Dark matter and future gamma-ray observations

133 GeV gamma-rays from galactic center and axion emission from dark matter

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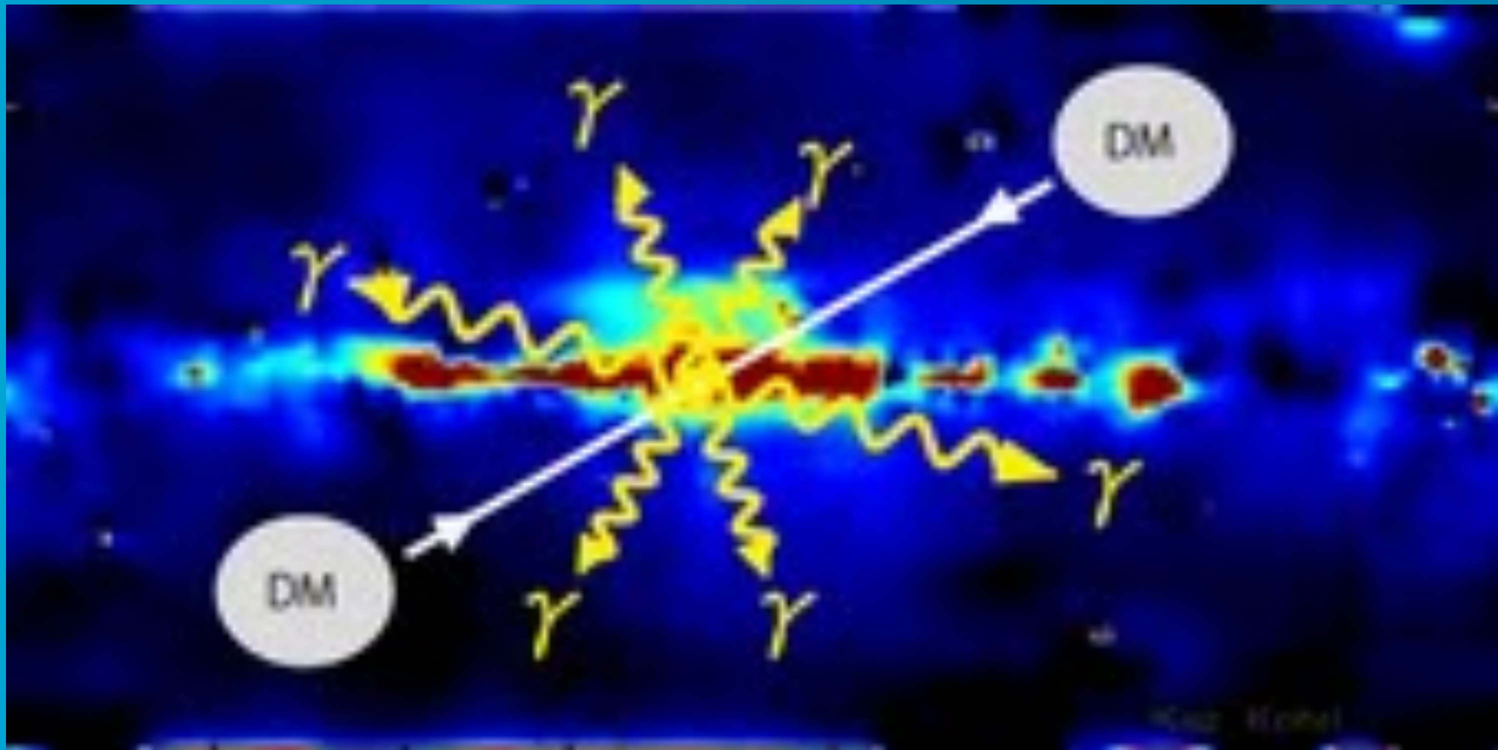
This work is based on

Yamanaka, Kohri, Nojiri and Ioka (2013) in preparation

Kohri, Park, and Rott (2013) in Preparation

Indirect detection of DM



Thermal freezeout

Boltzmann equation

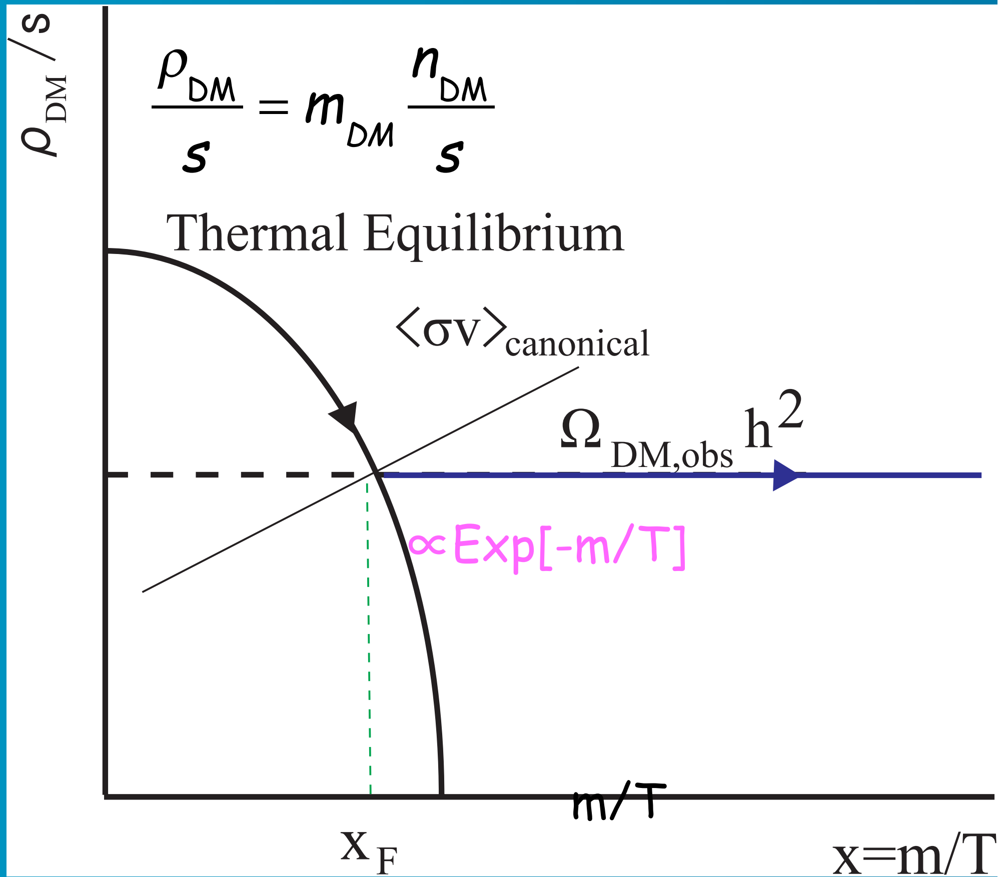
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle [(n_\chi)^2 - (n_\chi^{eq})^2]$$

$$n_\chi \sim \left. \frac{3H}{\langle \sigma v \rangle} \right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \sim m_\chi / 23$$

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle}{\left(0.1 / \text{TeV} \right)^2} \right)$$

$\Omega_\chi\, h^2$ does not depend on m_χ



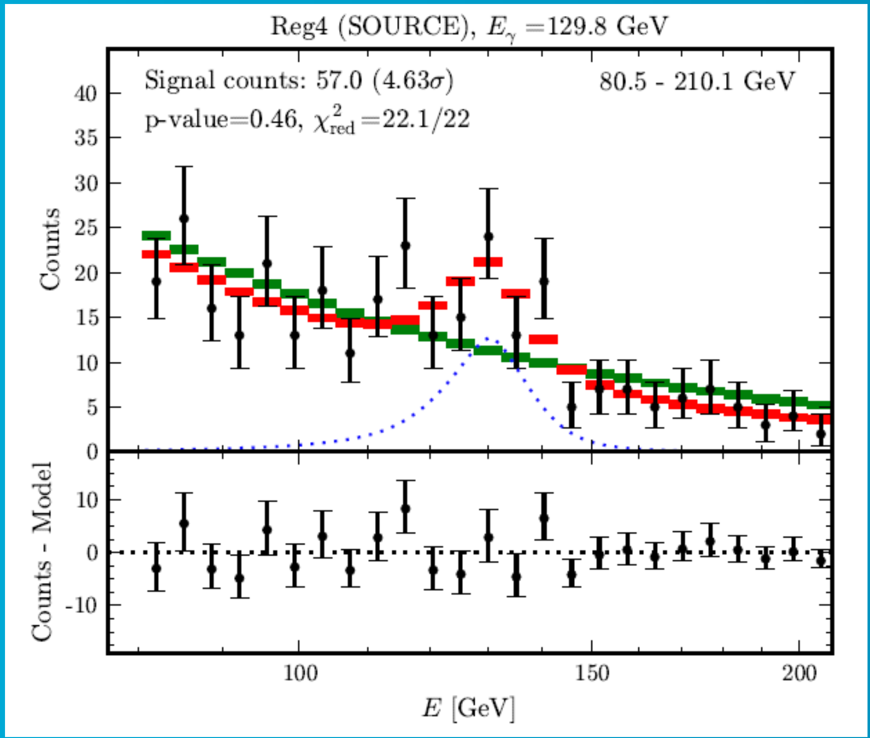
Predicting TeV Physics!!!

$$\langle \sigma v \rangle = 3 \times 10^{-26}\, cm^3 / s$$

130 GeV gamma-ray line(s)

4.63σ

- Observation and ann. DM interpretation



$\langle \sigma v \rangle_{DM+DM \to \gamma+\gamma}$ >~ $10^{-27} cm^3 / sec$

>~ $0.1 \langle \sigma v \rangle_{canonical}$

Depending on density profile (NFW,Einasto,isothermal-cored,...

For thermal production,

$\langle \sigma v \rangle_{canonical} = 3 \times 10^{-26} cm^3 / sec$

Weniger,arXiv1204.2797

Line width < 15 %

Possible other sources?

- Inverse Compton by electron with a peak structure produced in pulsars ($e+\gamma \rightarrow e+\gamma$)

  Aharonian, Khangulyan, Malyshev, 1207.0458

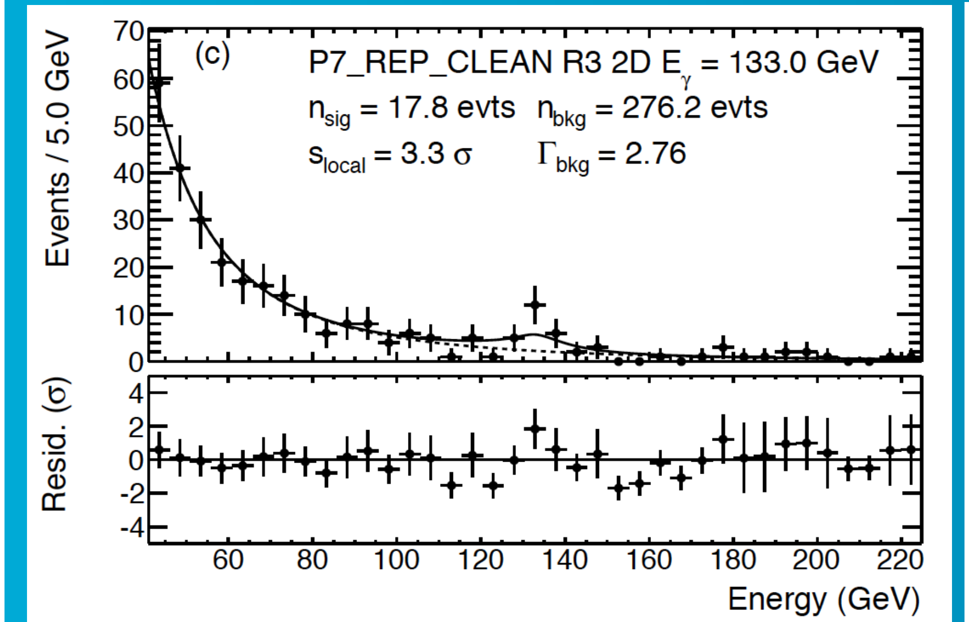
- Instrumental effects (seen in observations of Earth-Lim Emission)

  Ackermann et al, Fermi Collaboration (2013), arXiv:1305.5597

133 GeV gamma-ray from galactic center in Fermi-LAT satellite data

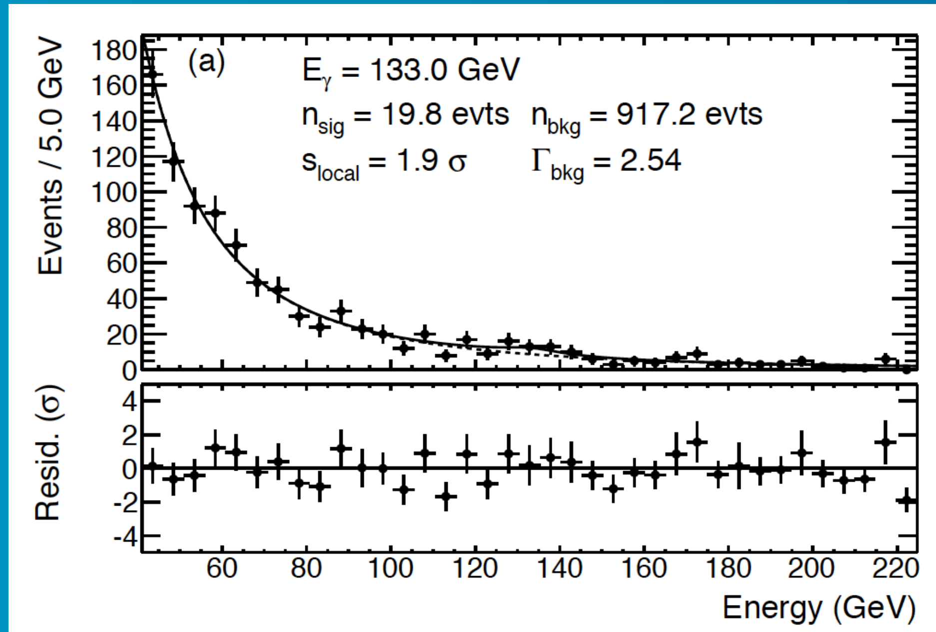
Ackermann et al, Fermi Collaboration (2013), arXiv:1305.5597

3.3σ



Local

1.9σ

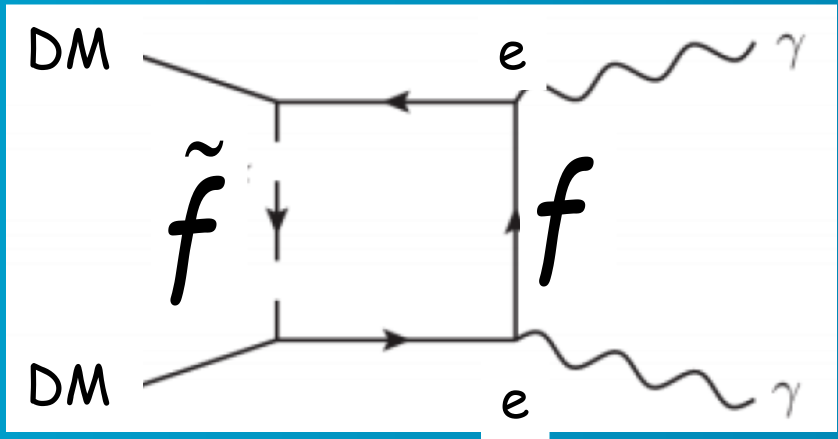


Global

In their DISCUSSION and SUMMARY, they wrote “More data and study are needed to clarify the origin of this feature.”

Annihilating Dark Matter?

- One-loop suppression



- Branching ratio

$$\mathrm{Br}(\mathrm{DM}+\mathrm{DM} \to \gamma+\gamma) \equiv \frac{\sigma(\mathrm{DM}+\mathrm{DM} \to \gamma+\gamma)}{\sigma_{\mathrm{total}}}$$

$$\sim \alpha^2 \sim 10^{-4}$$

Non-thermal DM with Large σ_{total}

- Bounds on branching fraction into gamma line from BBN + CMB bound on total σ (Independent of profile) Hisano, Kawasaki, KK, Moroi, Nakayama, Sekiguchi (09)

$$\frac{\sigma_{total}}{\sigma_{\gamma\gamma}} < 700$$

- Bounds on the line (γ+γ) to continuum (WW,ZZ)

$$\frac{\sigma_{total}}{\sigma_{\gamma\gamma}} < 30 - 100$$

Cohen, Lisanti, Slatyer, Wacker(12), Buchmuller, Garny (12)

Dark Matter annihilation/decay?

$$\langle\sigma v\rangle_{\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\,\mathrm{cm}^3 s^{-1}$$

$$\tau_\gamma = 1.24^{+1.20}_{-0.44} \times 10^{28} s$$

- Morphology of the density profile?

No much differences

Jong-Chul Park and Seong Chan Park (2012)

Can DM emit gamma-rays without continuum?

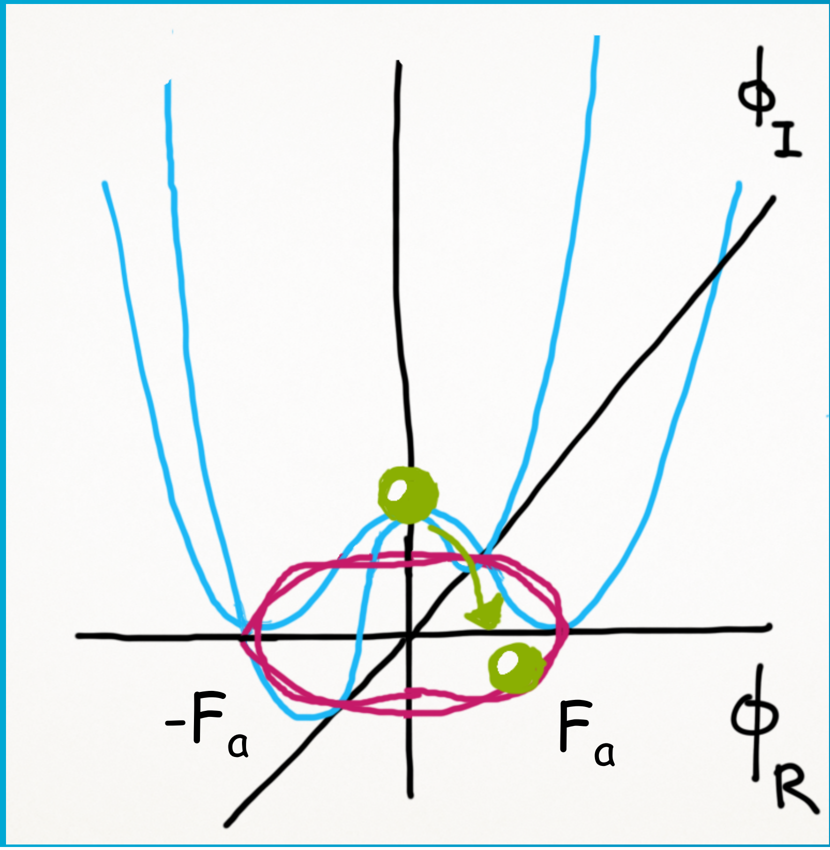
See also, Endo,Hamaguchi,Liew,Mukaida,Nakayama,arXiv:1301.7536

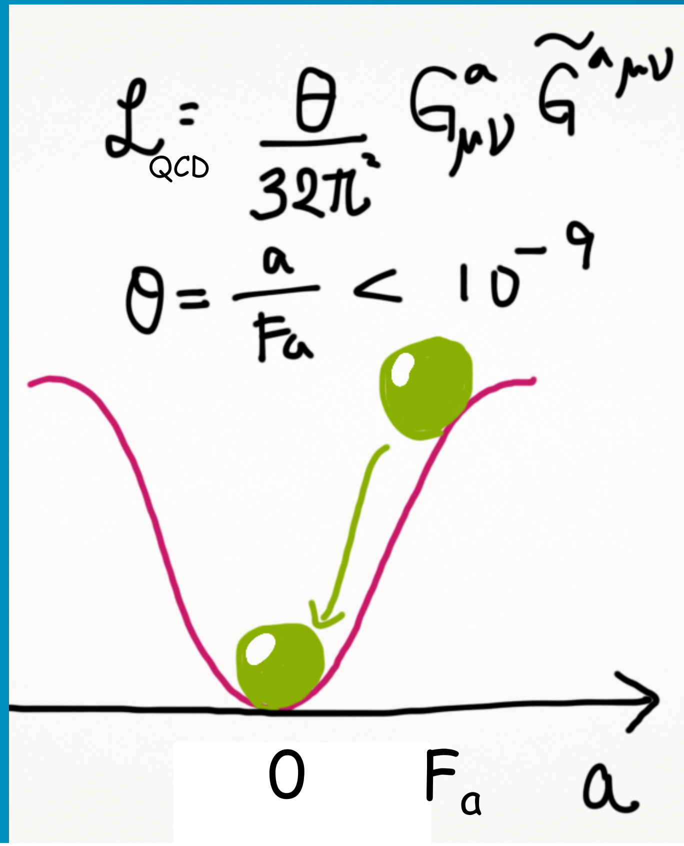
- We may use axion-photon conversion under magnetic field

Yamanaka, Kohri, Nojiri and Ioka (2013) in preparation

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 ($\Omega_a h^2 \leqq 0.1$)

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

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

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

Photon-ALP mixing in (string) axions

Axion-Like Particle (ALP)

- 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.)

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

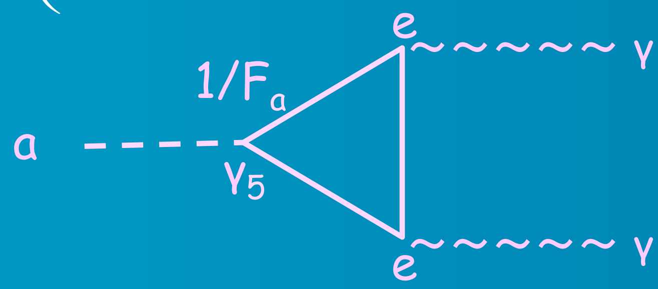
$$\left[\omega - i\partial_z - M^2/(2\omega)\right] A_j = 0$$

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)

a↔γ oscillation probability

- Probability

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

- 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 ($E>E_*$)

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

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

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

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

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 (like Hillas Condition)

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

- Oscillation length

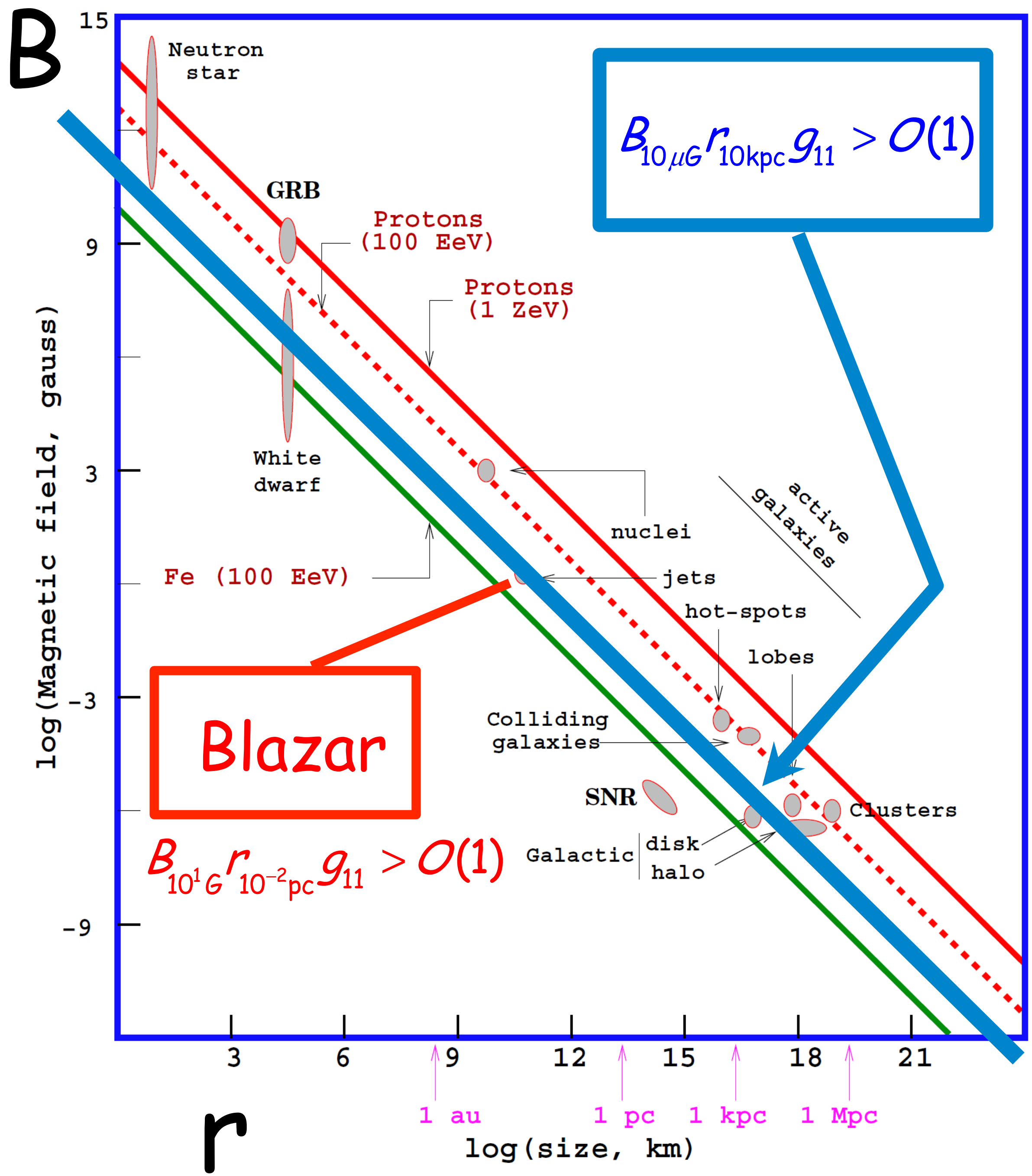
$$r_{Ha} = \frac{10\mathrm{kpc}}{g_{11}B_{10\mu G}}$$

Just within galaxy

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

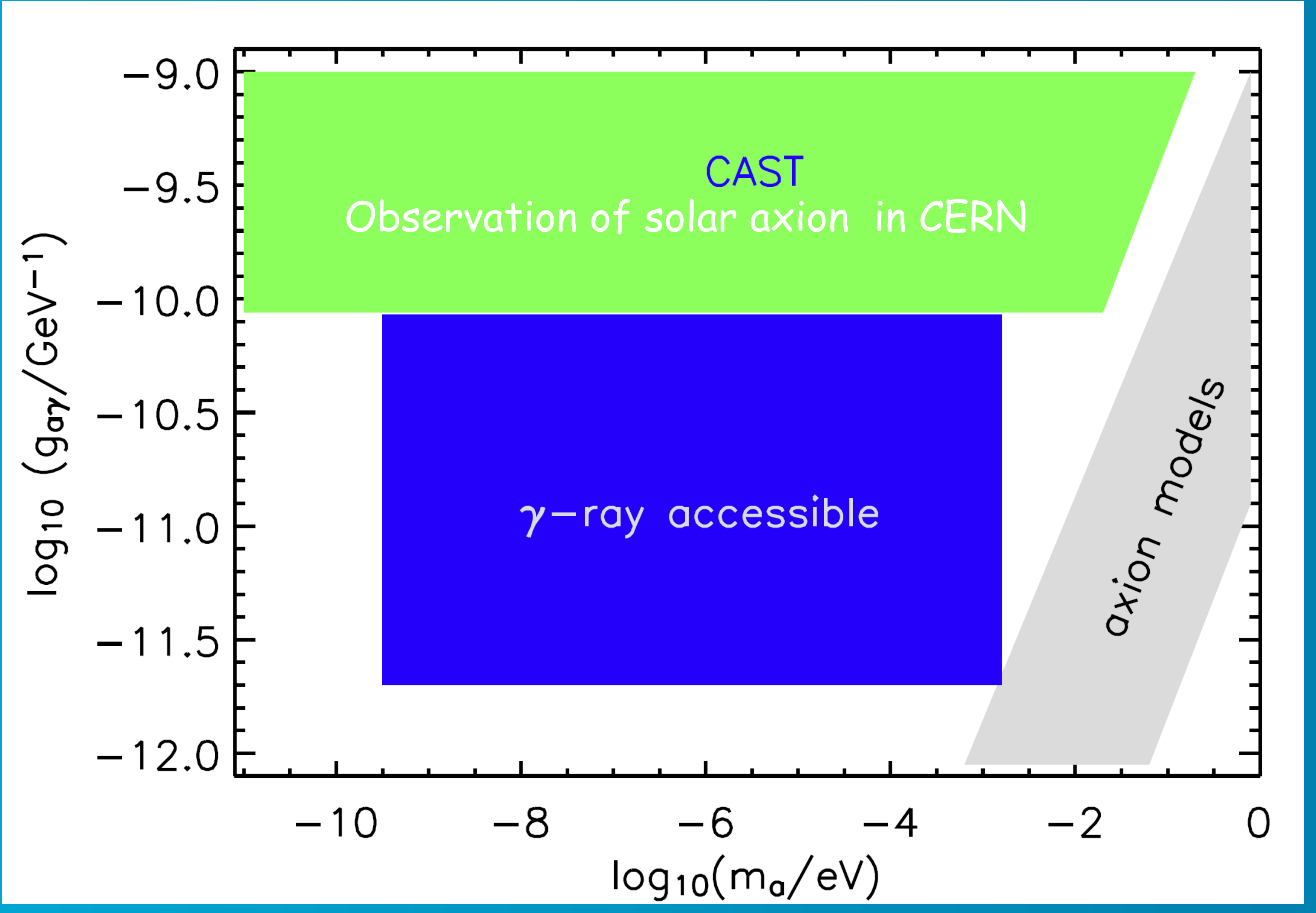
Distance from Blazars

Hillas Diagram



Hooper-Serpico (07)

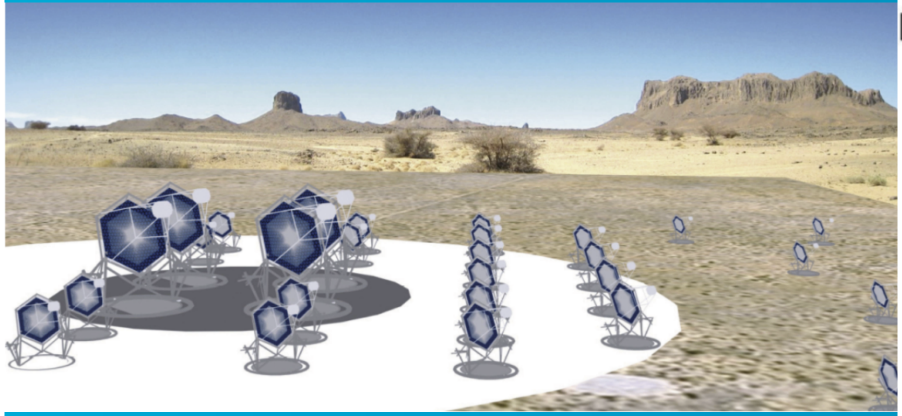
Gamma-ray accessible parameters

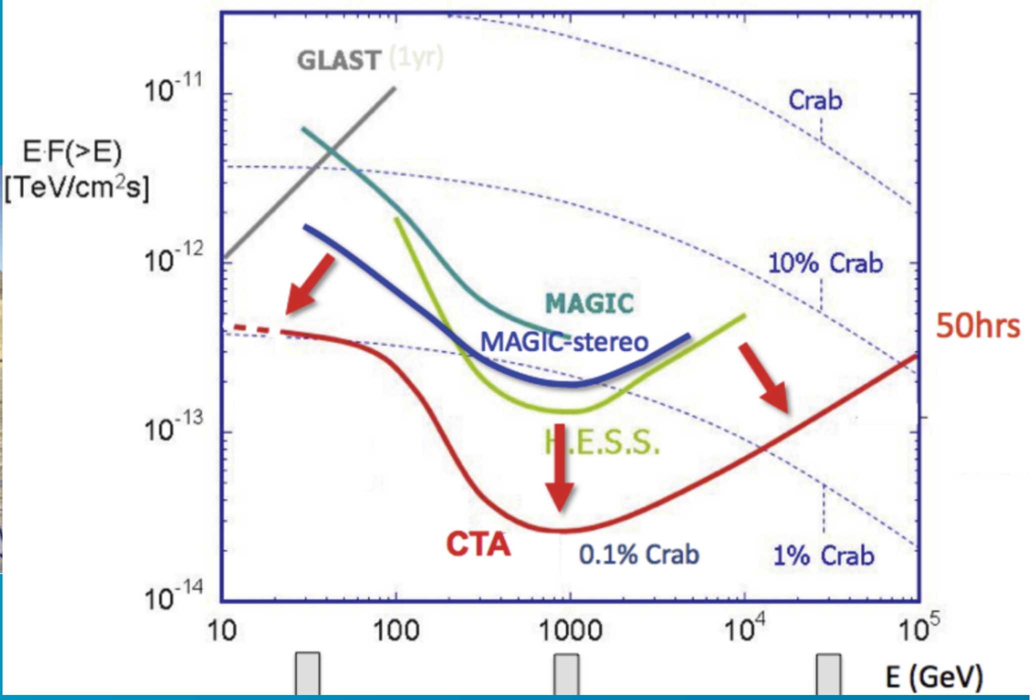


Hooper-Serpico (07)

Future TeV-gamma observation Cherenkov Telescope Array (CTA)

- One order of magnitude better sensitivity at TeV





Summary

- We have not had any clear explanations for 133 gamma-rays observed in Fermi
- We propose models in which gamma-rays can be converted from energetic axion emitted from decaying DM
- In future we will be check this scenario by CTA