Axion-like particles in the sky

Nearly massless pseudoscalars in astrophysics

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DESY

XXVI Workshop Beyond the Standard Model
Bad Honnef

Axions and axion-like particles from theory

In particle physics, spinless particles = the simplest case one can think of.

Examples:

- Axions [solution Strong CP problem];
- Chameleons [$f(R)$ theories];
- $\left\{ \begin{array}{l} \text{Scalars} \\ \text{Pseudoscalars} \end{array} \right\}$ [Super strings/Kaluza-Klein theories];
- ...

Axion-like particles

Axion-like particles (ALPs): generic feature of extensions of the Standard Model.

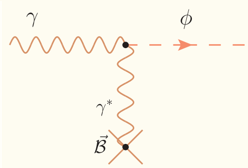
This kind of particles

- From the theoretical point of view: well motivated;
- From the experimental point of view: yet to be observed.

Not so invisible axions

Electromagnetic coupling that makes them extremely interesting to study

Similar to the Primakoff effect for π^0



Pseudoscalar ϕ:

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}})$$

[*Sikivie* (1983)], [*Maiani et al.* (1986)], [*Raffelt, Stodolsky* (1988)], ...

Consequences:

- possible 2-γ decay
  (though typically small m & g)
- new cooling channel
- axion-photon mixing
- ...

Affects all properties of light
(rich phenomenology!)
Highly relevant in astrophysics

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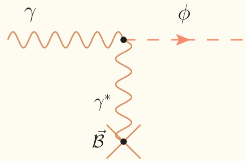

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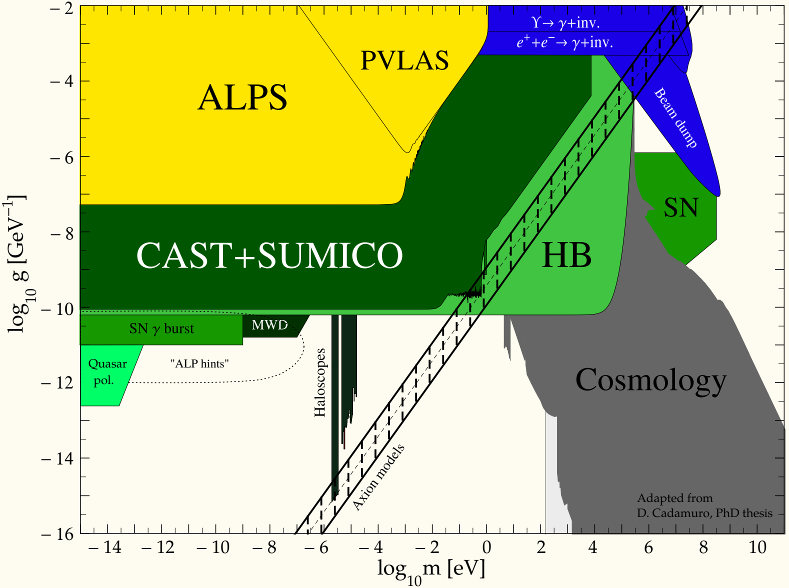
Searching for ALPs using their electromagnetic coupling



Dependences of ALP-photon mixing

$P_{\gamma \rightleftarrows \phi}$ depends on only 2 dimensionless parameters in a given $\vec{\mathcal{B}}$

$$\frac{1}{2}\mathrm{atan}\left(\frac{2g\mathcal{B}\omega}{m^2 - {\omega_\mathrm{p}}^2}\right) = \theta \qquad \frac{\Delta\mu^2 L}{\omega} = \frac{\sqrt{\left(2g\mathcal{B}\omega\right)^2 + \left(m^2 - {\omega_\mathrm{p}}^2\right)^2}\,L}{\omega}$$

$\sim \nu$ oscillations with 2 species (but $\Delta\mu^2(\omega)$) [*Raffelt, Stodolsky* (1988)]

NB: also holds for all Stokes parameters [*AP, Cudell, Hutsemekers* (2011)]

for a given ALP, mixing $\rightarrow$ more efficient with

- $\nearrow$ transverse field strength $\mathcal{B}$
- $\searrow$ momentum transfert: i.e. $\nearrow \omega$, $\searrow \omega_\mathrm{p} \sim \sqrt{n_\mathrm{e}}$

If "hints" really due to ALPs $\rightarrow$ same dependencies expected

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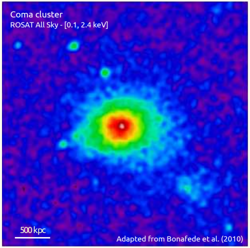
Soft X-ray excess in galaxy clusters

Galaxy clusters

X-ray continuum: thermal bremsstrahlung (T $\sim$ 7 keV)



What's the surprise?

Excess observed in soft X-rays ($\sim$ 0.1–1 keV)

- first in Coma [*Lieu et al.* (1996)], Virgo [*Bowyer et al.* (1996)]
- seen soon after in several clusters
- and by various instruments:

EUVE, ROSAT, XMM, CHANDRA, SUZAKU, BeppoSAX

(note: full agreement only for Coma)

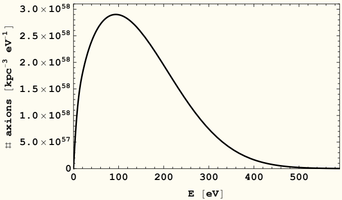
Long-standing puzzle difficult to explain with conventional astrophysics (thermal and non-thermal processes)

Soft X-ray excess in galaxy clusters

A Cosmic ALP Background Radiation from moduli decay ($m_\Phi \sim 10^6$ GeV) would have a spectrum in the extreme-UV, soft X-ray range today

[*Conlon, Marsh* (2013)], [*Angus et al.* (2013)]

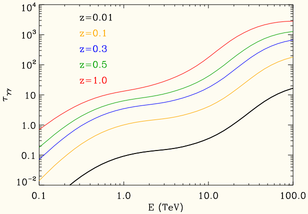
ALPs would convert in magnetic fields, in particular in cluster magnetic fields (over Mpc scales, and $\mathcal{B} \sim 1 - 10\ \mu$G)



They give $g \gtrsim \sqrt{0.5/\Delta N_{\rm eff}} \times 1.4 \times 10^{-13}$ GeV^{-1}, $m \lesssim 10^{-12}$ eV

- Clear predictions from a Cosmic ALP Background Radiation
  - excess should formally exist in all clusters (not only Coma)
  - follow only $\mathcal{B}$ field/electron density, not ICM
  - flux also only function of these
- $\Delta N_{\rm eff}$ preferred (2.7σ) when combining Planck+WP with HST

Universe transparency to gamma rays



Universe is not transparent to gamma rays at high-z: interactions with Extragalactic Background Light (EBL)

$$\gamma_{\mathrm{HE/VHE}} + \gamma_{\mathrm{EBL}} \to e^+ + e^-$$

see e.g. [*Dwek, Krennrich* (2013)]

What's the surprise?

Observations by Cherenkov telescopes (e.g. MAGIC, VERITAS, HESS) would indicate an anomalous transparency of the Universe to TeV γ

see e.g. [*Aharonian et al.* (2006)], [*Aliu et al.* (2008)], ...

Note: still an open question! see e.g. [*Biteau* (2013)]

Some astrophysical solutions; see e.g. [*Dwek, Krennrich* (2013)]

- less EBL? (not resolved, but lower limit)
- revise blazar model to make spectrum harder: e.g. hadronic jet

Universe transparency to gamma rays

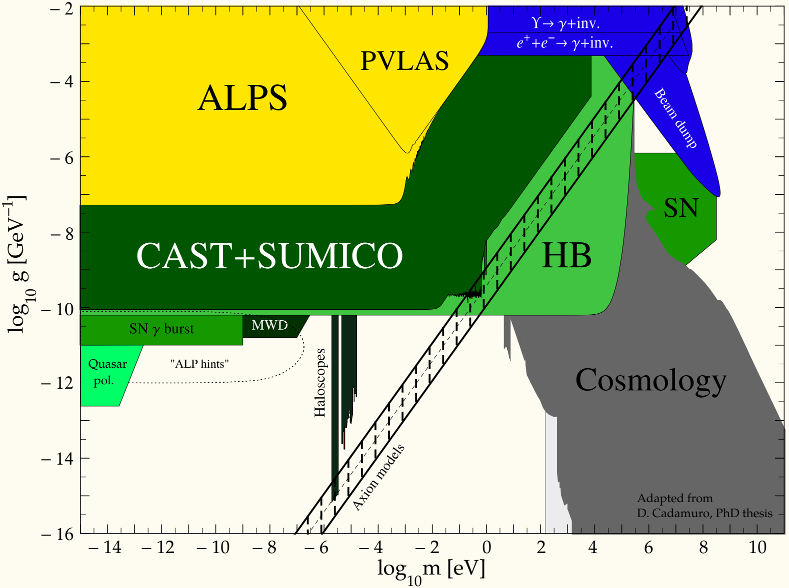
Various ALP-photon mixing scenarios:
mixing on the way/near the source + back-conversion in the Milky Way
[*de Angelis, Roncadelli, Mansutti* (2007)], [*Sánchez-Conde et al.* (2009)], [*Meyer, Horns* (2012)], ...

Would indicate $g \sim 10^{-11}$–10^{-10} GeV^{-1}, $m \lesssim 10^{-8}$ eV [*Horns et al.* (2012)]
NB: other GeV–TeV observations, same ALPs [*Mena, Razzaque* (2013)], [*Tavecchio et al.* (2012)], ...

Prediction: transparency of the Universe would then follow $\mathcal{B}$ field in the Galaxy

Could be checked with CTA [*Wouters, Brun* (2013)]

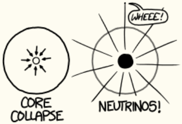
ALPS-II, IAXO: future experiments interested in this region



No prompt γ burst from SN1987A—in a nutshell

When a very massive star undergoes a core-collapse (SN type II)
proto-neutron star quickly radiates lots of neutrinos
$\rightarrow$ short, intense ν burst (optical flash comes hours later)

http://what-if.xkcd.com/73/



Light axion-like particles

1. would be copiously produced as well
2. would subsequently convert in the Galactic magnetic field

$\Rightarrow$ γ-ray burst (core temperature) coincidental with the ν one

SN1987A (only 50 kpc away)

- ν burst seen (great success!) by Kamiokande, IMB, and Baksan detectors

- Upper limit from Gamma-Ray Spectrometer
  Total fluence of photons with energies 25–100 MeV:
  $< 0.6\ \gamma\ \mathrm{cm}^{-2}$ @ 95% C.L.

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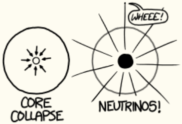

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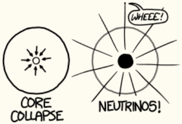

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No prompt γ burst from SN1987A—fresh look on the limit

Not observed $\rightarrow$ gives the most stringent bound for a wide range of masses

Important limit for the astrophysical window

- $g \lesssim 3 \times 10^{-12}$ GeV^{-1} [*Grifols, Massó, Toldrà* (1996)]
- $g \lesssim 10^{-11}$ GeV^{-1} [*Brockway, Carlson, Raffelt* (1996)]

both for $m \lesssim 10^{-9}$ eV

Criticism found in the literature; this bound is sometimes simply dismissed

- mass limit
- model for $\vec{\mathcal{B}}$ field
- SN simulations

We are revisiting this limit (A. Mirizzi, A. Ringwald, SN model by T. Fischer).
Stay tuned.

Summary

Axion-like particles

- can be expected to appear in extensions of the SM
- have very interesting and rather unique properties

Astrophysical puzzles jointly explained by the existence of a light ALP?

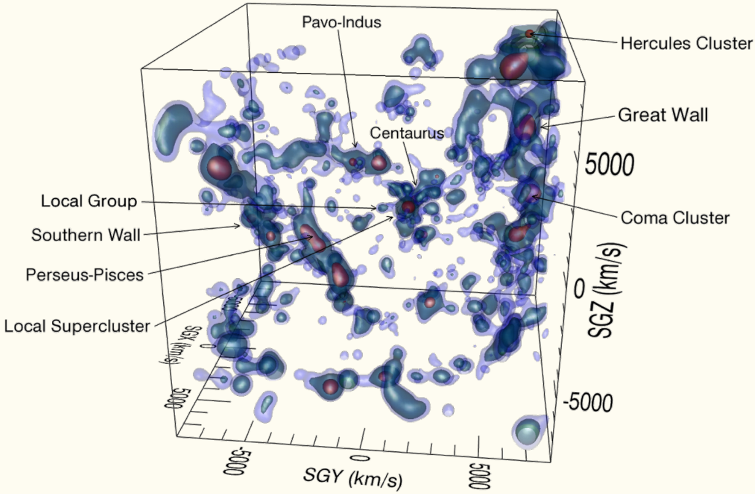
- observational status not always clear
- but again ALPs typically offer clear predictions $\rightarrow$ either discovery or limits

Important to know what's left of the parameter space in that low-mass region

- revisiting SN1987A bound
- upgraded experiments will provide a further check

Thank you

Cosmography of the local Universe



[Courtois et al. (2013)]