Axion Searches in Astrophysics

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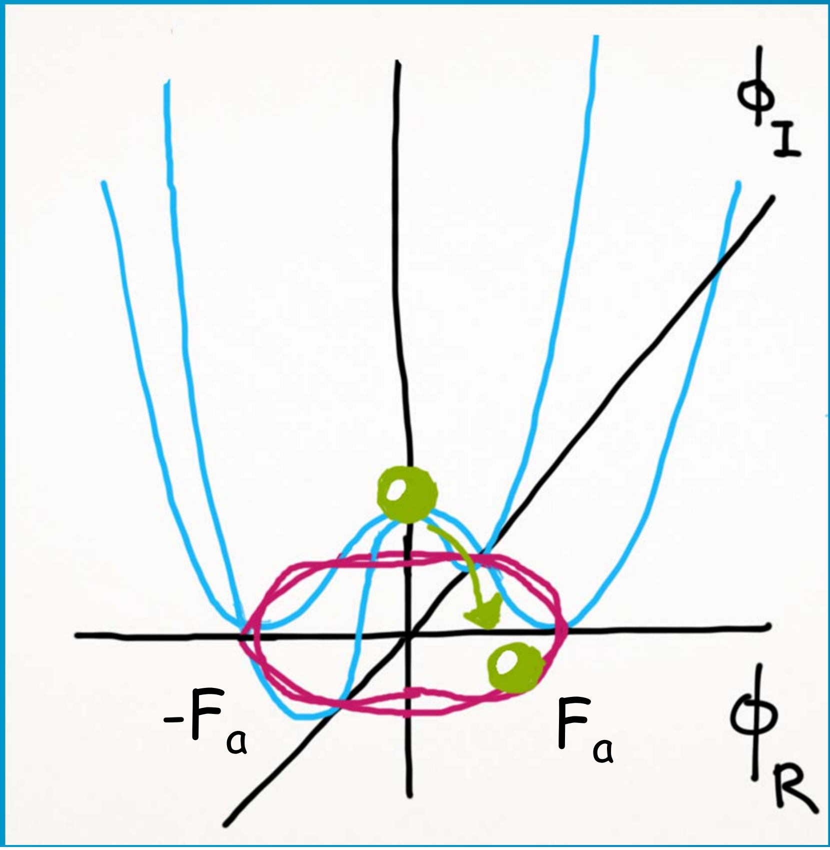
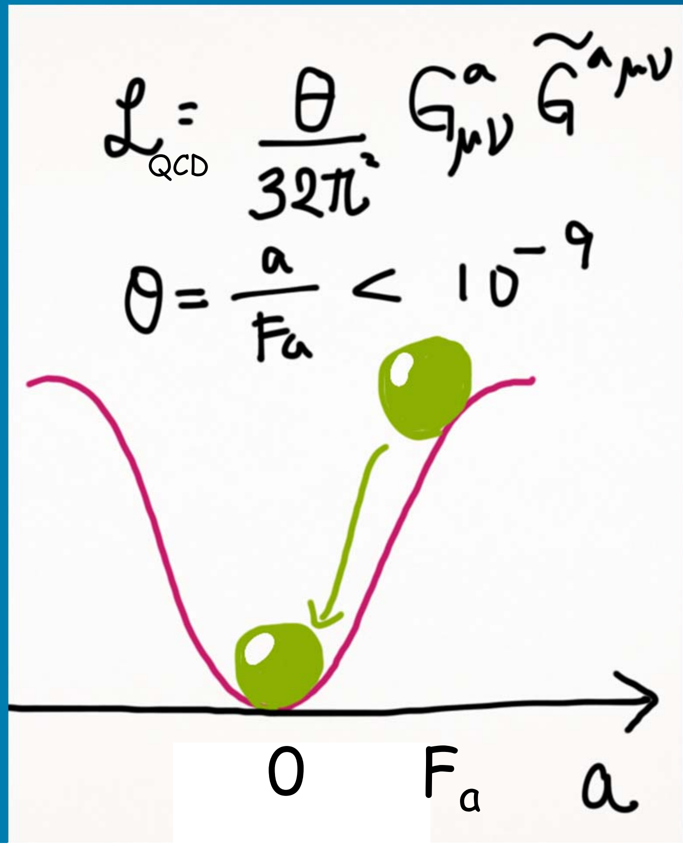
What is (QCD) axion?

- Breaking of U(1) Peccei-Quinn symmetry
- 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 ($\Omega_a h^2 \leqq 0.1$)

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

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

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

Photon-ALPs mixing in (string) axion

- Lagrangian

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

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

- 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.)

$$(\omega + i\partial_z)(\omega - i\partial_z) = (\omega + k)(\omega - i\partial_z) \sim 2\omega(\omega - i\partial_z)$$

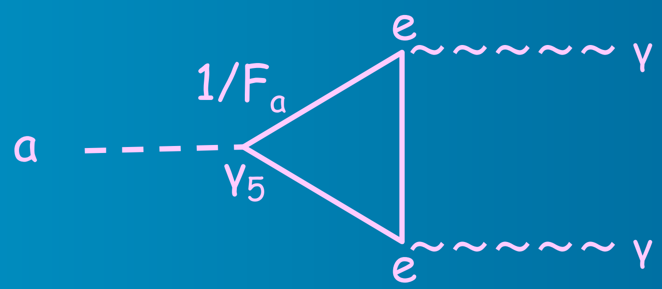
$$\left[\omega - i\partial_z - M^2/(2\omega)\right] A_j = 0$$

Axion coupling and mass

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

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

- Coupling



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

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

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>E$_*$)

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

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

$$= 1000\,\mathrm{TeV}\,\frac{m_{a,0.3\mu\mathrm{eV}}^2}{g_{11} B_{10\mu G}}$$

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

Phase of oscillation ($r>2/g_{a\gamma}B$)

$$g_{11} \equiv g_{a\gamma} / 10^{-11}\mathrm{GeV}^{-1}$$

$$B_{10\mu G} \equiv B / 10\mu G$$

$$r_{10\mathrm{kpc}} \equiv r / 10\mathrm{kpc}$$

- Phase

$$\frac{g_{a\gamma}Br}{2} \sim g_{11}B_{10\mu G}r_{10\mathrm{kpc}} \quad > 1$$

- Oscillation length

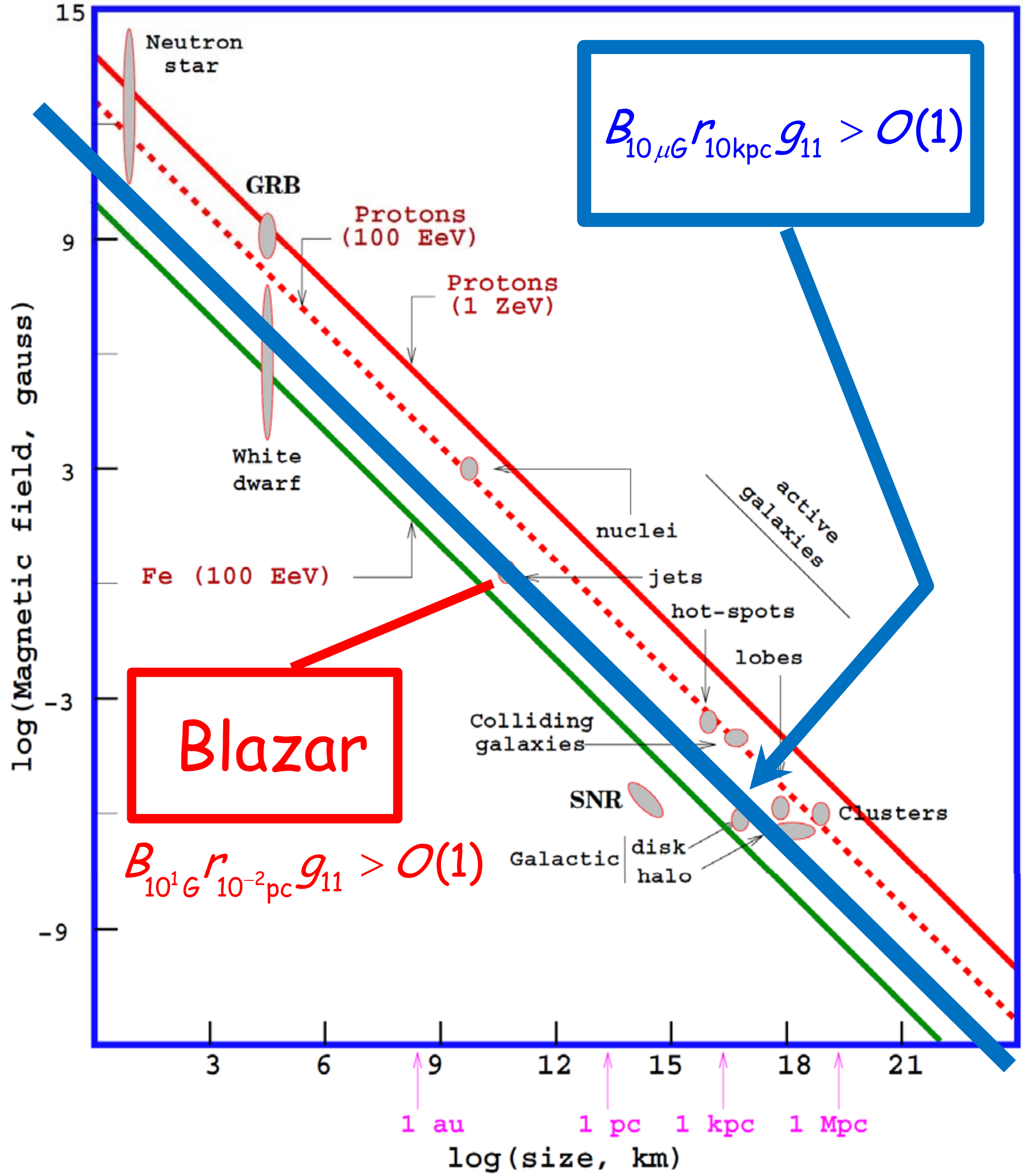
$$r_{Ha} = \frac{10\mathrm{kpc}}{g_{11}B_{10\mu G}}$$

Just within galaxy

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

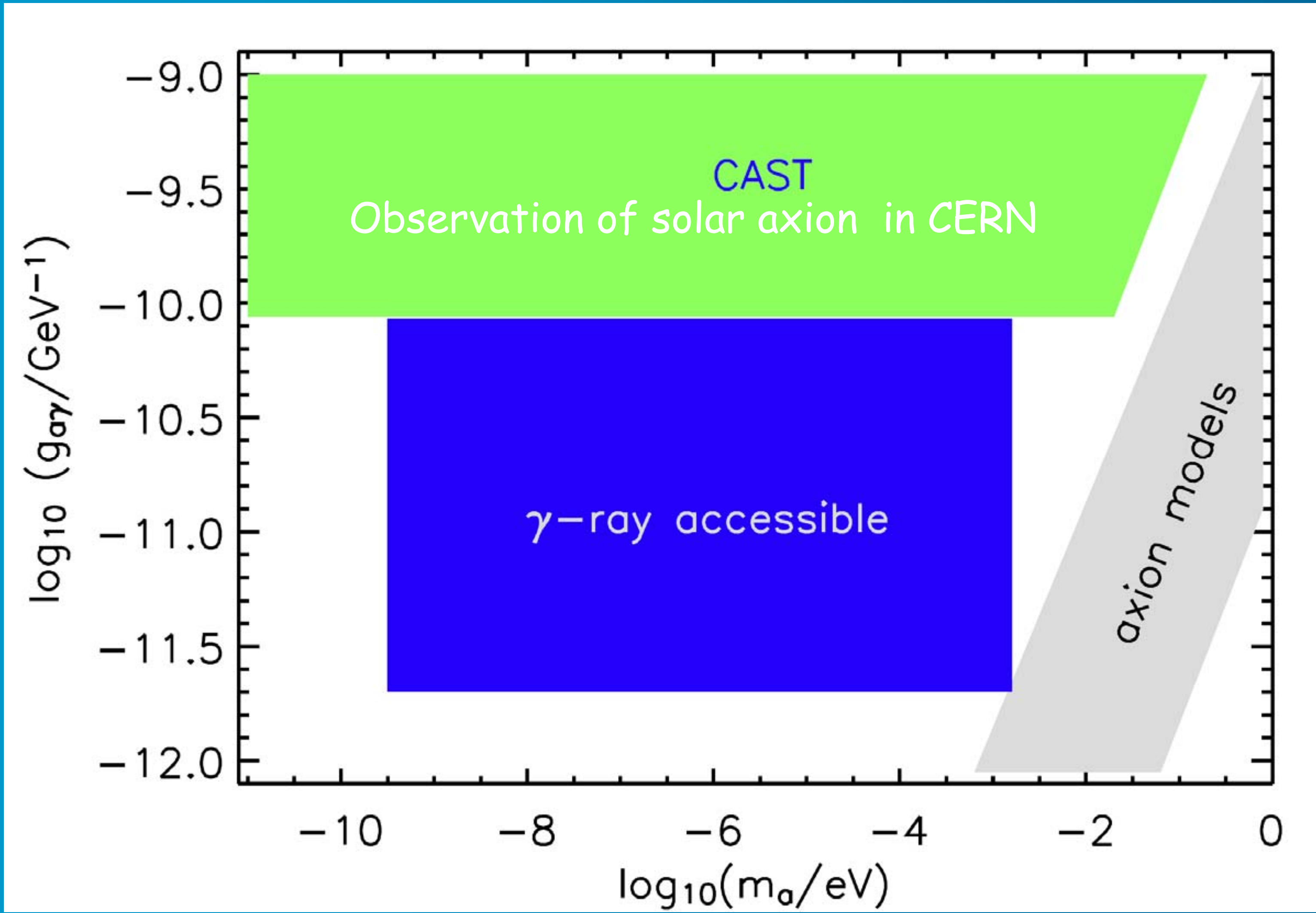
Distance from Blazars

Hillas Diagram



Hooper-Serpico (07)

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

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

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

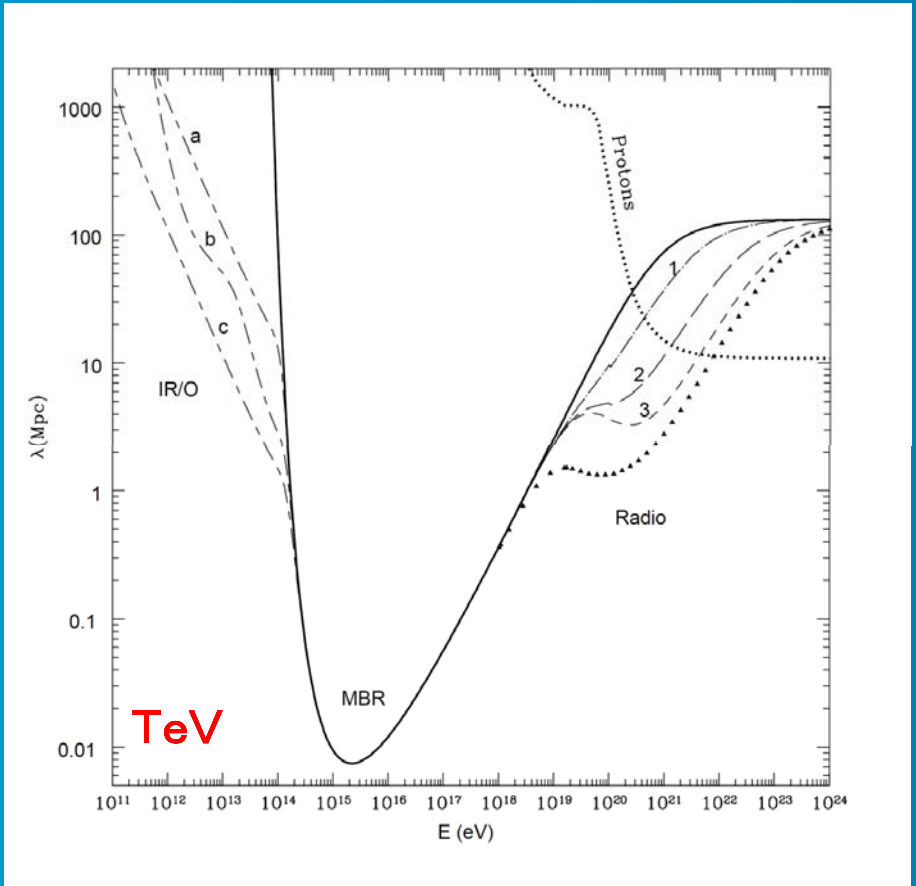
Gamma-ray horizon

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

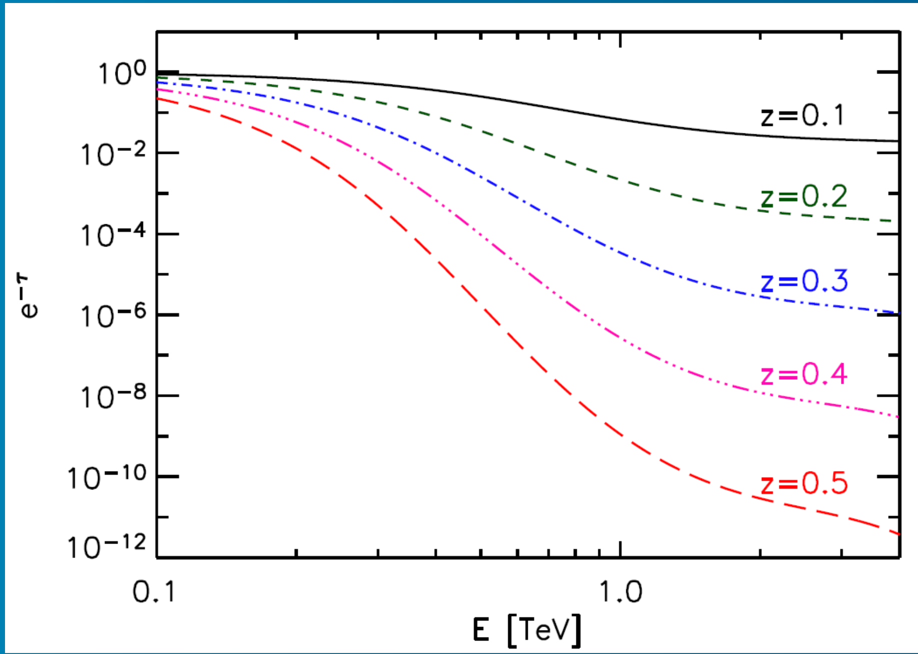
$$r_{H_\gamma}(E_\gamma) \sim \frac{1}{\sigma_{\mathrm{Thomson}}\, n_{\gamma,BG}(E_{\gamma,BG} = m_e^2 / E_\gamma)}$$

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

Gamma-ray horizon

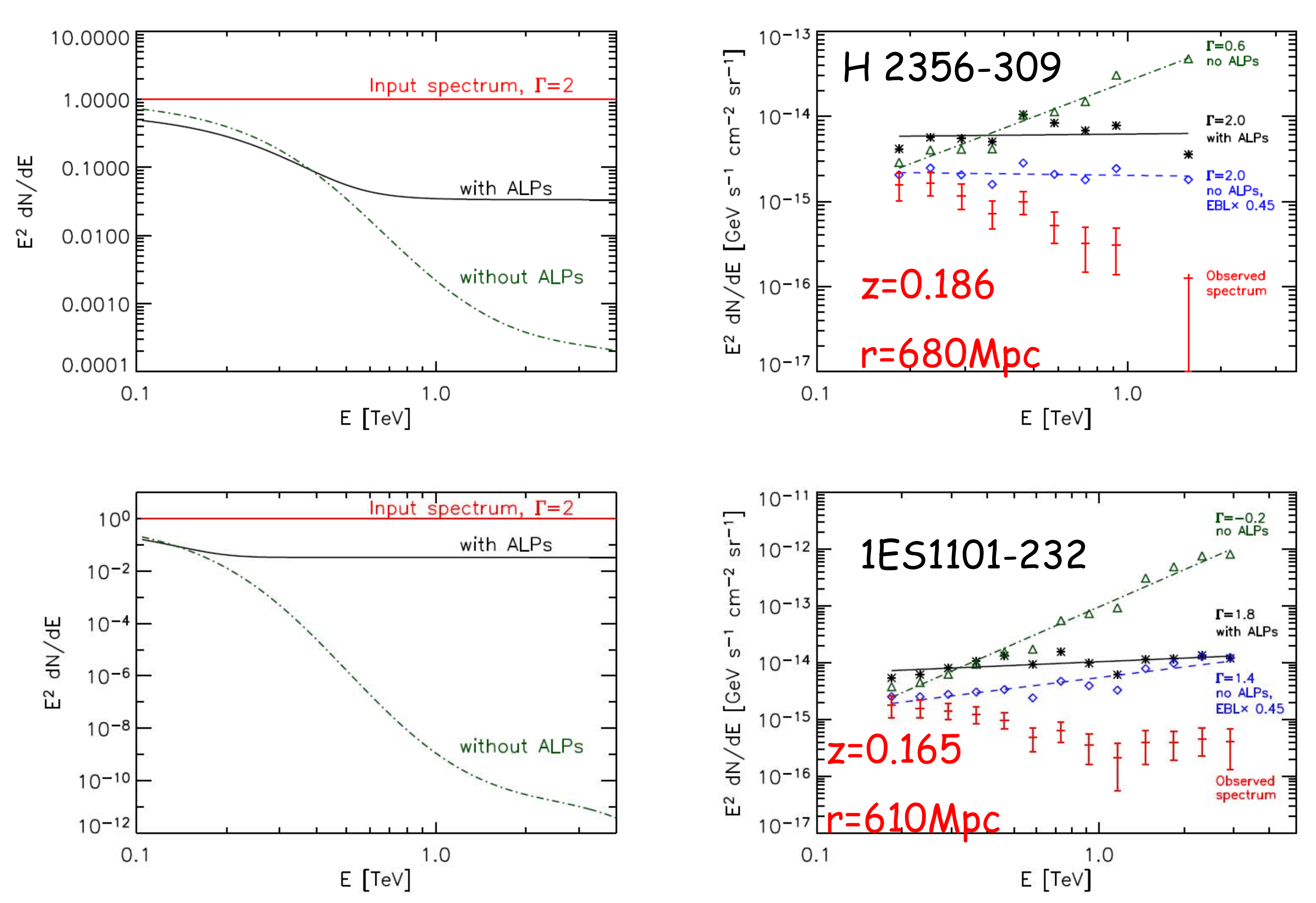


Coppi and Aharonian (97)



Shimet, Hooper, Serpico (08)

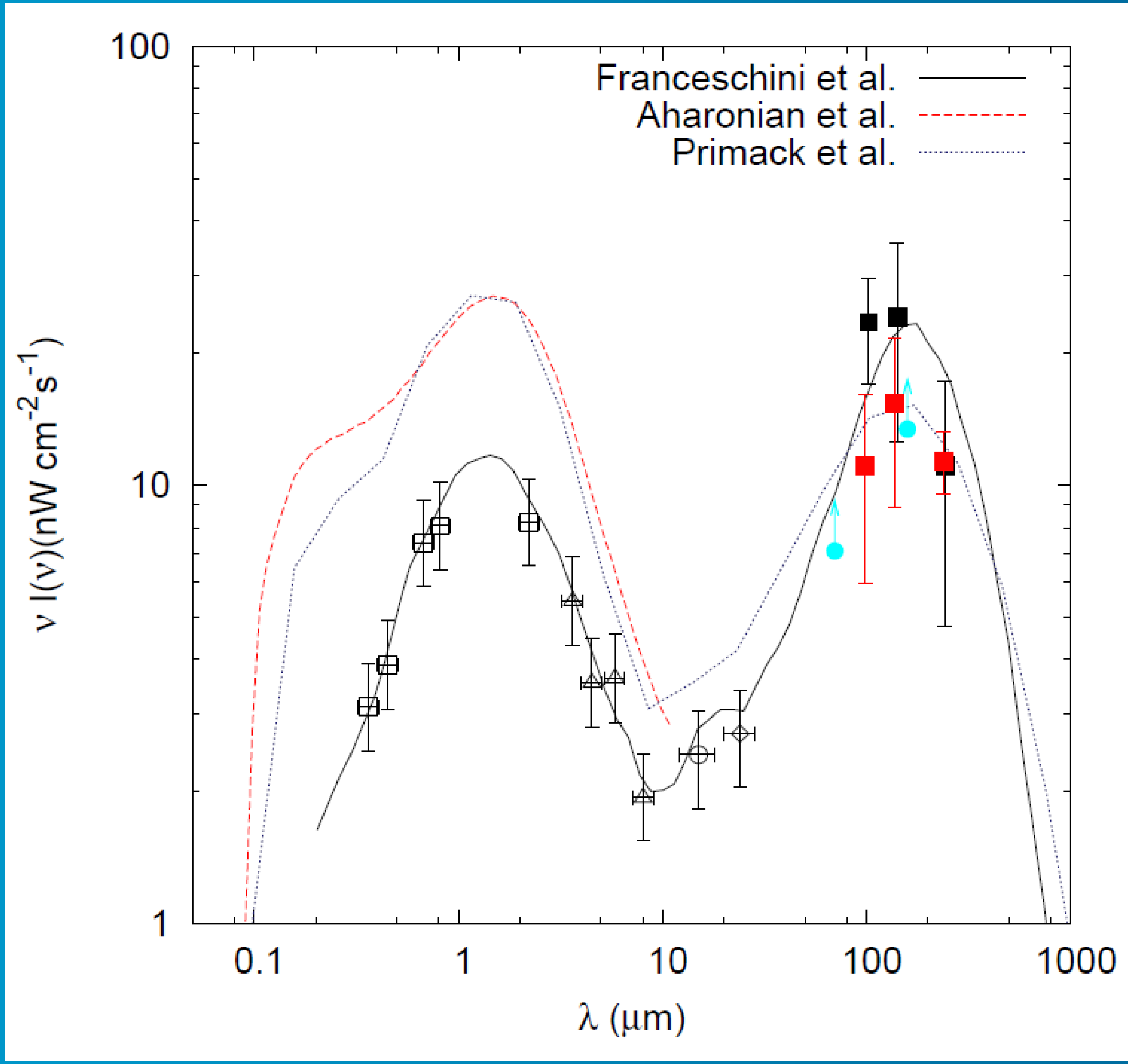
Spectrum reduction by axion mixing



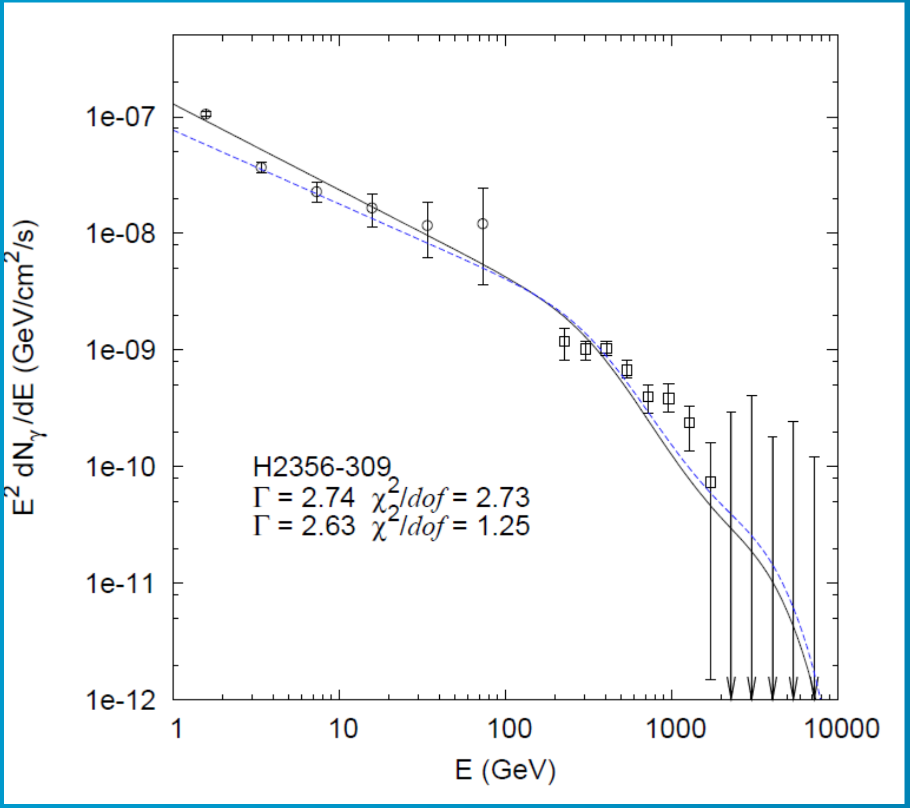
Shimet, Hooper, Serpico (08)

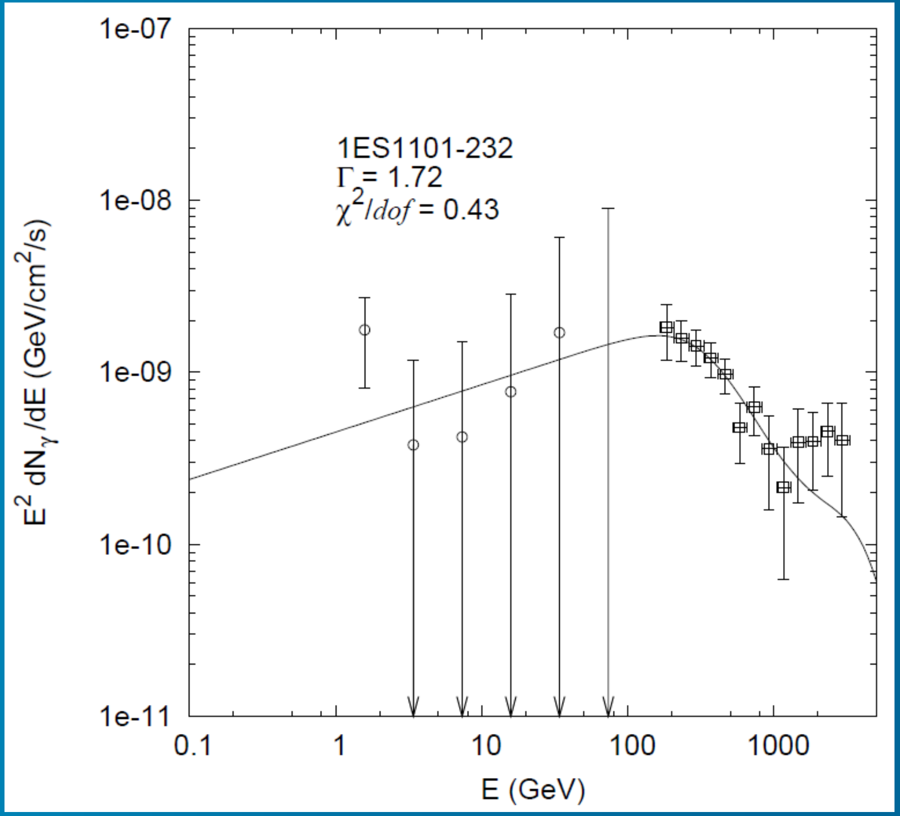
Uncertainties in the IR background

Belicov,Goodenough,Hooper('10)



We don't need axion?

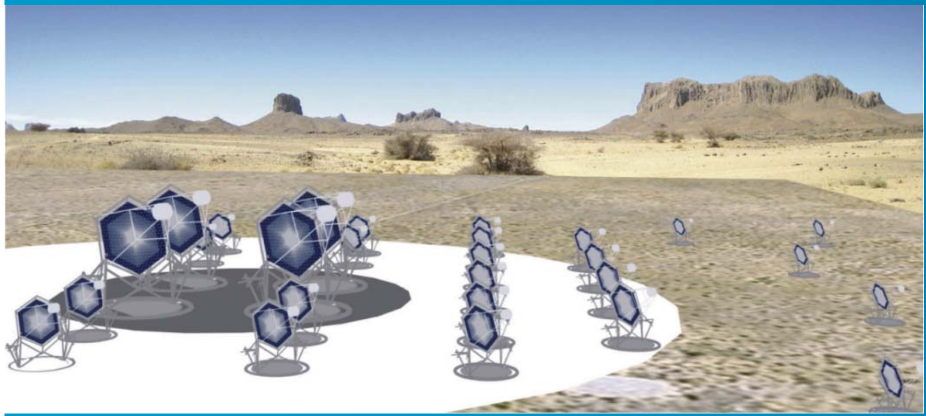


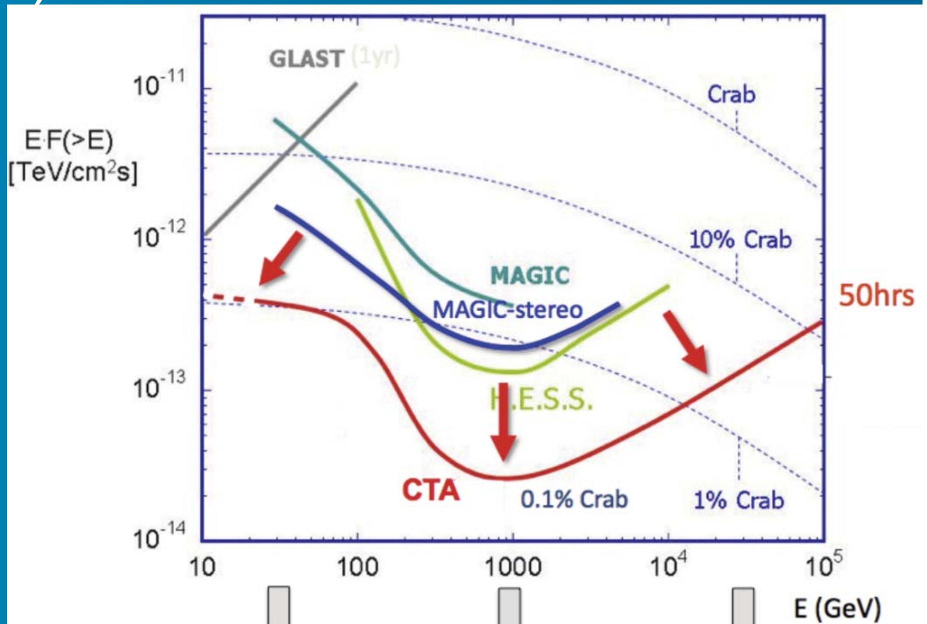


Belicov,Goodenough,Hooper('10)

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 an excess from the standard prediction