# Polarized light from Magnetars: QED effects and Axion(like) particles

L. Capparelli, L. Maiani and ADP

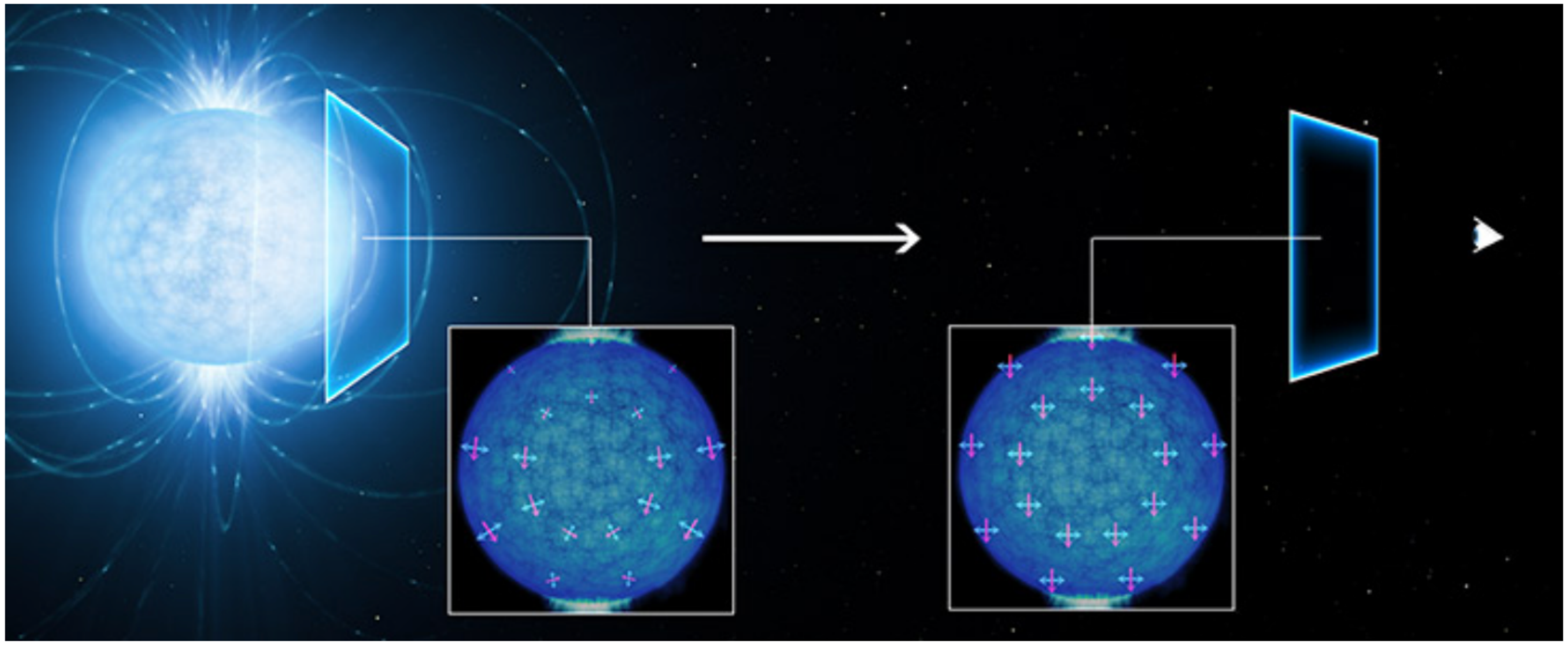
(in preparation)

# ESO Press Release Nov 2016

## First Signs of Weird Quantum Property of Empty Space?

### VLT observations of neutron star may confirm 80-year-old prediction about the vacuum

30 November 2016



**By studying the light emitted from an extraordinarily dense and strongly magnetised neutron star using ESO's Very Large Telescope, astronomers may have found the first observational indications of a strange quantum effect, first predicted in the 1930s. The polarisation of the observed light suggests that the empty space around the neutron star is subject to a quantum effect known as vacuum birefringence.**

Also reported from the Royal Astronomical Society, INFN etc.

# ABOUT RX J1865.5-3754

- MAGNETAR IN THE CONSTELLATION OF CORONA AUSTRALIS AT $\approx$ 400 LY. BELONGS TO THE M7 GROUP OF STARS DISCOVERED IN SOFT-X RAYS

- FROM X RAY SPECTRA

$$B \approx 10^{13} \div 10^{14}\, G$$

IS EXPECTED

- STAR SURFACE AT

$$T \approx 10^{6}\, K$$

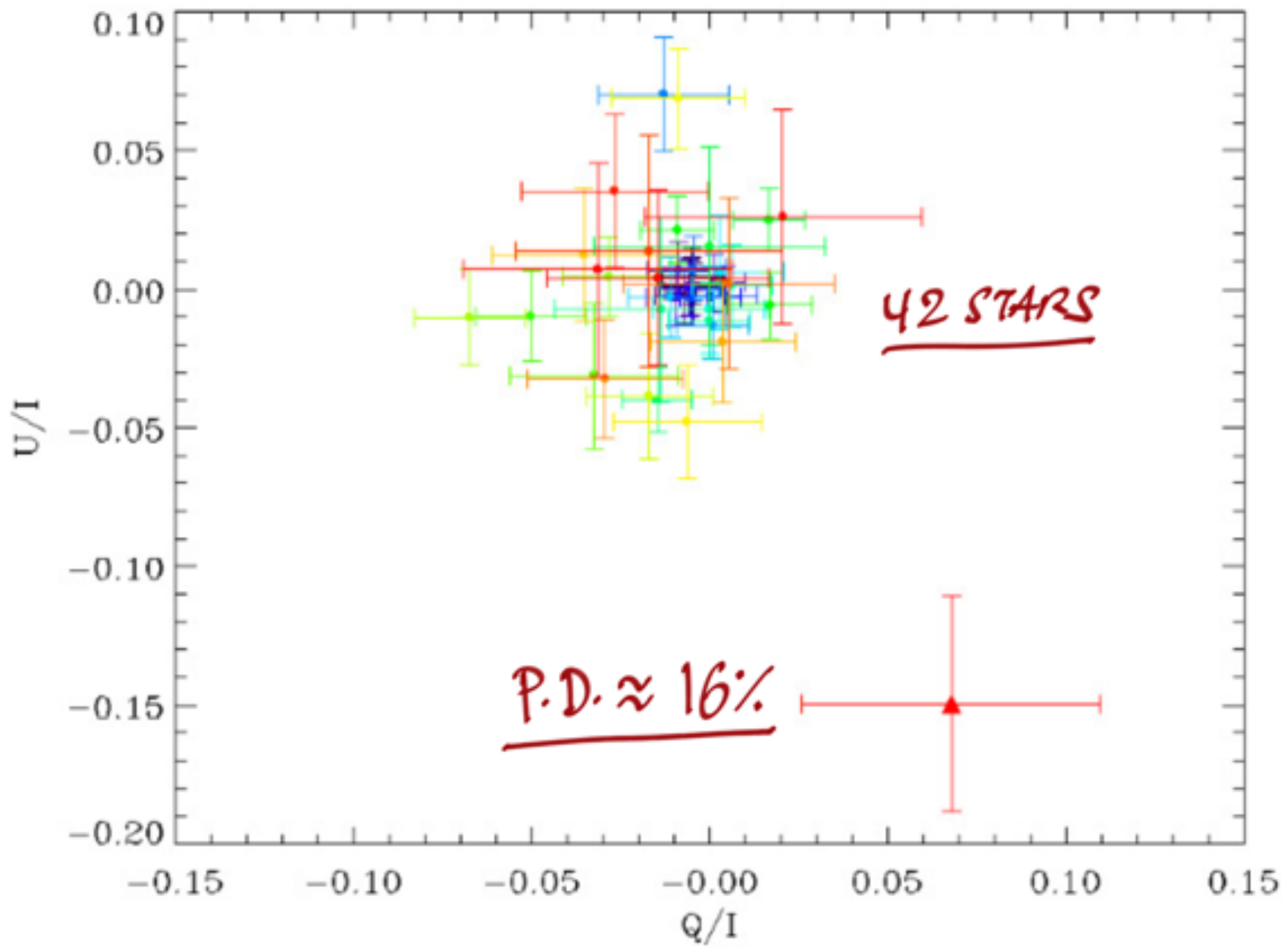
WITH AN ALMOST PERFECT B.B. SPECTRUM

- RADIATION IS EXPECTED TO BE LINEARLY POLARIZED ON THE STAR SURFACE $(R \approx 10\, km)$ WHERE THE $\vec{B}$ CHANGES SUBSTANTIALLY FROM POINT TO POINT

$\longrightarrow$ DRASTIC DEPOLARIZATION EFFECTS IN THE LIGHT COLLECTED AT $\infty$.

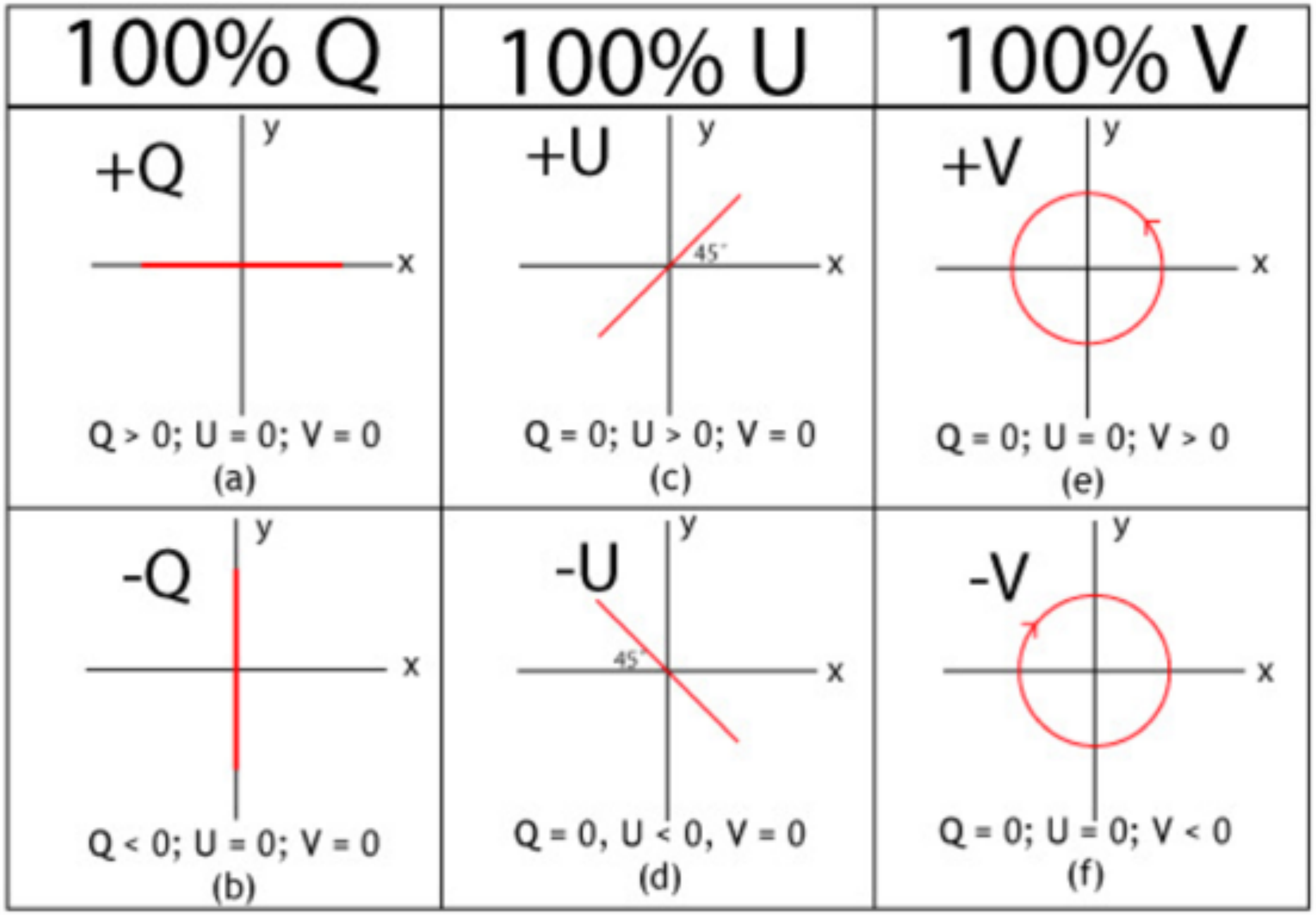
# LIGHT POLARIZATION FROM RX J1865.5−3754

MIGNANI ET AL. 1610.08323




$$
\begin{aligned}
I &= \langle E_x^2 \rangle + \langle E_y^2 \rangle \\
&= \langle E_a^2 \rangle + \langle E_b^2 \rangle \\
&= \langle E_\ell^2 \rangle + \langle E_r^2 \rangle
\end{aligned}
$$

# STOKES PARAMETERS




$$Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle$$

$$U = \langle E_a^2 \rangle - \langle E_b^2 \rangle$$

$$V = \langle E_l^2 \rangle - \langle E_r^2 \rangle$$

$(\hat{a}, \hat{b})$ rotated by 45° wrt $(\hat{x}, \hat{y})$

$$l = \frac{\hat{x} + i\hat{y}}{\sqrt{2}}$$

# CONCLUSIONS FROM MIGNANI & AL

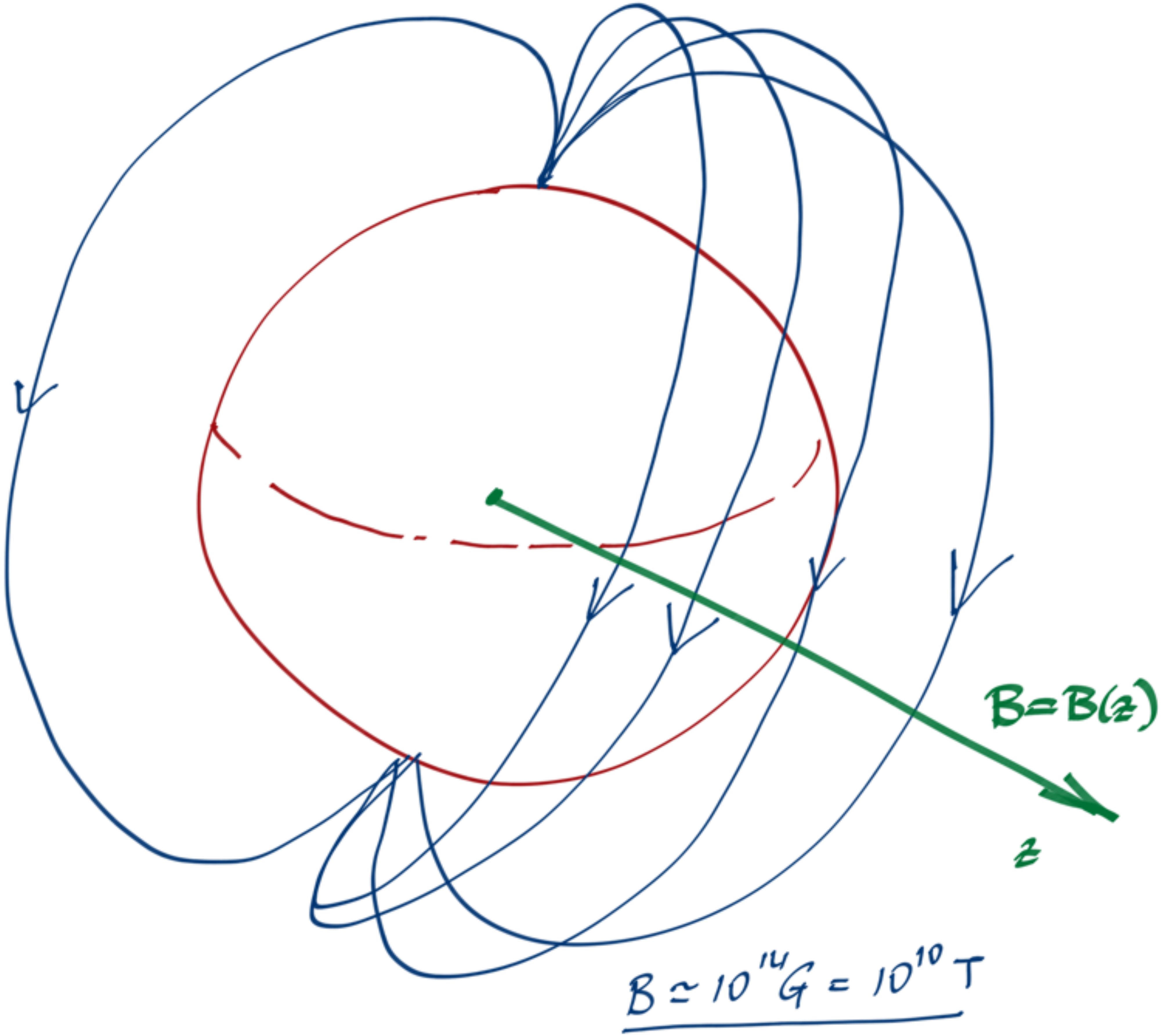
- THE MEASURED VALUE OF P.D. IS NEVER REPRODUCED BY MODELS WITH NO QED BIREFRINGENCE.

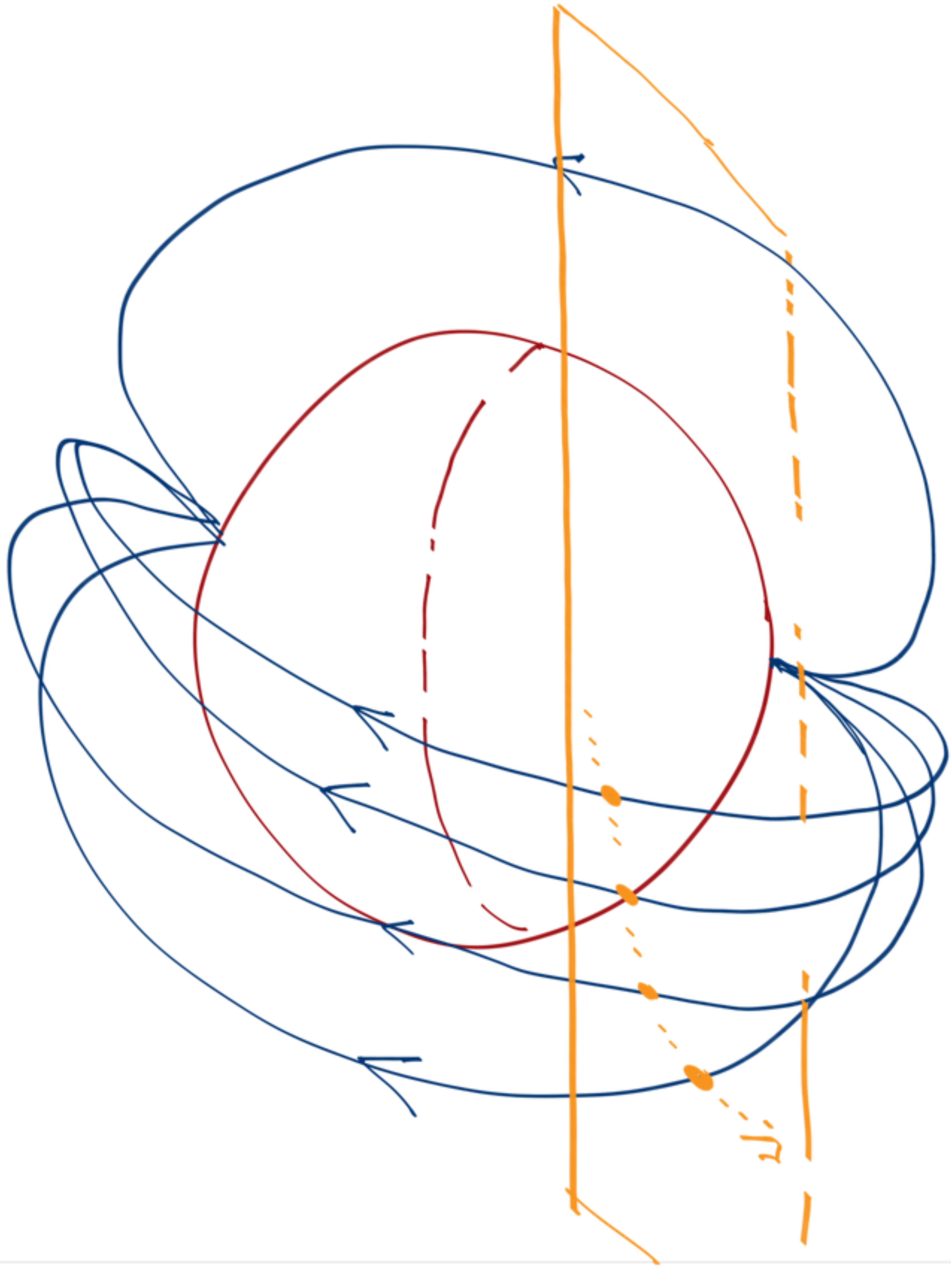
THE HIGHEST ATTAINABLE P.D. (NO QED) REQUIRES A PARTICULAR GEOMETRY

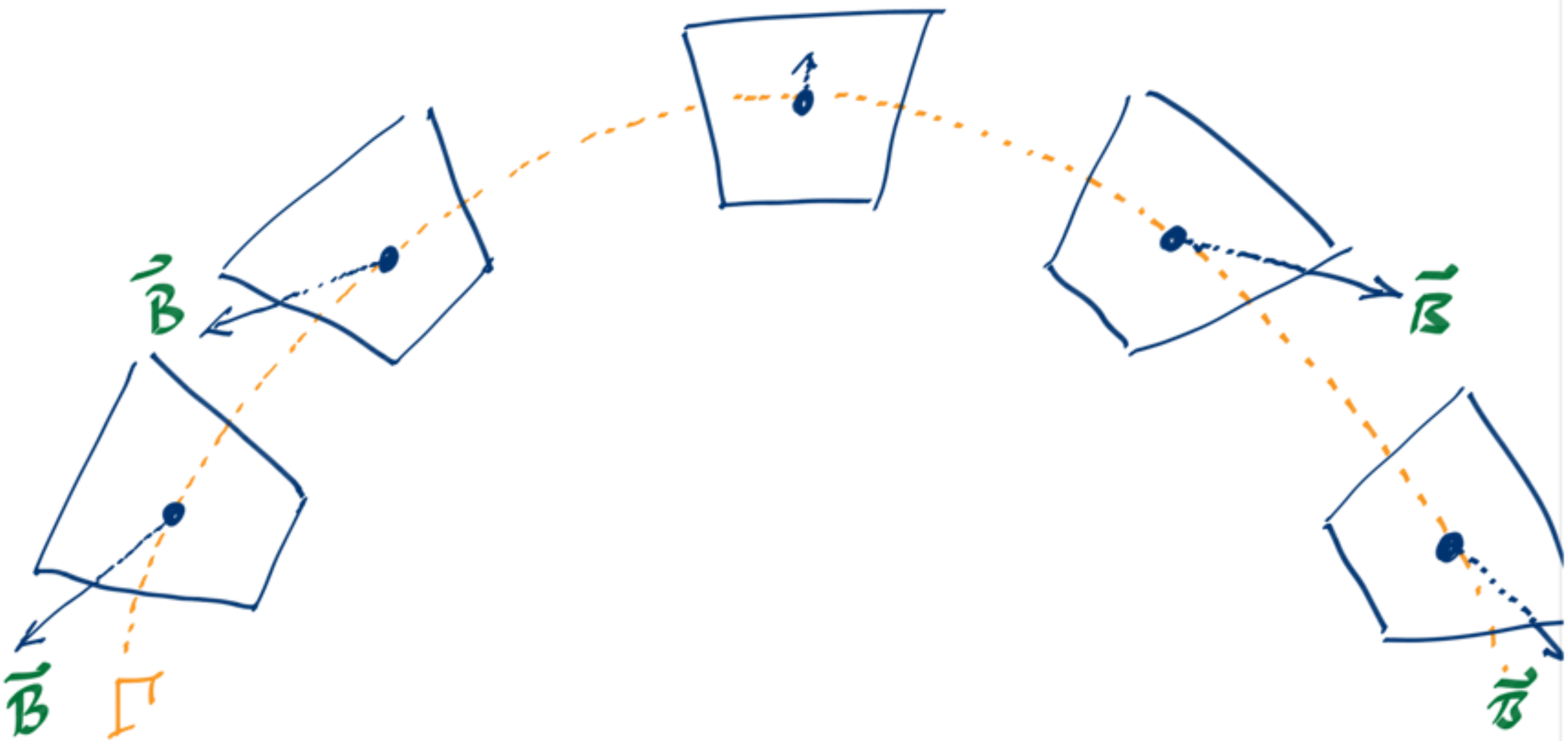

"VERY FIRST OBSERVATIONAL SUPPORT FOR QED VACUUM EFFECTS"

— Next steps —

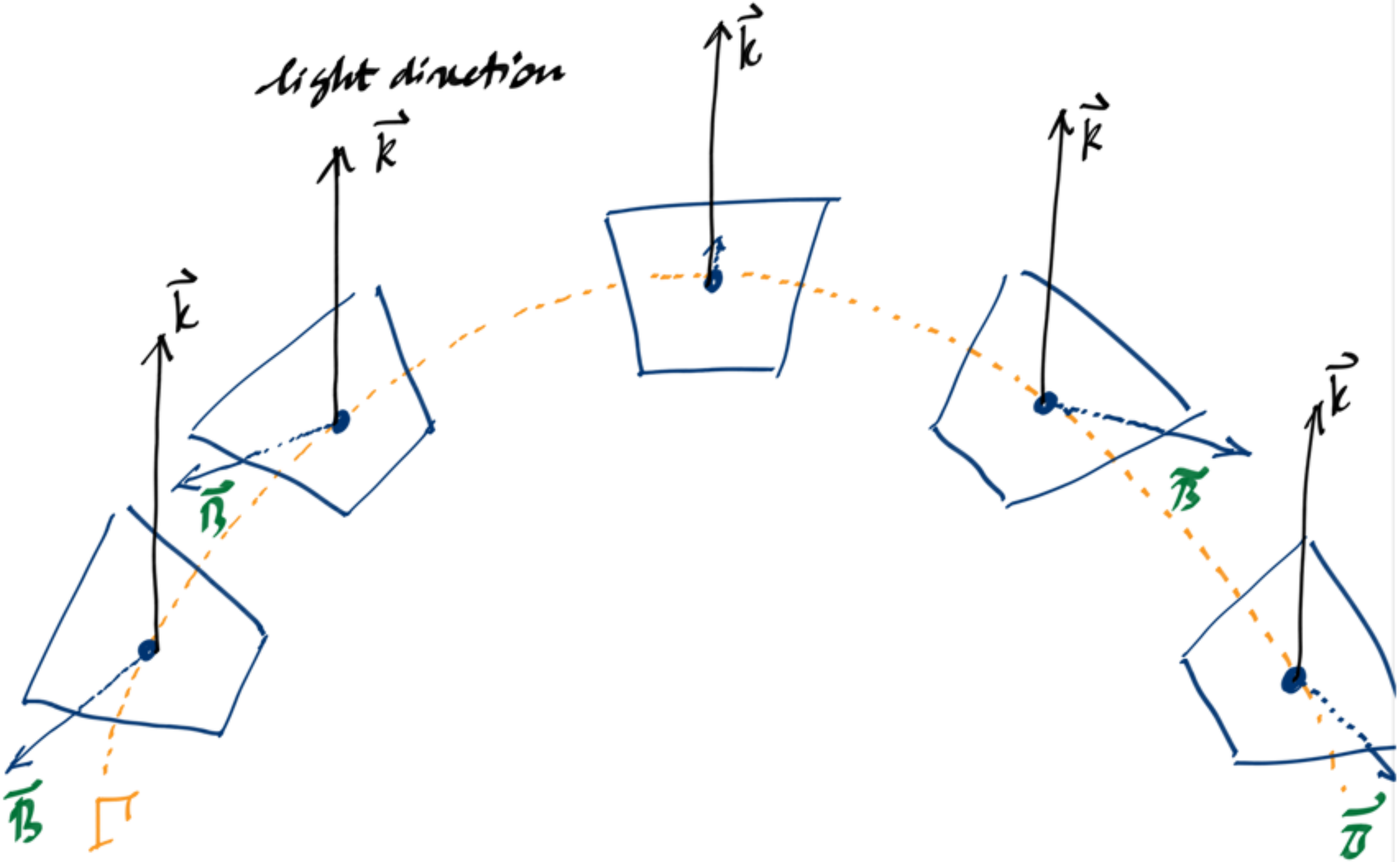
- FOLLOW UP IN ~JUNE ON RXJ...
- STUDY OTHER STARS IN M7 (fainter)
- POLARIMETRY AT NEXT GENERATION OF TELESCOPES (THE 30÷40m CLASS LIKE THE E.E.L.T.).

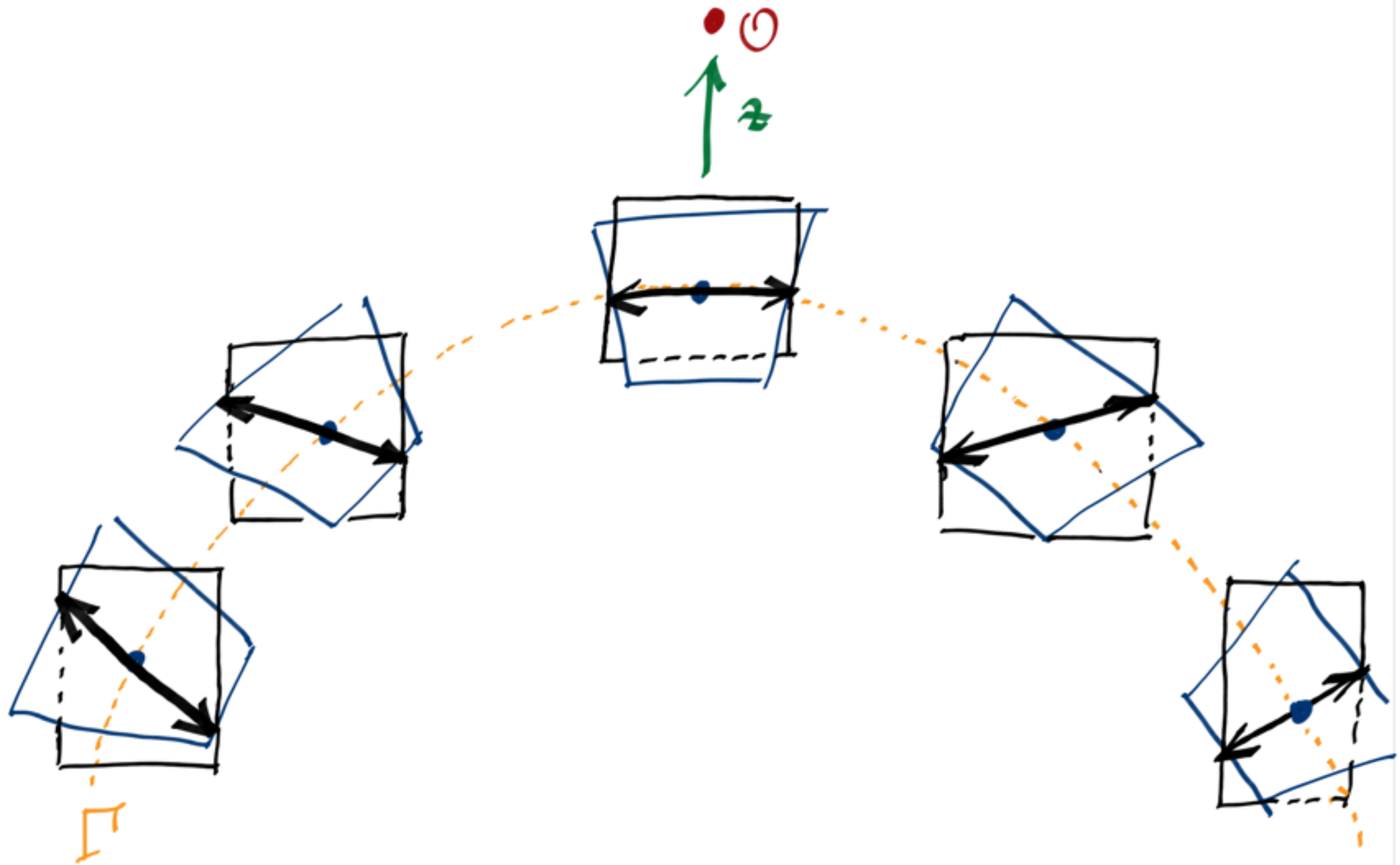

$B = B(z)$
$z$
$B \simeq 10^{14}\,G = 10^{10}\,T$






PLANES $\perp$ TO $\vec{B}$ AT $\sim$ THE STAR RADIUS.


light direction
$\vec{k}$
$\vec{k}$
$\vec{k}$
$\vec{k}$
$\vec{k}$
$\vec{B}$
$\vec{B}$
$\vec{B}$
$\vec{B}$


O
z

# QED BIREFRINGENCE

$$\mathcal{L} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) + \frac{2\alpha^2}{45 m^4}\left[\left(\vec{E}^2 - \vec{B}^2\right)^2 + 7\left(\vec{E}\cdot\vec{B}\right)^2\right]$$

$$D_i = \frac{\partial \mathcal{L}}{\partial E_i} \qquad H_i = -\frac{\partial \mathcal{L}}{\partial B_i}$$

$$D_i \equiv \epsilon_{ij} E_j$$

$$B_i \equiv \mu_{ij} H_j$$

$$\epsilon = (1+a)\mathbb{1} + q\,\hat{B}\hat{B}$$

$$\mu^{-1} = (1+a)\mathbb{1} + m\,\hat{B}\hat{B}$$

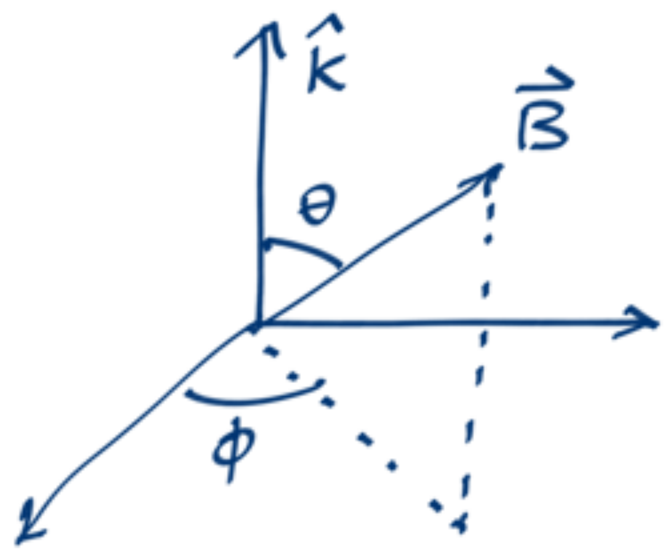
$$\begin{cases} a = -2\delta \qquad q = 7\delta \qquad m = -4\delta \\ \delta = \dfrac{\alpha}{45\pi}\left(\dfrac{B}{B_{QED}}\right)^2 \\ B^2_{QED} = \dfrac{m^2}{e} = 4.4\times 10^{13}\,G \end{cases}$$

# PROPAGATION OF WAVES

$$\left(\vec{\nabla}\times\vec{E}\right)_i = -\left(\frac{\partial\vec{B}}{\partial t}\right)_i = i\omega B_i = i\omega\mu_{ik}H_k$$

$$\left(\vec{\nabla}\times\vec{H}\right)_i = -\left(\frac{\partial\vec{D}}{\partial t}\right)_i = -i\omega D_i = -i\omega\epsilon_{ik}E_k$$

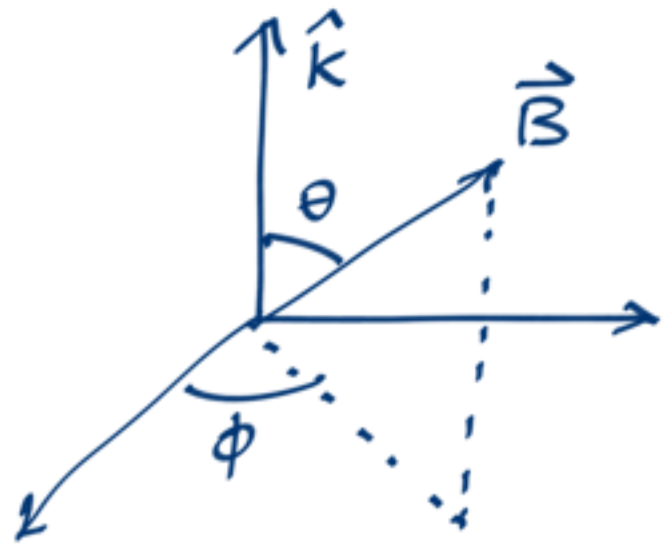
$$\vec{\nabla}\times\left(\underset{\sim}{\mu}\cdot\left(\vec{\nabla}\times\vec{E}\right)\right) = \omega^2\underset{\sim}{\epsilon}\cdot\vec{E}$$




$$\hat{B} = \hat{k}\cos\theta + \hat{x}(\sin\theta\cos\phi) + \hat{y}(\sin\theta\sin\phi)$$

# PROPAGATION OF WAVES

$$\vec{\nabla} \times \left( \underset{\sim}{\mu} \cdot \left( \vec{\nabla} \times \vec{E} \right) \right) = \omega^2 \underset{\sim}{\epsilon} \cdot \vec{E}$$




$$\frac{d}{dz}\begin{pmatrix} E_x \\ E_y \end{pmatrix} = i\,\frac{\omega}{2}\sin^2\theta \begin{pmatrix} q\cos^2\phi - m\sin^2\phi & \frac{q+m}{2}\sin 2\phi \\ \frac{q+m}{2}\sin 2\phi & q\sin^2\phi - m\cos^2\phi \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

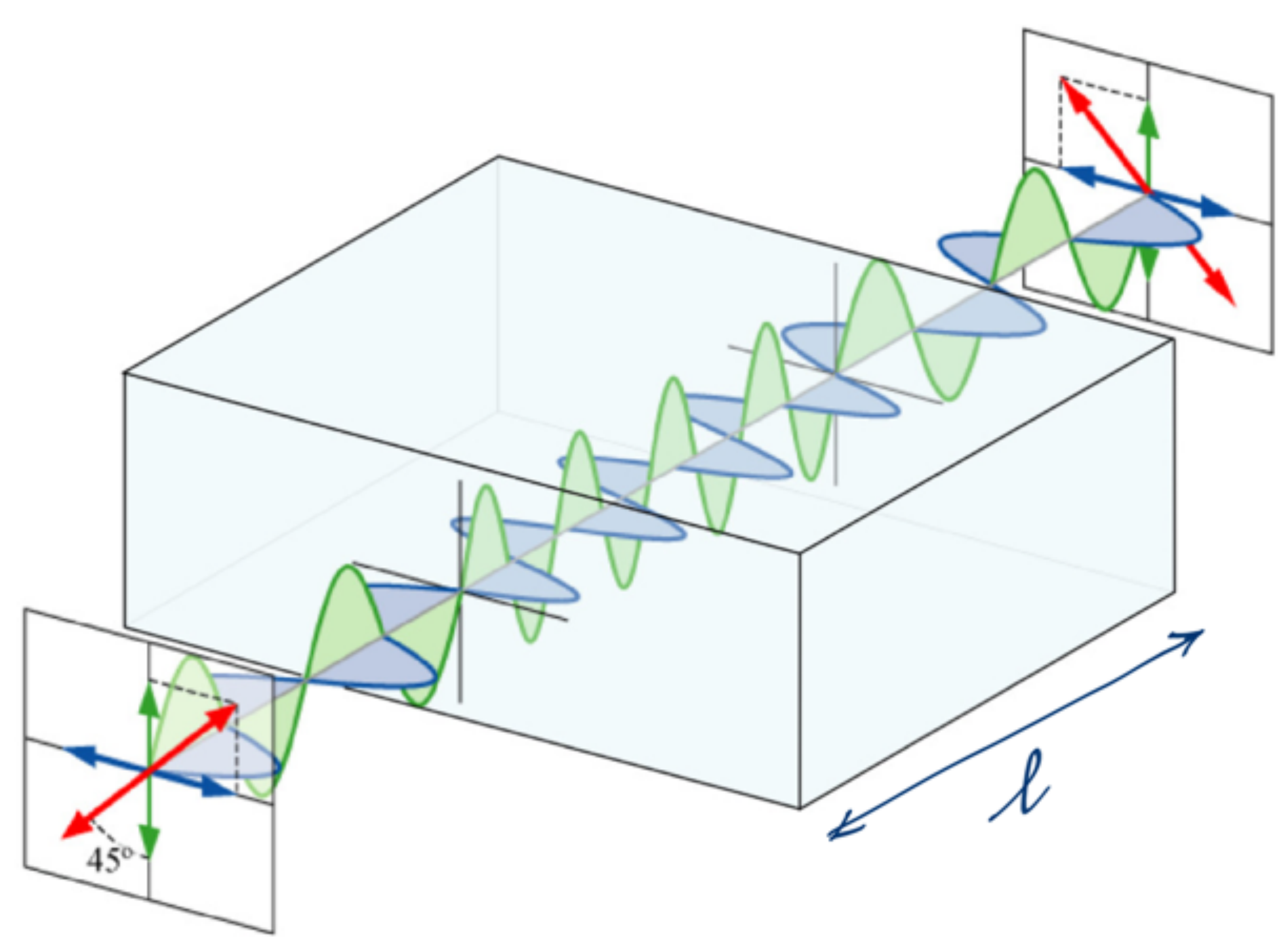
let $\phi = 0$, $\theta \simeq \pi/2$.

Then $E_y = E_\perp$, $E_x \simeq E_\parallel$.

Birefringence : $\Delta n \simeq (q+m)$

$\Delta n = 0$ in vacuum.

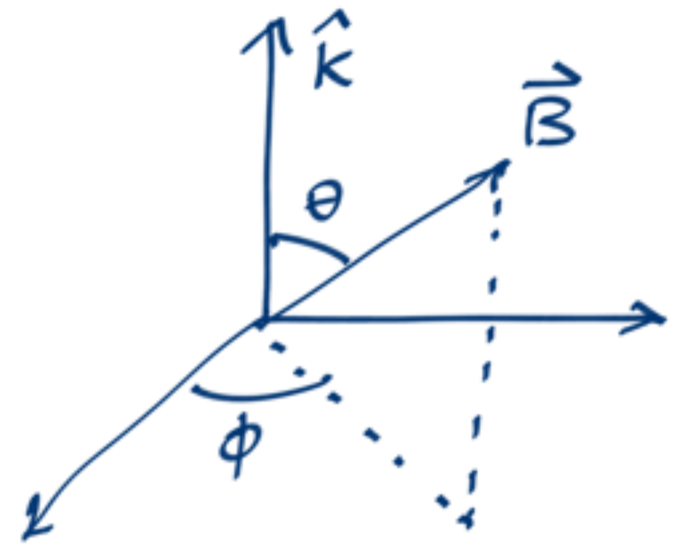
$$\ell = \frac{\lambda}{\Delta n}\frac{\Delta\phi}{2\pi} = \underbrace{\frac{1}{\omega\Delta n}}_{\bar{\ell}}\frac{\Delta\phi}{2\pi}$$




"IF B(z) VARIES ON LENGTH SCALE $\ell \gg \bar{\ell}$ THEN NORMAL MODES DO NOT MIX AND THE PROPAGATION IS $\approx$ ADIABATIC"

# PROPAGATION OF WAVES

$$\vec{\nabla}\times\left(\underset{\sim}{\mu}\cdot\left(\vec{\nabla}\times\vec{E}\right)\right)=\omega^2\underset{\sim}{\epsilon}\cdot\vec{E}$$




$$\frac{d}{dz}\begin{pmatrix}E_x\\E_y\end{pmatrix}=i\,\frac{\omega}{2}\sin^2\theta\begin{pmatrix}q\cos^2\phi-m\sin^2\phi & \frac{q+m}{2}\sin 2\phi\\ \frac{q+m}{2}\sin 2\phi & q\sin^2\phi-m\cos^2\phi\end{pmatrix}\begin{pmatrix}E_x\\E_y\end{pmatrix}$$

THESE TERMS MIX THE MODES, BUT
THEY CAN BE ROTATED AWAY BY SOME $R(\phi)$

**BUT NOT ONCE FOR ALL**

AS $R(\phi)$ CHANGES ALONG THE LIGHT
TRAVEL AS $\phi=\phi(z)$ **FOR** **$B=B(z)$**

# EQUATION FOR THE NORMAL MODES

$$\frac{d}{dz}\begin{pmatrix} E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} i\lambda_1 & \phi'(z) \\ \phi'(z) & i\lambda_2 \end{pmatrix}\begin{pmatrix} E_{\parallel} \\ E_{\perp} \end{pmatrix}$$

$y$

$$i\lambda_1 = i\frac{\omega}{2}q \qquad i\lambda_2 = -i\frac{\omega}{2}m$$

$$y'' - \left(\frac{\phi''}{\phi'} + i(\lambda_1 + \lambda_2)\right)y' + \left((\phi')^2 + i\lambda_2\frac{\phi''}{\phi'} - \lambda_1\lambda_2 - i\lambda_2'\right)y = 0$$

$\phi$ IS A SLOWLY VARYING FUNCTION OF $z$

NEGLECT $(\phi')^2$

FIND EXACT SOLUTION

$$\boxed{y(z) = E_{\parallel,0}\, e^{i\int^{z} dx\, \lambda_2(x)} \int_{R_{NS}}^{z} ds\, \phi'(s)\, e^{i\int^{s} dx\, (\lambda_1(x) - \lambda_2(x))}}$$

# EQUATION FOR THE NORMAL MODES

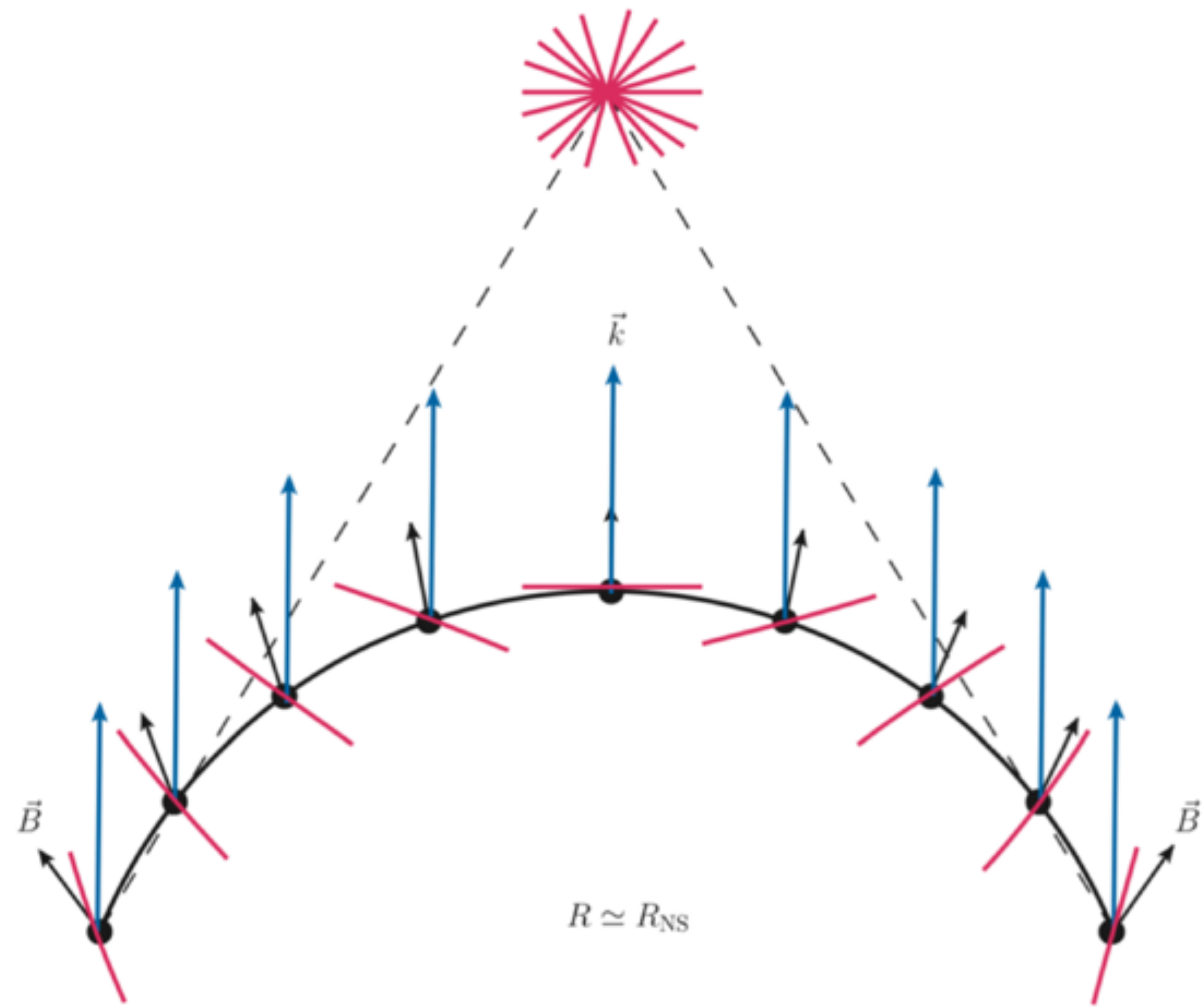
$$y(z) = E_{\parallel,0}\, e^{i\int^{z} dx\, \lambda_2(x)} \int_{R_{NS}}^{z} ds\, \phi'(s)\, e^{i\int^{s} dx\, \underbrace{(\lambda_1(x) - \lambda_2(x))}_{\omega\Delta n}}$$

THIS MEASURES THE GROWTH OF A COMPONENT WHICH WAS NOT INITIALLY PRESENT (say 100% $E_\parallel$ or $E_\perp$ on the star)

**THIS HAPPENS BECAUSE $B = B(z)$ IS NOT SO SLOW FUNCTION OF $z$** (not perfectly adiabatic change).

RESULT COMPATIBLE WITH LANDAU-ZENER THEOREM WHICH WOULD ESTIMATE A NON-ADIABATIC SWITCH THROUGH POLARIZATIONS

$$P \leq \left| \frac{\int_0^\infty \mathcal{E}(z)\, e^{i\omega\Delta n z}\, dz}{\int_0^\infty \mathcal{E}(z)\, dz} \right|^2$$



$\vec{k}$
$\vec{B}$
$\vec{B}$
$R \simeq R_{\rm NS}$

# THE CONTRIBUTION OF AN AXION (LIKE) PARTICLE

$$\mathcal{L} = -\frac{G}{4}\varphi F\tilde{F} \approx G\varphi E B \quad (\theta \approx \pi/2)$$

WE FIND THAT

$$\boxed{\begin{aligned} q \to q' &= q + B^2(z)\, F(z;X,Y) \\ F(z;X,Y) &= \frac{X^2}{(1+qY^2) + \sqrt{(2XYB)^2 + (1+qY^2)^2}} \end{aligned}}$$

where $X = G/m_a$

$Y = \omega/m_a$

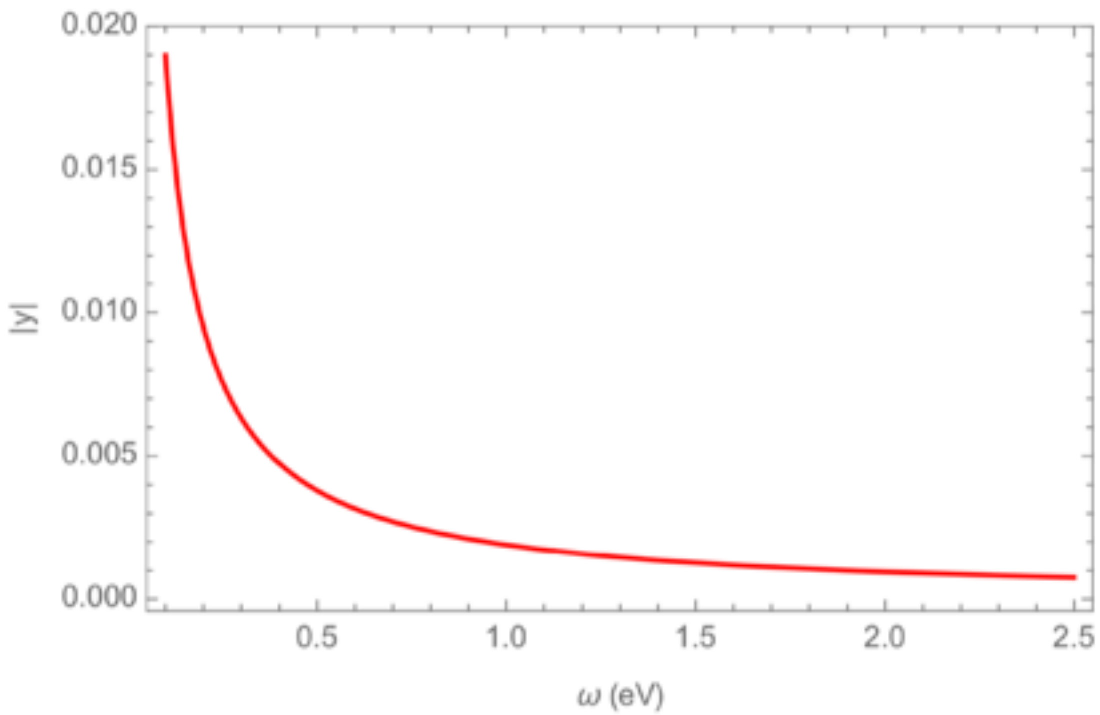
$$\rightarrow \int_{R_{NS}}^{R} dz\, e^{i\int^{z} dx\, (\lambda_1(x) - \lambda_2(x))} \approx \int_{R_{NS}}^{R} dz\, e^{i\lambda S(z)}$$

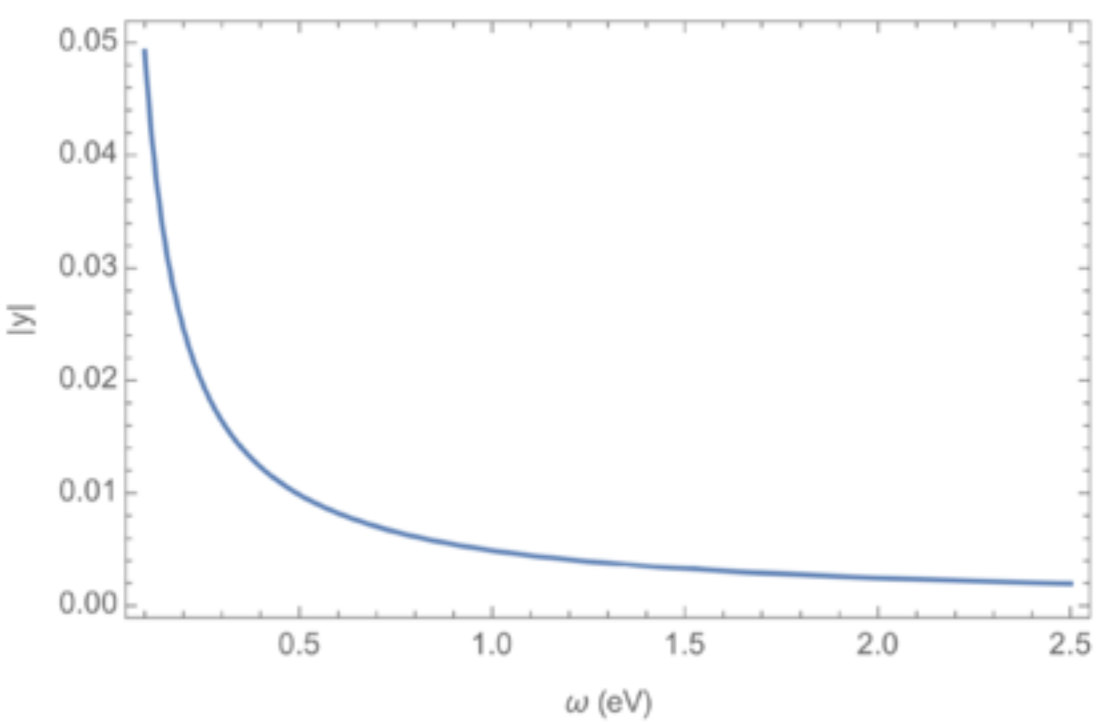
$$\lambda S(z) = \lambda \int^{z} \left(3\delta(x) + B^2(x)\, F(x;X,Y)\right)$$

# AN ASYMPTOTIC SOLUTION

$$y(R,\lambda) \sim \frac{1}{i\lambda S'(R)} e^{i\lambda S(R)} - \frac{1}{i\lambda S'(R_{NS})} e^{i\lambda S(R_{NS})} + O(\lambda^{-2})$$

$\lambda \to \infty$ ( when $\omega \sim$ VISIBLE & $z \sim O(100\,km)$ )




+ AXION

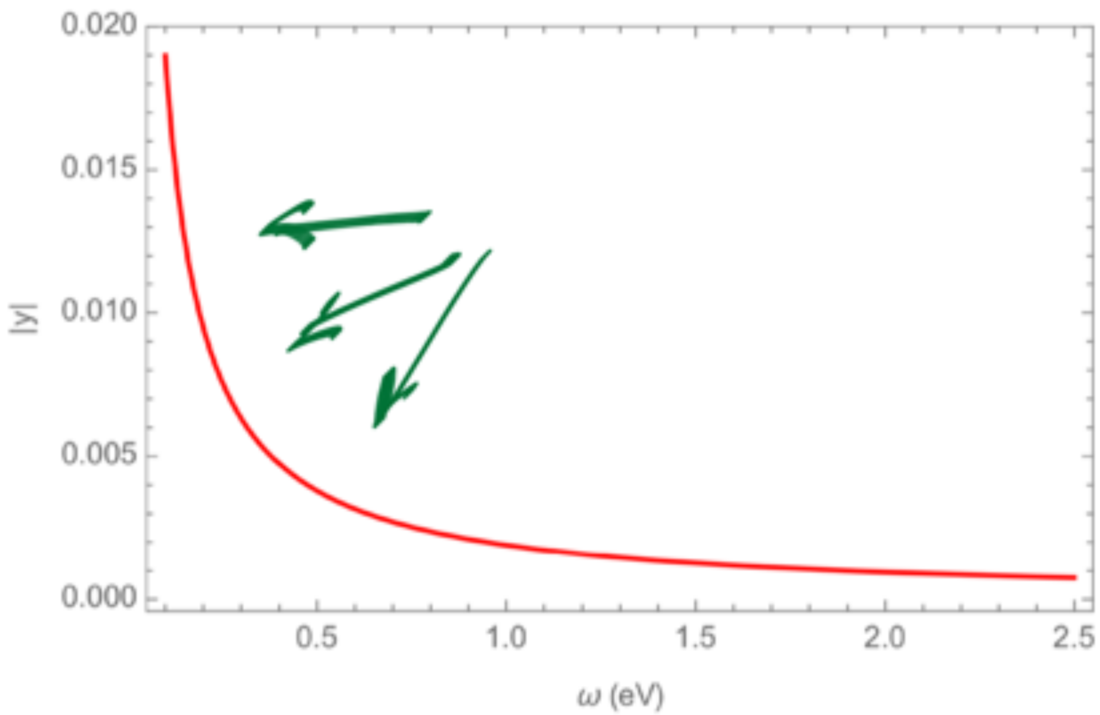
NO - AXION

$$\begin{cases} G = 10^{-7}\,GeV^{-1} \\ m = 10^{-2}\,eV \end{cases}$$

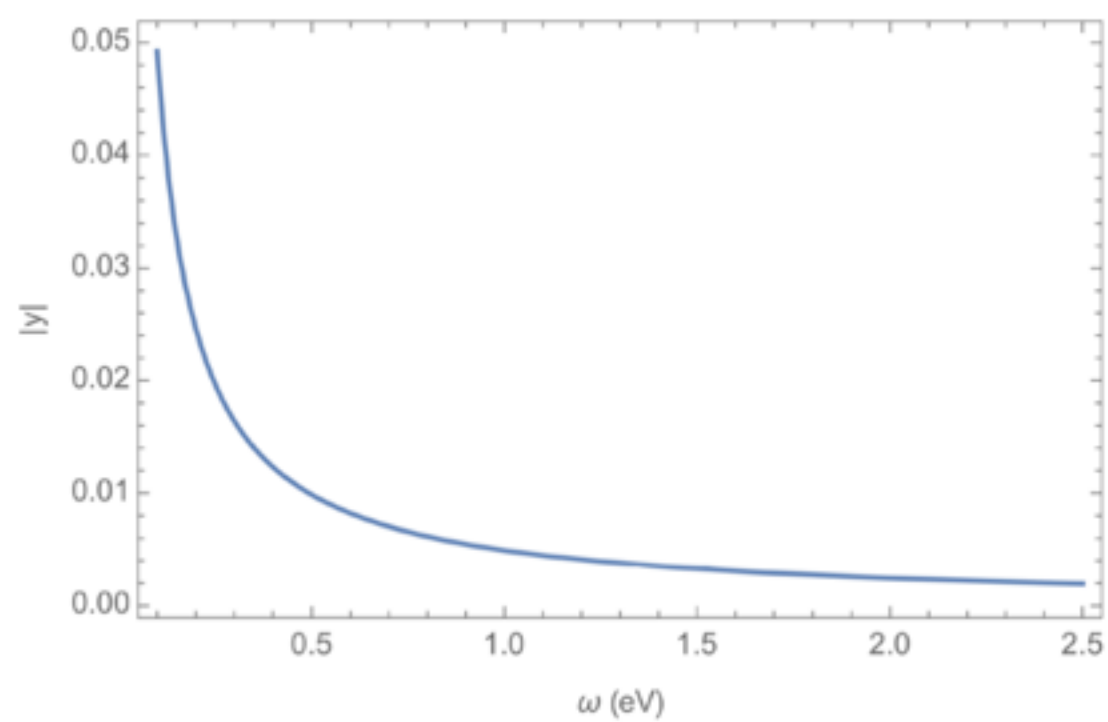
# AN ASYMPTOTIC SOLUTION

$$y(R,\lambda) \sim \frac{1}{i\lambda S'(R)} e^{i\lambda S(R)} - \frac{1}{i\lambda S'(R_{NS})} e^{i\lambda S(R_{NS})} + O(\lambda^{-2})$$

$\lambda \to \infty$ (when $\omega \sim$ VISIBLE & $z \sim O(100\,\mathrm{km})$)




+ AXION

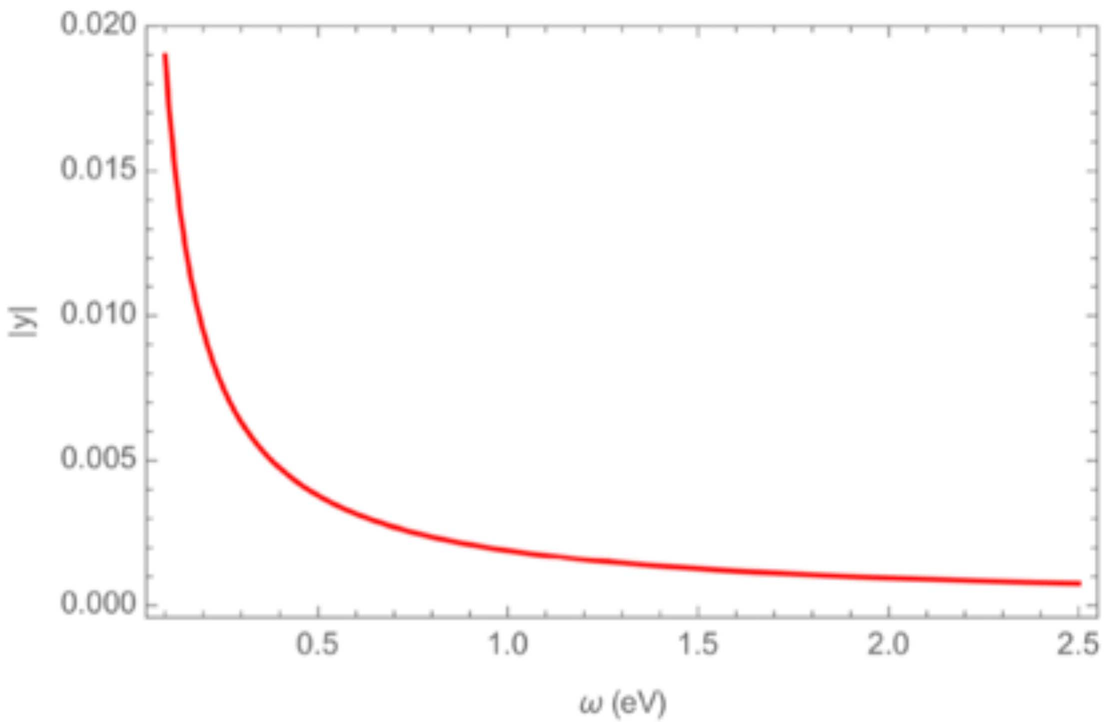


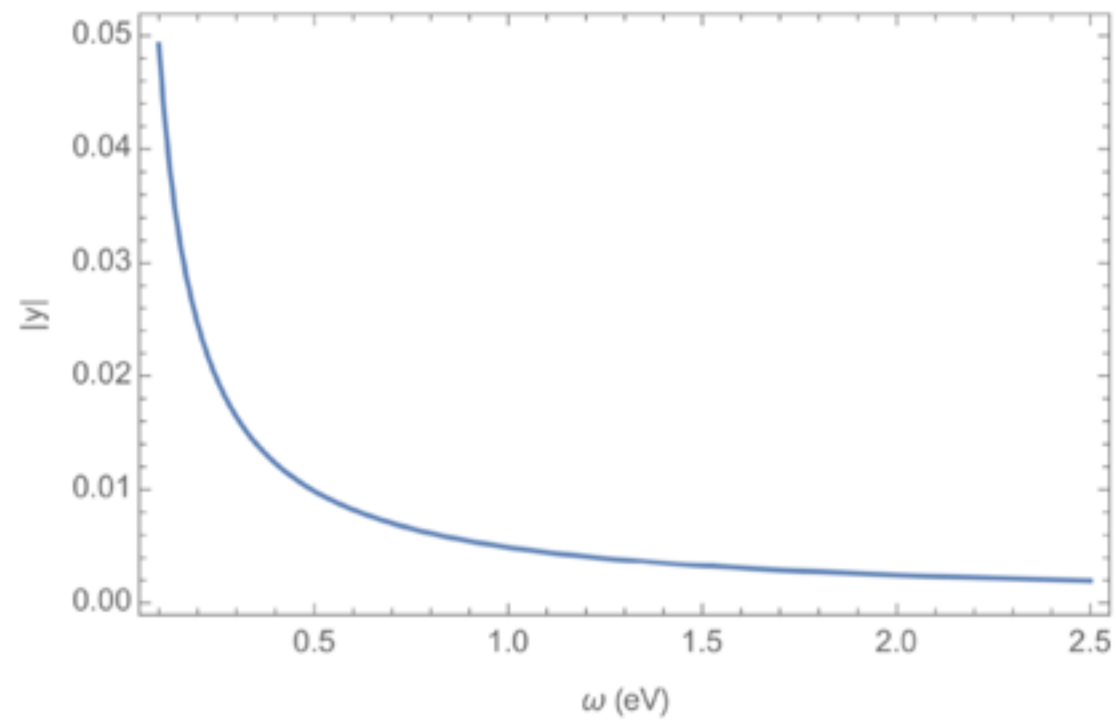

NO - AXION

$$\begin{cases} G = 10^{-7}\,\mathrm{GeV}^{-1} \\ m = 10^{-2}\,\mathrm{eV} \end{cases}$$

WOULD IT BE POSSIBLE TO STUDY HOW POLARIZATION CHANGES WITH $\omega$?

# AN ASYMPTOTIC SOLUTION




+ AXION

NO - AXION

$$\begin{cases} G = 10^{-7}\ \mathrm{GeV}^{-1} \\ m = 10^{-2}\ \mathrm{eV} \end{cases}$$

WOULD IT BE POSSIBLE TO STUDY HOW POLARIZATION CHANGES WITH $\omega$?

OBSERVE THAT THE STRONGER THE CONTRIBUTION OF THE AXION THE BETTER THE 'INITIAL' (ON THE STAR) POLARIZATION IS OBSERVED AT $\infty$.

# CONCLUSIONS

- IF MAGNETARS DO NOT SHOW QED BIREFRINGENCE
  NO ONE WILL DOUBT ABOUT QED...
- IF SOME POLARIZATION IS MEASURED / CONFIRMED
  HOW MUCH OF IT IS FROM QED?
  FROM AXIONS?
  FROM STANDARD EFFECTS?
- CHECKING THE DEPENDENCY OF THE P.D. ON THE $\omega$ OF LIGHT COULD BE INTERESTING! (MEASURING POLARIZ. IN THE FAR INFRARED? — UNFORTUNATELY THESE STARS ARE INVISIBLE AT LOWER FREQ.)
- THE ROLE OF AXION(LIKE) PARTICLES IN THIS CONTEXT APPEARS TO BE MODEST, UNTIL VERY HIGH PRECISIONS AREN'T MET AT MEASURING LIGHT POL.