Gegenschein signal from an inhomogeneous axion DM distribution

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QCD axion

QCD Lagrangian contains CP-violating terms:

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

$$= -\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a \theta$$

measurements of neutron electric dipole moment put a constraint

$$|\theta| < 1.3 \times 10^{-10}$$

One of the possible ways to explain this small θ is Peccei-Quinn symmetry (additional U(1) chiral symmetry which drives $\theta \to 0$)

PQ axion is already excluded by experimental constraints, but there are many other unexcluded models

e.g.) DFSZ axion, KSVZ axion

Axion-like Particles (ALPs)

Some other theories predict particles having similar interaction terms called as axion-like particle.

(e.g. compactifications of dimensions in string theory produce modulies, which decay into ALPs)

$$\mathscr{L}_{\mathrm{ALP-\ int.}} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a - a \sum_{\psi} g_{a\psi} \left(i \bar{\psi} \gamma^5 \psi \right) - a F_{\mu\nu} \sum_{\psi} \frac{g_{a\psi\gamma}}{2} \left(i \bar{\psi} \sigma^{\mu\nu} \gamma^5 \psi \right) + \ldots$$

interaction with EM fields

interaction with fermions

ALP-photon interaction

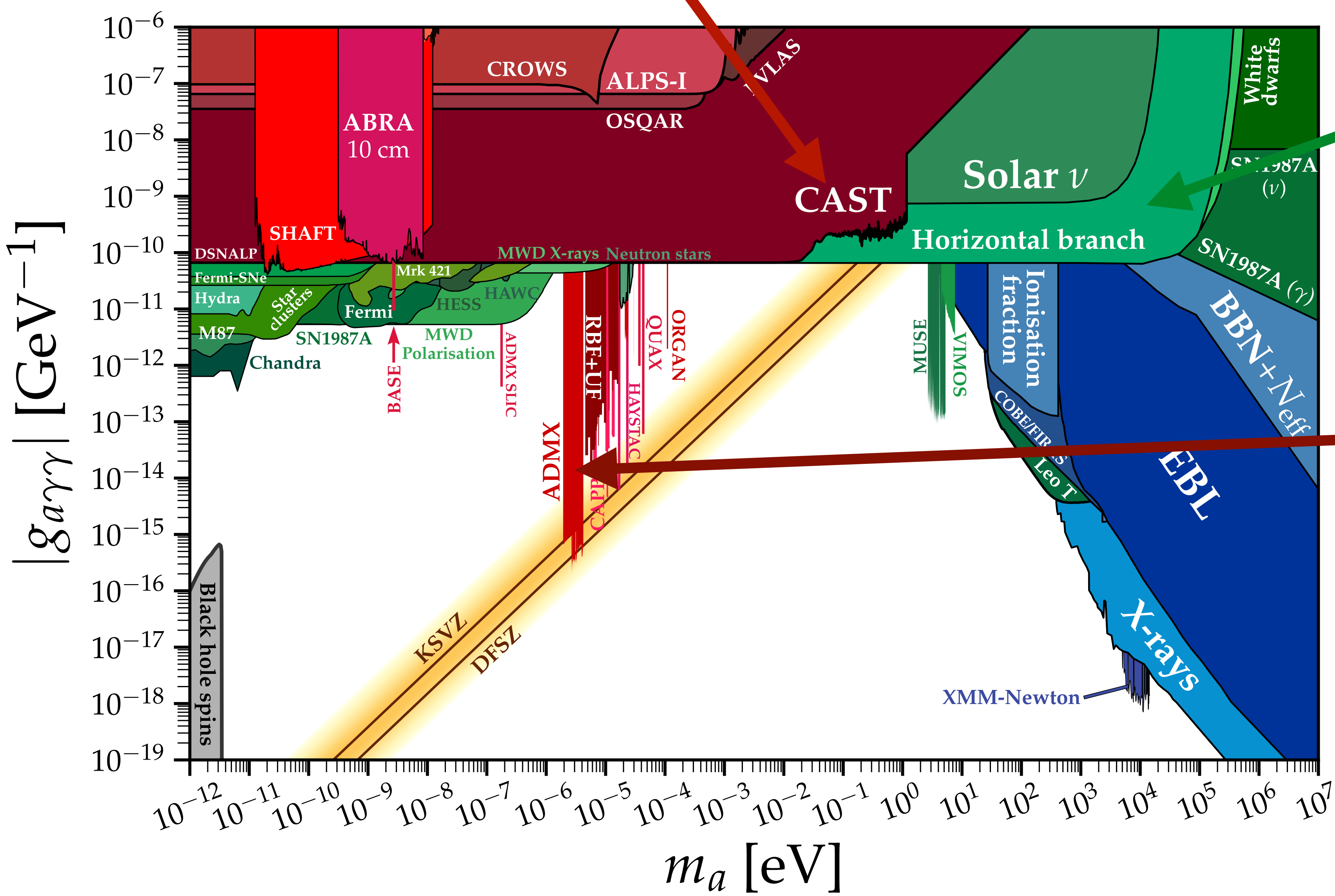
Current constraint on an ALP-photon coupling $g_{a\gamma}$

$$\mathscr{L}_{a\gamma-\text{ int.}} = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu} a = g_{a\gamma} a \mathbf{E}\cdot\mathbf{B}$$

direct detection of axion from the sun

ratio of stars in Horizontal Branch to Red Giant Branch

detect axion in the Galaxy with resonators



Stimulated decay of axion

Consider a process $a\left(\mathbf{p_a}\right) \to \gamma\left(\mathbf{p}_1\right) + \gamma\left(\mathbf{p}_2\right)$ and its inverse

Boltzmann equation:

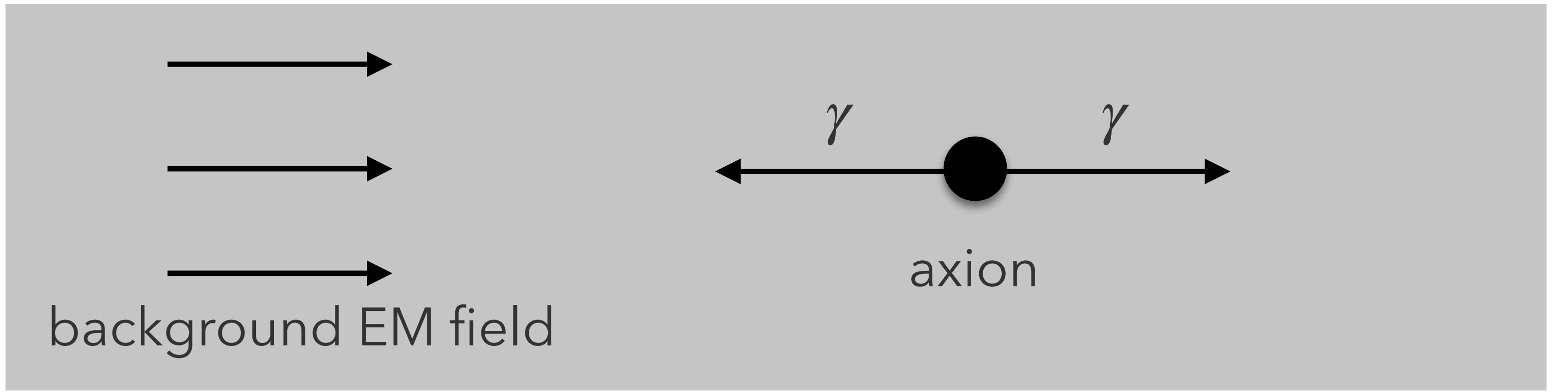
$$\frac{\mathrm{d}}{\mathrm{d}t} f_1 = \frac{1}{2E_1} \int \frac{\mathrm{d}^3 p_a}{(2\pi)^3 2E_a} \int \frac{\mathrm{d}^3 p_2}{(2\pi)^3 2E_2} \left|\mathscr{M}\right|^2 \left(f_a\left(1 + f_1 + f_2\right) - f_1 f_2\right)(2\pi)^4 \delta^4\left(p_a - p_1 - p_2\right)$$

stimulated decay of axion (Bose enhancement)

axion production from two photons (don't consider for now because its cross section is small in the Galaxy)

In the rest frame of axion, emitted photons

- have energy equal to a half of a mass of axion m_a
- are emitted back-to-back along the background EM wave



Stimulated decay of axion in the Galaxy

Cygnus A

- spectrum

$$\log S_{A\nu_d}(\nu_d) = a + b\log\nu_d + c\log^2\nu_d$$

$$(a = 4.695,\ b = 0.085,\ c = -0.178)$$

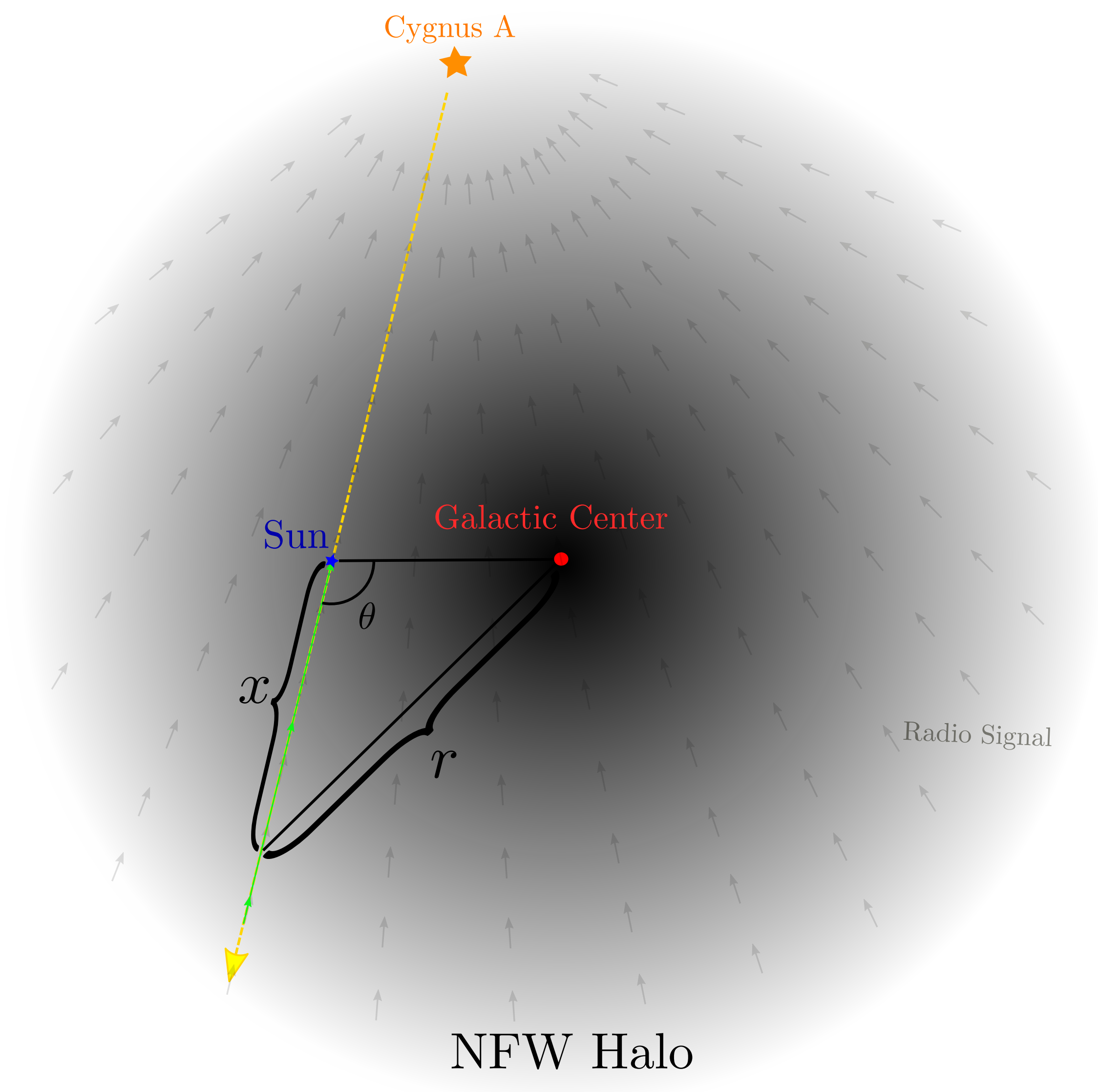
- $\simeq 232$ Mpc ($\gg R_{vir}$) away from the Earth

  $\rightarrow$ its photon flux can be approximated as constant inside the Galaxy

ALP in the Galaxy

- assumed to follow NFW profile

$$\rho_a(r) = \frac{\delta_c \rho_c}{(r/r_s)\left(1 + r/r_s\right)^2}$$



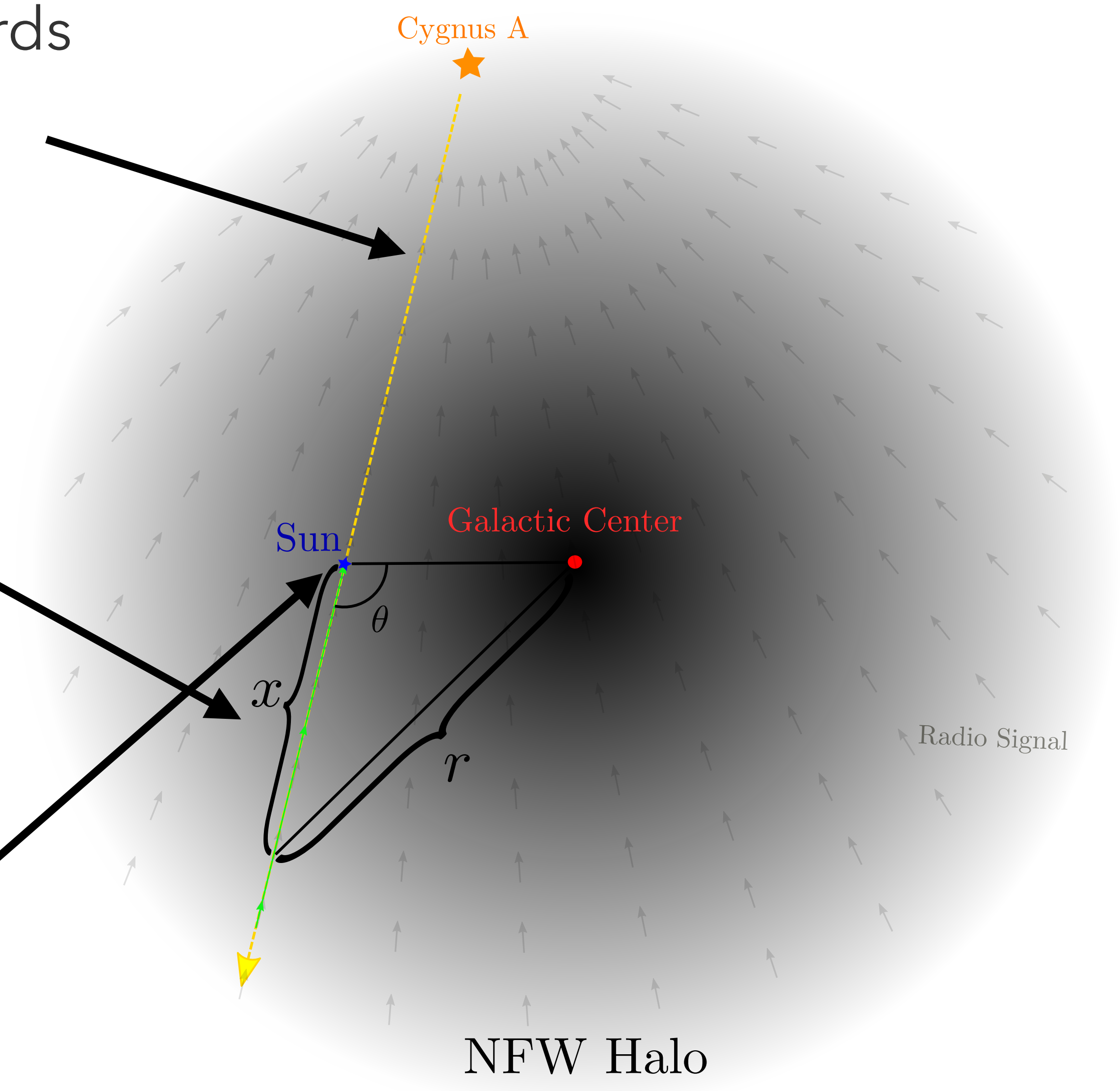
Oindrila Ghosh, Jordi Salvado, and Jordi Miralda-Escude (2020)

Gegenschein phenomenology

A photon from Cygnus A traveling towards the Earth (a yellow line)

Axion is stimulated to decay. Two back-to-back photons are emitted (a green line)

One of emitted photons gets to the Earth. (We observe a counterimage of a source)



Oindrila Ghosh, Jordi Salvado, and Jordi Miralda-Escude (2020)

Observed gegenschein intensity

The flux of gegenschein signal:

$$S_{Ag} = \frac{\hbar c^4}{16} g_{a\gamma\gamma}^2 S_{A\nu}\left(\nu_d\right) \int_0^{R_{vir}} dx\ \rho_a[r(x)]$$

$S_{A\nu}$: the flux of SNR seen by the earth

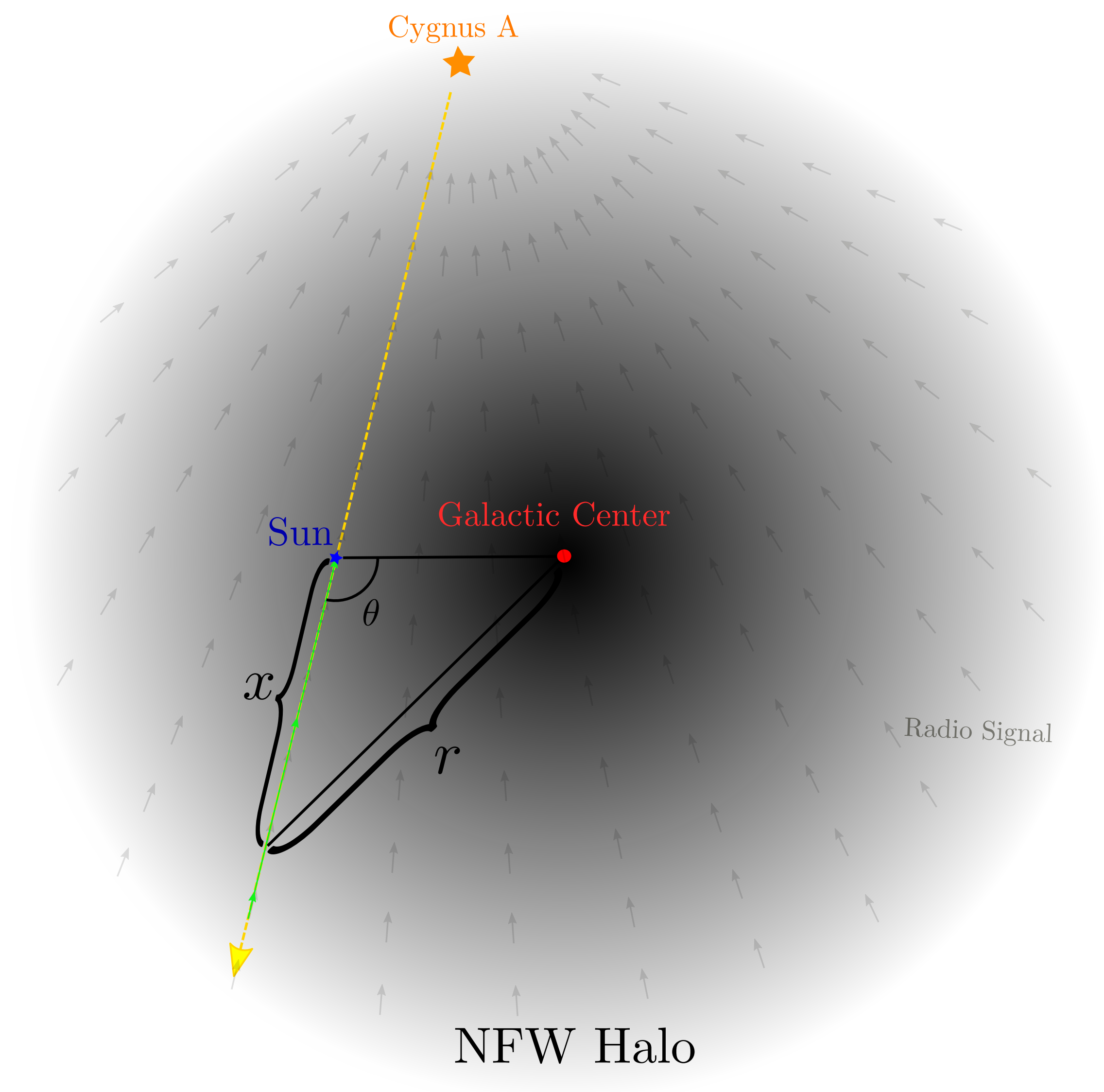
ρ_a: mass density of ALP

R_{vir}: virial radius of the Galaxy

$\rho_a(r)$ could be changed due to

- Formation of axion stars
- Mass segregation

Estimate effects of these phenomena on the gegenschein flux



Oindrila Ghosh, Jordi Salvado, and Jordi Miralda-Escude (2020)

Axion stars

Physics of a scalar field coupled to gravity is described by the action

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{16\pi G} R \right]$$

Trick to solve a resulting EoM:

Assuming axion is non-relativistic

$$\phi(\boldsymbol{r}, t) \approx \frac{1}{\sqrt{2m_a}} \left(\psi(\boldsymbol{r}, t) e^{-im_a t} + \psi^*(\boldsymbol{r}, t) e^{+im_a t} \right)$$

and taking an average over scales larger than m_a

Gross-Pitaevskii-Poisson equations are obtained

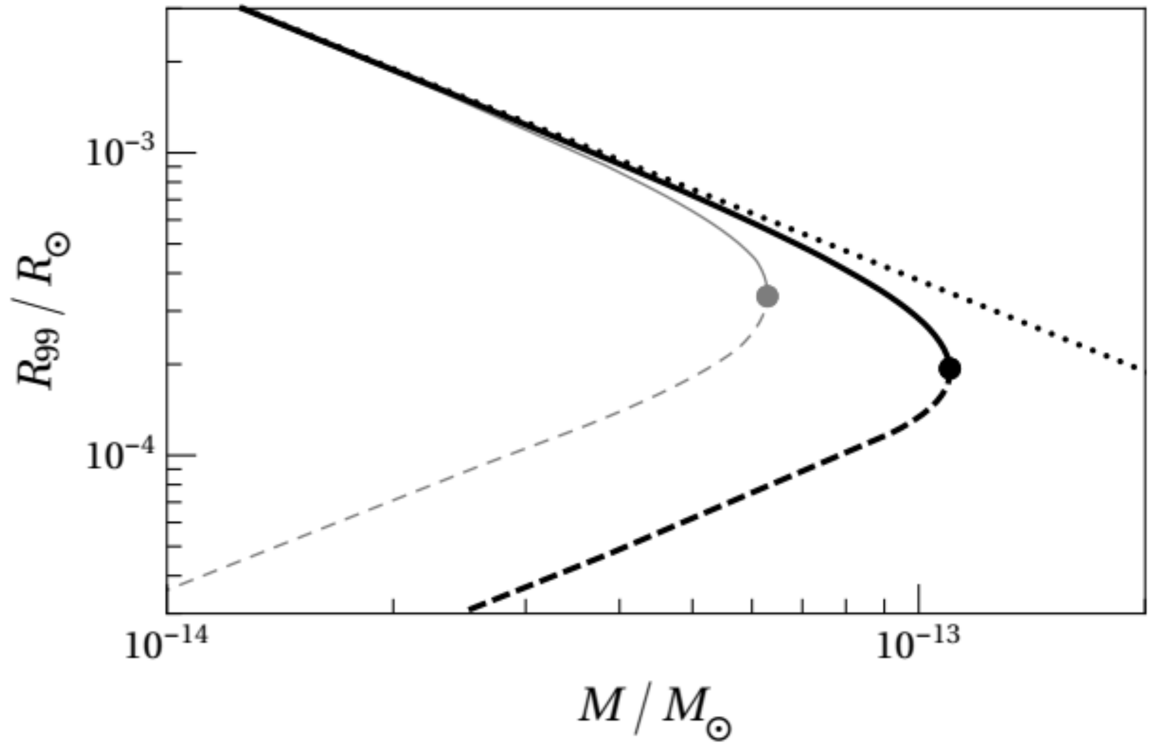
$$i\dot{\psi} = -\frac{1}{2m_a} \nabla^2 \psi + \left[V'_{\text{eff}} \left(\psi^* \psi \right) + m_a \Phi \right] \psi$$

$$\nabla^2 \Phi = 4\pi G m_a \psi^* \psi$$

Dilute axion stars

A dilute axion star

- one of the solution to GPP equations
- its quantum pressure is balancing its gravity
- its mass is $\lesssim 10^{-12} M_\odot$



($R_{99} - M$ relation for $m_a = 10^{-4}$ eV)

In our study, we used the relation

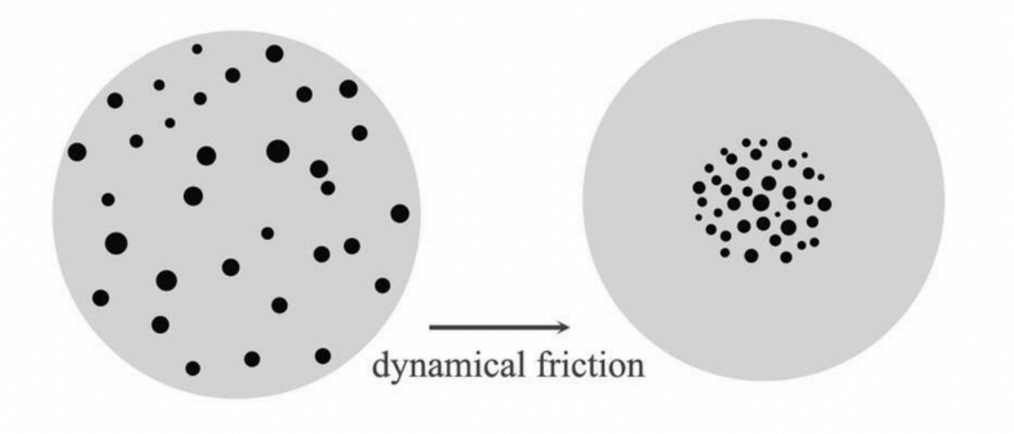
$$R_a^{\text{dilute}} \sim (270 \text{ km}) \left(\frac{10\mu\text{eV}}{m_a} \right)^2 \left(\frac{10^{-12} M_\odot}{M_a} \right)$$

and assumed $M_\odot = 10^{-12} M_\odot$

P.-H. Chavanis and L. Delfini (2011)

Dynamical friction

More massive component tends to be distributed closer to the center as a consequence of gravitational interactions

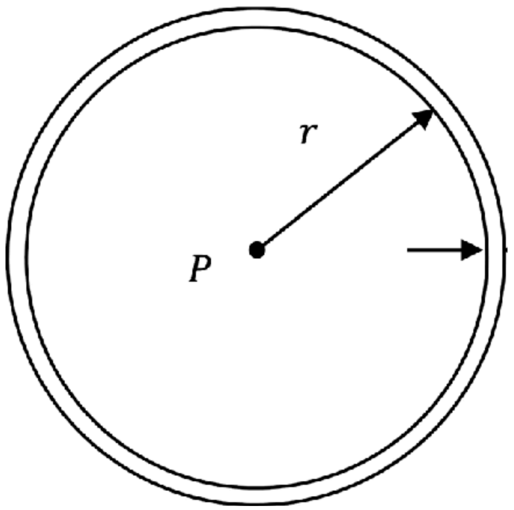


Assuming axion stars and stars follow Maxwell distribution, the energy transfer rate is given by:

$$\frac{dE_{AS}}{dt} = \frac{\sqrt{96\pi}G^2 m_{AS}\rho_s \ln\Lambda}{\left[\langle v_s^2\rangle + \langle v_{AS}^2\rangle\right]^{3/2}}\left[m_s\langle v_s^2\rangle - m_{AS}\langle v_{AS}^2\rangle\right]$$

For simplicity, we assume the effect of mass segregation is spherically symmetric and the virial theorem holds. The evolution of a radial shell is given by:

$$\frac{dr}{dt} = \frac{4\sqrt{2}\pi G^2\rho_s m_s}{\sigma}\ln\Lambda\left(\frac{\mathrm{d}\Psi(r)}{\mathrm{d}r}\right)^{-1}$$



Detectors

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

SKA telescope

- Covered range of frequency and a collecting area
  - SKA-low – $\nu = 50 - 350\ \mathrm{MHz},\ A = 410000\ \mathrm{m}^2$
  - SKA-mid – $\nu = 350 - 14000\ \mathrm{MHz},\ A = 33000\ \mathrm{m}^2$
- Efficiency of detector: $\eta \simeq 0.8$
- Bandwidth $\Delta\nu$: $\Delta\nu = 2.17\nu_d\sigma_d$
  - taken so that the maximum SNR is achieved (axion DM is assumed to follow Maxwell distribution)
  - a power within this bandwidth is reduced by a factor of $f_\Delta = 0.721$

The total power:

$$P_{\mathrm{signal}} = \eta A f_\Delta S_{Ag} = \eta A f_\Delta \frac{\hbar c^4}{16} g_{a\gamma\gamma}^2 S_{A\nu}\left(\nu_d\right) \int_0^{R_{vir}} dx \rho_a[r(x)]$$

Noise

The power of noise:

$$P_{\text{noise}} = 2k_B T \sqrt{\frac{\Delta\nu}{t_{\text{obs}}}}$$

Four contributions to the noise temperature T

- atmospheric radio wave $T \sim 3\ \mathrm{K}$
- CMB $T \sim 2.725\ \mathrm{K}$
- noise of receiver $T \sim 20\ \mathrm{K}$
- Synchrotron radiation from the Galactic or extragalactic system

$$T_{\text{bg}} = 60 \left(\frac{300\text{MHz}}{\nu}\right)^{2.55}\ \mathrm{K}$$

Constraint on $g_{a\gamma}$

$$P_{\text{signal}} = \eta A f_\Delta S_{Ag} = \eta A f_\Delta \frac{\hbar c^4}{16} g_{a\gamma\gamma}^2 S_{A\nu}\left(\nu_d\right) \int_0^{R_{vir}} dx \rho_a[r(x)]$$

$$P_{\text{noise}} = 2 k_B T \sqrt{\frac{\Delta\nu}{t_{\text{obs}}}}$$

$g_{a\gamma}$ which realize $P_{\text{signal}} / P_{\text{noise}} = n$ can be expressed as

$$g_{a\gamma}^{-2} = \frac{\hbar c^4 A \eta}{32 k_B T} \sqrt{\frac{t_{\text{obs}}}{\Delta\nu}} \frac{S_{A\nu}\left(\nu_d\right) f_\Delta}{n} \int_0^\infty dx \rho_a[r(x)]$$

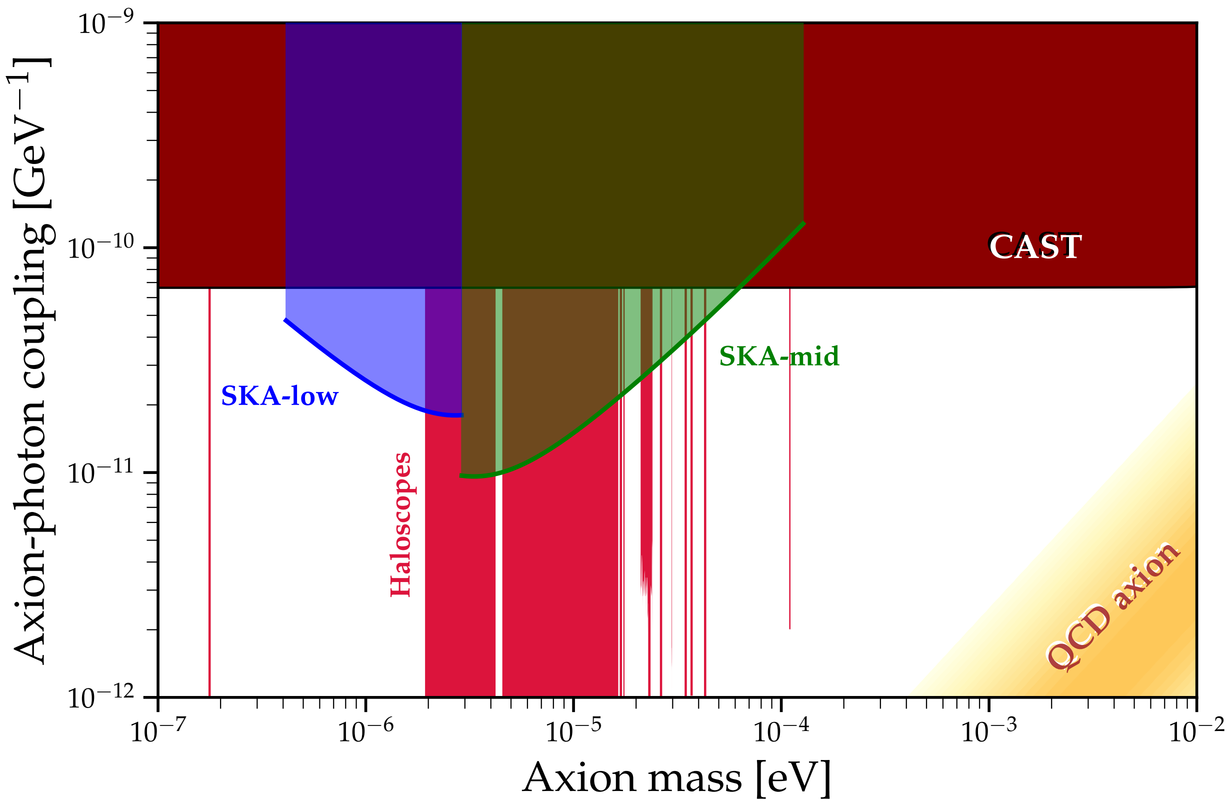
Since the gegenschein signal has not yet been observed, coupling constants larger than this $g_{a\gamma}$ are excluded.

Results

- Assuming 100 hours of observation by the SKA telescope, non-observation of the gegenschein flux gives a constraint on $g_{a\gamma}$

- As long as axion stars follow the NFW profile, the gegenschein flux doesn't change

- Dynamical friction also doesn't change the gegenschein flux



Oindrila Ghosh, Jordi Salvado, and Jordi Miralda-Escude (2020)

Summary

- Gegenschein signal is expected as a consequence of Bose enhancement
- Non-observation of gegenschein signal places an upper bound on $g_{a\gamma\gamma}$
- As long as axion stars follows the same distribution to axions, the gegenschein flux doesn't change
- Dynamical friction also makes only a tiny change in the gegenschein flux

Backup

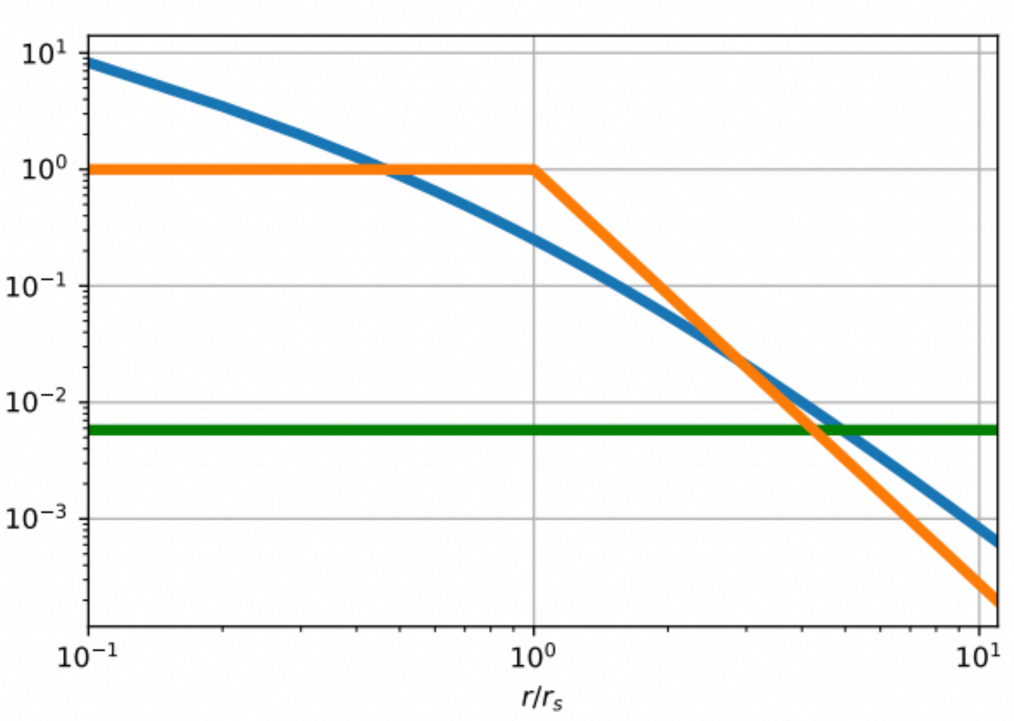
Results

Assume: 10% of mass within the virial radius forms dilute axion stars

Evaluate the gegenschein flux for three axion star distributions

- NFW profile (blue)
- constant (green)
- test function (orange)

$$n(r) \propto \begin{cases} 1 & (r \leq r_s) \\ \left(\frac{r_s}{r}\right)^{\alpha} & (r > r_s) \end{cases}$$



Distribution of AS	flux (NFW is set to 1)
NFW	1
test function	1.428
constant	0.923

Distribution of ALP

Distribution of axions follows the NFW profile:

$$\rho_a(r) = \frac{\delta_c \rho_c}{(r/r_s)\left(1 + r/r_s\right)^2} \qquad \delta_c = \frac{\Delta_{\rm vir}}{3} \frac{r_c^3}{\ln\left(1 + r_c\right) - r_c/\left(1 + r_c\right)}$$

δ_c : overdensity parameter

$r_s \simeq 20$ kpc : the scale radius

ρ_c : the critical density of the universe

$\Delta_{vir} = 200$

$R_{vir} \simeq 221$ kpc : the virial radius

$r_c \equiv R_{vir}/r_s$: concentration