SEARCHING FOR RELATIVISTIC AXIONS IN THE SKY WITH THE SQUARE KILOMETER ARRAY

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(Based on JCAP 08 (2023) 056 in collaboration with Arpan Kar, Sourov Roy and Jure Zupan)

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- ALPs are weakly interacting particles → Promising candidate for dark matter (DM)
- Several experiments exist (ADMX) or are under construction (DMRadio) to find evidence of ALPs

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HOW TO FIND THEM ?

MOTIVATION

- We show that the upcoming radio telescope – Square Kilometer Array (SKA) – will provide us a great opportunity to search for these **relativistic ALPs** through observations of certain dwarf spheroidal galaxies (dSph)

Square Kilometre Array Telescope

Source : https://www.skatelescope.org/the-ska-project/

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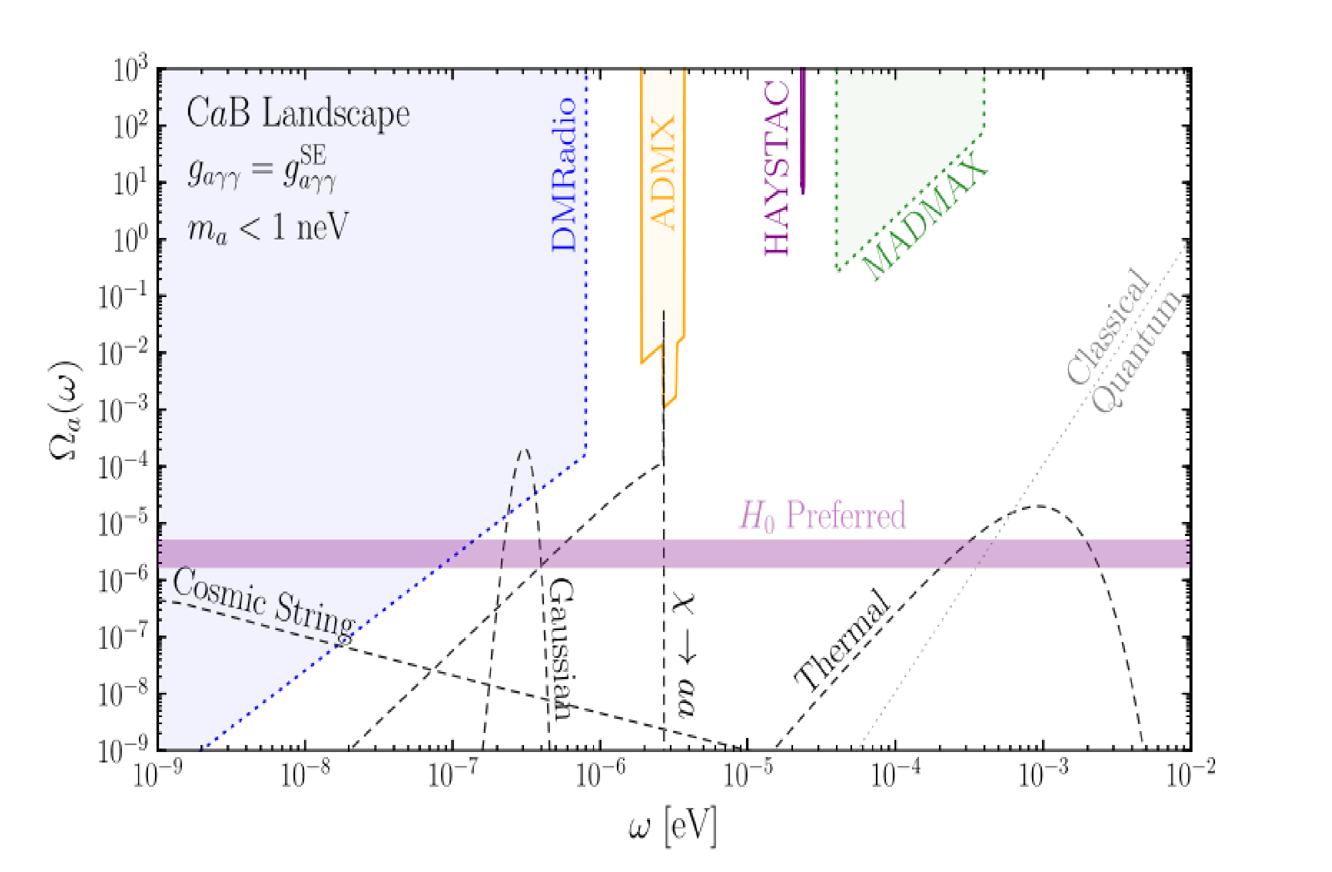

J. Dror et al, Phys. Rev. D 103, 115004 (2021))

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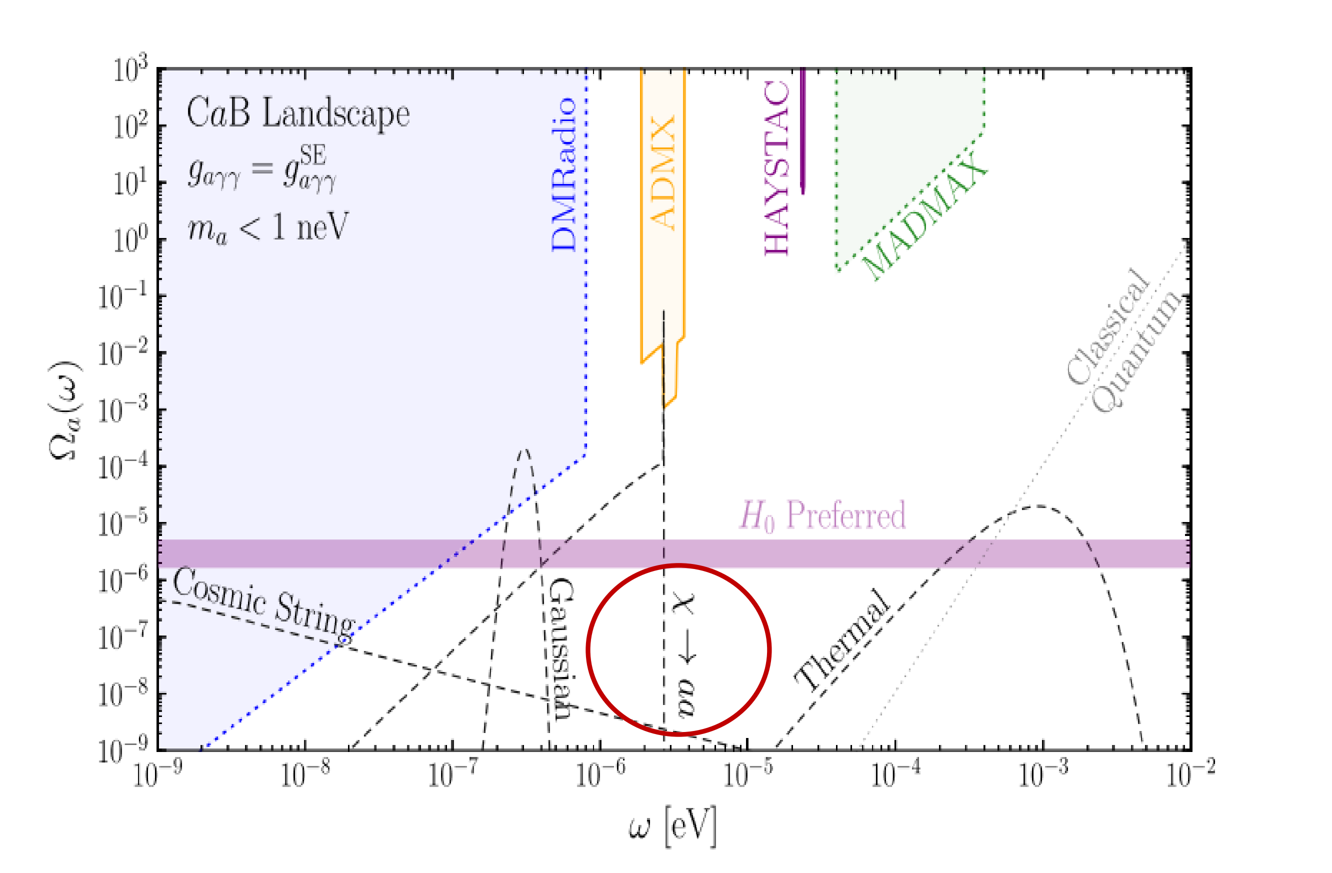

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RELATIVISTIC ALP PRODUCTION

- We consider the following scenario:

Mechanism and Assumptions

- Relativistic ALPs (a) are produced from the decay of DM χ

$$\chi \to aa$$

(M. Cicoli et al, Phys. Rev. D 90 (2014))

- χ is much heavier than the axion $(m_\chi \gg m_a)$ → **Produced ALPs are relativistic**
- The produced ALPs are stable
- χ is cosmologically stable, $\tau_\chi > t_U$

FLUX OF RELATIVISTIC ALPs

- Two possible sources of relativistic ALP flux from DM decay viz.,

Cosmic Axion Background (CAB)

- A homogeneous and isotropic ALP distribution produced from extragalactic DM decays

$$\left.\frac{dn_a}{d\omega}\right|_{\text{CAB}} = \int_{t=0}^{t_0} dt\,\hat{\boldsymbol{a}}^3 \Gamma_\chi e^{-\Gamma_\chi t} \frac{\rho_{\text{DM}}(t)}{m_\chi} \left.\frac{dN_a}{d\omega'}\right|_{\omega'=\omega/\hat{a}}$$

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Axions from DM Halo

- Decay of DM gravitationally bound inside the galaxy i.e., decay of halo DM.

$$\left.\frac{dn_a}{dt\,d\omega}\right|_{\mathrm{dSph}}(r) = \frac{e^{-t_U/\tau_\chi}}{m_\chi \tau_\chi} \frac{dN_a}{d\omega} \rho_{\mathrm{DM}}^{\mathrm{dSph}}(r)$$

Jeff A. Dror et al., Phys. Rev. D 103 (2021)

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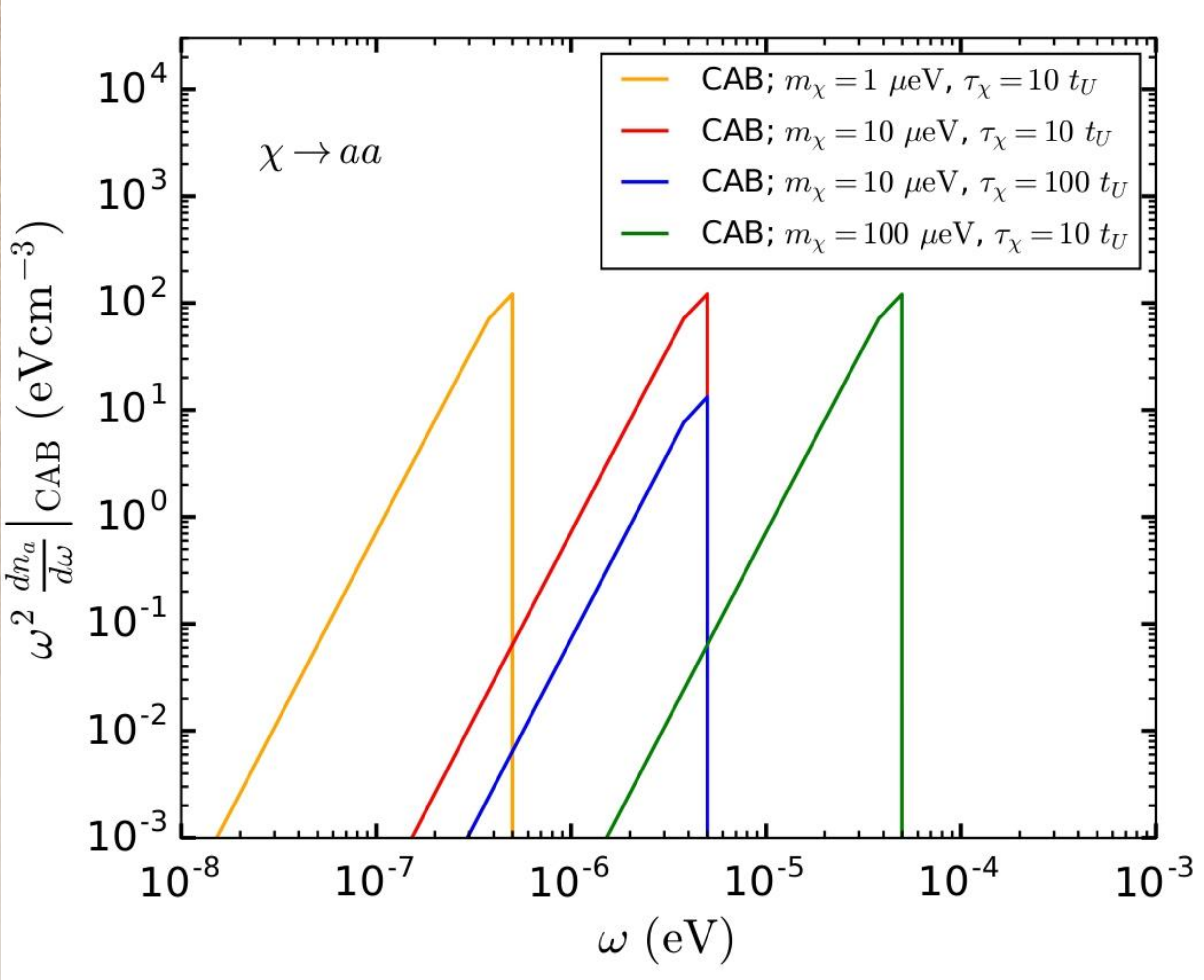

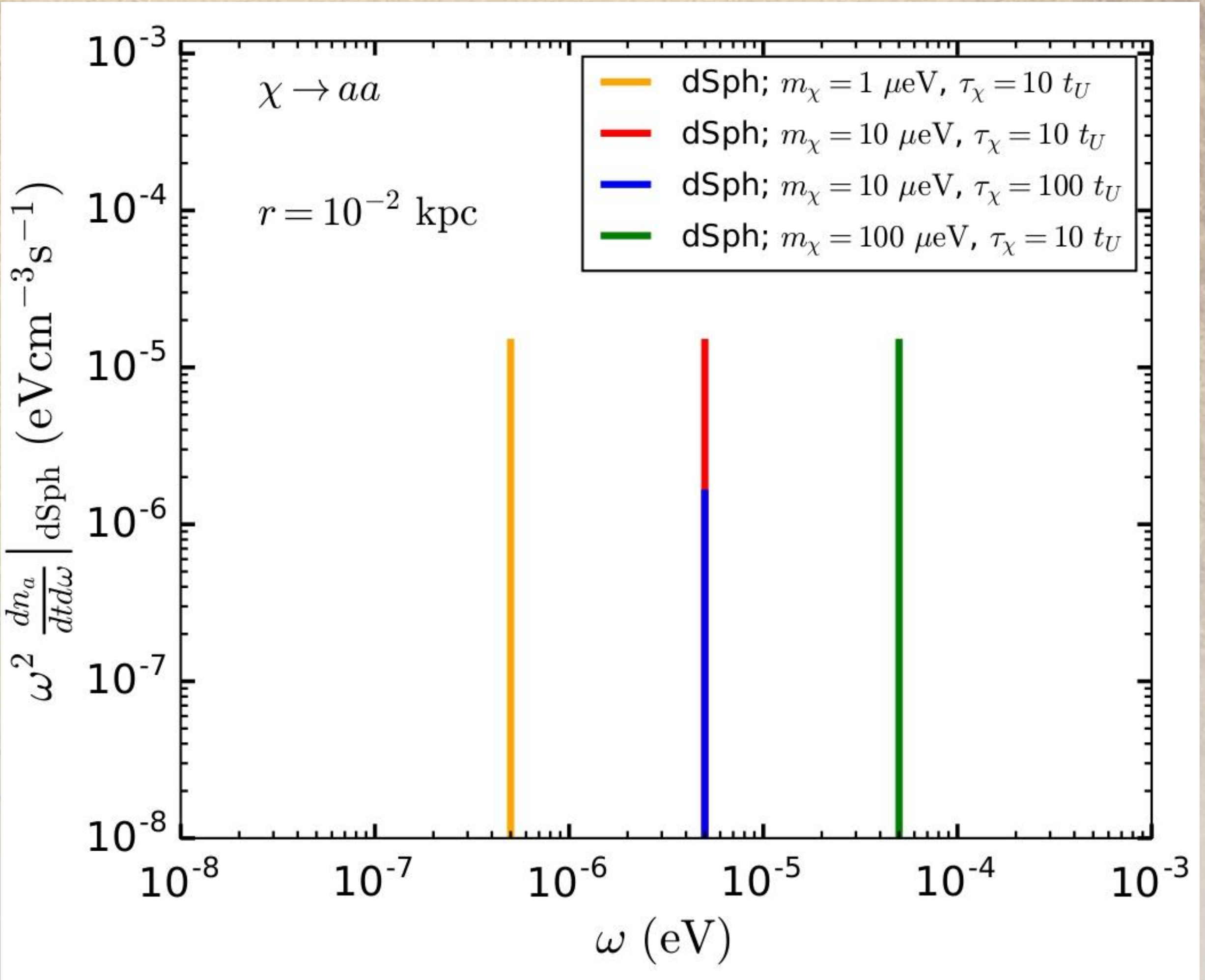

ALP-PHOTON OSCILLATION IN DWARF GALAXY

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- While traversing the dSph, ALPs can oscillate into photons in the magnetic field of the dSph due to their coupling with photons:

$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{g_{a\gamma\gamma}}{4} \boldsymbol{a F_{\mu\nu} \tilde{F}^{\mu\nu}}$$

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- The probability of ALPs oscillating into photons after traversing a distance L_{domain} in a regular, transverse magnetic field is

$$P_{a\gamma}(\omega) = sin^2(2\theta) sin^2\left(\frac{\Delta_{\mathrm{osc}} L_{\mathrm{domain}}}{2}\right)$$

(Georg Raffelt and Leo Stodolsky, Phys. Rev. D (1988))

RADIO SIGNAL FROM GALAXY

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- Assumption: A regular, fully coherent magnetic field extending throughout the dSph with $L_{domain} = R_{dSph}$
- With the above assumption, combining the differential number density of ALPs and the ALP ⟶ photon oscillation probability we obtain the photon flux originating from the dSph as

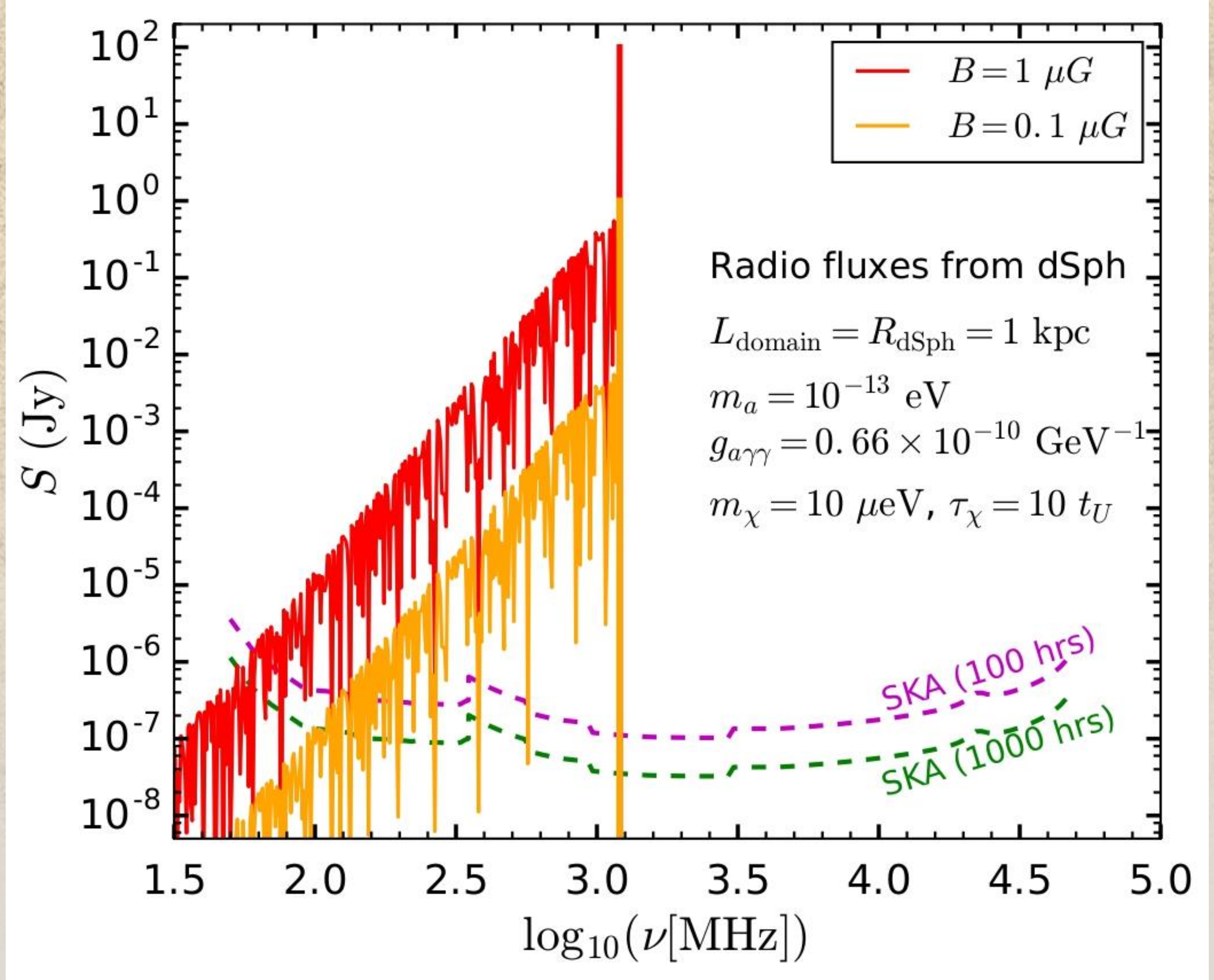
$$F = F|_{\mathrm{CAB}} + F|_{\mathrm{dSph}}$$

where

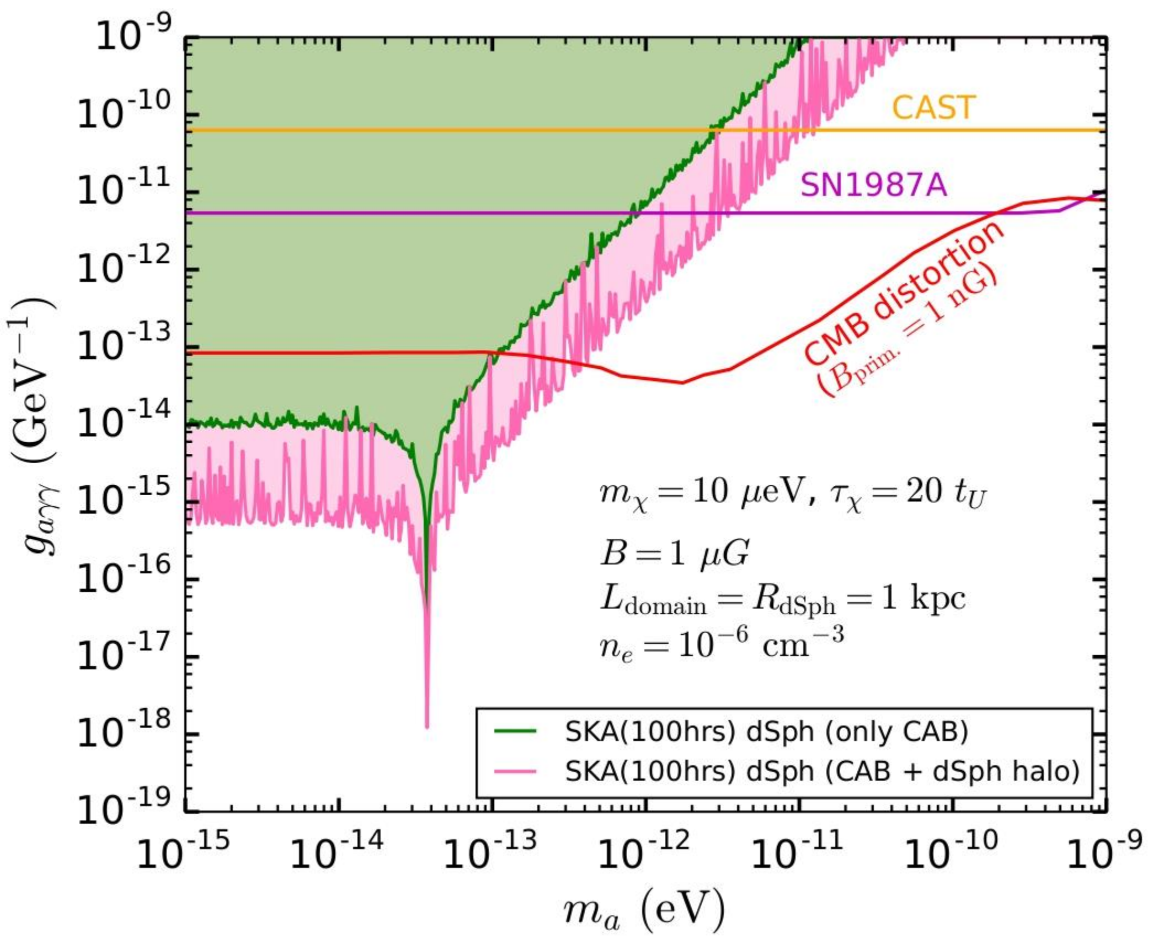
$$F\,|_{\mathrm{CAB}} = \frac{P_{a\,\gamma}(\omega)}{(R_{\mathrm{dSph}}/c)} \times \frac{1}{4\pi}\int_{\Omega}\int_{\mathrm{l.o.s}} d\Omega d\, s\ \omega^2 \frac{dn_a}{d\omega}\bigg|_{\mathrm{CAB}} \qquad F|_{\mathrm{dSph}} = P_{a\gamma}(\omega) \times \frac{1}{4\pi}\int_{\Omega}\int_{\mathrm{l.o.s.}} d\Omega ds\ \omega^2 \frac{dn_a}{dtd\omega}\bigg|_{\mathrm{dSph}}$$

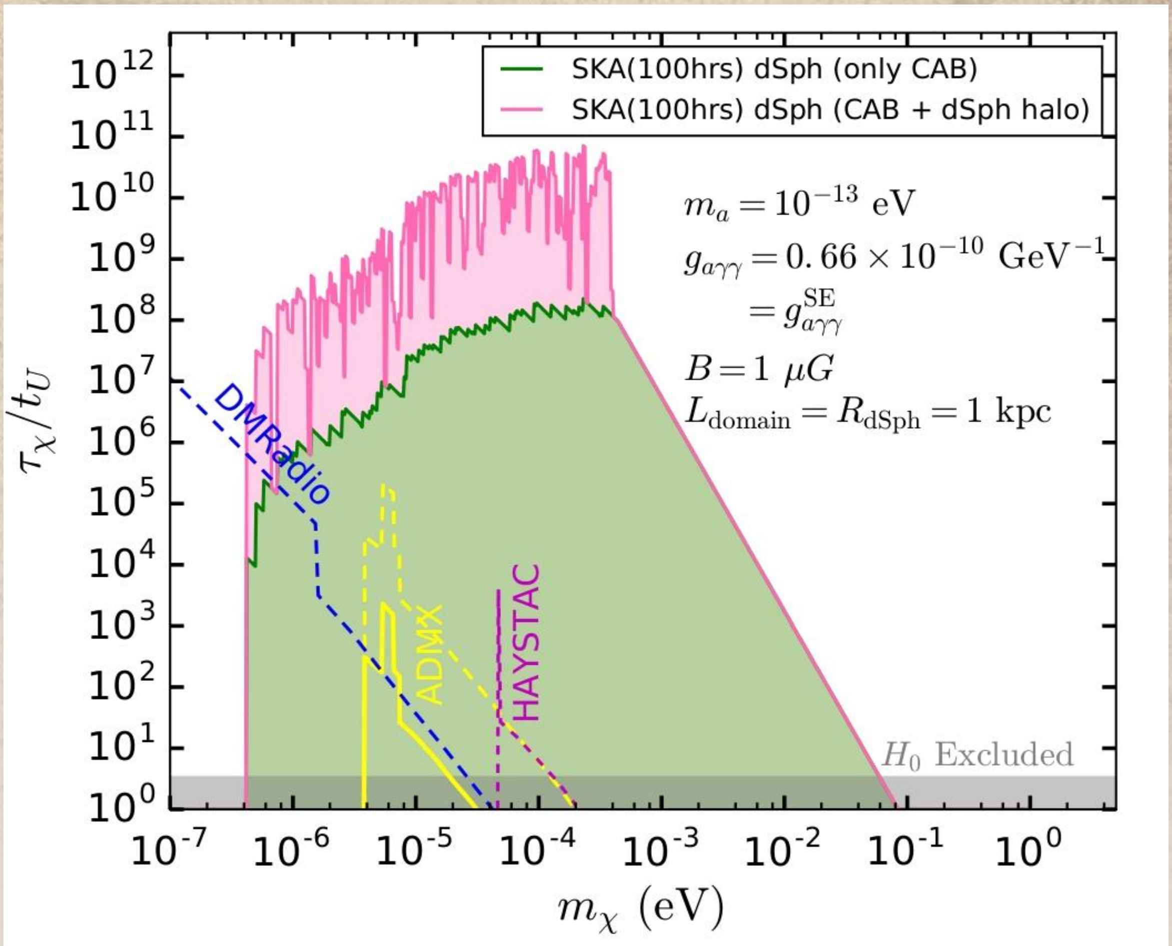
(J. P. Conlon and M. C. D. Marsh, Phys. Rev. Lett. 111 (2013); M. Cicoli et al., Phys. Rev. D 90 (2014))

RADIO SIGNAL FROM GALAXY



PROJECTED SKA CONSTRAINTS





(CAST collaboration, V. Anastassopoulos et al., Nature Phys. 13 (2017); A. Payez et al., JCAP 02 (2015); A. Mirizzi et al., JCAP 08 (2009))

EFFECT OF TURBULENT MAGNETIC FIELD

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- Galaxies, in general, contain a very complicated magnetic field structure
- This complicated magnetic field structure can be modelled simply as: $B = B_{\rm reg} + B_{\rm turb}$
- For $B_{\rm turb}$ we assume the "Cell Model"

Model Description

- The entire galaxy contains many small cells
- Length of the sides of each cell are same and are equal to $L_{\rm cell}$
- Inside each cell there exists a magnetic field of constant magnitude and fixed orientation
- The magnetic field in different cells are of different magnitude and are randomly oriented
- The mean value of the magnetic field (considering all the cells) is zero while the root mean square value is equal to $B_{\rm turb}$

(P. Carenza et al., Phys. Rev. D 104, 023003 (2021))

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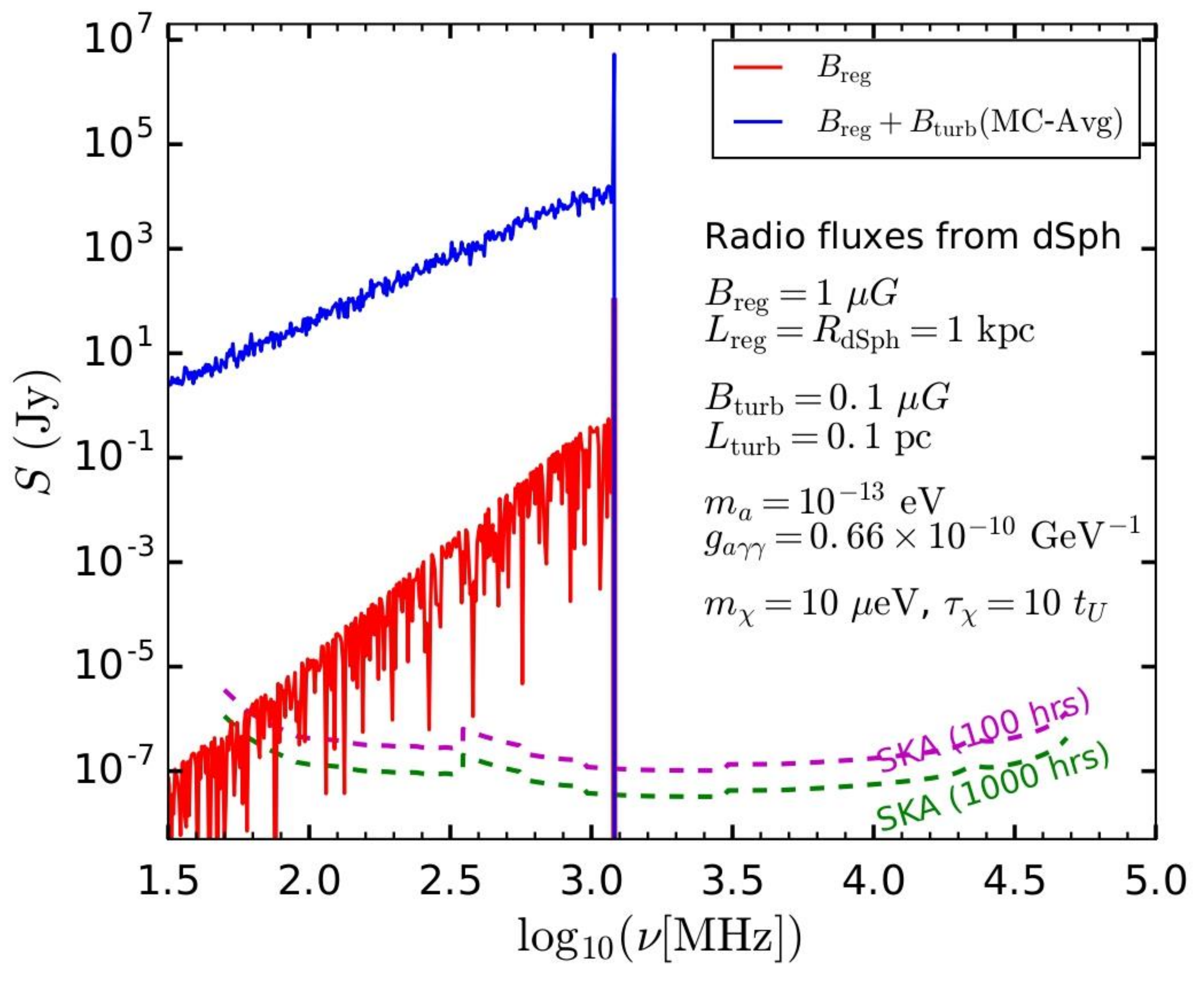

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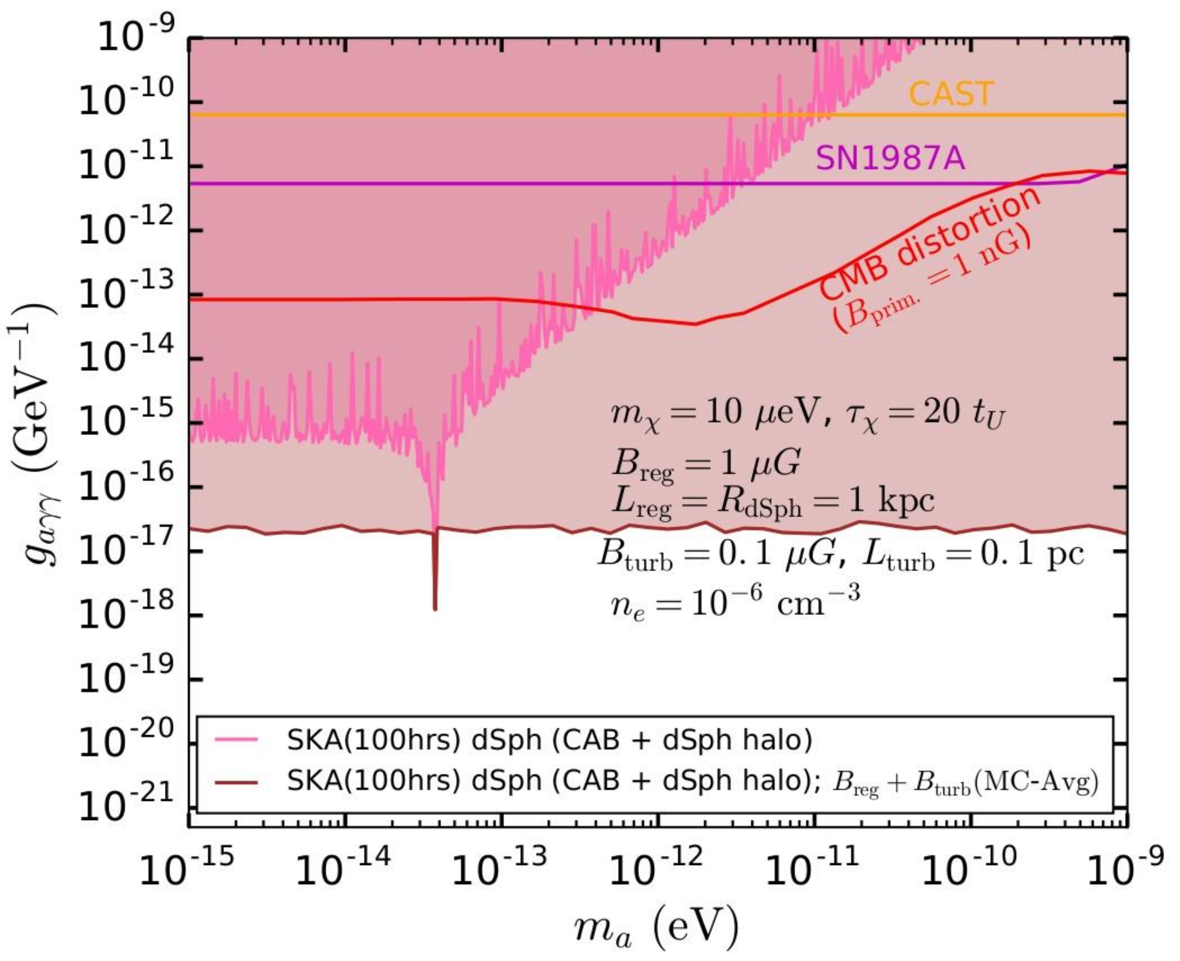
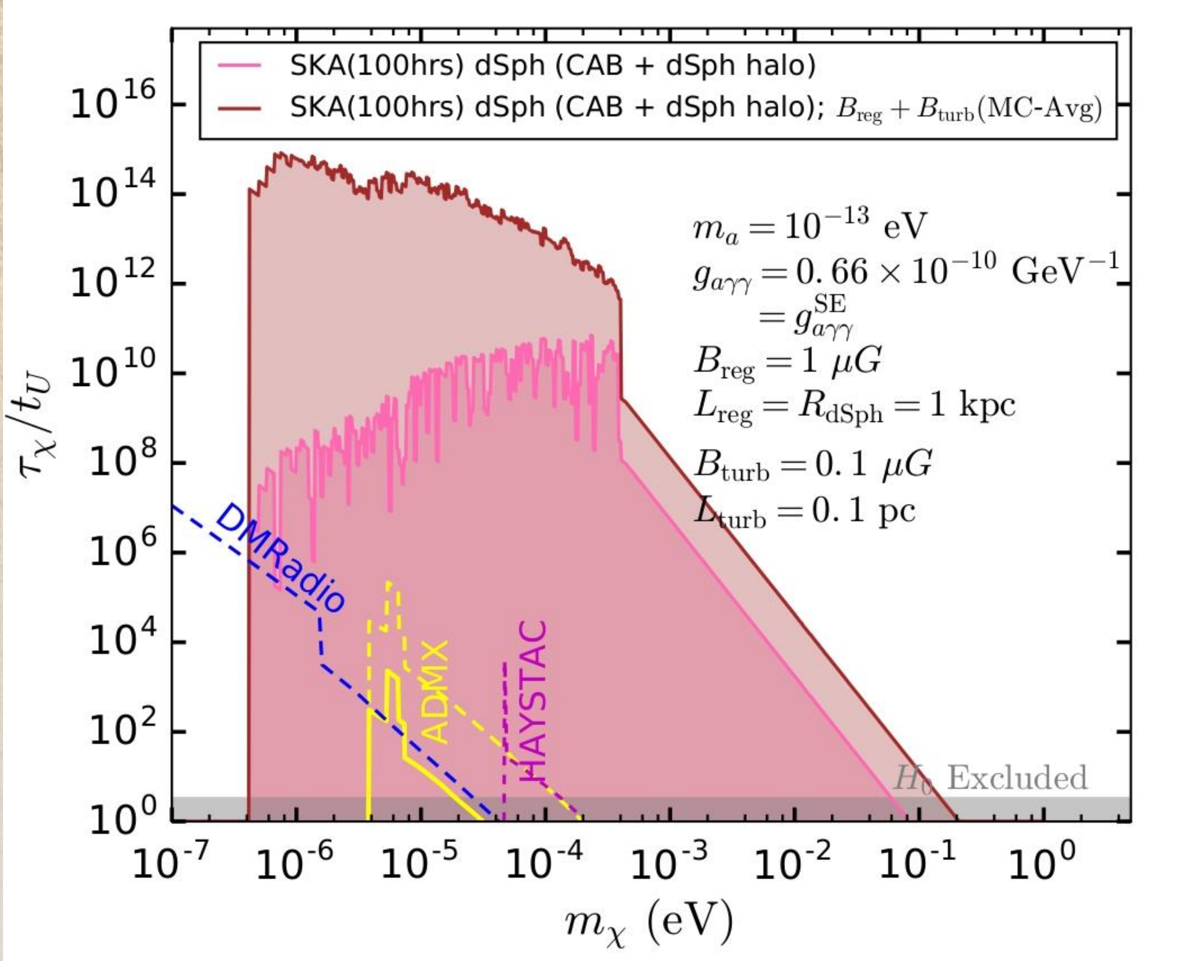




SUMMARY

- Relativistic ALPs could be produced from the decay of heavy DM particle
- Such ALPs, obtained from the decays of DM of mass in the range of a few μeV, would produce radio signals when they convert into photons in the magnetic fields of galaxies
- Observation of dwarf spheroidal galaxies such as Seg 1 via the future radio telescope, Square Kilometer Array, will help us explore as of yet unexplored regions of both the ALP and DM parameter spaces
- In this regard we see that the SKA sensitivity to relativistic ALPs will be much greater than many current and future axion direct detection experiments

THE END

BOSE ENHANCEMENT: OVERVIEW

- Consider the decay of a scalar particle into two scalars $\phi \to \chi\chi$
- Decay rate or time evolution of number density of ϕ is given by

$$\frac{dn_\phi}{dt} = -\int d\Pi_\phi d\Pi_\chi d\Pi_\chi (2\pi)^4 \delta^4(p_\phi - p_\chi - p_\chi)|M|^2[f_\phi(1+f_\chi)(1+f_\chi) - (1+f_\phi)f_\chi f_\chi]$$

- Assuming : $f_\phi \gg f_\chi$ and for $\omega_\chi = \frac{m_\phi}{2}$

$$\frac{dn_\phi}{dt} = -\Gamma_{\phi\to\chi\chi}(1+2f_\chi)n_\phi = -\Gamma_{\text{eff}}\, n_\phi$$

(A. Caputo et al., JCAP 03(2019) 027)

- For a large occupation number of χ, decay rate of ϕ is greatly enhanced – *Bose Enhancement*
- Consequence: *Stimulated decay of* ϕ *or stimulated emission of* χ

BOSE ENHANCEMENT: STIMULATED DECAY OF DARK MATTER

- Dwarf spheroidal galaxies have huge DM densities $\Rightarrow$ Decay of DM into axions can result in a huge ALP occupation
- Axion occupation number is given by: $f_a = \frac{n_a}{4\,\pi^2\omega^2\Delta\omega}$
- Large axion occupation number results in an effective decay width of DM much larger than the spontaneous decay width

$$\Gamma_{\text{eff}} = \Gamma_\chi(1 + 2f_a) \gg \Gamma_\chi$$

- Evolution of axion and DM densities

$$\frac{dn_a}{dt} = N_a\Gamma_{\text{eff}}n_\chi$$

$$\frac{dn_\chi}{dt} = -\Gamma_{\text{eff}}\,n_\chi$$

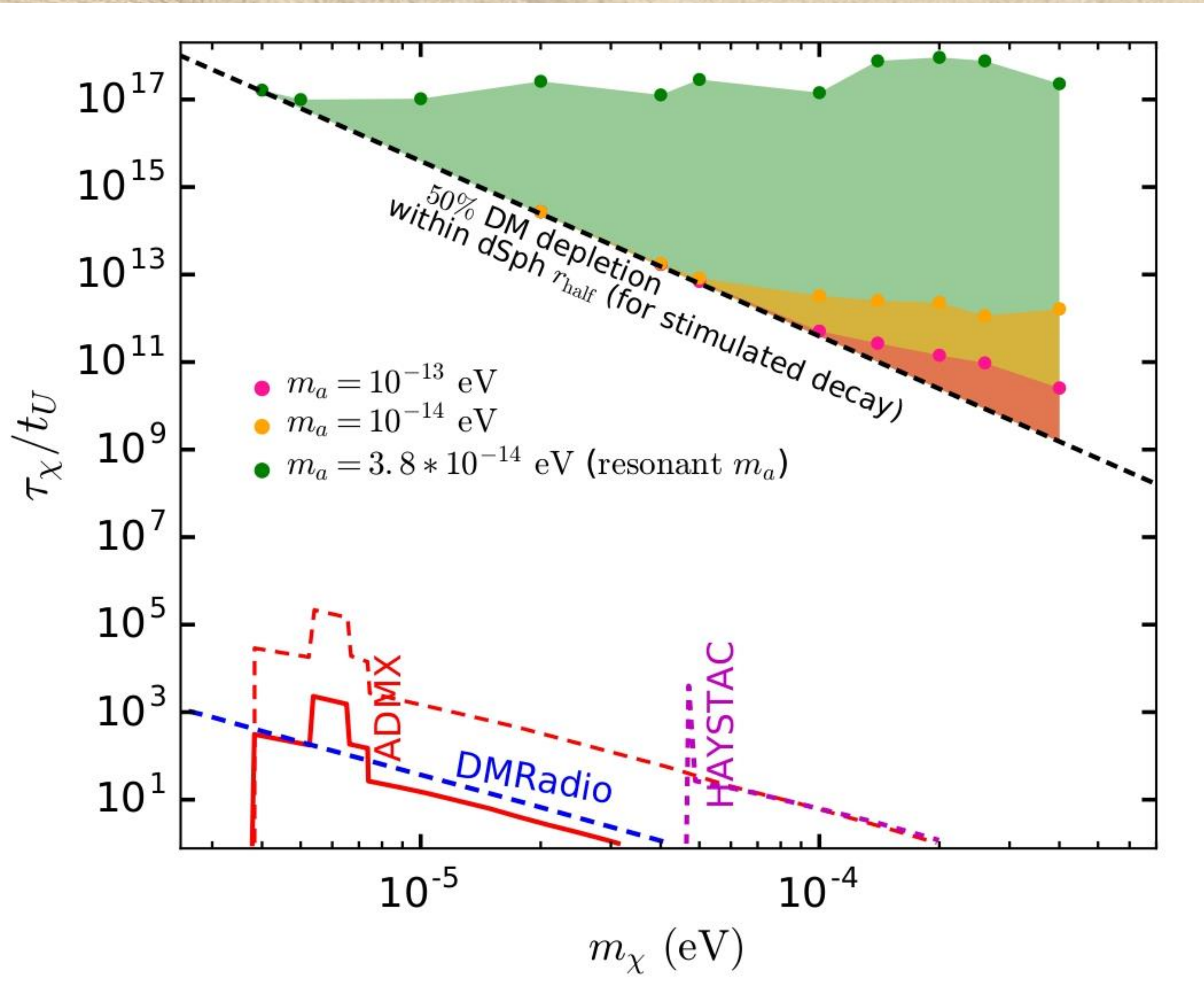
BOSE ENHANCEMENT: STIMULATED DECAY OF DARK MATTER

- Resulting photon flux due to the axions passing through the dSph

$$S(\nu) = P_{a\gamma} \, \frac{1}{4\pi} \int d\Omega \int_{\mathrm{l.o.s}} d\,s\,\omega\,\Gamma_{\mathrm{eff}}(s)\,\frac{dN_a}{d\omega}\,n_\chi(s)$$

- Note: We neglected the CAB contribution while calculating the effect of *Bose enhancement* on DM decay.

BOSE ENHANCEMENT: UPDATED PROJECTIONS



$$\tan(2\,\theta) = \frac{2\,\Delta_{a\gamma}}{\Delta_{\parallel} - \Delta_a}$$

$$\Delta_{\text{osc}} = \sqrt{(\Delta_{\parallel} - \Delta_a)^2 + 4\,\Delta_{a\gamma}^2}$$

$$\Delta_a = -\frac{m_a^2}{2\omega}$$

$$\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma\gamma} B_{\perp}$$

$$\Delta_{\parallel} = \Delta_{\text{pl}} + 3.5\Delta_{\text{QED}}$$

$$\Delta_{\text{pl}} = -\frac{\omega_{\text{pl}}^2}{2\omega}$$

$$\Delta_{QED} \propto \omega B_{\perp}^2$$