Prospects for Multimessenger Observations of Supermassive Black Hole Binaries with PTAs and Electromagnetic Observatories

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Abstract

Gravitational waves (GWs) from individual supermassive black hole binaries (SMBHBs) in the local universe are expected to be observed by pulsar timing arrays (PTAs) [1]. Multimessenger observations of SMBHBs will enable advances across astrophysics impossible with only GW or electromagnetic (EM) observations [2]. Using the Illustris-TNG cosmological simulations, we investigate the number and characteristics of galaxies within the PTA localization region [3]. We also investigate the feasibility of simultaneous EM observations of SMBHBs with an array of observatories.

Number of Galaxies in PTA Localization Regions

Building the localization volume in Illustris-TNG:

- Use sky localization estimates from Petrov et al. (2024) [4]
- Use simulation snapshots to build the PTA localization region in z and the sky localization plane until they cover the full sky localization uncertainty and extend to ~600 Mpc

Counting the galaxies:

- The total number of enclosed galaxies is large but knowledge of the mass of SMBHB lowers the number of potential host galaxies significantly

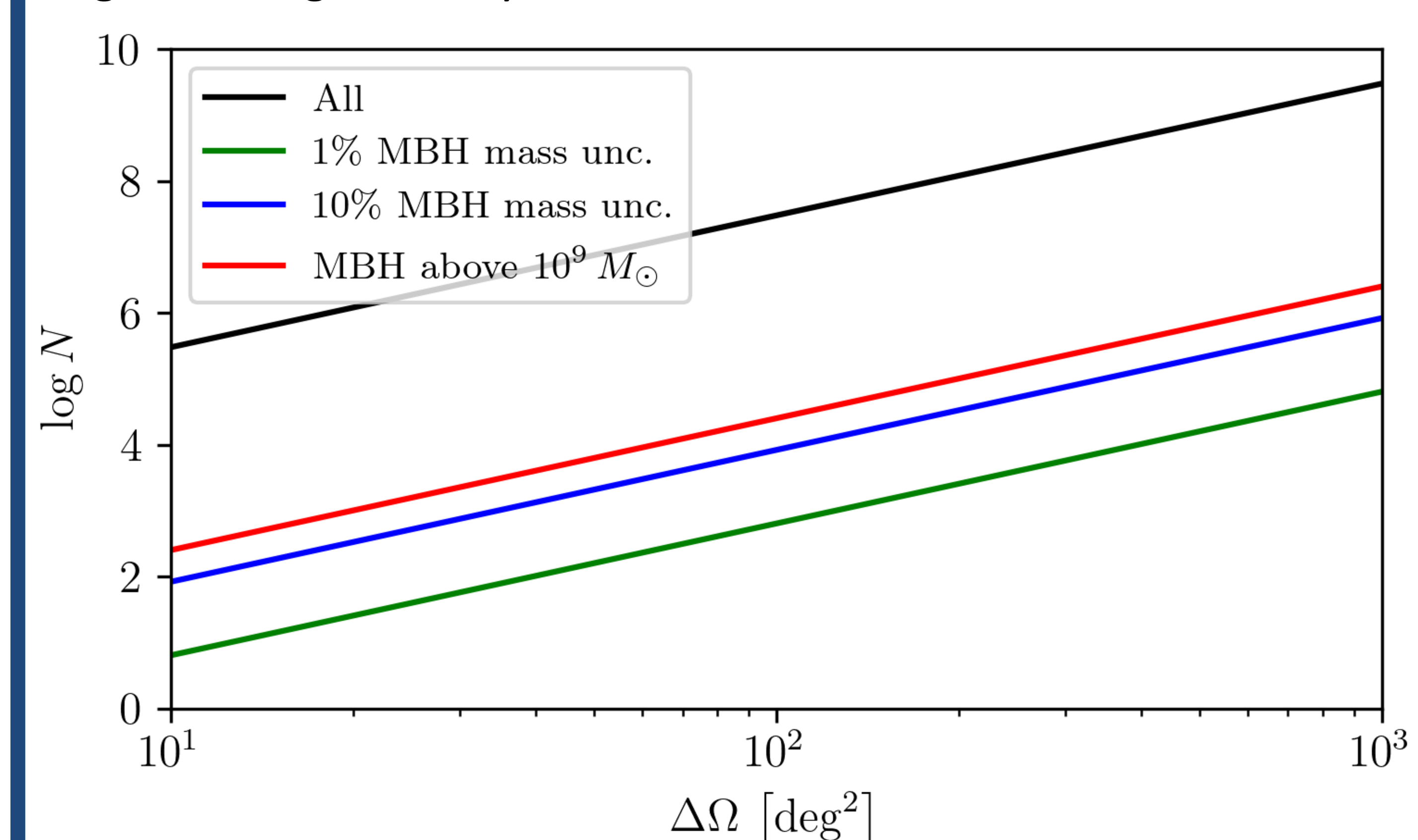

Figure 1: The number of galaxies in the PTA localization region extending to ~600 Mpc versus sky localization uncertainty. Sky localization uncertainty improves (decreases) with higher SNRs. The black line indicates the total number of galaxies in the localization region, the red line indicates the number of galaxies hosting SMBHs > $10^9\ M_\odot$, and the blue and green lines indicate the number of galaxies hosting MBHs with mass within 10 and one percent of $10^9\ M_\odot$, respectively. For the best-localized SMBHBs with the mass constraint there are ~10-10^2 of galaxies in the localization region. For poorly localized SMBHBs with the mass constraint there are ~$10^{4\text{-}5}$ galaxies in the localization region.

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Galaxy Properties in PTA Localization Regions

The PTA localization region is dominated by **gas rich, dim, ~ $10^{10}M_\odot$ galaxies with low-mass central SMBHs and low stellar masses & magnitudes** (solid lines in figures below). Galaxies hosting SMBHs > $10^9 M_\odot$ have **narrower distributions of stellar masses and magnitudes** and have a wide range of SFRs and gas fractions (dashed lines).

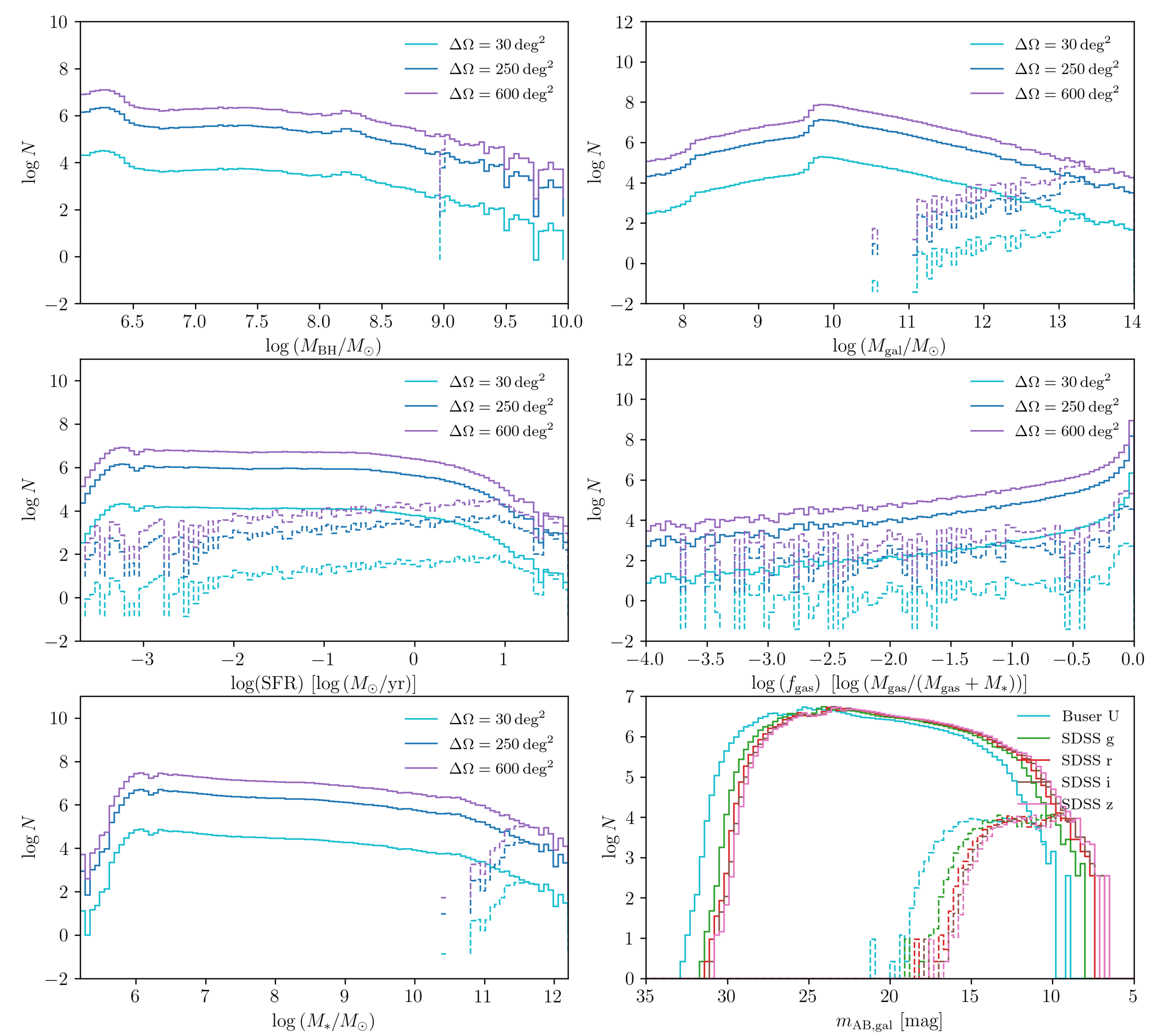

Figure 2: Distributions of properties for galaxies enclosed in the PTA localization region calculated for sky localization uncertainties of 30 deg^2 (cyan), 250 deg^2 (blue), and 600 deg^2 (purple). These properties include central SMBH mass (top left), total mass (top right), star formation rate (middle left), gas fraction (middle right), stellar mass (bottom left), and stellar magnitudes (bottom right, $\Delta\Omega = 250\ \mathrm{deg}^2$ only). The dashed lines show the distributions after cutting galaxies with central SMBH/potential SMBHB mass < $10^9 M_\odot$. In the stellar magnitudes plot, we show the distributions of apparent magnitudes in the Buser U and SDSS g, r, i, and z bands.

Works Cited

[1] Sesana et al. 2009, MNRAS 394, 2255. [2] Piro et al. 2022, MNRAS, 521, 2577. [3] Springel et al. 2018, MNRAS, 475, 676. [4] Petrov et al. 2024, ApJ, 976, 129. [5] Mangiagli et al. 2022, PRD, 106, 103017. [6] Lops et al. 2023, MNRAS, 519, 5962. [7] Dong-Páez et al. 2023, A&A, 676, A2. [8] Izquierdo-Villalba et al. 2023, A&A, 677, A123. [9] Bardati et al. 2024, ApJ, 961, 34.

Considering Observability of AGN-Like Emission

Observability will depend on:

- Telescope capabilities (FoVs, sensitivities, wavelength coverage, slew & response times, other technical aspects)
- Likelihood galaxies host SMBHBs of target mass based on galaxy properties
- Likelihood AGN-like emission associated with an SMBHB is above both a limiting flux/magnitude & host galaxy emission
- See Piro et al. (2022) [2], Mangiagli et al. (2022) [5], Lops et al. (2023) [6], Dong-Páez et al. (2023) [7], Izquierdo-Villalba et al. (2023) [8], Bardati et al. (2023) [9] for examples with LISA

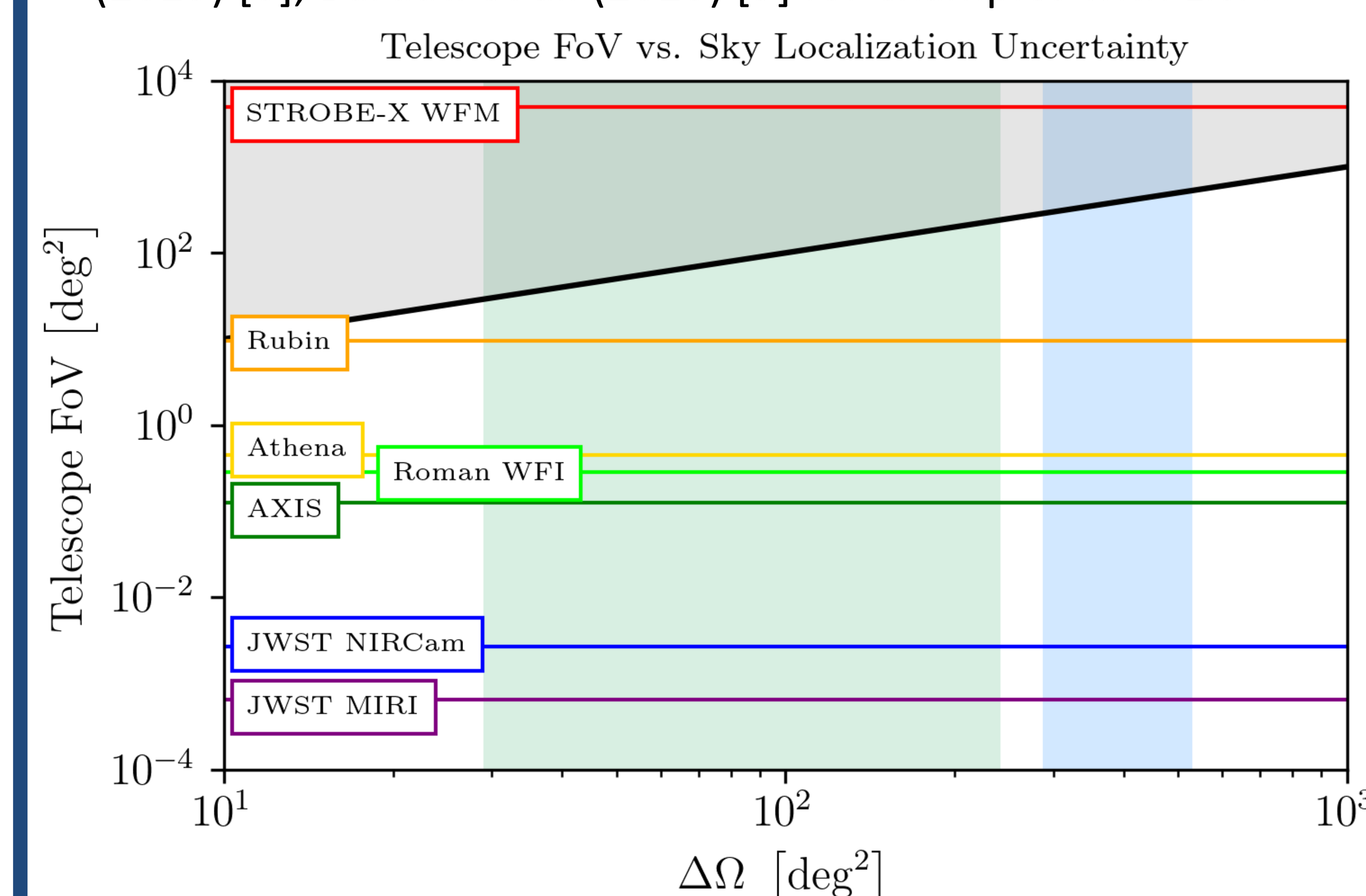

Figure 3: Telescope field of view (FoV) versus sky localization uncertainty ΔΩ. Horizontal, colored lines indicate the FoVs of various observatories. The green [blue] region indicates the range of 90% credible sky localizations found with SNR = 15 [SNR = 8] GW injections in Petrov et al. (2024) [4]. The gray region indicates FoV and ΔΩ combinations for which the FoV fully encompasses the sky localization uncertainty; in this case, telescopes could detect a potential PTA SMBHB host galaxy in one pointing (without tiling observations). Of the seven observatories shown, only STROBE-X WFM falls in this region. Telescopes with smaller FoVs could be used for targeted follow-up observations if a manageable selection of best-candidate host galaxies can be identified.

Conclusions and Future Work

The number of galaxies in the PTA localization region may be on the order of millions but decreases considerably if the SMBHB mass is known. Similarly, knowledge of the SMBHB mass substantially narrows the range of expected host properties, particularly for stellar mass and magnitudes, enabling more targeted EM follow-up searches. Prioritizing galaxies in the PTA localization region for observation and the likelihood that AGN-like emission from accreting SMBHBs within them can be detected will be paramount for successful multimessenger observations of individual PTA sources.