A Unique Multi-Messenger Signal of QCD Axion Dark Matter

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Edwards, MC, Kavanagh, Nissanke and Weniger, [arXiv:1905.04686]

Leroy, MC, Edwards and Weniger, [in progress]

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GRAPPA

GRavitation AstroParticle Physics Amsterdam

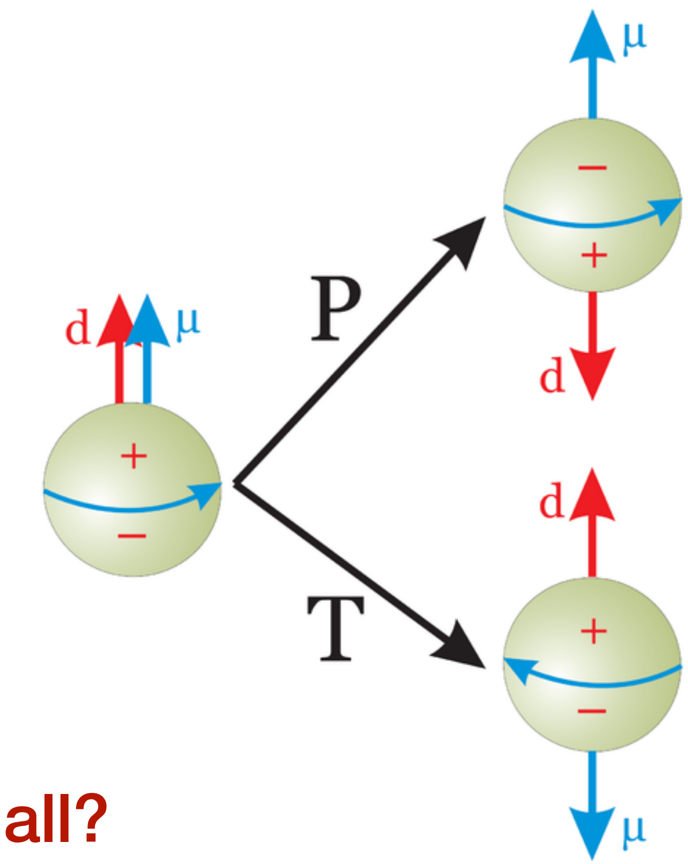
Strong-CP problem and QCD axion

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

- The QCD Lagrangian admits CP violating term:

$$\mathcal{L}_{\rm QCD} \supset -\left(m_q e^{i\theta_Y}\overline{\mathbf{q}}_L \mathbf{q}_R + {\rm h.c.}\right) - \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \theta_{\rm QCD}$$

→ CP violation $\theta = \theta_{\rm QCD} + N_f \theta_{\rm Y} = \mathcal{O}(1)$



- No evidence of CP violation in QCD sector

$|\theta| \leq 10^{-10}$ **Strong CP-problem: why theta is so small?**

It is dynamically solved by promoting θ to be a scalar field.

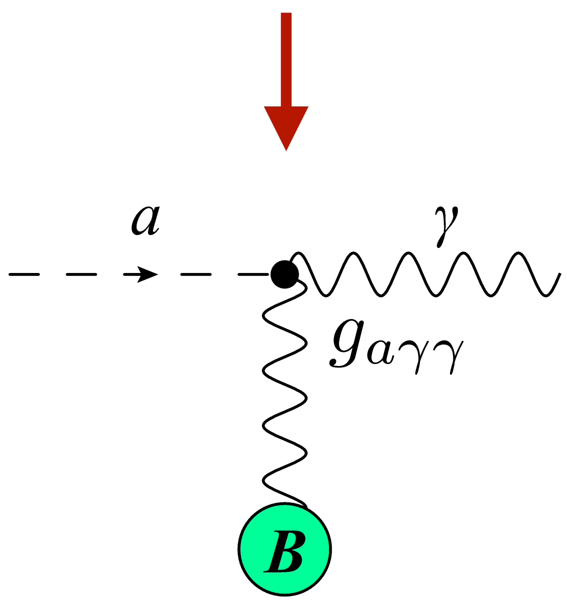
$$\theta_{\rm QCD} \to \theta_{\rm QCD}(x) = \frac{a(x)}{f_a} \quad \longrightarrow \quad \theta = \frac{\langle a \rangle}{f_a} \sim 0 \quad \text{at } f_a \gg 10^7 \text{ GeV}$$

Spontaneous Breaking of the Peccei-Quinn symmetry

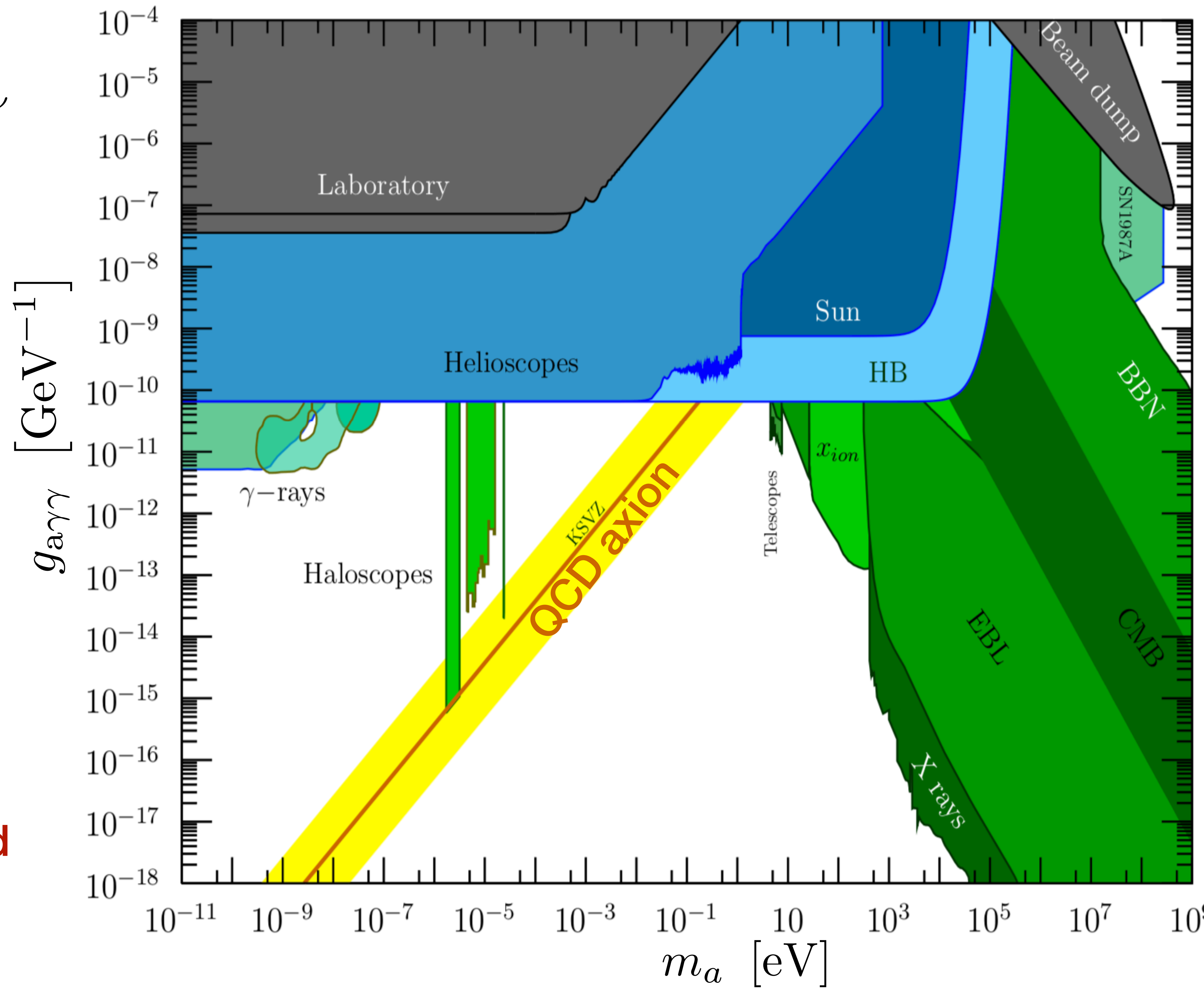
The axion parameters space

Most of the axion (direct and indirect) searches exploit its coupling to two photons.

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E}\cdot\boldsymbol{B}$$

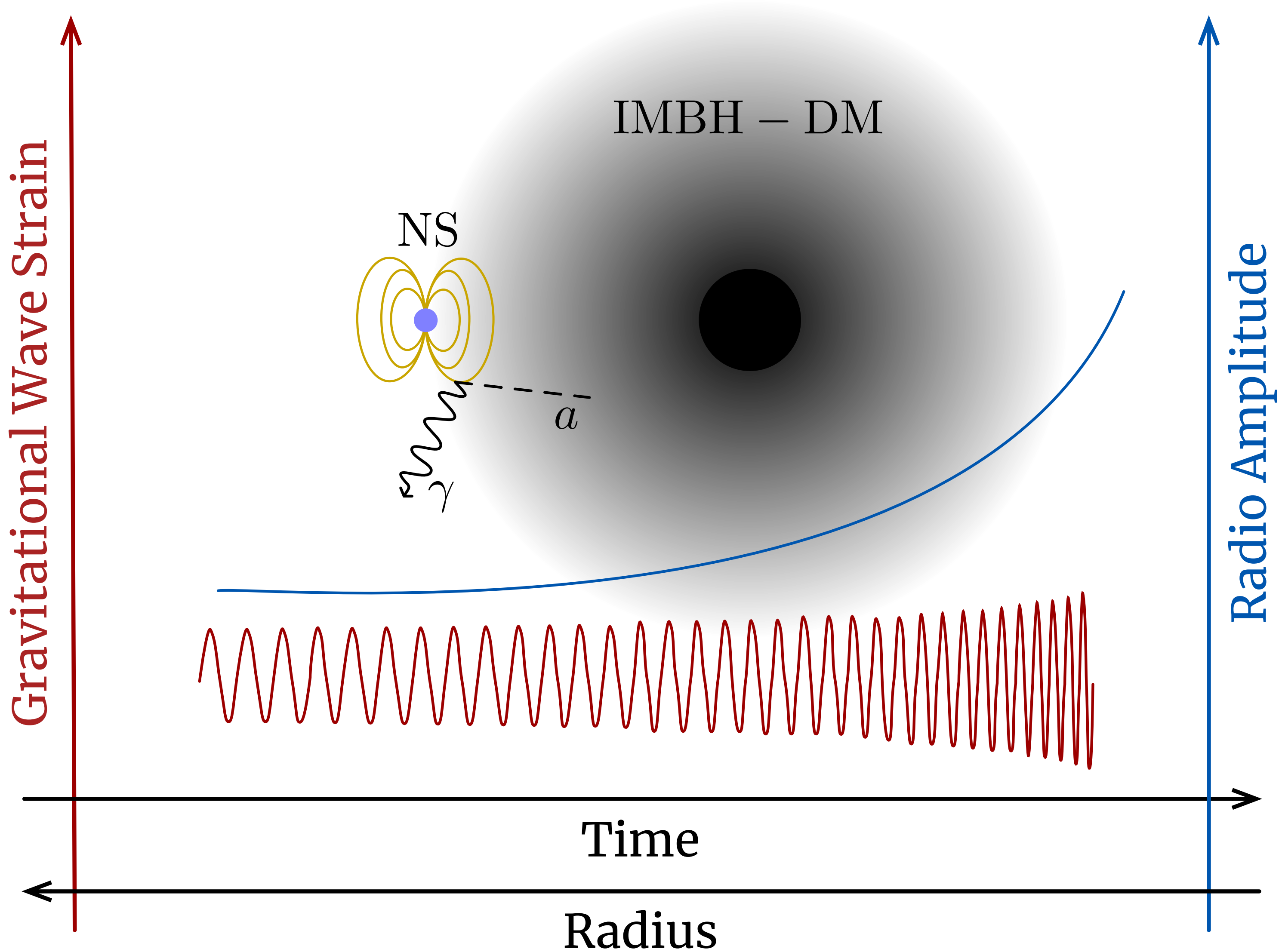


Axion-Photon conversion in an external magnetic field



Multi-messenger Signal — GW + EM

Observation of Black Hole—Neutron Star inspirals with an Axion DM spike



Plot legend

$M_{\rm IMBH} = 10^4\ M_\odot$

$M_{\rm NS} = 1.4\ M_\odot$

a: axion

γ: photon

GW

Distinct phase shift in the Gravitational Wave strain

+

EM

Radio emission from axion-photon conversion in the NS magnetosphere

Intermediate Mass Black Holes

IMBHs are the least constrained mass window:

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

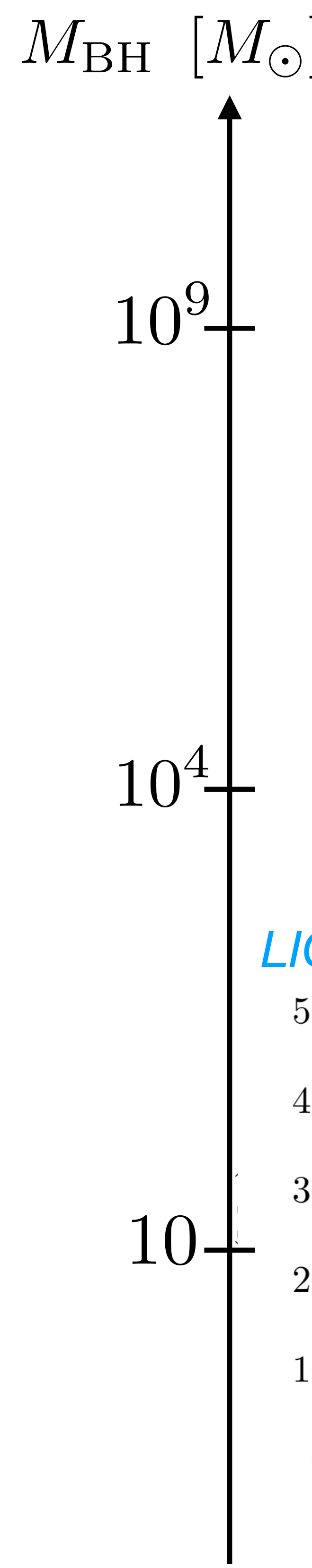
No detection by GWs so far, but evidences of their existence in the centre of small galaxies and in globular clusters.

*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

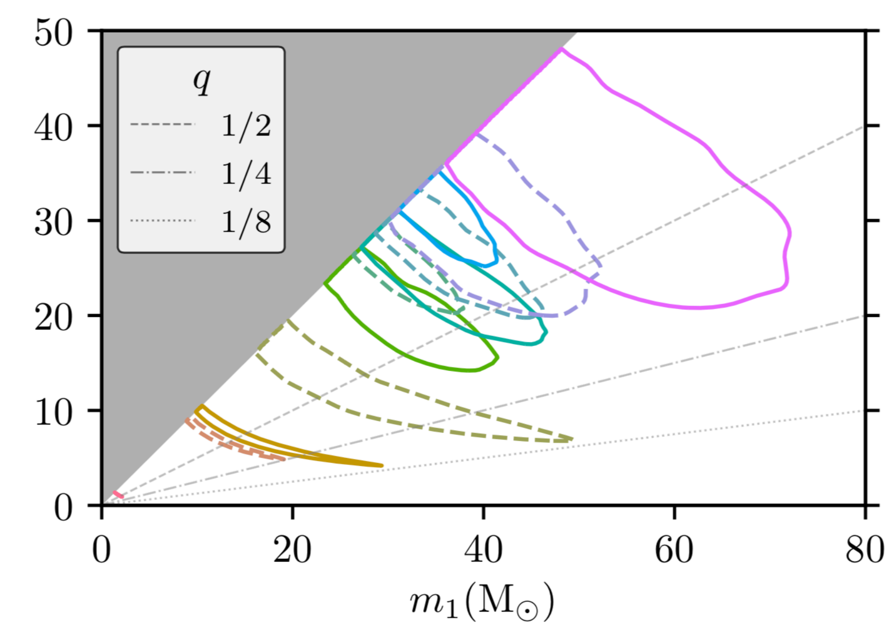
*Taniguchi et al., **Publ. Astron. Soc. Jap. 52 (2000)**; Begelman et al., **MNRAS 370 (2006)**; Carr and Rees, **MNRAS 206 (1984)***



*Event Horizon Telescope, **Astrophys.J. 875 (2019)***

Intermediate Mass BH

*LIGO and Virgo, **Phys. Rev. X9 (2019)***

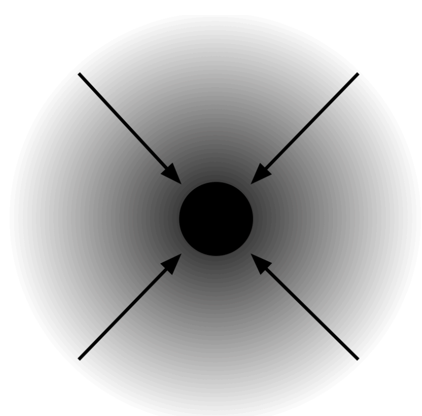


Dark Matter Spike

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

DM halo

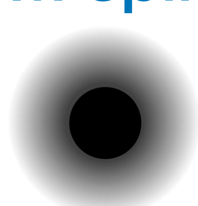
$z = 20$



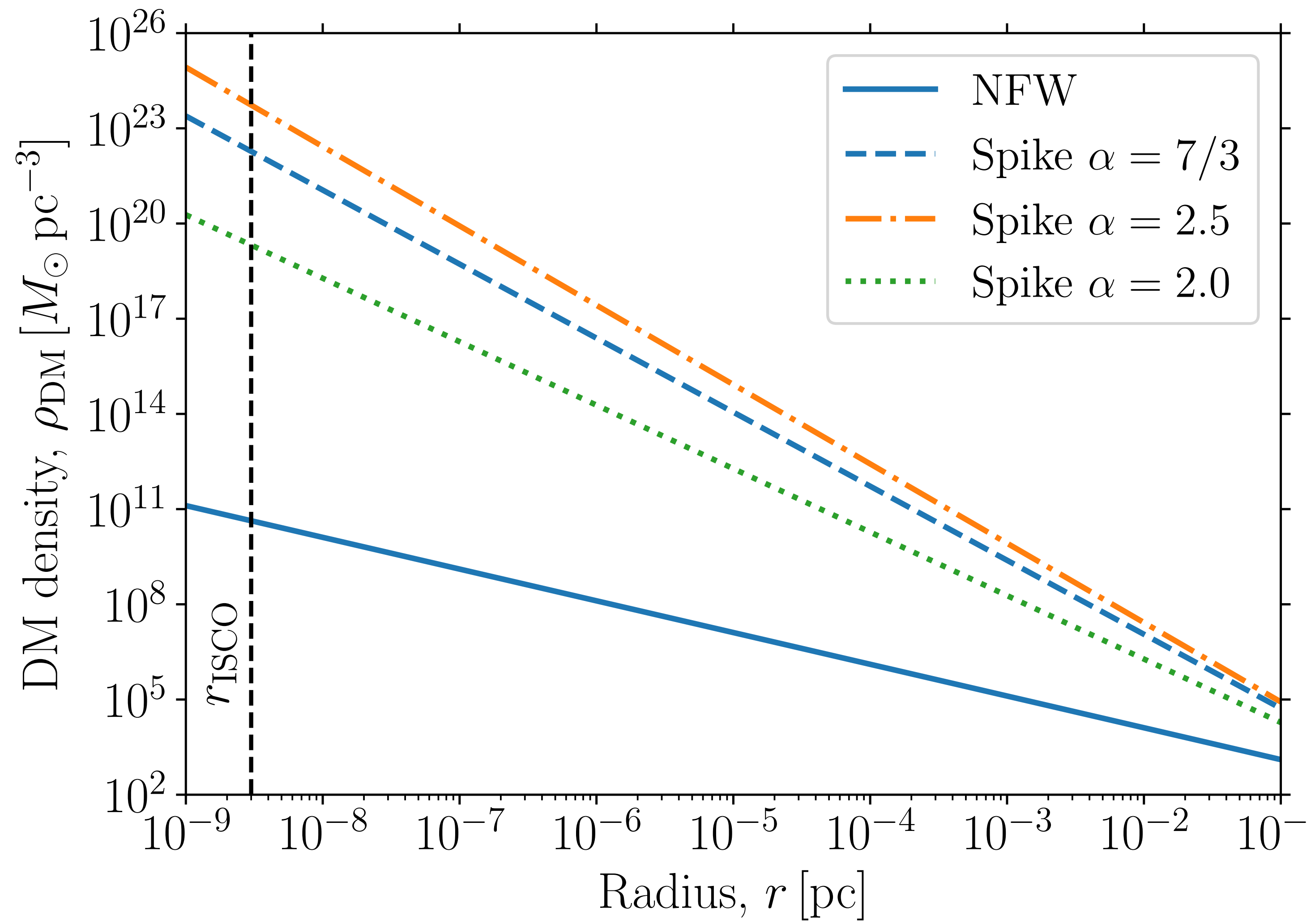
$$\rho_{\rm DM} \propto r^{-\alpha_{\rm init}}$$

DM spike

$z = 0$



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



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

It can be destroyed by mergers and by the presence of energetic accretion disk (baryonic matter).

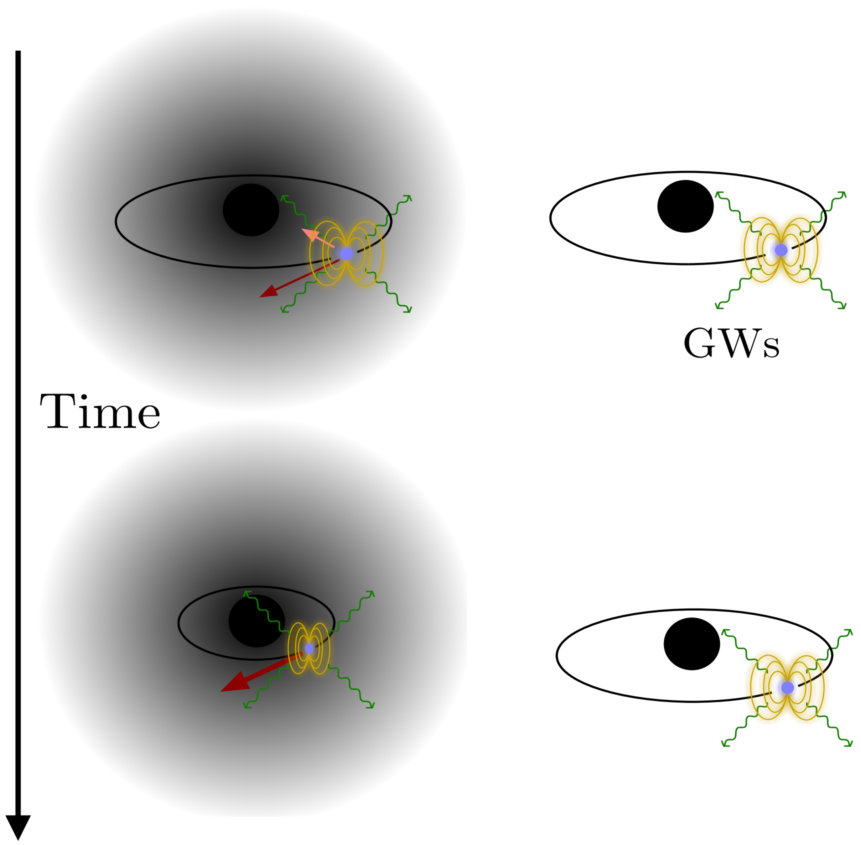
*Navarro, Frenk, White, **Astrophys.J. 462 (1996)**; Gondolo and Silk, **PRL 83 (1999)**; Zhao and Silk, **PRL 95 (2005)**; Bertone, Zentner and Silk, **PRD 72 (1999)**.*

Gravitational Wave Signal — Dynamical Friction

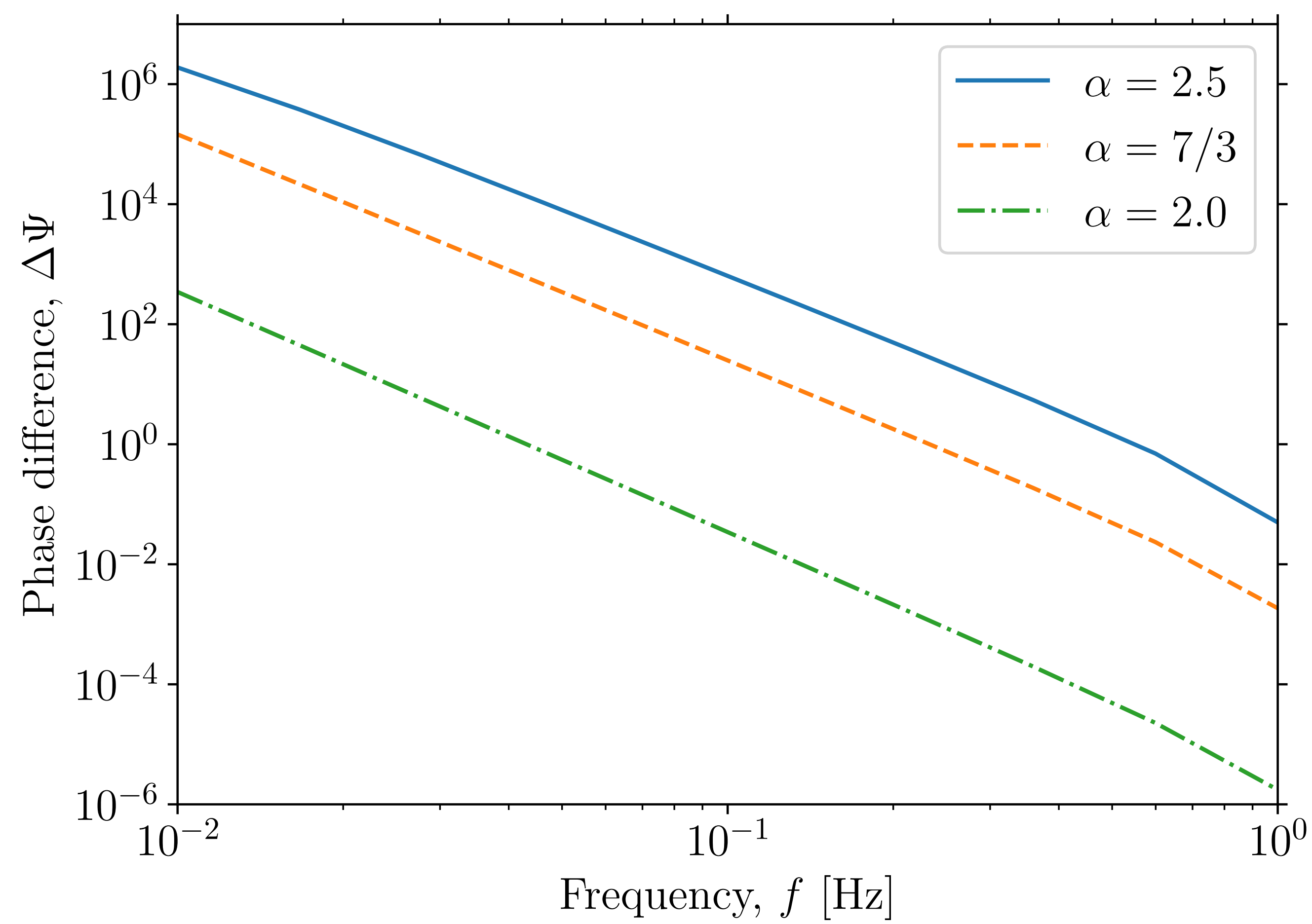
The presence of a DM halo causes additional energy loss through Dynamical Friction:

$$-\frac{dE_{\mathrm{orbit}}}{dt} = \frac{dE_{\mathrm{GW}}}{dt} + \frac{dE_{\mathrm{DF}}}{dt} \quad \textit{with} \quad \frac{dE_{\mathrm{DF}}}{dt} = 4\pi G^2 \ln\Lambda \frac{M_{\mathrm{NS}}^2\,\rho_{\mathrm{DM}}}{v_{\mathrm{NS}}}$$

Inspiral takes less time than in vacuum



Phase shift in the GW signal



Measuring the phase shift constrains the DM density

*See **Kavanagh's talk** and also Eda et al., **PRL 110 (2013), PRD 91 (2015)***

LISA Sensitivity — Dark Matter density

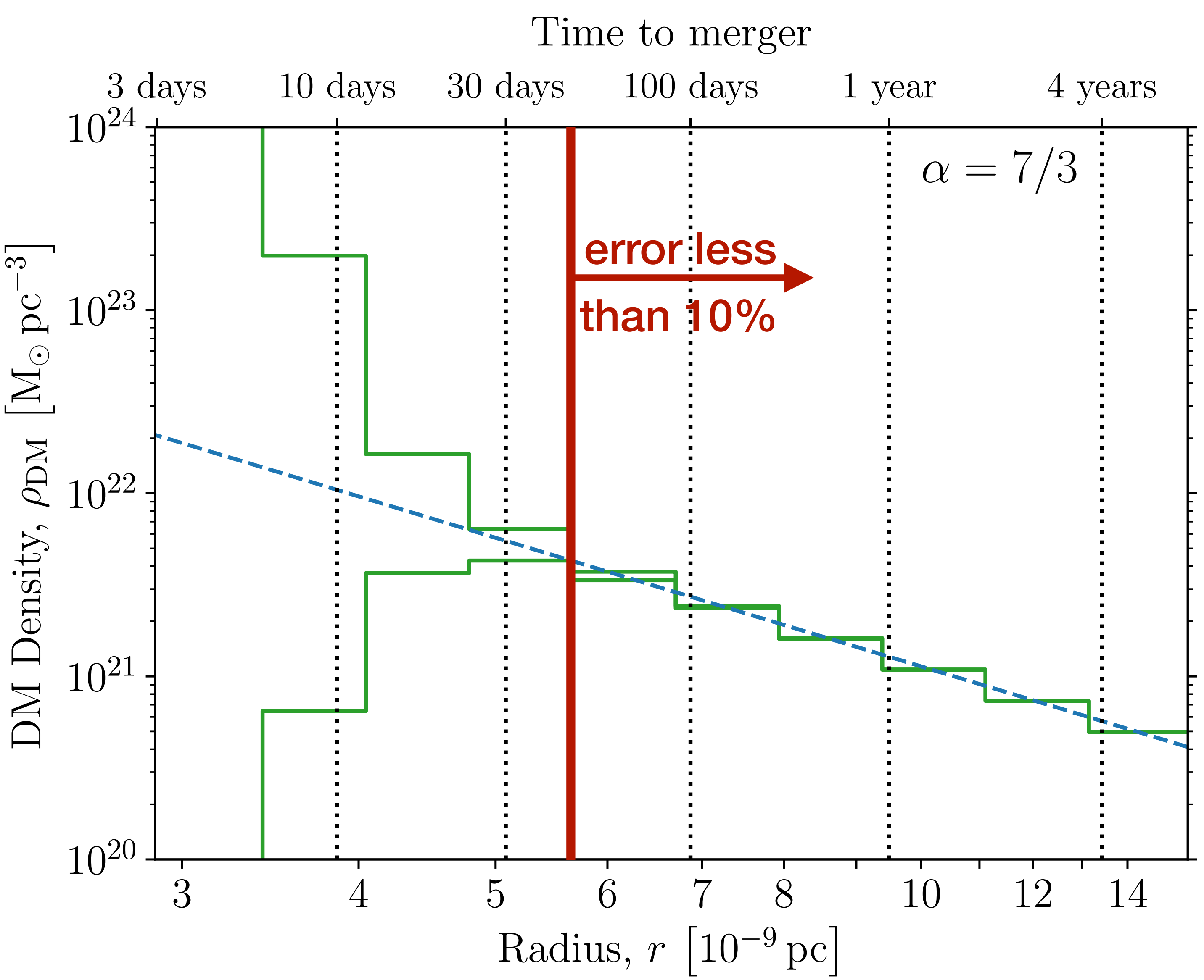
LISA will observe these objects for **5 years** prior to merger, with an expected detection rate of

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

The uncertainty on DM density at small radii increases:

- GW dominates over DF;
- Small number of cycles (less time) at a given radius;
- LISA sensitivity decreases at higher frequencies (signal ending at 0.44 Hz).

*LISA Collaboration, **arXiv:1702.000786**; Fragione et al., **Astrophys.J, 856 (2018)***



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

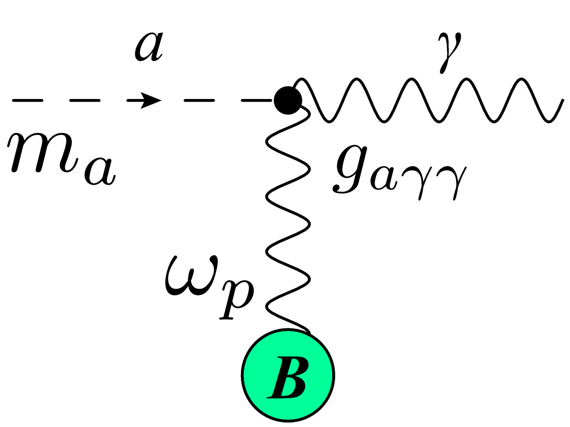
Neutron Stars — Axion-Photon conversion

Old NSs are highly abundant in globular clusters, being the dominant stellar mass object merging to IMBHs.

They have:

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

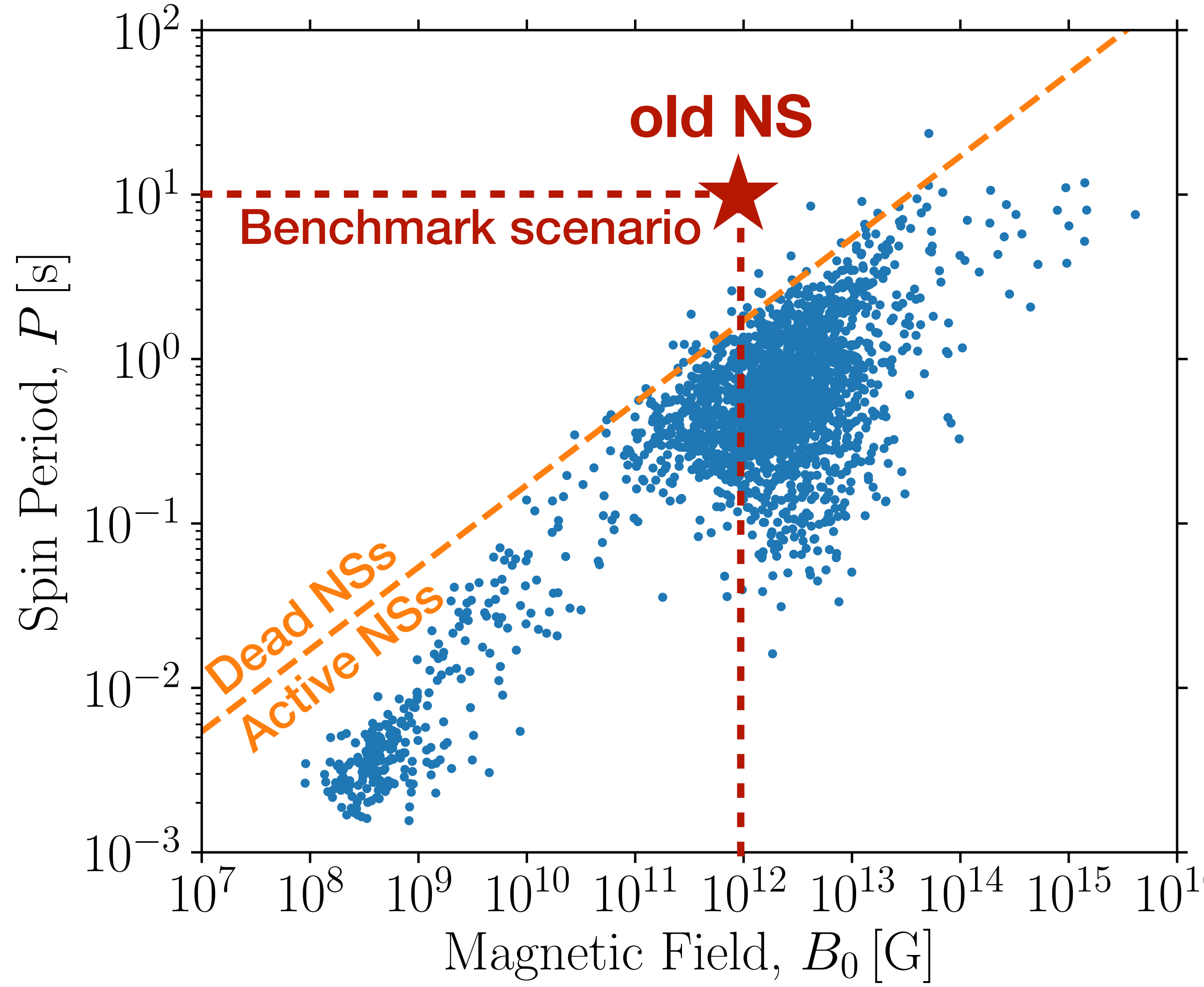
Resonant Axion-Photon Conversion



resonance

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

ATNF Pulsar Catalogue



Manchester et al., ***Astron.J. 129 (2005)***
(the catalogue contains ***only*** nearby active pulsar in the galactic disk, the population of old is uncertain)

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

$$p_{a\gamma} \sim \frac{g^2_{a\gamma\gamma} B\left(r_c\right)^2 L^2_{\mathrm{conv}}}{2\, v_c}$$

Flux density →

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

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 $\rho_{\mathrm{DM}}\left(r_c\right)$

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

Dark Matter phase-space distribution

The DM phase-space distribution is completely defined by the **spike slope α**:[1]

$$f(v|r) = 4\pi v^2 \frac{f(\mathcal{E})}{\rho(r)} \qquad \textit{with} \qquad f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2} \propto \mathcal{E}^{\alpha-3/2}$$

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

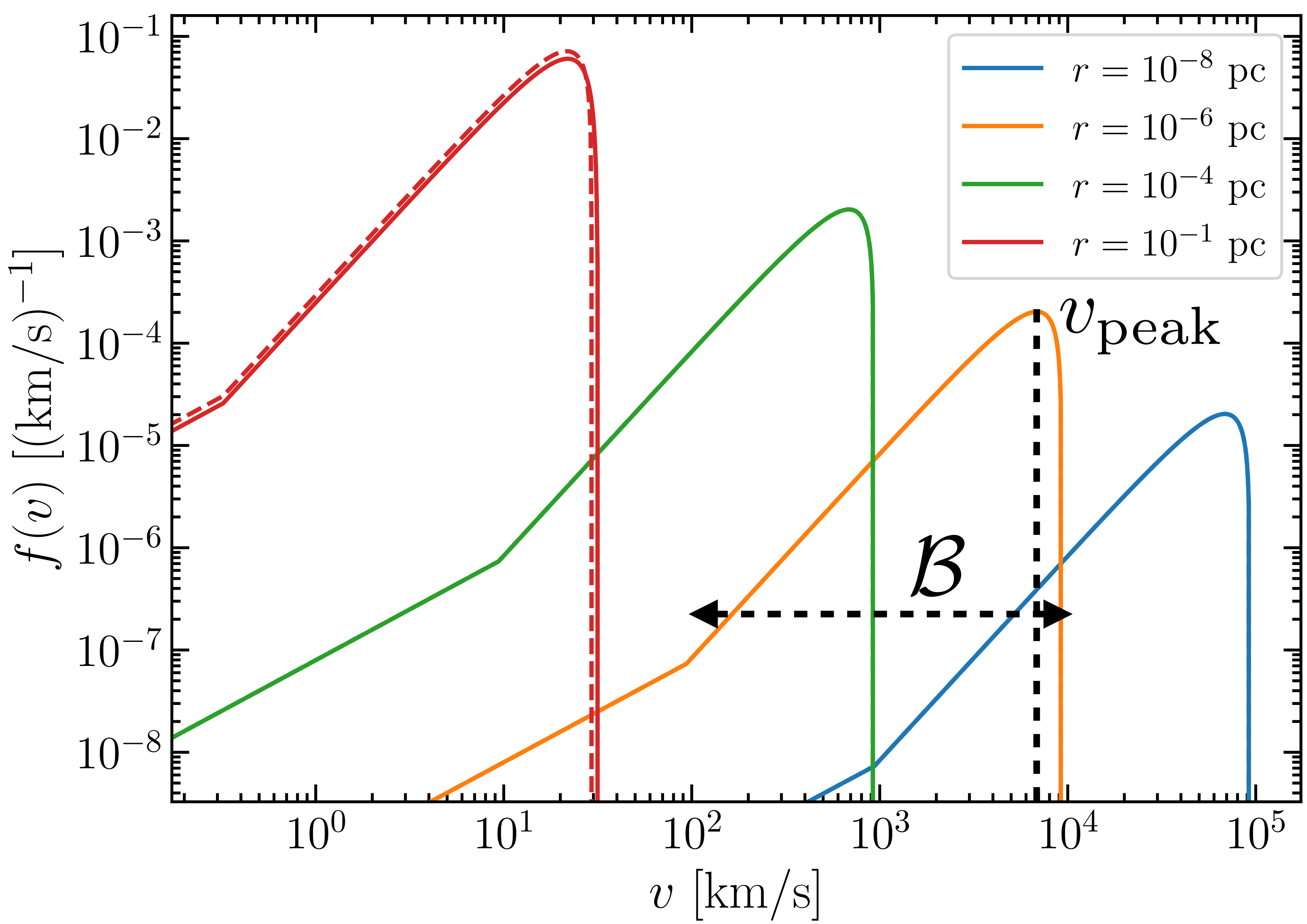
$$v_c^2 \sim v_{\rm peak}^2 + \frac{2\,G\,M_{\rm NS}}{r_c}$$

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

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

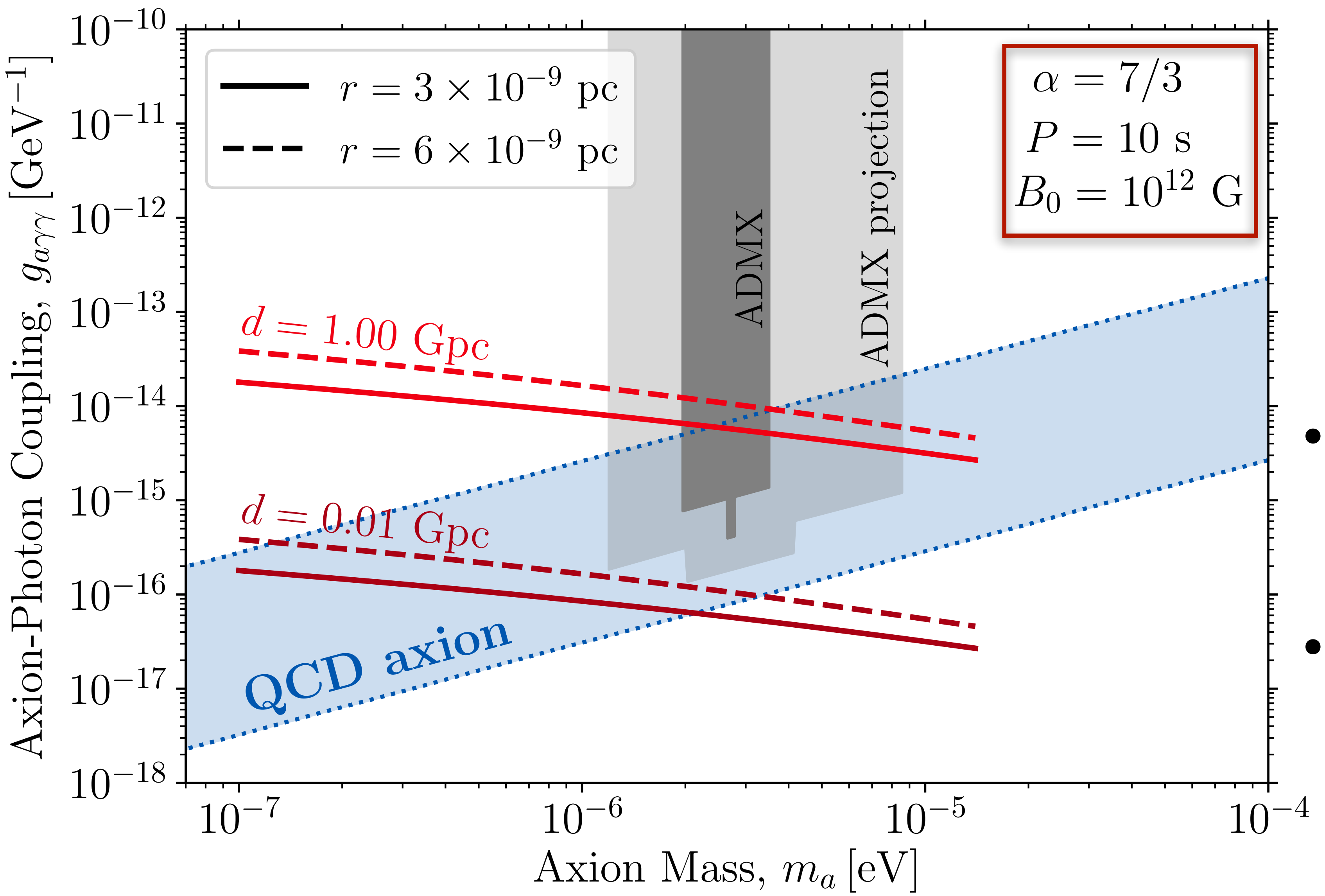
$$\rho_{\rm DM}^{r_c}\, f_{r_c}(\mathbf{v}) = \rho_{\rm DM}^{\infty}\, f_\infty(\mathbf{v}_\infty)$$

DM velocity distribution



[1]*Notation:* $\Psi = GM_{\rm BH}/r$ *gravitational potential* $\quad \mathcal{E} = \Psi(r) - v^2/2$ *relative energy*

Square Kilometre Array Sensitivity



Minimum Observable Signal
(SNR = 1)

$$S_{\rm min} = \frac{\rm SEFD}{\sqrt{2\,\mathcal{B}\,T_{\rm obs}}}$$

- SKA System-Equivalent Flux Density: $\mathrm{SEFD} = 0.098\,\mathrm{Jy}$

  *Bull et al., **arXiv:1810.02680***

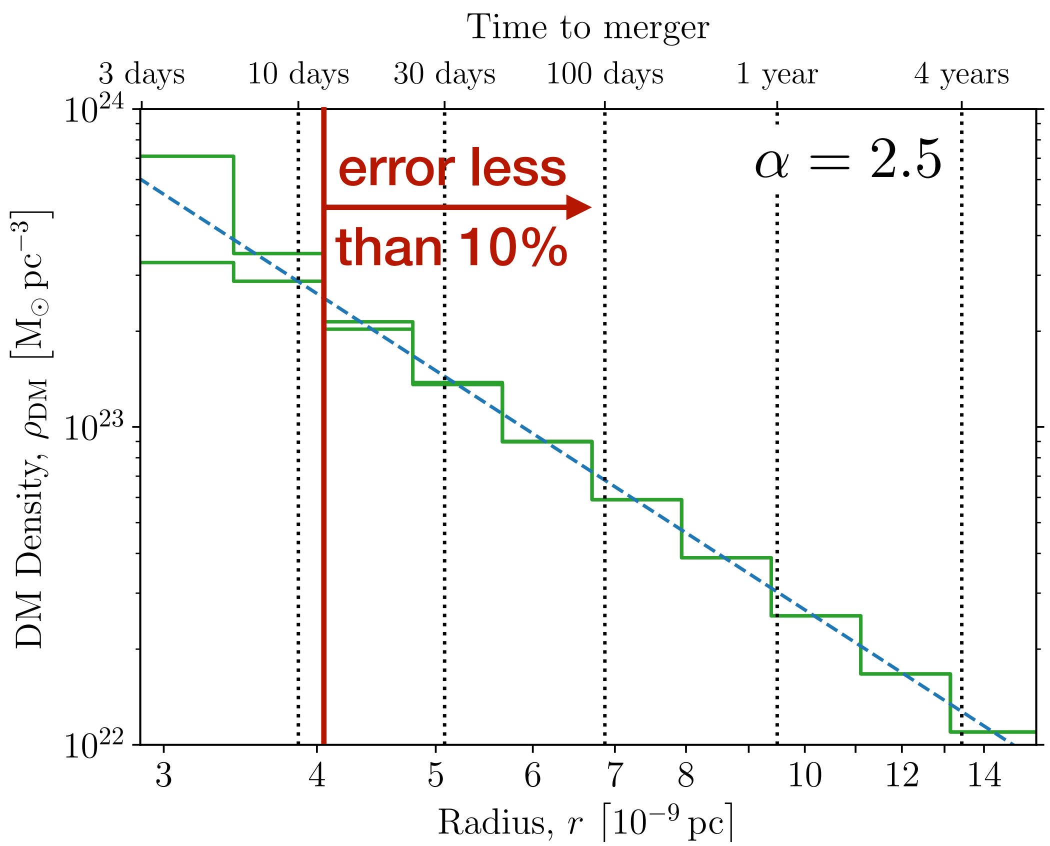
- Observation time (time of last orbit): $T_{\rm obs} = 100$ h

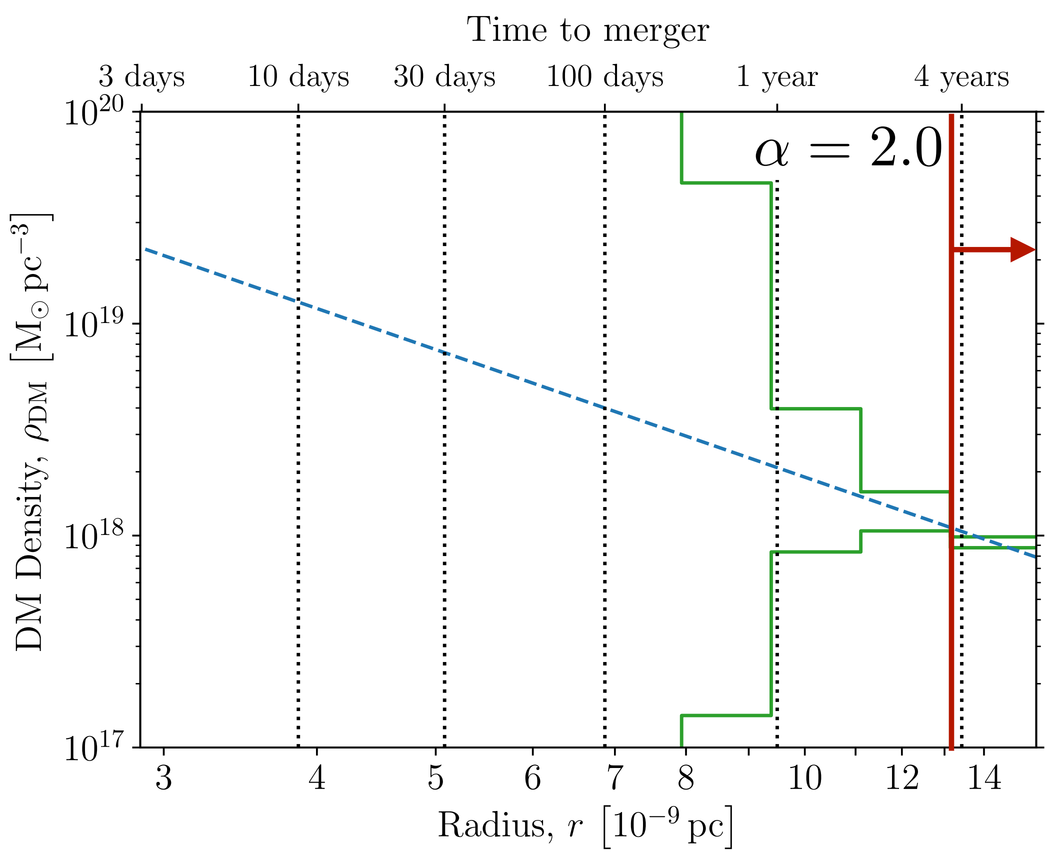
SKA will explore the QCD axion in the mass range $10^{-7} - 10^{-5}$ eV

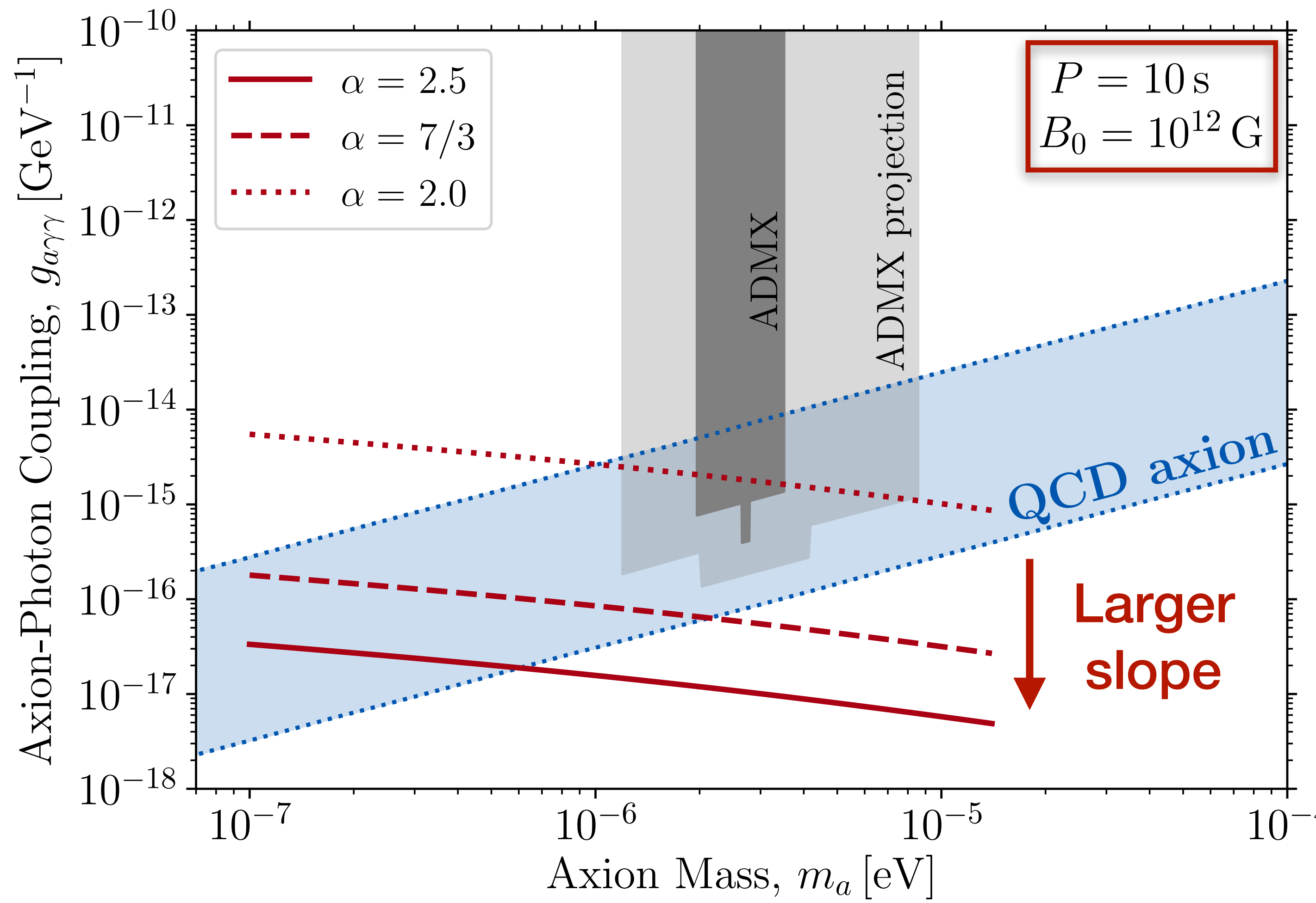
- *Minimum mass*: lowest frequency probed by SKA
- *Maximum mass*: conversion exterior to NS $r_c \leq r_{\rm NS} = 10$ km

Conversion radius

Dependence on spike slope





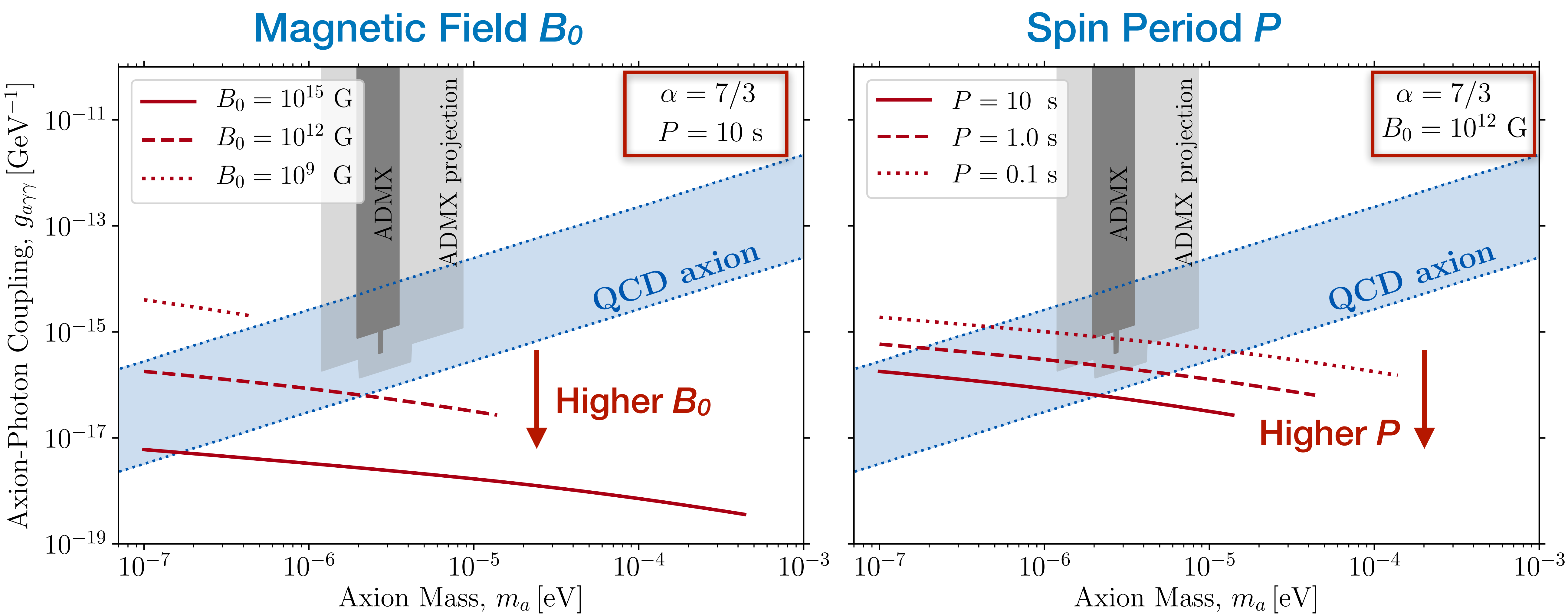


The larger the slope, the larger the DM density close the IMBH.

→ **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

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

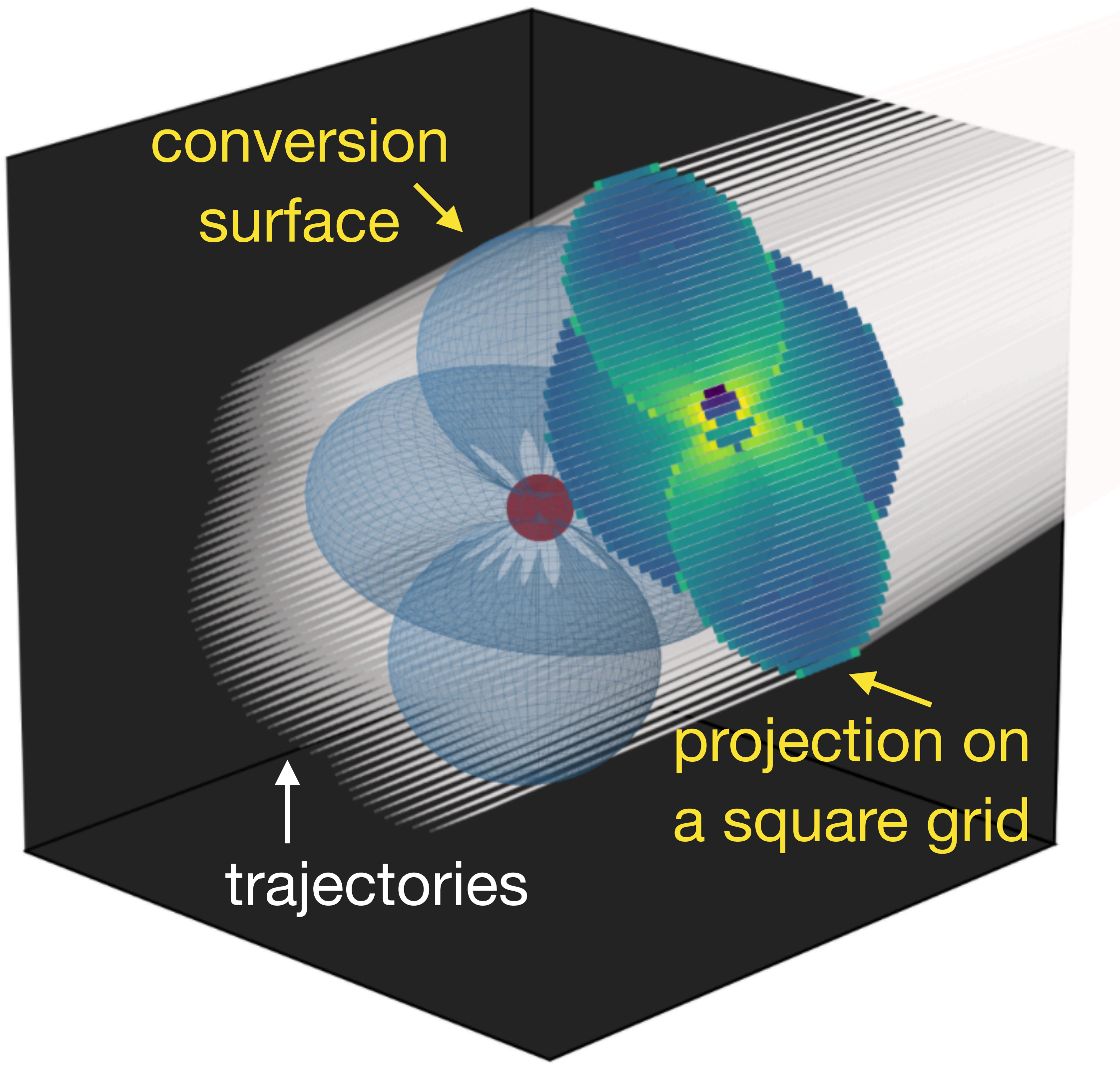
Independent of NS parameters

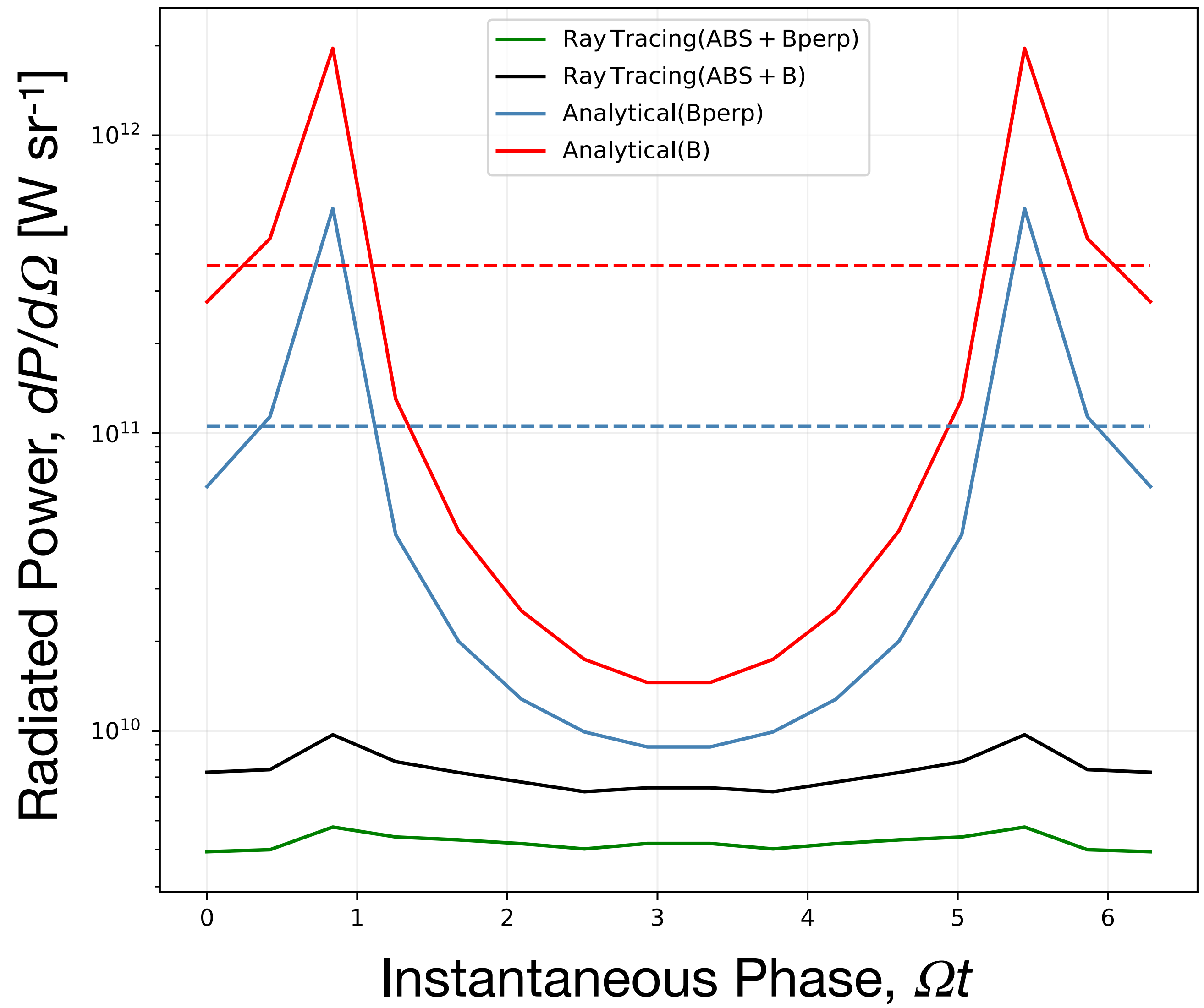
Viewing angle (benchmark value)

Refining the radio signal computation

Previous analytical calculation of the radio signal was based on the assumption of having **radial trajectories only**. Instead, we perform a **ray-tracing computation!**

See Leroy's talk





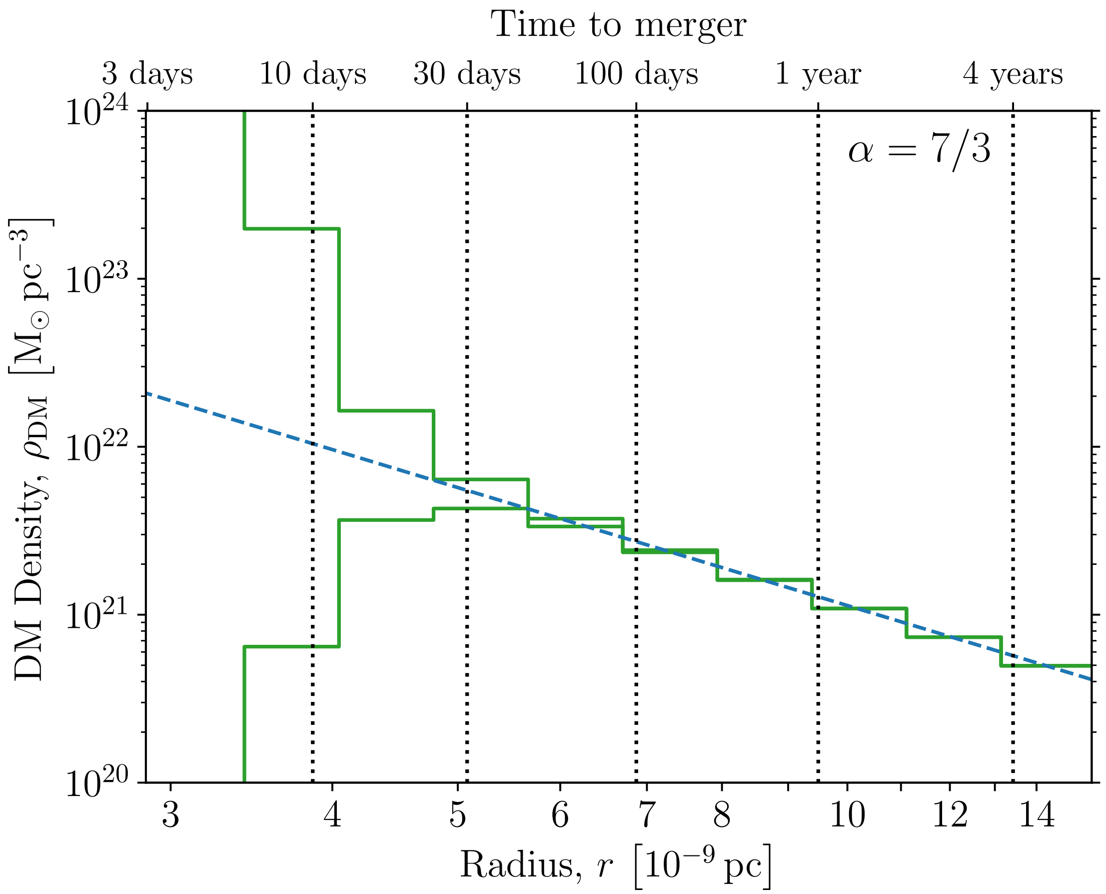
All trajectories considered

No time-dependence of the signal

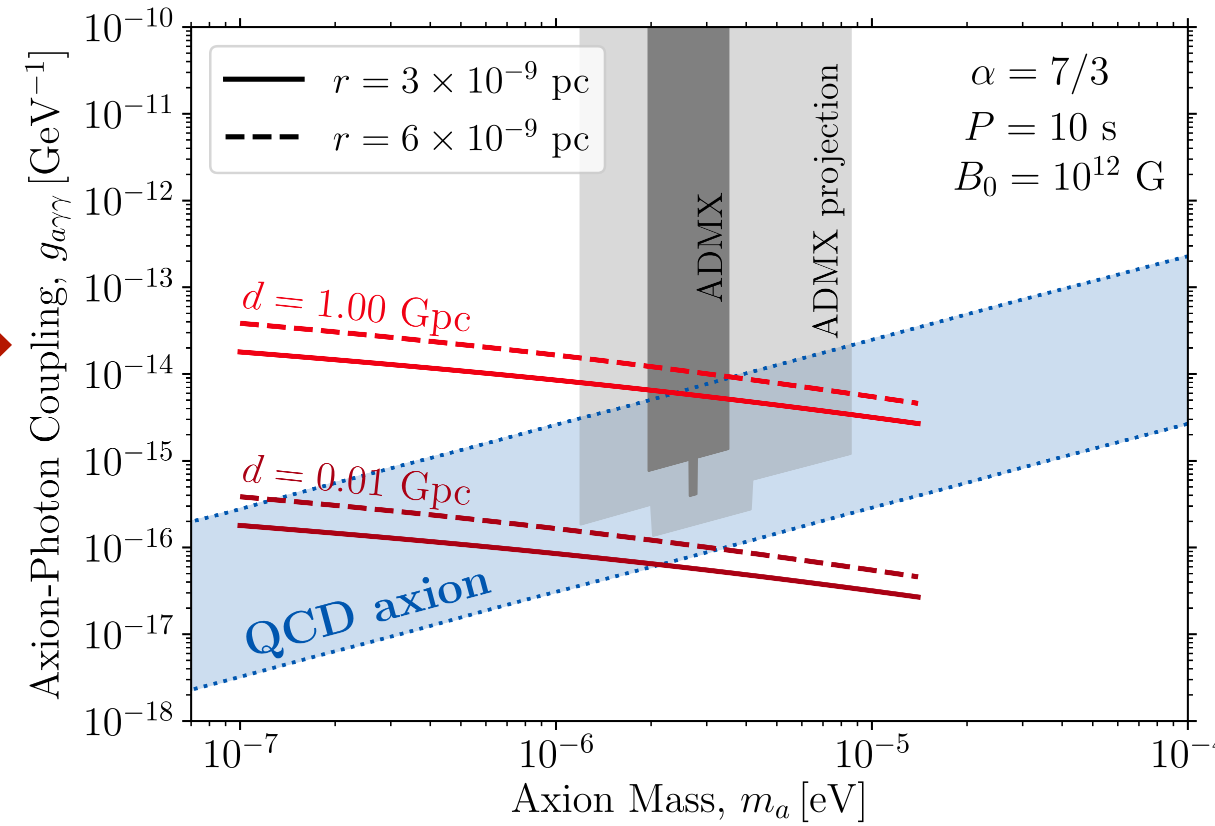
*Leroy, MC, Edwards and Weniger, **in progress***

Conclusions

GW



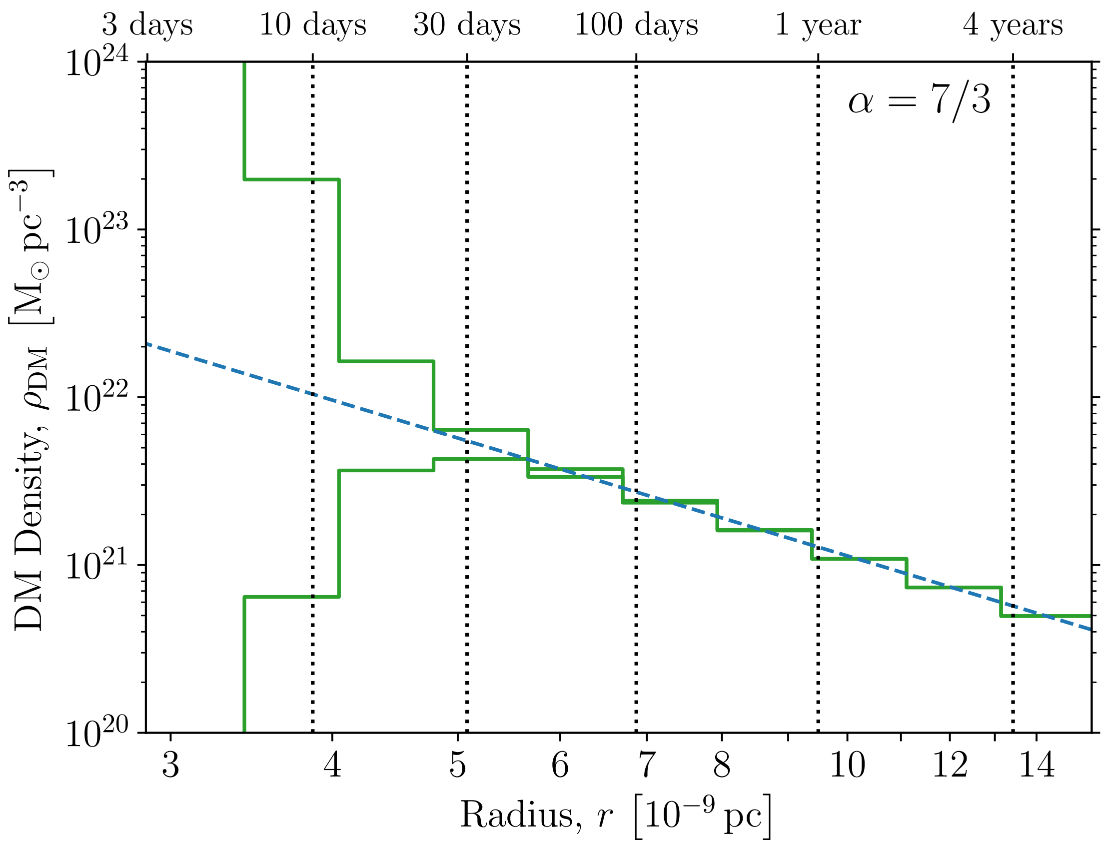
EM (radio)



- The GW constraints on the DM density can be directly fed into the EM signal calculation, so predicting the expected radio emission.
- Difficult to set robust limits due to the uncertainty in the NS properties, magnetic field etc.
- Such multi-messenger observations would be a smoking-gun signature of the QCD axion dark matter.

Conclusions

GW



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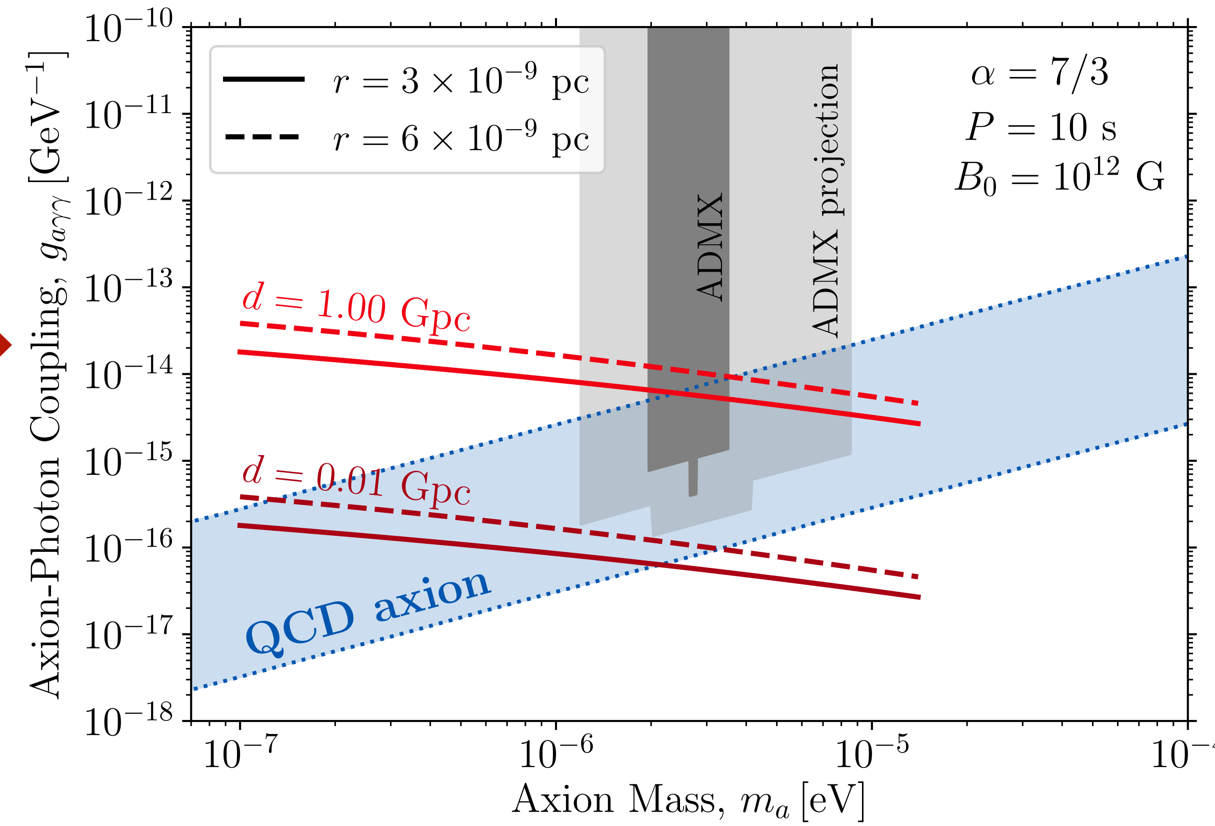

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Thank you for your attention