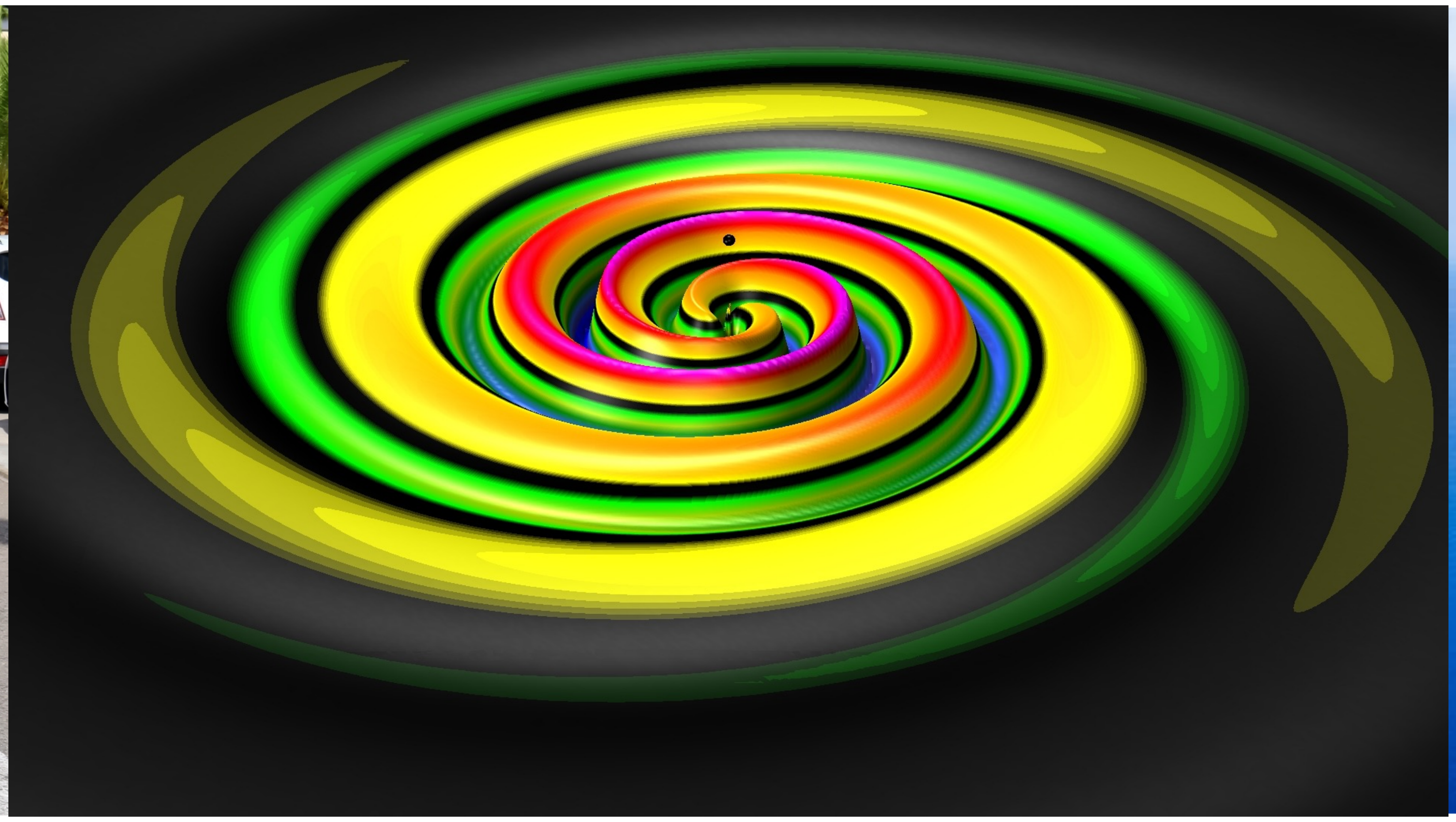
Activities of the LIGO/LISA UIB group

Sascha Husa for the UIB group
Alicia Sintes, David Keitel, Marta Colleoni, Pep Covas [now AEI], Cecilio García, Antoni Ramos Buades [now AEI], Héctor Estellés, Maite Mateu, Rodrigo Tenorio, Alicia Calafat, Rafel Jaume, Friso Snel, Joan Moragues, Lluc Planas, Miquel Duran, Angela Borchers Pascual, Sandra Calafell, Maria Rosselló



Virtual Iberian GW Meeting - 19/10/2020

The LIGO/LISA UIB team

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Beatriz Galindo, joined 01/2020

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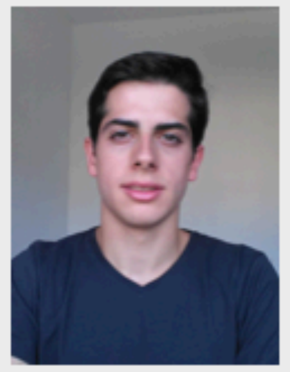

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upcoming opening
- put your name here -

Graduate Students

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PhD student
to join soon
to work on CW
with D. Keitel.

Master

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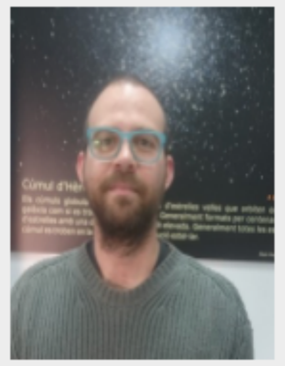

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Joan Moragues

+ several
undergraduate
students

Lluc Planas,
Miquel Duran

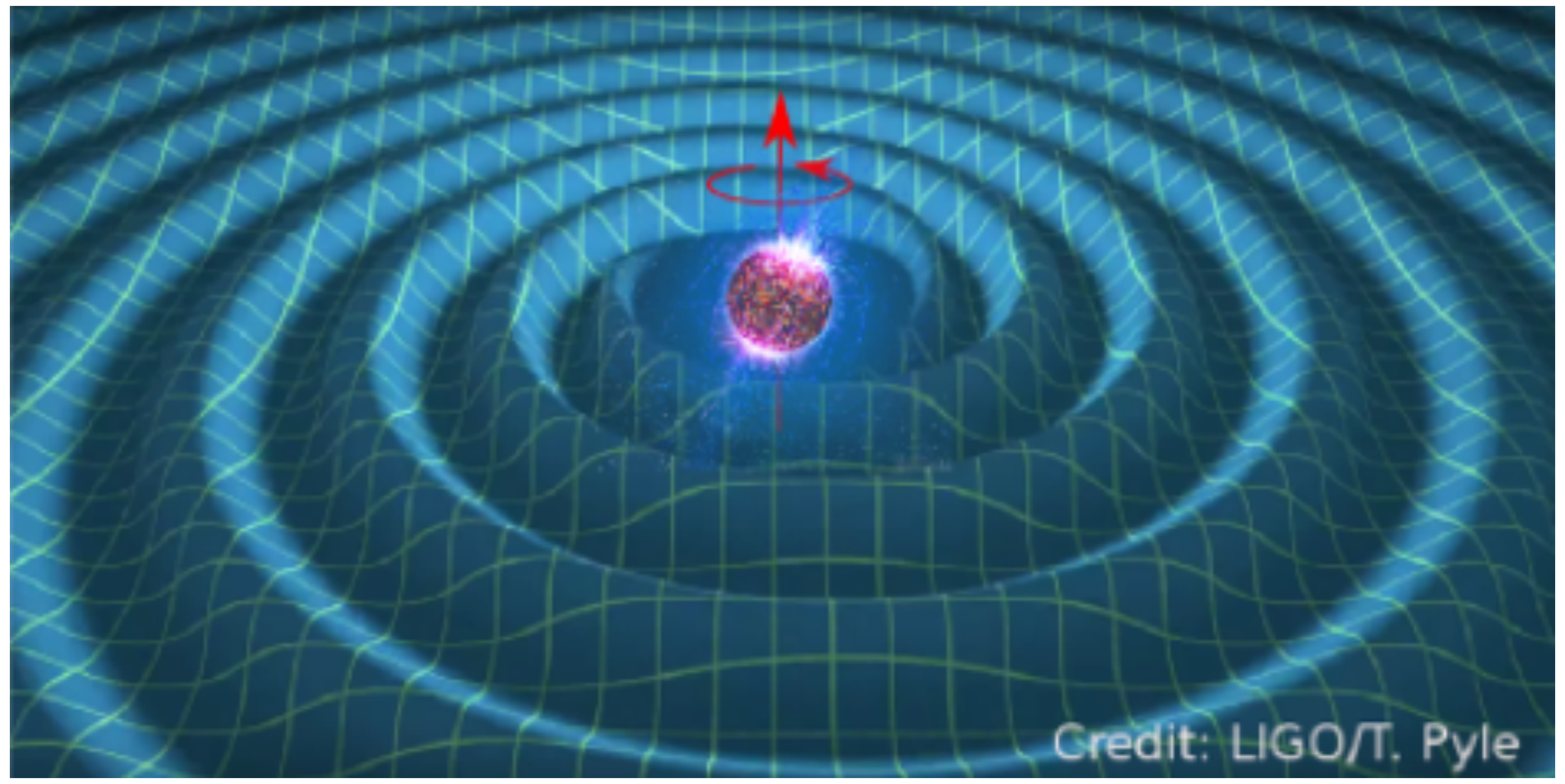
Main Areas of Activities

- Searches for Continuous Gravitational Waves, contributions to LVC CW search group.
- Compact Binary Coalescence (CBC) - contributions to LIGO CBC/waveforms and CBC/PE groups, LISA waveforms working group and waveforms work packages.
  - Modelling of CBC signals, numerical relativity, self-force calculations and EMRIs.
  - CBC Parameter estimation.
  - Searches for lensed events.
- Long transients (e.g. BNS merger remnants).
- Einstein Telescope (ET).
- Outreach, organising meetings (initiated Iberian GW Meetings).

Continuous Wave searches with LIGO & Virgo

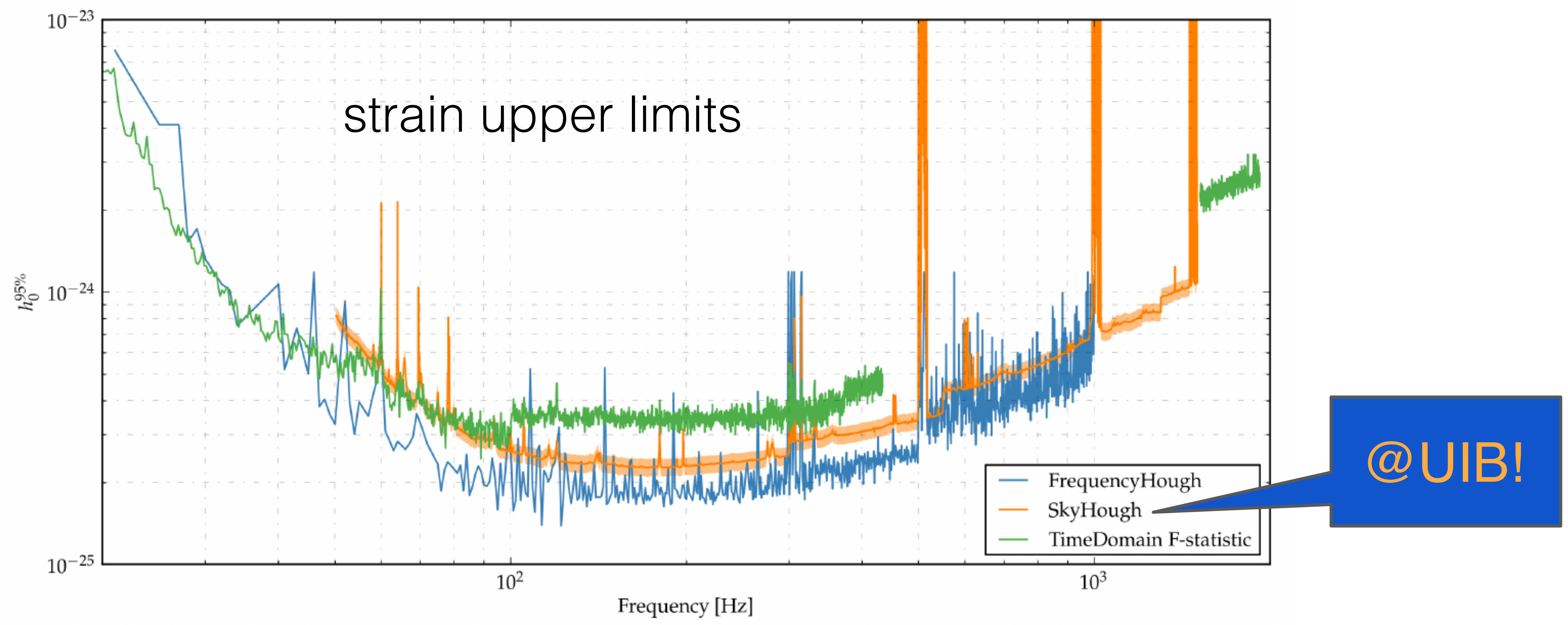
- Spinning deformed NSs emit very weak, persistent, quasi-monochromatic GWs.
- Detection strategy:
    - integrate signal over ~O(year) of data
    - fully coherent matched filter prohibitive (except in targeted searches for known pulsars)

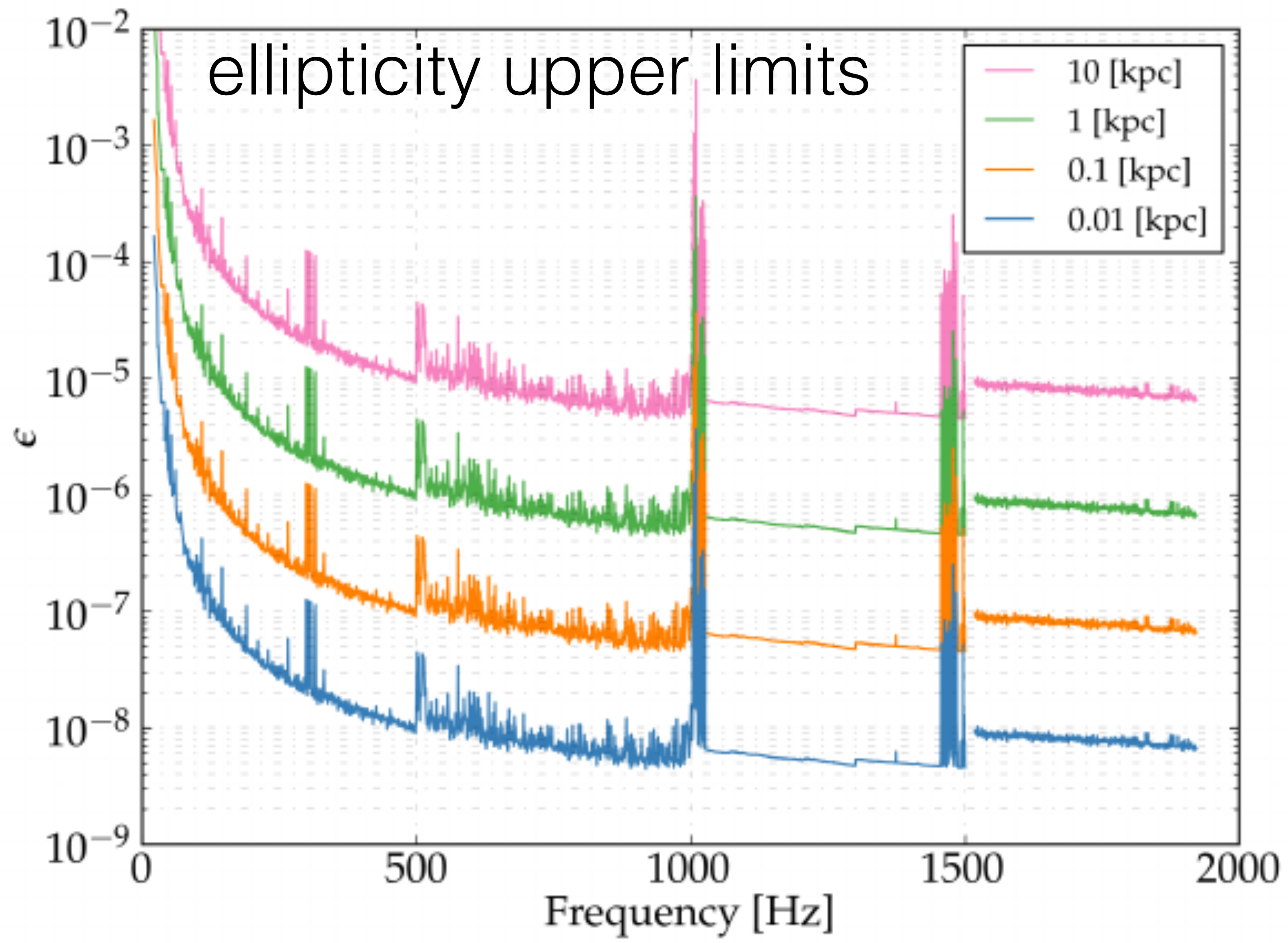
      → semi-coherent methods



local CWers:
- Alicia Sintes
- David Keitel
- Rodrigo Tenorio
- Joan Moragues
- +1 predoc to start soon w/DK
- Pep Covas (PhD UIB -> postdoc AEI)

- O2 all-sky blind search [LVC, PRD100.024004 (2019)], upper limits already constrain NS properties:



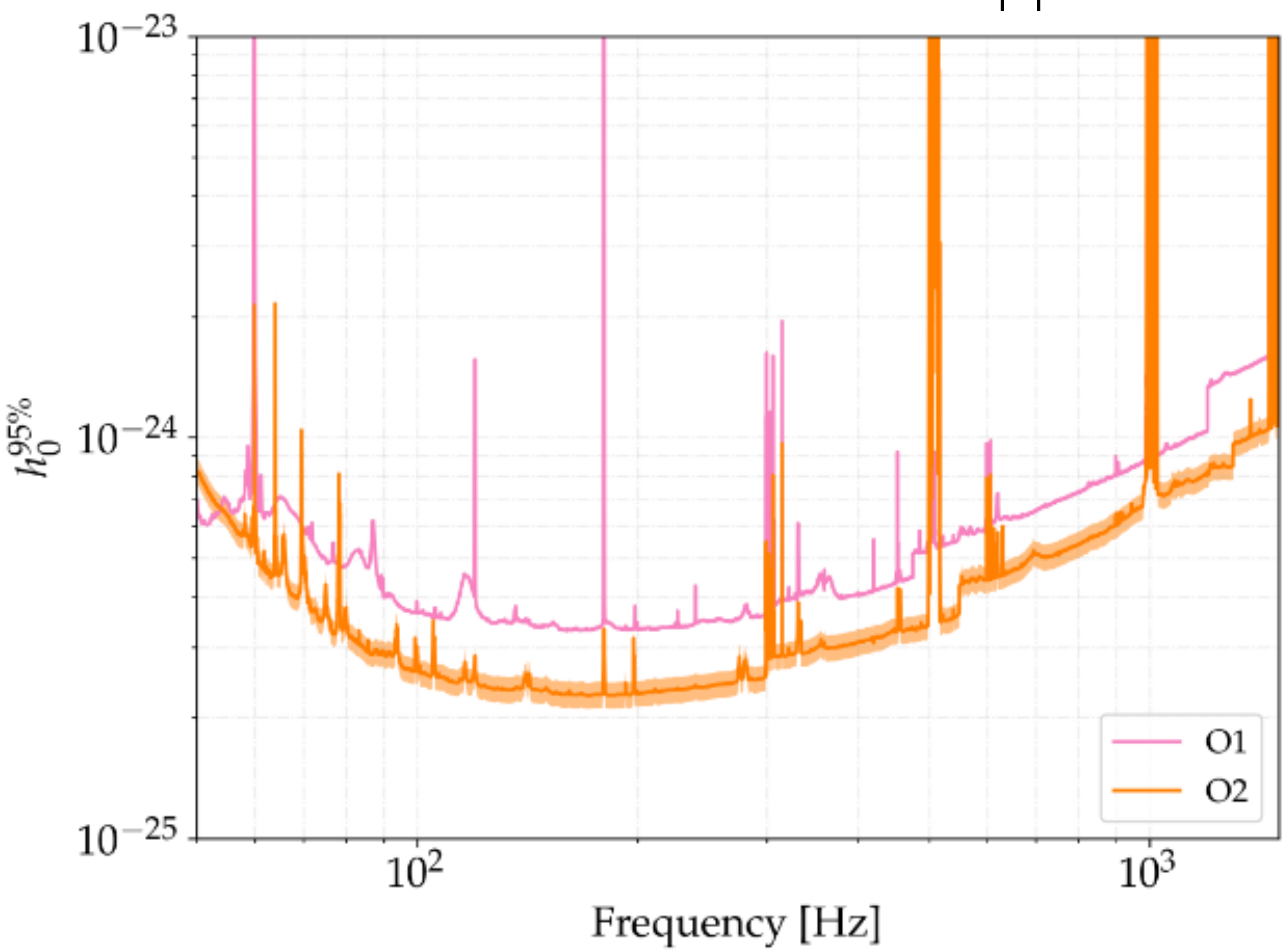


Pep Covas (former), Alicia Sintes, Rodrigo Tenorio

Continuous Waves: the SkyHough search

- **all-sky search for CW from *unknown* isolated neutron stars**
- hierarchical scheme:
  - sweep wide parameter space regions using computationally cheap techniques
  - focus on interesting regions using more sensitive strategies
- **most efficient CW pipeline within the LVK**
  - Exploit sky correlations across neighbouring candidates!
- latest results: [PRD100.024004 (2019)]
- A. Sintes part of original developers ([Krishnan+ PRD70.082001, 2004]),
- used since LIGO S2, actively developed @UIB:
  - optimize template placement
  - parallelization using Graphical Processing Units (GPUs)
  - discriminate interesting parameter-space regions using Machine Learning techniques

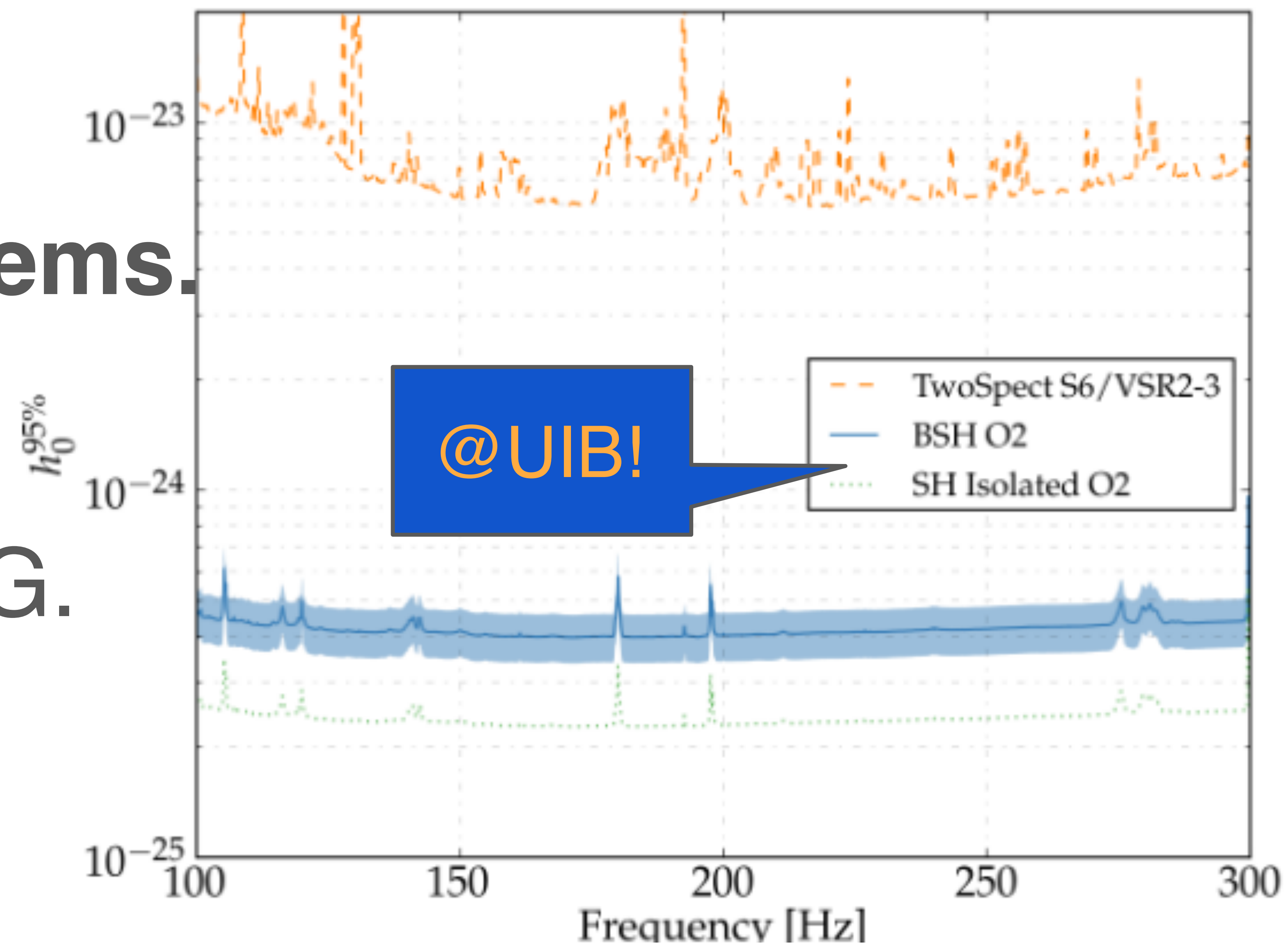
strain upper limits

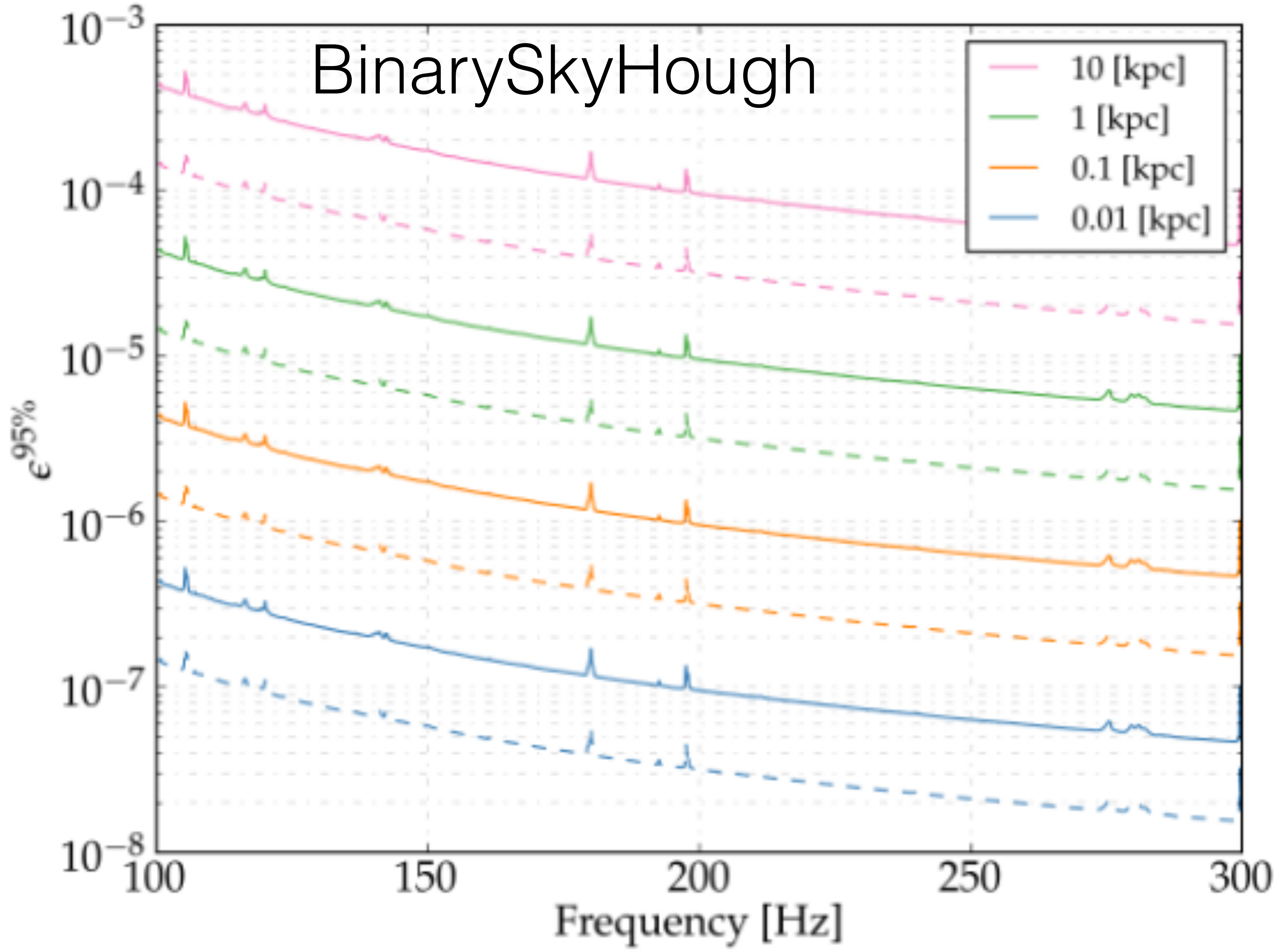


Alicia Sintes, Pep Covas (former), Rodrigo Tenorio, others in the past

Continuous Waves: BinarySkyHough

- Extend SkyHough to **include sources in binary systems.**
- **Use GPUs** to deal with the increased dimensionality.
- Computational resources provided by BSC/RES + LDG.
- First all-sky search using Advanced LIGO data:
  - P. B. Covas & A. M. Sintes [Phys. Rev. Lett. 124, 191102 (2020)]
  - Most constraining results since S6!
- **Closes sensitivity gap between searches for isolated NSs and those in binaries.**
- Current work:
  Early-O3 all-sky search performed by UIB.
- Paper coming soon - stay tuned!



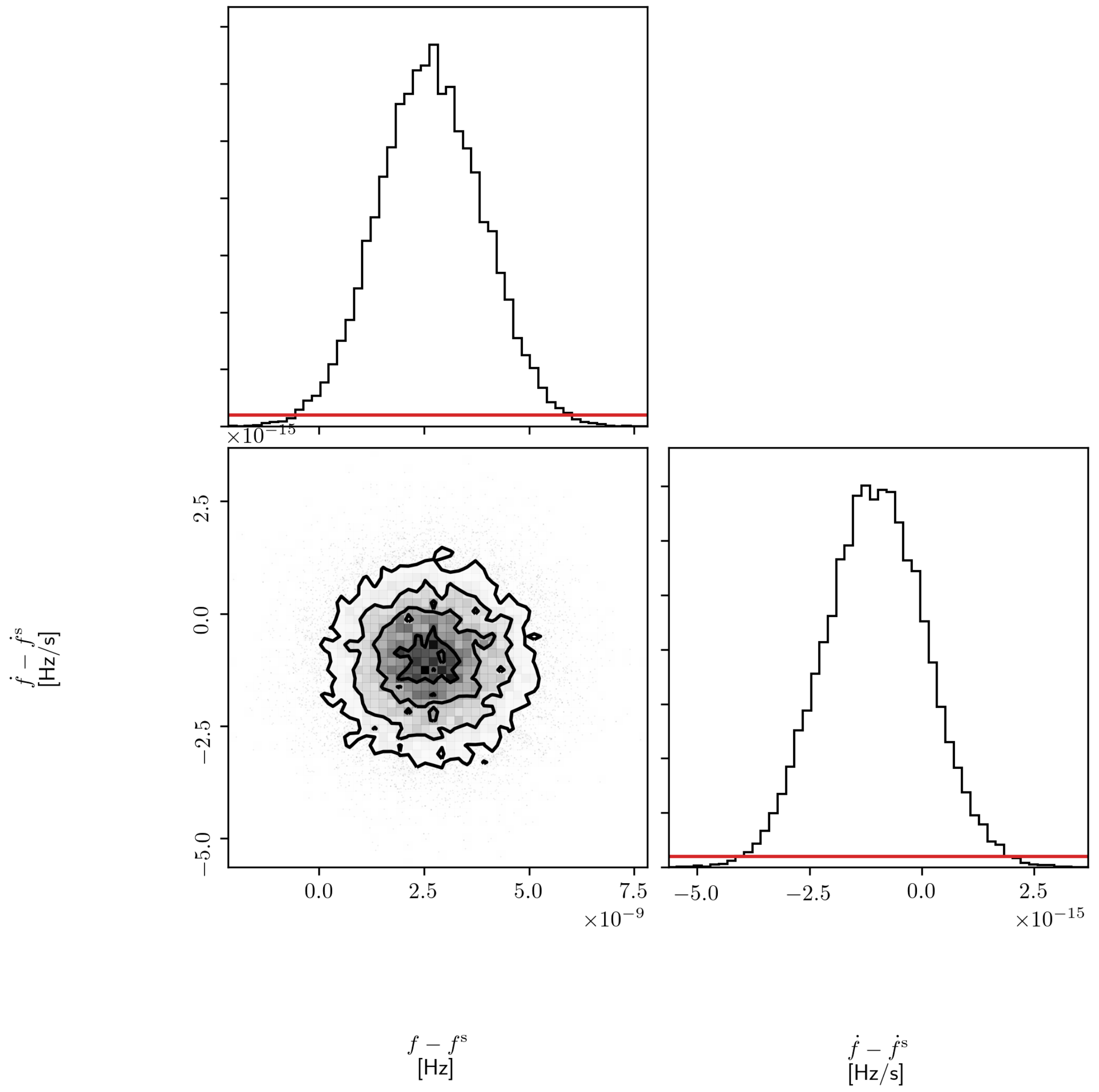


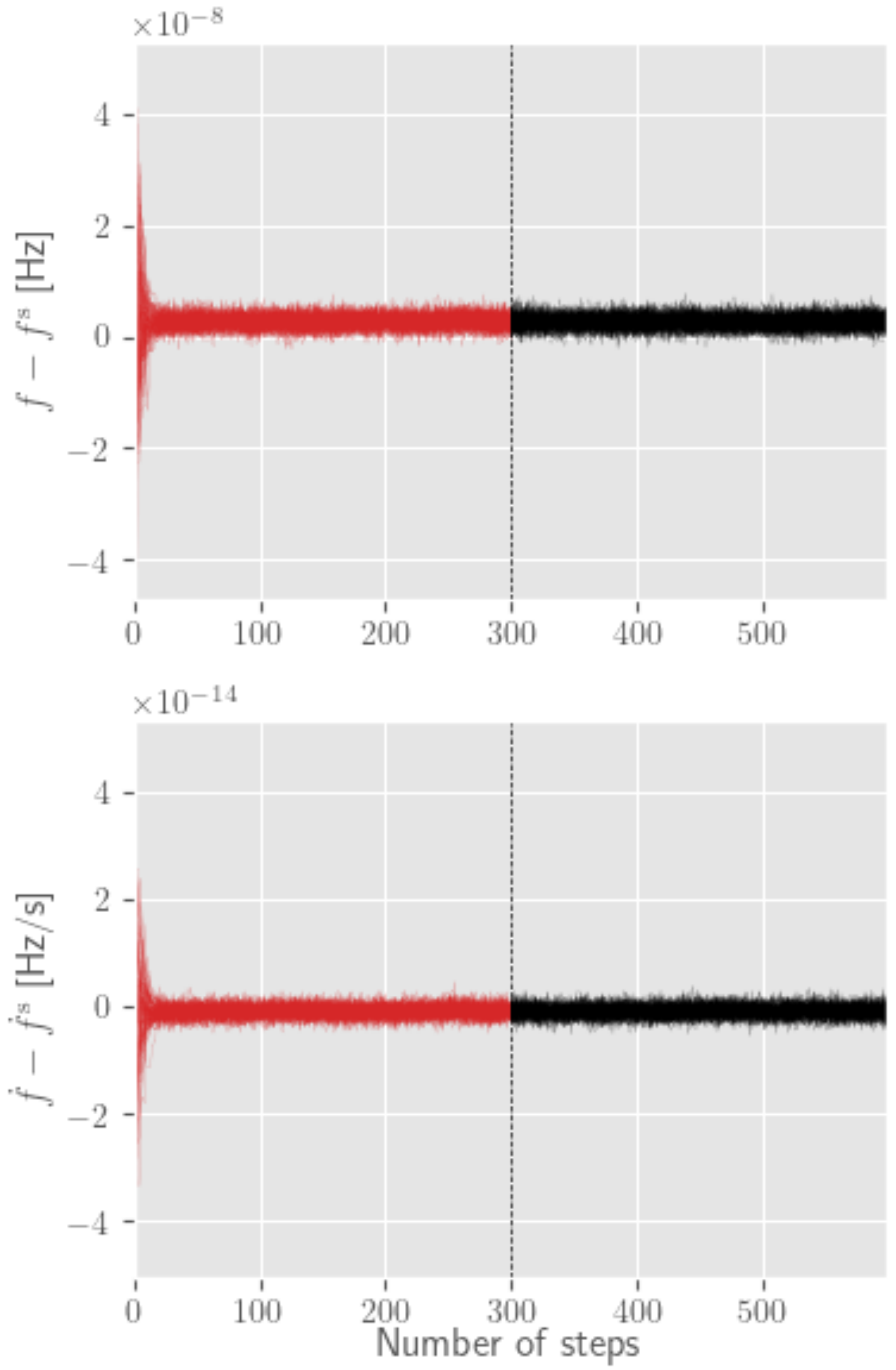
Pep Covas (former), Alicia Sintes & Rodrigo Tenorio

Continuous Waves: PyFstat package

F-statistic: standard max-likelihood detection method for CW

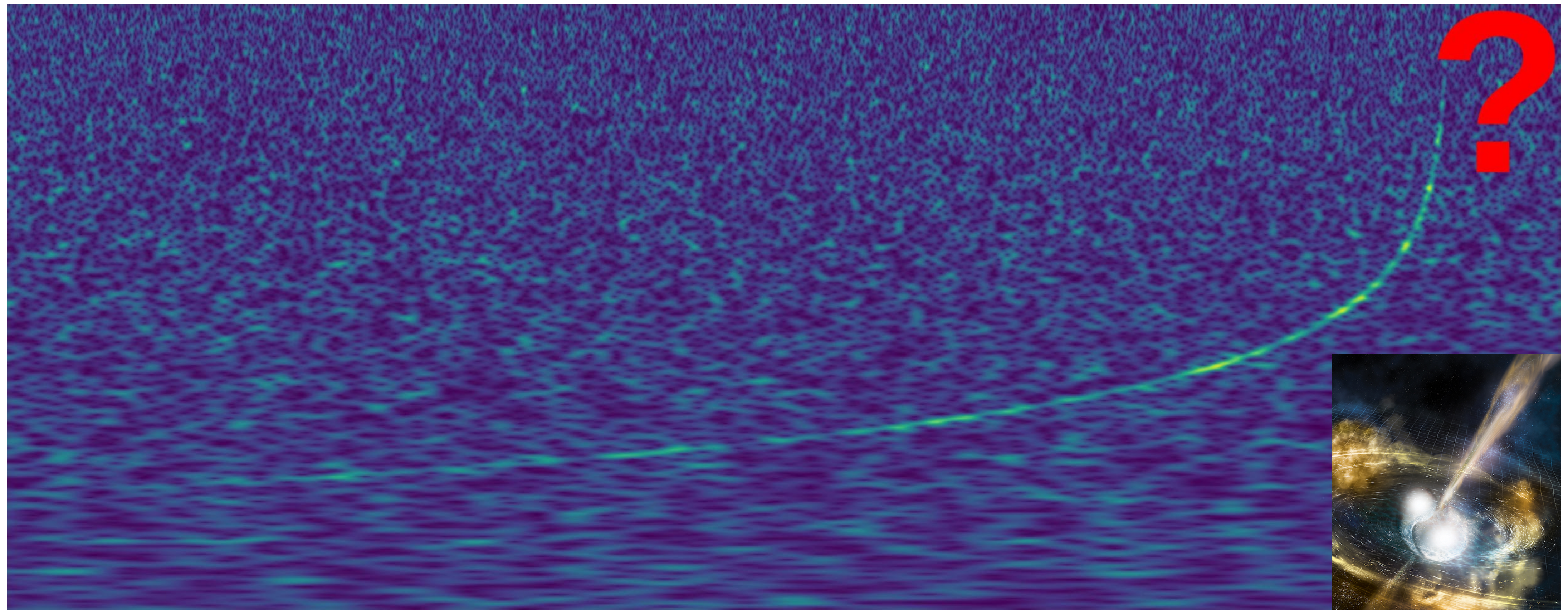
- “python package for GW analysis with the F-statistic” - **standard tool for searches**
- https://github.com/PyFstat/PyFstat/
- convenient python access to analysis functionality in LALSuite
- Originally developed by G. Ashton for hierarchical MCMC follow-up of isolated-NS CW candidates. [Ashton&Prix, PRD97.103020]
- **D. Keitel now main maintainer**, R.Tenorio contributing binary functionality and many other improvements.
- **Used for BinarySkyHough outlier followup**
- additional GPU code (pyCUDA) for transient searches, see next slides

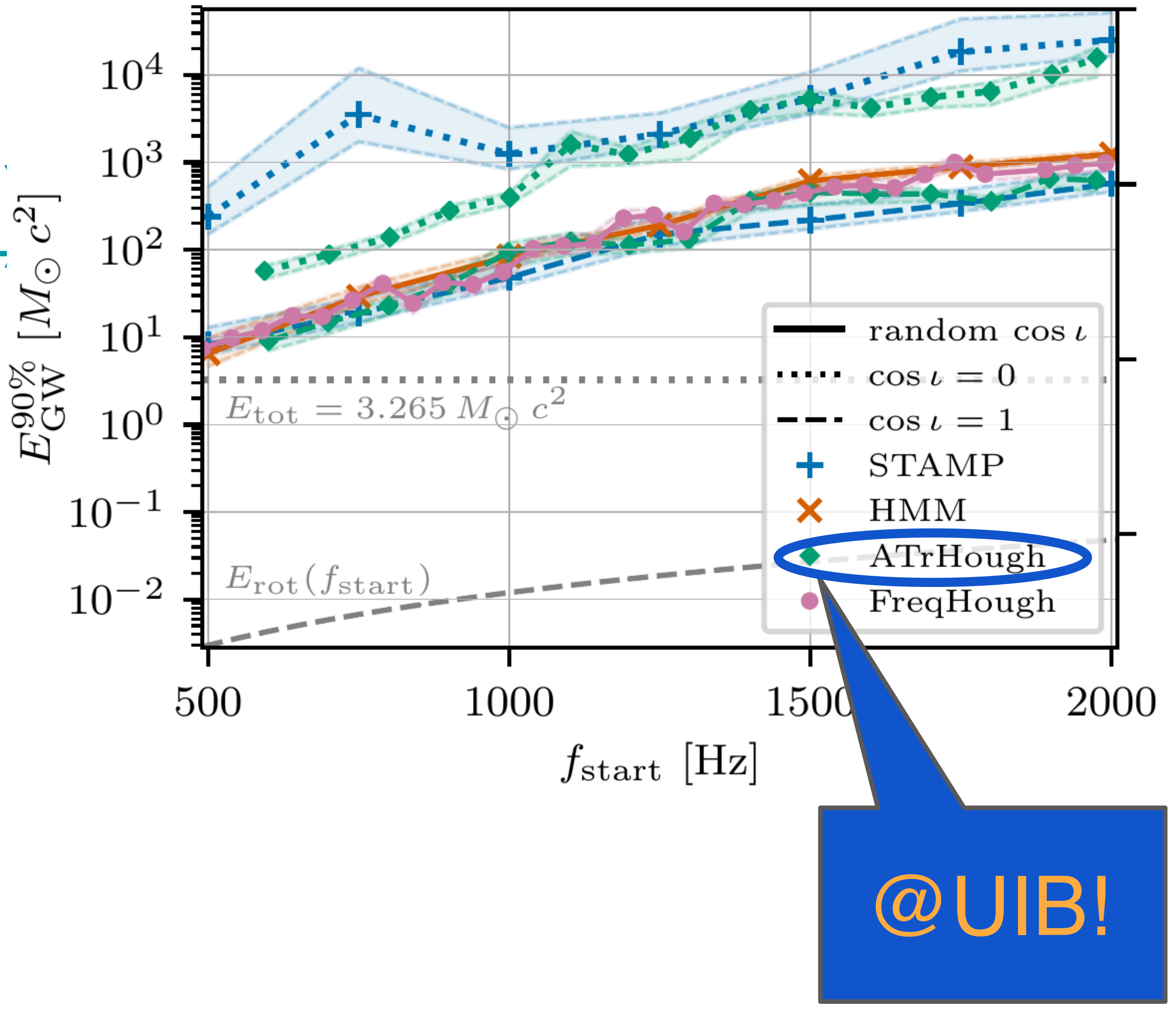




Long-duration transient GWs: BNS postmerger

- GW170817: first BNS detected in GWs, "nearby" at ≈ 40 Mpc
- remnant: BH, NS→BH, or NS?
- LVC searches for short- and long-duration signals from potential NS remnant: ApJL851:L16 (2017) / ApJ875:160 (2019)
- **New search:** Oliver, Keitel & Sintes, PRD99.104067 (2019) **"Adaptive Transient Hough" method, modified SkyHough pipeline for newborn NSs with rapid power-law spindown**
- Pipeline to be revived for future candidates, could be adapted to other long-duration transient signals too.

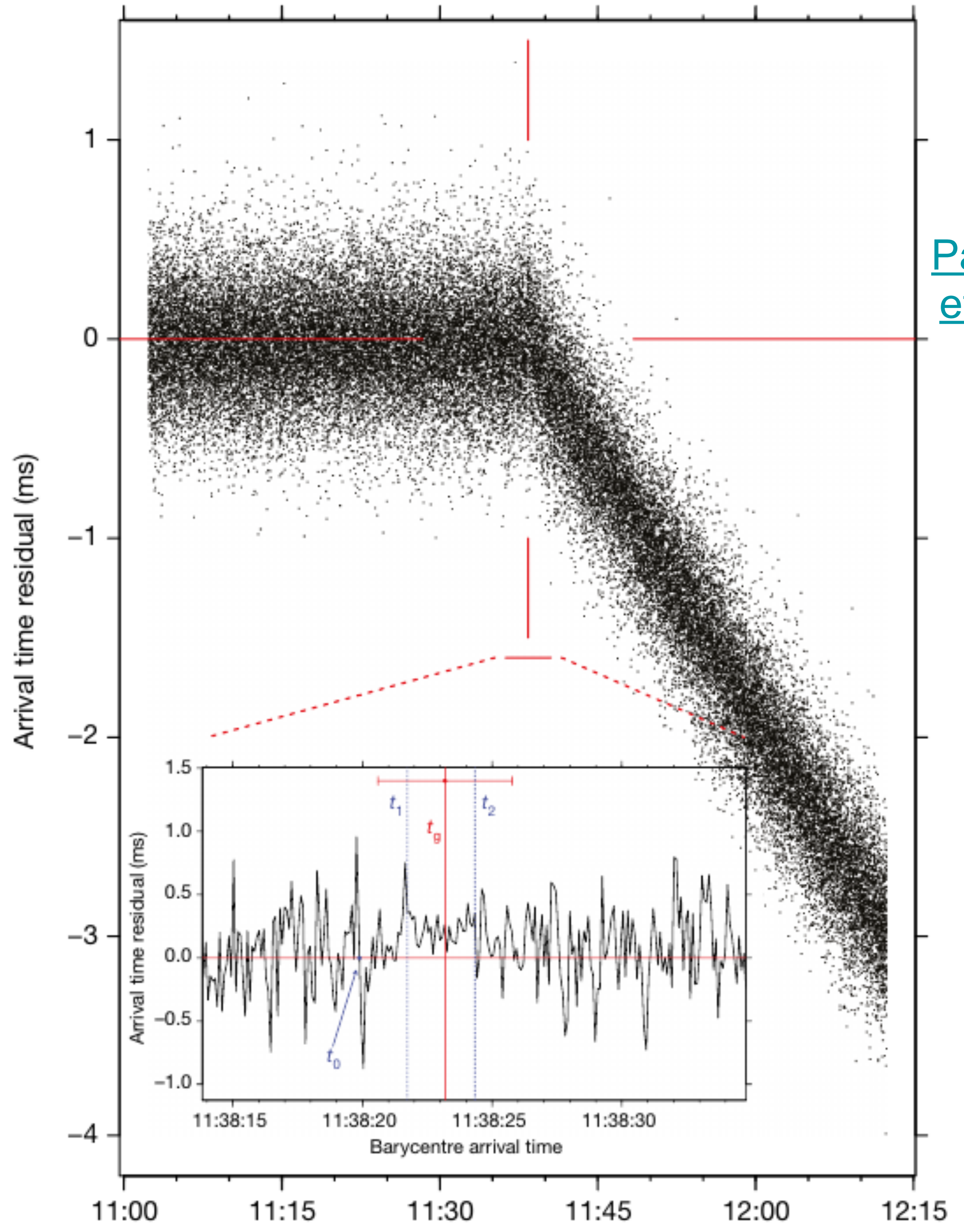




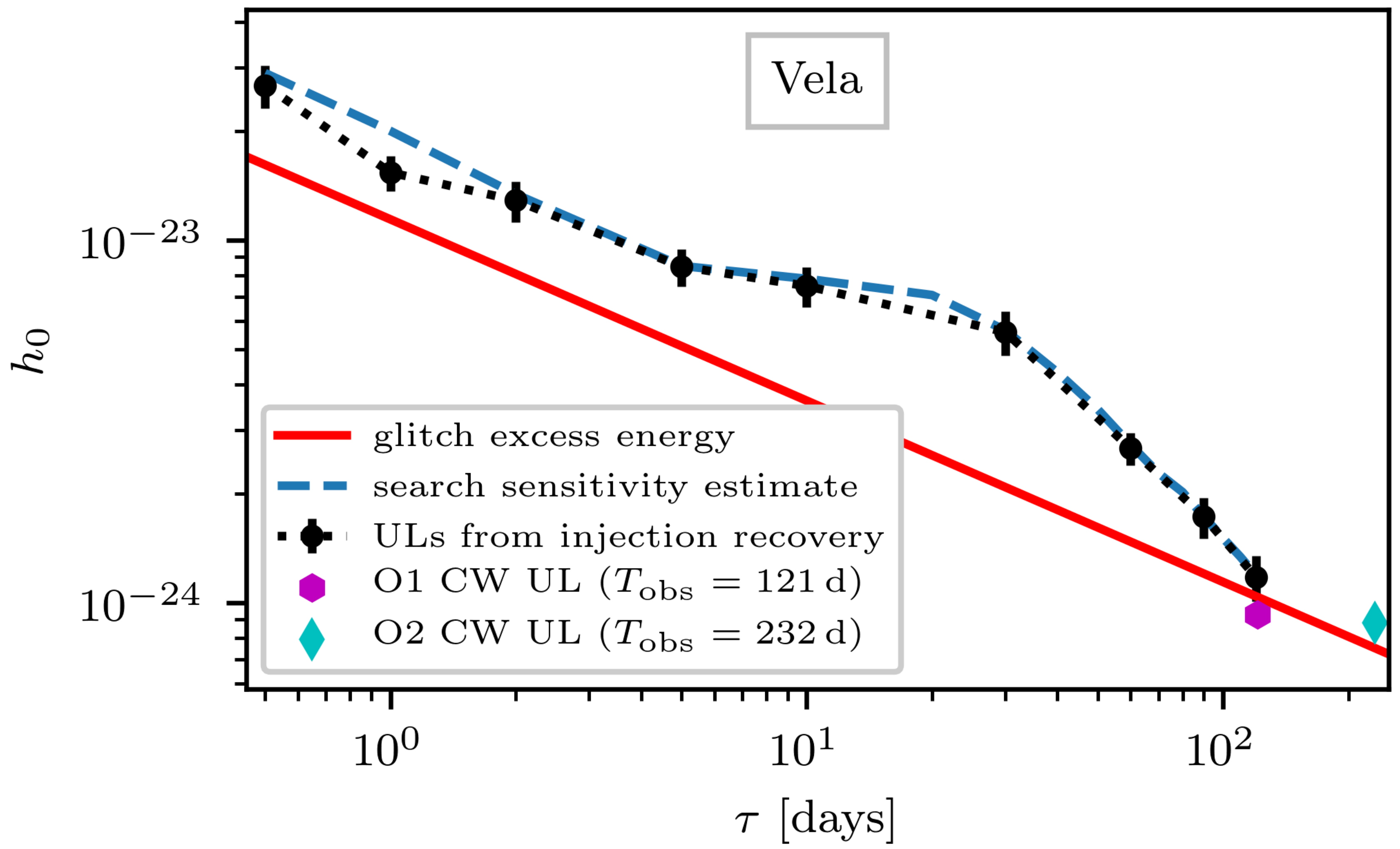
Miquel Oliver (former), David Keitel & Alicia Sintes

Long-duration transient GWs: glitching pulsars

- pulsar glitches: sudden spin-up events,
  mechanism unclear: starquakes? suprafluid recoupling?
- Glitch could trigger transient GWs through several channels.
- search on O2 open data, Keitel et al., PRD100.064058 (2019):
  Crab and Vela pulsars, transient F-statistic method.
- Vela O2 results close to beating indirect upper limit on h0 given by “all released energy goes into GWs” assumption.
- **From O3 on**, similar searches are part of plans in LVC white paper - **we are working on it!**
- emission models poorly constrained → interesting field for developing new analysis methods, e.g. machine learning



Palfreyman et al. 2018



David Keitel, Joan Moragues, future PhD student

DetChar: Line Identification & Mitigation

- Persistent instrumental noise impacts CW searches.
    - It looks essentially like a CW!
- In-place detector characterization work through the **LIGO Fellows programme**.
- **Research stays @ LIGO Hanford** (aLIGO O1, O2, O3):
    - identification and mitigation of instrumental and environmental noise sources
    - study of non-linear coupling effects amongst instrumental noise
    - P. B. Covas+ Phys. Rev. D 97, 082002 (2018)

Pep Covas (former),
Miquel Oliver
(former),
Rodrigo Tenorio

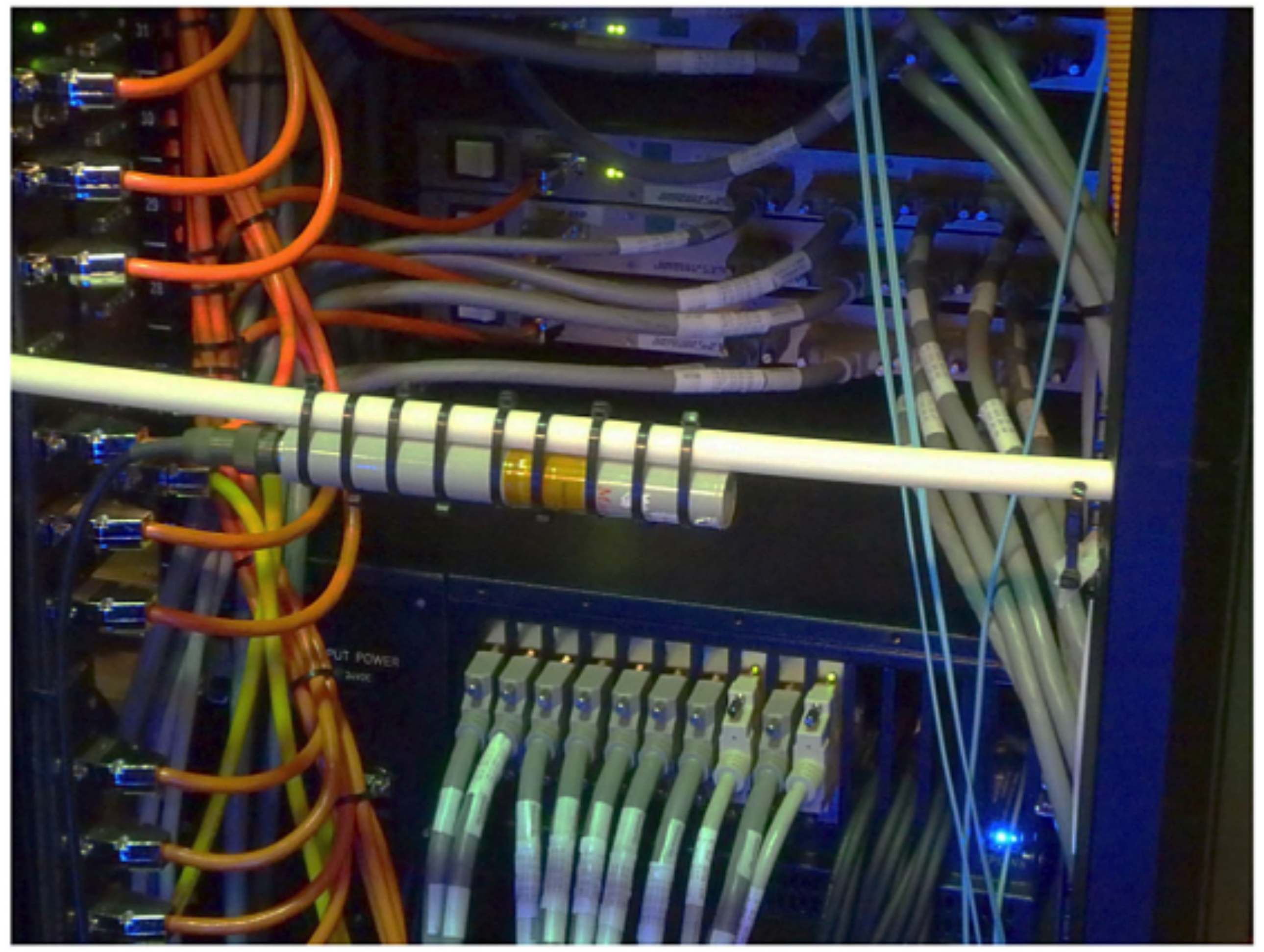
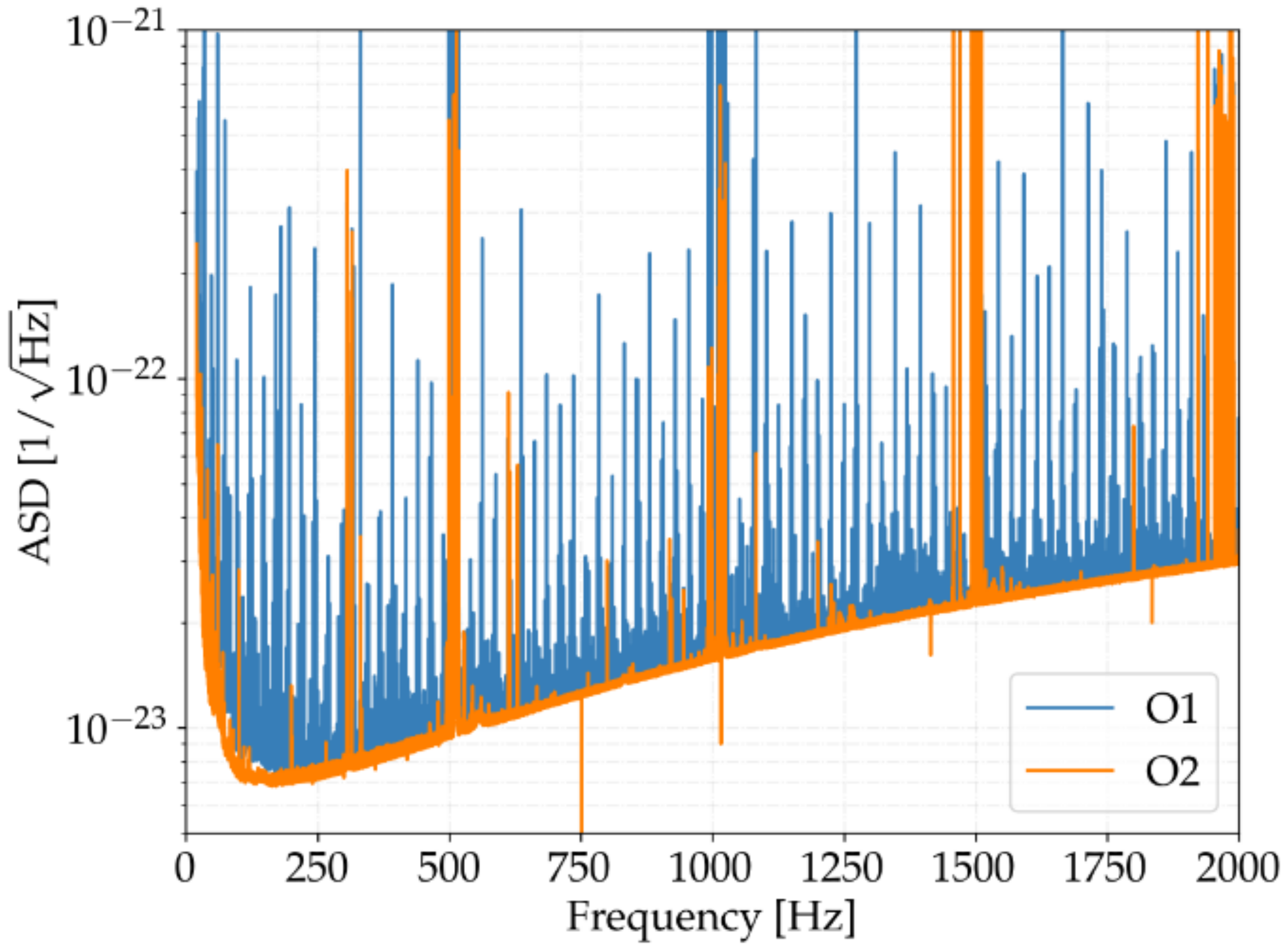
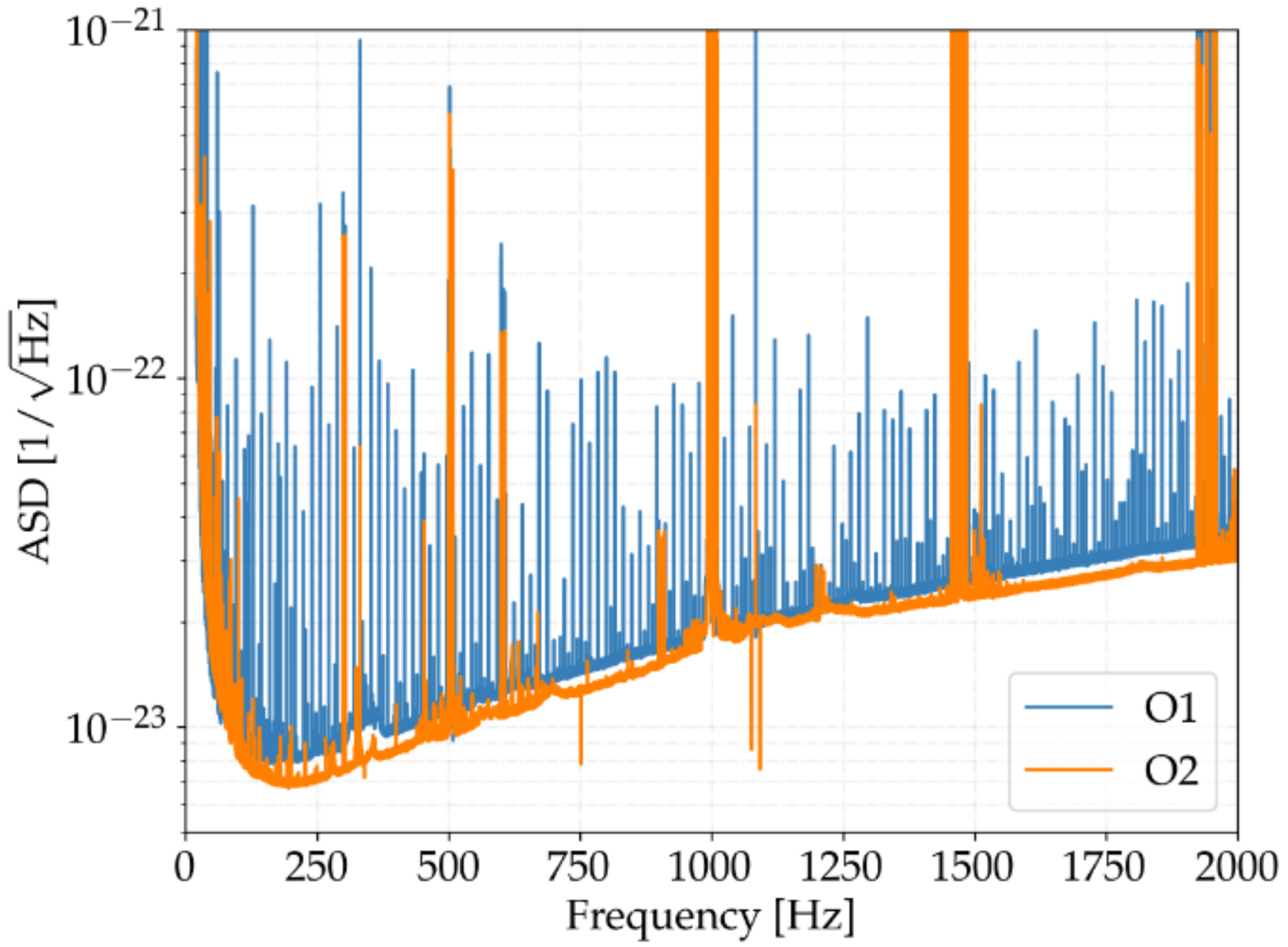


FIG. 3. Method of monitoring electronic components and cables for frequencies of instrumental lines found in the data.

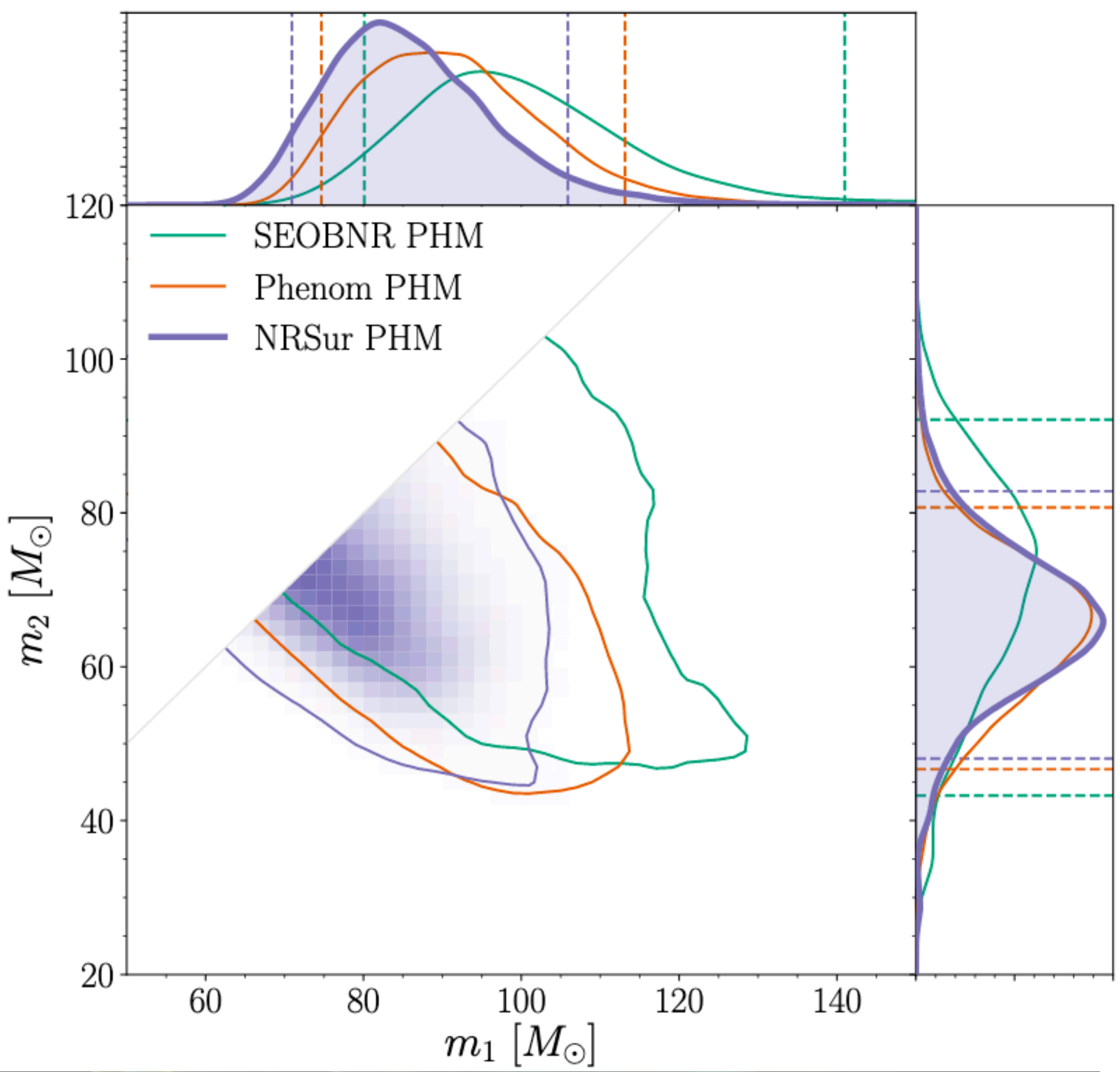




CBC Waveform Modelling & Parameter Estimation

SH, M. Colleoni, H. Estellés, C. García, D. Keitel, R. Jaume, M. Mateu, A. Calafat, L. Planas, M. Duran, F. Snel, M. Rosselló, A. Borchers Pascual

LVK, GW190512, Astrophys. J. Lett. 900, L13 (2020)

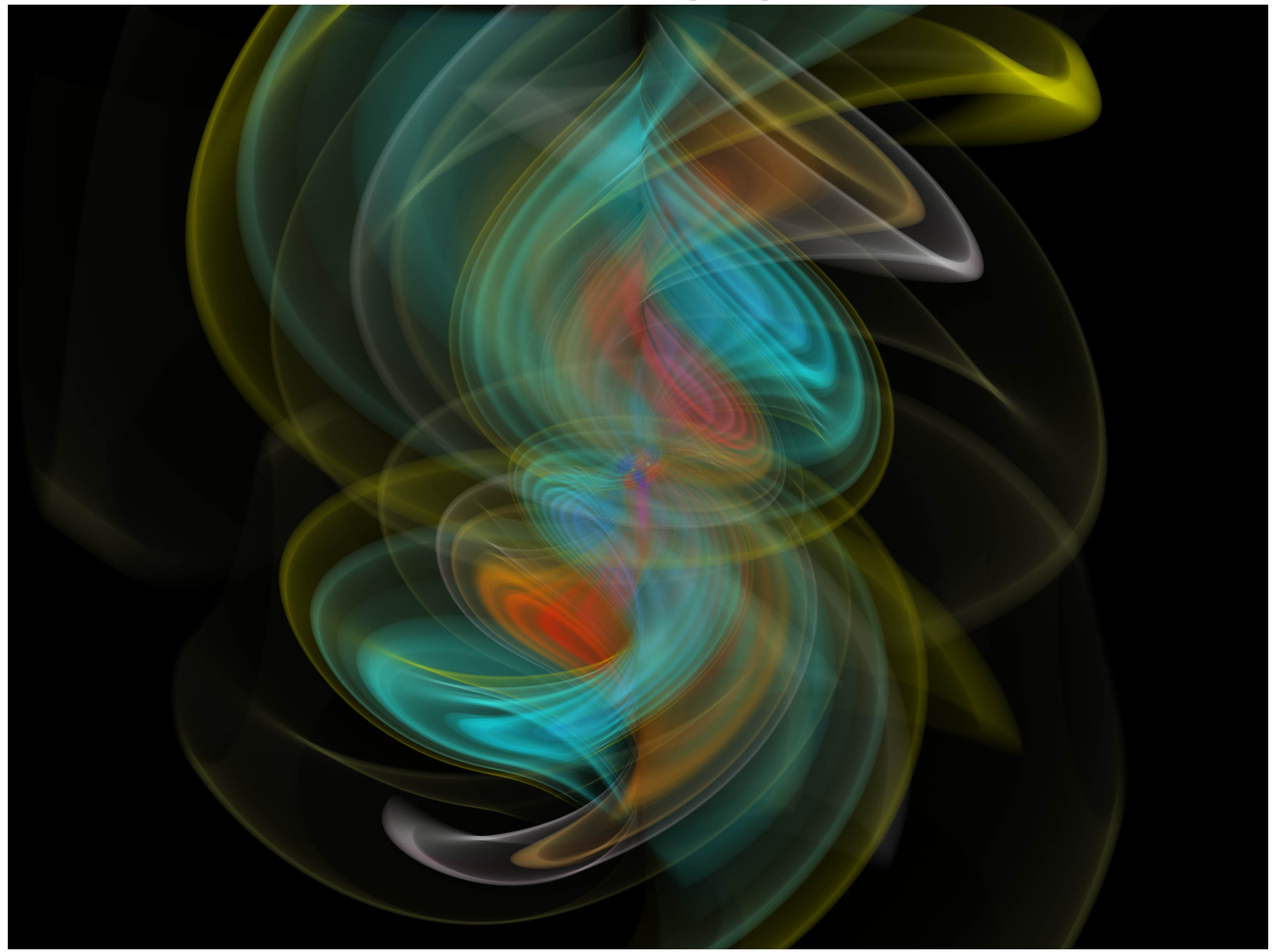


- **2-step LIGO/Virgo Compact binary coalescence group workflow (LISA ???):**
  - **Searches -> detection:** matched filtering or un-modelled “burst” searches
  - **Bayesian parameter estimation:** using MCMC, nested sampling, possibly DNN

Our scope: From solving Einstein’s equations to estimating source properties

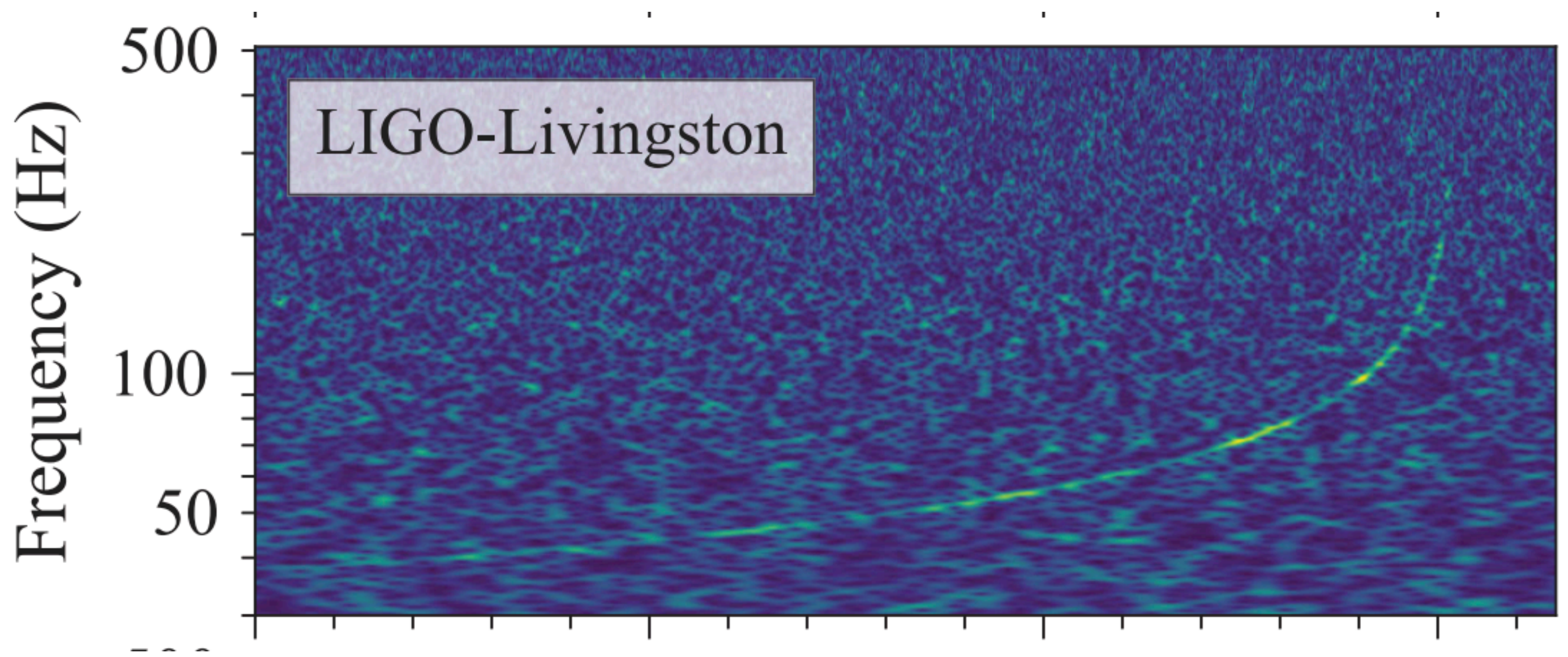
Identification of sources is limited by many factors: detector sensitivity, noise characterisation, detecting the sources, …

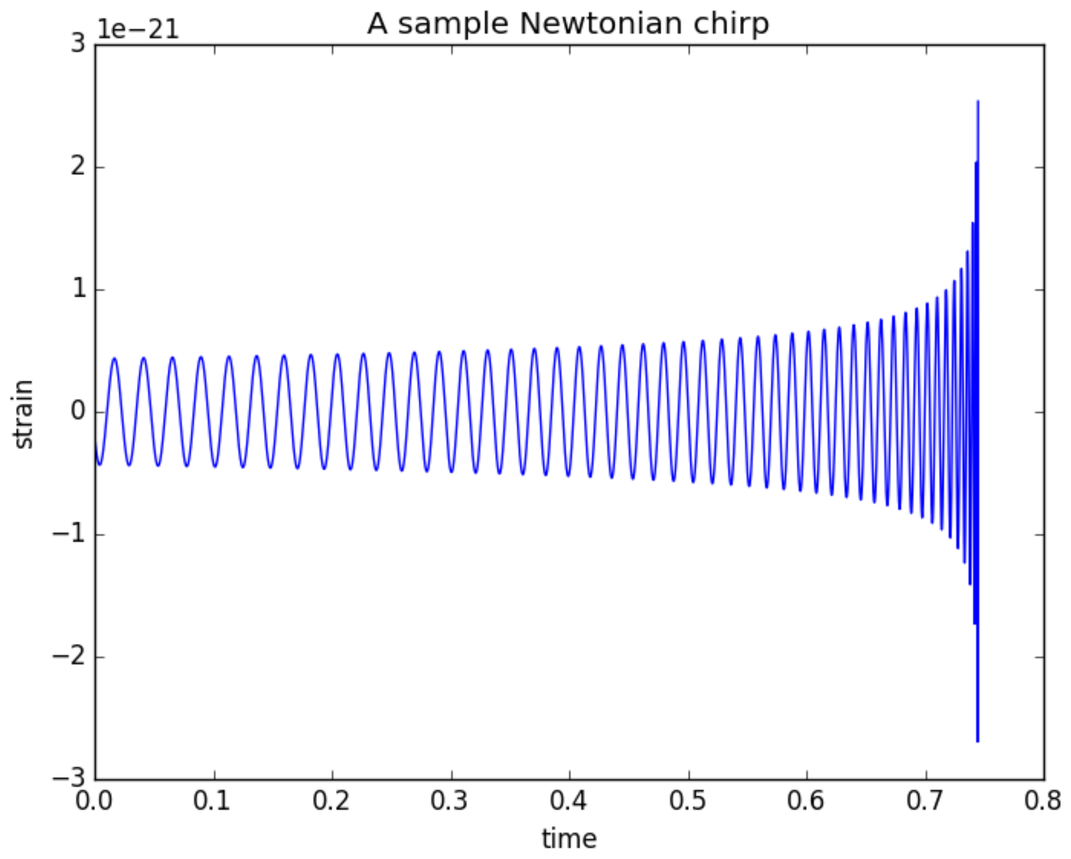
Accuracy, completeness & computational cost of waveform models.



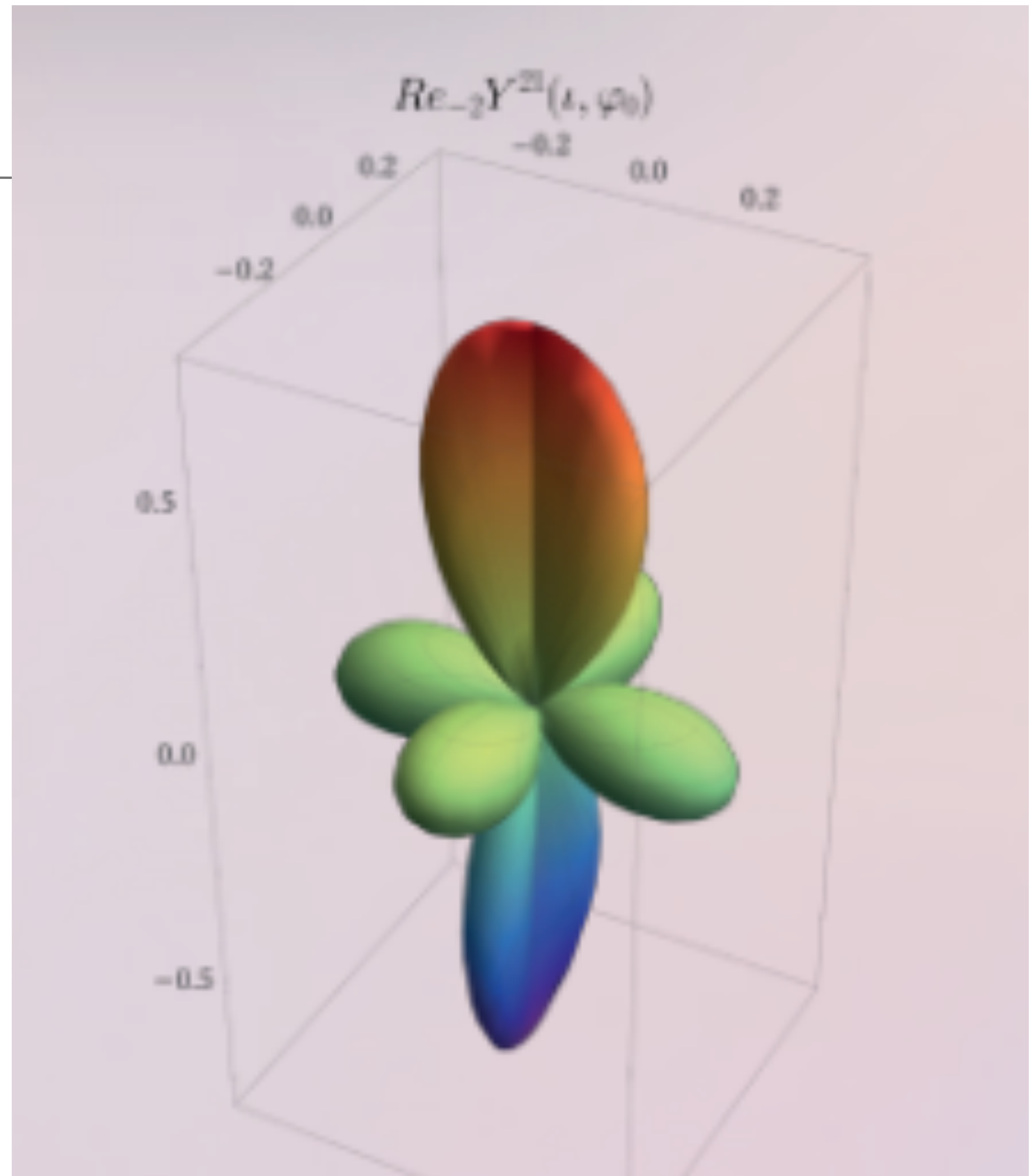
From Chirps to generic waveforms

CBC data analysis methods have initially been developed based on post-Newtonian inspiral waveforms and the dominant quadrupole spherical harmonics. Newtonian point particles + energy loss from quadrupole formula:





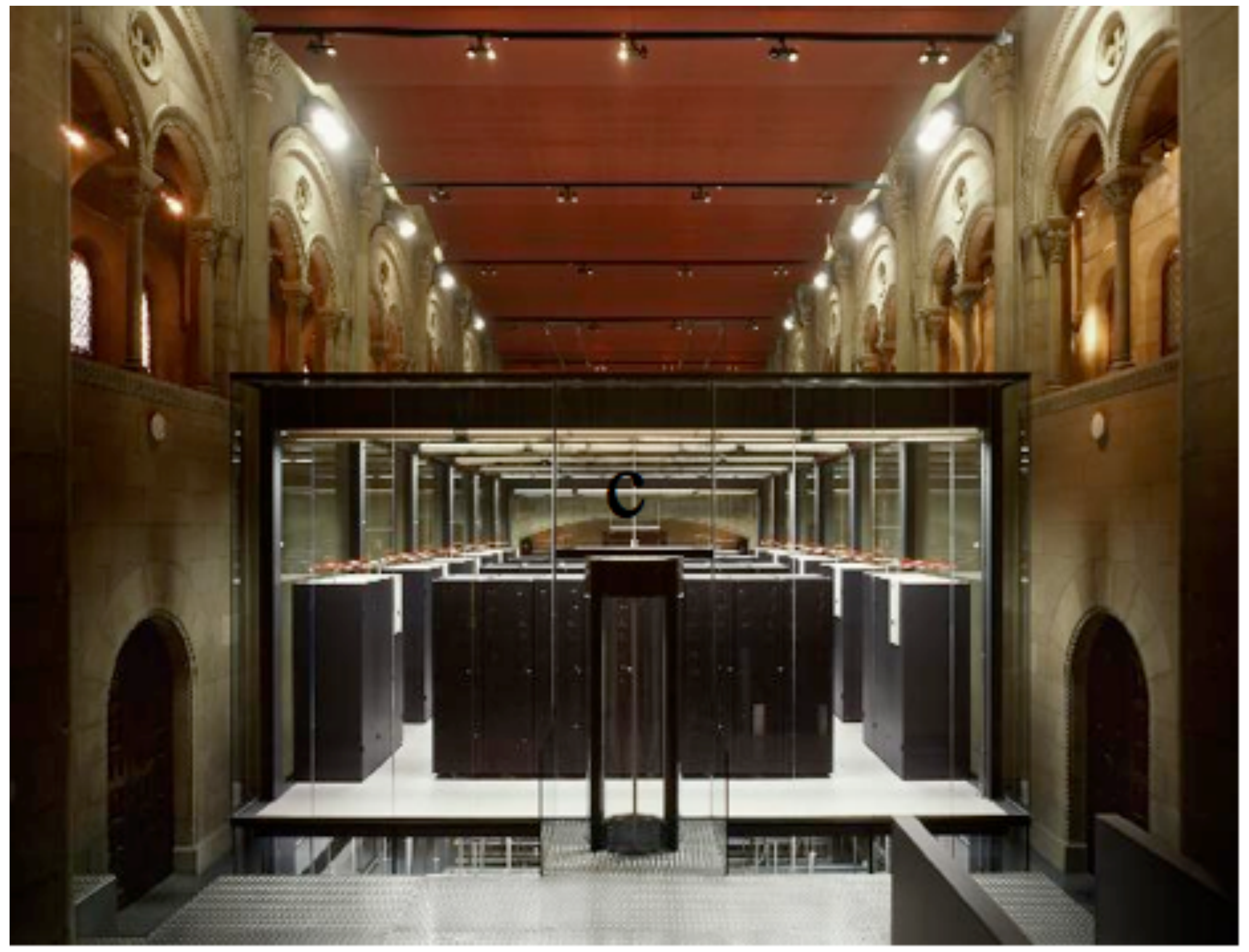
LSC+Virgo, PRL 119 161101 (2017)



Quadrupole wave pattern

CBC data analysis in the advanced detector era uses inspiral-merger-ringdown (IMR) waveform models which are synthesised from catalogues of numerical relativity simulations and data from perturbation formalisms.

Generic BBH parameter space in GR: 9 dimensions (mass as a scale factor) - large for exploring with simulations that cost > 100 000 CPU hours.



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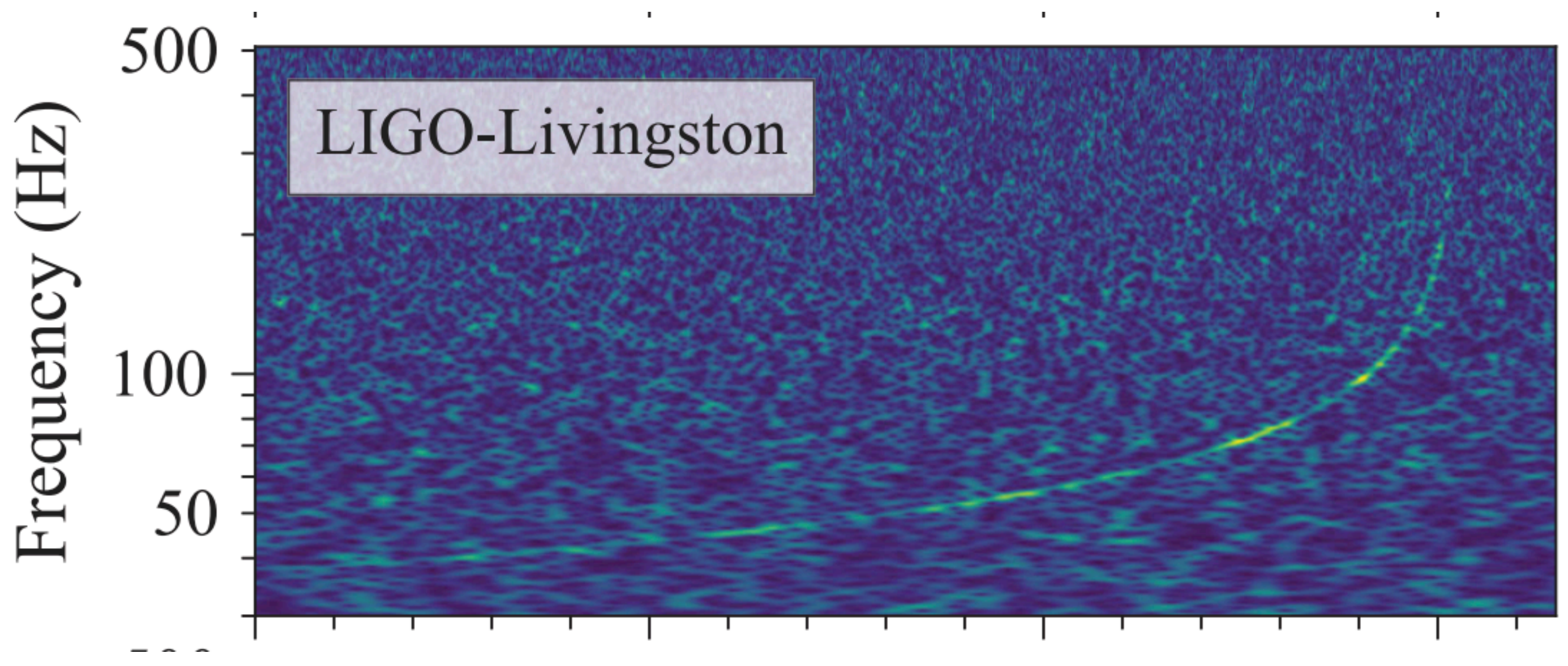

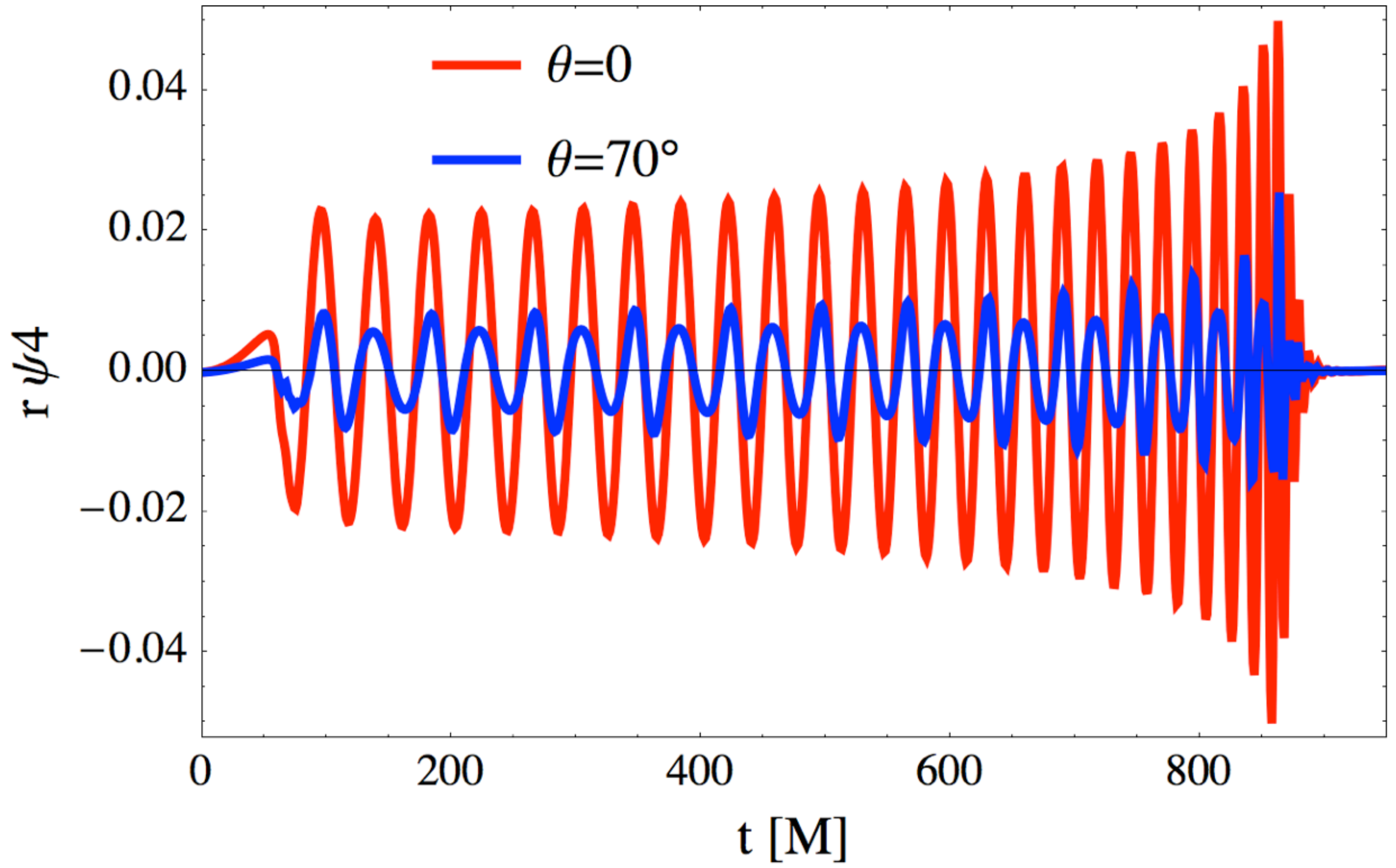

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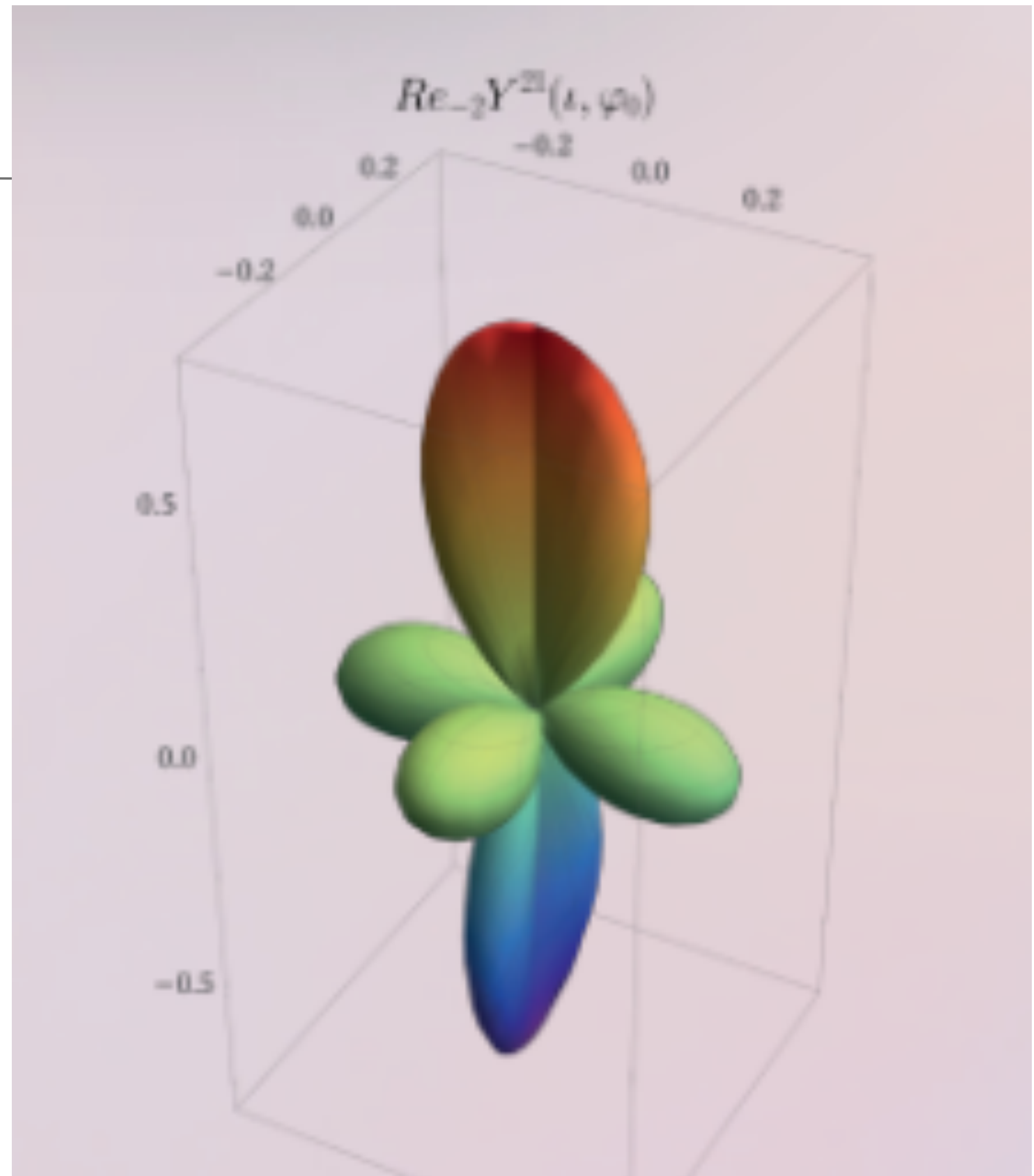

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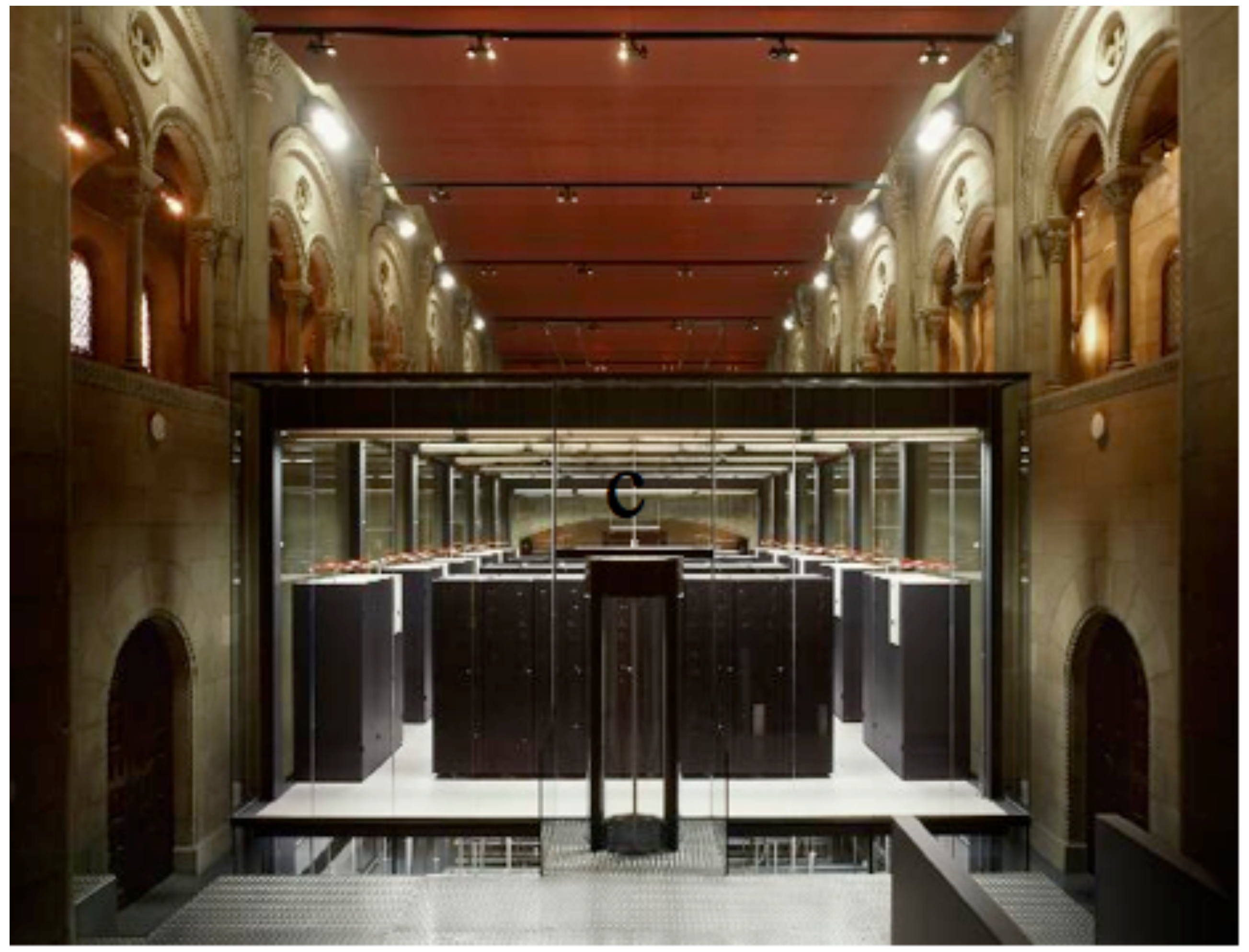

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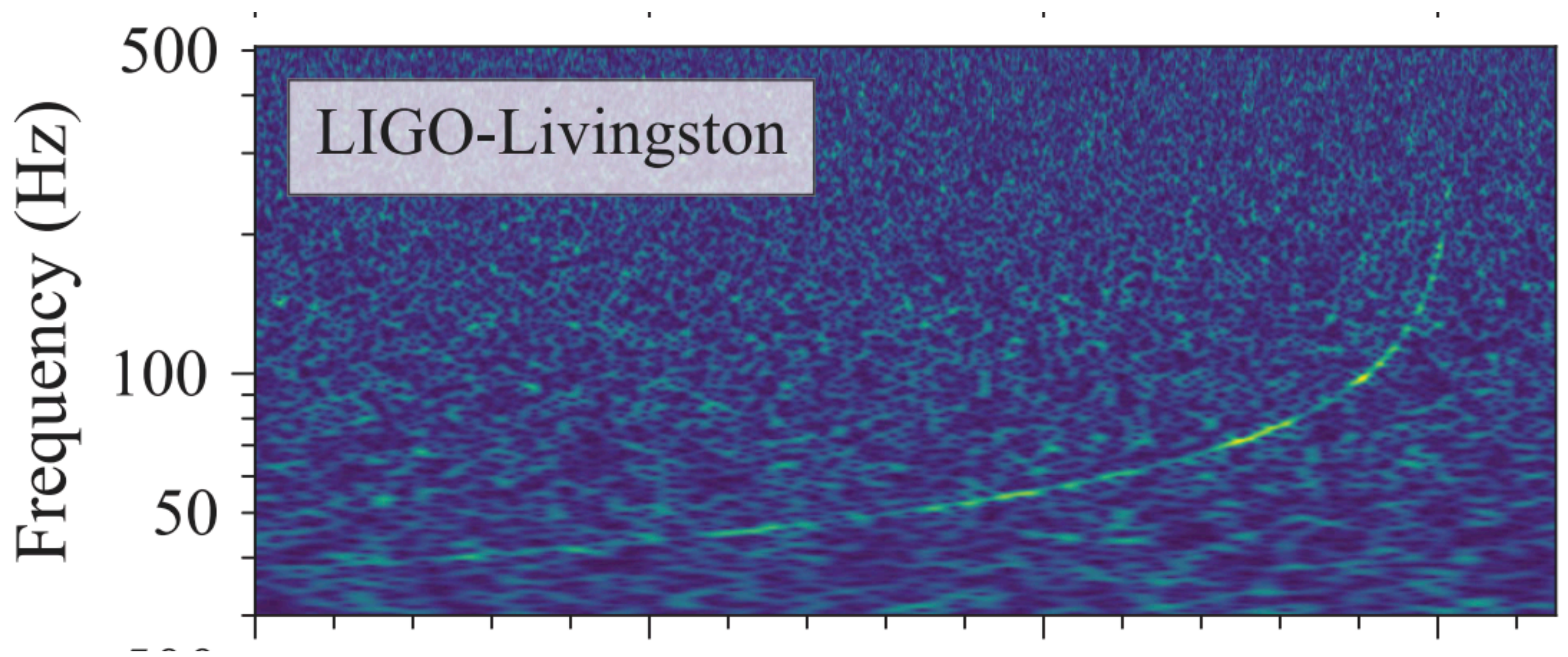
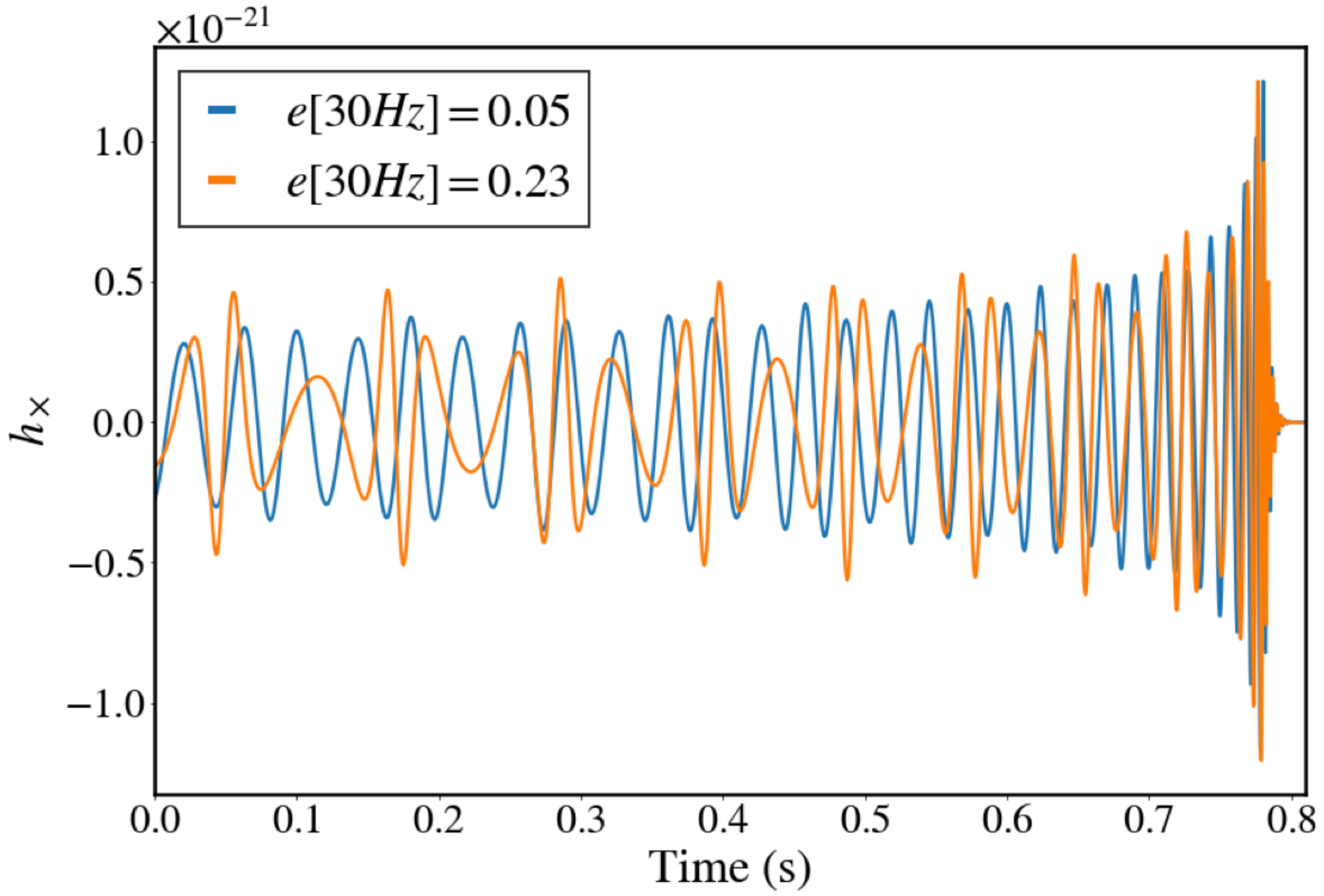
Newtonian point particles + energy loss





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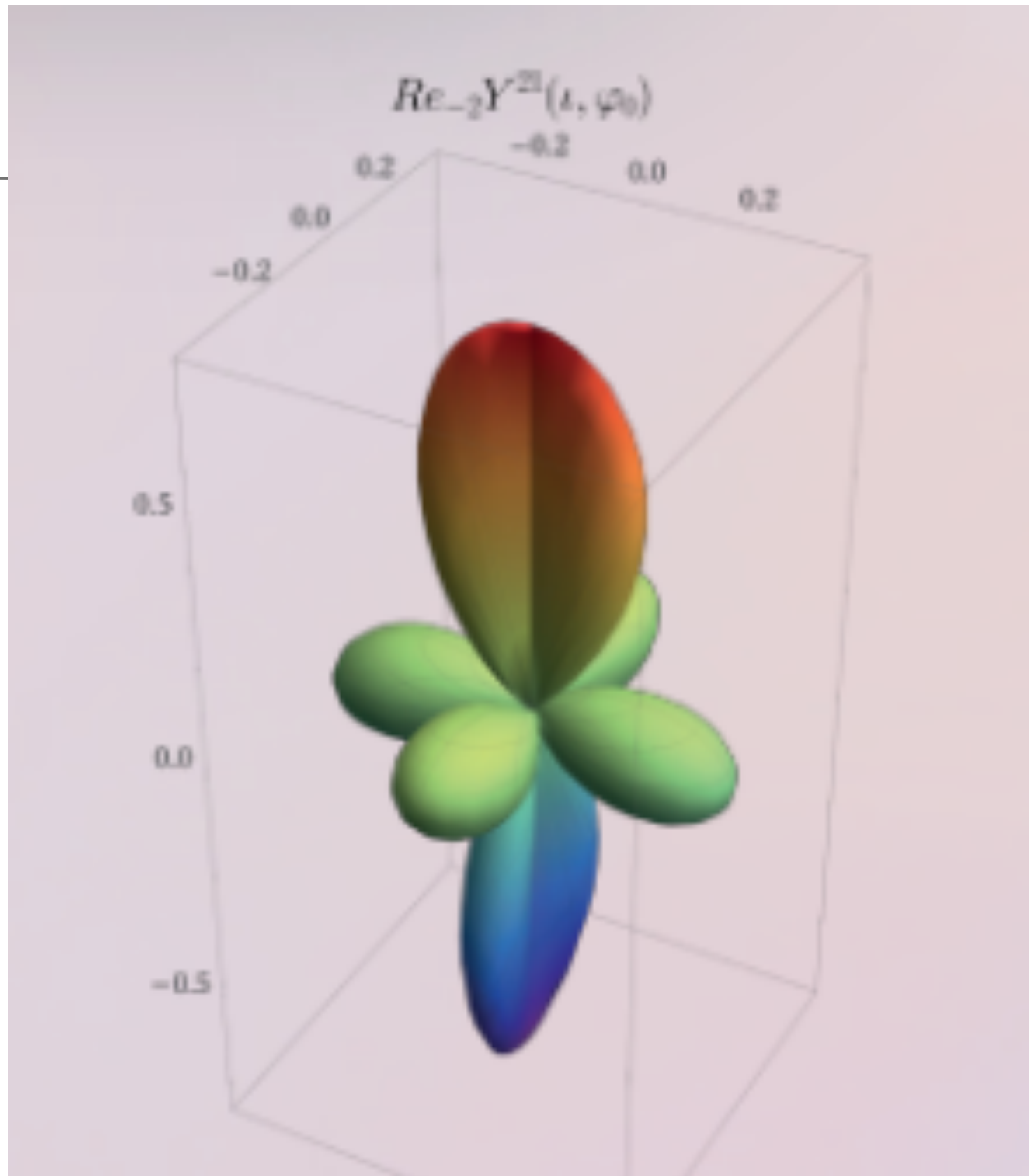

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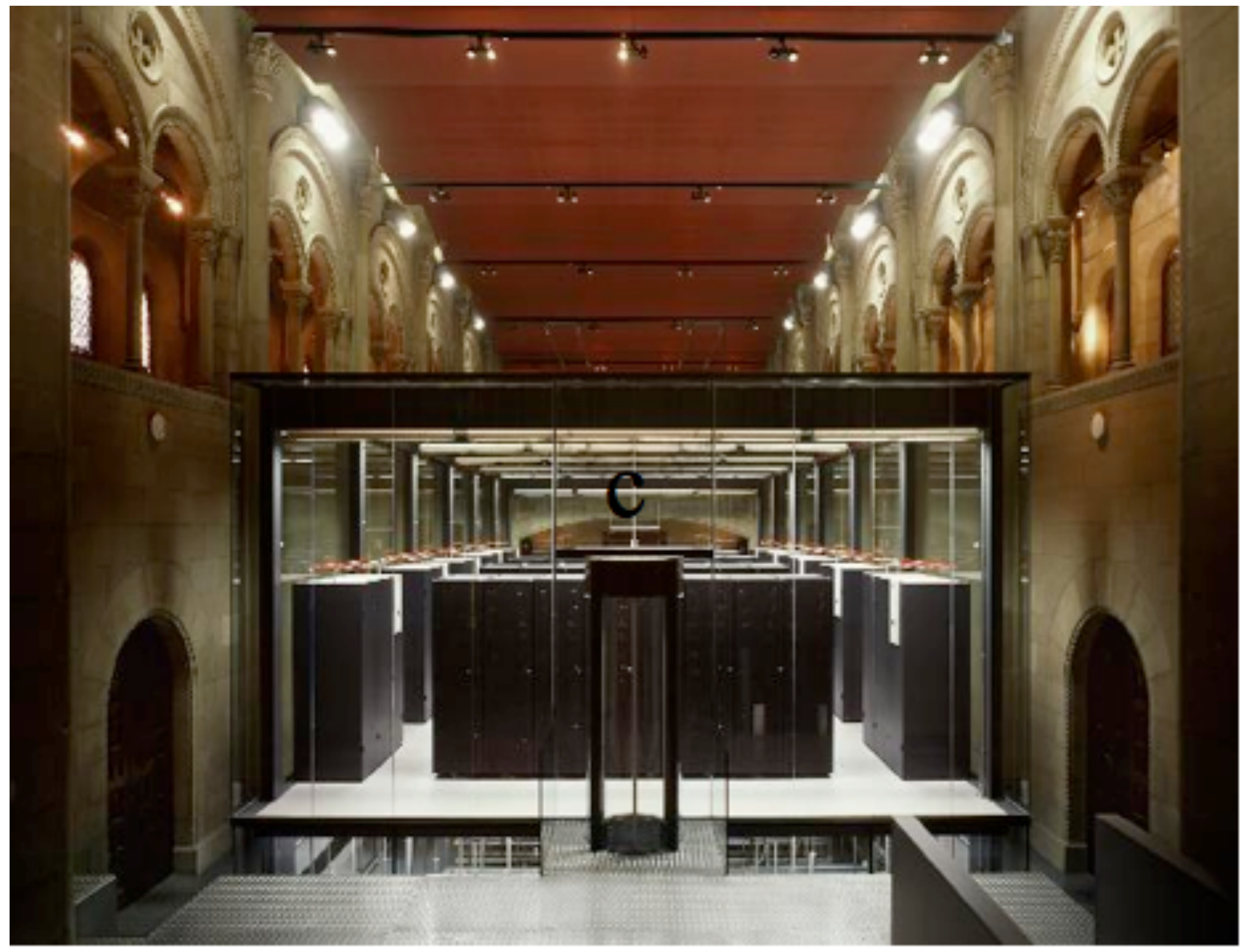


Waveform Modelling Strategies

Universitat de les Illes Balears

1. Ansatz in terms of suitable functions (mode amplitudes + phases, …), possibly their parameterisation.
2. Fit ansatz to each waveform in a catalogue.
3. Fit coefficients across parameter space.

Currently 3 main strategies with different emphasis:

- **effective one body (EOB)** - push perturbative methods as far as possible
  - model energy + flux of a particle in effective metric, then integrate ODEs numerically.
  - Slow - need a fast model of the phenomenological EOB model.
- **"Surrogate models:"** ROM for numerical data - algorithms to interpolate large parameter spaces
  - No intermediate phenomenological model, fast evaluation of EOB or NR data directly.
- **phenomenological models** - phenomenological understanding of the waveforms
  - piecewise closed form expressions (3-4 regions) - extreme compression of information, fast.

Generation 3: PhenomD/PhenomPv2/PhenomHM

Generation 4: PhenomX*, PhenomT*

IMRPhenomX* and IMRPhenomT* waveform families

Universitat de les Illes Balears

C. García, M. Colleoni+

H. Estellés+

frequency domain

lowest computational cost for matched filtering

3 years of development time, 13 authors, publicly available in LALSuite since 02-04/2020.

time domain

- cleaner distinction of inspiral/merger/ringdown for tests of GR
- foreseen to facilitate modelling of strong field regime for eccentricity, precession.

Under LVC review, expected public in LALSuite ~ 02/2021.

- Non-precessing models fully calibrated to NR+EOB
  - 22 mode: IMRPhenomXAS + IMRPhenomT (~~IMRPhenomD~~)
  - Add further modes IMRPhenomXHM + IMRPhenomTHM (~~IMRPhenomHM~~)
- Precessing models: extended to precession using “twisting approximation”
  - IMRPhenomXP + IMRPhenomTP (~~IMRPhenomPv2~~)
  - **IMRPhenomXPHM + IMRPhenomTPHM** (~~IMRPhenomPv2, IMRPhenomPv3, Pv3HM~~)

XPHM

Life cycle of CBC waveforms: development, review & maintenance

- LVC contributions according to *LVC Program* and *Data Analysis White Paper*
  - Development initially in Mathematica
  - LALSuite C implementation
  - LVC review of LALSuite code
    (~5 months for non-precessing PhenomX,
    ~ 2 months for precession)
  - => Code public after review
  - Commitment to maintenance and support, resolve issues in applications.
- LISA: still need to define interfaces, conventions, establish review, …
  (white papers in preparation)
  - SH leading waveforms work package “Efficient MBHB models”

.

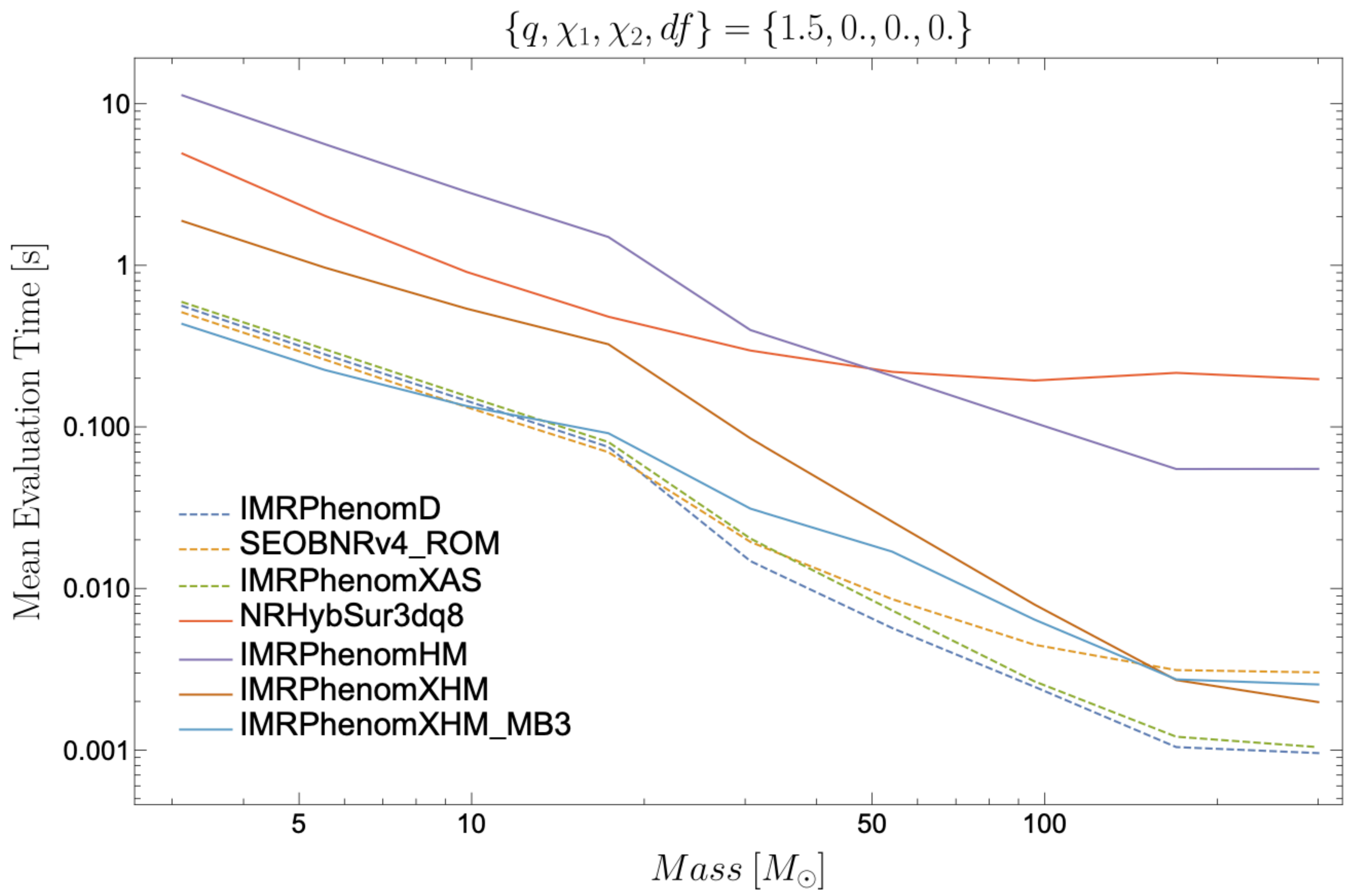
UIB 2020 Phenom* papers

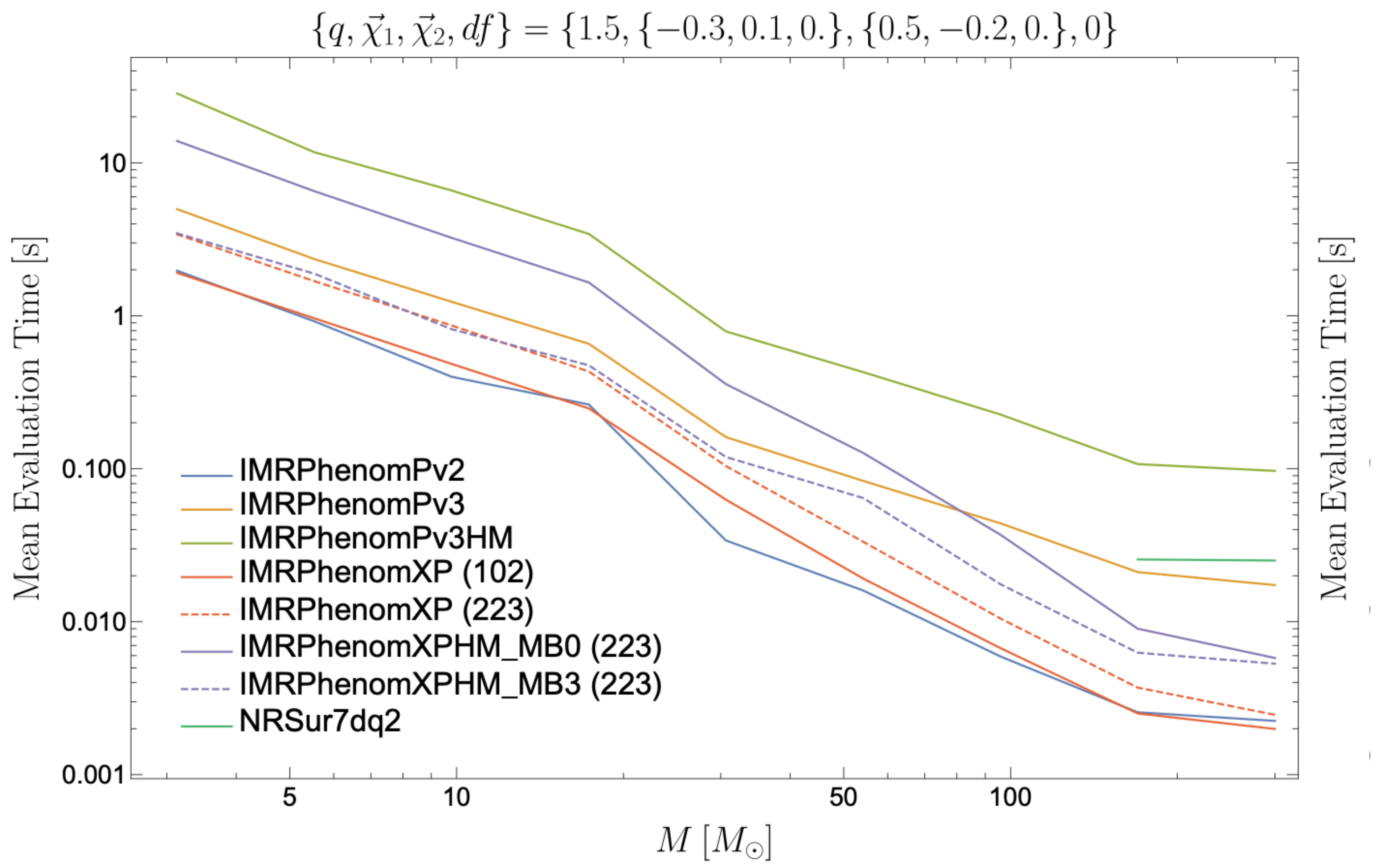
- *C. García-Quirós+, PRD, 102, 064002*
- *G. Pratten+, PRD, 102, 064001*
- A. *Ramos-Buades+, PRD, 101, 103014*
- G. Pratten+, arXiv:2004.06503
- Cecilio García-Quirós+, arXiv:2001.10897
- H. Estellés+, 2004.08302
- In prep.: “IMRPhenomTHM”, “IMRPhenomTPHM”.
  IMRPhenomXE

Waveform model evaluation speed

Fastest WF model with sub-dominant harmonics.

In part due to “multibanding” acceleration based on interpolation [Cecilio García-Quirós+, arXiv:2001.10897]





$M_{\min}[M_\odot]$	ΔT	IMRPhenomXP	IMRPhenomPv2	IMRPhenomPv3	SEOBNRv4P	IMRPhenomXPHM	IMRPhenomPv3HM	SEOBNRv4PHM	NRSurd7q4
20	4 s	8.6	5.7	29.1	2691.4	31.8	160.3	4259.9	-
	8 s	16.8	11.2	56.4	2976.6	52.8	311.7	4540.9	-
60	4 s	5.8	4.1	29.4	1492.1	21.4	161.7	3016.2	60.5
	8 s	11.4	8.0	56.6	1483.9	36.3	312.8	2951.5	59.9

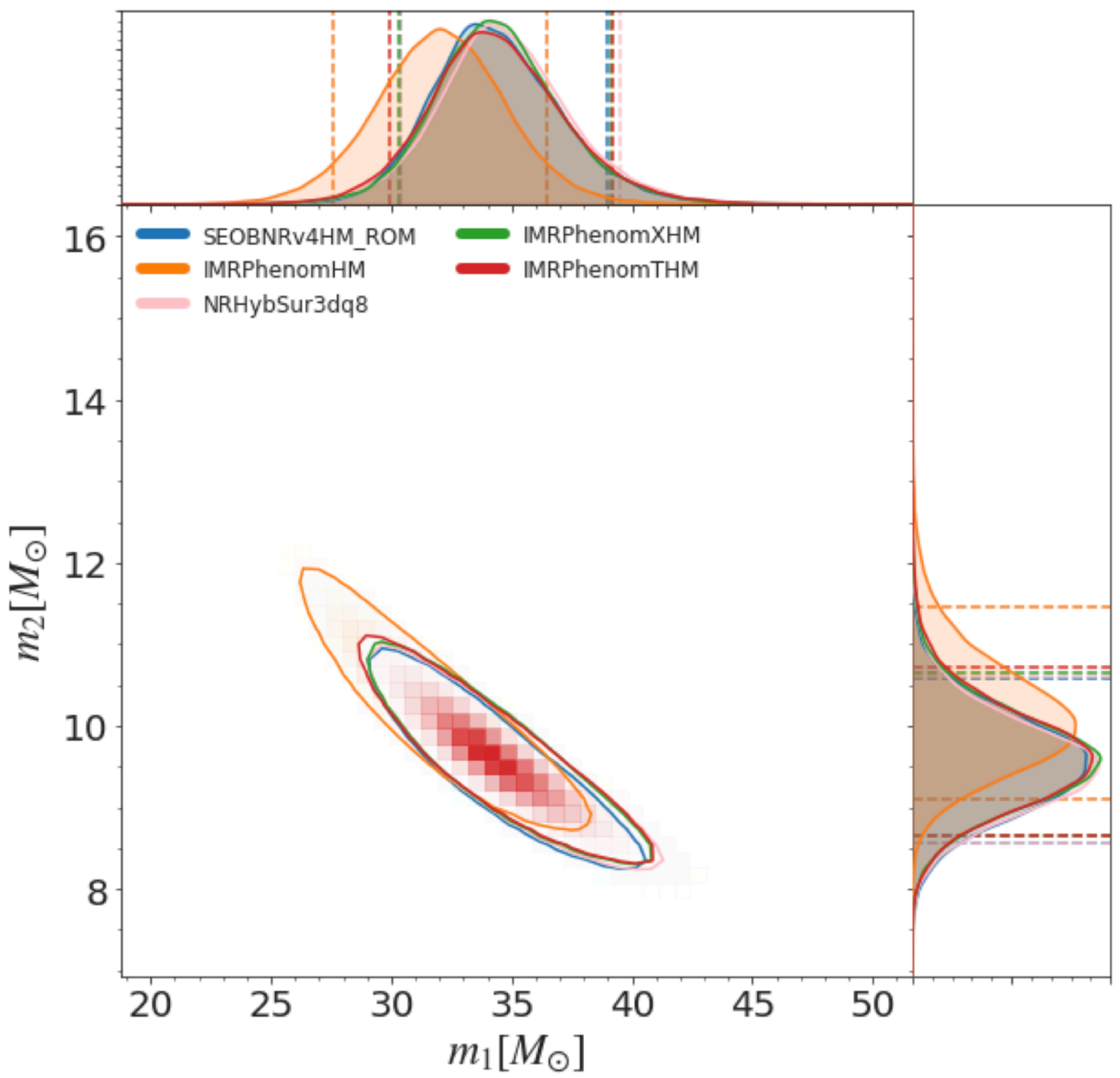
“Pv3” angles

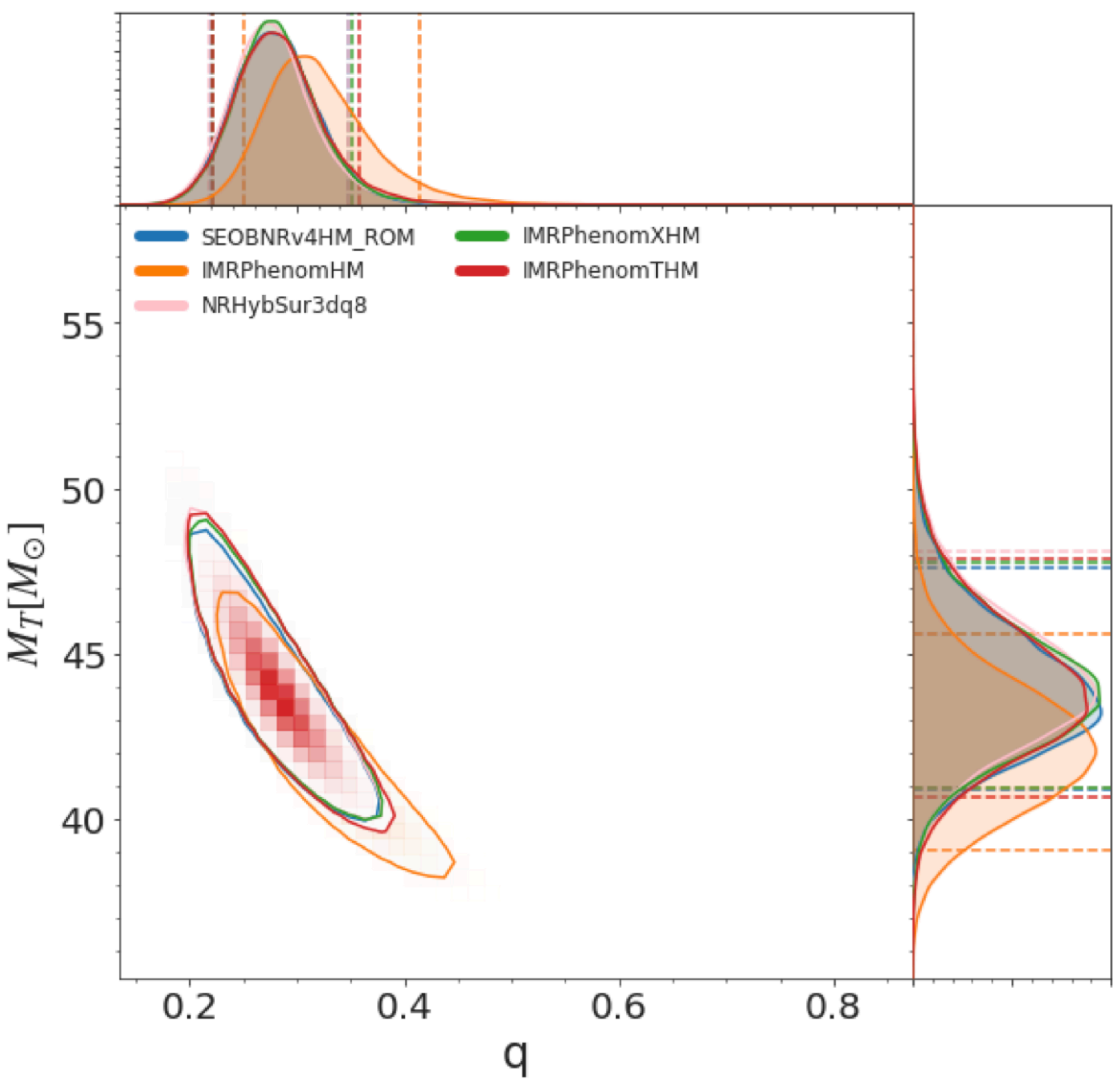
TABLE I. Mean likelihood evaluation time in milliseconds for several precessing models for equal masses. The numbers represent averages over a mass range of $[M_{min}, 100]\ M_\odot$ with $M_{min} = 20, 60 M_\odot$ and random spin orientations and magnitudes. The first column indicates the data analysis segment length in seconds.

Accuracy of non-precessing models

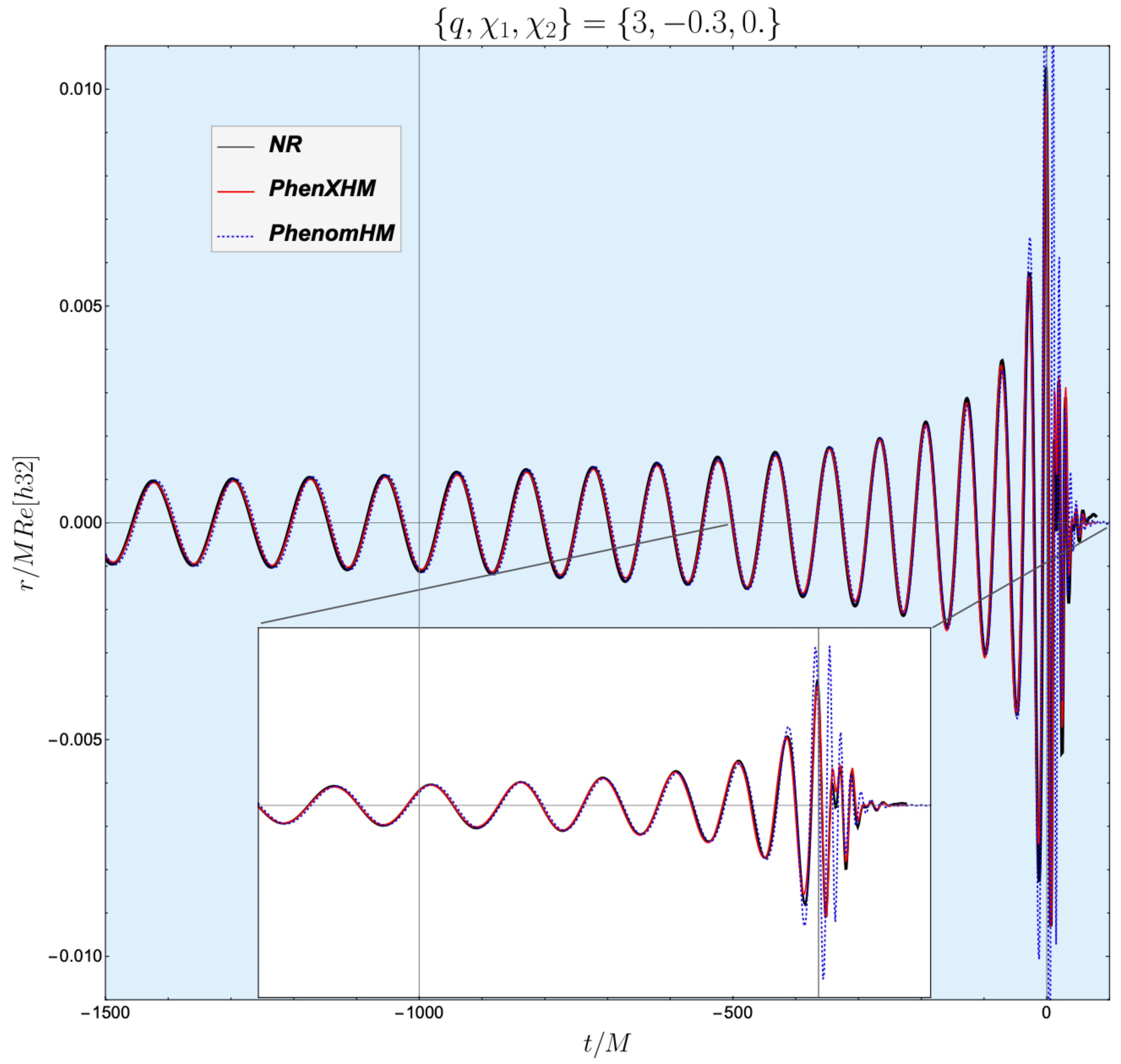
Find excellent agreement between current generation of waveform models, significant deviations for IMRPhenomHM (previous generation).

Example: PE results for GW190412 [Colleoni+, arXiv:2010.05830]





includes mode mixing for l=2,m=2 and l=3,m=2 spherical harmonics



Systematic studies with HM (sub-dominant spherical harmonics)

Model publications include re-analyses of GW150914 and GW170729

Completed case study: GW190412 (M. Mateu: python code to automatise runs)
74 published PE runs with parallel Bilby + LALInference (cross-checks)

New LVC PE code base
Runs carried out on RES nodes MareNostrum4 (BSC)
And Picasso (U Malaga)

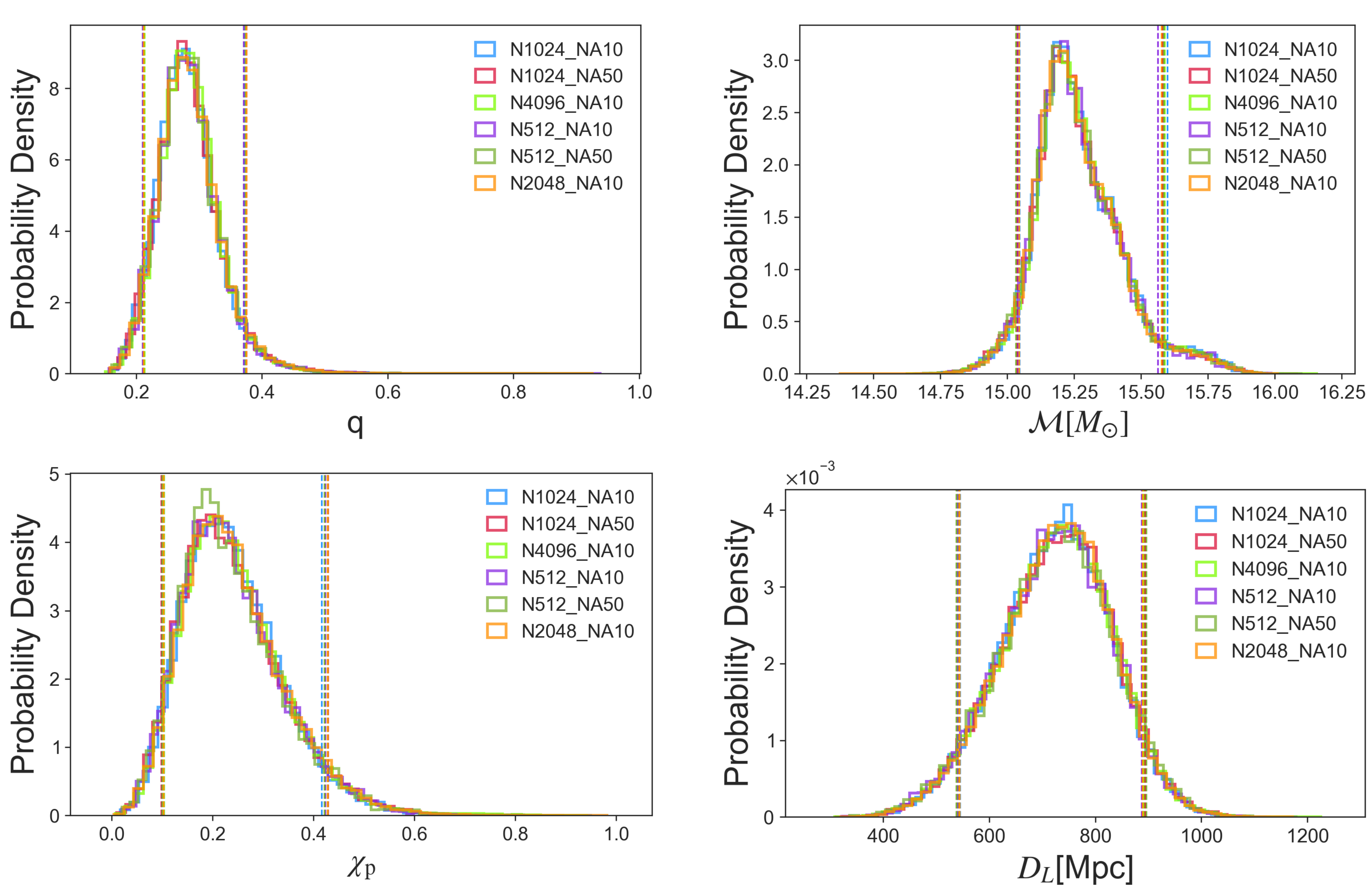
Traditional LVC PE code
within LALSuite

M. Colleoni+, Towards the routine use of subdominant harmonics in gravitational-wave inference:
re-analysis of GW190412 with generation X waveform models arXiv:2010.05830,
Posterior sample release: https://zenodo.org/record/4079188#.X4sHcC8Rq_I

Current work: complete re-analysis of GWTC1 as a preparation for O3.

- Similarly detailed studies as for GW190412 ~ 1 week on RES resources
- Low-resolution runs with aggressive multibanding ~ 30 minutes to a few hours for BBH events, high resolution runs hours to days depending on mass, parallelisation settings …
- Possible application:
  distance estimates with higher modes within ~ hour (hypothetical GW190521 type EM counterparts)

GW190412 runs with PhenomX: convergence

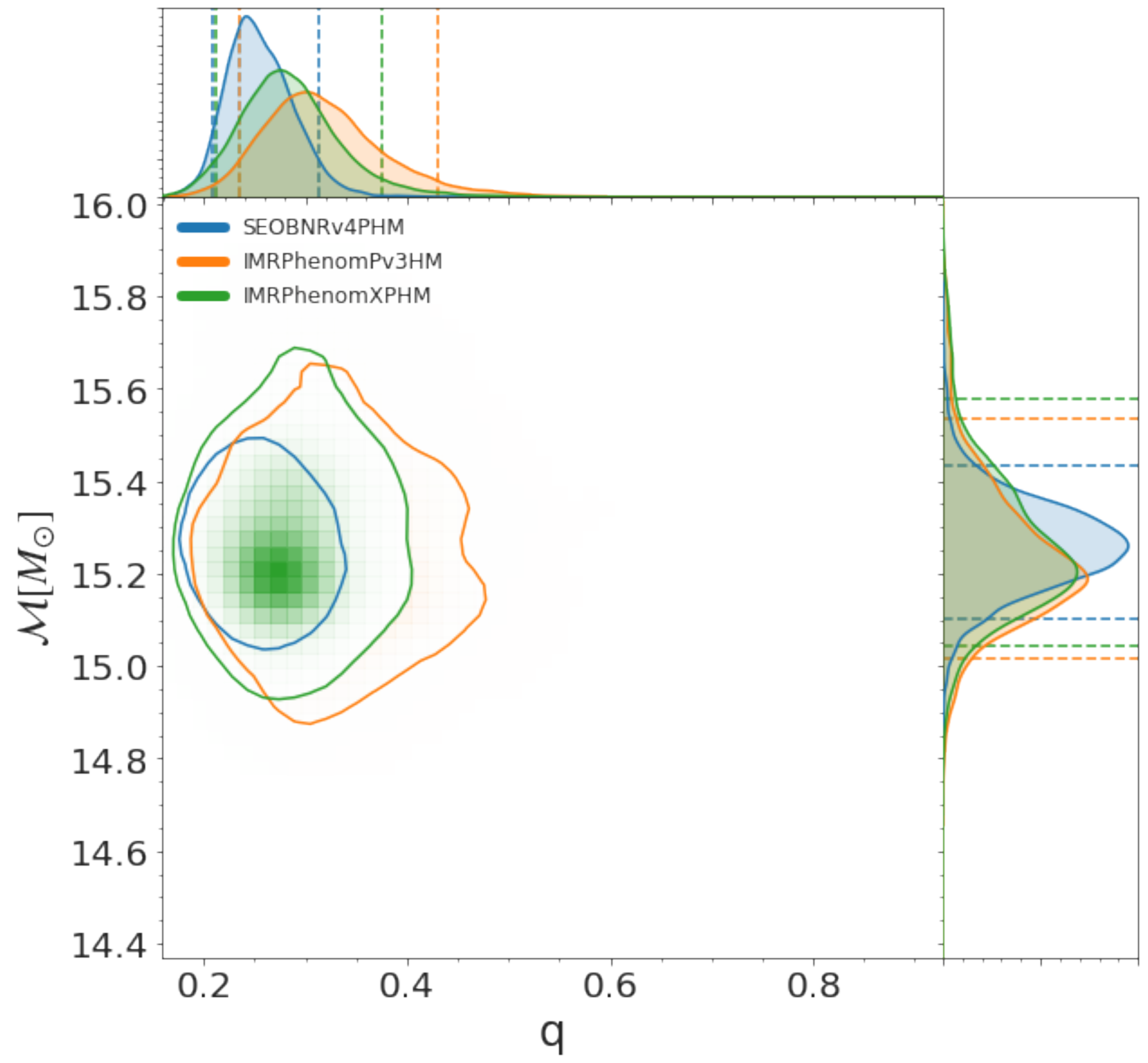


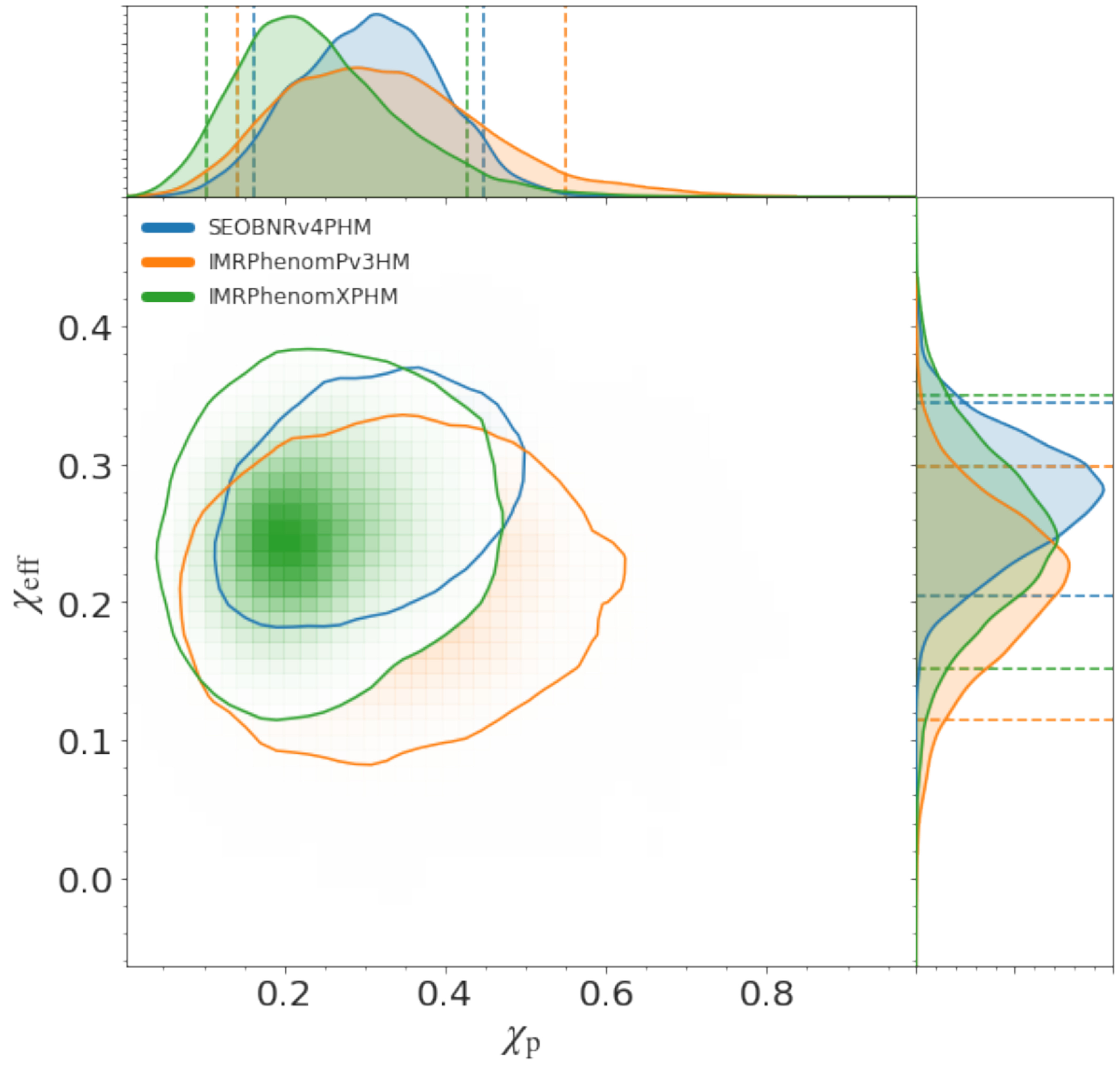
- nlive=512, nact=10, already produces reasonable results with a wallclock runtime of ~7 hrs on 96 cores

- There are still many open questions regarding best practices for configuring PE runs!

GW190412 with precession:

- PhenomXPHM results closer to SEOB than old PhenomPv3HM, except for χ_p - measuring spin precession is still an issue!





- SEOBNRv4PHM/IMRPhenomPv3HM: LVC sample release
- IMRPhenomXPHM: same priors, nlive=2048, nact=10, walks=200, maxmcmc=15K, dist. marg.

Eccentric waveforms I

Eccentricity work lead by A. Ramos Buades
(PhD UIB -> PostDoc AEI)
in collaboration with U. Zurich (Haney, Tiwari)

A first survey of spinning eccentric black hole mergers: Numerical relativity simulations, hybrid waveforms, and parameter estimation, Antoni Ramos-Buades+, Phys. Rev. D 101, 083015 (2020)

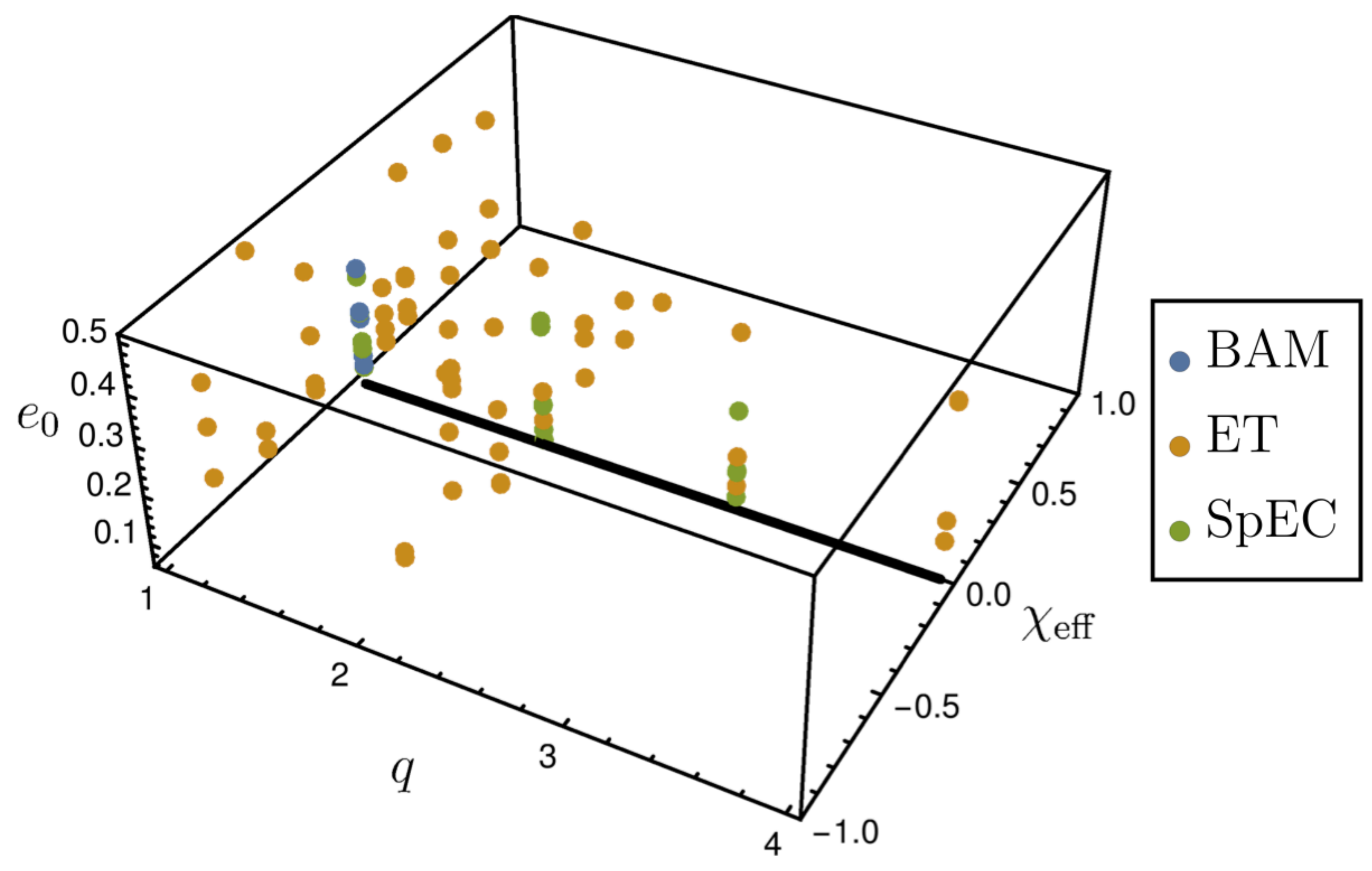
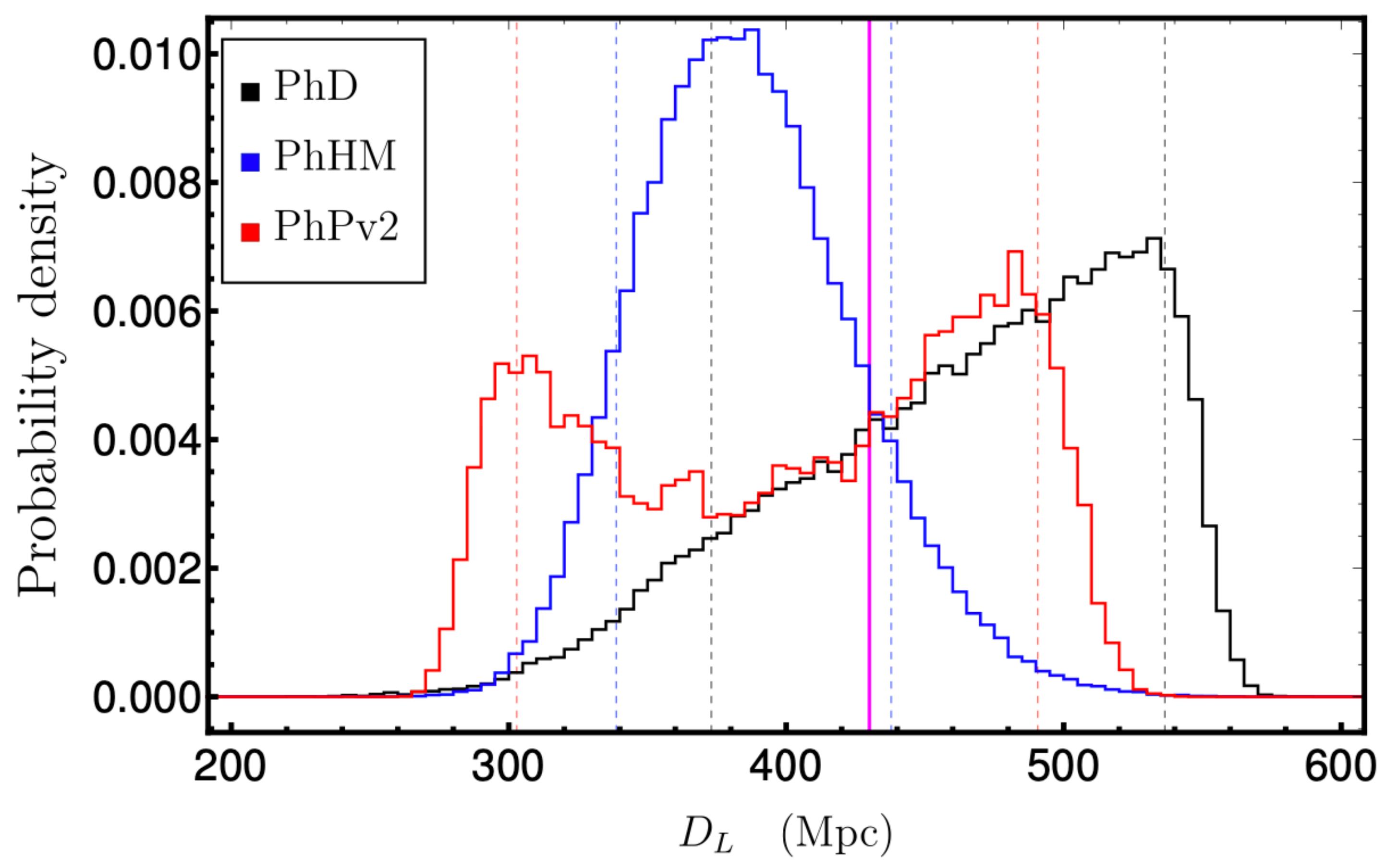


Figure 1: Initial eccentricity e_0, mass ratio q and effective spin parameter $\chi_{\rm eff} = (m_1\chi_{1,z} + m_2\chi_{2,z})/(m_1 + m_2)$ for the numerical relativity simulations generated with the BAM, EinsteinToolkit and SpEc [56] codes. The thick black line represents the cases with $\chi_{\rm eff} = 0$.

Largest catalog of eccentric spinning NR waveforms to date, Including generic WFs (spin precession + ecc.)

DA application: determine parameter bias of quasi-circular WF for eccentric events.



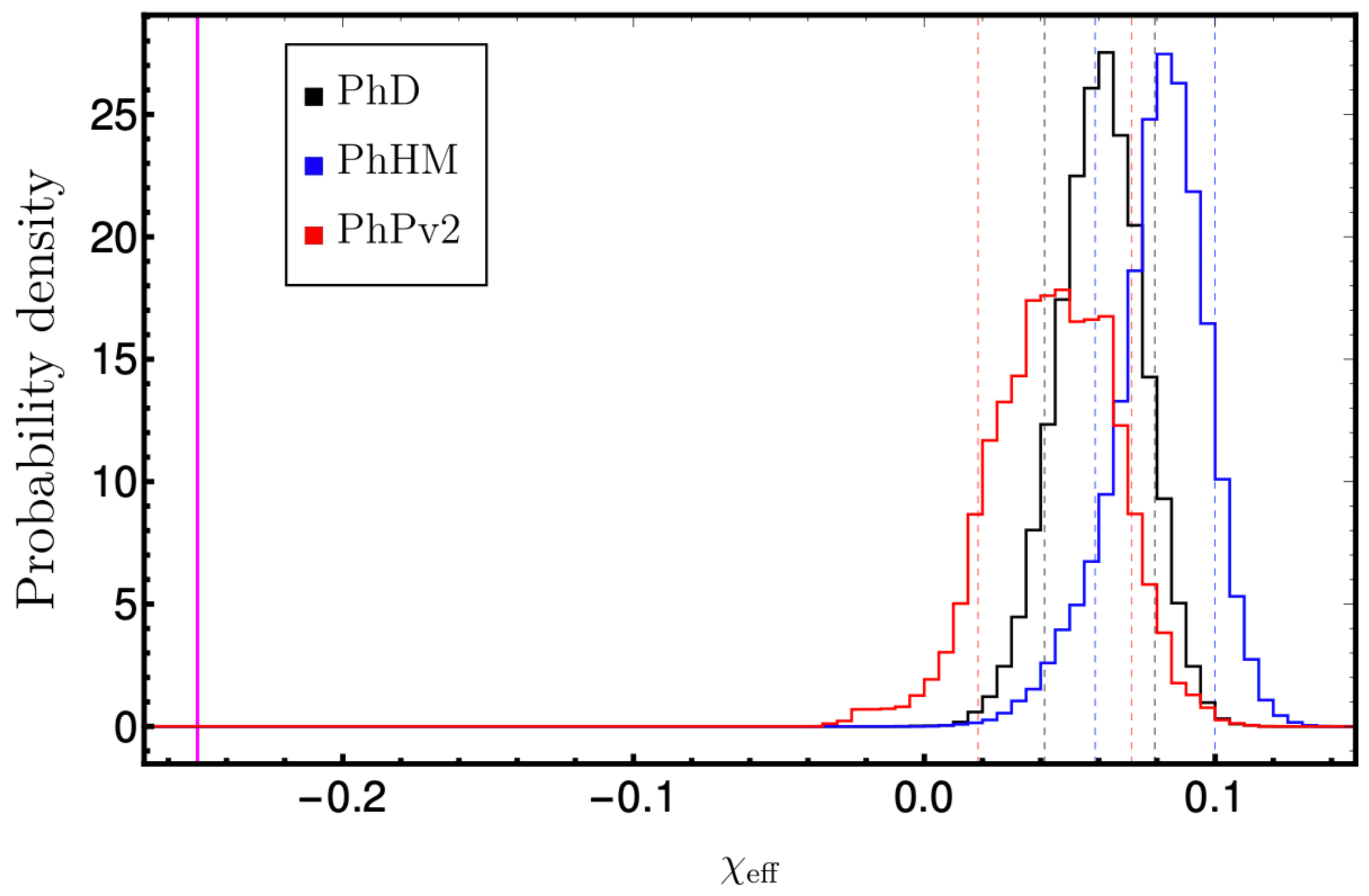
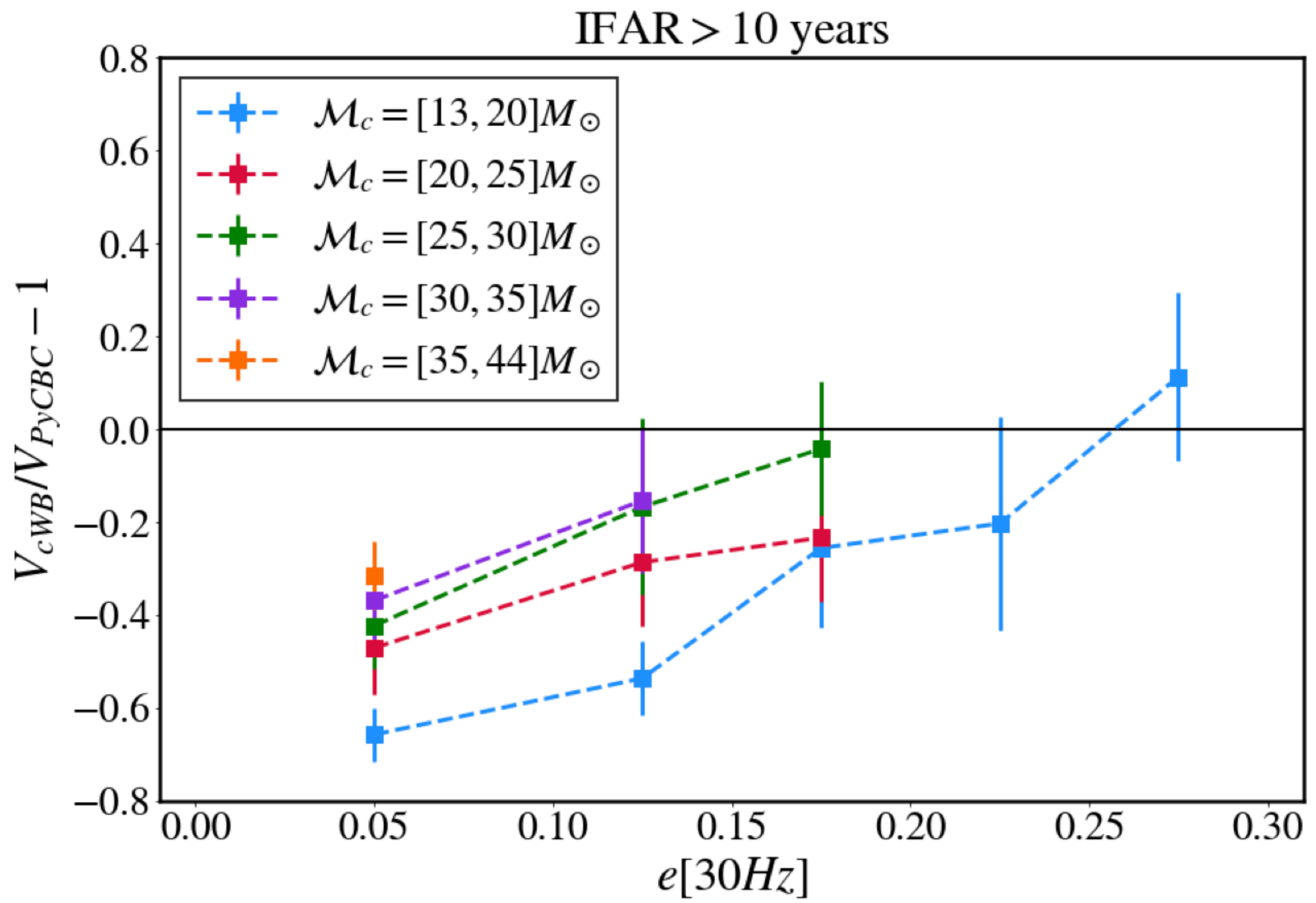


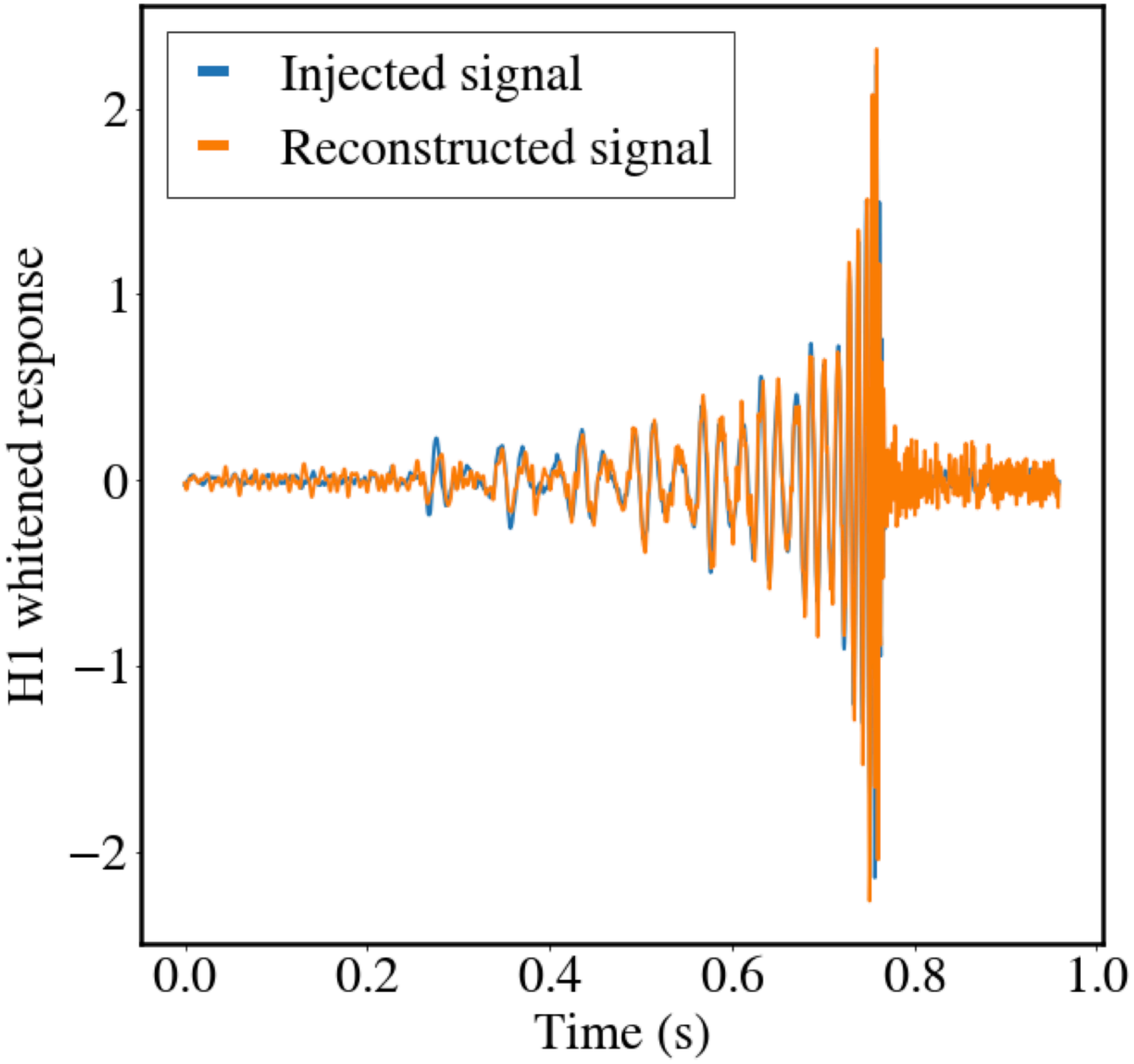
Figure 9: Posterior probability distributions for the injected spinning eccentric hybrid waveform, with initial eccentricity $e_0 = 0.420 \pm 0.006$. The vertical dashed lines correspond to 90% credible regions. The thick vertical magenta line represents the injected value. The black, blue and red curves represent distributions sampled using the IMRPhenomD, IMRPhenomHM and IMRPhenomPv2 approximants, respectively.

Eccentric waveforms II

Impact of eccentricity on the gravitational wave searches for binary black holes: High mass case
Authors: Antoni Ramos-Buades, Shubhanshu Tiwari, Maria Haney, Sascha Husa
Phys. Rev. D 102, 043005 (2020)

Further applications:
- compare sensitivity of pyCBC matched filter search pipeline to cWB un-modelled search pipeline
- test waveform reconstruction of cWB pipeline



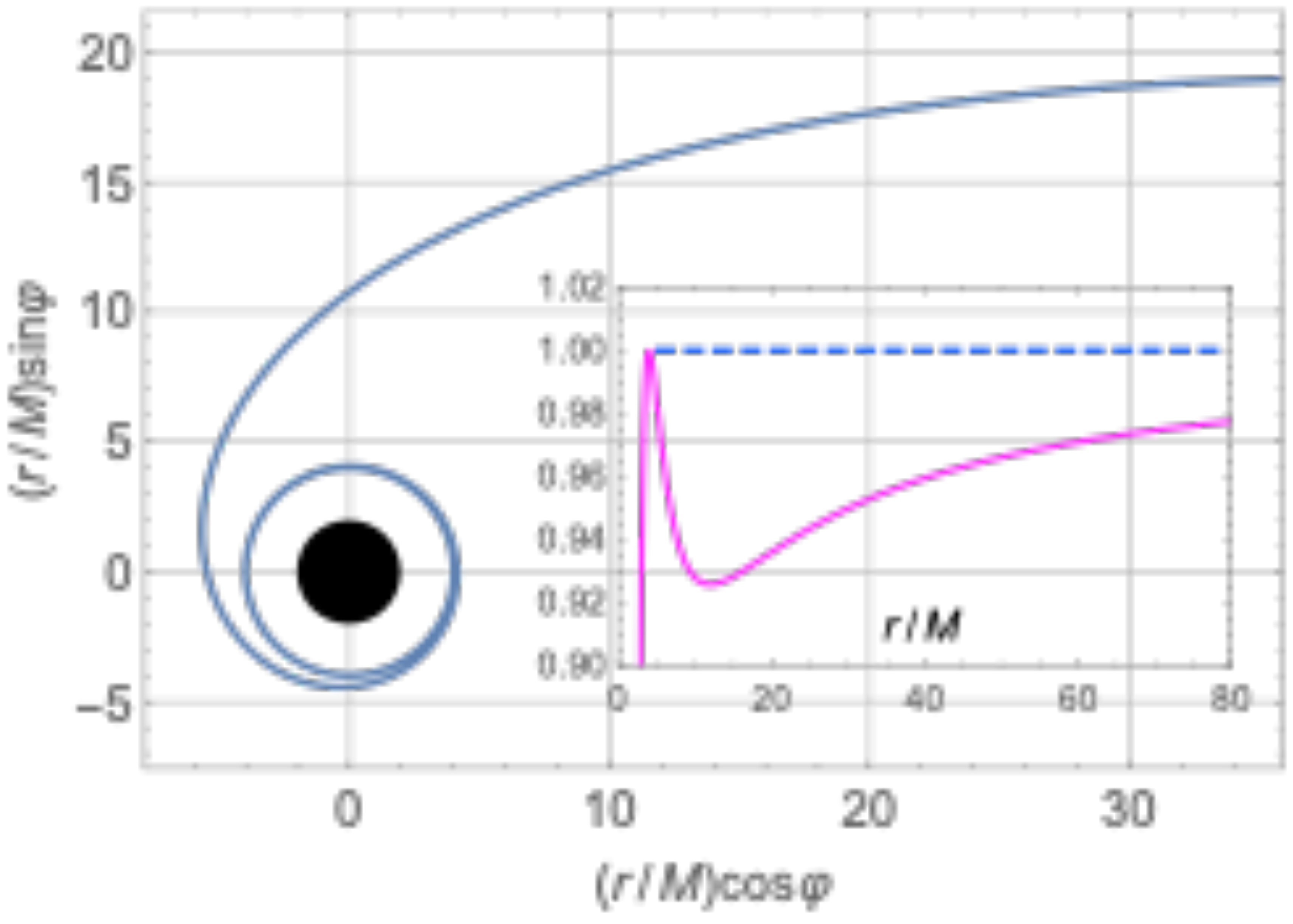


Time-domain methods to compute the first-order self-force (Marta Colleoni)

1) **Time-domain methods are expected to handle strongly-eccentric orbits better than current frequency-domain codes**
   -> useful in covering the parameter space in self-force calculations (relevant to evolve self-forced inspirals (V. de Meent + 2018))

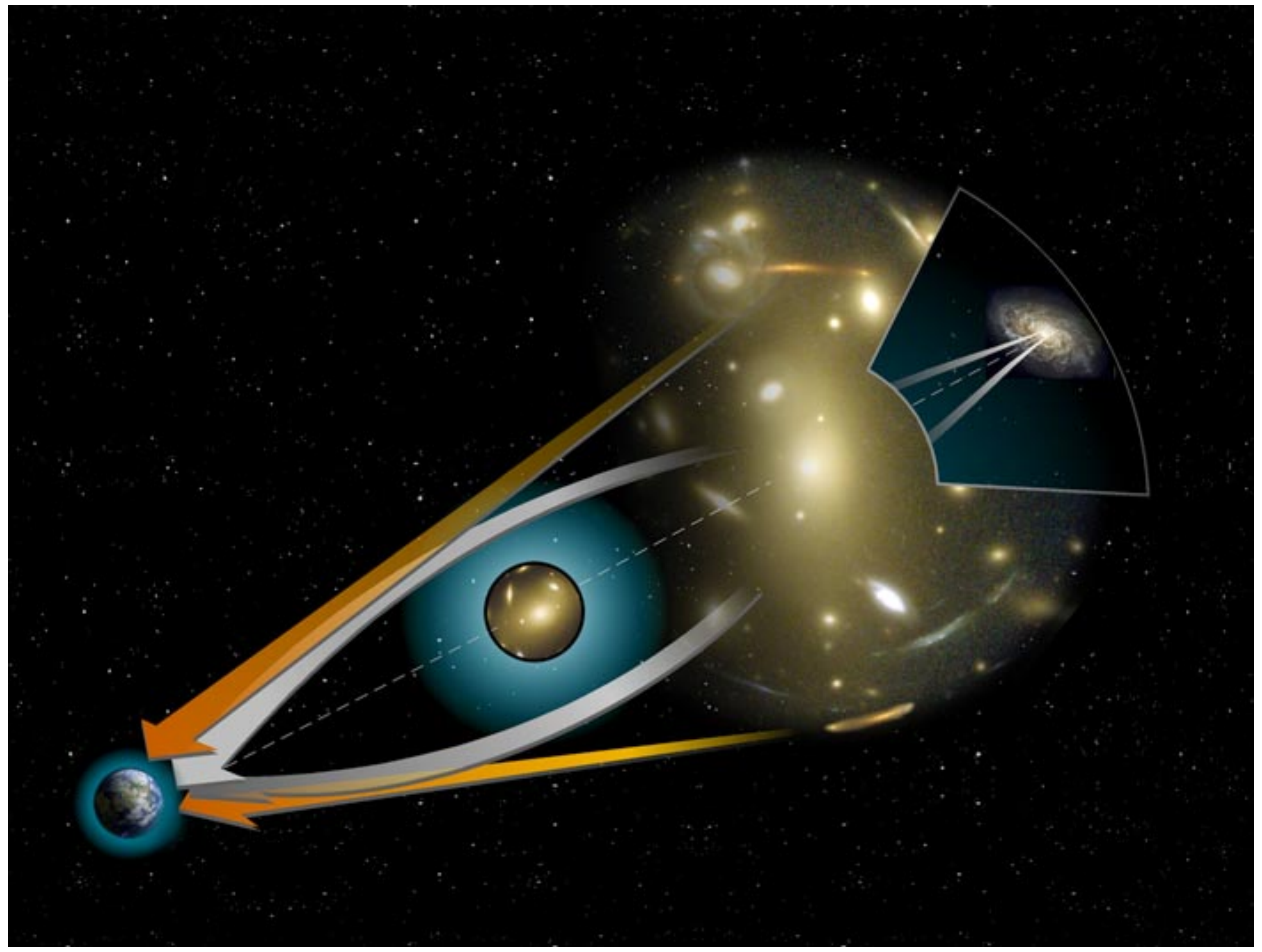
2) **Renewed interest in scatter orbits**

- can constrain higher-order terms in the post-Minkowskian dynamics (Damour ’16, Damour ’19)
- can provide better access to strong-field physics, but also a link to asymptotic quantities (mass, angular momentum) that can be readily compared with the EOB/PN formalism (Damour ’10, Barack+ ‘19)
- gravitational waves from hyperbolic encounters might be detected by 3G detectors (Mukherjee+ ’20)



Gravitational Lensing of Gravitational Waves I

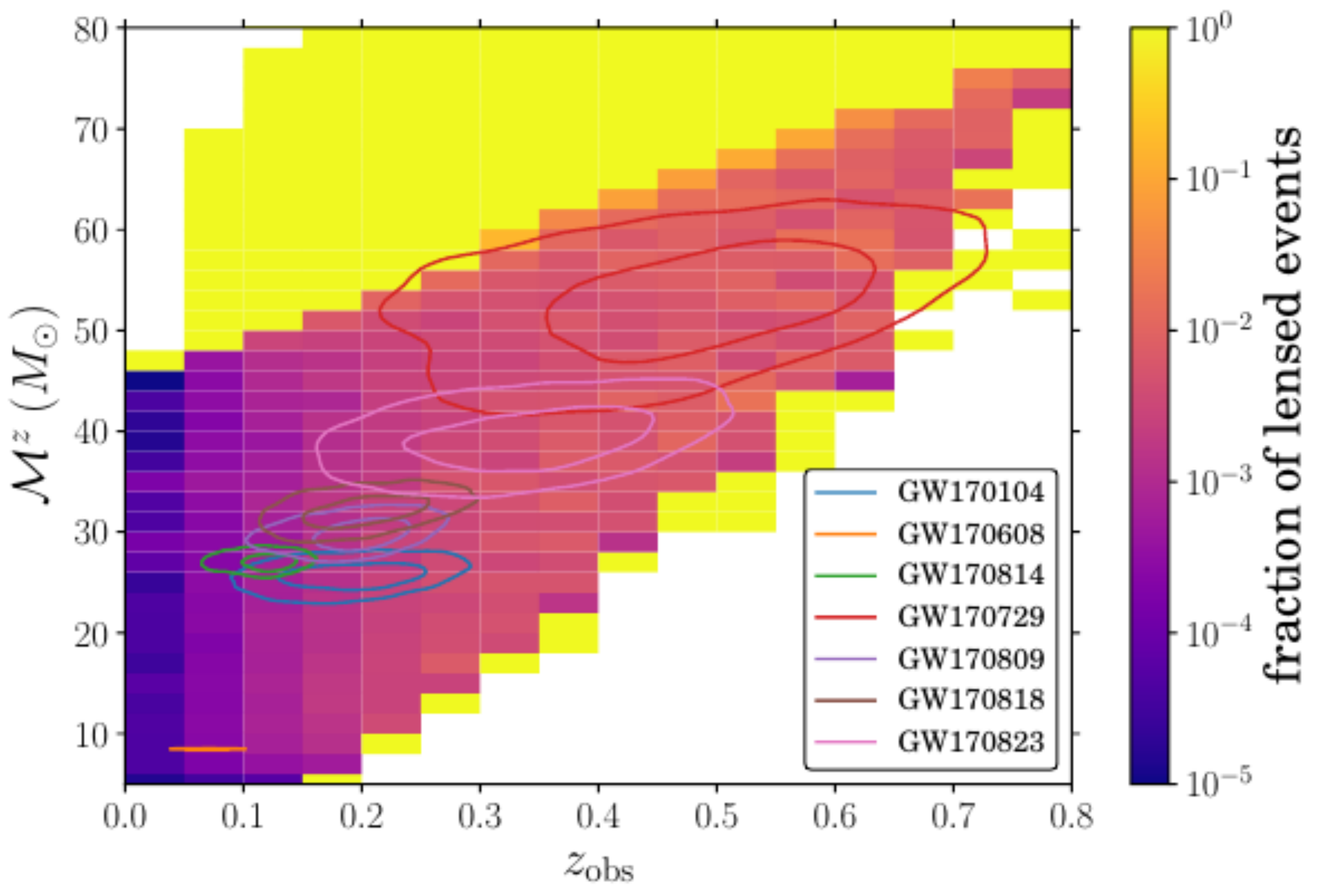
- Just like light, GWs can be deflected, magnified and distorted by massive galaxies or clusters acting as gravitational lenses.

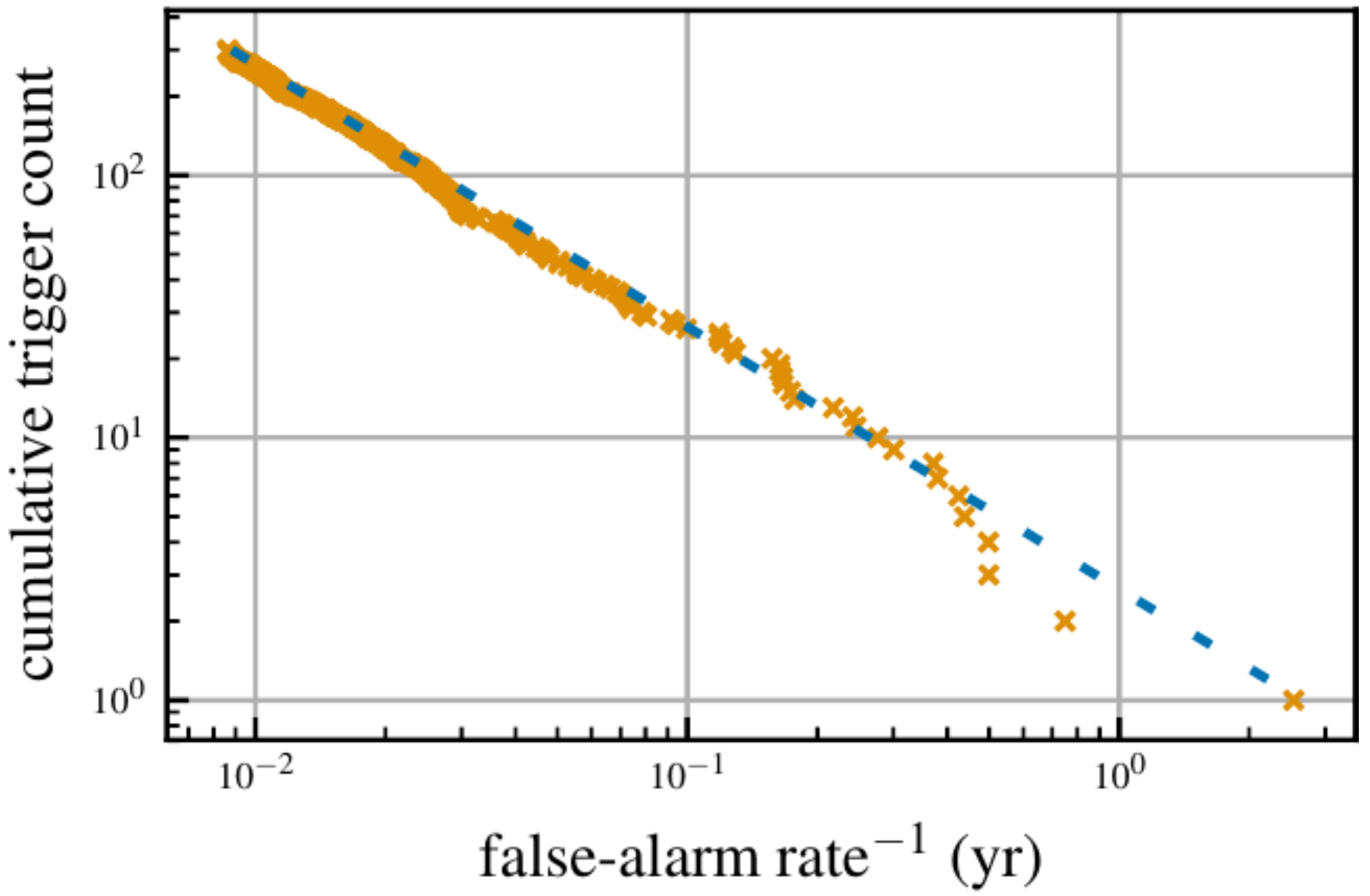


- **LIGO&Virgo already detect BBHs from cosmological distances (z~1), so lensing could in principle be in action on some events.**
- **Prior expected rate is still small, ~O(1/1000).**
- Effects to look for:
  - excess of events from apparently heavy sources (actually just magnified?)
  - multiple events with consistent parameters (lensed images of a single source?)
  - microlensing-induced distortions of the waveforms
- **Lensing of GWs will become an even hotter topic with the increased event rates and cosmological reach of future detectors (ET, LISA).**

Gravitational Lensing of Gravitational Waves II

- Search for those 3 signatures in GWTC-1 BBH events: Hannuksela, Haris, Ng, Kumar, Mehta, Keitel, Li & Ajith, ApJL874:L1 (2019)
- **No evidence so far for excess magnified events, multiple images or microlensing.**





- Search for sub-threshold lensed counterpart images in full O1&O2 data: McIsaac, Keitel et al., PRD102.084031 (2020)

- **Search for lensing signatures in O3 data: part of LIGO-Virgo white paper plans, D. Keitel co-manager of the analysis and paper writing efforts.**

Future work

- Prepare for discoveries of continuous waves, lensed events, merger remnants.
- Prepare for challenging CBC events that are harder to understand (GW190521 a first example).
- Upgrade PhenomX/T waveform models for O4, GPU implementation?
- Tests of GR: extend models to “exotic physics”, parameterized tests.
- Further develop automatisation of PE pipeline for HPC clusters.
- Implementation and optimisation of waveform models for LISA, (speeding up) LISA parameter estimation.
- Study applications of phenomenological waveform modelling approach to study EMRIs and speeding up self-force calculations.