Polarisation from axion-photon mixing

and the relevance of X-ray polarimetry in astrophysics

Alexandre Payez

X-ray polarisation in astrophysics—a window about to open?

Stockholm, Aug 27th 2014

Talk based on [arXiv:1308.6608]

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.

Axions and axion-like particles from theory

Axions and ALPs: ID Card

- Neutral pseudoscalar particles, like π^0
- But also: scalar ALPs
- Very (*very*) small mass
- Interact very (*very*) weakly

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$\left.\right\} \propto 1/f$

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- Interact very (*very*) weakly
- One of the leading CDM candidates ←
- Couple with light

Can be of cosmological importance

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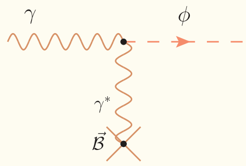
Can be of astrophysical importance
(≡ (mostly) observing light from distant objects)

Not so invisible axions

An 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:

- new cooling channel
- possible 2-γ decay
  (though typically tiny m and g)
- optical activity (slowly varying ϕ_{bckg})
- axion-photon mixing in $\vec{\mathcal{B}}$
- ...

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

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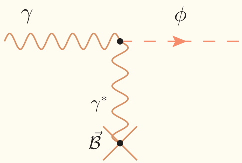

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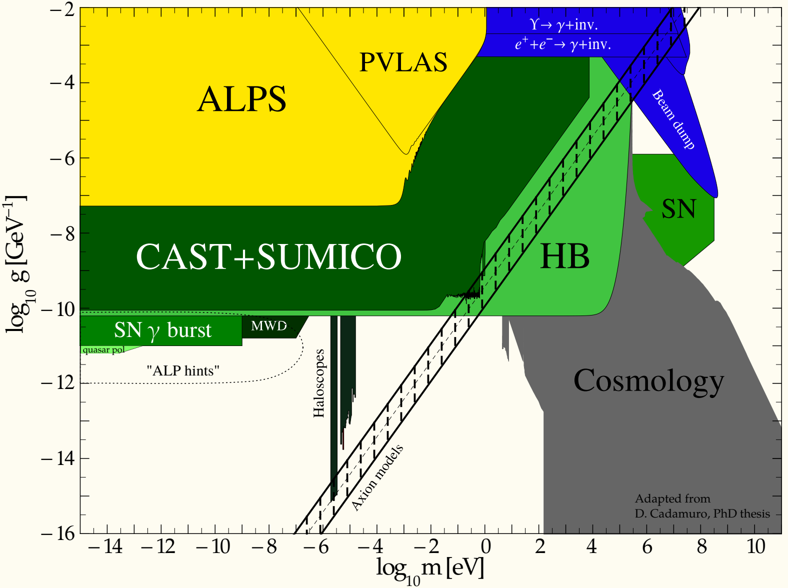
Searching for ALPs using their electromagnetic coupling



Axion-like particles couple to *one* direction of polarisation

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  ⇒ Changes linear polarisation
- (Linear) Birefringence:
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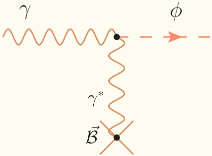

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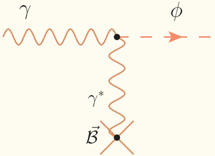

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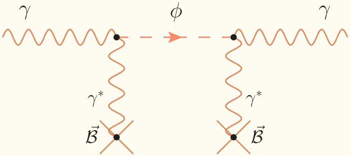
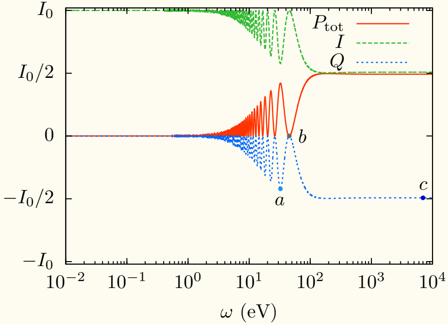


Instructive case: single region of constant magnetic field

Consequences of the mixing on Stokes parameters, defined in the basis $(\vec{e}_\perp, \vec{e}_\parallel)$

figures from [arXiv:1308.6608]; see also [*Das et al.* (2005)], [*Burrage, Davis, Shaw* (2009)]



initially unpolarised light, $\forall\omega$

Results at the end of the average magnetic field in a supercluster ($L \sim 10$ Mpc)
$m = 10^{-14}$ eV, $n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} = 0.2\ \mu$G & $g = 10^{-11}$ GeV^{-1})

Different regimes

(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

At exactly which ω such features happen is determined by the external parameters

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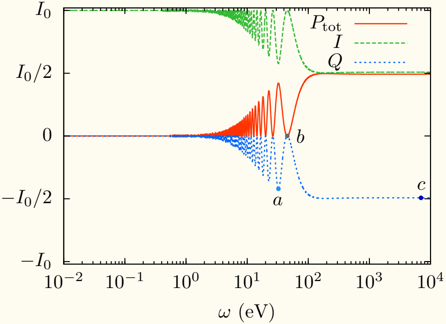

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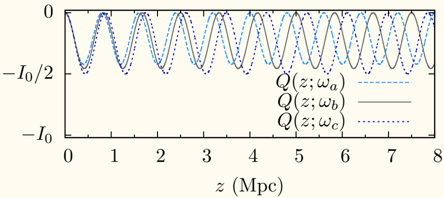

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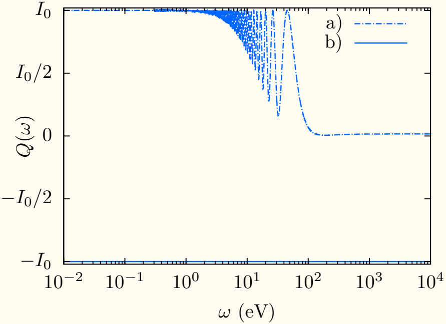

initially 100% polarised light ($Q_0 \neq 0$), $\forall\omega$

a) $Q_0 = I_0$
b) $Q_0 = -I_0$

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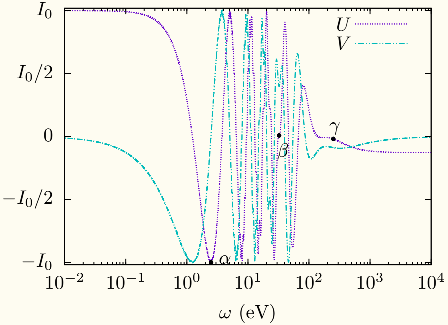

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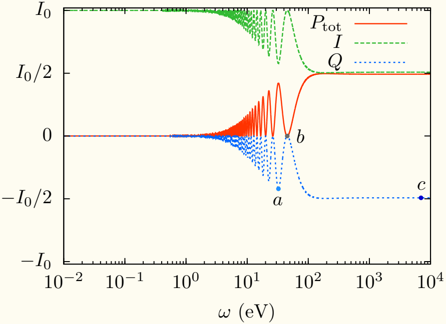

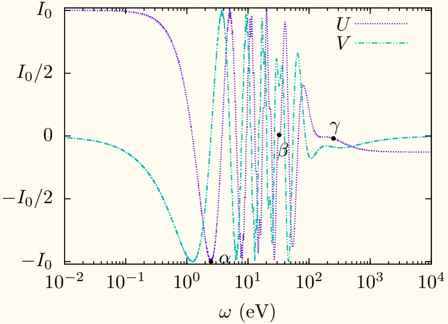

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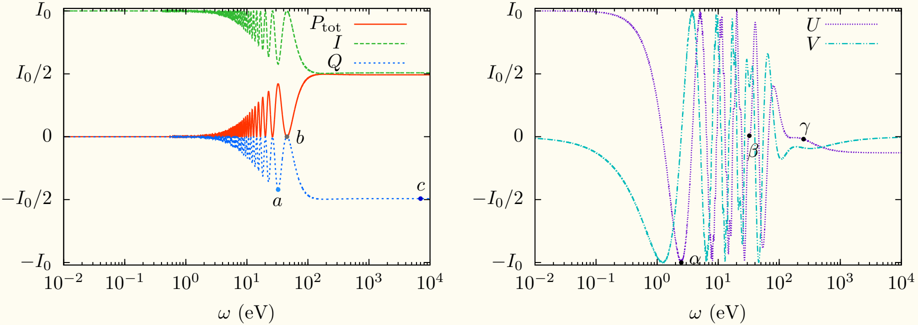

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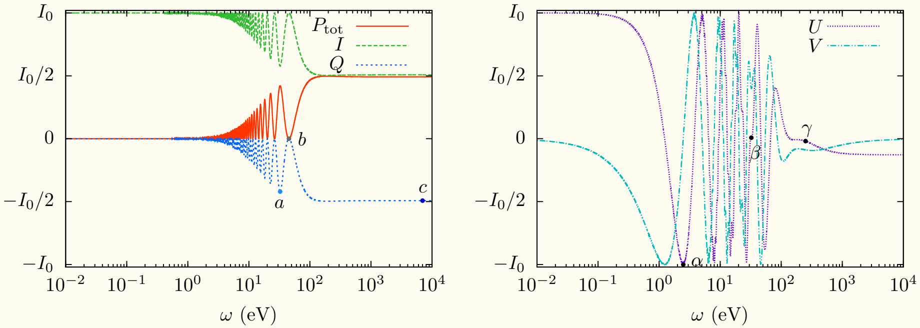

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Dependencies of axion-photon mixing

$P_{\gamma_\parallel \rightleftarrows \phi}$ depends on only 2 dimensionless parameters [*Raffelt, Stodolsky* (1988)]

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$\sim \nu$ oscillations with 2 species (but $\Delta\mu^2(\omega)$)

NB: plasma frequency

Also true for all Stokes parameters, in all regimes [*Payez, Cudell, Hutsemékers* (2011)]

only requires $\omega^2 \gg {\omega_\text{p}}^2$ and $\Delta\mu^2$: always the case for the applications of interest for us

For a given ALP with $m \ll \omega_\text{p}$, the mixing with photons is more efficient when

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

Mixing quickly inefficient if the momentum transfert becomes too large

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Polarimetry is a useful tool to search for axion-like particles

The mixing can be very efficient at producing polarisation

$\Rightarrow$ derive constraints

Recent examples

→ rotation of UV polarisation angle ($\leftrightarrow$ quasar morphology)
[*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]

→ consider quasar classes with smallest intrinsic polarisations in visible
$\Rightarrow$ compare amount due to the mixing with observations (p_{lin} and p_{circ})
[*Payez, Cudell, Hutsemékers* (2012)], Review of Particle Properties (PDG)

no evidence for non-zero p_{circ} at 3σ
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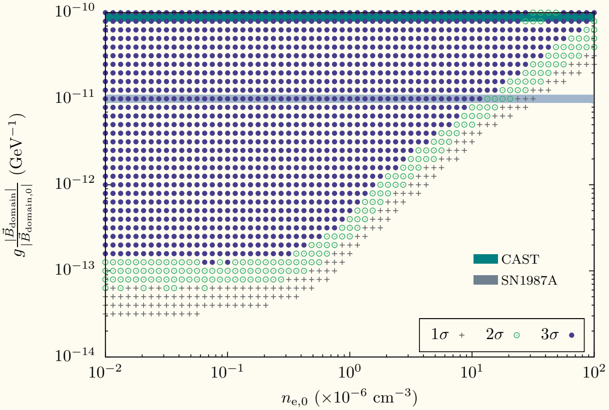
The most stringent limit on the mixing for ultralight ALPs is from polarimetry

Might say something about the medium, and not about ALPs though [*Payez* (2013)]



$g \lesssim 6.3 \times 10^{-12}\ \mathrm{GeV}^{-1} \left(\frac{n_{e,0}}{10^{-5}\ \mathrm{cm}^{-3}}\right)^{1.3} \left(\frac{|\vec{B}_{\rm domain,0}|}{|\vec{B}_{\rm domain}|}\right)$, for $n_{e,0}$ between 10^{-6} and 10^{-5} cm^{-3}

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More reliable limits could be obtained using galaxy clusters

since magnetic field and electron density better determined

However:

electron density too high for the mixing to take place in visible light
$\Rightarrow$ Need X-rays to avoid being only sensitive to the resonant case

Light from distant sources should be characterised by at least some amount of polarisation if axion-photon mixing happens along the way [*Harari, Sikivie* (1992)]

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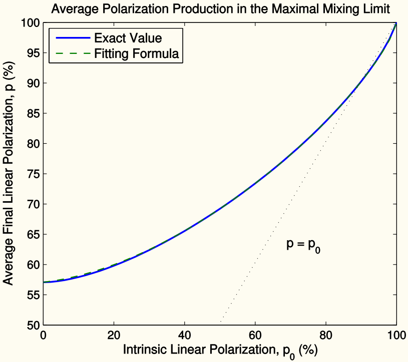
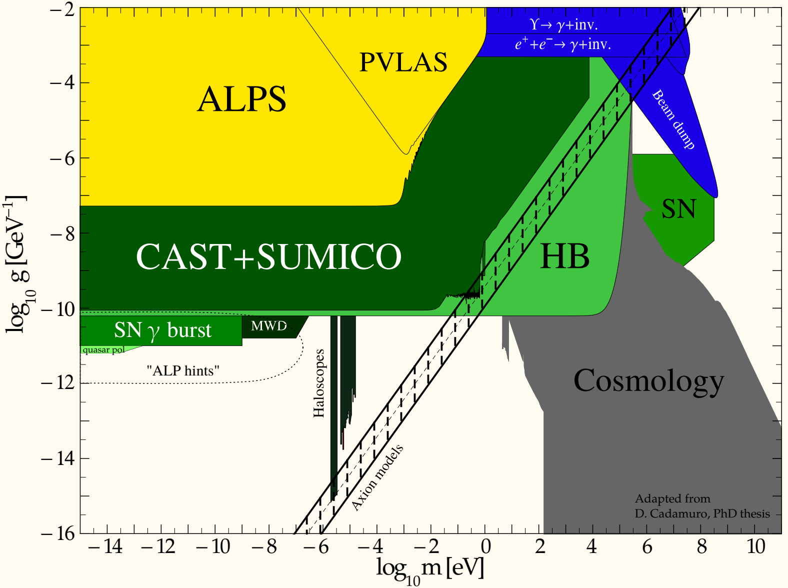
X-rays would be in the strong mixing regime in $|\vec{B}_{\rm csm}| \sim 1$ nG, $n_e \sim 10^{-7}$ cm^{-3}

ALPs would then for instance affect GRB polarisation, *e.g.* [*Bassan, Mirizzi, Roncadelli* (2010)]

Chameleons [*Burrage, Davis, Shaw* (2009)]



X-ray polarimetry in astrophysics could definitely help



Summary

Axion-like particles

- are generic predictions appearing in extensions of the SM of particle physics
- might actually contribute to dark matter, dark radiation or dark energy
- are actively searched for, but astrophysics still does better than experiments

Axion-photon mixing

- has very distinctive signatures, especially concerning polarisation (energy-dependent dichroism and birefringence, following $\mathcal{B}$ and n_e)
- is more efficient at high energies

X-ray polarimetry in astrophysics

- would be sensitive to a part of the "ALP hints" region
- could therefore either lead to new constraints or to a discovery

If such particles exist,
they will probably be first seen in astrophysics

Appendix

Stokes parameters as functions of two pure numbers

[*Payez, Cudell, Hutsemékers* (2011)]

In a given $\vec{\mathcal{B}}$, in the restricted case $\phi(0) = 0$, the Stokes parameters read

$$I(z) = I_0 - \frac{1}{2}\left(I_0 + Q_0\right)\sin^2 2\theta \sin^2\left(\frac{1}{4}\frac{\Delta\mu^2}{\omega}z\right)$$

$$Q(z) = I(I_0 \rightleftarrows Q_0)$$

$$U(z) = U_0\left\{(\mathrm{s}\theta)^2\cos\left(\frac{1}{2}(\mathrm{c}\theta)^2\ \frac{\Delta\mu^2}{\omega}z\right) + (\mathrm{c}\theta)^2\cos\left(\frac{1}{2}(\mathrm{s}\theta)^2\ \frac{\Delta\mu^2}{\omega}z\right)\right\}$$
$$+ V_0\left\{(\mathrm{s}\theta)^2\sin\left(\frac{1}{2}(\mathrm{c}\theta)^2\ \frac{\Delta\mu^2}{\omega}z\right) - (\mathrm{c}\theta)^2\sin\left(\frac{1}{2}(\mathrm{s}\theta)^2\ \frac{\Delta\mu^2}{\omega}z\right)\right\}\mathrm{sign}(\theta)$$

$$V(z) = U(U_0 \to V_0, V_0 \to -U_0),$$

with $\mathrm{c}\theta \equiv \cos(\theta)$ and $\mathrm{s}\theta \equiv \sin(\theta)$.

The dependencies are actually the same if $\phi(0) \neq 0$, therefore the relevant parameters which drive the change of polarisation remain the two aforementioned dimensionless quantities even in that more general case.

New constraints on axion-like particles

[*Payez, Cudell, Hutsemékers* (2012)]
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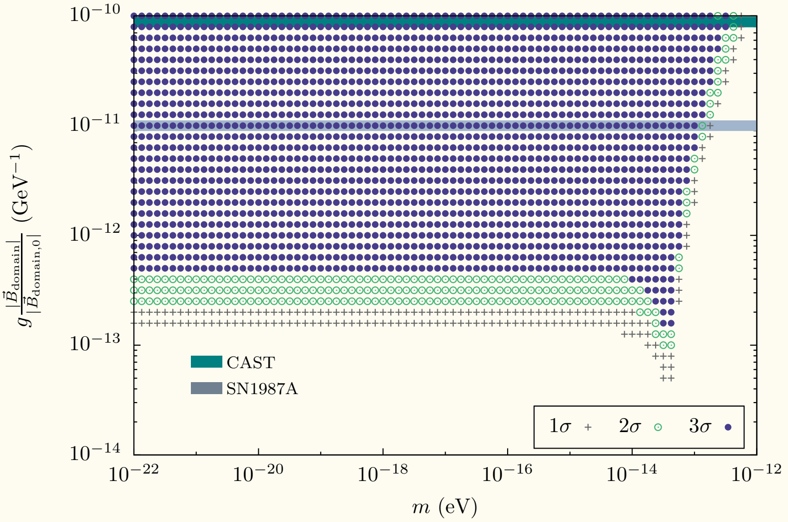

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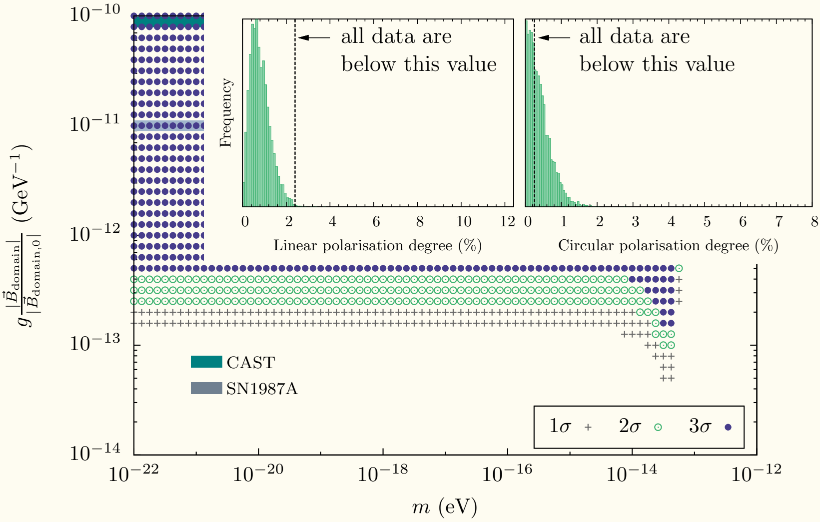

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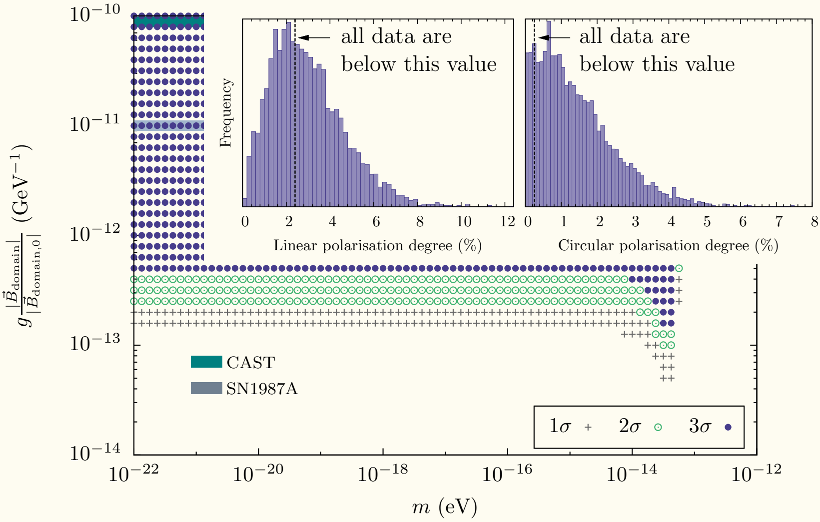
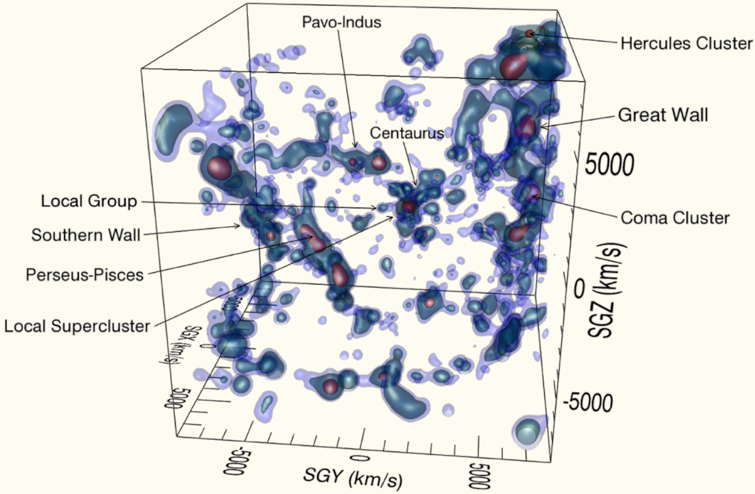
[*Payez, Cudell, Hutsemékers* (2012)]
Review of Particle Properties (PDG)



Cosmography of the local Universe

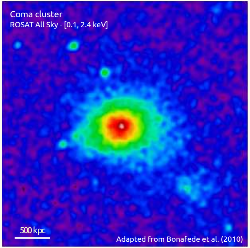


[Courtois et al. (2013)]

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)

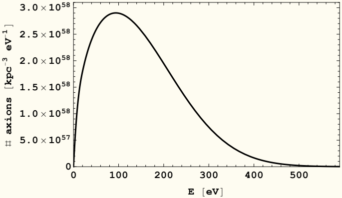
Long-standing puzzle difficult to explain with conventional astrophysics (thermal and non-thermal processes)

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

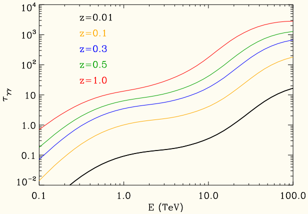
- Clear predictions from a Cosmic ALP Background Radiation
  - excess should formally exist in all clusters (not only Coma)
  - follow only $\mathcal{B}$ field/electron density, not ICM
  - flux also only function of these
- $\Delta N_{\rm eff}$ preferred (2.7σ) when combining Planck+WP with HST

Universe transparency to gamma rays

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

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

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)], ...

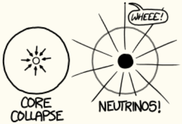
Prediction: transparency of the Universe would then follow $\mathcal{B}$ field in the Galaxy

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

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:

$$< 0.6\ \gamma\ \mathrm{cm}^{-2}\ @\ 95\%\ \mathrm{C.L.}$$

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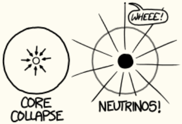

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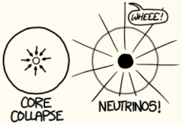

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No prompt γ burst from SN1987A—a fresh look

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 have revisited this limit (coll. with Evoli, Fischer, Giannotti, Mirizzi, Ringwald)
Writing in progress.