A Unique Multi-Messenger Signal of QCD Axion Dark Matter

Marco Chianese

3rd South American Dark Matter workshop, 2-4 December 2020

- Edwards, MC, Kavanagh, Nissanke, Weniger, PRL 124 (2020) 16 [arXiv:1905.04686]
- Leroy, MC, Edwards, Weniger, PRD 101 (2020) 12 [1912.08815]

University of Amsterdam

GRAPPA

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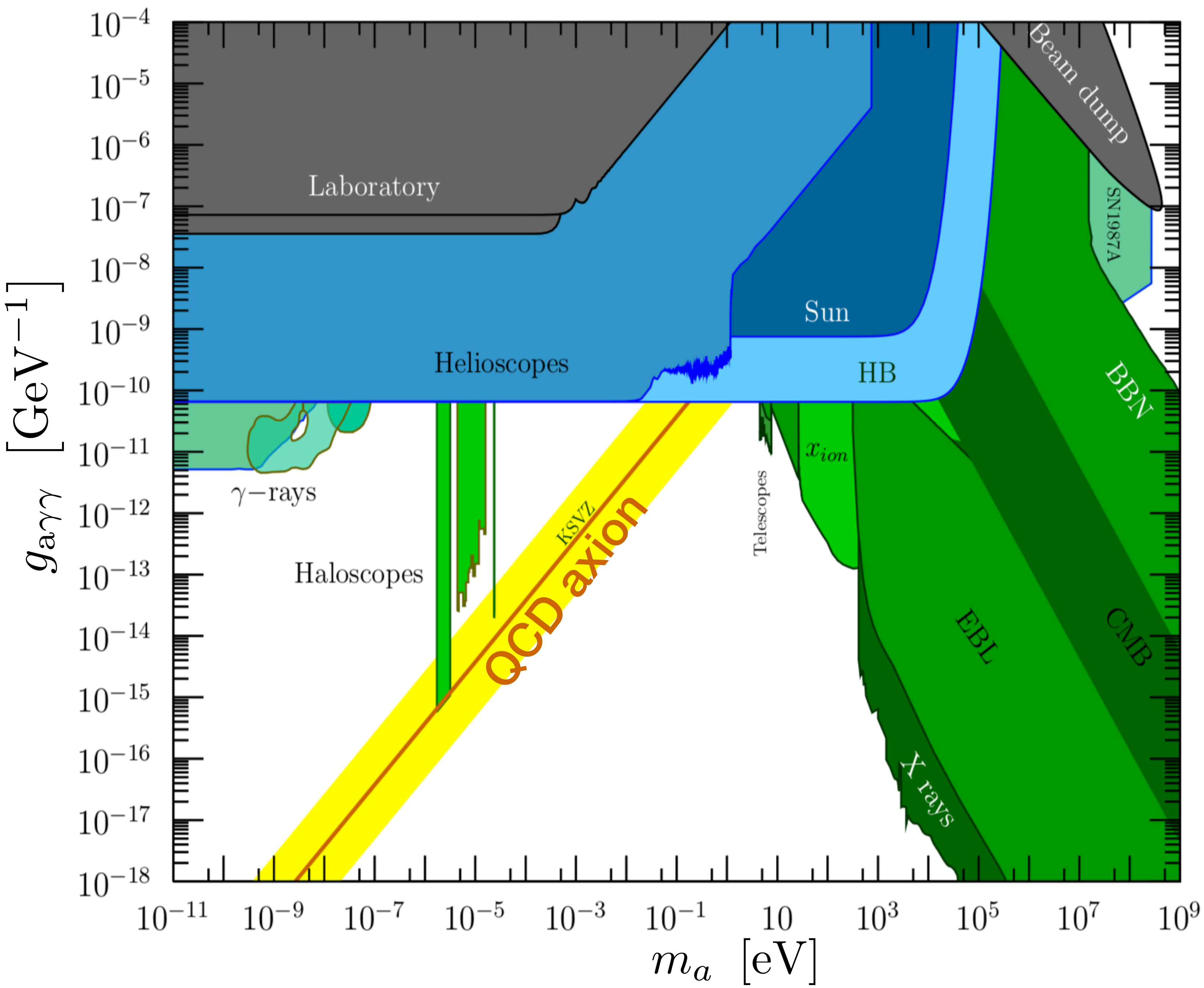
What is the axion?

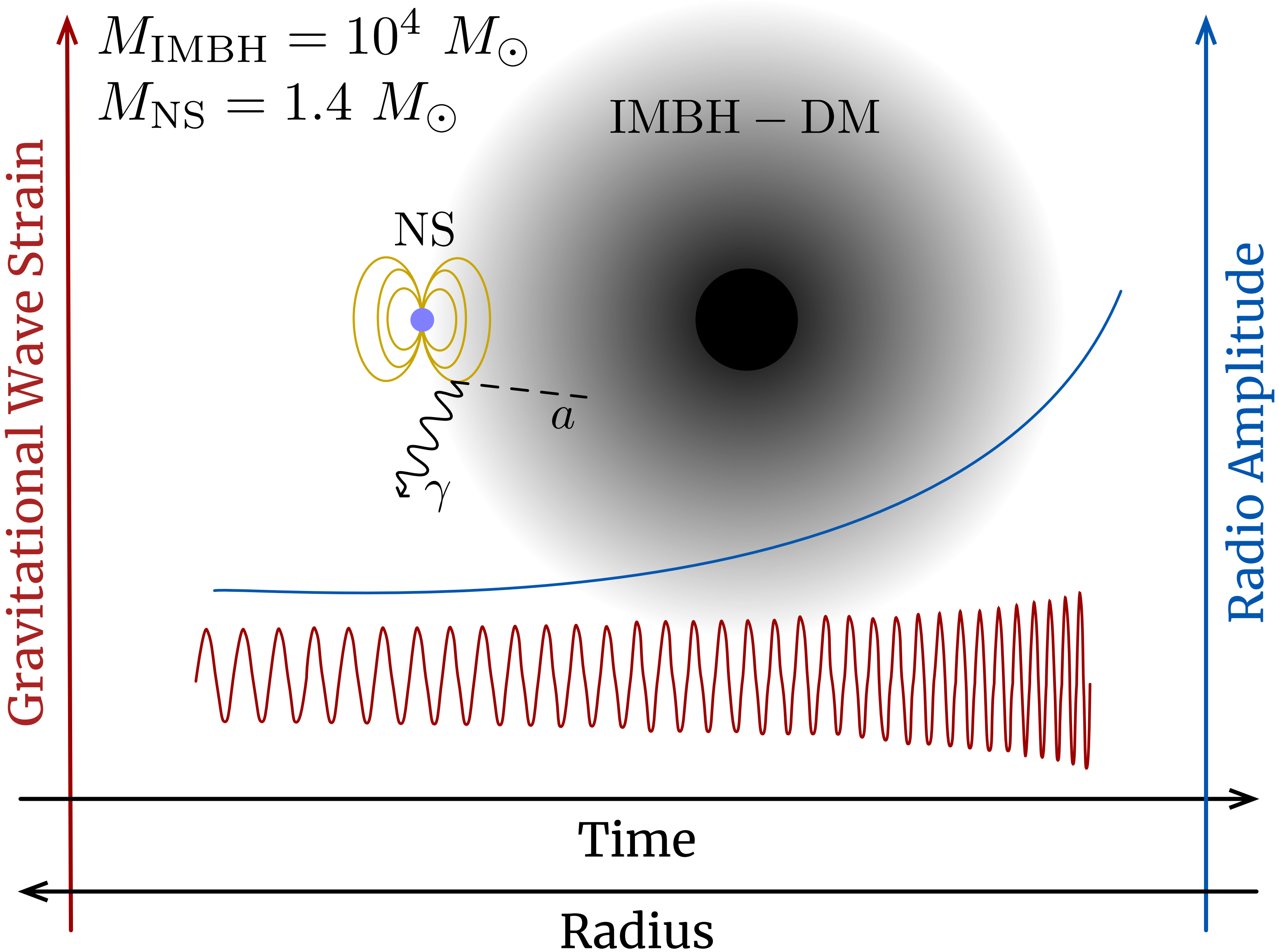
- Originally introduced to solve the QCD strong CP problem
- Axion Like Particles (APLs) predicted in many BSM theories
- It is a viable DM candidate
- Most of the axion searches exploits its coupling $g_{a\gamma\gamma}$ to photons

Axion-photon conversion in an external magnetic field



Reviews: Irastorza and Redondo, ***PPNP 102 (2018)***
Di Luzio et al., ***PR 870 (2020)***

Multi-messenger signal of QCD axion



Gravitational Waves

Distinct phase shift in the GW strain

and

Electromagnetic emission

Radio emission from axion-photon conversion in the NS magnetosphere

Astrophysical system

Inspirals of intermediate-mass Black Hole (IMBH) and Neutron Star (NS) with an axionic DM spike

Experimental setup (forecast)

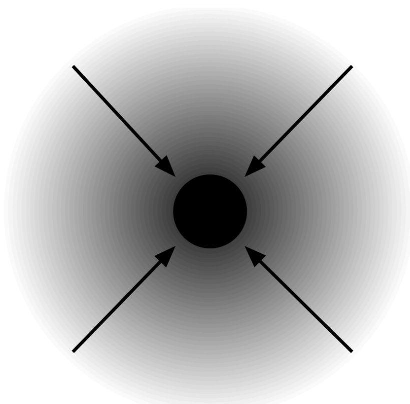
- LISA GW-interferometer
- SKA radio telescope

Dark Matter Spike

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

DM halo

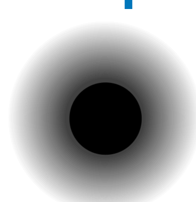
$z = 20$



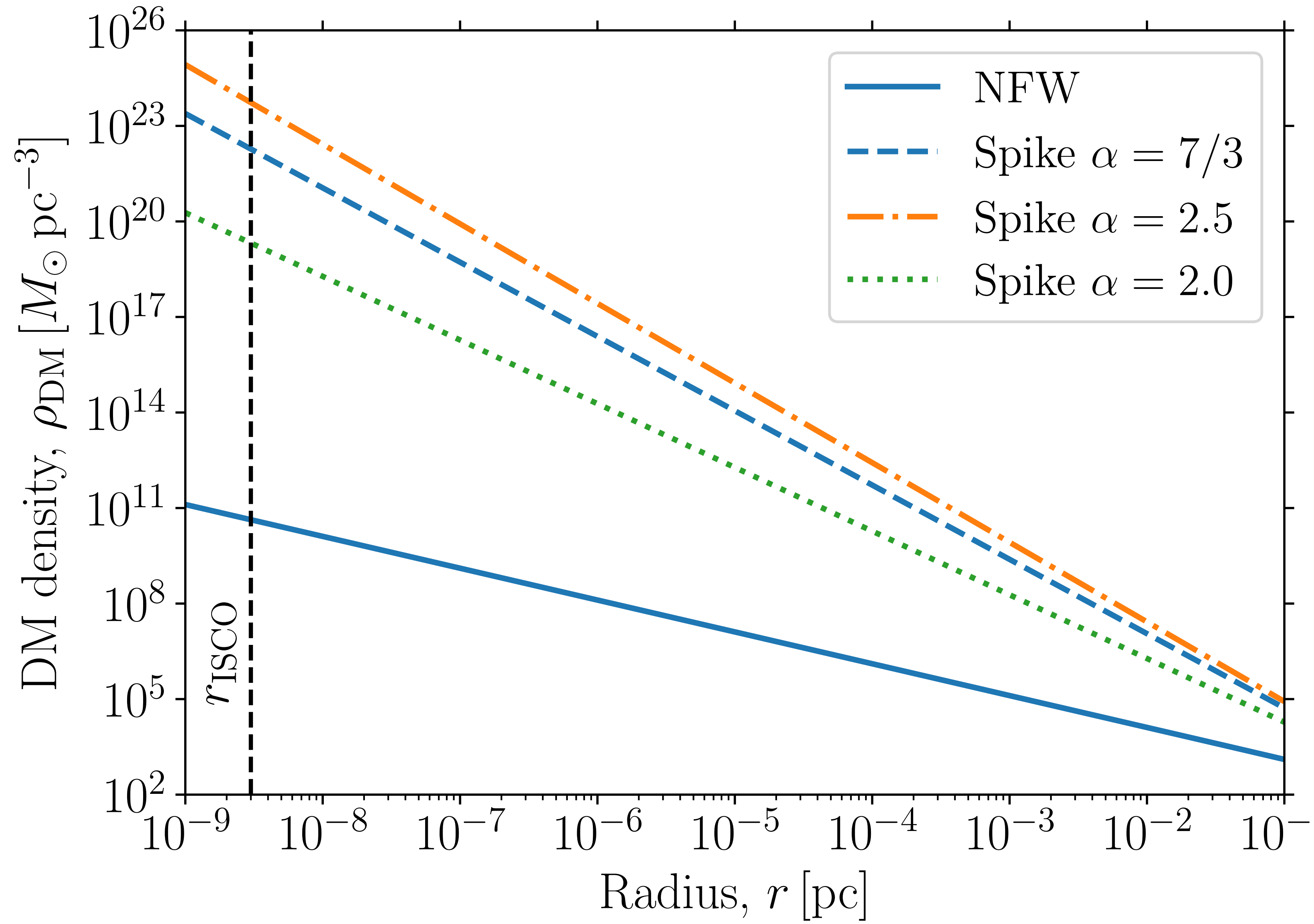
$$\rho_{\mathrm{DM}} \propto r^{-\alpha_{\mathrm{init}}}$$

DM spike

$z = 0$



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

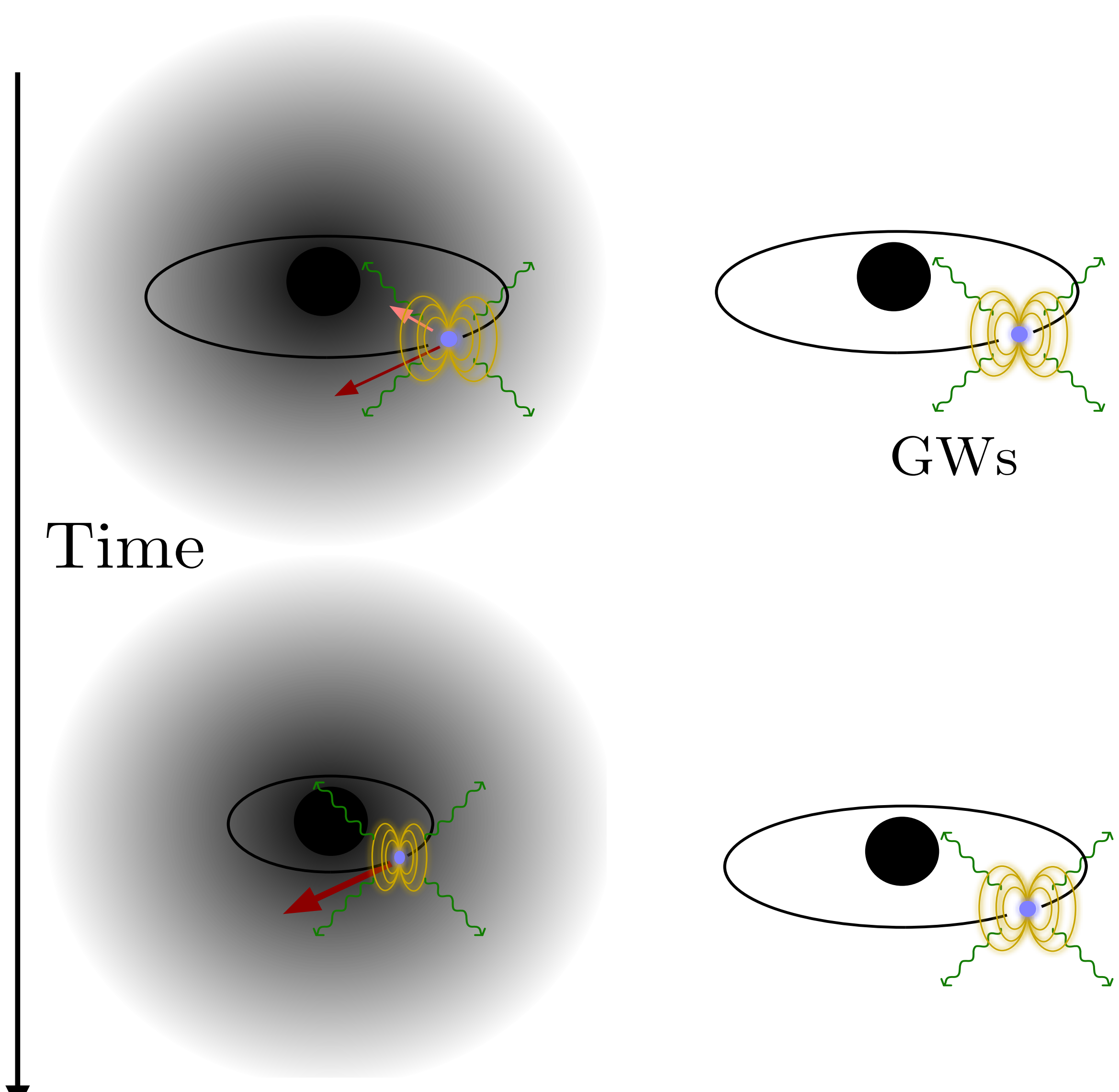


The DM density is **extremely enhanced** towards innermost stable circular orbit (ISCO).

*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



with DM spike *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

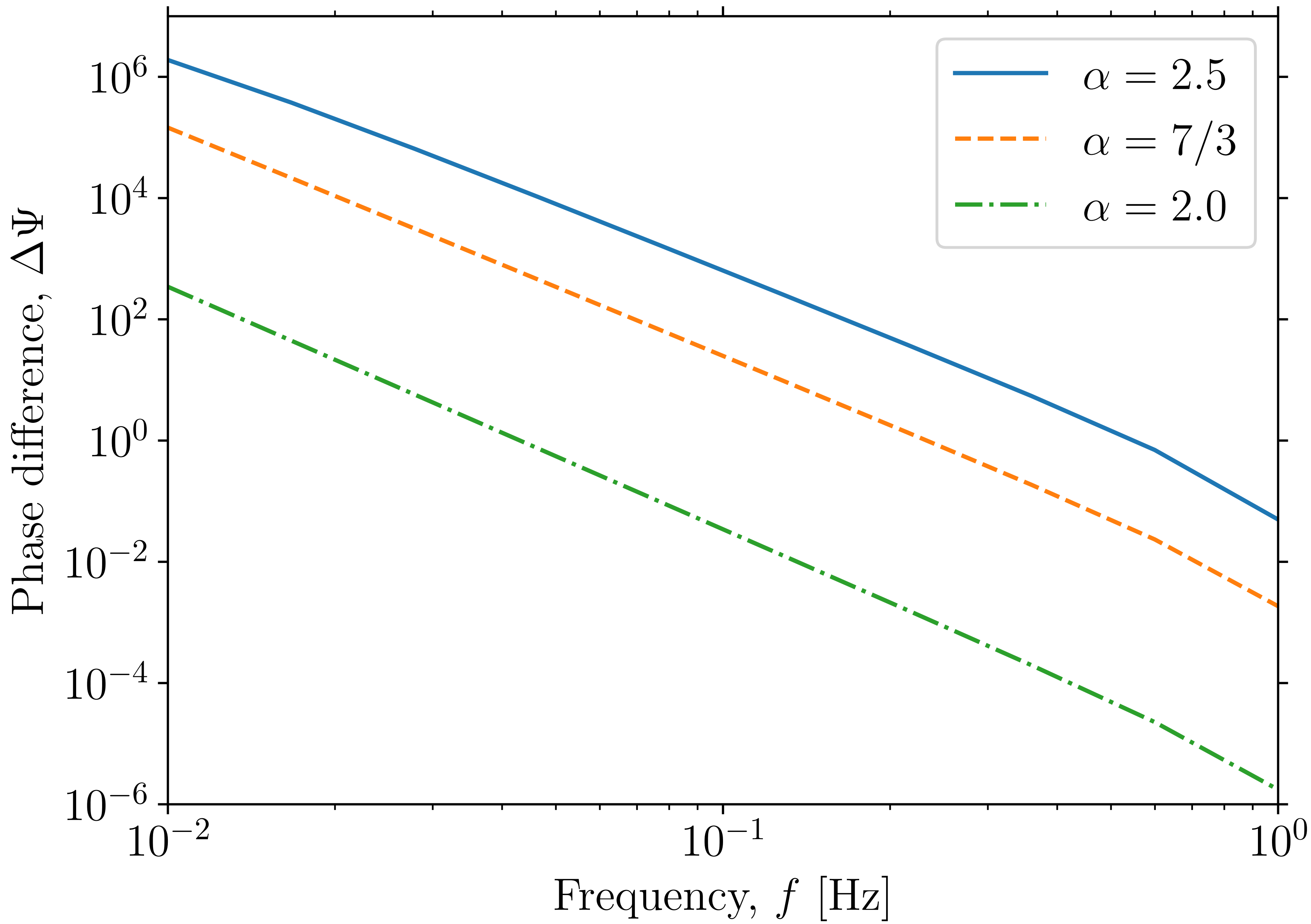
$$\frac{\mathrm{d}E_{\mathrm{DF}}}{\mathrm{d}t} = 4\pi\,G^2 \ln\Lambda \frac{M_{\mathrm{NS}}^2\,\rho_{\mathrm{DM}}(r)}{v_{\mathrm{NS}}}$$

Eda et al., ***PRL 110 (2013), PRD 91 (2015);***
Kavanagh et al., ***PRD 102 (2020)***

see Bradley Kavanagh's talk at 13:40 (GMT-3)!

Gravitational Wave signal: dynamical friction

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



Gravitational Wave signal: dynamical friction

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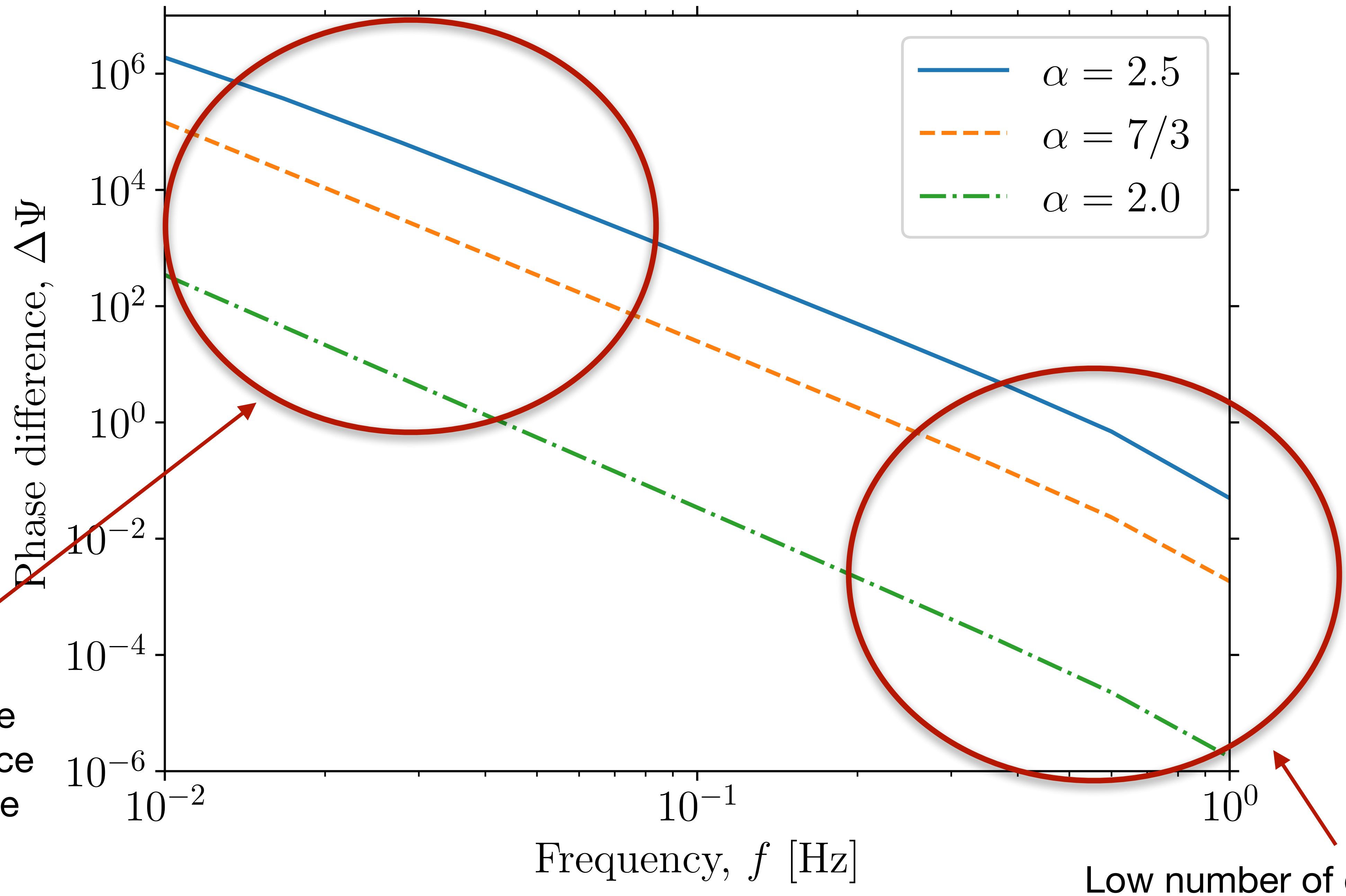
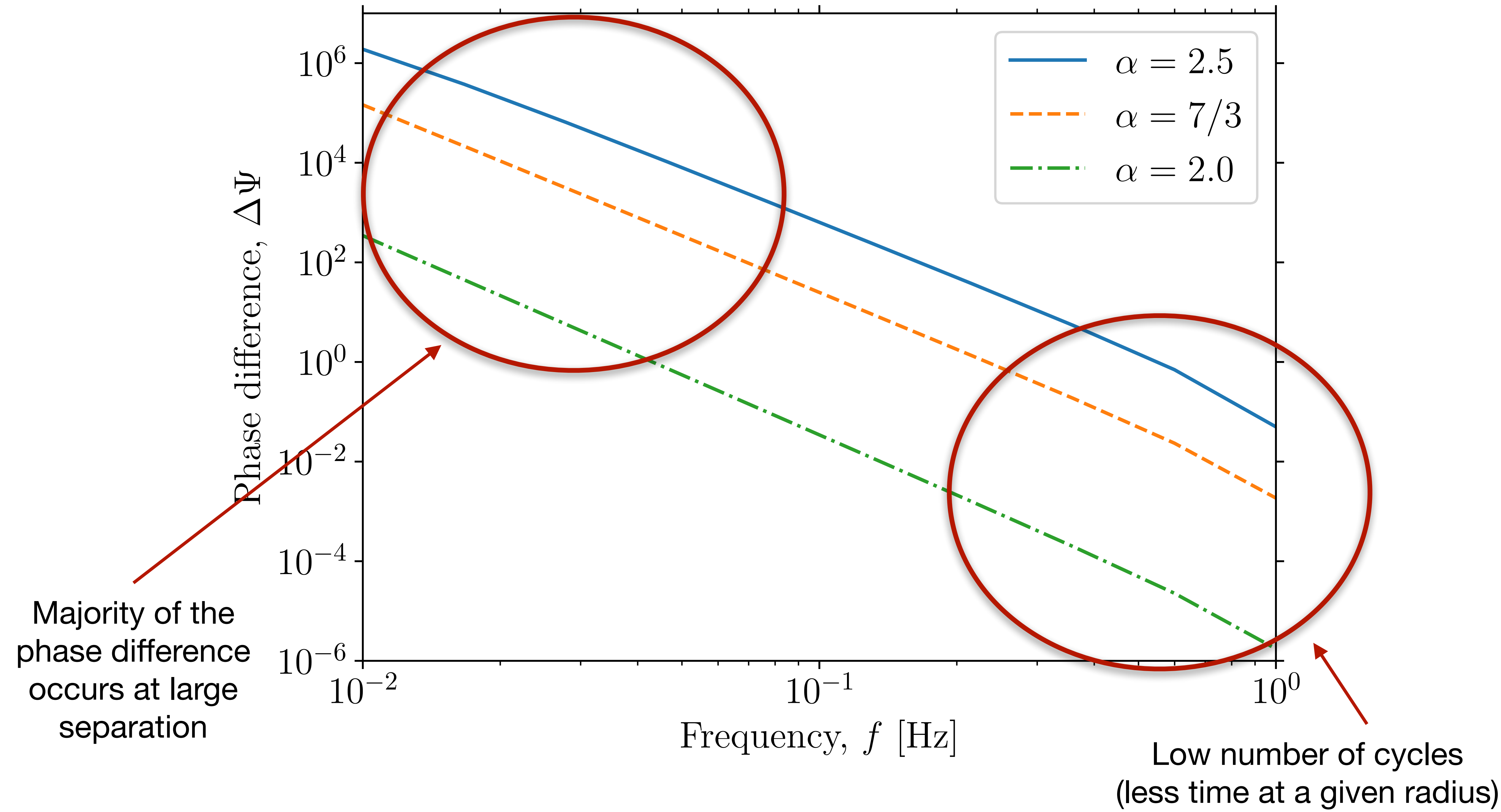


Majority of the phase difference occurs at large separation

Low number of cycles (less time at a given radius)

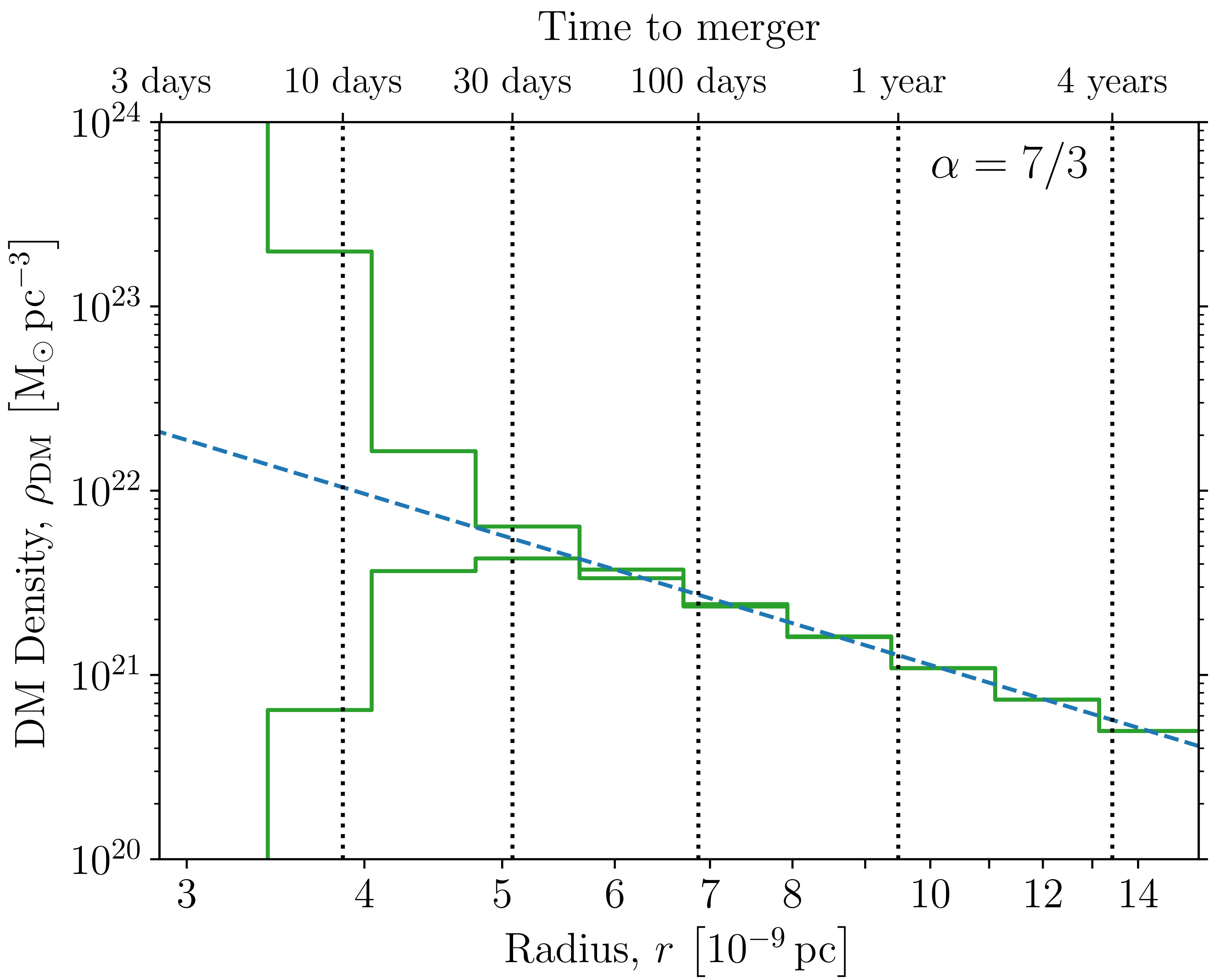
Gravitational Wave signal: dynamical friction

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

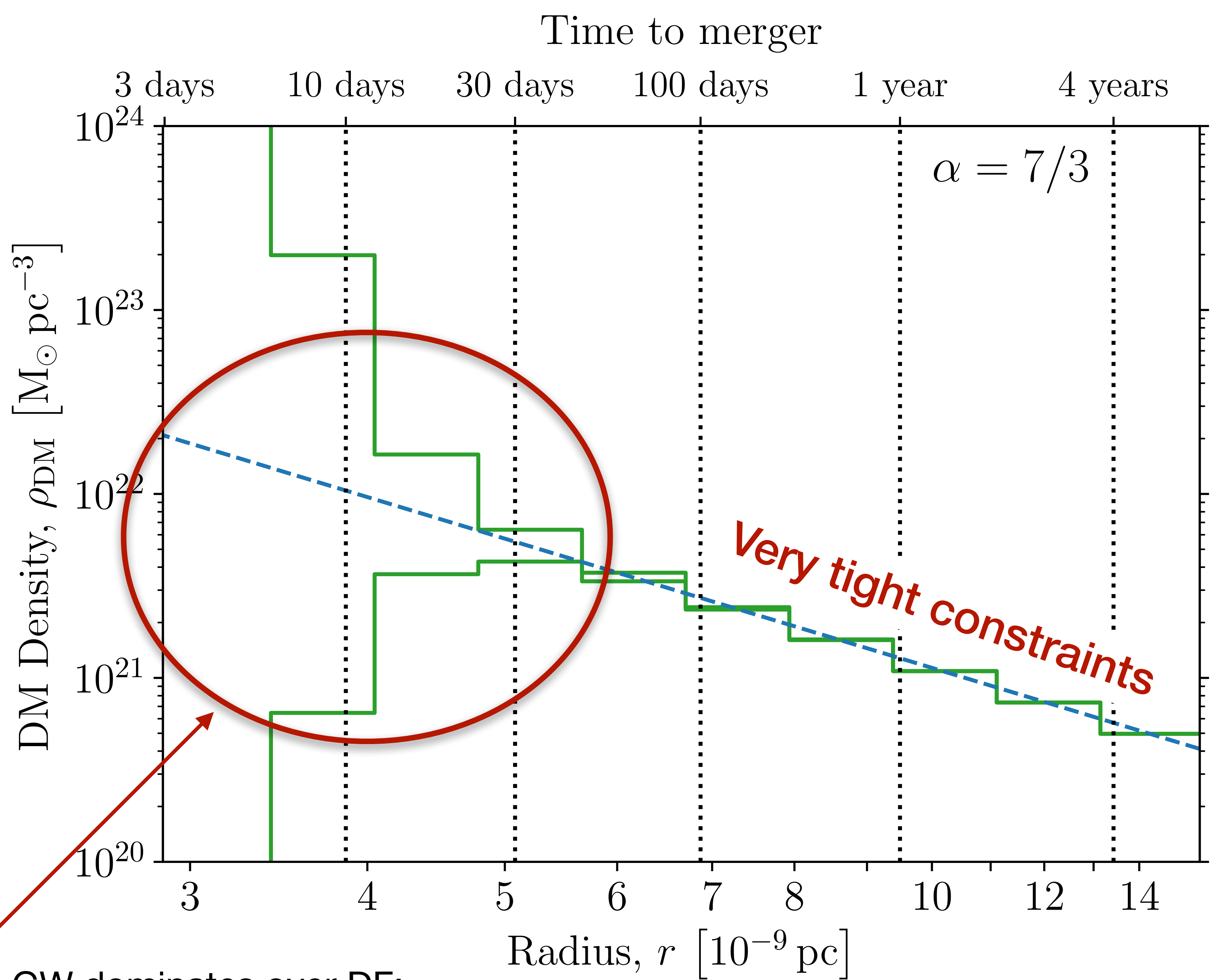


Measuring the phase shift constrains the DM density

LISA sensitivity



LISA sensitivity



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)

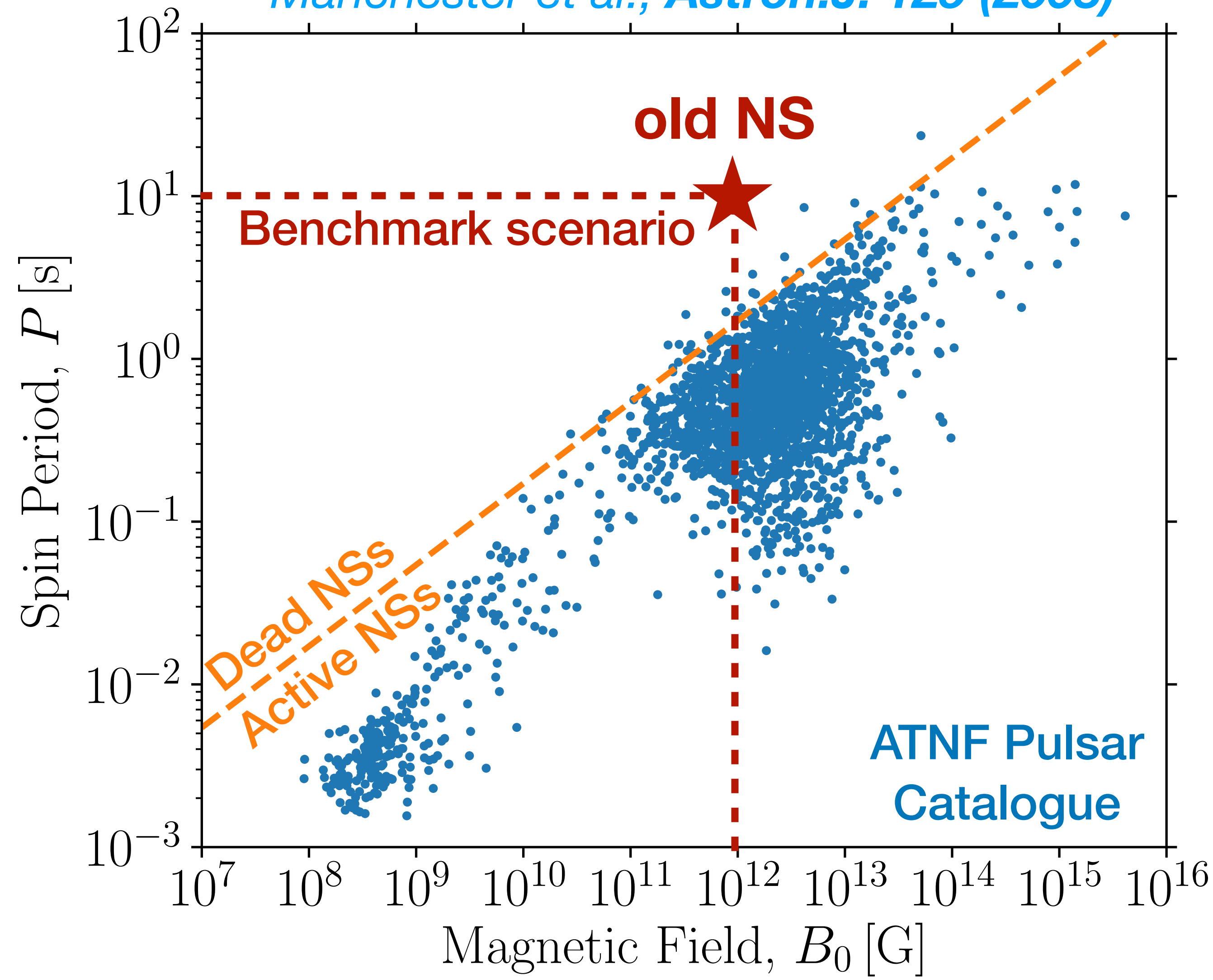
**Caveats*: measurements of individual masses and spins (high order post-Newtonian effects)

Radio signal: axion-photon conversion

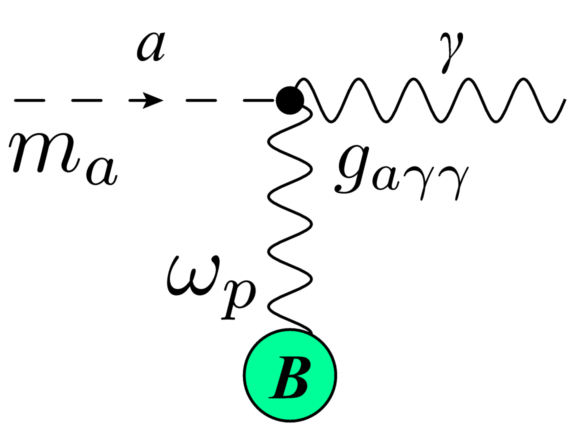
Neutron Stars have:

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

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



Resonant Axion-Photon Conversion



resonance

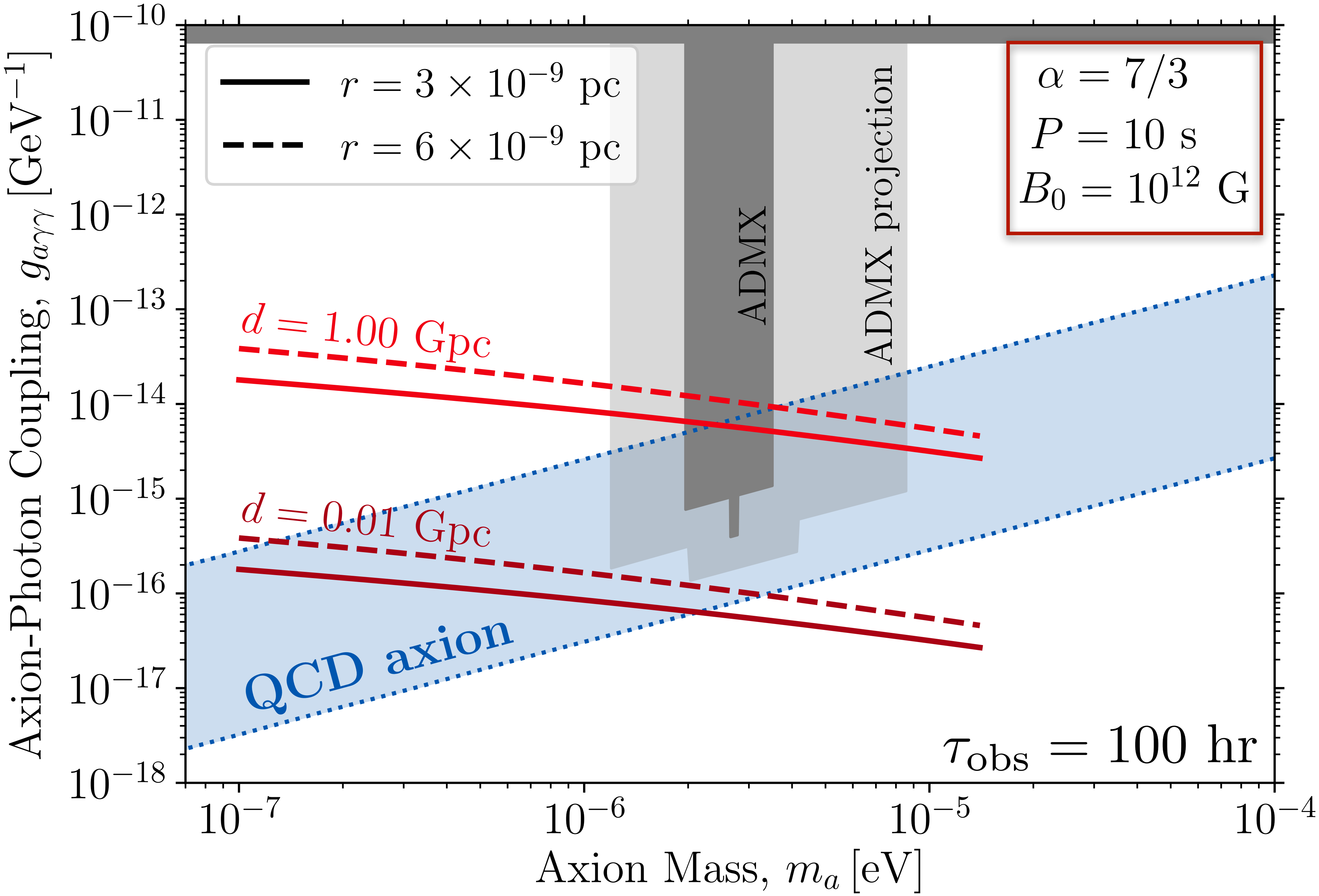
$$\omega_p(r_c;\, B_0,\, P) = m_a$$

For *radial trajectories*, the radiated power is:

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

*see also: Huang et al., **PRD 93 (2018)**; Hook et al., **PRL 121 (2018)**; Safdi et al., **PRD 99 (2019)**; Battye et al., **PRD 102 (2020)**; Foster et al., **PRL 125 (2020)**; Darling, **PRL 125 (2020)**.*

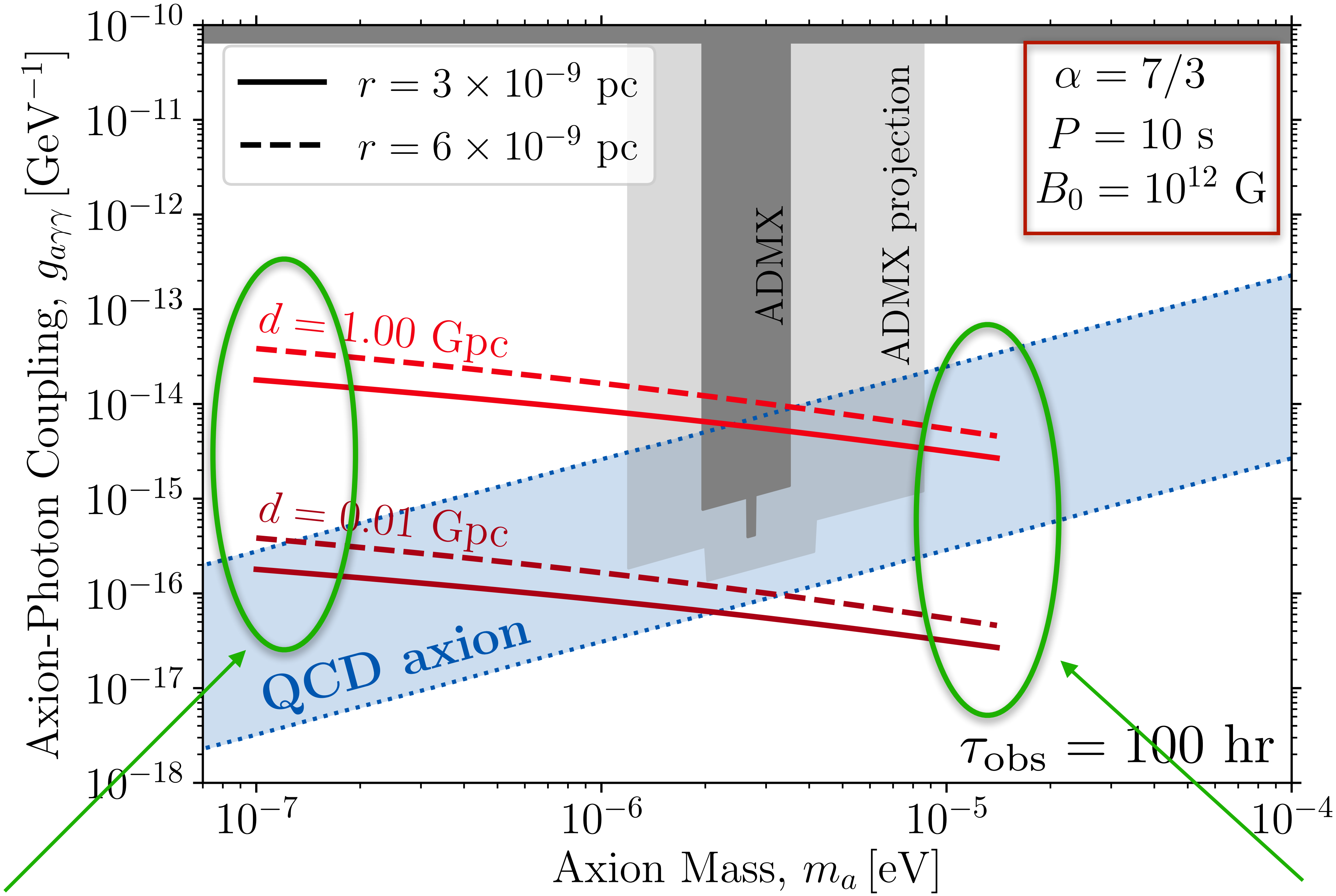
SKA sensitivity



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

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

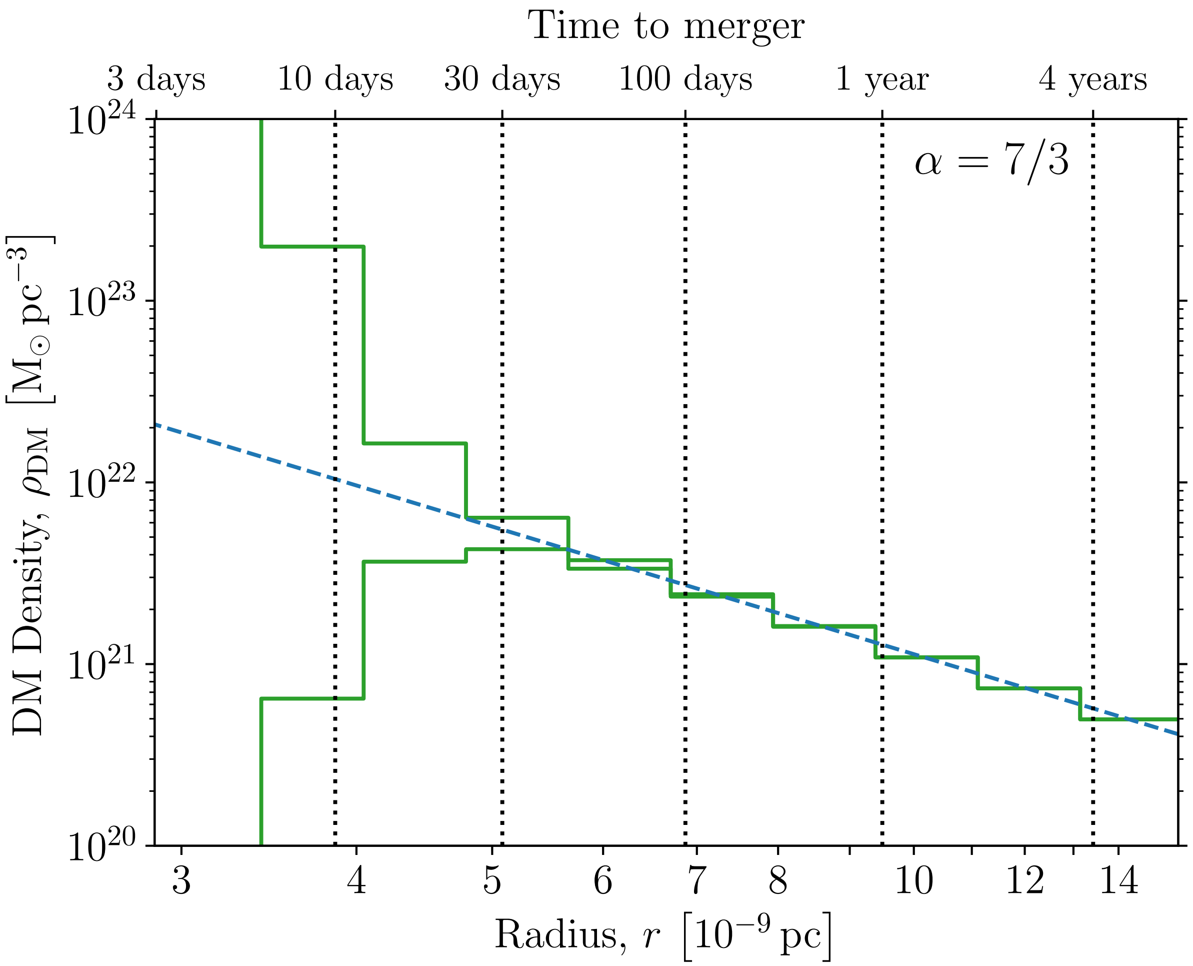
SKA sensitivity

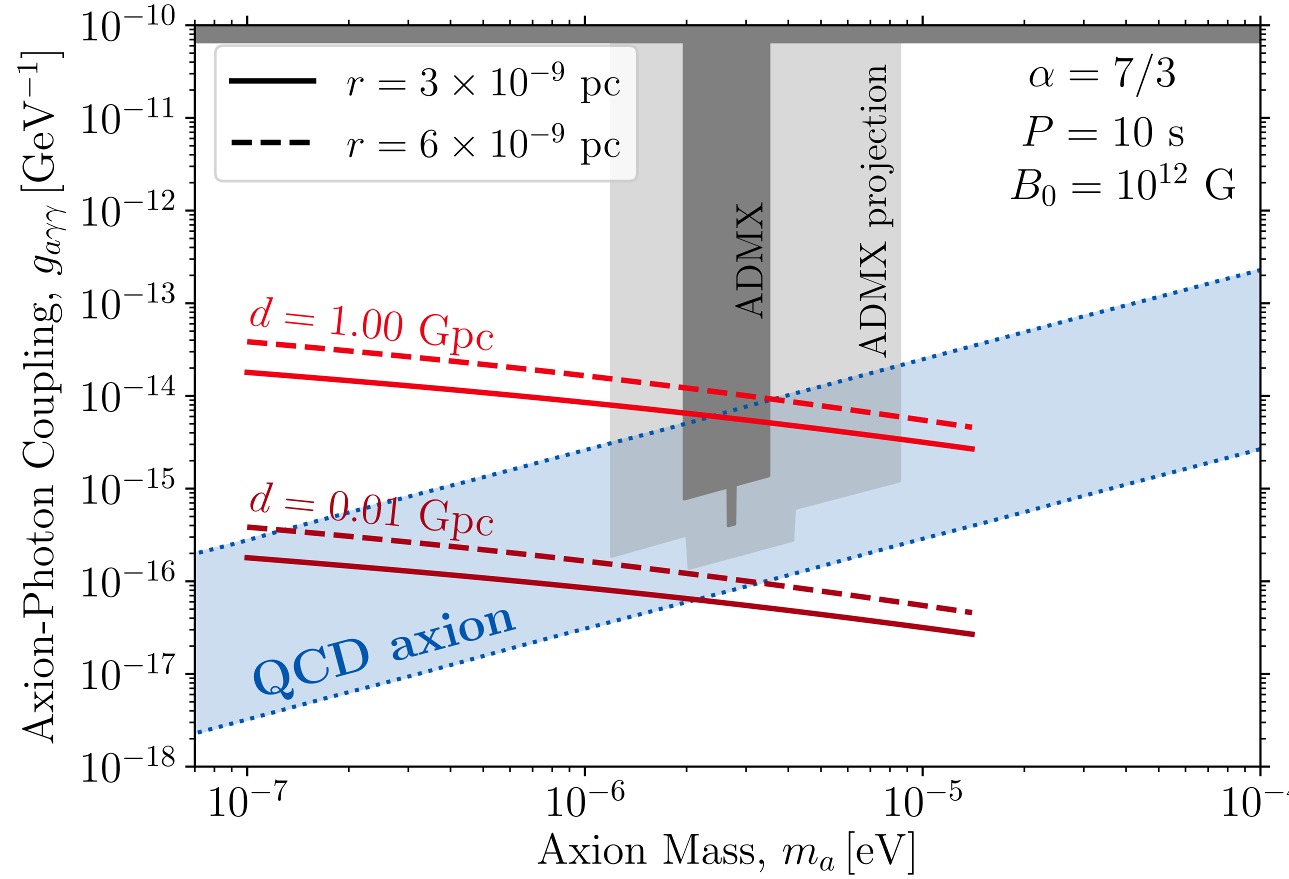


Lower cut-off: set by lowest frequency probed by SKA

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

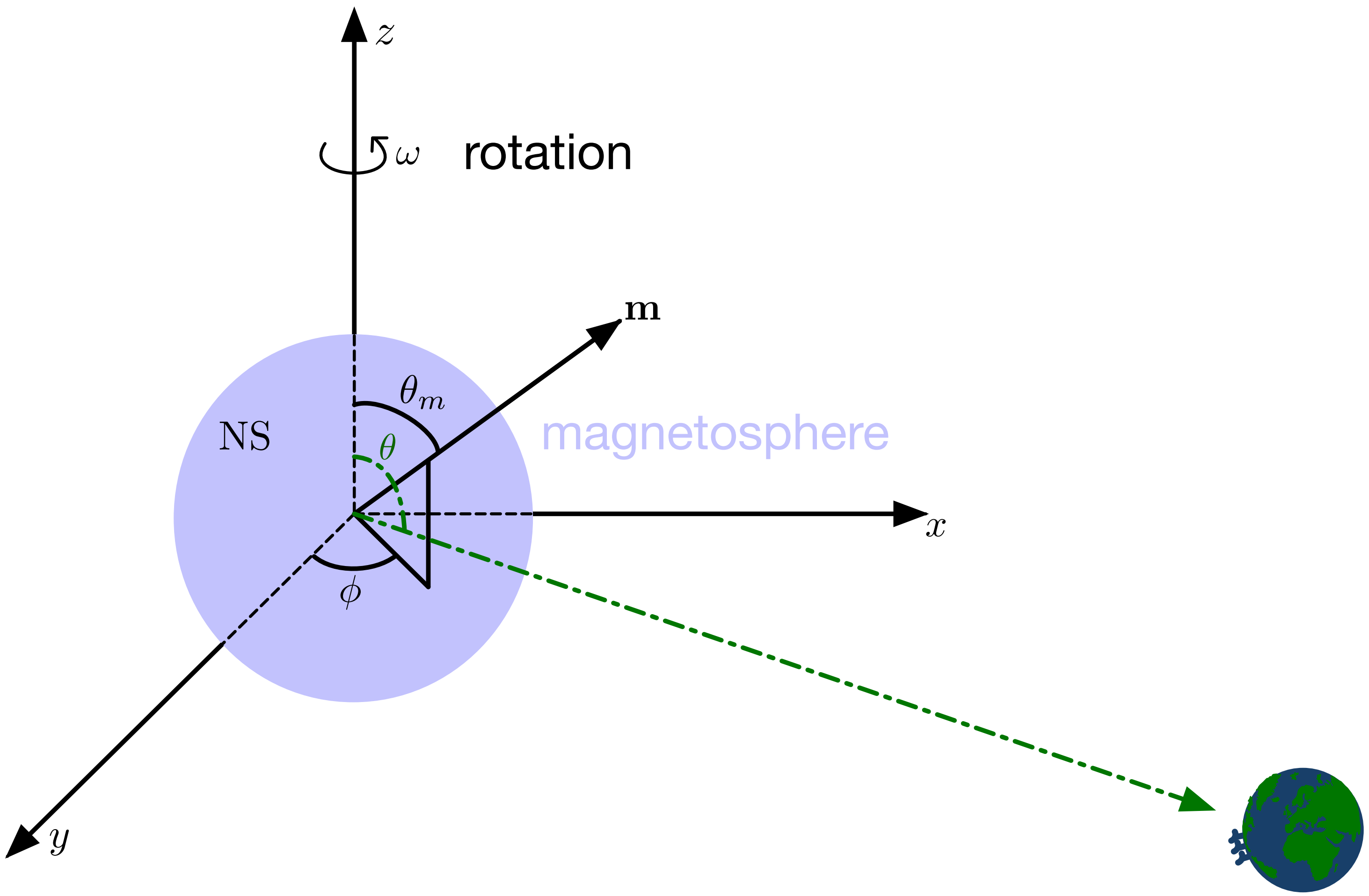
Take-home messages





- 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.

Numerical ray-tracing calculation



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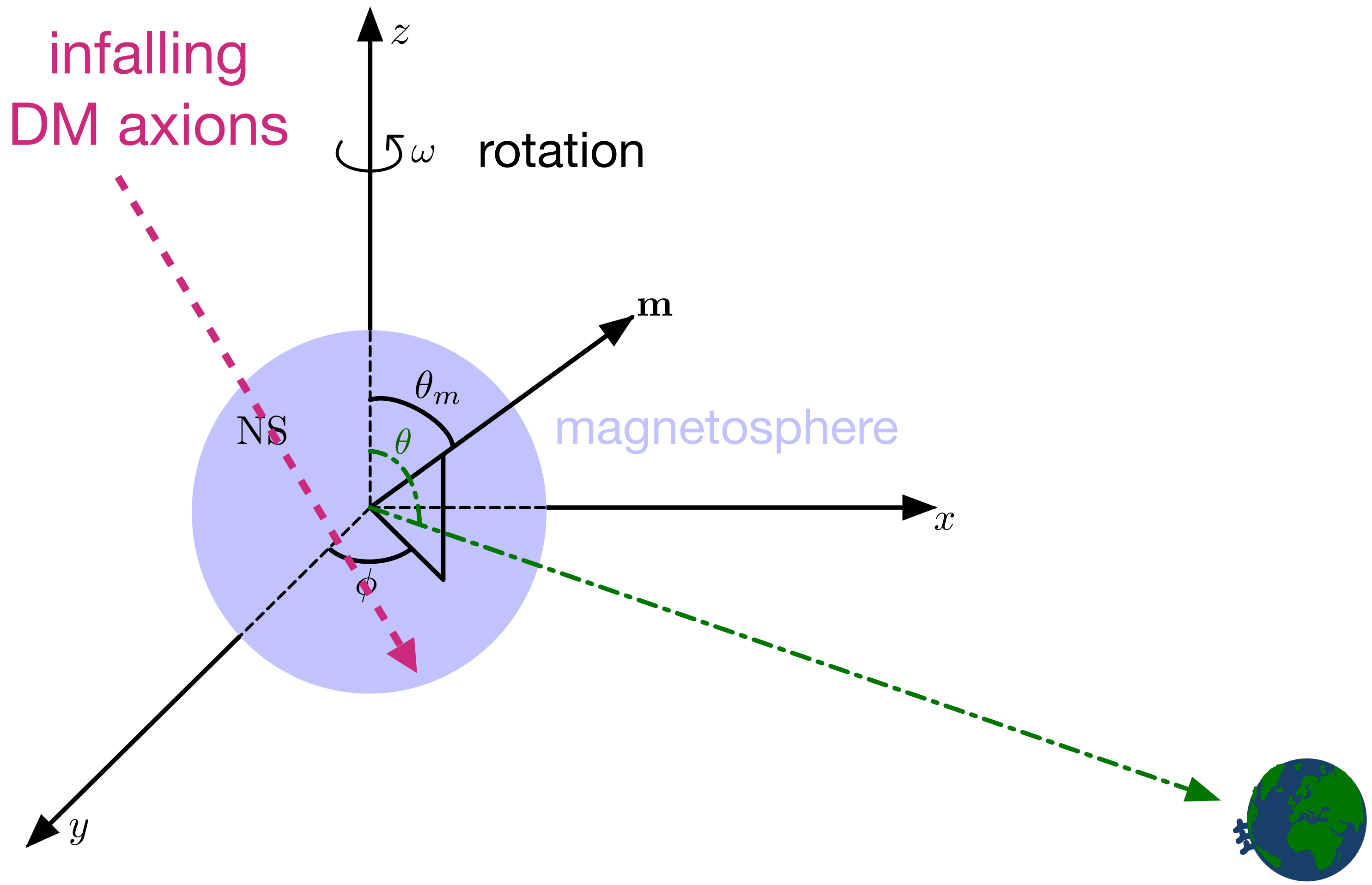
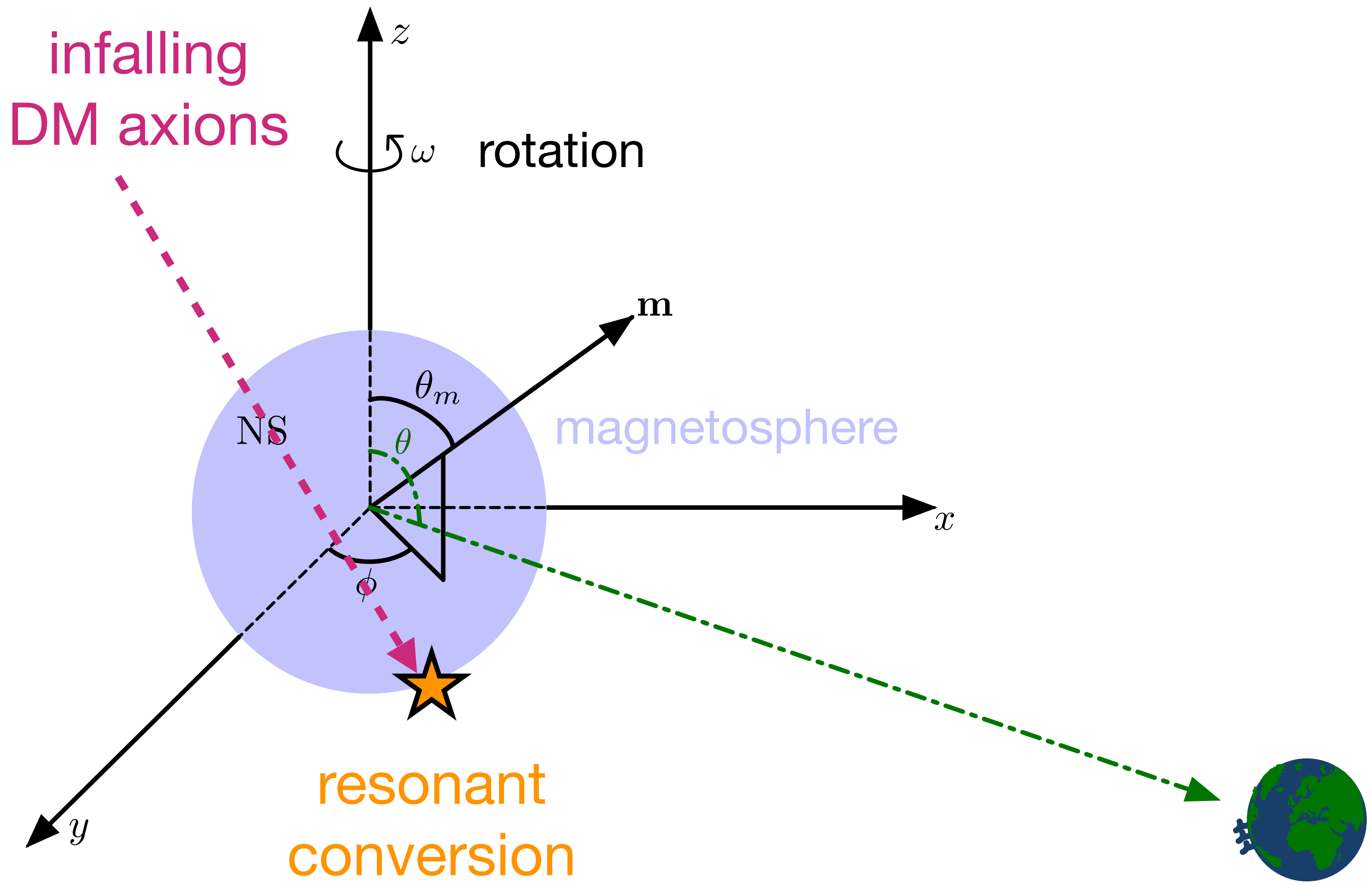


Phase-Space Distribution (PSD)

Using Liouville's theorem, we get:

- Isotropic PSD (not radial!)
- DM density and velocity at NS surface
- Intrinsic bandwidth of the radio signal

Numerical ray-tracing calculation



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Goldreich-Julian magnetosphere

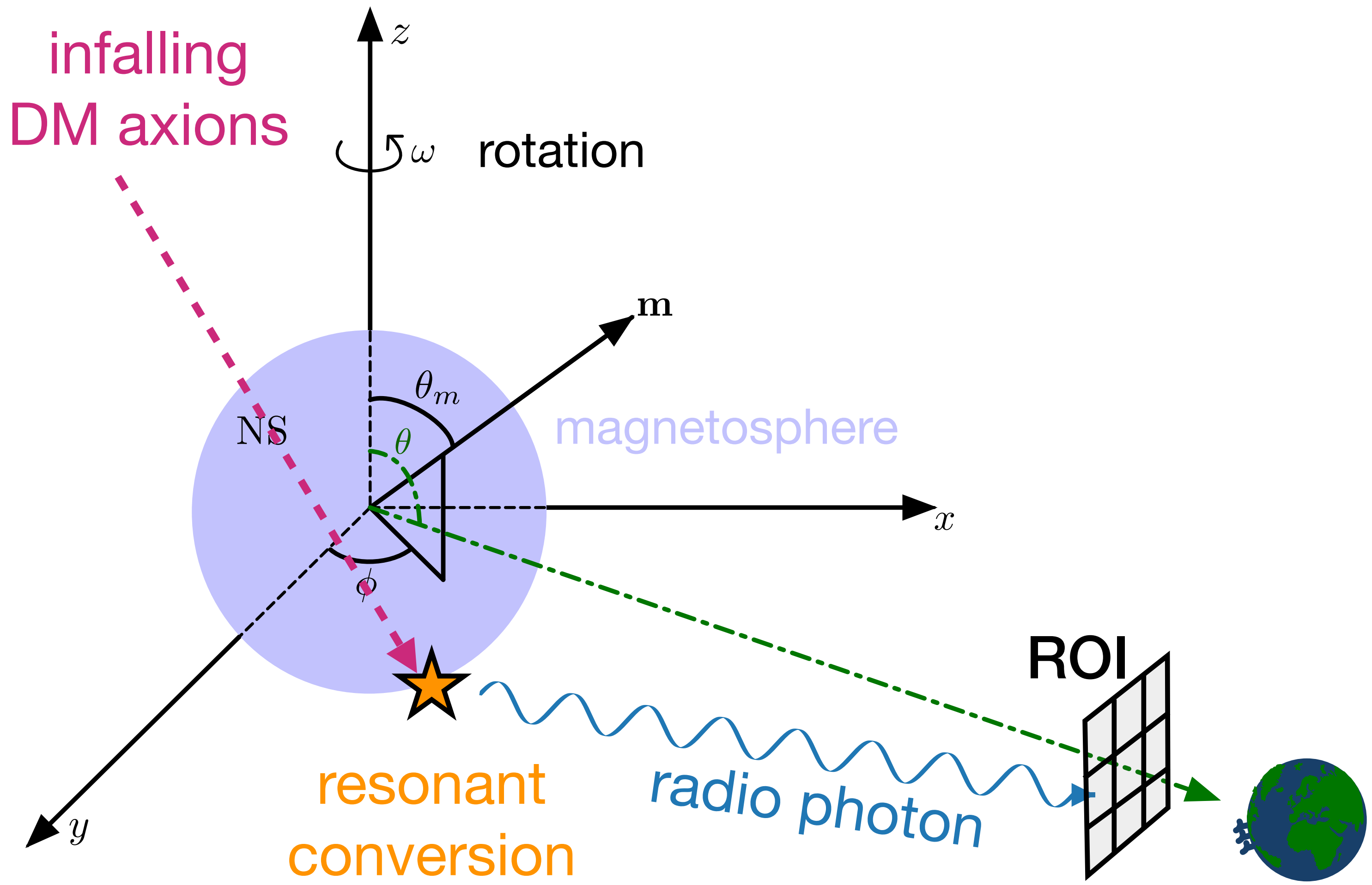
- Dipole magnetic field along the direction ***m*** (θ_m = misalignment angle)
- Well-defined plasma mass ω_p
- Resonant conversion surface:

$$\omega_p(\boldsymbol{r}_c, t) = m_a$$

- Conversion probability:

$$P_{a\to\gamma} = \frac{\pi}{2}\left(g_{a\gamma\gamma}B_\perp\right)^2 \frac{1}{v_c|\omega_p|'}$$

Numerical ray-tracing calculation



3D ray-tracing calculation

- We define photon trajectories according to a pixellated Region Of Interest (ROI)
- We back-propagate the photons to compute the radiated power for each pixel

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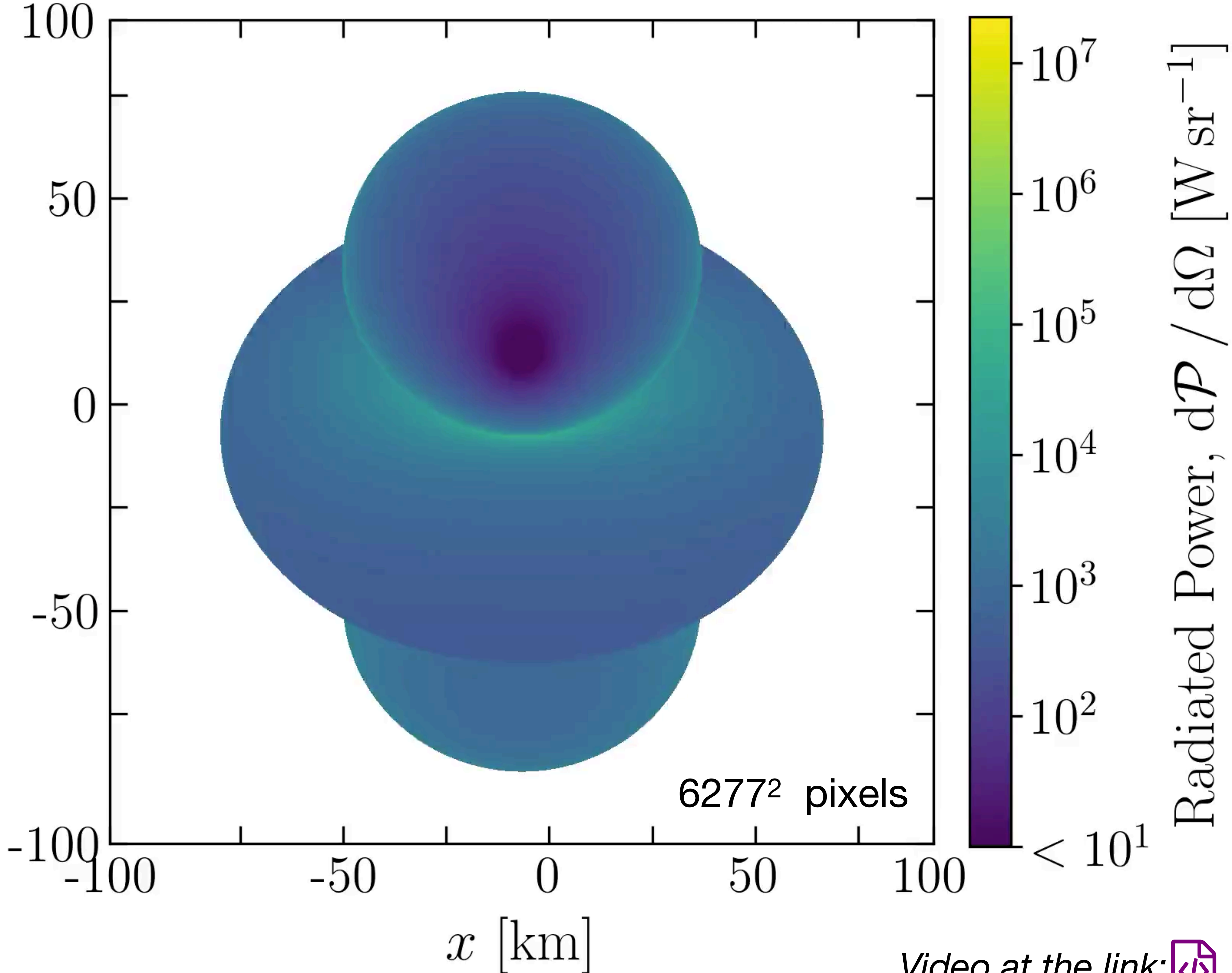
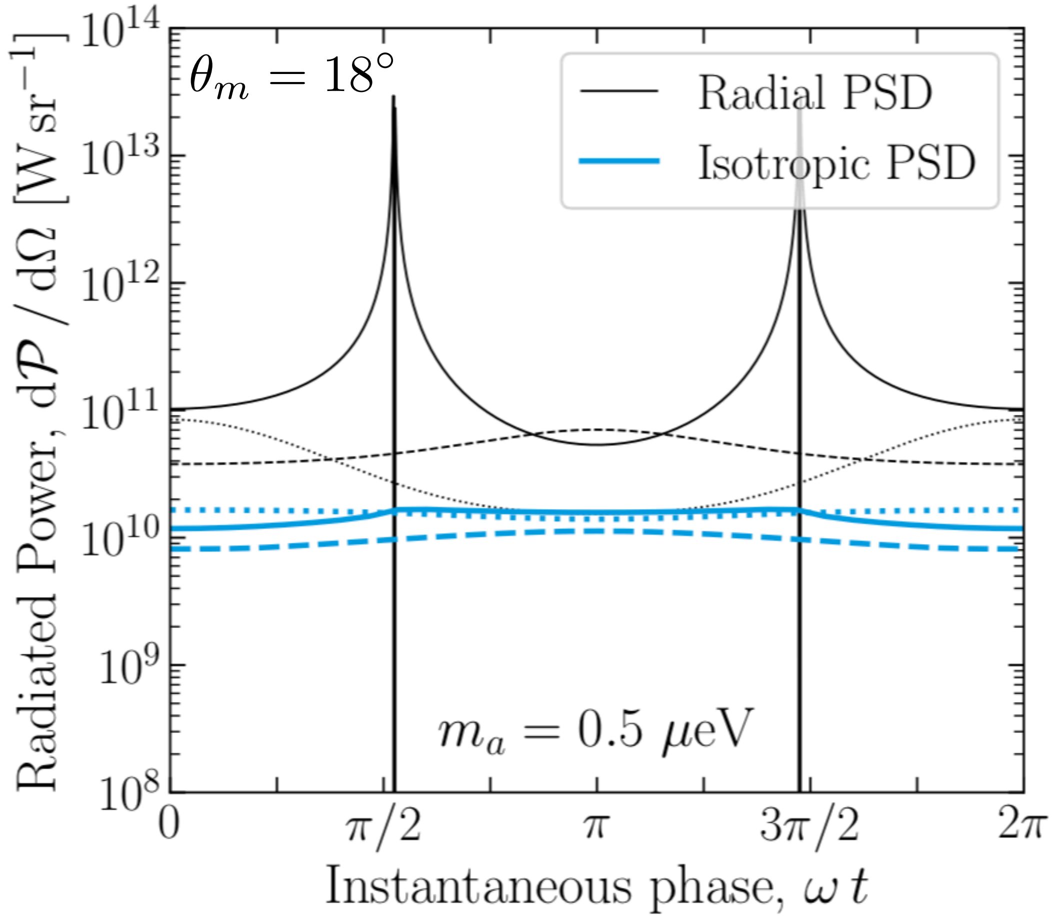
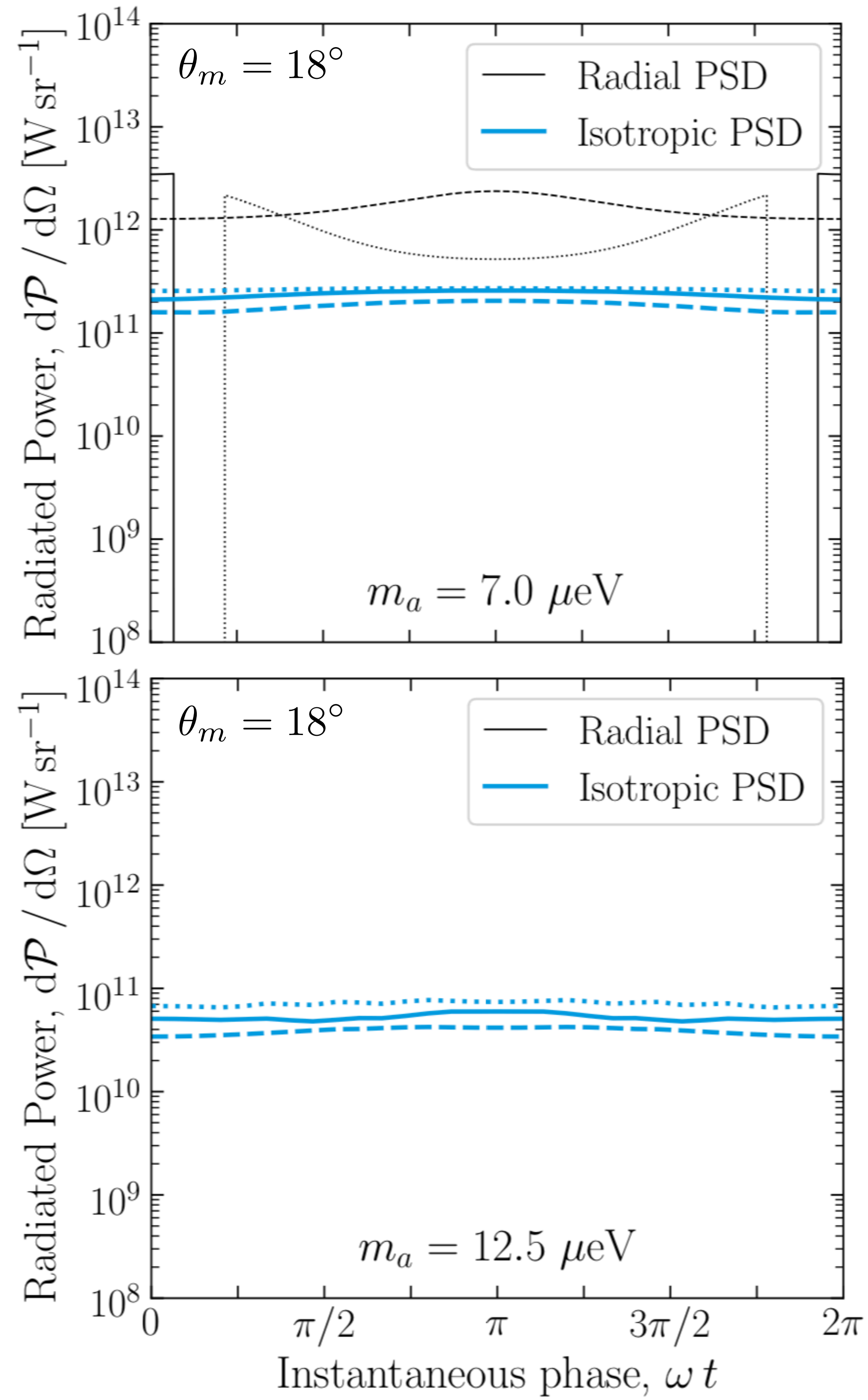
Simulation of NS J0806.4-4123



Video at the link:

Radiated power: isotropic *vs* radial PSD

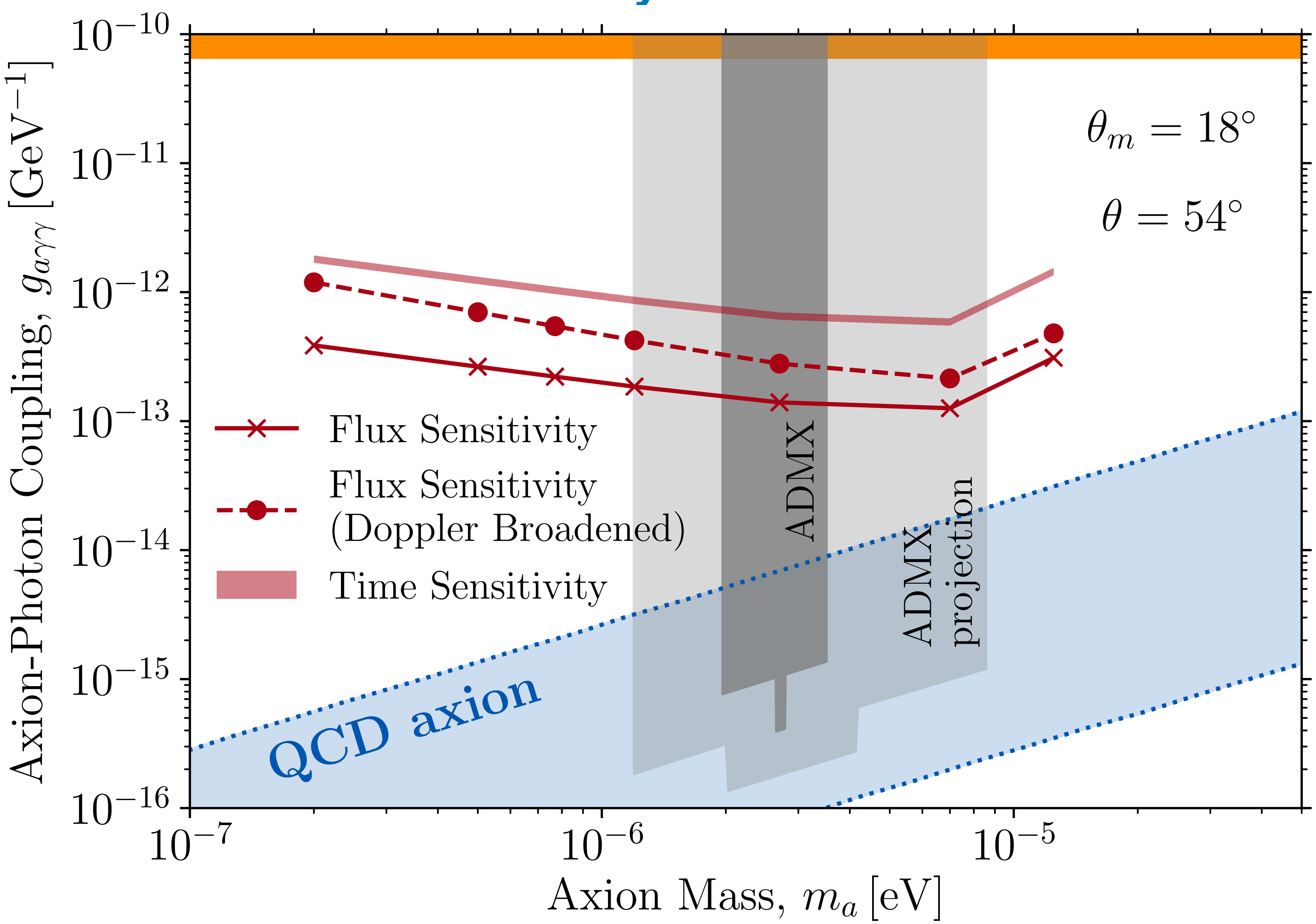




Main results

- The signal normalization is typically a factor of 2-10 smaller.
- Radio signal is still present at large axion masses ($m_a \gtrsim 10\ \mu\text{eV}$)
- Time variability is almost washed out

Conclusions



Main results

- sensitivity reduced up to a factor of 3
- extended to larger axion masses
- time variability hard to detect

Take-home messages

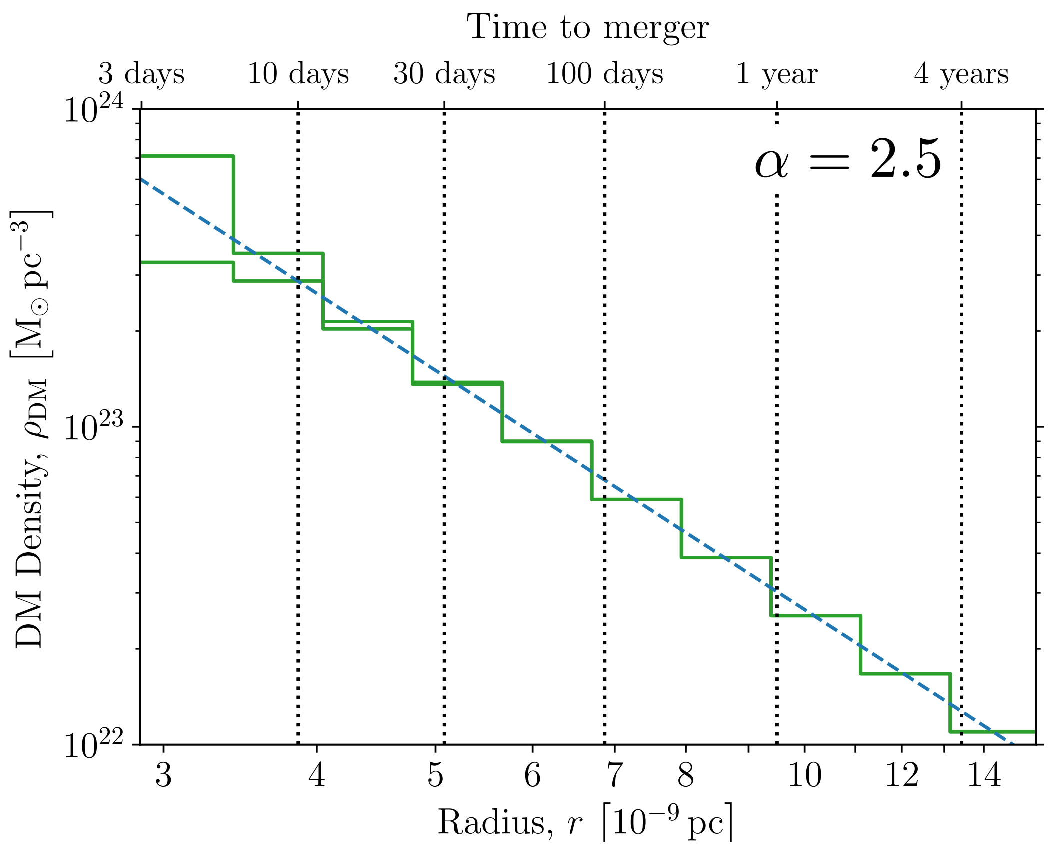
- crucial step forwards in calculating the true signal
- ray-tracing code can be generalized (NS plasma simulations, 3D axion-photon mixing equations)

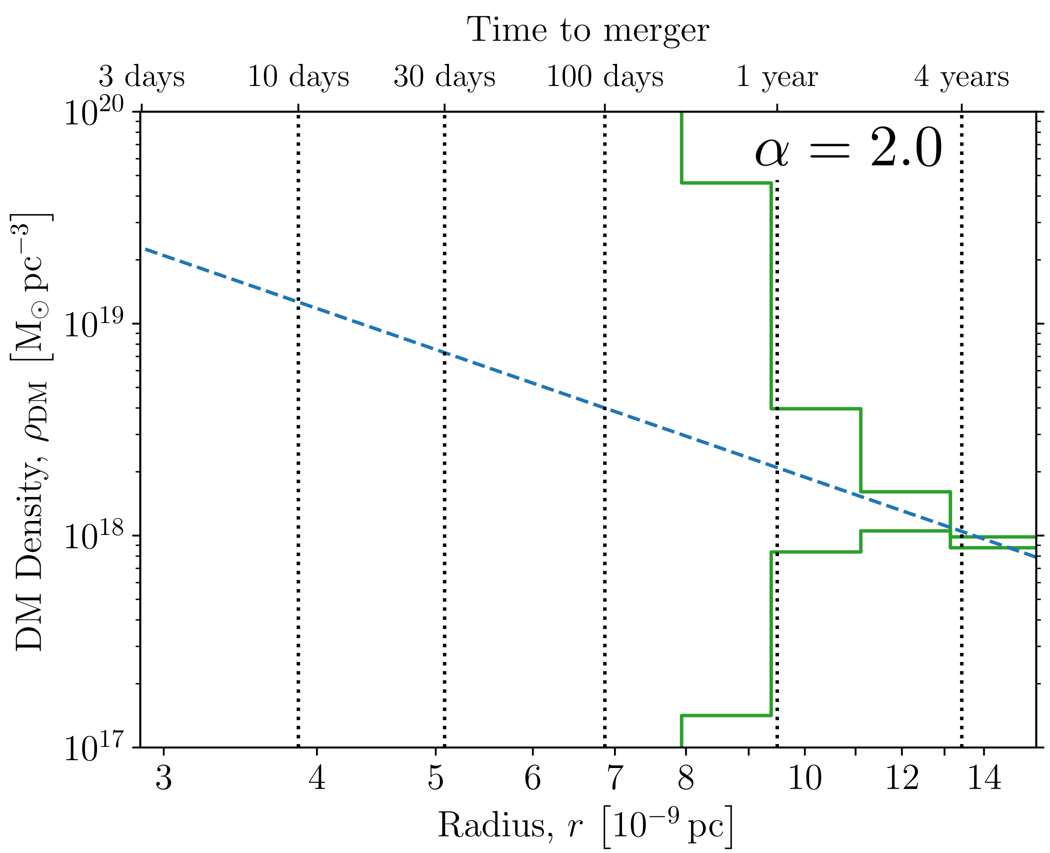
public code at

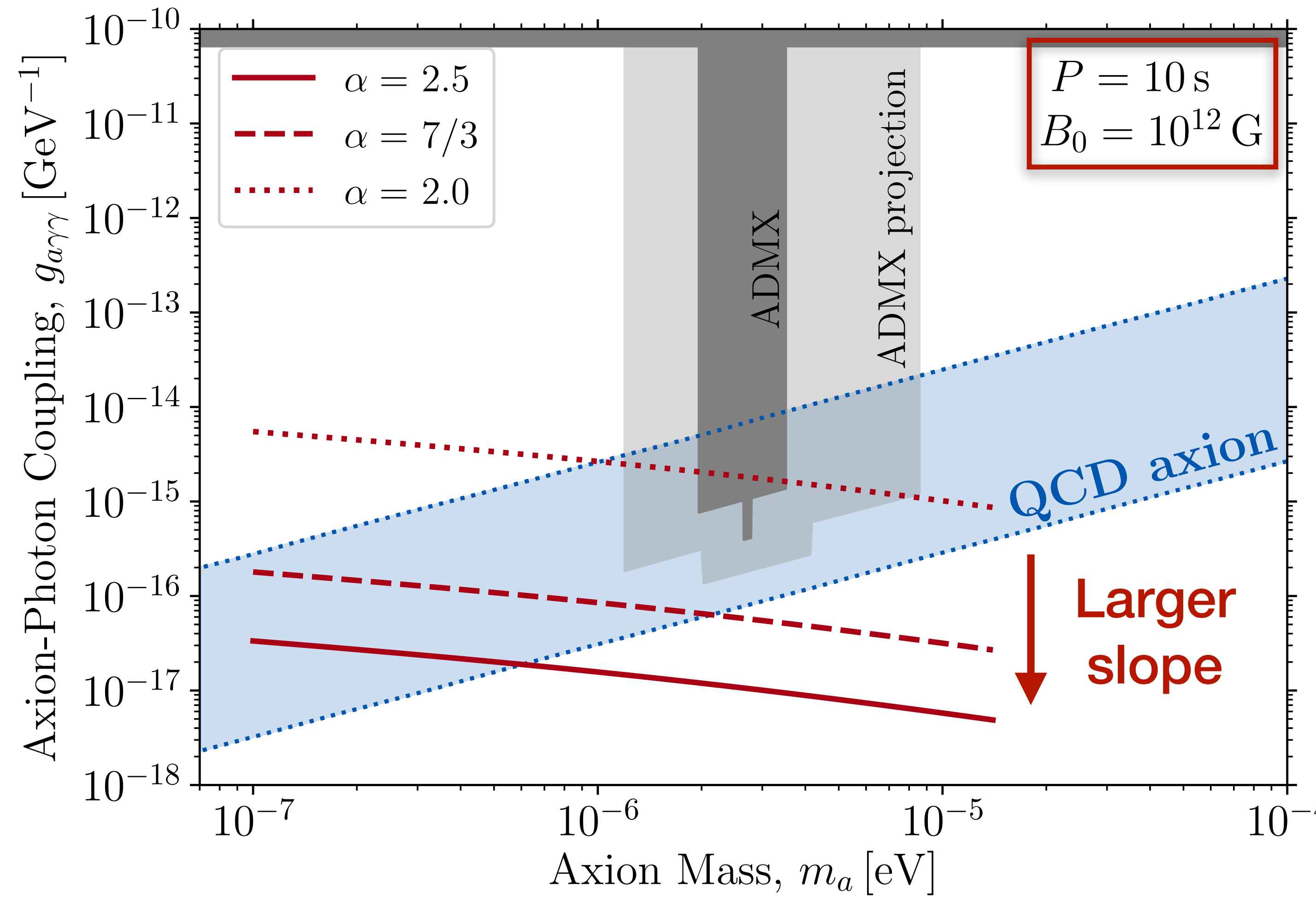
Thanks for listening

BACKUP SLIDES

Dependence on the spike slope





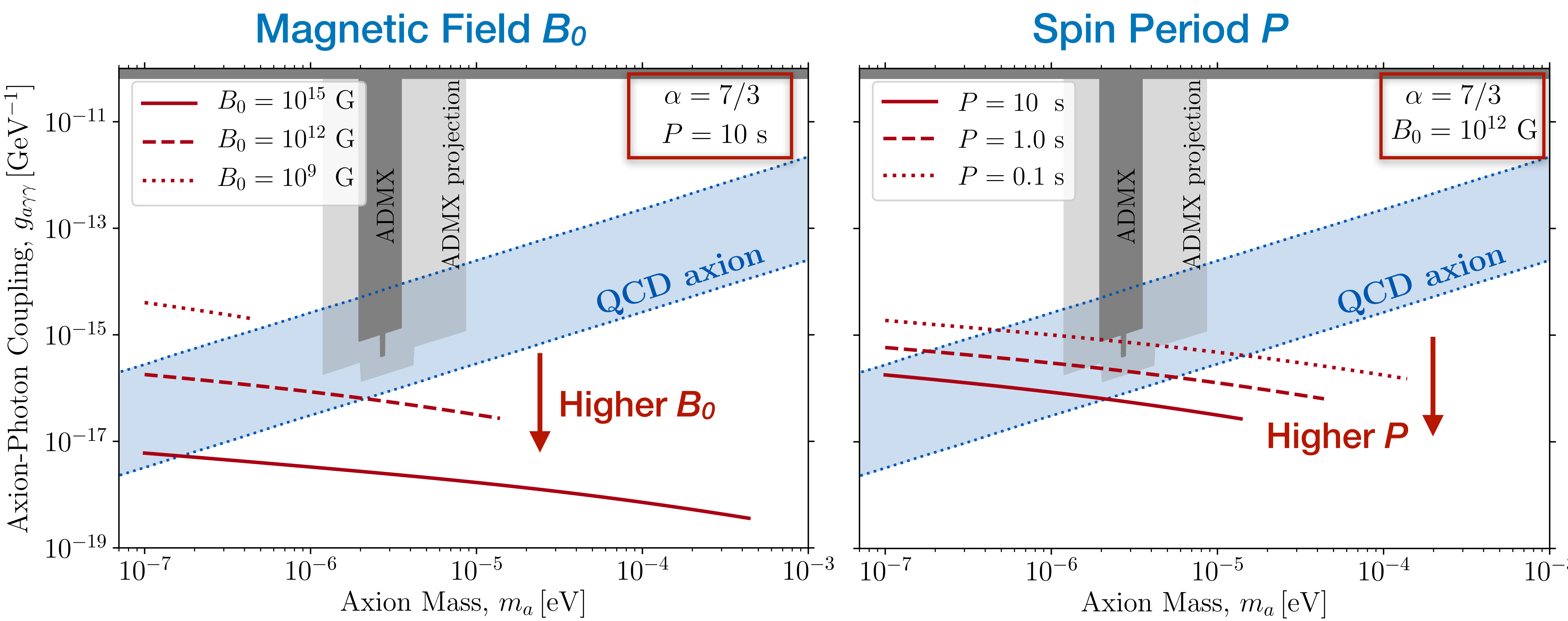


- The larger the slope, the larger the DM density close the IMBH.

→ **Larger Radio Signal!**

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

Dependence on NS parameters



The radiated power of the radio signal roughly scales as

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

Independent of NS parameters

Viewing angle (benchmark value)

Average and variance over NS rotation