Phenomenological Aspects of Axion-Like Particles in Cosmology and Astrophysics

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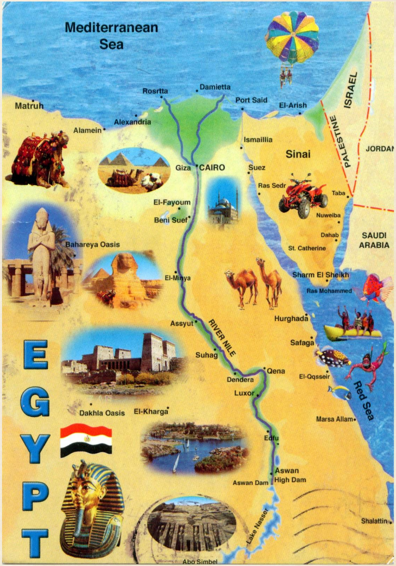
Outline

1. Background.
2. Introduction and motivation.
3. Axion Dark Matter and Cosmology.
4. Phenomenology of ALPs Coupling with Photons in the Jets of AGNs.
5. Potential of SKA to Detect CDM ALPs with Radio Astronomy.
6. Conclusion and future work.

Background: Egypt, Sohag City



Background: Sohag University

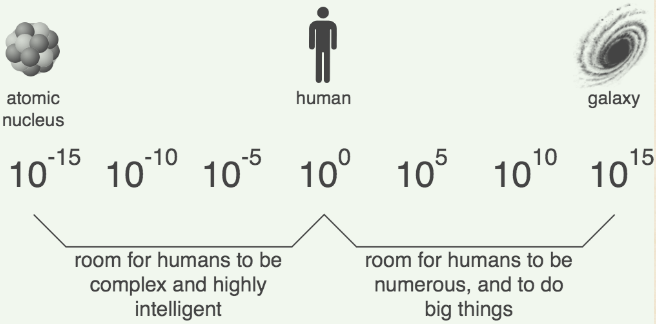
Background: AIMS-Ghana

Background: Wits University, Johannesburg, South Africa

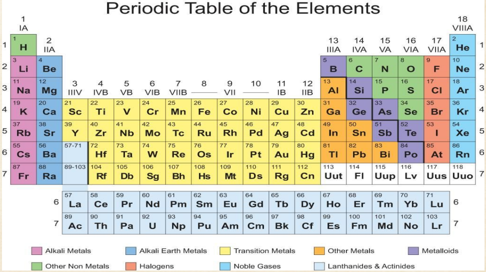
Background: ASP-2018, Windhoek, Namibia

Introduction

- Have you ever question the nature of your reality?
- Our current best understanding for the structure of our universe is based on the SMPP together with the SMC.



Standard Model of Particle Physics

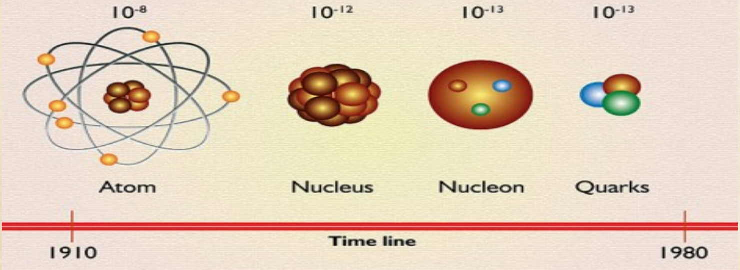


Periodic Table of the Elements

	1 IA	2 IIA	3 IIIV	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA	
1	1 H																	2 He	1
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	2
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	3
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	4
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	5
6	55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	6
7	87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo	7

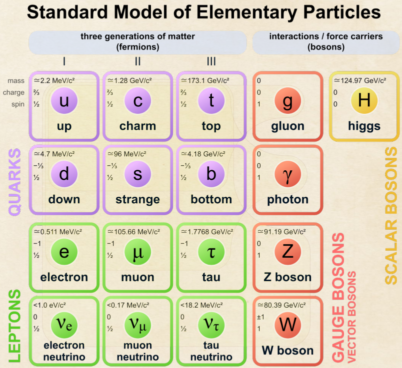
6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	6
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	7

Alkali Metals · Alkali Earth Metals · Transition Metals · Other Metals · Metalloids
Other Non Metals · Halogens · Noble Gases · Lanthanides & Actinides



Standard Model of Particle Physics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

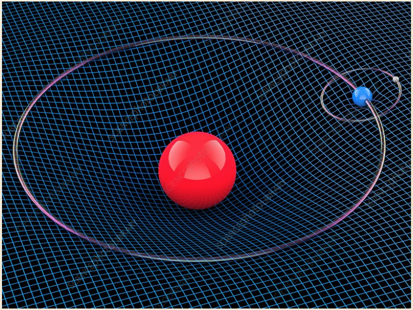


Standard Model of Cosmology

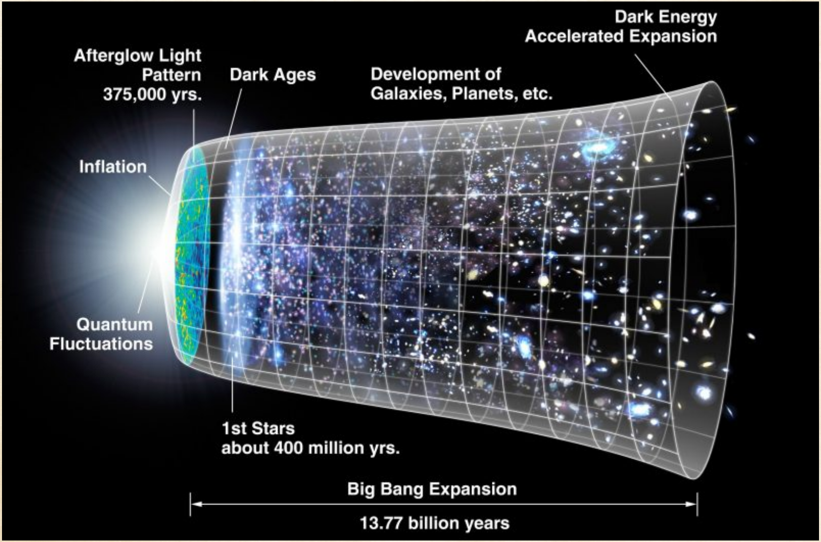
Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$



Standard Model of Cosmology



Problems with the standard models

- Gravity puzzle.
- The gauge hierarchy problem.
- Origin of the mass.
- Neutrino mass.
- Flavor problem.
- Matter-antimatter asymmetry.
- The strong CP problem.
- Inflation.
- Dark matter and dark energy.

Models beyond the standard models

- Supersymmetric theories.
- Extra-dimensional theories.
- Grand unified theories.
- Theories of everything.

Understanding the nature of DM is in the core of all these models! So what is going on?

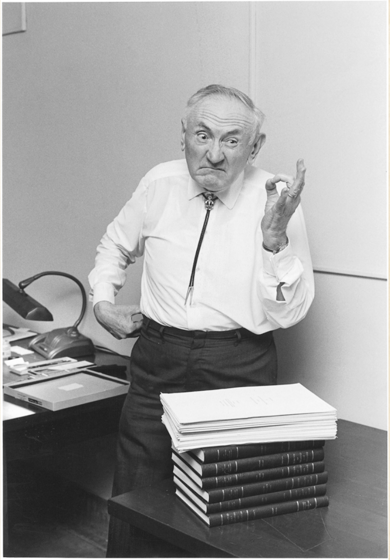
What is dark matter?

- Well, I don't know what dark matter is!
- Direct information on cosmology can be obtained by observational tests.
- Explaining the contradictions required additional sort of matter can not be observed by all observational techniques.
- It does not interact strongly enough with anything we can readily detect or see, so it is basically invisible to us and referred to as "Dark Matter".

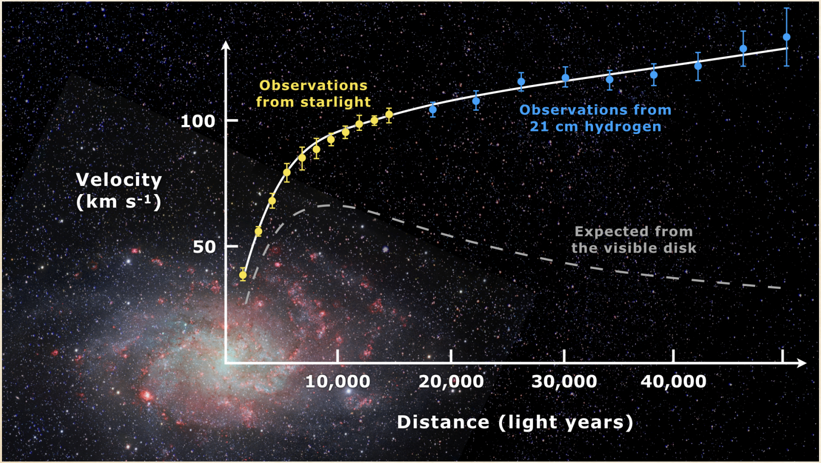
First evidence for dark matter

- Fritz Zwicky (1898-1974) 1930's: Studied the motion of galaxies within the Coma cluster, found they are moving too fast to remain confined by Coma's gravitational field. Why is Coma still there?

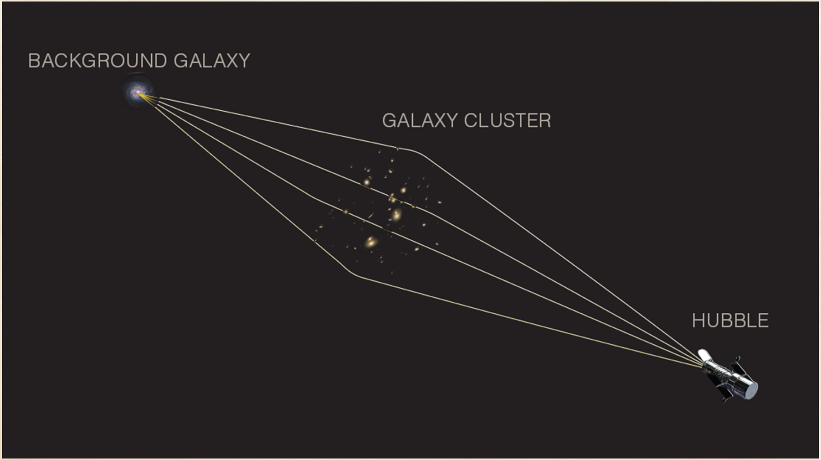
- The gravity of something that we can't see must be keeping the galaxies from flying off into space: Dark Matter.



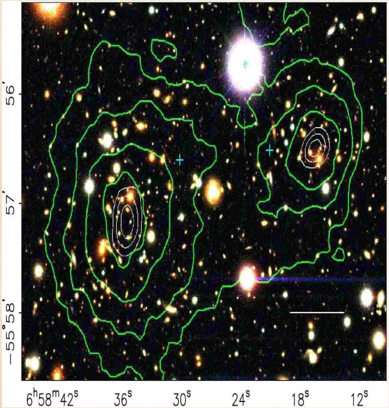
Galactic rotation curves

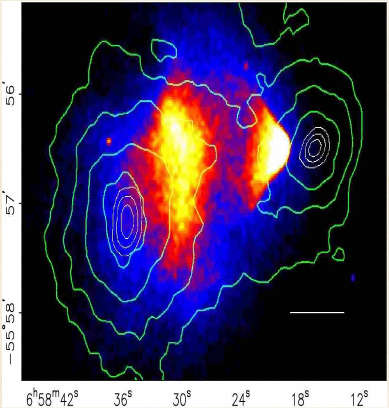


Gravitational lensing

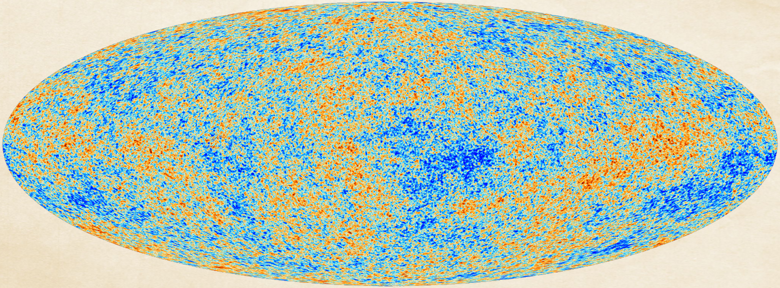


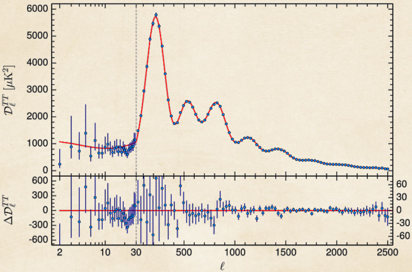
Bullet Cluster



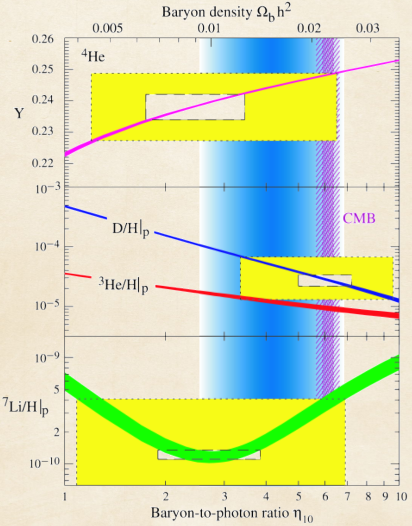


Cosmic Microwave Background

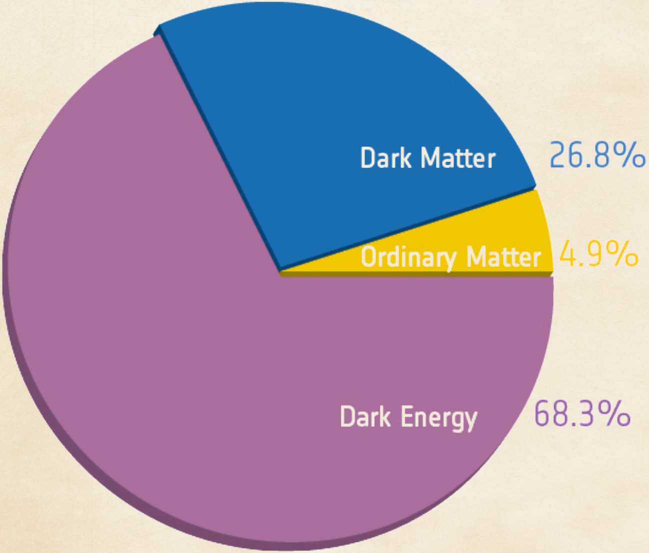




Big bang nucleosynthesis



The contents of the universe



The problem of Dark Matter

- If dark matter not exists, there is a big problem with our standard theory of gravity, or
- If dark matter exists, there is a big problem with our standard model of particle physics,
- or both!

Let us move now to the next question ....

What we know/don't-know about DM?

- Relic abundance.
- Electrically neutral.
- Collisionless.
- Temperature.
- Stability.
- Non-baryonic nature.
- Fluid.

- Mass??
- Spin??
- Decays??
- Elementary??
- ⋮
- No Idea!!

None of the known particles suitable enough to be the DM!!

Dark matter candidates

- Astrophysical objects - Disfavored
  - MAssive Compact Halo Object (MACHO)
  - Black holes

- Particle Dark Matter
  - Weakly Interacting Massive Particle (WIMP)
  - Sterile Neutrinos
  - Supersymmetric particles like: Gravitinos, Neutralinos
  - Axions and axion-like particles

The strong CP problem

- Axions: pseudo-scalar bosons associated to the solution of the strong CP problem in QCD.
- $\mathcal{L}_{\text{QCD}} \rightarrow$ global symmetry: $SU(N)_L \otimes SU(N)_R \otimes [U(1)_V \otimes U(1)_A]$.
- The axial symmetry neither represents a symmetry nor is spontaneously broken $\rightarrow$ $U(1)_A$ problem.
- This problem explained due to the complex structure of the QCD vacuum $\Rightarrow \mathcal{L}_\theta = \bar{\theta}(g_s^2/32\pi^2)F_a^{\mu\nu}\tilde{F}^a_{\alpha\beta}$.
- The extra term is a source of CP violation.
- But experimentally, $|\tilde{\theta}| < 10^{-10} \Rightarrow$ fine tuning needed.

Axion solution

- Peccei–Quinn solution: extend the SM with additional axial $U(1)_{PQ}$ global symmetry.
- Spontaneously broken at some high scale $\Rightarrow$ axion is the resulting Goldstone mode.
- The interactions between axions and gluons, generate an axion potential witch makes $\bar{\theta}$ dynamically relaxes to zero.
- Axions must solve the strong CP problem and suggested as dark matter candidate.

Axion-like particles

- Many string theory models extend the SM by new symmetries and there can be many other ALPs.
- They are characterized by their coupling to two photons, $g_{a\gamma}$ which directly related to the axion mass m_a.
- ALPs have the same properties of the QCD axions but their masses and coupling to photons are unrelated.
- ALPs show as very promising dark matter candidates.

Phenomenology of axions and ALPs

- The coupling of axion with gluons makes possible the mixing with pions as well.

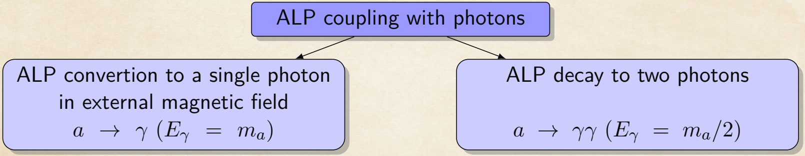
- The mixing with pions generates couplings of the axions to photons (Primakoff effect)

$$\ell_{a\gamma} = -\frac{1}{4} g_{a\gamma} \mathrm{F}_{\mu\nu} \tilde{\mathrm{F}}^{\mu\nu} a = g_{a\gamma} \, \mathbf{E} \cdot \mathbf{B} \, a$$

- The axion-two-photon coupling constant:

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} C_{a\gamma}$$

How to search for ALPs?



- These two mechanisms are using in my work to explain a number of astrophysical phenomena and to constrain ALP properties.

Probing a CAB within the jets of AGN

- Many string theory models motivate the existence of a homogeneous CAB analogous to the CMB.
- Recent work explain the Coma cluster soft X-ray excess due to CAB ALPs conversion into photons in the magnetic field of galaxy clusters.
- We test this scenario using the astrophysical environment of the M87 AGN jet to constrain the ALP-photon coupling parameter.

ALP-photon mixing model

- For propagation in the z-direction and very relativistic ALPs, the evolution equations of ALP-photon coupling model:

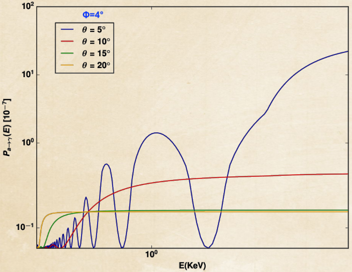
$$i\frac{d}{dz}\begin{pmatrix} A_\perp(z) \\ A\|(z) \\ a(z) \end{pmatrix} = -\begin{pmatrix} \Delta_\perp \cos^2\xi + \Delta_\| \sin^2\xi & \cos\xi\sin\xi(\Delta_\| + \Delta_\perp) & \Delta_{a\gamma}\sin\xi \\ \cos\xi\sin\xi(\Delta_\| + \Delta_\perp) & \Delta_\perp \sin^2\xi + \Delta_\| \cos^2\xi & \Delta_{a\gamma}\cos\xi \\ \Delta_{a\gamma}\sin\xi & \Delta_{a\gamma}\cos\xi & \Delta_a \end{pmatrix} \begin{pmatrix} A_\perp(z) \\ A\|(z) \\ a(z) \end{pmatrix}$$

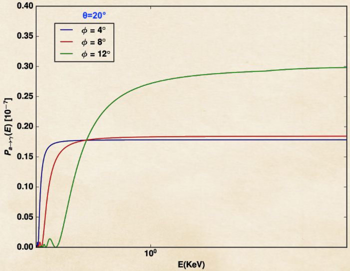
- The strongest mixing occurs at energy range depends on: m_a & $g_{a\gamma}$ and the transverse magnetic field and the electron density profile:

$$\mathbf{B}_T(r,R) = J_s(r)\cdot B_*\left(\frac{R}{R_*}\right)^{-1}\,\mathrm{G} \quad \& \quad n_e(r,R) = J_s(r)\cdot n_{e,*}\left(\frac{R}{R_*}\right)^{-1}\,\mathrm{cm}^{-3}$$

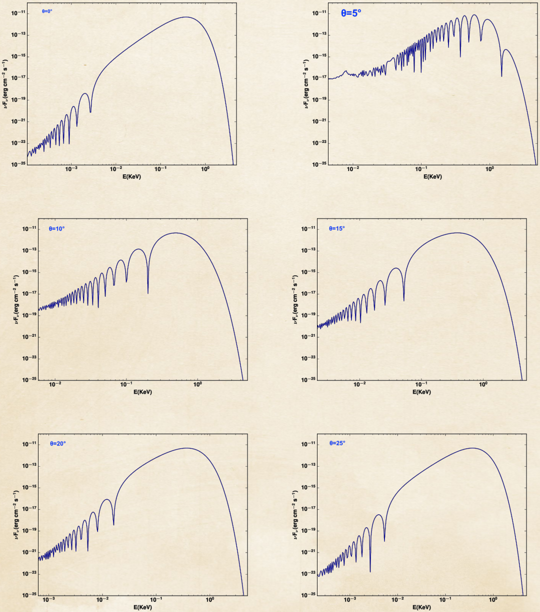
ALP-photon conversion probability

- The probability for ALPs to convert into photons after traveling a certain distance is $P_{a\to\gamma} = |A_{\parallel}(E)|^2 + |A_{\perp}(E)|^2$.
- We checked the role of the misalignment angle θ and the jet opening angle of ϕ.
- The maximum conversion probability occurs when the misalignment angle θ is close to the opening angle of the AGN jet ϕ.





M87 AGN energy spectra

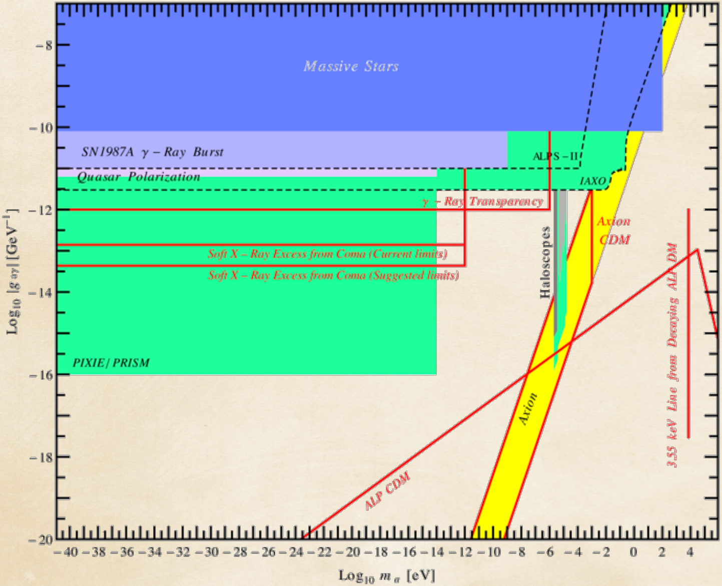


Summery of result I

θ (°), $\phi = 4°$	$g_{a\gamma}$ (GeV^{-1})	ϕ (°), $\theta = 20°$	$g_{a\gamma}$ (GeV^{-1})
0	$\lesssim 3.91 \times 10^{-13}$	4	$\lesssim 6.56 \times 10^{-14}$
5	$\lesssim 9.17 \times 10^{-15}$	8	$\lesssim 2.32 \times 10^{-14}$
10	$\lesssim 7.50 \times 10^{-15}$	12	$\lesssim 7.99 \times 10^{-15}$
15	$\lesssim 2.08 \times 10^{-14}$		
20	$\lesssim 6.56 \times 10^{-14}$		
25	$\lesssim 1.98 \times 10^{-13}$		

- The overall X-ray emission for the M87 AGN [Flux (0.3-8) keV $\sim 3.76 \times 10^{-12}$ **erg** cm^{-2} s^{-1}].
- These results cast doubt on the current best fit value on $g_{a\gamma} \sim 2 \times 10^{-13}$ GeV^{-1} obtained in the Coma cluster soft X-ray excess CAB model.
- Instead we suggest a new constraint that the largest allowed value of $g_{a\gamma} \lesssim 6.65 \times 10^{-14}$ GeV^{-1}.

Parametric space of ALP mass-coupling



Potential of SKA to detect CDM ALPs decays

- ALPs may spontaneously decay with lifetime:

$$\tau_a \equiv \Gamma_{\rm pert}^{-1} = \frac{64\pi}{m_a^3 g_{a\gamma}^2} \gg t_0$$

- ALPs $\Rightarrow$ Bose-Einstein condensate (BEC) $\Rightarrow$ thermalize to spatially localized clumps.
- Stimulated decay of ALPs is also possible with effective decay rate:

$$\Gamma_{\rm eff} = \Gamma_{\rm pert}(1 + 2f_\gamma)$$

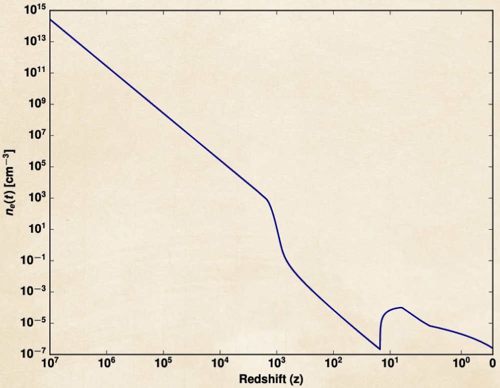
- Photon occupation number can receive Bose enhancement and grows exponentially.
- Equation of Motion for photons is a Mathieu equation (resonance possible):

$$\ddot{s}_{\boldsymbol{k},\pm} + \left[k^2 + \omega_p^2 \mp g_{a\gamma} k \omega_0 a_0 \sin(\omega_0 t)\right] s_{\boldsymbol{k},\pm} = 0$$

Plasma density evolution

- Photons propagating in a plasma acquires an effective mass equal to the plasma frequency:

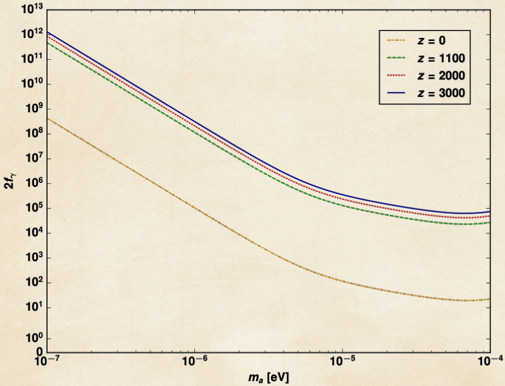
$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$



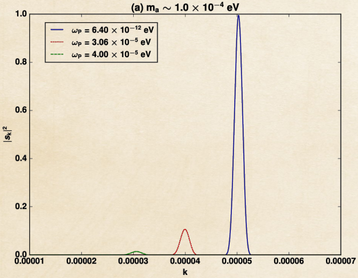
The stimulated emission factor

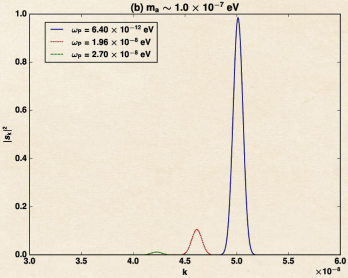
- The stimulated decay produces an enhancement of the ALPs decay rate by factors arising from

$$f_\gamma \simeq f_{\gamma,\text{CMB}} + f_{\gamma,\text{gal}} + f_{\gamma,\text{extra-gal}}$$



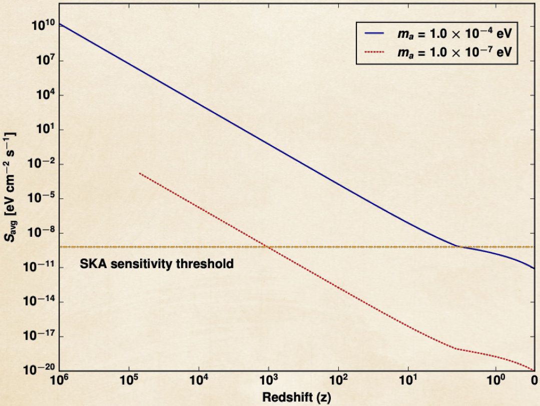
The effect of cosmic plasma





Estimating the average radio flux

$$S_{\text{avg}} = \frac{m_a \Gamma_{\text{eff}}}{4\pi d_L^2}\, \bar{n}_{\text{ac}}\; dV_c$$



Summery of result II

- We find that neither the current cosmic plasma nor the plasma in the galactic halos can prevent the stimulated decay of ALP with the 10^{-7}–10^{-4} eV mass range.

- Interestingly, the radio signal produced via the stimulated decay of ALPs in the 10^{-7}–10^{-4} eV mass range is expected to be within the reach of the next-generation of the SKA radio telescopes.

Conclusion

- Axions appears in the solution to the strong CP problem.
- ALPs are suggested by many string theory models.
- ALPs seem to be suitable candidates for dark matter.
- The coupling between ALPs and photons may allow for ALPs conversion or decay to photons.
- Result I: Suggest new constraints on the ALP-photon coupling lower than the current limits used to explain the Coma cluster soft X-ray excess.
- Result II: Shows that the next-generation of the SKA telescopes might be able to detect a radio signal produced via the stimulated decay of ALPs.

Current and future work

- Estimating the radio flux from ALP stimulated decay for a number of astrophysical objects.
- Examine the capability of the CAB to explain the EDGES 21 cm anomaly.
- Investigate whether ultra-light ALPs can solve the core-cusp problem.

Thanks a lot! ☺