Magnetic-field models and constraints on axion-like particles from the lack of irregularities in high-energy spectra

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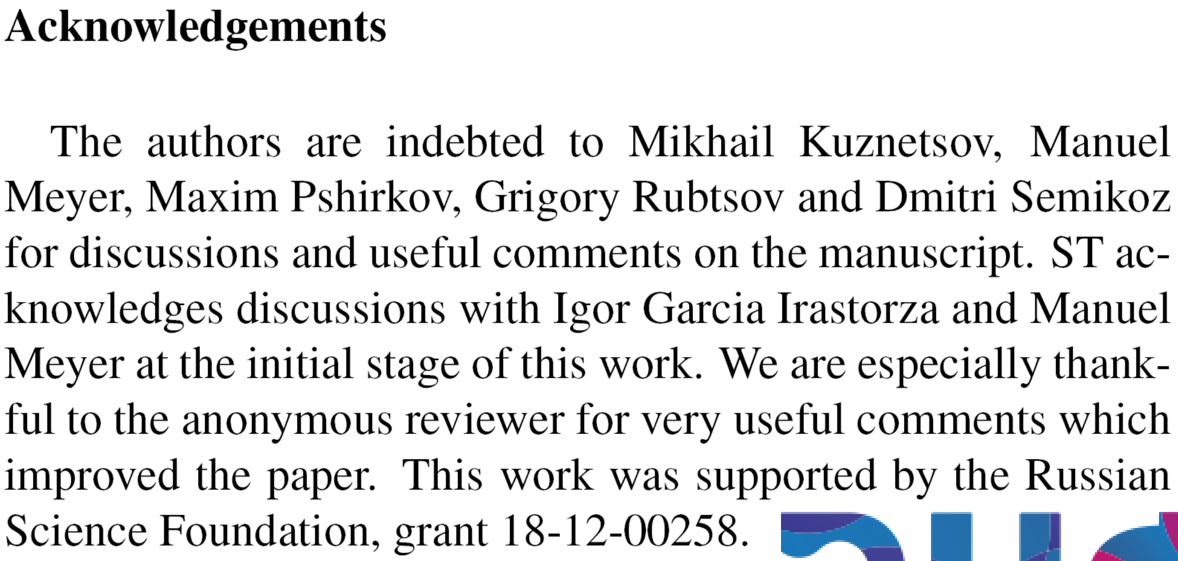

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Axion-like particles (ALPs)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}\underset{\Uparrow}{m}^2 a^2 - \frac{1}{4}\underset{\Uparrow}{g}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

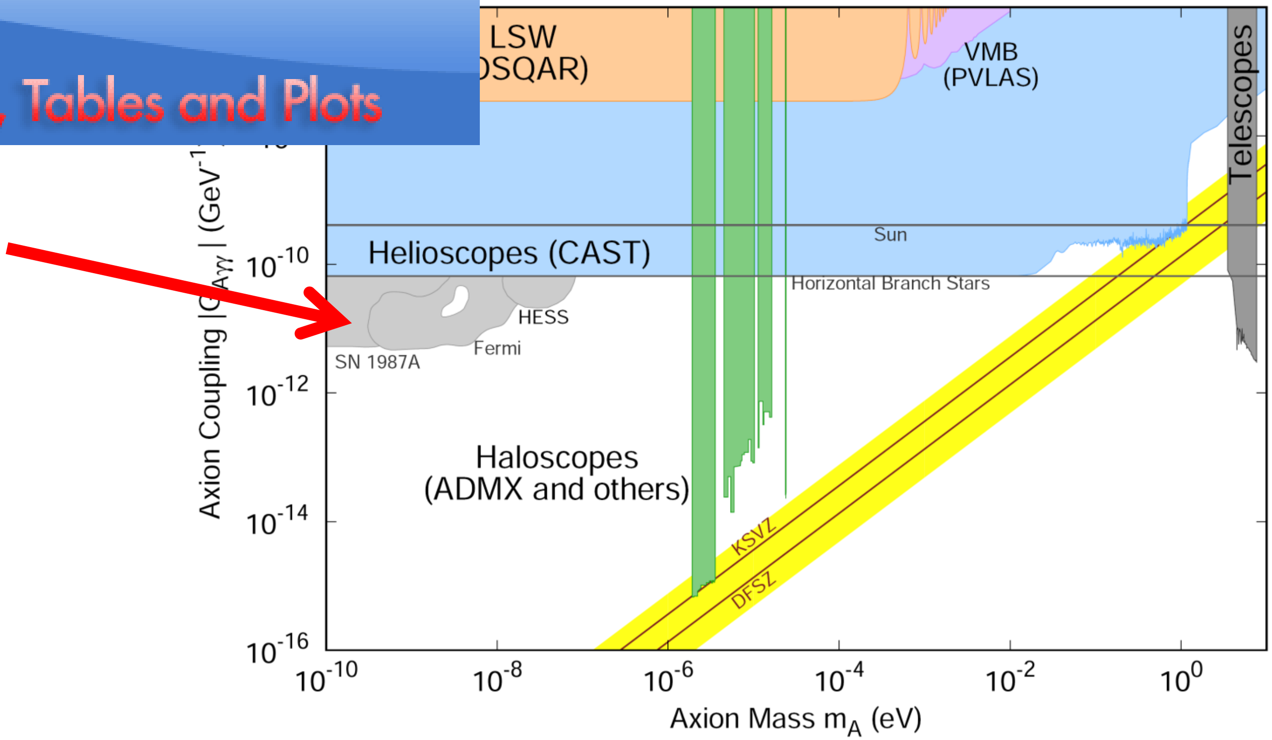
- like the QCD axion, but with independent mass and coupling
- photon-ALP mixing in external magnetic field (oscillations)
- conversion depends on mass, coupling, energy and field
- can be searched with gamma-ray astronomy

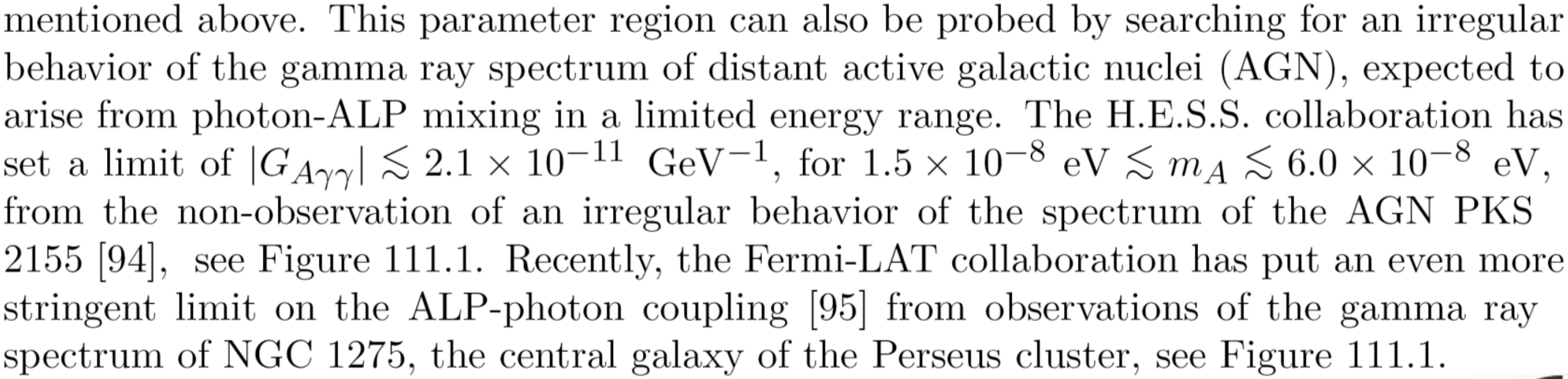
ALPs and gamma-ray astronomy

- strong mixing – “anomalous transparency of the Universe”
  - ✓conversion and reconversion helps photons to survive wrt pair production on background radiation
  - ✓deal with the overall suppression of the spectrum at high energies (low statistics)
  - ✓strong sources with firm redshifts
  - ✓indications to anomalies, unsettled

- medium-size mixing – oscillatory features in the spectrum
  - ✓energy dependence similar to neutrino oscillations
  - ✓for given ALP parameters, lower energies than “transparency”
  - ✓needs a good spectral resolution and good knowledge of the field
  - ✓strong constraints reported

PDG particle data group Reviews, Tables and Plots




mentioned above. This parameter region can also be probed by searching for an irregular behavior of the gamma ray spectrum of distant active galactic nuclei (AGN), expected to arise from photon-ALP mixing in a limited energy range. The H.E.S.S. collaboration has set a limit of $|G_{A\gamma\gamma}| \lesssim 2.1 \times 10^{-11}$ GeV^{-1}, for 1.5×10^{-8} eV $\lesssim m_A \lesssim 6.0 \times 10^{-8}$ eV, from the non-observation of an irregular behavior of the spectrum of the AGN PKS 2155 [94], see Figure 111.1. Recently, the Fermi-LAT collaboration has put an even more stringent limit on the ALP-photon coupling [95] from observations of the gamma ray spectrum of NGC 1275, the central galaxy of the Perseus cluster, see Figure 111.1.

Targets of previous searches

- NGC 1275
    - ✓good spectrum by Fermi LAT
    - ✓central radio galaxy of the Perseus cluster
    - ✓strong constraints: *Fermi LAT collaboration, PRL 2016*
    - ✓magnetic field modeled, never measured!

- PKS 2155-304
    - ✓good spectrum by HESS
    - ✓belongs to a small group of galaxies
    - ✓strong constraints: *HESS collaboration, PRD 2013*
    - ✓magnetic field modeled, never measured!

- etc.

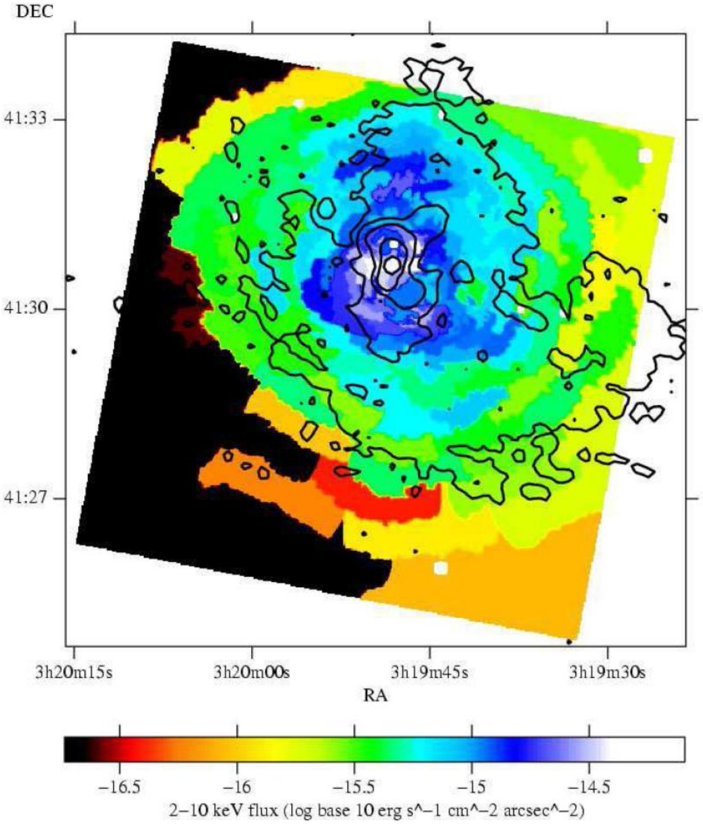
Magnetic-field model dependence

- Example of Fermi-LAT constraints from NGC 1275
  - ✓Fermi LAT assumed purely **turbulent** field with 6 free parameters
  - ✓normalization indirectly related to observations, other parameters fiducial

  - ✓ central radio galaxy is expected to have large-scale **regular** field
  - ✓ X-ray cavity (radio mini-halo) observed around NGC 1275

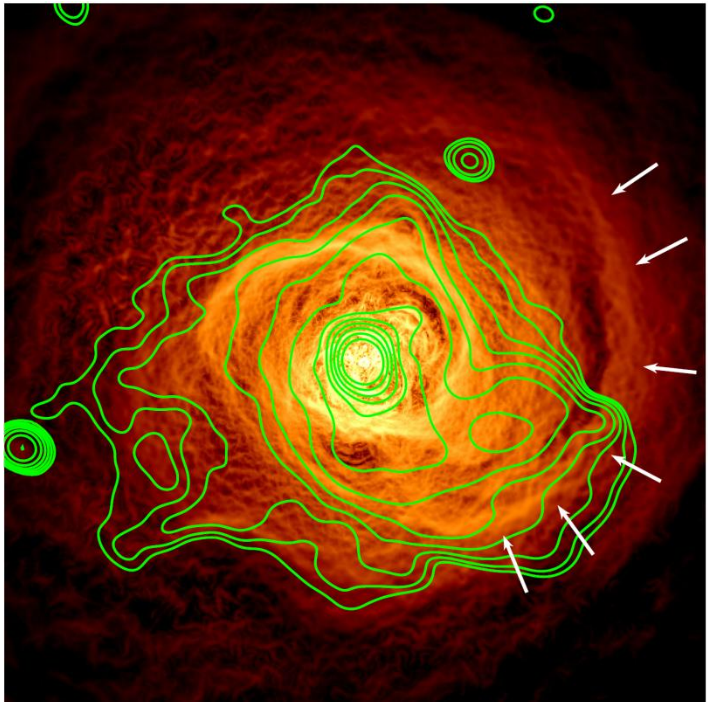
- ➢ **take another model of the Perseus cluster magnetic field (purely regular field of the X-ray cavity)**
- ➢ **obtain constraints on ALP parameters and compare them with those obtained with the Fermi-LAT field model**
- ➢ **resulting constraints are orders of magnitude weaker!**
- ➢ **the actual field is an unknown combination of regular and turbulent components**
- ➢ **the method is good, but sources with measured fields should be used!**

The X-ray cavity / radio mini-halo in Perseus



CHANDRA 2-10 keV

Sanders, Fabian, Dunn 2005

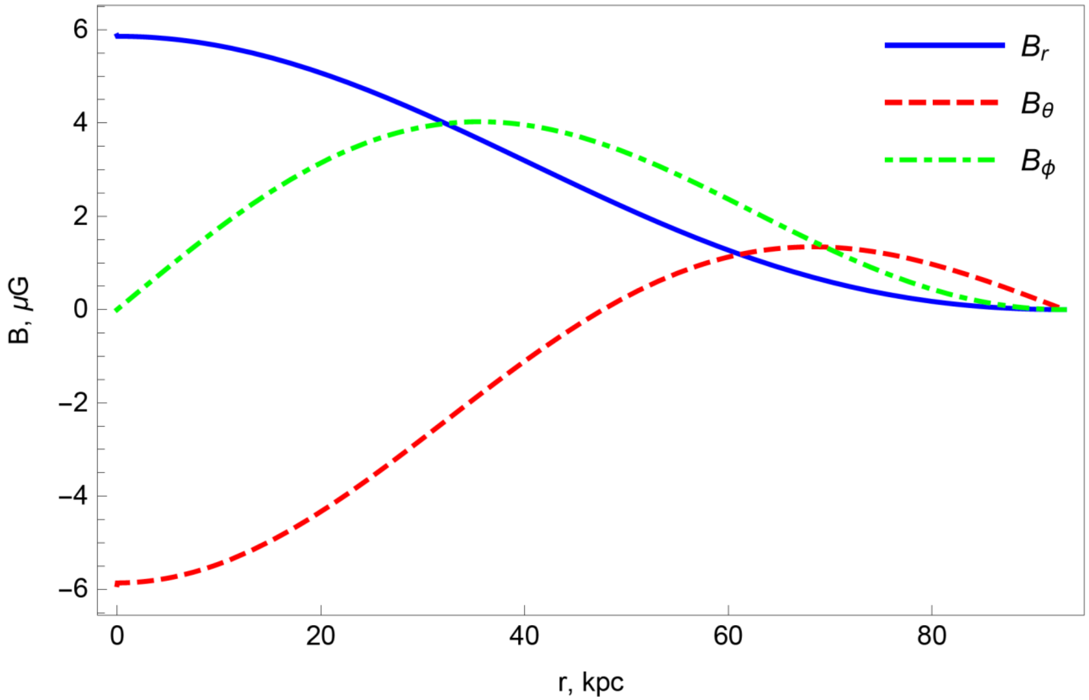


VLA 270-430 MHz

Gendron-Marsolais et al. 2017

The X-ray cavity magnetic field

Gourgouliatos, Braithwaite and Lyutikov 2010



$$B_r = 2\cos\theta f(r_1)/r_1^2,$$

$$B_\theta = -\sin\theta f'(r_1)/r_1,$$

$$B_\phi = \alpha\sin\theta f(r_1)/r_1,$$

where

$$f = C\left(\alpha\cos(\alpha r_1) - \sin(\alpha r_1)/r_1\right) - F_0 r_1^2/\alpha^2,$$

$$F_0 = C\alpha^2\left(\alpha\cos\alpha - \sin\alpha\right),$$

α is the lowest nonzero root of $\tan\alpha = 3\alpha/(3-\alpha^2)$, $r_1 \equiv r/R$

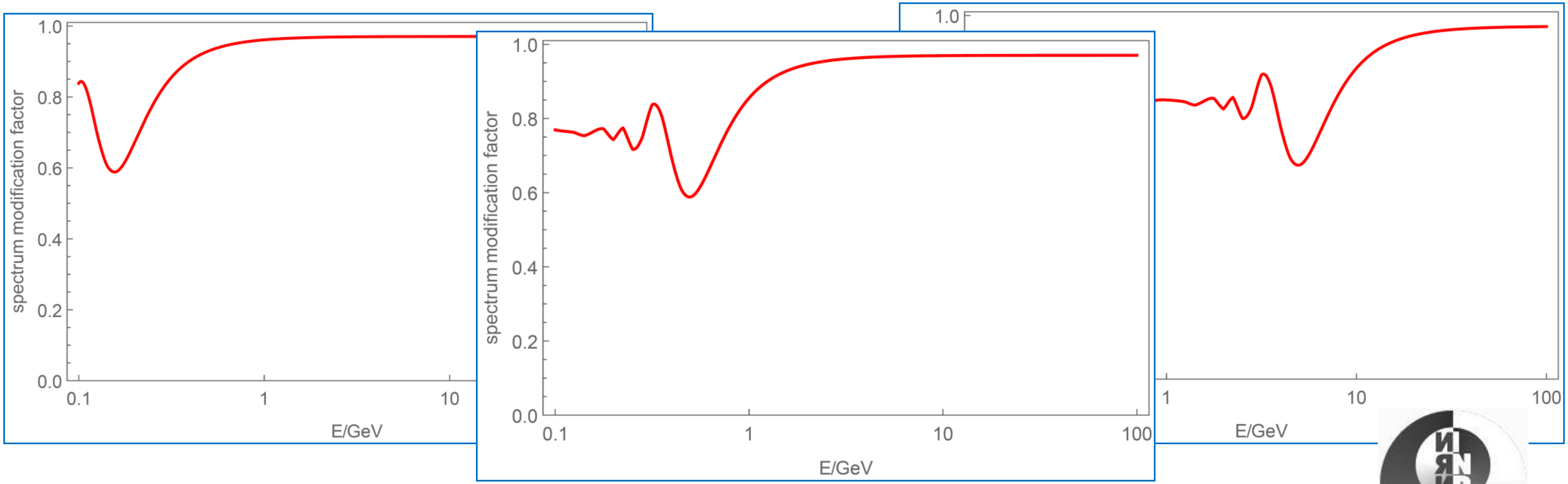
[*Pshirkov et al.* Galactic field added]

Spectral irregularities

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m^2a^2 - \frac{1}{4}gaF_{\mu\nu}\tilde{F}^{\mu\nu}$$

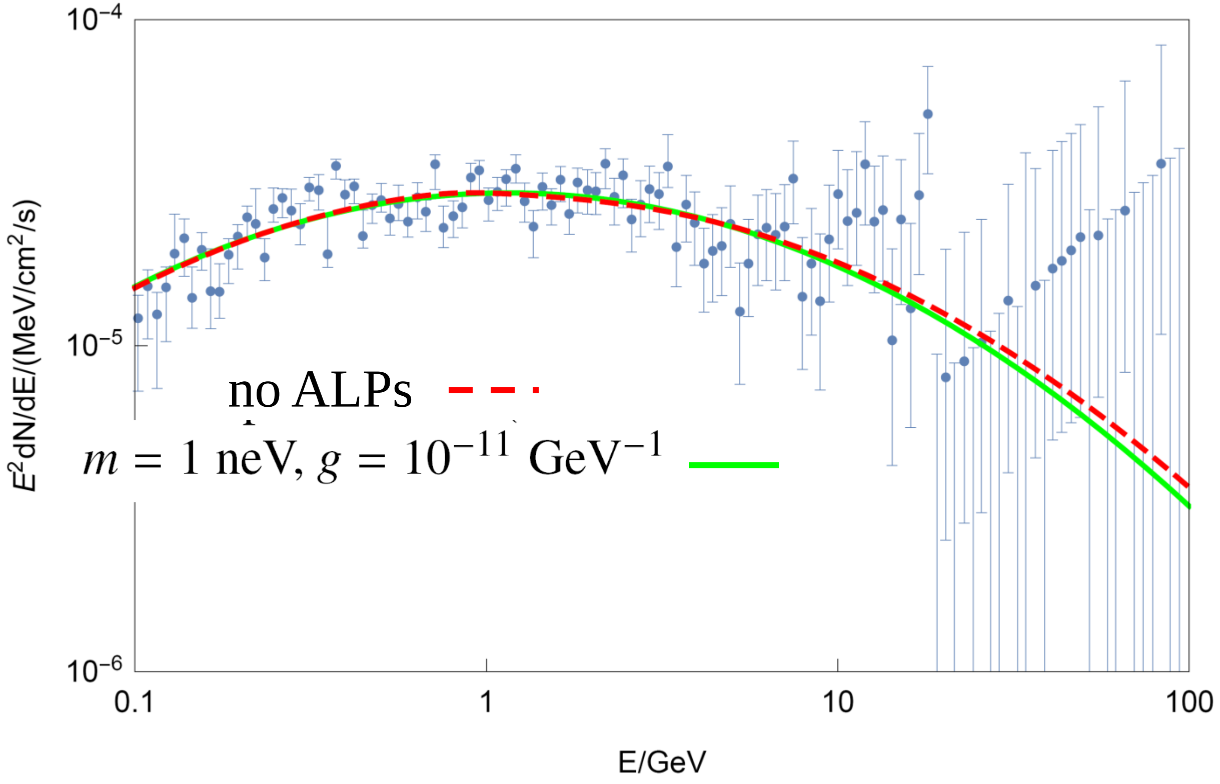
$$i\frac{d\rho(y)}{dy} = \left[\rho(y), \mathcal{M}(E,y)\right], \qquad \mathcal{M} = \frac{1}{2}\begin{pmatrix} 0 & 0 & -igB_\theta \\ 0 & 0 & -igB_\phi \\ igB_\theta & igB_\phi & \frac{m^2}{E} \end{pmatrix}$$

$$\rho(0) = \mathrm{diag}\,(1/2, 1/2, 0) \quad \Rightarrow \quad \rho_{11}(y) + \rho_{22}(y)$$



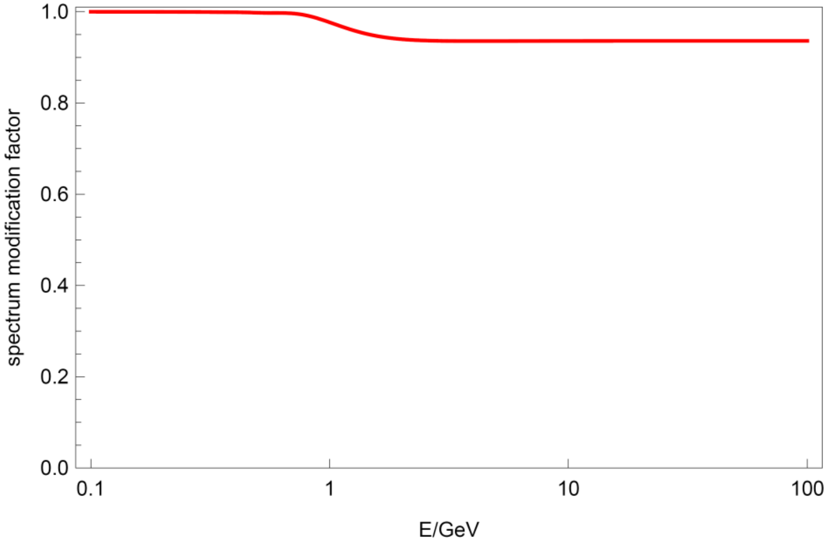
Comparison to Fermi-LAT data

fit log-parabola $F(E) = F_0\,(E/E_0)^{-(\alpha+\beta\log(E/E_0))}$ times modification factor to data



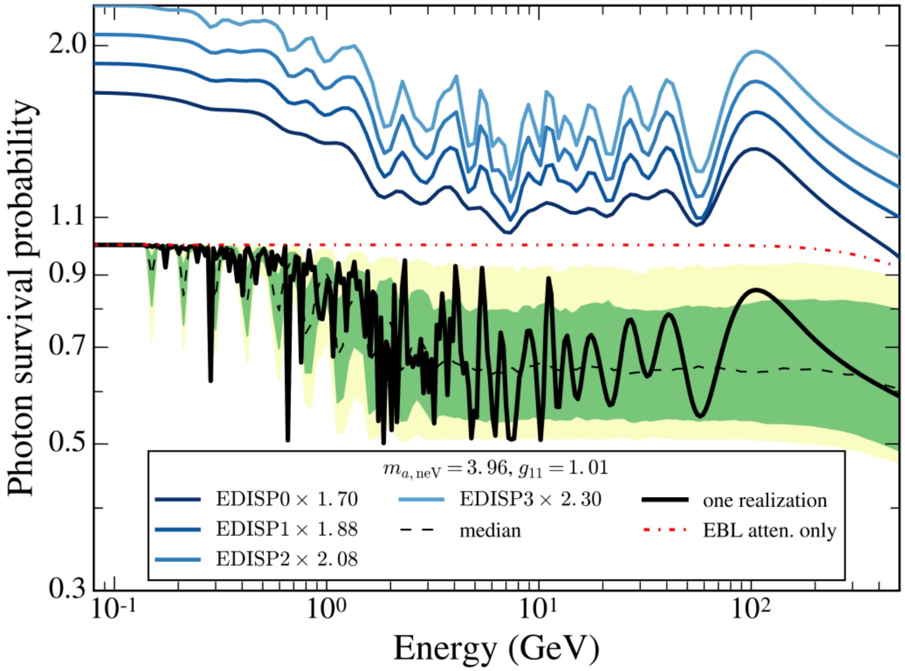
both fits are good, but these *m* and *g* are excluded for the Fermi-LAT field model!

Why?!

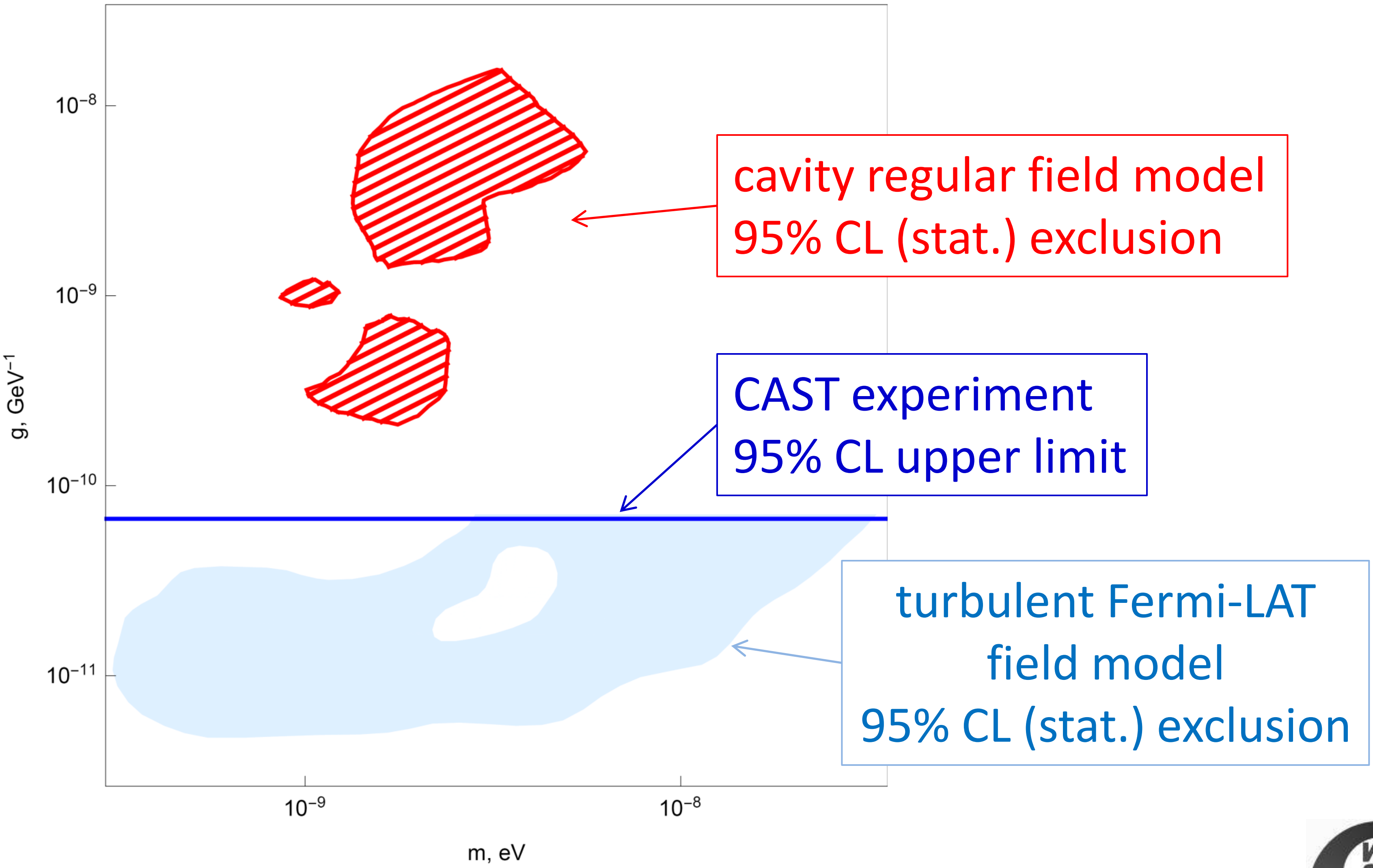


regular cavity field model

turbulent Fermi-LAT field model



Comparison of 95% CL (stat.) constraints

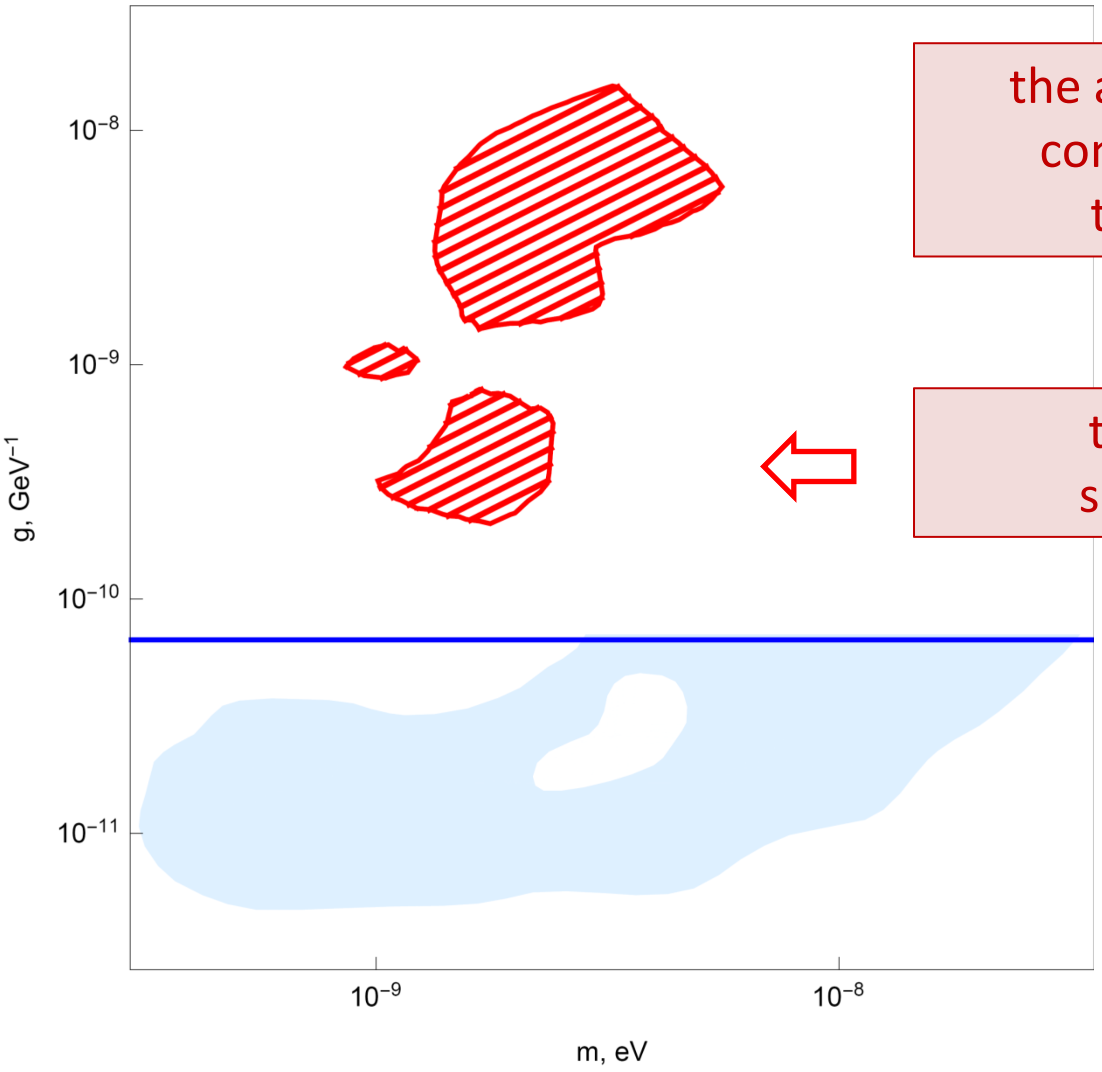


cavity regular field model
95% CL (stat.) exclusion

CAST experiment
95% CL upper limit

turbulent Fermi-LAT
field model
95% CL (stat.) exclusion

Comparison of 95% CL (stat.) constraints



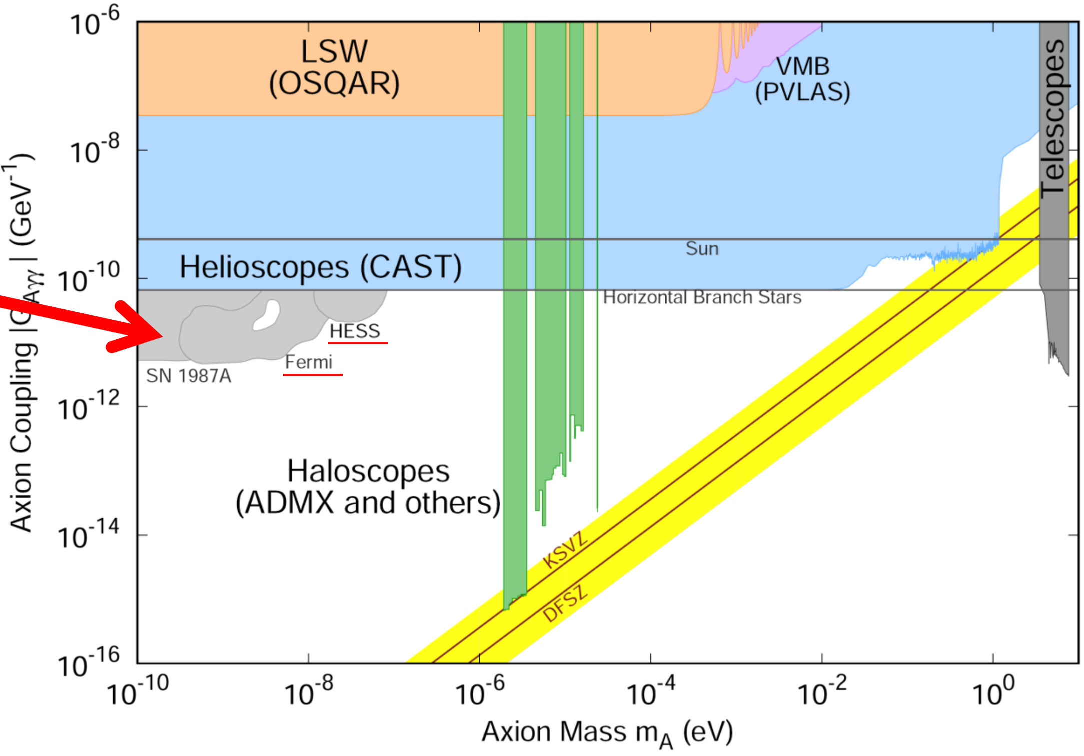
the actual field is an unknown combination of regular and turbulent components

the actual constraint is somewhere in between

Conclusions

- to use the spectral irregularities to give a certain CL constraint on particle properties, one needs not only a good spectrum but also *measured* magnetic fields

- constraints obtained before (e.g. Fermi LAT and HESS) are subject to orders-of-magnitude systematic uncertainties



- corresponding parameter space awaits future studies - ALPS-IIc, TASTE, babyIAXO...