Constraints on compact dark matter from gravitational-wave microlensing

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Introduction

- Almost 25% of the mass-energy content of the universe is filled with an unknown form of matter - 'Dark Matter' (DM) - interacting only via gravity.
- If a significant fraction of DM is in the form of compact objects, they will cause microlensing effects in the gravitational-wave (GW) signals observable by LIGO and Virgo.
- From the non-observation of microlensing signatures in the binary black hole (BBH) events from the O1, O2 and O3a runs, we constrain the *fraction of compact dark matter* (f_{DM}) in the mass range $10^2 - 10^5 \mathrm{M}_{\odot}$.

Gravitational lensing

- Deflection of electromagnetic/gravitational waves from their path due to the presence of an intermediate potential.
- 1. Lensing in geometric optics limit: $\lambda_{\text{wave}} < R_{\text{Sch}}$ constant magnification, generally true for light.
- 2. Lensing in wave optics limit: $\lambda_{\text{wave}} \sim R_{\text{Sch}}$ Frequency dependent magnification, can happen for GWs.

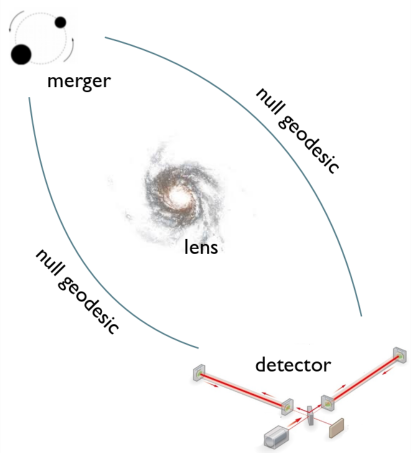
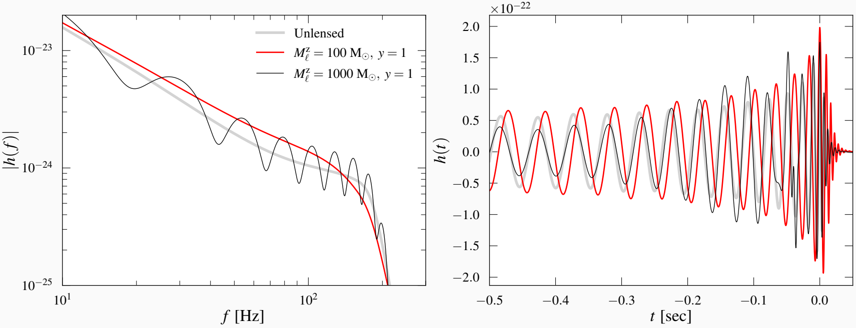


Figure 1: Schematic diagram of gravitational lensing

Microlensing of GWs by a point mass lens

- $\boxed{h_\ell(f) = F(f, M_\ell^z, y) h_U(f)}$ U: unlensed, ℓ: lensed

  $F(f, M_\ell^z, y)$: frequency dependent magnification.



Bayesian model selection

- Odds ratio ($\mathcal{O}^{\ell}_{\mathrm{U}}$) between hypotheses H_ℓ (signal is lensed) and H_{U} (signal is unlensed):

$$\boxed{\mathcal{O}^{\ell}_{\mathrm{U}} = \frac{P(H_\ell|\mathrm{data})}{P(H_{\mathrm{U}}|\mathrm{data})} = \frac{P(H_\ell)}{P(H_{\mathrm{U}})}\frac{P(\mathrm{data}|H_\ell)}{P(\mathrm{data}|H_{\mathrm{U}})}}$$

$$\boxed{\mathcal{O}^{\ell}_{\mathrm{U}} = \textbf{prior odds} * \mathcal{B}^{\ell}_{\mathrm{U}}} \quad [\mathcal{B}^{\ell}_{\mathrm{U}} = \textbf{Bayes factor}]$$

For lensed signals,

$$\boxed{\mathcal{O}^{\ell}_{\mathrm{U}} >> 1}$$

- Parameter estimation (PE) done on 18 GW events from O1 and O2 runs, using both lensed and unlensed templates, suggests no confident lensing signature.

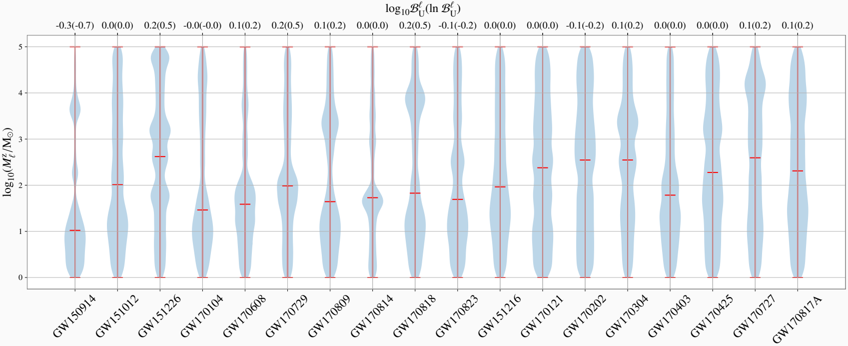


Figure 2: Bayes factor for O1 and O2 events

- $N_{\text{events}} = 18\ (\text{O1} + \text{O2}) + 36\ (\text{O3a}) = 54$
- max of $\ln \mathcal{B}^{\ell}_{\text{U}} = 1.15 \implies$ No compelling evidence of microlensing.

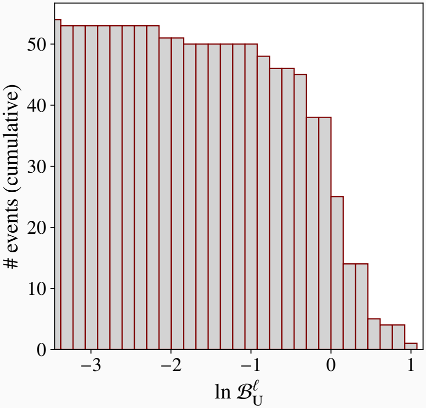


Figure 3: Distribution of Bayes factors ($\ln \mathcal{B}^{\ell}_{\text{U}}$) for O1, O2, O3a events

Computing posterior on the fraction of lensed events

- Given $N = 54$ total detection and $N_\ell = 0$ lensed detection, we compute the posterior on their Poisson means Λ and Λ_ℓ.
- This allows us to compute the posterior on the lensing fraction $u := \frac{\Lambda_\ell}{\Lambda}$

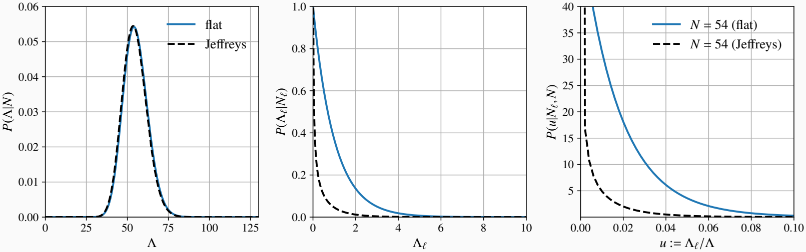
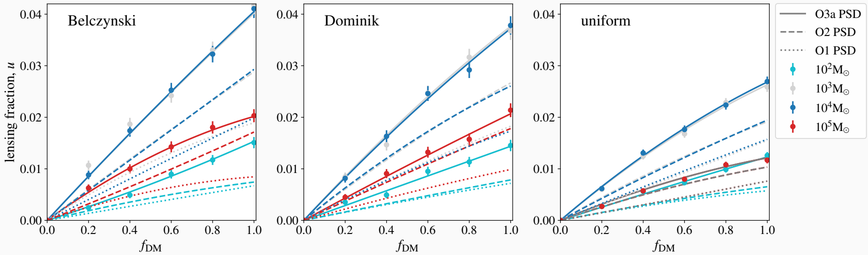


Figure 4: posterior distribution of i) total events (Λ), ii) lensed events (Λ_ℓ), iii) lensed events ratio ($\frac{\Lambda_\ell}{\Lambda}$).

Relating DM fraction with the lensing fraction

- Simulate a population of BBHs following some distribution models
- Compute the fraction of detectable lensed events ($\ln \mathcal{B}^{\ell}_{\mathrm{U}} > 1.15$) in the LIGO-Virgo network for different f_{DM} values
- Assume MACHOs are distributed uniformly in comoving volume
- The posterior on f_{DM} can be computed from the posterior of u as:

$$p(f_{\mathrm{DM}}|N_\ell = 0, N = 54) = p(u|N_\ell = 0, N = 54)\left|\frac{\mathrm{d}u}{\mathrm{d}f_{\mathrm{DM}}}\right|$$



Posterior on $f_{\rm DM}$

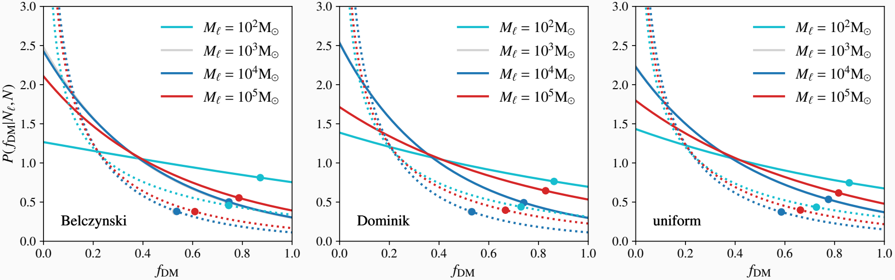
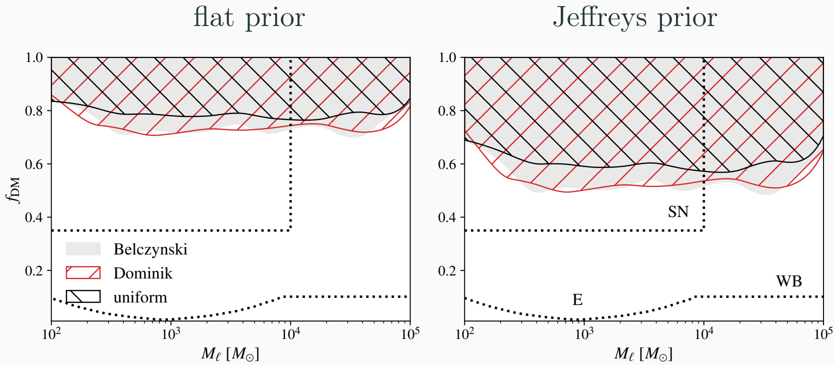


Figure 5: Posterior on $f_{\rm DM}$ assuming i) flat prior (solid) and ii) Jeffreys prior (dotted) on Λ and Λ_ℓ.

Upper limits on f_{DM} (90%)



Future Bounds

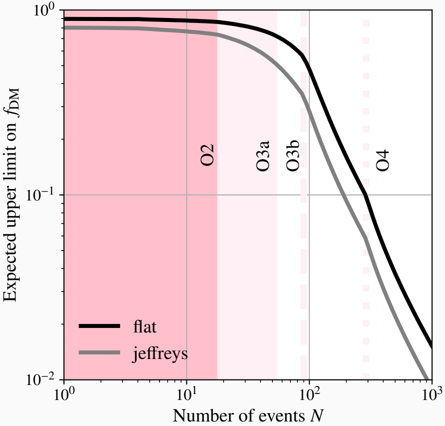


Figure 6: Expected $f_{\rm DM}$ upper limits from future detection.

Summary and Future work

- Non-observation of microlensing signature in GWs helps us put upper bound on f_{DM}.
- The limits depend on the assumed redshift distribution of BBHs as well as the Bayesian priors used in the analysis. Nevertheless, we are able to place upper bounds on $f_{\mathrm{DM}} \sim 0.5 - 0.8$.
- These bounds will get significantly better in the next few years with the increased number of events and increased lensing optical depth (lensing probability).
- Ongoing work (part of the LIGO-Virgo collaboration) is on obtaining the improved constraints using the O3b data.

Thank you for your valuable time :)