Axion: A Brief Introduction

(a partial review)

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Outline

- Short theoretical introduction
- Axion Interaction Channels
- Where and How to Search Cosmological Axions
- Extraterrestrial Evidence ?

Conclusions

The strong CP problem

- The QCD lagrangian contains a term that foresees CP violation

Standard QCD Lagrangian contains a CP violating term

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\le\bar{\Theta}\le 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

The parameter θ is unprescribed by the theory, it is expected to be $\theta \sim 1$. QCD interaction actually depends on θ through its difference with the **phase of the quark mass matrix**:

$$\bar{\theta} = \theta - \arg\det(m_1, m_2, \ldots, m_n).$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \bar{\Theta}\, 10^{-16}\, e\,\mathrm{cm} \approx \frac{\bar{\Theta}}{10^2}\mu_n < 3\times 10^{-26}\, e\,\mathrm{cm}$$

$\bar{\Theta} \lesssim 10^{-10}$ Why so small?

VERY FINE TUNING! -> STRONG CP PROBLEM

Dynamical Solution

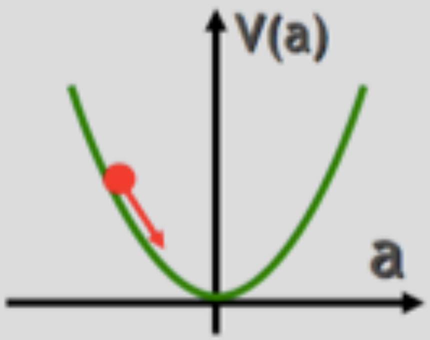
Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

Re-interpret $\bar{\Theta}$ as a dynamical variable (scalar field)

$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

- $a(x)$: Pseudo-scalar axion field
- f_a: Peccei-Quinn scale, Axion decay constant

$$L_{CP} = -\frac{\alpha_s}{8\pi}\bar{\Theta}\,\mathrm{Tr}(G\tilde{G}) \;\Rightarrow\; L_{CP} = -\frac{\alpha_s}{8\pi}\frac{a(x)}{f_a}\,\mathrm{Tr}(G\tilde{G})$$



Potential (mass term) induced by L_{CP} drives $a(x)$ to CP-conserving minimum

CP-symmetry dynamically restored

Axions generically couple to gluons and mix with π^0

$$\begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

$f_\pi \approx 93$ MeV
Pion decay constant

Peccei Quinn simmetry

- Peccei and Quinn (1977) proposed to solve the strong CP problem by postulating the existence of a global $U_{PQ}(1)$ *quasi*simmetry (it is spontaneously broken).
- The **axion** (Weinberg 1978, Wilczeck 1978) is the **pseudo Goldstone boson** associated with the spontaneous breakdown of the PQ simmetry.
- With the PQ quasisimmetry the fine tuning problem can be solved

$$\overline{\theta} = \theta - \arg\det(m_1, m_2, \ldots, m_n) - \frac{a(x)}{f_a}$$

a(x) – **axion field**
f_a – **axion decay constant**

f_a is the quantity that determines all the low energy phenomena of the axion

The "standard" axion

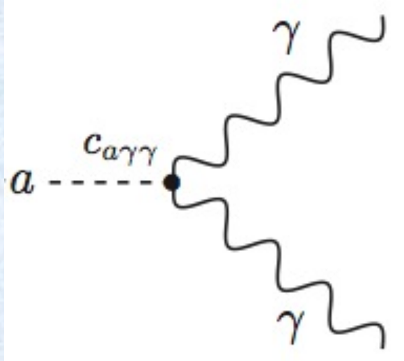
- The axion is a **light pseudoscalar boson**, its properties can be derived using current algebra techniques
- The axion is the light cousin of the π^0 :

$$m_a f_a \approx m_\pi f_\pi$$

m_p = 135 MeV – pion mass
f_p = 93 MeV – pion decay constant

$$m_a \simeq 0.6 \ \text{eV} \frac{10^7 \ \text{GeV}}{f_a}$$

- The axion, like the pion, **couples to two photons**



- Originally it was thought that f_a @ electroweak scale v_{weak}(250 GeV) → **$m_a \approx 100$ keV**

RULED OUT BY ACCELERATOR EXPERIMENTS

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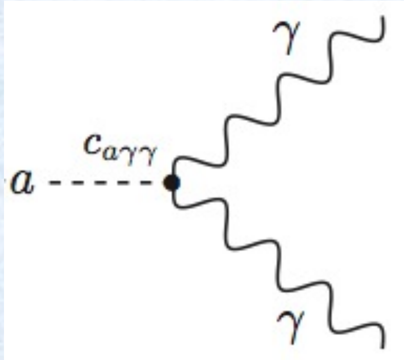

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RULED OUT BY ACCELERATOR EXPERIMENTS

The "invisible" axion

- **No upper bound on axion decay constant**: $f_a \gg v_{weak}$

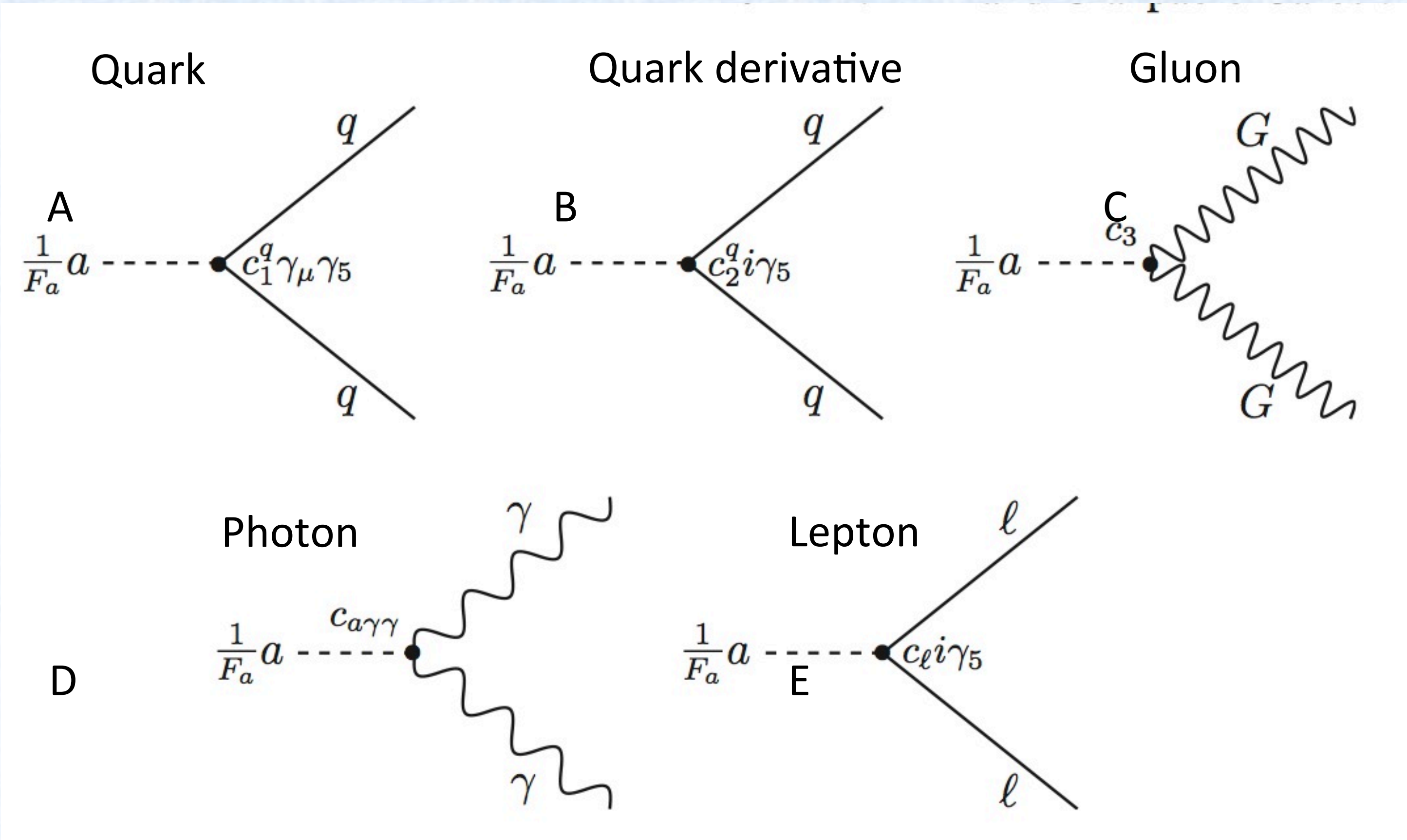
- **New axion models** with addition of scalar fields or Higgs doublets carrying the $U_{PQ}(1)$ charge
- The strength of the axion interaction depends on the assignment of the $U_{PQ}(1)$ charge to quarks and leptons.
- There are two (main) models:

Kim-Shifman-Vainstein-Zakharov (KSVZ)
(Kim 1979; Shifman, Vainstein, and Zhakharov 1980)

Dine-Fischler-Srednicki- Zhitnitskii (DFSZ)
(Zhitnitskii 1980; Dine, Fischler, and Srednicki, 1981a, 1981b)

Axion interactions

- **Several interactions are possible: they are model dependent**



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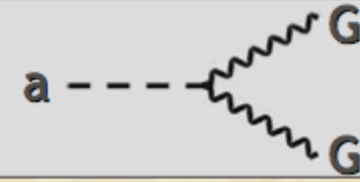
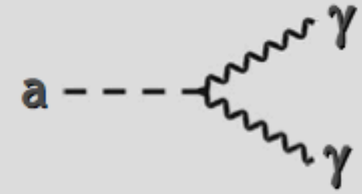
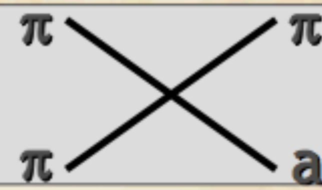
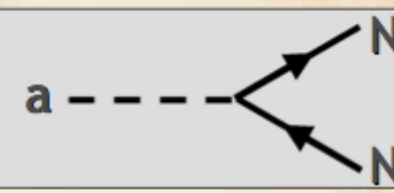
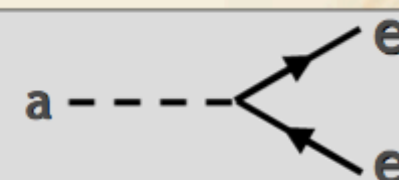
Axion Properties

<table>
<tr><td>Gluon coupling
(Generic property)</td><td>$$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$$</td><td>
</td></tr>
<tr><td>Mass</td><td>$$m_a = \frac{0.6\,\mathrm{eV}}{f_a/10^7\,\mathrm{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$$</td><td></td></tr>
<tr><td>Photon coupling</td><td>$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}a$$
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$</td><td>
</td></tr>
<tr><td>Pion coupling</td><td>$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \ldots)\partial^\mu a$$</td><td>
</td></tr>
<tr><td>Nucleon coupling
(axial vector)</td><td>$$L_{aN} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\partial_\mu a$$</td><td>
</td></tr>
<tr><td>Electron coupling
(optional)</td><td>$$L_{ae} = \frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\,\partial_\mu a$$</td><td>
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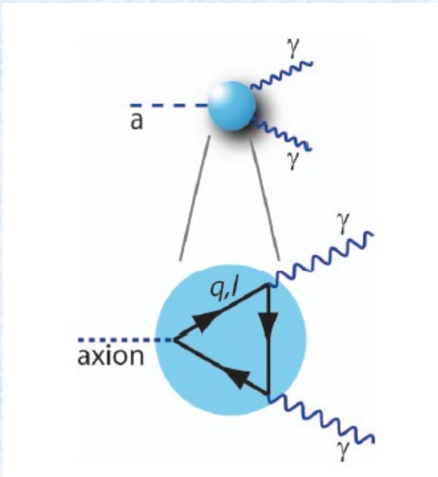
Axion interactions 2

- Axion interactions are model dependent



Axion photon photon

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi}\frac{m_a}{m_\pi f_\pi}$$

Axion electron electron

$$L_{aee} = -g_e \bar{e} i\gamma_5 e a$$

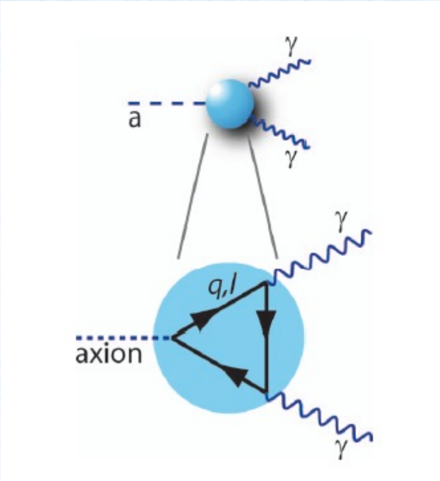
$$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07\times 10^{-11} m_a$$ **(DFSZ)**

g_e = 0,001g_e DFSZ (KSVZ)

All couplings are extremely weak!

Axion interactions 3

- Axion interactions are now model dependent



Axion photon photon

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g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

- If the axion mass is lighter than 2 m_e, we can calculate its lifetime

$$\tau(a \to 2\gamma) = \frac{2^8\pi^3}{g_\gamma^2\alpha^2}\frac{f_a^2}{m_a^3} \cong \frac{3.65\times10^{24}}{g_\gamma^2}\left(\frac{\text{eV}}{m_a}\right)^5 \text{s}$$

$$\cong \frac{0.8\times10^7 t_U}{g_\gamma^2}\left(\frac{\text{eV}}{m_a}\right)^5$$

Where $t_U \approx 4\ 10^{17}$ s is the age of the Universe

For $g_\gamma \approx 1$ an axion of mass 24 eV has the lifetime corresponding to t_U.

Axion Electron interaction

- The interaction of the axion with the a spin ½ particle

$$L = \bar{\psi}(x)(i\hbar\partial\!\!\!/_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

- In the non relativistic approximation:

  Cold Dark Matter Cosmological Axions

$$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

The interaction term has the form of a **spin - magnetic field interaction** with $\vec{\nabla}a$ playing the role of an effective magnetic field

$$H_a = -\vec{S}\cdot\left[\frac{g_p}{m_e}\nabla a\right]$$

Galactic axions

With the following hypothesis:

- the expected cosmic axion density $\rho \simeq 300$ MeV/cm^3. As the axion mass should be in the range 10^{-6}eV $< m_a < 10^{-2}$eV, which represents a very high density;
- axion velocities are distributed according to Maxwell distribution (non relativistic Bose distribution):

$$\rho(|\vec{p}|) = (\sqrt{\pi} p_0)^{-3} \exp(-|\vec{p}|^2 / p_0^2) \qquad (8)$$

  where $p_0 = m_a v_g$, being v_g the dispersion velocity in the Galaxy.
- Due to Galaxy rotation, the rest frame laboratory is moving through the local axion cloud in such a form that the observed momentum distribution is $\rho(\vec{p} - \vec{p_s})$, where $\vec{p_s} = m_a \vec{v}_\odot$, with $\vec{v}_\odot \approx 270$ km/s, the velocity of the sun through the Galaxy.

$$H_a = -\vec{S} \cdot \left[\frac{g_p}{m_e} \nabla a \right]$$

$$E_a = \frac{\hbar}{2} \frac{g_p}{2m_e} \frac{p_s}{\hbar} a_0 = g_L \mu_B \frac{1}{4} B_a$$

$$B_a = \frac{1}{\gamma} \frac{g_p}{m_e} \sqrt{\frac{\rho_a \hbar^3}{m_a c}} \frac{p_s}{\hbar} = 9.2 \cdot 10^{-23} \left(\frac{m_a}{10^{-4}\,\text{eV}} \right)$$

PRL 113, 201301 (2014) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2014

Axion Dark Matter Detection Using Atomic Transitions

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(Received 9 September 2014; published 14 November 2014)

Dark matter axions may cause transitions between atomic states that differ in energy by an amount equal to the axion mass. Such energy differences are conveniently tuned using the Zeeman effect. It is proposed to search for dark matter axions by cooling a kilogram-sized sample to millikelvin temperatures and count axion induced transitions using laser techniques. This appears to be an appropriate approach to axion dark matter detection in the 10^{-4} eV mass range.

$$\mathcal{L}_{a\bar{f}f} = -\frac{g_f}{2f_a}\partial_\mu a\ \bar{f}(x)\gamma^\mu\gamma_5 f(x)$$

$$H_{a\bar{f}f} = +\frac{g_f}{2f_a}\left(\vec{\nabla}a\cdot\vec{\sigma} + \partial_t a\ \frac{\vec{p}\cdot\vec{\sigma}}{m_f}\right)$$

ZEEMAN TRANSITION RATE With 1 Mole of Polarized Electrons

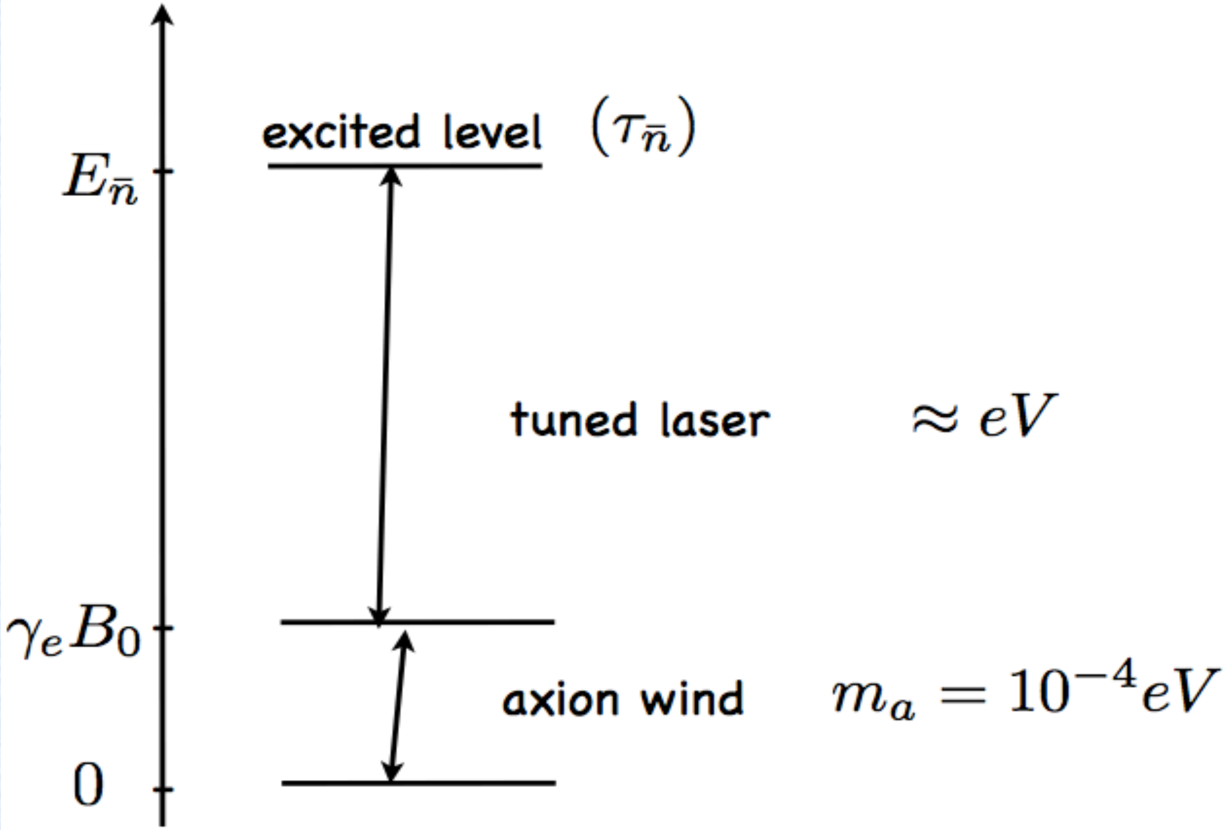
$$N_A R_i = g_i^2 N_A v^2 \frac{2\rho_a}{f_a^2}\min(t,t_1,t_a)$$

$$N_A R_i = \frac{2*10^3}{\sec}\left(\frac{\rho_a}{GeV/cm^3}\right)\left(\frac{10^{11}GeV}{f_a}\right)^2\left(\frac{v^2}{10^{-6}}\right)\left(\frac{\min(t,t_1,t_a)}{\sec}\right)$$

Hz Rate

Atomic transitions from DM wind

Sikivie 2014



Requires:

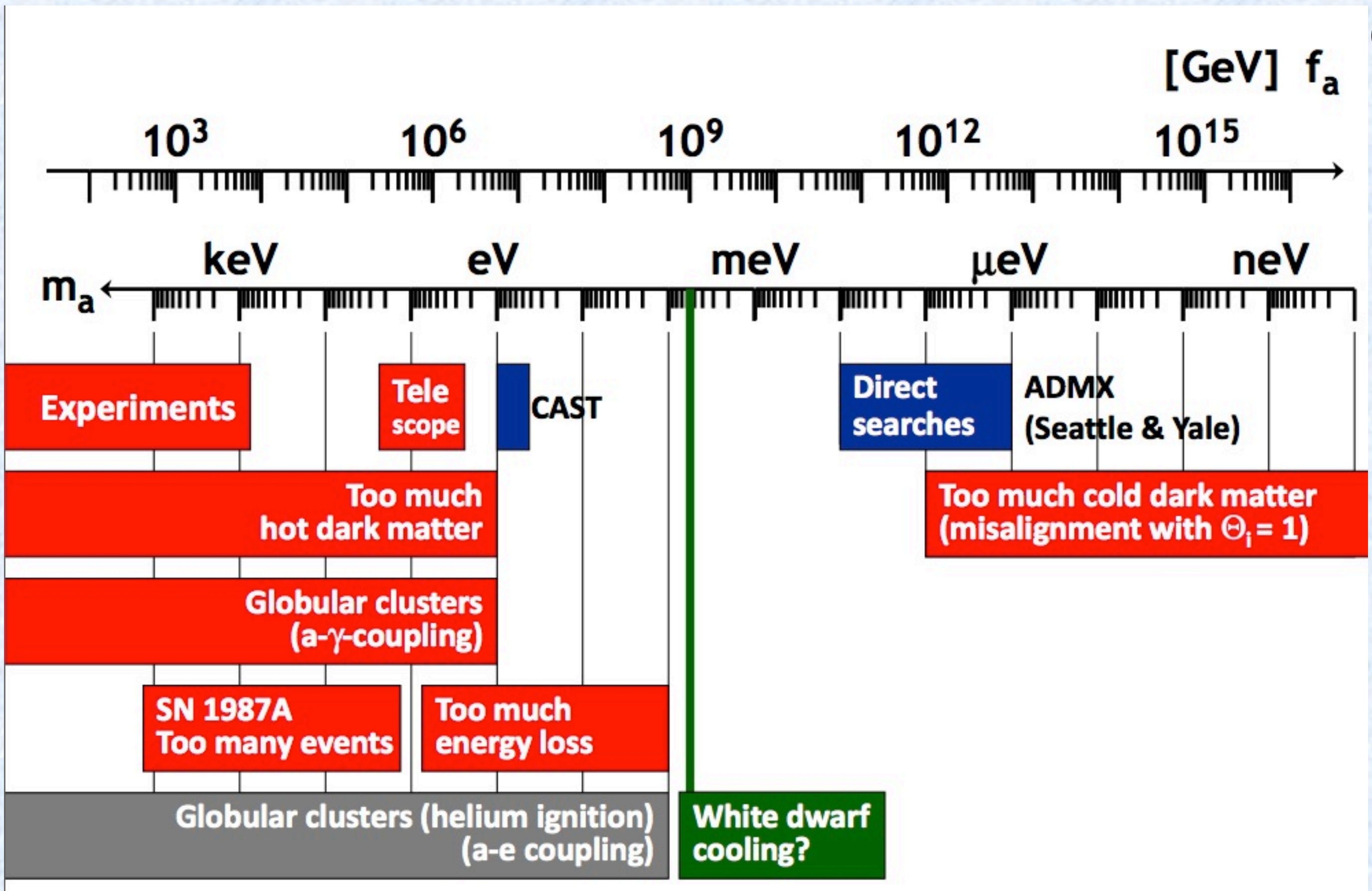
$$T \lesssim 10\ mK\left(\frac{m_a}{10^{-4}eV}\right)$$

to depopulate one spin state in absence of axion wind

Photon rate from de-excited atoms:

$$\frac{dN}{dt} \approx n_M 10^{-3}\ Hz \frac{min(t, t_a, \tau_{\bar{n}})}{10^{-6} sec}$$

Does the axion exist?

- While the standard Peccei Quinn Weinberg Wilczeck (PQWW) axion was soon ruled out (Electro Weak Scale F = 250 GeV), the other **axion (DFSZ, KSVZ) continues to evade all current experimental limits**
- 

discovery

Excluded

Searches

Hint

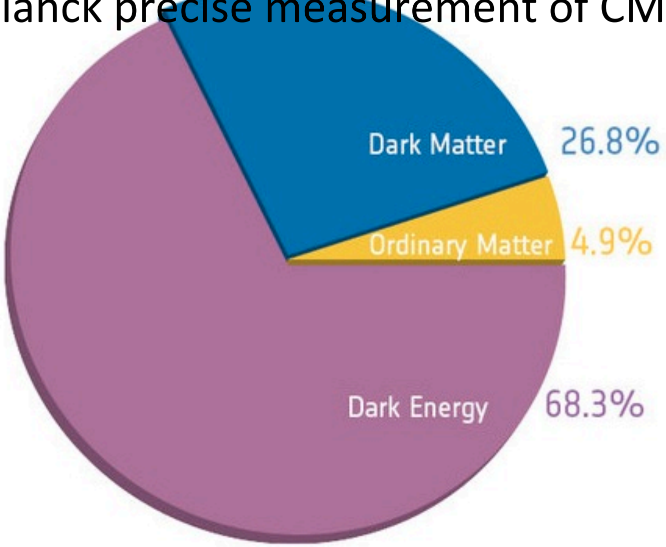
From G. Raffelt talk in Vistas in Axion Physics, INT, Seattle, 23–26 April 2012

Axions in the outer space

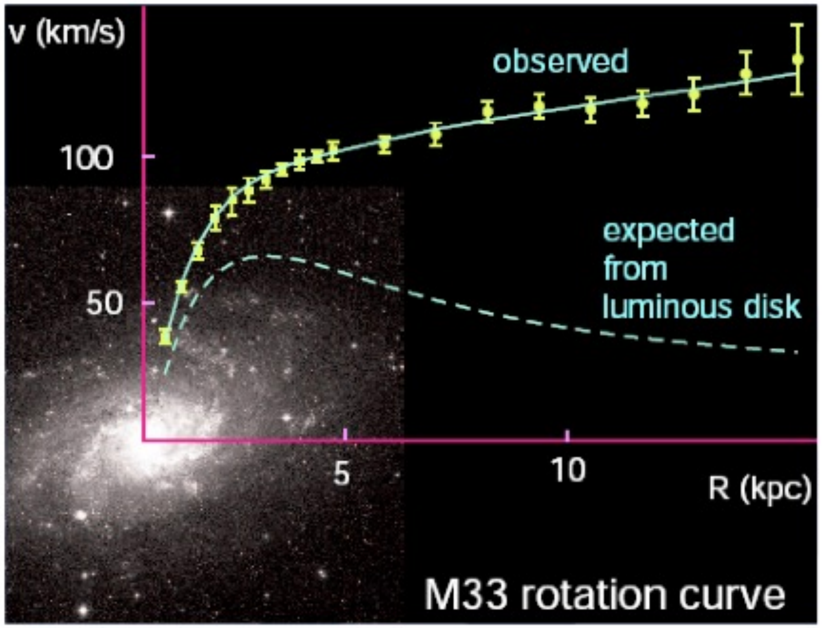
- As we have seen a **light axion** (m_a < eV) has lifetime that can be longer than the age of the Universe. This kind of axion is indeed important for cosmology.
- **Are they a main component of Dark Matter?**

http://www.esa.int/For_Media/Photos/Highlights/Planck

Composition of the Universe after Planck precise measurement of CMB



Typical rotational curve of galaxys

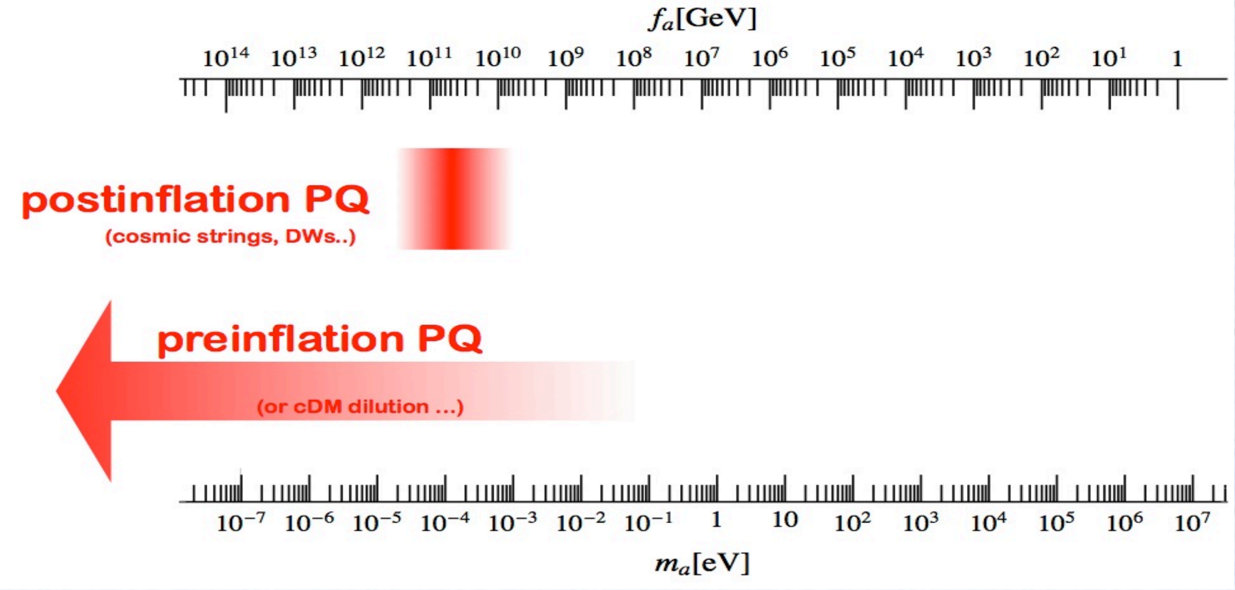


P. Salucci

Axions are weakly interacting, stable on cosmological times, non relativistic

Cosmological axion

- In the early universe axions are produced by processes involving quarks and gluons **-> hot dark matter (BAD)**
- In addition, axions produced by the "vacuum realignment mechanism": relaxation of the axion field after breakdown of the PQ simmetry -> **Cold dark matter (GOOD)**
- The expected cosmic mass density of axions depends on whether inflation happens after or before PQ breakdown



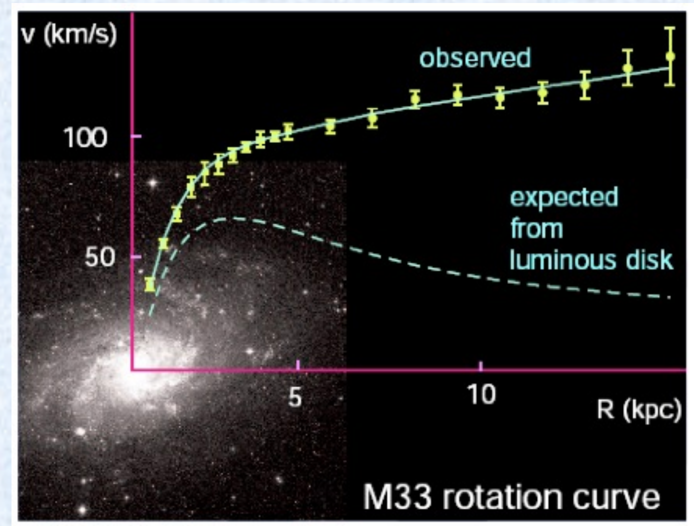
Allowed regions of mass/coupling constant

From J. Redondo talk at Dark Matter: a light move DESY 2013

Axions in the galactic halo

- In order to explain galaxy rotation curves, an **halo of dark matter** is hypothesize
- Accepted value for local dark matter density

$$\rho_{DM} = 0.3 - 0.45\ \mathrm{GeV/cm^3}$$

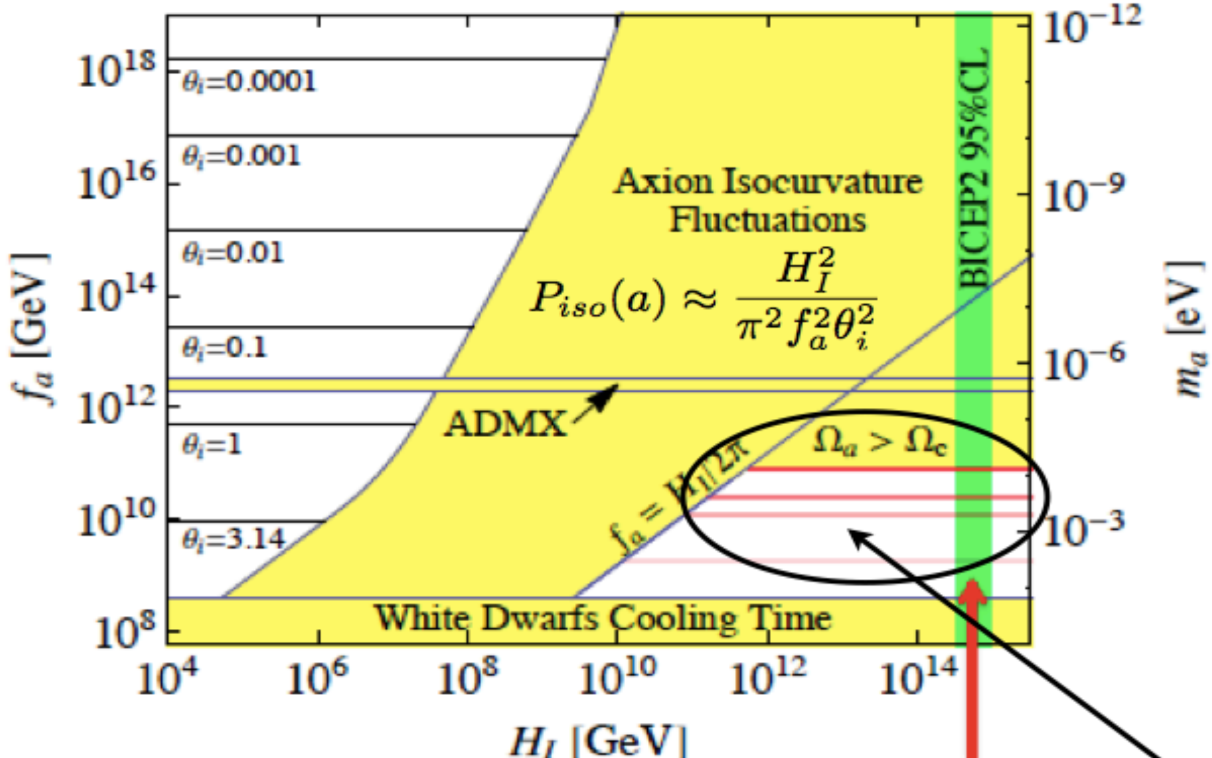


- Cold dark matter component is thermalized and has a Maxwellian velocity distribution
- There might be a non-thermalized component with sharper velocity distribution

From BARBIERI TALK JAN 2015

QCD Axions in cosmology

$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$

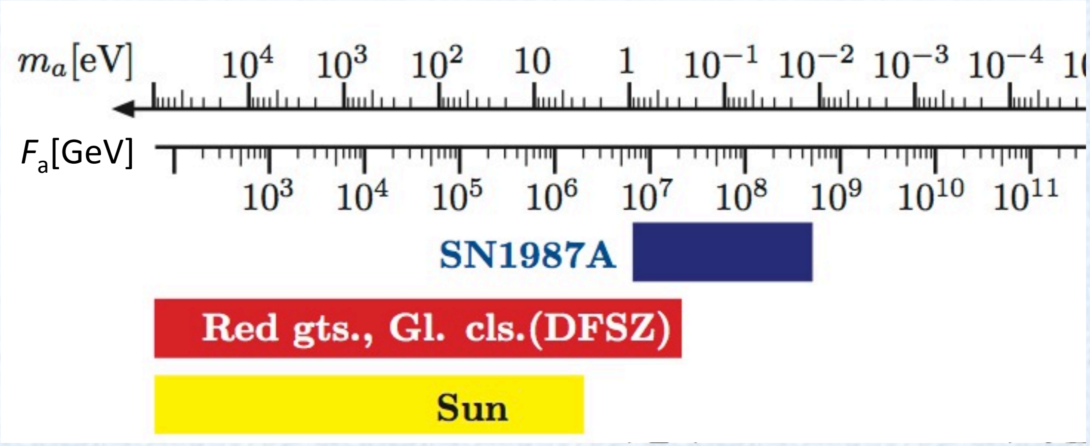


$$\Omega_a h^2 \approx 0.16\left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

(Axion Like Particles: m and f unrelated)

Axion and stars

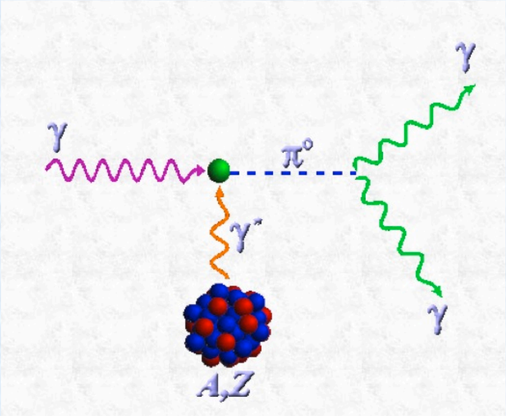
- Axions have very small masses and therefore **can be emitted without important threshold effects from stars**, in analogy to neutrinos
- The method to constrain axion models is basically the overall **energy loss rate**
- We may use the **axion couplings to γ, p, n, and e to study the core evolution of a star**. Simple bounds are obtained by comparing the energy loss rates by axion and by neutrino emission



Can we detect Cosmological Axions?

- Searching for “invisible axion” extremely challenging
- Most promising approach to date: use axion-photon-photon vertex

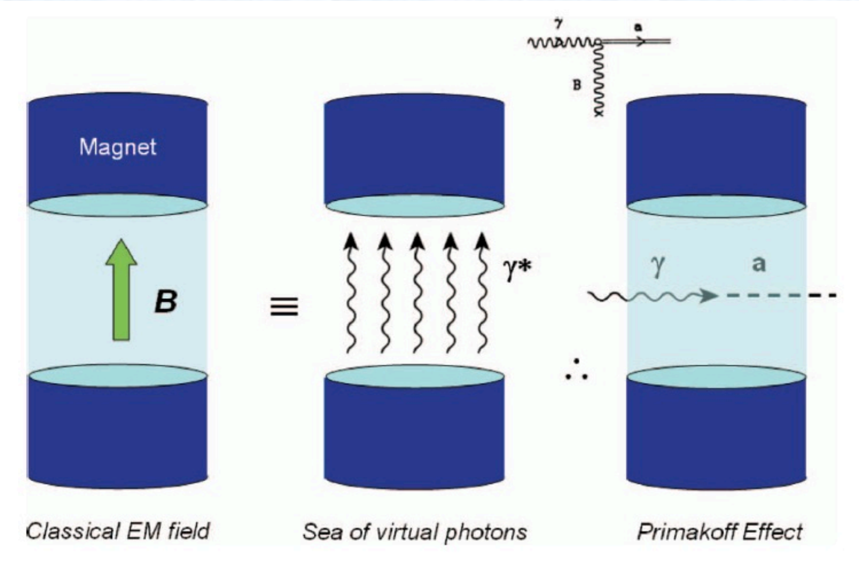
Primakoff effect:
scattering from an electromagnetic field (virtual photon)



In the presence of an **external field** (magnetic or electric) the **axion and the photon mix** and give rise to **oscillation/conversion**

$$L = g_{a\gamma\gamma}\vec{E}\cdot\vec{B}a$$

Higher magnetic field are easily obtainable than electric fields



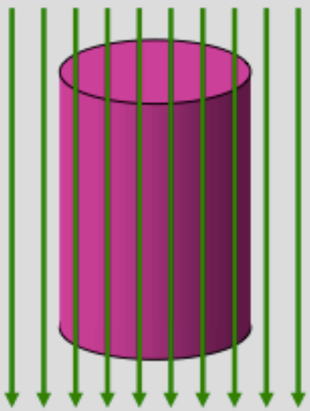
G. Carosi et al, Contemp. Phys. 49, 281 (2008)

Search for Galactic Axions (Cold Dark Matter)

DM axions	m_a = 10-3000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$

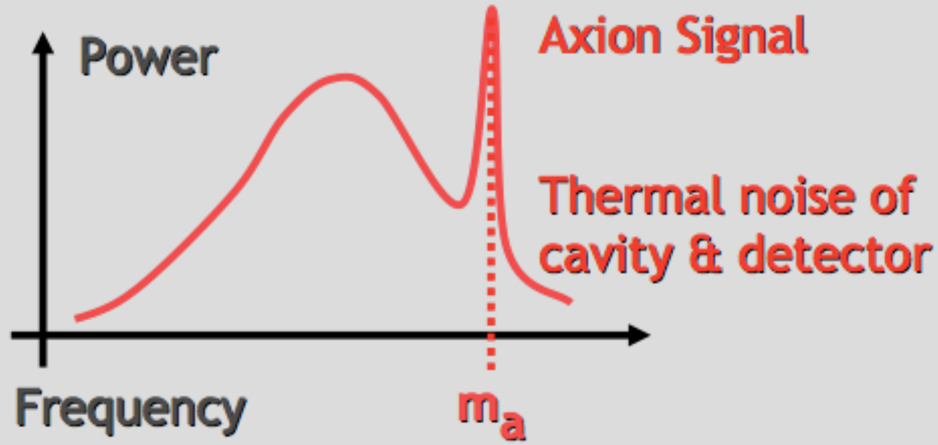
→ **Microwave Energies (1 GHz ≈ 4 μeV)**

Axion Haloscope (Sikivie 1983)

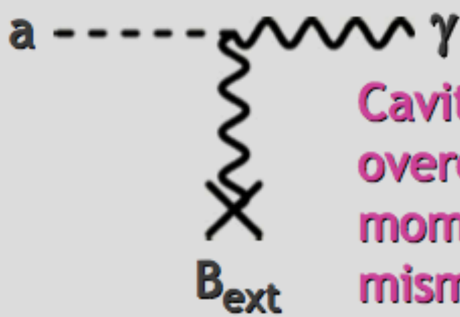


$B_{ext} \approx 8$ Tesla

Microwave Resonator $Q \approx 10^5$



Primakoff Conversion



Cavity overcomes momentum mismatch

Power of galactic axion signal

$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm^3}}\right)$$

From BARBIERI TALK JAN 2015

AXION ELECTRON/NUCLEUS SPIN COUPLING: DETECTION FEASIBILITY

The coupling to spin

$$L = \bar{\psi}(x)(i\hbar\partial\!\!\!/_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \quad \left(g_s = 10^{-(12\div17)} g_p \frac{GeV}{m_\Psi}\right)$$

DFSZ $g_p(e) \approx 1$

KSVZ $g_p(e) \approx 10^{-3}$

NRL: $$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma} \qquad \gamma = \frac{e}{2m_\Psi}$$

A coupling to the spin <u>and</u> to the Electric field

$$L \approx \frac{\alpha_S}{4\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \Rightarrow \quad d\,\vec{\sigma}\cdot\vec{E}$$

$$d \approx 10^{-16}\frac{a}{f_a}(e\cdot cm)$$

From BARBIERI TALK JAN 2015

The axion as a source of an effective $\vec{B}$

1. By the Dark Matter wind

$$\vec{B}_{eff} = \frac{g_p}{e}\vec{\nabla} a = \frac{g_p}{e} m_a \vec{v}\, a_0 \cos m_a t$$

$m_a \approx 10^{-4} eV$ (as reference) $\omega = m_a \approx 100\ GHz$

$f_a \approx 10^{11} GeV$

$m_a\ a_0 \approx \sqrt{\rho_{DM}} \approx 0.3\ GeV/cm^3$ $v \approx 10^{-3}$

coherence length $\lambda_a^C \approx \frac{1}{m_a v} \approx 3\ m$

coherence time $\tau_a \approx \frac{2\pi}{m_a v^2} \approx 10^{-4}\ sec$

$$B_{eff} \approx 10^{-22}\ Tesla \frac{m_a}{10^{-4} eV}$$

(on electrons)

(1000 bigger on nucleons)

From BARBIERI TALK JAN 2015

Comparing numbers

(From the Dark Matter wind)

$$\gamma_e B_{eff}(e) \approx \gamma_N B_{eff}(N) \approx 10^{-26} eV \frac{m_a}{10^{-4} eV}$$

$$d\ E \approx 10^{-27} eV \frac{E}{10^8 V/cm}$$ (CASPEr)

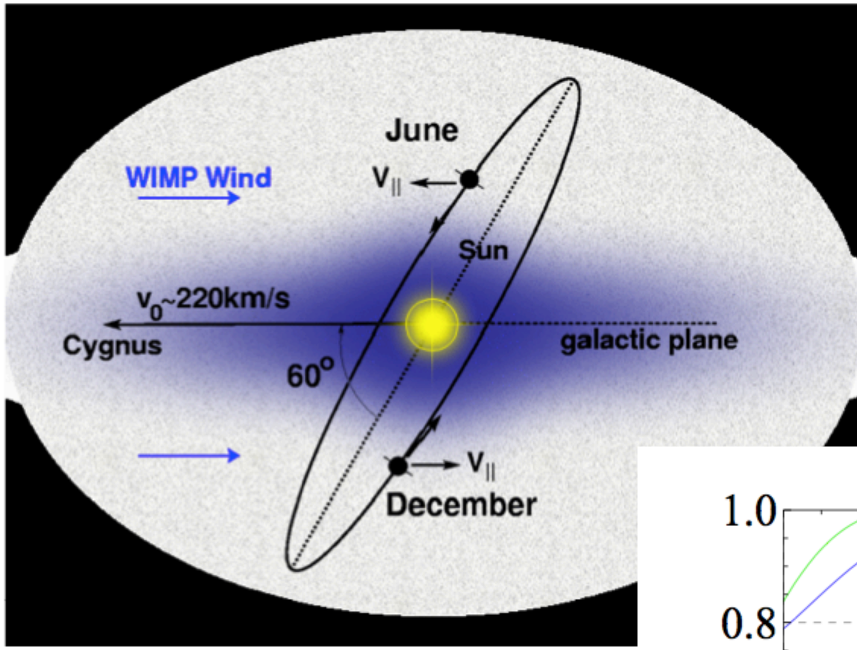
versus, e.g. (Gabrielse et al)

$$\Delta(g-2)_e < 10^{-13} \ \Rightarrow \ \gamma_e B \lesssim 10^{-17} eV \frac{B}{5\ Tesla}$$

$$d_e < 10^{-28} e \cdot cm \ \Rightarrow \ d_e E \lesssim 10^{-17} eV \frac{E}{10^{11} V/cm}$$

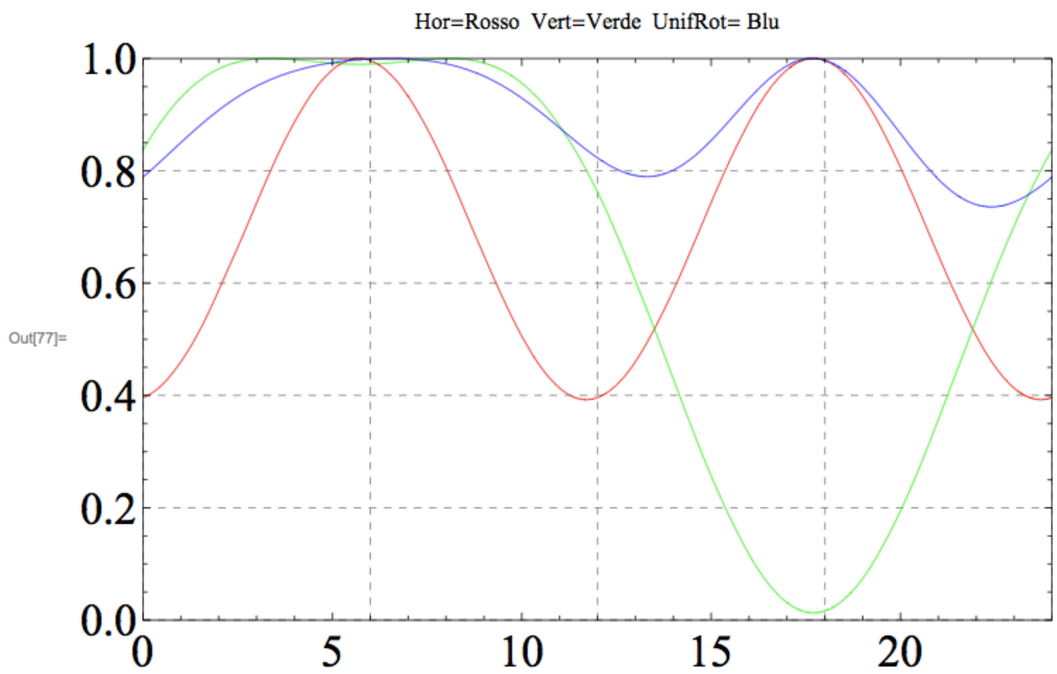
Need to work on some resonant phenomenon

Beam Pattern Reconstruction



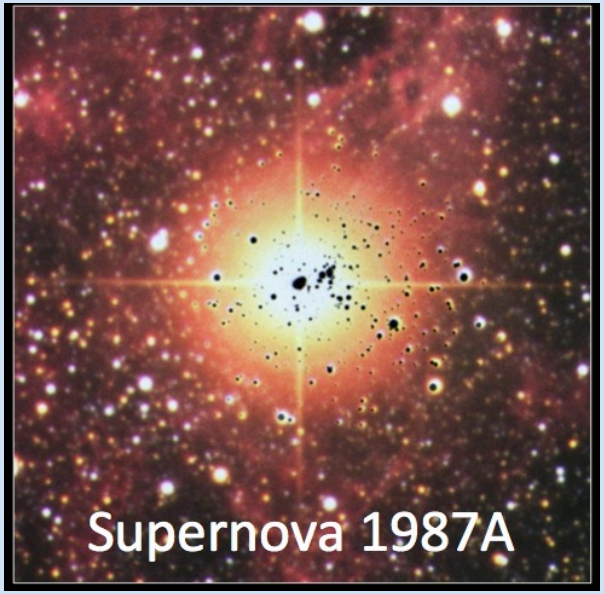
EFFETTO DIREZIONALE

SPIN ELETTRONE -ASSIONE



Propagation of the photon in the cosmo

- Large scale magnetic B fields exist in astrophysics
- Even if fields are very low (μG, nG), they extend over a very large length L.
- The product BL can then be large: ALPs oscillation with the photon can then be studied



- **SN1987A: ALPs emission due to Primakoff production in core**
- **ALPs partially converted into γ rays in galactic magnetic field (GMF)**
- **No γ rays burst observed in coincidence with SN1987A neutrinos**

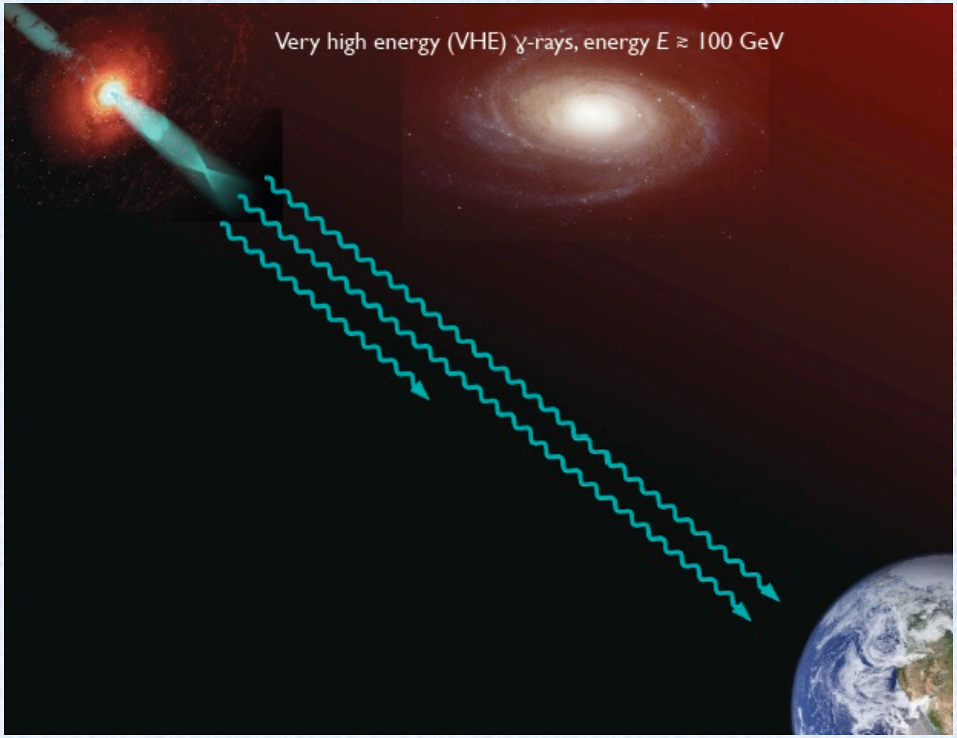
$$g_{a\gamma\gamma} \leq 1\times 10^{-11}\,\mathrm{GeV}^{-1} \text{ for } m_a \leq 10^{-9}\,\mathrm{eV}$$

Propagation of the photon in the cosmo

- Magnetically induced oscillations between photons and Axion-like particles can **modify the photon flux from distant sources**, featuring:
  - Frequency dependent dimming
  - Modified polarization
  - **Avoiding absorption by propagation in the form of axion**

This modification can be crucial in the behavior of Very High Energy (VHE, energy > 100 GeV) γ **rays from extragalactic sources**

Typical sources: Active Galactic Nuclei (**AGN**) measured with Imaging Air Cherenkov Detector (**IACT**)

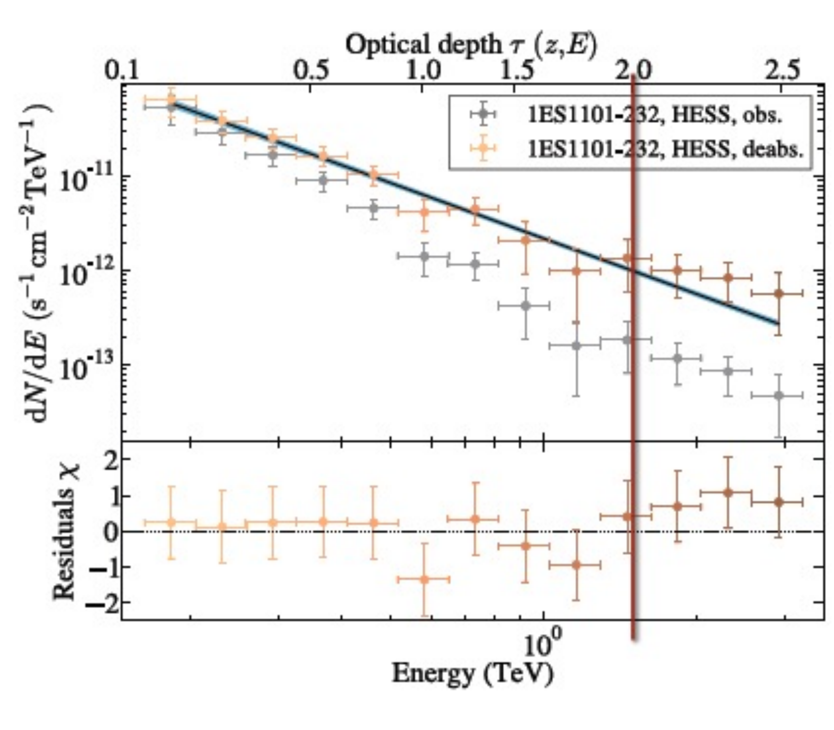


VHE photons from distant sources

- Gamma rays can interact with **cosmic photon background** (EBL) and produce e-p pairs
- **Optical depth τ is not zero** and the flux follows an exponential law

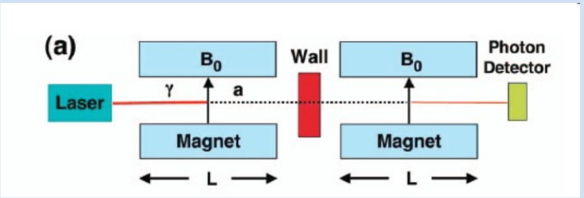
$$\phi_{\mathrm{obs}}(E_\gamma) \;=\; \phi_{\mathrm{s}}(E_\gamma) \,\times\, \exp\left(-\tau(E_\gamma, z_{\mathrm{s}})\right)$$

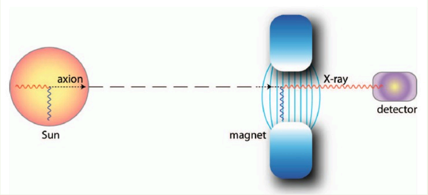
- At present there are **tension between models and data** for energies > 1 TeV

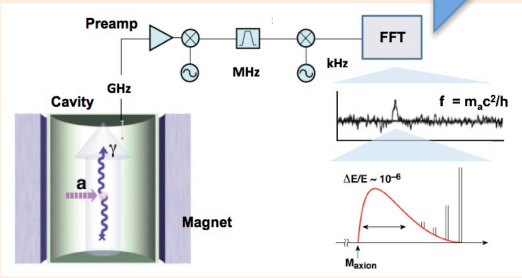


Comparison

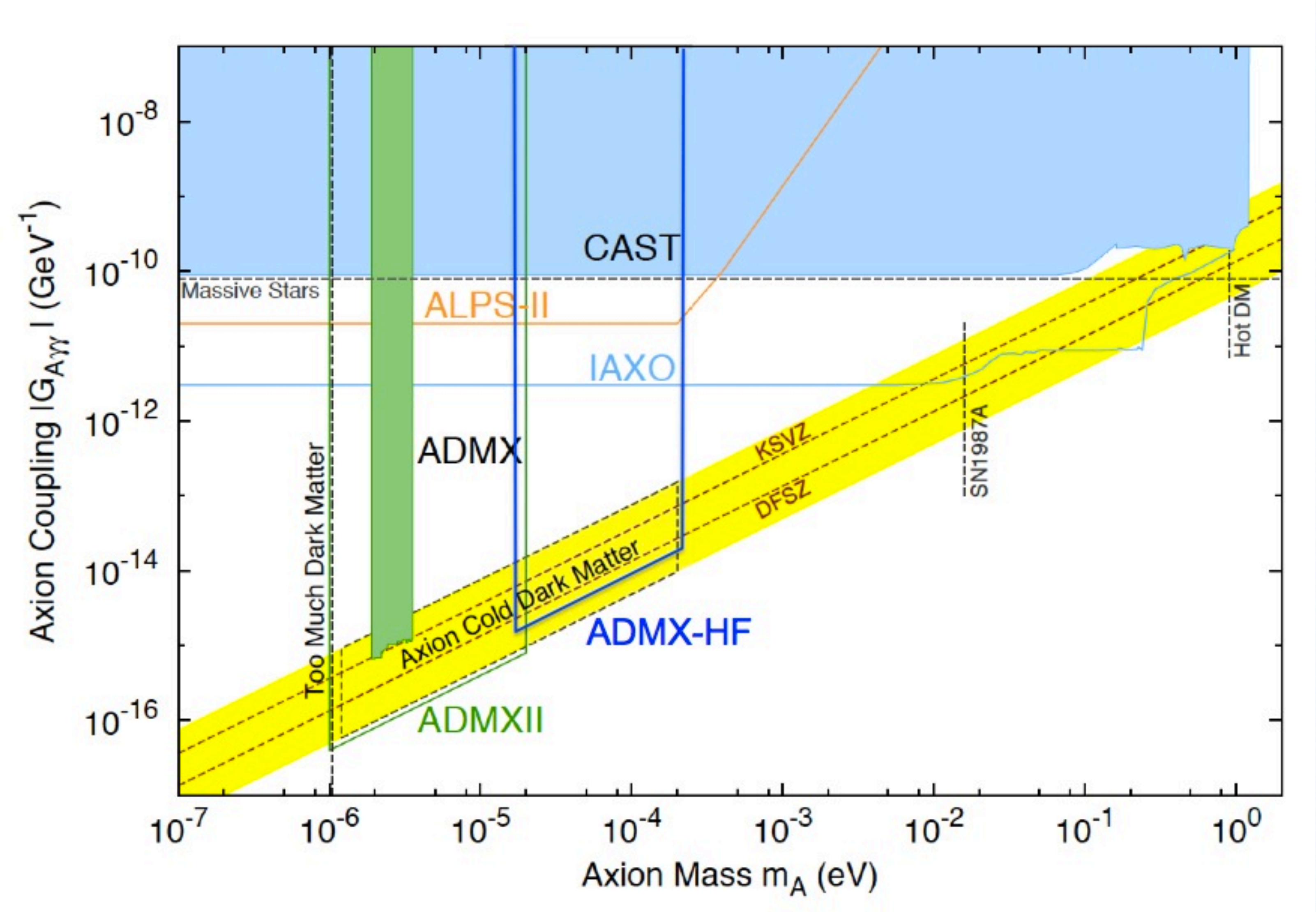
Lab Experiments	Helioscopes	Haloscopes
Axion Like Particle	ALPS & QCD Axion	ALPS & **QCD Axion**
Wide band experiment	Wide band experiment	Resonance experiment
Optical photons	X rays photons	Microwave photons
Model independent	Model dependent	Strong model dependency
Low axion flux	Medium axion flux	High axion flux
Low sensitivity to alps coupling	Good sensitivity to alps coupling	Reaches KSVZ axion model







Global perspectives



http://lanl.arxiv.org/pdf/1405.3685v1.pdf

Conclusions

- A partial review of various Axion Matter Interaction has been presented
- The Axion, invented to solve a specific problem of QCD, became a perfect Dark Matter candidate:
  - It can be searched for in dedicated experiments (Haloscopes)
  - Helioscopes and terrestrial experiment don't seems to be able to reach the parameter space for an axion DM candidate
- Axion like particles came also into the scene. They might be as well good DM candidates
- Several efforts in different physics fields can help to find or rebut the existence of this exotic particle