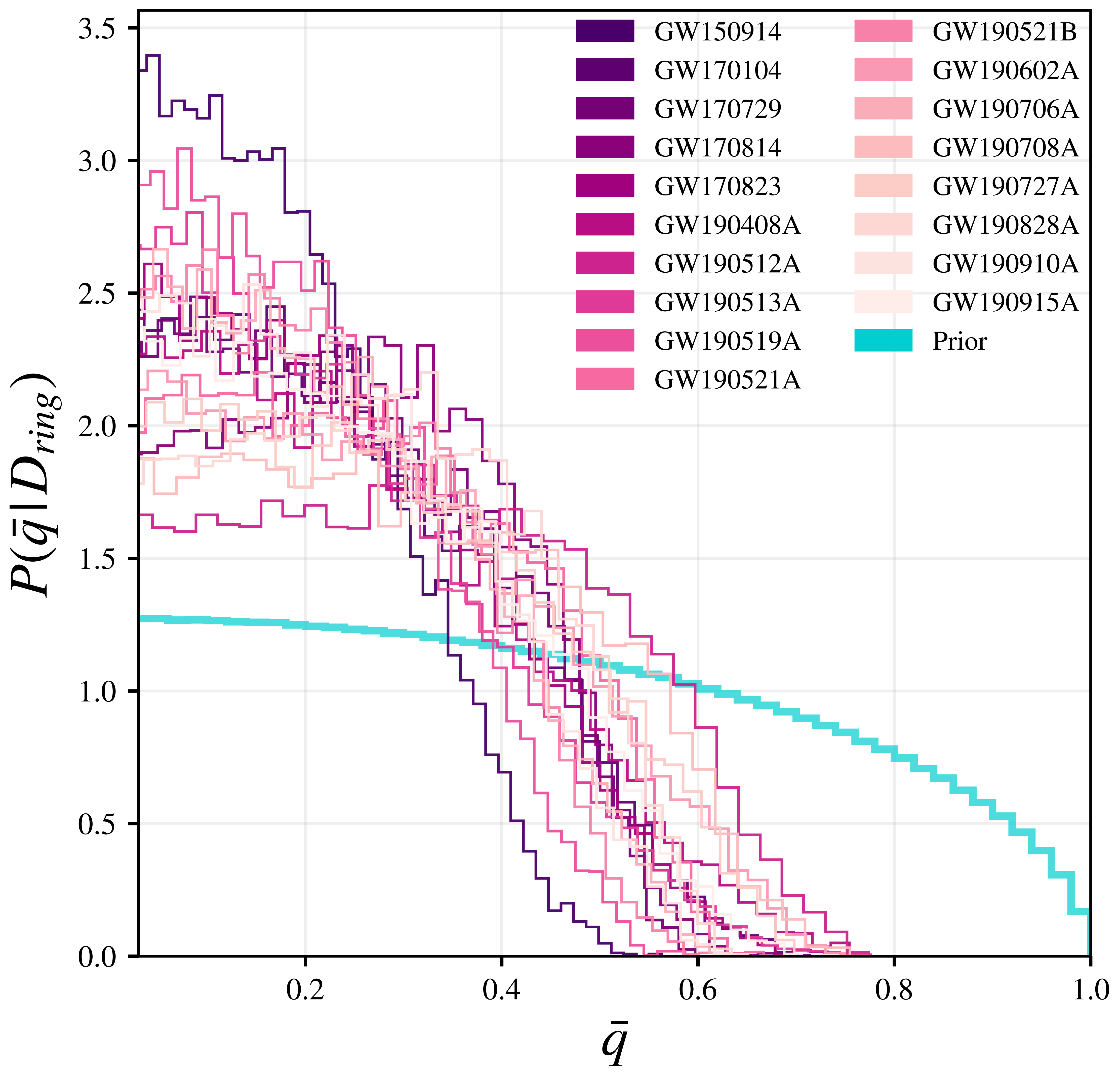


LVC, Phys. Rev. Lett. 116, 221101 (2016)

KERR-NEWMAN OBSERVATIONAL CONSTRAINTS

- Maximum amount of charge compatible with current observations

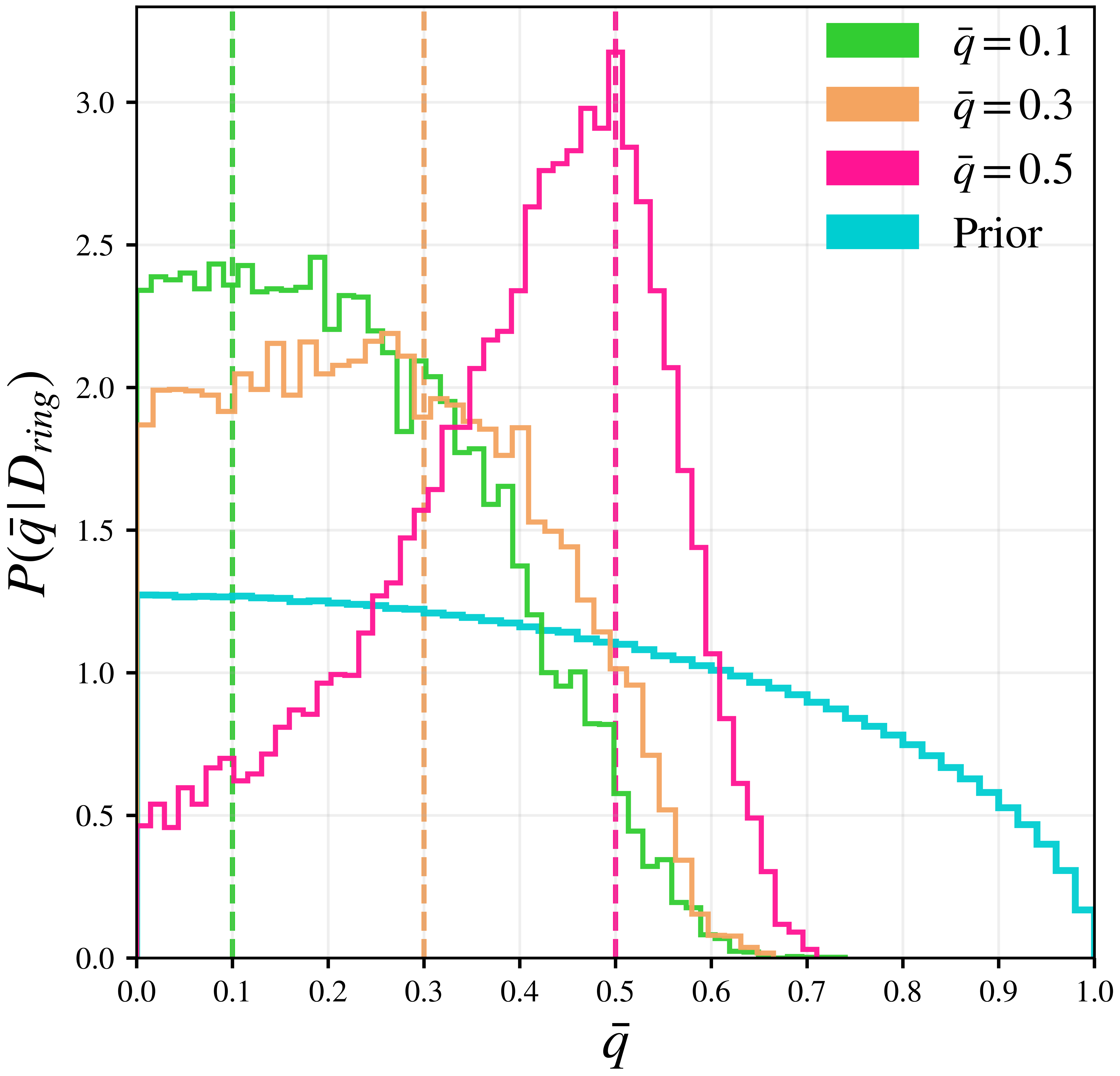
- Best event (GW150914) gives: $\bar{q} < 0.33$



Carullo+, arXiv:2109.13961

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
- Charge confidently measured **only** for **high values**
- Need more info to break **spin-charge correlations**

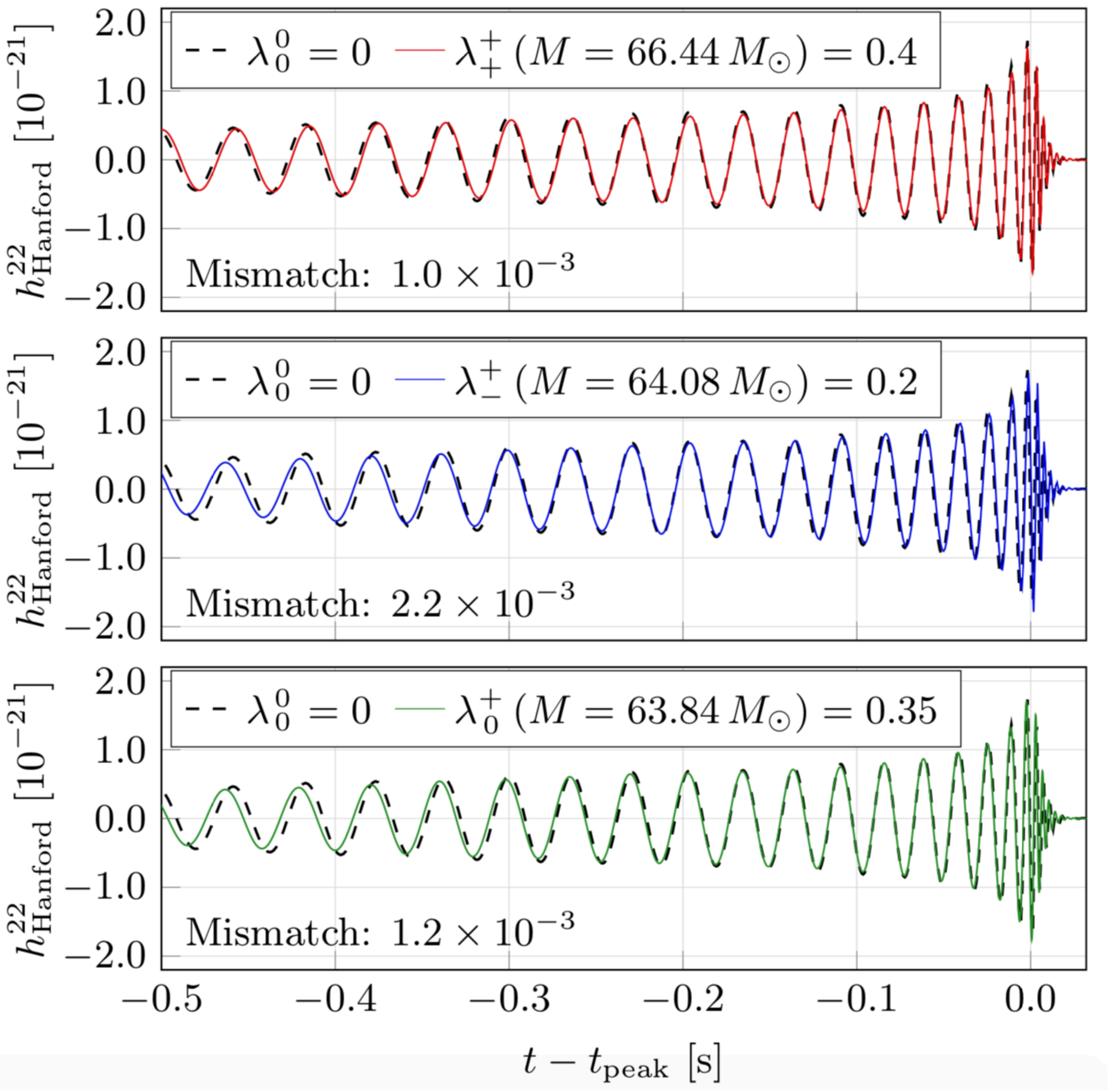


Carullo+, arXiv:2109.13961

KERR-NEWMAN TEMPLATE

Bozzola, Paschalidis, arXiv:2006.15764

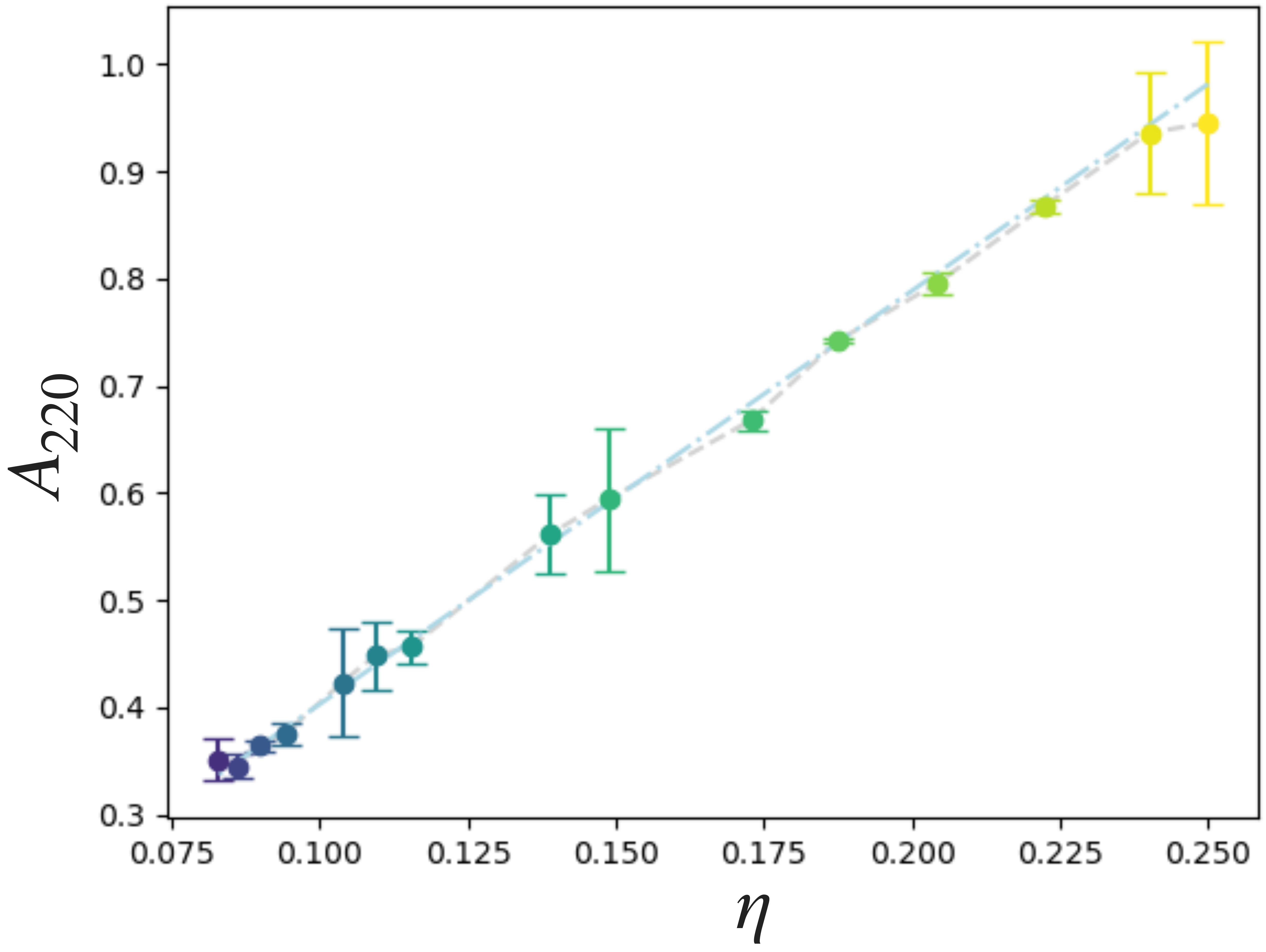
- Currently:
  - Comparing against fully relativistic numerical simulations
  - Predict amplitudes
  - Search for additional modes



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

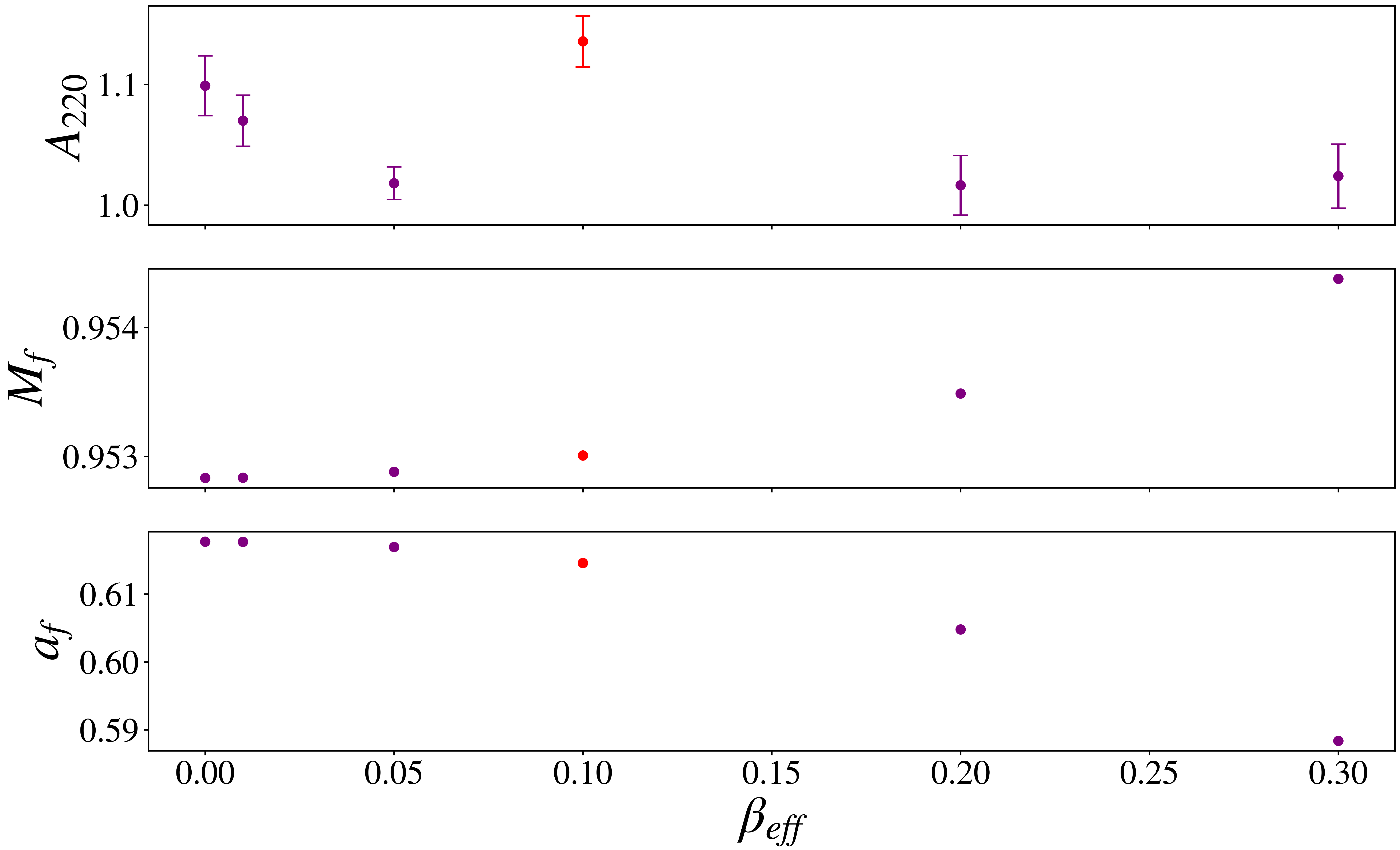
KERR-NEWMAN POST-MERGER TEMPLATE

- Example:
    - Dependence of linear ringdown amplitude with symmetric mass ratio



KERR-NEWMAN POST-MERGER TEMPLATE

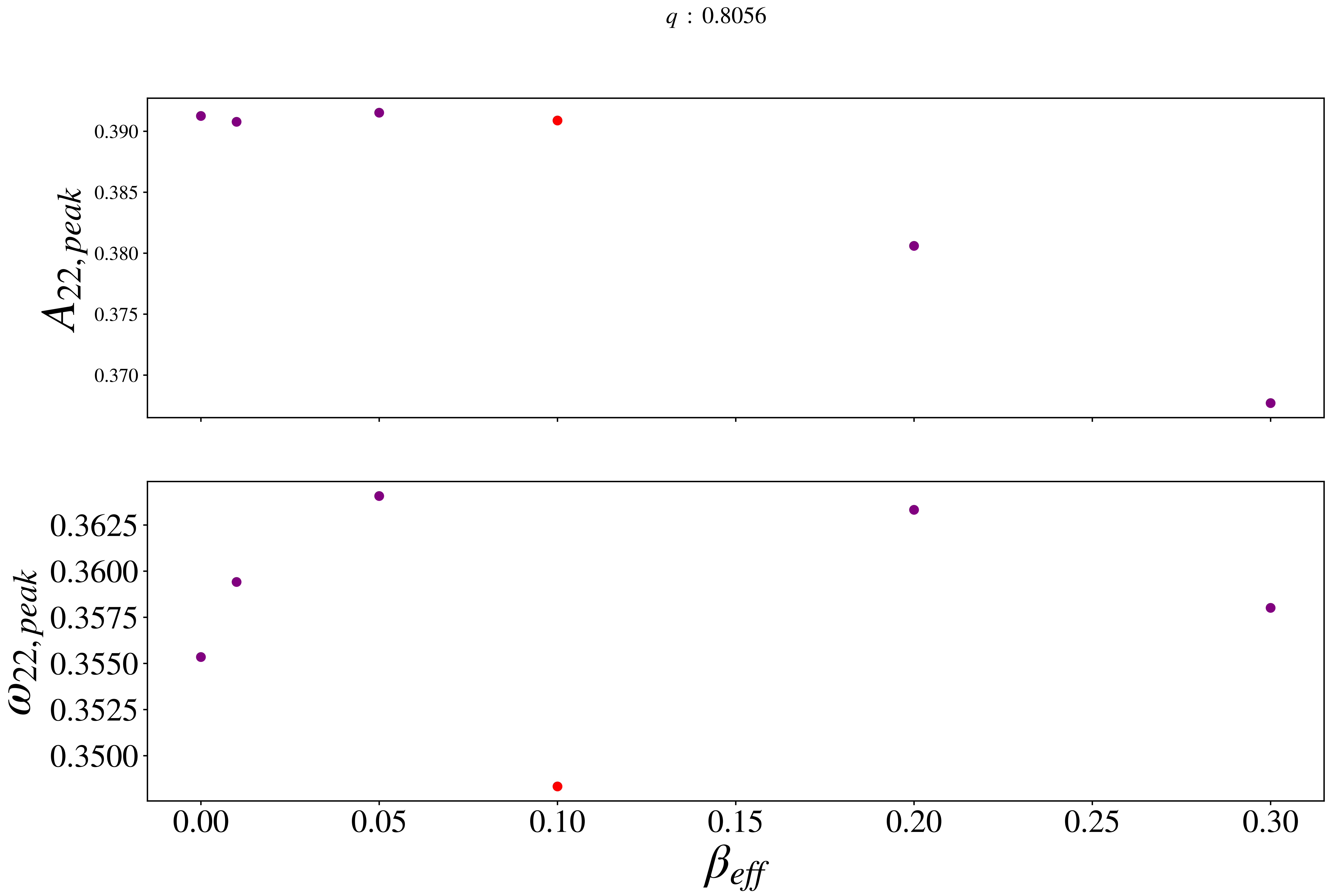
q : 0.8056



$$\beta_{\rm eff} = \frac{m_1\beta_1 + m_2\beta_2}{m_1 + m_2}$$

$$\beta_i = q_i/m_i$$

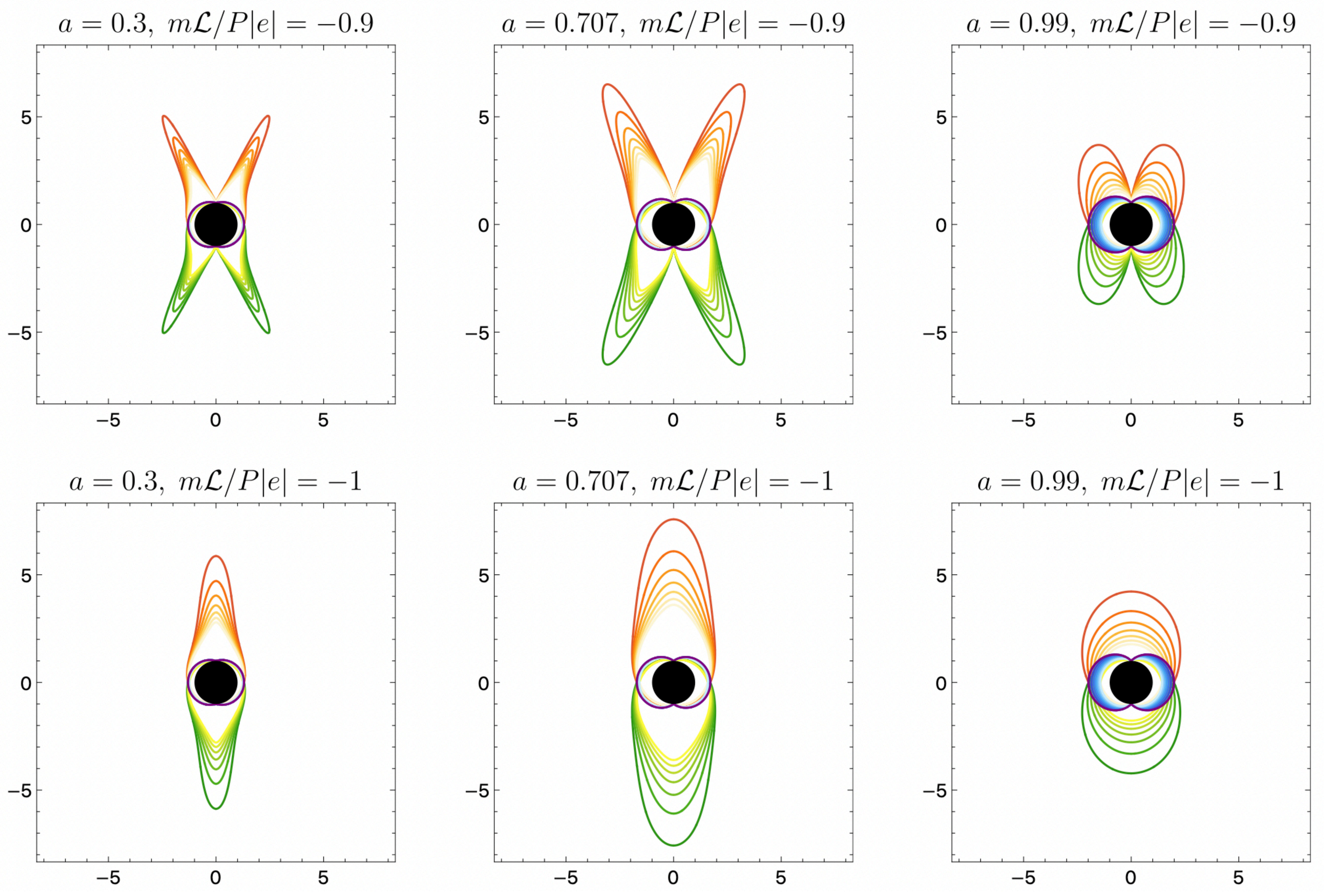
KERR-NEWMAN POST-MERGER TEMPLATE



Beyond electric charges

KERR-NEWMAN TEMPLATE

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



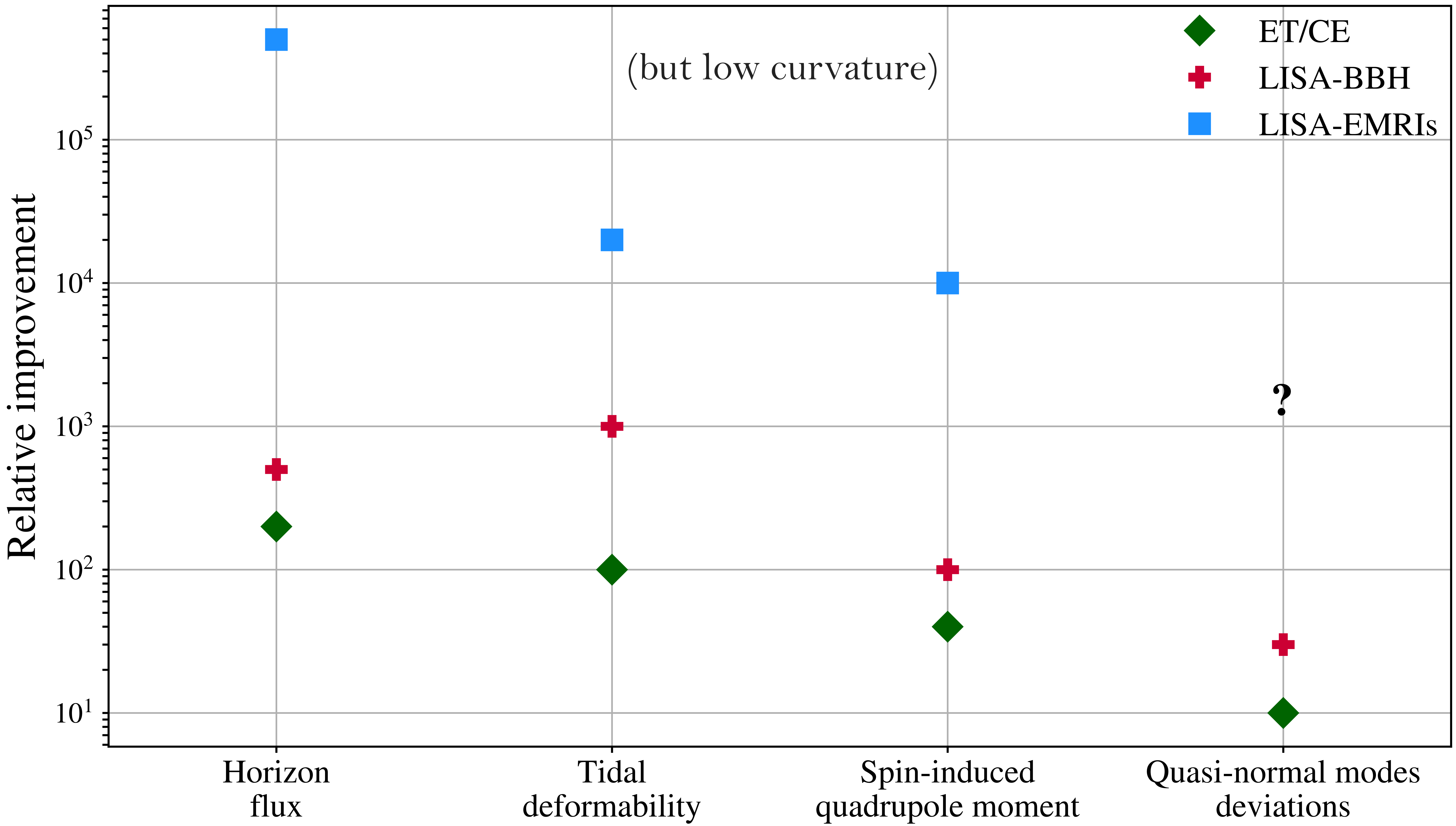
Regions of negative energy states of an electric particle in the field of a rotating magnetic BH

Dyson, Pereñiguez - arXiv:2306.15751

WHAT'S MISSING

- Quantify accuracy of available PN templates
- Build an EOB template (or improve existing one)
- Merge with ringdown results to create a full model

SPACE SUPREMACY



Babak+, arXiv:1703.09722 Cardoso-Pani, arXiv:1904.05363 Datta+, arXiv:1910.0784 Maselli+, arXiv:1910.12893

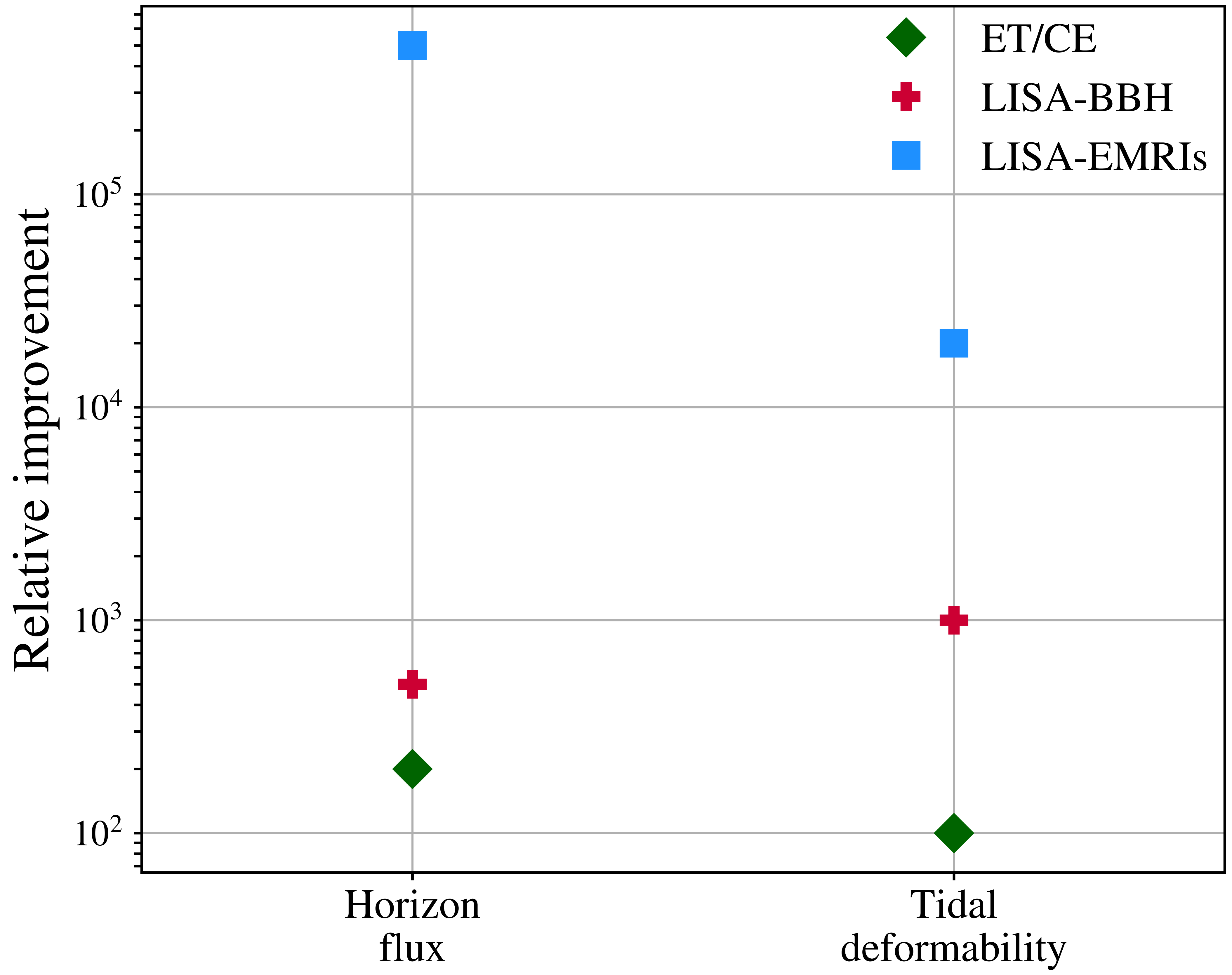
HORIZON FLUX (TIDAL HEATING)

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

- Currently, **slowly-varying perturbations**. EOB: resummed $\mathcal{F}^H$. Accuracy for comparable/ intermediate q?

- **Eccentricity** boost to this measurement?

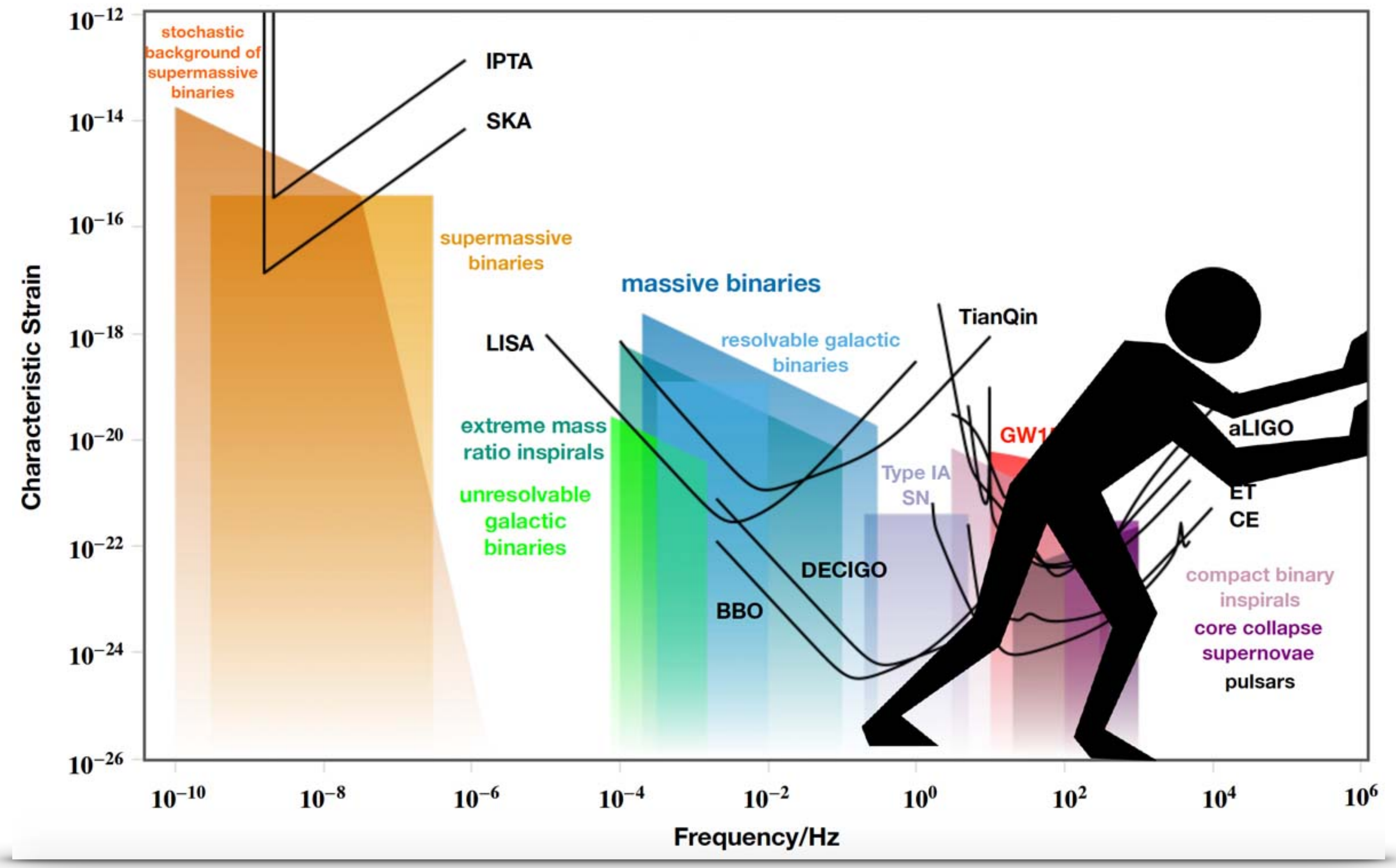
Current precision 1 ± 20



Alvi, 0107080 Poisson+, 0907.0874-1211.1686 Nagar+, 1112.2840
Lovelace+,1110.2229 Bernuzzi+, 1207.0769 Taracchini+, 1305.218
Cardoso+, 1701.01116 Maselli+, 1703.10612 Saketh+, 2212.13095
Lai-Li, 1807.01840 Datta+, 1910.07841

ULTRA HIGH-FREQUENCY GRAVITATIONAL WAVES

- Funny stuff might happen at high frequency, more than low frequency



arXiv:2011.12414

ctc.cam.ac.uk/activities/UHF-GW.php