# Profiling Dark Matter Spikes with Gravitational Waves


**Prolay K. Chanda**

Visiting Post Doctoral Fellow

Tata Institute of Fundamental Research

PH.D. (University of Illinois Chicago)



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In Collaboration with:

Avinash Tiwari, Shasvath J. Kapadia, Susmita Adhikari, Aditya Vijaykumar, and Basudeb Dasgupta

# Key Ideas

- The presence of a Central Black Hole can result in a steep dark matter (DM) density spike near the centre of the DM halo.
- We propose a new method to probe the DM spike profile by gravitational wave (GW) observations.
- The study is purely gravitational, independent of the particle nature of the DM.
- However, once the nature of the spike profile is inferred, it can lead to interesting insights about the particle physics of DM.

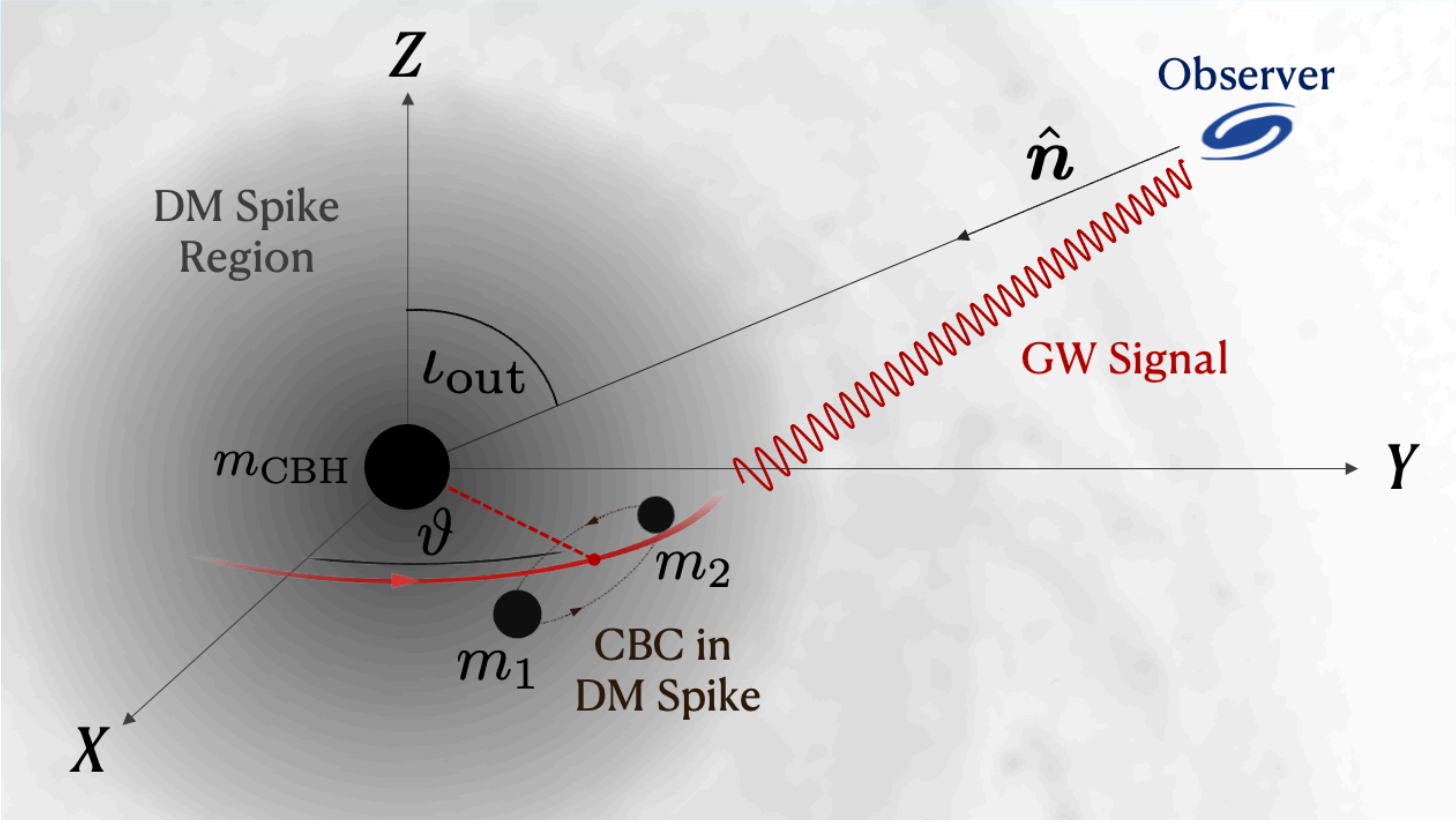
# DM Spike in the Presence of a Central Black Hole

- An adiabatically growing black hole at the center of a DM halo produces a density spike profile, $\rho(r) \propto r^{-\gamma_{\rm sp}}$, $\gamma_{\rm sp} = (9 - 2\gamma_i)/(4 - \gamma_i)$, extending up to a radial distance $r_{\rm sp}$. (Gondolo and Silk, 1999)
- The exact nature of the spike depends on the initial profile and other astrophysical effects.
- We focus on Milky Way-like galaxies, where net acceleration and jerk, etc., are larger, offering better prospects than dwarf galaxies.

# A Schematic Diagram

- A Central Black hole at the center.

- A Compact Binary Coalesce(CBC) orbiting around it.

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# Using GW to probe DM spike: Method

- A compact binary with steady motion is indistinguishable from a stationary one with an effective mass scaled by $(1 + z_c)(1 + z_d)$, accounting for cosmological ($z_c$) and Doppler shifts due to constant speed ($z_d$).

- If the system has a changing velocity - like line-of-sight acceleration, jerk, snap, etc., - its signal shows time-dependent modulations.

(Yunes et al. 2010, Bonvin et al. 2016, Vijakykumar et al. 2023)

$$\tilde{h}_{\rm TV}(f) \propto \tilde{h}(f) e^{i \sum_{n=1}^{\infty} \Delta\Psi_{-4n}(f;\Gamma_n)} .$$

- The acceleration and the higher time derivatives, jerk, snap, etc., encode the gravitational potential information that the CBC is moving in. $\Phi(r) = \Phi_{\rm CBH} + \Phi_{\rm DM}$

- Therefore, a careful measurement of the kinematic parameters determines the nature of the inner DM density profile.

# The Kinematics

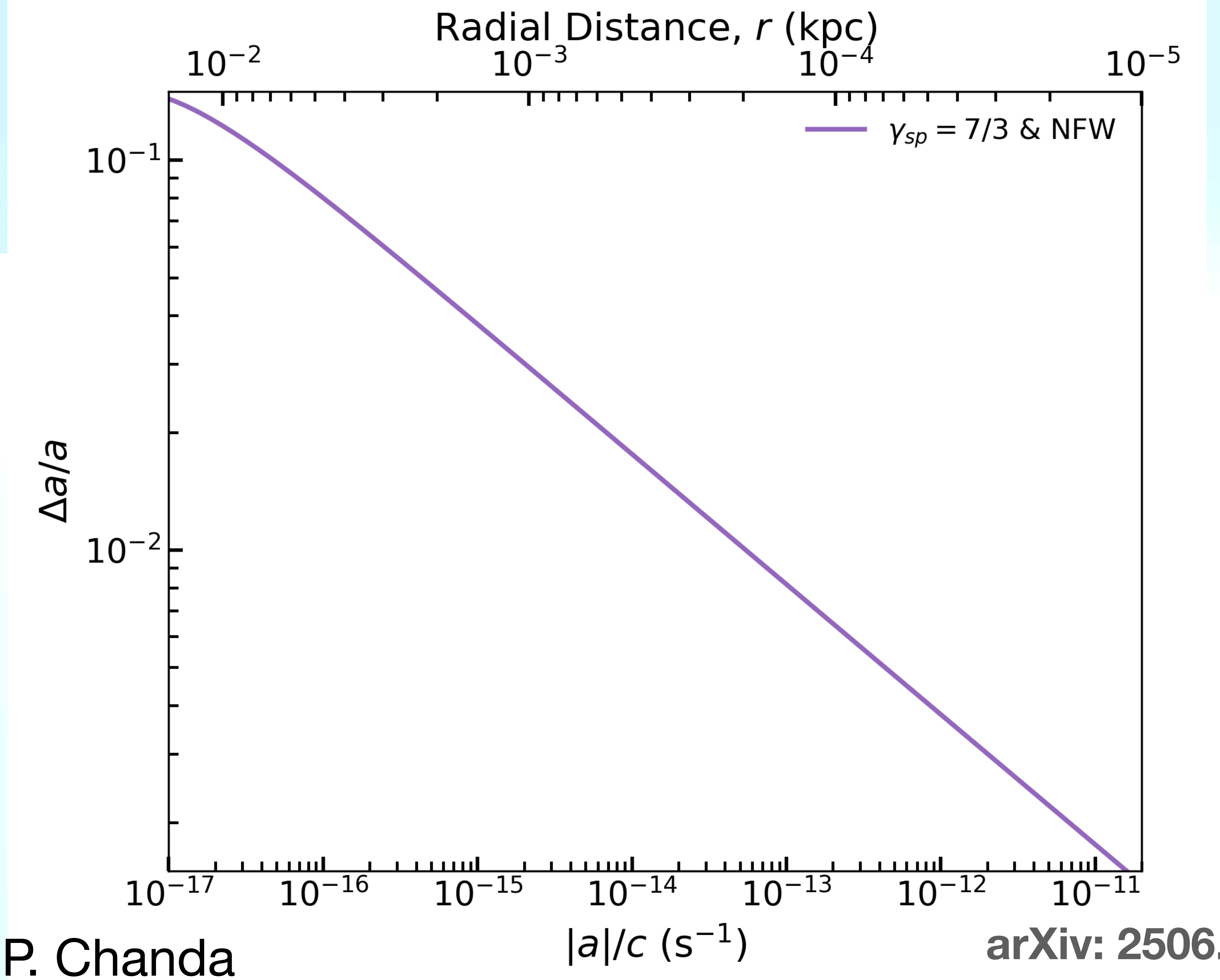
- $M_{\rm enc} = M_{\rm CBH} + \dfrac{4\pi\rho_0 r^{3-\gamma_{\rm sp}}}{3-\gamma_{\rm sp}}, \qquad \Phi(r) = \dfrac{4\pi G\rho_0 r^{2-\gamma_{\rm sp}}}{(\gamma_{\rm sp}-2)(\gamma_{\rm sp}-3)} - \dfrac{GM_{\rm CBH}}{r}$
- $a_r = -\dfrac{GM_{\rm CBH}}{r^2} - \dfrac{4\pi G\rho_0 r^{1-\gamma_{\rm sp}}}{3-\gamma_{\rm sp}}$

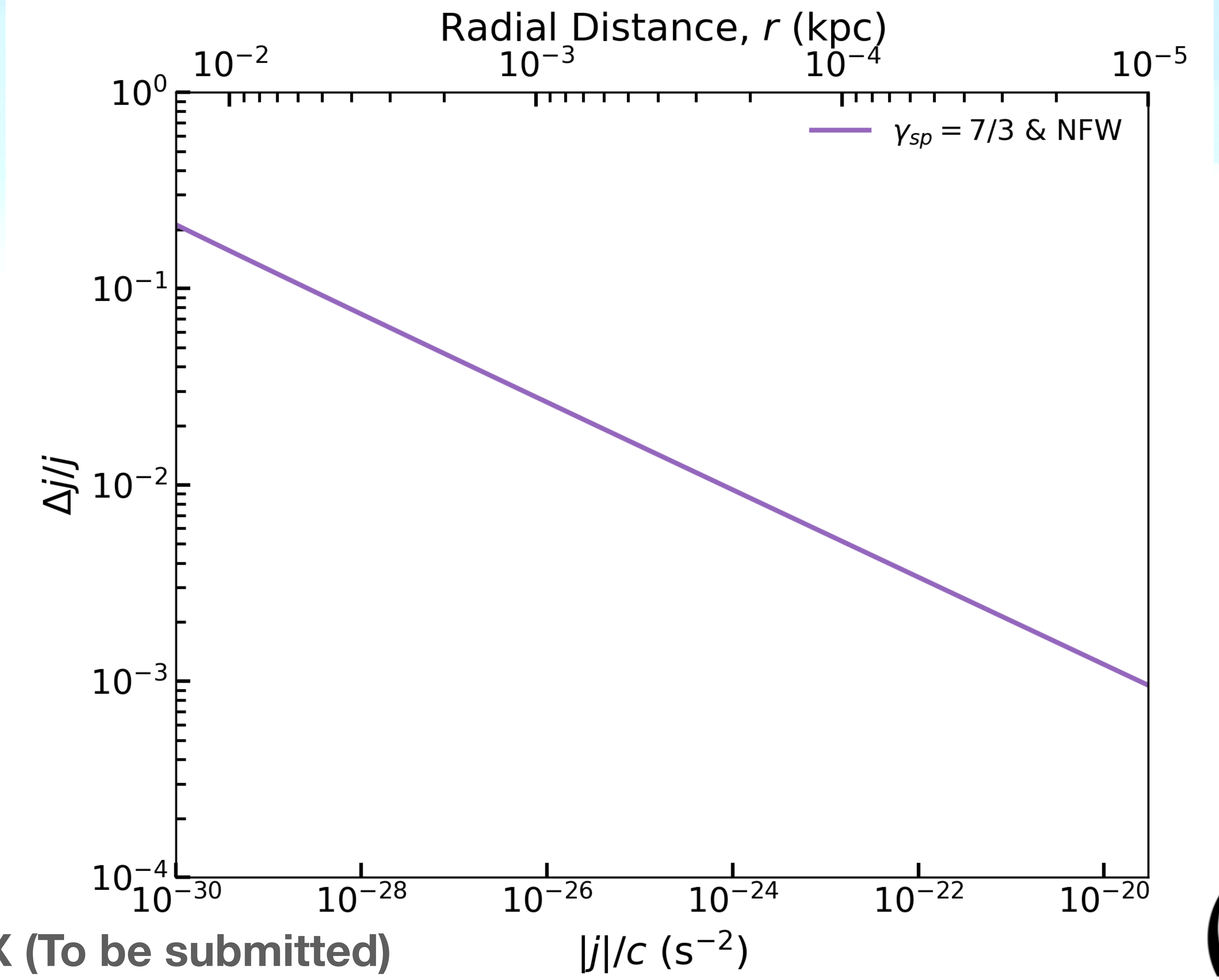
$$j_r = v_r\left(\frac{2GM_{\rm CBH}}{r^3} - \frac{4\pi(1-\gamma_{\rm sp})G\rho_0 r^{-\gamma_{\rm sp}}}{3-\gamma_{\rm sp}}\right)$$

- $j_\vartheta = \Omega\left(-\dfrac{GM_{\rm CBH}}{r^2} - \dfrac{4\pi G\rho_0 r^{1-\gamma_{\rm sp}}}{3-\gamma_{\rm sp}}\right)$

# Identifying the Most Sensitive Region

- The detectability of the kinematic parameters decreases radially outwards, while the differentiability between different density profiles increases (We mean up to the radius $r_{\rm sp}$, beyond that, NFW dominates, and the information about the effects of the CBH).
- Therefore, a careful analysis is necessary to figure out a 'sweet spot' ( $\sim 0.01$ pc).

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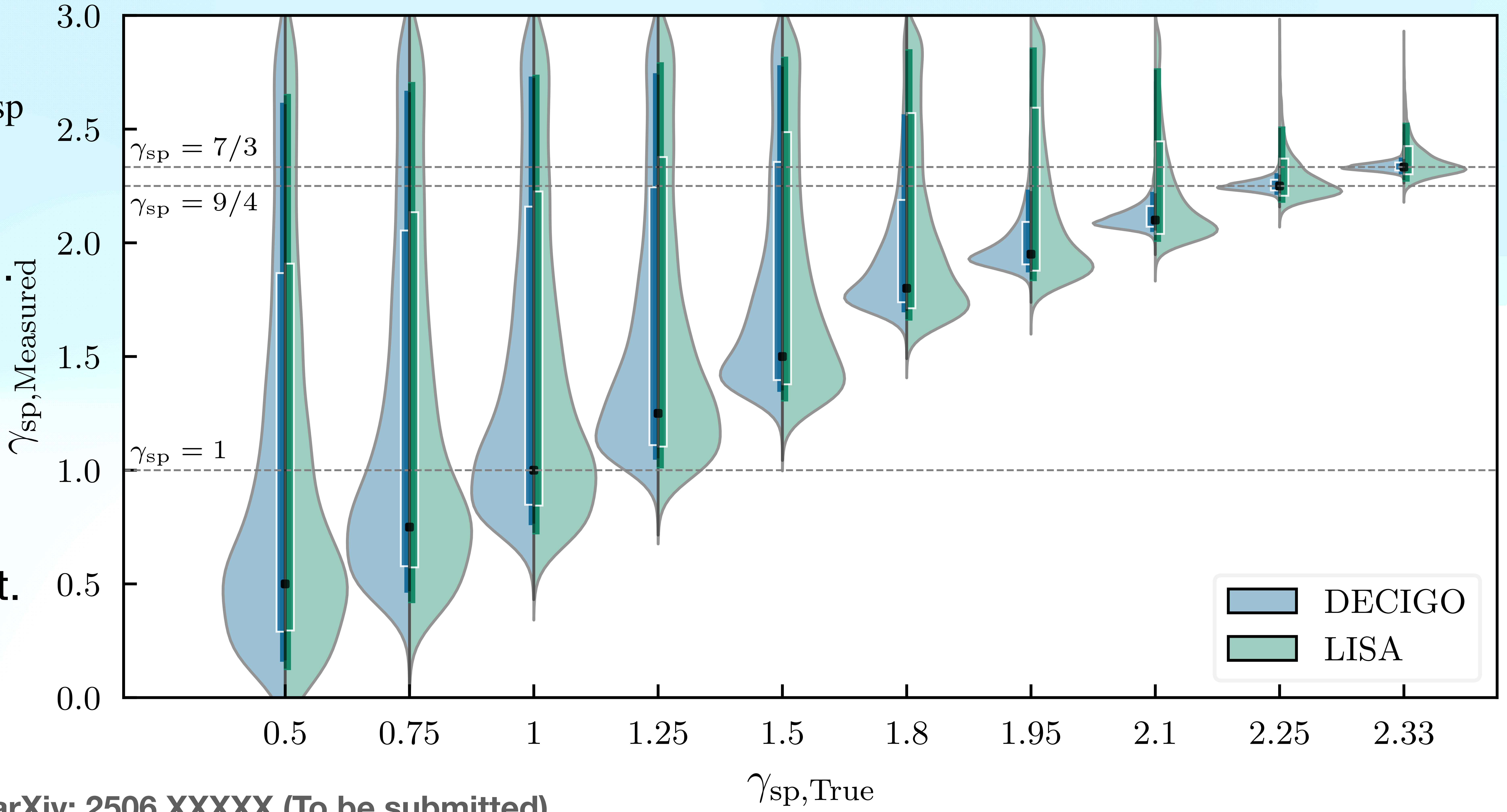
# Results

- Violin plots represent the 1-d posteriors for the density exponent $\gamma_{sp}$.

- Larger DM mass within $r_{sp}$ modifies contributes more to the gravitational potential.

- The violin plots on the right shows that with a steeper spike profile, the analysis is more efficient.

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# Other Effects

- The contribution of the Dynamical Friction (DF) is negligible $dE_{\rm DF}/dt \sim \rho/v$, whereas the GW energy loss scales as $R_0^{-5}$.
- We are inspecting a region closer to the black hole.
- For this reason, we do not consider an evolving halo due to the effects of the dynamical friction.
- The tidal effects due to the CBH on the CBC are also found to be negligible.

# Advantages and Conclusions

- Our method is clean in a way that the kinematic properties our purely gravitational, and they directly provide the information about the gravitational potential of the inner halo, and, therefore, the spike profile.

- It's important to note that because of the acceleration, jerk, snap, …etc, the modulation of the GW wave is time varying. Therefore, our method isn't vulnerable to the degeneracy of a larger black hole inside, but clearly confirms the presence of a DM halo.

- The dynamical friction poses several complexities, such as the evolution of the DM density profile over CBC lifetime. Also, the detectability of the GW dephasing due to dynamical friction isn't guaranteed to be detected.

- The DM annihilation products carry information about the inner DM density profile. However, one needs to assume the DM self-annihilated and other DM particle physics details. It's also important to distinguish these signals from the ones originating from separate astrophysical effects.

# Future Prospects

- A successful detection through our methods can be another indirect evidence for DM.
- Identification of the DM halo profile around a BH through this method will help in the confirmation of existing halo formation theories or will hint towards an improved analysis.
- The inner structure of dark matter halos encodes valuable information about the microphysical properties of dark matter. In particular, the formation and evolution of the central region can reveal the presence and strength of self-interactions, as expected in self-interacting dark matter (SIDM) scenarios.
- Similarly, a suppressed or shallow density spike near the core may indicate dark matter self-annihilations. Such features can offer crucial insights into the particle nature of dark matter and its possible connections to the Standard Model (SM).

# Thank you!
# Gracias!