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SUMMER SCHOOL ON ASTROPARTICLE PHYSICS AND COSMOLOGY

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AXIONS: A REVIEW

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Please note: These are preliminary notes intended for internal distribution only.

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Spontaneous Symmetry Breaking

$$\mathcal{L} = (\partial_\mu \varphi)(\partial^\mu \varphi)^* - V(\varphi\varphi^*)$$

Potential V is symmetric under

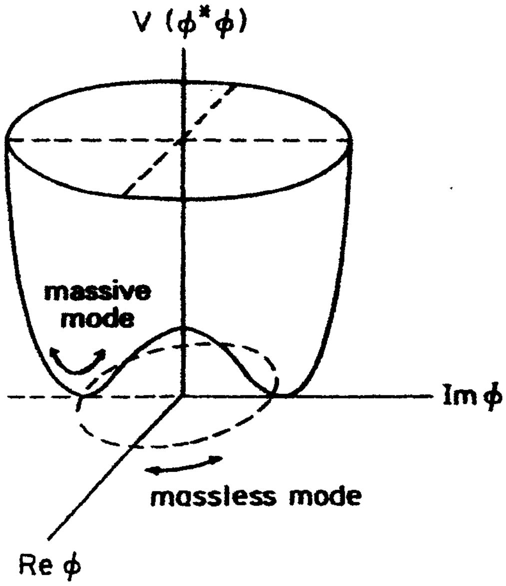
$$\varphi \to e^{i\alpha}\varphi$$

If V has degenerate vacua
(for example, $V = (\varphi\varphi^* - v^2)^2$)

GOLDSTONE THEOREM applies;
implies zero-mass Nambu-Goldstone boson

Well tested Applications:
- Solid state physics (Zero modes)
- In gauge theories, with local symmetries
  (get Massive Gauge Bosons)

The subject of the TALK is on an
Hypothetical Application:
- Axion (Quasi NG boson)



Classical modes in the scalar field with symmetry-breaking potential

The Strong CP Problem

QCD Lagrangian

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}(i\not{D} - M)q$$
$$+ \ \theta \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \ + \ldots$$

$\theta - term$

- contains dual $\tilde{G}^a_{\mu\nu} = (1/2)\epsilon_{\mu\nu\rho\sigma} G^{a\rho\sigma}$
- is Lorentz Invariant
  and Gauge Invariant $\Rightarrow$ should be in $\mathcal{L}_{\text{QCD}}$
- is $\sim \vec{E} \cdot \vec{B} \Rightarrow$ is CP-violating

quark sector

- $q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad M = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$

If we perform $U(1)_A$ rotation
on a quark field:

$$u \longrightarrow e^{i\alpha\gamma_5} \, u$$

(chiral: $u_L \ \rightarrow \ e^{-i\alpha} u_L, \ u_R \rightarrow e^{i\alpha} u_R$)

then quark mass term is NOT invariant

$$\mathcal{L}_{\text{mass}} = -m_u \, \bar{u}_L u_R + \text{h.c.} \ \longrightarrow \ -m_u \, e^{2i\alpha} \, \bar{u}_L u_R + \text{h.c.}$$

Conclusion : $\quad m \neq 0 \quad \Rightarrow$ NO symmetry

Naively $m_u = 0 \Rightarrow$ symmetry. But NOT true.

Noether current j_5^μ

$$\delta\mathcal{L} \sim \partial^\mu(\bar{u}\gamma_\mu\gamma_5 u) = \partial^\mu j_5^\mu$$

is anomalous

$$\partial^\mu j_5^\mu = \frac{\alpha_s}{4\pi} G \cdot \tilde{G} \neq 0$$

(ABJ anomaly,
$U(1)_A$ does not survive quantum effects)

$$\mathcal{L}_{CP}(\theta) = \theta \frac{\alpha_s}{8\pi} G \cdot \tilde{G} \to \mathcal{L}_{CP}(\theta - 2\alpha)$$

When $m = 0$, set $\alpha = \theta/2$ so that
θ-term is rotated away

BUT, $m_u \neq 0$ in the real world (it seems)
so $\mathcal{L}_{CP}$ present in the theory

Still another possibility for not having $\mathcal{L}_{CP}$:
θ is a free parameter; put $\theta = 0$
One then has to face
at least <u>two problems</u>

Problems

1)

Presence of θ-term necessary to solve $U(1)_A$-problem:
Why η' is not a Nambu-Goldstone boson?

2)

There are additional contributions from electroweak sector to $\mathcal{L}_{CP}$.
Masses from ew SSB are complex in general

$$\mathcal{L}_{\text{mass}} = -|m|e^{i\varphi}\bar{u}_L u_R + \text{h.c.}$$

To have $\mathcal{L}$ with real masses, use chiral rotation

$$u_L \to e^{i\varphi/2} u_L \qquad u_R \to e^{-i\varphi/2} u_R$$

so that

$$\begin{aligned} \mathcal{L}_{\text{mass}} &= -|m|\bar{u}_L u_R + \text{h.c.} \\ &+ \varphi \frac{\alpha_s}{8\pi} G \cdot \widetilde{G} \end{aligned}$$

Physics depends on

$$\bar{\theta} = \theta + \text{Arg Det } M$$

(Even if $\theta = 0$, in general $\bar{\theta} \neq 0$)

Observational consequences of $\mathcal{L}_{CP}$

Originates neutron edm

$$d_n \sim \frac{e}{m_n}\,\bar{\theta}\,\frac{m_u m_d}{m_u + m_d}\frac{1}{\Lambda_{\rm QCD}}$$

Experimentally

$$d_n < 0.63 \times 10^{-25}\ e\,\mathrm{cm}$$

leads to bound

$$\bar{\theta} < 10^{-9}$$

Strong CP-problem:

Why is $\bar{\theta}$ so small?
We would have expected $\theta_{\rm QCD}$ and Arg Det M not far from O(1)
and we have no reason to expect
such fine-tuned cancellation (unrelated origins)

Axions: A Review

Contents:

- Strong CP-problem

  We shall concentrate on the
  consequences (axion)
  of Peccei-Quinn solution to strong CP-problem
  (not the unique solution)

- The axion and its properties
- Limits on axion parameters
- Looking for the axion
- Axion-like particles

Eduard Massó
UAB

The Axion and its properties

The PQ solution to the strong CP problem: Introduce new global chiral symmetry $U(1)_{PQ}$ and use the freedom to rotate $\bar{\theta}$ away.

SSB of $U(1)_{PQ}$ at energy $\sim f_a$
$\Rightarrow$ NG boson: axion, $a \sim f_a \bar{\theta}$

Axion, as all NG bosons, couple derivatively

$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 + c_i \frac{1}{2 f_a} (\bar{\Psi}_i \gamma^\mu \gamma_5 \Psi_i)(\partial_\mu a)$$

$\Psi_i = e, p, n$, etc, $c_i = O(1)$ model dependent

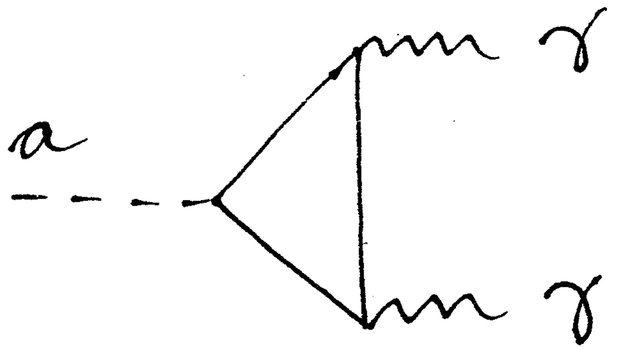
But, the axion is special since
it has to reproduce the anomaly
and there is a new (non-derivative) term

$$\mathcal{L} \supset \frac{1}{f_a} \frac{\alpha_s}{8\pi} \, G \cdot \tilde{G} \; a$$

At low (Λ_{QCD}) energies, $G \cdot \tilde{G}\; a$ term
1) generates potential $V(\theta)$ which makes $\bar{\theta} \to 0$
2) generates axion mass

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} = 0.6 \text{ eV } \frac{10^7 \text{ GeV}}{f_a}$$

mass tiny if f_a is large



Coupling to 2 fotons:

$$\mathcal{L} \supset c_\gamma \frac{\alpha}{\pi f_a} F \cdot \tilde{F} \; a = -g_{a\gamma} \vec{E}\vec{B}\, a$$

(important from the point of view of possible detection)

— — — — — — — — — — — — — — — — — —

All c_i mild model dependent except for the electron:

Models with $c_e \neq 0$ (DFSZ type)
Models with $c_e = 0$ (KSVZ type)
KSVZ is "hadronic axion"
not coupled to e (at tree level)

$a\gamma\gamma$ coupling:

$c_\gamma = 0.36$ (DFSZ type)
$c_\gamma = -0.97$ (KSVZ type)

Limits to Axion parameters

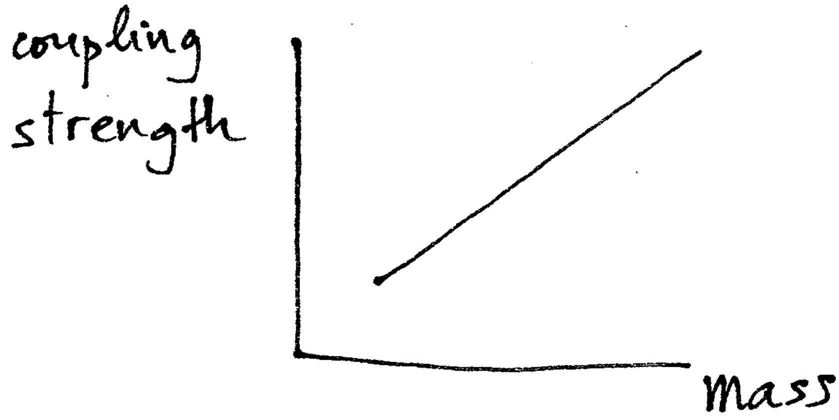
Find constraints to properties using:

1. Laboratory

2. Astrophysical

3. Cosmological

In fact, only <u>one</u> parameter to bound: f_a or m_a
lighter $\longleftrightarrow$ less interacting



1. HIGH-ENERGY LABORATORY EXPS

Take into account processes like:

<u>meson decays</u>

$$\begin{aligned} J/\Psi &\to \gamma a \\ \Upsilon &\to \gamma a \\ K^+ &\to \pi^+ a \\ \pi^+ &\to e^+ \nu_e a\,; \quad a \to e^+ e^- \end{aligned}$$

<u>beam dump</u>

$$p(e^-)N \to aX\,; \quad a \to \gamma\gamma, e^+e^-$$

<u>nuclear deexcitation</u>

$$N^* \to Na\,; \quad a \to \gamma\gamma, e^+e^-$$

Conclusion:

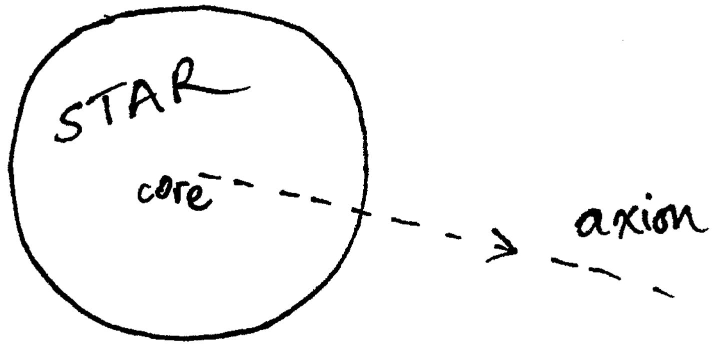
$$f_a > 10^4\,\mathrm{GeV} \qquad m_a < 1\,\mathrm{keV}$$

This excludes $f_a \sim$ Fermi scale
(original PQ suggestion)

2. ASTROPHYSICAL LIMITS

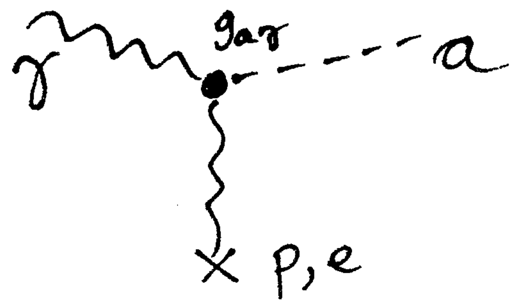
are able to push (very much) terrestial limits

"Too" efficient energy drain would be inconsistent with observation



Horizontal branch stars in Globular Clusters

main production is from Primakov



$$g_{a\gamma} < 0.6 \times 10^{-10}\,\text{GeV} \quad \Rightarrow \quad f_a > 10^7\,\text{GeV}$$

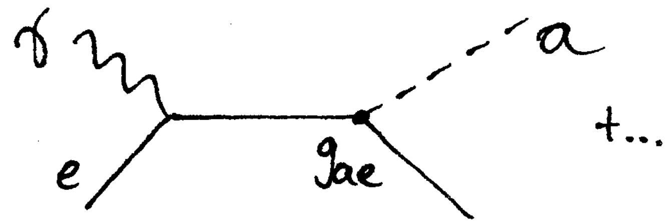
rule out interval:

$$0.4\,\text{eV} < m_a < 200\,\text{keV}$$

($m_a > 200\,\text{keV}$ is too heavy to be produced)

When $c_e \sim 1$ (DSVZ axion)

main production is from Compton

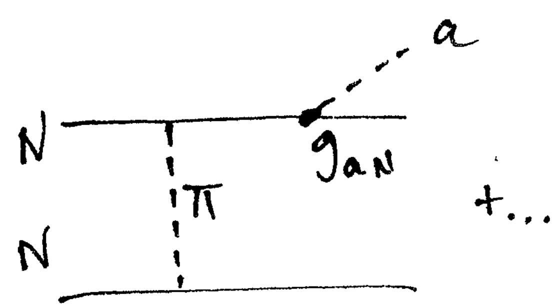


$$g_{ae} = c_e \frac{m_e}{f_a} < 2.5 \times 10^{-13}$$

which enlarges forbidden region:

$$0.01\,\text{eV} < m_a < 200\,\text{keV}$$

SN 1987A main production is from Axion Bremsstrahlung



Duration of ν signal in Earth detectors forbids:

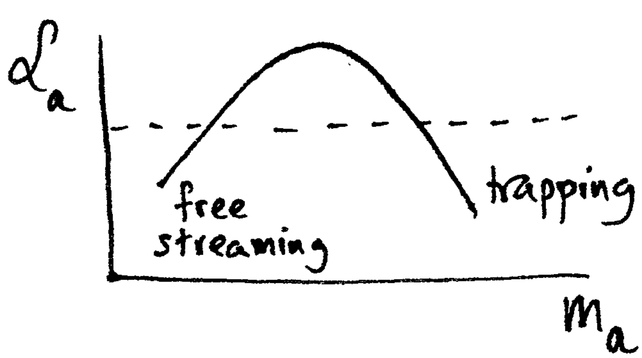
$$3 \times 10^{-10} < g_{an} = c_n \frac{m_n}{f_a} < 3 \times 10^{-7}\ \text{GeV}$$

or, in terms of masses, excludes

$$0.01\,\text{eV} < m_a < 10\,\text{eV}$$

(upper limit: trapping in the SN)

Axion luminosity:



3. COSMOLOGICAL CONSTRAINTS

put lower limits to m_a

Axion (cosmological) history

Start at high temperatures $T \gg f_a$

1 at $T \sim f_a$

SSB of $U(1)_{PQ}$, all $< a >$ equally likely,
but naturally expect $< a > \sim f_a$.

$$\text{initial angle}: \quad \bar{\theta}_1 \sim \frac{< a >}{f_a} \sim 1$$

2 at $T \sim 1$ GeV

QCD effects turn on $\Rightarrow$ potential $V(\bar{\theta})$
And $V(\bar{\theta})$ forces $\bar{\theta} \to 0$ (CP-conserving value)

θ angle was "misaligned":
start with $\bar{\theta} = \bar{\theta}_1 \sim 1$, and will relax to $\bar{\theta} \to 0$

Field oscillations contribute to
cosmic energy density

$$\Omega h^2 \simeq 2 \times 10^{\pm 0.4} F(\bar{\theta}_1)\bar{\theta}_1^2 \left(\frac{10^{-6}\,\text{eV}}{m_a}\right)^{1.18}$$

(F takes into account anharmonic effects).

Vac~~c~~uum Misalignment Mechanism:

Axion is born

1. non-thermal
2. non-relativistic

Interesting range for cosmology is

$$\Omega h^2 \sim 1 - 0.1 \quad \Rightarrow \quad m_a \sim 10^{-3} - 10^{-6}\,\text{eV}$$

Axion could be CDM

If $F(\overline{\theta}_1)\overline{\theta}_1^2 \sim 1$ get lower bound to mass

$$10^{-6}\,\text{eV} < m_a$$

BUT

for smaller values of initial $\overline{\theta}_1$, looser bound

(Apart from value of $\overline{\theta}_1$, there are other cosmological uncertainties)

Other axion source: String-produced axions

Unless inflation occurs at $T < f_a$,
axion strings survive and decay into axions

Debate on the importance of string mechanism
Two "scools"

- $\Omega_{\text{string}} \sim \Omega_{\text{misalign}}$
- $\Omega_{\text{string}} \sim 10\,\Omega_{\text{misalign}}$

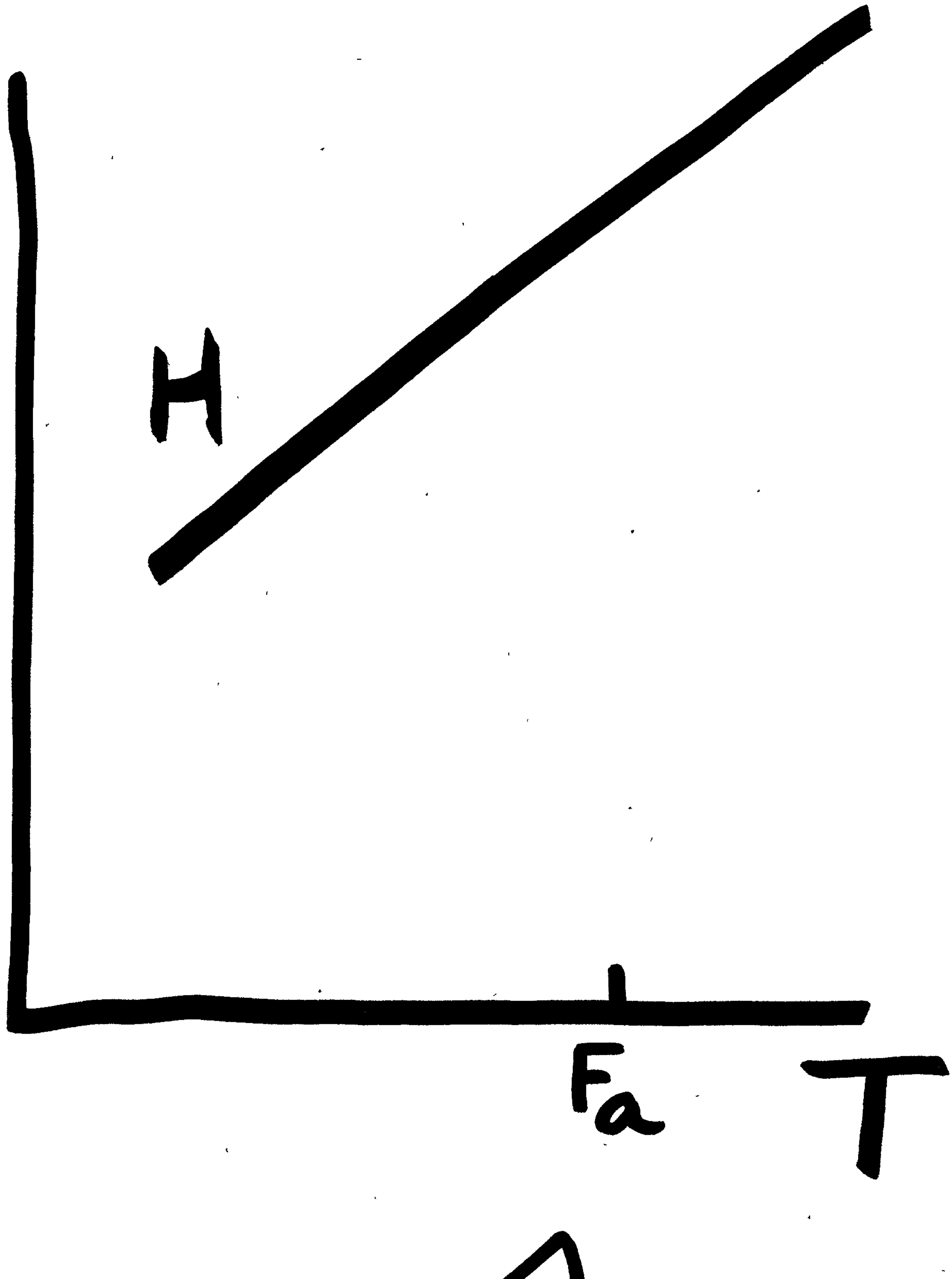
Domain Walls?

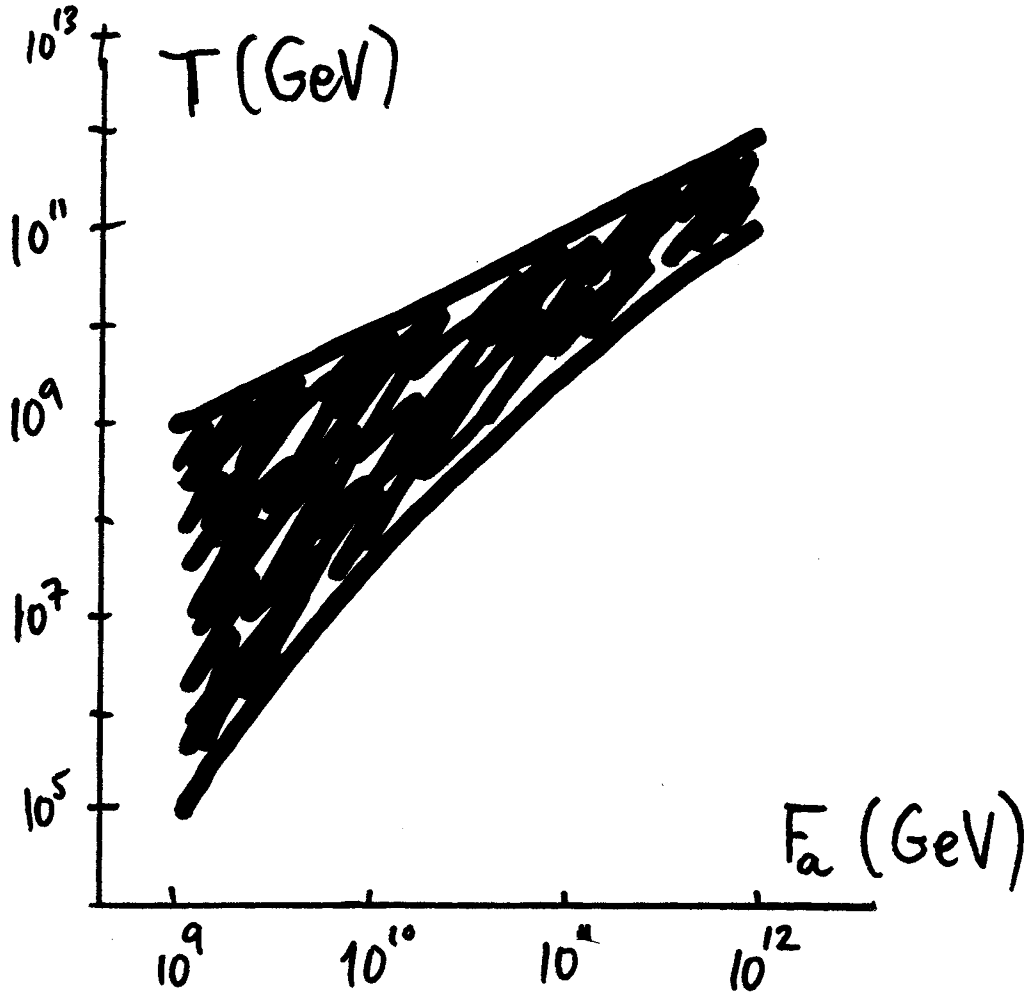
Thermal Axions

1) For $f_a < 1.2 \times 10^{12}$ GeV
there is thermal density but small:

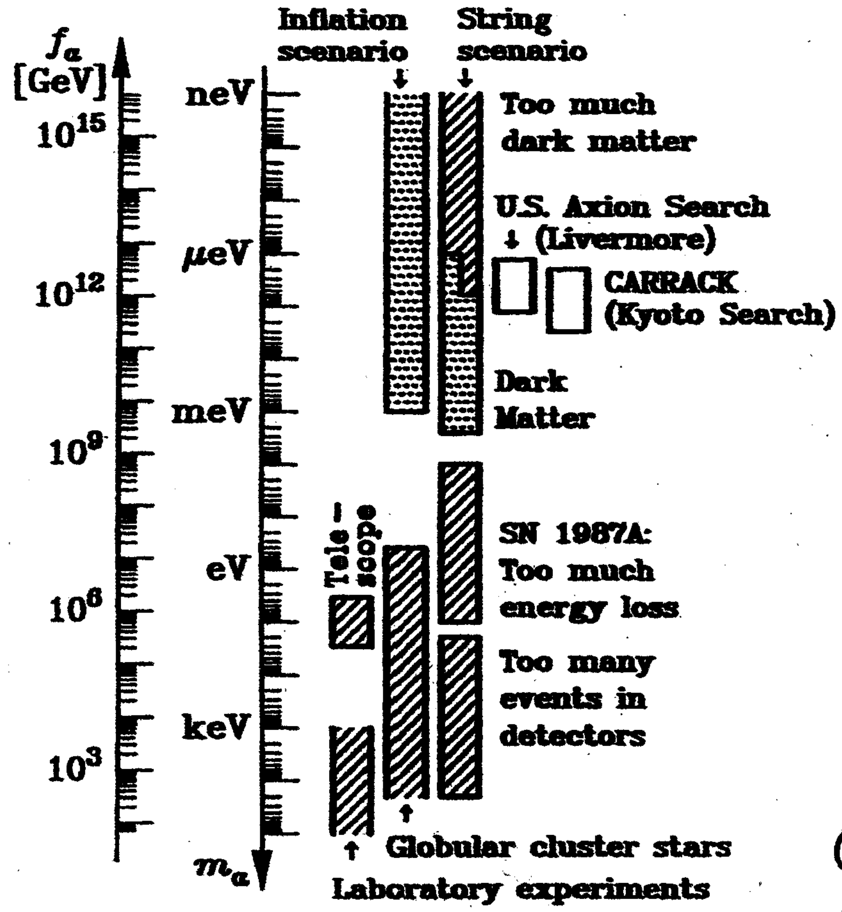
$$n_a(\text{today}) \simeq 7.5\,\text{cm}^{-3}$$

2) Thermalization range:


H
Fa
T
TIME



T (GeV)
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
F_a (GeV)
10^{9}
10^{10}
10^{11}
10^{12}

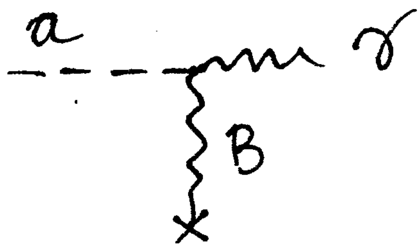


G. Raffelt
PDG

Figure 12. Astrophysical and cosmological exclusion regions (hatched) for the axion mass m_a or equivalently, the Peccei-Quinn scale f_a. An "open end" of an exclusion bar means that it represents a rough estimate; its exact location has not been established or it depends on detailed model assumptions. The globular cluster limit depends on the axion-photon coupling; it was assumed that $E/N = 8/3$ as in GUT models or the DFSZ model. The SN 1987A limits depend on the axion-nucleon couplings; the shown case corresponds to the KSVZ model and approximately to the DFSZ model. The dotted "inclusion regions" indicate where axions could plausibly be the cosmic dark matter. Most of the allowed range in the inflation scenario requires fine-tuned initial conditions. In the string scenario the plausible dark-matter range is controversial as indicated by the step in the low-mass end of the "inclusion bar." Also shown is the projected sensitivity range for the galactic dark-matter search experiments.

Looking for the Axion

Crucial observation (Sikivie):
Axion-photon mixing
in B-field
($\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma}\vec{E}\vec{B}a$)

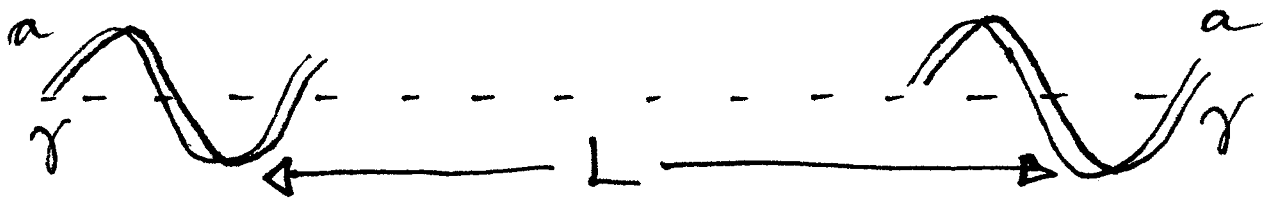


Contribution:
$\vec{E}\vec{B} \Rightarrow$ transverse external $B_T \parallel$ polarization $\vec{E}$

Another observation:
Interaction States $\neq$ Propagation States

$$|a'> = \cos\varphi\,|a> - \sin\varphi\,|\gamma>$$
$$|\gamma'> = \sin\varphi\,|a> + \cos\varphi\,|\gamma>$$

Probability of transition $P \sim g_{a\gamma}^2 \sim 1/f_a^2$
enhanced when $a-\gamma$ conversion is coherent :



$$|k_{\gamma'} - k_{a'}|\,L \ll 2\pi$$

(Valid when $g_{a\gamma}B_T \ll L$ and $m_a^2/2E \ll E$)

$$P(a \to \gamma) = \frac{1}{4}\, g_{a\gamma}^2\, B_T^2\, L^2$$

The Search:

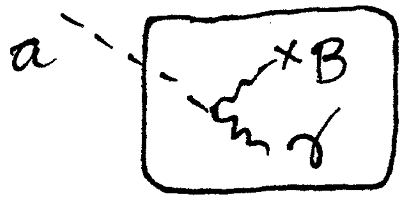
1. Conversion of Galactic Halo axions

2. Conversion of Solar axions

3. Production and detection in Laboratory experiments

Sometimes interesting to "decouple" f_a from m_a relation (more later)

1. HALOSCOPE:
SEARCH OF HALO AXIONS



- would produce μ-wave fotons (1 GHz = 4 μeV) with very small dispersion

$$h\nu = E \simeq m_a(1 + \beta^2/2) \quad \beta \sim 10^{-3}$$

There are already second-generation exps:

△ US large scale experiment sensitive in the range

$$2.9 < m_a < 3.3 \ \mu\text{eV}$$

already excludes KSVZ axions as constituting the whole of CDM

$$\rho = 7.5 \times 10^{-25} \ \text{g cm}^{-3}$$

Near future: $1 < m_a < 10\,\mu$eV

△ Kyoto exp. (CARRACK)
Under development, will use Rydberg atoms technique to detect μ-wave fotons

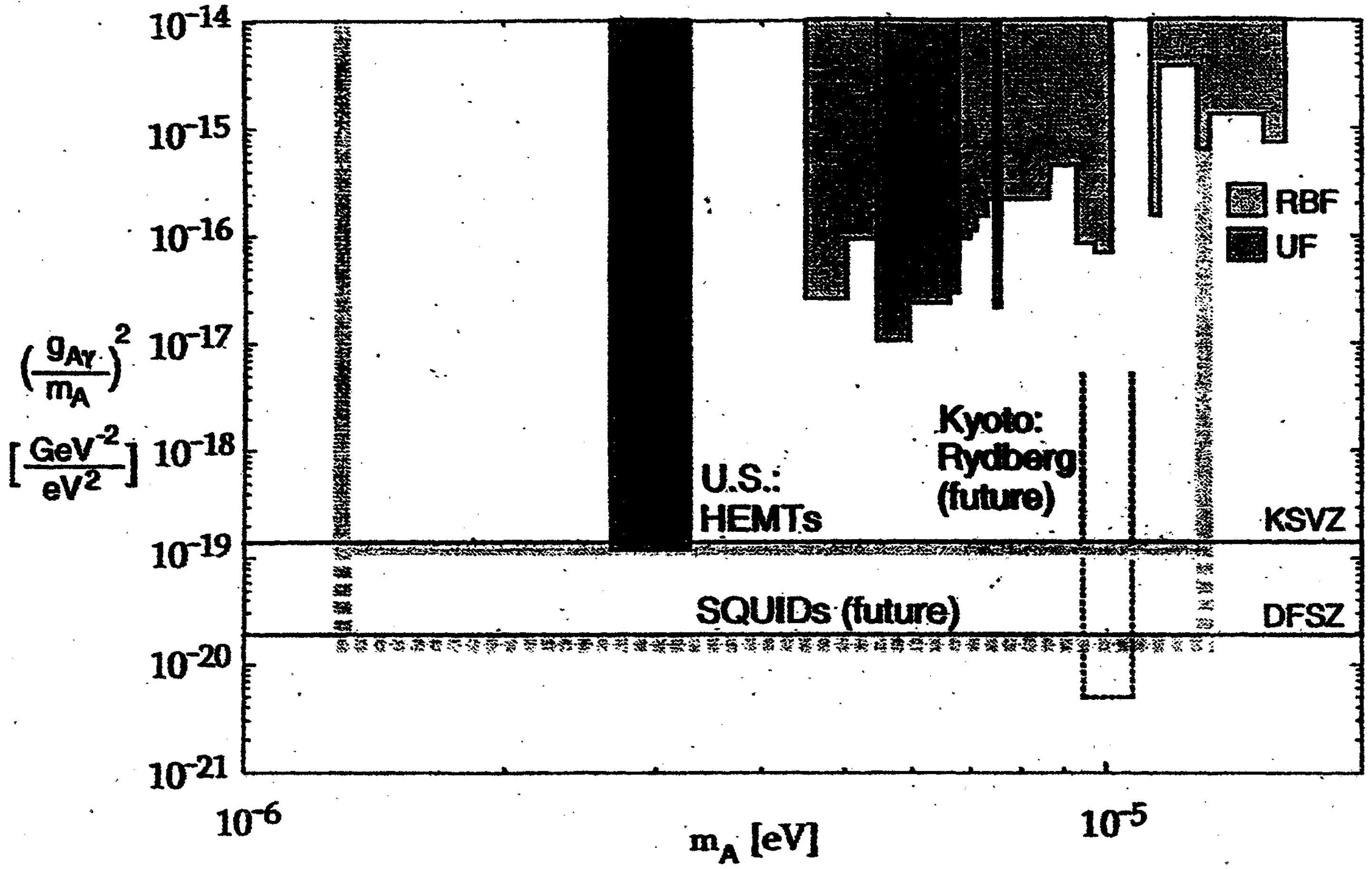


Figure 2: Exclusion region from the microwave cavity experiments, where the plot is flattened by presenting $(g_{A\gamma}/m_A)^2$ vs. m_A. The first-generation experiments (Rochester-BNL-FNAL, "RBF" [9]; University of Florida, "UF" [10]) and the US large-scale experiment in progress ("US" [11]) are all HEMT-based. Shown also is the full mass range to be covered by the latter experiment (shaded line), and the improved sensitivity when upgraded with DC SQUID amplifiers [12] (shaded dashed line). The expected performance of the Kyoto experiment based on a Rydberg atom single-quantum receiver (dotted line) is also shown [13].

Hagmann, van Bibber, Rosenberg
PDG

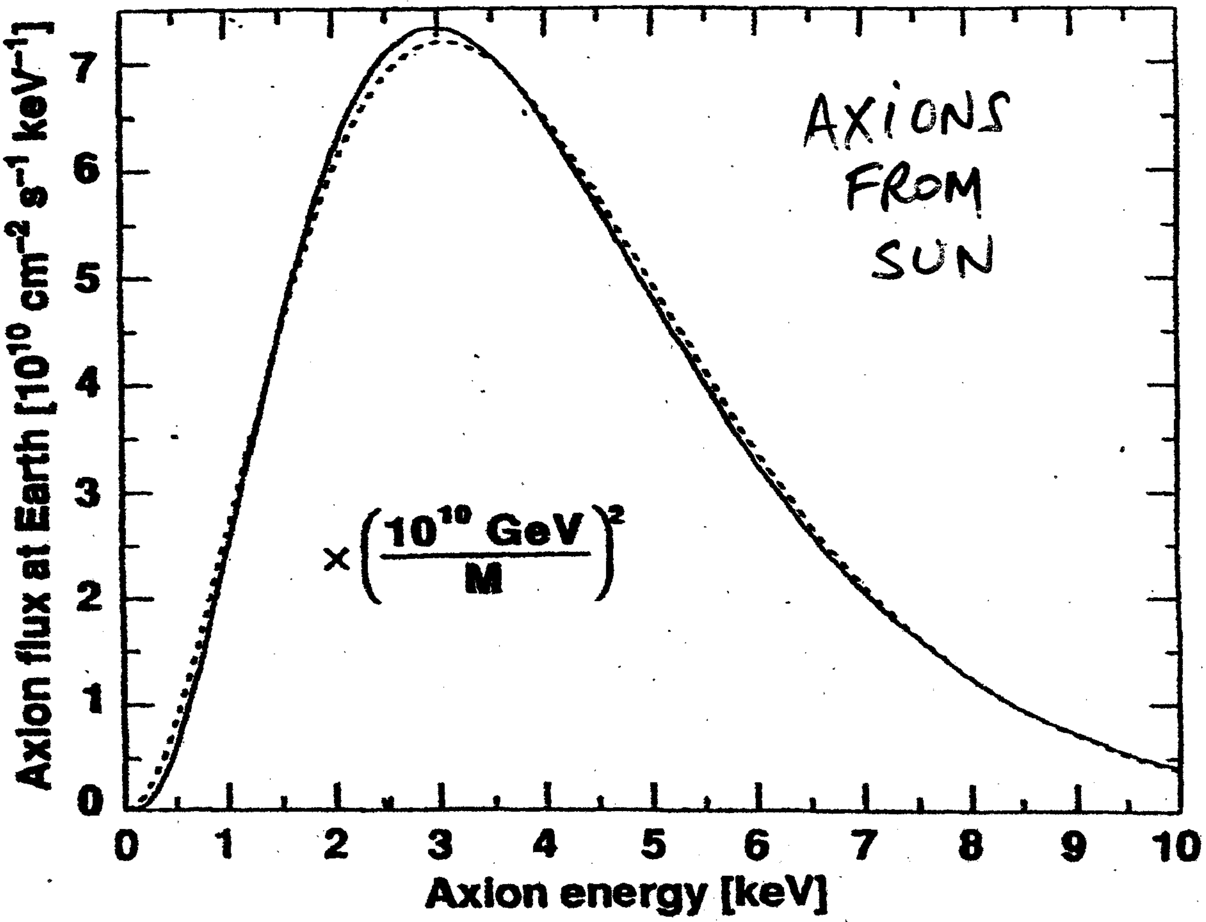


FIG. 2. Differential solar axion flux at the Earth. We assume that axions are only produced by the Primakoff conversion of blackbody photons in the solar interior ("hadronic axions"), and we assume a standard solar model (Ref. 26). The axion-photon coupling strength M is defined in Eq. (3). The solid line arises from a numerical integration over the Sun, the dashed line is an analytical approximation to this result as given in Eq. (9).

Van Bibber et al. M. ~~Turner~~

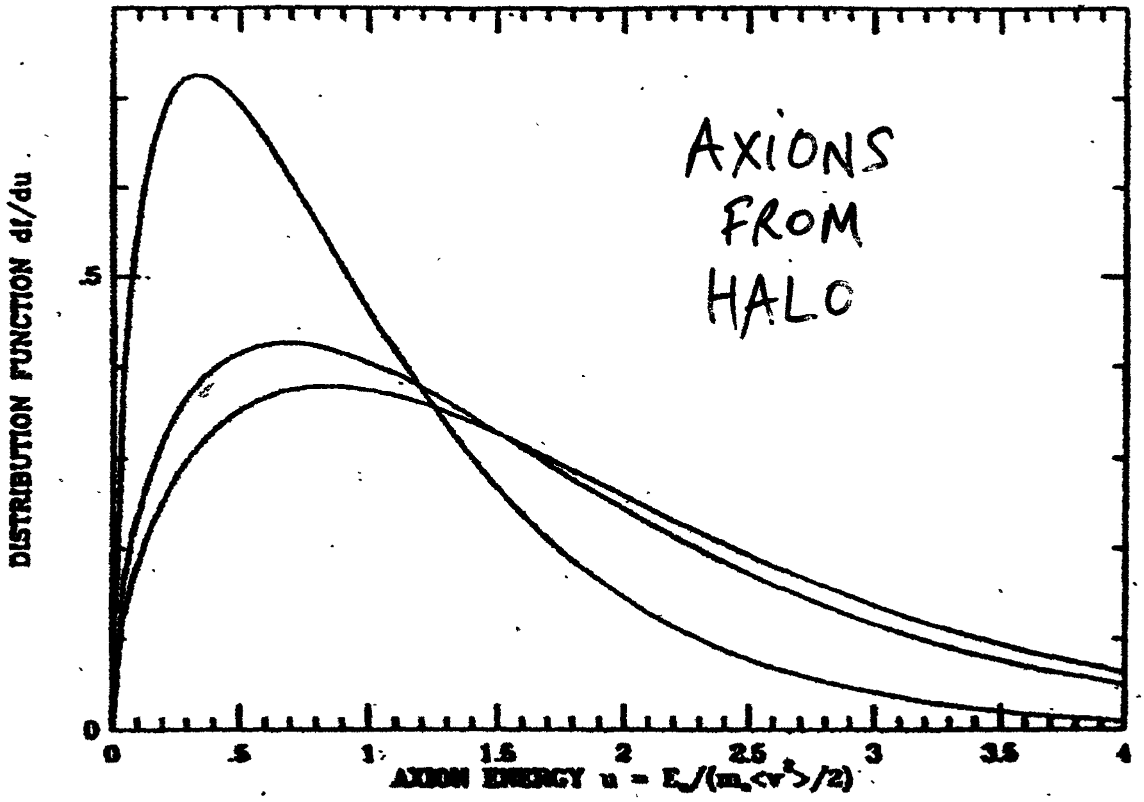


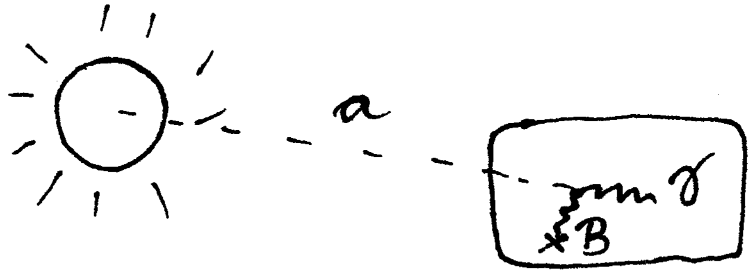
FIG. 1. Local phase-space distribution function df/du for cosmic axions. The axion kinetic energy $E_a = u(m_a\bar{v}^2/2)$, which corresponds to a frequency of $980u\,(m_ac^2/10^{-5}\text{ eV})$ Hz. The distribution function in the rest frame of the Galaxy (tallest and narrowest), in the laboratory frame in June (shortest and broadset), and in the laboratory frame in December are shown.

M. Turner

2. HELIOSCOPE:
SEARCH FOR SOLAR AXION CONVERSION

- note is independent of DM hypothesis
- γ energies $E \sim$ a few keV (X-rays)

2.A Magnetic Search



No signal seen. Limit (Tokyo):

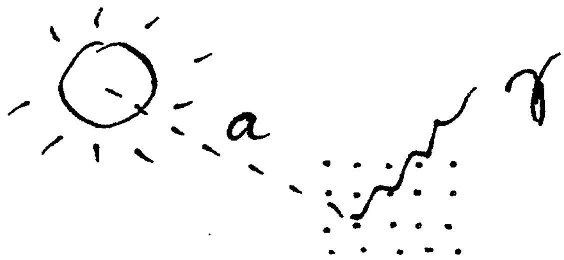
$$g_{a\gamma} < 6 \times 10^{-10}\ \text{GeV}^{-1} \qquad m_a < 0.03\,\text{eV}$$

Improved recently up to $0.05 < m_a < 0.26$ eV

[Use gas to enhance possible signal
$\omega_{\text{plasmon}} \Rightarrow k_{\gamma'} - k_{a'} \simeq (m_a^2 - \omega_{\text{pl}}^2)/2E$]

Future: CAST at CERN

2.B Crystal Search (Bragg-Primakov)



Coherent $a \to \gamma$
conversion in a crystal
when angle of incidence satisfies Bragg cond.

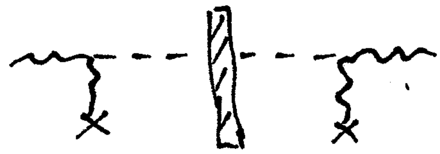
Limit (Cosme-II, SOLAX)

$$g_{a\gamma} < 2.7 \times 10^{-9}\ \text{GeV}^{-1} \qquad m_a < 1\,\text{keV}$$

3. LABORATORY SEARCHES

- **Independent of DM AND solar hypothesis**

3.A Light shining through a wall



$g_{a\gamma} < 6.7 \times 10^{-10}$ GeV^{-1} $\quad m_a < 0.03\,\text{eV}$

3.B Laser polarization experiments

Since $\boldsymbol{E}_{\parallel}$ affected but not $\boldsymbol{E}_{\perp}$,
there are physical consequences:
rotation of plane of polarization, birefrigence

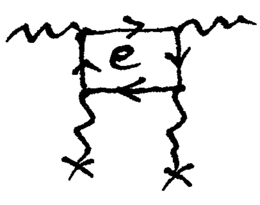
PVLAS experiment
PRELIMINARY: they get a signal.

Working hard to see if it is from New Physics.

Would correspond to

$g_{a\gamma} \sim 2 \times 10^{-7}$ GeV^{-1} $\quad m_a \sim 10^{-2} - 10^{-3}\,\text{eV}$

Also interesting for "conventional physics"
Should in the future "see"
QED light-light box-diagram



Axion-like particles

(1) NG bosons (massless) from SSB
example: family symmetry $\Rightarrow$ familons
(Who ordered the muon? - Rabi)
example: Lepton-number sym. $\Rightarrow$ majorons

there could be other examples
perhaps with mass (quasi-NG)

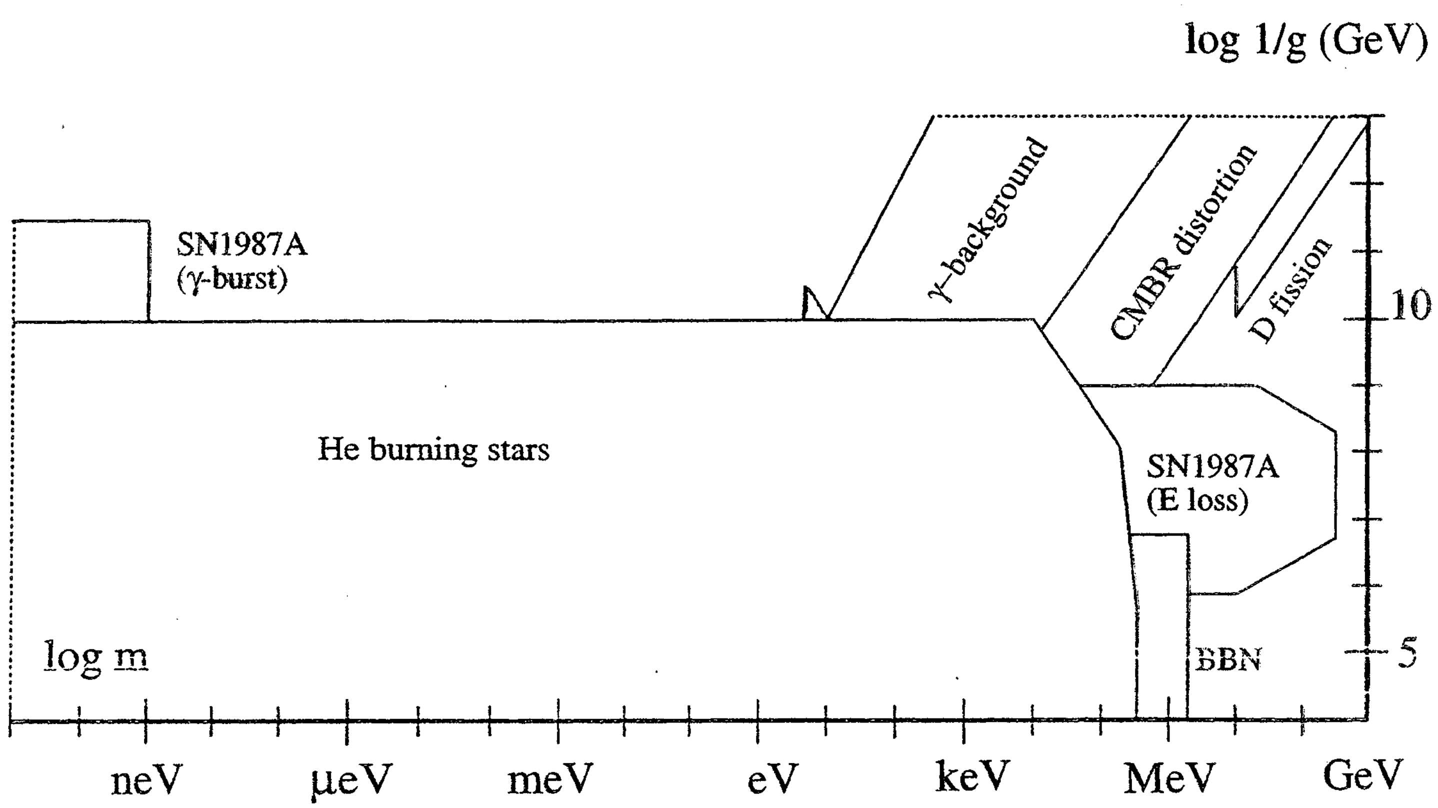
(2) Contibutions to axion mass
from (more) exotic sources
Consequence: $m_a - f_a$ relation broken

Then
Interesting to analyze experimental constraints
with two free parameters: mass and coupling.

Take coupling $\rightarrow$ boson-γ-γ
since it is the one that leads to exp. signals
(If exp. signal ever seen in "axion experiment",
it could be a boson different from axion)

Boson φ with mass m and coupling g

$$\mathcal{L} = \frac{1}{8}\, g\ \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}\ \varphi$$

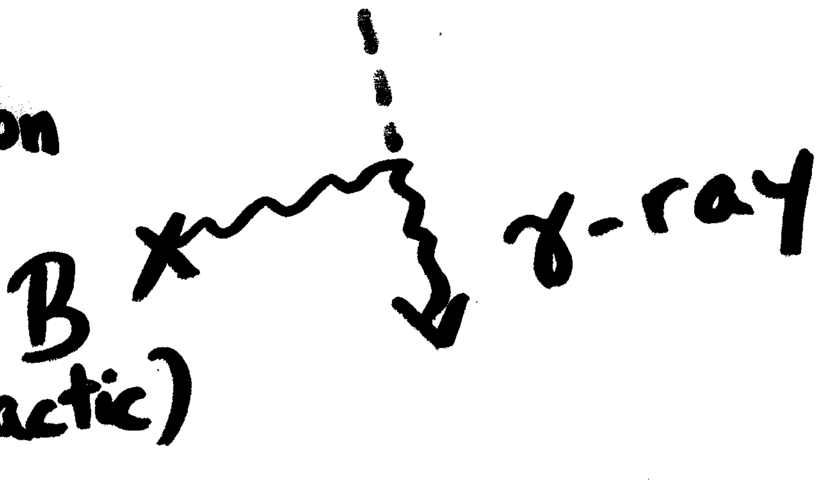


Massó, Toldrà

⓪ γ-rays from SN

Production

Conversion



Detection

Require $m < 10^{-9}$ eV

⇒ not relevant for axions

• Still many questions, for example:

familons:
coupling to 3rd family
very poorly constrained
(Feng et al, PR D57,1998)

• and unexpected possibilities, for example:

"Dimming Supernovae Without Cosmic Acceleration" (Csaki et al, PRL88,161302,2002)

Axion-like particle with

$$m_\varphi \sim 10^{-16} \text{ eV}$$

$$\frac{1}{g} \sim 4 \times 10^{11} \text{ GeV}$$

20-30% of photons from SNe
oscillate into φ
in presence of a extra-galactic $B \sim 10^{-9}$ G

CONCLUSIONS

AXION is

- theoretically motivated
  (elegant solution to strong CP problem)

- quite precise properties
  (only one free parameter)

- lab + astr + cosmo
  constrain properties

- upcoming experiments
  may find it
  or exclude it

- axion-like bosons
  interesting physics