A Unique Multi-Messenger Signal of QCD Axion Dark Matter

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- Edwards, MC, Kavanagh, Nissanke and Weniger, [arXiv: 1905.04686](https://arxiv.org/abs/1905.04686)

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QCD axion: solution for Strong-CP problem

The QCD axion is a viable and theoretically well-motivated Dark Matter candidate.

- The QCD Lagrangian admits CP violating term θ: $\mathcal{L}_{\rm QCD} \supset -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta$

- However, no evidence of CP violation in QCD sector: $|\theta| \leq 10^{-10}$

Strong CP-problem: why θ is so small?

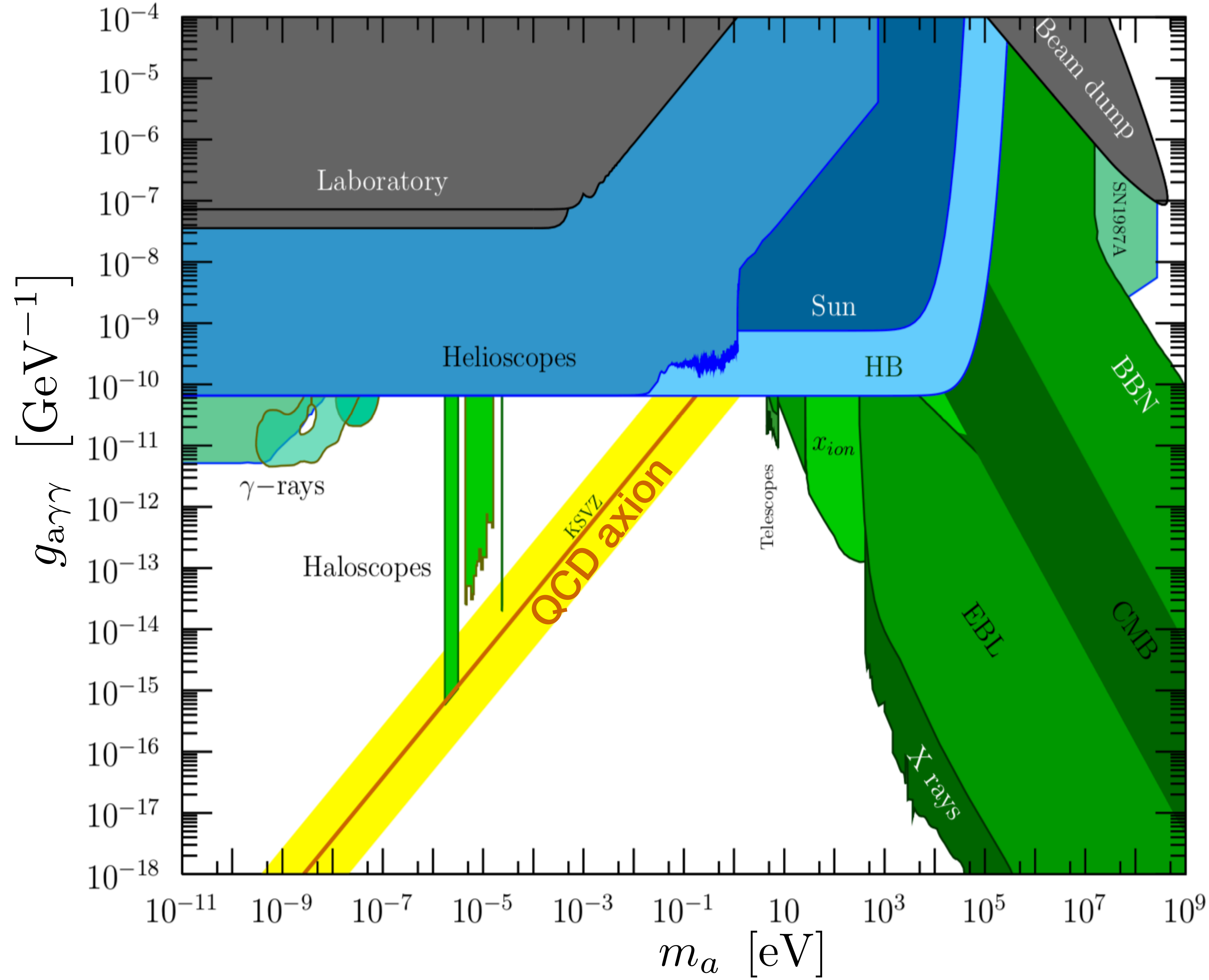
- It is dynamically solved by promoting θ to be a scalar field, the axion.

Most of the axion searches exploits its coupling to the photon field.

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

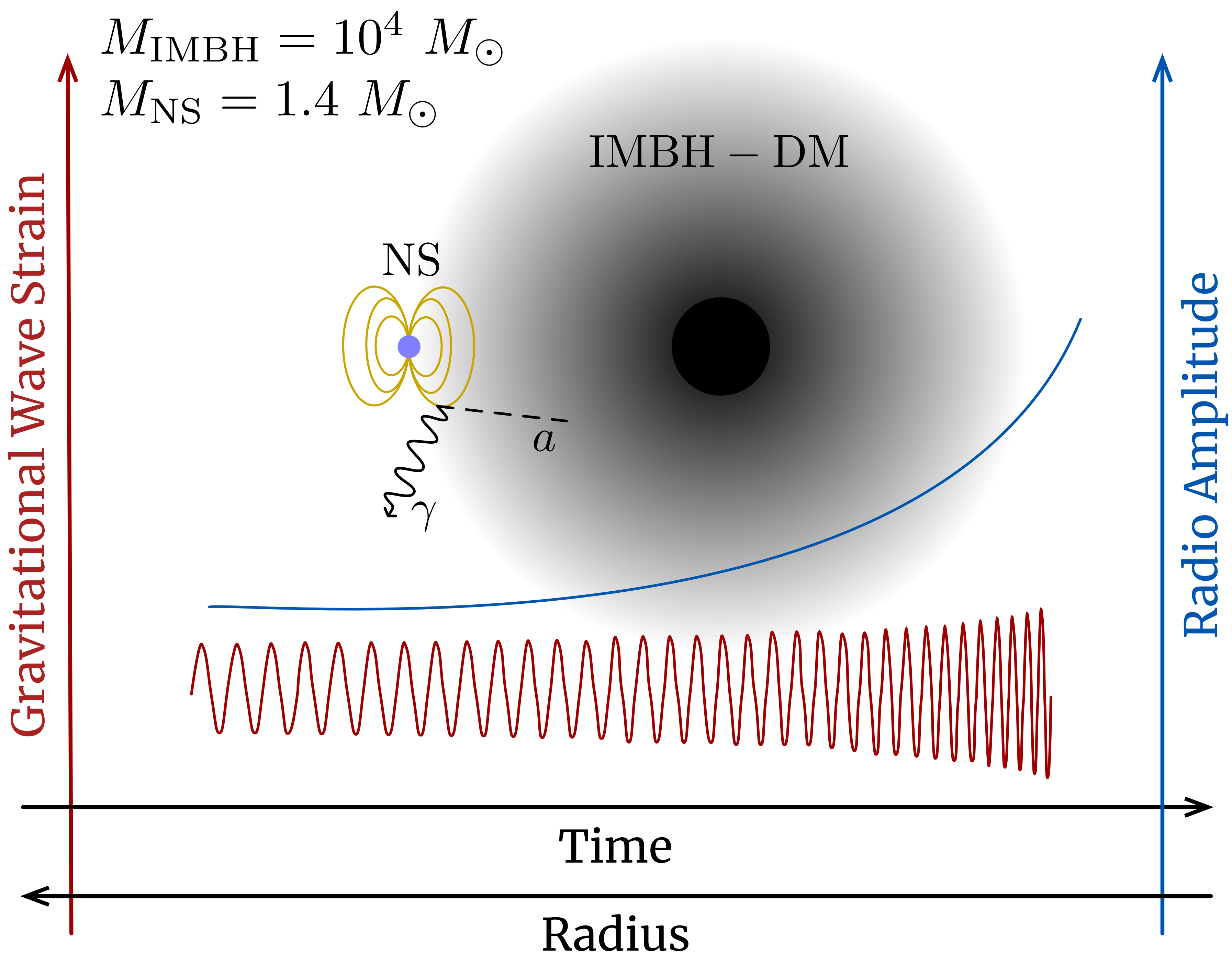
Axion-photon conversion in an external magnetic field

Axion parameter space



Irastorza and Redondo, ***Prog.Part.Nucl.Phys. 102 (2018)***

Multi-messenger Signal of QCD axion



GW

Distinct phase shift in the Gravitational Wave strain

Inspirals of Intermediate Mass Black Hole and Neutron Star

EM

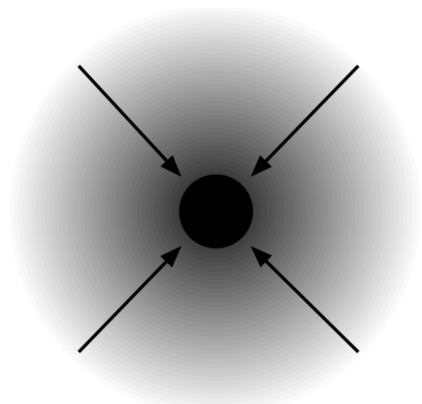
Radio emission from axion-photon conversion in the NS magnetosphere

Dark Matter Spike

IMBHs may exist in DM haloes and form a DM spike through their adiabatic growth.

DM halo

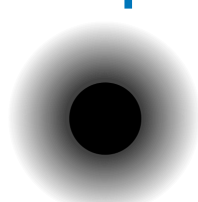
$z = 20$



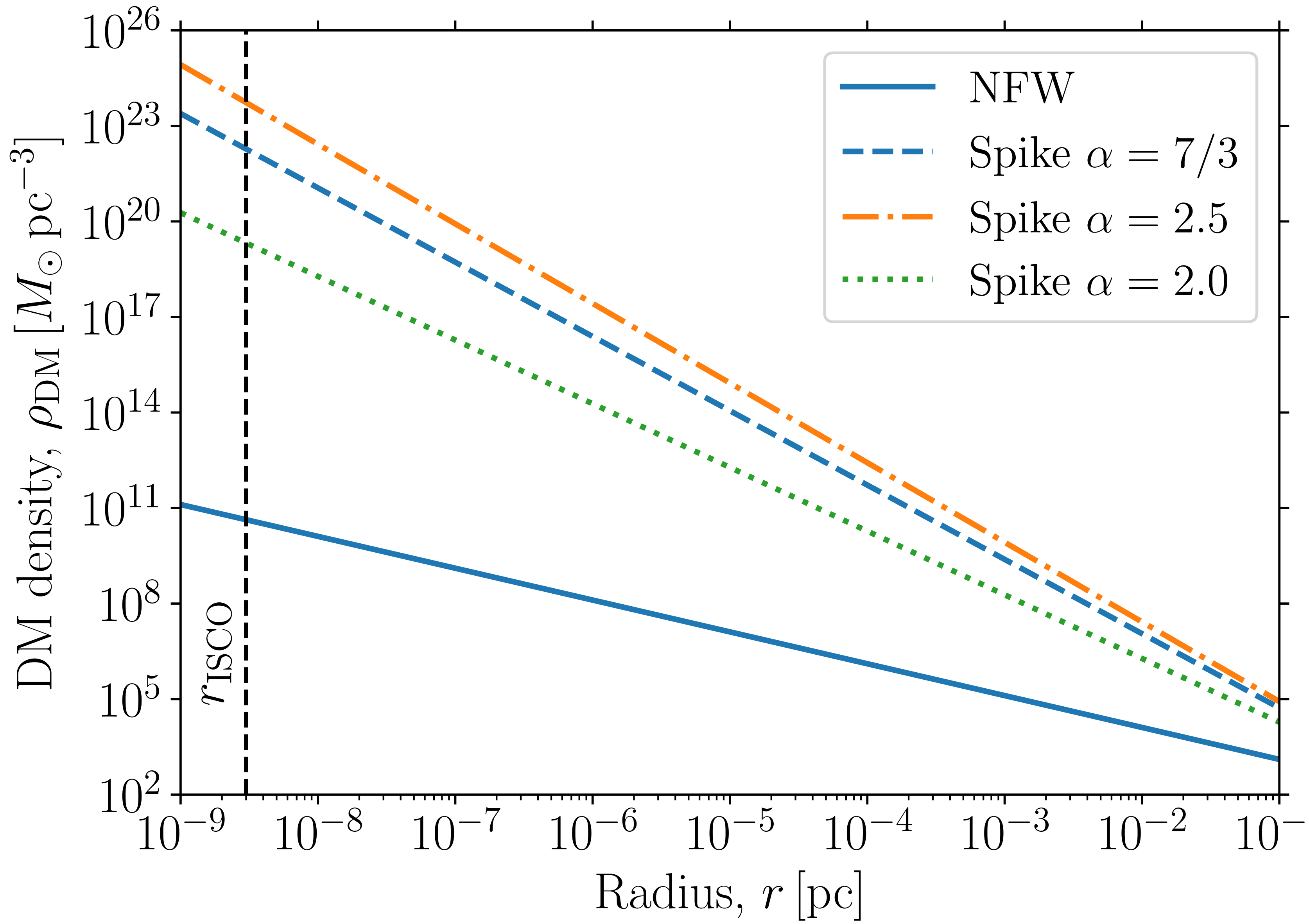
$$\rho_{\mathrm{DM}} \propto r^{-\alpha_{\mathrm{init}}}$$

DM spike

$z = 0$



$$\rho_{\mathrm{DM}} = \rho_{\mathrm{sp}} \left(\frac{r}{r_{\mathrm{sp}}}\right)^{-\alpha}$$

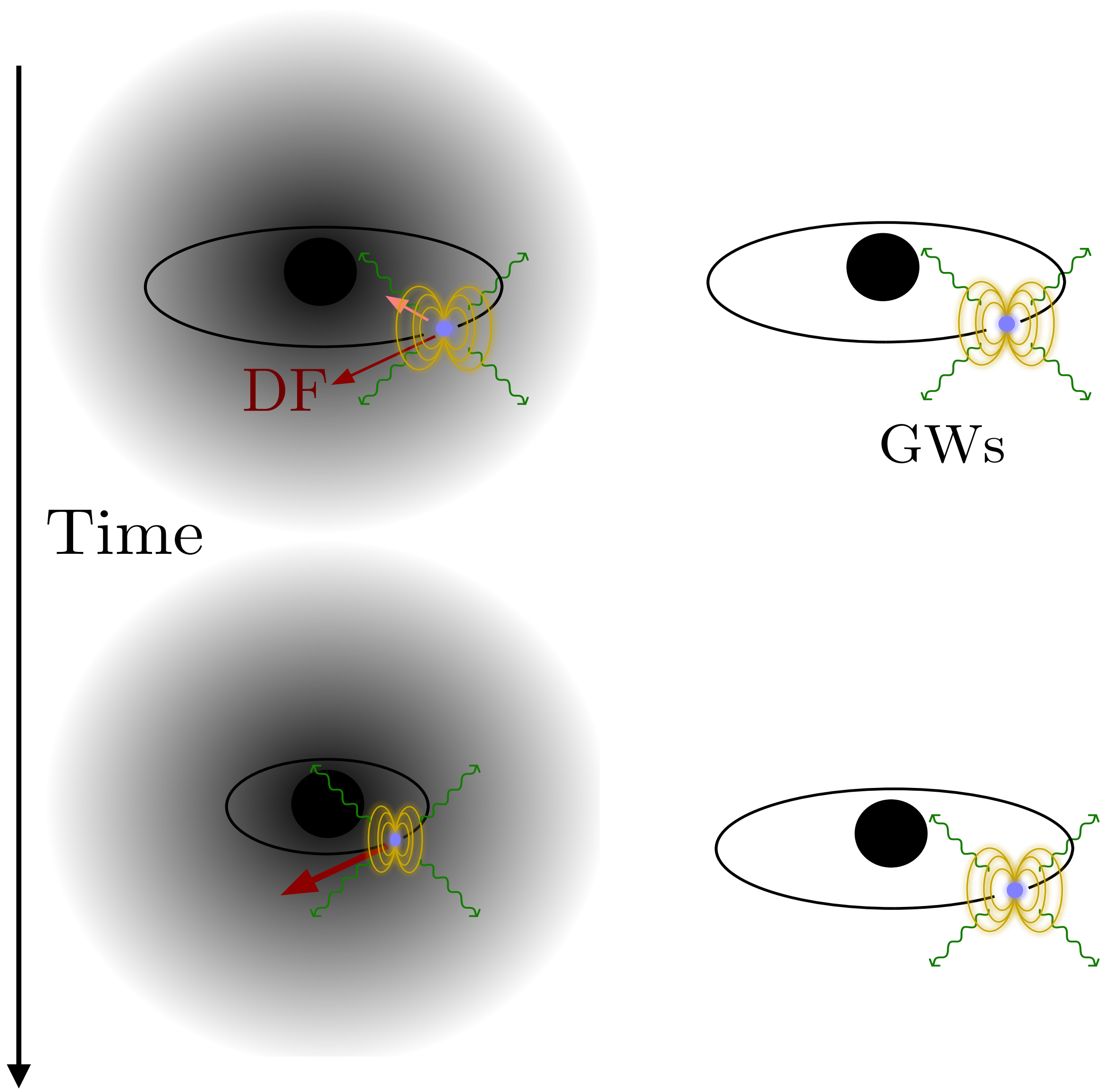


The DM density is **extremely enhanced** towards innermost stable circular orbit (ISCO).

*Navarro, Frenk, White, **ApJ 462 (1996)**; Gondolo and Silk, **PRL 83 (1999)**; Zhao and Silk, **PRL 95 (2005)**; Bertone, Zentner and Silk, **PRD 72 (1999)**.*

Gravitational Wave Signal — Dynamical Friction

Inspiral takes less time than in vacuum



The presence of a DM halo causes additional energy loss:

$$-\frac{\mathrm{d}E_{\mathrm{orbit}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} + \frac{\mathrm{d}E_{\mathrm{DF}}}{\mathrm{d}t}$$

vacuum

- GW emission

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{32}{5}\frac{G\,M_{\mathrm{NS}}^2}{c^5} r^4\,\omega_s^6$$

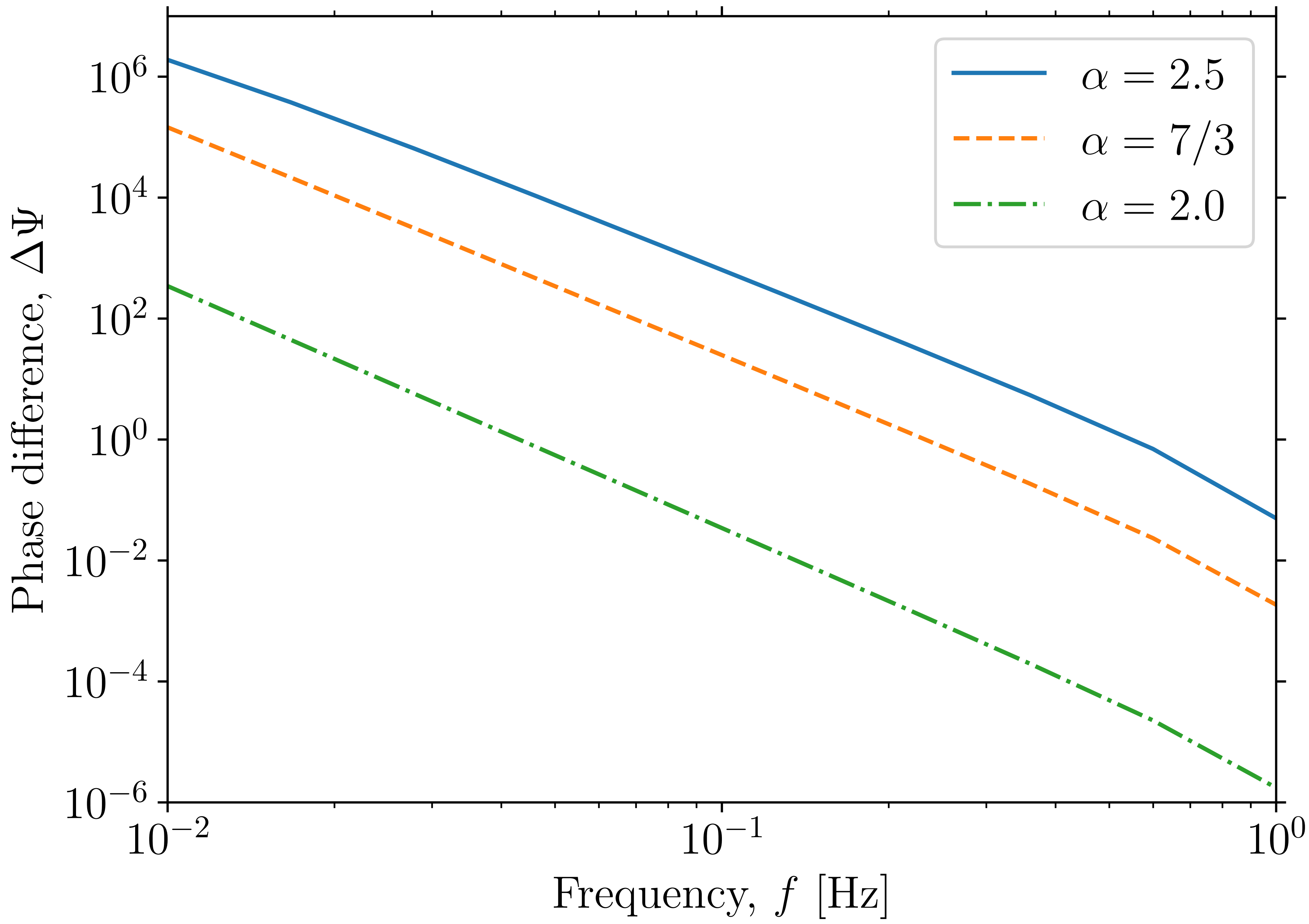
- Dynamical Friction

$$\frac{\mathrm{d}E_{\mathrm{DF}}}{\mathrm{d}t} = 4\pi\,G^2 \ln\Lambda \frac{M_{\mathrm{NS}}^2\,\rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}}$$

Eda et al., ***PRL 110 (2013), PRD 91 (2015)***

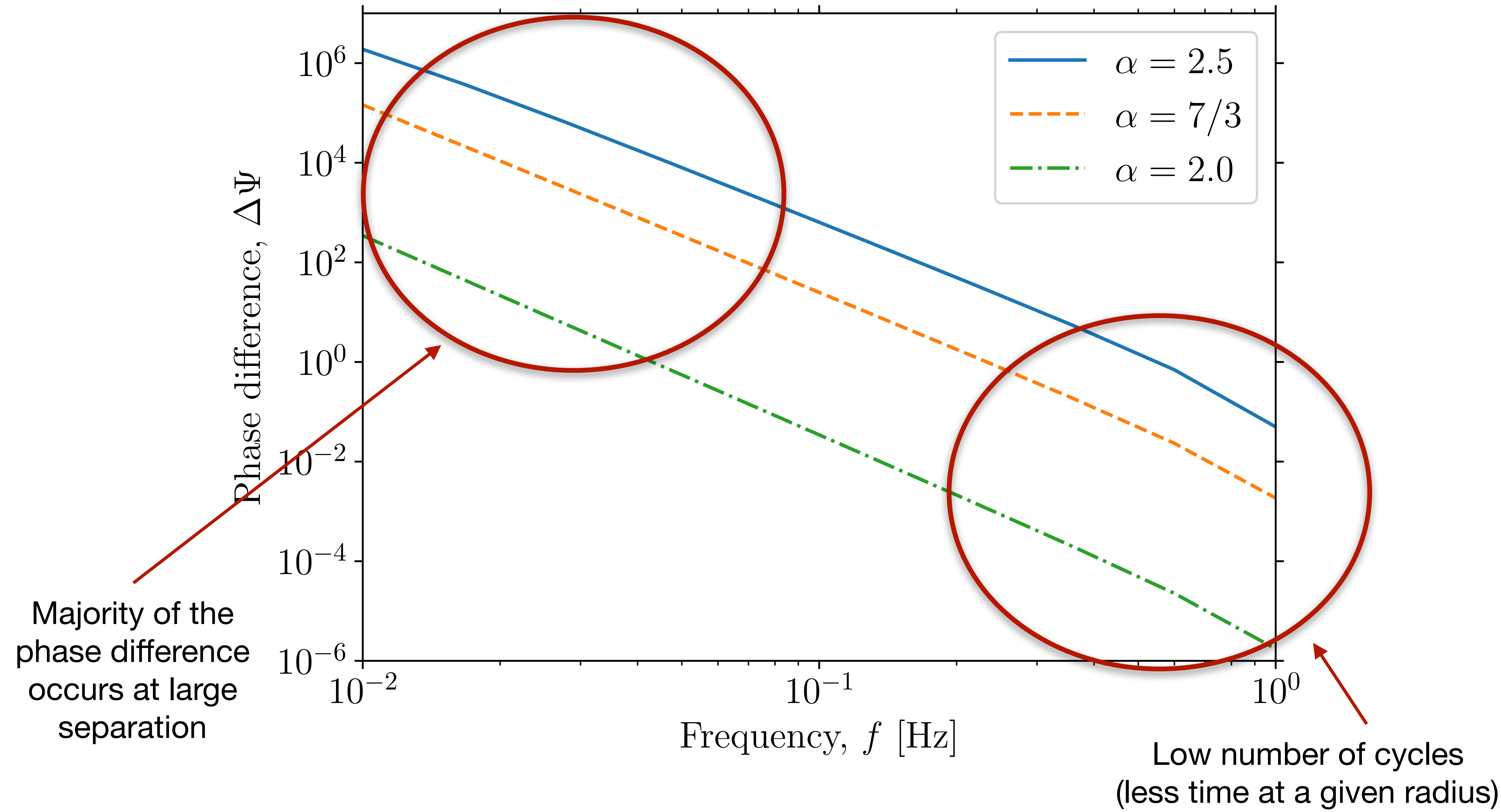
Gravitational Wave Signal — Dynamical Friction

Inspiral takes less time than in vacuum → Phase shift in the GW signal



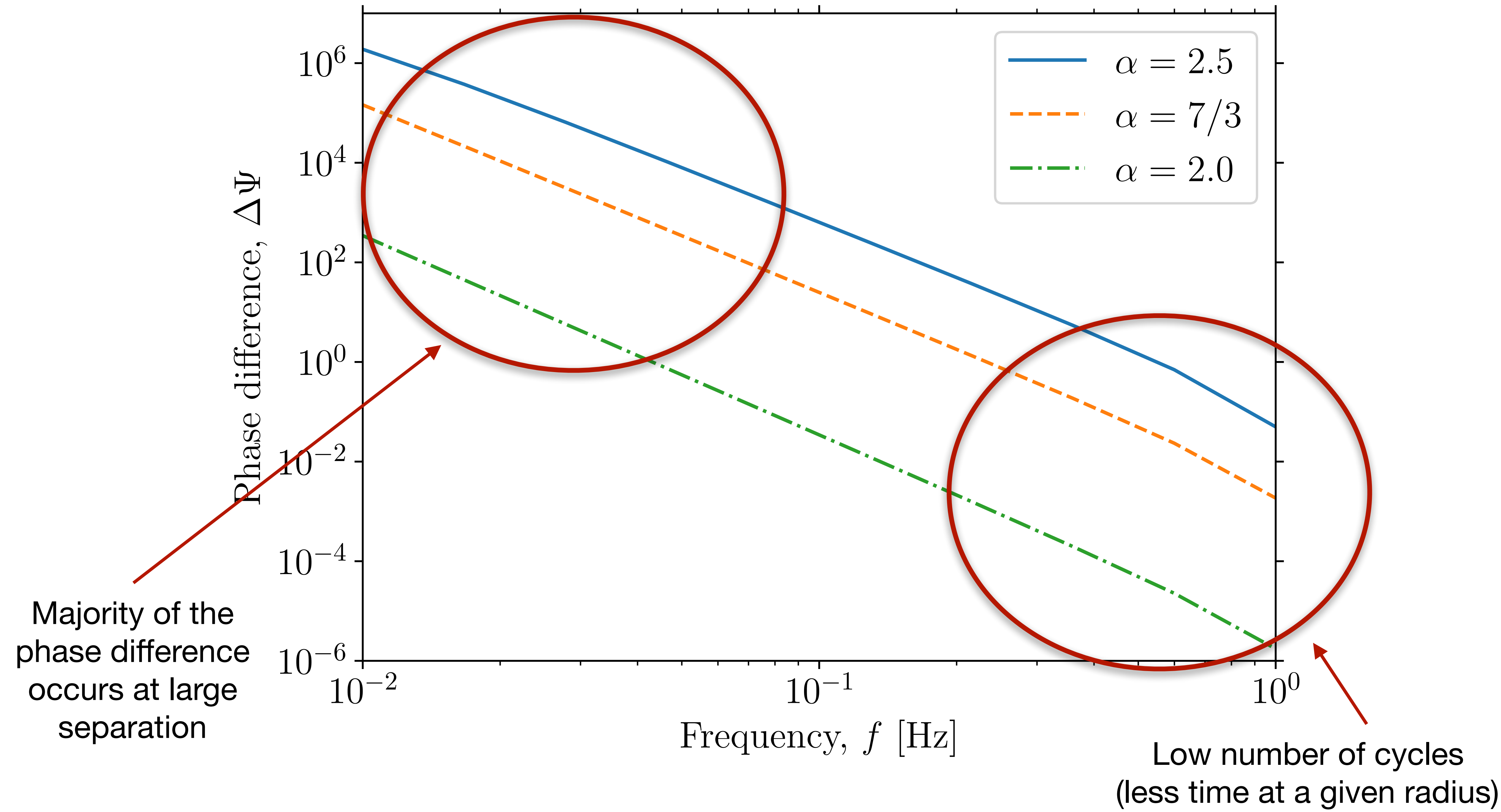
Gravitational Wave Signal — Dynamical Friction

Inspiral takes less time than in vacuum → Phase shift in the GW signal



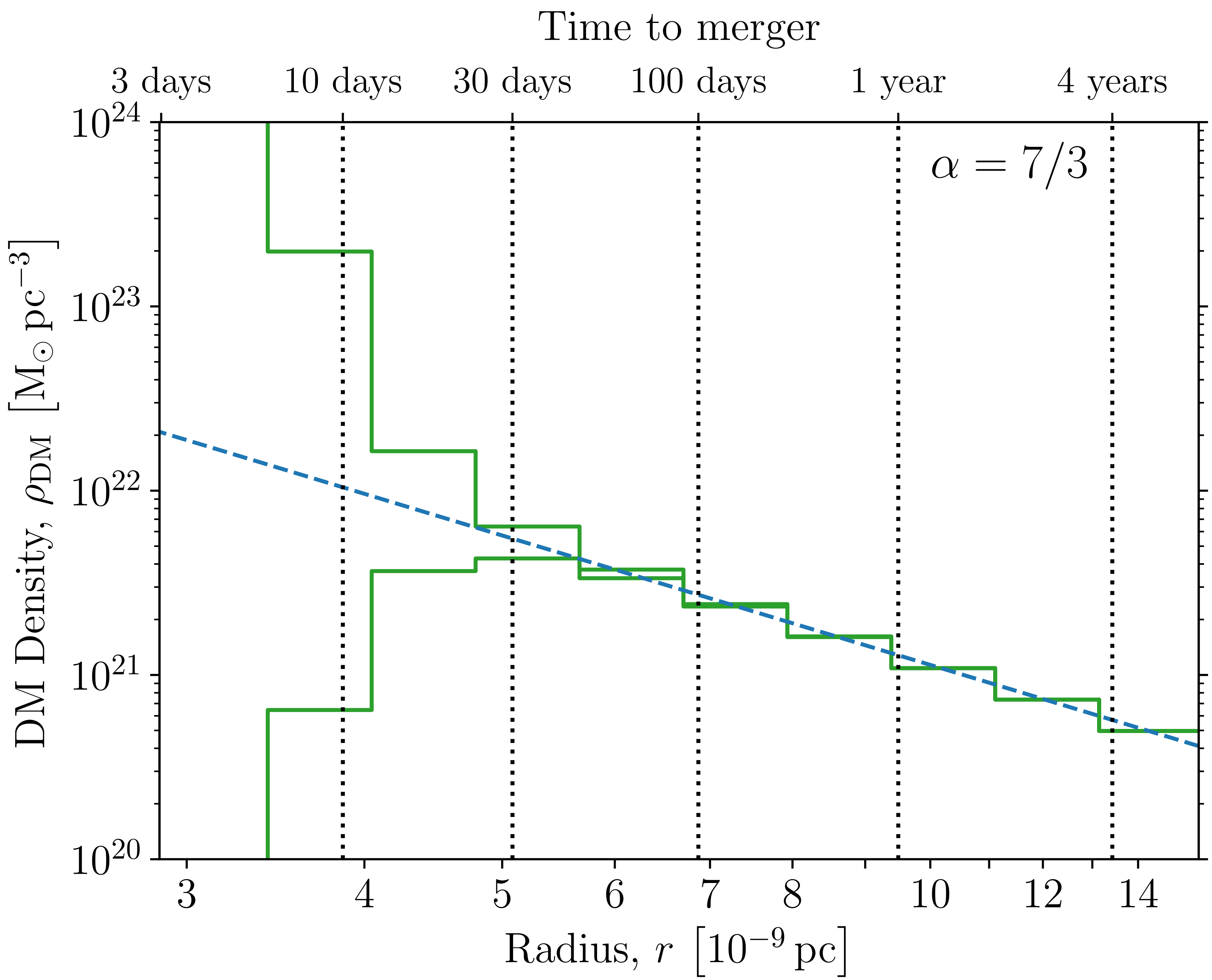
Gravitational Wave Signal — Dynamical Friction

Inspiral takes less time than in vacuum → Phase shift in the GW signal

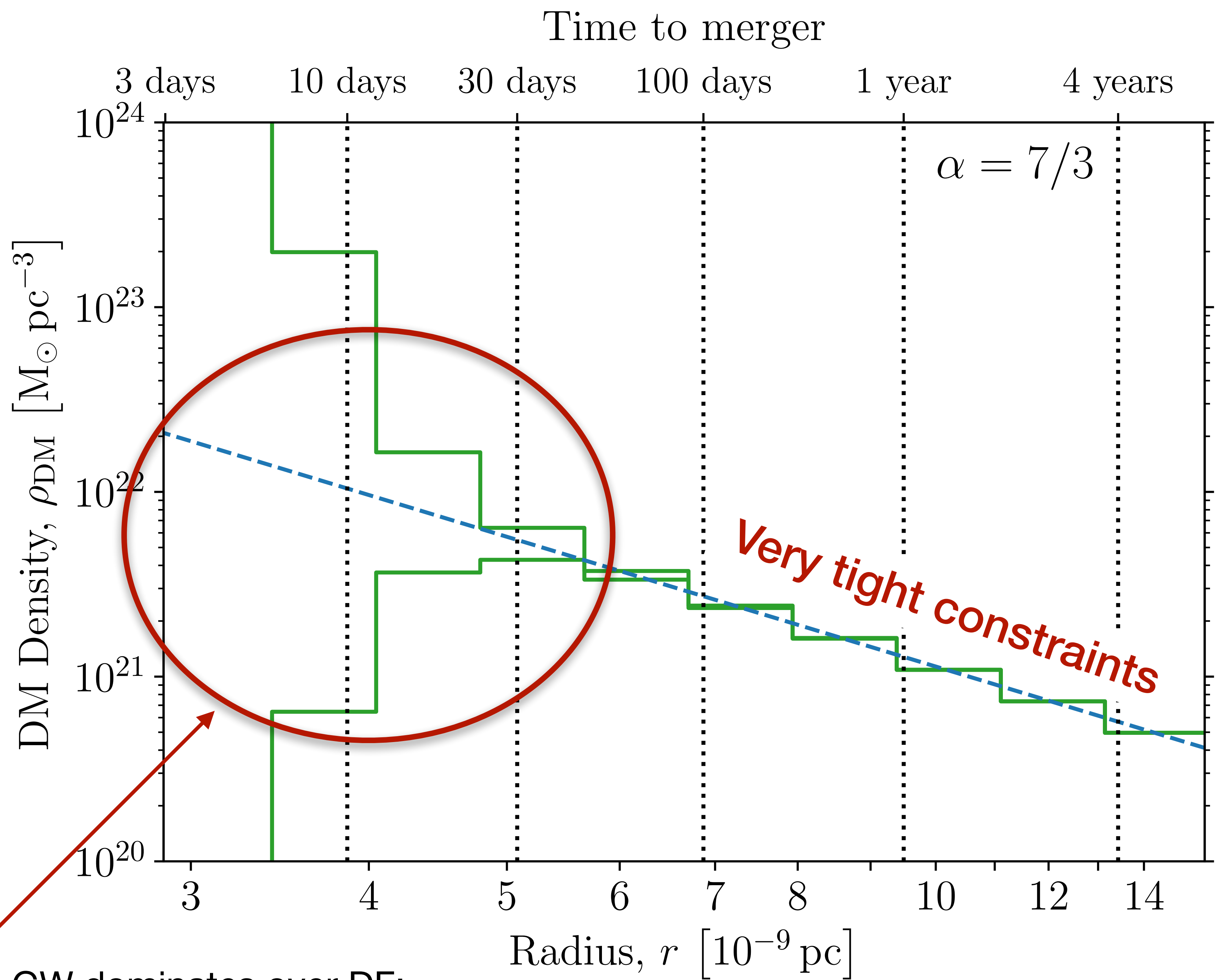


Measuring the phase shift constrains the DM density

LISA Sensitivity — Dark Matter density



LISA Sensitivity — Dark Matter density



Three effects: *1)* GW dominates over DF; *2)* low number of cycles; *3)* LISA sensitivity decreases at higher frequencies (signal ends at 0.44 Hz)

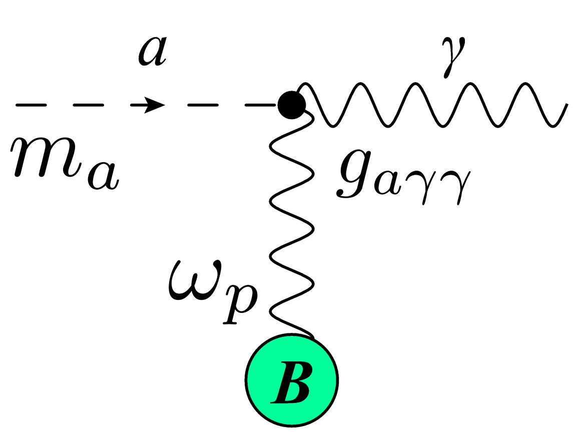
**Caveats*: measurements of individual masses and spins (high order post-Newtonian effects)

Neutron Stars — Axion-Photon conversion

Neutron Stars have:

- extremely high magnetic fields
- long spin periods
- a surrounding dense plasma that provides an effective photon mass ω_p

Resonant Axion-Photon Conversion

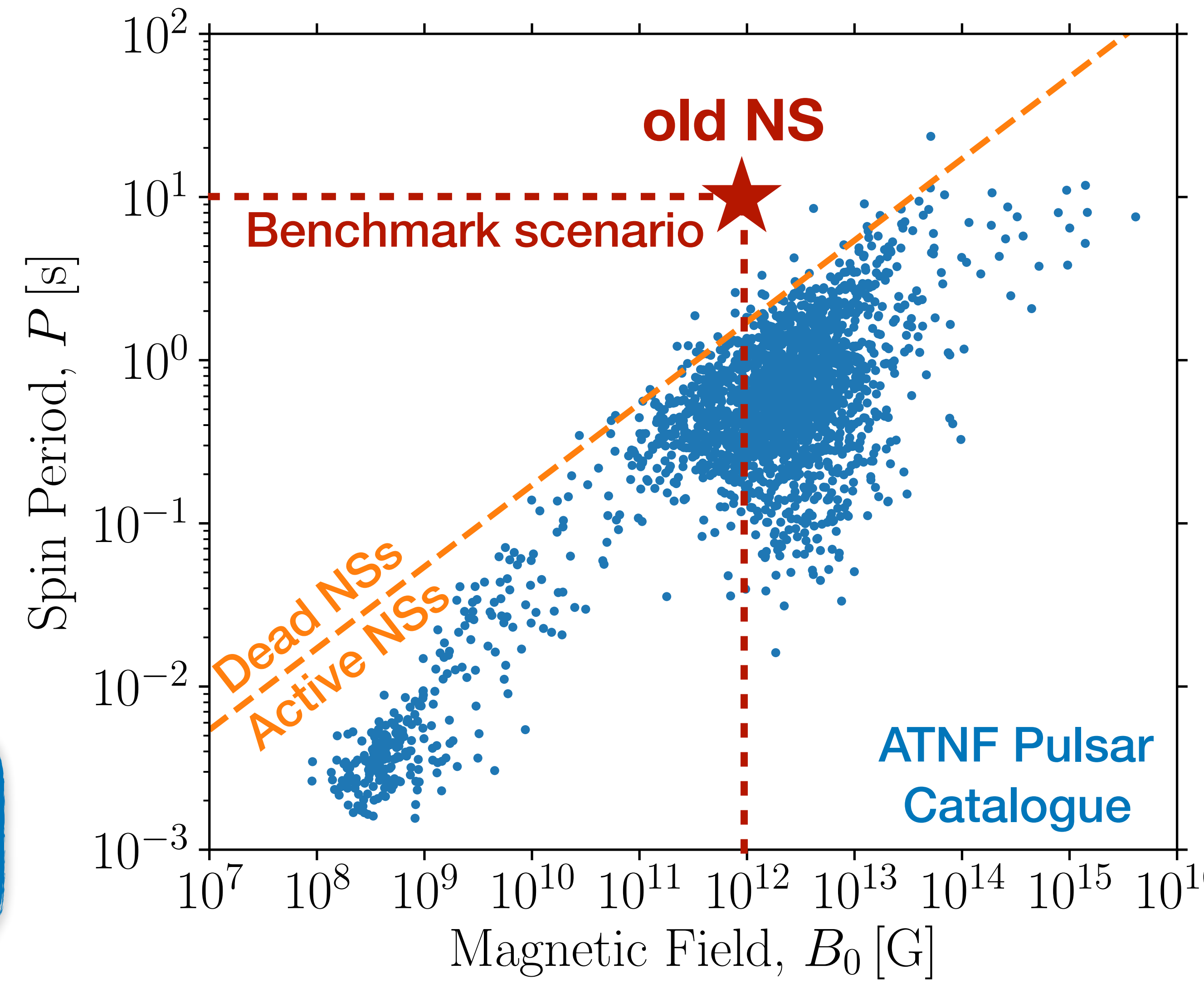


resonance

$$\omega_p(r_c;\, B_0,\, P) = m_a$$

For *radial trajectories*, the radiated power is:

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



Manchester et al., ***Astron.J. 129 (2005)***

(the catalogue contains ***only*** nearby active pulsar in the galactic disk, the population of old NSs is uncertain)

see also: Huang et al., ***PRD 93 (2018)****, Hook et al.,* ***PRL 121 (2018)****, Safdi et al.,* ***PRD 99 (2019)***

Dark Matter phase-space distribution

Thanks to **Eddington's inversion formula**, it is completely determined by the spike slope.

$$f\,(v|r) = 4\pi v^2 \frac{g(r,v)}{\rho(r)} \qquad \textit{with} \qquad g(r,v) \sim \left[\frac{G\,M_{\rm BH}}{r} - \frac{v^2}{2}\right]^{\alpha-\frac{3}{2}}$$

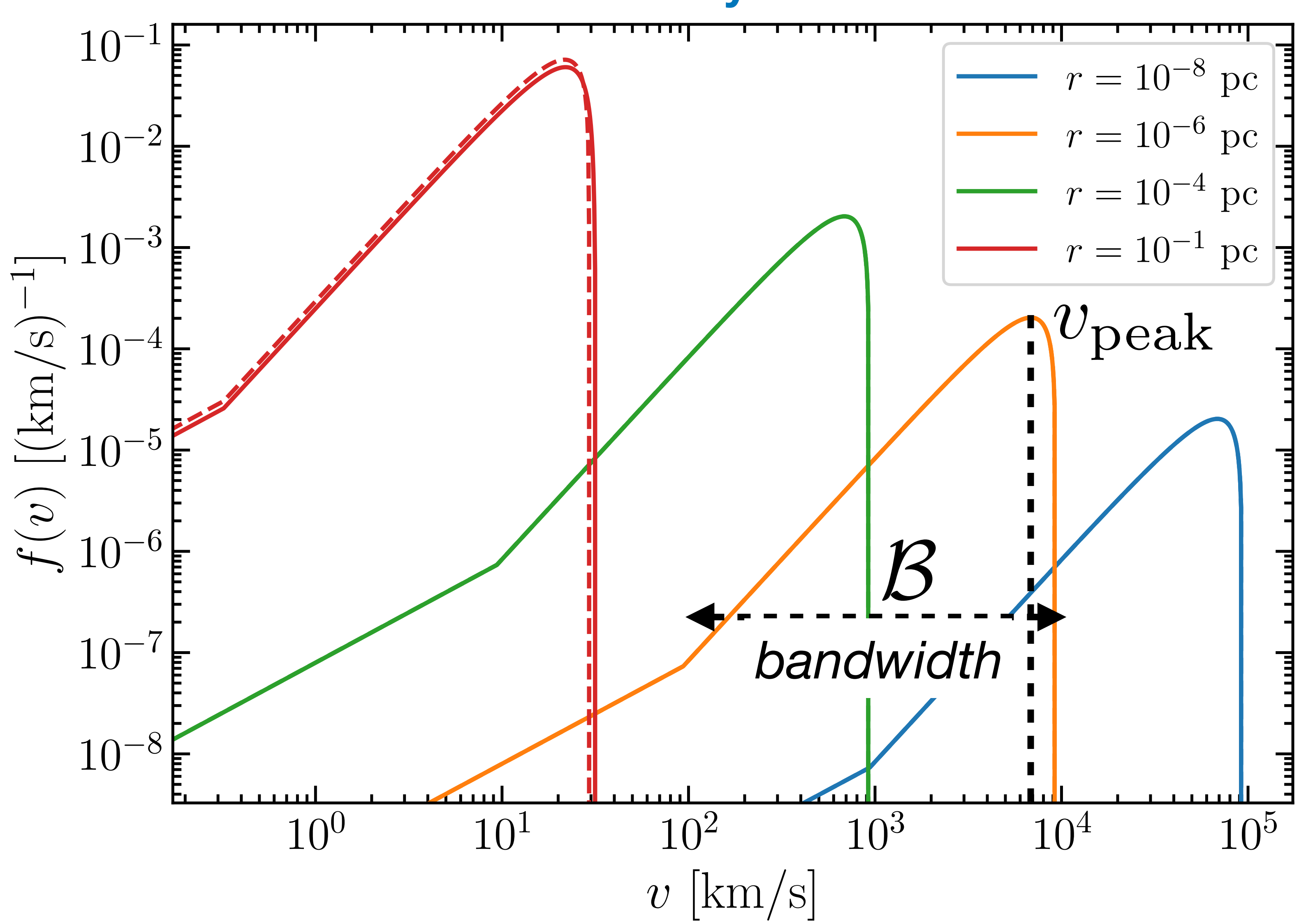
- The **DM velocity** at the conversion radius is found to be:

$$v_c^2 \sim v_{\rm peak}^2 = \frac{2\,G\,M_{\rm BH}}{r_c}\left[\alpha - \frac{1}{2}\right]^{-1}$$

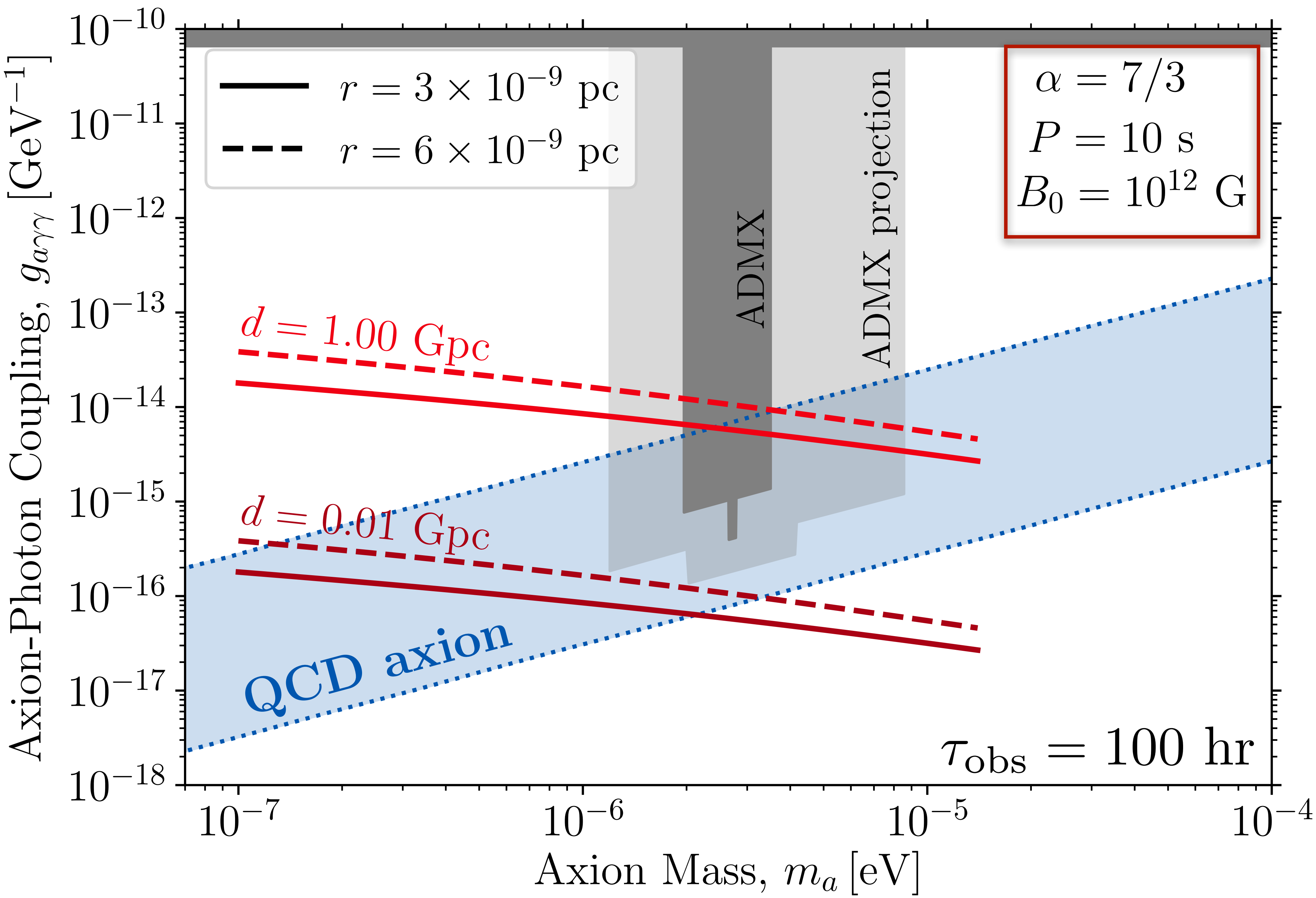
- The **DM density** is obtained by means of the **Liouville's theorem**:

$$\rho_{\rm DM}^{r_c}\, f_{r_c}\left(\mathbf{v}\right) = \rho_{\rm DM}^{\infty}\, f_{\infty}\left(\mathbf{v}_{\infty}\right)$$

DM velocity distribution



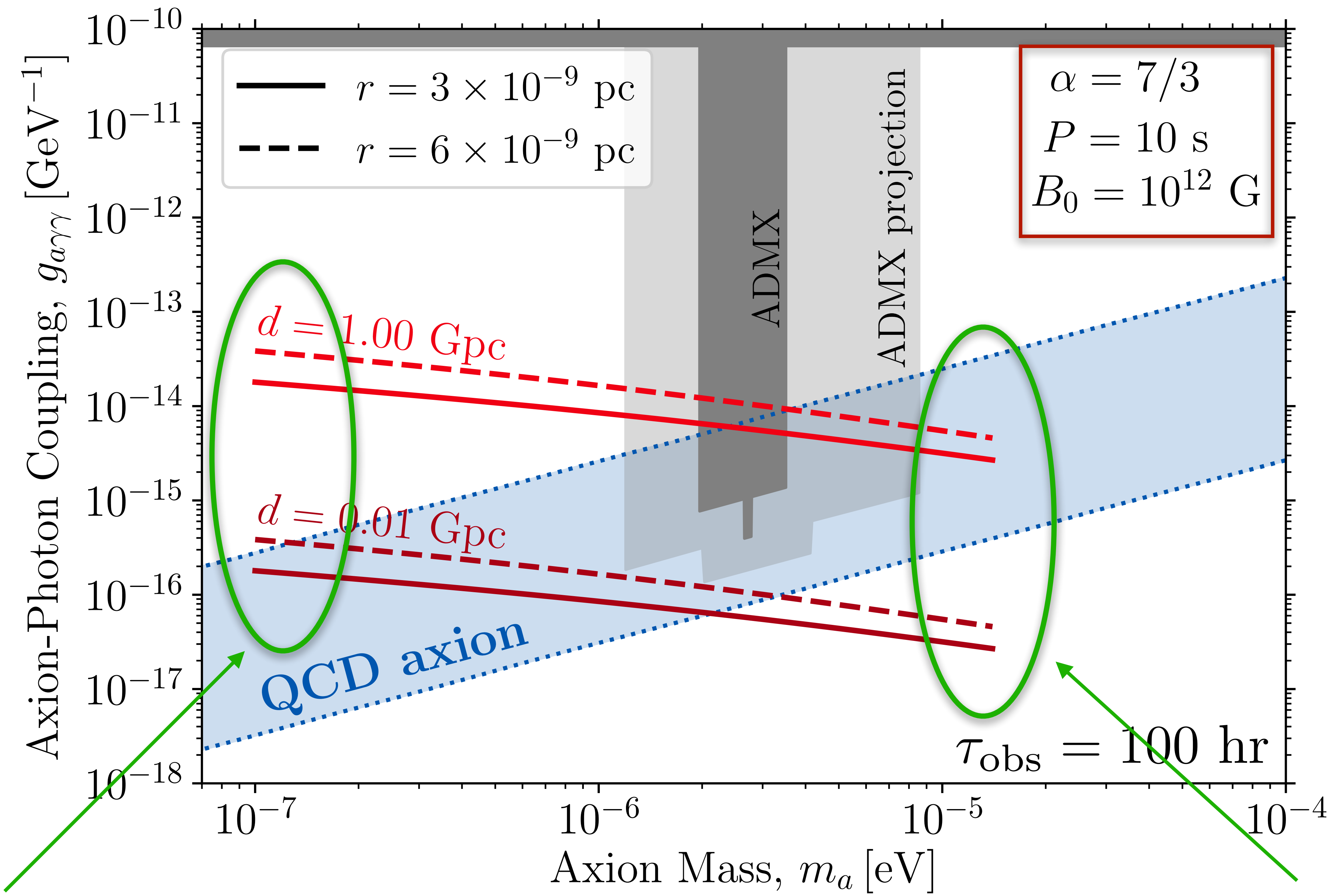
Square Kilometre Array Sensitivity



Detection rate in LISA: $\mathcal{R} \sim 3 - 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$

*Fragione et al., **ApJ 856 (2018)***

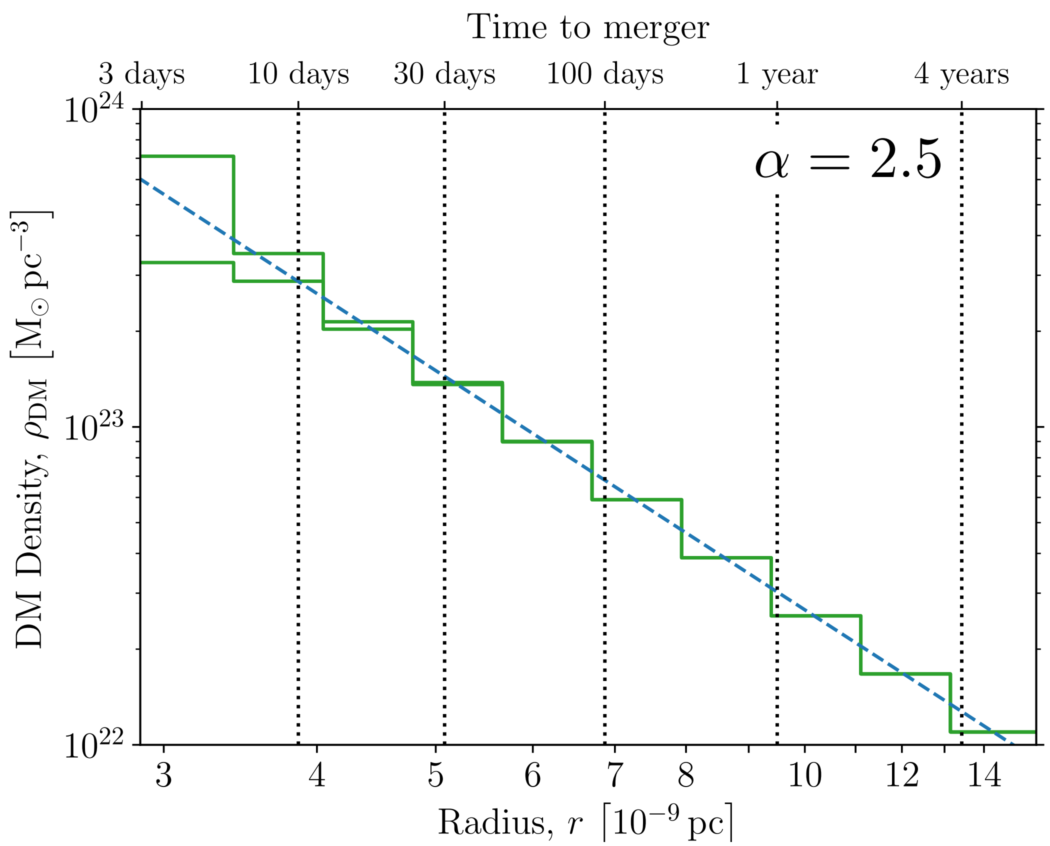
Square Kilometre Array Sensitivity

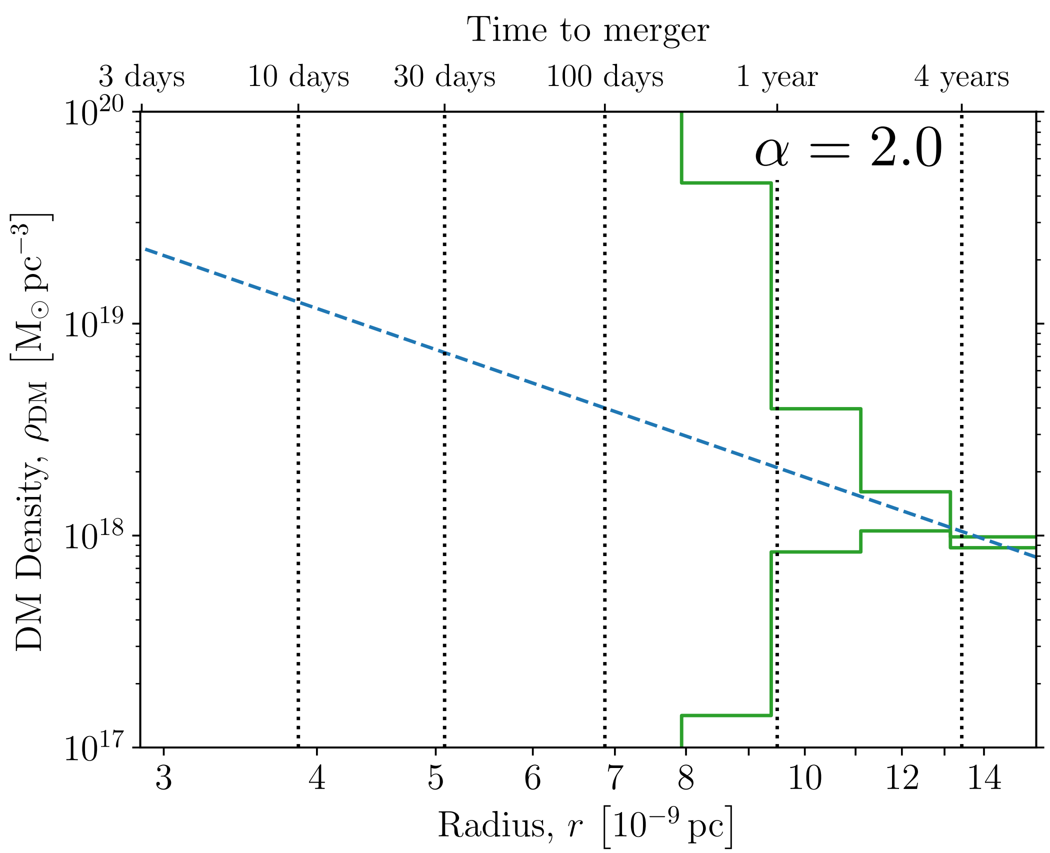


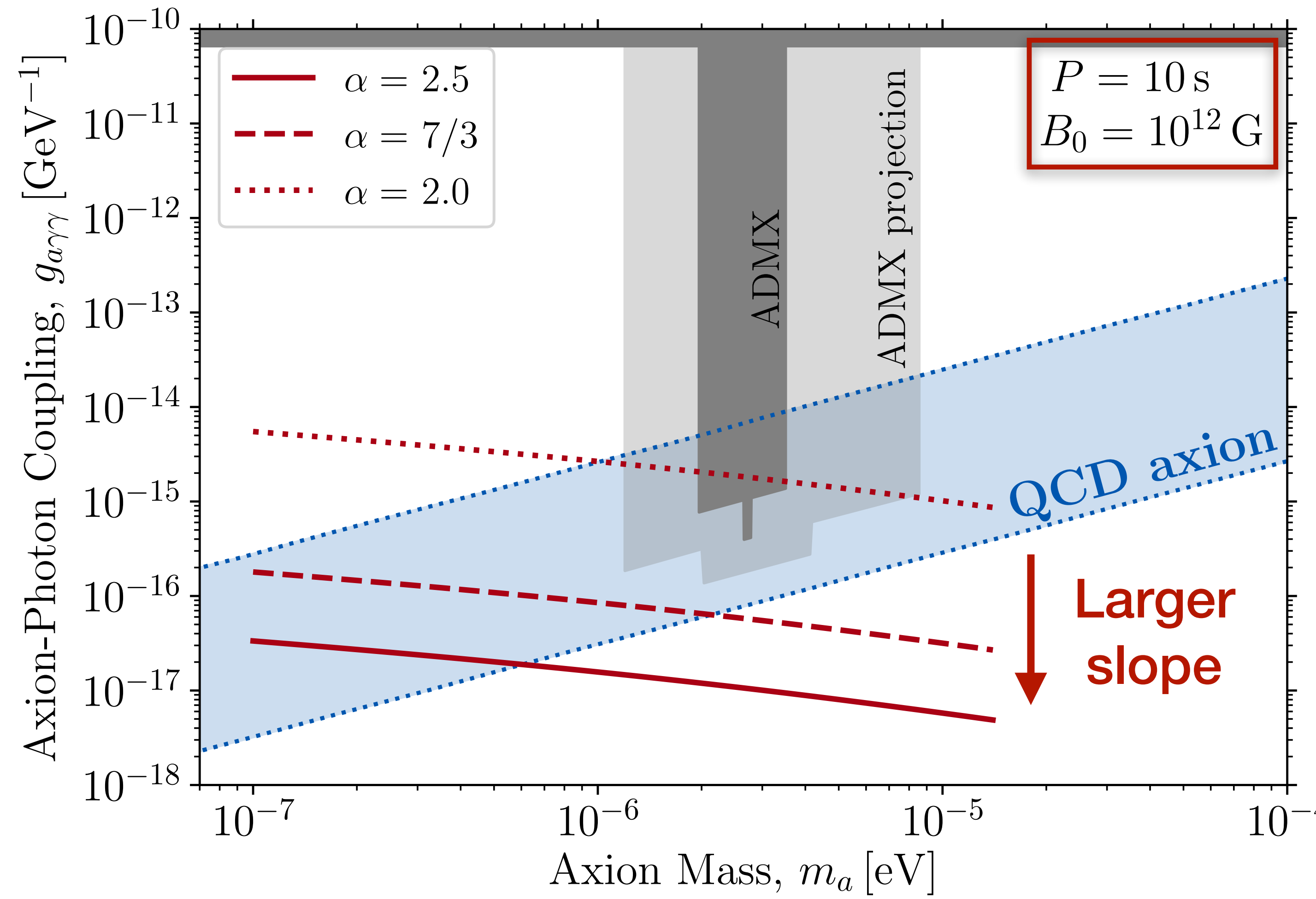
Lower cut-off: set by lowest frequency probed by SKA

Upper cut-off: conversion to photon must occur outside the NS

Dependence on the spike slope







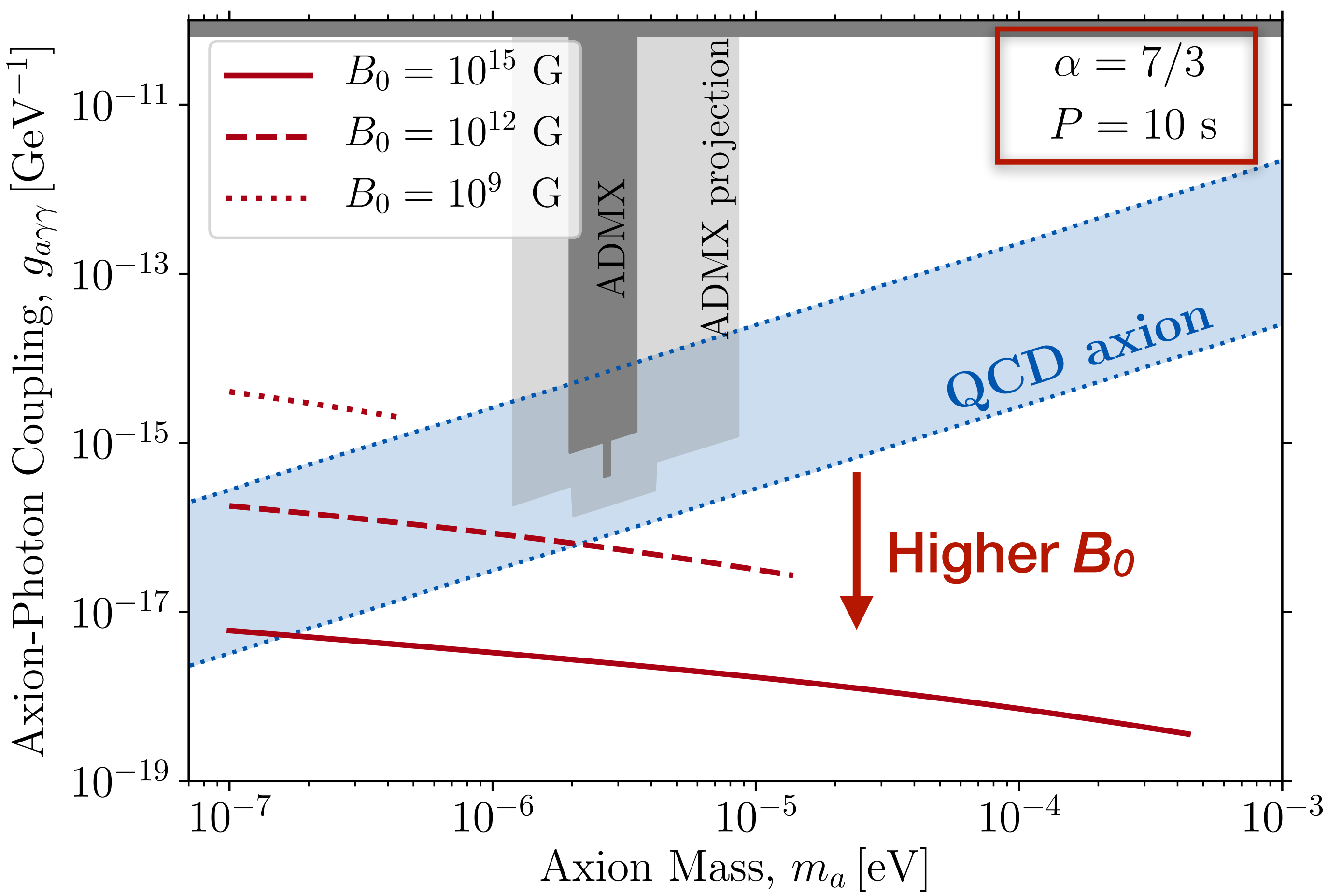
- The larger the slope, the larger the DM density close the IMBH.

→ **Larger Radio Signal!**

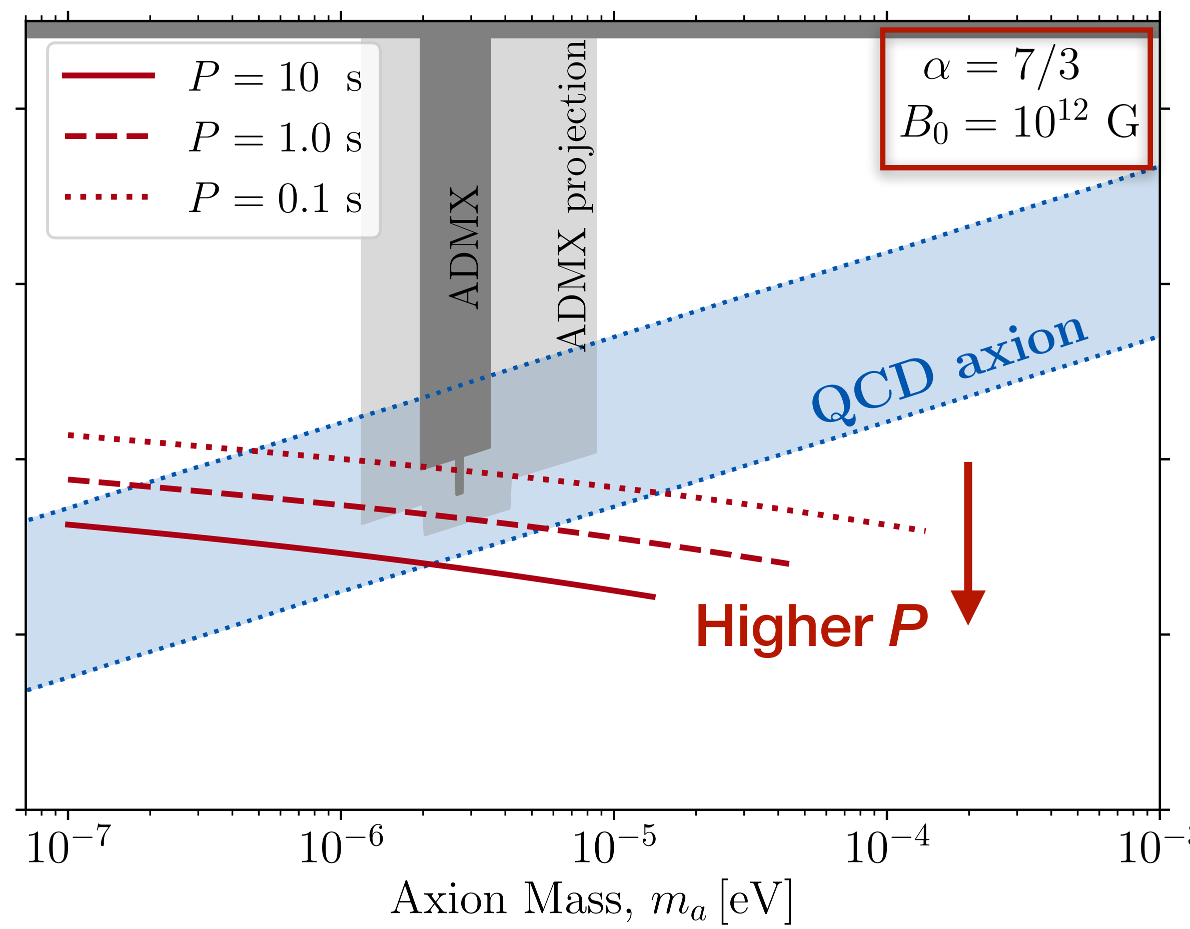
- For small values of the spike slope, the GW phase difference becomes difficult to probe.

Dependence on NS parameters

Magnetic Field B_0



Spin Period P



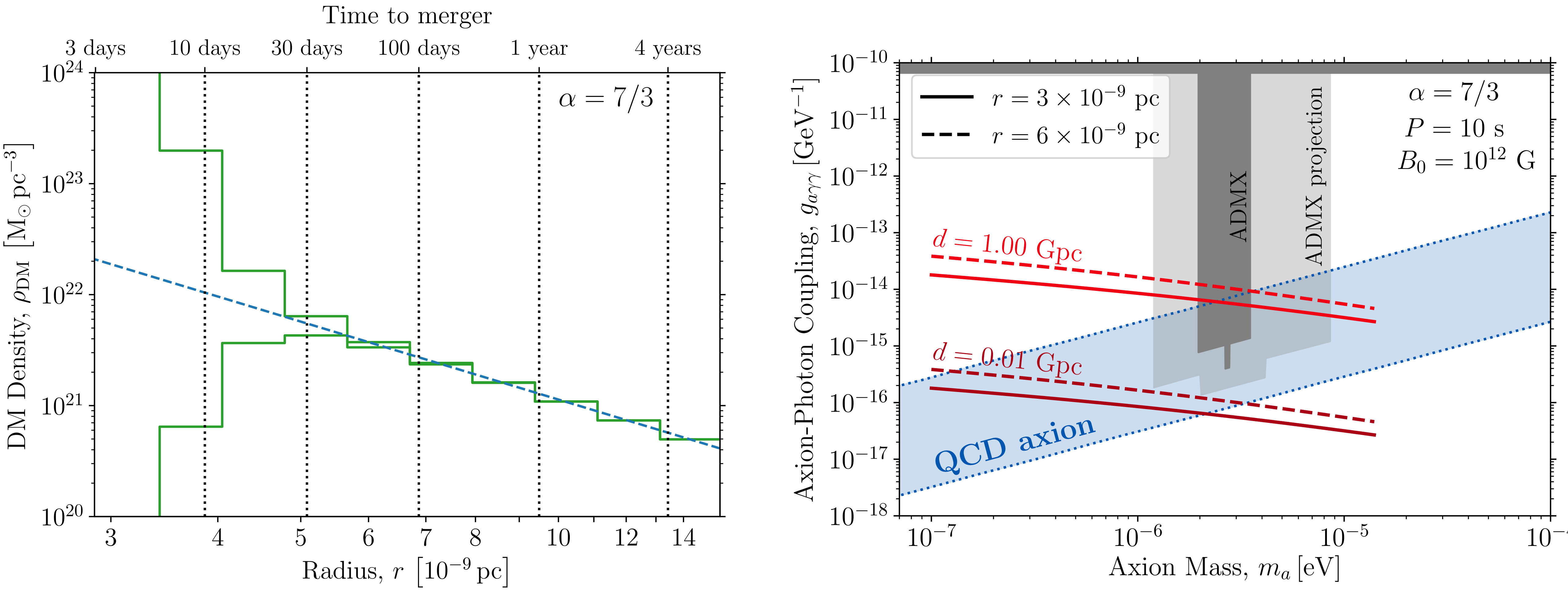
The radiated power of the radio signal roughly scales as

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} \sim B_0\, P \left(\frac{3\cos^2\theta + 1}{|3\cos\theta - 1|}\right) \underbrace{\left[g_{a\gamma\gamma}^2\, m_a\, \rho_{\mathrm{DM}}(r_c)\, v_c\right]}_{\text{Independent of NS parameters}} \quad \text{with} \quad \theta = \pi/2$$

Independent of NS parameters

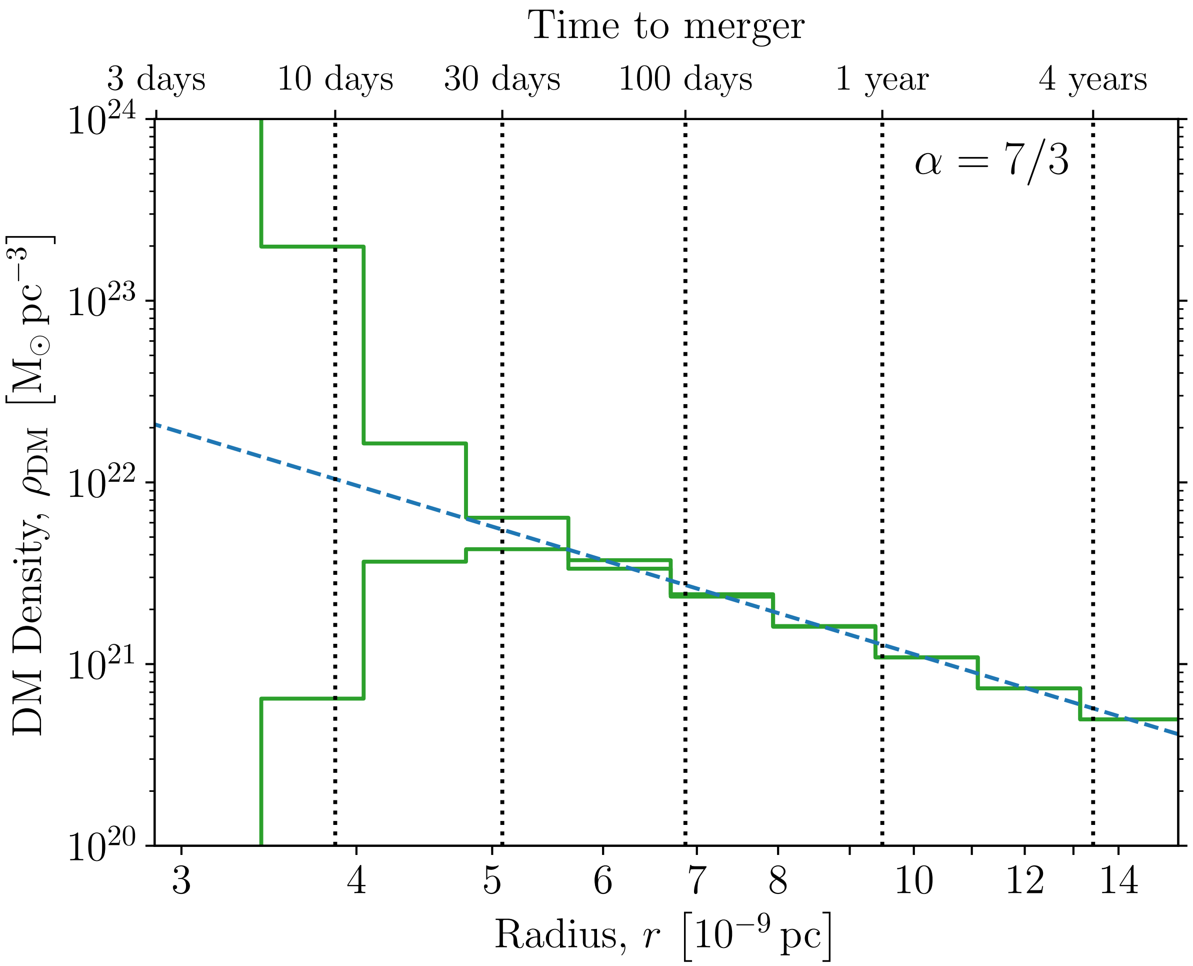
Viewing angle (benchmark value)

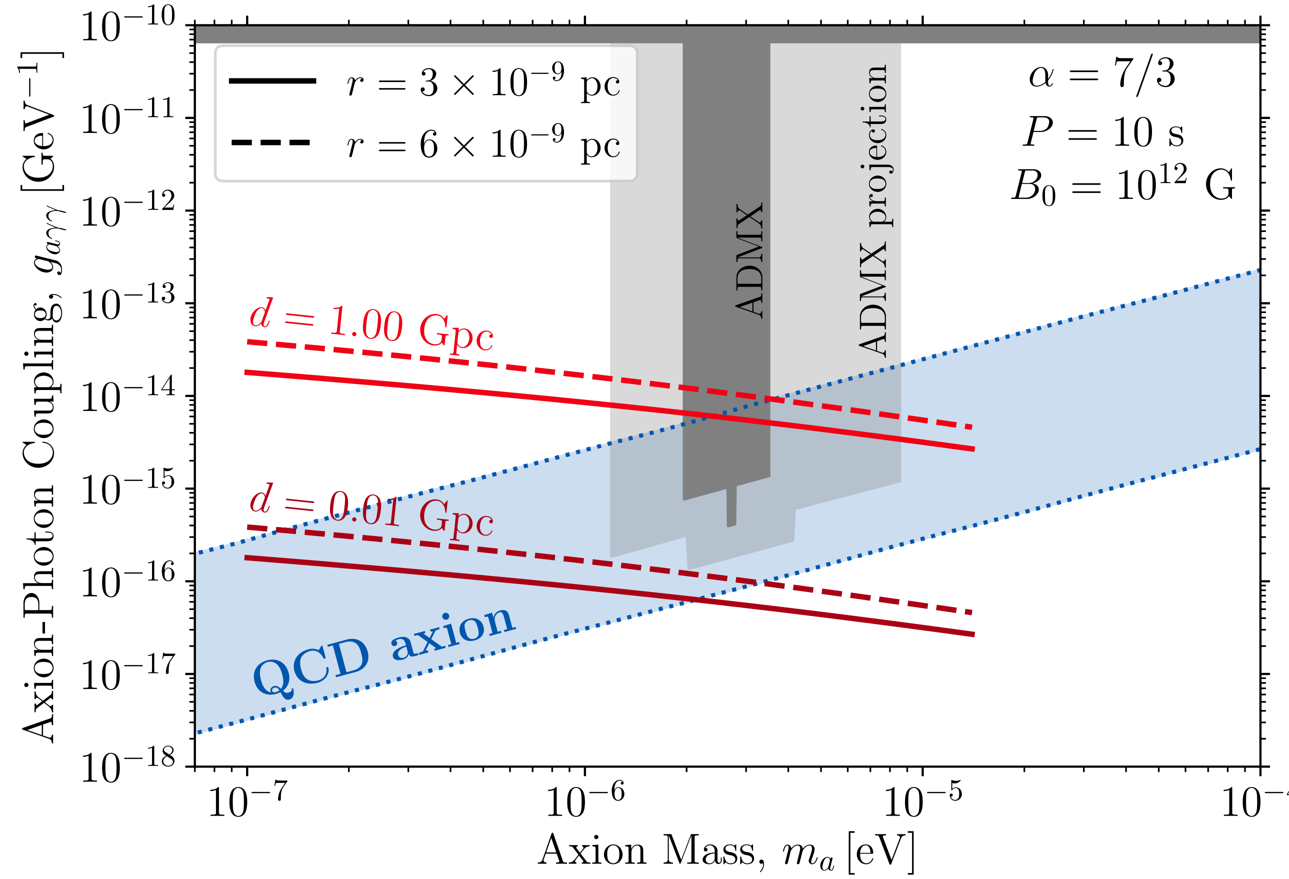
Take-home messages



- Difficult to set robust limits due to the uncertainty in the NS properties
- Extremely complementary to direct axion searches
- QCD axion Dark Matter can be potentially discovered through multi-messenger observations with future GW detectors and radio telescopes.

Take-home messages





- Difficult to set robust limits due to the uncertainty in the NS properties
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- QCD axion Dark Matter can be potentially discovered through multi-messenger observations with future GW detectors and radio telescopes.

Thanks for listening

BACKUP SLIDES

Intermediate Mass Black Holes

IMBHs are the least constrained mass window:

$$M_{\mathrm{IMBH}} = 10^3 - 10^5 \, M_\odot$$

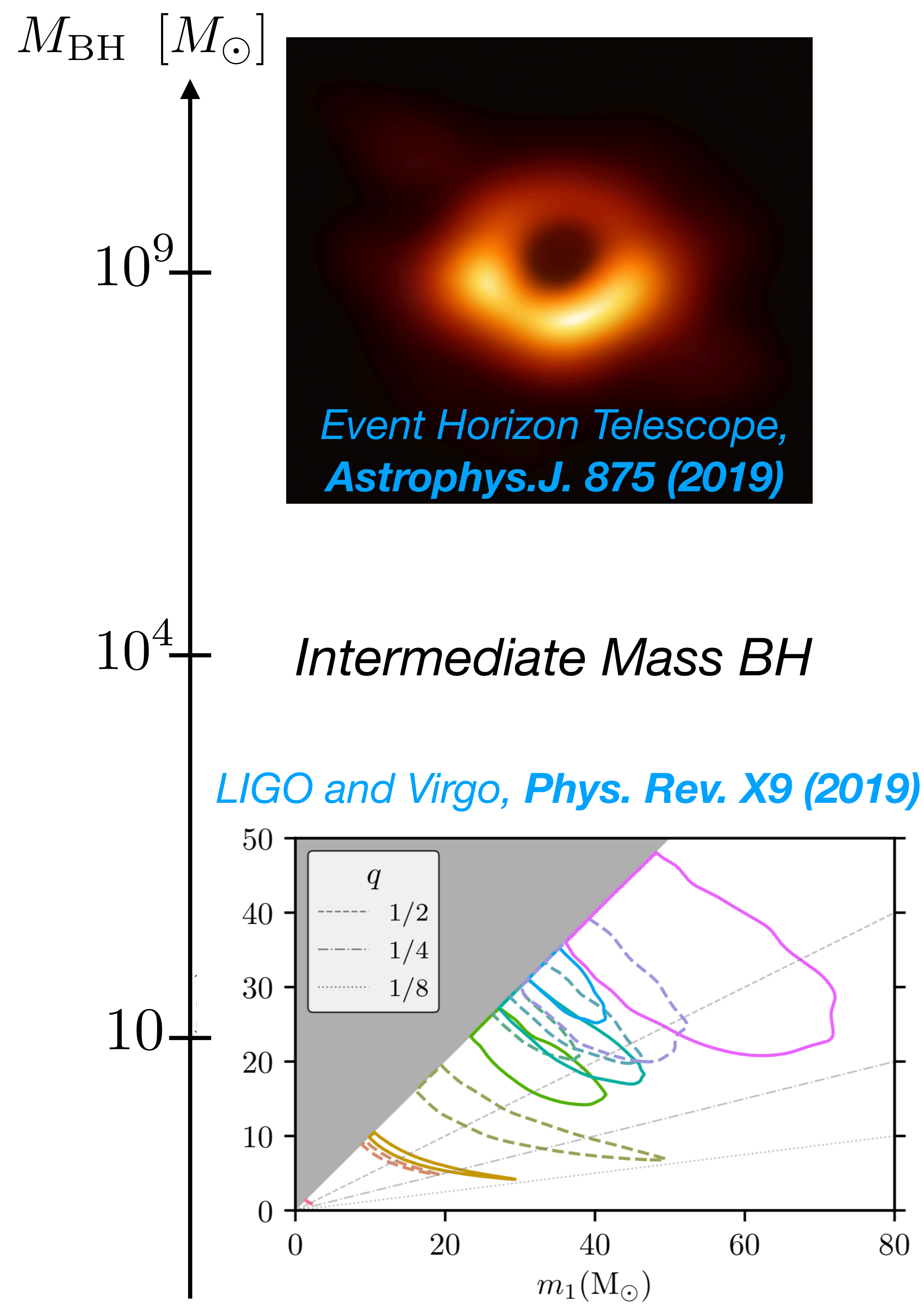
No detection by GWs so far, but evidences of their existence in the centre of small galaxies and in globular clusters.

*Miller and Hamilton, **MNRAS 330 (2002)**; Webb et al., **Science 337 (2012)**; Ballone et al., **MNRAS 480 (2018)**; Woo et al., **arXiv:1905.00145***

Different possibile formation mechanisms:

- Mergers of stellar mass objects
- Collapse of gas clouds at high redshift
- Collapse of large primordial density perturbations before BBN

*Taniguchi et al., **Publ. Astron. Soc. Jap. 52 (2000)**; Begelman et al., **MNRAS 370 (2006)**; Carr and Rees, **MNRAS 206 (1984)***



Radio Signal

We consider the Goldreich-Julian model for the NS magnetosphere:

- the resonant conversion radius

$$r_c(B_0,\, P,\, m_a) :\ \omega_p = m_a/2\pi$$

- the conversion probability

$$p_{a\gamma} \sim \frac{g_{a\gamma\gamma}^2 B\,(r_c)^2\, L_{\rm conv}^2}{2\, v_c}$$

Flux density →

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

Dependence on the Dark Matter six-dimensional phase-space distribution function:

Eddington's inversion formula
(isotropy and spherical symmetry)

and

Liuoville's theorem

→

- DM velocity v_c
- Bandwidth of the radio signal $\mathcal{B}$
- DM density $\rho_{\rm DM}\,(r_c)$

*Goldreich and Julian, **ApJ 157 (1969)**, Huang et al., **PRD 93 (2018)**,*
*Hook et al., **PRL 121 (2018)**, Safdi et al., **PRD 99 (2019)***