Eccentric or Circular? Reanalyzing GW events for orbital eccentricity signatures with IMRPhenomTEHM

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Universitat de les Illes Balears | AC3 Institute of Applied Computing & Community Code.

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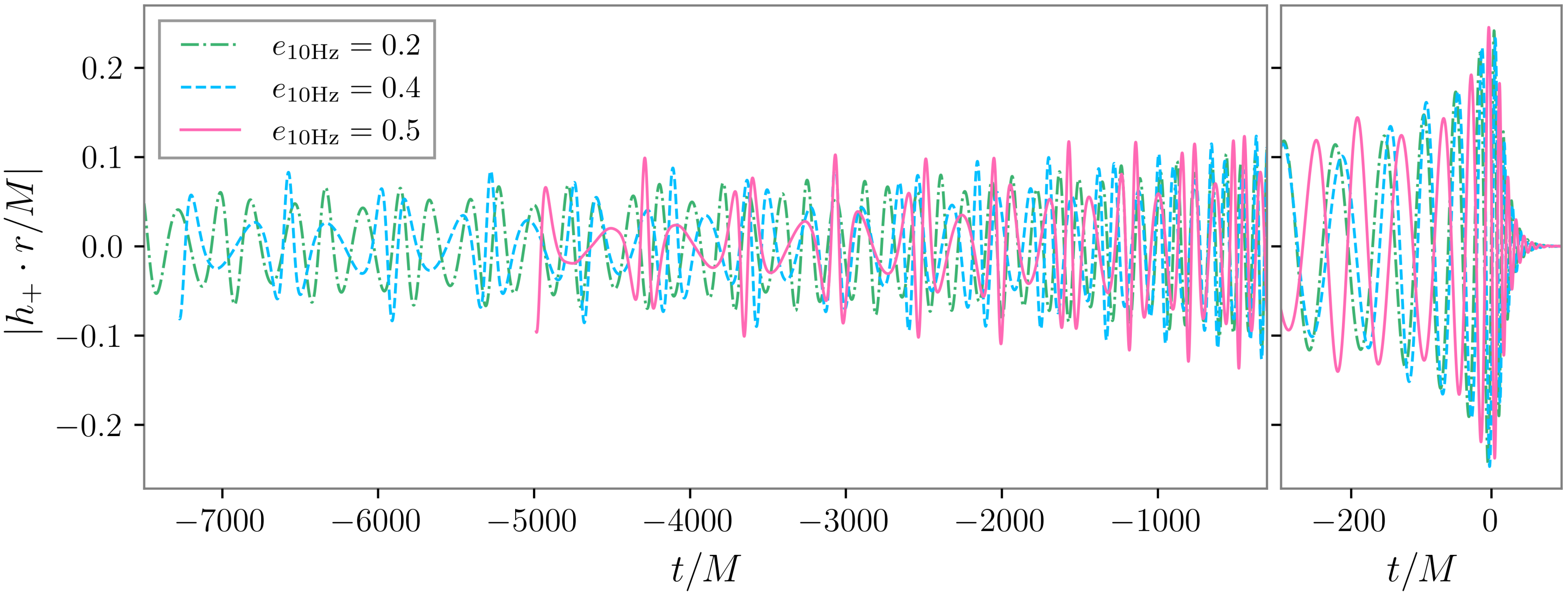
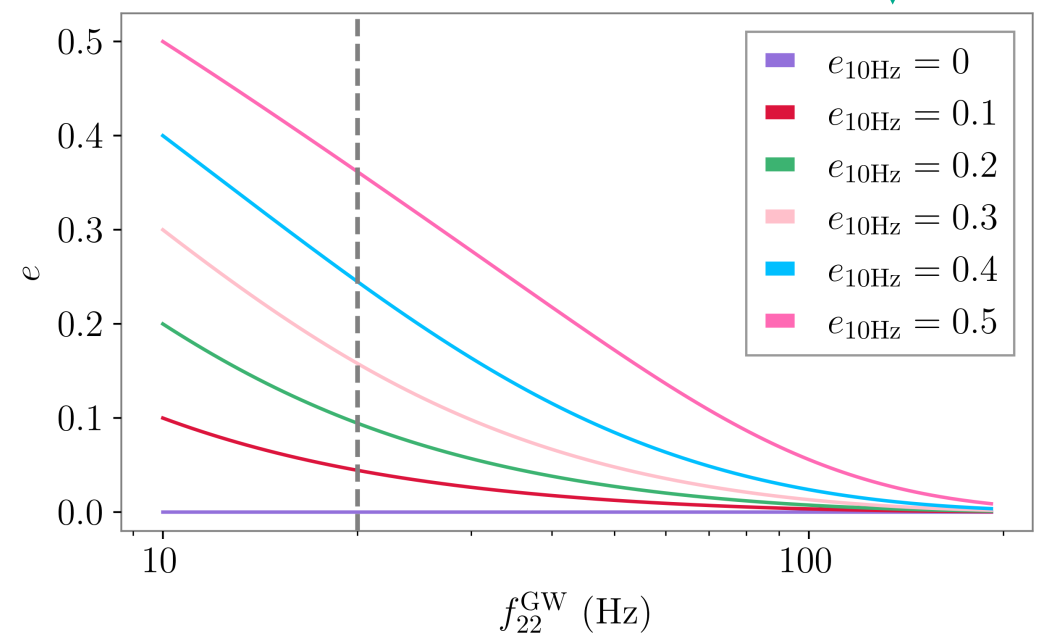
Eccentricity in IMR Black Hole Binary Models

Inspiral-Merger-Ringdown (IMR) Waveform Models → Detect & Characterize GWs.

- Most models assume a QUASI-CIRCULAR (QC) inspiral since ECCENTRICITY is expected to be radiated away:
  - **Non-spinning** (1D), **aligned-spinning** (3D), **spin-precessing** (7D).
  - Different families: `EOB`, `NRSur`, `IMRPhenom`.
- **Ongoing progress** incorporating ECCENTRICITY in IMR models → DYNAMICAL FORMATION in BBHs.
  - Due to **rapid circularization** → **eccentric effects** mostly in the **inspiral**.
    - QC MERGER-RINGDOWN in non-NR-calibrated models.
    - Recent progress in PN FORMALISM! (See Gonzalo's talk).
  - Newly **available IMR eccentric models**:
    - **EOB framework:** `TEOBResumS-Dali`, `SEOBNREHM`, `SEOBNRv4EHM`, `SEOBNRv5EHM`; **NR-Surrogates:** `NRSurEcc`, **Others:** `EN/SIGMA`, `EccentricIMR`.
    - **IMRPhenom family:** `IMRPhenomXE` (see Toni's talk), `IMRPhenomTEHM`.

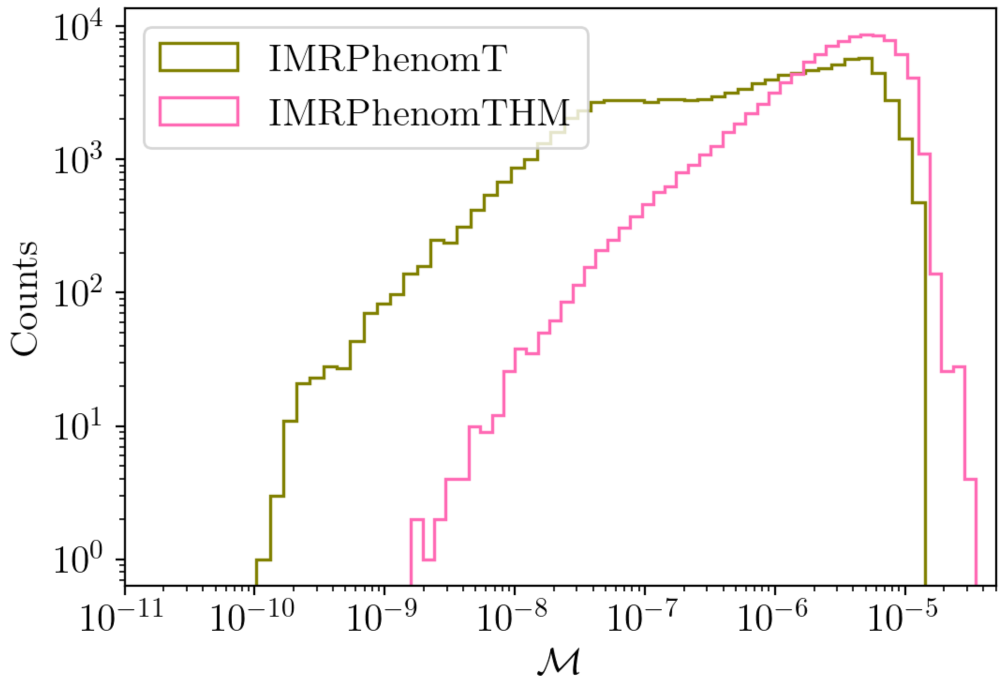


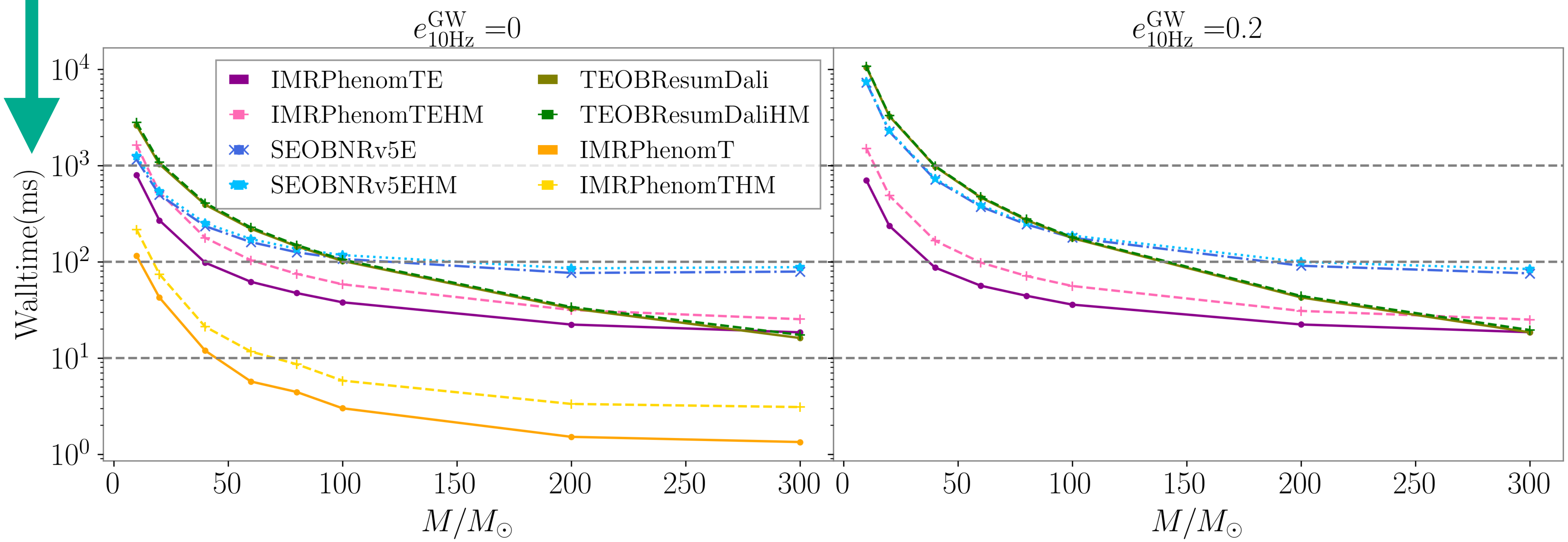


TIME DOMAIN MULTIPOLAR SPINNING ECCENTRIC WAVEFORMS $(q, \chi_1^L, \chi_2^L, e_{\rm ref}, l_{\rm ref})$, built on `IMRPhenomTHM` [Estellés+22], for $(l,|m|) = \{(2,|2|),(2,|1|),(3,|3|),(4,|4|),(5,|5|)\}$: `IMRPhenomTEHM` [Planas+25, 2503.1306].

Python IMPLEMENTATION in **phenomxpy** [García-Quirós+25].

- Smooth transition at $e \to 0$
- COVERAGE: $q \in [1,20]$, $|\chi_1| \leq 0.99$, $e_{10\rm Hz} \lesssim 0.4$ due to eccentricity expansions.
- Allows for $f_{\rm min} < f_{\rm ref}$.
- FAST CODE → enables large scale BBH PE analysis.





IMRPhenomTEHM: Construction

1. **Compute** the `IMRPhenomTHM` waveform ($e=0$).
2. **Solve** secular evolution equations for $x(t)=(GM\omega/c^3)^{2/3}$, $e_t(t)$, $l(t)$, $\lambda(t)$ in MH gauge up to merger.

$$
\begin{aligned}
\dot{x} &= \dot{x}^{\rm THM} + \delta\dot{x}_{e\neq 0} \\
\dot{e} &= \dot{e}^{\rm Newt} + \dot{e}^{\rm 1PN} + \dot{e}^{\rm 1.5PN} + \dot{e}^{\rm 2PN} + \dot{e}^{\rm 2.5PN}_{\rm SS} + \dot{e}^{\rm 3PN}_{\rm SS} + \dot{e}^{\rm 3PN}_{\rm inst} + \dot{e}^{\rm 3PN}_{\rm tail} \\
\dot{l} &= \dot{l}^{\rm Newt} + \dot{l}^{\rm 1PN} + \dot{l}^{\rm 1.5PN} + \dot{l}^{\rm 2PN}_{\rm inst} + \dot{l}^{\rm 2.5PN}_{\rm tail} + \dot{l}^{\rm 3PN}_{\rm SS} + \dot{l}^{\rm 3PN}_{\rm inst} \\
\dot{\lambda} &= x^{3/2}
\end{aligned}
$$

$$
\begin{aligned}
\delta\dot{x}_{e\neq 0} = {} & \delta\dot{x}^{\rm Newt}_{e\neq 0} + \delta\dot{x}^{\rm 1PN}_{e\neq 0} + \delta\dot{x}^{\rm 1.5PN}_{e\neq 0} + \delta\dot{x}^{\rm 2PN}_{e\neq 0} + \delta\dot{x}^{\rm 2.5PN,tail}_{e\neq 0} \\
& + \delta\dot{x}^{\rm 2.5PN,SS}_{e\neq 0} + \delta\dot{x}^{\rm 3PN}_{e\neq 0} + \delta\dot{x}^{\rm 3PN,SS}_{e\neq 0} + \delta\dot{x}^{\rm 3PN,tail}_{e\neq 0}
\end{aligned}
$$

3. **Obtain** $\omega_{22}^{\rm TEHM}$ and $2\psi_{\rm orb}^{\rm TEHM}$.
4. **Evaluate** $\tilde{h}_{lm}^{\rm THM}(x,e_t,l) = H_{lm}^{\rm THM}(x)e^{-i\cdot\psi_{lm}(x,e)}$.
5. **Evaluate** eccentric amplitude corrections $H_{lm}^{\rm PN,ecc}(x,l,e)$ and $W(l)$ up to merger in QK parametrization + modified harmonic (MH) PN gauge:
   - **Non-spinning PN Terms:** 3PN for (2,2), (2,1), (4,4), (5,5), and 2.5PN for (3,3).
     - Ebersold+19 ($H^{lm}_{\psi}(x,e,\xi) = H^{lm}_{\rm inst} + H^{lm}_{\rm hered} + H^{lm}_{\rm post-ad}$), $O(e^6)$).
   - **Spinning PN Terms (SO and SS):** 2PN for (2,2), (2,1), (3,3) and no spinning (4,4), (5,5).
     - Henry+23 ($H^{lm}_{\psi}(x,e,\xi) = H^{lm}_{\rm inst} + H^{lm}_{\rm tail} + H^{lm}_{\rm mem}$, $O(e^6)$).
6. **Obtain** PhenomTEHM modes

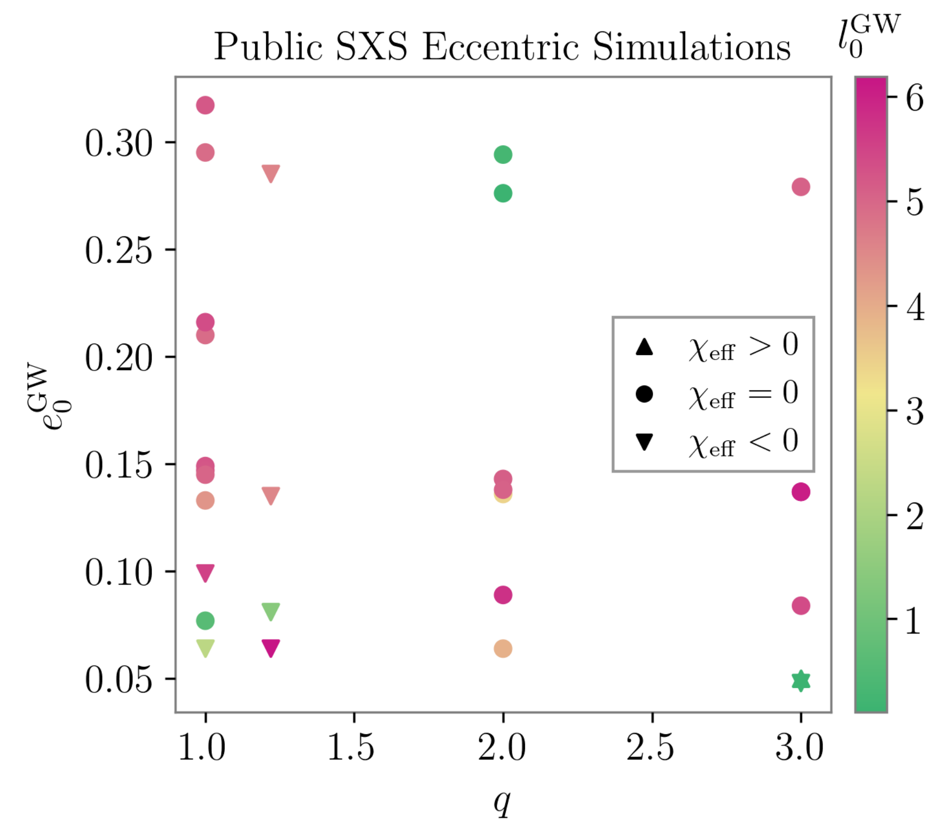
Oscillatory phase contribution (3PN $\mathcal{O}(e^{12})$)

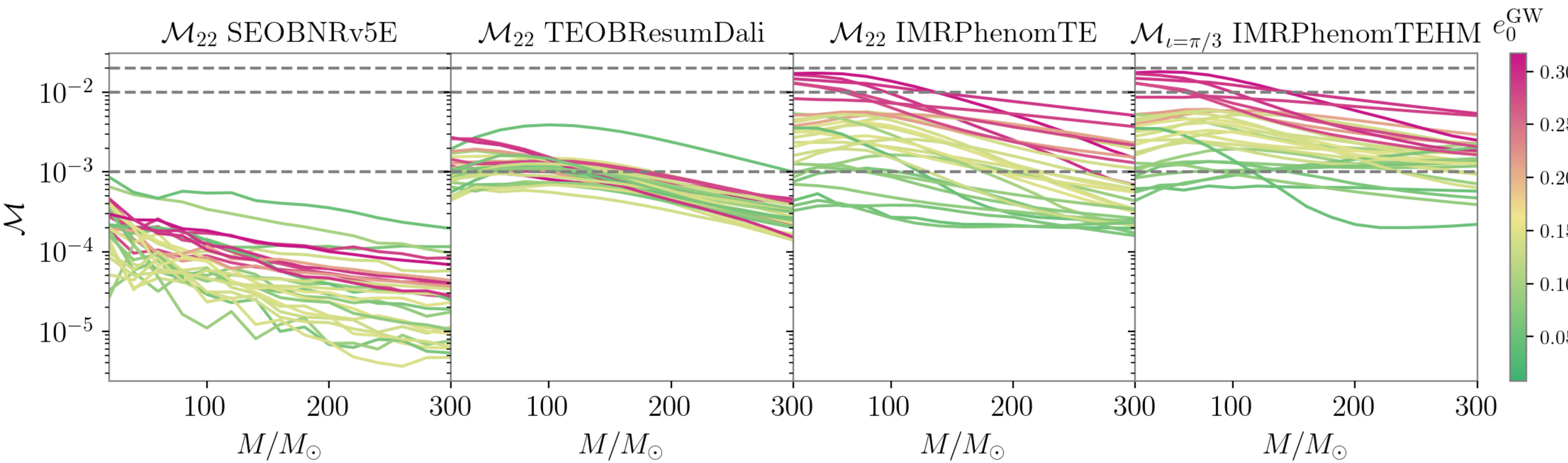
$$
h_{lm}^{\rm TEHM} = \left(\tilde{h}_{lm}^{\rm THM} + \frac{8GM\eta}{c^2R}\sqrt{\frac{\pi}{5}}\left[xH^{lm}(x,e,l) - x^{e=0}H^{lm}_{e=0}(x^{e=0})\right]e^{-im\lambda}\right)e^{-imW(l)}
$$

IMRPhenomTEHM: Results

Mismatches Against 28 public Eccentric NR SXS Simulations

- **Insignificant Degradation** when including higher modes (HMs).
- **Mismatches** below 2% for all cases (optimization over $e, l, f_{\text{min}} + \varphi$ if HMs).
- **Less accurate** than other models but much **more efficient**.
- **Further Validation** due to the limited coverage of NR simulations.
    - Parameter estimation (PE) studies.





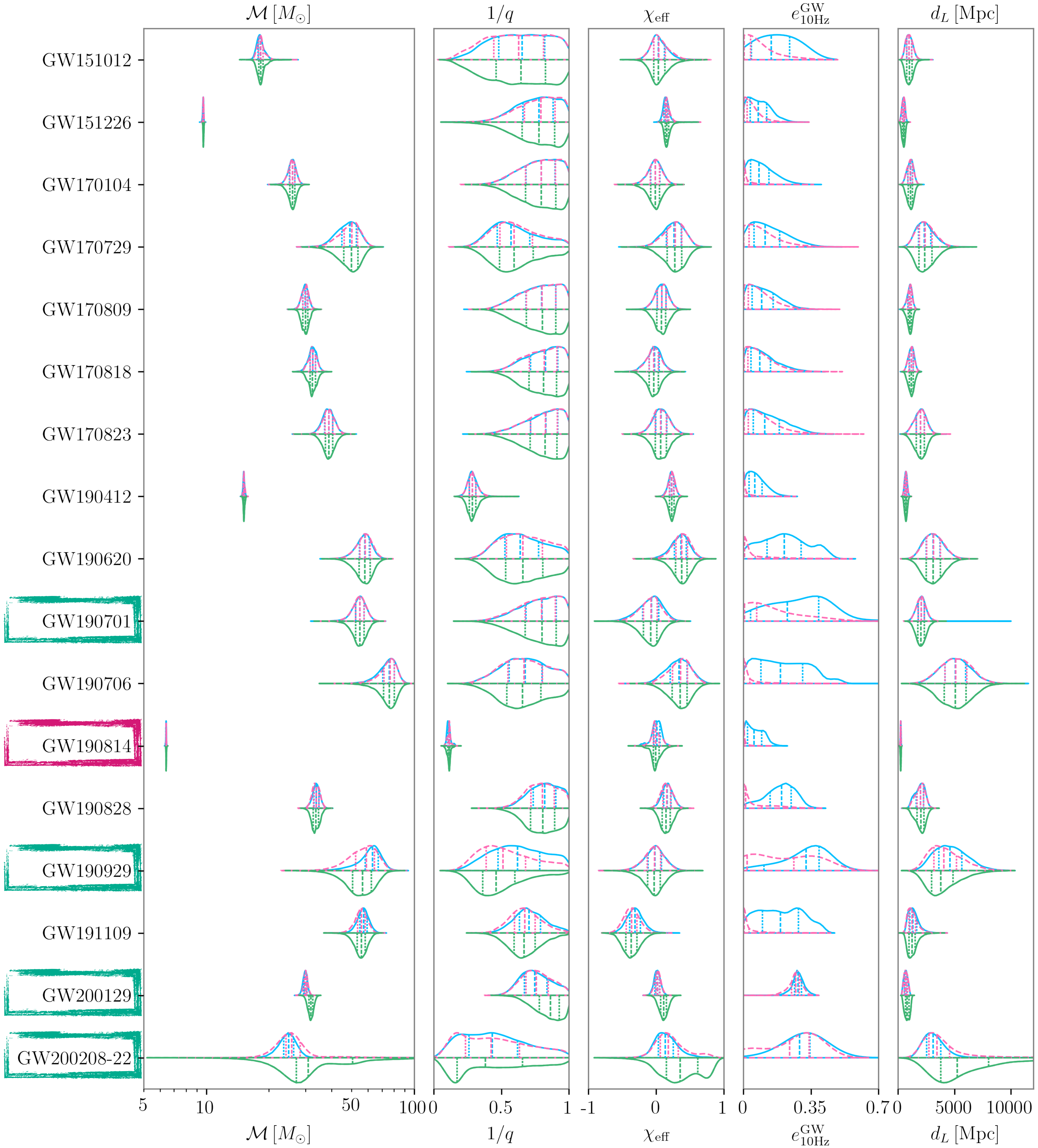
BBH Parameter estimation with IMRPhenomTEHM

Eccentric Analysis of 17 GW BBH events with IMRPhenomTEHM [Planas+25, 2504.1583].

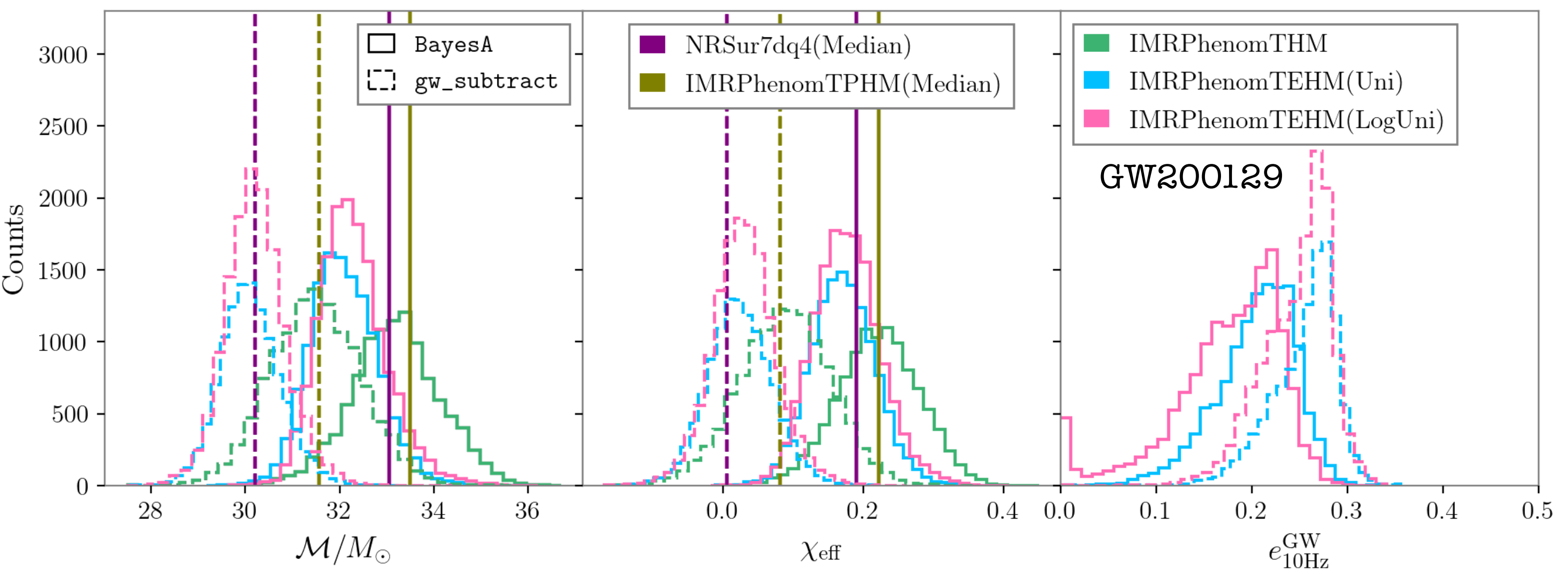
- Standard PE pipelines for QC models (Bilby, bilby_pipe, dynesty).
- QC: THM (green) + Two eccentric priors: Uniform (blue), LogUniform (pink).
- Signs of **eccentricity** in 4 events:
  - GW200129
  - GW200208_22
  - GW190701
  - GW190929
- First full IMR eccentric analysis of GW190814: (NS/B?)BH event.

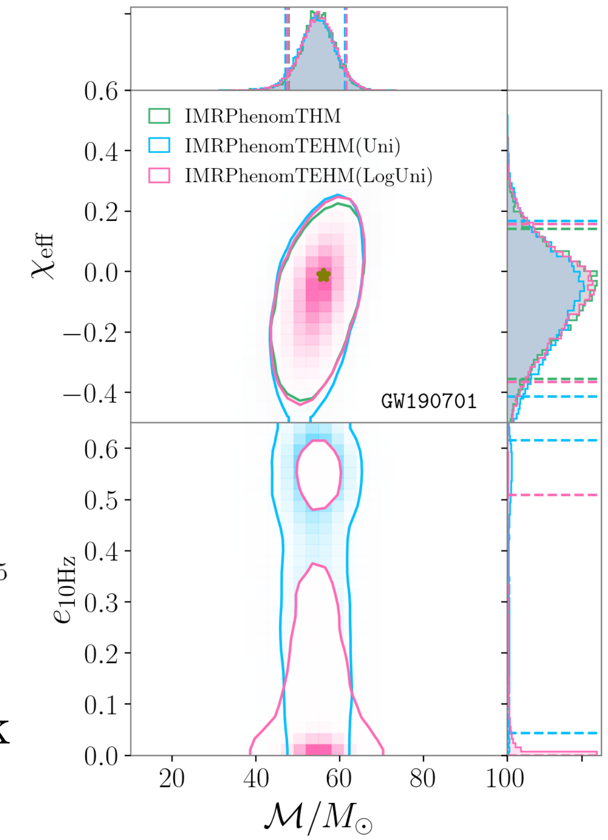
↓

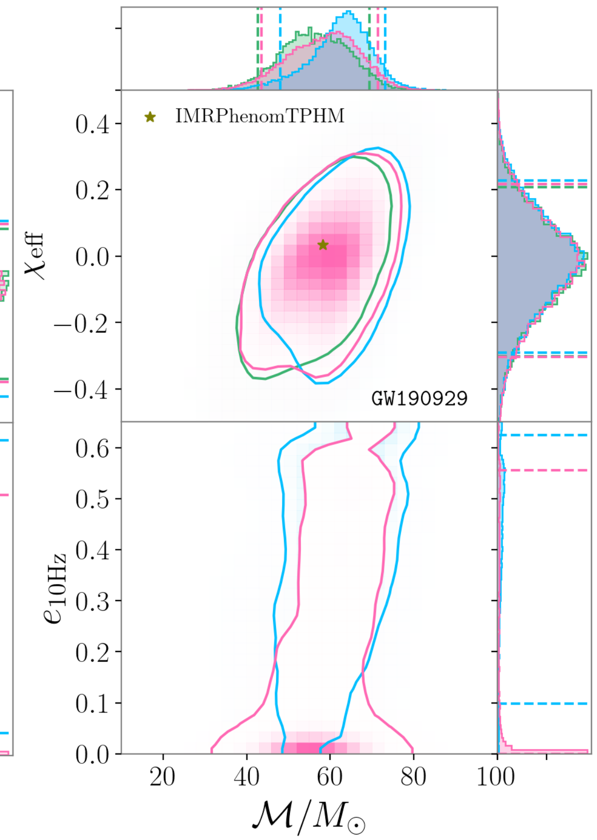
First IMR NSBH reanalysis



BBH Parameter estimation with IMRPhenomTEHM





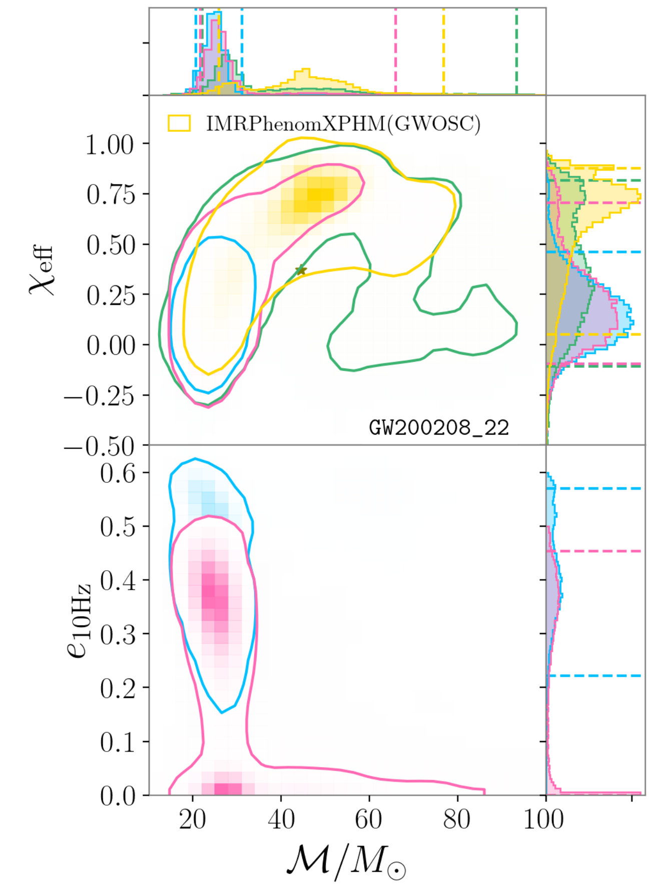


GW200129: **Dynamical formation hints**: precession, kick velocity, eccentricity… but **known glitch in L1**.

- Different Deglitching Methods: `gw_subtract`, `BayesWave(A,B,C)`
- e support for any deglitching procedure and prior: $\log_{10}\mathscr{B}^{\rm Uni}_{\rm E/QC} \in [1.86, 5.1]$; $\log_{10}\mathscr{B}^{\rm LogUni}_{\rm E/QC} \in [1.3, 4.2]$.

GW200208_22: **low SNR** event.

- Tested different PE resolutions.
- Marginal eccentric support: $\log_{10}\mathscr{B}_{\rm E/QC} \in [0.5, 1.1]$.



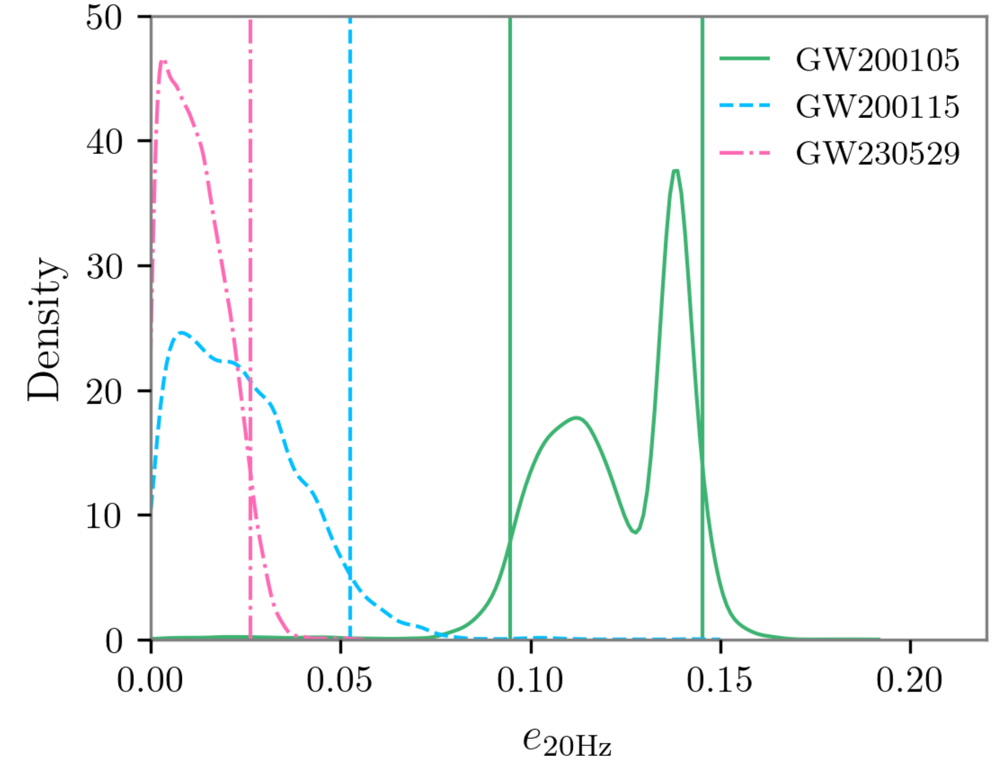
GW190701, GW190929: very **high mass events**.

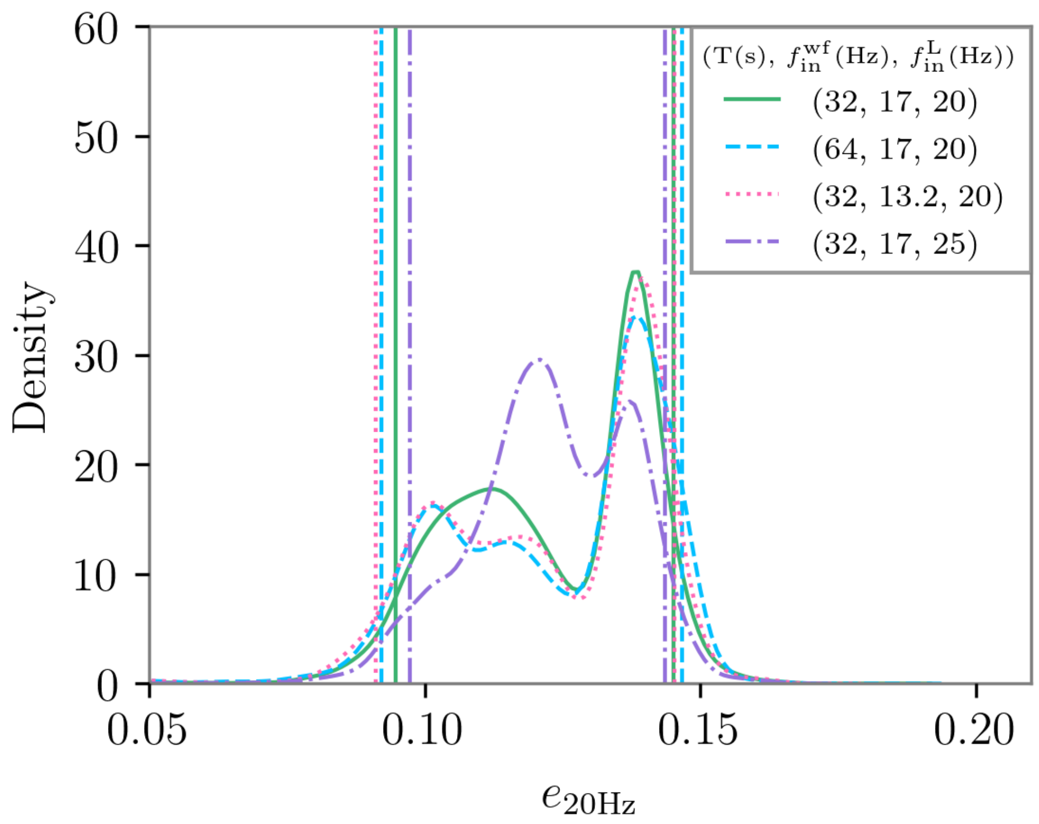
- Weak support for eccentricity: $\log_{10}\mathscr{B}_{\rm E/QC} > 0$.
- Breakdown of QC merger/ringdown approximation.

IMR Eccentric NSBH Analysis

Eccentric Analysis of the 3 confirmed NSBH GW events with `IMRPhenomTEHM` [Planas+25, 2506.01760].(GW191219 high q!)

- Standard PE techniques (Bilby, parallel_bilby, dynesty)
- First full **IMR eccentric analysis** of 3 NSBH events!
  - GW200105: confirms recent claims of eccentricity [Morras+25, 2503.1539] with a PN inspiral-only eccentric-precessing code [Morras+25, Phys. Rev. D 111].
  - GW200115 & GW230529: no eccentric support.
- **Further investigations** of GW200105: different **eccentric priors**, TD eccentric **waveform systematics**, and **data quality**.

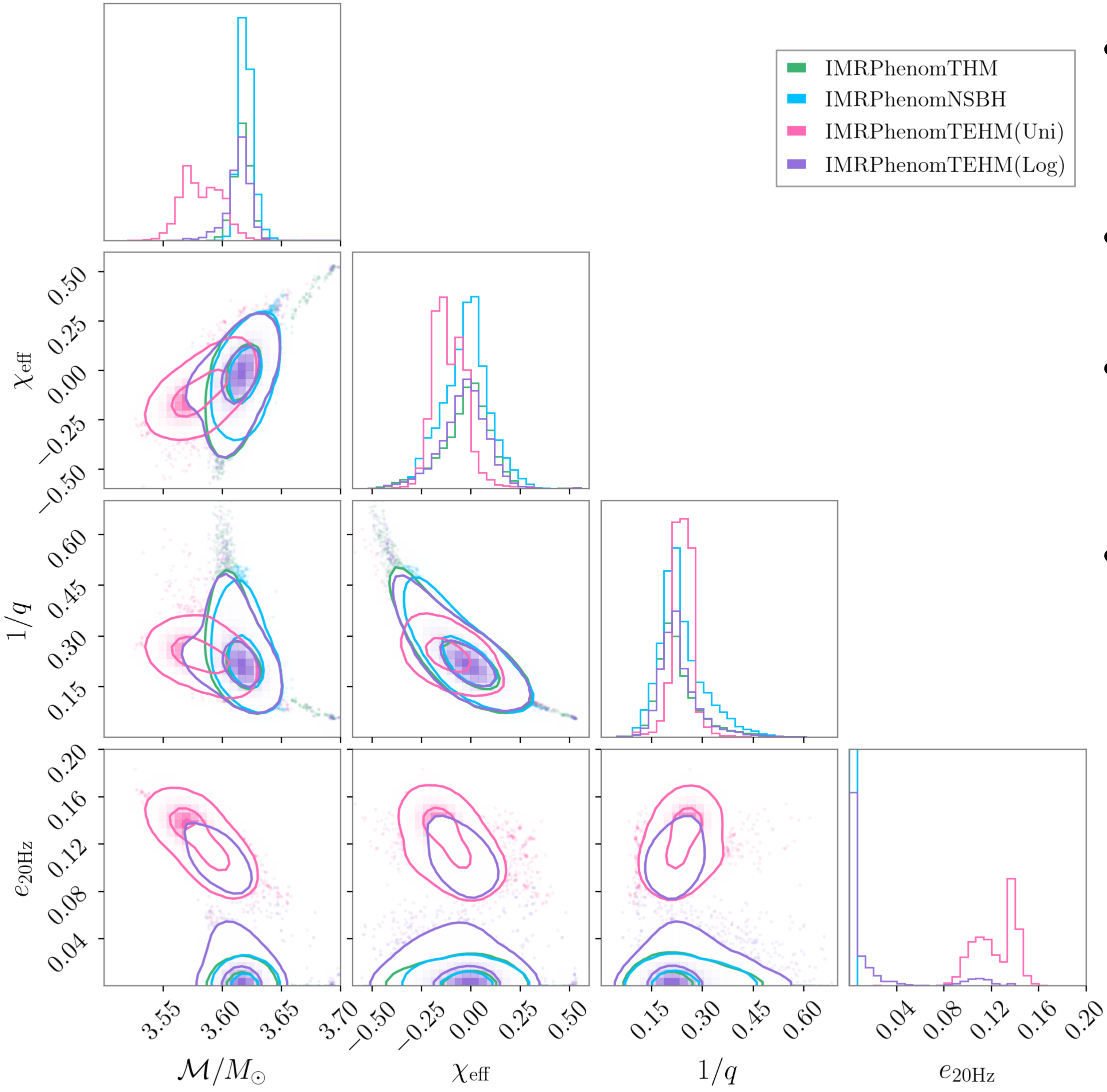




Same 90% CI of $e_{20\mathrm{Hz}} \sim 0.09 - 0.15$ vs $e_{20\mathrm{Hz}}^{\mathrm{pyEFPE}} = 0.048 - 0.152$.

- **Starting WF generation:** TD multipolar eccentric models are compositions of HMs and mean anomaly harmonics: extra conditioning required to have all modes in band at the start of likelihood (L) integration. For $l \leq 3$ modes, $f_{\mathrm{min}}^{\mathrm{wf}} = 13.3$ Hz.
- **Signal duration (D):** short signal durations → poor FD resolution at low frequencies: d$f = 1/D$ Hz.
- **Data Quality:** know scattered light below 25Hz for L1.

IMR Eccentric NSBH Analysis: GW200105



- `IMRPhenomTHM` recovers official analysis with `IMRPhenomNSBH`: **matter effects neglegible** due to high mass ratio.
- **Biases** in recovered parameters when neglecting eccentricity, mostly for **masses** and **spins**.
- **LogUniform prior** provides **support for eccentricity**, in contrast to what was found for [Morras+25, 2503.1539].
- **Bimodality found** in eccentricity (thus also masses and spins) for GW200105. Extra **investigations** required:
  - **Accumulation of likelihood and SNR** in frequency:
  - 20-30 Hz range: **negligible**.
  - Almost **saturation** at ~400 Hz.
  - The two waveforms are **different** originally($\mathscr{M} \sim 0.4$), but when projected into the detectors, $\mathscr{M} \sim 0.06$, and even lower when the integration starts later!

Conclusions

We present the first IMR eccentric analysis of BBH & NSBH events with IMRPhenomTEHM.

- state-of-the-art TD phenomenological waveform model for aligned-spin binaries in eccentric orbits.
    - Coded up in the new phenomxpy[García-Quirós+25] python package.
        - Extremely efficient: only 2-5 times slower than IMRPhenomTHM.
        - Internal code review to start soon → Code publication.
    - Coverage: $q \in [1,20], |\chi_1| \leq 0.99$, $e_{10\text{Hz}} \lesssim 0.4$ due to eccentricity expansions.
        - Robustness tested against NR + SEOBNRv5EHM + PE studies.
- Analysis performed with standard PE CBC pipelines → Most Efficient IMR Eccentric model to Date!
- GW200129 & GW200105 show signs of eccentricity, supported across different models, data variations and samplers.
        - Both GW200105 & GW200129 are glitched events... Casuality?
- Found some Waveform & Data Systematics ($f_{\text{min}}^{\text{wf}}$, D, f_{min}^{L}) affecting eccentric PE analysis.
    - Higher impact in the early inspiral: low-mass events!
    - GW200105: bimodal structure within same Credible Interval (indifferent for the eccentricity observation), but extra Caution Might be needed for eccentric analysis.
- Next steps:
    - Incorporation of (2,0) mode into IMRPhenomTEHM (see [Rosselló+24] and Maria's talk!).
    - Development of IMRPhenomTPEHM.

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