What Can Neutron Stars Tell Us about QED and Vice Versa?

Jeremy Heyl

17 April 2018

Ilaria Caiazzo, Roberto Mignami, Roberto Taverna, Roberto Turolla, Silvia Zane, and others.

Outline

An Old Prediction

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

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935.)

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Es …

The electrodynamics of the vacuum based on the quantum theory of the electron

V. WEISSKOPF

Mathematisk-Fysiske Meddelelser det Kgl. Danske Videnskabernes Selskab, 14(6): 3–39 (1936).

[Weisskopf's paper was originally printed with the following English-language abstract.]
This paper deals with the modifications introduced into the electrodynamics of the vacuum by Dirac's theory of the positron. The

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PHYSICAL REVIEW VOLUME 82, NUMBER 5 JUNE 1, 1951

On Gauge Invariance and Vacuum Polarization

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts

(Received December 22, 1950)

This paper is based on the elementary remark that the extraction of gauge invariant results from a formally gauge invariant theory is ensured if one employs methods of solution that involve only gauge covariant quantities. We illustrate this statement in connection with the problem of vacuum polarization by a prescribed electromagnetic field. The vacuum current of a charged Dirac field, which can be expressed in terms of the Green's function of that field, implies an addition to the action integral of the elec-

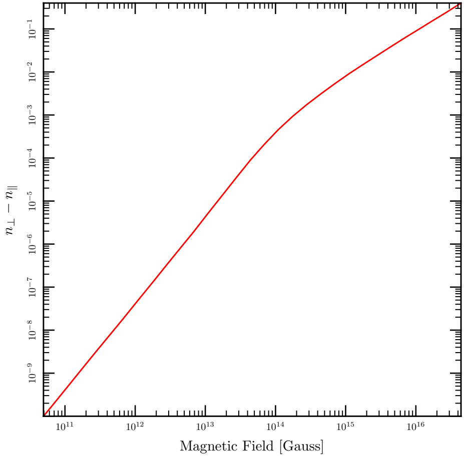
a spin zero neutral meson arising from the polarization of the proton vacuum. We obtain approximate, gauge invariant expressions for the effective interaction between the meson and the electromagnetic field, in which the nuclear coupling may be scalar, pseudoscalar, or pseudovector in nature. The direct verification of equivalence between the pseudoscalar and pseudovector interactions only requires a proper statement of the limiting processes involved. For arbitrarily varying fields, perturbation methods can

Index of Refraction

$$\Delta n = 4 \times 10^{-24}\mathrm{T}^{-2} B^2$$

What could be a signature of this birefringence?

- A time delay: $\Delta t \sim 10^{-3} R/c \sim 10\mathrm{ns}$?



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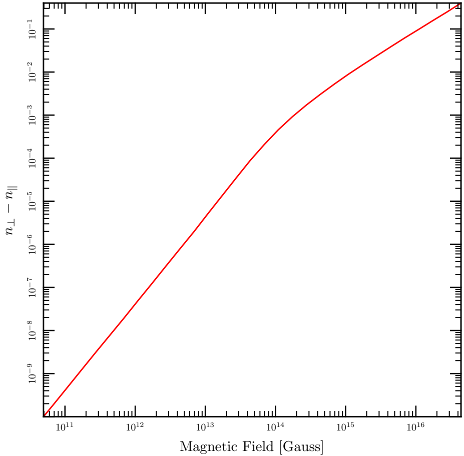
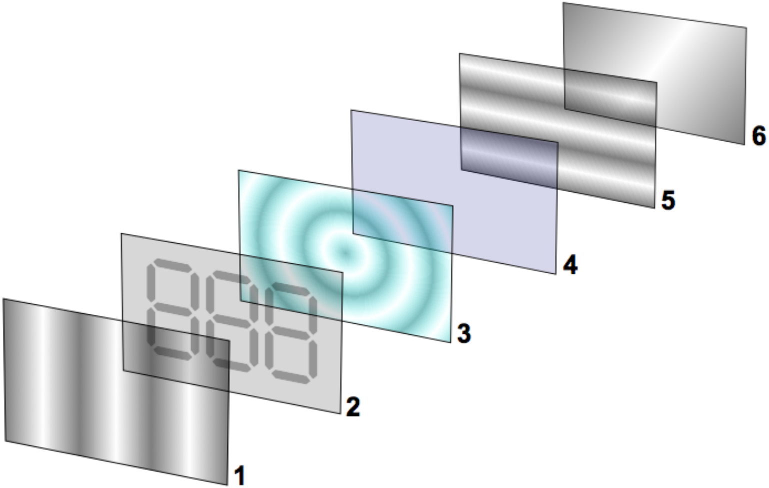
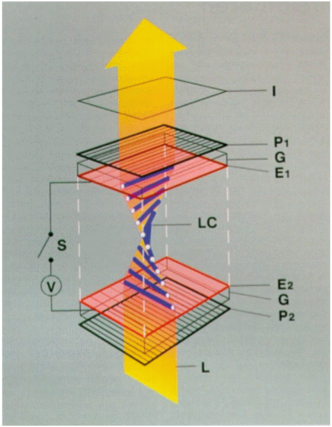
- A time delay: $\Delta t \sim 10^{-3} R/c \sim 10\mathrm{ns}$?
- This seems a bit too subtle.

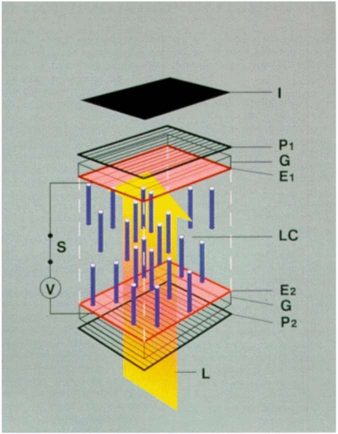


Liquid Crystal Displays



Liquid Crystal Displays





Wikipedia

Polarization-Limiting Radius

The radius at which the polarization stops following the birefringence is called the polarization-limiting radius. Beyond here the modes are coupled.

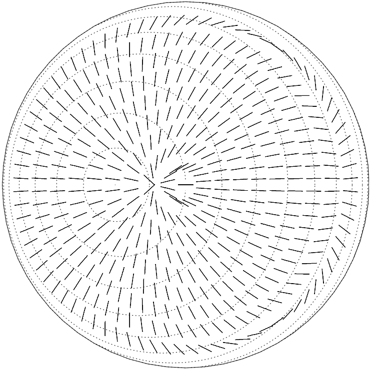
Polarization-Limiting Radius

The radius at which the polarization stops following the birefringence is called the polarization-limiting radius. Beyond here the modes are coupled.

The polarization-limiting radius for a dipole field is

$$\begin{aligned} r_{\rm pl} &\equiv \left(\frac{\alpha}{45}\frac{\nu}{c}\right)^{1/5}\left(\frac{\mu}{B_{\rm QED}}\sin\beta\right)^{2/5} \\ &\approx 1.9\times 10^7\left(\frac{\mu}{10^{30}\ \rm G\ cm^3}\right)^{2/5}\left(\frac{E}{4\ \rm keV}\right)^{1/5}(\sin\beta)^{2/5}\ \rm cm, \end{aligned}$$

Why does this matter?



$r_{\rm pl}/R = 0$

Heyl, Shaviv, Lloyd 03

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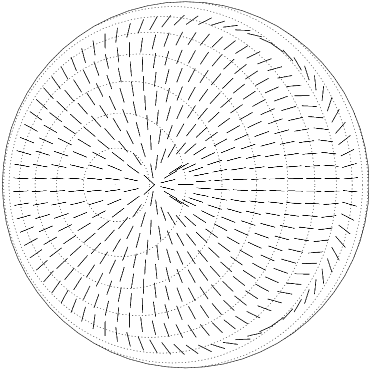

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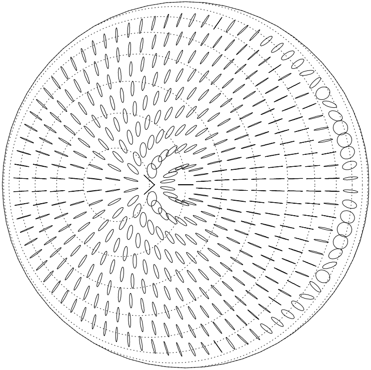

$r_{\rm pl}/R = 1.9$ (AM Her, AMSP)

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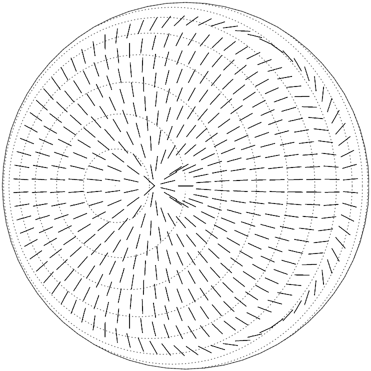

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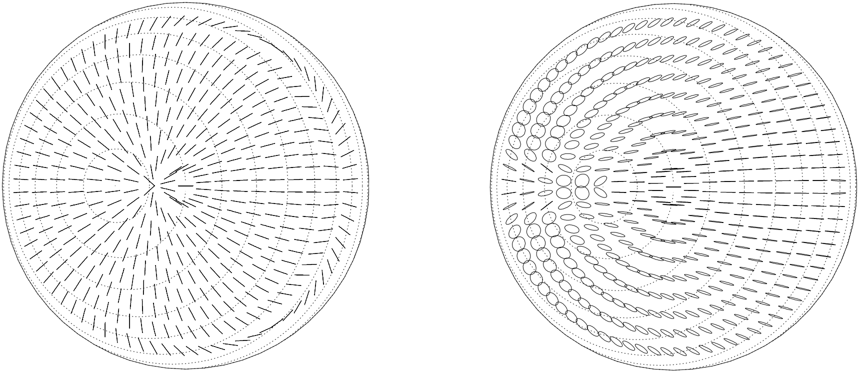
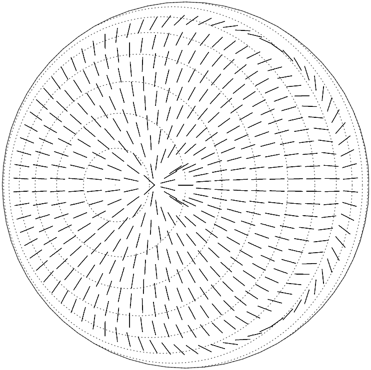


$r_{\rm pl}/R = 0$

Heyl, Shaviv, Lloyd 03

$r_{\rm pl}/R = 12$ (XRP)

Why does this matter?



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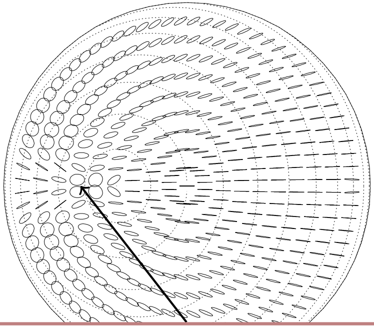

Quasi-Tangential Region *Wang, Lai 09*

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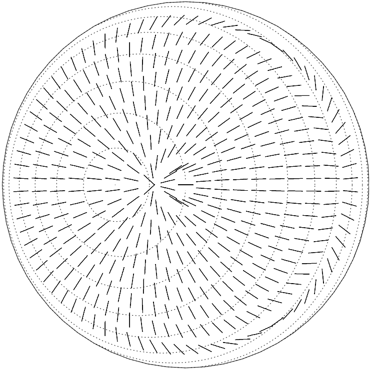

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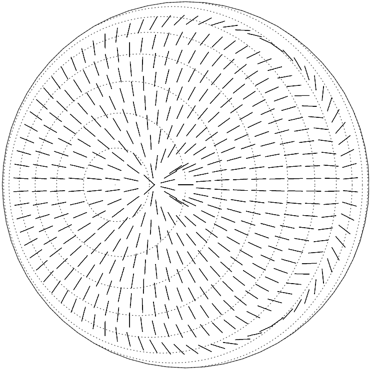

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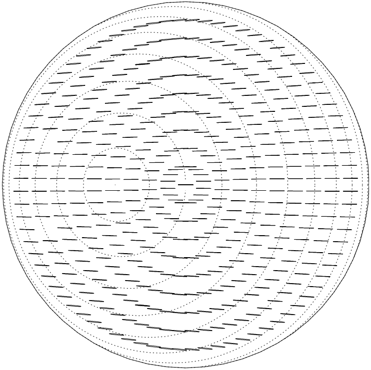


$r_{\rm pl}/R = 76$ (Magnetar)

Places to Look

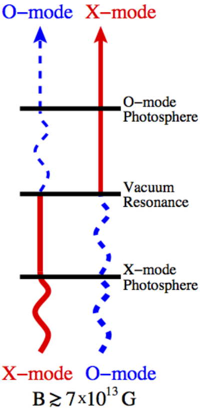
	Radius	Magnetic Field	μ_{30}	$r_{\rm pl}$ at 4 keV
Magnetar	10^6	10^{15}	10^{33}	3.0×10^8
XRP	10^6	10^{12}	10^{30}	1.9×10^7
ms XRP	10^6	10^9	10^{27}	1.2×10^6
AM Her	10^9	10^8	10^{35}	1.9×10^9

Vacuum-Plasma Resonance

Deep in the atmosphere of the neutron star the plasma dominates, while outside the vacuum dominates.
For large strengths of the magnetic field, the vacuum resonance may lie between the photospheres

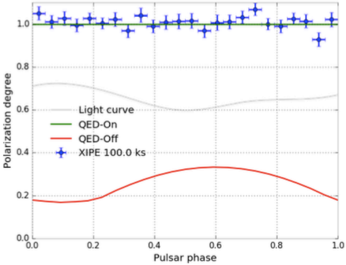
$$B \gtrsim B_l \approx 6.6 \times 10^{13} T_6^{-1/8} E_1^{-1/4} S^{-1/4} \mathrm{G}$$

where $S = 1 - e^{-E/kT}$.
This can have a strong effect on the appearance of spectral features and the high-energy slope. Ho, Lai 04



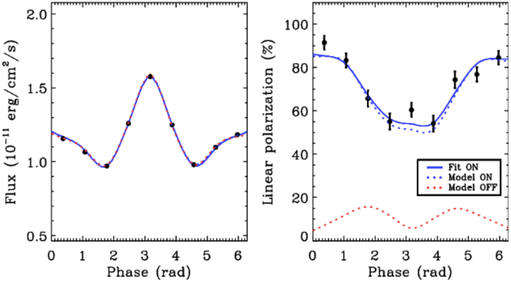
Magnetar Emission

Thermal



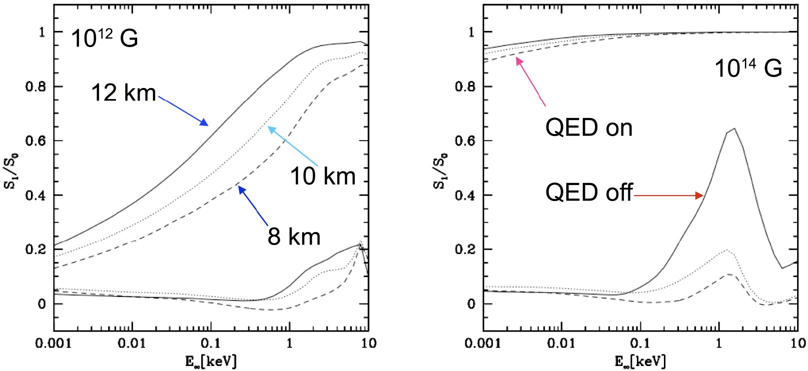
Caiazzo & Heyl 2016; 4U 0142+61

Non-thermal



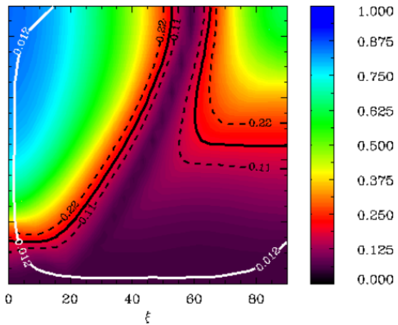
Taverna et al. 2016; SGR 1806-20 (350ks)

Realistic Hydrogen Atmosphere

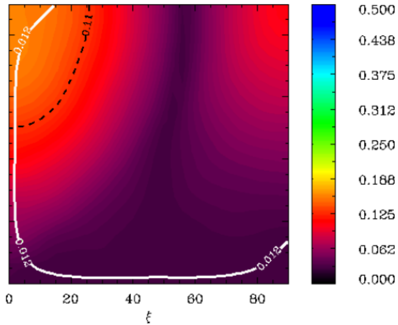


Heyl, Shaviv, Lloyd 03

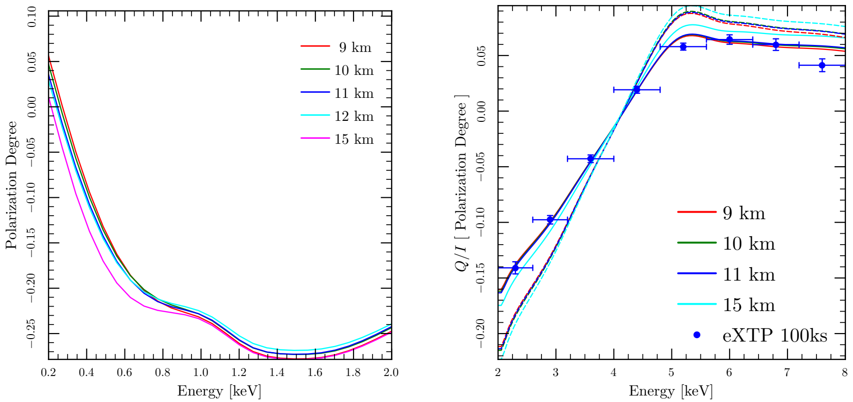
RX J1856.5-3754



Mignami et al. 2016



Her X-1



Caiazzo & Heyl 2017

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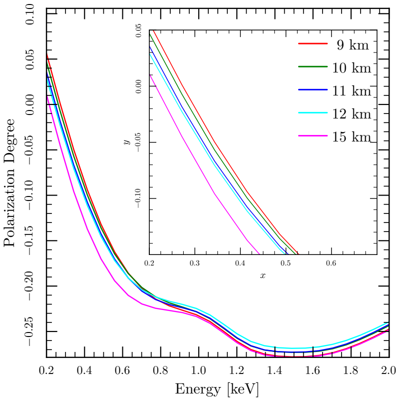

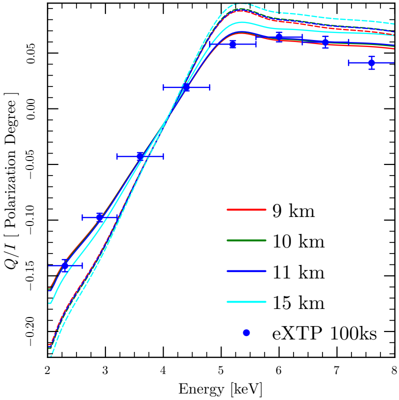

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