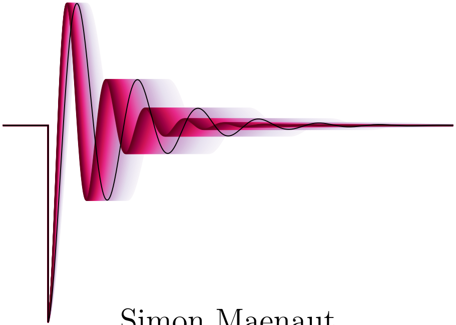
pyRing for LISA



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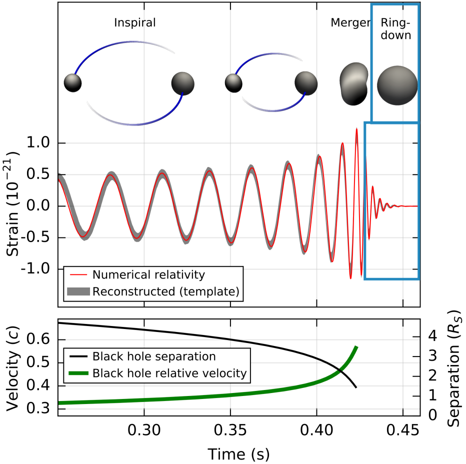
8 May 2024

KU LEUVEN

BINARY BLACK HOLES COALESCENCES

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



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

SCIENCE GOALS

- **Testing** the emission:
  - Remnant compact object **nature**;
    Are we really observing black holes?
  - General Relativity predictions for **spectral emission**;
    Is General Relativity a correct description of gravity at high curvatures?
  - Black Hole **Uniqueness Theorems**;
    Do non-extremal black holes have additional hairs?
  - Possible **quantum horizon** effects and classical **BH thermodynamics**.
    Is our classical description of black holes valid?

MISSING PHYSICS?

- Why merger-ringdown GW observations compared to **other experiments?**
  - **Largest curvature** regime experimentally accessible;
  - Highly **dynamical** regime;
  - Ringdown searches for new physics in LVK band expected to be **clean**
  - **Gauge** the contribution of **missing physics** for precision tests:
  - In LISA?

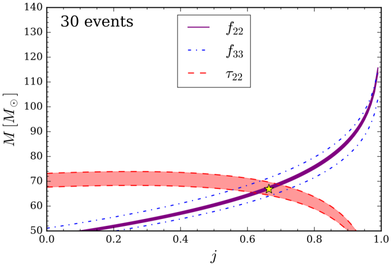
Barausse, Cardoso, Pani, PRD 89 (2014) 104059

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave **multipoles**:

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

Brito, Buonanno, Reymond, PRD (2018)



- Perturbation theory predicts spectrum.
  In Kerr, $\{\omega_{lmn}(M,a), \tau_{lmn}(M,a)\}$ (*"final state conjecture"*)

- Measure $\{\omega_1 = \omega_{220}, \tau_1 = \tau_{220}\} \rightarrow \{M, a\}$
  Measure $\{\omega_2 = \omega_{330}\}$ (now predicted) $\Longrightarrow$ test **G**eneral **R**elativity

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

WARNING AND GOAL

- Spectroscopy from binary mergers, **systematics**-plagued measurements:
  - "**Ringdown start time**" uncertainty (ill-defined)
  - **Dynamical evolution** of the system (e.g. mass&spin change with time)
- Affect **measurement precision**, but also **physical interpretation**
- Difference between:
  - **Fitting** post-peak **waveform** with bunch of damped-sinusoids
  - **Extract physical** vibrational black hole **spectrum**

WHAT IS PYRING?

- Python package for **B**lack **H**ole ringdown analysis, model comparison and parameter estimation.
    - Can handle interferometric, simulated or numerical relativity data.
    - Natively incorporates several analytical ringodwn templates.
    - Supports parametrised tests of **G**eneral **R**elativity and a variety of quasi-normal modes spectrum predictions for emissions alternative to the Kerr solution.
- Internally reviewed for scientific usage by the **LIGO-V**irgo-**K**agra collaboration.
- Routinely used to produce catalogs of BH ringdown properties and related tests of GR by the LVK collaboration.

pyRing TECHNICAL DETAILS

- Fully time domain formulation, both likelihood and waveform models
- Relies on gwpy for data access and LAL for all the antenna patterns
- Core computational operations in cython, everything else in python

Code and documentation

- LVK repostiory: git.ligo.org/lscsoft/pyring
- Full documentation: lscsoft.docs.ligo.org/pyring
- Test of models vs NR: github.com/GCArullo/bayRing

Carullo+ 1902.07527, Isi+ 1905.00869, LIGO & Virgo 2010.14529

SCIENCE OUTPUT

- Additional studies that made use of this software:
  - Impact of noise on overtone detection in GW150914: arXiv:2201.00822;
  - GWTC-3 Testing GR LVK catalog: arXiv:2112.06861;
  - GW190521 waveforms consistency and astrophysical implications: arXiv:2112.06856;
  - Models and constraints of ringdown in the presence of U(1) black hole charges: arXiv:2109.13961;
  - Constraints on braneworld gravity: arXiv:2106.05558;
  - Verification of the Bekenstein-Hod bound: arXiv:2103.06167;
  - Constraints on alternative theories of gravity using the ParSpec formalism: arXiv:2102.05939;
  - Investigations and observational constraints on the area quantisation hypothesis: arXiv:2011.03816;
  - GWTC-2 Testing GR LVK catalog: arXiv:2010.14529;
  - GW190521 discovery: arXiv:2009.01075 and physics implications: arXiv:2009.01190;
  - Spectroscopy of Rotating Black Holes Pierced by Cosmic Strings: arXiv:2002.01695.
  - Probing the Purely Ingoing Nature of the Black-hole Event Horizon arXiv:1912.07058;

pyRing RINGDOWN MODELS

- Simple superposition of damped sinusoids
- Models with predicted complex frequency for Kerr
- Models with Kerr spectrum and amplitude predictions
- Tidal Effective One Body post-merger (TEOBPM) model
- Many other models...

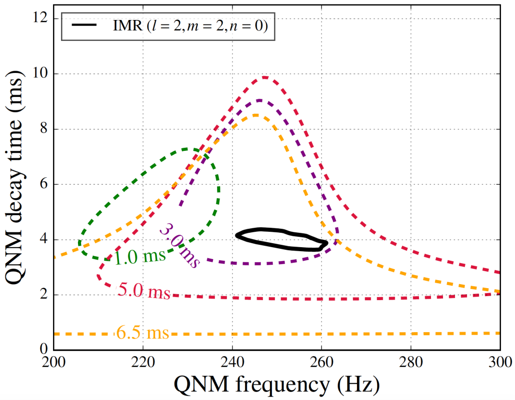
See pyRing documentation for more details.

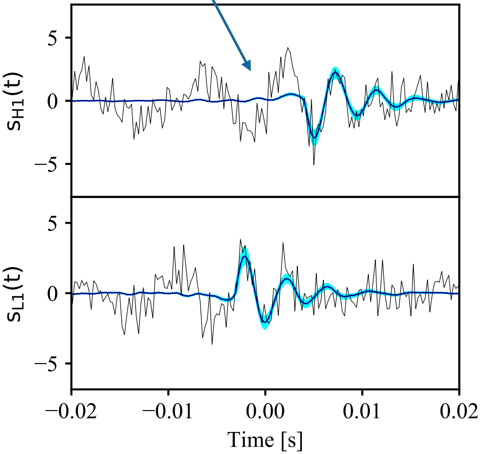
A ZOO OF POSSIBILITIES

- All models mentioned before, available
- Together with many more models/options:
  - **Quadratic modes** London+, 1404.3197, Cheung+, 2208.07374, Mitman+, 2208.07380, Baibhav+, 2302.03050, Cheung+, 2310.04489
  - Tails Carullo-De Amicis, 2310.12968
  - Black hole charges Carullo+, 2109.13961, Gu+, 2310.10447
  - **Parameterised GR deviations** (agnostic/Parspec) LVK, 2112.06861 Carullo, 2102.05939
  - Beyond-GR corrections (EsGB, dCS, EFTs, …) Silva+, 2205.05132
  - Braneworld, area-quantisation, … Mishra+, 2311.03556, Laghi+, 2011.03816
  - Older models (Kamaretsos+) Kamaretsos,+, 1406.3201
  - …

GW150914: THE DAY WE SAW A BLACK HOLE RINGING

- **F**requency **D**omain: ringdown abrupt start contaminates inference when FFT-ing (Gibbs phenomena)





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

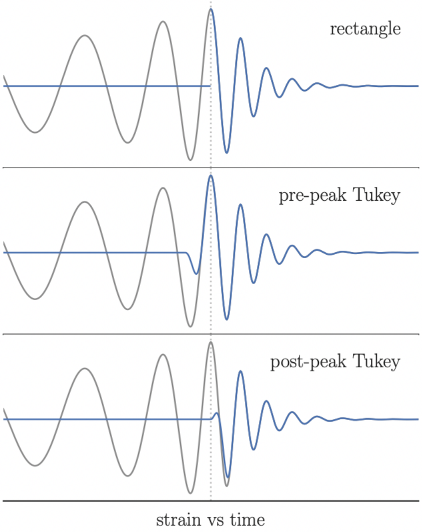
Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)

BLACK HOLE SPECTROSCOPY

- Cure: window

Carullo+, 1805.04760

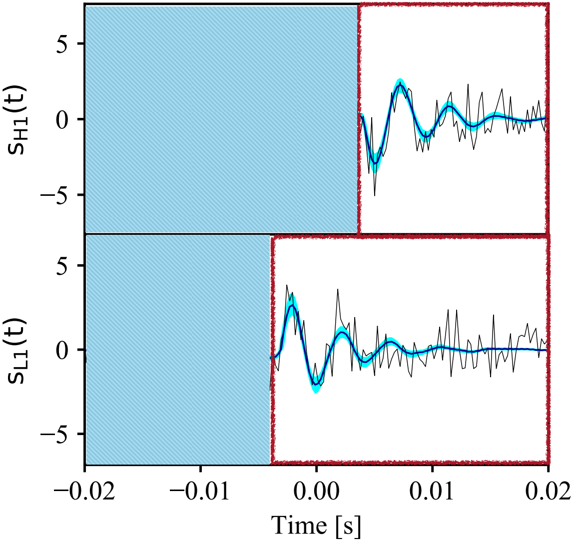
  - **Pro**: simple, FD analysis
  - **Cons**: lose SNR, need optimise window parameters



Isi, Farr, 2107.05609

BLACK HOLE SPECTROSCOPY

- **Time-Domain** approach:
  - **Isolate** ringdown portion
  - **Avoid** spurious frequencies from abrupt t_{start}, stay in time-domain (no FFT)



White noise, no-merger: Del Pozzo, Nagar, 1606.03952
Coloured noise: Carullo, Del Pozzo, Veitch, 1902.07527
Full solution: Isi, Farr, 2107.05609

TIME DOMAIN BLACK HOLE SPECTROSCOPY

- No longer **diagonal** likelihood

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

- Keep full correlation **matrix** (Toeplitz)

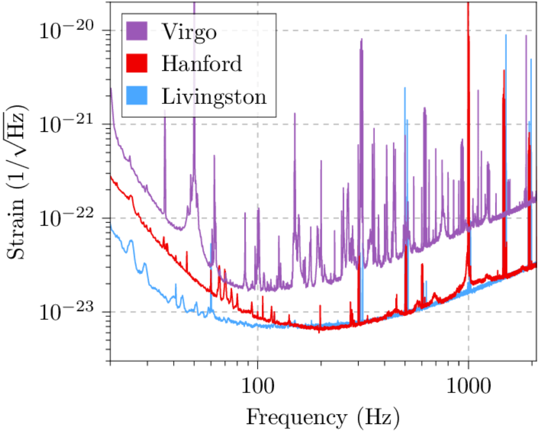
$$\ln P\,(d \mid s) = -\frac{1}{2}\sum_{i,j=0}^{N-1} (d_i - s_i)\, C_{ij}^{-1}\, (d_j - s_j)$$

$$C_{ij} = \rho\,(|i-j|)$$

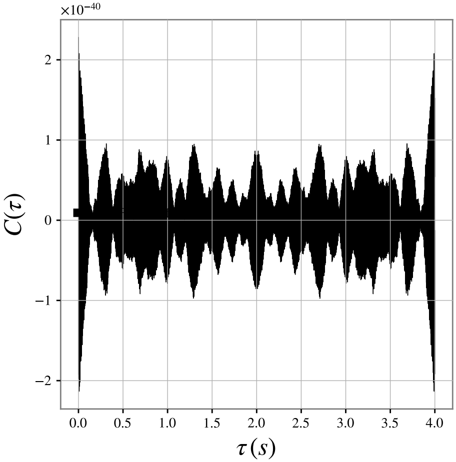
$$\hat{\rho}(k) = \frac{1}{N_\rho}\sum_{i=0}^{N_\rho - 1} n_i n_{i+k}$$

TIME DOMAIN BLACK HOLE SPECTROSCOPY

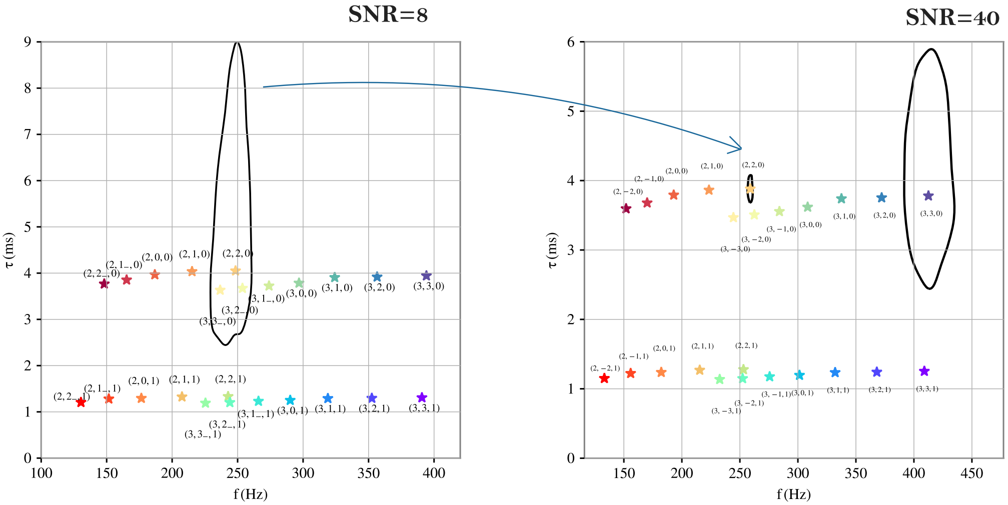
- The familiar:



- Becomes:



FUTURE BLACK HOLE SPECTROSCOPY



OPEN PROBLEMS

- Precession
  Finch-Moore, 2102.07794
  Hamilton-London-Hannam, 2301.06558
- Eccentricity
  Carullo+, 2309.07228
- Impact of memory/BMS frame
  Zertuche+, 2110.15922
- High-precision multi-mode fits
  Baibhav+, 2302.03050
  Cheung+, 2310.04489
  Zertuche+, 2110.15922
- Quadratic modes
  London+, 1404.3197
  Cheung+, 2208.07374
  Mitman+, 2208.07380
  Baibhav+, 2302.03050
  Cheung+, 2310.04489

LISA specifics

Work in progress

1. Completely different detector response and reference frame
2. Indirect measurement of the strain (TDI variables X, Y, Z or A, E, T)
3. Calculation of LISA specific auto-covariance and cross-covariance functions

- LISA Wiki: Ringdown Tests Of The No-hair Theorem With LISA
- Gitlab: gitlab.in2p3.fr/simon.maenaut/pyring
- Zulip: fpwg-projects.zulipchat.com

LISA challenges

1. LISA response (adiabatic approximation) from LISA GW Response ✓
2. Calculate TDI variables quickly from strain (linear interpolation) ✓
3. Compute ACF and CCF from LISA PSD and CSD for TDI variables
4. Implement multi-channel likelihood calculation for a single detector
5. Validate parameter-estimation, especially for high SNR signals

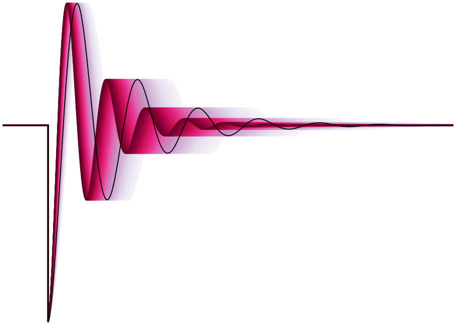
$$\boxed{C(p,q) = R\left(\frac{p-q}{f_s}\right) = \int_{-\frac{f_s}{2}}^{+\frac{f_s}{2}} S_n(f) e^{2j\pi f \frac{p-q}{f_s}} df}$$

Future outlook

Including ongoing LISA FPWG Ringdown projects

- Apply pyRing on latest LISA data challenge (high SNR) SMBHBs mergers
- Validation with injections of waveforms in LISA noise simulations
- Study the sensitivity to potential beyond GR ringdown effects
- Open questions on ringdown (see earlier) not specific to LISA
- Various ideas to study this dynamic strong gravity regime...

Thank you for your attention



ALTERNATIVE FORMALISMS

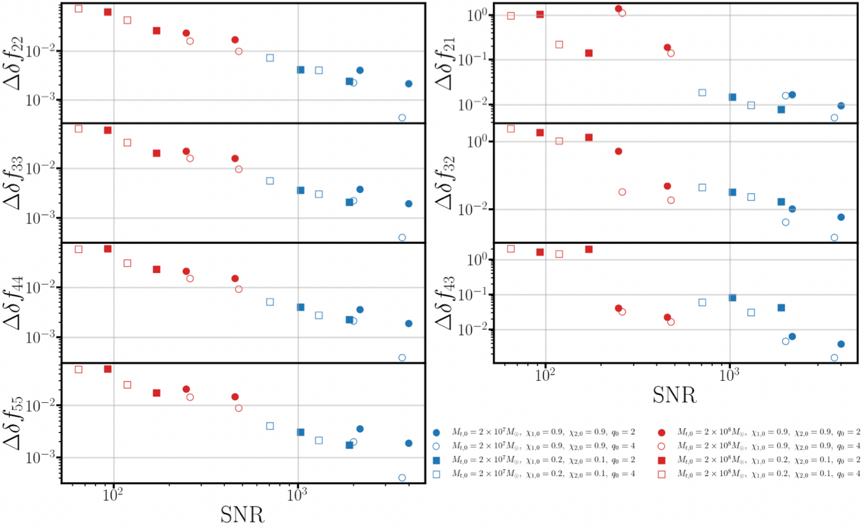
- TD not the only option
  - Stay in FD, filter-out pre-merger ("in-painting")
    Equivalent to TD, more expensive (efficient) for short (long) segments

Capano+. 2105.05238
Isi, Farr, 2107.05609

  - Stay in FD, model agnostically pre-merger ("marginalise"), e.g. superposition of wavelets

Finch-Moore, 2205.07809

FUTURE BLACK HOLE SPECTROSCOPY



Toubiana+, 2307.15086