A Unique Multi-Messenger Signal of QCD Axion Dark Matter

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Edwards, MC, Kavanagh, Nissanke and Weniger, **arXiv:190504686**
Leroy, MC, Edwards and Weniger, **in progress**

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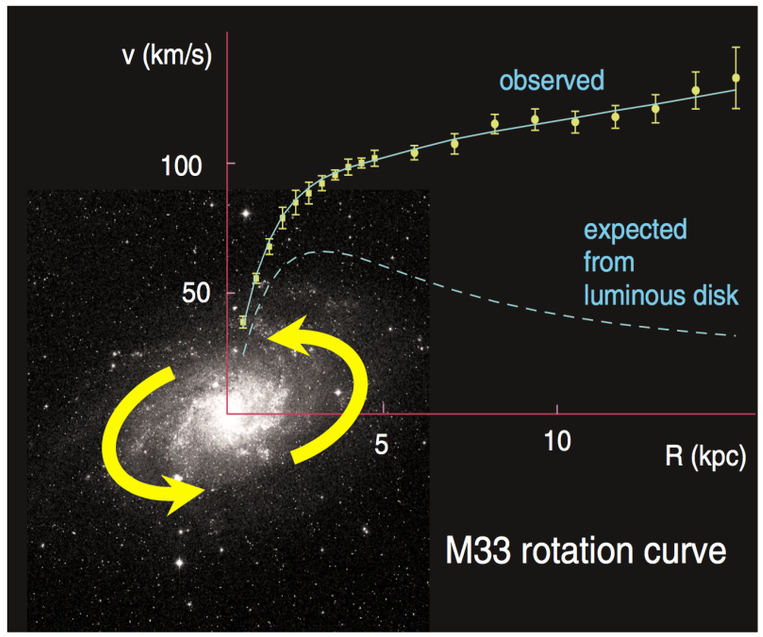
GRAPPA
GRavitation AstroParticle Physics Amsterdam

Cold Dark Matter

Galactic Rotation Curves

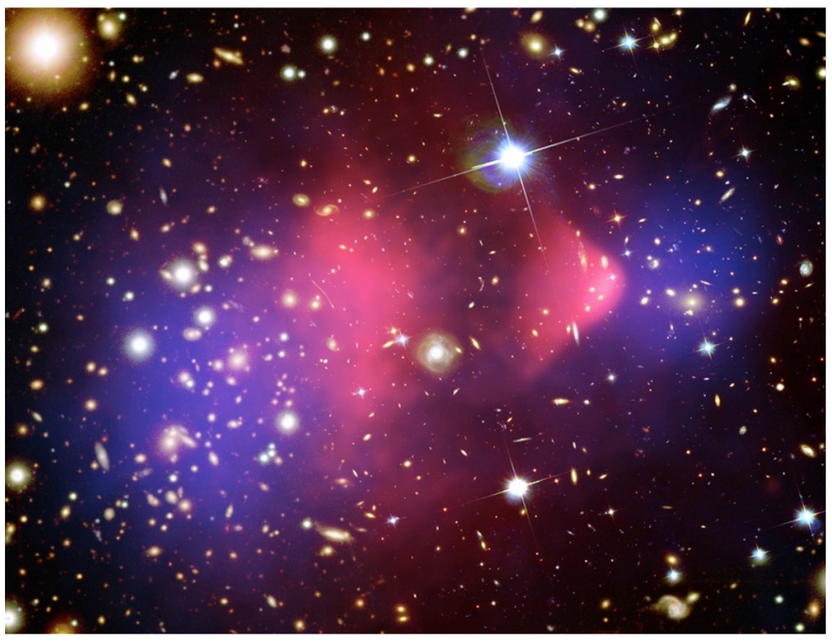


10 kpc

Galaxy Clusters

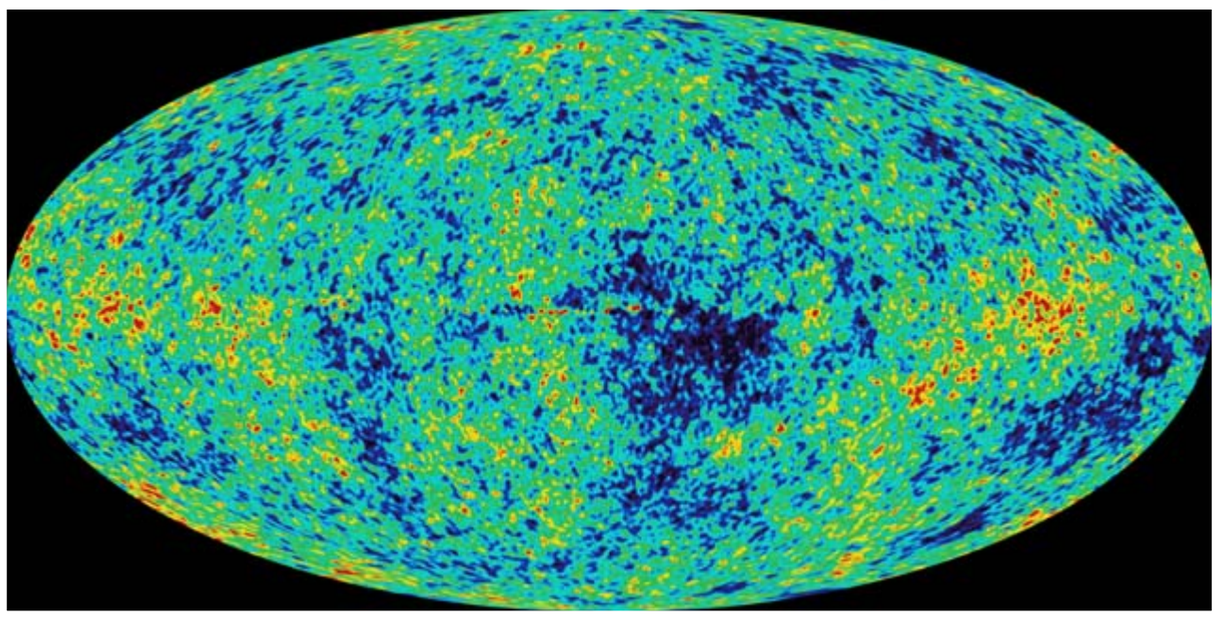
100 kpc

Bullet Clusters

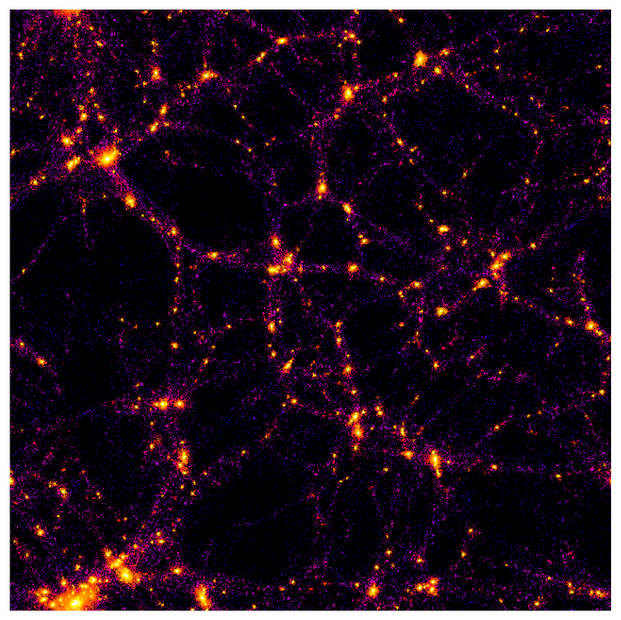


1–10 Mpc

Cosmic Microwave Background



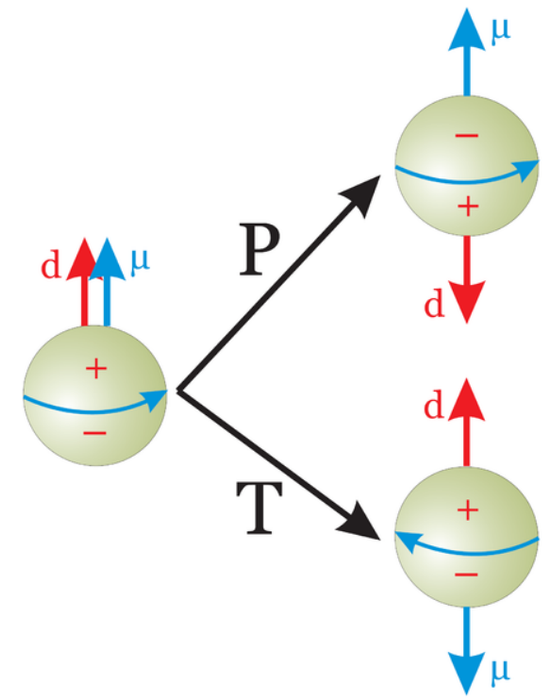
Structures Formation



Cosmological Scales

Strong-CP problem and QCD axion

The **QCD axion is a viable Dark Matter candidate** that, at the same time, solve the Strong-CP problem of quantum chromodynamics.



The QCD Lagrangian admits a Charge-Parity (CP) violating term

$$\mathcal{L}_{\mathrm{QCD}} \supset -\frac{\alpha_s}{8\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \, \theta_{\mathrm{QCD}}$$

No evidence of CP violation has ever been observed in QCD

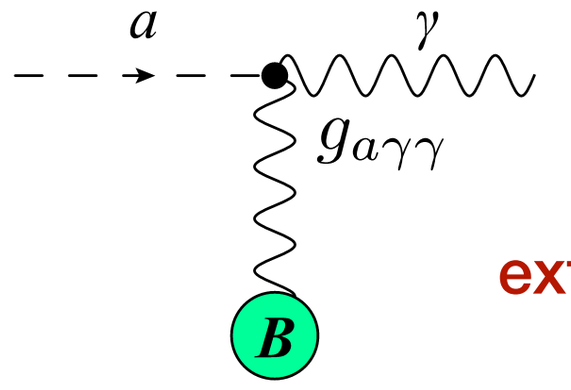
$|\theta_{\mathrm{QCD}}| \leq 10^{-10}$ **Strong CP-problem: why theta is so small?**

Promoting theta to a scalar field, the axion *a*, allows the CP-violating term to dynamically reach zero.

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

Most of the axion searches exploits its coupling to the photon:

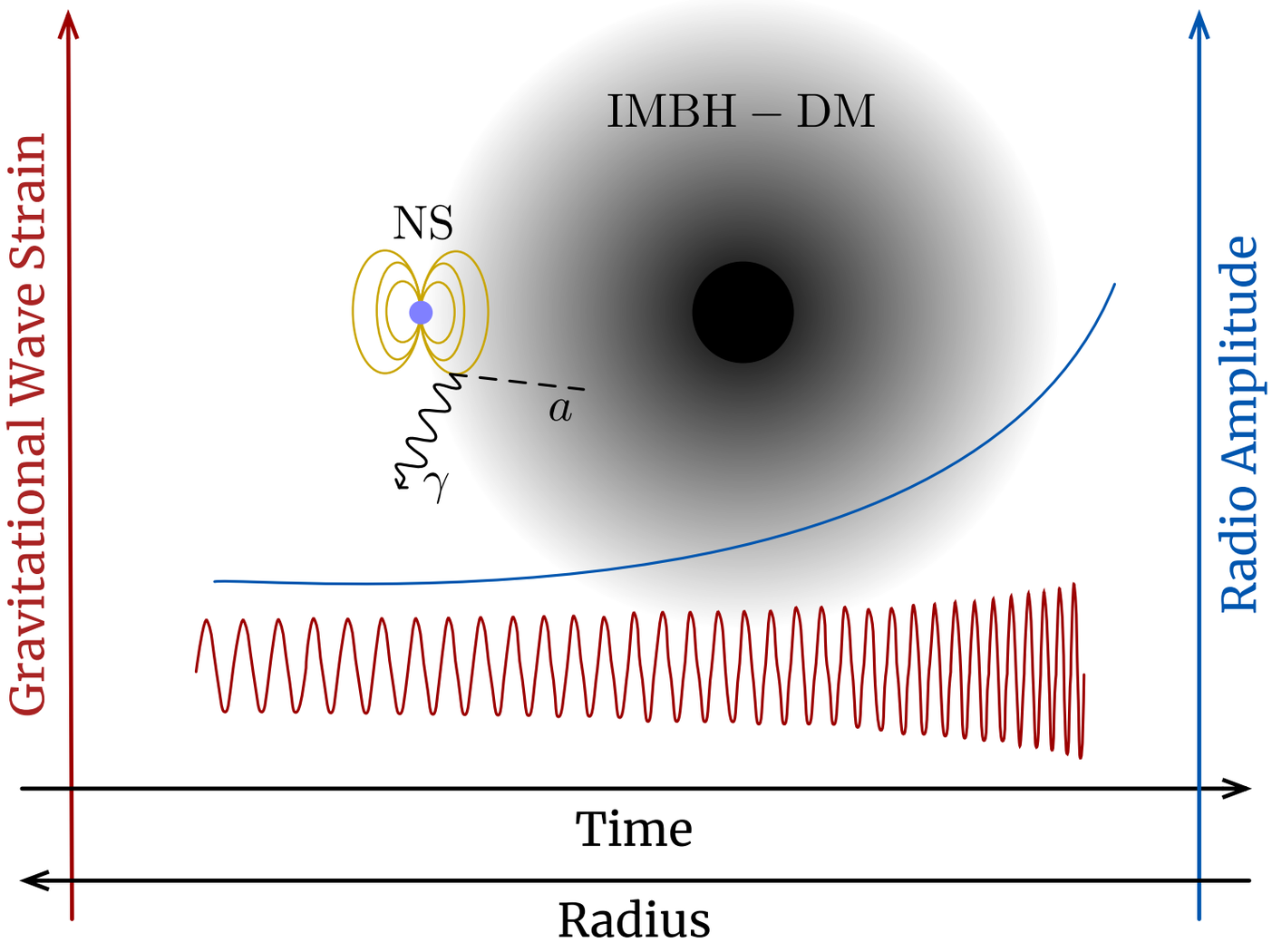
$$\begin{aligned} \mathcal{L} &\supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \\ &= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B} \end{aligned}$$



Axion-Photon conversion in an external magnetic field

Multi-messenger Signal — GW + EM

Observation of Black Hole—Neutron Star inspirals with an Axion Dark Matter spike.



GW

Distinct phase shift in the Gravitational Wave strain

+

EM

Radio emission from axion-photon conversion in the NS magnetosphere

Intermediated Mass Black Holes

IMBHs are the least constrained mass window:

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

They have not been detected by GWs, but there are evidences of their existence in the centre of 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***

They can form through different 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)***

M87 Black Hole Shadow

$$M_{\rm BH} = 6.5 \times 10^9\, M_\odot$$

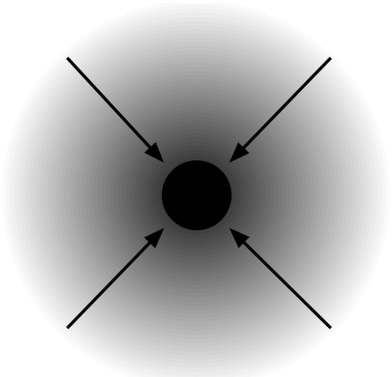
Event Horizon Telescope, ***Astrophys.J. 875 (2019)***

Dark Matter Spike

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

DM halo

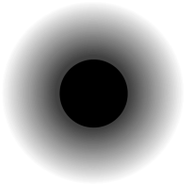
$z = 20$



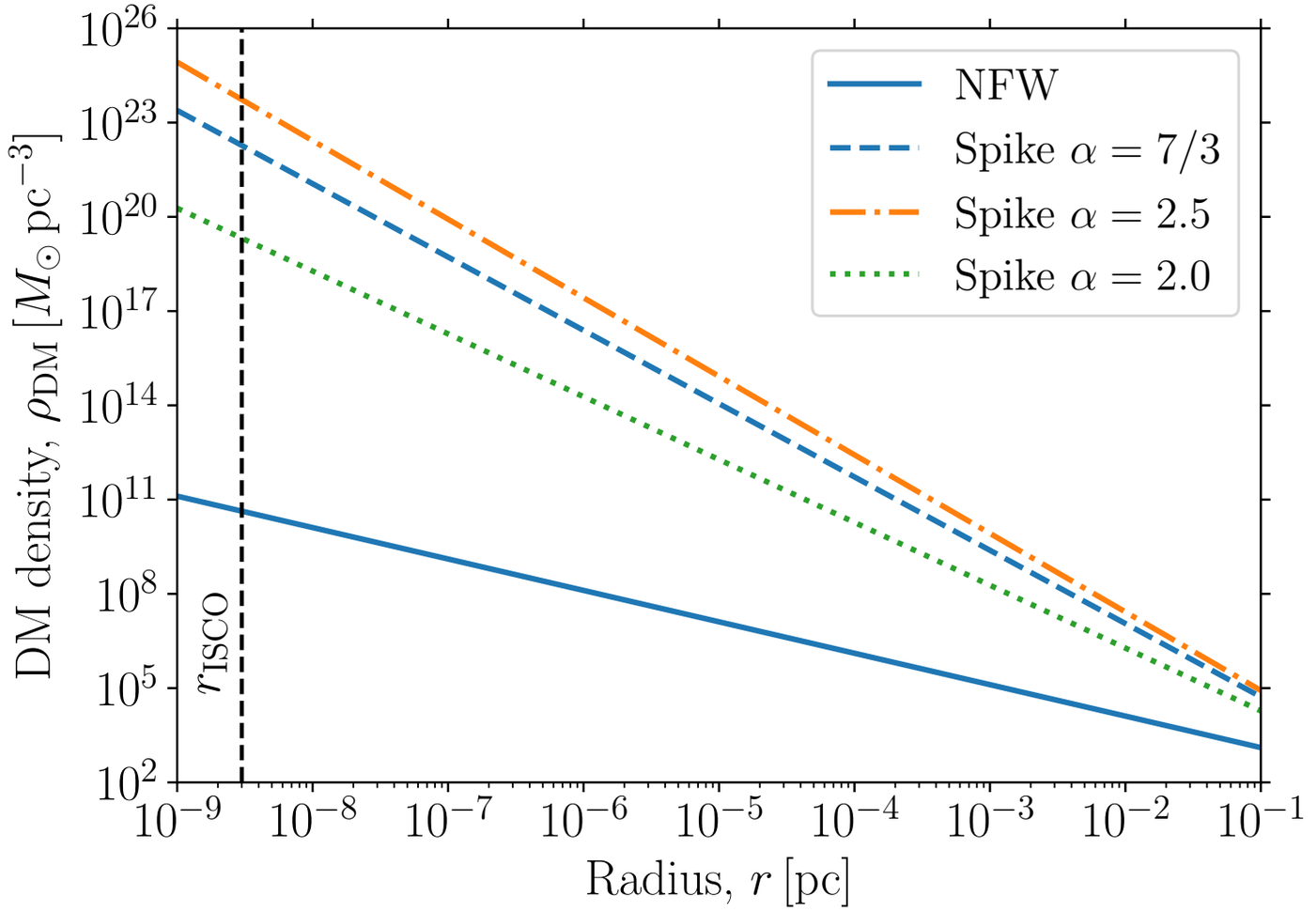
$$\rho_{\rm DM} \propto r^{-\alpha_{\rm init}}$$

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).

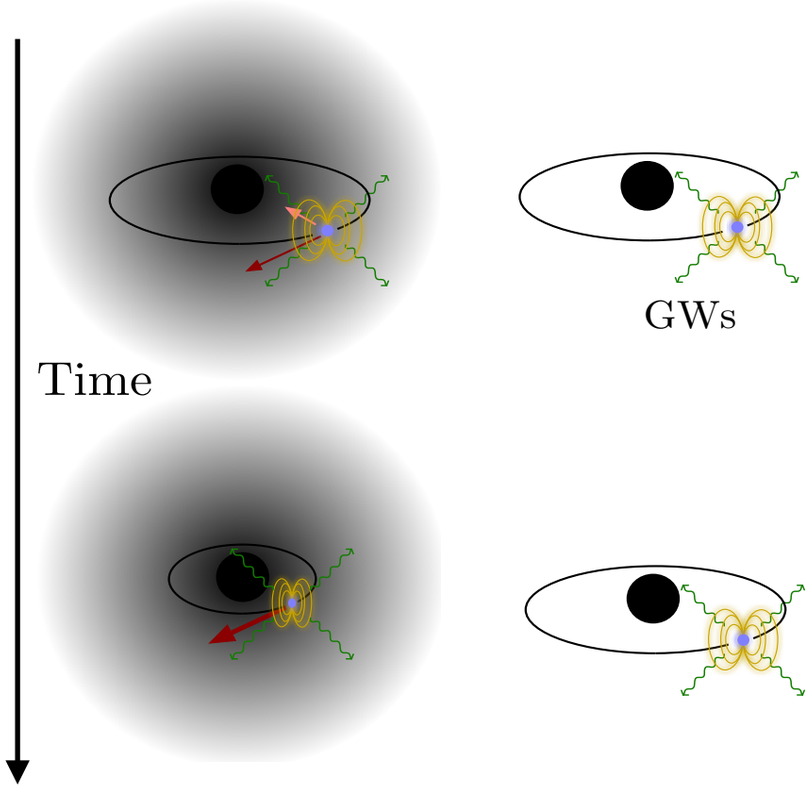
*Navarro, Frenk, White, **Astrophys.J. 462 (1996)**; Gondolo and Silk, **PRL 83 (1999)**; Zhao and Silk, **PRL 95 (2005)**; Bertone, Zentner and Silk, **PRD 72 (1999)**.*

Gravitational Wave Signal — Dynamical Friction

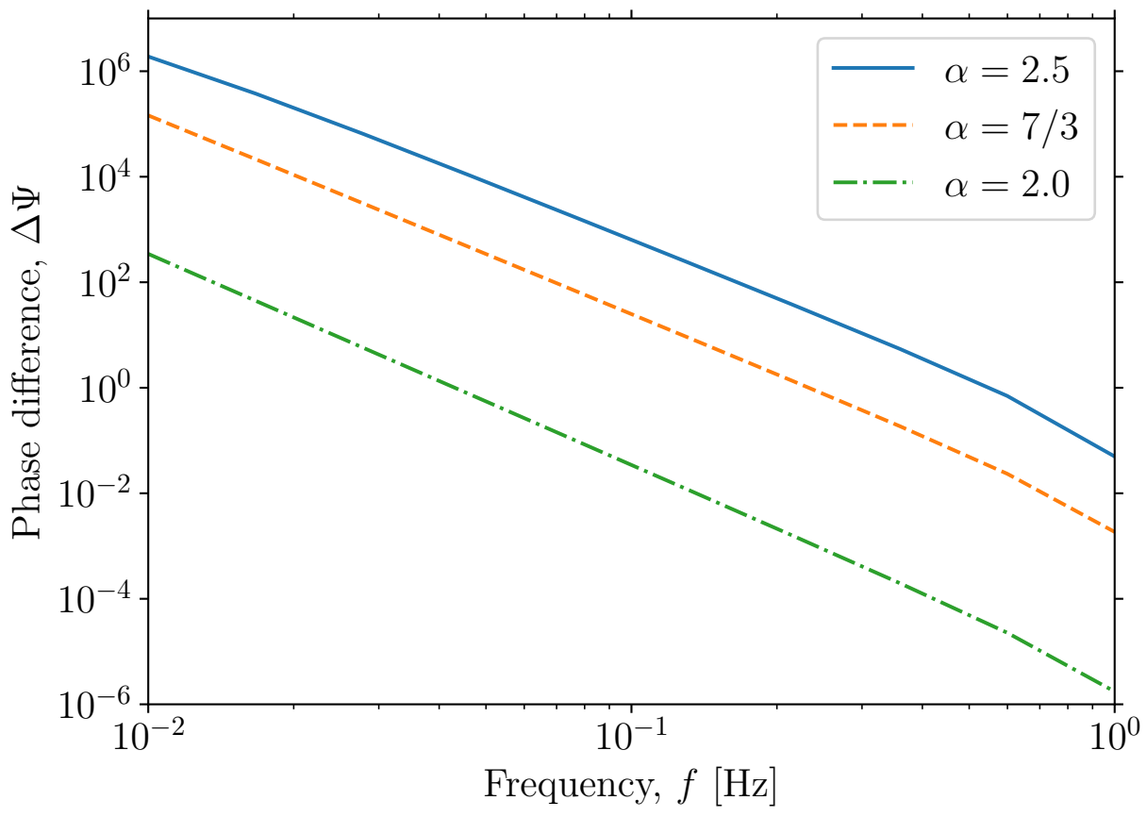
The presence of a DM halo causes additional energy loss through Dynamical Friction:

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

Inspiral takes less time than in vacuum



Phase shift in the GW signal



Measuring the phase shift constrains the DM density

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

LISA Sensitivity — Dark Matter density

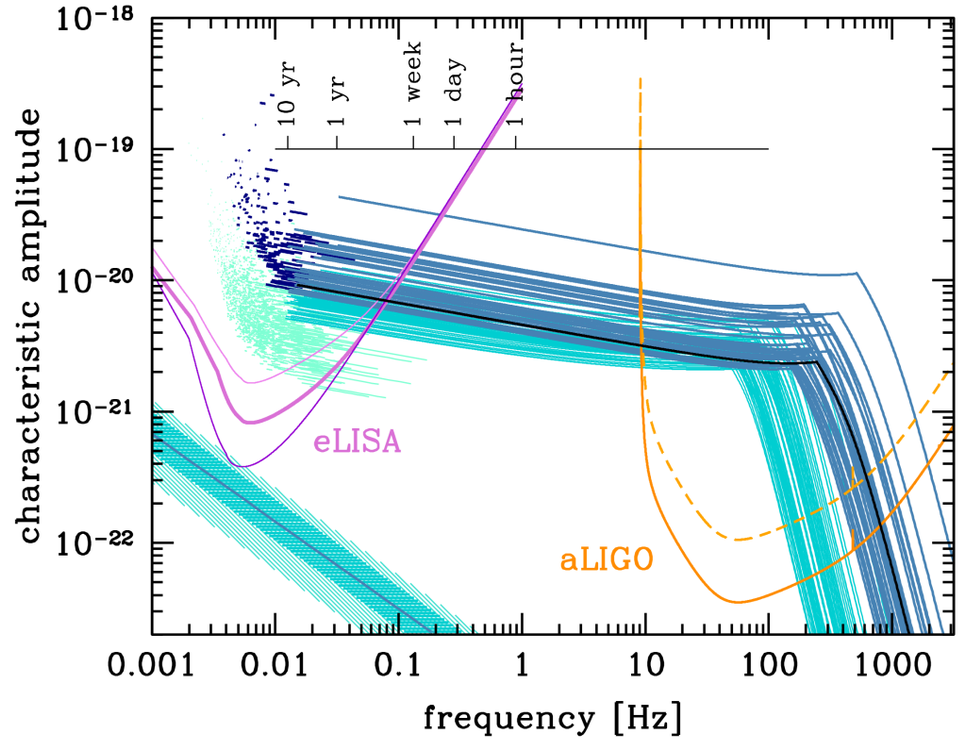
In case of a benchmark system as

$$M_{\rm IMBH} = 10^4\, M_\odot \quad \text{and} \quad M_{\rm NS} = 1.4\, M_\odot$$

the LISA detection rate will be approximately

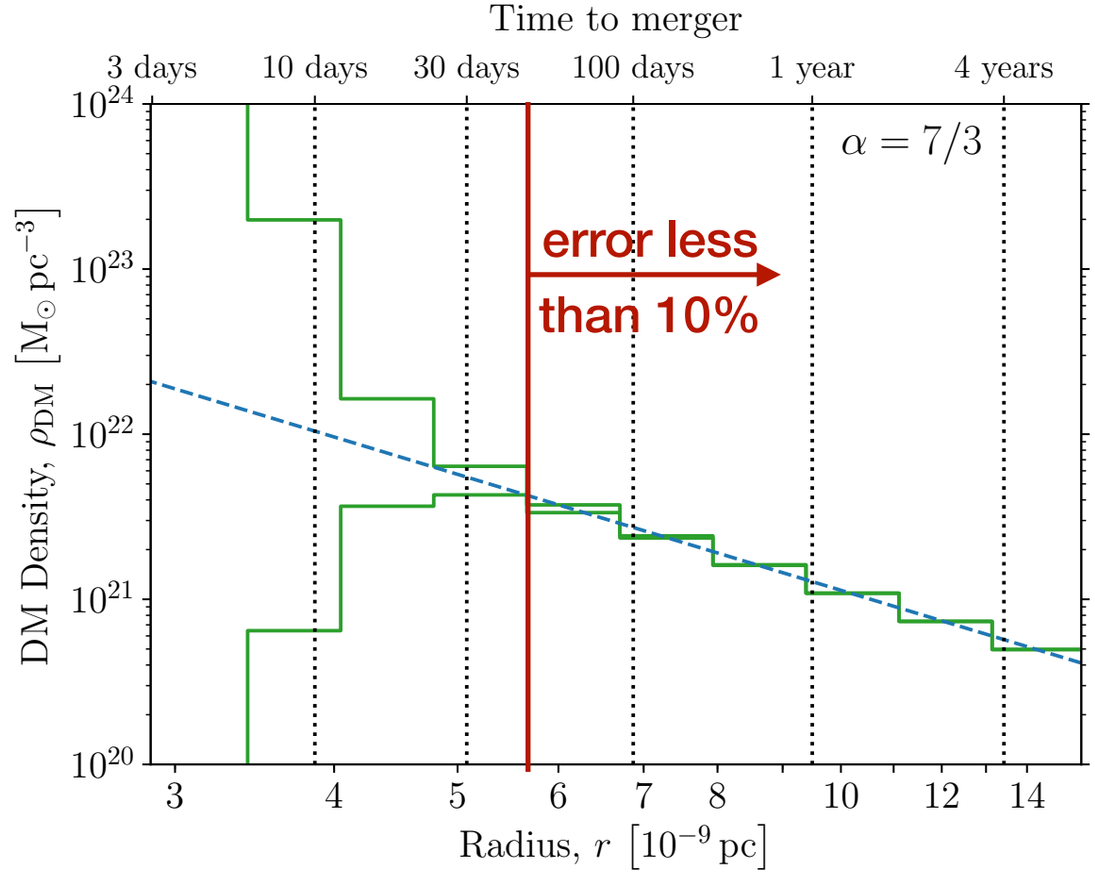
$$\mathcal{R} \sim 3 - 10\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

LISA will observe these objects for **5 years** prior to merger.



The uncertainty on DM density at small radii increases:

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



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

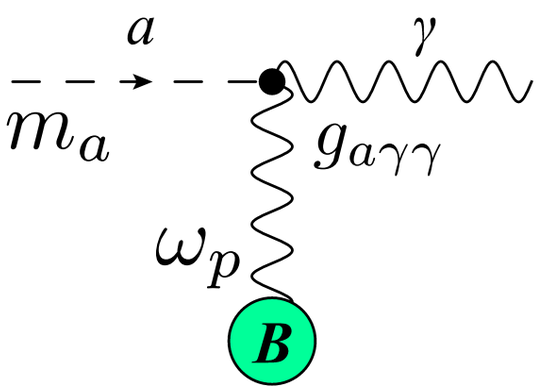
Neutron Stars — Axion-Photon conversion

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

They have:

- extremely high magnetic fields
- a surrounding dense plasma that provide an effective photon mass

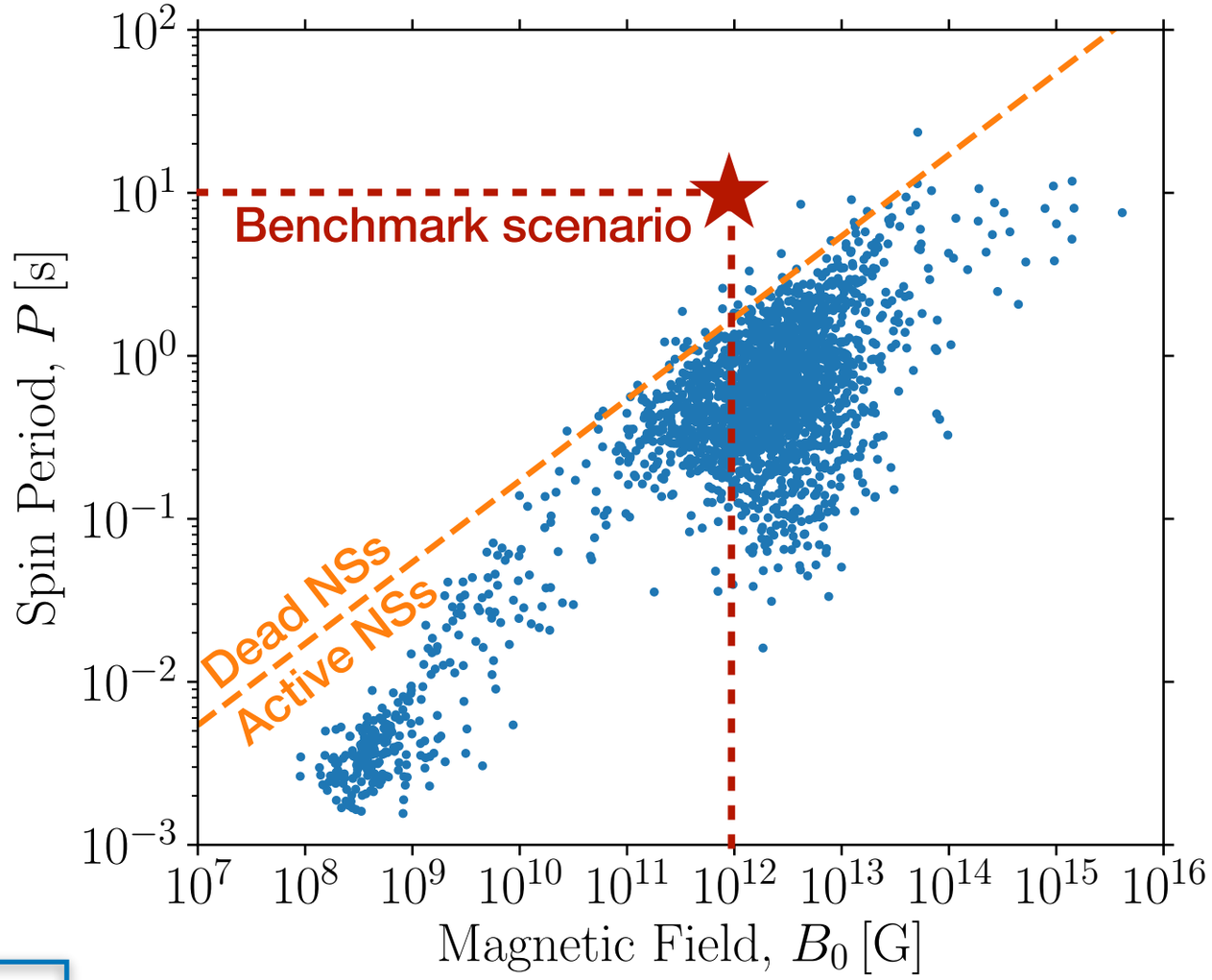
Resonant Axion-Photon Conversion



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)

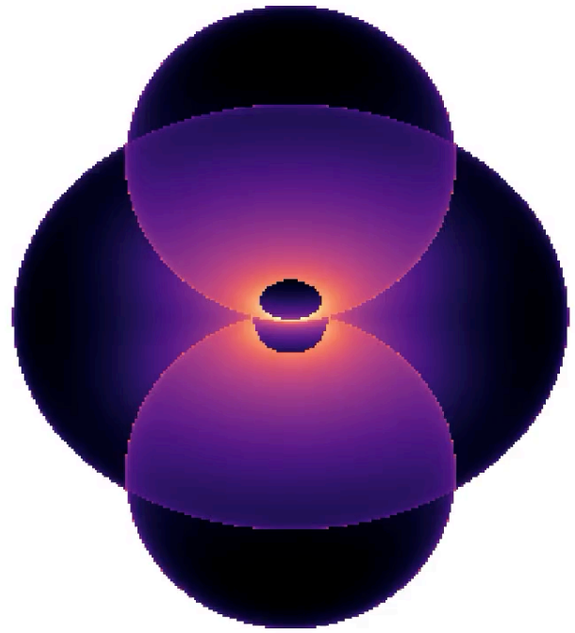
Radio Signal

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

The resonant conversion at the radius

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

Conversion Surface



where the **conversion probability** is

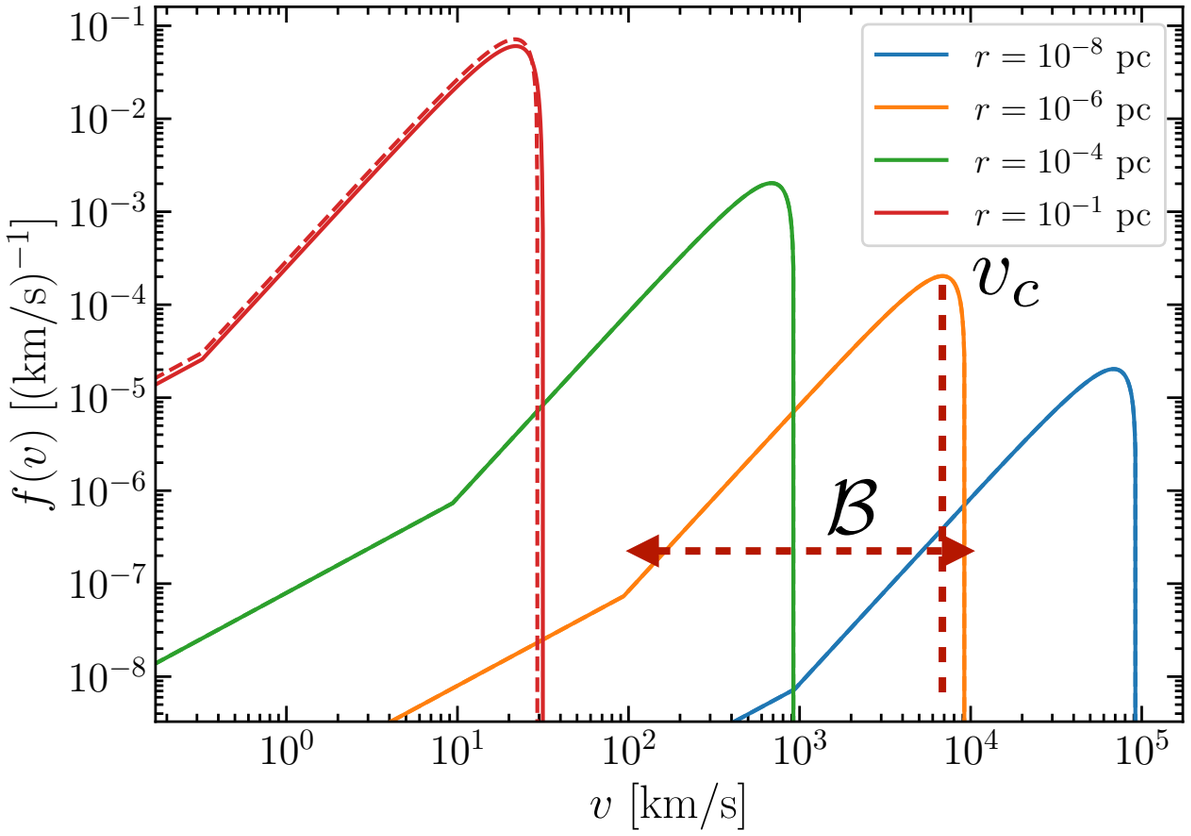
$$p_{a\gamma} = \frac{g_{a\gamma\gamma}^2 B(r_c)^2 L_{\rm conv}^2}{2 v_c}$$

Then, the **flux density** of the signal is

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

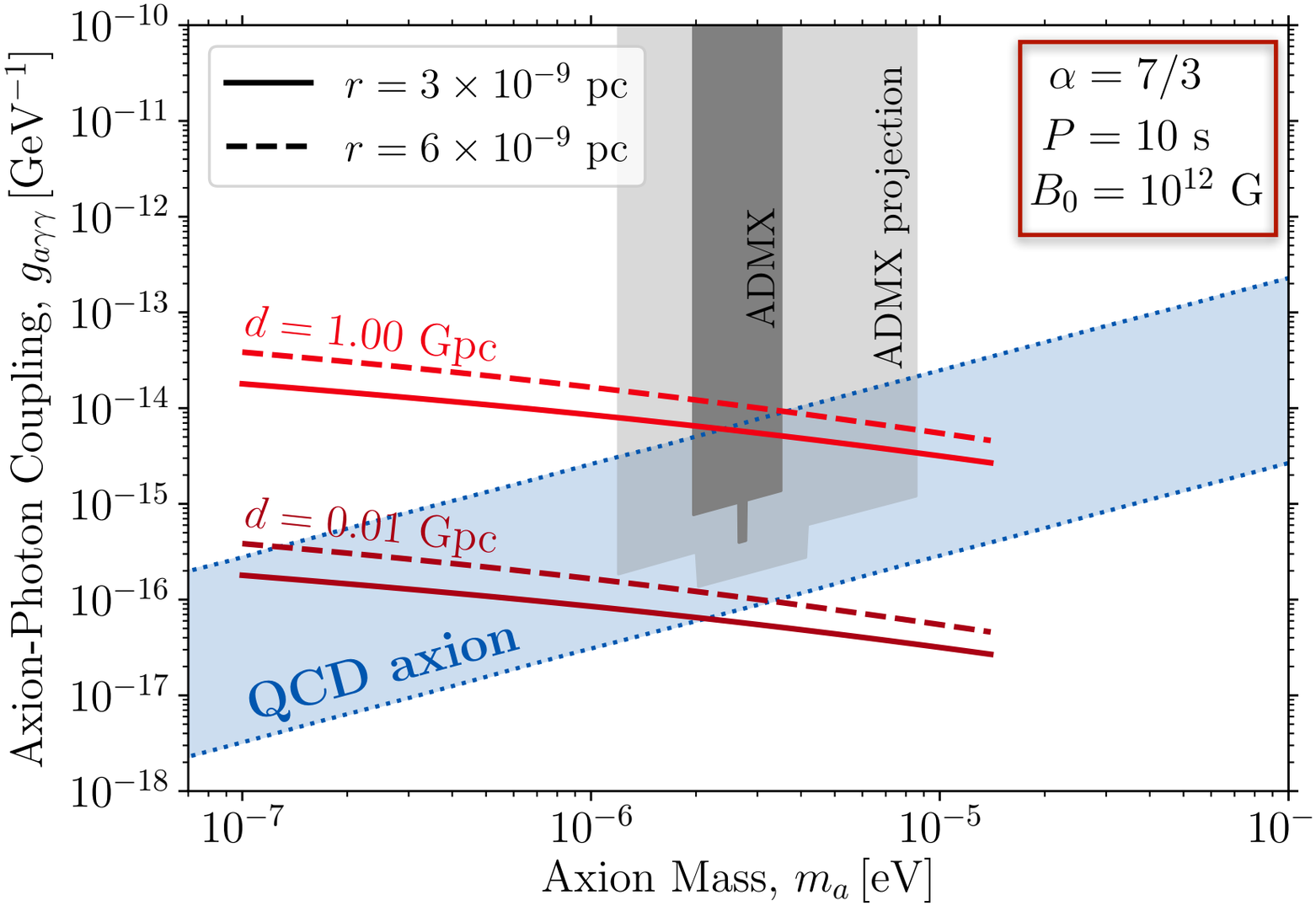
It depends on the DM velocity distribution through v_c and the bandwidth $\mathcal{B}$.

Eddington's formula
(isotropy and spherical symmetry)



See also: Huang et al., ***PRD 93 (2018)****, Hook et al.,* ***PRL 121 (2018)****, Safdi et al.,* ***arXiv:1811.01020***

Square Kilometre Array Sensitivity



Not much time variation, we use signal to noise calculation.

Minimum Observable Signal
(SNR = 1)

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

- SKA System-Equivalent Flux Density: $\rm SEFD = 0.098$

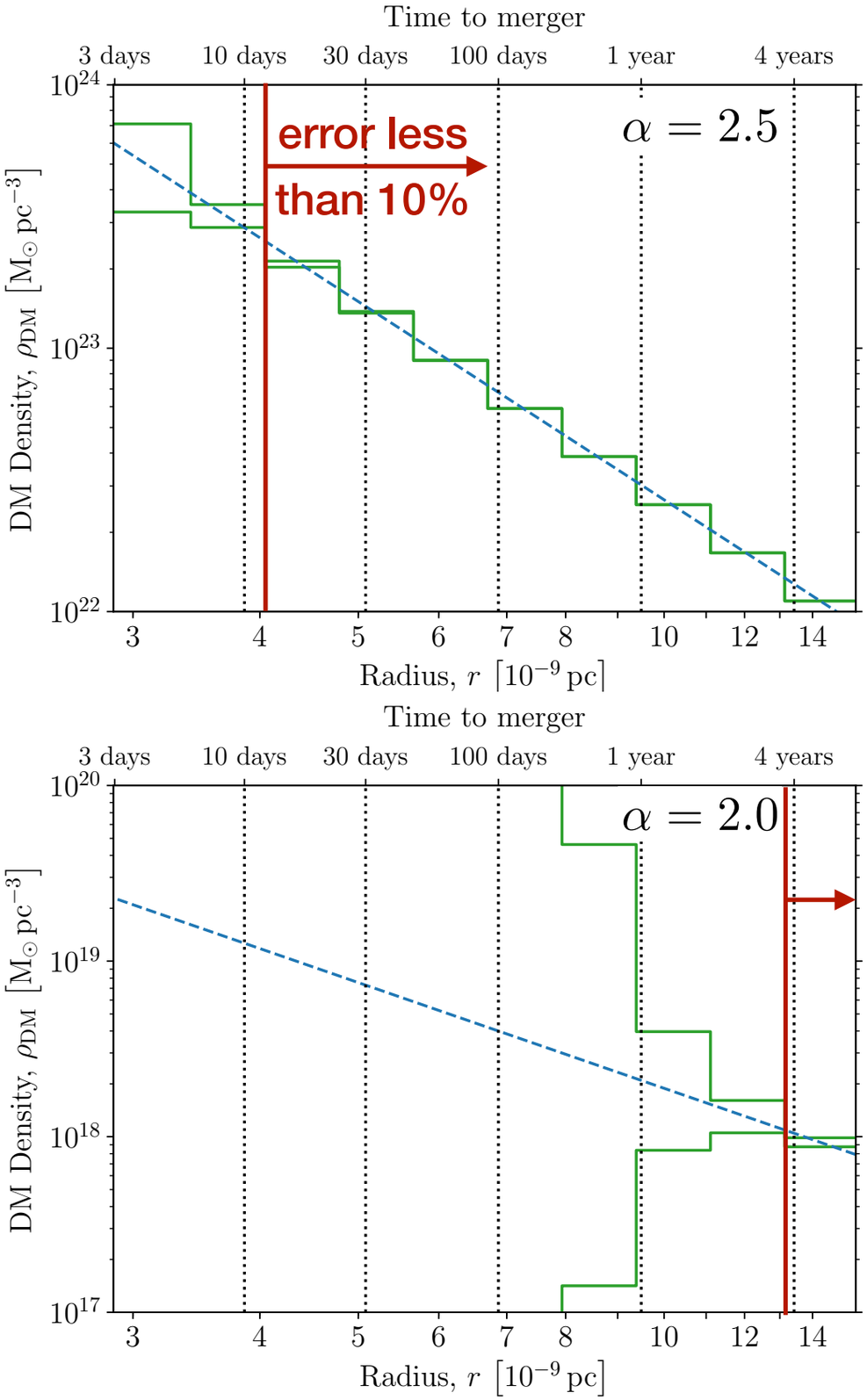
  Bull et al., ***arXiv:1810.02680***

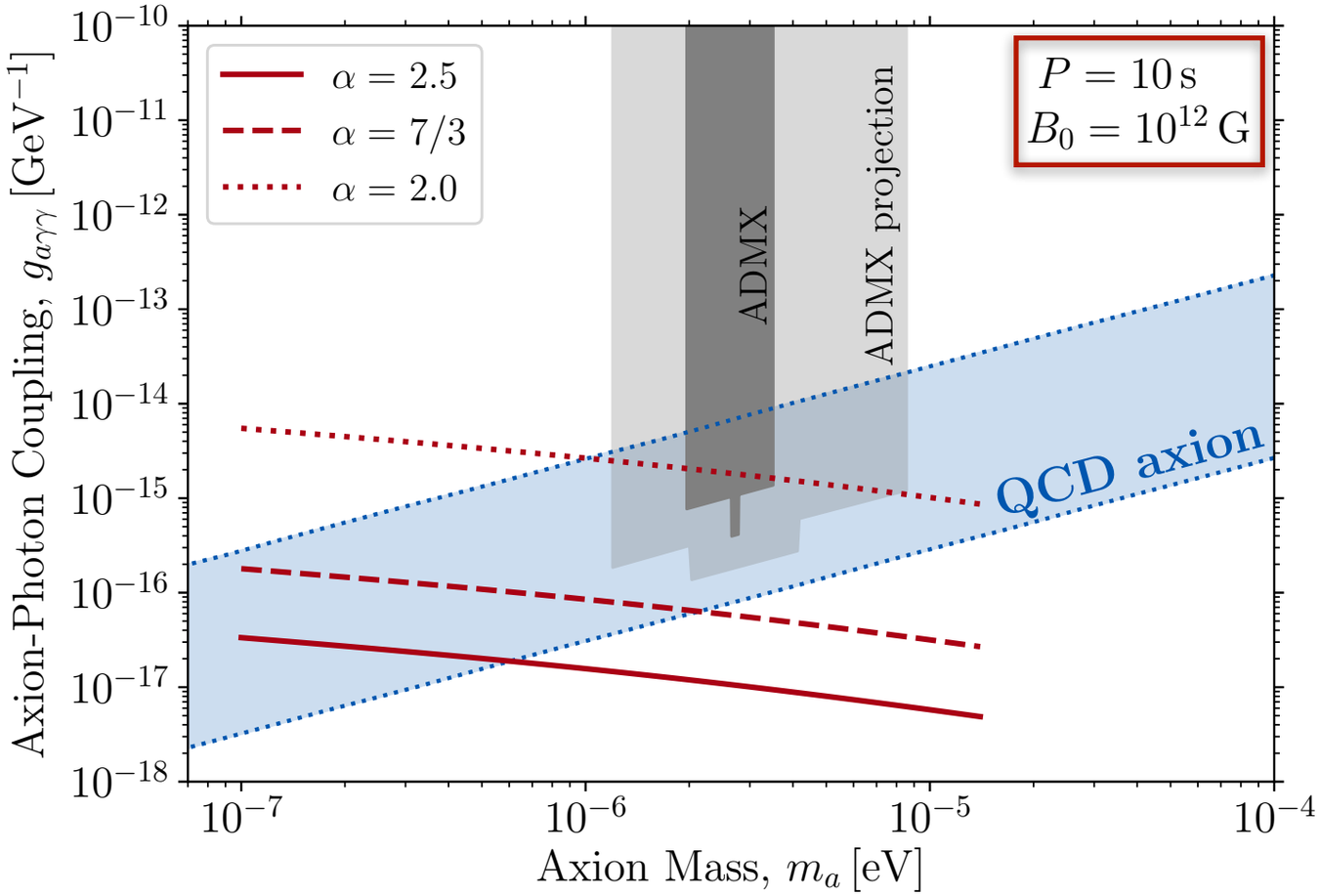
- Observation time (last orbit *r*): $T_{\rm obs} = 100$ h

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

- Minimum mass: axion treated as a particle $\lambda = \dfrac{h}{m_a c} \lesssim 0.01$ km — **Compton wavelength**
- Maximum mass: conversion exterior to NS $r_c \leq r_{\rm NS} = 10$ km — **Conversion radius**

Dependence on spike slope





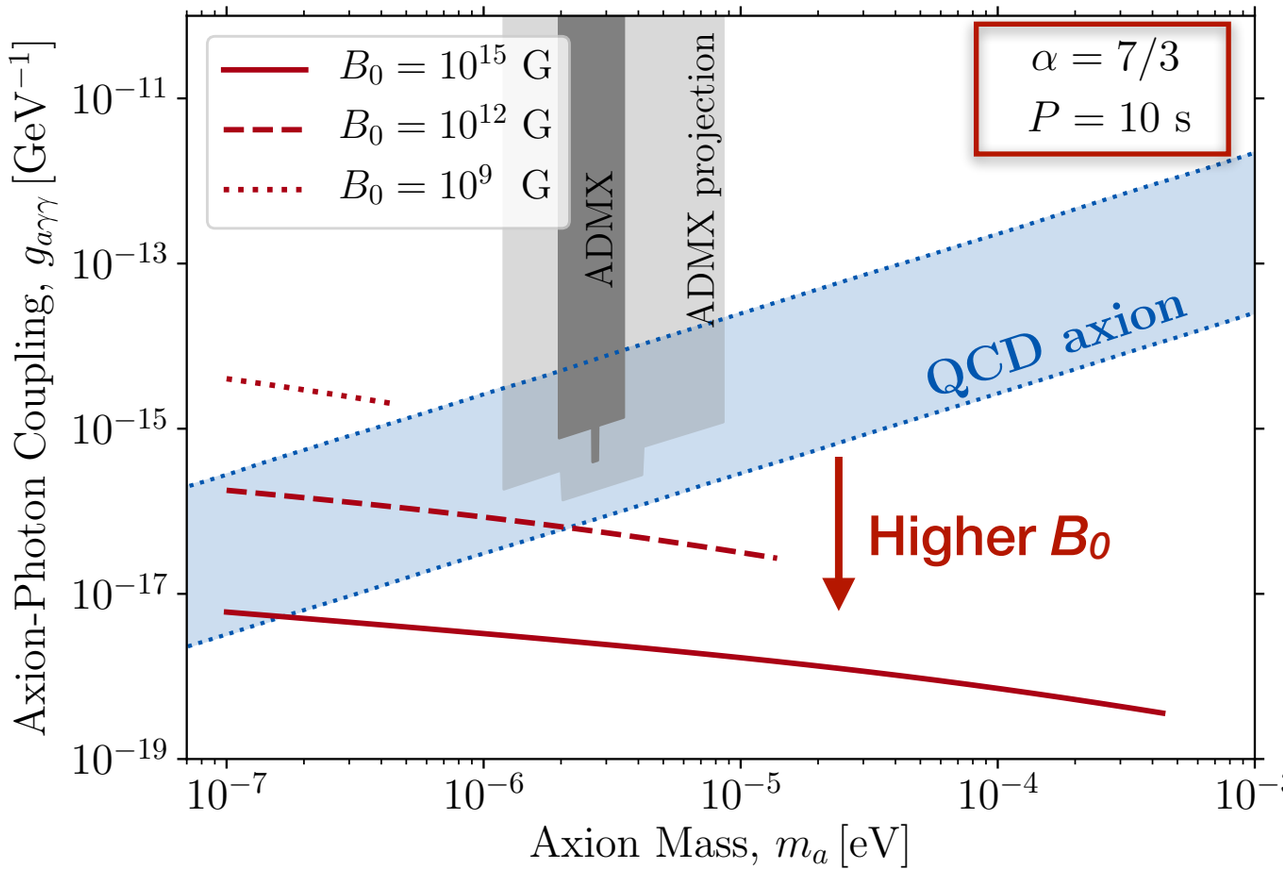
The larger the slope, the larger the DM density close the IMBH.

→ **Larger Radio Signal!!!**

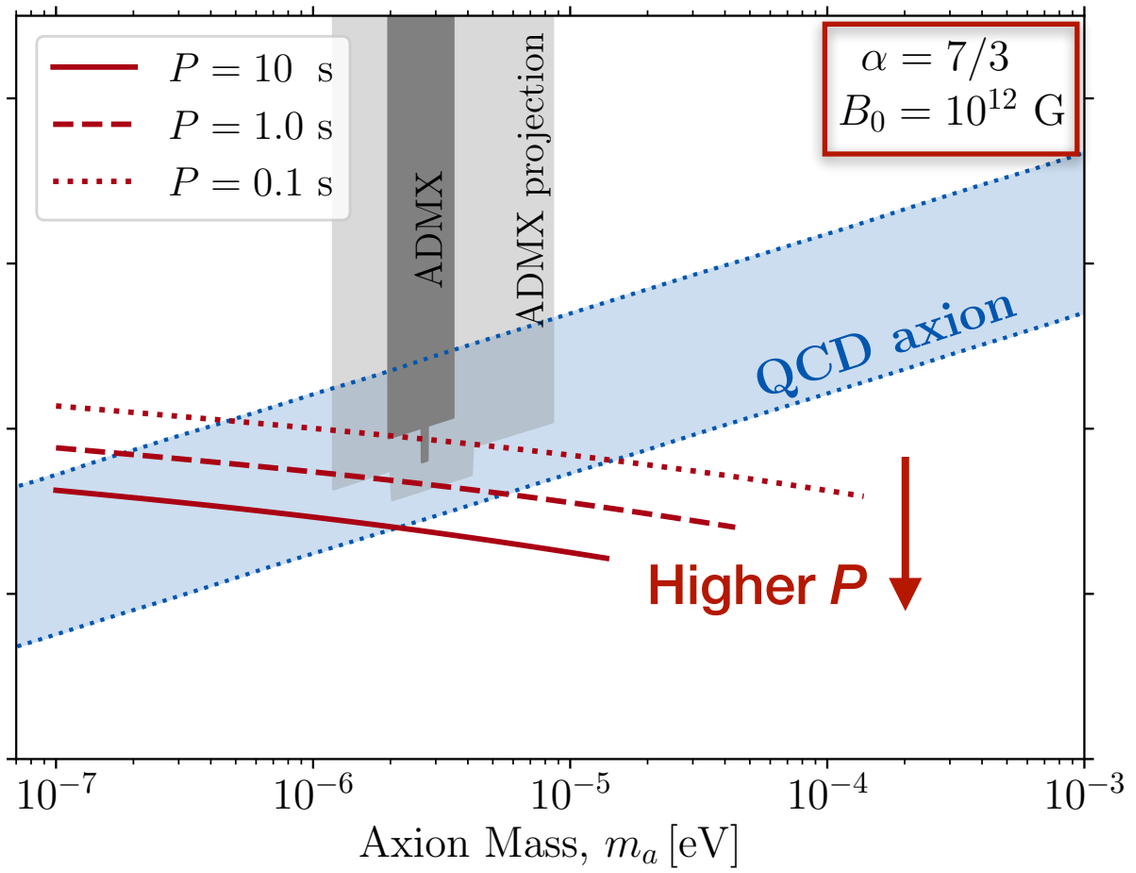
For small values of the spike slope, the phase difference in the GW signal becomes difficult to probe.

Dependence on NS parameters

Magnetic Field B_0



Spin Period P

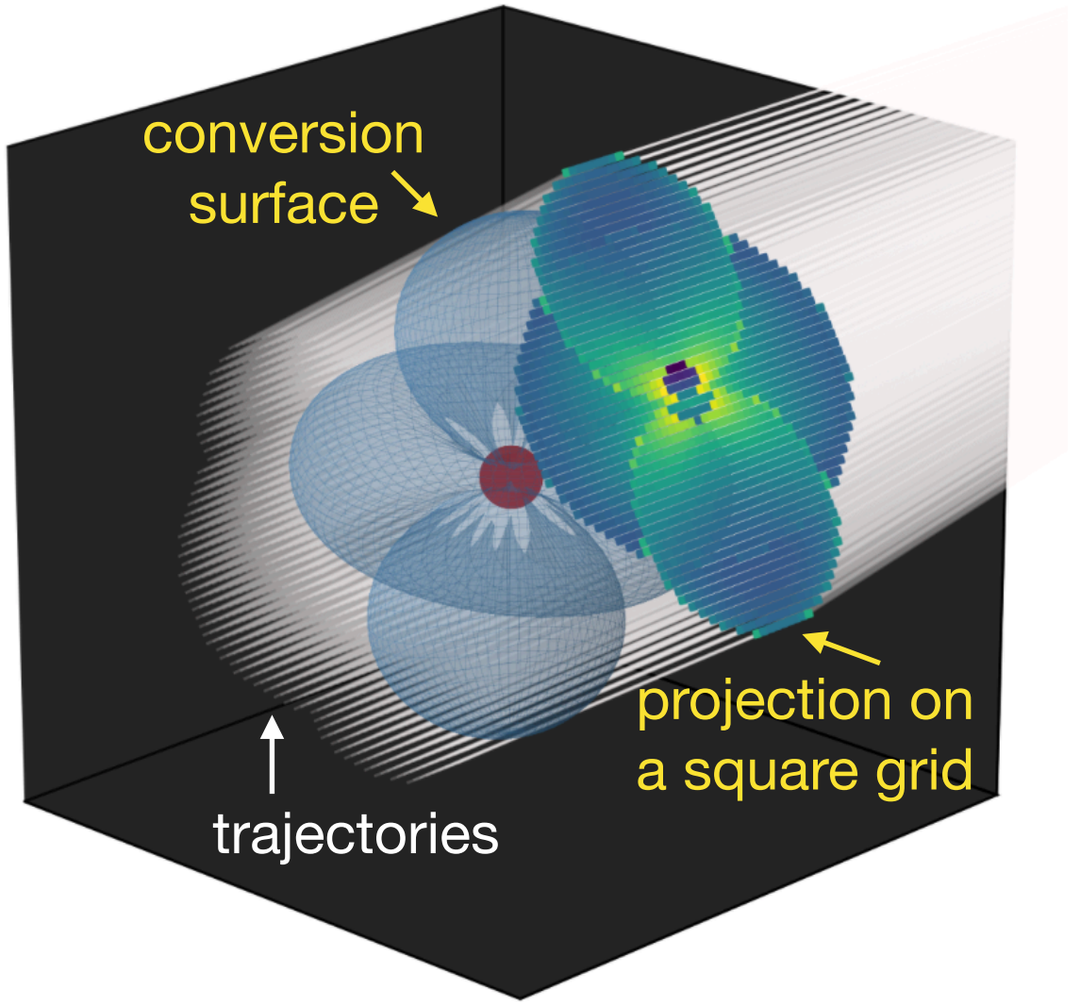


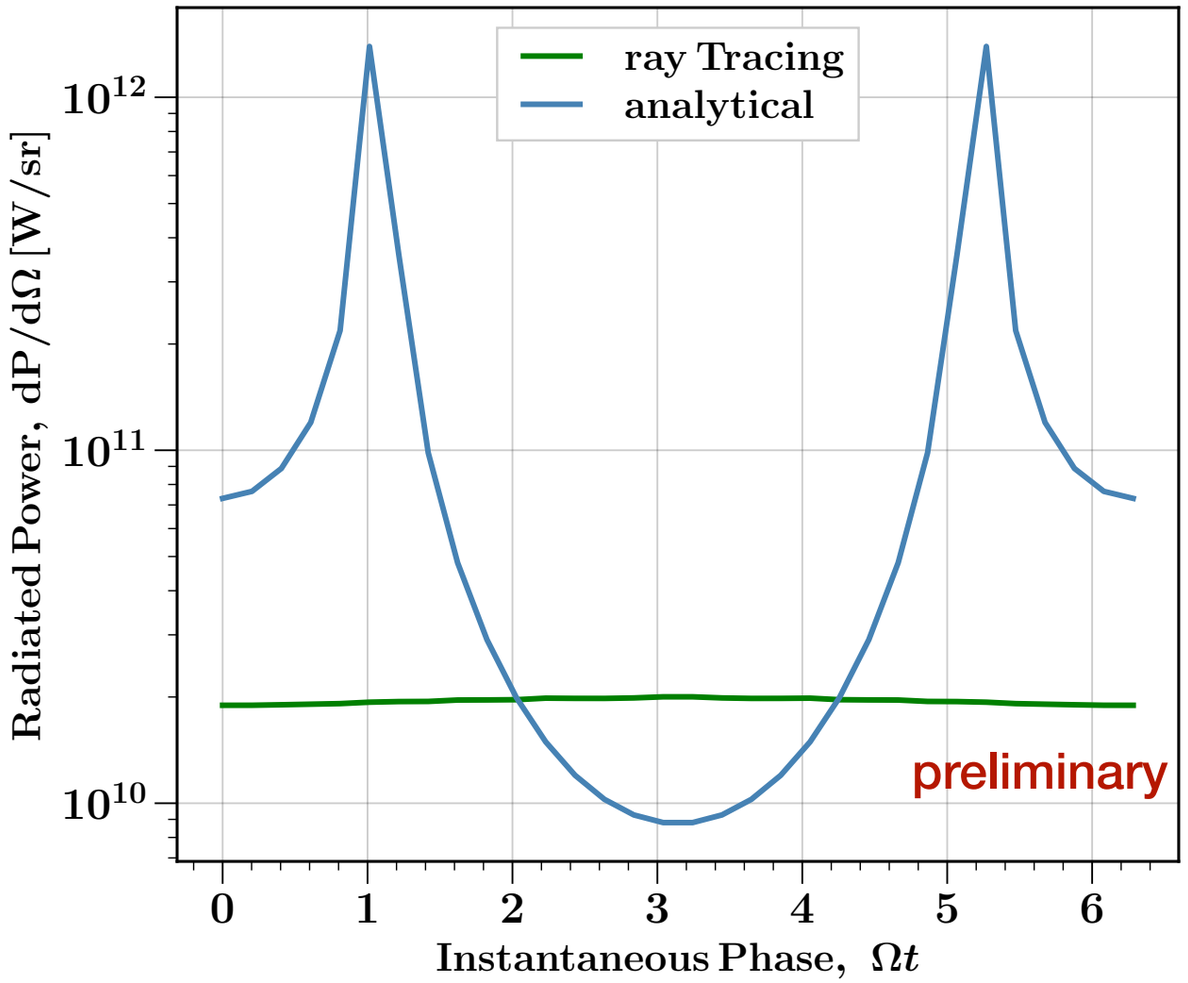
The radiated power of the radio signal roughly scales as

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

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**.





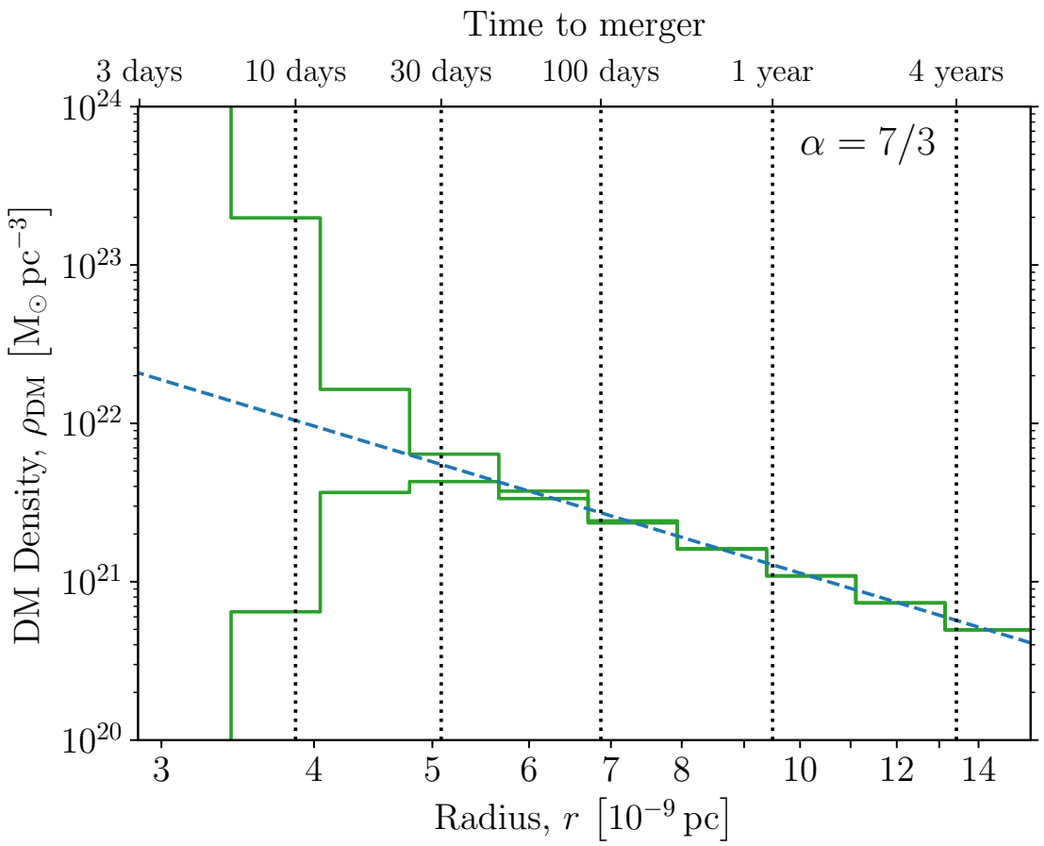
All trajectories considered

No time-dependence of the signal

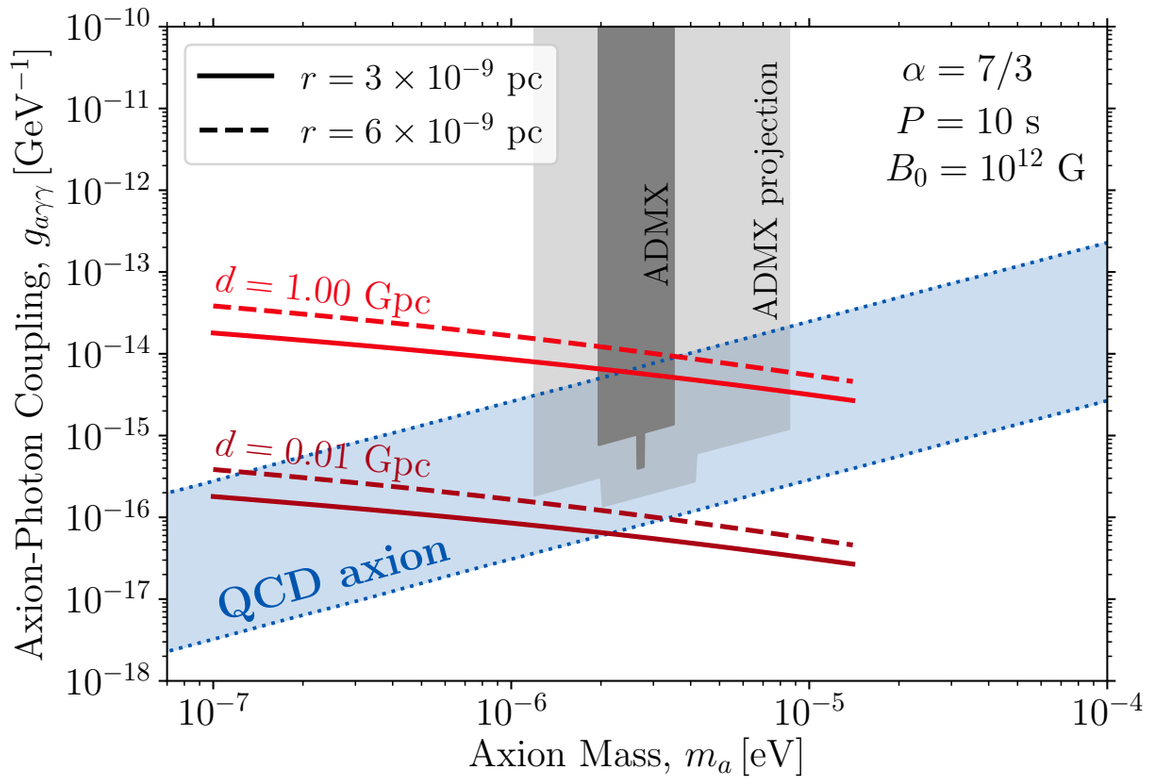
Leroy, MC, Edwards and Weniger, **in progress**

Conclusions

GW



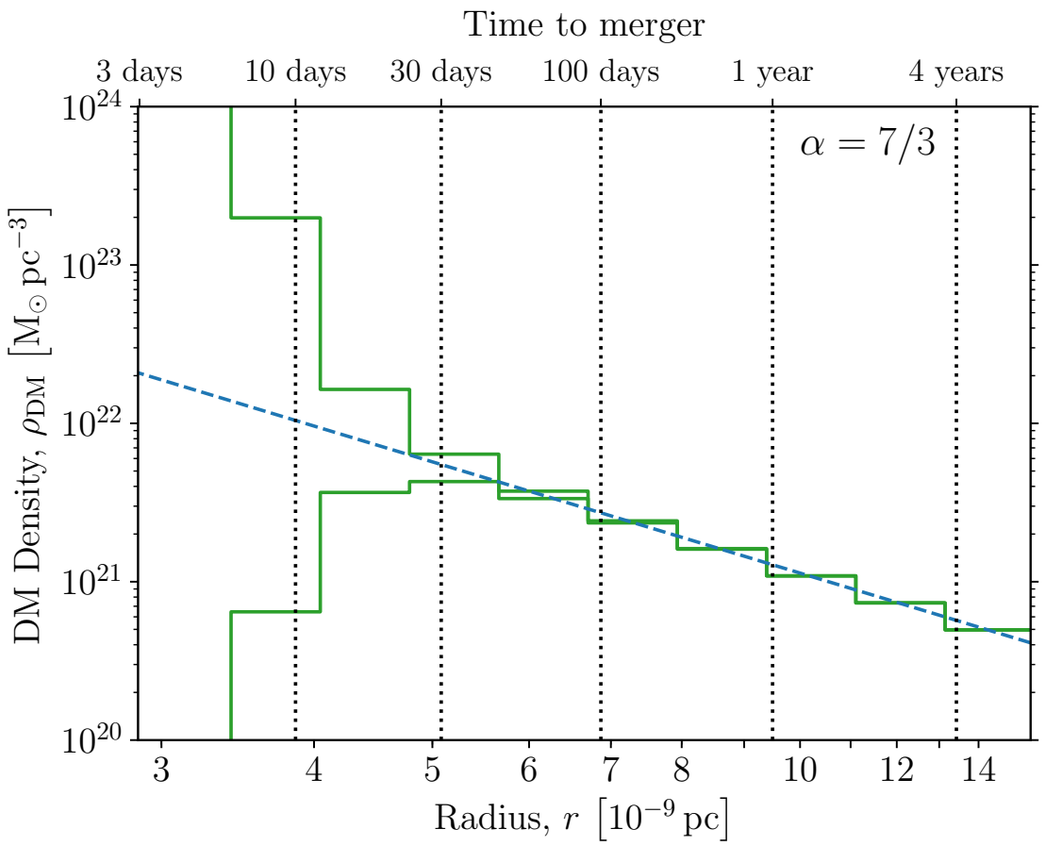
EM (radio)



- 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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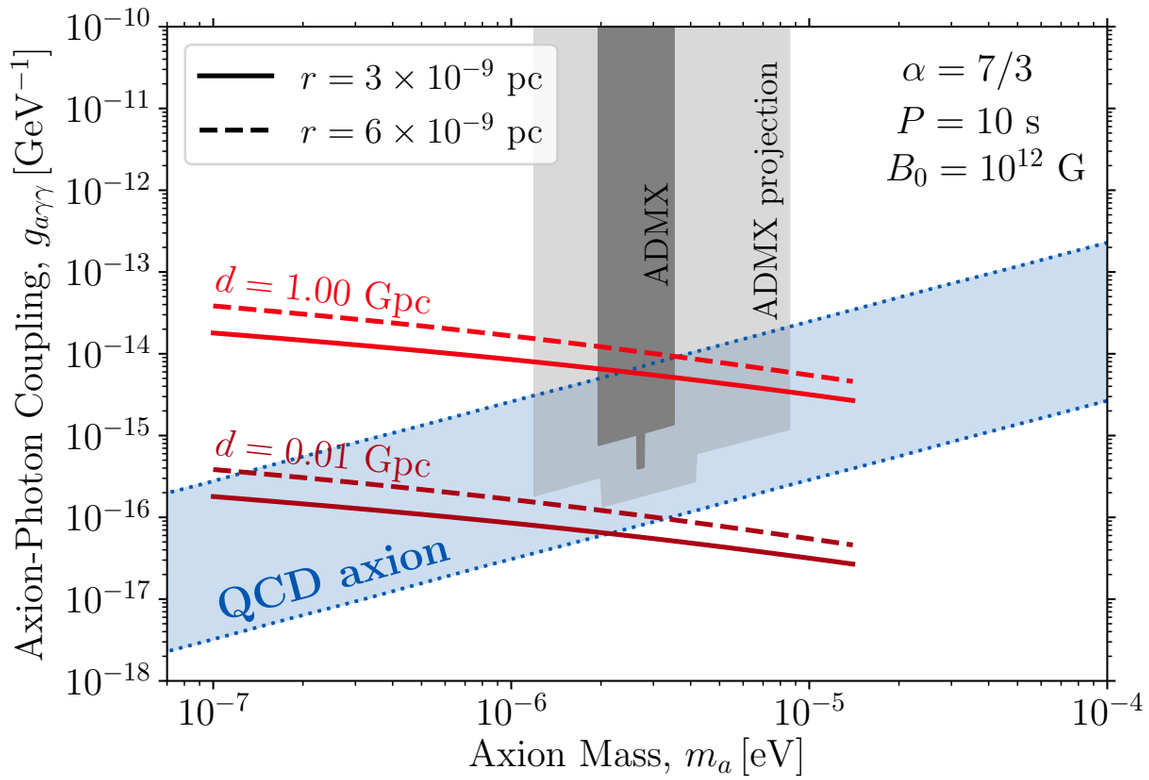

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Thanks for your attention