Axion-Like Particles (and dark matter) in terms of CTA

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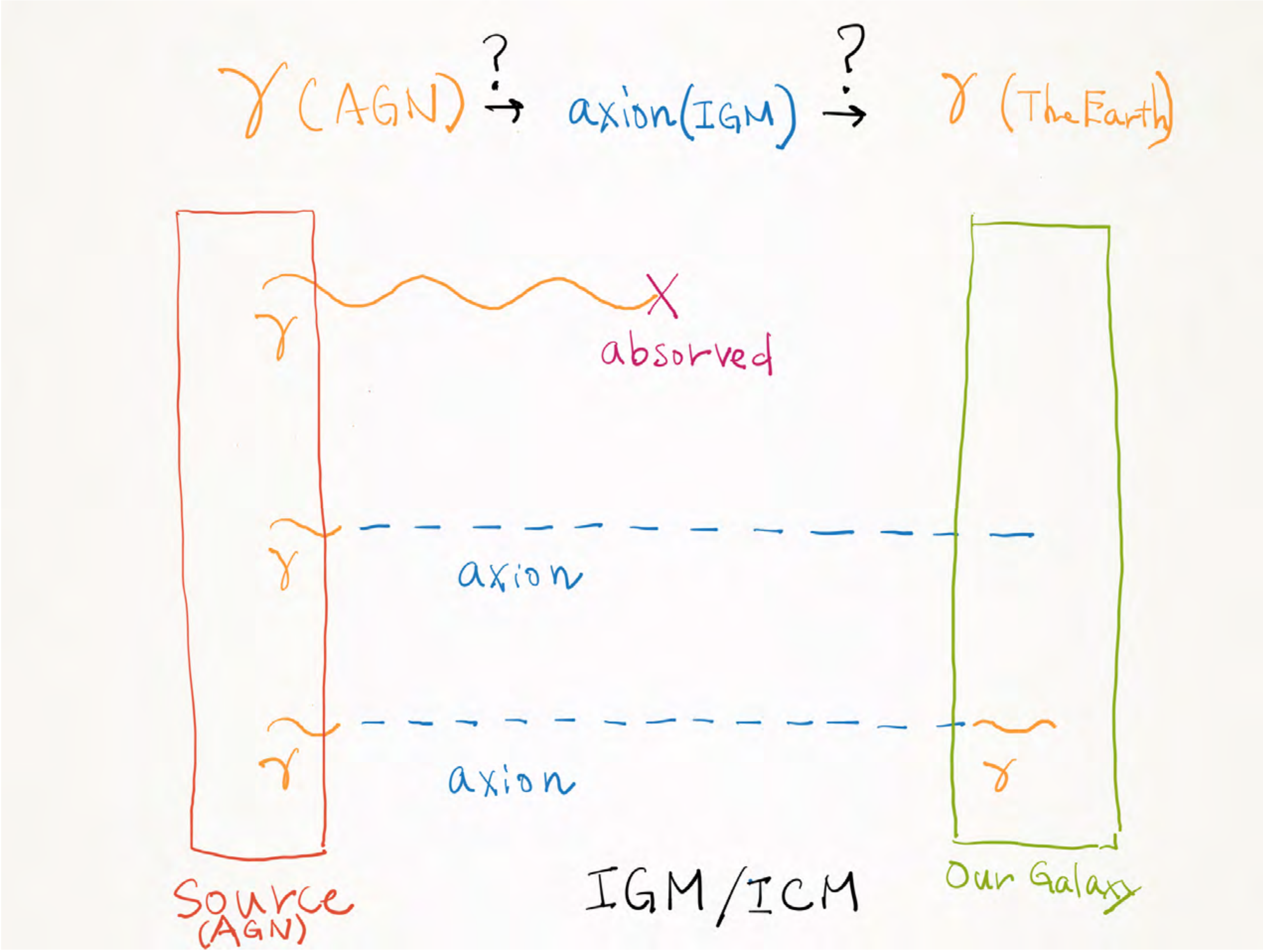
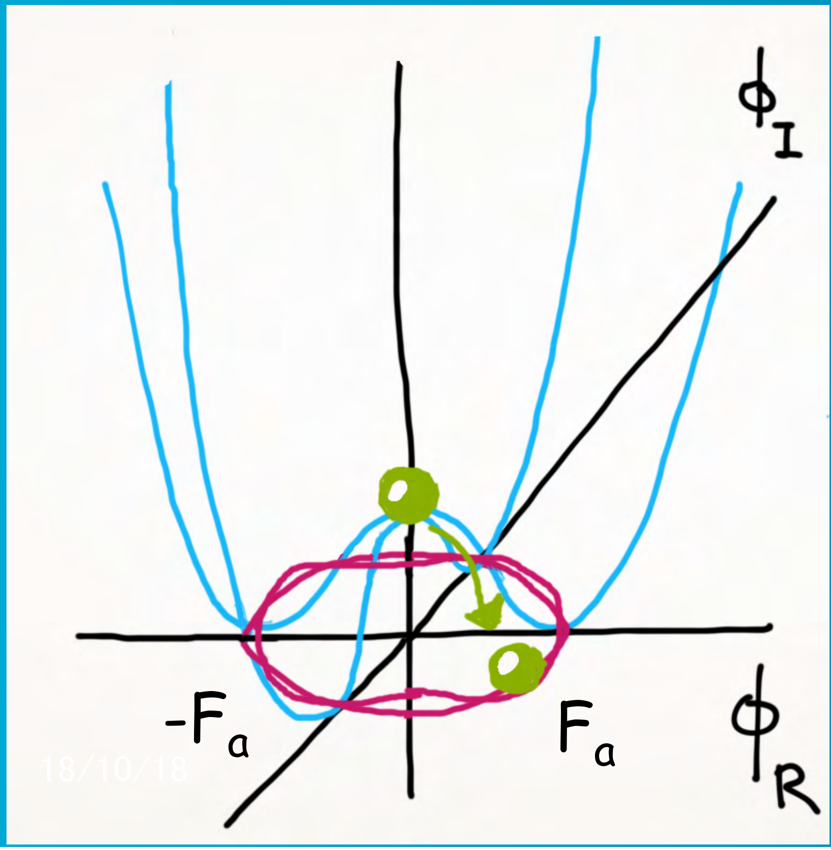
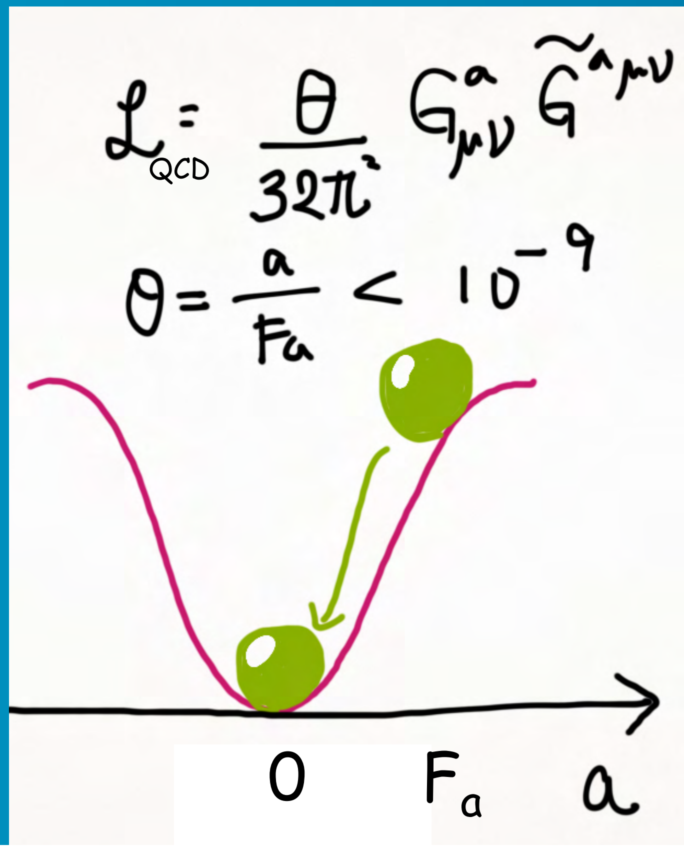


γ (AGN) ?→ axion(IGM) ?→ γ (The Earth)
γ
absorved
γ
axion
γ
axion
γ
Source (AGN)
IGM/ICM
Our Galaxy

What is (QCD) axion?

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

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

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

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

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

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

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

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,

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

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 (like Hillas Condition)

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

- Oscillation length

$$r_{ha} \sim \frac{10\mathrm{kpc}}{g_{11} B_{10\mu \mathrm{G}}} \sim \frac{10^3\mathrm{Mpc}}{g_{11} B_{n\mathrm{G}}} \sim \frac{10^{-1}\mathrm{pc}}{g_{11} B_{10\mathrm{G}}}$$

at within the MW Galaxy | at Inter Galactic Space | within a jet in AGN

Energy range for oscillation ($E>E_*$)

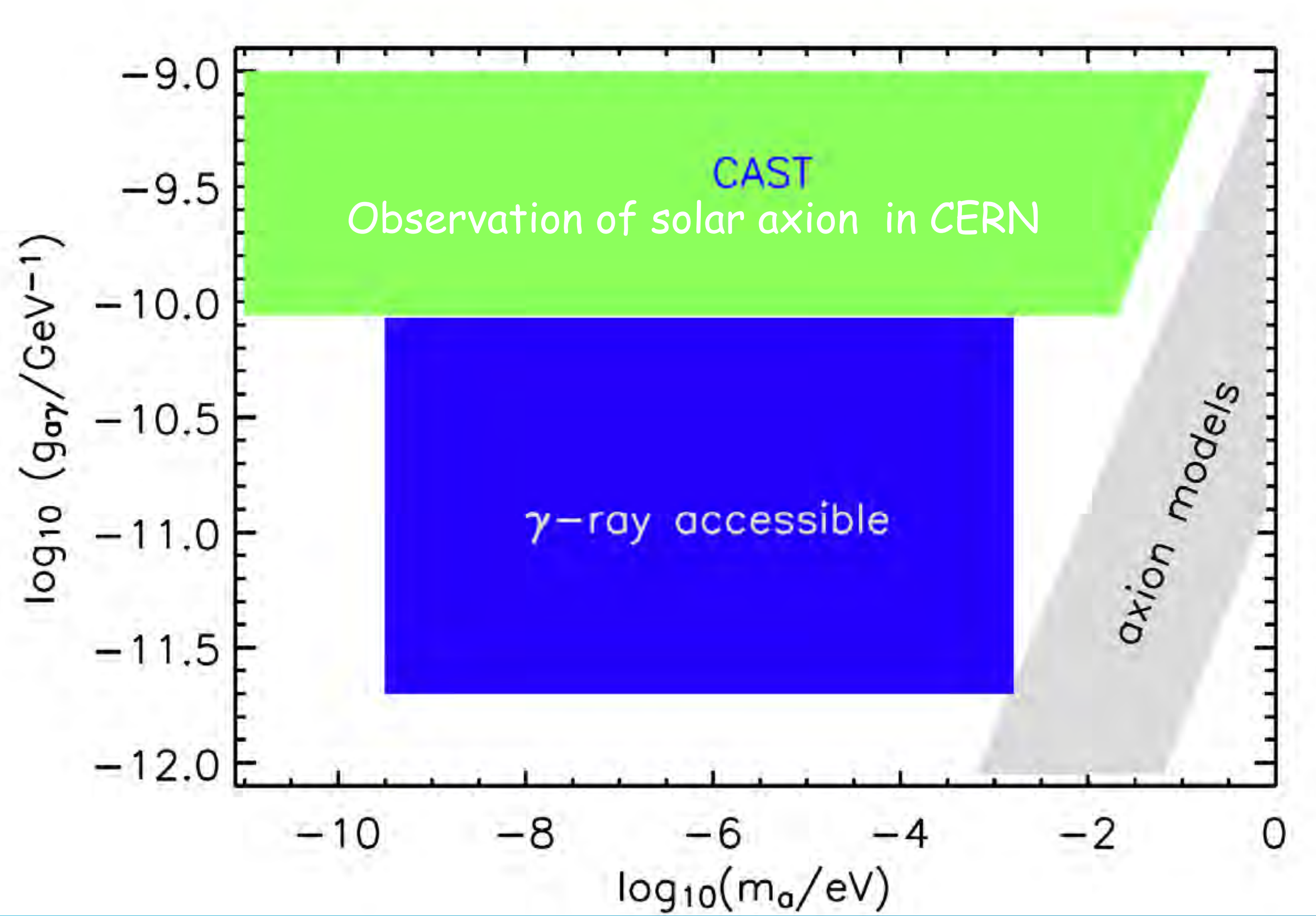
$$E_\gamma > E_* = m_a^2/(2g_{a\gamma}B)$$

$$E_* \sim \frac{10\mathrm{GeV}\, m_{a,n\mathrm{eV}}^2}{g_{11}B_{10\mu\mathrm{G}}} \sim \frac{10^2\mathrm{TeV}\, m_{a,n\mathrm{eV}}^2}{g_{11}B_{n\mathrm{G}}} \sim \frac{10\mathrm{keV}\, m_{a,n\mathrm{eV}}^2}{g_{11}B_{10\mathrm{G}}}$$

at within the MW Galaxy — at Inter Galactic Space — within jets in AGN

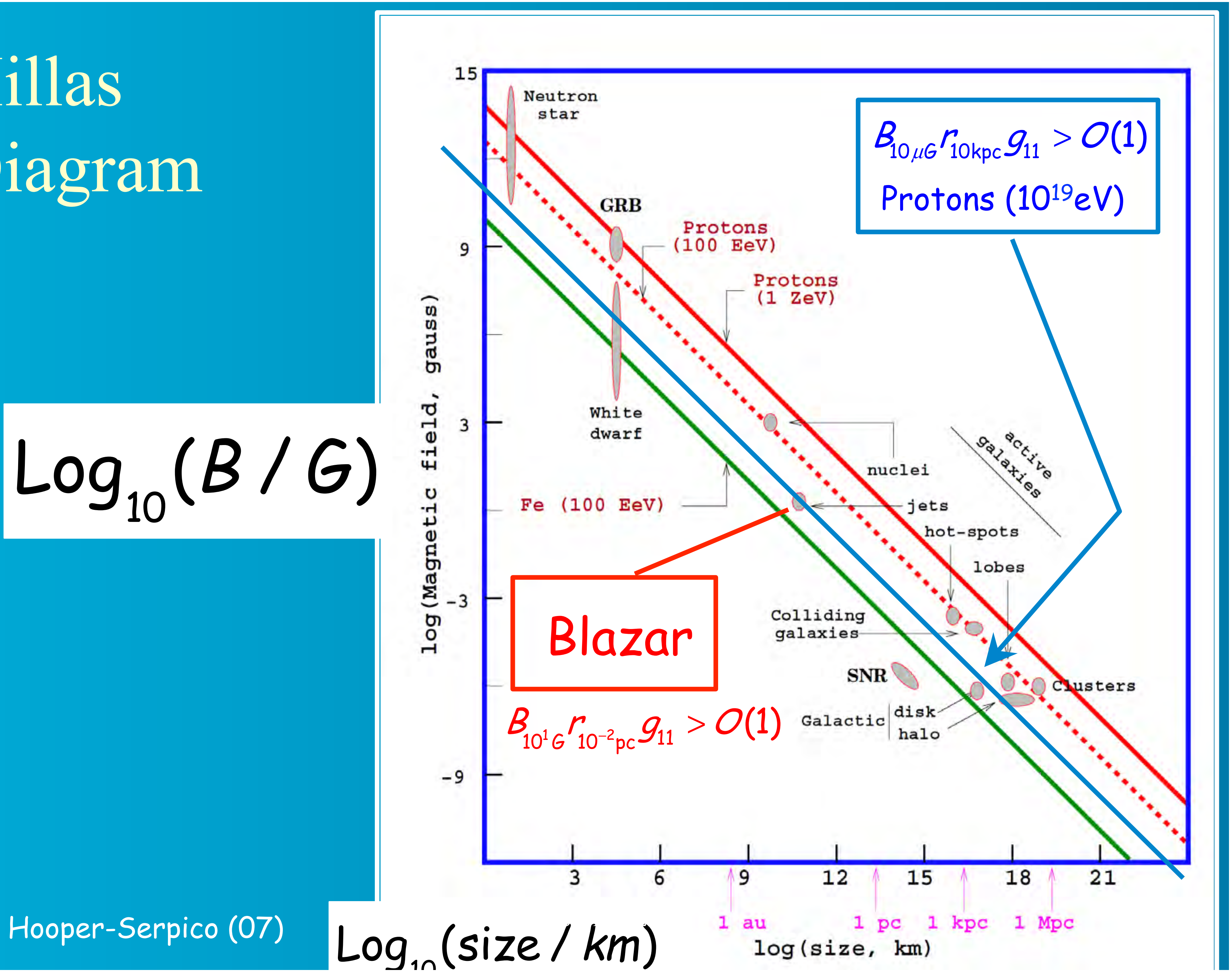
$$g_{11} \equiv g_{a\gamma}/10^{-11}\mathrm{GeV}^{-1}, B_{10\mu G} \equiv B/10\mu G, r_{10\mathrm{kpc}} \equiv r/10\mathrm{kpc}$$

Gamma-ray accessible parameters



Hooper-Serpico (07)

Hillas Diagram



Hooper-Serpico (07)

Three Coincidences within an AGN jet

Three sites should have coincided for

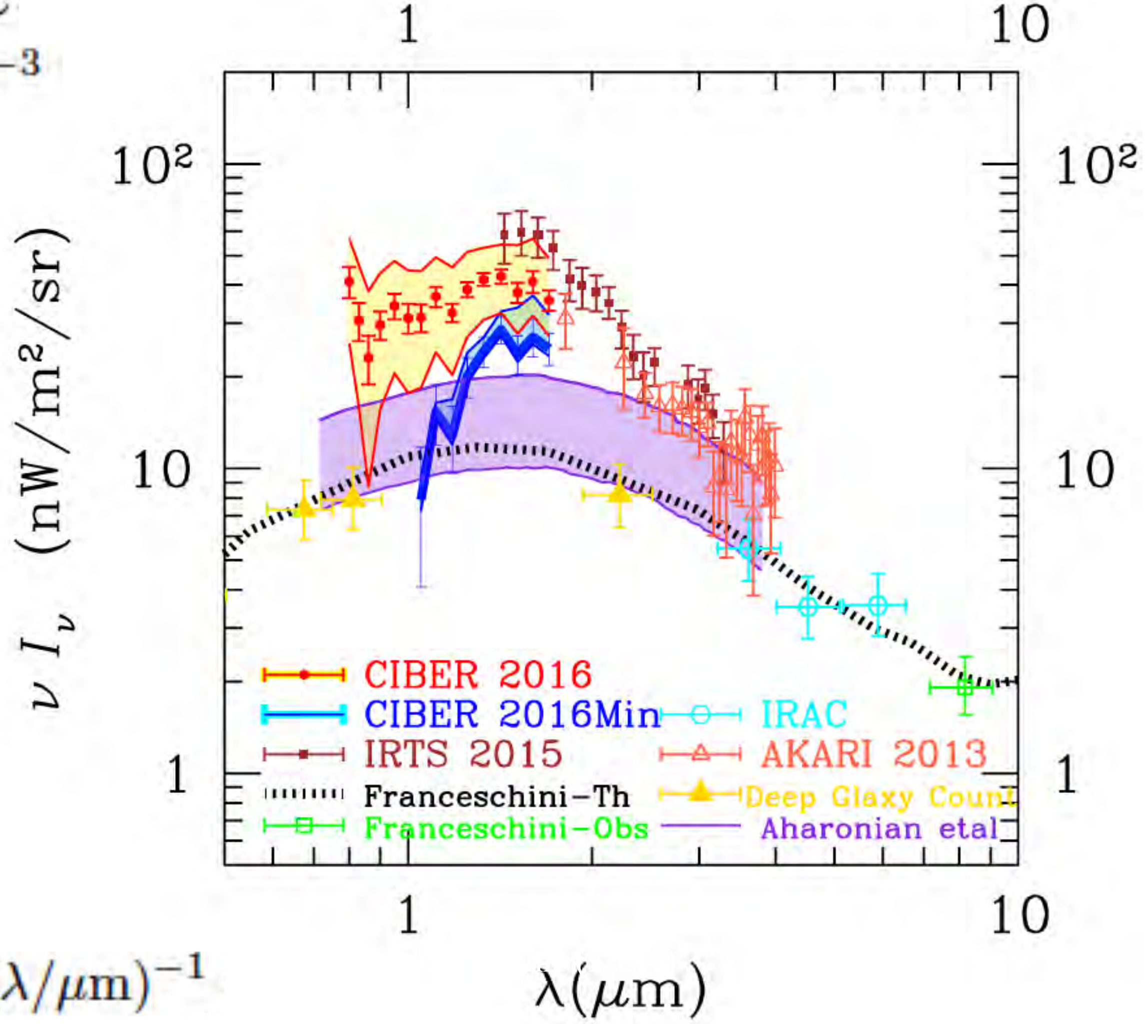
1. Accelerations of proton
2. Photon production through p-γ
3. Axion-photon conversions

It is remarkable that we have not assumed anything about structures of magnetic field at the source

Cosmic Infrared Background (CIB) by CIBER 2017, IRTS 2013, Akari 2013

S. Matsuura *et al.* [CIBER Collaboration], Astrophys. J. 839, 7 (2017)

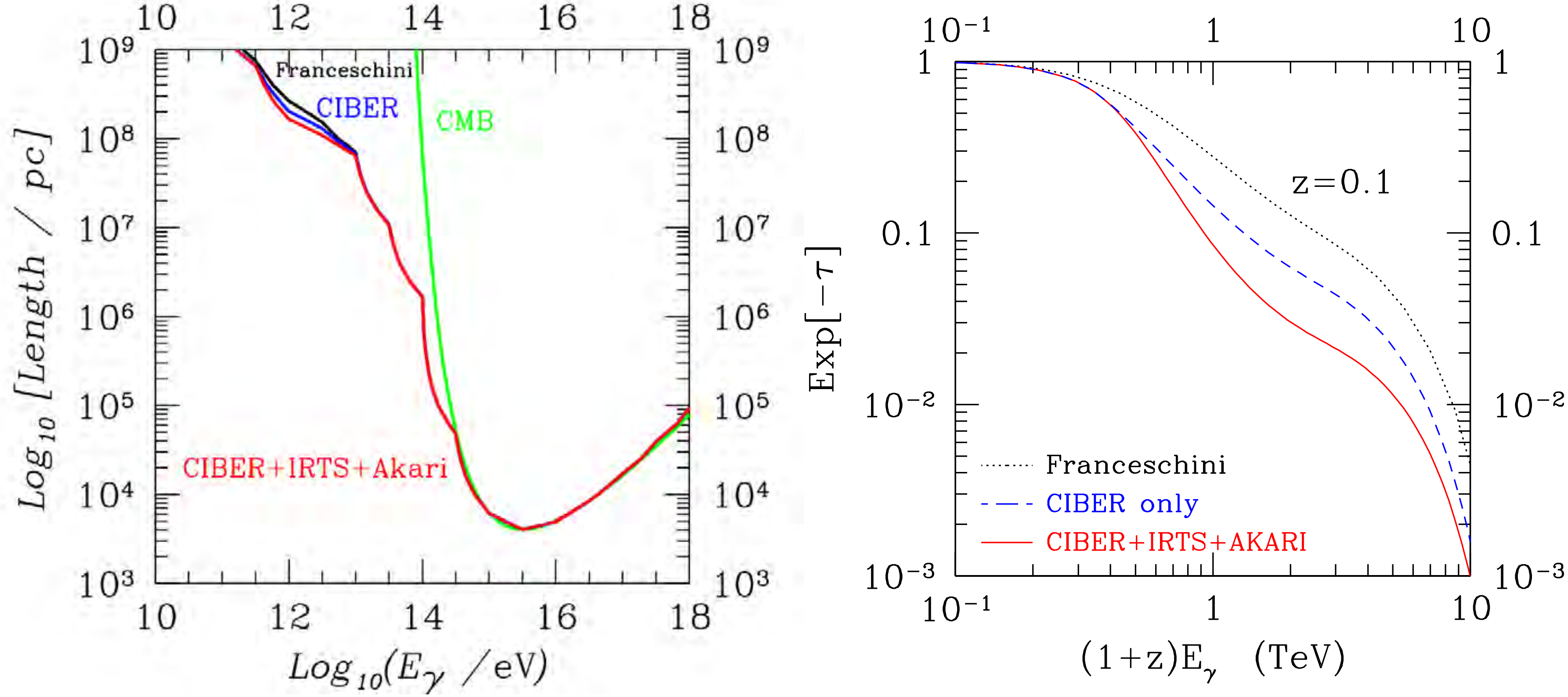
$10 \mathrm{nWcm}^2 \mathrm{sr}^{-1} \sim 2 \times 10^{-3} \mathrm{eVcm}^{-3}$



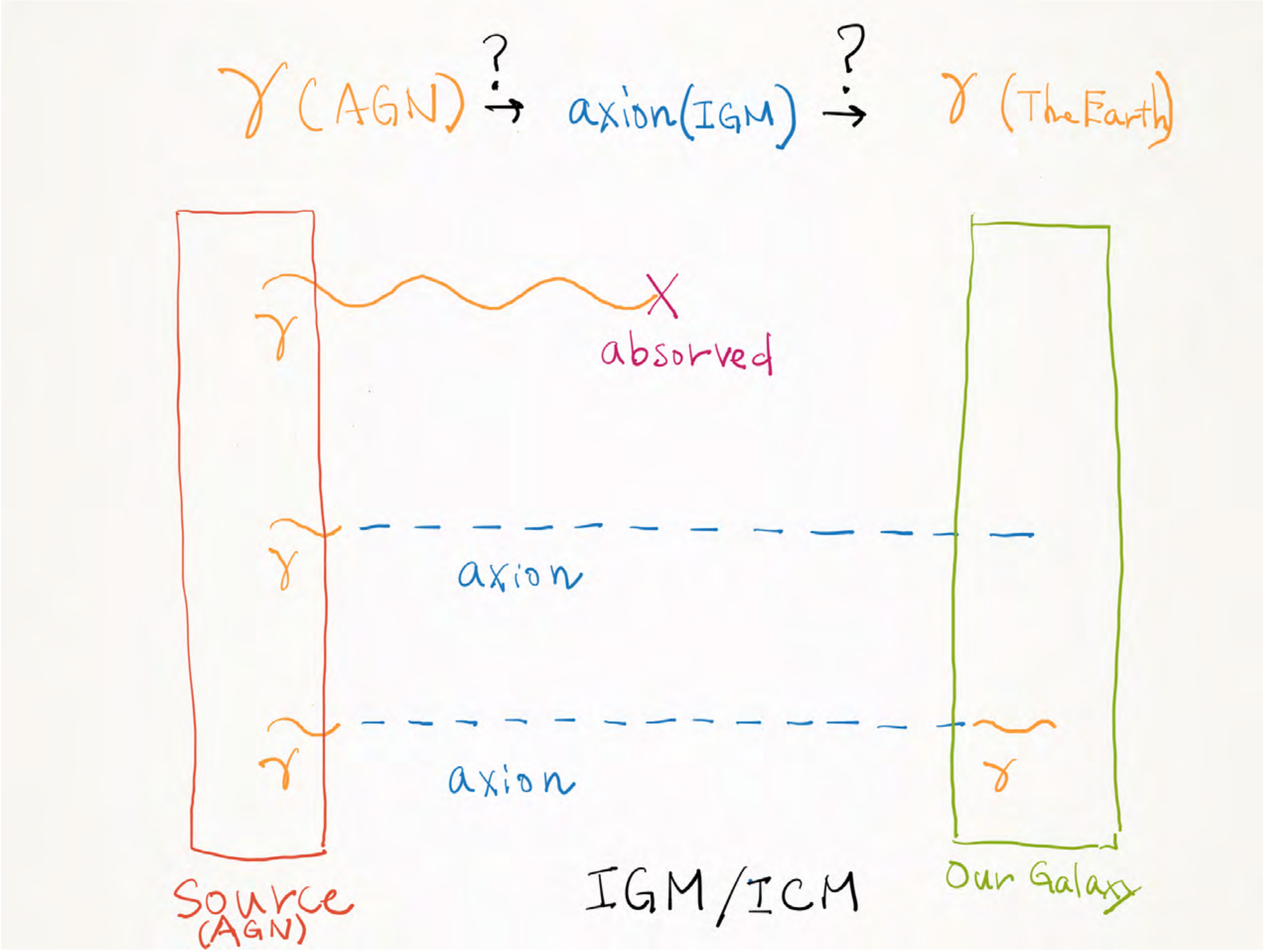
$E_{\gamma \mathrm{BG}} \sim 1.23 \ \mathrm{eV}(\lambda/\mu\mathrm{m})^{-1}$

Gamma-ray horizon through

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



Kohri and Kodama, arXiv:2017.05189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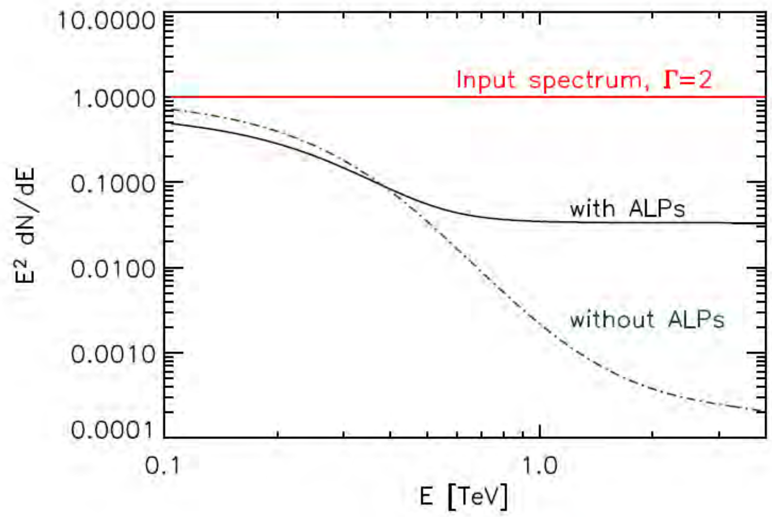
Spectrum reduction by axion mixing

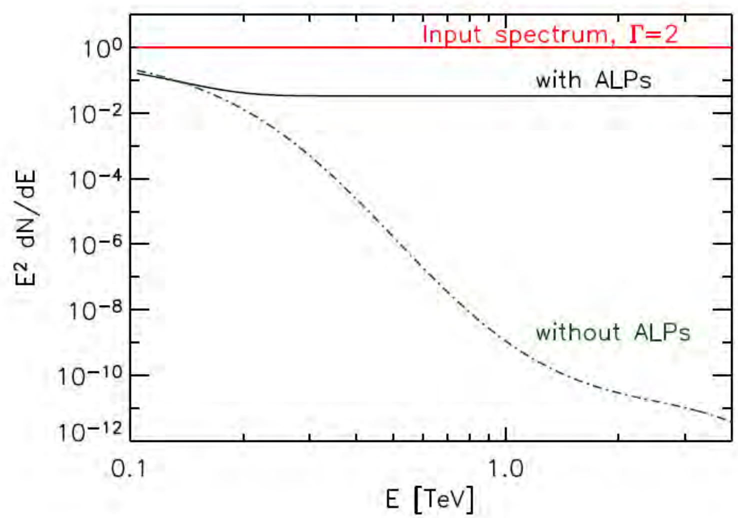
Shimet, Hooper, Serpico (08)



H 2356-309

z=0.165

r=610Mpc



1ES1101-232

z=0.186

r=680Mpc

We need axion

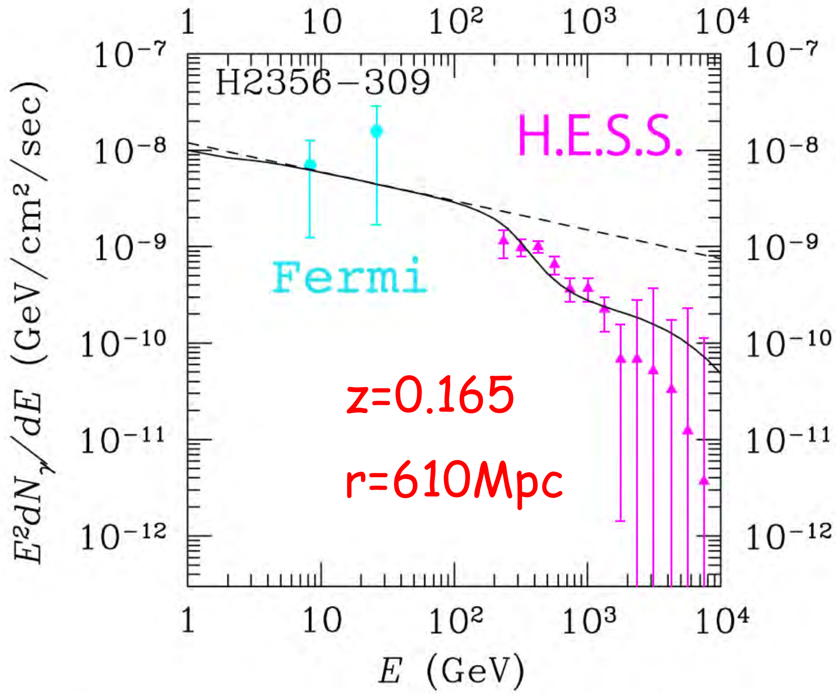


FIG. 3: Gamma-ray spectrum fitted to the data of H2356 309 (the redshift is $z = 0.165$ which gives the distance ~ 610 Mpc). Here, we adopted $g_{a\gamma} = 3.2 \times 10^{-11}\text{GeV}^{-1}$ and $m_a = 3.2 \times 10^{-9}$ eV. The reduced χ^2 is estimated to be $\chi^2/\text{d.o.f} = 1.1$, which is improved from the case without axion $\chi^2/\text{d.o.f} = 2.2$. The fitted value of the photon index is $\Gamma_s = 2.3$. We followed

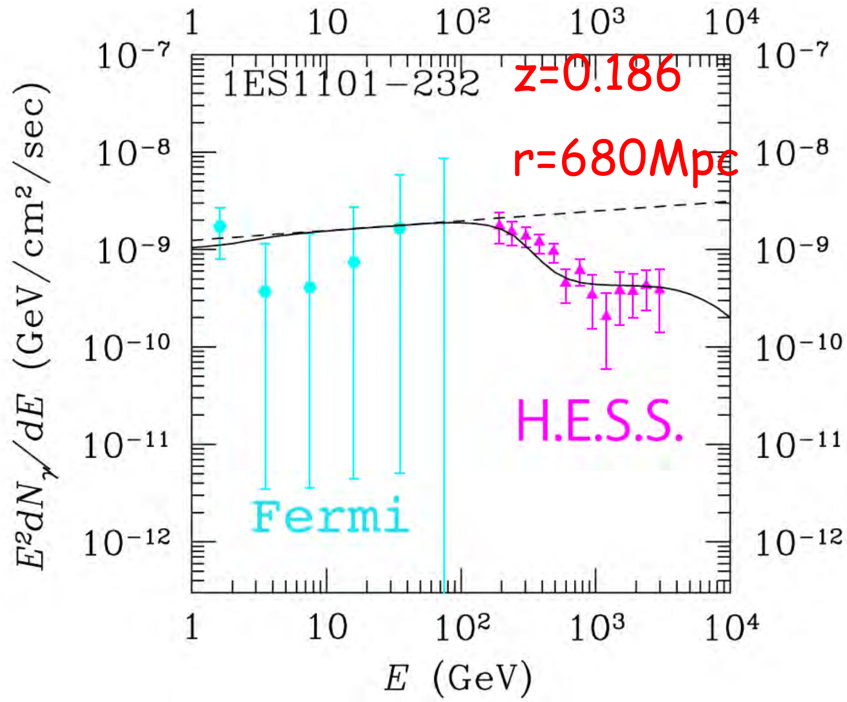
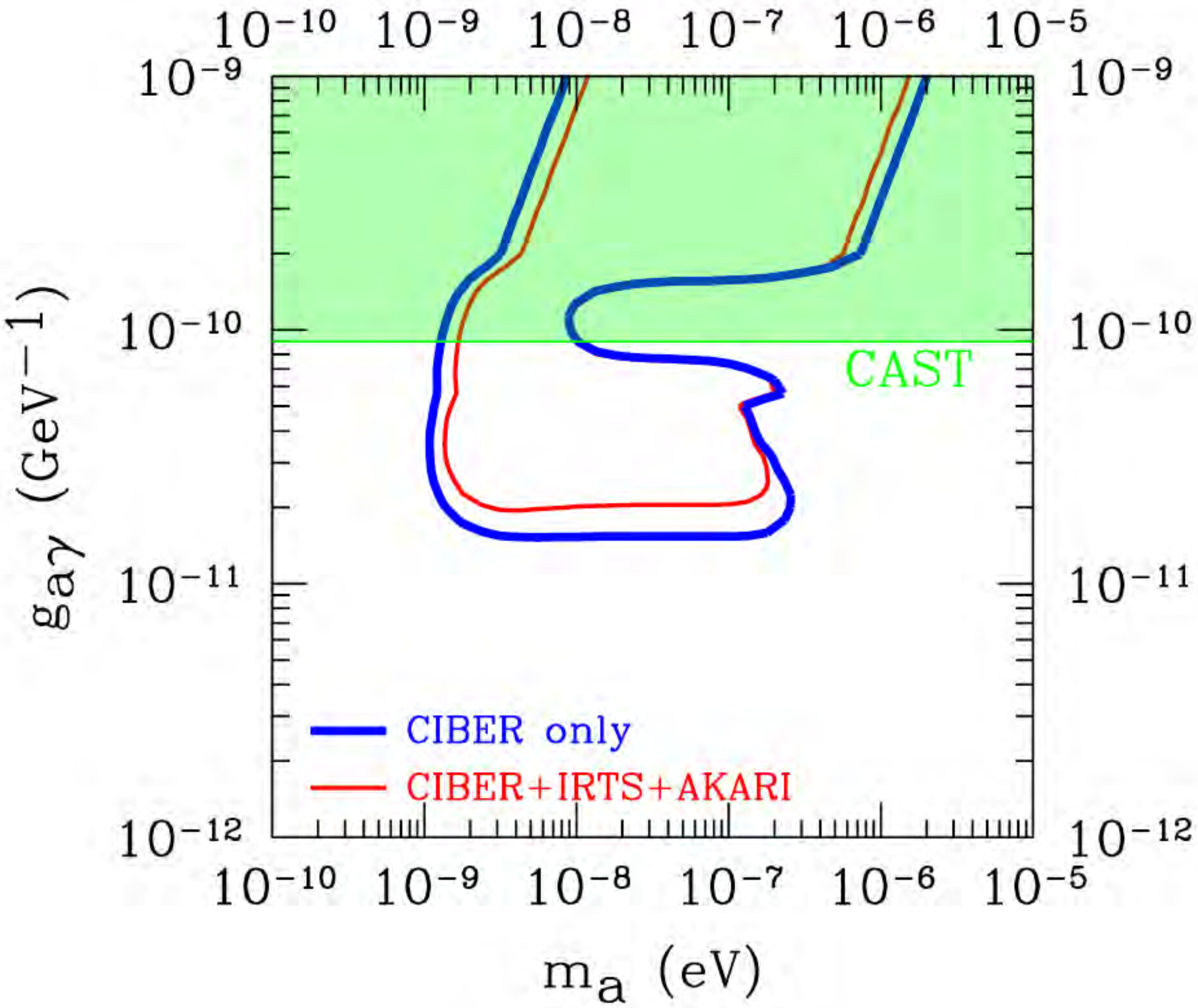


FIG. 4: Sames as Fig. 3, but for 1ES1101 232 (the redshift is $z = 0.186$ which gives the distance ~ 680 Mpc.). The reduced χ^2 is estimated to be $\chi^2/\text{d.o.f} = 0.69$, which is improved from the case without axion $\chi^2/\text{d.o.f} = 2.0$. The fitted value of the photon index is $\Gamma_s = 1.9$.

Kohri and Kodama, arXiv:2017.05189

An axion solution



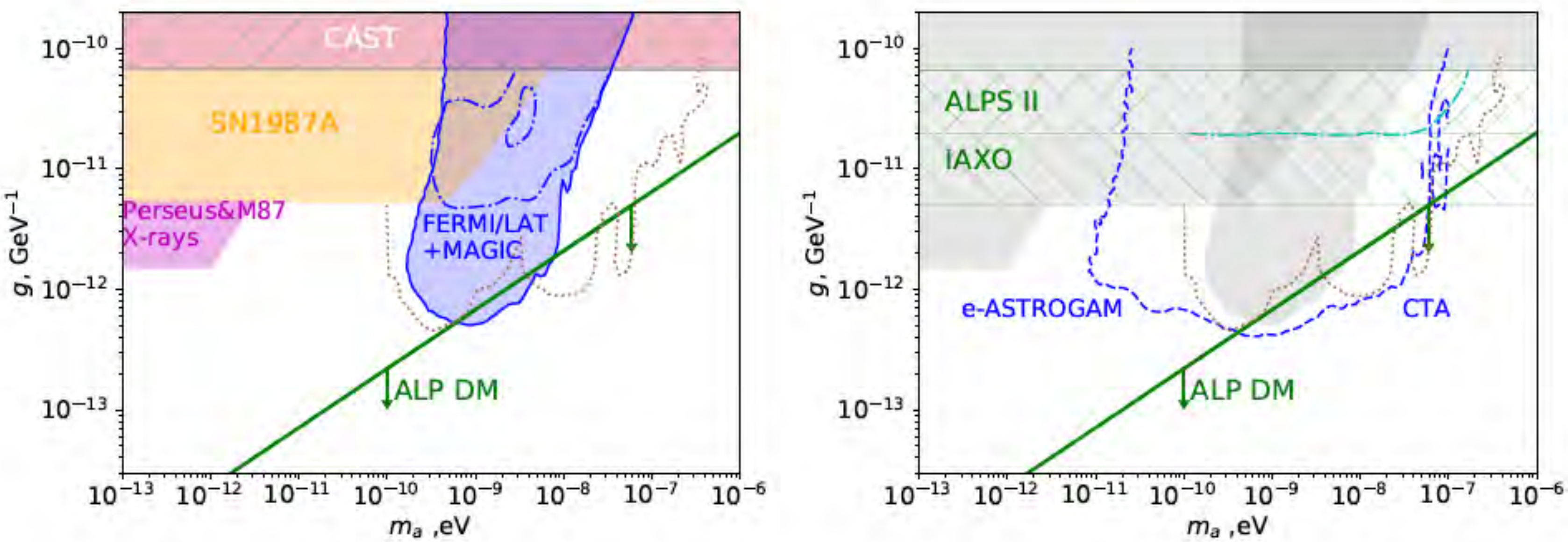
Kohri and Kodama, arXiv:2017.05189

Constraints on ALP-photon coupling by X-ray observations (Fermi/LAT and MAGIC) of NGC 1275 embedded in Perseus cluster

D. Malyshev, A. Neronov, D. Semikoz, A. Santangelo, J. Jochum, arXiv:1805.04388

Assuming, $B \propto n_e^{0.5}$ ➡ $B(r) = \begin{cases} B_0 & if \quad r \leq r_0 \\ B_0 \cdot (r/r_0)^{-0.5} & if \quad r > r_0 \end{cases}$

$B_0 = 15\mu G; \quad r_0 = 40 \text{ kpc}$



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