GW190521: a binary black hole merger inside an active galactic nucleus?

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Background

- May 21 2019: LIGO and Virgo detect the gravitational wave (GW) event GW190521; a Binary Black Hole (BBH) merger between a 85 solar mass and 66 solar mass black hole.

- Approximately 34 days after GW190521, the Zwuicky Transient Facility (ZTF) observed ZTF19abanrhr; a flare in an Active Galactic Nucleus (AGN) near the GW event.

Background

- The AGN (AGN J124942.3+344929) is reported to have a constant luminosity for the year surrounding the event; unlikely that the flare is part of intrinsic variability of the source.
- BBH mergers in AGN expected to produce electromagnetic (EM) counterparts.
- Is there an association between the GW and flare events? A previous paper (Ashton et al.) found little evidence, but this paper suggests otherwise.

Motivation

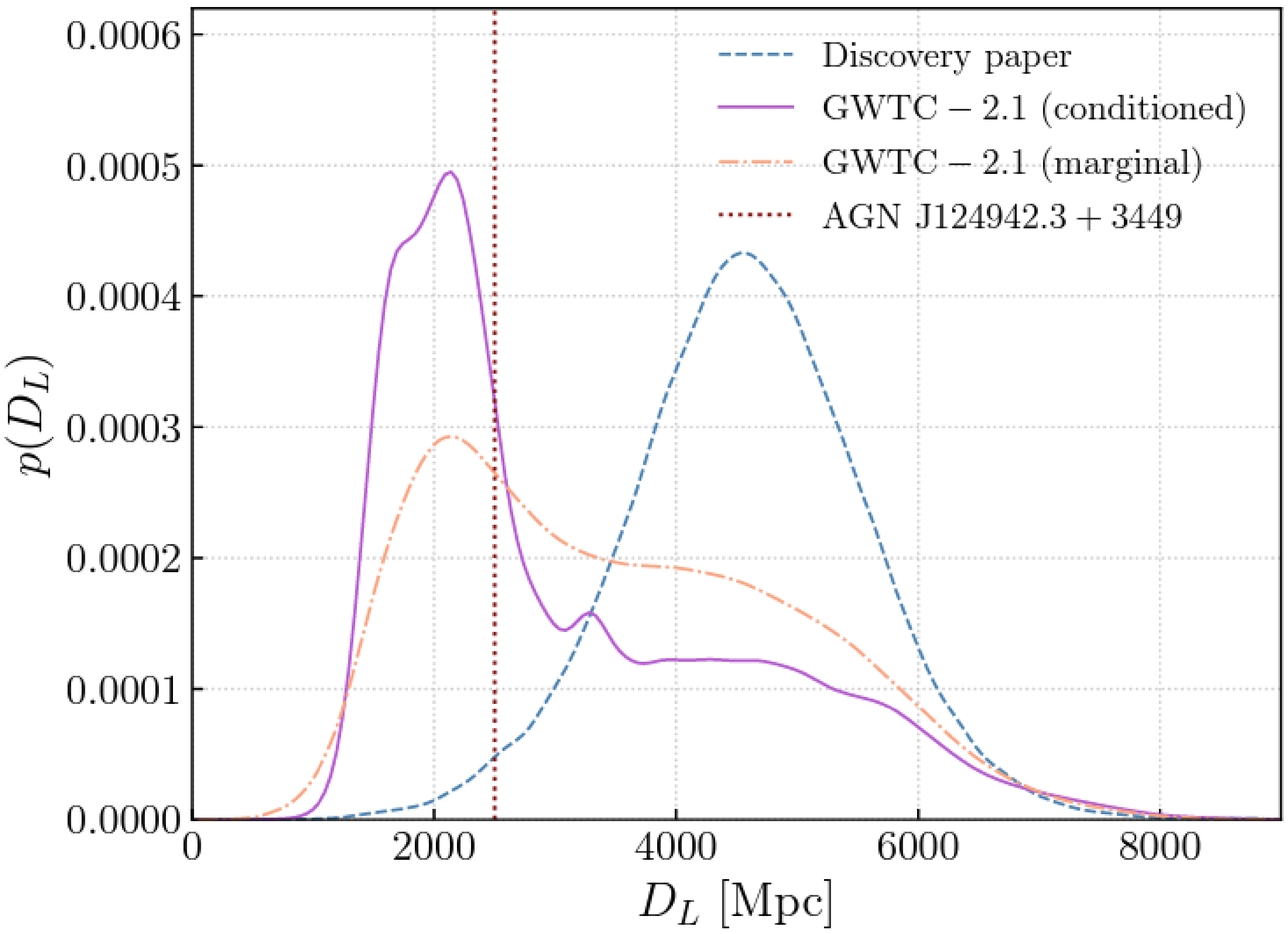
- When analyzing the odds of association between two astrophysical events, significant contribution comes from the three-dimensional spatial overlap (in our case, the GW and EM events).

- Prior works only find marginal evidence in favor of association between the two events.

Motivation

- Fig. (1): posterior on luminosity distance vs luminosity distance.

- More recent data release (GWTC-2.1) provides more robust waveforms than used in the discovery paper, motivating the need for further analysis.



Methods: Environmental Effects

- A BBH residing in an AGN is influenced by different environmental effects (mainly from the supermassive black hole (SMBH)), e.g. observed mass and distance of the source being altered.

- Motion of the BBH when orbiting the SMBH induces a relativistic redshift.

- Gravitational potential of the SMBH induces a gravitational redshift.

Methods: Environmental Effects

- For a redshifted source: detected mass given by eq. (4):

$$M_1^{z,\mathrm{eff}} = (1 + z_\mathrm{c})(1 + z_\mathrm{rel})(1 + z_\mathrm{grav})M_1$$

- Effective distance of the source given by eq. (5):

$$D_L^{\mathrm{eff}} = (1 + z_\mathrm{rel})^2(1 + z_\mathrm{grav})D_L$$

- Environmental effects can be accounted for by using these effective parameters.

Methods: Bayesian Statistical Framework

- Main "figure of merit" is the odds ratio $\mathcal{O}_C^A$, given by eq. (6):

$$\mathcal{O}_C^A = \frac{p(\mathcal{H}_A|d)}{p(\mathcal{H}_C|d)} = \frac{p(d|\mathcal{H}_A)}{p(d|\mathcal{H}_C)}\frac{p(\mathcal{H}_A)}{p(\mathcal{H}_C)} = \mathcal{B}_C^A\mathcal{P}_C^A$$

- Combines previous knowledge/belief on the analyzed phenomenon (the "prior odds" $\mathcal{P}_C^A$) with information from available data included in the Bayes' factor $\mathcal{B}_C^A$.

Bayesian Statistical Framework: Association Model

- Association Model ($\mathcal{H}_A$): flare and GW share a common origin and location, thus, sky position fixed to the AGN location.

- Parameters for GW posterior probability density: $(M_1^{z,eff}, D_L^{eff})$.

Bayesian Statistical Framework: Association Model

- Prior for $(M_1^{z,eff}, D_L^{eff})$ given by eq. (14):

Bayesian Statistical Framework: Association Model

- Prior for $(M_1^{z,eff}, D_L^{eff})$ given by eq. (14):

$$p(M_1^{z,\mathrm{eff}}, D_L^{\mathrm{eff}}|\mathcal{H}_A) = \int p(M_1^{z,\mathrm{eff}}, D_L^{\mathrm{eff}}|z_\mathrm{c}, r, \theta, M_1, \mathcal{H}_A)\times$$
$$\times\, p(z_\mathrm{c}|\mathcal{H}_A)p(r|\mathcal{H}_A)p(\theta|\mathcal{H}_A)p(M_1|\mathcal{H}_A)\mathrm{d}z_c\mathrm{d}r\mathrm{d}\theta\mathrm{d}M_1\,,$$

with the first term in the integral given by eq. (15):

$$p(M_1^{z,\mathrm{eff}}, D_L^{\mathrm{eff}}|z_\mathrm{c}, r, \theta, M_1, \mathcal{H}_A) =$$
$$\delta\Big(D_L^{\mathrm{eff}} - (1+z_\mathrm{rel}(r,\theta))^2(1+z_\mathrm{grav}(r))D_L(z_\mathrm{c},\Omega)\Big)\times$$
$$\times\,\delta\Big(M_1^{z,\mathrm{eff}} - (1+z_\mathrm{rel}(r,\theta))(1+z_\mathrm{grav}(r))(1+z_c)M_1\Big)\,.$$

Bayesian Statistical Framework: Coincidence Model

- EM counterpart not associated with the GW event; appears within the same sky location by chance.

- Sky position is not conditioned on the sky position of the AGN

Bayesian Statistical Framework: Coincidence Model

- Only redshift present is cosmological, so the prior for (M_1^z, D_L) is given by eq. (17):

$$p(M_1^z, D_L|\mathcal{H}_C) = \int p(M_1^z|M_1, z_{\rm c}, \mathcal{H}_C)p(D_L|z_{\rm c}, \mathcal{H}_C)\times$$
$$\times\, p(M_1|\mathcal{H}_C)p(z_{\rm c}|\mathcal{H}_C)\mathrm{d}z_{\rm c}\mathrm{d}M_1\,. \quad (17)$$

Methods: GW Posterior Probability Density

- For every event in the LVK catalogs, a set of samples drawn from their Parameter Estimation posterior distribution was released.

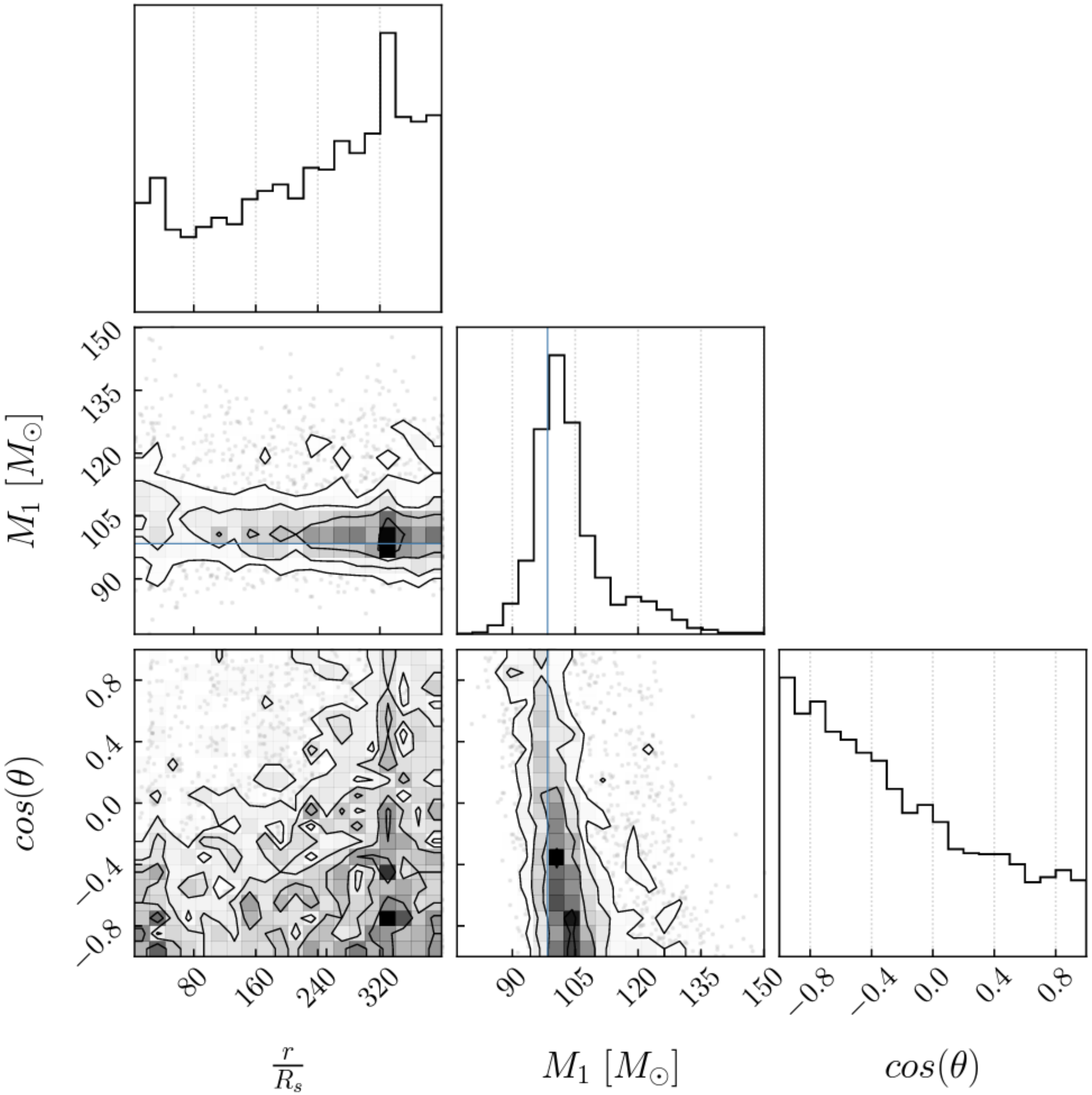
- Made use of posterior samples released within GWTC-2.1 to infer an analytical approximant.

- Using the approximant, able to condition and/or marginalize the posterior distribution $p(M_1^{z,eff}, D_L^{eff}, \alpha, \delta | d)$ over sky position (α, δ).

Results

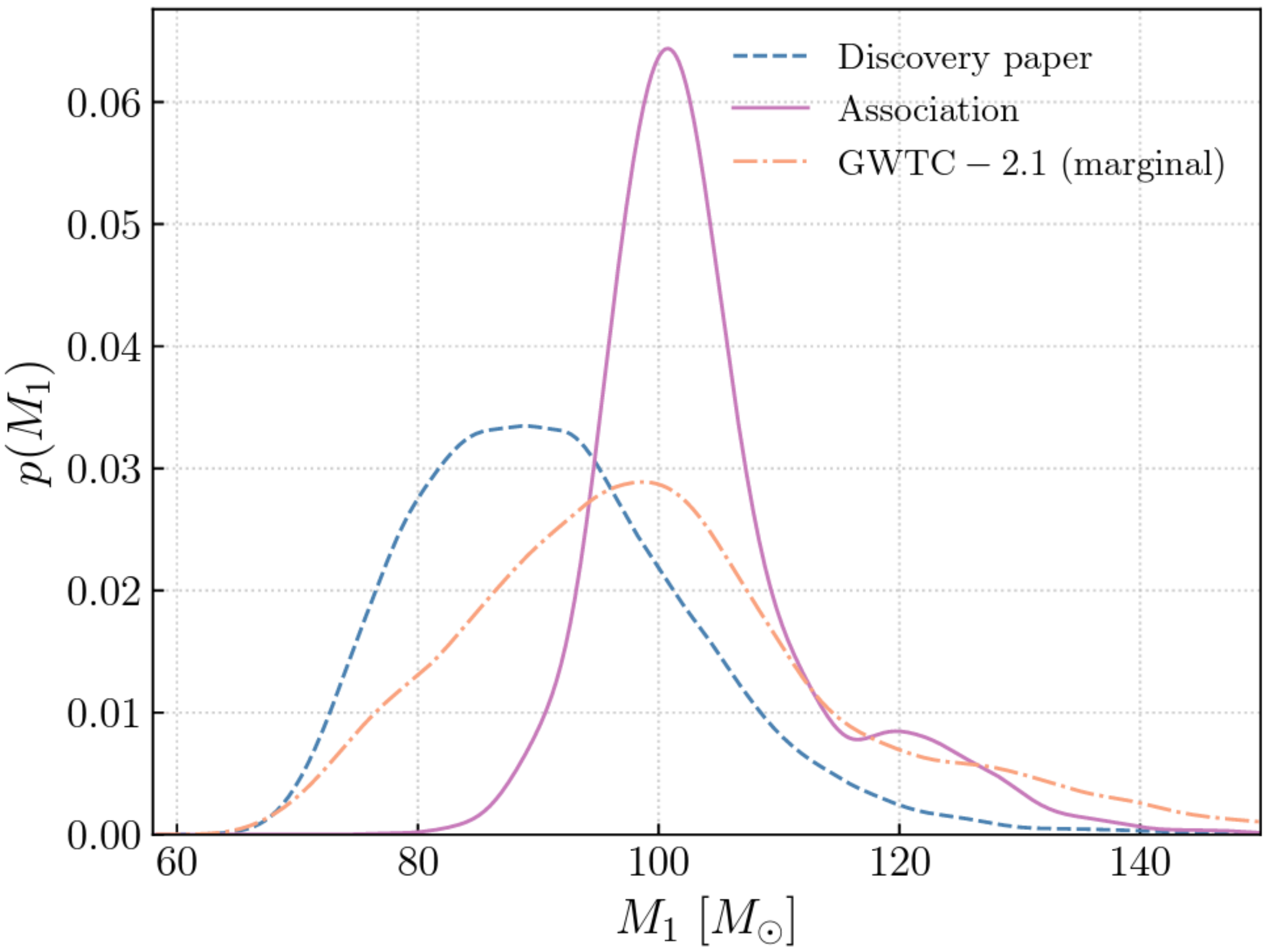
- Fig. (3): posterior distribution for the parameters of the association model.

- Radial distance consistent with described prior, BBH motion toward observer is favored.



Results

- Fig. (4): comparing primary mass posterior probability densities.
- Association model and GWTC-2.1 probability densities peak at higher masses than that of the discovery paper.



Results

- Using a nested sampling algorithm, able to compute the evidence for each of the two models:
  - Bayes' factor favors the common origin hypothesis: $\log \mathcal{B}_C^A = 8.5 \pm 0.1$
  - When using the same odds prior as the Ashton et al. paper ($\mathcal{P}_C^A = 1/13$), the odds ratio $\log \mathcal{O}_C^A = 6.0 \pm 0.1$, confidently relating the EM signal to the GW event.
  - Hubble constant: $H_0 = 79.2_{-9.6}^{+17.6} km \cdot s^{-1} \cdot Mpc^{-1}$, consistent with literature.

Summary

- Investigated the possibility of the AGN flare ZTF19abanrhr being the EM counter part of the BBH merger GW190521, identifying AGN J124942.3+344929 as the host galaxy of the GW event.

- Created a model that accounts for environmental effects due to the proximity of the BBH to the SMBH.

- Found that the GW is likely blueshifted.

- Calculated the odds ratio and found that GW190521 and ZTF19abanrhr are likely associated with each other, meaning GW190521 is likely to have originated in AGN J124942.3+34492.