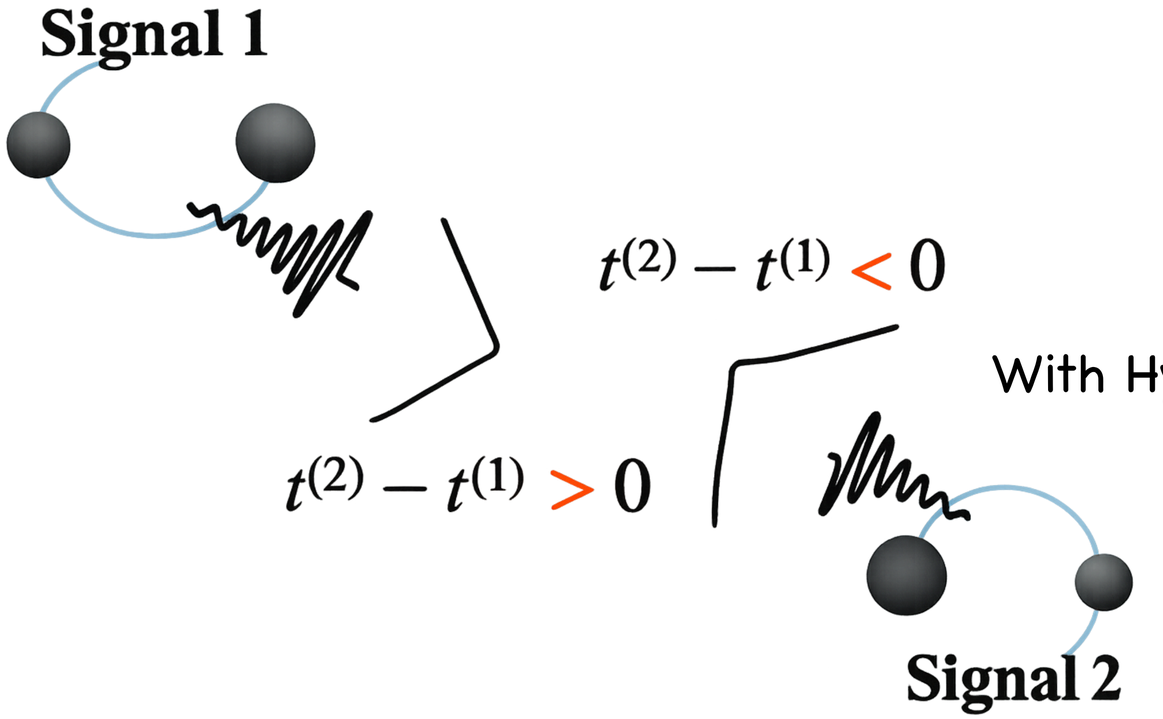
Overlapping Gravitational-Wave Signals: Parameter-Estimation Biases in the LVK Era and Implications for 3G Detectors



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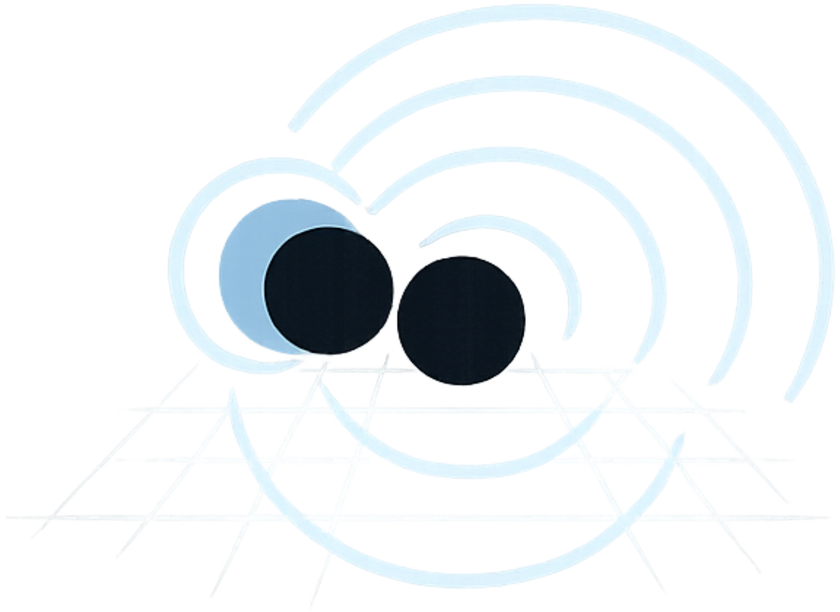
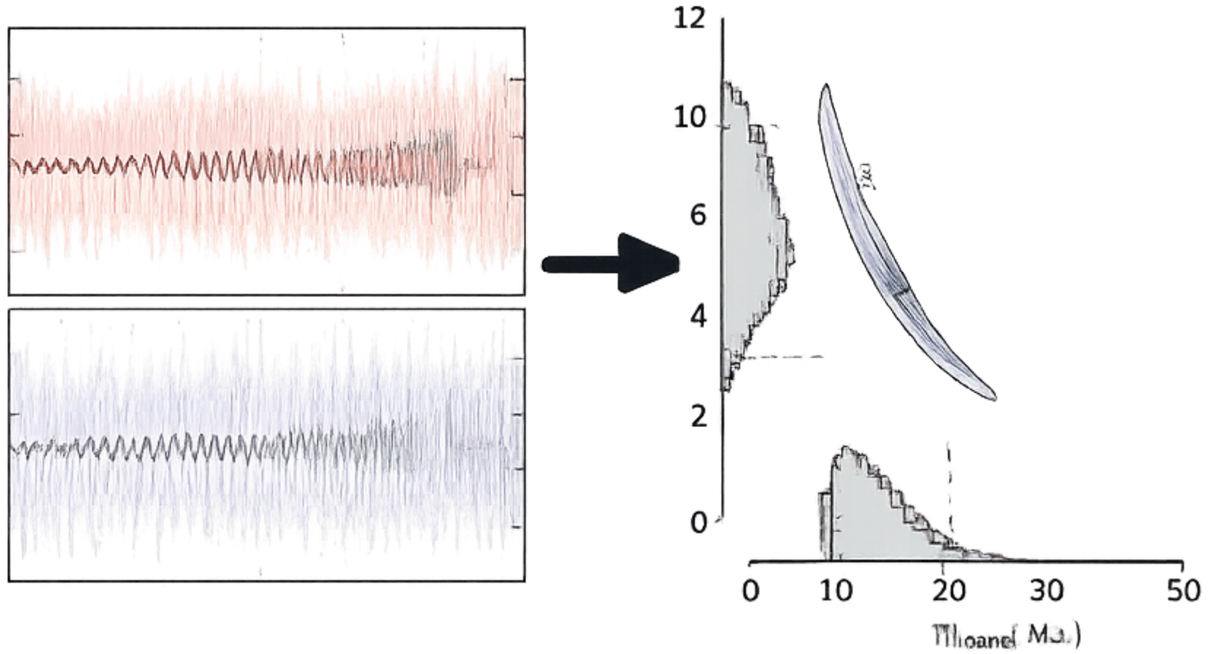
With Hyung Won Lee (Inje U.) and Young-min Kim (KASI)

2025.11.21 KSHEP Fall Meeting @CNU

Gravitational Waves and Parameter Estimation



COMPACT BINARY COALESCENCE



Why study parameter-estimation biases from overlapping GW signals?

- Although no CBC–CBC overlaps (within 100 ms–a few seconds) have been confirmed in O3–O4 LVK catalogs, overlapping scenarios remain physically possible.
- Simulation and injection studies show that overlapping CBC signals can cause strong parameter-estimation biases in mass, distance, spins, and merger time.
- Real LVK data already contain CBC–glitch overlaps, demonstrating that overlapping structures can occur and can significantly bias PE if not modeled. (S. Hourihane et al., Phys. Rev. D 106, 042006 (2022))

When Do Overlapping GW Signals Occur?

- Temporal Overlap
  - Two CBCs arrive within ~10–1000 ms (BBH inside BNS/BHNS inspiral).
- Frequency Similarity
  - Similar masses/chirp masses → similar df/dt → harder to separate.
- Geometric Alignment
  - Similar sky location & polarization → nearly identical detector response.
- SNR Contrast
  - loud signal masks or biases weaker one.
- 3G Detectors
  - Longer duration + higher event rate → overlaps become inevitable.

Research Goals

- Quantify PE biases from overlapping CBCs using single-signal injection simulations.
- Identify overlap-induced spectral signatures in the frequency domain.
- Evaluate the impact on LVK single-signal PE pipelines.
- Define requirements for overlapping-aware PE methods for 3G detectors.
- Extend diagnostics to real O3/O4 LVK data (future work).

Frequency-domain effects from overlapping CBC signals

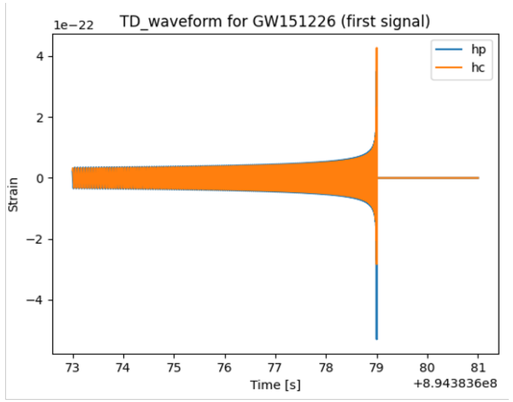
- Time-offset overlap produces interference in the Fourier domain.
- Overlap modifies spectral features: peak shift, broadening, ripples.
- Explained by the relations: $\tilde{h}(f) = \tilde{h}_1(f) + \tilde{h}_2(f)\, e^{-2\pi i f \Delta t}$

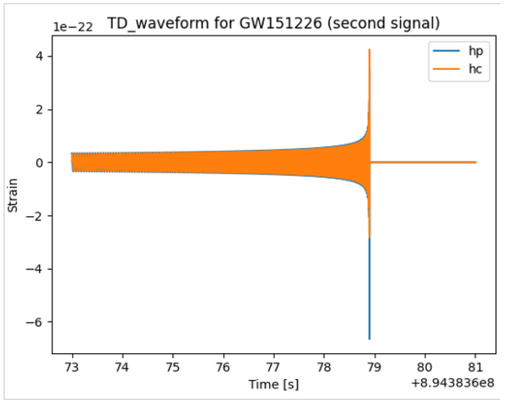
$$|\tilde{h}(f)|^2 = |\tilde{h}_1(f)|^2 + |\tilde{h}_2(f)|^2 + 2\,\mathrm{Re}\left[\tilde{h}_1(f)\,\tilde{h}_2^*(f)\, e^{-2\pi i f \Delta t}\right]$$

- Leads to biases in chirp mass, spin, and coalescence time in single-signal PE.
- These distortions match earlier findings (Relton & Raymond 2021; Samajdar 2021; Pizzati 2022).

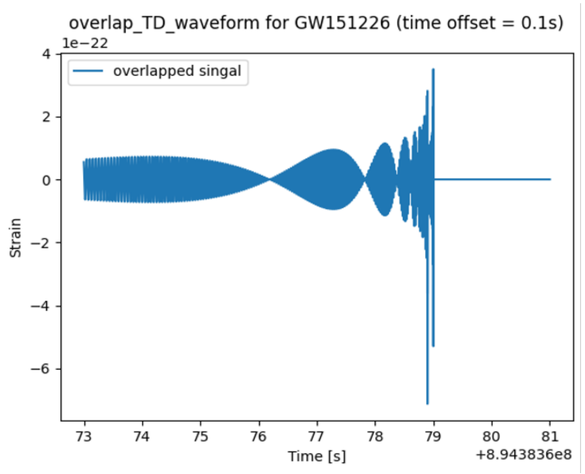
Frequency-domain effects from overlapping CBC signals

- Overlapped FFT shows peak shifts, interference-induced ripples, and spectral broadening, consistent with literature.

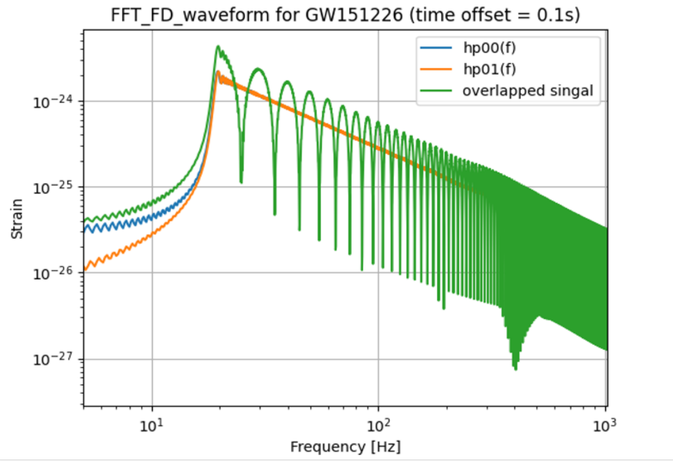




overlapping



FFT

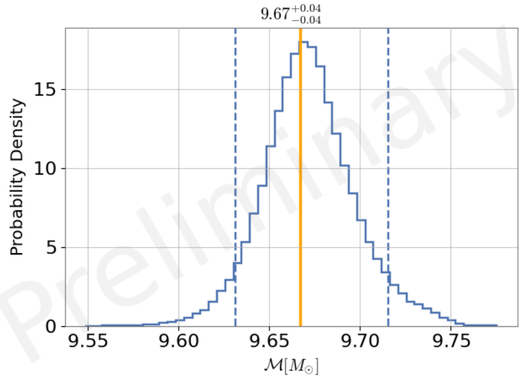


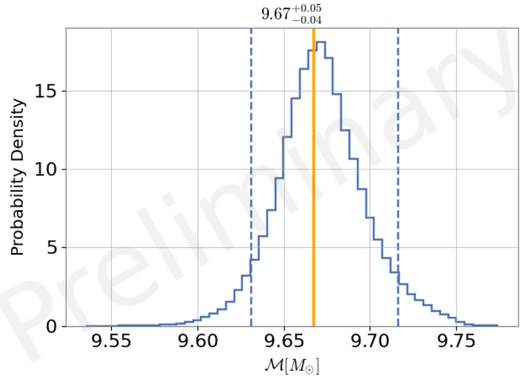
Simulation Setups

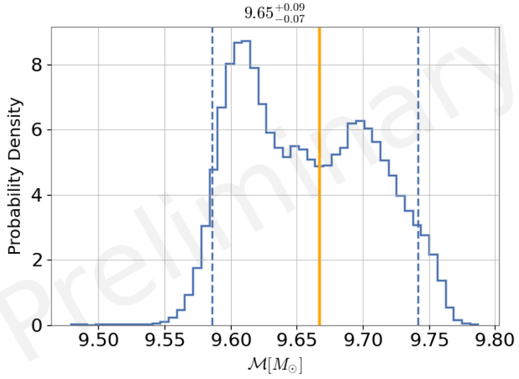
- Target events: GW150914-like (high-mass BBH) & GW151226-like (lower-mass BBH)
- Two-signal configuration:
  - Signal 1 & Signal 2 with controlled differences in coalescence time (Δ t), luminosity distance, sky location
  - Injected overlap levels explored
- Waveform models:
  - TaylorF2 (TF2) – inspiral-only PN model
  - IMRPhenomD – full IMR aligned-spin model
- Detector sensitivity:
  - aLIGO + AdV (O3/O4-like) PSDs
  - Zero-noise injections for clean frequency-domain comparison
- SNR settings:
  - Network SNR tuned to ~20 per overlap configuration

Injection Simulation Results - Chirp mass bias

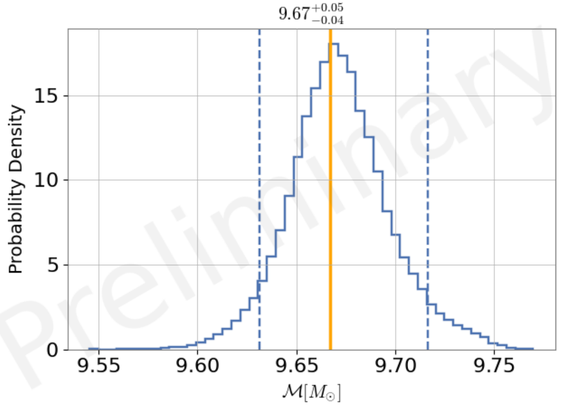
GW151226-TF2-time(0.1s)

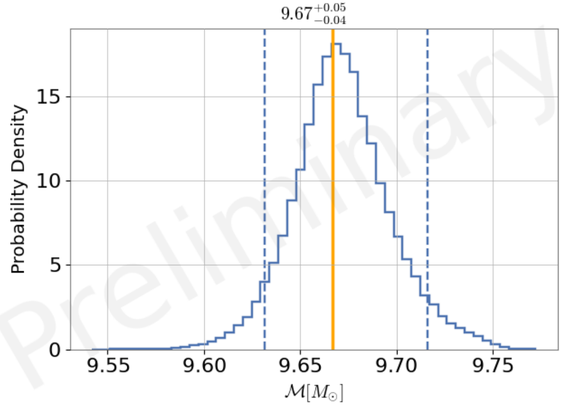


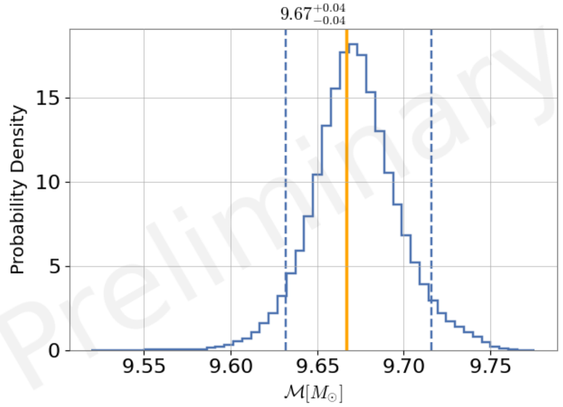




GW151226-TF2-time(2.0s)



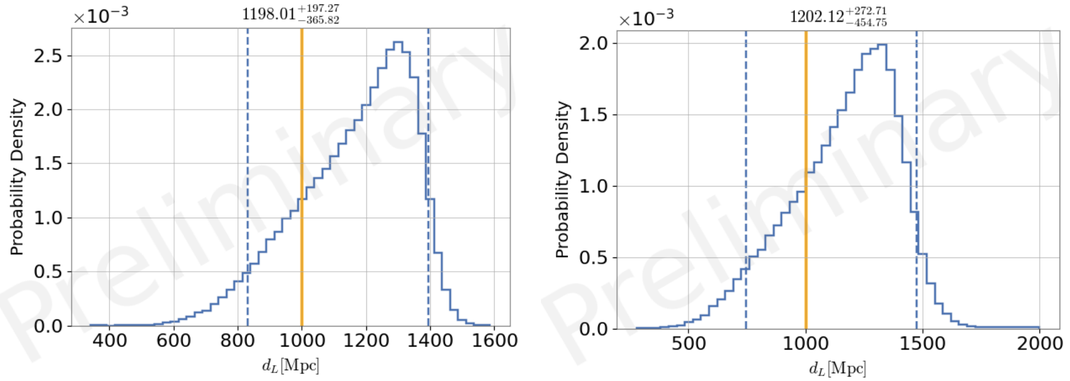


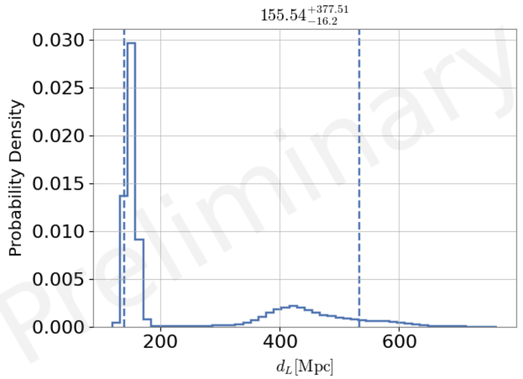


- When $\Delta t(c) < 0.1$ s, the posterior shifts significantly, producing noticeable chirp-mass bias.
- Most severe when both signals have similar masses → strong spectral blending and PE confusion.

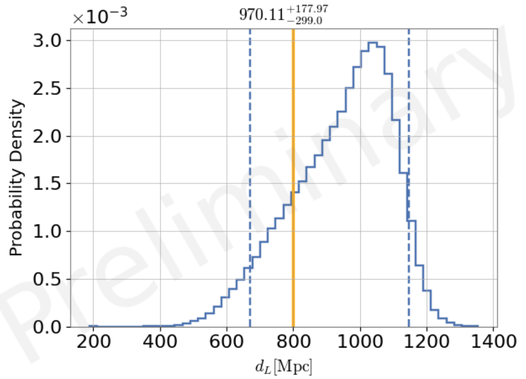
Injection Simulation Results - Distance Bias

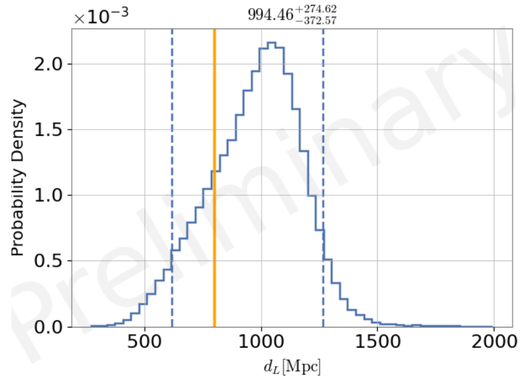
GW150914-TF2-Loc-R.A

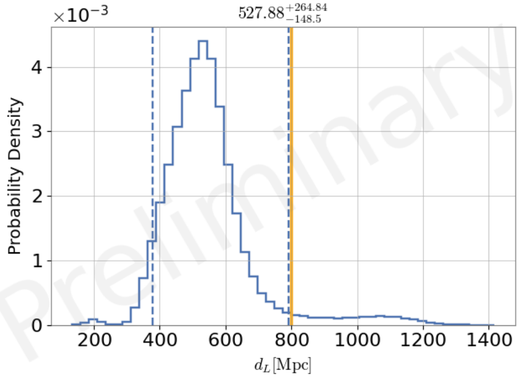




GW151226-TF2-Loc-R.A







- Overlapping signals artificially increase or decrease the observed amplitude → systematic errors in luminosity distance.

Diagnostics for Identifying Overlapping GW Signals

- Frequency-domain distortion : Peak shift, ripples, spectral broadening
- Posterior anomalies : Multimodal or biased posteriors
- **Bayes-factor test** : $\ln K = \ln Z_{2\ \mathrm{sig}} - \ln Z_{1\ \mathrm{sig}}$
- **Residual structure** : Chirp-like patterns in $r(f) = d(f) - h_{1\mathrm{sig}}(f)$
- Detector inconsistency : H1/L1/V1 PE mismatch
- Time-frequency features : Double chirp tracks or excess power

Future Outlook — Overlapping Signals in 3G Detectors

- Higher sensitivity $\longrightarrow$ 10^5–10^6 CBCs/yr $\longrightarrow$ frequent overlaps.
- 1–2 Hz sensitivity $\longrightarrow$ hours-long BNS signals $\longrightarrow$ overlaps become the default.
- Severe FD blending $\longrightarrow$ single-signal templates fail.
- PE biases amplified; spurious spin/precession more likely.
- Need overlapping-aware PE: multi-signal PE, hierarchical subtraction, ML-based separation.

Conclusion

- Higher sensitivity $\longrightarrow$ 10^5–10^6 CBCs/yr $\longrightarrow$ frequent overlaps.
- 1–2 Hz sensitivity $\longrightarrow$ hours-long BNS signals $\longrightarrow$ overlaps become the default.
- Severe FD blending $\longrightarrow$ single-signal templates fail.
- PE biases amplified; spurious spin/precession more likely.
- Need overlapping-aware PE: multi-signal PE, hierarchical subtraction, ML-based separation.

Next Steps

- Apply diagnostics to real O3/O4 LVK data.
- Test robustness under real detector noise.
- Identify high-trigger-density segments.
- Develop overlap-aware PE strategies.

PE highlight

GWTC-4 Production Team

GWTC-4 Production Team

IMRPhenomXPHM-SpinTaylor

SEOBNRv5PHM

NRSur7dq4

IMRPhenomXO4a

Daniel Williams 4:06 PM

Hi everyone, just an update that GWTC-4.0 hit the arxiv today with your results in it!
https://arxiv.org/abs/2508.18082

I'm very proud of everything we did to put this together; this was an excellent team-effort, and you all should be proud of it. The paper is currently going through final circulation, so the full authorlist will appear on the version which is submitted to the journal next week.

7 8 5 1

Eccentricity PE Task Force

Eccentricity PE Task Force

- The Eccentric PE Task Force has been set up to propose, develop and perform review tests for eccentric PE, with a view to including eccentric analyses in future LVK catalogues.

Eccentric PE Task Force members and roles

Last edited by **Isobel Romero-Shaw** 3 weeks ago

- Isobel Romero-Shaw - lead
- Teagan Clarke - deputy lead
- Md Arif Shaikh - gw-eccentricity expert
- Gayathri Vivekananthaswamy - populations and burst expert
- Anuradha Gupta - general review, TGR expert

Waveform experts:

- Aldo Javier Gamboa Castillo - SEOB
- Danilo Chiaramello - TEOB
- Lluc Planas - Phenom

Analysis pipeline experts:

- Nihar Gupte - DINGO
- Aditya Vijaykumar - BILBY
- Jake Lange - RIFT

Analysts:

- Ben Patterson
- Snehal Tibrewal
- Alice Bonino
- Shubhagata Bhaumik
- JeongCho Kim

감사합니다.