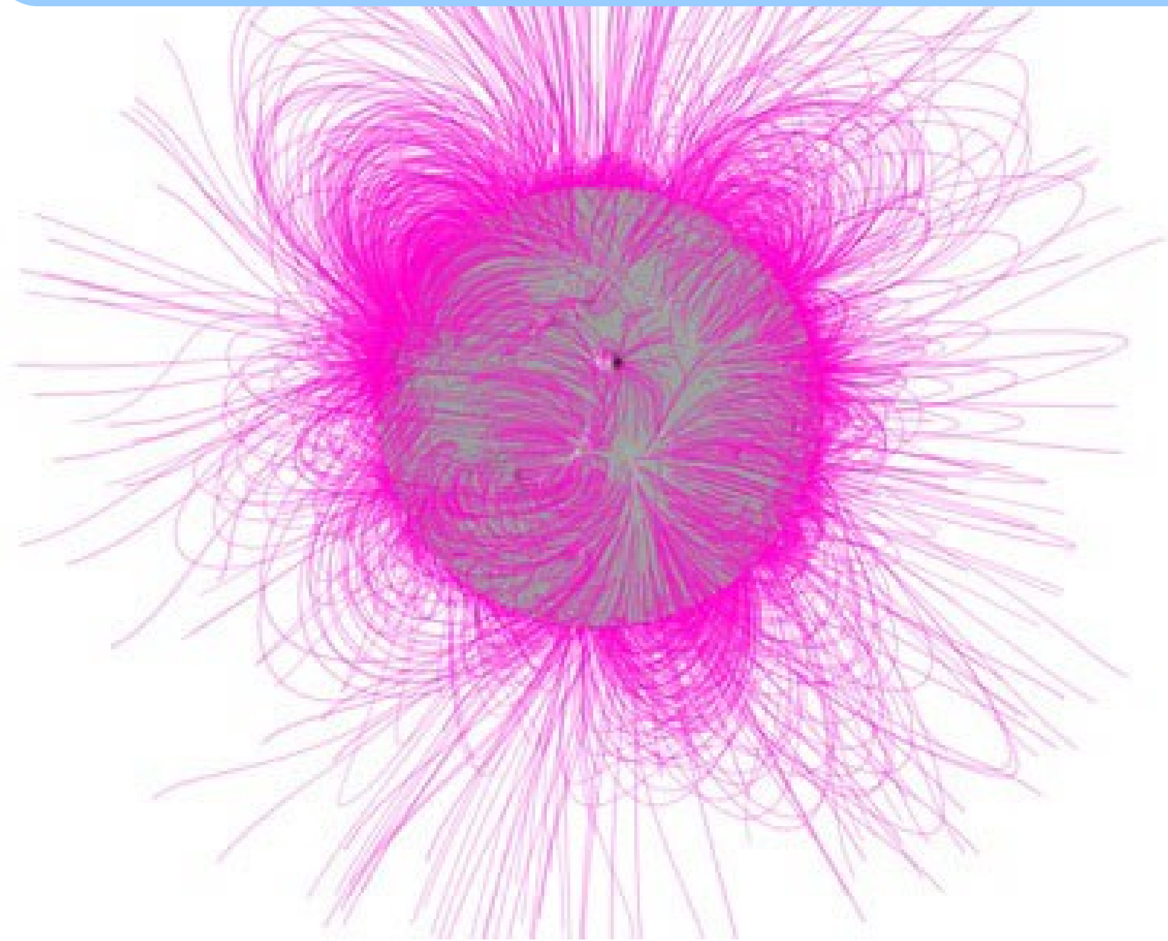
Constraints on axion-like particles from magnetic white dwarfs

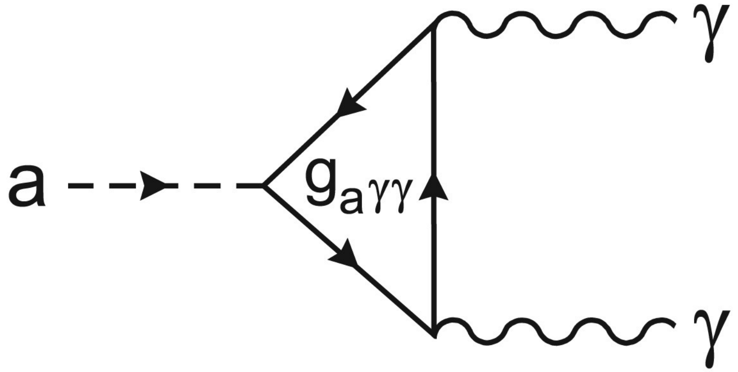


Ramandeep Gill
University of British Columbia

Article ref: R. Gill and J. Heyl, 2011, Phys. Rev. D. 84, 085001
ArXiv: 1105.2083

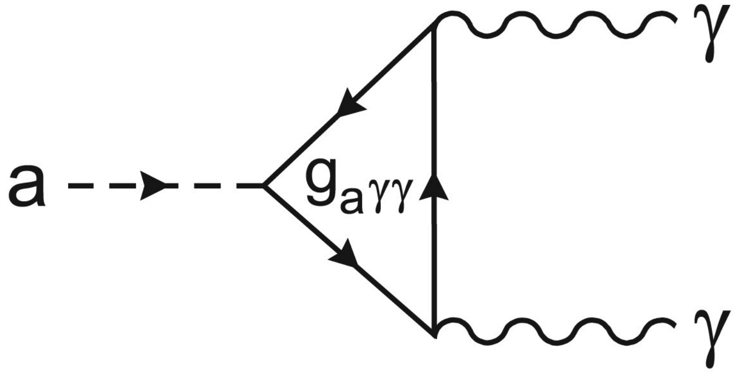
Axion-like particles

- Sub-meV scale pseudo-scalar bosons
- Spin = 0
- Two photon vertex with $g_{a\gamma\gamma}$



Axion-like particles

- Sub-meV scale pseudo-scalar bosons
- Spin = 0
- Two photon vertex with $g_{a\gamma\gamma}$

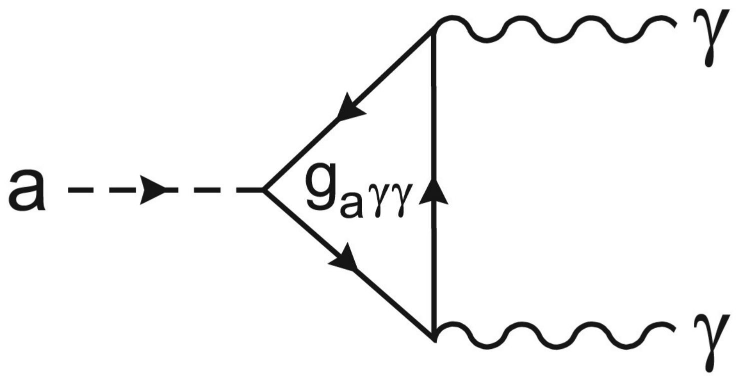


- No relation between mass and coupling strength

$$m_a \approx 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a}\right)$$

Axion-like particles

- Sub-meV scale pseudo-scalar bosons
- Spin = 0
- Two photon vertex with $g_{a\gamma\gamma}$

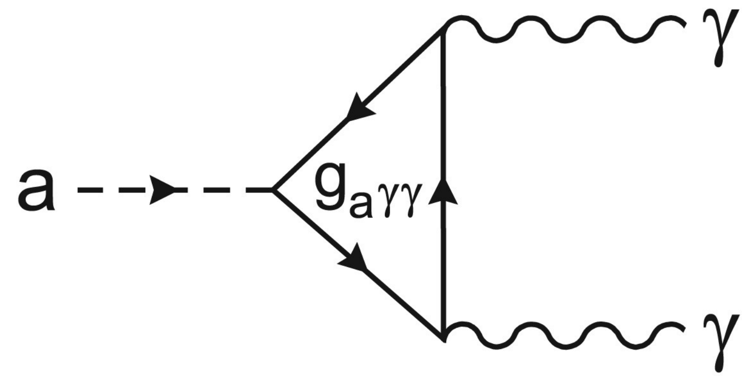


- No relation between mass and coupling strength

$$\cancel{m_a \approx 6\ \mathrm{eV} \left(\frac{10^6\ \mathrm{GeV}}{f_a}\right)} \quad \Rightarrow \quad \{m_a,\ g_{a\gamma\gamma}\}$$

Axion-like particles

- Sub-meV scale pseudo-scalar bosons
- Spin = 0
- Two photon vertex with $g_{a\gamma\gamma}$



- No relation between mass and coupling strength

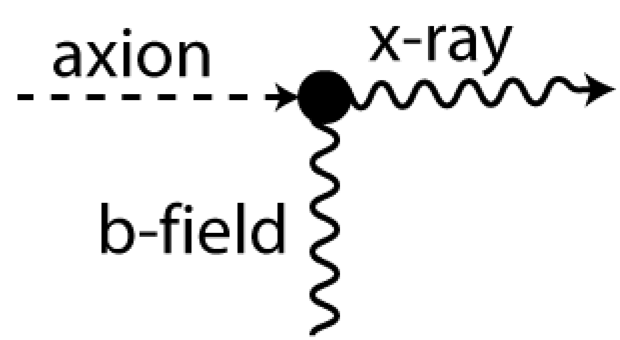
$$\cancel{m_a \approx 6 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a}\right)}$$

$$\{m_a,\ g_{a\gamma\gamma}\}$$

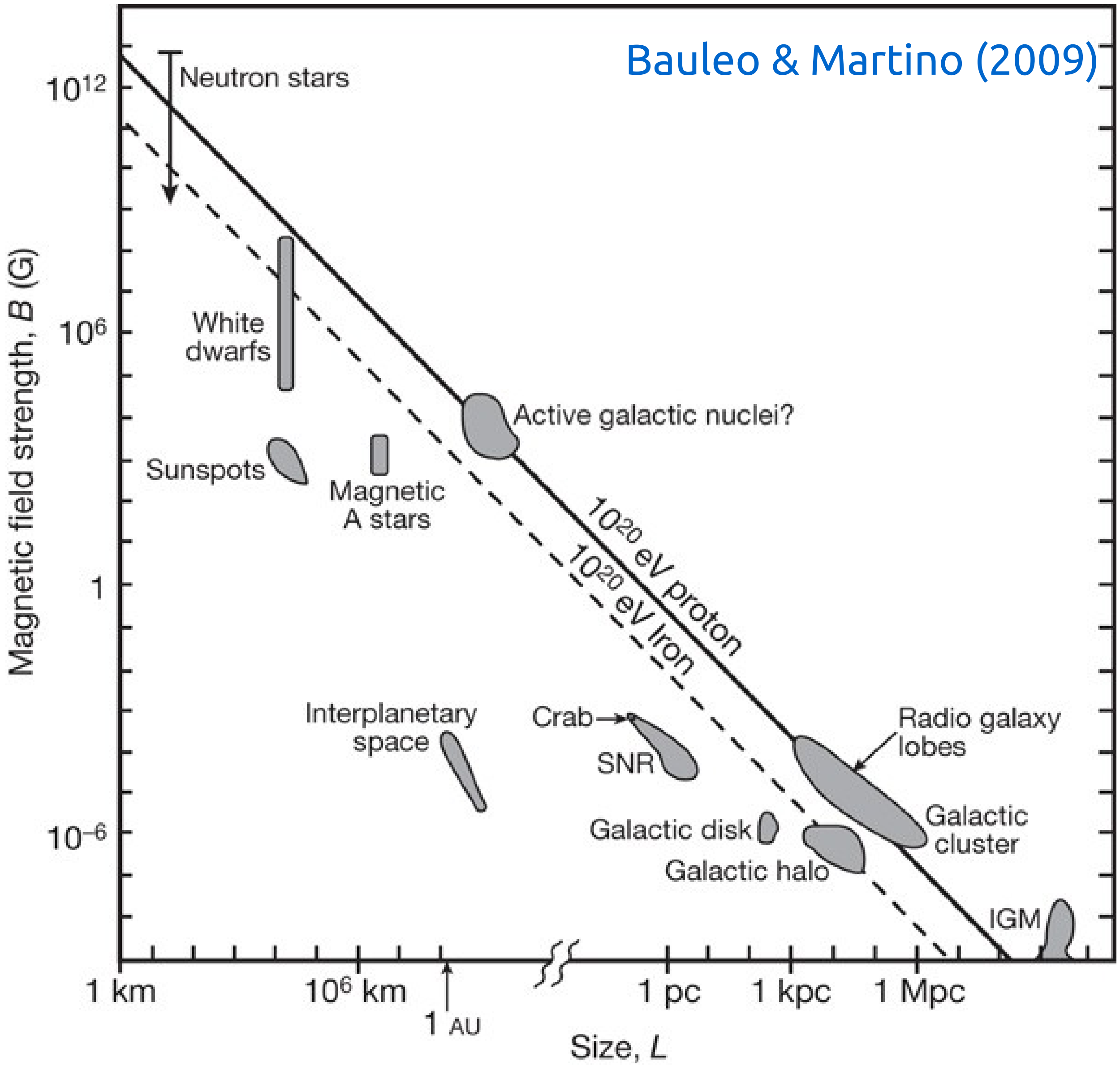
- Produced via the Primakoff process

$$\mathfrak{L}_{int} = g_{a\gamma\gamma}\ a\ \mathbf{E} \cdot \mathbf{B}$$

$$P_{\gamma\to a} \approx \frac{1}{4}\ g^2_{a\gamma\gamma}\ B^2\ l^2$$



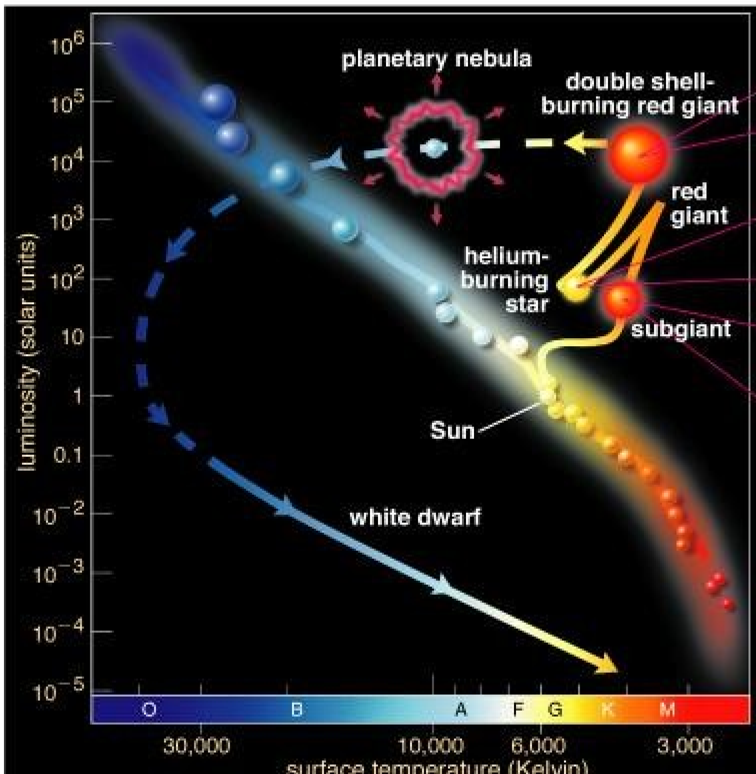
Magnetic fields in astronomy

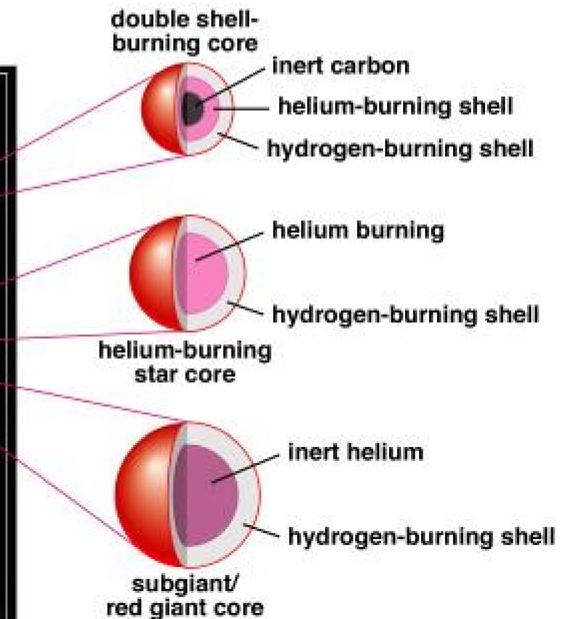


White dwarfs

- Main sequence stars with $M \lesssim 8\ M_\odot$ leave a compact remnant - a white dwarf
- $M_{WD} \sim 0.6\ M_\odot, \quad R_{WD} \sim 1\% R_\odot \approx 7 \times 10^8\ \mathrm{cm} \qquad T_{\rm eff} \sim 10^3 - 10^5 \mathrm{K}$

H-R diagram

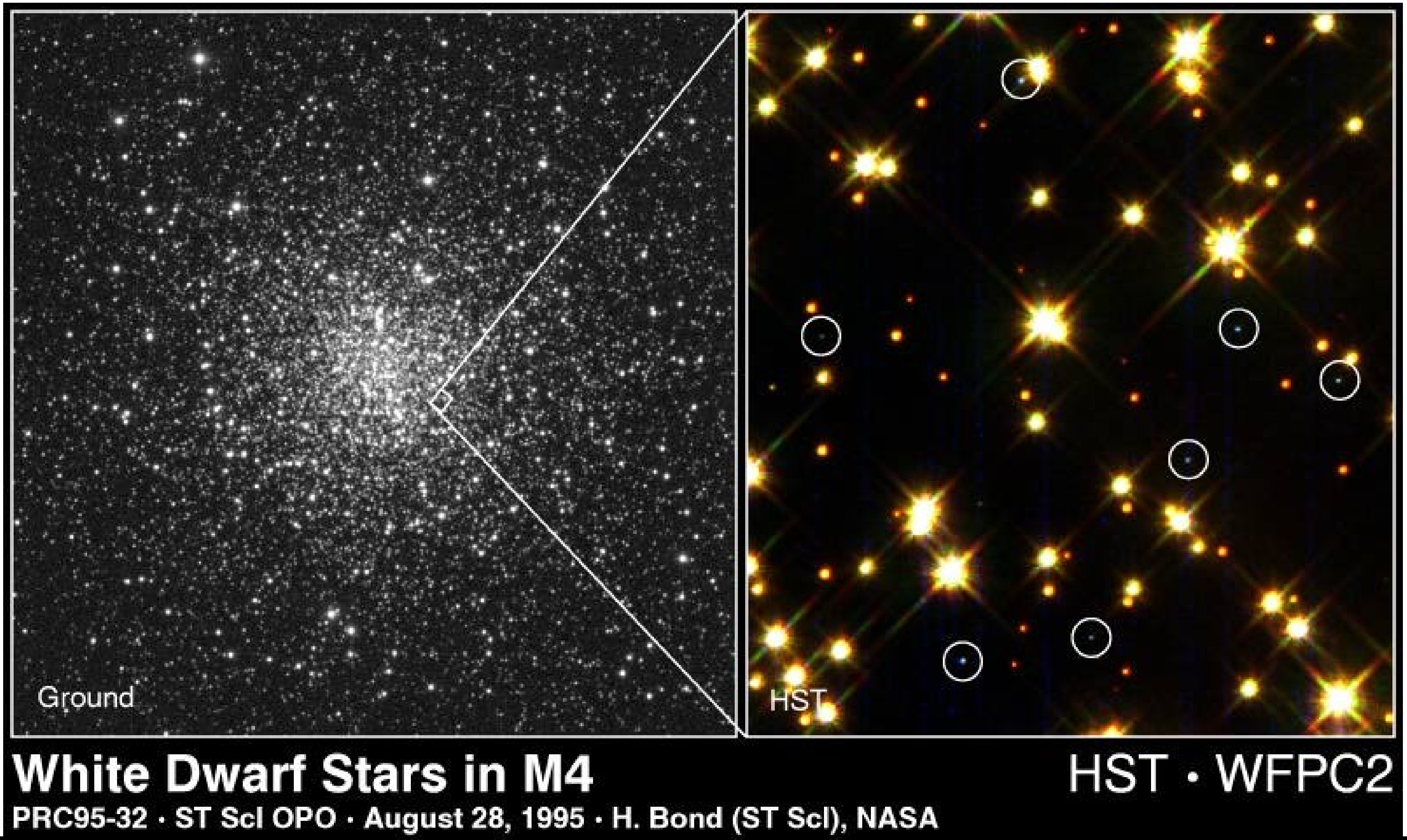




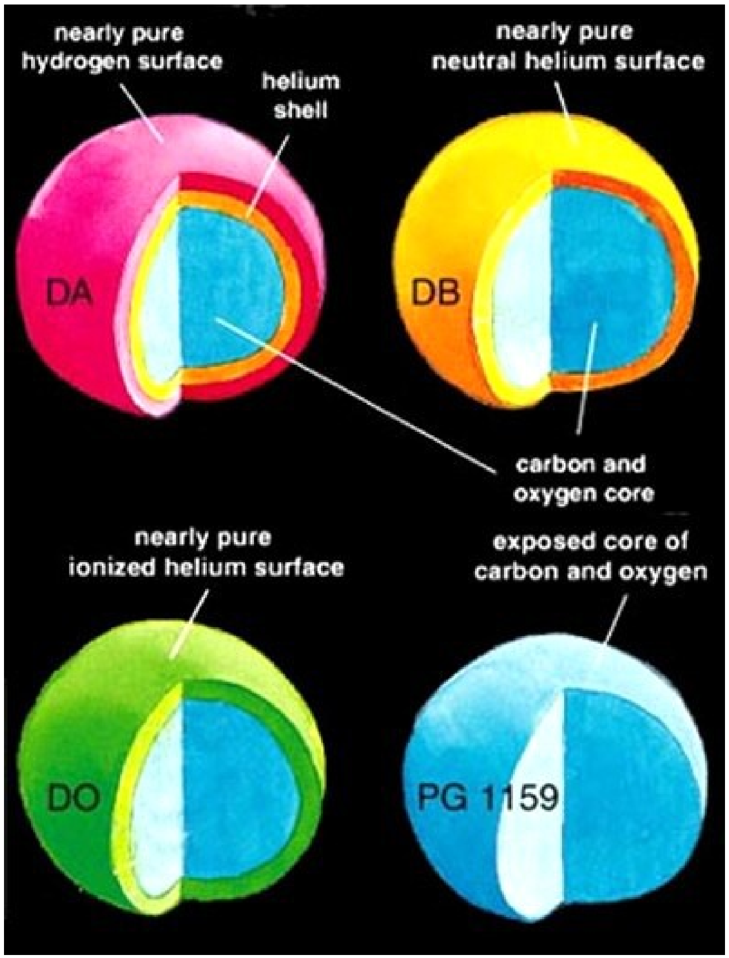
Cat's eye nebula

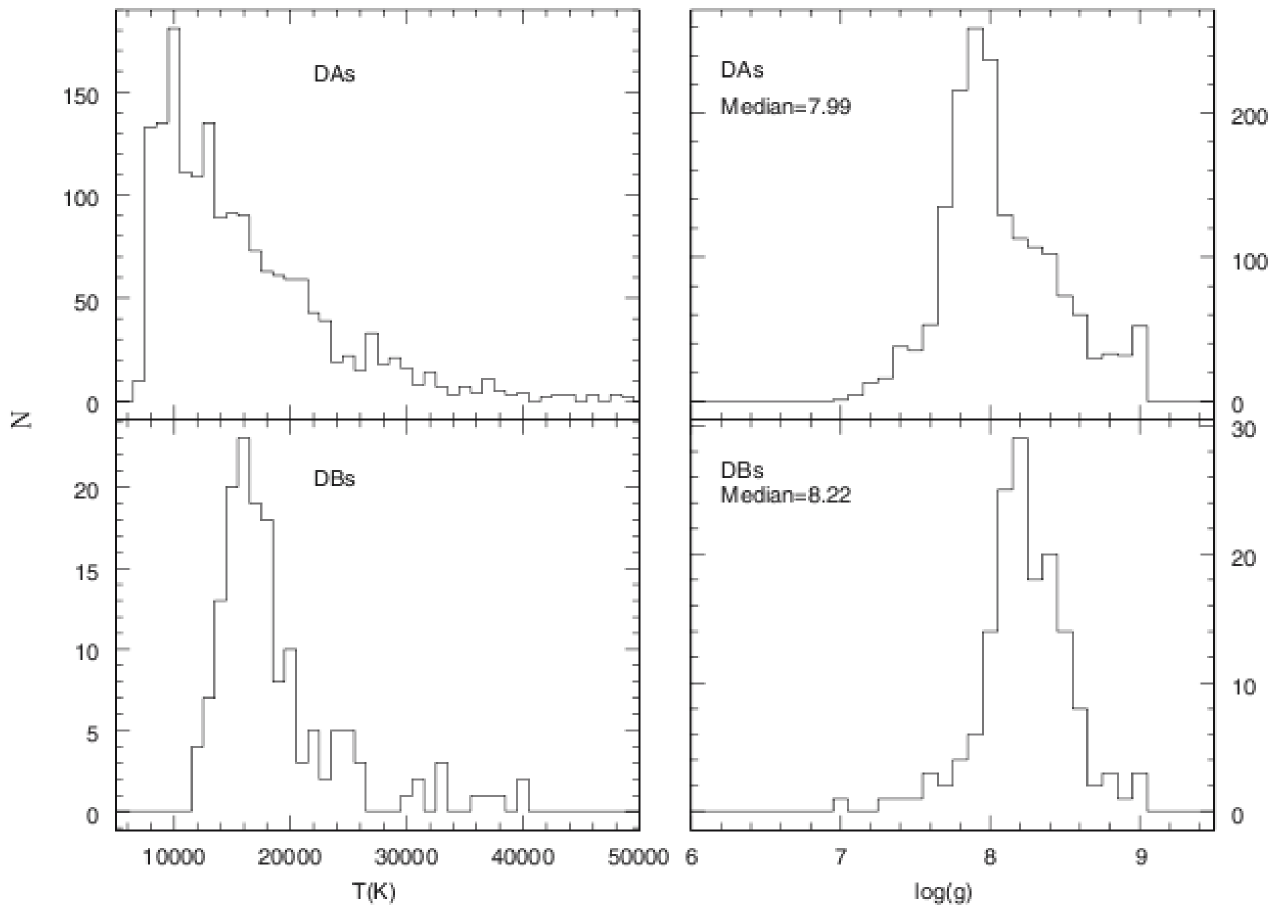
White dwarfs

- Main sequence stars with $M \lesssim 8\ M_{\odot}$ leave a compact remnant - a white dwarf
- $M_{WD} \sim 0.6\ M_{\odot}, \quad R_{WD} \sim 1\% R_{\odot} \approx 7 \times 10^{8}\ \text{cm} \qquad T_{\text{eff}} \sim 10^{3} - 10^{5}\text{K}$



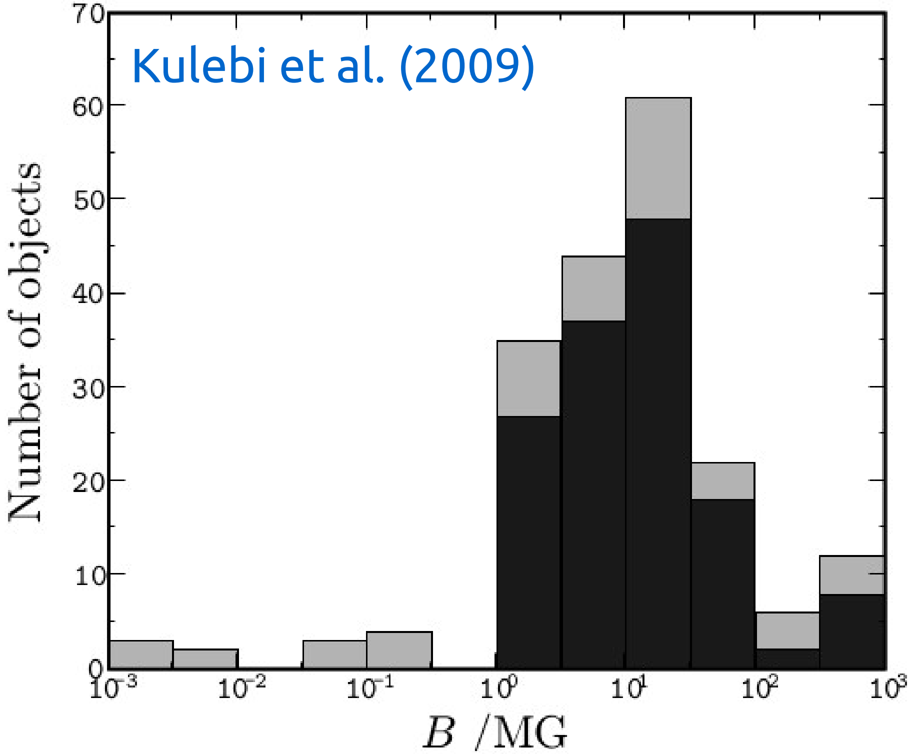
White dwarfs





Magnetism in white dwarfs

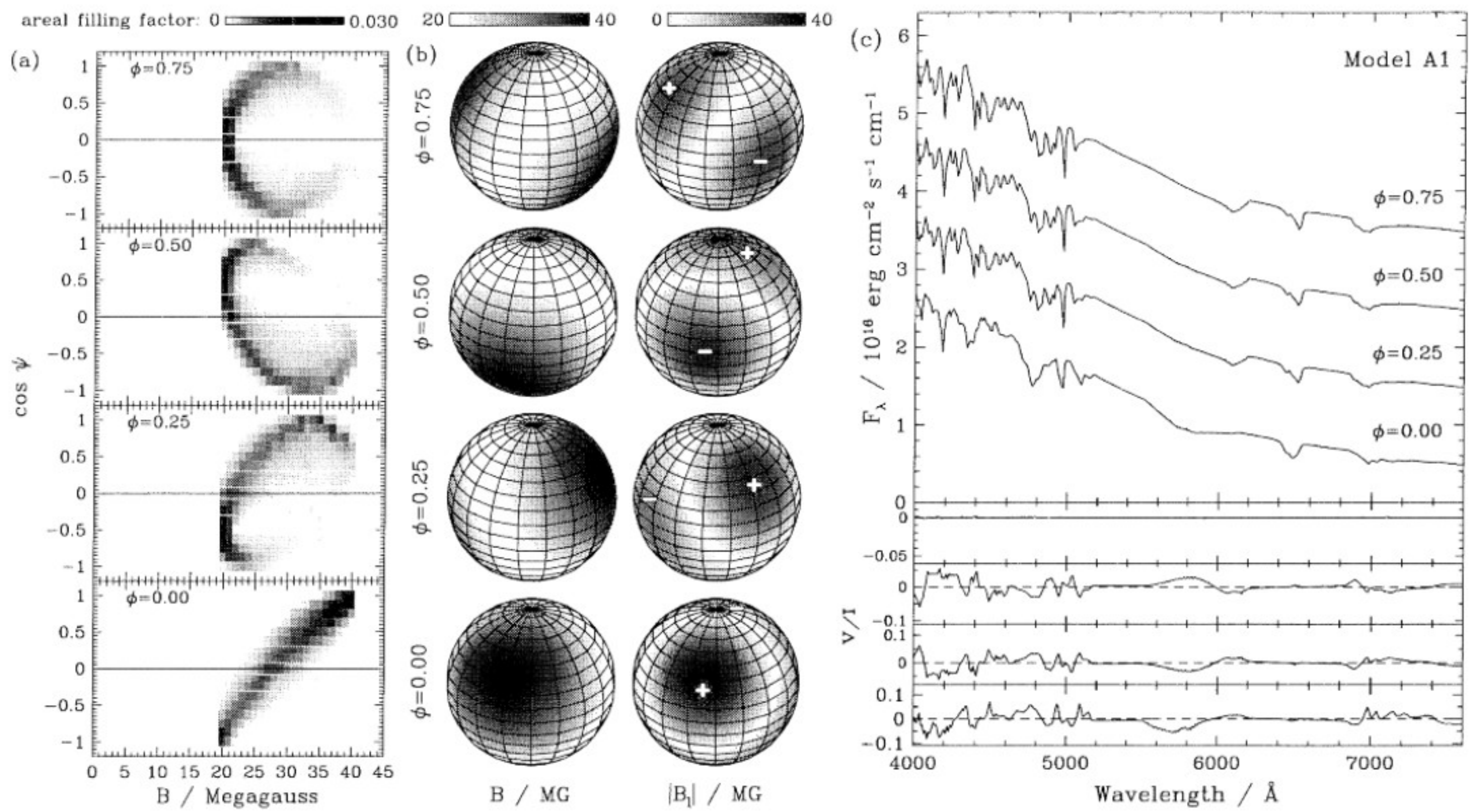
- Only 10% of WDs are magnetized with $B_s \gtrsim 1\ \mathrm{MG}$



Magnetism in white dwarfs

- Only 10% of WDs are magnetized with $B_s \gtrsim 1\ \mathrm{MG}$
- Magnetism in WDs is detected through Zeeman spectropolarimetry

Euchner et al. (2002)



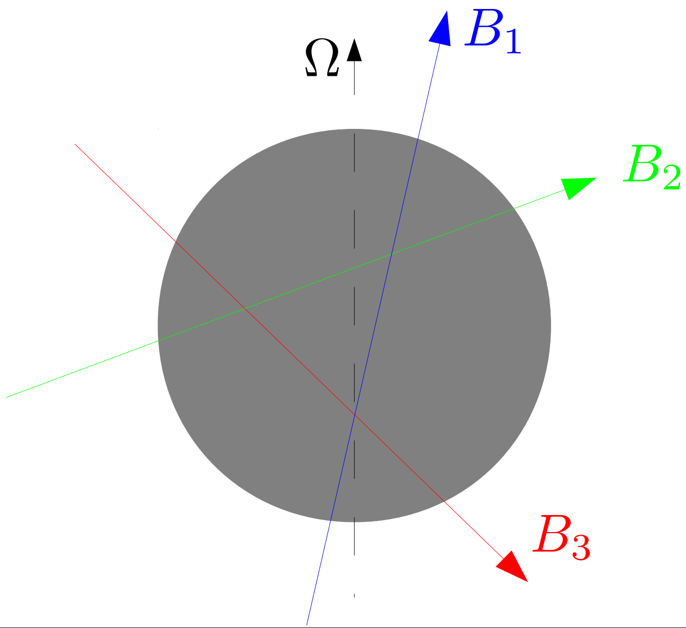
Magnetism in white dwarfs

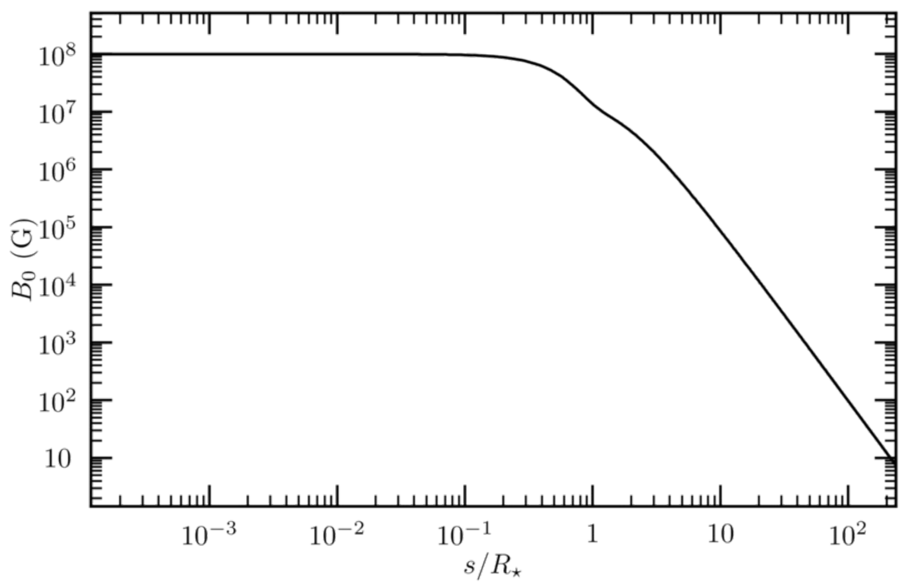
- Only 10% of WDs are magnetized with $B_s \gtrsim 1\ \mathrm{MG}$
- Magnetism in WDs is detected through Zeeman spectropolarimetry.
- Generally, several dipole components contribute.

Magnetism in white dwarfs

- Only 10% of WDs are magnetized with $B_s \gtrsim 1$ MG
- Magnetism in WDs is detected through Zeeman spectropolarimetry.
- Generally, several dipole components contribute.

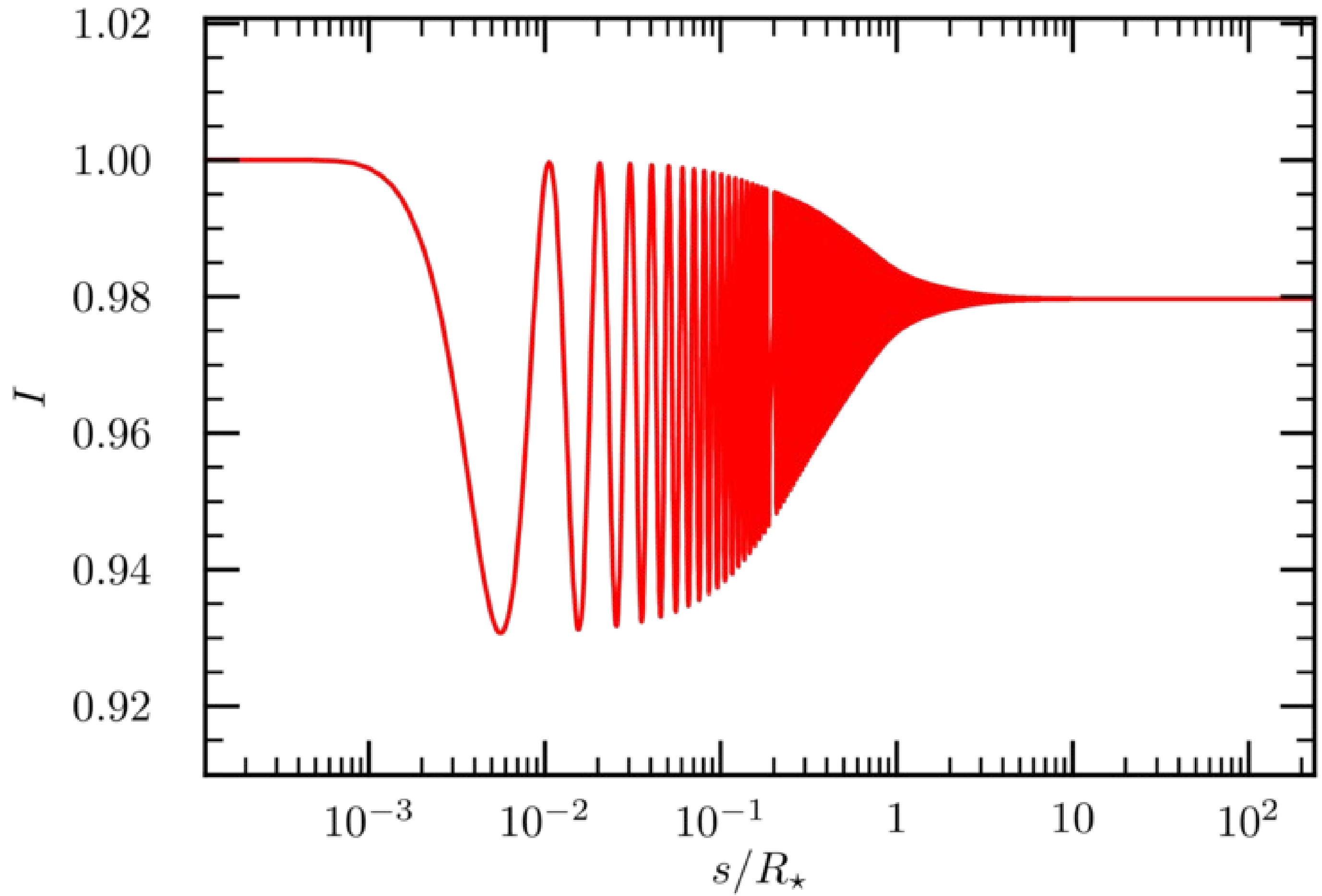
Off-centered non-aligned three dipole model





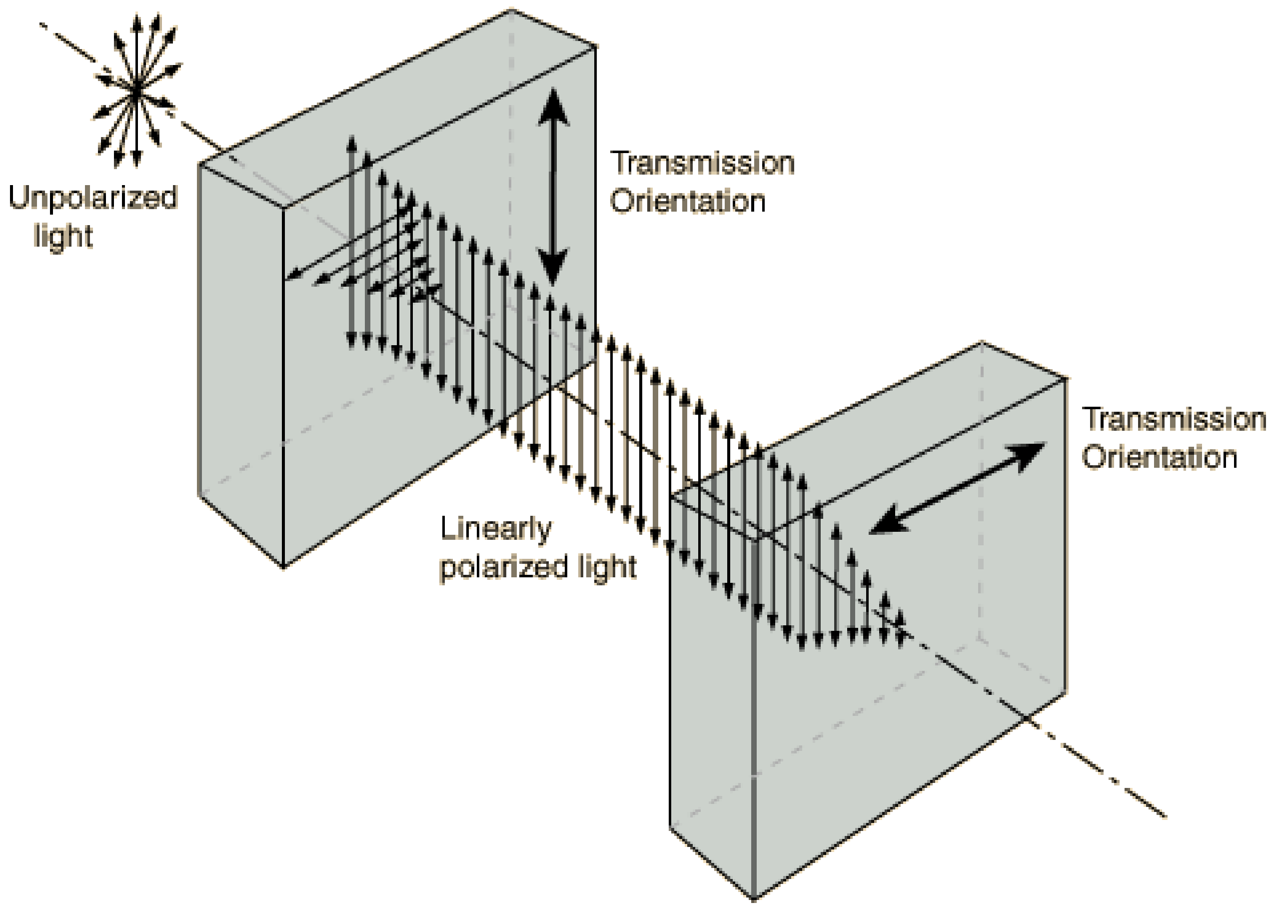
Signature of photon-ALP oscillation

Conversion of the $E_{||}$ mode causes an overall dimming of the total intensity

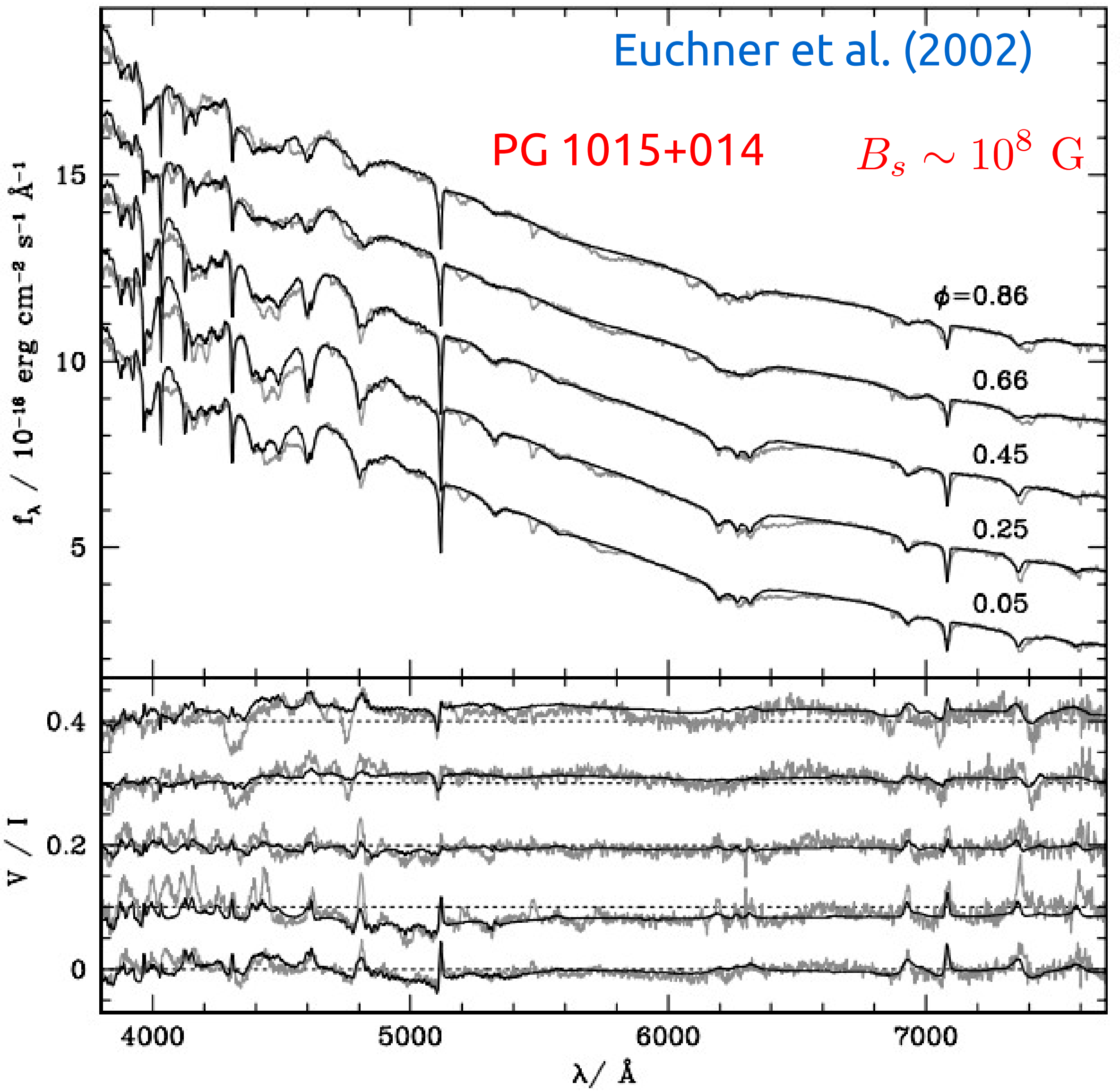


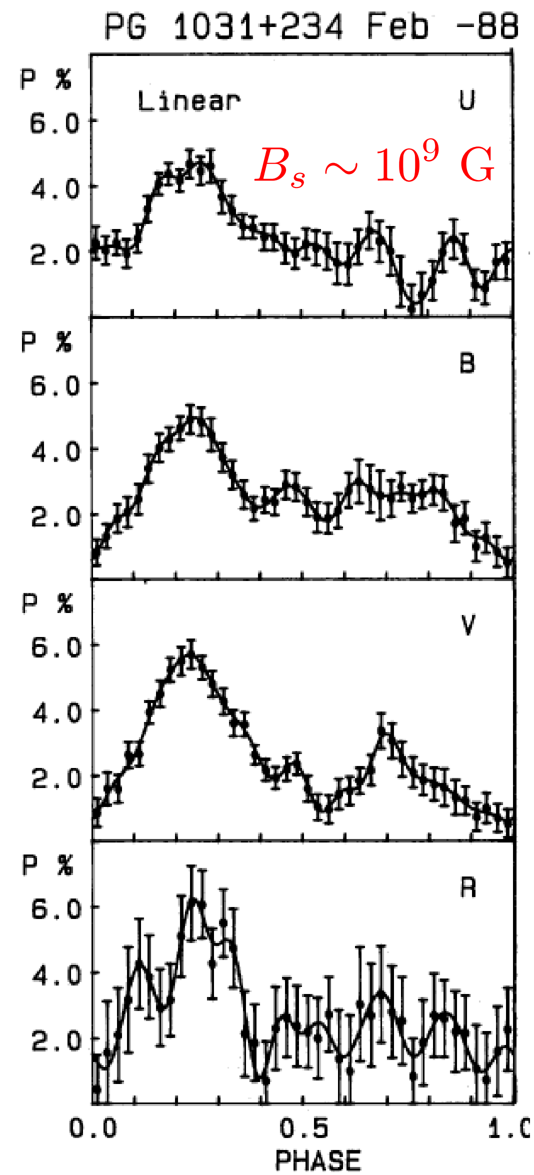
Signature of photon-ALP oscillation

The ALP-field acts as a dichroic filter and imparts additional linear polarization



What do observations of mWDs tell us?

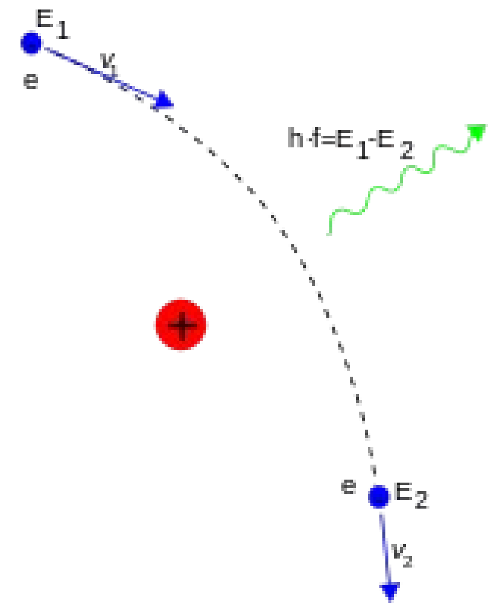


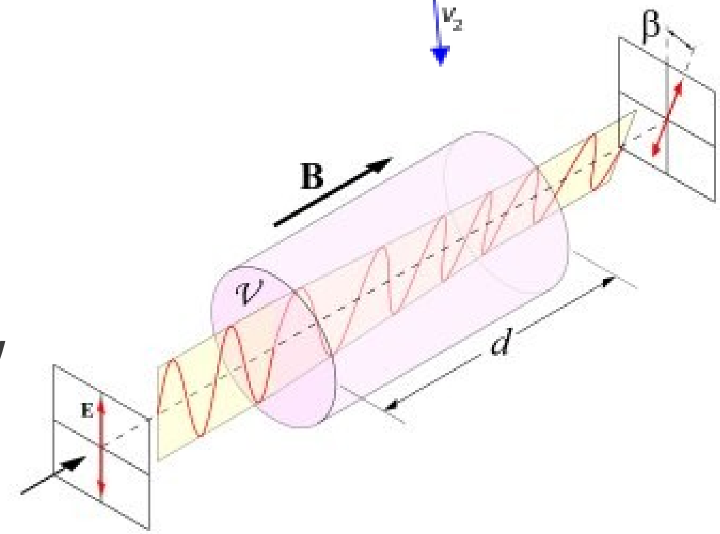


What do observations of mWDs tell us?

The emerging radiation is affected by:

- Magnetic Circular Dichroism – bound-free, magneto-bremsstrahlung, cyclotron abroption
- Birefringence – Voigt and Faraday effect
- Vacuum Birefringence
- Radiative transfer effects – atomic and molecular absorption edges





Typically:

- the optical and UV radiation is highly circularly polarized
- $P_L \sim 5\%$ due to Faraday rotation

ALP-photon mode coupling

Atmospheric plasma profile

Cold electron-proton plasma

$$\rho(r) = \rho_0 \exp\left(-\frac{r - R_\star}{H_\rho}\right) + \rho_\infty$$

$$H_\rho = \frac{2k_B T}{m_e g_\star} \simeq 1.65 \times 10^4 \text{ cm} \qquad \rho_0 \sim 10^{-10} \text{ g cm}^{-3} \qquad \rho_\infty \sim 10^{-20} \text{ g cm}^{-3}$$

$$T \sim 10^4 \text{ K} \qquad \log(g)(\text{cm s}^{-2}) \simeq 8$$

ALP-photon mode coupling

Atmospheric plasma profile

Cold electron-proton plasma

$$\rho(r) = \rho_0 \exp\left(-\frac{r - R_\star}{H_\rho}\right) + \rho_\infty$$

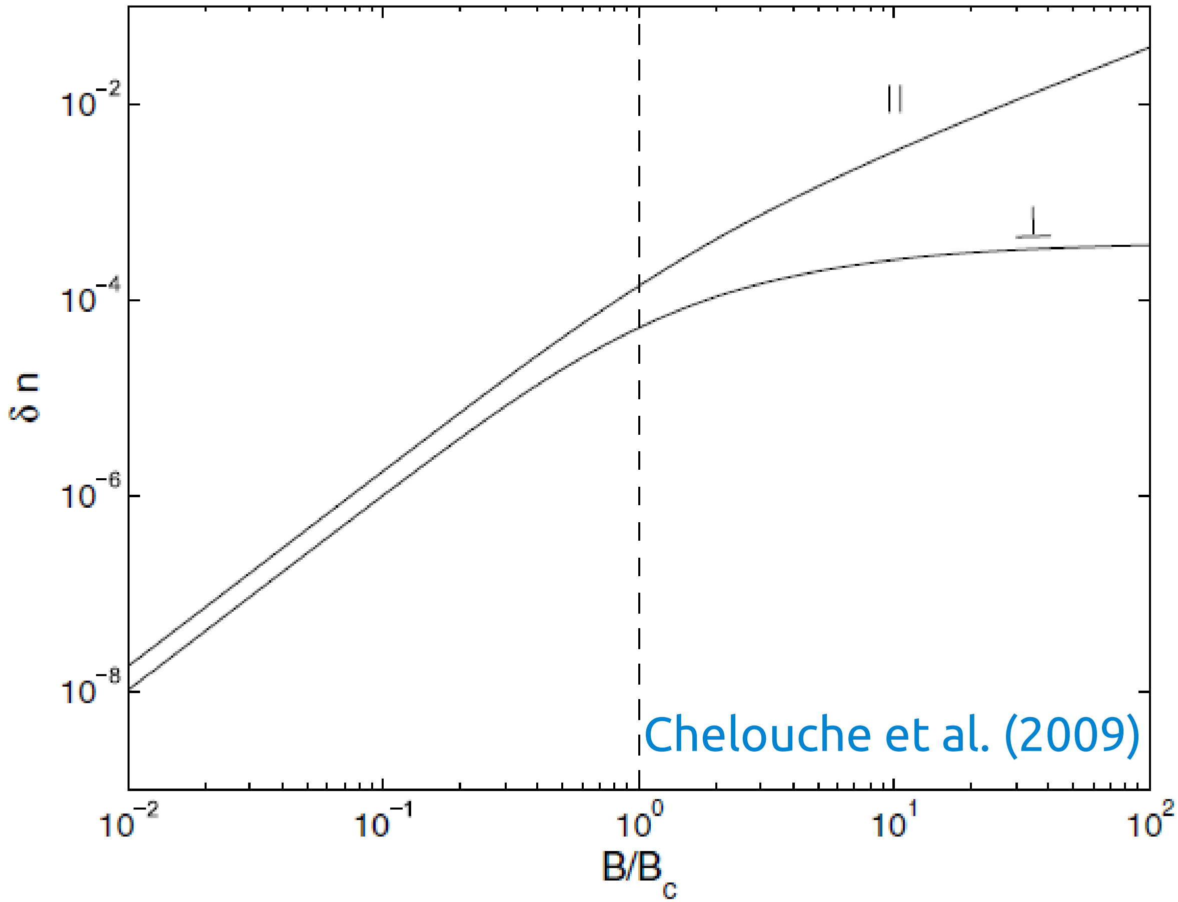
$$H_\rho = \frac{2k_B T}{m_e g_\star} \simeq 1.65 \times 10^4 \text{ cm} \qquad \rho_0 \sim 10^{-10} \text{ g cm}^{-3} \qquad \rho_\infty \sim 10^{-20} \text{ g cm}^{-3}$$

$$T \sim 10^4 \text{ K} \qquad \log(g)(\text{cm s}^{-2}) \simeq 8$$

$$\mathfrak{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

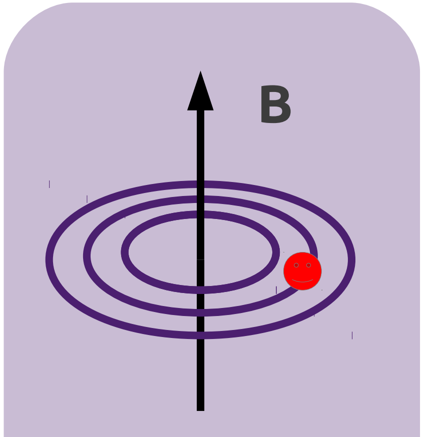
$$+\frac{\alpha^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$

Vacuum corrections



$$\delta n_{\perp} \simeq \frac{4}{2} \frac{\alpha}{45\pi} \left(\frac{B}{B_c} \right)^2 \qquad \delta n_{\parallel} \simeq \frac{7}{2} \frac{\alpha}{45\pi} \left(\frac{B}{B_c} \right)^2$$

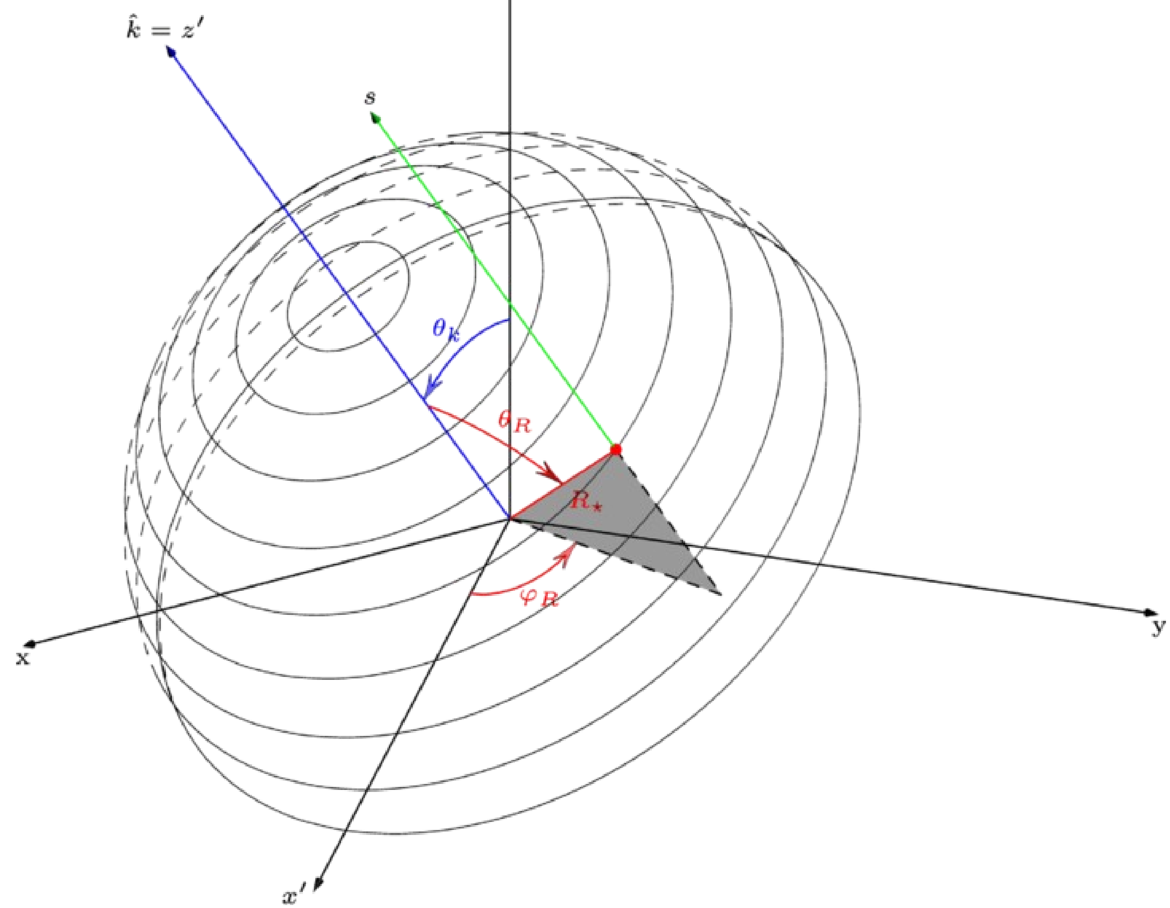
$$B_c = 4.414 \times 10^{13} \text{ G}$$



$$\hbar\omega_c = m_e c^2$$

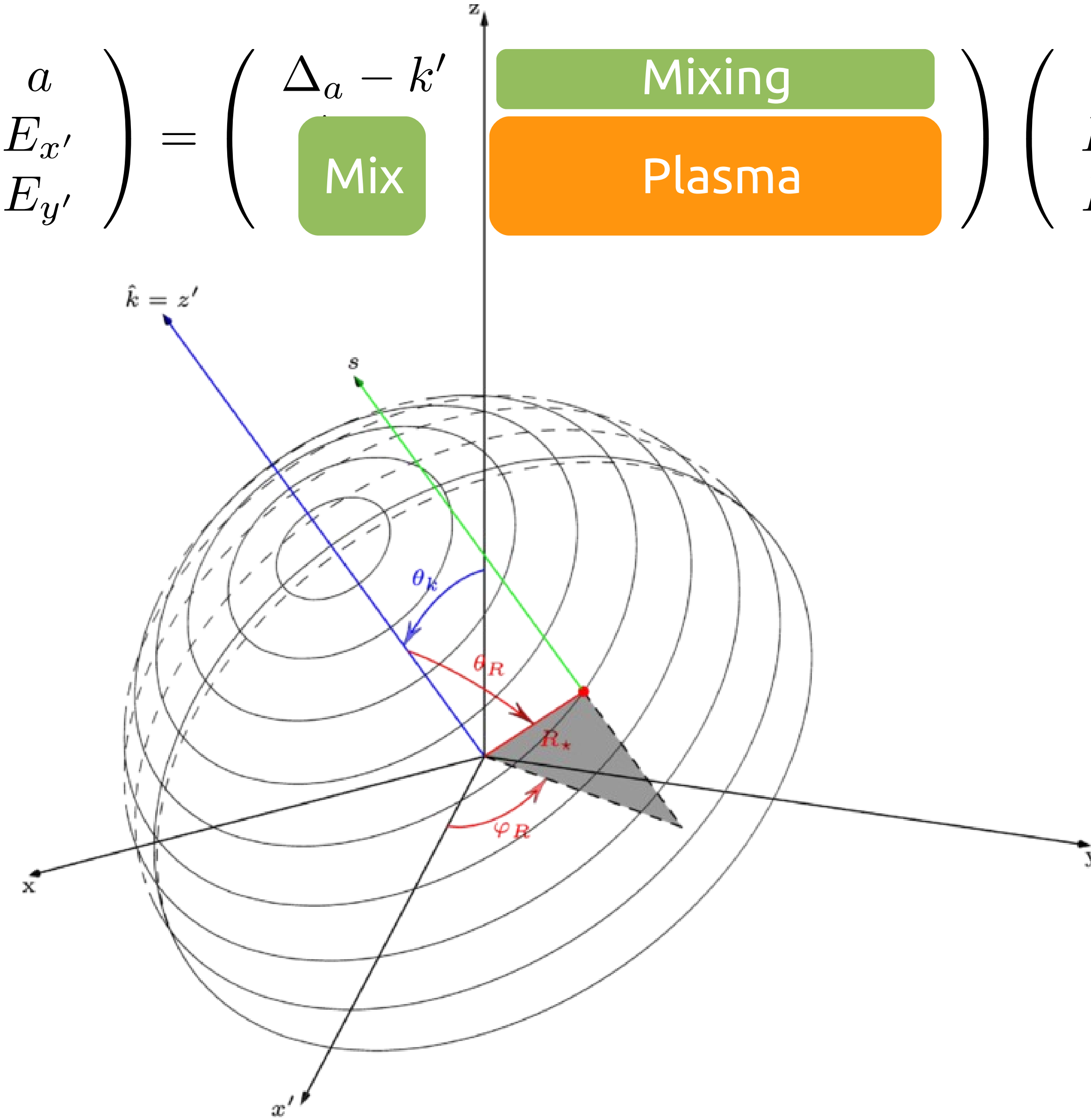
ALP-photon mode coupling

$$i\frac{d}{ds}\begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix} = \begin{pmatrix} \Delta_a - k' & \Delta_{Mx'} & \Delta_{My'} \\ \Delta_{Mx'} & i\chi'_{11} - k' & i\chi'_{12} \\ \Delta_{My'} & i\chi'_{21} & i\chi'_{22} - k' \end{pmatrix}\begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix}$$



ALP-photon mode coupling

$$i\frac{d}{ds}\begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix} = \begin{pmatrix} \Delta_a - k' & \text{Mixing} \\ \text{Mix} & \text{Plasma} \end{pmatrix} \begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix}$$



ALP-photon mode coupling

$$i\frac{d}{ds}\begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix} = \begin{pmatrix} \Delta_a - k' & \text{Mixing} \\ \text{Mix} & \text{Plasma} \end{pmatrix} \begin{pmatrix} a \\ E_{x'} \\ E_{y'} \end{pmatrix}$$

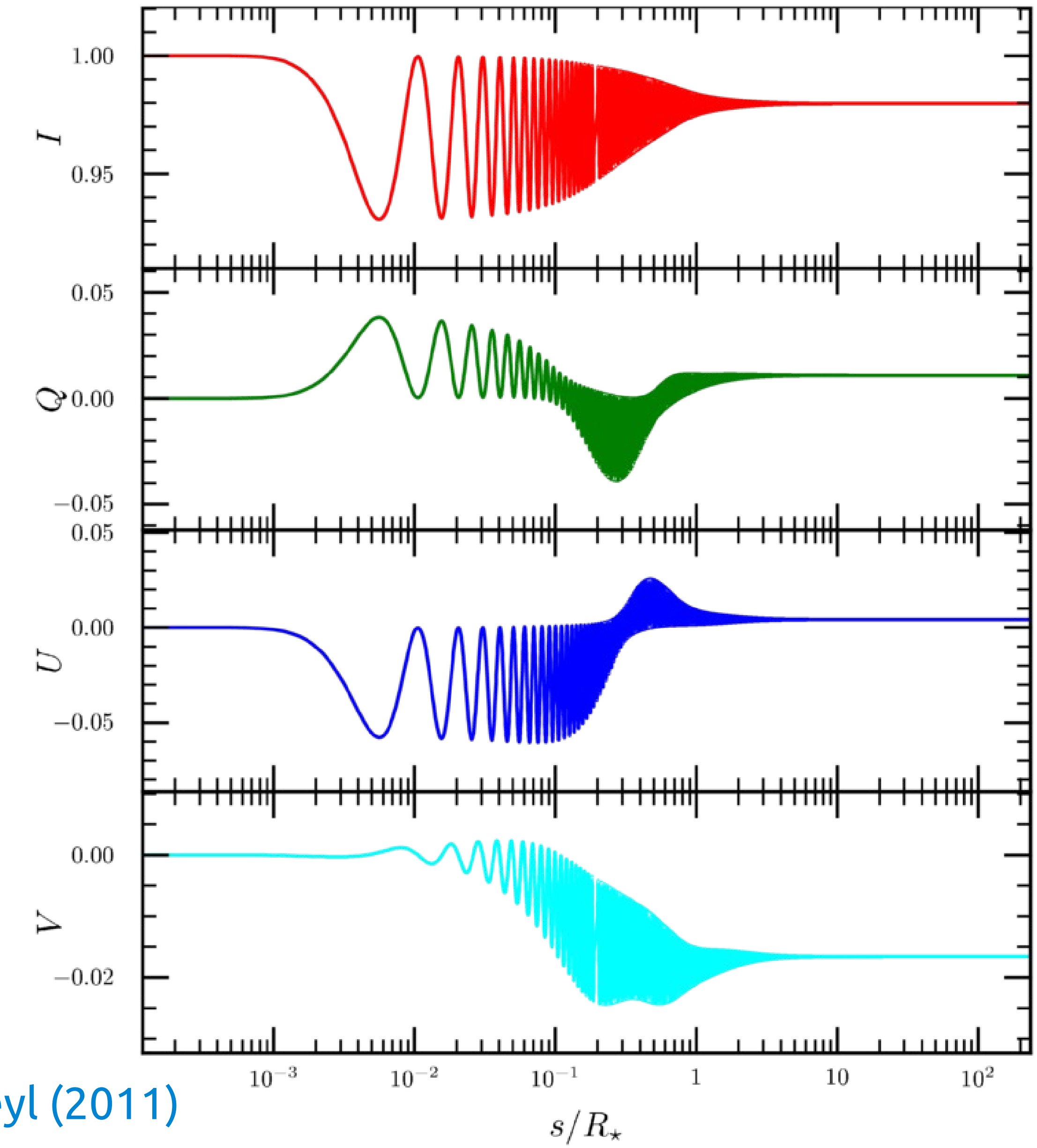
Stokes Vector

$$\begin{aligned} I &= \|E_{x'}\|^2 + \|E_{y'}\|^2 \\ Q &= \|E_{x'}\|^2 - \|E_{y'}\|^2 \\ U &= E_{x'}E^*_{y'} + E_{y'}E^*_{x'} \\ V &= -i(E_{x'}E^*_{y'} - E_{y'}E^*_{x'}) \end{aligned}$$

Stokes parameters

$$P_L = \frac{\sqrt{\langle Q \rangle^2 + \langle U \rangle^2}}{\langle I \rangle}$$

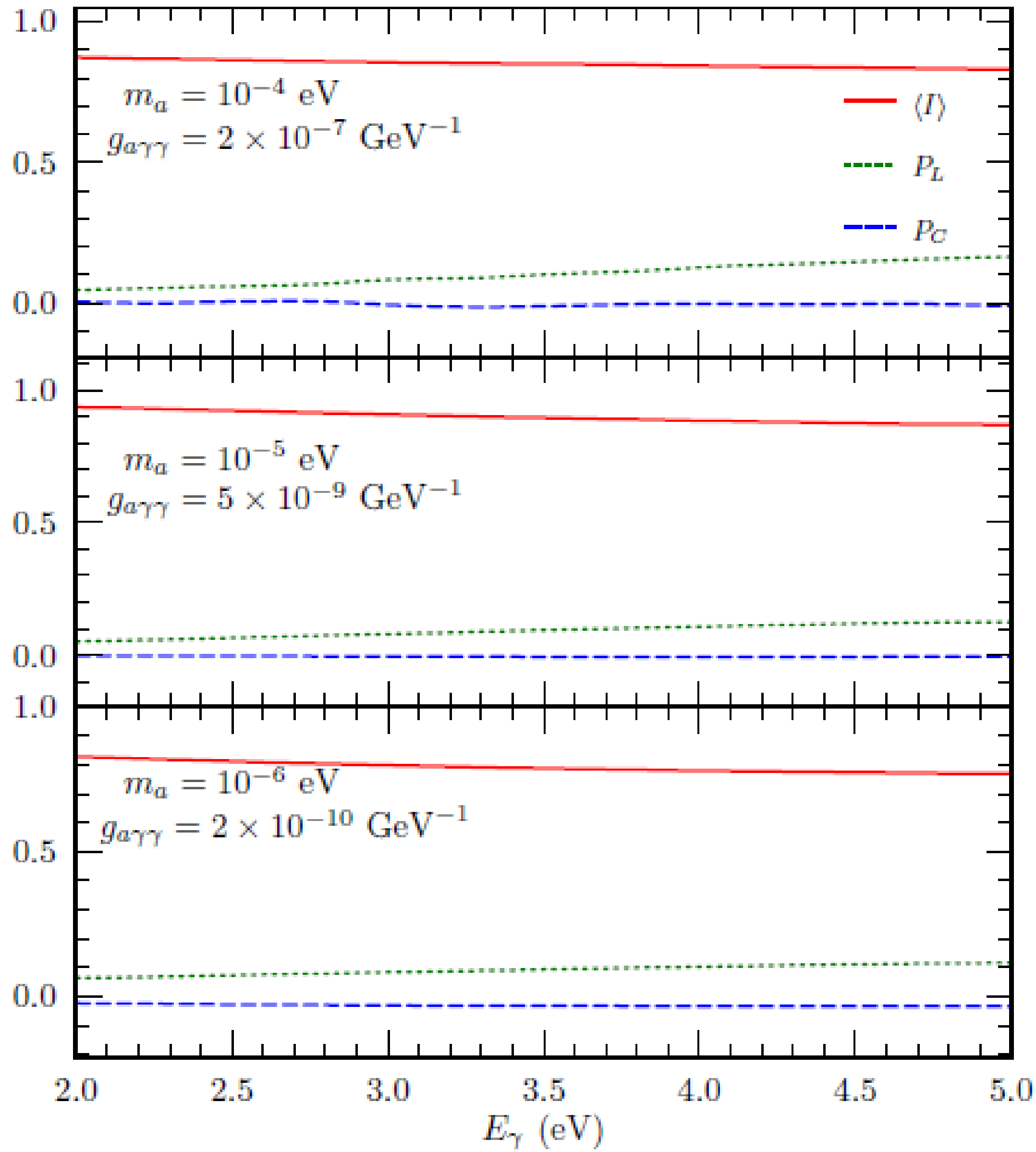
$$P_C = \frac{\langle V \rangle}{\langle I \rangle}$$



Gill & Heyl (2011)

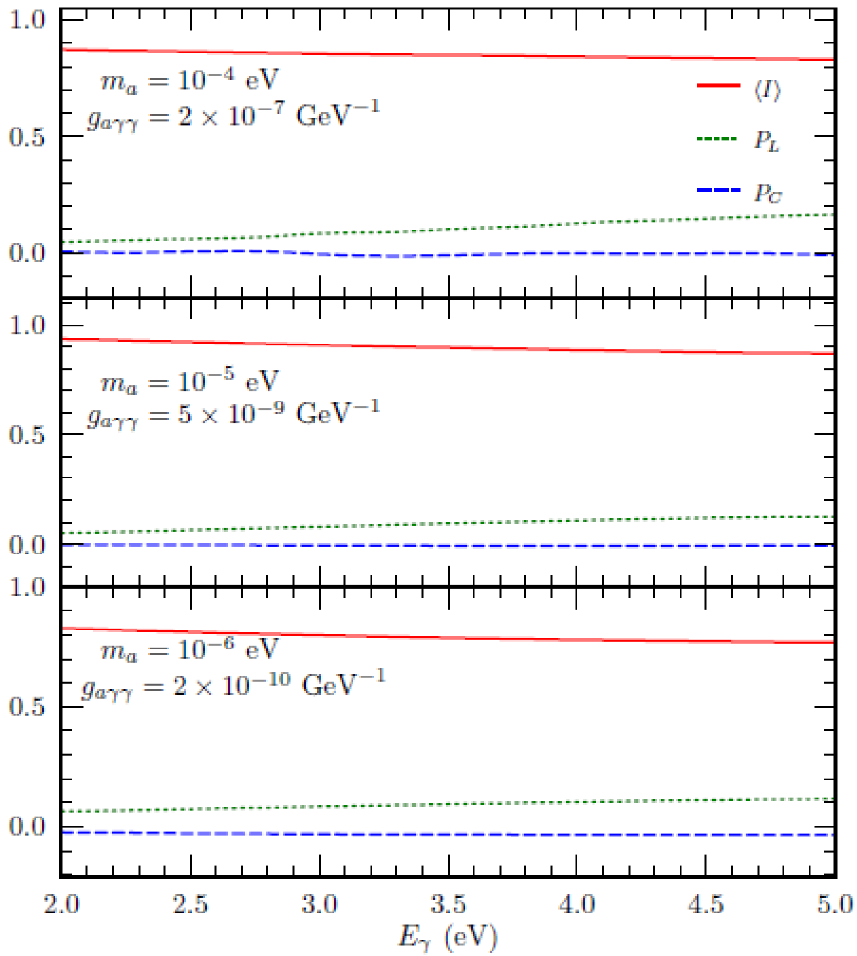
Constraints on ALP properties

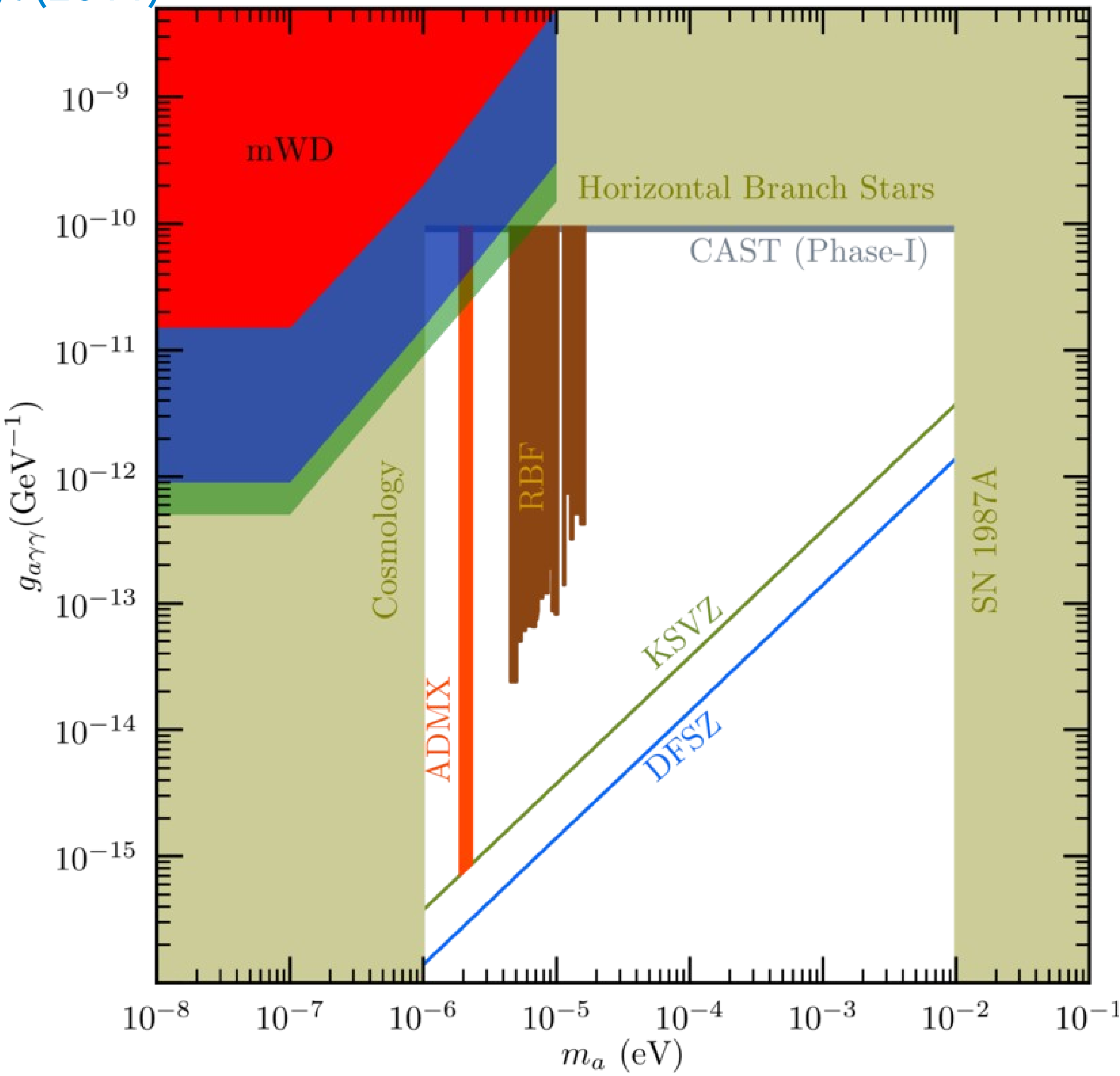
Gill & Heyl (2011)



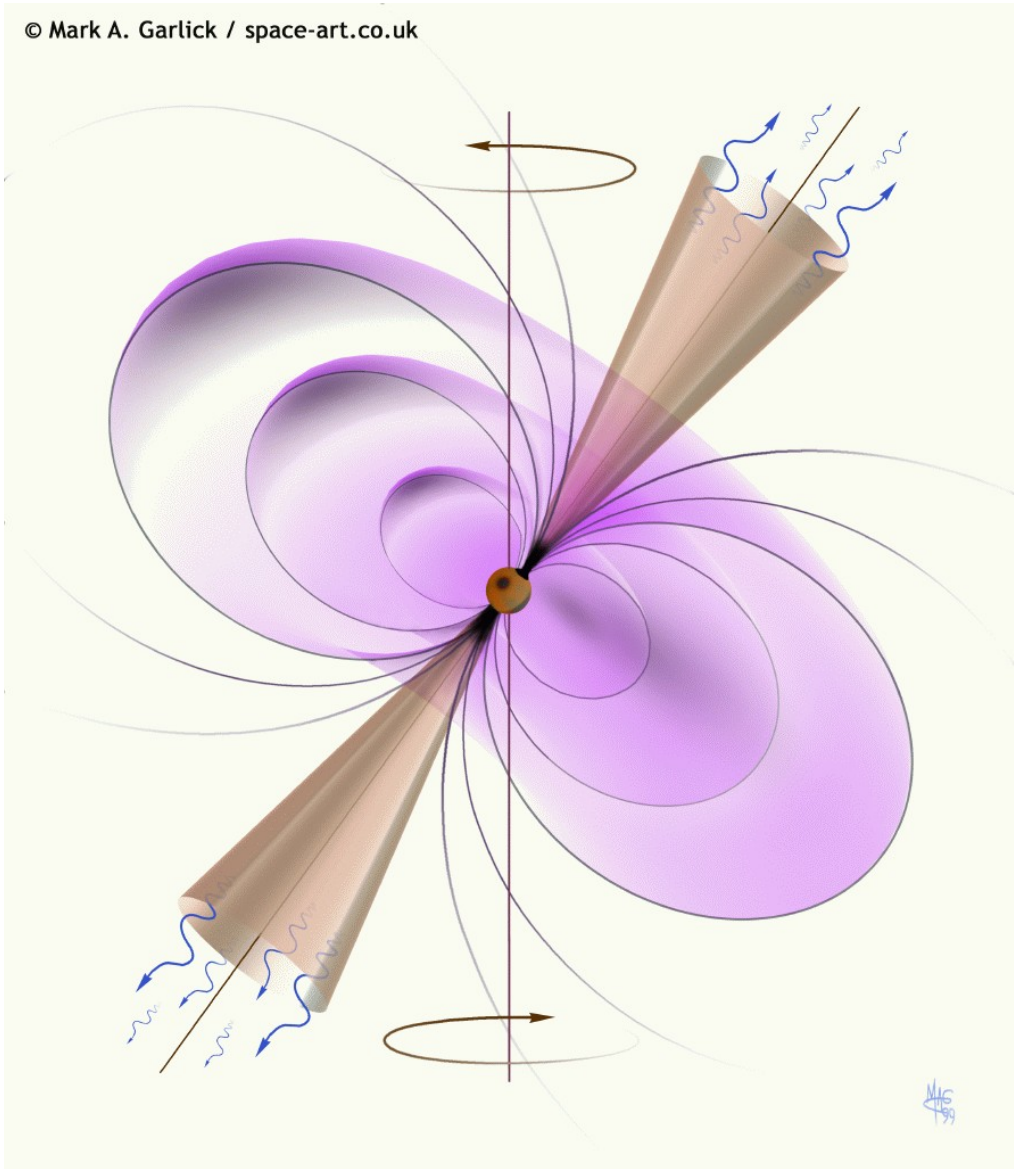
Constraints on ALP properties

Gill & Heyl (2011)

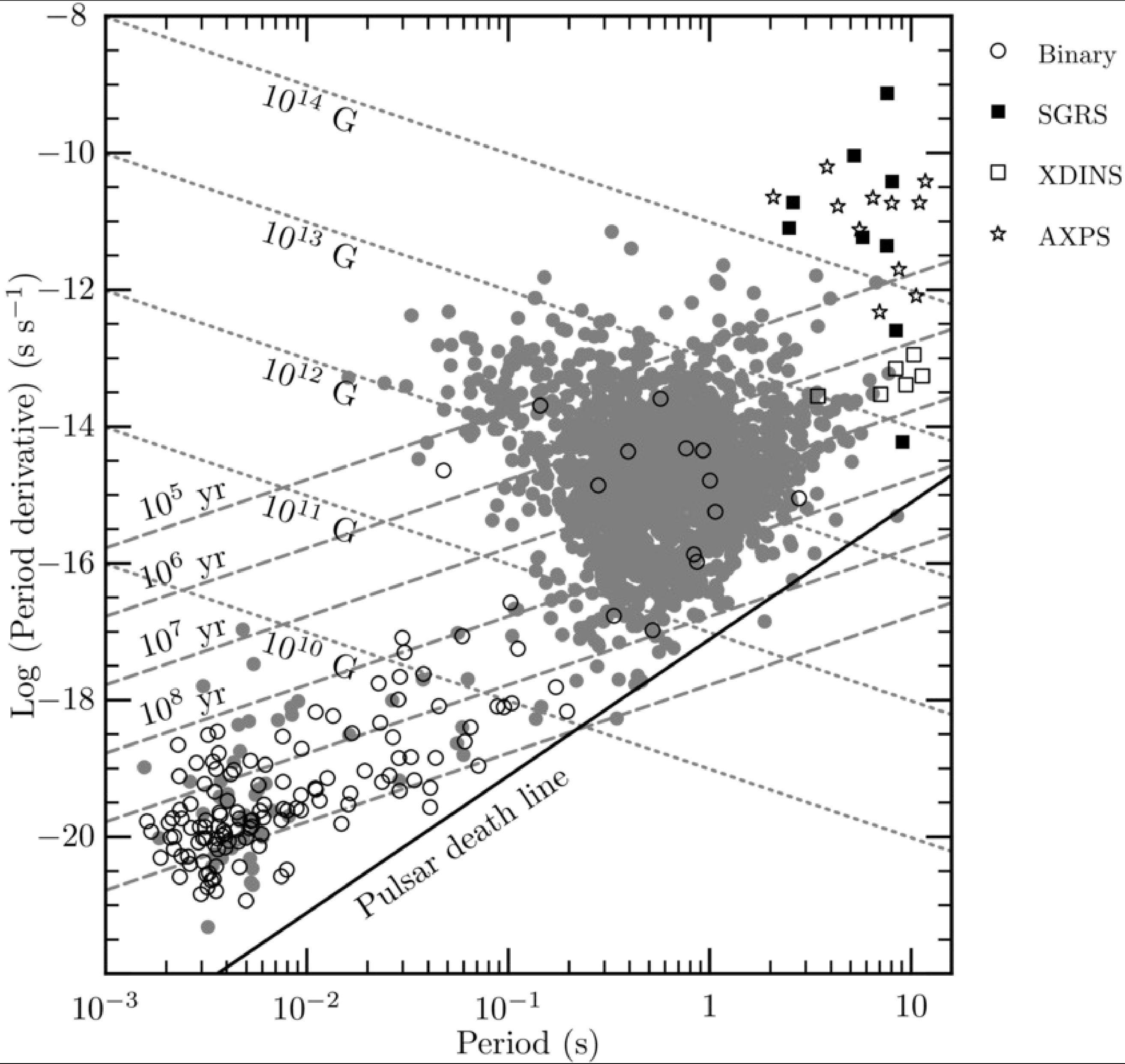




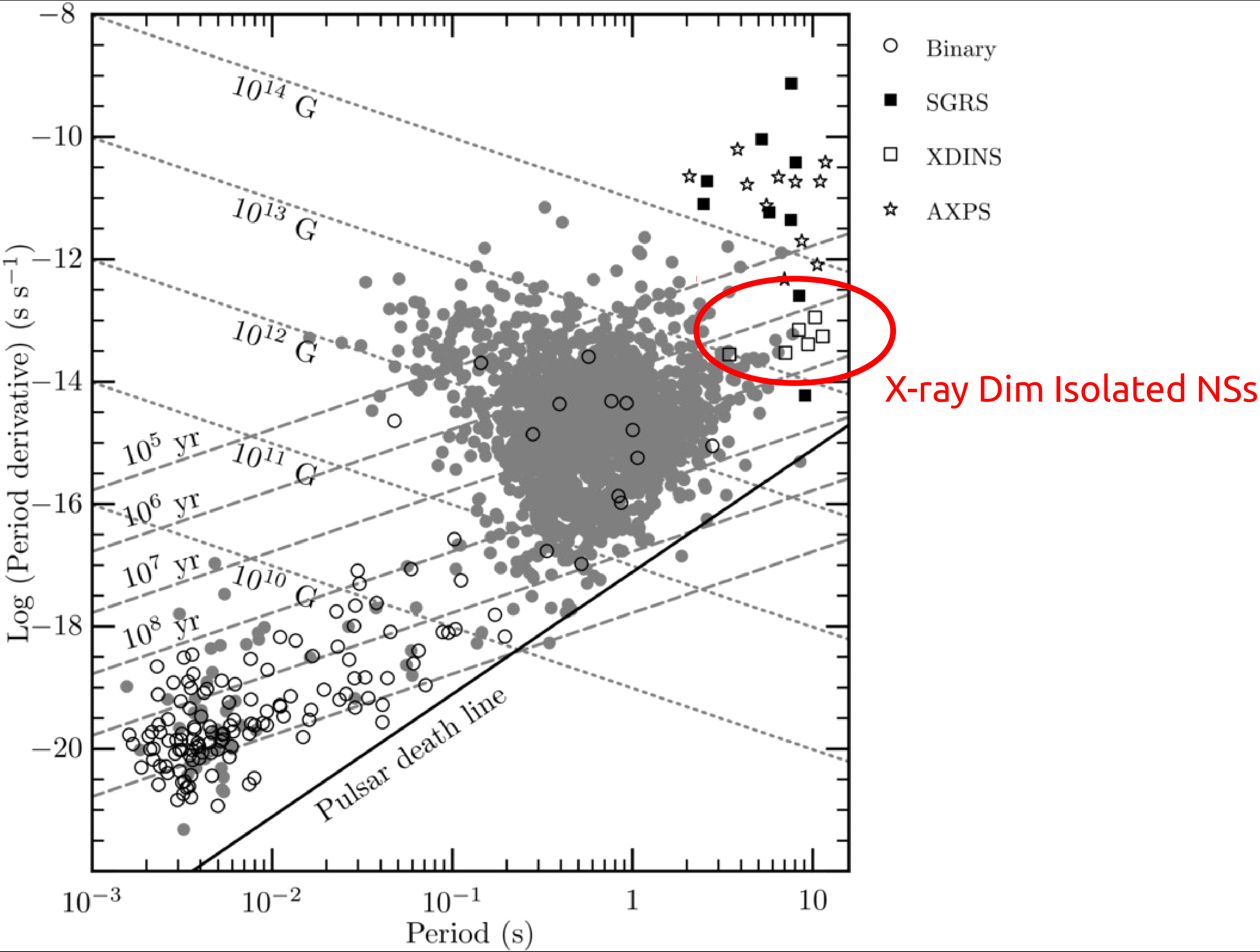
ALP physics with NSs



P-Pdot diagram of NSs

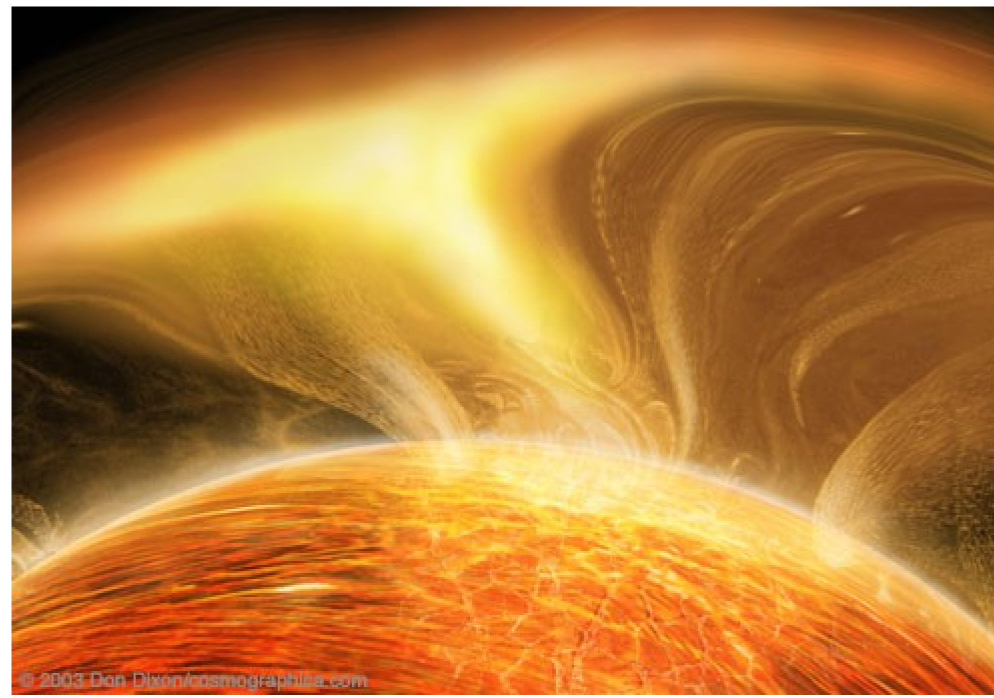


P-Pdot diagram of NSs



ALP physics with NSs

- Extremely strong fields: $B \gtrsim 10^{12}\ \mathrm{G}$
- Effective temperature: $T_s \sim 0.5\ \mathrm{keV}$
- Want to look at the thermal spectrum
- Vacuum polarization becomes important!
- Need to consider relativistic plasma effects, and radiative transfer effects, also gravitational effects.
- Atmospheric models are available.




GEMS
Gravity and Extreme Magnetism SMEX
Opening the Frontier of X-ray Polarization to Probe the Mysteries of the Universe

GEMS


GEMS
Gravity and Extreme
Magnetism SMEX
Opening the Frontier
of X-ray Polarization
to Probe the Mysteries
of the Universe

Summary

- MWDs can be employed to put strong constraints on the properties of ALPs.
- These constraints can possibly be improved by simulating the effects of the atmosphere in greater detail.
- Can also study other particles that are similar in their production mechanisms to ALPs, such as Chameleons, etc.
  (See Konstantin Zioutas talk)
- Polarization studies of strongly magnetized NSs can help to constrain ALP properties even further.