Axion-like particles in astrophysics

An introduction to the phenomenology of their electromagnetic coupling

Alexandre Payez

Astroparticle Physics with Multiple Messengers

Hamburg, September 10th 2014

Outline

1. Meet the axions
   - Axions and axion-like particles from theory
   - A rich phenomenology, interesting for astrophysics
2. Axion–photon mixing inside external magnetic fields
   - Formalism of the mixing
   - Some rather unique signatures
3. ALPs searches and constraints
4. Astrophysical hints of light axion-like particles?
5. Summary

Looking for physics beyond the Standard Model

Particles arising in BSM extensions are not necessarily on the heavy side

→ They may have escaped detection not because of large energy needed

but due to highly suppressed couplings (akin to ν within the SM)

Astroparticle physics

Great to look for such particles since their signatures could accumulate enough

Meet the axions

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];
- { Scalars / Pseudoscalars } [Super strings/Kaluza–Klein theories];
- Chameleons [$f(R)$ theories];
- ...

} Axion-like particles

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

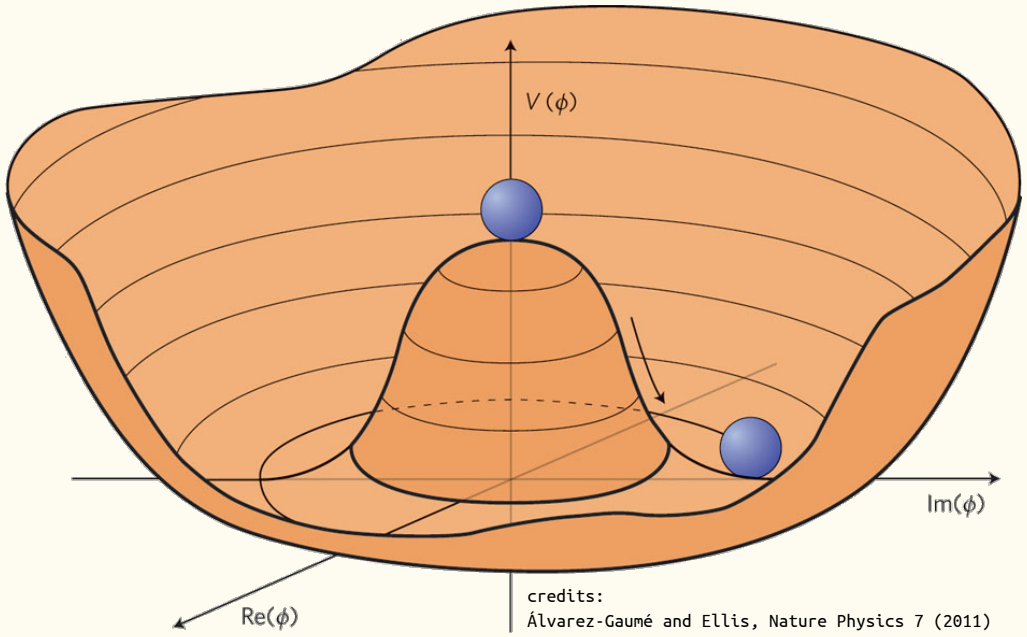
This kind of particles

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

Spontaneous symmetry breaking and Goldstone's theorem

Whenever a continuous symmetry of the theory is not respected by its fundamental state, we have a spontaneous symmetry breaking

Develop the theory around the chosen minimum (as in Lagrangian mechanics)



Example:
Let's take a Mexican-hat potential

Presence of a zero-curvature mode

If the symmetry is global

$\Downarrow$

corresponds to a massless scalar:
a Nambu–Goldstone boson

Brout–Englert–Higgs: spontaneous symmetry breaking of local (gauge) symmetries

Pseudo-Nambu–Goldstone bosons

No massless scalars within the Standard Model

However: pions are much lighter than the rest of the meson spectrum

$\Downarrow$

pseudo-Nambu–Goldstone bosons of an approximate chiral symmetry of QCD

since it's not an exact symmetry, they are not massless and they can decay

$$m_\pi{}^2 = -\frac{1}{f_\pi{}^2}\frac{(m_u + m_d)}{2}\langle 0|\bar{u}u + \bar{d}d|0\rangle$$

Axion-like particles are (pseudo-)Nambu–Goldstone bosons from BSM theories

- arise whenever global symmetries are spontaneously broken ($f \ggg f_\pi, \Lambda_{\mathrm{QCD}}$)
- low-energy effects: study effective (non-renormalisable) couplings $\propto 1/f$
- mass suppressed by the energy scale where there is new physics

Pseudo-Nambu–Goldstone bosons

No massless scalars within the Standard Model

However: pions are much lighter than the rest of the meson spectrum

$\Downarrow$

pseudo-Nambu–Goldstone bosons of an approximate chiral symmetry of QCD

since it's not an exact symmetry, they are not massless and they can decay

$$m_\pi{}^2 = -\frac{1}{f_\pi{}^2}\frac{(m_u + m_d)}{2}\langle 0|\bar{u}u + \bar{d}d|0\rangle$$

Axion-like particles are (pseudo-)Nambu–Goldstone bosons from BSM theories

- arise whenever global symmetries are spontaneously broken ($f \ggg f_\pi, \Lambda_{\mathrm{QCD}}$)
- low-energy effects: study effective (non-renormalisable) couplings $\propto 1/f$
- mass suppressed by the energy scale where there is new physics

Origin of the QCD axion in QFT in a nutshell

An actual example is of course the famous QCD axion

There is a small story leading to this particle; let's give a real quick overview

Lagrangian of quantum chromodynamics for the two lightest quarks

$$\mathcal{L}_{\text{QCD}}^{\text{fermions}} = \bar{u}\big(i\gamma^\mu D_\mu - m_u\big)u + \bar{d}\big(i\gamma^\mu D_\mu - m_d\big)d$$

Global symmetries: $\mathrm{U}(1)_V$, $\mathrm{U}(1)_A$, $\mathrm{SU}(2)_V$ and $\mathrm{SU}(2)_A$ if $m_u = m_d = 0$.

Noether's theorem

"To any continuous symmetry of $\mathcal{L}$ is associated a conserved current."

Approximation of zero-mass quarks $\Rightarrow$ 8 conserved currents.

Origin of the QCD axion in QFT in a nutshell

An actual example is of course the famous QCD axion

There is a small story leading to this particle; let's give a real quick overview

Lagrangian of quantum chromodynamics for the two lightest quarks

$$\mathcal{L}_{\text{QCD}}^{\text{fermions}} = \bar{u}\big(i\gamma^\mu D_\mu - m_u\big)u + \bar{d}\big(i\gamma^\mu D_\mu - m_d\big)d$$

Global symmetries: $\mathrm{U}(1)_V$, $\mathrm{U}(1)_A$, $\mathrm{SU}(2)_V$ and $\mathrm{SU}(2)_A$ if $m_u = m_d = 0$.

Noether's theorem

"To any continuous symmetry of $\mathcal{L}$ is associated a conserved current."

Approximation of zero-mass quarks $\Rightarrow$ 8 conserved currents.

Spontaneous breaking of chiral symmetry

However, chiral symmetries $U(1)_A$ and $SU(2)_A$ are not symmetries of the vacuum
$\Rightarrow$ Spontaneous symmetry breaking.

Goldstone's theorem

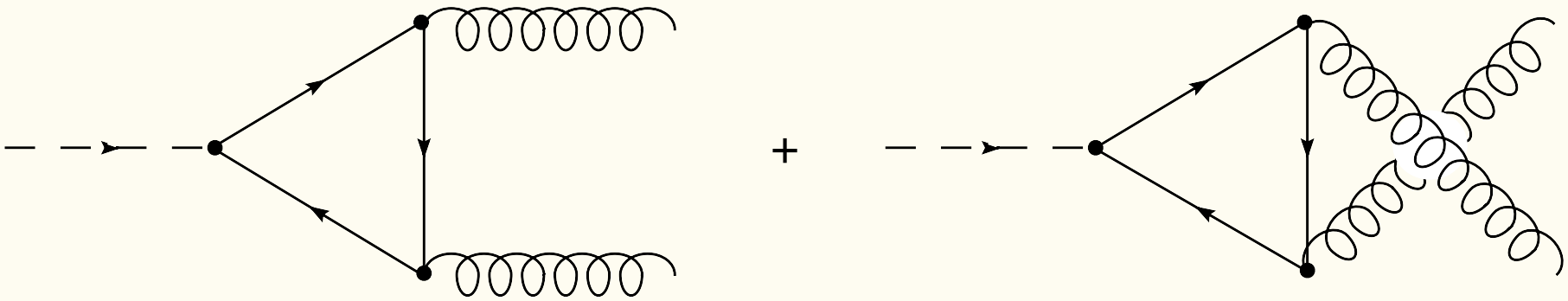
To each spontaneously broken generator of continuous global symmetries
$\Rightarrow$ massless scalar field: Nambu–Goldstone boson.

- Spontaneous breaking of $SU(2)_A$ $\Rightarrow$ 3 pions V
- Spontaneous breaking of $U(1)_A$ $\Rightarrow$ $?$

$U(1)_A$ problem
[*Weinberg* (1975)]

Quantum corrections: axial anomaly

Quantum anomalies may spoil classically conserved currents



[*Adler* (1969)], [*Bell, Jackiw* (1969)]

- $SU(2)_A$: current still conserved
- $U(1)_A$:

$$\begin{aligned} \partial_\mu j^{\mu 5} &\propto \epsilon^{\alpha\beta\mu\nu} G^c_{\alpha\beta} G^c_{\mu\nu} \\ &\propto \partial_\mu K^\mu \end{aligned}$$

Additional term in the Lagrangian: $\mathcal{L} \propto \int \partial_\mu j^{\mu 5} d^4x \neq 0?$

$|\theta\rangle$ vacuum and strong CP problem

't Hooft

QCD (non-abelian theory)
Topological effects prevent
the integral from vanishing.

['t Hooft (1976)]

$|\theta\rangle$ vacuum

$\Rightarrow$ Vacuum one has to consider:
a linear combination of $|n\rangle$
topologically distinct vacua
$=$ $|\theta\rangle$ vacuum

and then, the $U(1)_A$ problem is solved

Price to pay:

$$\mathcal{L}_\theta \propto \theta G^c_{\mu\nu} \widetilde{G}^{c\mu\nu}$$

CP violation

Strong CP Problem

CP conserved in QCD:
upper limit on neutron EDM
$\Downarrow$
$\theta < 10^{-10}$!

$|\theta\rangle$ vacuum and strong CP problem

't Hooft

QCD (non-abelian theory)
Topological effects prevent
the integral from vanishing.

['t Hooft (1976)]

$|\theta\rangle$ vacuum

$\Rightarrow$ Vacuum one has to consider:
a linear combination of $|n\rangle$
topologically distinct vacua
$=$ $|\theta\rangle$ vacuum

and then, the $U(1)_A$ problem is solved

Price to pay:

$$\mathcal{L}_\theta \propto \theta G^c_{\mu\nu} \widetilde{G}^{c\mu\nu}$$

CP violation

Strong CP Problem

CP conserved in QCD:
upper limit on neutron EDM
$\Downarrow$
$\theta < 10^{-10}$!

Peccei–Quinn solution and the axion

Peccei–Quinn solution to the strong CP problem

New continuous global symmetry: $\mathrm{U}(1)_{\mathrm{PQ}}$ whose spontaneous breaking

$\Rightarrow$ dynamical compensation of the θ term: $\theta \to \theta + \frac{\phi(x)}{f_{\mathrm{PQ}}}$ [*Peccei, Quinn* (1977)]

Goldstone's theorem, once again

$\Rightarrow$ Pseudo Nambu–Goldstone boson: axion

[*Weinberg* (1978)], [*Wilczek* (1978)]

End of our QCD axion interlude.

Note, if several axion-like particles couple to $G^c_{\mu\nu}\widetilde{G}^{c\,\mu\nu}$, their linear combinaison $\to$ QCD axion; see e.g. [*Dias et al.* (2014)]

Peccei–Quinn solution and the axion

Peccei–Quinn solution to the strong CP problem

New continuous global symmetry: $\mathrm{U}(1)_{\mathrm{PQ}}$ whose spontaneous breaking

$\Rightarrow$ dynamical compensation of the θ term: $\theta \to \theta + \frac{\phi(x)}{f_{\mathrm{PQ}}}$ [*Peccei, Quinn* (1977)]

Goldstone's theorem, once again

$\Rightarrow$ Pseudo Nambu–Goldstone boson: axion

[*Weinberg* (1978)], [*Wilczek* (1978)]

End of our QCD axion interlude.

Note, if several axion-like particles couple to $G^c_{\mu\nu}\widetilde{G}^{c\,\mu\nu}$, their linear combinaison $\to$ QCD axion; see e.g. [*Dias et al.* (2014)]

Peccei–Quinn solution and the axion

Peccei–Quinn solution to the strong CP problem

New continuous global symmetry: $\mathrm{U}(1)_{\mathrm{PQ}}$ whose spontaneous breaking

$\Rightarrow$ dynamical compensation of the θ term: $\theta \to \theta + \frac{\phi(x)}{f_{\mathrm{PQ}}}$ [*Peccei, Quinn* (1977)]

Goldstone's theorem, once again

$\Rightarrow$ Pseudo Nambu–Goldstone boson: axion

[*Weinberg* (1978)], [*Wilczek* (1978)]

End of our QCD axion interlude.

Note, if several axion-like particles couple to $G^c_{\mu\nu}\widetilde{G}^{c\,\mu\nu}$,
their linear combinaison $\to$ QCD axion; see e.g. [*Dias et al.* (2014)]

In summary, what properties would they have?

Axions and ALPs: ID Card

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

In summary, what properties would they have?

Axions and ALPs: ID Card

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

$\Big\}\ \propto 1/f$

Not expected at super-colliders
(possible detection requires dedicated experiments)

In summary, what properties would they have?

Axions and ALPs: ID Card

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

Can be of cosmological importance
(peculiar cosmology: misalignment mechanism, topological defects, .. see *e.g.* [*Arias et al.* (2012)])

In summary, what properties would they have?

Axions and ALPs: ID Card

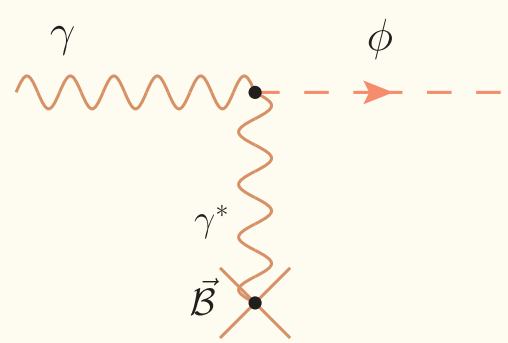
- Very (*very*) small mass
- Interact very (*very*) weakly
- (One of the leading CDM candidates)
- Couple with light ←

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:

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

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

Consequences:

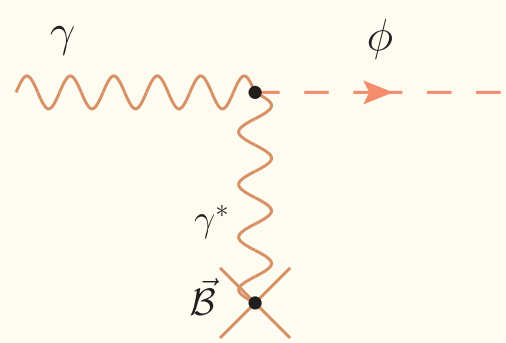
- new cooling channel
- possible 2-γ decay
  (though typically tiny m and g)
- optical activity (slowly varying ϕ_{bckg})
- axion-photon mixing in $\vec{\mathcal{B}}$
- ...

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

Not so invisible axions

An electromagnetic coupling that makes them extremely interesting to study

Similar to the Primakoff effect for π^0



Pseudoscalar ϕ:

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

[*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 $\vec{\mathcal{B}}$
- ...

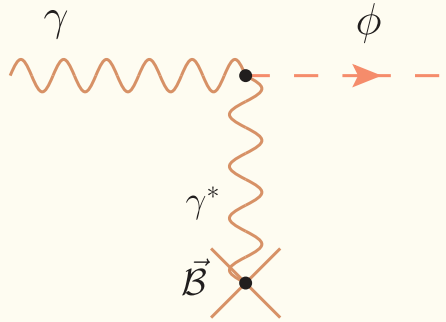
Affects all properties of light
(rich phenomenology!)
Highly relevant in astrophysics

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

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

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

- Dichroism: selective absorption of one component of the light.



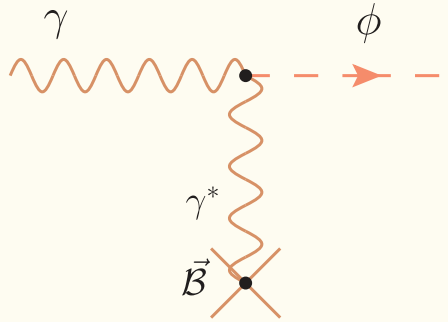
- Birefringence: different velocities. Phase-shift between $\vec{\mathcal{E}}_{r,\parallel}$ and $\vec{\mathcal{E}}_{r,\perp}$

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

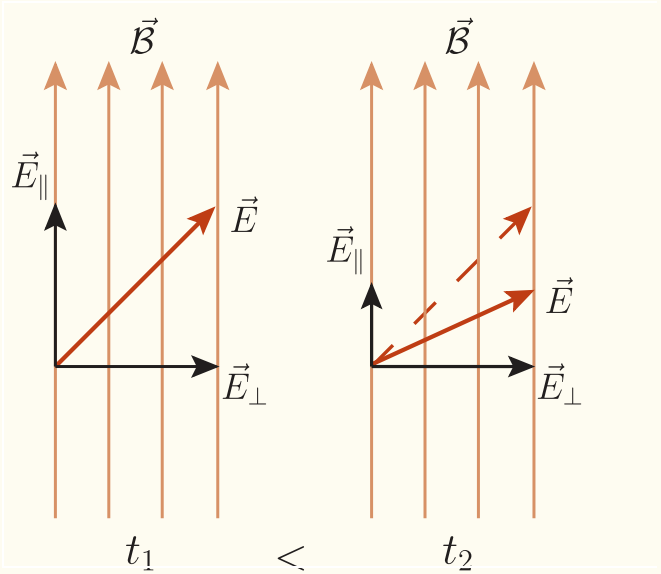
Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

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

- Dichroism: selective absorption of one component of the light.



- Birefringence: different velocities. Phase-shift between $\vec{\mathcal{E}}_{r,\parallel}$ and $\vec{\mathcal{E}}_{r,\perp}$

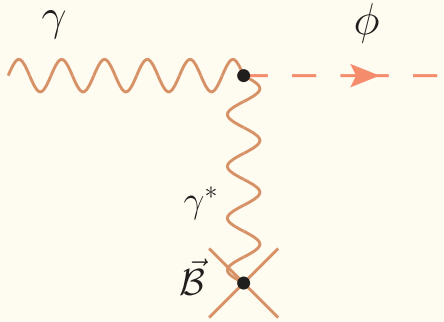


Axion-like particles couple to *one* direction of polarisation

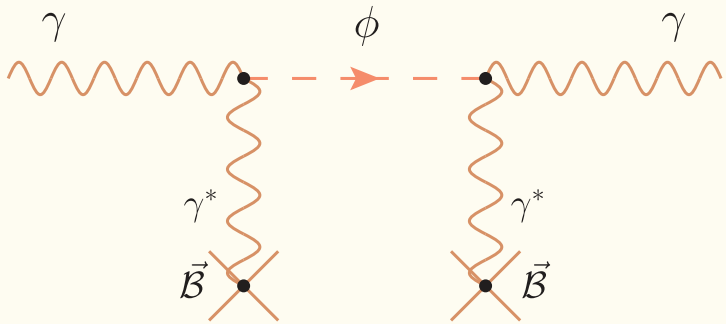
Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

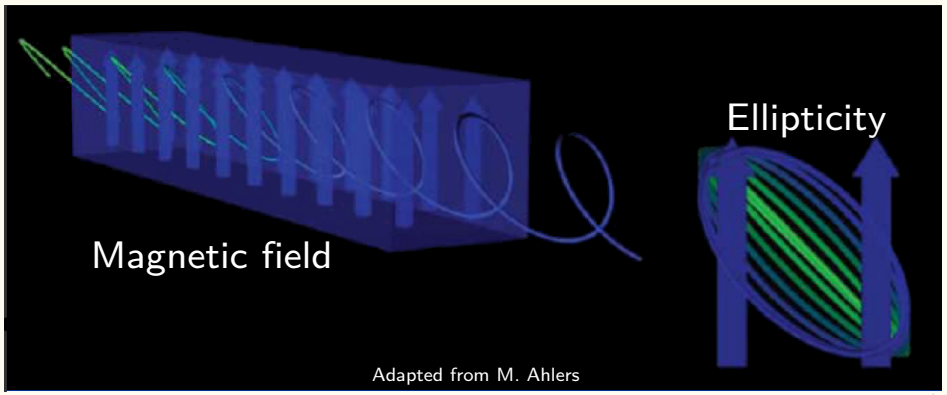
[*Sikivie* (1983)], [*Maiani et al.* (1986)], [*Raffelt, Stodolsky* (1988)], ...

- Dichroism: selective absorption of one component of the light.



- Birefringence: different velocities. Phase-shift between $\vec{\mathcal{E}}_{r,\parallel}$ and $\vec{\mathcal{E}}_{r,\perp}$



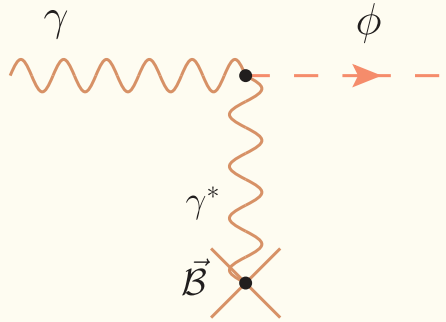


Axion-like particles couple to *one* direction of polarisation

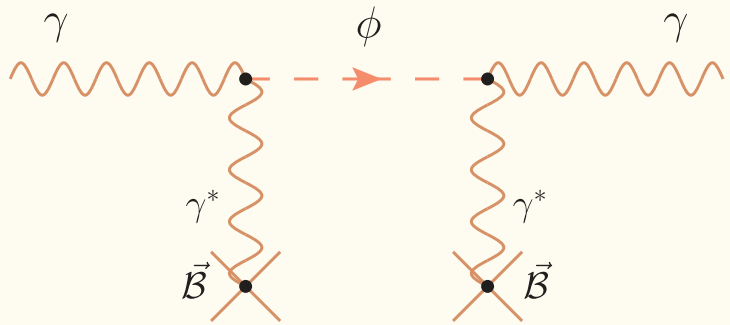
Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

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

- Dichroism:
  $\Rightarrow$ Changes linear polarisation



- Birefringence:
  $\Rightarrow$ Changes circular polarisation

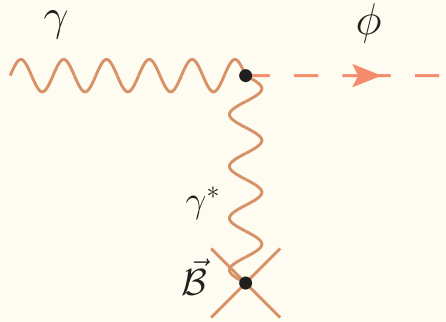


Axion-like particles couple to *one* direction of polarisation

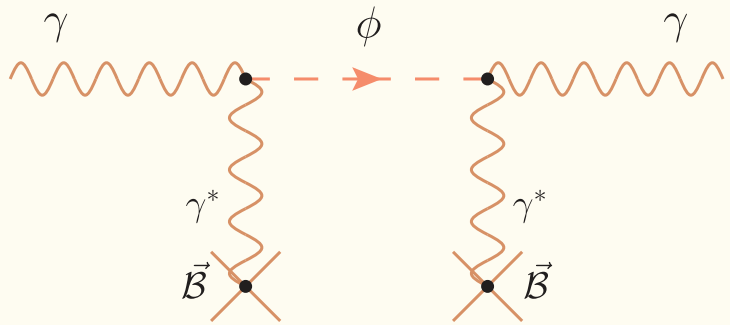
Pseudoscalar ϕ: $\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{4}\, g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} = -g\phi(\vec{E}\cdot\vec{B}) = -g\phi(\vec{\mathcal{E}}_r\cdot\vec{\mathcal{B}}) = -g\phi(\vec{\mathcal{E}}_{r,\parallel}\cdot\vec{\mathcal{B}})$

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

- Dichroism:
  $\Rightarrow$ Changes linear polarisation

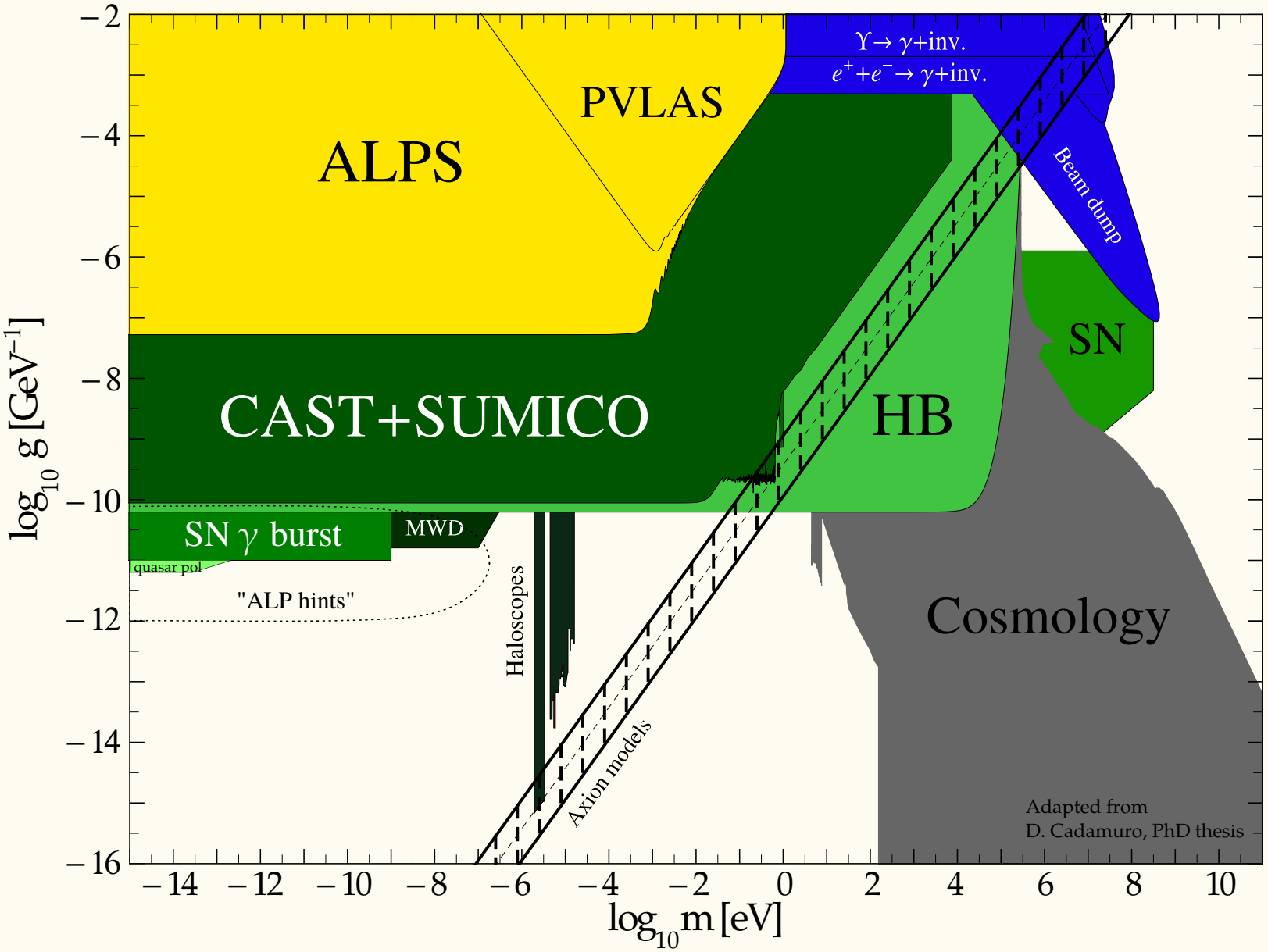


- Birefringence:
  $\Rightarrow$ Changes circular polarisation



NB: similar effects for scalar ALPs

Searching for ALPs using their electromagnetic coupling



Axion–photon mixing inside external magnetic fields

Derivation of the general equations

For studying pseudoscalar axion-like particles, an appropriate Lagrangian density is

$$\mathcal{L} = \frac{1}{2}\,(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}\,m^2\phi^2 - \frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}\,g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Working out the Euler–Lagrange equations for the fields

$$\partial^\beta\Big(\frac{\partial\mathcal{L}}{\partial(\partial^\beta\chi)}\Big) - \frac{\partial\mathcal{L}}{\partial\chi} = 0, \qquad \text{for a given field } \chi;$$

one obtains

$$\partial_\beta F^{\beta\alpha} = g(\partial_\beta\phi)\widetilde{F}^{\beta\alpha}$$

and

$$\Box\phi + m^2\phi = \frac{1}{4}gF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

We see that the electromagnetic fields acts as a source term for the ϕ field and vice-versa

Derivation of the general equations

For studying pseudoscalar axion-like particles, an appropriate Lagrangian density is

$$\mathcal{L} = \frac{1}{2}\,(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}\,m^2\phi^2 - \frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}\,g\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Working out the Euler–Lagrange equations for the fields

$$\partial^\beta\left(\frac{\partial\mathcal{L}}{\partial(\partial^\beta\chi)}\right) - \frac{\partial\mathcal{L}}{\partial\chi} = 0, \qquad \text{for a given field } \chi;$$

one obtains

$$\partial_\beta F^{\beta\alpha} = g(\partial_\beta\phi)\widetilde{F}^{\beta\alpha}$$

and

$$\Box\phi + m^2\phi = \frac{1}{4}gF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

We see that the electromagnetic fields acts as a source term for the ϕ field and vice-versa

Derivation of the general equations

In terms of electric and magnetic fields

This leads to the modified Maxwell's equations in vacuum:

$$\begin{cases} \vec{\nabla} \cdot \vec{E} = g\left(\vec{B} \cdot \vec{\nabla}\phi\right) \\ -\dfrac{\partial \vec{E}}{\partial t} + \vec{\nabla} \times \vec{B} = g\left(\vec{E} \times \vec{\nabla}\phi - \vec{B}\dfrac{\partial \phi}{\partial t}\right) \\ \vec{\nabla} \times \vec{E} + \dfrac{\partial \vec{B}}{\partial t} = 0 \\ \vec{\nabla} \cdot \vec{B} = 0 \end{cases}$$

While for ϕ, we have

$$\frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi + m^2 \phi = -g\left(\vec{E} \cdot \vec{B}\right)$$

Thus far

Very general, but the equations can be simplified by restricting their scope

System of equations describing the mixing in $\vec{\mathcal{B}}$

For ϕ, γ propagation in an external magnetic field, the wave equations simplify to

$$\frac{\partial^2 \vec{\mathcal{E}}_\mathrm{r}}{\partial t^2} - \nabla^2 \vec{\mathcal{E}}_\mathrm{r} + \omega_\mathrm{p}^2 \vec{\mathcal{E}}_\mathrm{r} = g\vec{\mathcal{B}}\frac{\partial^2 \phi}{\partial t^2},$$
$$\frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi + m^2 \phi = -g\left(\vec{\mathcal{E}}_\mathrm{r} \cdot \vec{\mathcal{B}}\right),$$

at 1st order in g; for ALPs with $m^2 \lll \omega^2$; and introducing the plasma frequency ω_p

$\omega_\mathrm{p} \equiv \sqrt{\frac{4\pi\alpha n_\mathrm{e}}{m_\mathrm{e}}}$ acts as an effective mass (dispersion relation)

where we have written

$\vec{\mathcal{E}}_\mathrm{r}$	the electric field of the electromagnetic radiation
$\vec{\mathcal{B}}$	the external magnetic field transverse to the direction of propagation

Let's now solve this system of coupled partial differential equations in a toy model

Instructive toy model: homogeneous magnetic field $\vec{\mathcal{B}}$

Physically, $\vec{\mathcal{B}}$ provides a preferred direction in the transverse plane

Let's work in the basis $(\vec{e}_\perp, \vec{e}_\parallel)$, and consider a polarisation basis $\vec{E}_{\perp,\parallel}$
$\Rightarrow$ can reconstruct any light beam $\vec{\mathcal{E}}_\mathrm{r}$

Searching for plane-wave solutions of type $e^{-i\omega t}$ for ϕ and $A_{\perp,\parallel} = |\vec{A}_{\perp,\parallel}|$

NB: $\vec{E}_{\perp,\parallel} = i\omega \vec{A}_{\perp,\parallel}$ (temporal gauge)

We get:

- Equations of motion for $A_\parallel$ and ϕ:

$$\left[\left(\omega^2 + \frac{\partial^2}{\partial z^2}\right) - \mathcal{M}\right] \begin{pmatrix} A_\parallel \\ \phi \end{pmatrix} = 0$$

- $A_\perp$ does not feel the interaction at all (decoupled)

Instructive toy model: homogeneous magnetic field $\vec{\mathcal{B}}$

Mass matrix $\mathcal{M}$: off-diagonal terms inside a magnetic field $\rightarrow$ mixing matrix $\vec{\mathcal{B}}$

$$\mathcal{M} = \begin{pmatrix} {\omega_p}^2 & -g\mathcal{B}\omega \\ -g\mathcal{B}\omega & m^2 \end{pmatrix}$$

$\Rightarrow$ in a magnetic field, $A_\parallel$ and ϕ are no longer the eigenmodes of propagation

$\vec{\mathcal{B}}$ triggers a mixing between ALPs and photons
and also compensates for their spin mismatch
} big difference with ν oscillations

Diagonalisation

$\rightarrow$ mass eigenvalues, μ_+ and μ_- for the propagation eigenstates (mixtures of $A_\parallel$ and ϕ)

$${\mu_\pm}^2 = \frac{1}{2}({\omega_p}^2 + m^2) \pm \frac{1}{2}\Delta\mu^2, \qquad \text{with } \Delta\mu^2 \equiv \sqrt{(2g\mathcal{B}\omega)^2 + ({m^2} - {\omega_p}^2)^2}$$

$\rightarrow$ mixing angle: $\theta = \frac{1}{2}\mathrm{atan}\left(\frac{2g\mathcal{B}\omega}{m^2 - {\omega_p}^2}\right)$

Instructive toy model: homogeneous magnetic field $\vec{\mathcal{B}}$

Mass matrix $\mathcal{M}$: off-diagonal terms inside a magnetic field $\rightarrow$ mixing matrix $\vec{\mathcal{B}}$

$$\mathcal{M} = \begin{pmatrix} {\omega_p}^2 & -g\mathcal{B}\omega \\ -g\mathcal{B}\omega & m^2 \end{pmatrix}$$

$\Rightarrow$ in a magnetic field, $A_\parallel$ and ϕ are no longer the eigenmodes of propagation

$\vec{\mathcal{B}}$ triggers a mixing between ALPs and photons
and also compensates for their spin mismatch
} big difference with ν oscillations

Diagonalisation

$\rightarrow$ mass eigenvalues, μ_+ and μ_- for the propagation eigenstates (mixtures of $A_\parallel$ and ϕ)

$${\mu_\pm}^2 = \frac{1}{2}({\omega_p}^2 + m^2) \pm \frac{1}{2}\Delta\mu^2, \qquad \text{with } \Delta\mu^2 \equiv \sqrt{(2g\mathcal{B}\omega)^2 + ({m^2} - {\omega_p}^2)^2}$$

$\rightarrow$ mixing angle: $\theta = \frac{1}{2}\text{atan}\left(\frac{2g\mathcal{B}\omega}{m^2 - {\omega_p}^2}\right)$

Instructive toy model: homogeneous magnetic field $\vec{\mathcal{B}}$

Eventually, we don't detect mixtures of $A_\parallel$ and ϕ, we detect photons

$\Rightarrow$ re-write everything in terms of $A_\perp$, $A_\parallel$ and ϕ:

$$A_\perp(z) = A_\perp(0)\ e^{ik_E z},$$

$$A_\parallel(z) = A_\parallel(0)\ \left(\cos^2\theta\ e^{ik_C z} + \sin^2\theta\ e^{ik_D z}\right) + \phi(0)\ \frac{\sin 2\theta}{2}\left(e^{ik_C z} - e^{ik_D z}\right),$$

$$\phi(z) = A_\parallel(0)\ \frac{\sin 2\theta}{2}\left(e^{ik_C z} - e^{ik_D z}\right) + \phi(0)\ \left(\sin^2\theta\ e^{ik_C z} + \cos^2\theta\ e^{ik_D z}\right)$$

$k_E = \sqrt{\omega^2 - {\omega_\mathrm{p}}^2}$ and $k_\phi = \sqrt{\omega^2 - m^2}$
k_C and k_D are respectively $k_+ = \sqrt{\omega^2 - {\mu_+}^2}$ and $k_- = \sqrt{\omega^2 - {\mu_-}^2}$ when $\omega_\mathrm{p} > m$ (and the other way around when $m > \omega_\mathrm{p}$)

From this $\rightarrow$ build observables.

Conversion probability

Conversion probability in a given $\vec{\mathcal{B}}$ [*Raffelt, Stodolsky* (1988)]

$$P_{\gamma_{\parallel} \rightleftarrows \phi} = \sin^2 2\theta \sin^2 \left(\frac{1}{4} \frac{\Delta\mu^2}{\omega} z \right)$$

depends on only 2 dimensionless parameters

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

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

For a given ALP, the mixing with photons is more efficient when

- $\nearrow$ transverse field strength $\mathcal{B}$
- $\searrow$ momentum transfert: i.e. $\nearrow \omega$, $\searrow m^2 - {\omega_\text{p}}^2$

Mixing quickly inefficient if the momentum transfert becomes too large

$\Rightarrow$ a given ω determines the different environments where mixing could take place

Conversion probability

Conversion probability in a given $\vec{\mathcal{B}}$ [*Raffelt, Stodolsky* (1988)]

$$P_{\gamma_{\parallel} \rightleftarrows \phi} = \sin^2 2\theta \sin^2 \left(\frac{1}{4} \frac{\Delta\mu^2}{\omega} z \right)$$

depends on only 2 dimensionless parameters

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

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

For a given ALP, the mixing with photons is more efficient when

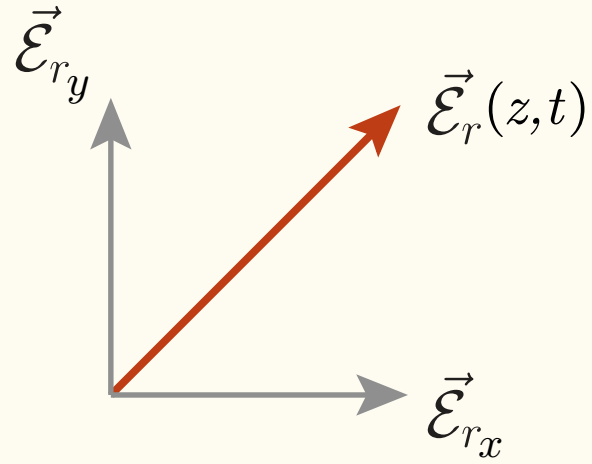
- $\nearrow$ transverse field strength $\mathcal{B}$
- $\searrow$ momentum transfert: i.e. $\nearrow \omega$, $\searrow m^2 - {\omega_\text{p}}^2$

Mixing quickly inefficient if the momentum transfert becomes too large

$\Rightarrow$ a given ω determines the different environments where mixing could take place

Stokes parameters

Decomposition in an orthonormal basis



Built from intensities

$$\begin{cases} I &= \text{Total intensity} \\ Q &= |\uparrow|^2 - |\rightarrow|^2 \\ U &= |\nearrow|^2 - |\searrow|^2 \\ V &= \text{Circular polarisation} \end{cases}$$

Complete description of polarisation

- polarisation degrees

$$p_{\text{lin}} = \frac{\sqrt{Q^2+U^2}}{I}, \quad p_{\text{circ}} = \frac{|V|}{I}$$

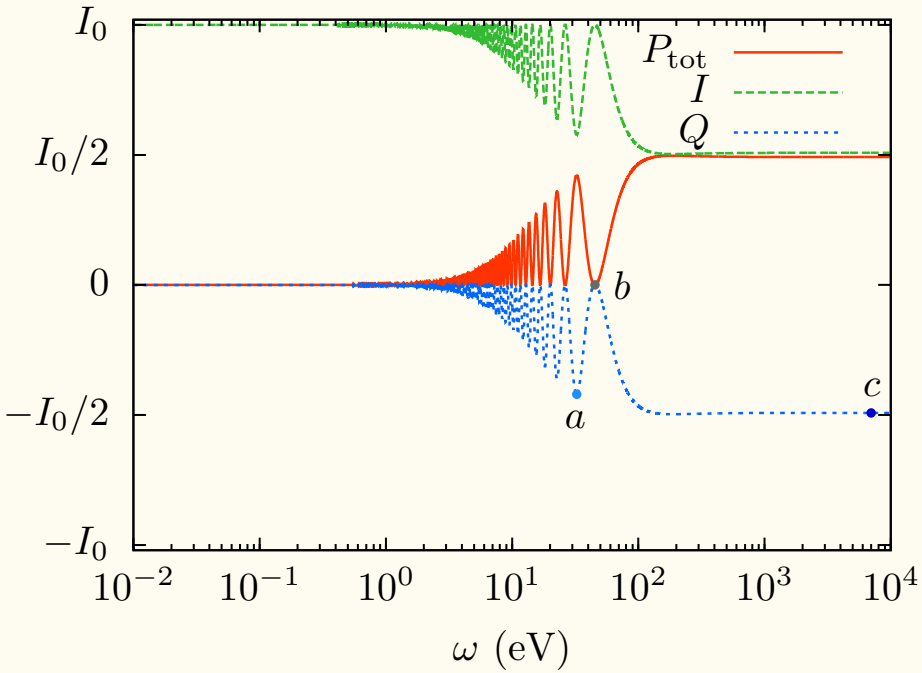
- polarisation angle

$$\varphi = \frac{1}{2}\text{atan}\left(\frac{U}{Q}\right)$$

A quick look at the simplest case

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 (ultralight ALP)
$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

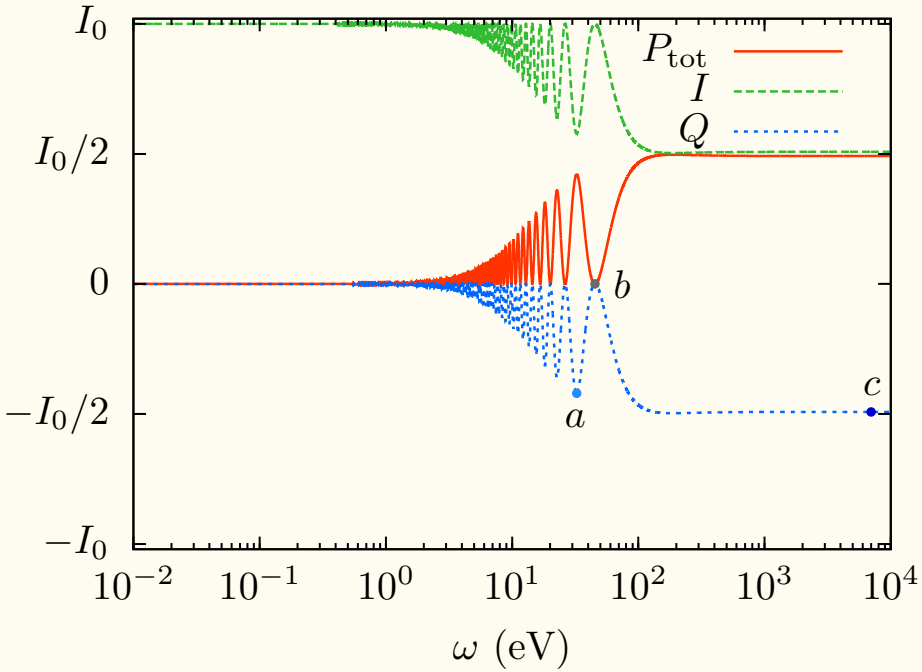
Different regimes

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

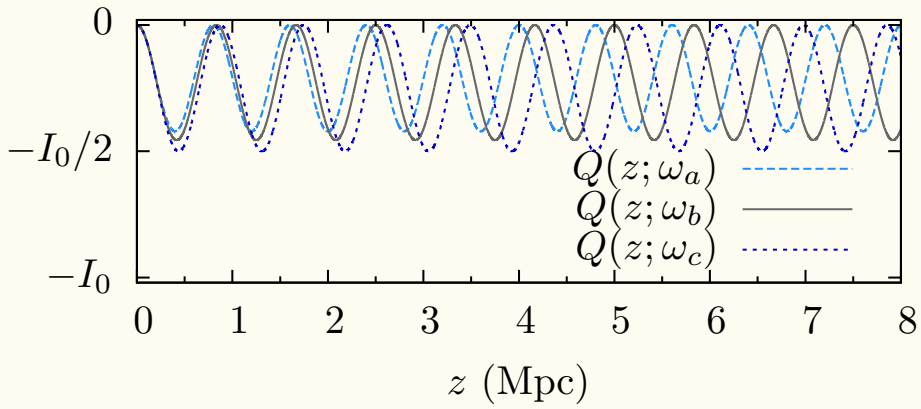
A quick look at the simplest case

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 (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

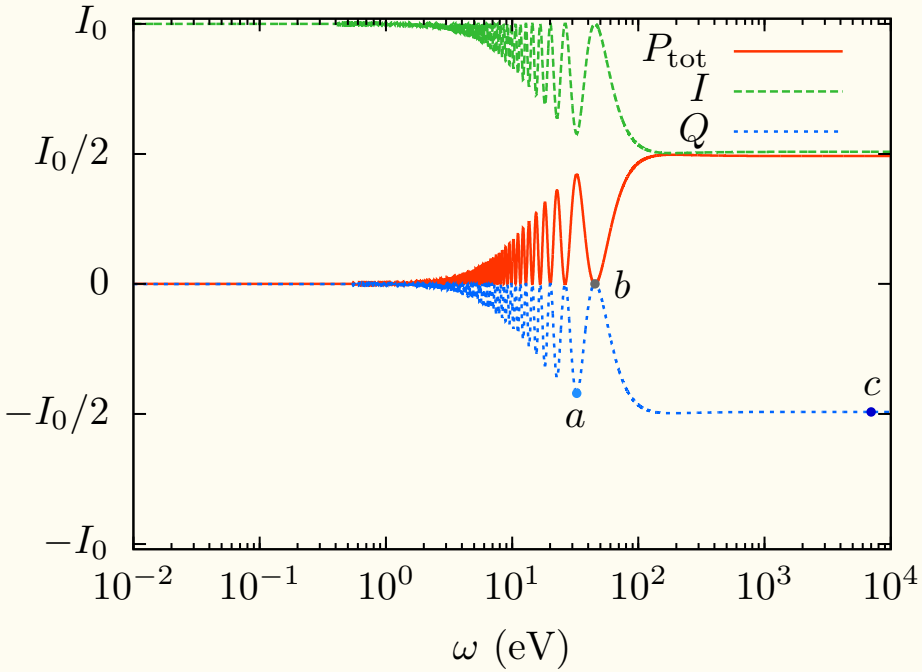
Different regimes

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

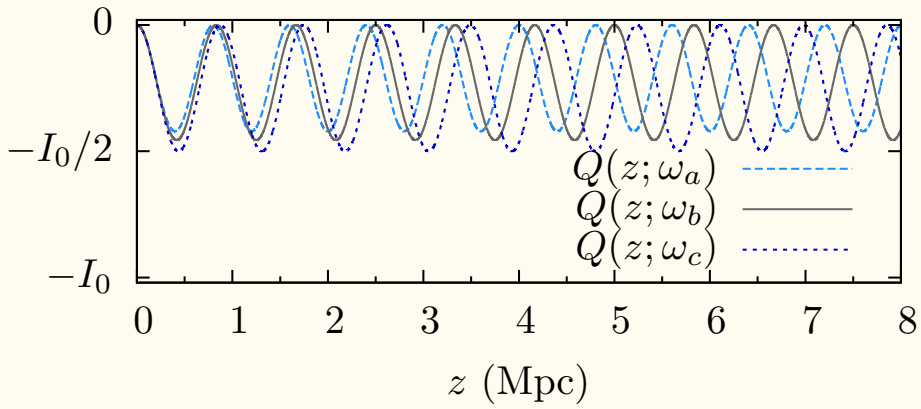
A quick look at the simplest case

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 (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

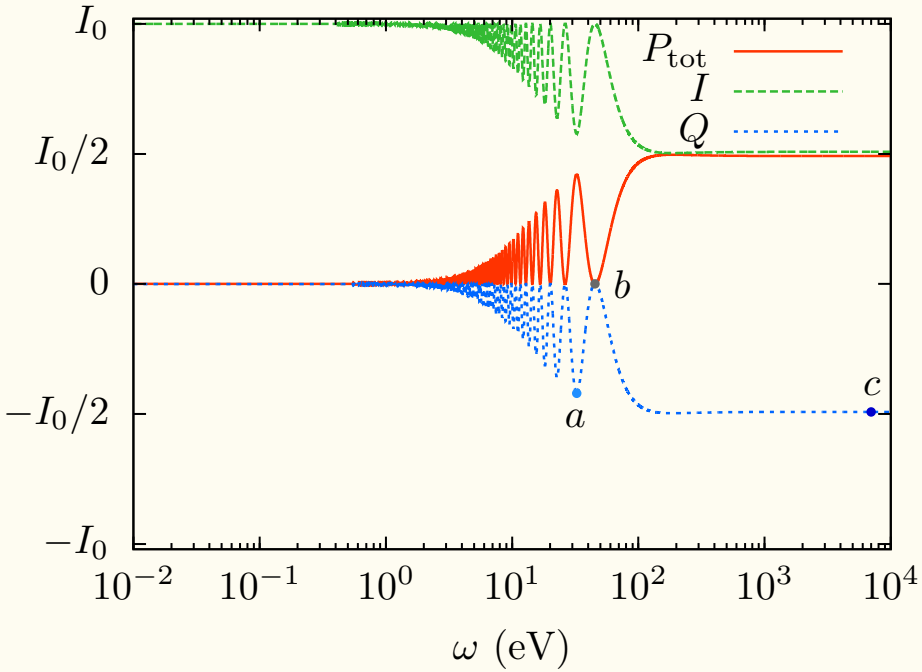
Different regimes

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

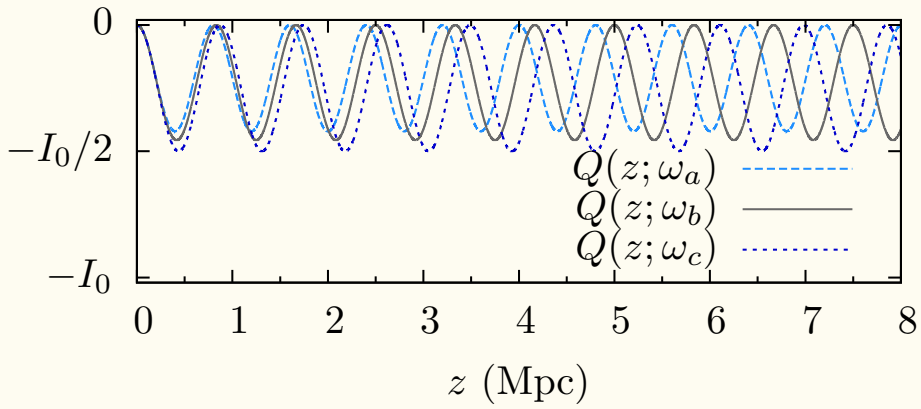
A quick look at the simplest case

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 (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

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

Stokes parameters as functions of two pure numbers

In a given $\vec{\mathcal{B}}$, for a pure initial photon beam, 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 $\mathrm{s}\theta \equiv \sin(\theta)$.

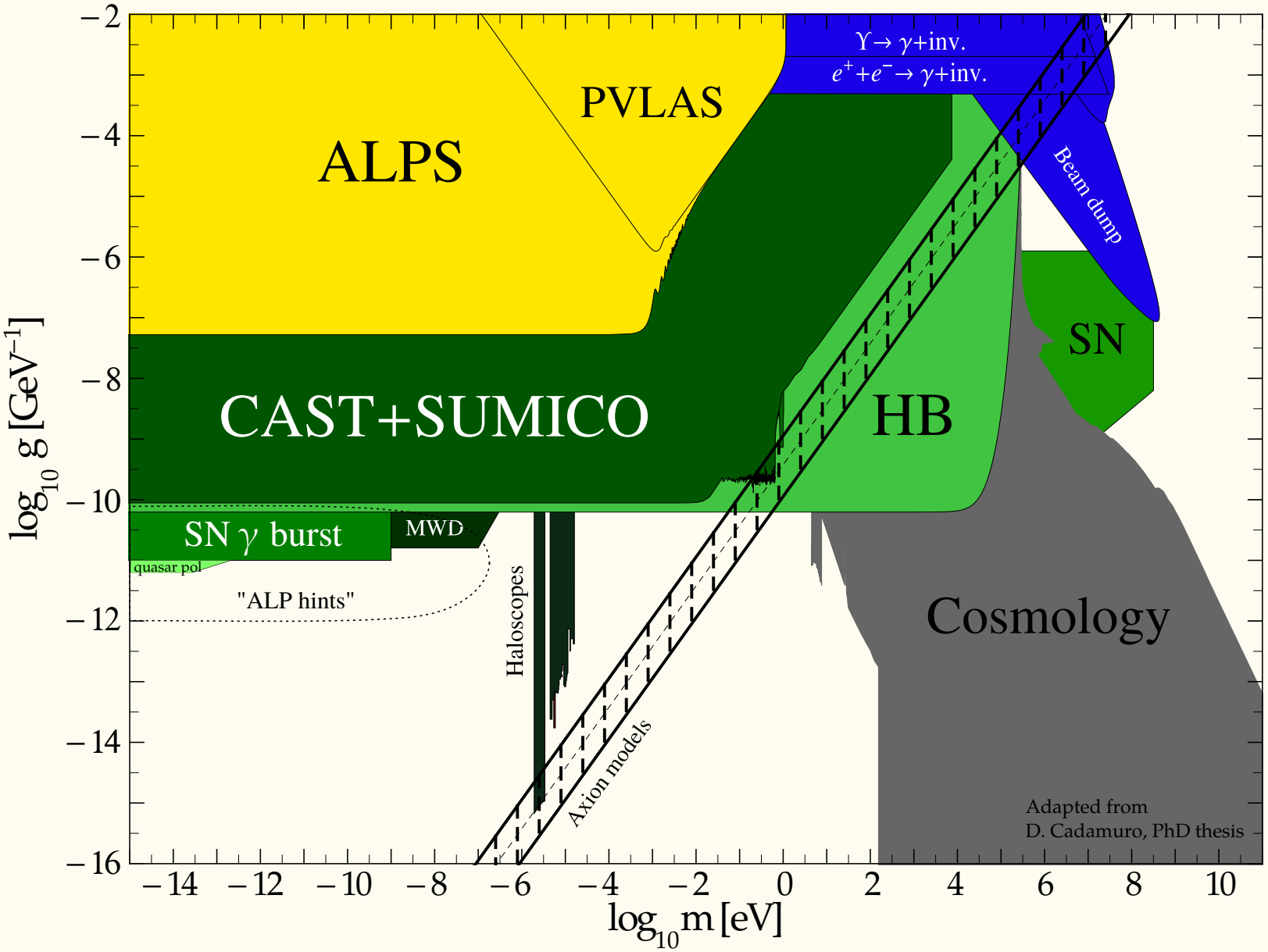
Also depend only on two parameters (valid in all regimes) [*Payez, Cudell, Hutsemékers* (2011)]

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

NB: actually same dependencies, even if $\phi(0) \neq 0$

ALPs searches and constraints

Searching for ALPs using their electromagnetic coupling



PVLAS—Polarizzazione del Vuoto con LASer

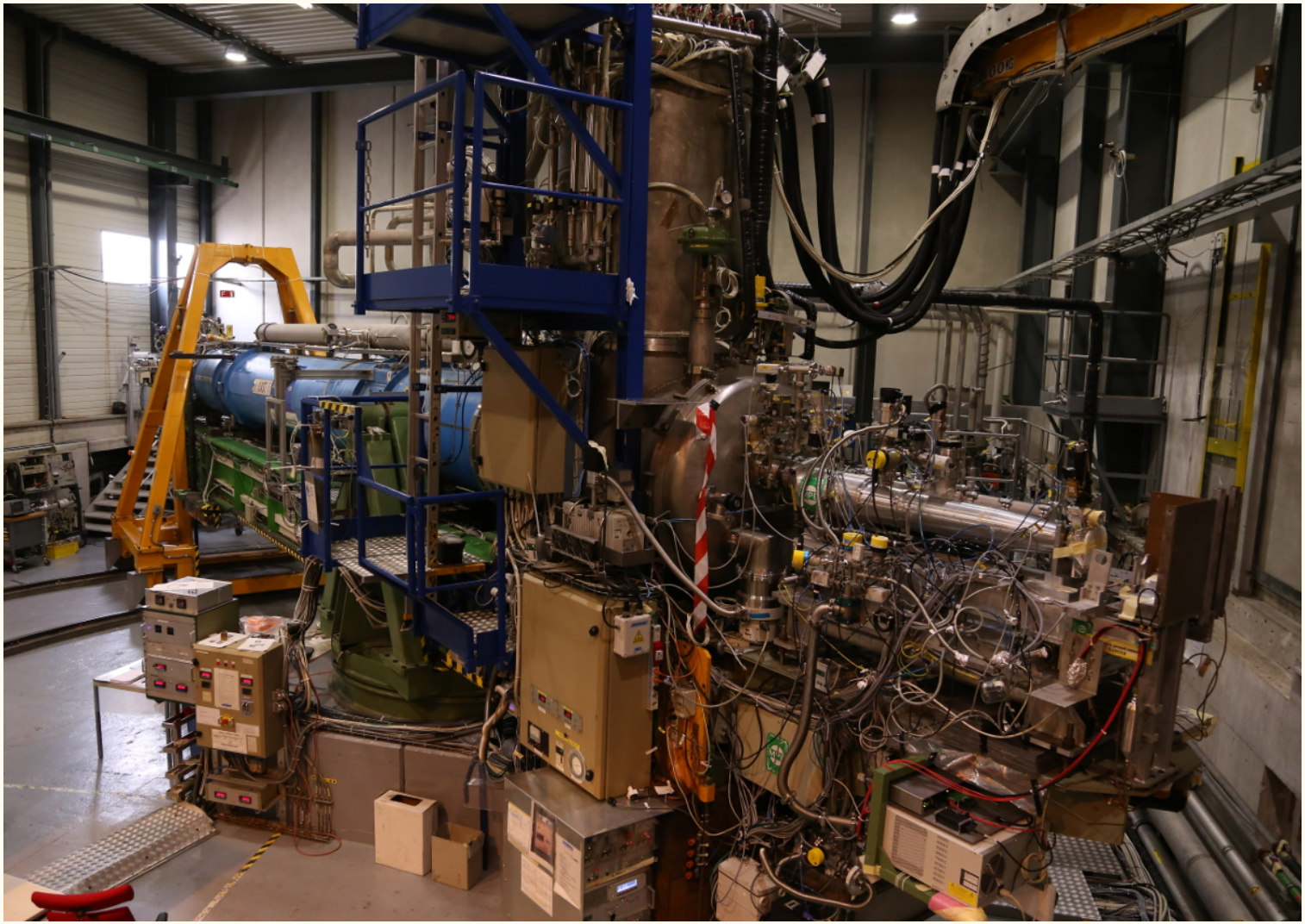
Looking at polarisation

ALPS—Any Light Particle Search

Light shining through a wall

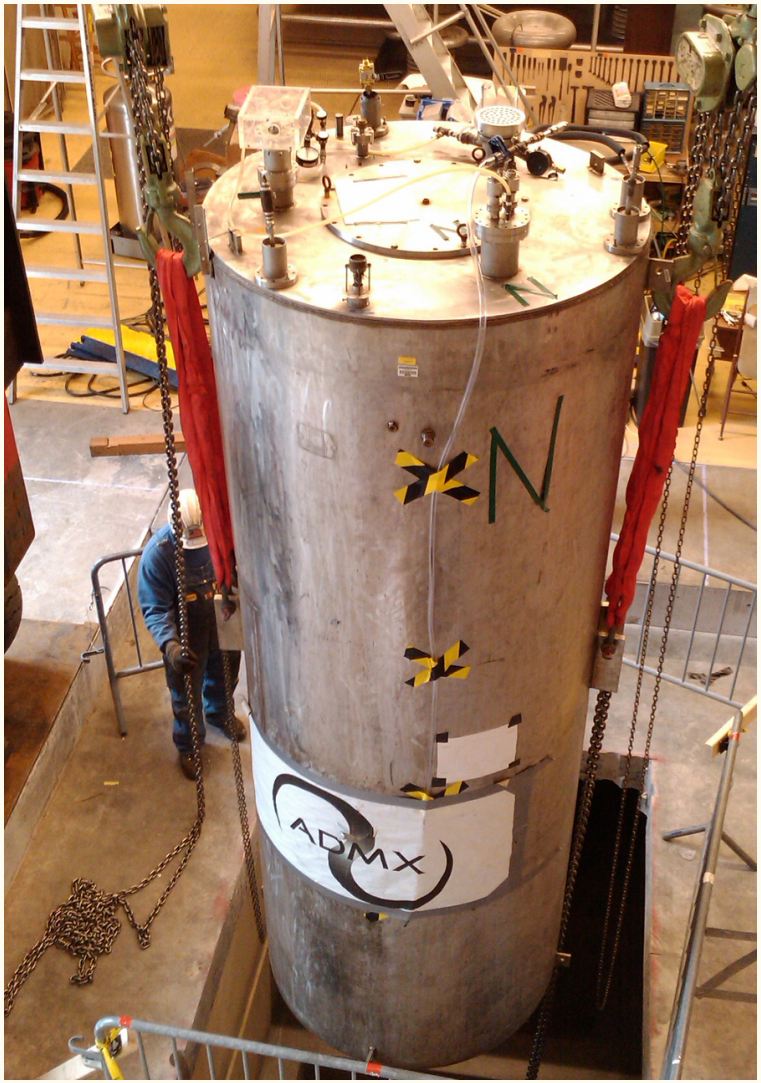
(DESY, Hamburg)

CAST—CERN Axion Solar Telescope



Helioscope

ADMX—Axion Dark Matter eXperiment



Haloscope

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

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)]

The mixing can be very efficient at producing polarisation

$\Rightarrow$ derive constraints

Recent examples

- $\rightarrow$ quasars: rotation of UV polarisation angle ($\leftrightarrow$ quasar morphology)
  [*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]
- $\rightarrow$ magnetic white dwarfs: limit on p_{lin} in magnetosphere $|\vec{\mathcal{B}}_e| \gtrsim 10^8$ G
  [*Gill and Heyl* (2011)]
- $\rightarrow$ 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)

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

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)]

The mixing can be very efficient at producing polarisation

$\Rightarrow$ derive constraints

Recent examples

- $\rightarrow$ quasars: rotation of UV polarisation angle ($\leftrightarrow$ quasar morphology)
  [*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]
- $\rightarrow$ magnetic white dwarfs: limit on p_{lin} in magnetosphere $|\vec{\mathcal{B}}_e| \gtrsim 10^8$ G
  [*Gill and Heyl* (2011)]
- $\rightarrow$ 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)

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

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)]

The mixing can be very efficient at producing polarisation

$\Rightarrow$ derive constraints

Recent examples

- $\rightarrow$ quasars: rotation of UV polarisation angle ($\leftrightarrow$ quasar morphology)
  [*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]
- $\rightarrow$ magnetic white dwarfs: limit on p_{lin} in magnetosphere $|\vec{\mathcal{B}}_e| \gtrsim 10^8$ G
  [*Gill and Heyl* (2011)]
- $\rightarrow$ 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)

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

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)]

The mixing can be very efficient at producing polarisation

$\Rightarrow$ derive constraints

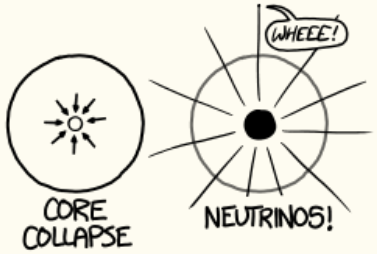
Recent examples

- $\rightarrow$ quasars: rotation of UV polarisation angle ($\leftrightarrow$ quasar morphology)
  [*Horns et al.* (2012)], [*di Serego Alighieri et al.* (2010)]
- $\rightarrow$ magnetic white dwarfs: limit on p_{lin} in magnetosphere $|\vec{\mathcal{B}}_e| \gtrsim 10^8$ G
  [*Gill and Heyl* (2011)]
- $\rightarrow$ 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 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)

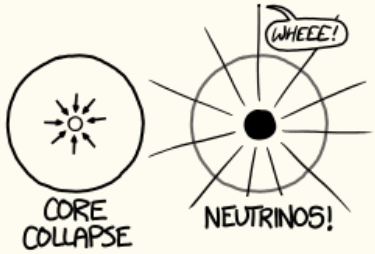
- ν burst seen (great success!) by Kamiokande, IMB, and Baksan detectors

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

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)

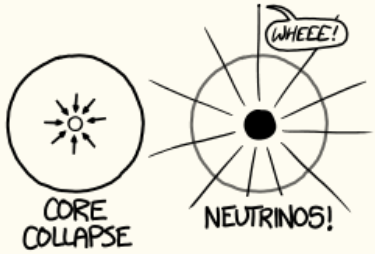
- ν burst seen (great success!) by Kamiokande, IMB, and Baksan detectors

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

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.

No prompt γ burst from SN1987A—in a nutshell

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

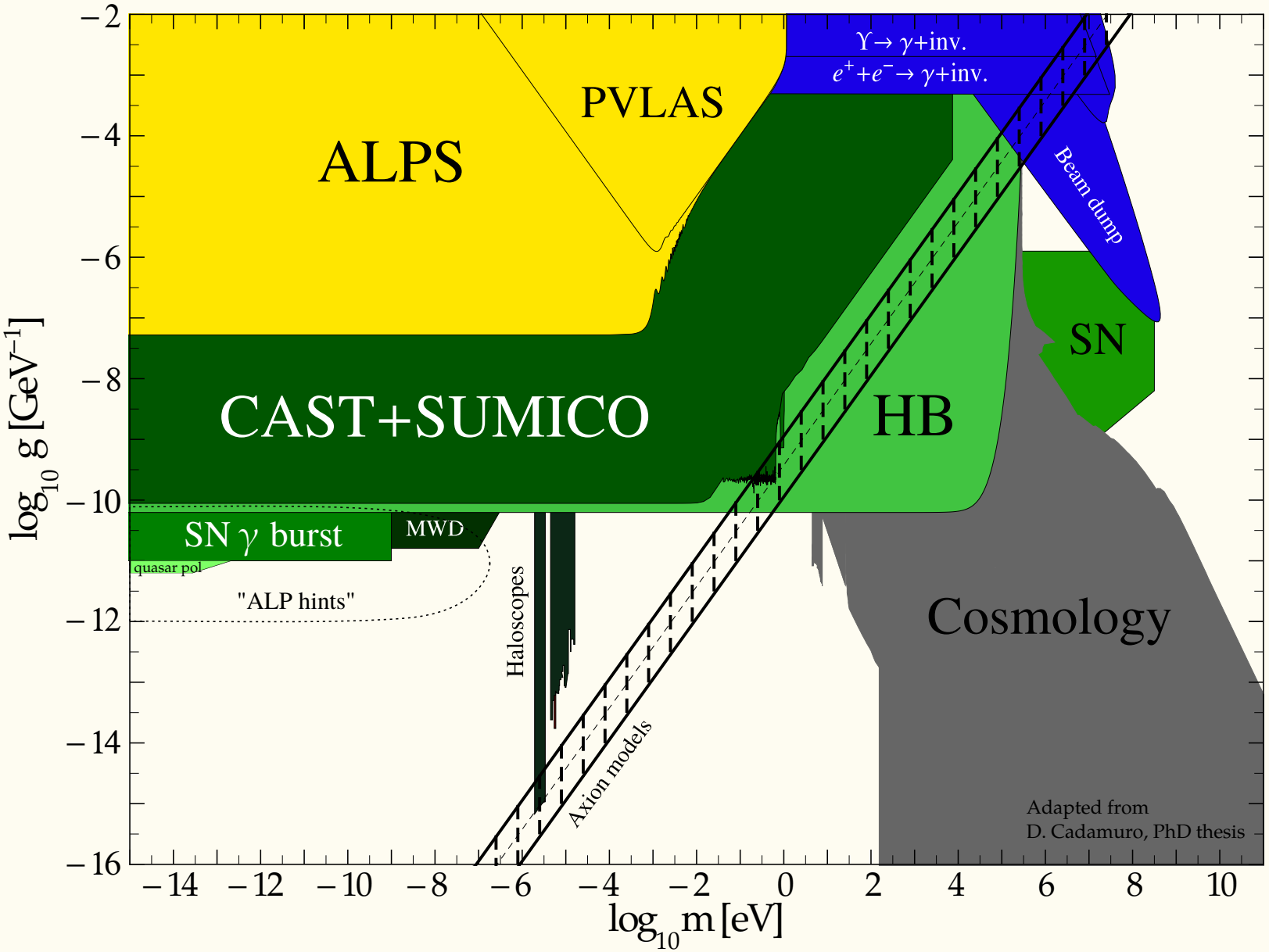
Important limit for the astrophysical window

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

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

Astrophysical hints of light axion-like particles?

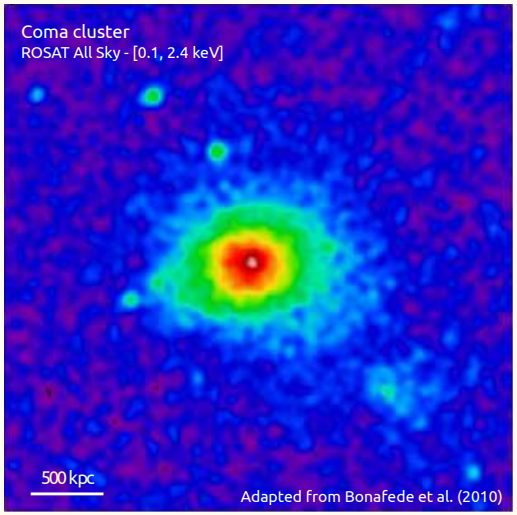
Searching for ALPs using their electromagnetic coupling



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)

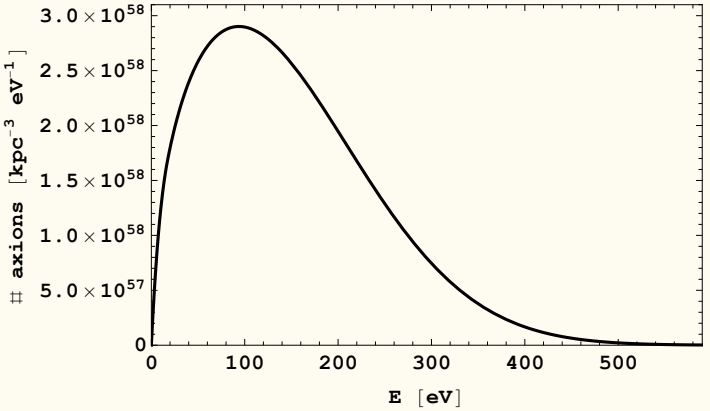
Long-standing puzzle difficult to explain with conventional astrophysics (thermal and non-thermal processes)

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

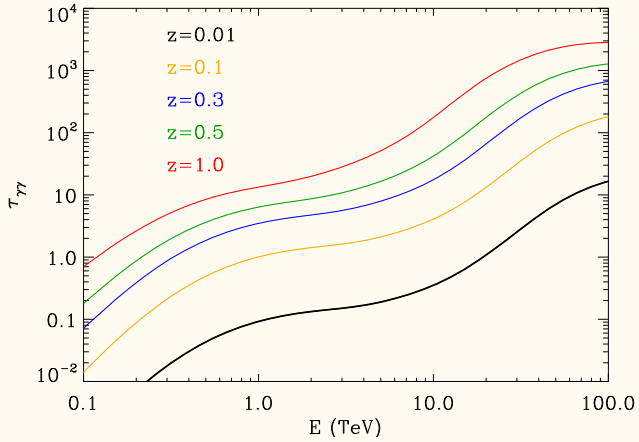
- Clear predictions from a Cosmic ALP Background Radiation
  - excess should formally exist in all clusters (not only Coma)
  - follow only $\mathcal{B}$ field/electron density, not ICM
  - flux also only function of these
- $\Delta N_{\rm eff}$ preferred (2.7σ) when combining Planck+WP with HST

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?

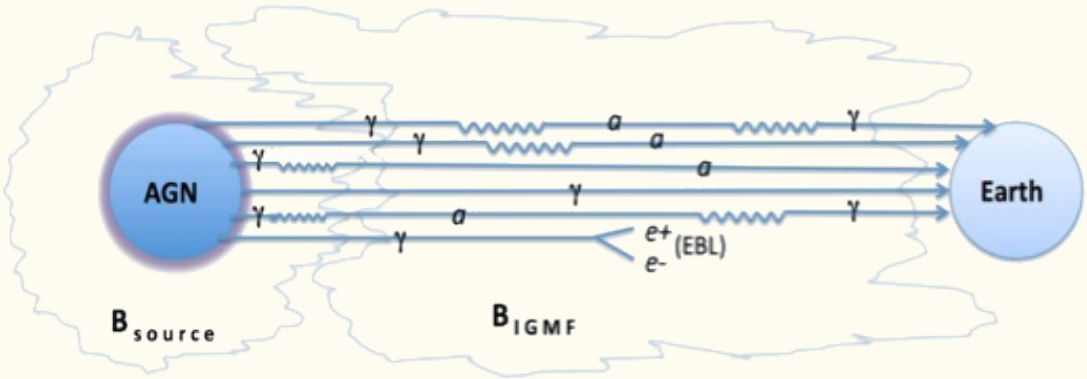
Observations by Cherenkov telescopes (e.g. MAGIC, VERITAS, HESS) would indicate an anomalous transparency of the Universe to TeV γ

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



credits: Sánchez-Conde et al. (2009)

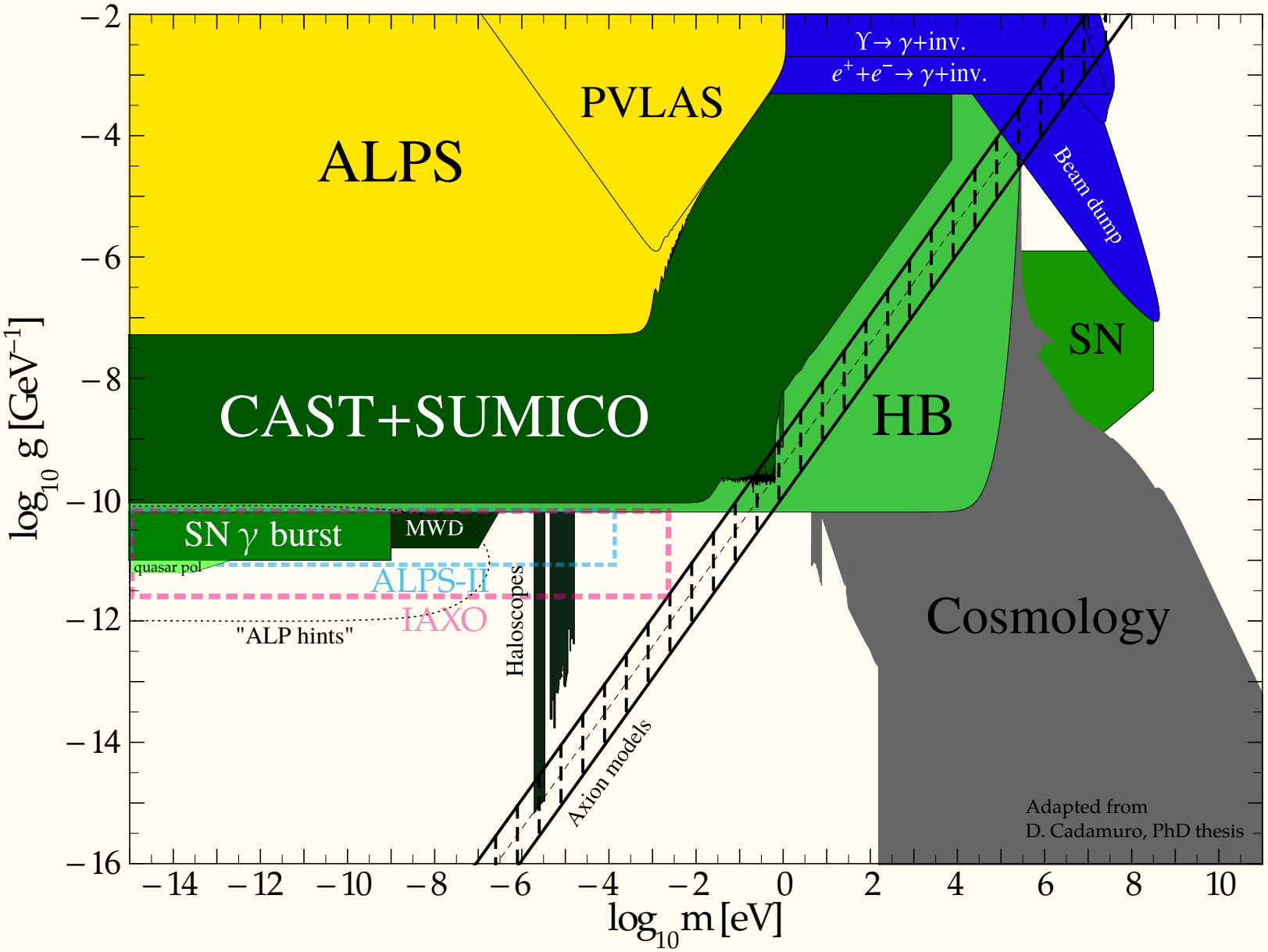
Various ALP-photon mixing scenarios:
e.g., mixing on the way/near the source + back-conversion in the Milky Way
[*de Angelis, Roncadelli, Mansutti* (2007)], [*Sánchez-Conde et al.* (2009)], [*Meyer, Horns* (2012)], ...

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)]

Prospects: upgrade of the ALPS experiment, IAXO



Summary

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, together with the axion: dedicated experiments

Axion-photon mixing

- has very distinctive signatures, which follow $\mathcal{B}$ and n_e
- same thing for polarisation (energy-dependent dichroism and birefringence)
- is more efficient at high energies

If these particles exist, they could have many effects in astrophysics, including:

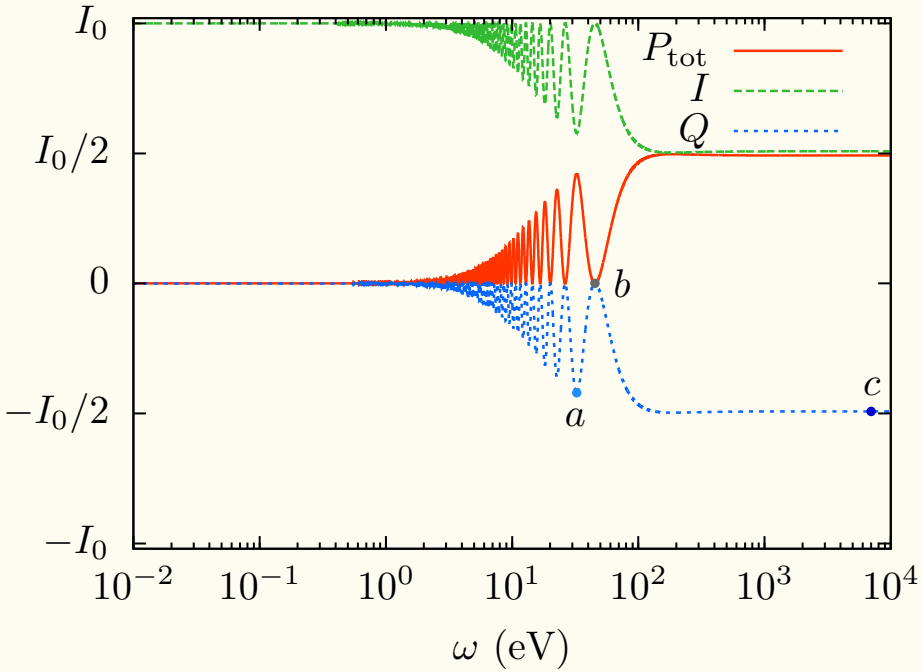
- production in stellar plasma
- modification of the opacity of the Universe to very-high-energy photons
- modification the polarisation of distant sources, including quasars and GRBs
- conversion, at least formally, in any magnetic field

Appendix

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 (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

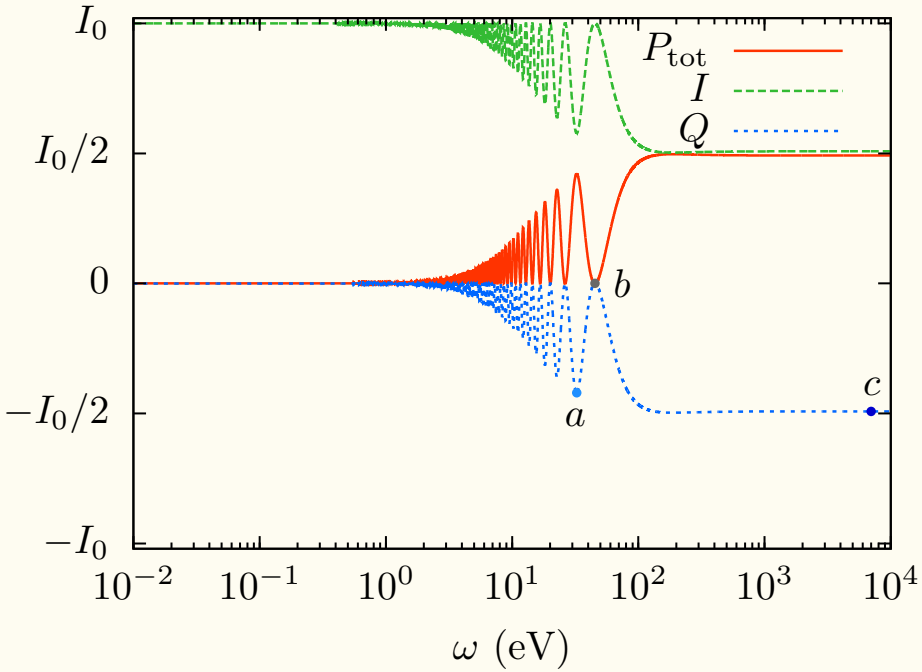
(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

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

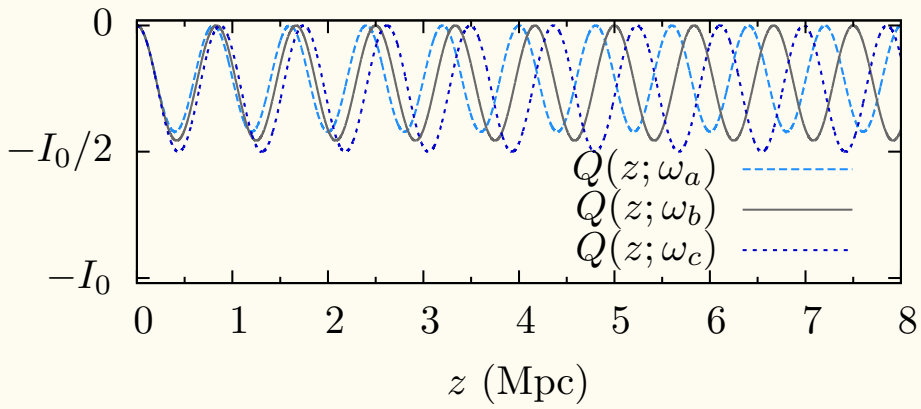
Instructive case: single region of constant magnetic field

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 (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

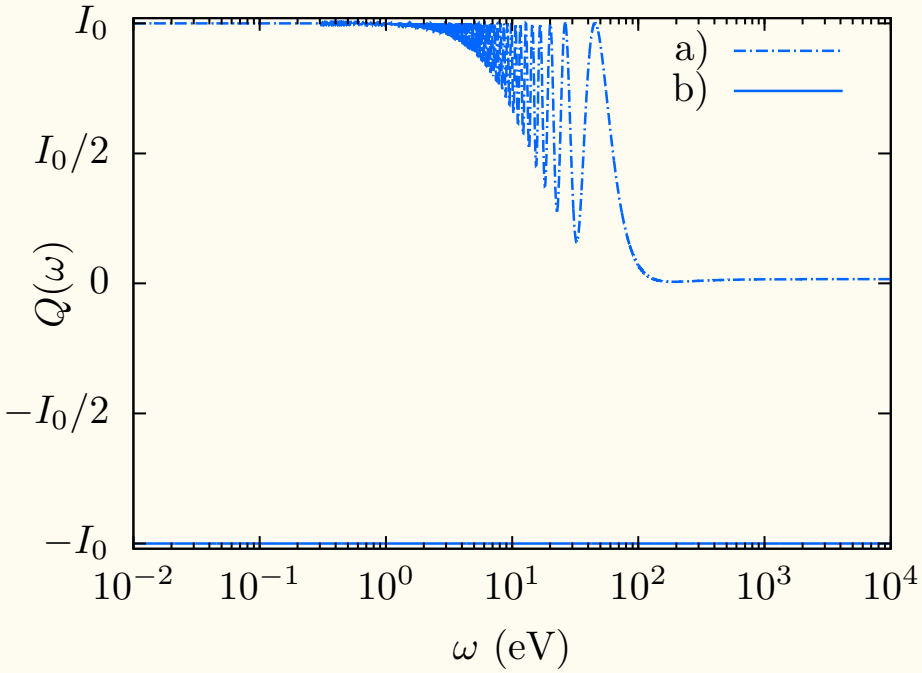
(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

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

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

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

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

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

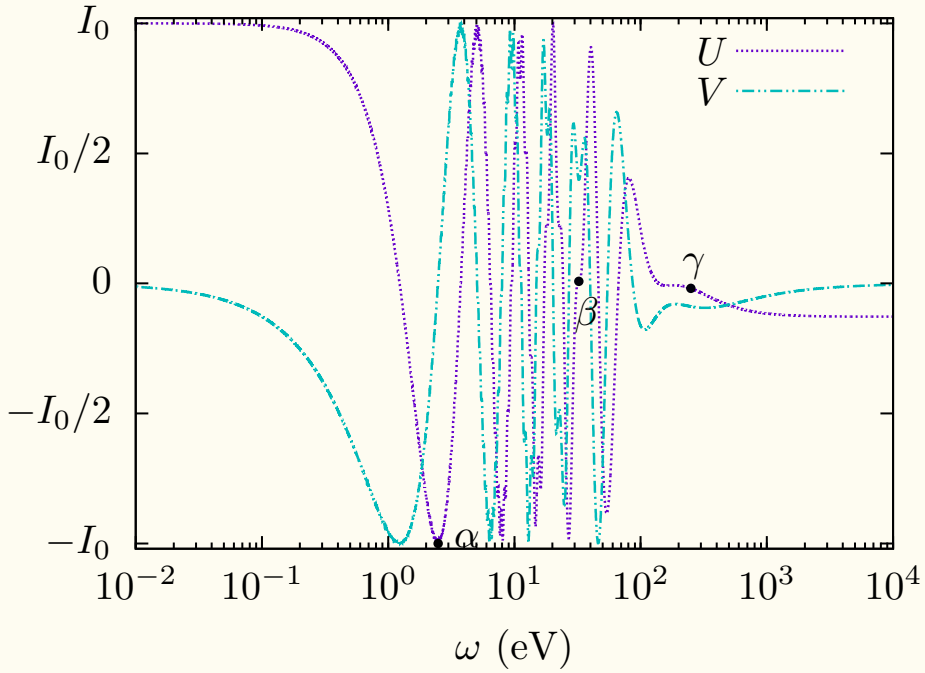
At exactly which ω such features happen is determined by the external parameters

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 100% polarised light ($U_0 = I_0$), $\forall \omega$



Results at the end of the average magnetic field in a supercluster (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

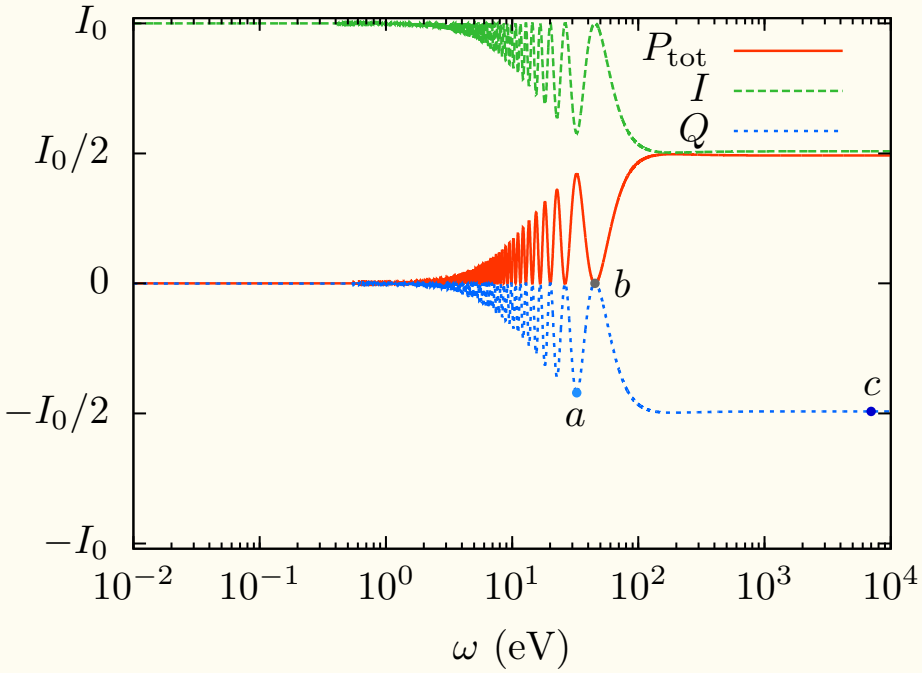
(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

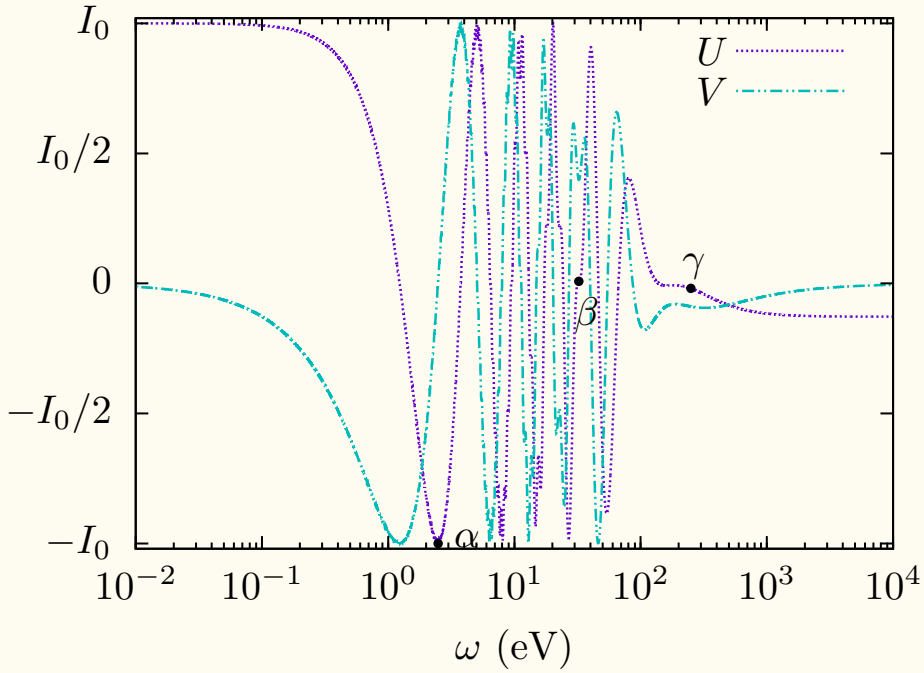
At exactly which ω such features happen is determined by the external parameters

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)]





Results at the end of the average magnetic field in a supercluster (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

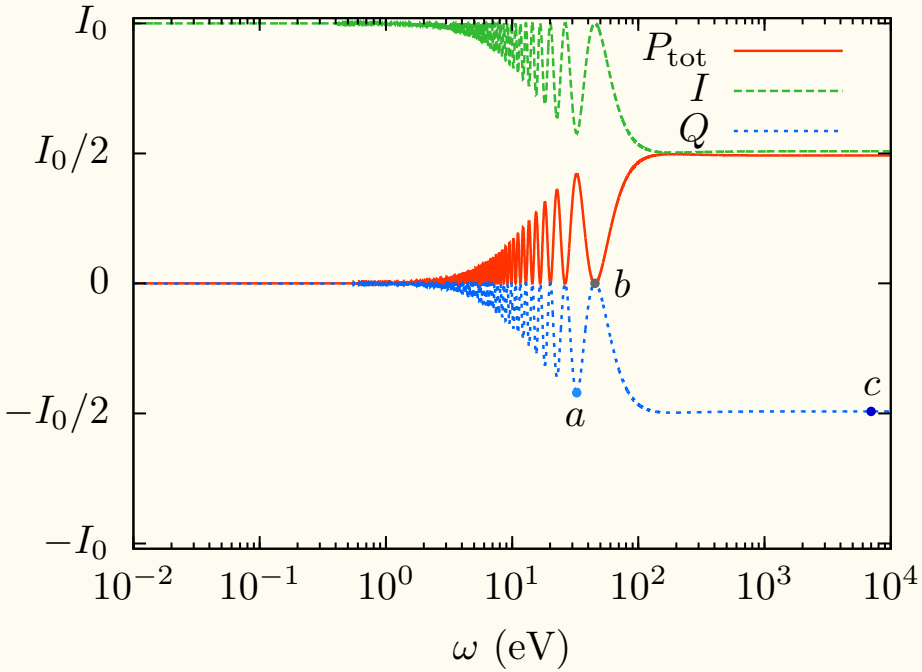
(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

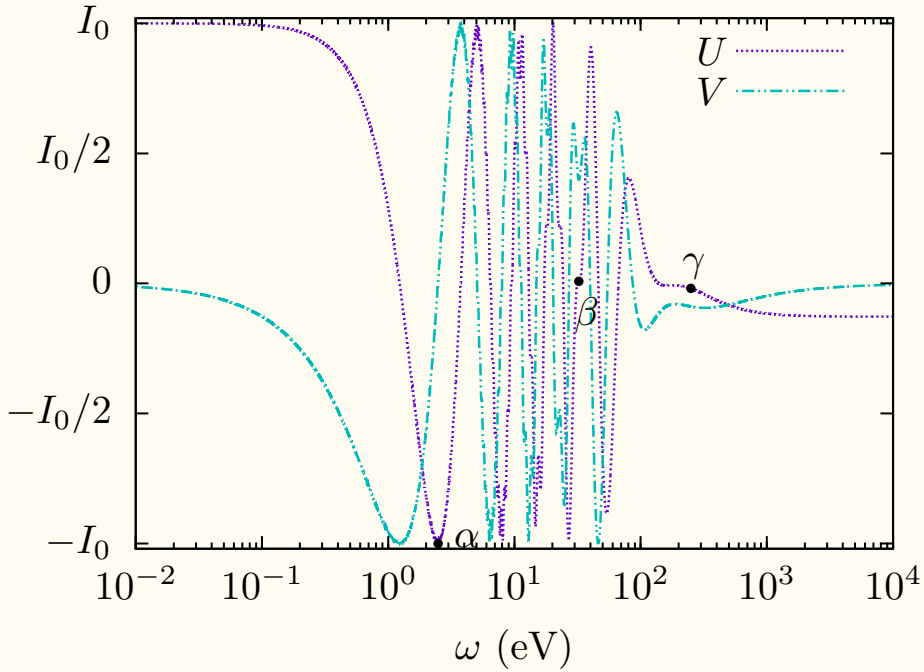
At exactly which ω such features happen is determined by the external parameters

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)]





Results at the end of the average magnetic field in a supercluster (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ GeV^{-1})

Different regimes

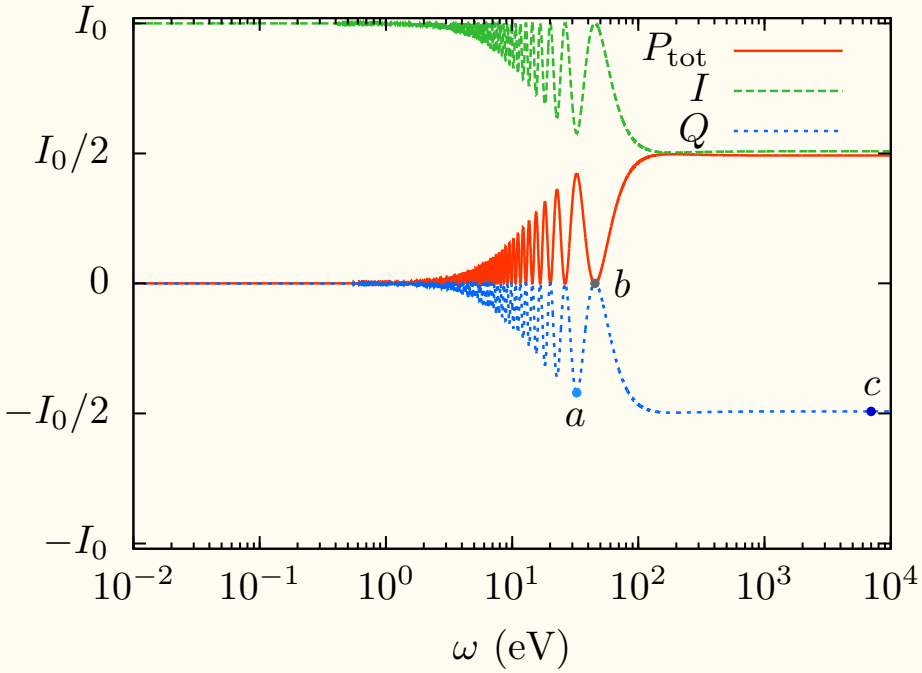
(*e.g.*, strong mixing: strong dichroism, while no circular polarisation if $V_0 = 0$)

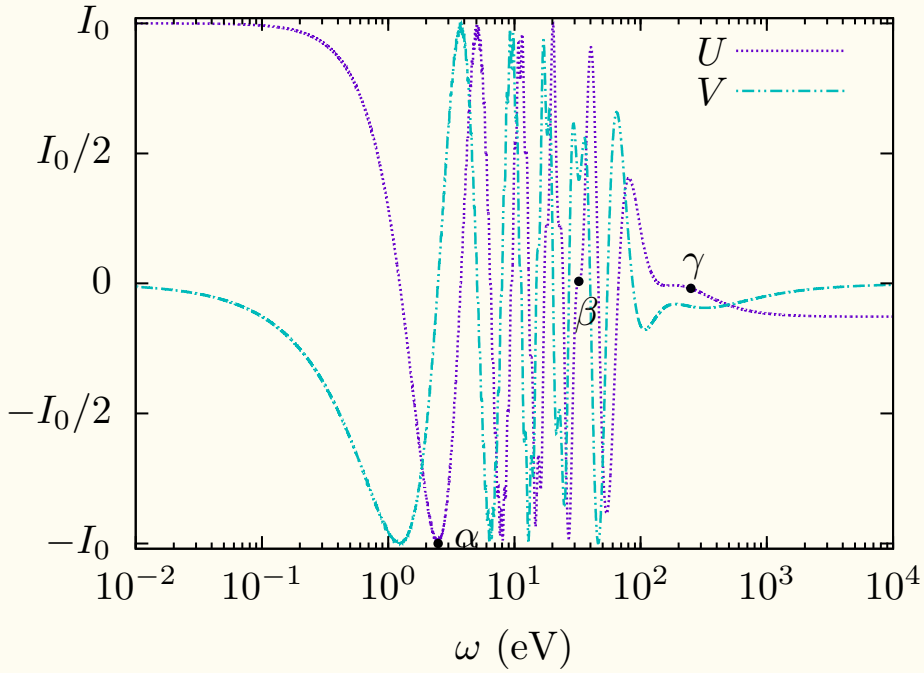
At exactly which ω such features happen is determined by the external parameters

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)]





Results at the end of the average magnetic field in a supercluster (ultralight ALP)

$n_e = 10^{-6}$ cm^{-3}, $g\mathcal{B} = 4.5 \times 10^{-29}$ eV (*e.g.* $\mathcal{B} \sim 0.2$ μG & $g = 10^{-11}$ 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

For completeness

Lagrangian of quantum chromodynamics for the two lightest quarks

$$\mathcal{L}_{\text{QCD}}^{\text{fermions}} = \bar{u}\left(i\gamma^\mu D_\mu - m_u\right)u + \bar{d}\left(i\gamma^\mu D_\mu - m_d\right)d$$

Global symmetries: $\text{U}(1)_V$, $\text{U}(1)_A$, $\text{SU}(2)_V$ and $\text{SU}(2)_A$ if $m_u = m_d = 0$.

- global phase $\text{U}(1)_V$

$$\psi \to \psi' = e^{i\alpha}\psi$$

- (usual) isospin $\text{SU}(2)_V$

$$Q \to Q' = e^{i\frac{1}{2}\vec{\alpha}\cdot\vec{\sigma}}Q$$

- chiral phase $\text{U}(1)_A$

$$\psi \to \psi' = e^{i\eta\gamma^5}\psi$$

- isospin $\text{SU}(2)_A$

$$Q \to Q' = e^{i\frac{1}{2}\vec{\eta}\cdot\vec{\sigma}\gamma^5}Q$$

where σ^i are the Pauli matrices; ψ represents either u or d; Q represents a doublet, $Q = \binom{u}{d}$

Different couplings for scalars and pseudoscalars

$\vec{E} = \vec{\mathcal{E}}_r + \vec{\mathcal{E}}, \quad \vec{B} = \vec{\mathcal{B}}_r + \vec{\mathcal{B}};$

$\vec{\mathcal{E}}_r$, $\vec{\mathcal{B}}_r$: orthogonal fields of the radiation
reminder: $\vec{\mathcal{E}}_r$ defines the direction of polarisation
$\vec{\mathcal{E}}$, $\vec{\mathcal{B}}$: possible external transverse fields
for astrophysical applications: usually $\vec{\mathcal{B}} \neq 0$, $\vec{\mathcal{E}} = 0$

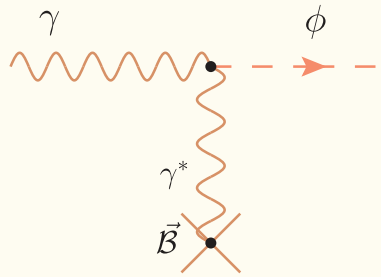
- γ polarised // to $\vec{\mathcal{B}}$ in the case of pseudoscalar ϕ:

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

- γ polarised $\perp$ to $\vec{\mathcal{B}}$ in the case of scalar ϕ:

$$\mathcal{L}_{\phi\gamma\gamma,\mathrm{sc}} = \frac{1}{4}\, g\phi F_{\mu\nu}F^{\mu\nu} = \frac{1}{2} g\phi(\vec{B}^2 - \vec{E}^2)$$

and in $(\hat{\vec{B}})^2$ there is $\vec{\mathcal{B}}\cdot\vec{\mathcal{B}}_r$ ($\neq 0$ for non-zero coupling)



The phenomenology, however remains extremely similar.