CTA Workshop, in 30th September, ICRR

Axion and CTA

Kazunori Kohri （郡　和範）

Cosmophysics Group, IPNS, KEK and Sokendai

Abstract

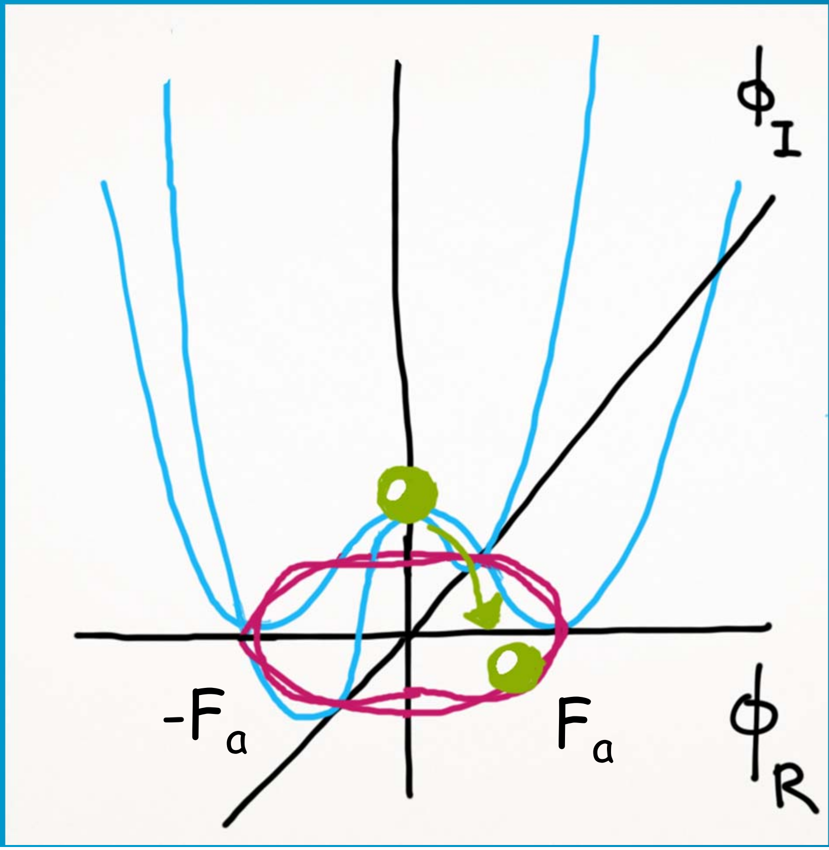
- Variety of axion like particles (ALPs) are predicted in string theory.

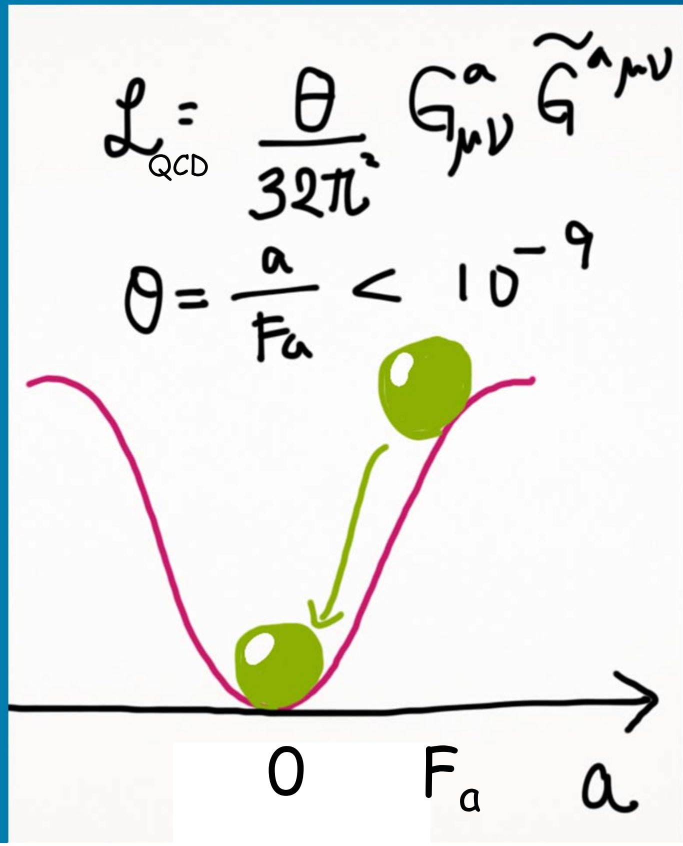
- If the ALP couples to photon like the QCD axion, photon can travel beyond the horizon of e+e- pair production through the conversion from photon to ALP.

- We may detect this feature in future gamma-ray experiments

What is (QCD) axion?

- Breaking of U(1) Peccei-Quinnsymmetry
- Nambu-Goldstone boson (angular component) is called “axion”





How large is F_a ?

$$\mathcal{L}_{int} \sim \frac{a}{F_a} F_{\mu\nu} \tilde{F}_{\mu\nu}$$

See also, $m_a \sim \frac{m_\pi F_\pi}{F_a}$ in QCD axions (not string axions)

- Dark matter axion ($\Omega_a h^2 \leqq 0.1$)

$$F_a \leq 10^{12}\,\mathrm{GeV} \iff 10^{-6}\,\mathrm{eV} \leq m_a$$

- In order not to cool red giant and/or SN1987A,

$$10^{10}\,\mathrm{GeV} \leq F_a \iff m_a \leq 10^{-4}\,\mathrm{eV}$$

Photon-ALPs mixing

- Lagrangian

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= g_{a\gamma}a\,\vec{E}\bullet\vec{B}$$

- Mass matrix

$$M^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -g_{a\gamma}B\omega \\ 0 & -g_{a\gamma}B\omega & m_a^2 \end{pmatrix} \begin{matrix} A_{\perp} \\ A_{\parallel} \\ a \end{matrix}$$

$$\begin{matrix} A_{\perp} & A_{\parallel} & a \end{matrix}$$

Dispersion relation

- Klein-Gordon Equation (propagation along with z-axis)

$$\left[-\partial_t^2 + \partial_i \partial^i - M^2\right] A_j$$
$$= \left[\omega^2 + \partial_z^2 - M^2\right] A_j = 0$$

- Linearized equation (useful to discuss disp.-rel.)

$$\left(\omega + \mathrm{i}\partial_z\right)\left(\omega - \mathrm{i}\partial_z\right) = \left(\omega + \mathrm{k}\right)\left(\omega - \mathrm{i}\partial_z\right) \sim 2\omega\left(\omega - \mathrm{i}\partial_z\right)$$

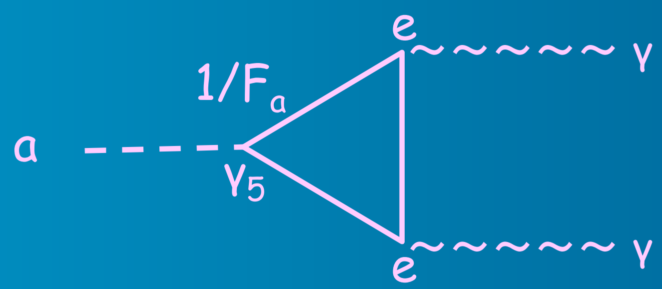
$$\left[\omega - i\partial_z - M^2/(2\omega)\right] A_j = 0$$

Axion coupling and mass

- Eigen values

$$m_{1,2} = \frac{1}{4\omega}\left(m_a^2 \pm \sqrt{m_a^4 + \left(g_{a\gamma} B\omega\right)^2} \right)$$

- Coupling



$$g_{a\lambda} = \xi \frac{\alpha}{2\pi} \frac{1}{F_a} \qquad \left(\xi \sim O(1) \text{ which depends on models}\right)$$

See also, $m_a \sim \frac{m_\pi F_\pi}{F_a}$ in QCD axions (not string axions)

Mixing angle and oscillation length

- Mixing angle

$$\sin^2 2\theta = \frac{\left(g_{a\gamma} B\omega\right)^2}{\left(g_{a\gamma} B\omega\right)^2 + m_a^4} = \frac{1}{1 + \left[m_a^2 / \left(g_{a\gamma} B\omega\right)\right]^2}$$

- Oscillation length (of plane wave $e^{i\omega r}$)

$$r_{osc}^{-1} = \omega_1 - \omega_2 = \sqrt{k^2 + m_1^2} - \sqrt{k^2 + m_2^2} \sim \frac{m_1^2 - m_2^2}{2\omega}$$

$$= \frac{g_{a\gamma} B}{2} \sqrt{1 + \left[m_a^2 / \left(g_{a\gamma} B\omega\right)\right]^2}$$

Oscillation probability

- Probability

$$P_{a\leftrightarrow\gamma} = \frac{1}{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\sin^2\left[\frac{g_{a\gamma}Br}{2}\sqrt{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\right]$$

- For efficient oscillation,

$$E_\gamma > E_* = \frac{m_a^2}{2g_{a\gamma}B} \quad \text{and} \quad r \geq r_{Ha} \equiv \frac{2}{g_{a\gamma}B}$$

Energy range for oscillation

$$E_* = \frac{m_a^{\ 2}}{2 g_{a\gamma} B} = \mathrm{TeV} \frac{m_{a,0.1n\mathrm{eV}}^{\ \ 2}}{g_{11} B_{\mathrm{nG}}}$$

$$= 10^{19}\mathrm{eV} \frac{m_{a,0.3\mu\mathrm{eV}}^{\ \ 2}}{g_{11} B_{\mathrm{nG}}}$$

$$= 1000\mathrm{TeV} \frac{m_{a,\mathrm{neV}}^{\ \ 2}}{g_{11} B_{10\mu G}}$$

$$g_{11} \equiv g_{a\gamma} / 10^{-11}\mathrm{GeV}^{-1},\ B_{10\mu G} \equiv B / 10\mu G,\ m_{a,\mu\mathrm{eV}} \equiv m_a / \mu\mathrm{eV}$$

Phase of oscillation

$$g_{11} \equiv g_{a\gamma} / 10^{-11}\mathrm{GeV}^{-1}$$
$$B_{10\mu G} \equiv B / 10\mu G$$
$$r_{10\mathrm{kpc}} \equiv r / 10\mathrm{kpc}$$

- Phase

$$\frac{g_{a\gamma} B r}{2} \sim g_{11} B_{10\mu G} r_{10\mathrm{kpc}}$$

- Oscillation length

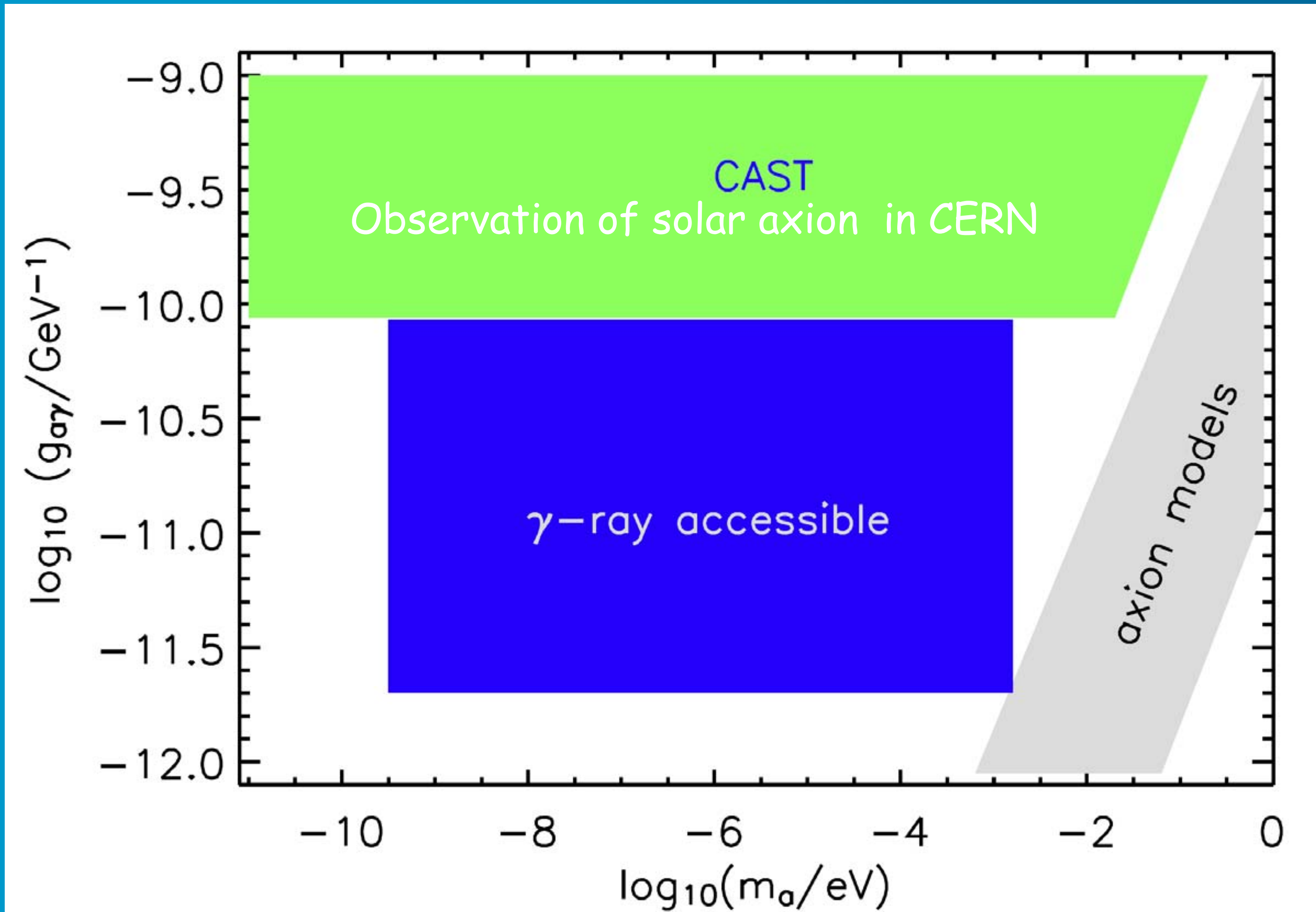
$$r_{Ha} = \frac{10\mathrm{kpc}}{g_{11} B_{10\mu G}}$$

Just within galaxy

$$= \frac{100\mathrm{Mpc}}{g_{11} B_{nG}}$$

Extra cluster of galaxy

Gamma-ray accessible parameters



Hooper-Serpico (07)

Gamma-ray horizon due to e^+e^- production

- Gamma-gamma collision and electron-positrorn production

$$\gamma_{CR} + \gamma_{BG} \rightarrow e^+ + e^-$$

- Threshold energy

$$E_\gamma \geq E_{th} \sim \frac{m_e^2}{E_{\gamma_{BG}}} \sim 10\,\mathrm{TeV}\left(\frac{E_{\gamma_{BG}}}{0.1\,\mathrm{eV}}\right)^{-1} \quad \text{IR}$$

$$\sim 10^{19}\,\mathrm{eV}\left(\frac{E_{\gamma_{BG}}}{10^{-7}\,\mathrm{eV}}\right)^{-1} \quad \text{Radio}$$

Gamma-ray horizon

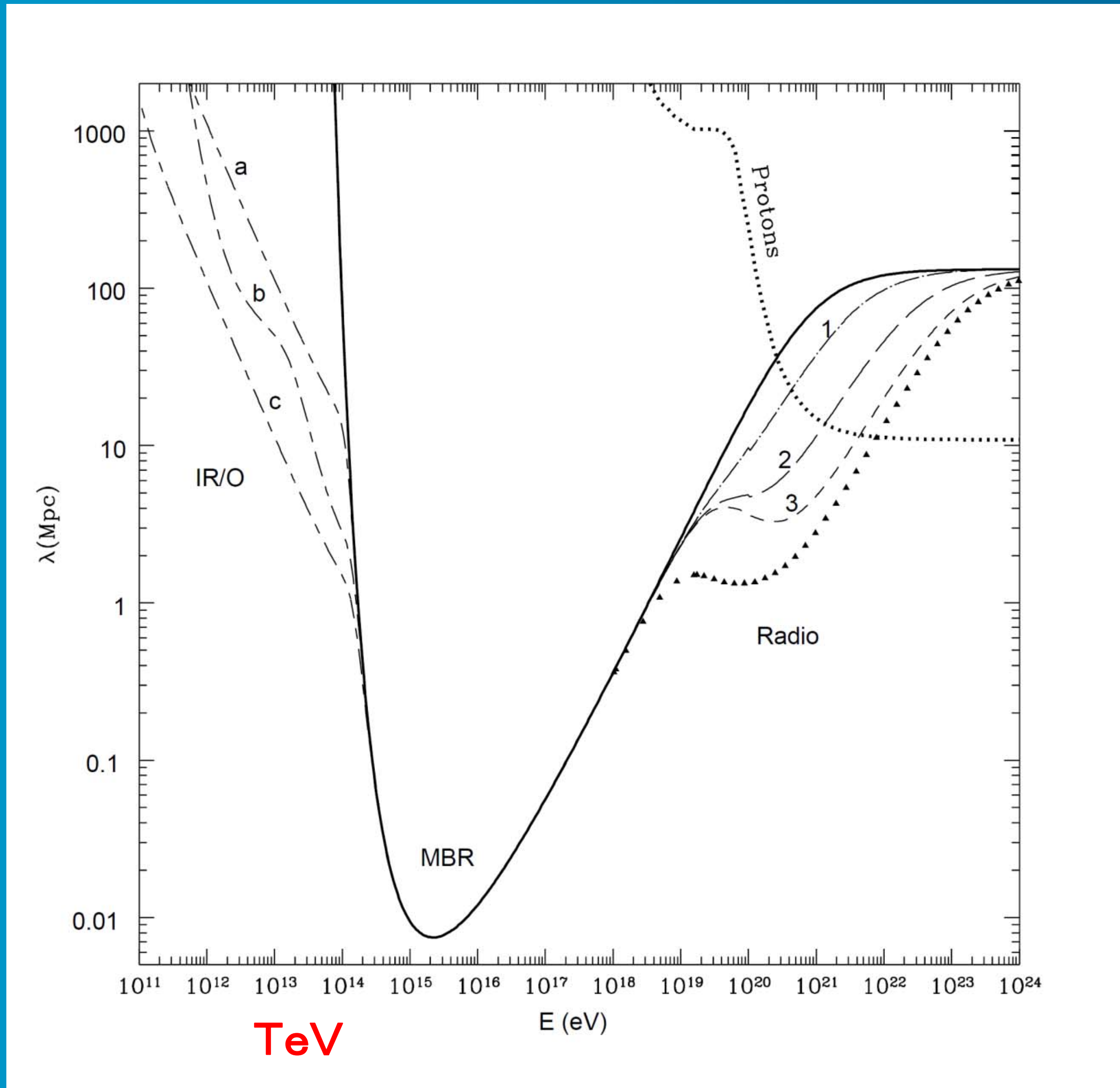
$$\gamma_{CR} + \gamma_{BG} \rightarrow e^{+} + e^{-}$$

$$r_{H_\gamma}(E_\gamma) \sim \frac{1}{\sigma_{\text{Thomson}} n_{\gamma,BG}(E_{\gamma,BG} = m_e^2 / E_\gamma)}$$

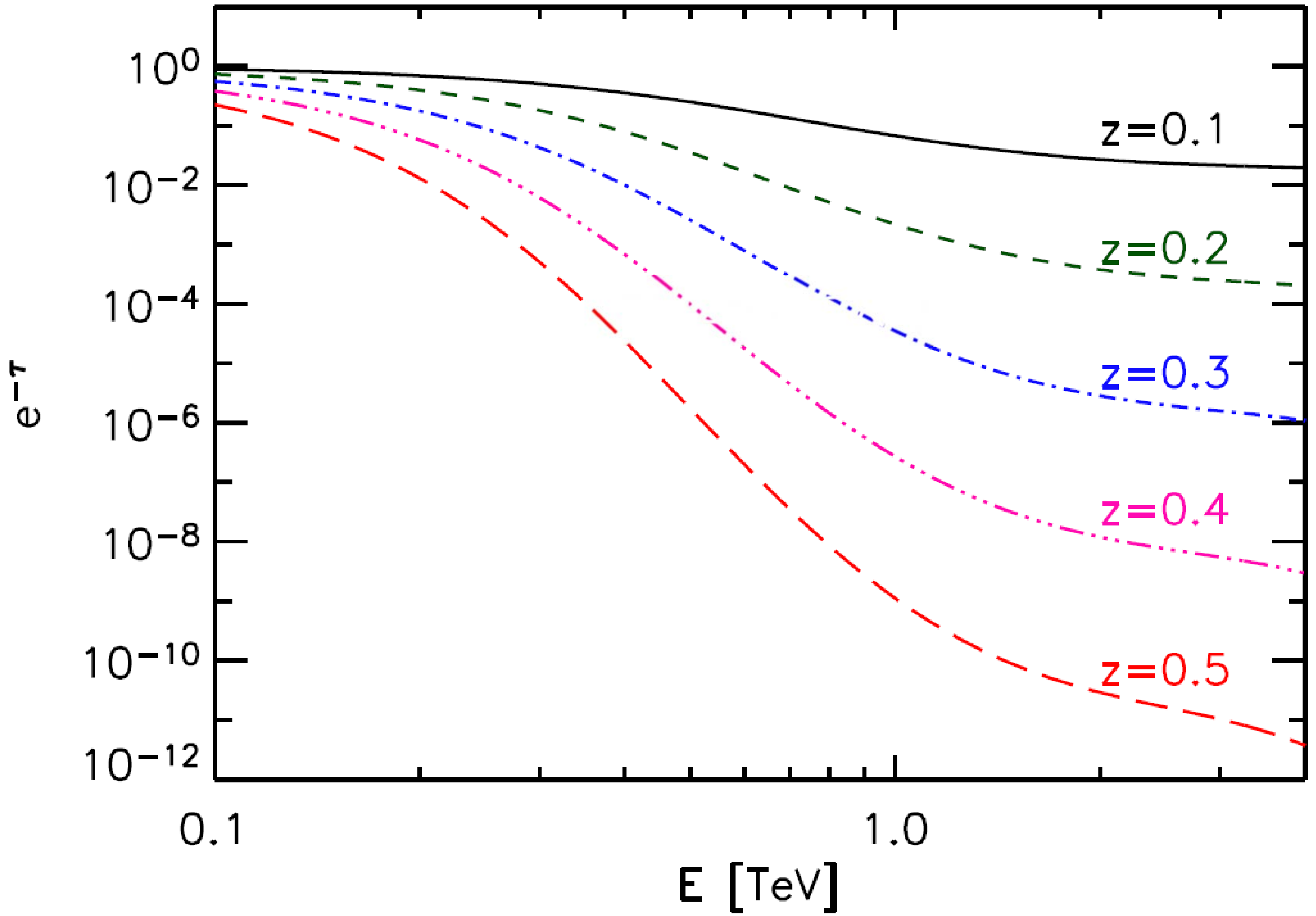
$$\sim 10^{-2}\,\text{Mpc}\left(\frac{n_{\gamma,BG}(E_{\gamma,BG} = m_e^2 / E_\gamma)}{400\,/\,\text{cm}^3}\right)^{-1}$$

TeV gamma-rays

Gamma-ray horizon

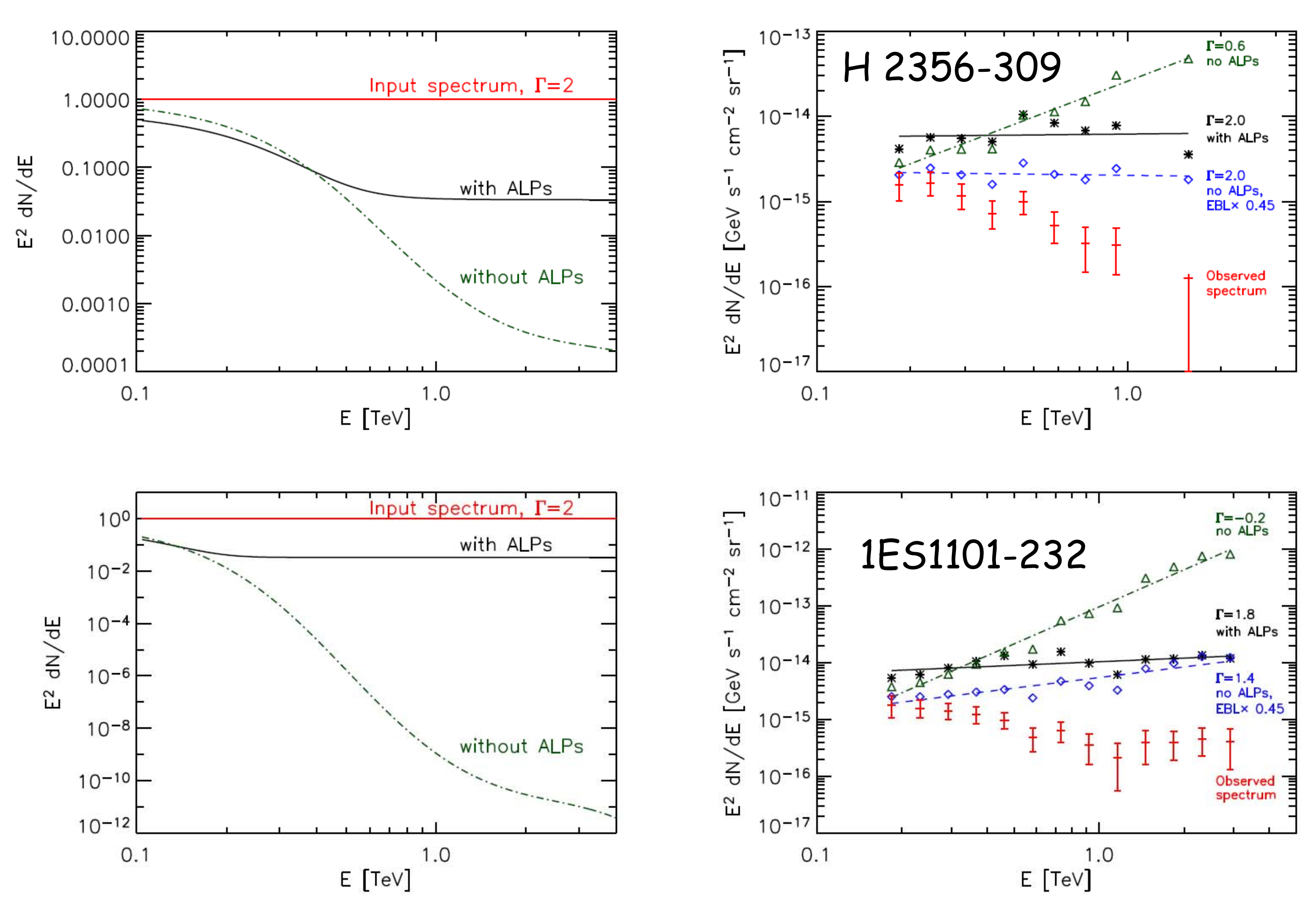


Coppi and Aharonian (97)



Shimet, Hooper, Serpico (08)

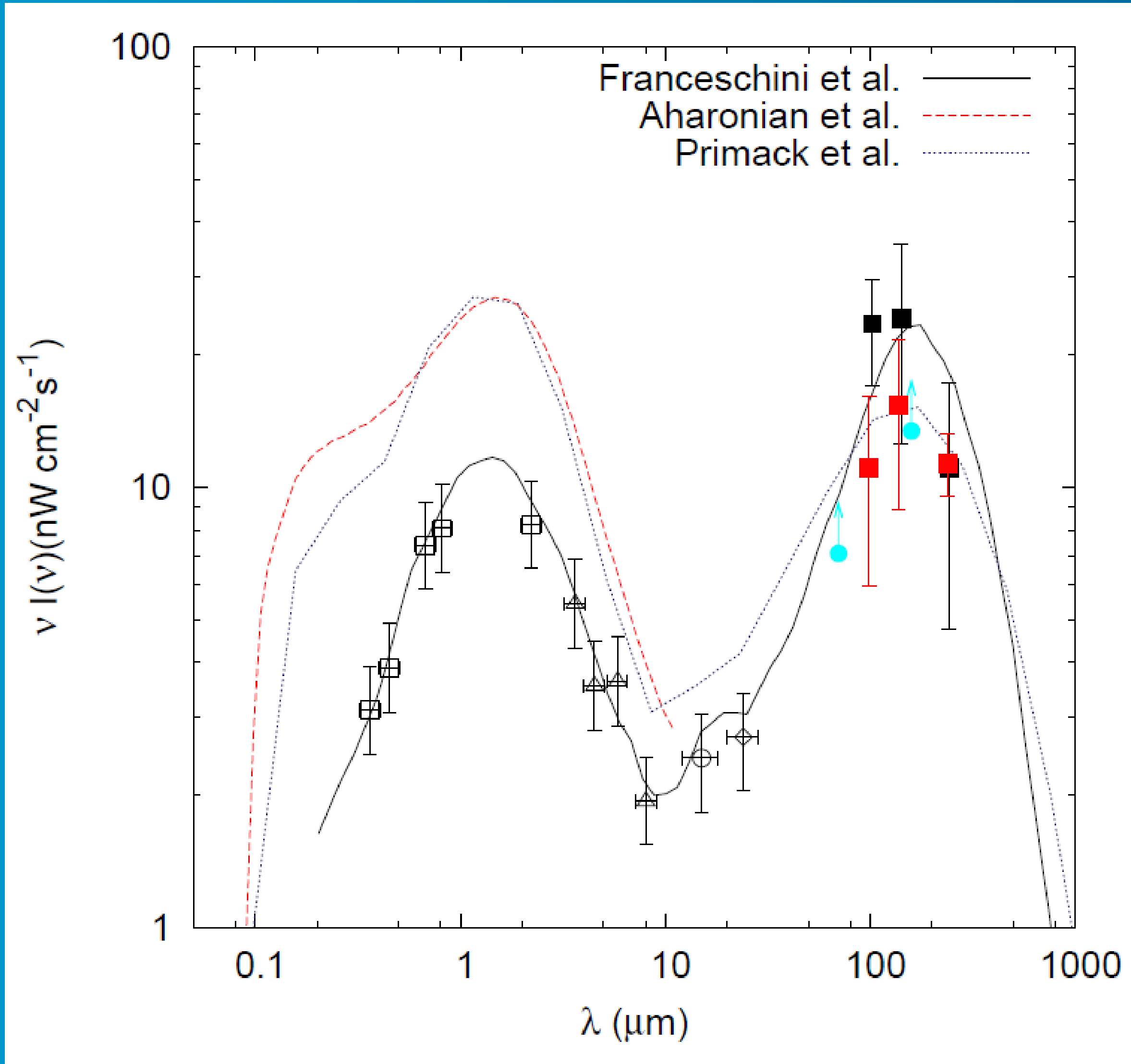
Spectrum reduction by axion mixing



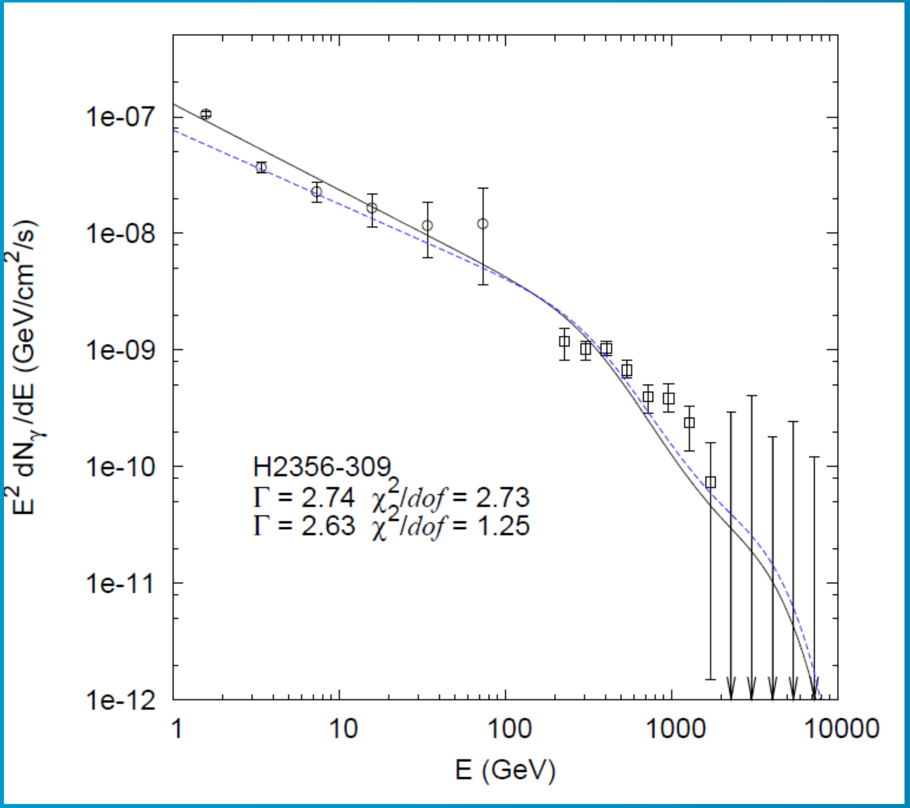
Shimet, Hooper, Serpico (08)

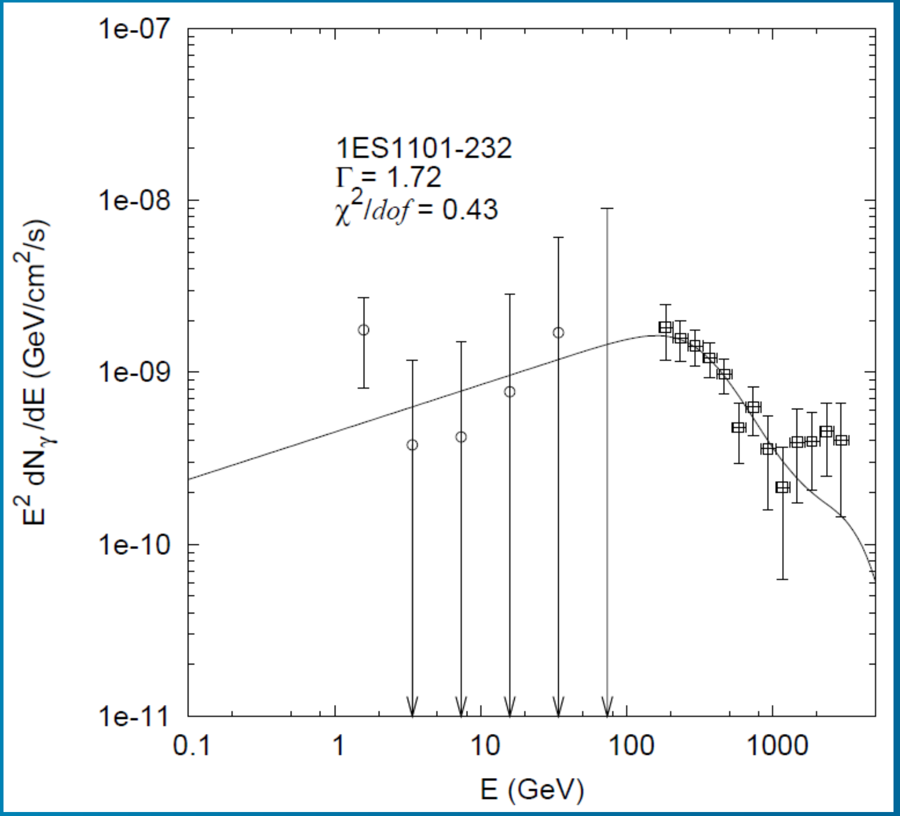
Uncertainties in the IR background

Belicov,Goodenough,Hooper('10)



Consistent with no axion?

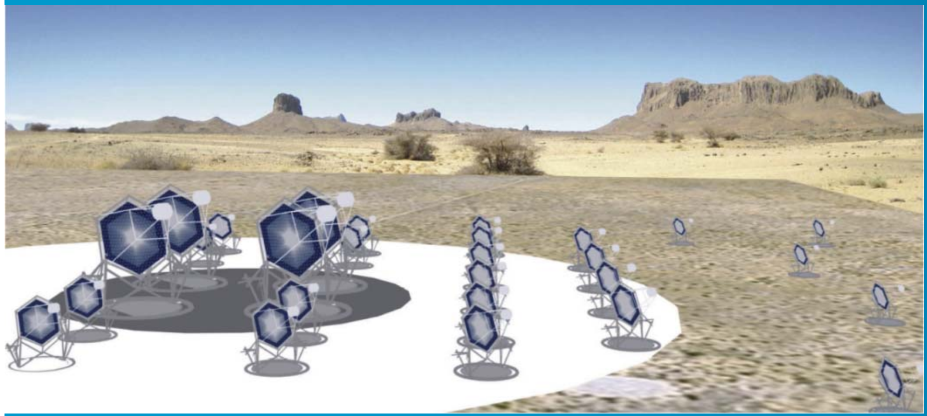


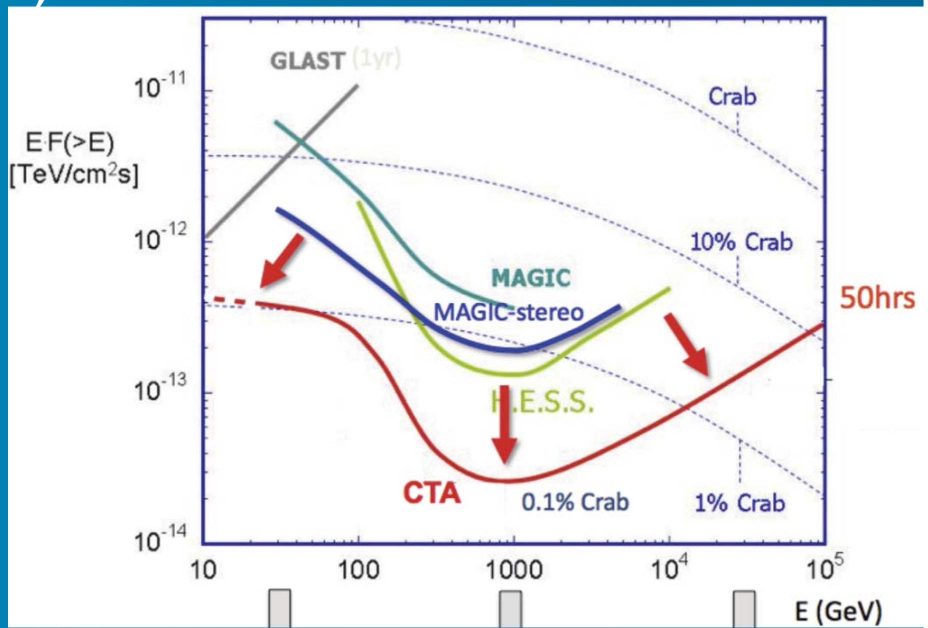


Belicov,Goodenough,Hooper('10)

Future TeV-gamma observation Cherenkov Telescope Array (CTA)

- One order of magnitude better sensitivity at TeV
- Precise observation of the Extragalactic-Background Light (EBL)





Summary

- Photon can travel beyond its horizon of electron-positron production through the mixing between photon and axion

- Future observation such as CTA (TeV) will reveal the nature of (string) axions by observing deficit or excess from the standard prediction