A Unique Multi-Messenger Signal of QCD Axion Dark Matter

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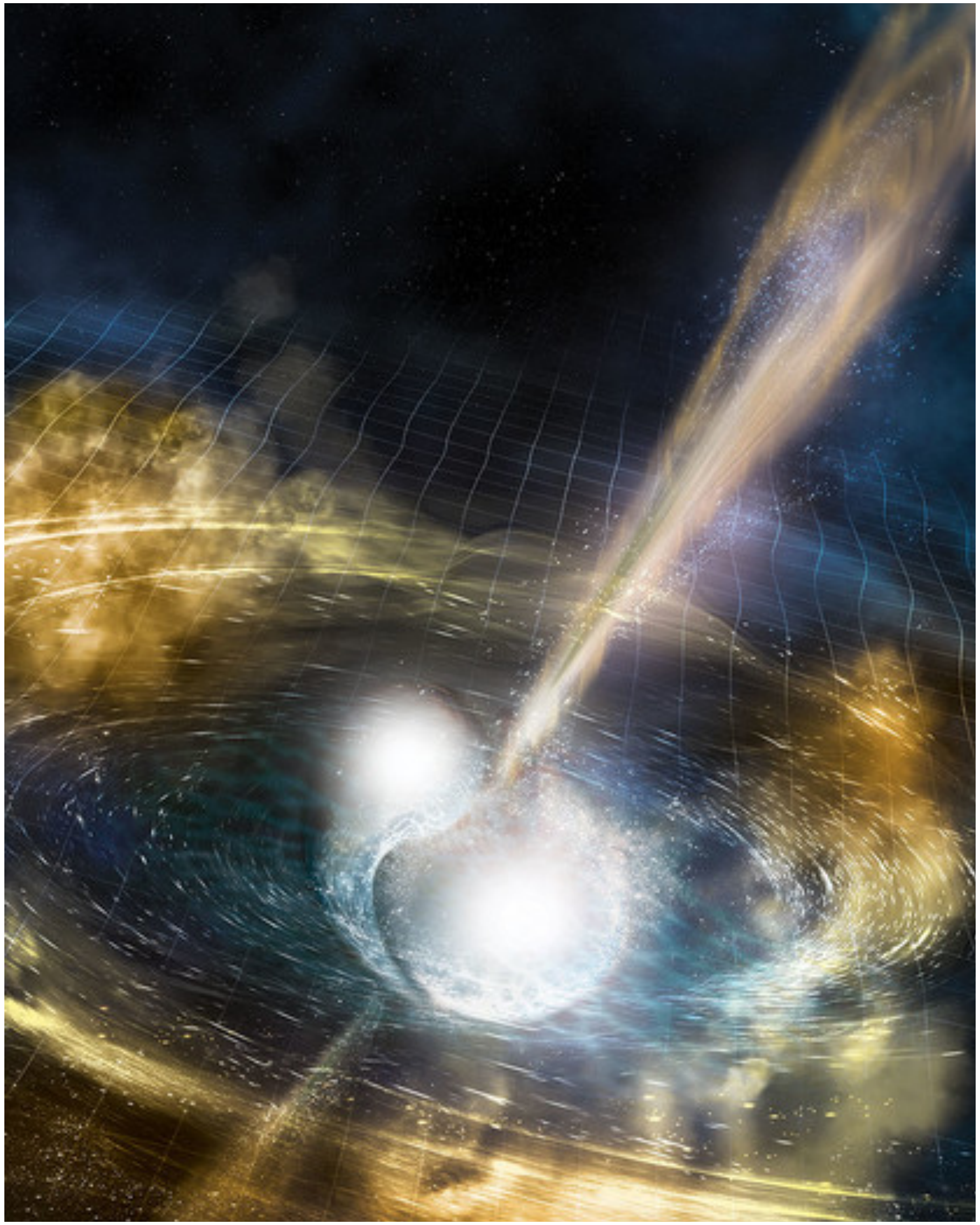
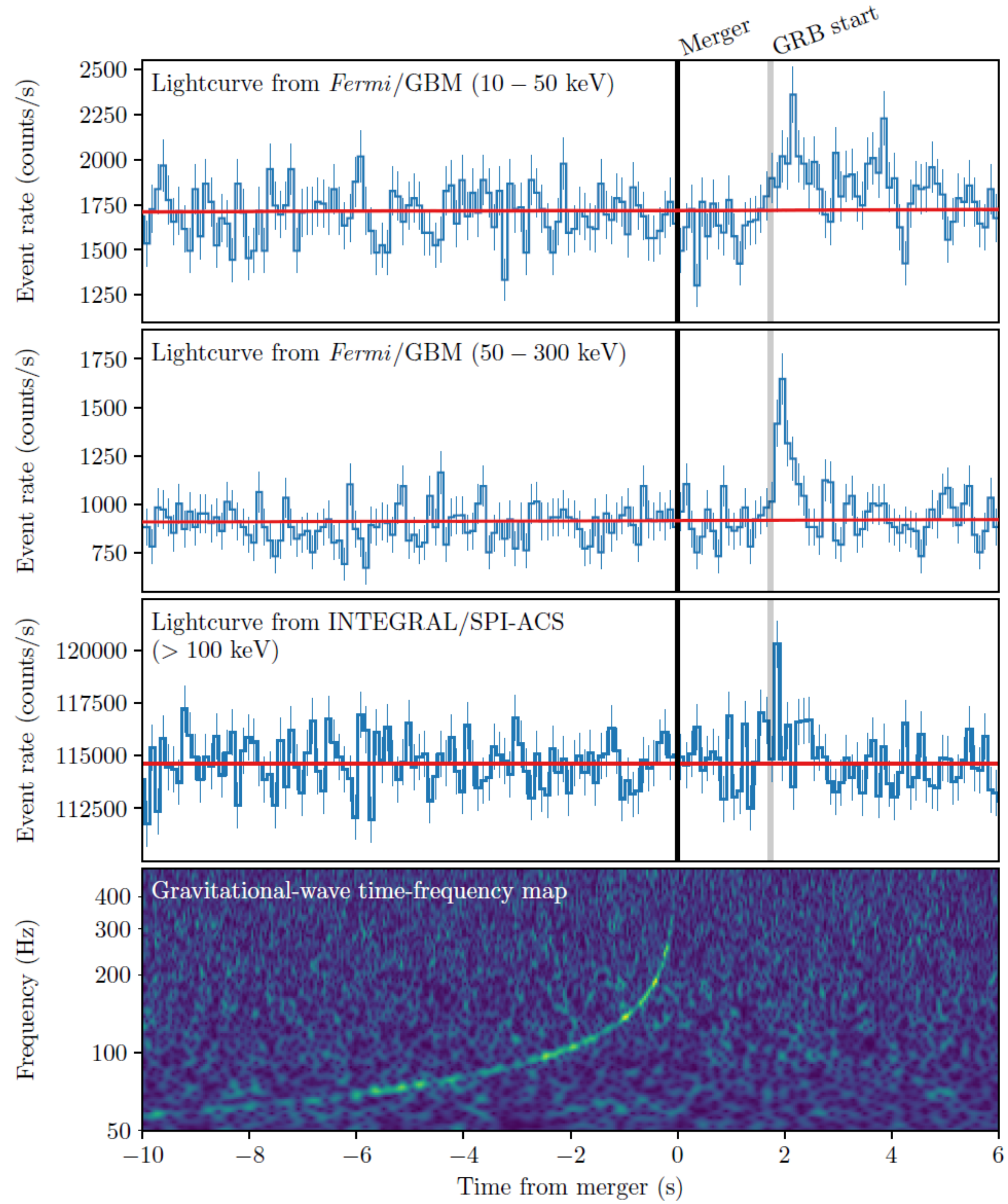
Multi-Messenger Astrophysics is Here





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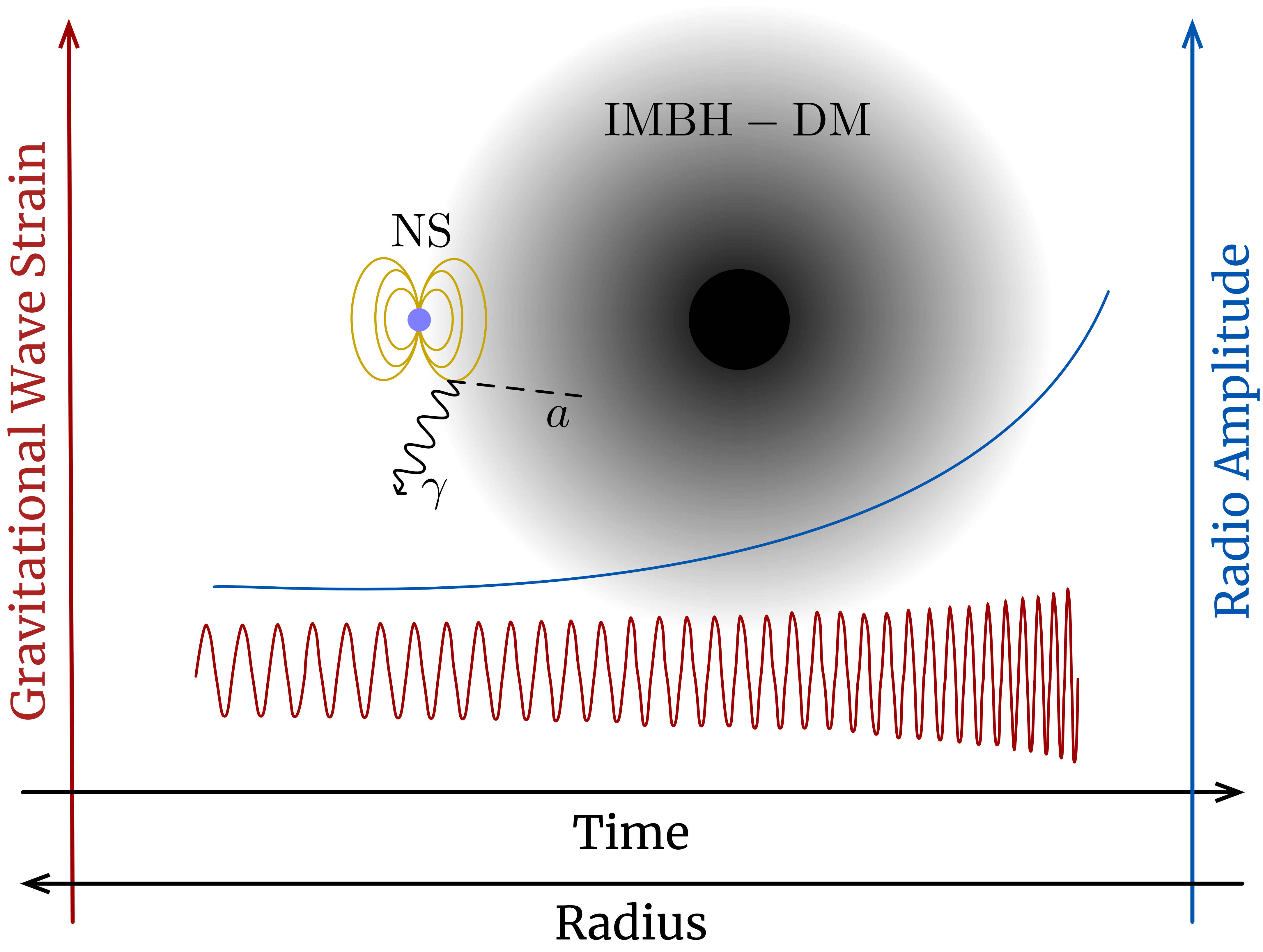
Multi-Messenger Signal of QCD Axion

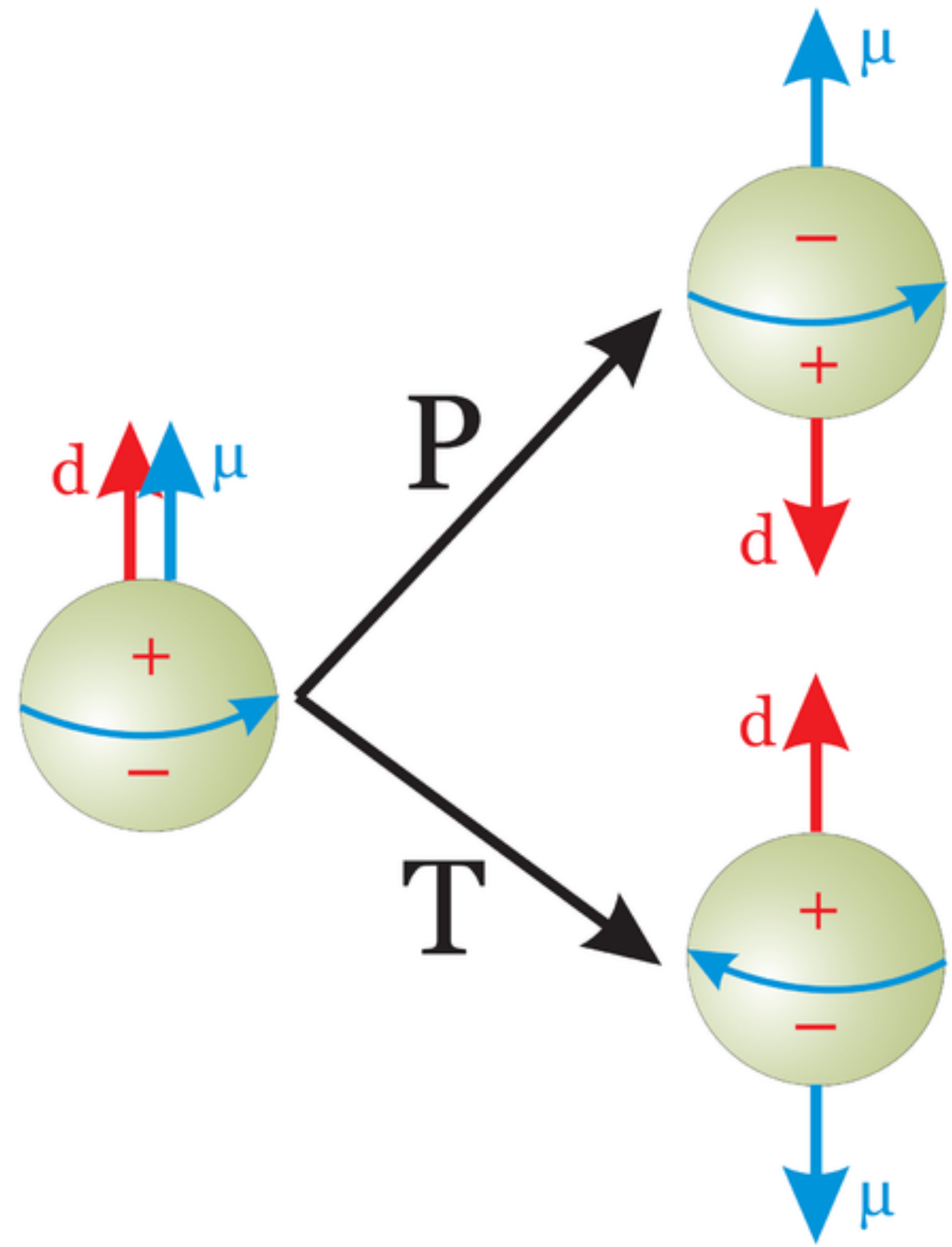


QCD Axion Dark Matter

- The strong interaction also admits a **CP violating term in its Lagrangian**
- Promoting theta to a field allows the CP-violating term to dynamically reach zero
- Goldstones theorem then produces a boson, **the axion**

$$\mathcal{L} = -\frac{g_s^2 \theta}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$|\theta| < 10^{-10}$ $|\theta| \neq \mathcal{O}(1)$

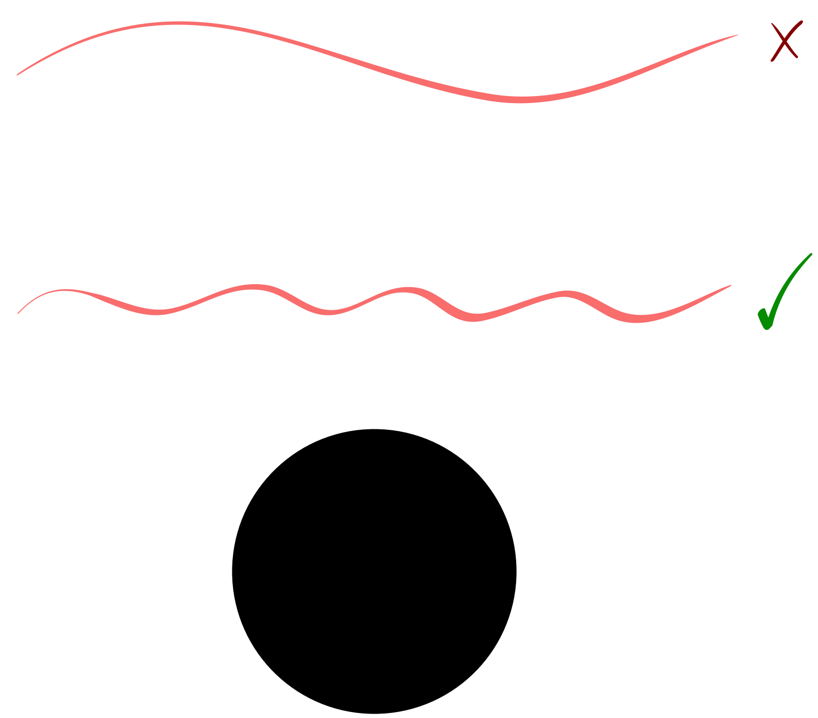


Axion Dark Matter

- **Axion like particles (ALPS)** are generic predictions from various other extensions to the standard model

- Can be considered as particles in astrophysical settings; **Compton wavelength is relatively small**

$$\lambda = \frac{h}{mc}$$



$$m > 10^{-7}\mathrm{eV}$$

1904.12803

Intermediate Mass Black Holes

- Intermediate mass BHs are the least constrained mass window, between **10^3 and 10^5 solar masses**
- The are thought to be quite abundant in star clusters such as **globular clusters** as well as in small galaxies
- They can form through multiple channels:
  1. Merging of many stellar mass BHs
  2. Merger and consequent collapse of massive stars

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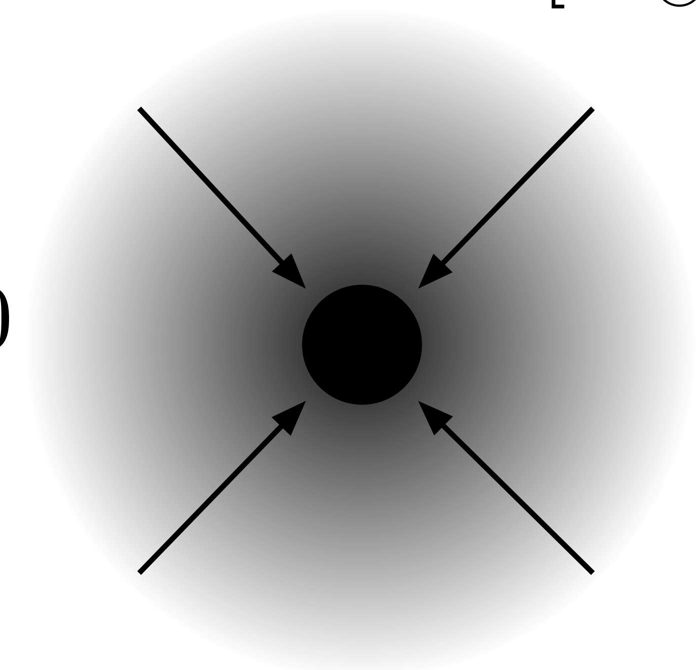
Mini-Spike from a Dark Matter Halo

$$M_{\rm DM} = 10^6\ [{\rm M}_\odot]$$

$z = 20$



- These IMBHs can be born in mini-halos of **10^6 solar masses**
- Assume that the growth of the central BH is **adiabatic**

$$f_{\rm ini}(E, L) \rightarrow f_{\rm fin}(E, L)$$

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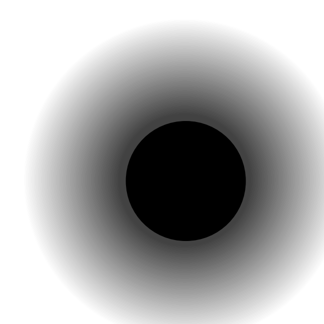
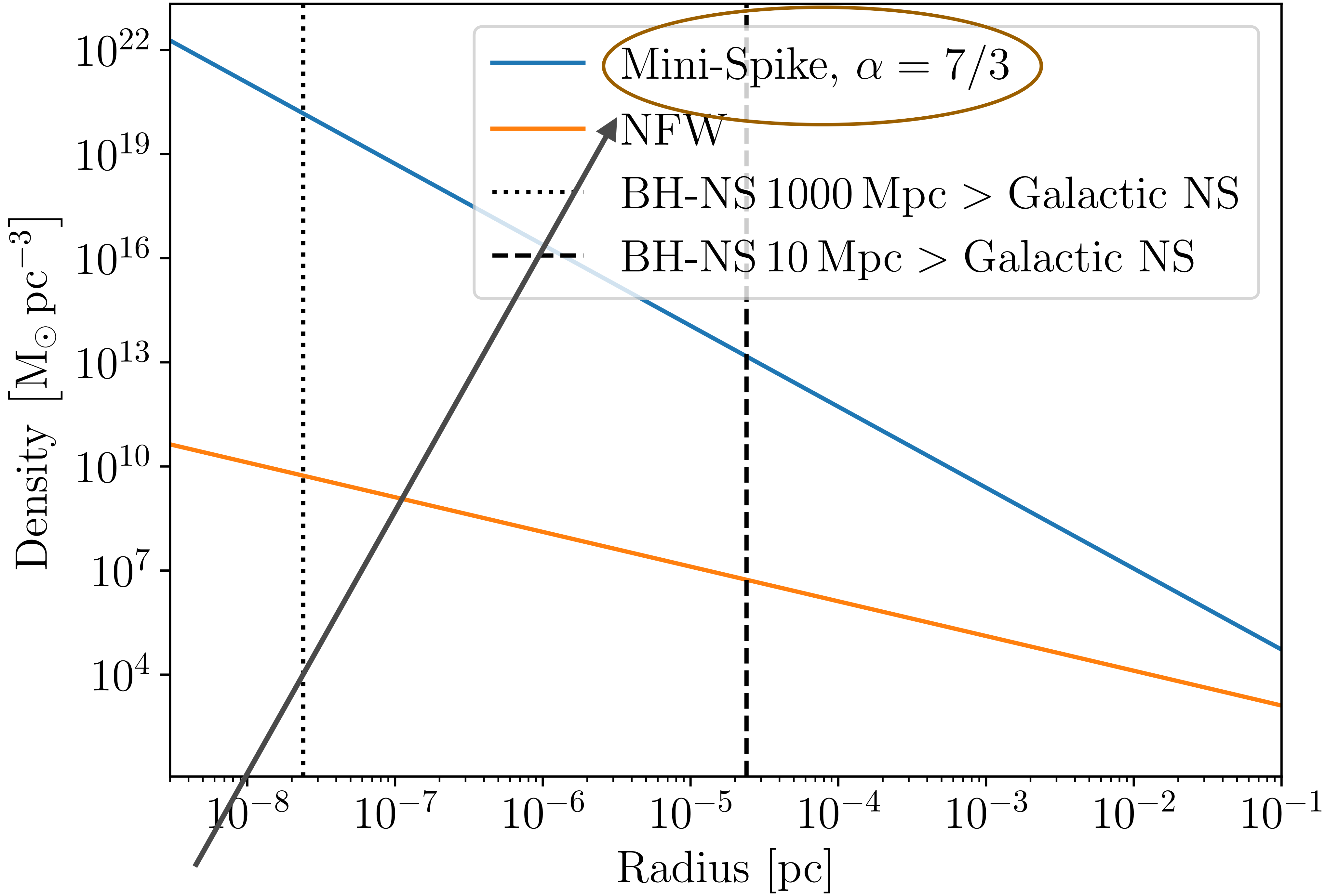
$z = 0$

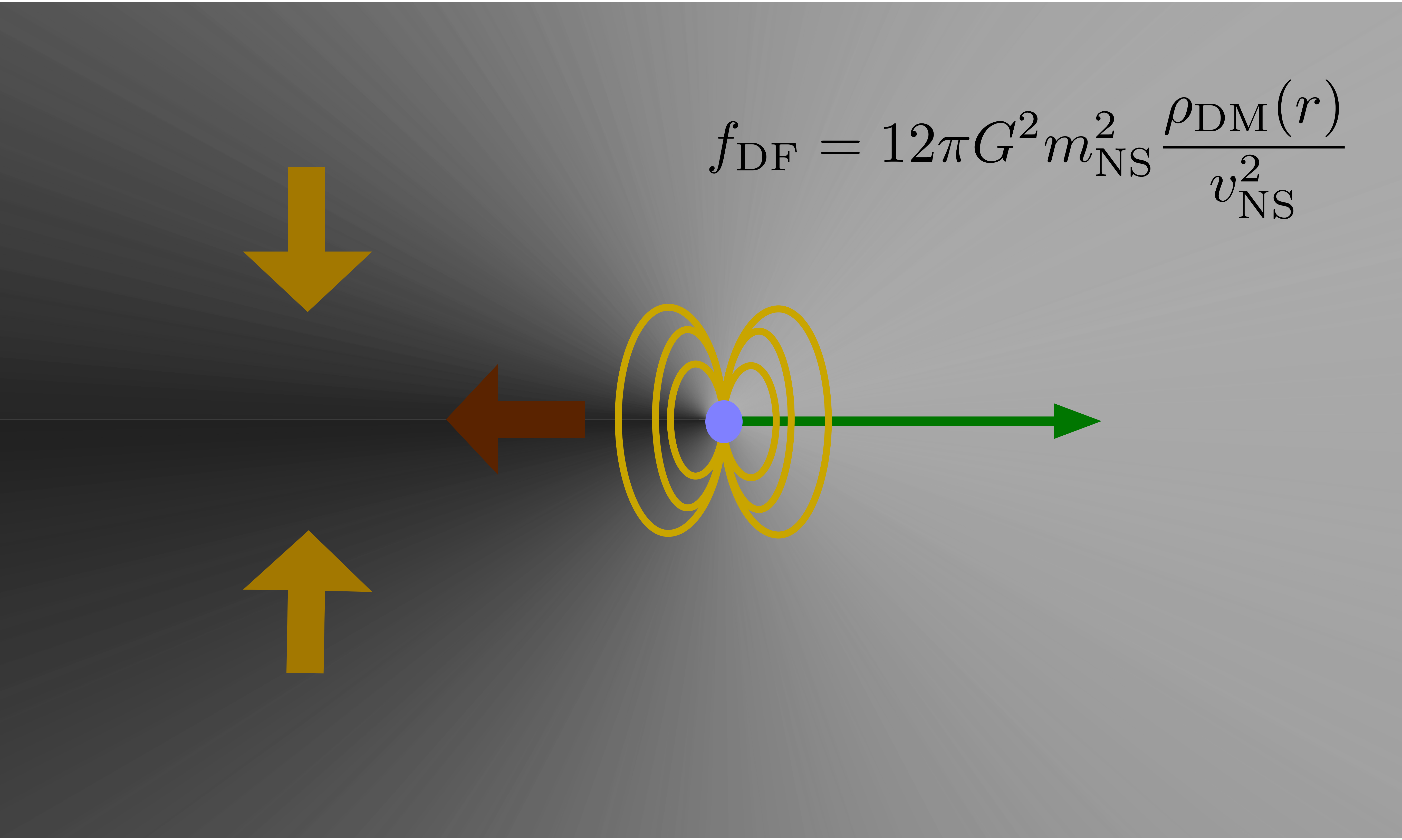


Structure of the Mini-Spike



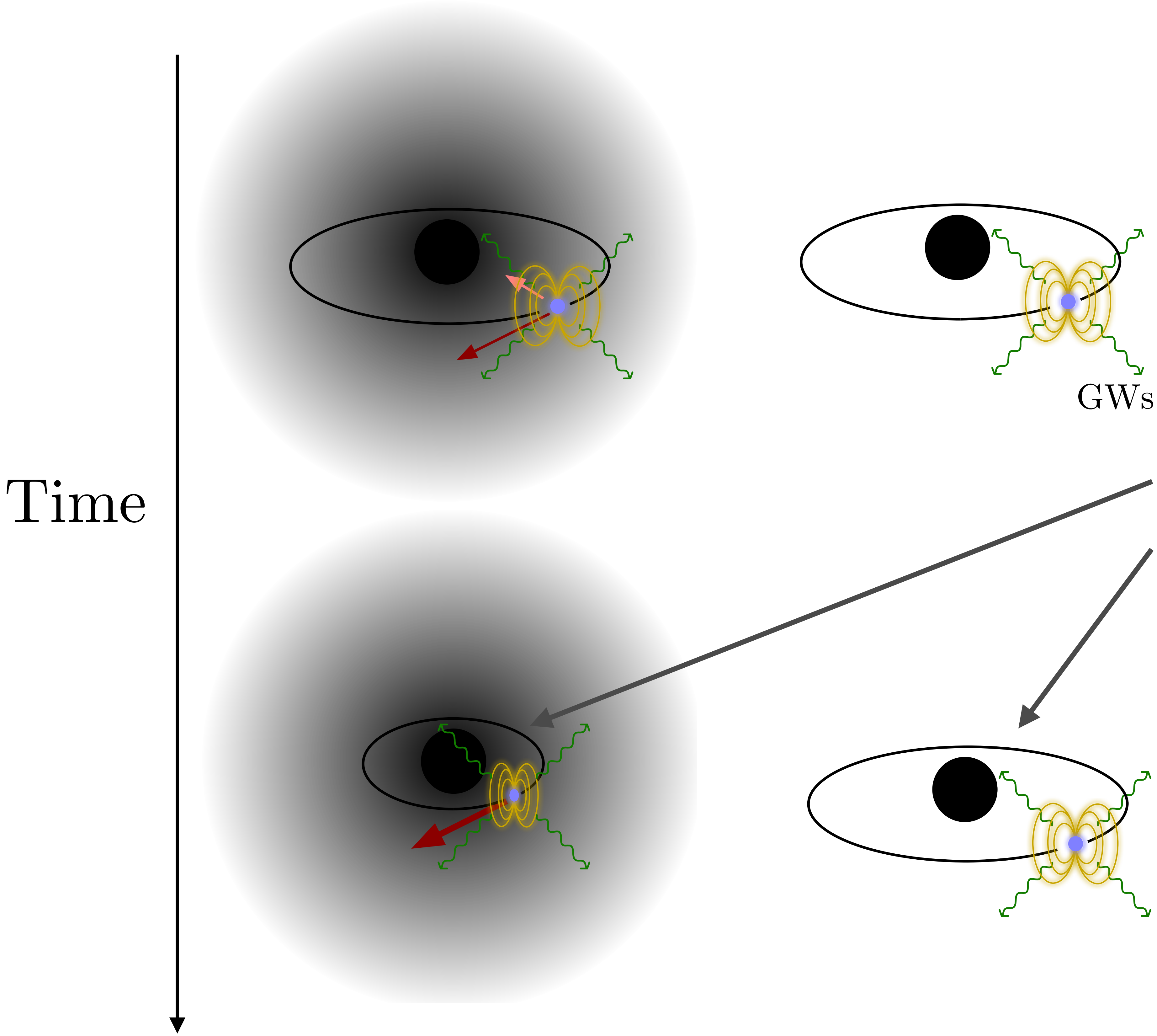
Density slope depends on
initial slope

Dynamical Friction



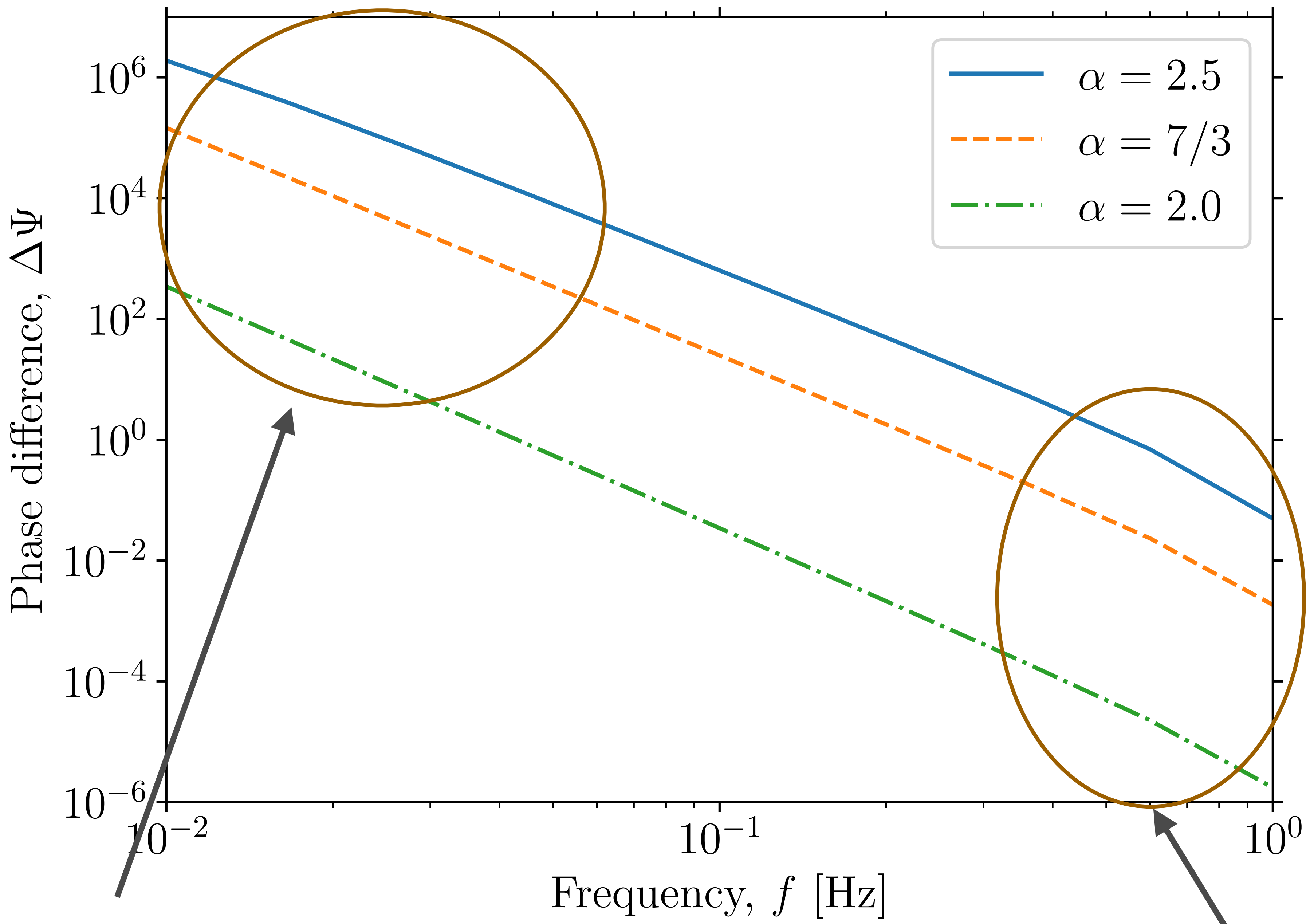
$$f_{\mathrm{DF}} = 12\pi G^2 m_{\mathrm{NS}}^2 \frac{\rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}^2}$$

Dynamical Friction in a Binary System



The smaller partner will reach merger **faster than in a vacuum** inspiral = Change in Phase evolution

Dephasing of the GW Signal



Majority of the phase difference occurs at **large separations**

Number of **cycles low in the final stages** of the evolution

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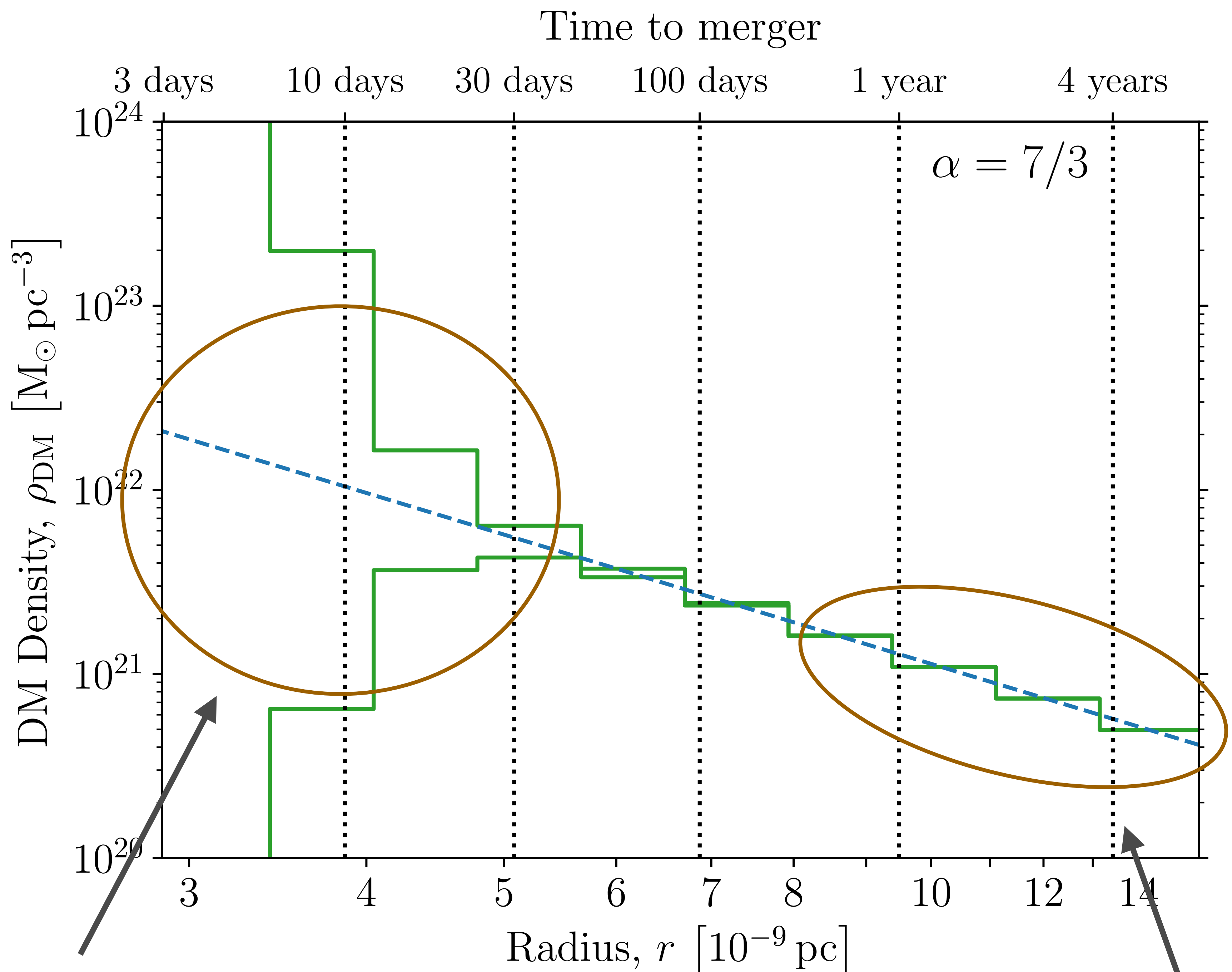
Gravitational Waves Constrain the Slope of the Density Profile



Effect on GW small towards the end of the inspiral

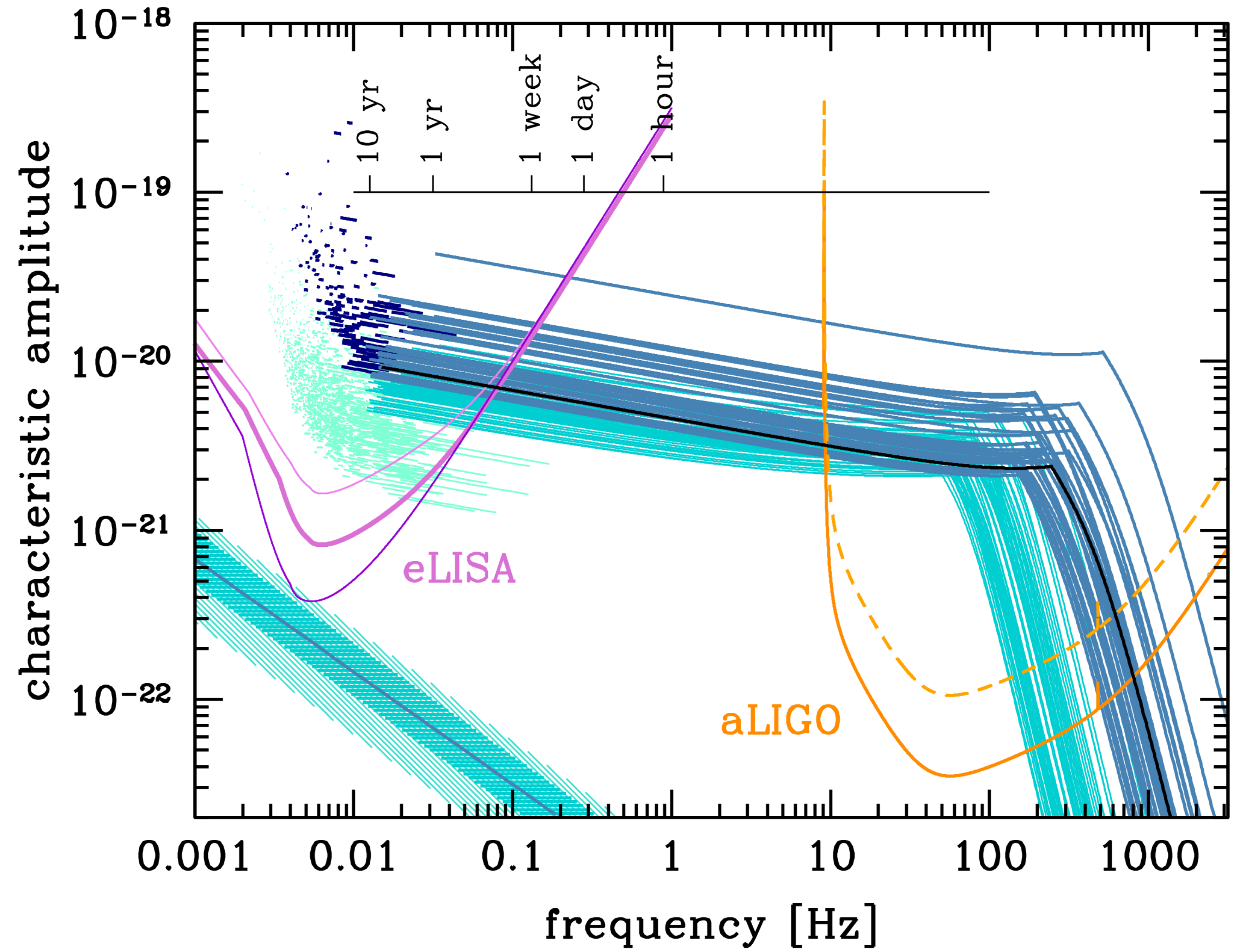
Tight constraints at larger radii

Rates and Lisa Sensitivity

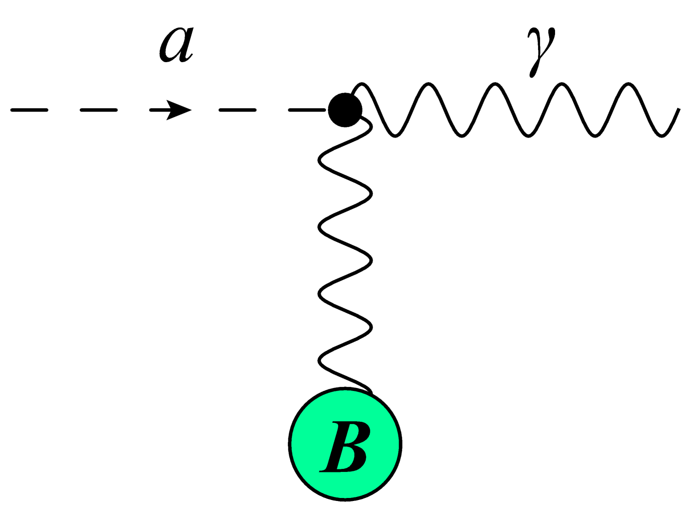
- Uncertainty in IMBH formation channels make merger rate calculations **extremely uncertain**
- Lisa will see these objects for **5 years prior to merger**

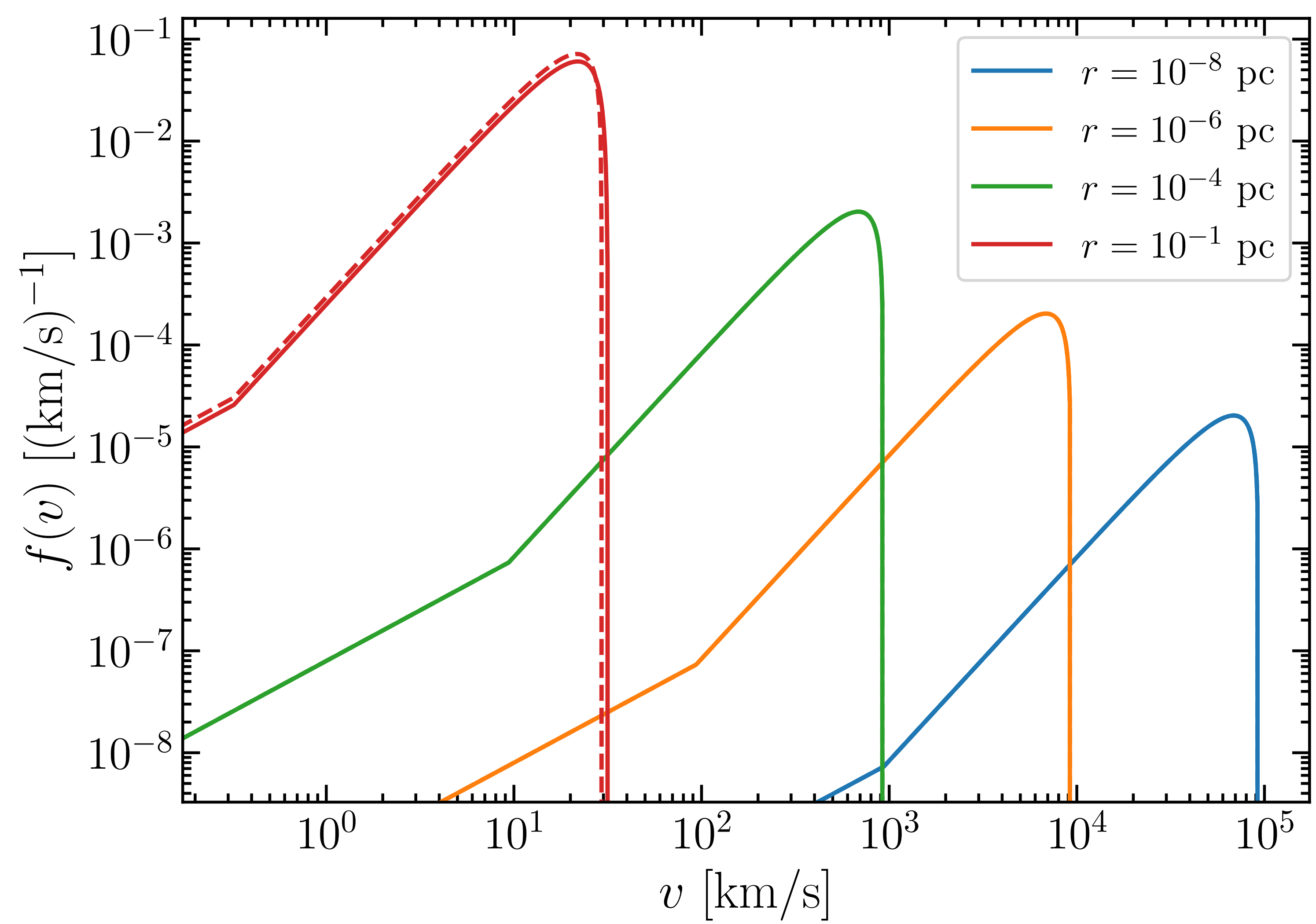
$$\mathcal{R} \sim 3 - 10\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Rates for IMBH mergers with stellar mass objects



Increased Velocity of DM reduces the Signal





- The finite electron density in the plasma gives the **photon an effective mass**
- Signal is dependent on the **velocity distribution of the DM**

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}\right)_{\Psi=0}\right]$$

$$\mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Constant Signal — Not Modulated by NS Spin

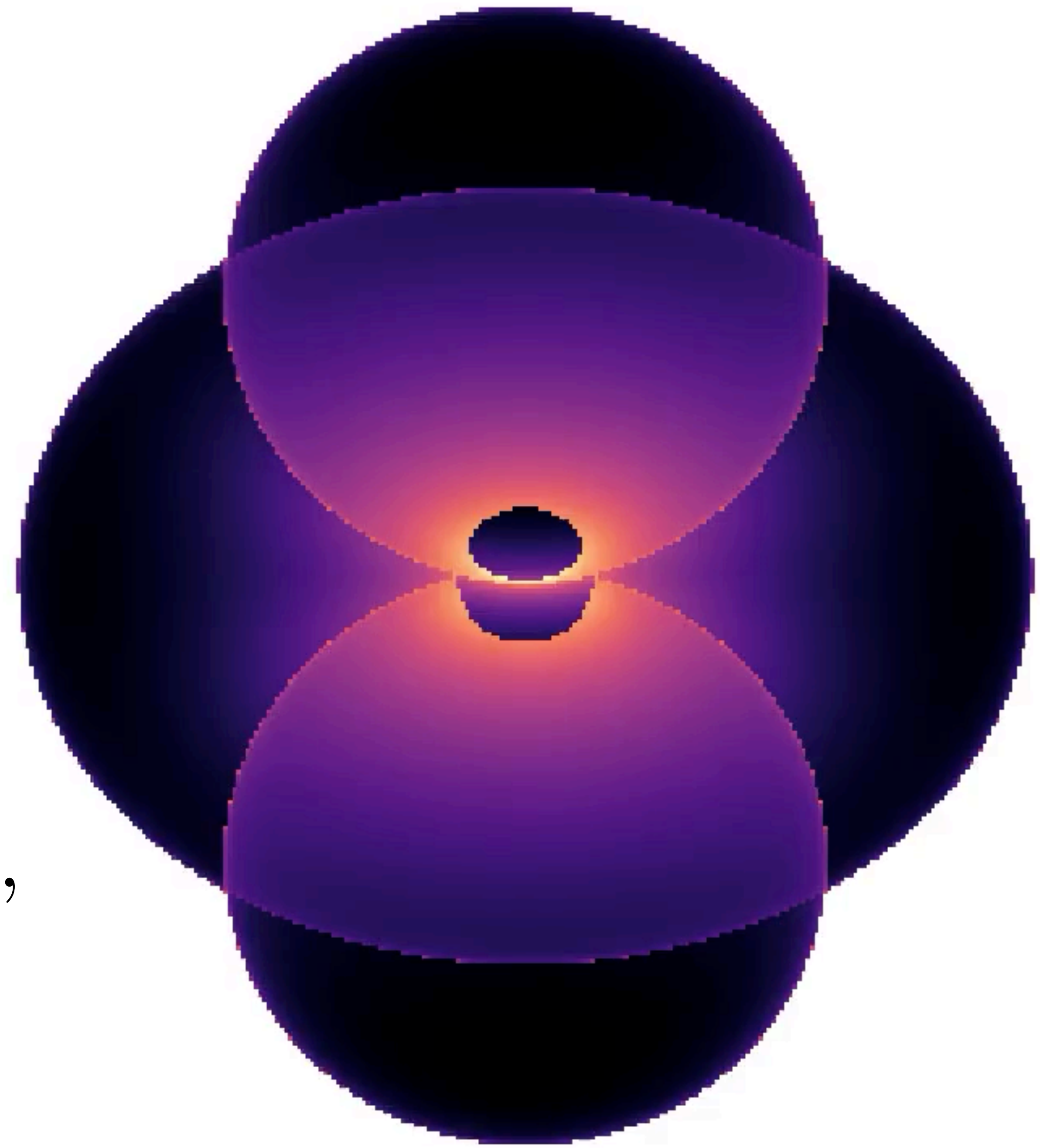
Time variations due to rotation of NS are averaged out

Cannot observe **Doppler shift from rotation around the BH**, since the velocity of the NS is slower than the DM

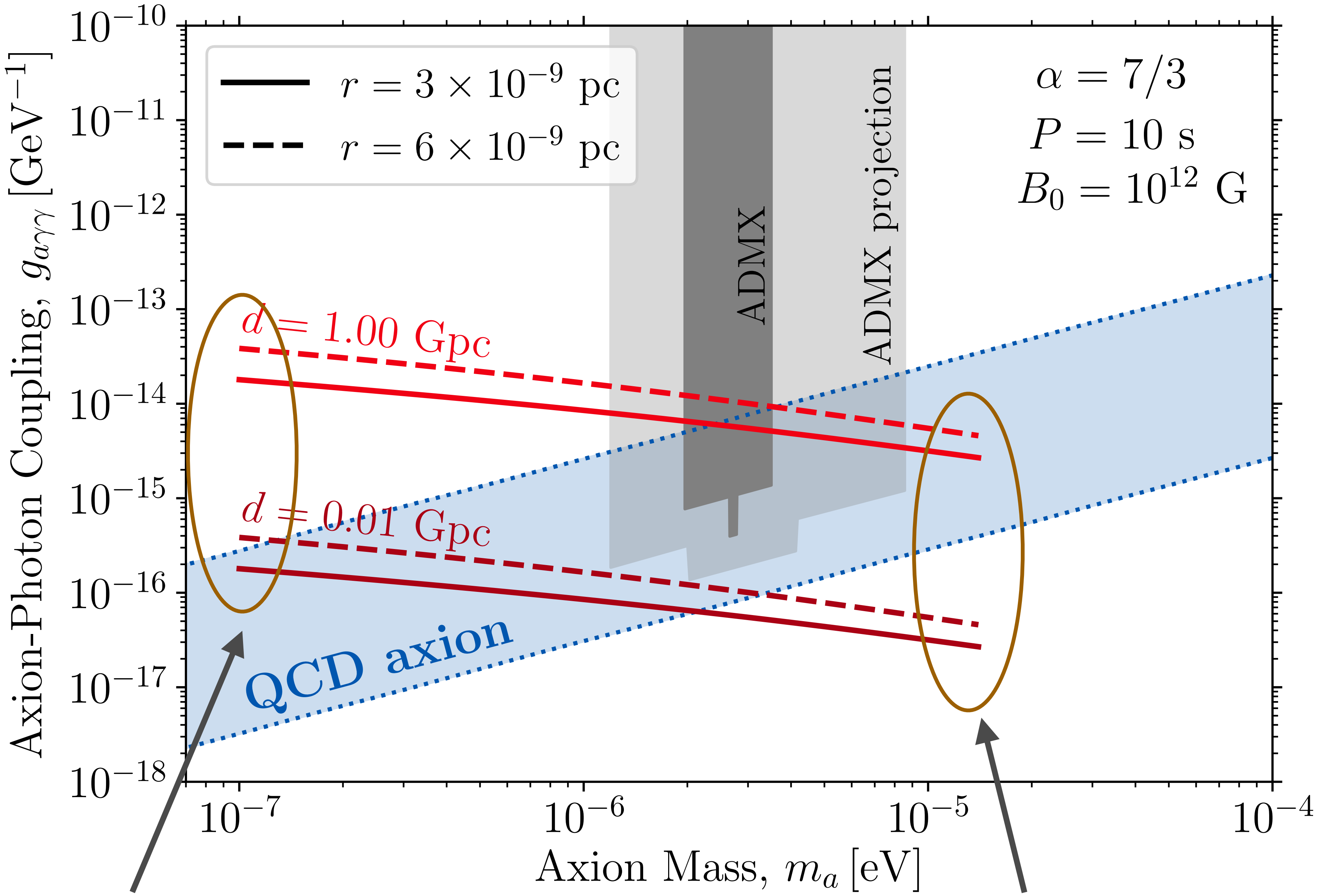
1804.03145

$$\frac{d\mathcal{P}}{d\Omega} \sim 2 \times p_{a\gamma}\rho_{\rm DM}(r_c)v_c r_c^2\,,$$

$$p_{a\gamma} \propto \frac{g_{a\gamma\gamma}^2 B(r_c)^2}{2v_c}$$



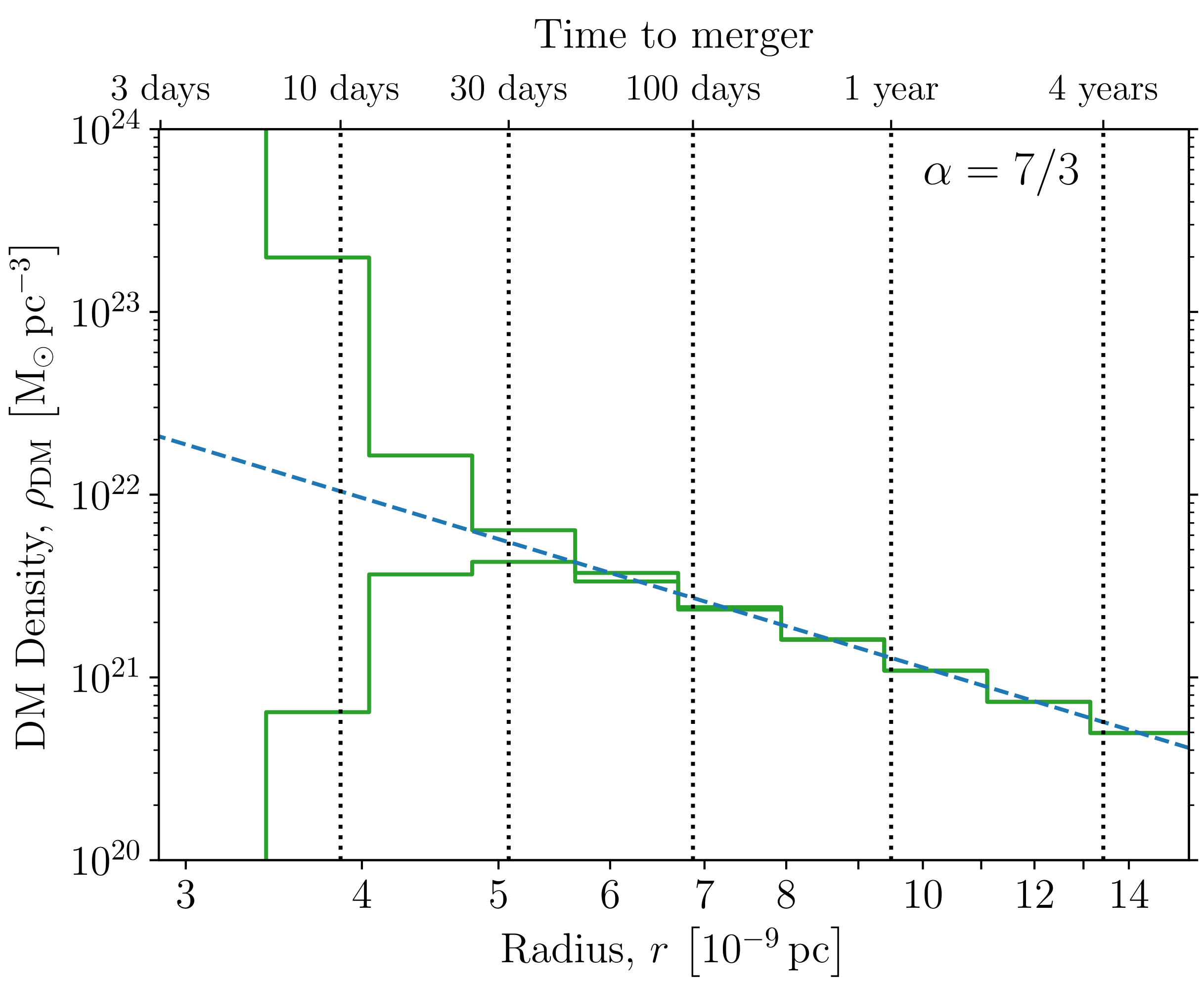
Sensitivity of SKA

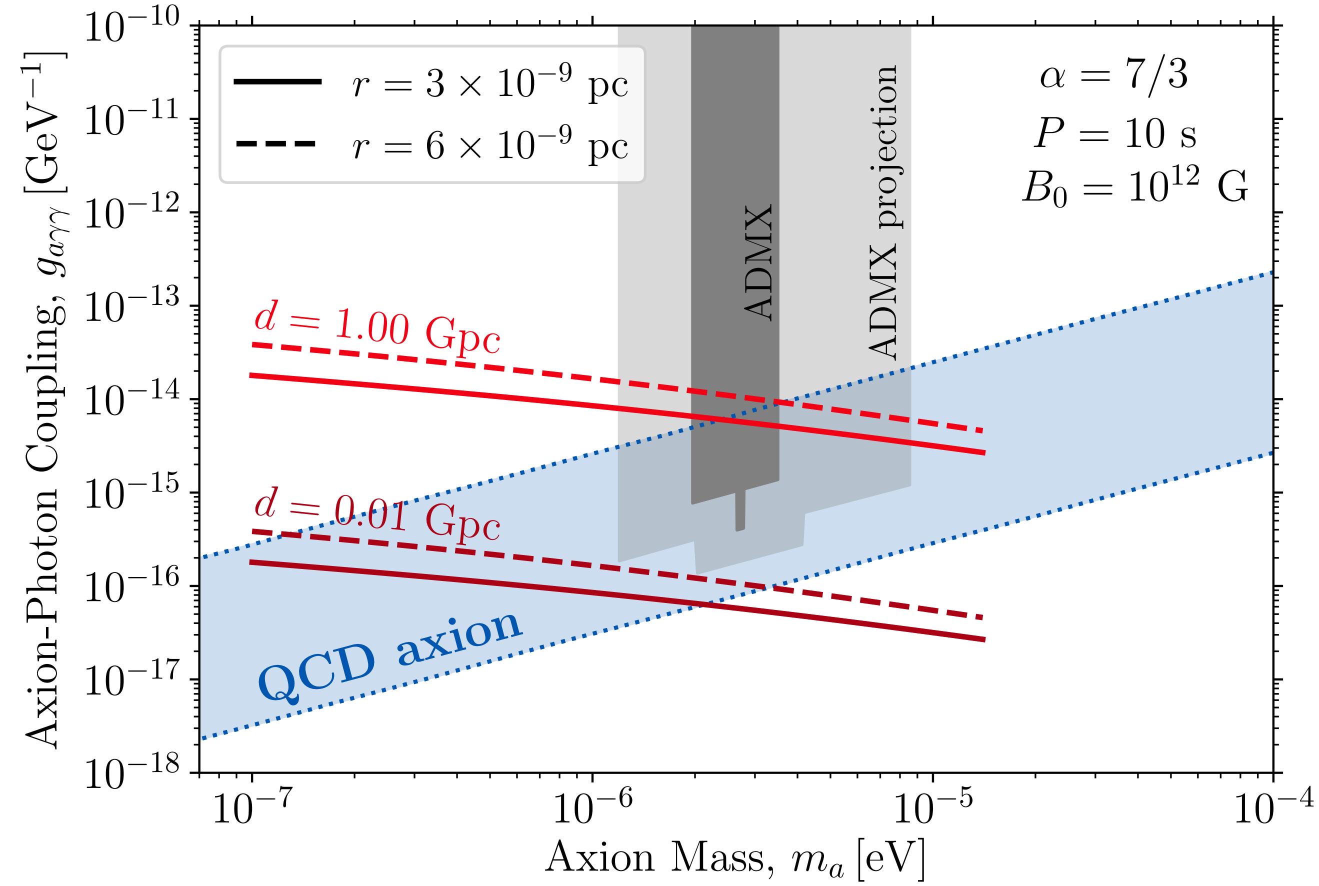


Lower cut off - set by **frequency range of radio telescopes**

Upper cut off - conversion to photons must happen **outside of the NS**

Two Messengers can be Combined for Robust Signal





Difficult to set robust limits due to the **uncertainty in the NS properties**, magnetic field etc.

If many are found, utilising **NS population properties** will allow for a more robust constraint

Conclusions

Multi-messenger Astrophysics can be used to **probe fundamental physics** in extreme astrophysical environments

QCD Axion Dark Matter can **potentially be discovered** with future GW and radio observations