Axion discovery opportunities: from microwaves to high energy astrophysics

Pasquale D. Serpico

Laboratoire Leprince-Ringuet, Paris 12 Jan. 2009

Outline

- Introduction to the strong CP problem & solutions: the birth of axions
(and some alternatives?)

- Axions & Cosmology
(or… how to turn a problem into a resource)

- Short Summary of Past/Current Searches for (Invisible?) “Axions”
(Haloscopes, Helioscopes, Lasers… and Lightsabers)

- New astronomy window: GeV-TeV sky!
We discuss how and why “axion” particles might have a measurable effect on high energy gamma spectra, with some characteristic signatures

The Strong CP problem

$$L_{CP} = \theta \frac{N_f g^2}{32\pi^2} Tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Standard QCD Lagrangian contains a CP violating term

$$\theta \to \bar{\theta} = \theta - Arg(\det M_q)$$

Due to non-trivial topological structure of QCD vacuum, $0<\theta_{QCD}<2\pi$

Phase "rotated away" from quark mass matrix (complex couplings in Higgs sector)

$\bar{\theta}$ induces a neutron EDM violating experimental limits unless $\bar{\theta}<10^{-10}$

One way to see this is to "remove" the θ–term and replace it via the "mass-term"

$$i\bar{\theta}\frac{m_u m_d}{m_u + m_d}(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d) \quad (2 \;\; flavours)$$

Again, one of the nasty "fine-tuning" problems of the SM asking for an explanation (like hierarchy, baryon asymmetry…)

Is the term there in the first place?

No easy way around accepting the reality of that "topological" term in QCD

the presence of this anomaly is required to solve the "U(1) problem":
QCD for 3-massless quarks has a symmetry

$$U(3)_L \otimes U(3)_R = U(1)_V \otimes SU(3)_V \otimes U(1)_A \otimes SU(3)_A$$

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B-number conservation

$SU(3)_{flavor}$
(exact in $m_q \rightarrow 0$ limit)

"Chiral" SSB,
"light" meson octet
(massless in $m_q \rightarrow 0$ limit)

If broken by "chiral" SSB,
meson octet$\rightarrow$ nonet
Anomaly means no quantum
symmetry in the first place,
explains $m(\eta') \sim 2\, m(\eta)$!

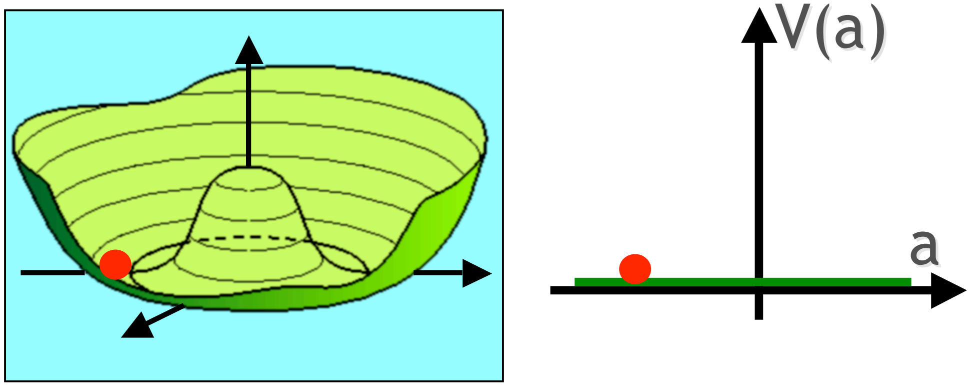
Let's explore some physical explanations for the smallness of θ

Axions: θ → a/f$_a$

- One cannot solve the problem with known symmetries. Peccei, Quinn '77 proposed to solve it by a new axial $U(1)_{PQ}$ symmetry (1977), requiring a second Higgs doublet. This simmetry is spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode (Weinberg,Wilczek '78)

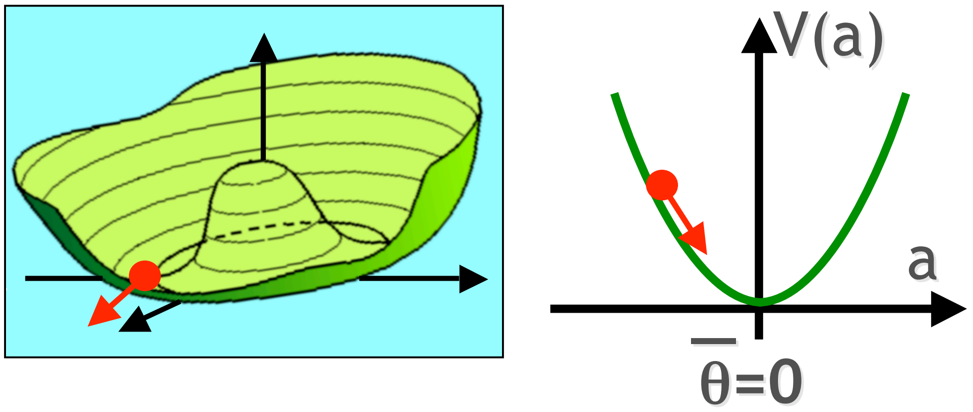
At $E \approx f_a$

- $U_{PQ}(1)$ spontaneously broken
- The axion is the m=0 (Goldstone) mode settling at some value "θ" in the "Mexican hat"



At $E \approx \Lambda_{QCD} \ll f_a$

- $U_{PQ}(1)$ explicitly broken by chiral SSB & the Mexican hat tilts
- In the potential induced by L_{CP} the (now-massive) a(x) dynamically restores the CP-conserving minimum



Alternative solutions?

- If one quark is massless, the phase is unphysical: but appears excluded!

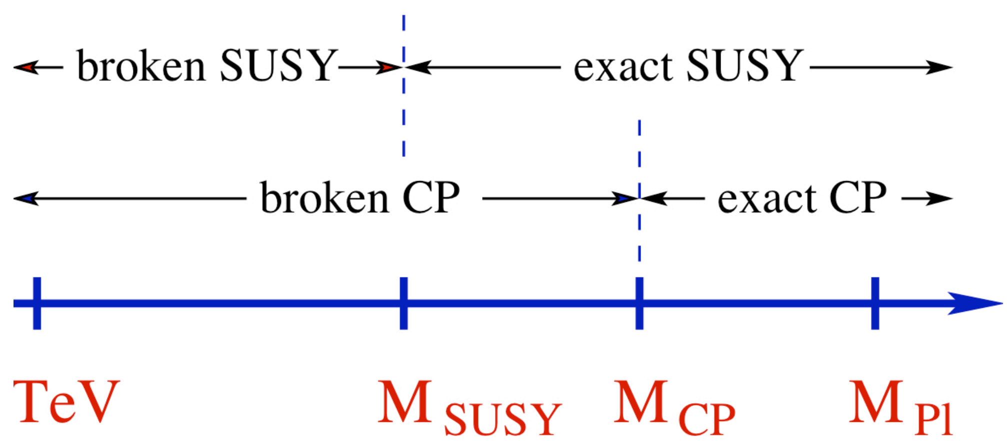
$$i\bar{\theta}\,\frac{m_u m_d}{m_u + m_d}(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d) \quad (2\ \ flavours)$$

Spontaneous CP-violation

- No CP-violation at high scale, only *induced* after SSB.
- Very high scale required (before Inflation) to avoid cosmological problems
- Suppressing θ at leading order is not enough ($<10^{-10}$!)
- Needs to account for weak CP violation! Independent mechanism?
- Some (often involved) mechanism required

Example: use SUSY breaking at "low scale". No strong CP problem due to SUSY non-renormalization theorem. KM phase "unprotected", can be generated already after CP breaking

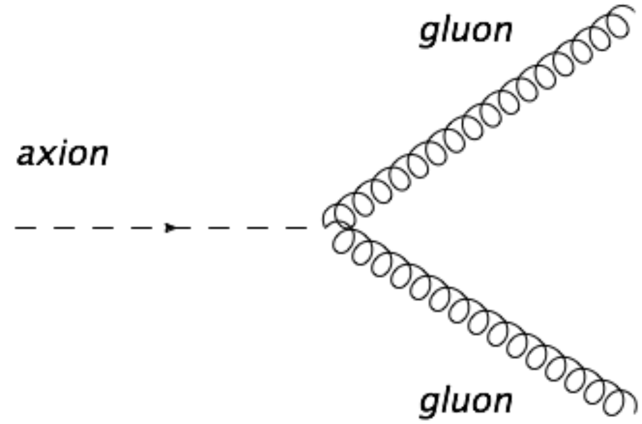
G. Hiller and M. Schmaltz,
Phys. Rev. D 65, 096009 (2002)



How to detect axions? Couplings…

"Defining coupling": Axions generically couple to gluons and mix with π^0

$$L_{agg} = \frac{\alpha_s}{8\pi\ f_a} a\, G_{\mu\nu} \tilde{G}^{\mu\nu}$$



- they can couple to fermions, but more model-dependent (especially for leptons)
- Axions satisfy $m_\pi f_\pi \approx \kappa\ m_a f_a$ where one expects $\kappa \sim O(1)$
- effective 2-γ coupling $g_{a\gamma\gamma} = \xi\ \alpha/2\pi f_a \propto m_a$ (important for phenomenology)

If EW scale, $f_a \approx$ Higgs vev & $m_a \approx 0.01$-1 MeV. Negative results from Lab searches

"Beam Dump", $K^+ \to \pi^+ a$, $\pi^+ \to e^+ \nu\, a$, $J/\psi^+ \to \gamma\, a$,… eventually followed by $a \to \gamma\gamma$

For $f_a \gg f_\pi$ Invisible axions, "super-weakly" coupled, long-lived, very light.

Most searches use $g_{a\gamma\gamma}$. Both at production & detection a factor f_a^{-2} is involved

→ usually indirect searches or astrophysical/cosmological production

Axions as cold dark matter

• To avoid the formation of "domain walls" with different values of θ_i , usually cosmology requires that inflation takes place after $U(1)_{PQ}$ breaking.

• When $T \lesssim \Lambda_{QCD}$ axions the potential tilts, and the energy stored in the "offset" position of θ_i converts into "coherent oscillations of the a field" → behaves as non-relativistic, cold gas of axions. Abundance given by

$$\Omega_{a,\mathrm{mis}}\, h^2 \simeq 0.1\, \bar{\theta}^2 \left(\frac{\Lambda_{\mathrm{QCD}}}{200\,\mathrm{MeV}}\right)^{-0.7} \left(\frac{m_a}{10\,\mu\mathrm{eV}}\right)^{-1.18}$$

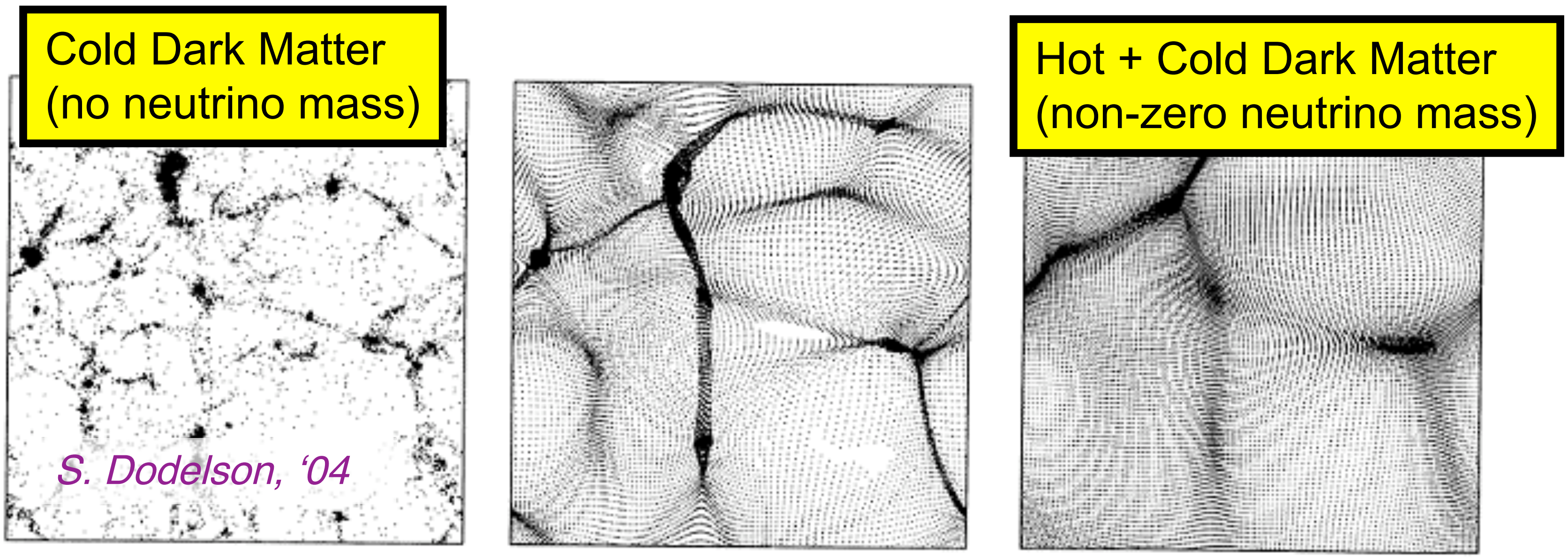
• *Note*: Dark matter fraction not calculable from first principles: random number chosen by process of spontaneous symmetry breaking (→ anthropic arguments?)

• Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation. Strong CMBR bounds on isocurvature fluctuations. Scale of inflation required to be $\lesssim 10^{13}$ GeV Beltrán, García-Bellido & Lesgourgues hep-ph/0606107

Axions as a hot dark matter component

• For axion couplings corresponding to ~eV-range masses, a thermal population will arise "late" due to hadron-hadron scattering, in particular $\pi\,\pi \rightarrow \pi\, a$

• Low-mass thermal relics affect structure formation as hot dark matter, e.g. ν's



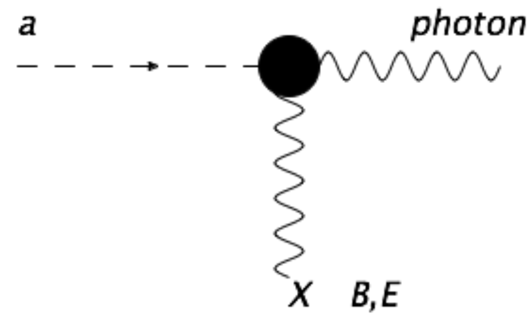
• Limit from CMB, LSS, etc. of the order m_a < 1.0 [0.4 eV] (95% CL)

Hannestad et al. arXiv:0803.1585 [Melchiorri et al. arXiv:0705.2695, if Lyα used]

Lab tests of "invisible" axions

- Basic Process: Axions-photon transitions in external E or B field (originally discussed for π^0 by Henri Primakoff, 1951)

P. Sikivie, PRL 51,16 (1983)



➢ Stellar Constraints:

Processes in the plasma (including Primakoff production) produce axions; limits can be put from avoiding excessive energy drain

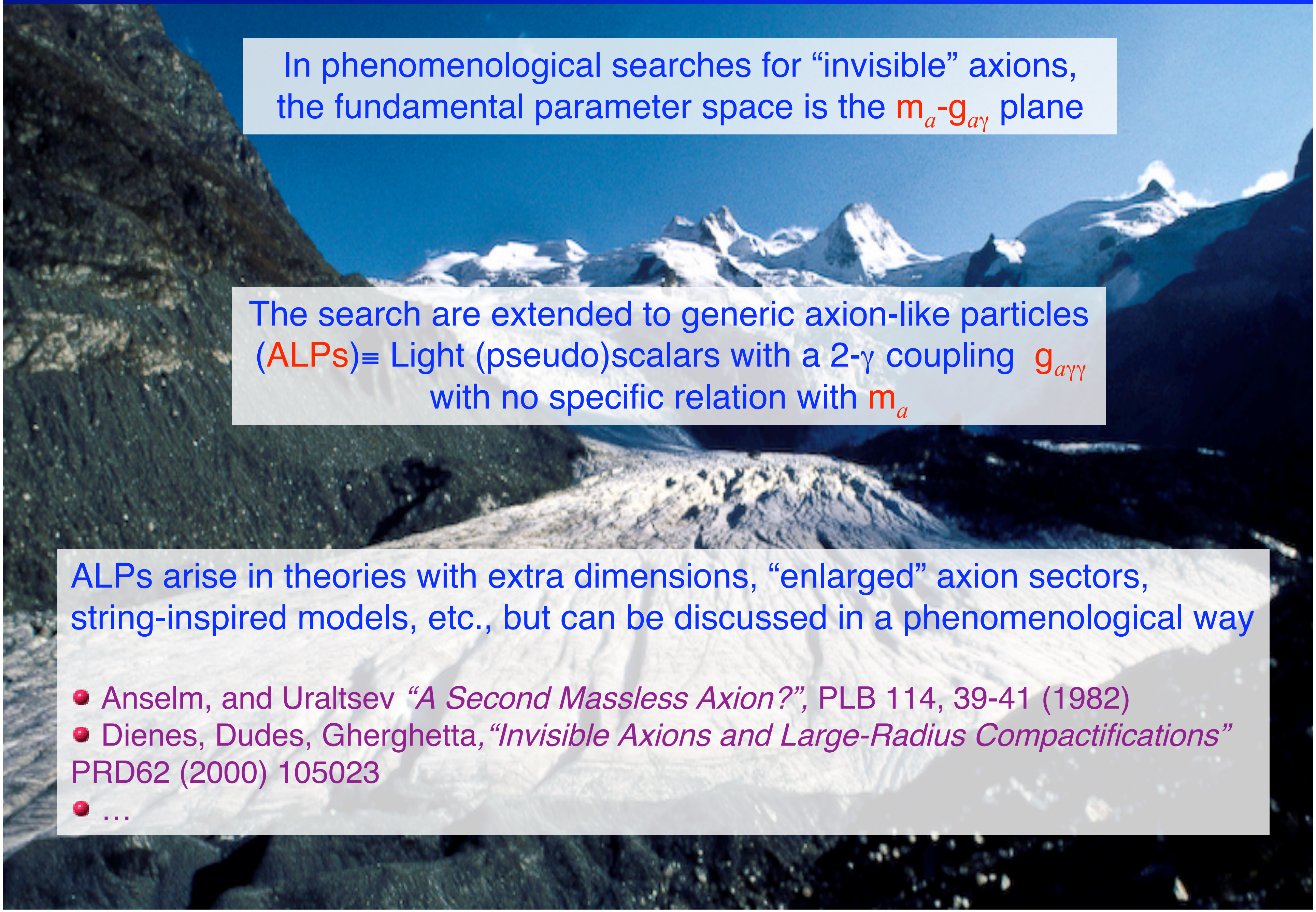
➢ Axion helioscope:

Look at the Sun through a dipole magnet. Macroscopic, static B-field can provide a large coherent transition rate over a big volume (low-mass axions)

➢ Axion haloscope:

Look for cold dark-matter axions with a microwave resonant cavity

From axions to ALPs



In phenomenological searches for “invisible” axions, the fundamental parameter space is the m_a-$g_{a\gamma}$ plane

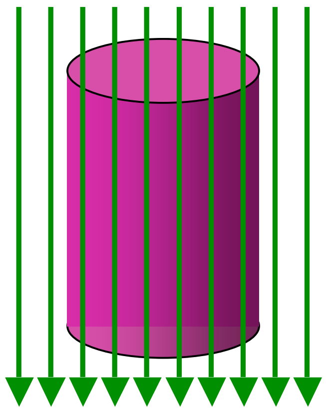
The search are extended to generic axion-like particles (ALPs)≡ Light (pseudo)scalars with a 2-γ coupling $g_{a\gamma\gamma}$ with no specific relation with m_a

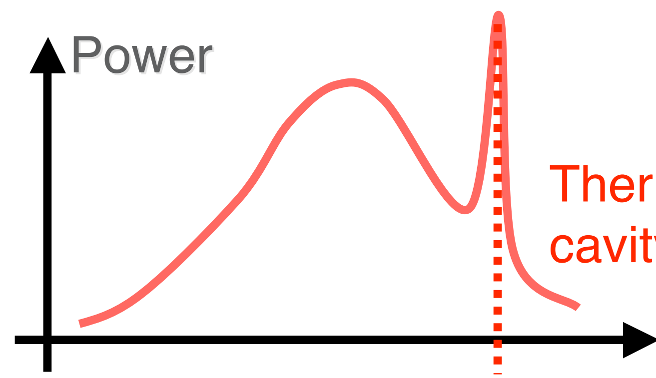
ALPs arise in theories with extra dimensions, “enlarged” axion sectors, string-inspired models, etc., but can be discussed in a phenomenological way

- Anselm, and Uraltsev *“A Second Massless Axion?”,* PLB 114, 39-41 (1982)
- Dienes, Dudes, Gherghetta*,“Invisible Axions and Large-Radius Compactifications”* PRD62 (2000) 105023
- …

Haloscopes: searches for Cold Dark Matter Axions

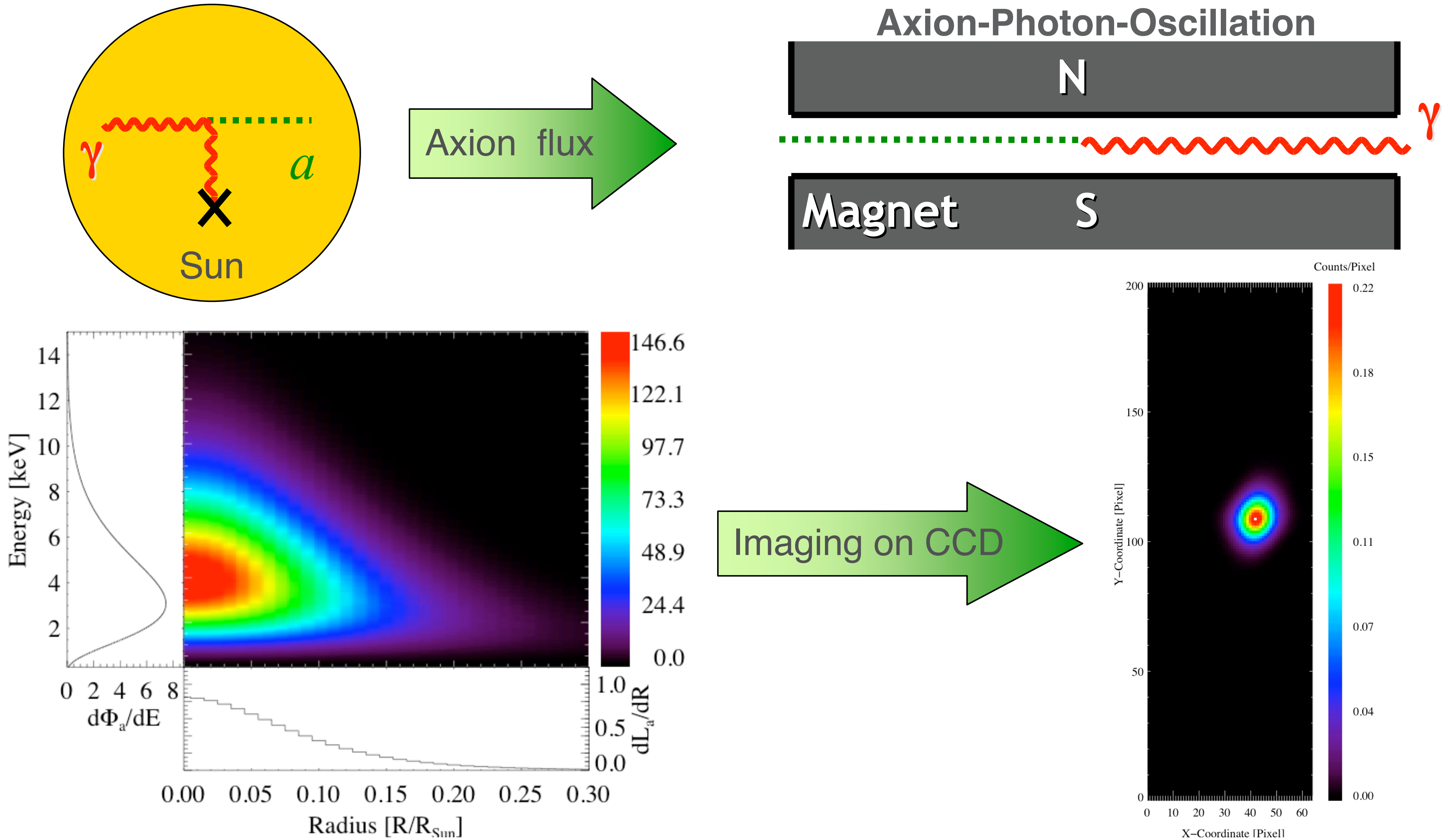
m_a = 1-1000 μeV → Resonance at Microwave Energies (1 GHz ≈ 4 μeV)
$v_a \approx 10^{-3}$ c → $E_a \approx (1 \pm 10^{-6})\, m_a$ → very, very narrow!





Currently pursued by ADMX (LLNL, Florida, Berkeley, NRAO)
To probe higher masses, higher frequency cavities must be developed
Significant R&D needed (partially in progress)

Helioscopes: searches for Solar axions

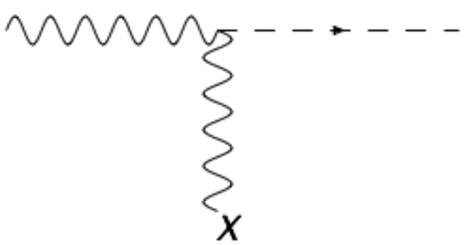


- Tokyo Axion Helioscope ("Sumico")
- CERN Axion Solar Telescope (CAST)

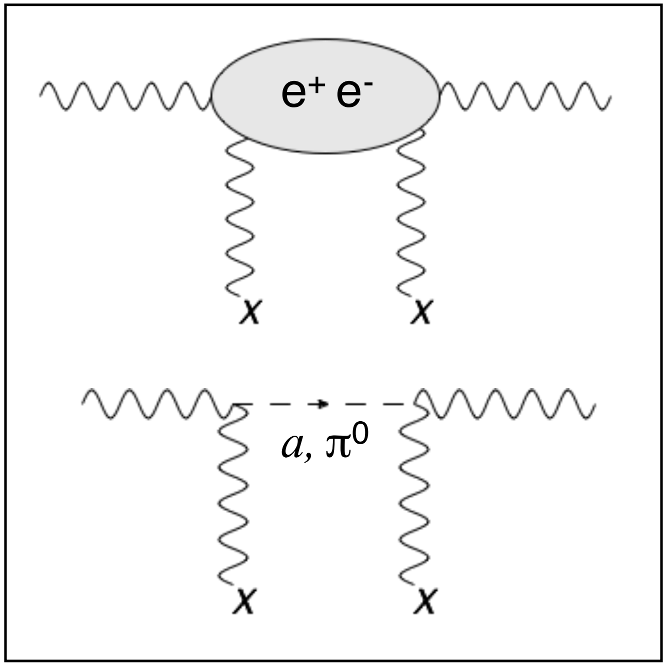
Alternative: Bragg conversion in crystal
Bounds from WIMP DM experiments!
(SOLAX, COSME, DAMA, CDMS...)

Pure Lab bounds from Laser Experiments

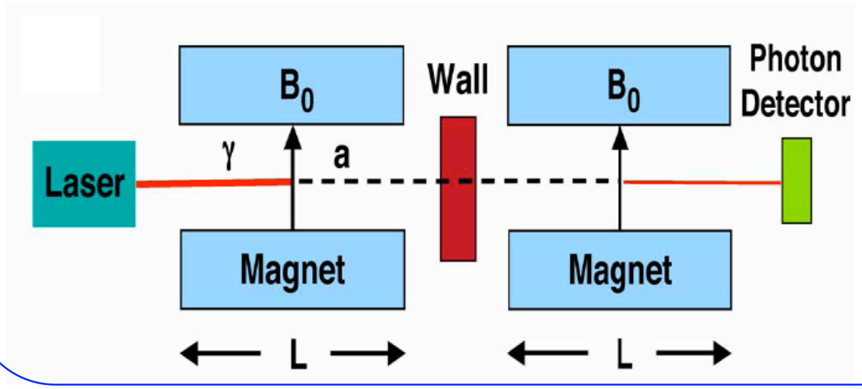
Dichroism
Rotation of plane of polarization by *loss of one component* into ALP channel when Passing through a B-field



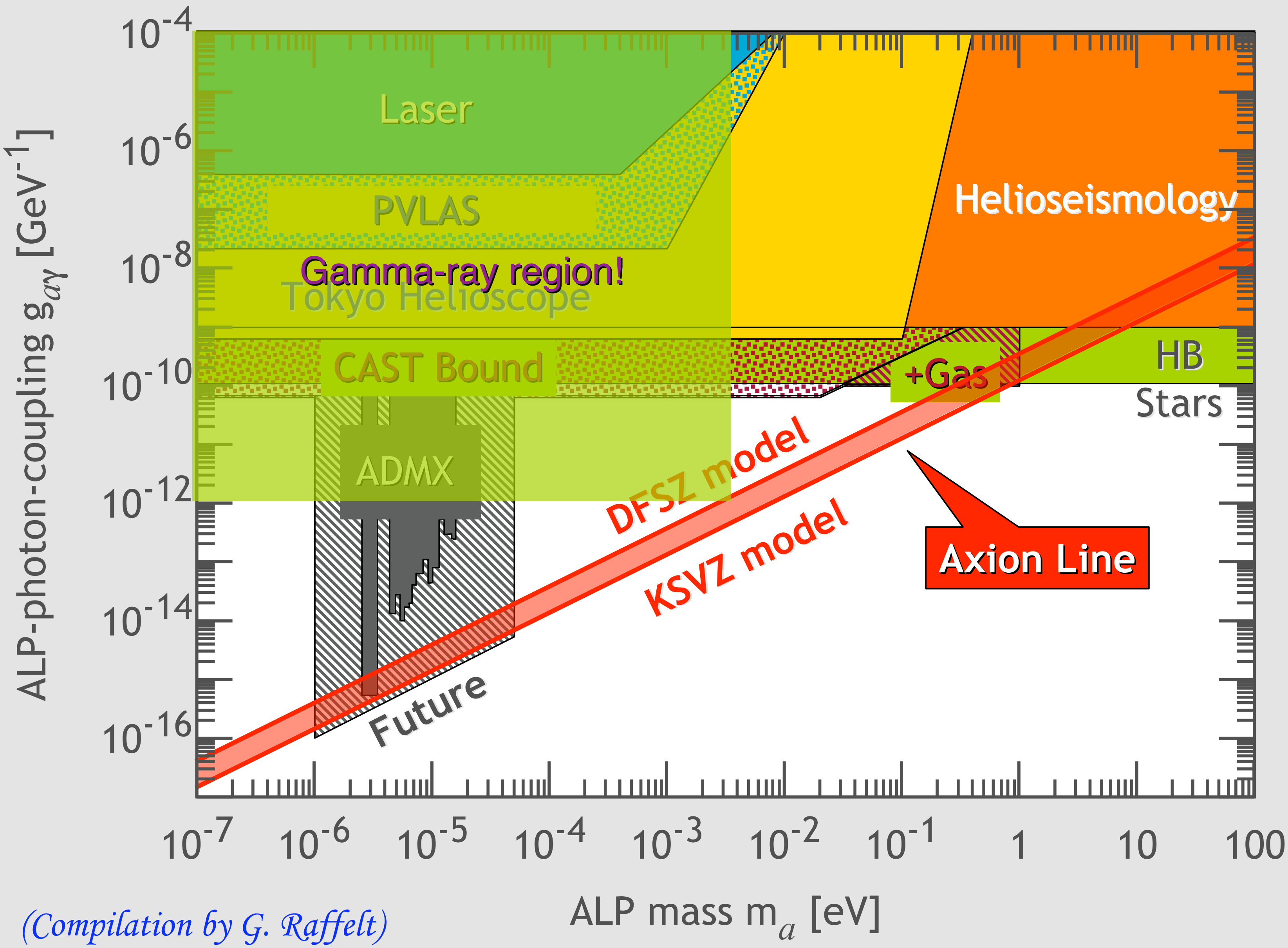
Birefringence
Magnetically induced in vacuum: Ellipticity of beam that was originally linearly polarized (in matter: Cotton-Mouton effect, in vacuum: also caused by QED)



"Shining light through a wall"

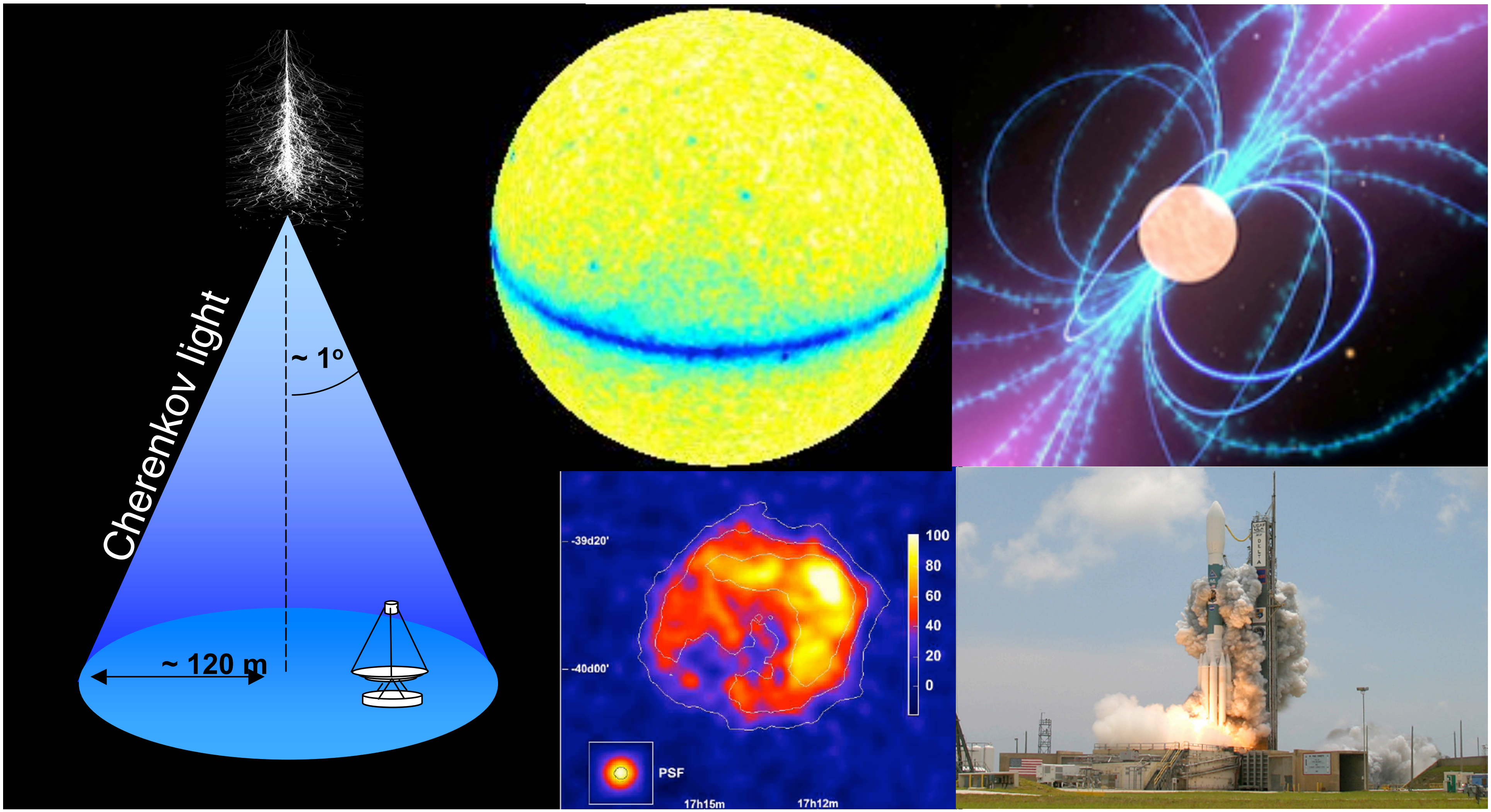


Limits on ALP-photon coupling vs. mass

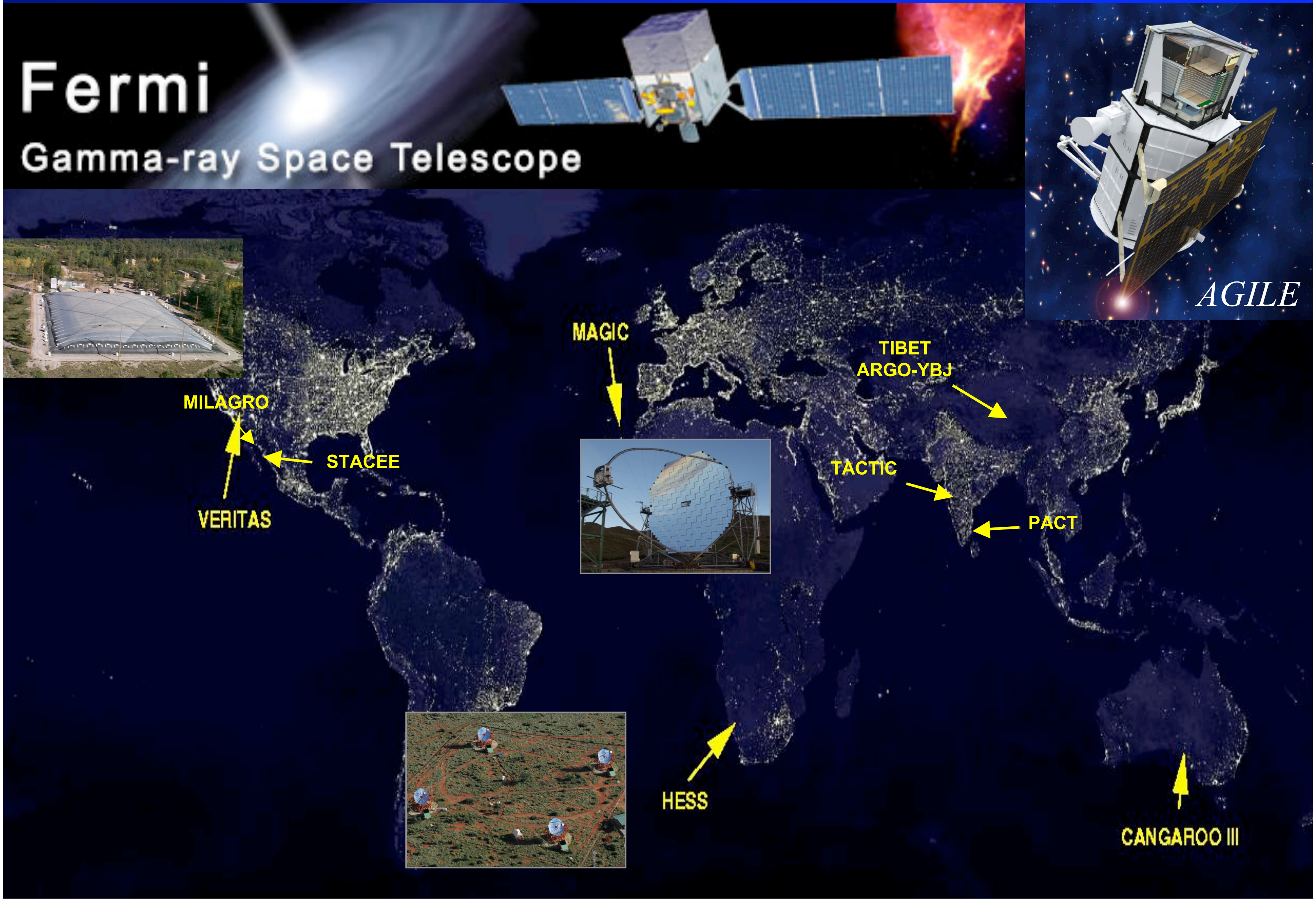


(Compilation by G. Raffelt)

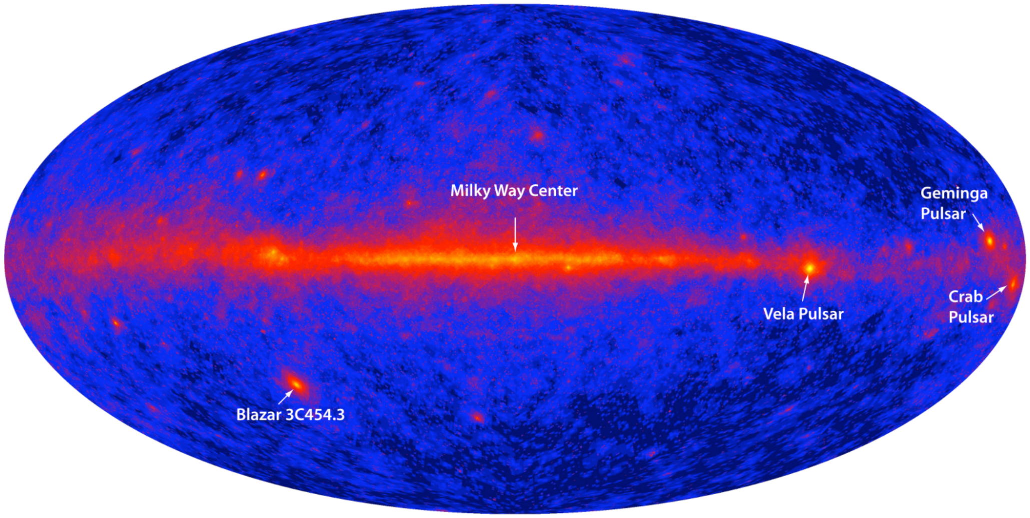
the birth of a new astronomy

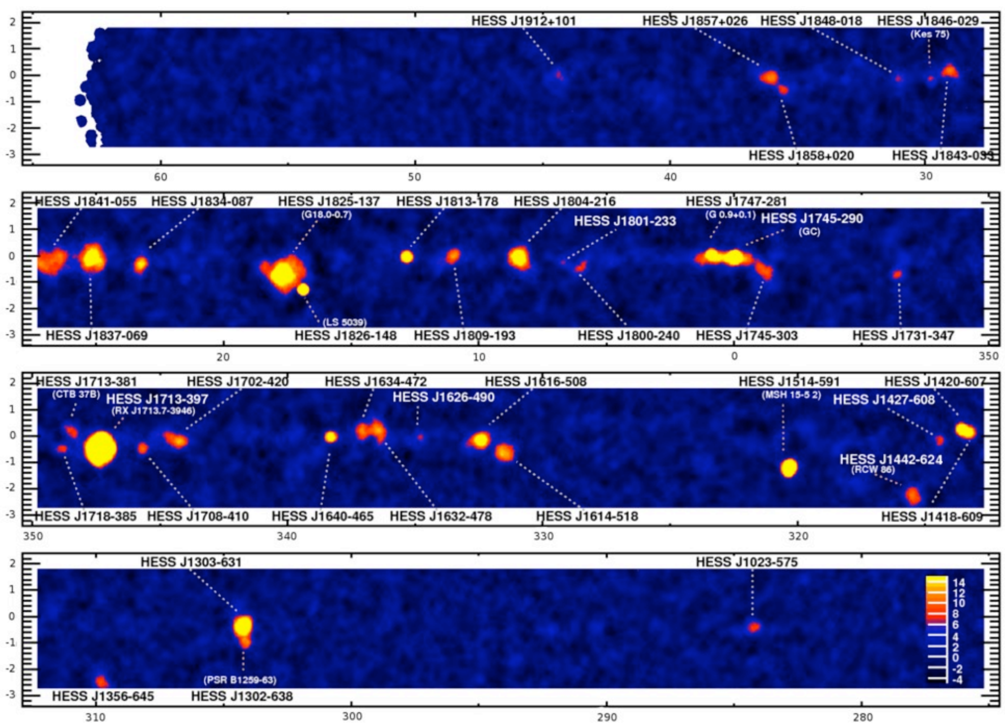


High Energy & Very High Energy γ-ray telescopes



Gamma Skymaps





axion footprints in γ-rays?
(after all, they're everywhere…)

ALPs and gamma ray astronomy

For a photon propagating in a domain of size s with uniform field B polarized along its direction, a neutrino-like oscillation probability formula holds

$$P_{osc} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma}Bs}{2}\sqrt{1+\left(\frac{K}{E}\right)^2}\right]$$

$$\sin^2(2\theta) = \frac{1}{1+(K/E)^2} \qquad K = \frac{m^2}{2g_{a\gamma}B}$$

- Natural transition regime falls in the γ-ray range $\qquad K_{GeV} = \dfrac{m^2_{\mu eV}}{0.4\, g_{11} B_G}$

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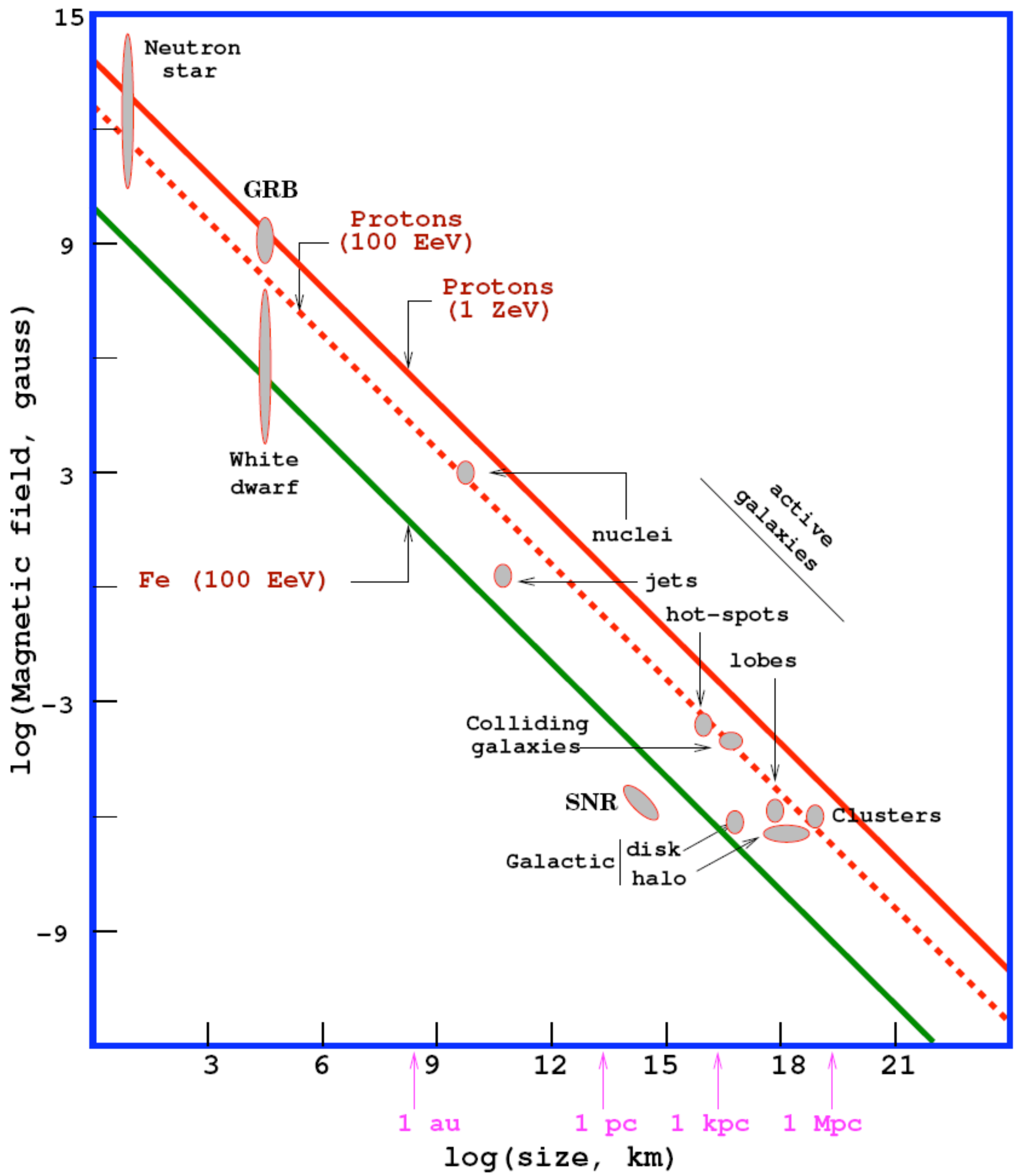
- Large phases (and thus large conversions) for unexplored range of coupling naturally expected for Hillas-efficient cosmic-ray accelerators! $15\,g_{11}B_G s_{pc} \geq 1$

$$E_{\max} \approx 9.3\times 10^{20}\,eV \times B_G s_{pc}$$

- Objects where $B_G s_{pc} \geq 0.3$ must exist in nature!

Hillas Plot… for ALPs



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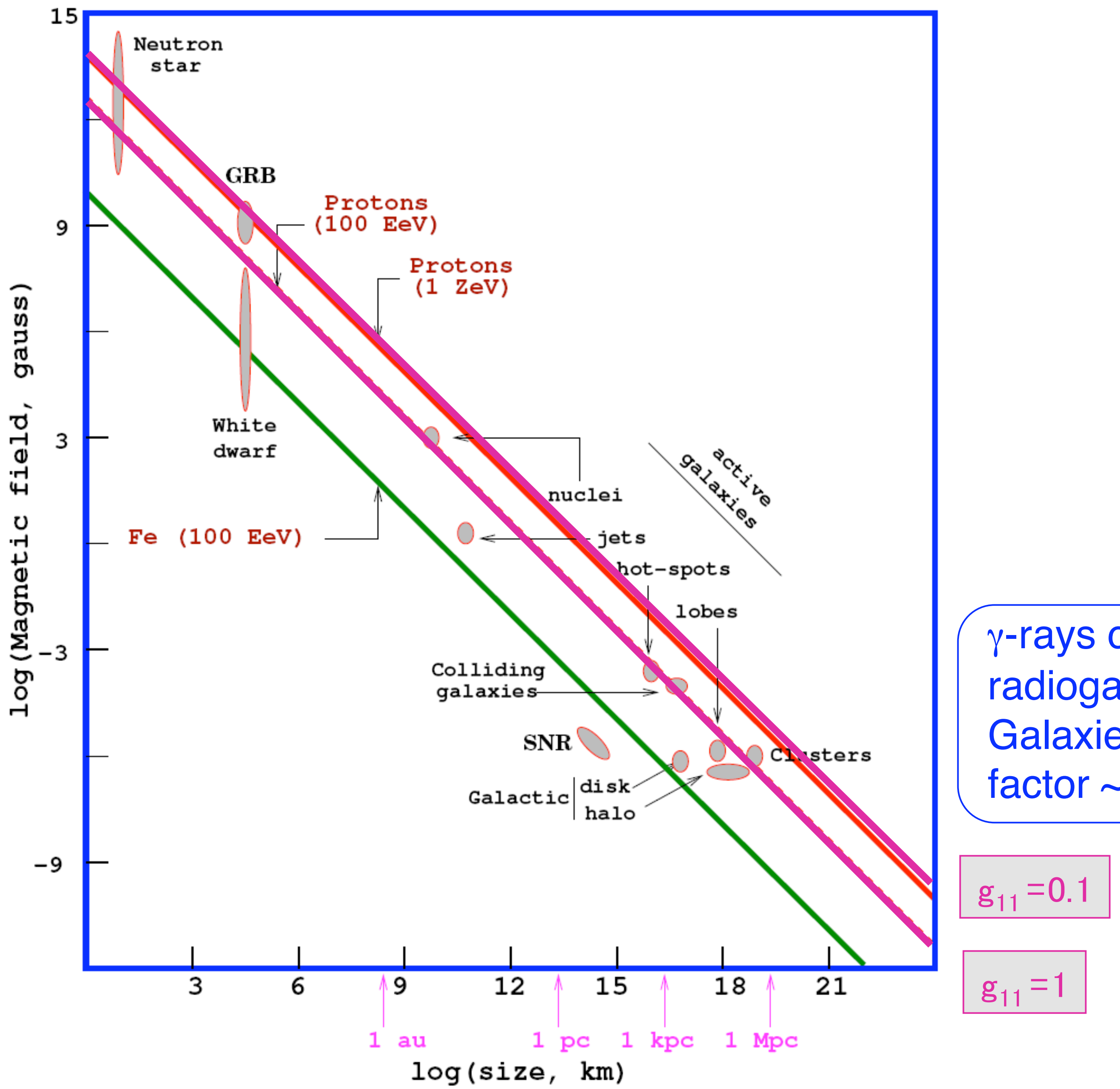

γ-rays crossing AGN cores, radiogalaxy hot-spots, cluster of Galaxies, etc. probe couplings a factor ~30 below present bounds

CAST bound
$g_{11}<8.8$ (95% CL)
$g_{11}=g_{a\gamma}/(10^{-11}\ \mathrm{GeV}^{-1})$

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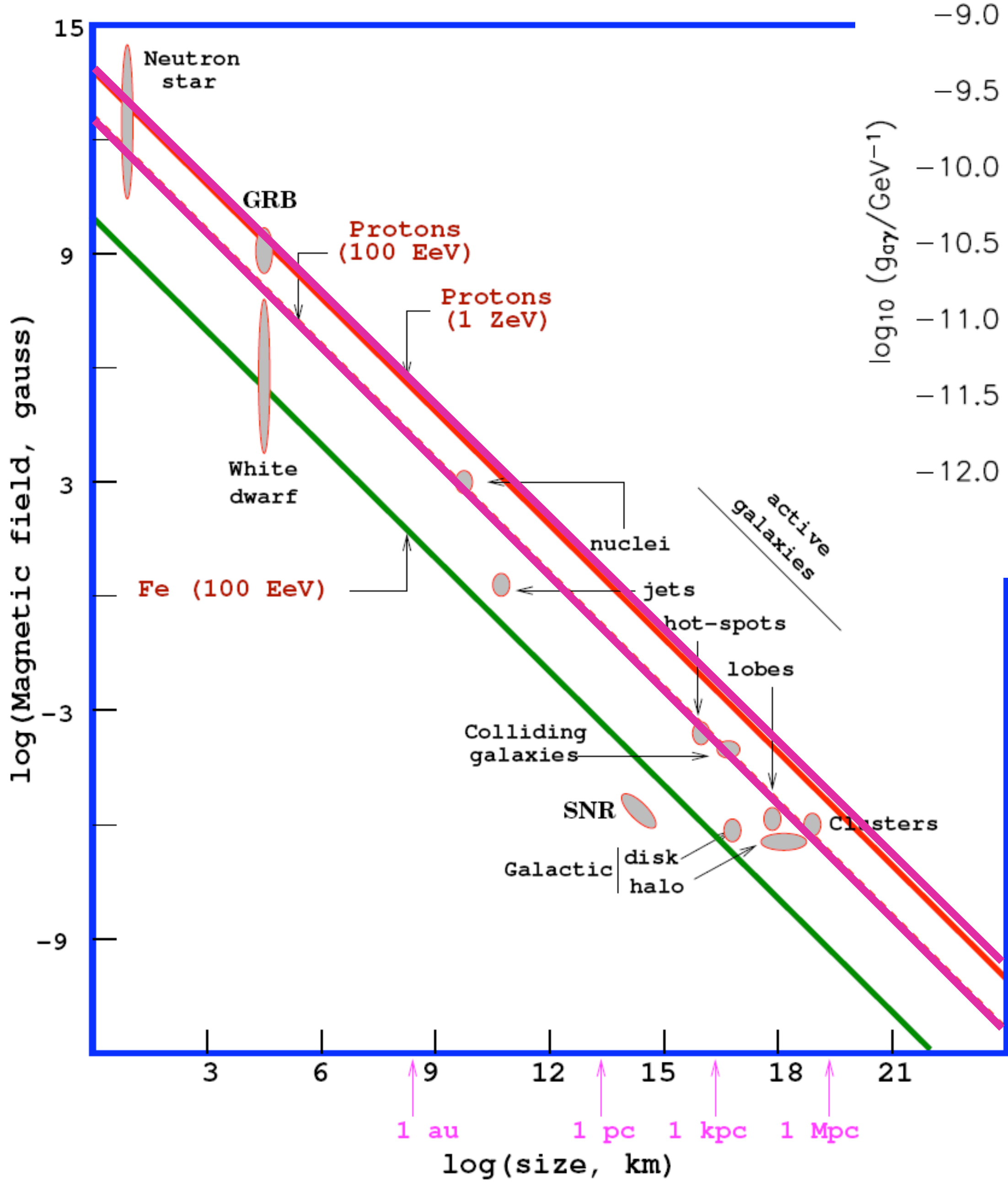

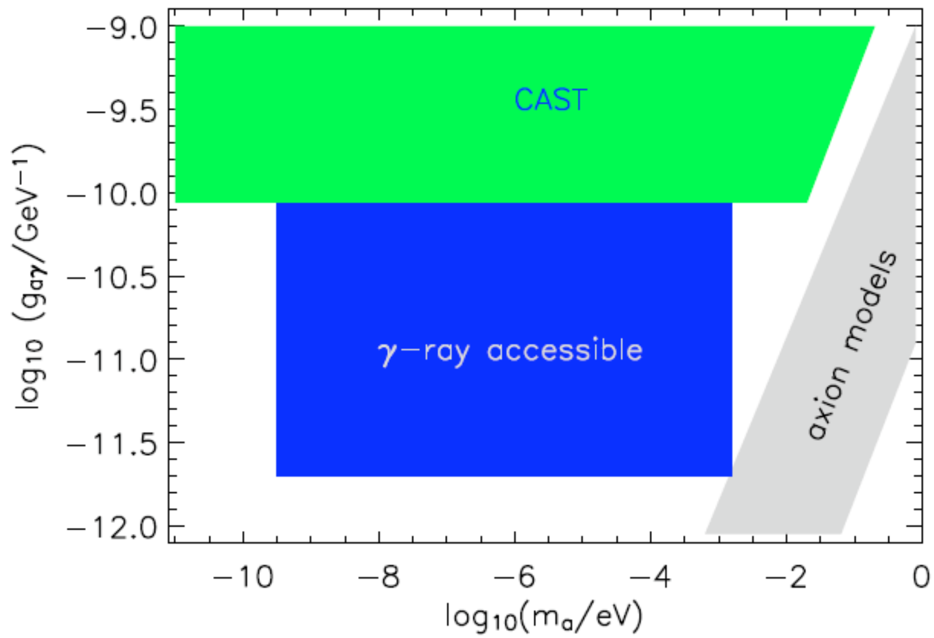

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$g_{11}=0.1$

$g_{11}=1$

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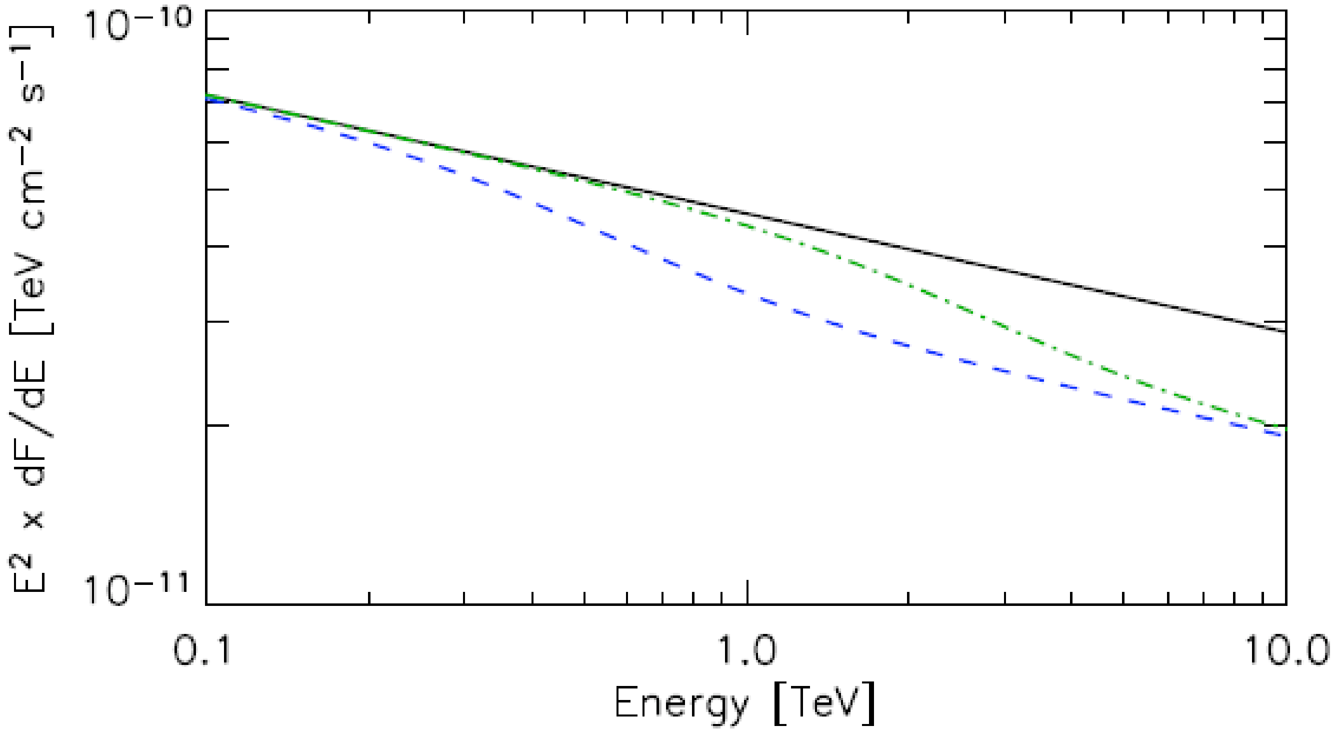
$g_{11}=g_{a\gamma}/(10^{-11}\ \mathrm{GeV}^{-1})$

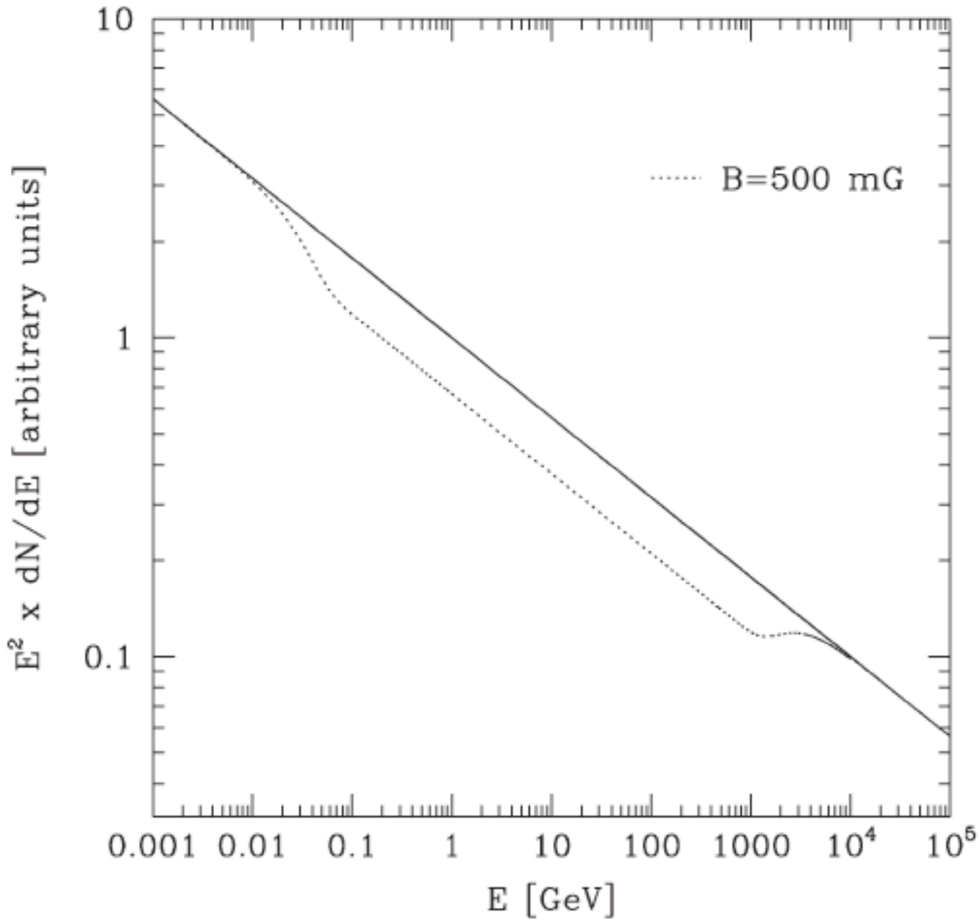
ALPs spectral signatures



$$F_a(E) \approx \left[1 - \frac{A}{1+(K/E)^2}\right] F_0(E)$$

D. Hooper and PS, Phys. Rev. Lett. 99, 231102 (2007)
K. Hochmuth and G. Sigl, Phys. Rev. D 76 123011 (2007)
A. De Angelis, O. Mansutti, M. Roncadelli, Phys. Lett. B 659, 847 (2008)

Limits of validity



$$\tan(2\theta) = \frac{2\Delta_B}{\Delta_{pl} + \Delta_{CM} - \Delta_a}$$

$$\Delta_a = \frac{m_a^2}{2E}$$

$$\Delta_{pl} = \frac{\omega_{pl}^2}{2E}$$

$$\Delta_B = \frac{g_{a\gamma} B_t}{2}$$

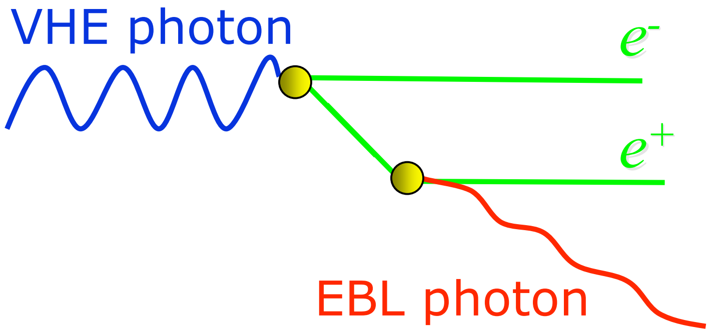
$$\Delta_{CM} = -\frac{\alpha}{45\pi}\left(\frac{B_t}{B_{cr}}\right)^2 E$$

- At sufficiently high plasma density and/or B-field intensity, the mixing is suppressed. For fixed parameters, at high E original spectrum recovered although hard to measure for realistic objects (the same holds for resonant features)

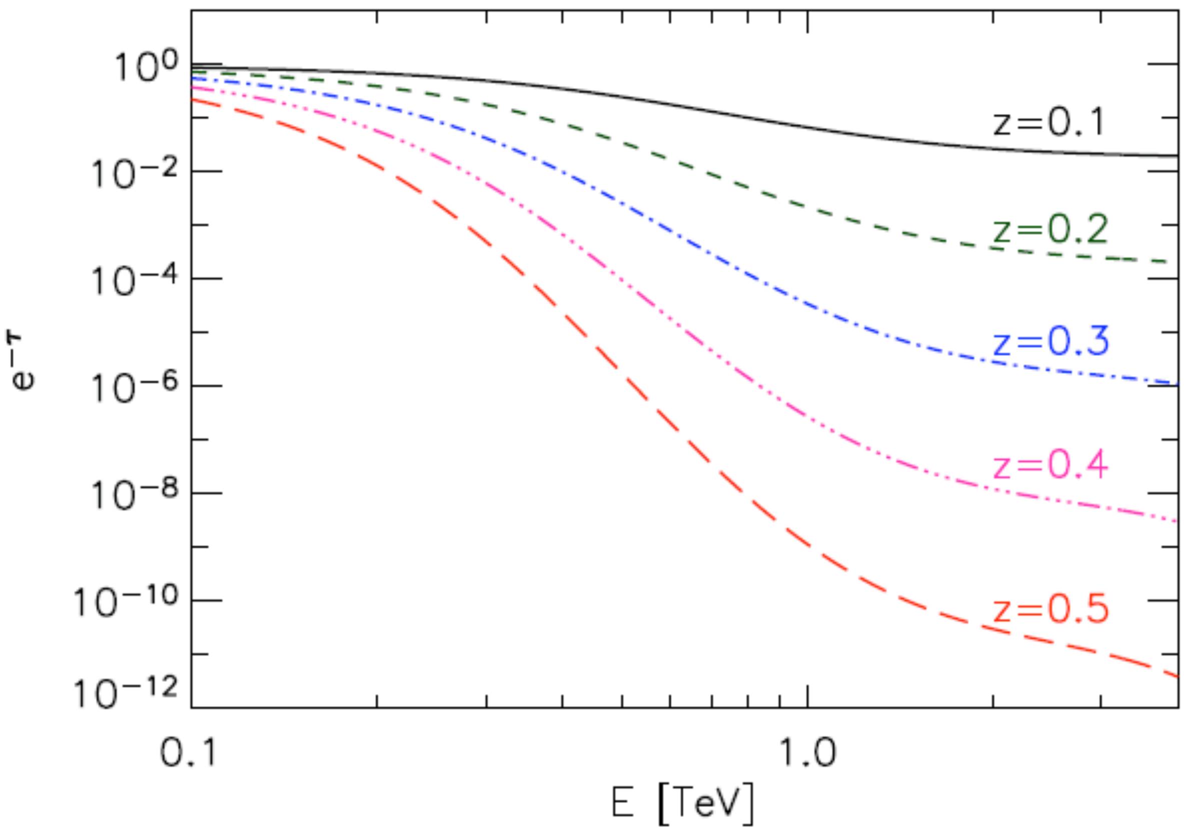
For details, see in particular K. Hochmuth and G. Sigl, PRD 76 123011 (2007)

ALP-induced “transparency”

A(nother) TeV crisis?

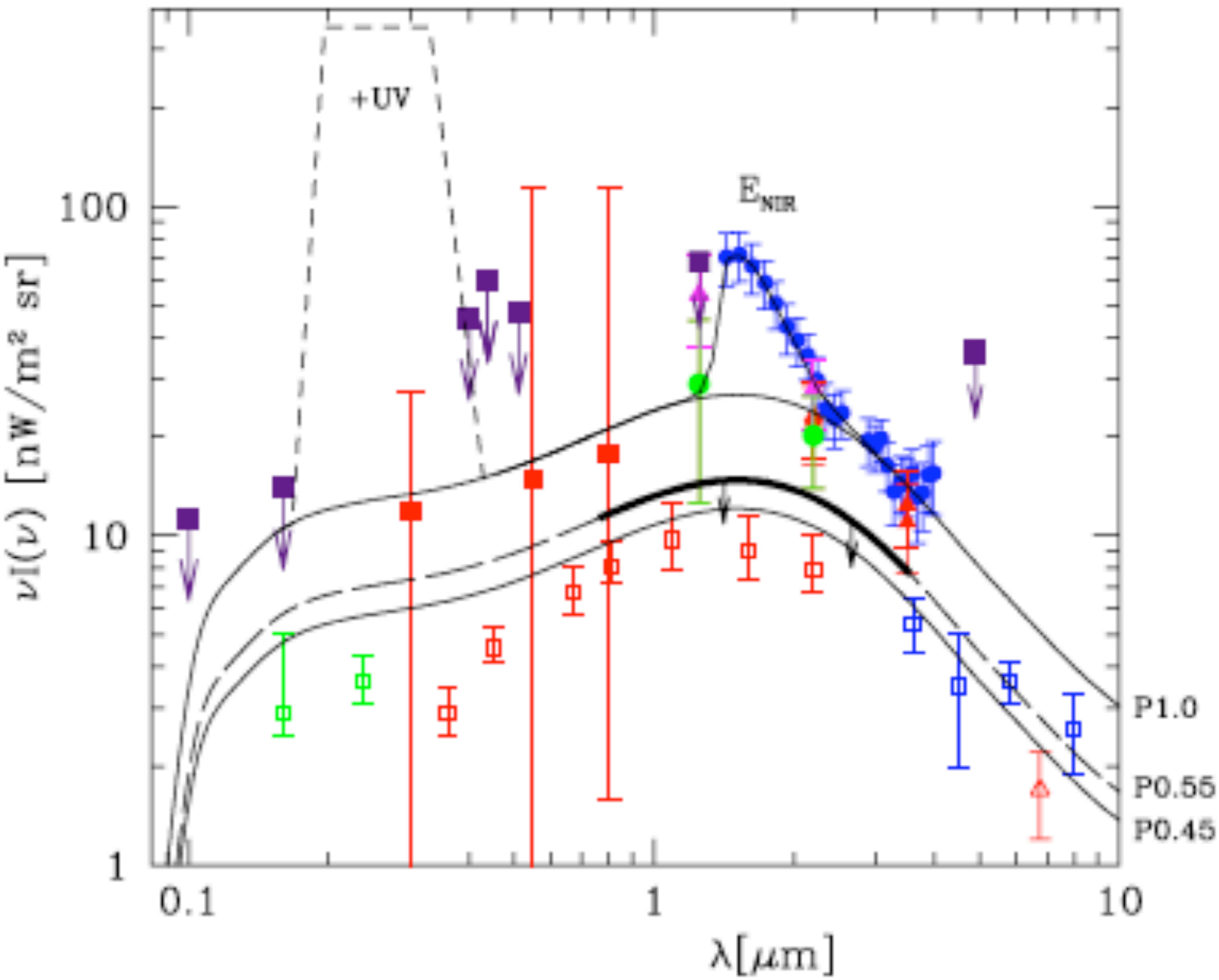


Universe is opaque to VHE γ's, due to EBL absorption. The 10-100 GeV (GLAST) range is the last e.m. probe of the deep universe



Yet TeV data may point to $\tau_{theory} > \tau_{obs}$!!!

Example (from HESS)



Nature 440:1018-1021,2006.

Some possible astrophysical solutions

Correcting observed spectra for absorption even by the lowest EBL indicates very hard source spectrum out to TeV energies ($\Gamma<2$) Conventional SSC model and/or acceleration mechanisms in trouble?

- Stecker & Scully, arXiv:0710.2252

$\rightarrow$ relativistic shocks producing $1.0<\Gamma<1.5$

(how typical can be these spectra? Large angle scattering required!)

- Aharonian, Khangulyan, Costamante, arXiv:0801.3198

$\rightarrow \tau_{source} \gg 1$, $\gamma \approx 100$

(extreme energetics required. Neutrino signals soon?)

- Boettcher, Dermer, Finker, arXiv:0804.3515

$\rightarrow$ Compton upscatter of CMB photons in the extended jet

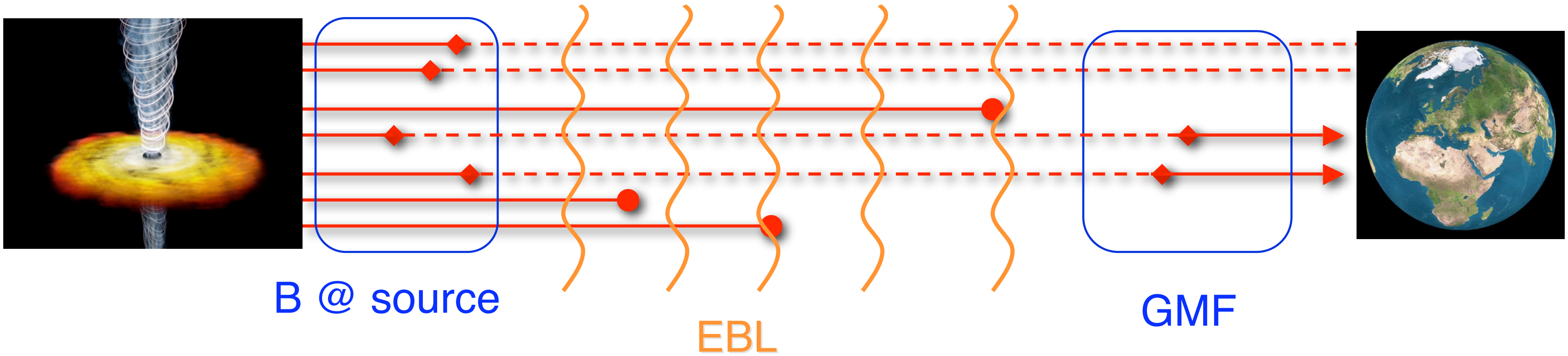
(ad hoc, additional component?)

All "logical possibilities", but not a priori theoretically expected: these are "postdictions"! In these cases, it is worth exploring other explanations…

Some solutions involving new physics

- Kifune, ApJ 518, L21, 1999 → Violation of Lorentz Invar. (now excluded?)
- De Angelis, Mansutti, Roncadelli, PRD 76, 121301, 2007 → ALPs in EGMF
- Simet, Hooper, PS, PRD 77, 063001, 2008 → ALPs in source & GMF

[see also D. Hooper and PS, Phys. Rev. Lett. 99, 231102 (2007)]

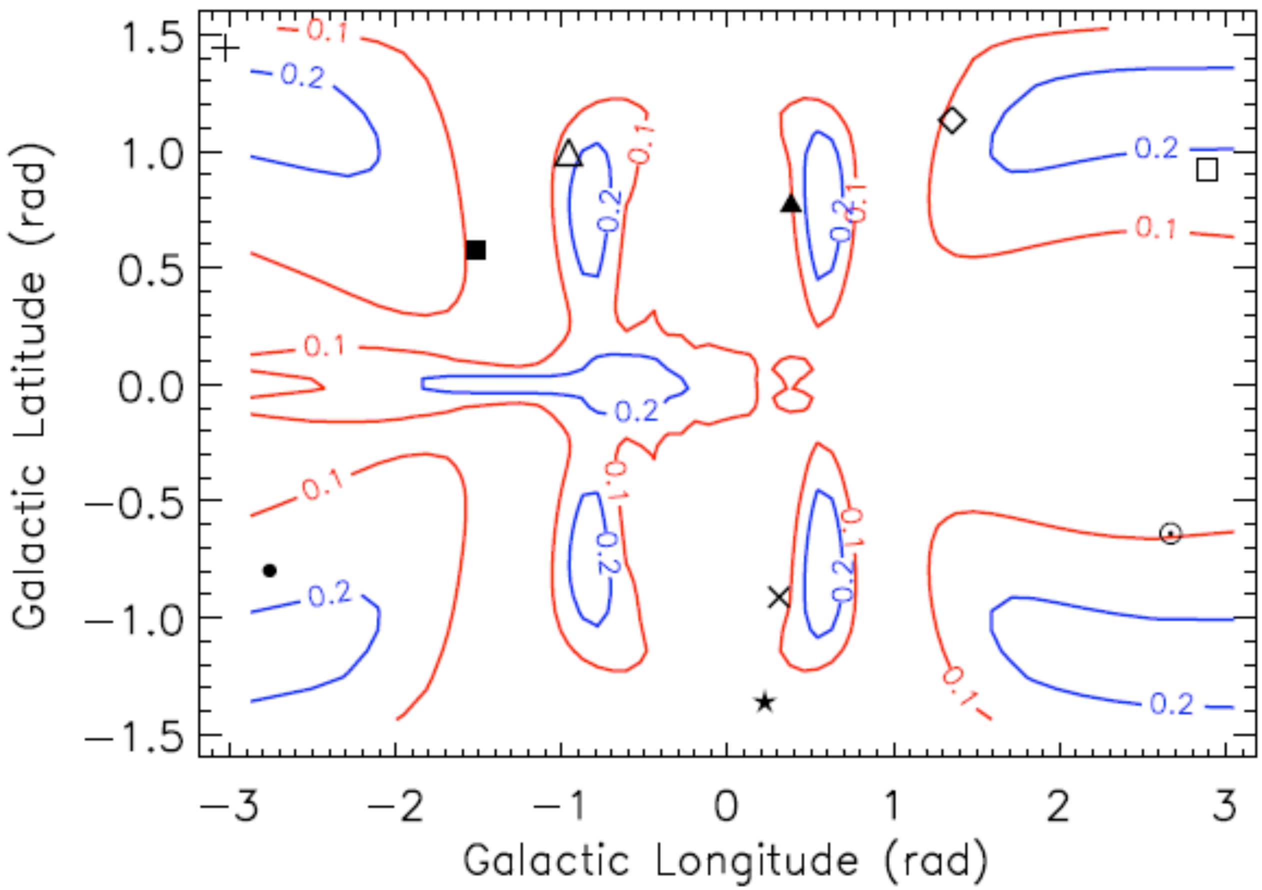


We showed already that astrophysical accelerators produce ALP fluxes.

Is a significant back-conversion in Galactic Magnetic Field possible?

Solving the TeV crisis with the Galactic Axionscope

We showed that it is well possible that AGN produce a TeV ALP flux. In a smaller region of the parameter space, a fraction >10% of this flux can convert back into photons in the *Magnetic Field of the Milky Way*

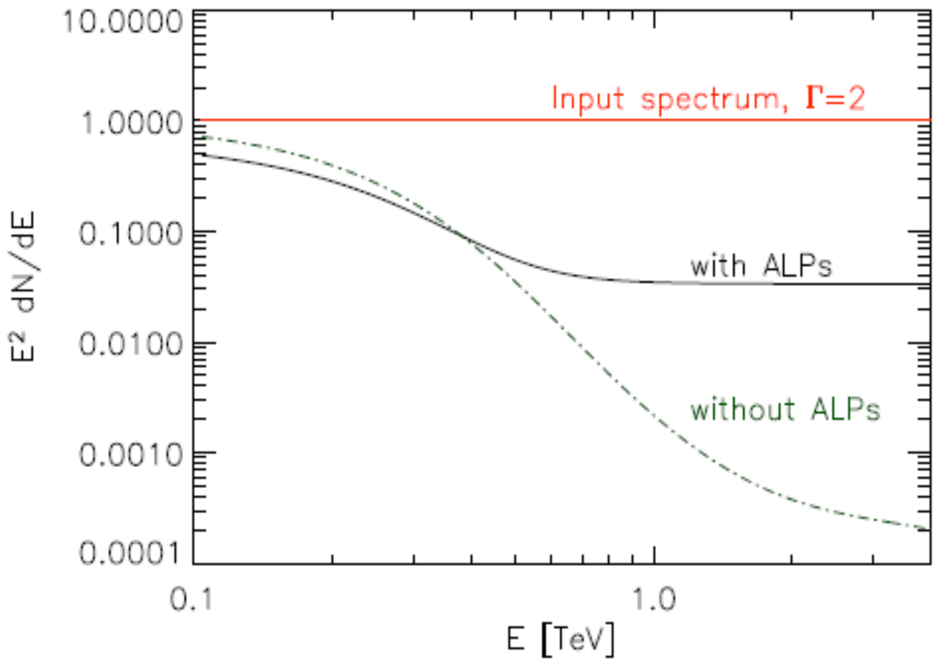


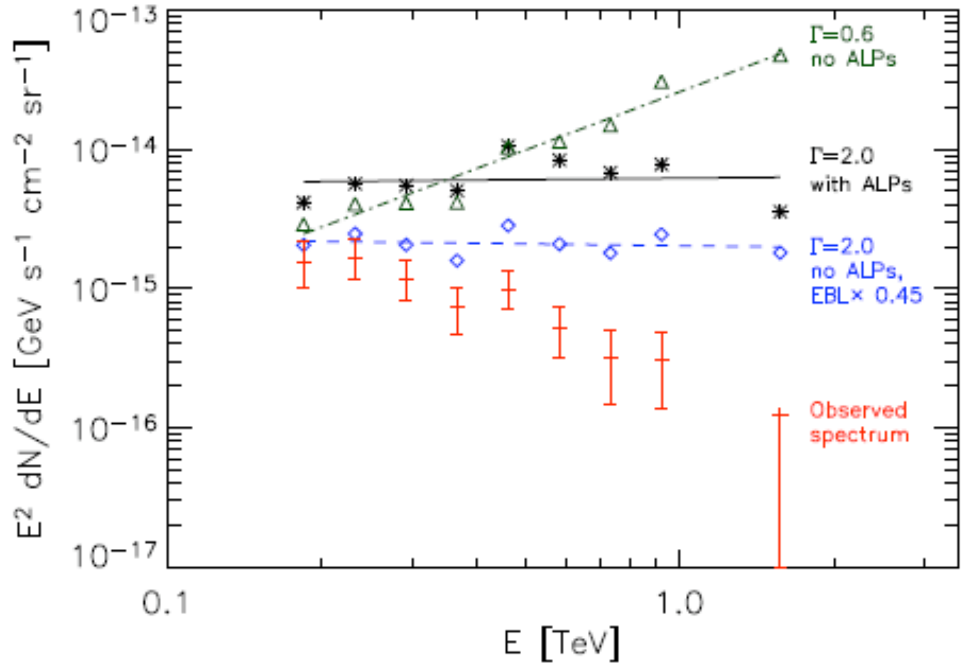
Object	z	Symbol
3C279	0.536	△
PG 1553+113	> 0.25	▲
1ES1011+496	0.212	□
1ES 0347-121	0.188	●
1ES1101-232	0.186	■
1ES1218+304	0.182	+
H 2356-309	0.165	⋆
1ES 0229+200	0.140	⊙
H 1426+428	0.129	◇
PKS 2155-304	0.117	×

g_{11}=5, m_a~neV

An Example: H 2356-309, z=0.165

Assuming reconversion probability in the Galaxy of 10%





Detailed predictions are model-dependent (GMF only roughly known)
Main model-independent predictions:

- effective EBL suppression direction-dependent (l,b-dependence)

- At GeV energies, FERMI may see dimming in the diffuse flux from directions having large FR measurements or anomalously hard TeV spectra of far AGNs

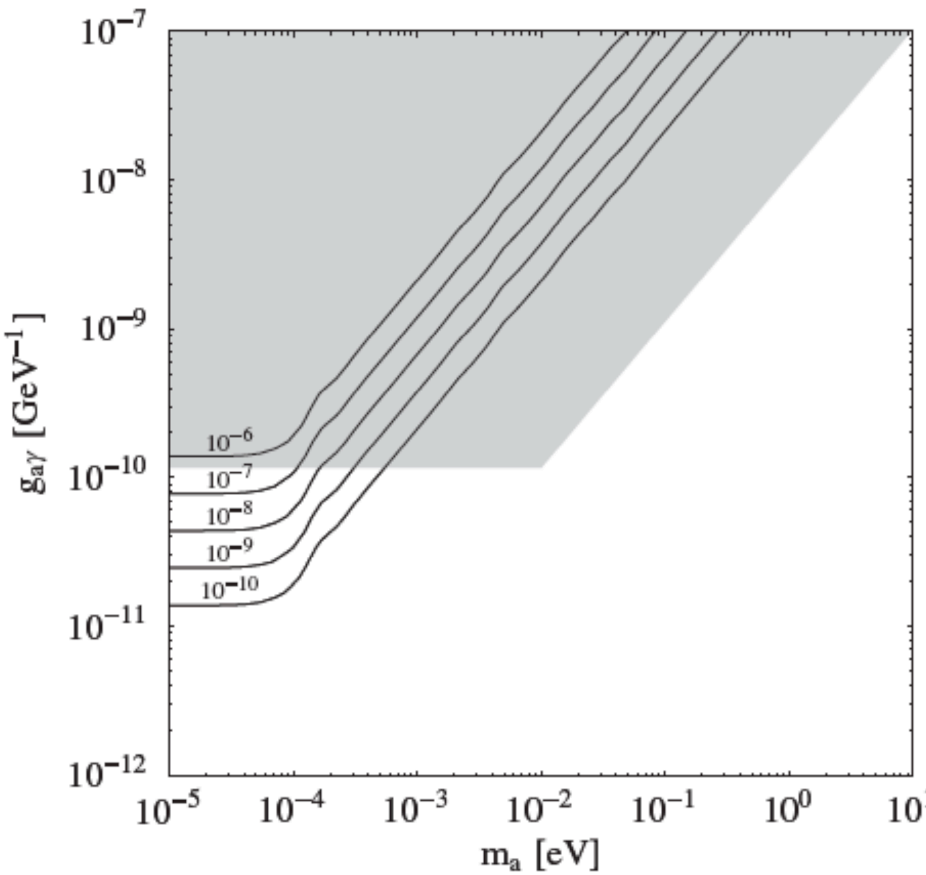
Other ALP signatures from space: Earth axionscope

- Geomagnetic conversion of solar ALPs into x-rays based on the fact that the Earth is a relatively weak but fairly large magnet.

- The night side of the Earth is not reached by solar x-rays, while ALPs from solar core can traverse the entire Earth without absorption.

- On the night side of the Earth, there is a steady upward going stream of solar ALPs but no solar x-rays.

- Analysis of SUZAKU satellite X-ray Imaging Spectrometer data on background in “Earth Shadow” in progress



H. Davoudiasl, P. Huber, PRL 97, 141302 (2006); JCAP 0808:026,2008

For prospects from compact objects: D. Chelouche et al. 0806.0411; 0810.3002

Summary

- The so-called "strong CP-problem" is still unsolved. Unless we are ready to accept "one more puzzling coincidence" in the SM, it requires new physics.

- The simplest solution implies the existence of a very weakly coupled, light Particle, the Axion. Still undetected… but it might be almost invisible!

- Despite experimental difficulties, there is a vital search program going on, also because of the links that axions have with astrophysics (footprints in stellar phenomena?) and cosmology (e.g. dark matter)

- I' ve tried to convince you that the young field of gamma-ray astrophysics provides further opportunities for discovery. Signatures of Axion(like) particles can be searched for in gamma-ray spectra both by ACTs and by FERMI

- By considering the additional role of the Galactic Magnetic Field, the same mechanism offers a way to avoid TeV absorption on the EBL, solving perhaps what appear as observational puzzles