Forecasting detections of gravitational-wave tails from LIGO data

PPC 2022

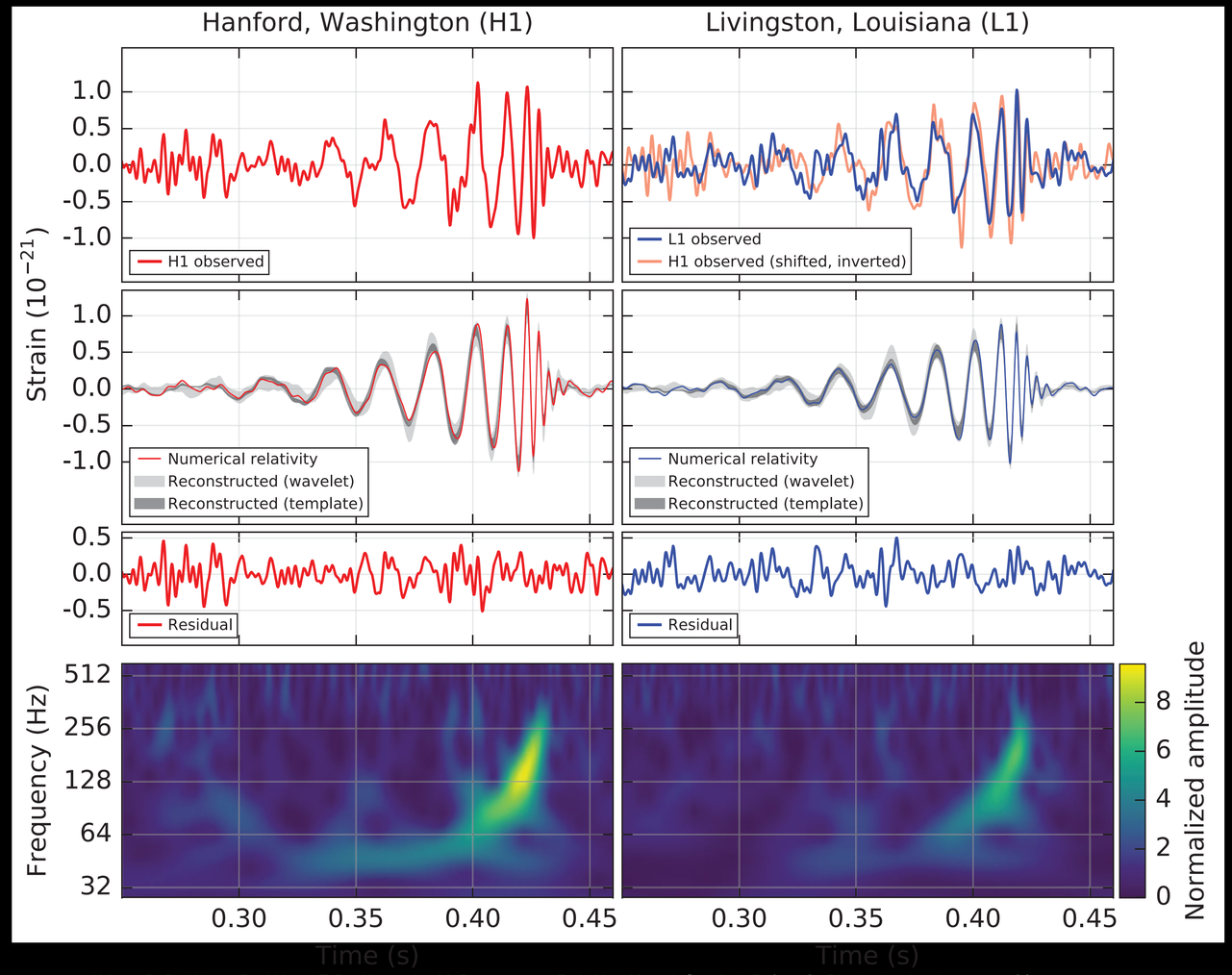
Matthew Carney

Collaborators: Jeremy Baier, Les Wade, Maddie Wade, Glenn Starkmann, Craig Copi, Jim Mertens

Washington University in St. Louis

The search for GWs

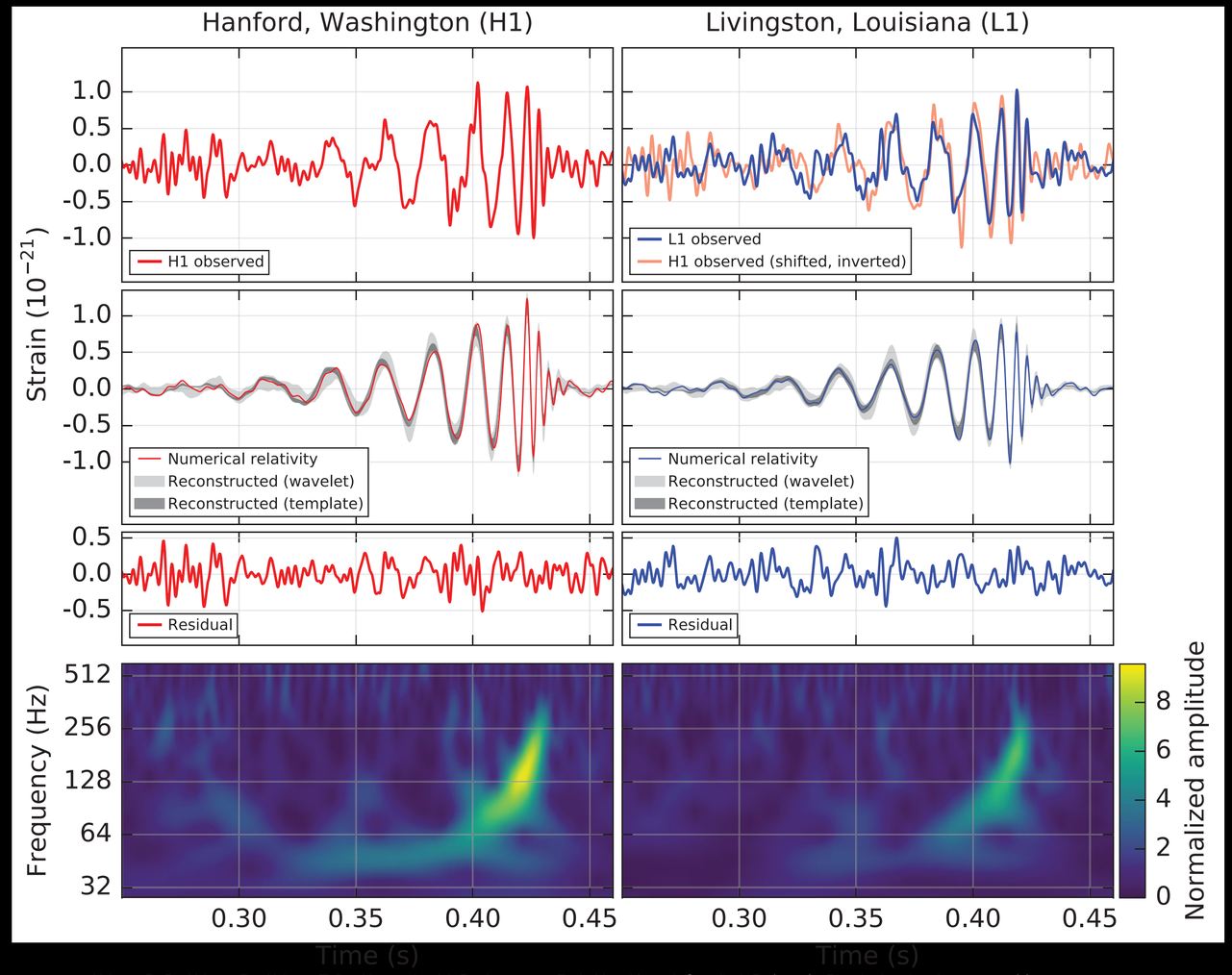
- 9/15/14 - First confirmed detection of GW's from binary black hole (BBH) merger
- Represents two major breakthroughs:
  - New form of "astronomy"
  - New tests of fundamental gravitational effects



Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & Cavalieri, R. (2016). Physical review letters, 116(6), 061102.

The search for GWs

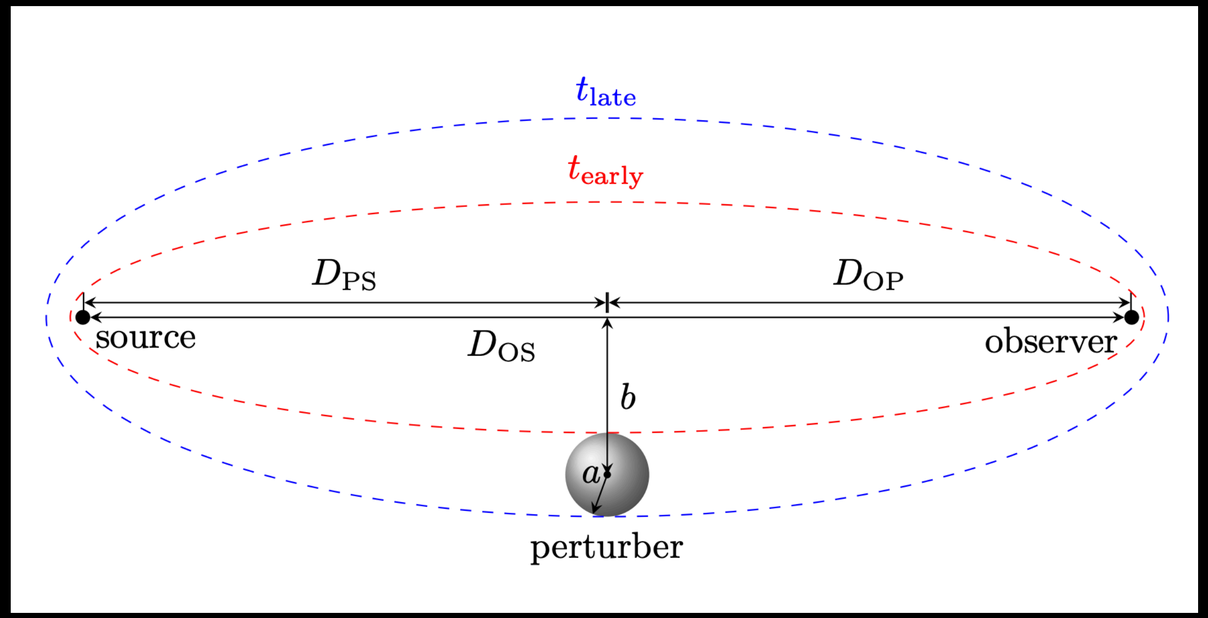
- 9/15/14 - First confirmed detection of GW's from binary black hole (BBH) merger
- Represents two major breakthroughs:
  - New form of "astronomy"
  - New tests of fundamental gravitational effects



Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & Cavalieri, R. (2016). Physical review letters, 116(6), 061102.

Gravitational Glint

- Similar to lensing
- Predicted “tails” of gravitational wave signals
- Near-identical (scaled) signal at a later time
- Dependent on geometry of system, n_E, and mass of perturber, M_P



Copi, C., & Starkman, G. D. (2022). arXiv preprint arXiv:2201.03684.

$$n_E \equiv \sqrt{\frac{4G_N M_P}{c^2}\frac{D_{OP}D_{PS}}{D_{OS}}}$$

Gravitational Glint

- Total strain will be original signal + echo

$$h(t) = h_s(t) + \epsilon h_s(t - \Delta t)$$

- Adds a phase factor in frequency space

$$\tilde{h}(f) = \tilde{h}_s(f)(1 + \epsilon e^{-2\pi f \Delta t})$$

- Where $\tilde{h}_s(f) = \mathcal{F}\{h_s(t)\}$ is the Fourier transform of the original signal
- Want to constrain the two parameters $\{\epsilon, \Delta t\}$
  - related to the system's geometry and perturber mass

Gravitational Glint

Eventually,

$$\{\epsilon, \Delta t\} \rightarrow \{M_P, n_E\}$$

- Total strain will be original signal + echo

$$h(t) = h_s(t) + \epsilon h_s(t - \Delta t)$$

- Adds a phase factor in frequency space

$$\tilde{h}(f) = \tilde{h}_s(f)(1 + \epsilon e^{-2\pi f \Delta t})$$

- Where $\tilde{h}_s(f) = \mathcal{F}\{h_s(t)\}$ is the Fourier transform of the original signal
- Want to constrain the two parameters $\{\epsilon, \Delta t\}$
  - related to the system's geometry and perturber mass

Parameter Estimation

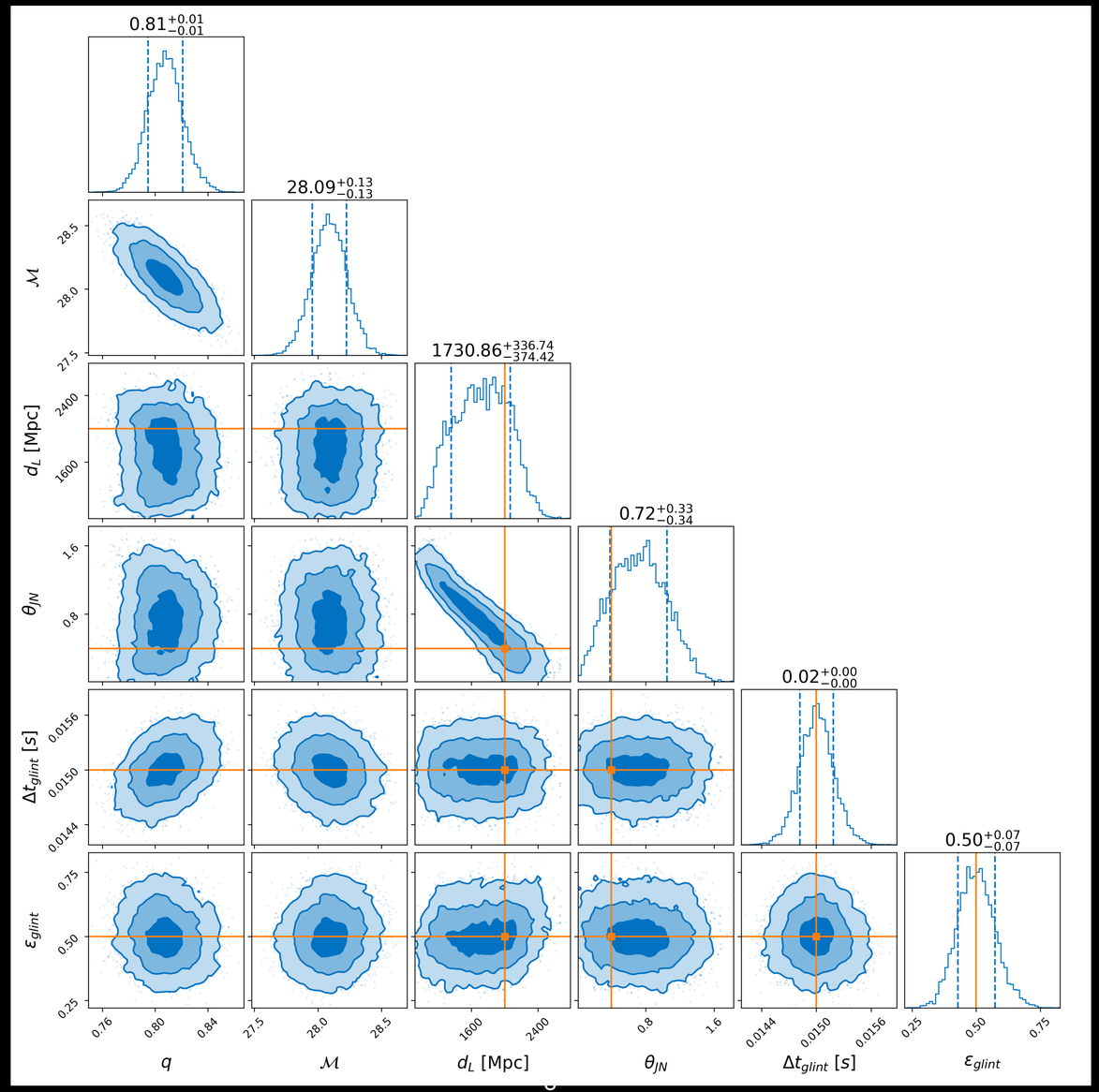
- High-dimensional parameter space
  - 16+ independent parameters
- Markov-chain Monte Carlo and nested sampling algorithms
  - Samples Bayesian *posterior* distribution (and evidence)
- Modified to include effect of a generic echo signal characterized by amplitude and time shift, $\{\epsilon, \Delta t\}$

Ashton, G., Hübner, M., Lasky, P. D., Talbot, C., Ackley, K., Biscoveanu, S., ... & Thrane, E. (2019). The Astrophysical Journal Supplement Series, 241(2), 27.

Simulated results: fiducial BBH, restricted

$\epsilon_{glint} = 0.5$

$\Delta t_{glint} = 0.015$



Simulated results

Bayes factors = (Evidence with echo recovery) / (Evidence without echo recovery)						
	0.01	0.2	0.4	0.6	0.8	1
0.00375	-2.638	-2.827	2.008	21.49	47.977	80.561
0.0075	-2.484	-2.555	2.758	21.223	46.689	82.01
0.015	-2.681	-2.513	5.555	27.358	57.232	89.392
0.5	-2.563	-2.303	6.774	27.625	60.51	100.067
1	-2.794	-2.742	7.105	28.4	60.621	100.192
			Key			
-5	-3	-1	0	1	3	5
Very Strong	Strong	Positive		Positive	Strong	Very Strong

Simulated results: fine tuning

- Finer search for turn-over point
  - Fix $\Delta t = 0.015s$
  - Smaller increments in ϵ

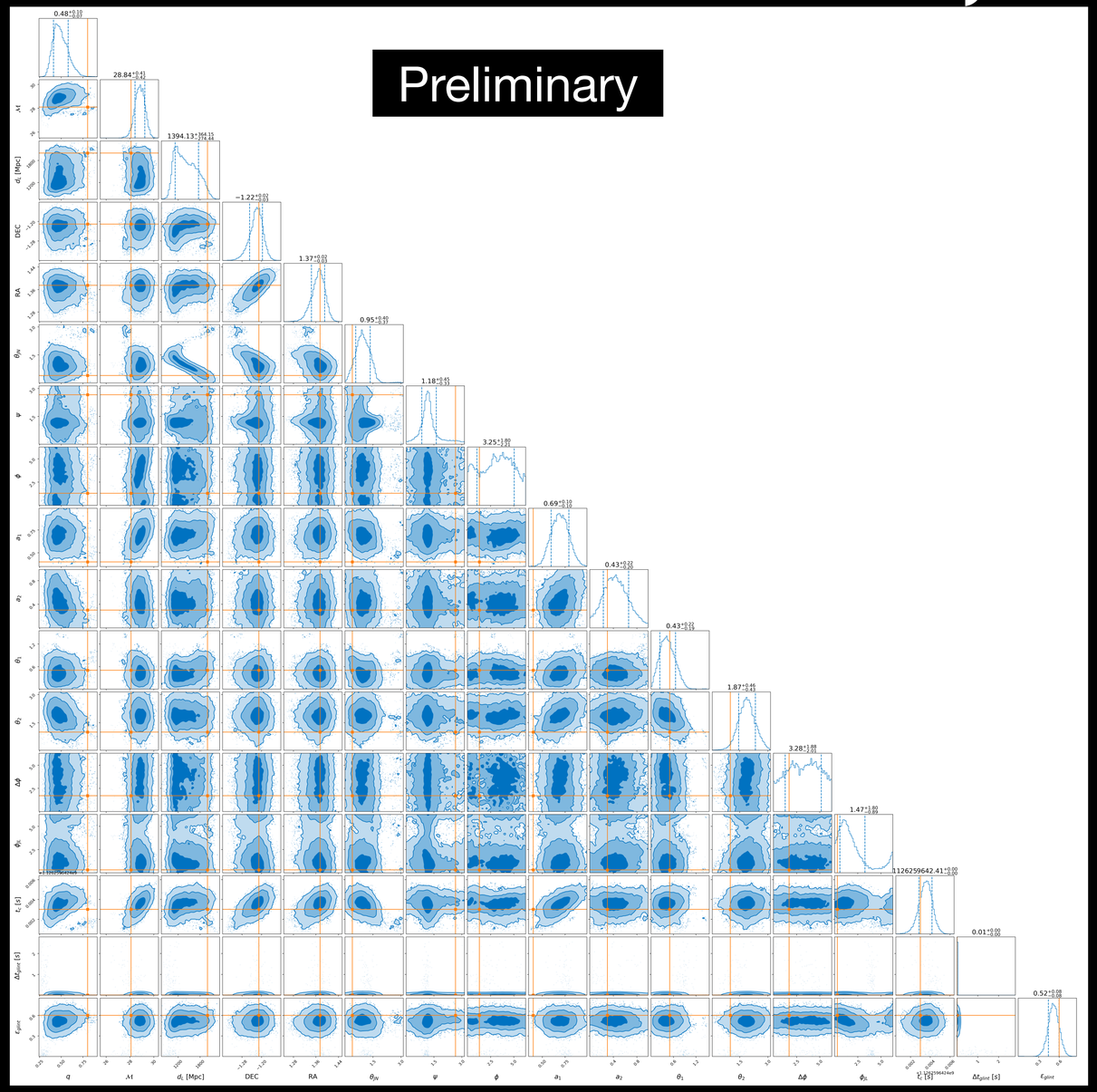
	Fine combing runs, dt=0.015s
0.218	-2.535
0.236	-2.39
0.254	-2.238
0.272	-1.876
0.29	-1.448
0.309	-0.119
0.327	0.699
0.345	1.948
0.363	3.714
0.381	4.645

Glint model becomes preferred at $\epsilon \approx 3.1$

Simulated results: fiducial BBH, restricted

$\epsilon_{glint} = 0.6$

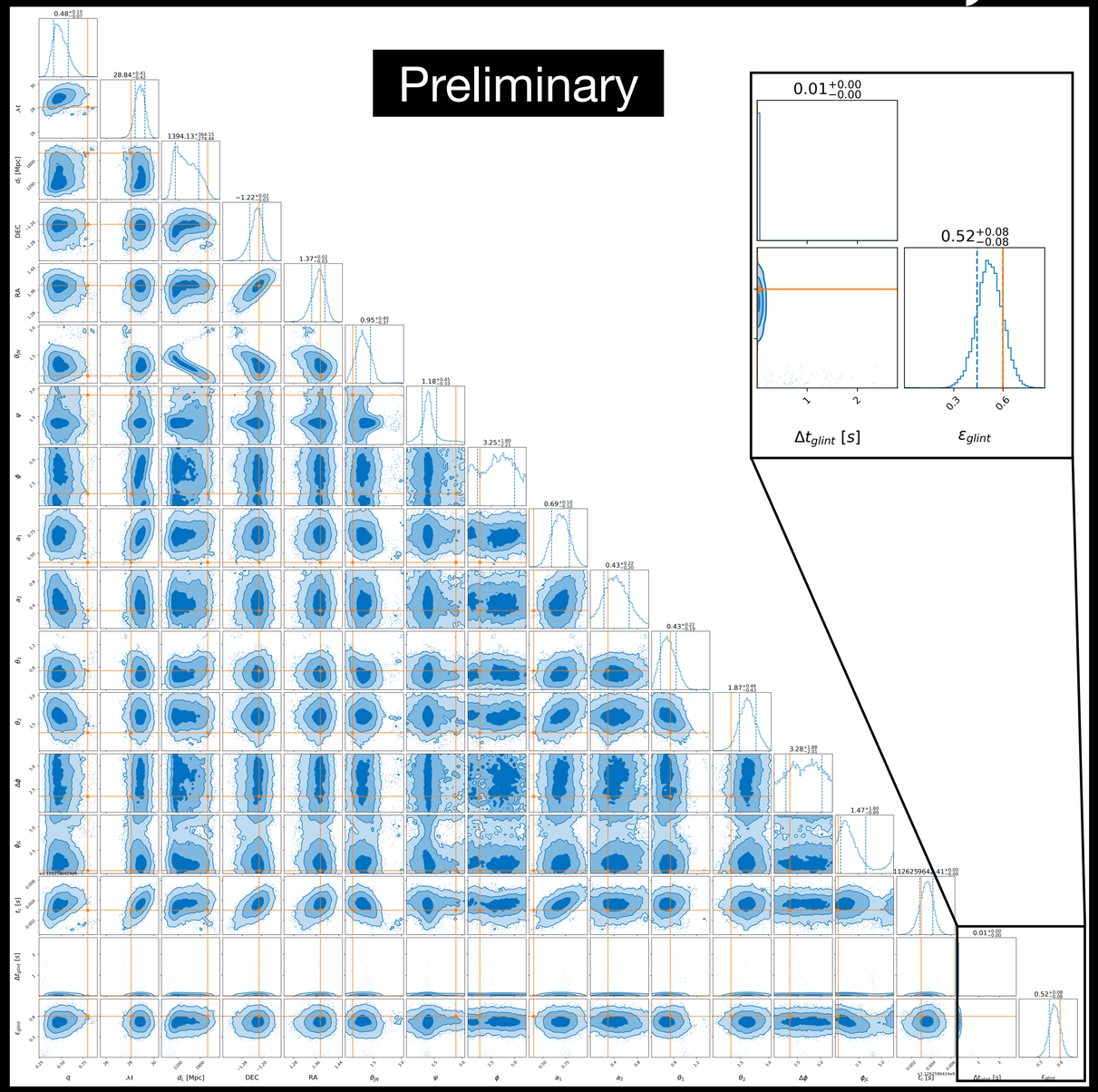
$\Delta t_{glint} = 0.005$



Simulated results: fiducial BBH, restricted

$\epsilon_{glint} = 0.6$

$\Delta t_{glint} = 0.005$



$$\ln \frac{Z_{glint}}{Z_{std}} \approx 4.336$$

Conclusions

- GW astronomy provides direct probe of new gravitational effects
  - Gravitational glint effect produces a near-identical signal
  - Potentially present in existing LIGO/Virgo data
- Addition of Glint parameters improves Bayesian evidence in injection study for reduced-dimensionality model
  - Preliminary results show improved evidence for full parameter-space model
- Analysis of LIGO/Virgo data coming soon