The QED-GRB Connection

(some things you should remember if the field is strong)

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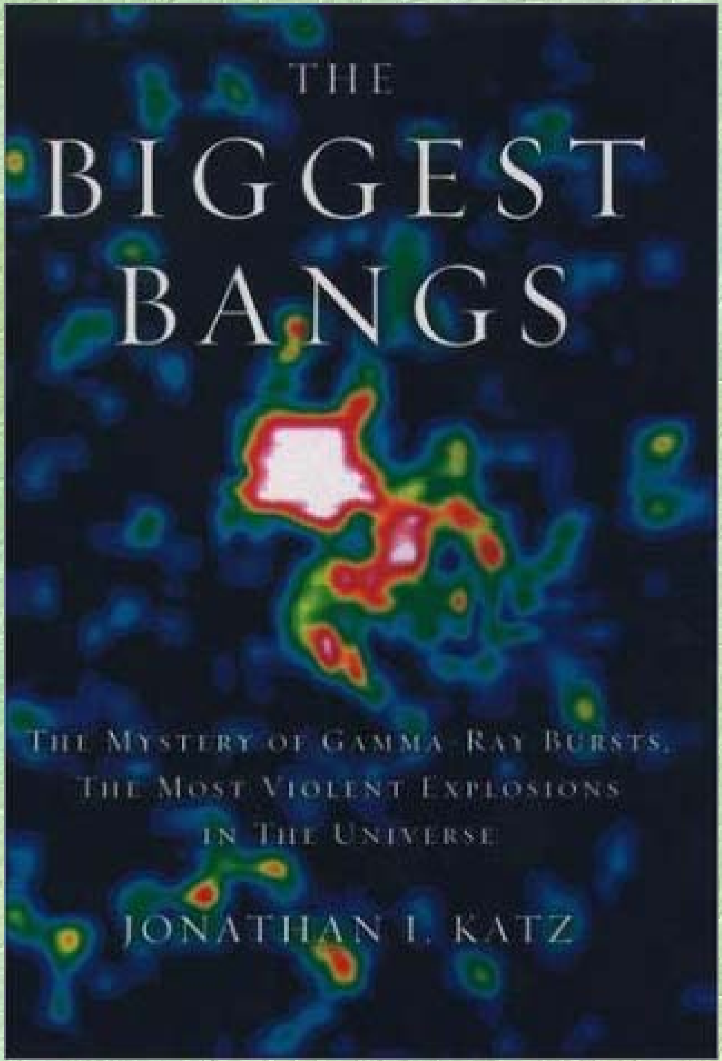
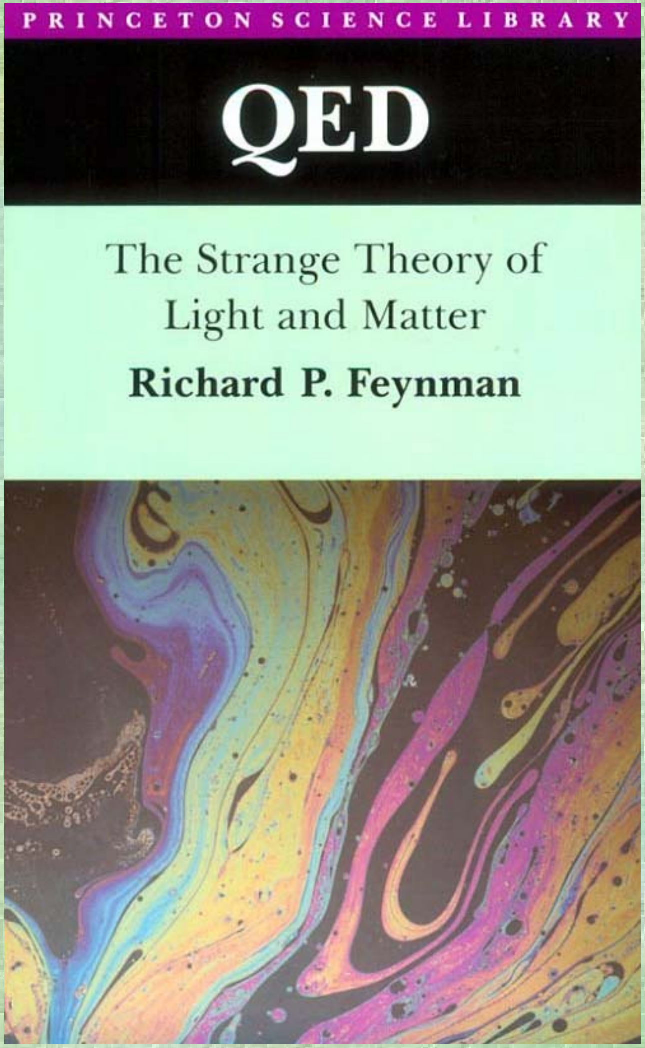
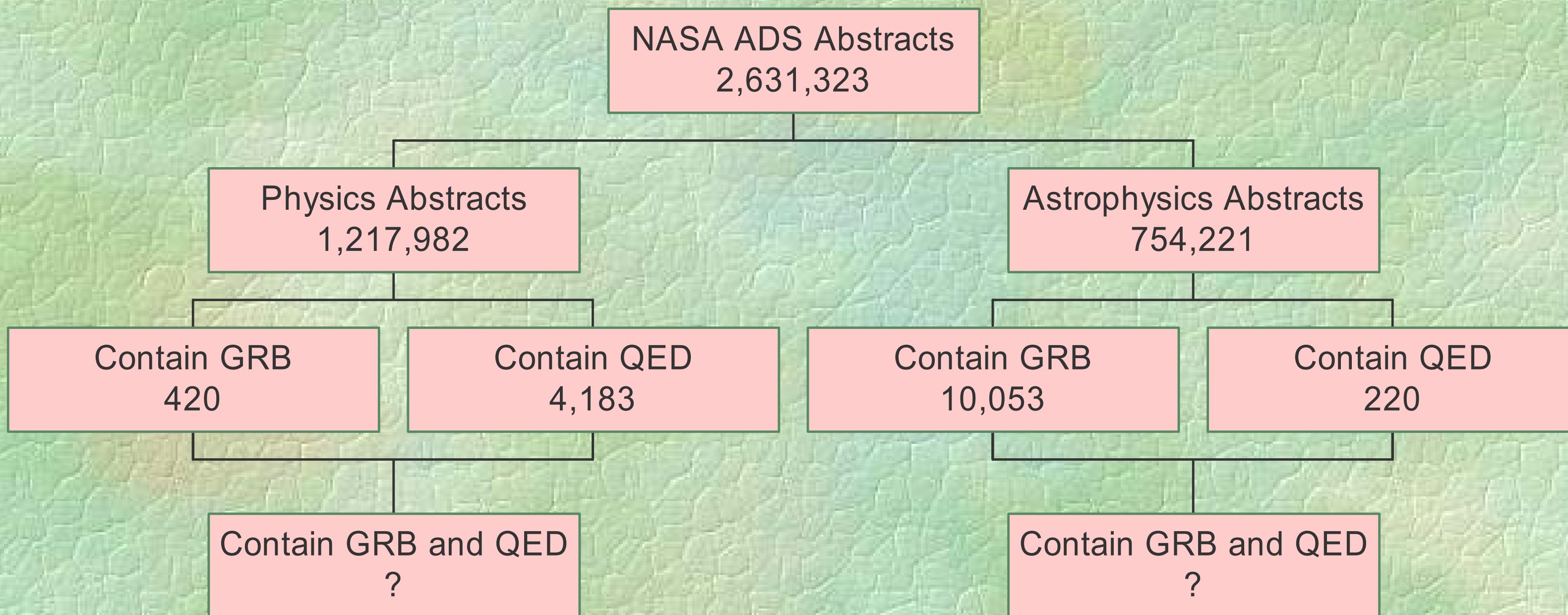
GRBs and QED in the Literature

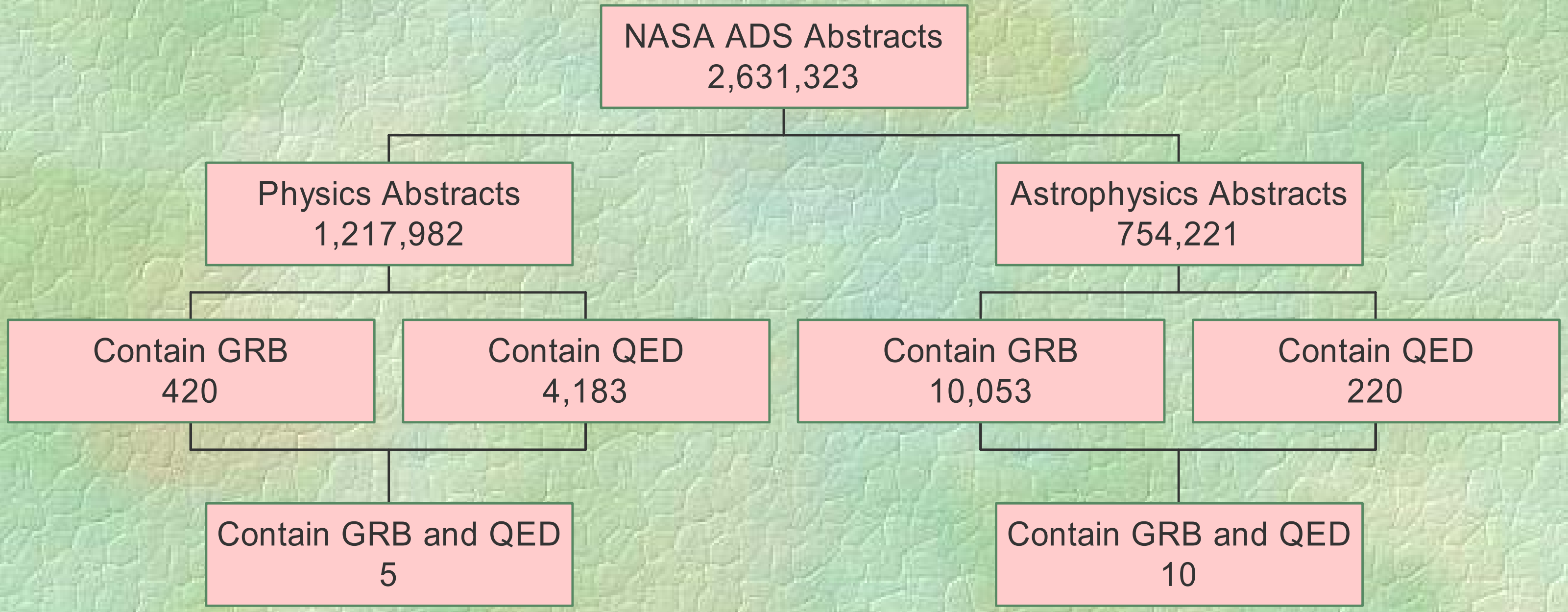




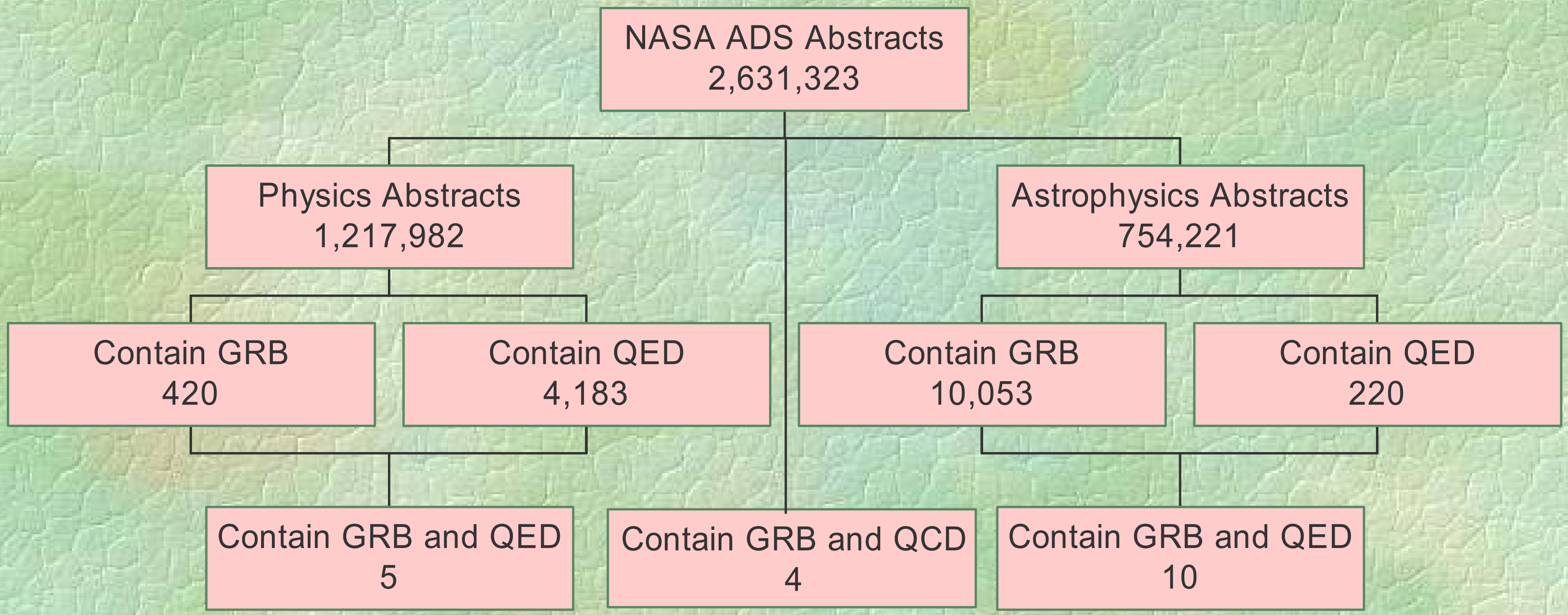
GRBs and QED in the Literature



GRBs and QED in the Literature



GRBs and QED in the Literature



- However, if I were pedantic, I would claim that every talk at this conference relies on QED (with the possible exception of those by Eli Waxman and Vicki Kalogera).

QED Corrections

- In a strong magnetic field, electrons, both real and virtual, occupy Landau levels.
  - Rates for processes that involve electrons can be significantly different due to the new phase-space structure.
  - The vacuum can be an active participant in physical processes that we observe.
  - The equations governing the electromagnetic field are non-linear.

The field scales of the GRB

- The critical magnetic field strength for QED is 4.4×10^{13} G (1.3×10^{-11} cm^{-1}).
  - The electron cyclotron energy equals its mass.
- Estimates of the magnetic field in a GRB:
  - MHD central engine (Rees Tuesday) - 10^{15} G
  - Kerr BH (van Putten Tuesday) - 10^{15} G
  - Equipartition - $8 \times 10^{16} (\varepsilon_B E_{51})^{1/2} R_6^{-3/2}$ G
  - Magnetar (Usov 1992) - 10^{16} G
  - Virial Magnetic Field is $\sim M/R^2 \sim 10^{18}$ G

The length scales of the GRB

- To account for the rapid time variability, the $r_{engine} \sim 10^{6\text{-}7}$ cm.
- To avoid making pairs, the γ–rays must be emitted at $r > 10^{13}$ cm where $B \sim 10^{6\text{-}8}$ G, well below $B_{QED.}$
- The afterglow comes from $r > 10^{15}$ cm.
- If strong-field QED matters, it will be important in the engine.

What processes may be crucial?

- Vacuum magnetization
- Vacuum breakdown
- Vacuum polarization
- Photon splitting/merging
- Phase-space structure for real electrons
- Strong-field-QED dynamic Casimir effect

Vacuum Magnetization

- For $B > B_{\mathrm{QED}}$ the vacuum carries a magnetization which increases nonlinearly with the strength of the magnetic field. This nonlinearity may alter the geometry of the field (HH97).
- The magnetization of the plasma is generally negligible.
- If $E^2 > B^2$ or $E \cdot B \neq 0$, the magnetization becomes complex.

Vacuum Breakdown

- The magnetized vacuum is stable because there are no magnetic monopoles.
- However, frame dragging near a Kerr black hole converts a magnetic field into an electric field, such that $E{\cdot}B \neq 0$ (H01).
  - A magnetized Kerr black hole with $B > 10^{12}$ G is unstable to pair production. Even in vacua pairs will be produced driving $E{\cdot}B \Rightarrow 0$.
  - The Goldreich-Julian density is ~ 10^{17} e^- cm^{-3} or one hundredth the density of air.

Toward an BH Magnetosphere

- Start with Wald's solution for the electromagnetic field surrounding a rotating black hole.
- A vacuum solution to Maxwell's equations:

Vector potential

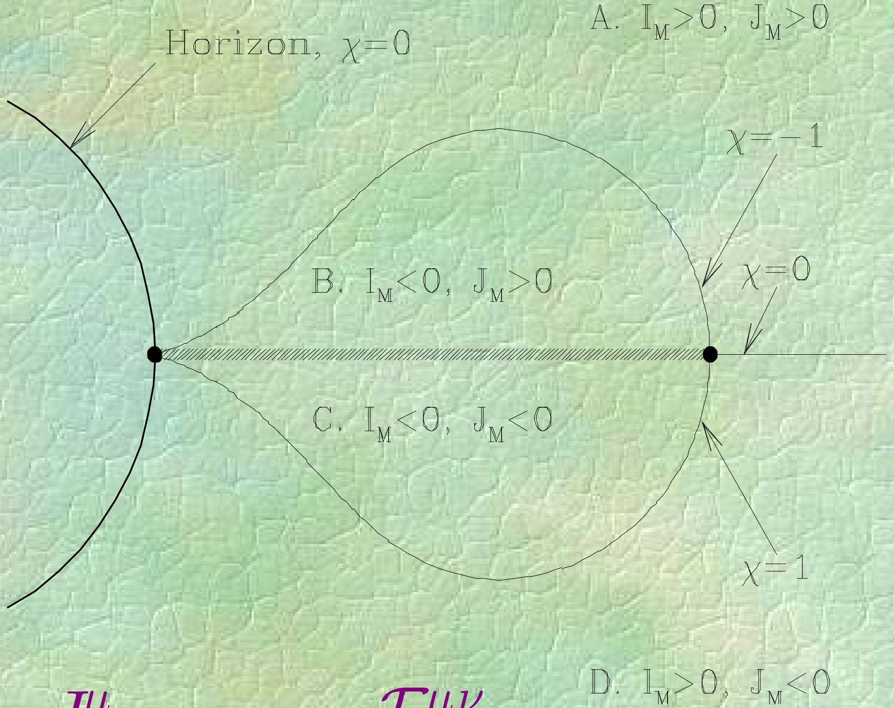
$$A^\mu = \sum_i A_i \psi^\mu_{(i)}$$

Killing vector

- Satisfy the MHD condition by adding an axion field χ (Thompson & Blaes '98).

Structure of the Wald Field

- The EM field surrounding a rotating black hole divides the surrounding spacetime into four regions.
- The MHD condition is satisfied everywhere except at the 4 corners.
- Here, the required current density diverges.



$$J^{\mu} = -\chi_{;\nu}\mathcal{F}^{\mu\nu}$$

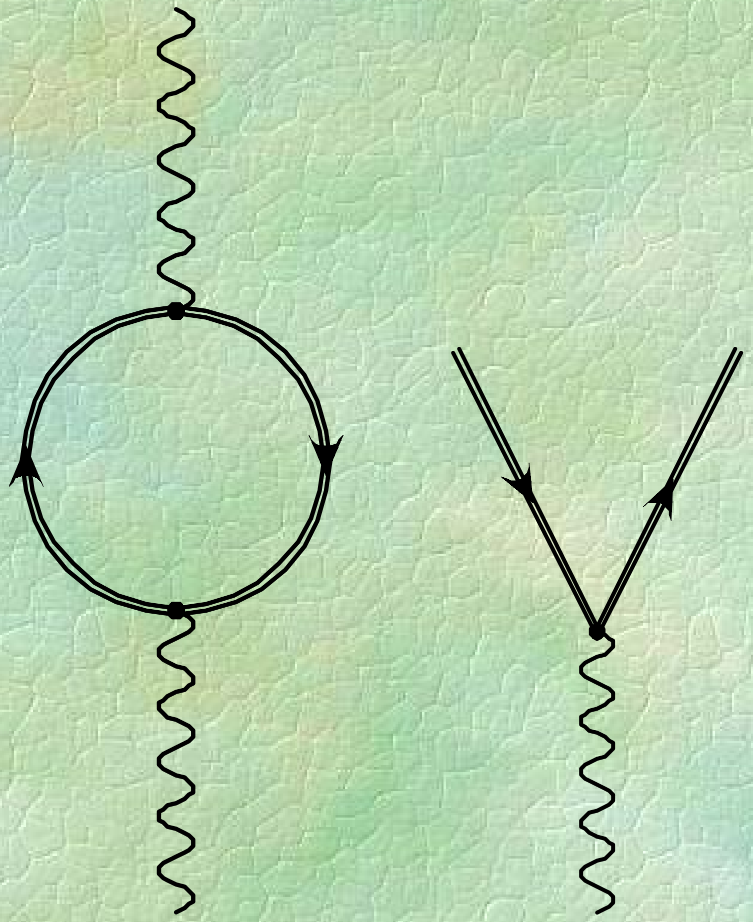
$$I_{\mathrm{M}} = G^{\mu\nu}G_{\mu\nu};\ J_{\mathrm{M}} = \mathcal{G}^{\mu\nu}G_{\mu\nu}$$

Vacuum Polarization

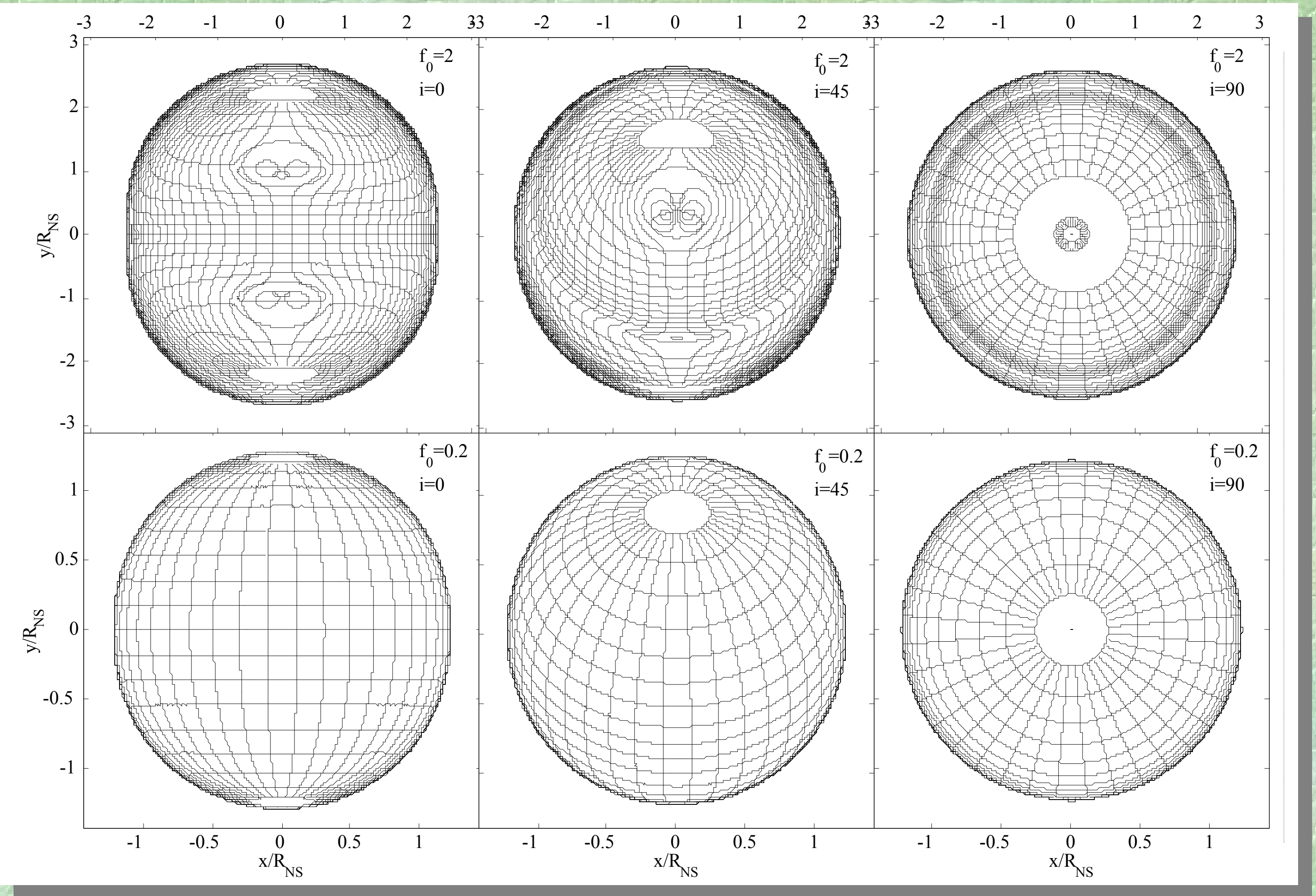
- The index of refraction for the parallel mode is significantly larger than 1 for $B > 10^{14}$ G:

$$(n-1) \approx \frac{\alpha}{6\pi} \frac{B}{B_{\rm QED}} \approx \frac{B}{10^{17}\rm G}$$

- Photon paths are bent (SHL99).
- Photons carry more momentum.
- Photons pair produce.

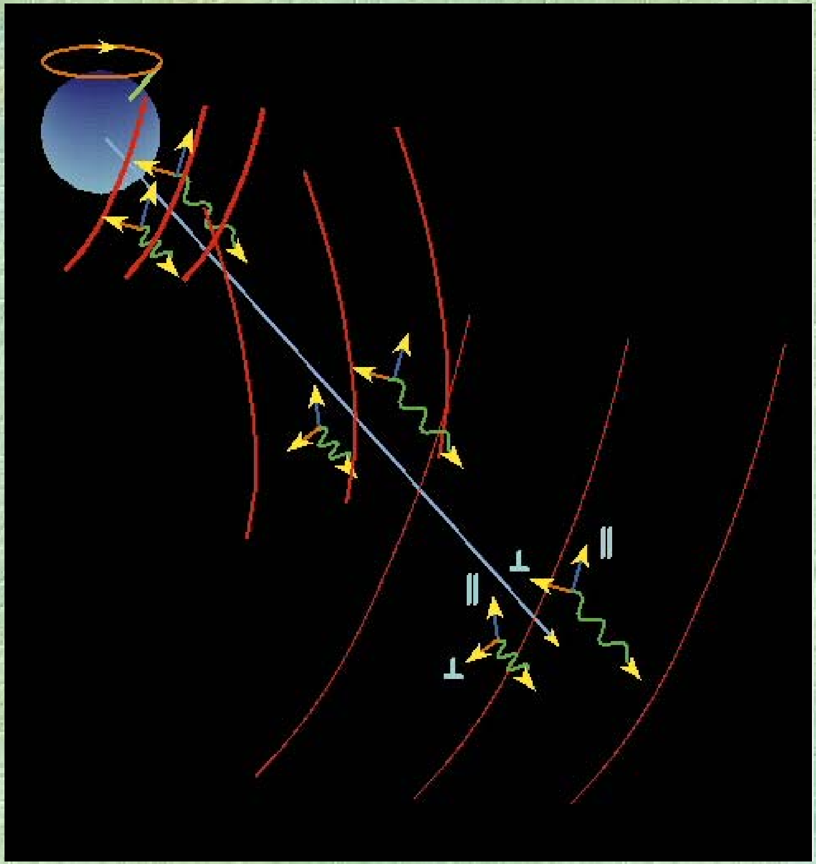


Lensing of a Neutron Star



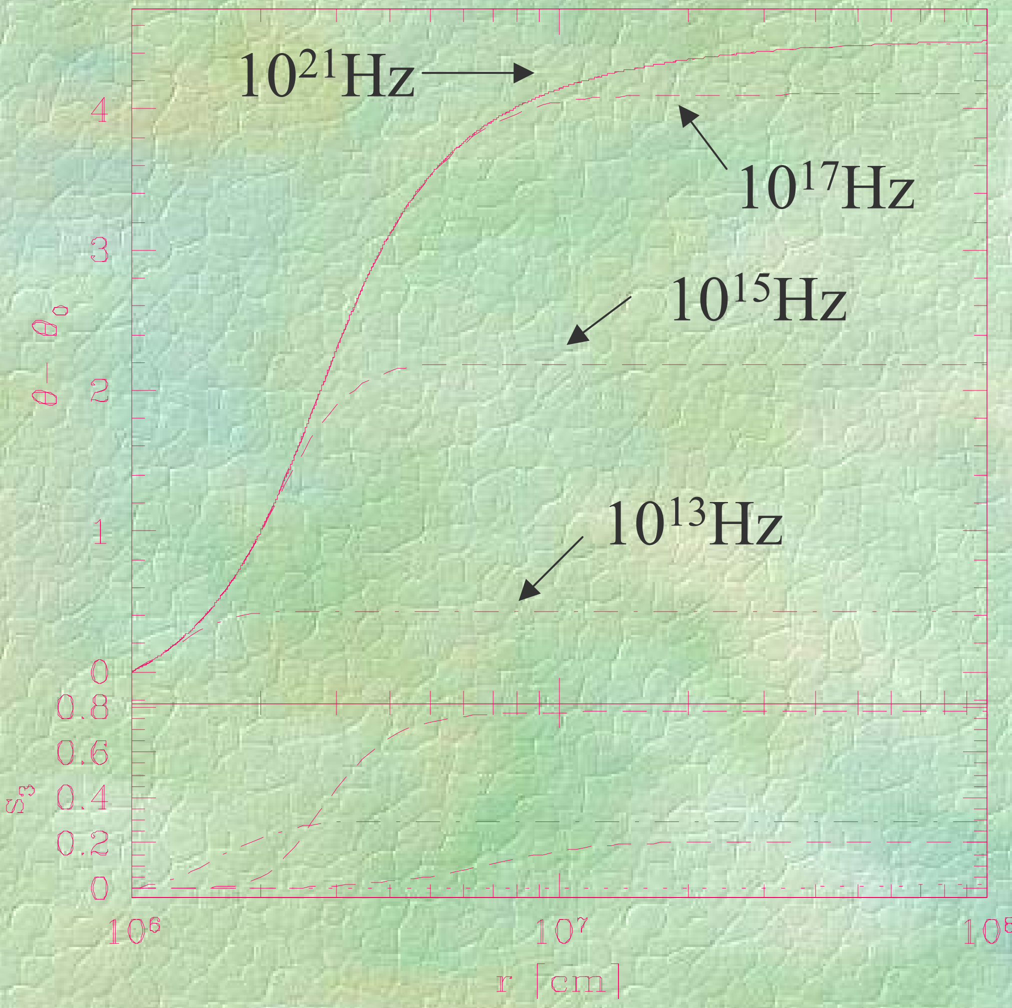
Polarization from Neutron Stars

- The traveling modes for light in the magnetosphere are decoupled by the plasma and the vacuum (HS00).
- Radiation from disparate parts of the magnetosphere evolves so that its polarization is parallel.

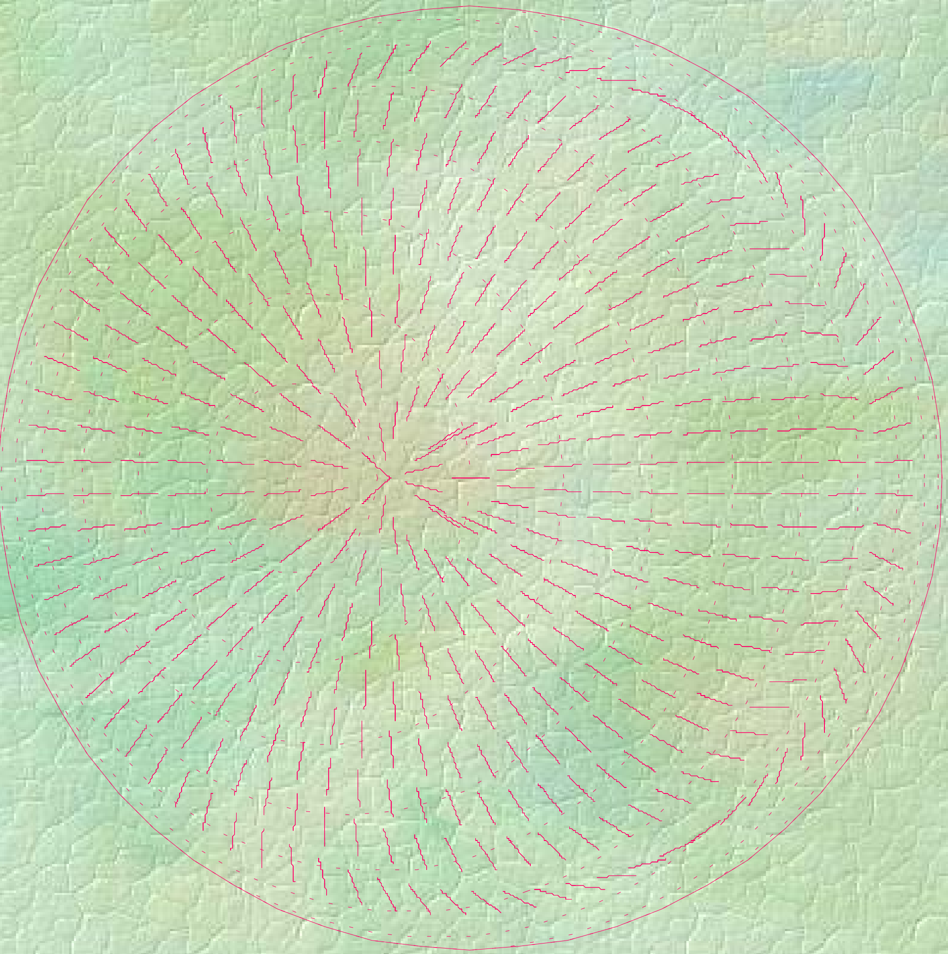


Polarization-Limiting Radii

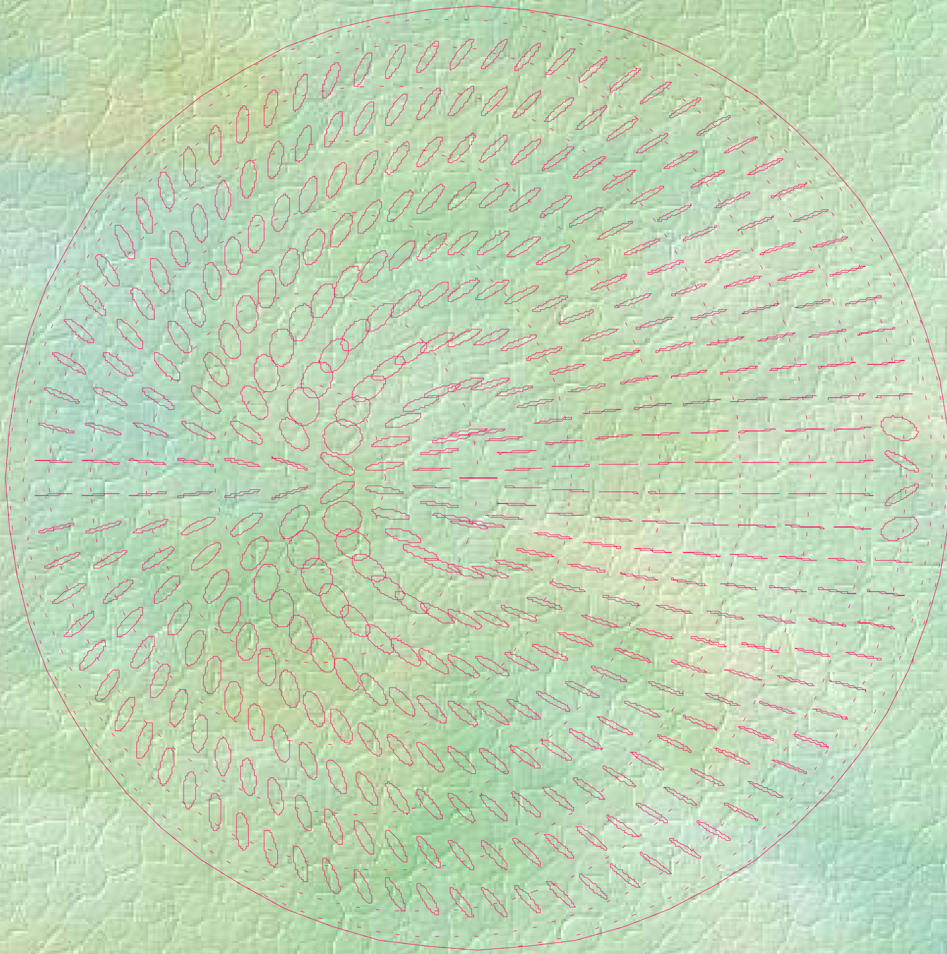
- The polarization modes of high-energy photons couple further from the stellar surface than those of low-energy photons.
- Also, if the direction of the magnetic field changes appreciably during coupling we get a circular component.



Low-Energy Polarized Images

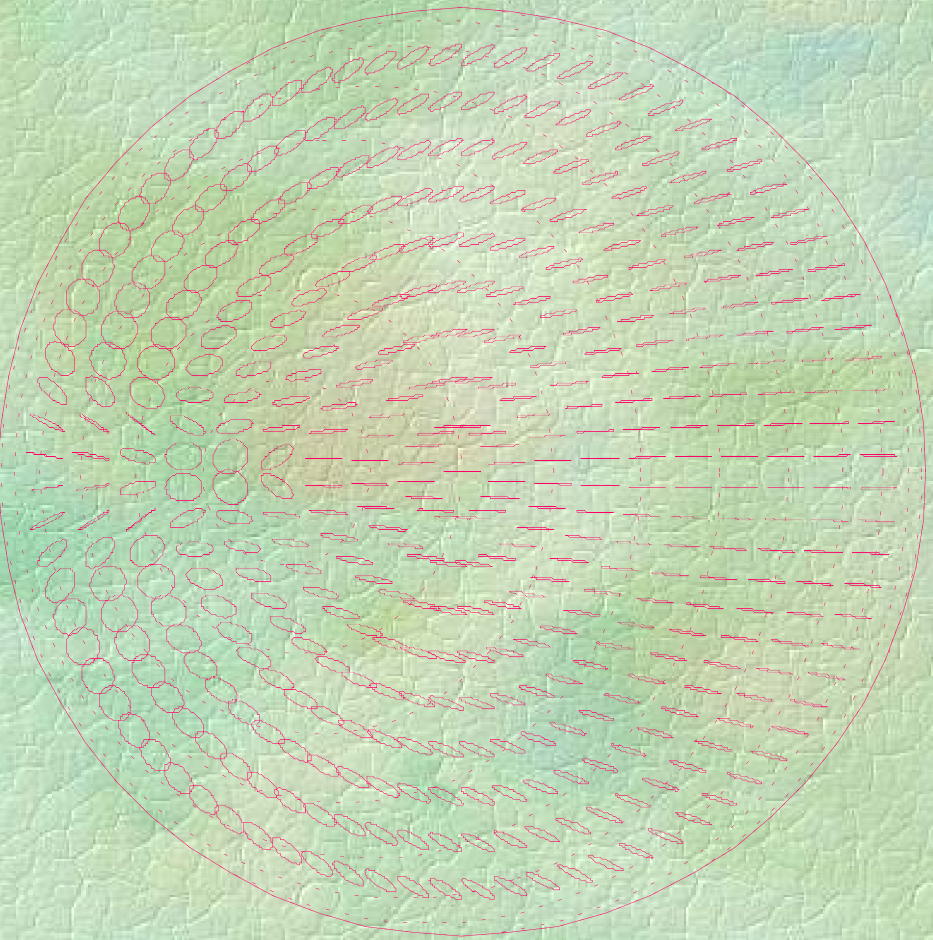


Zero Hz - QED neglected



10^{15} Hz - Optical/UV

High-Energy Polarized Images

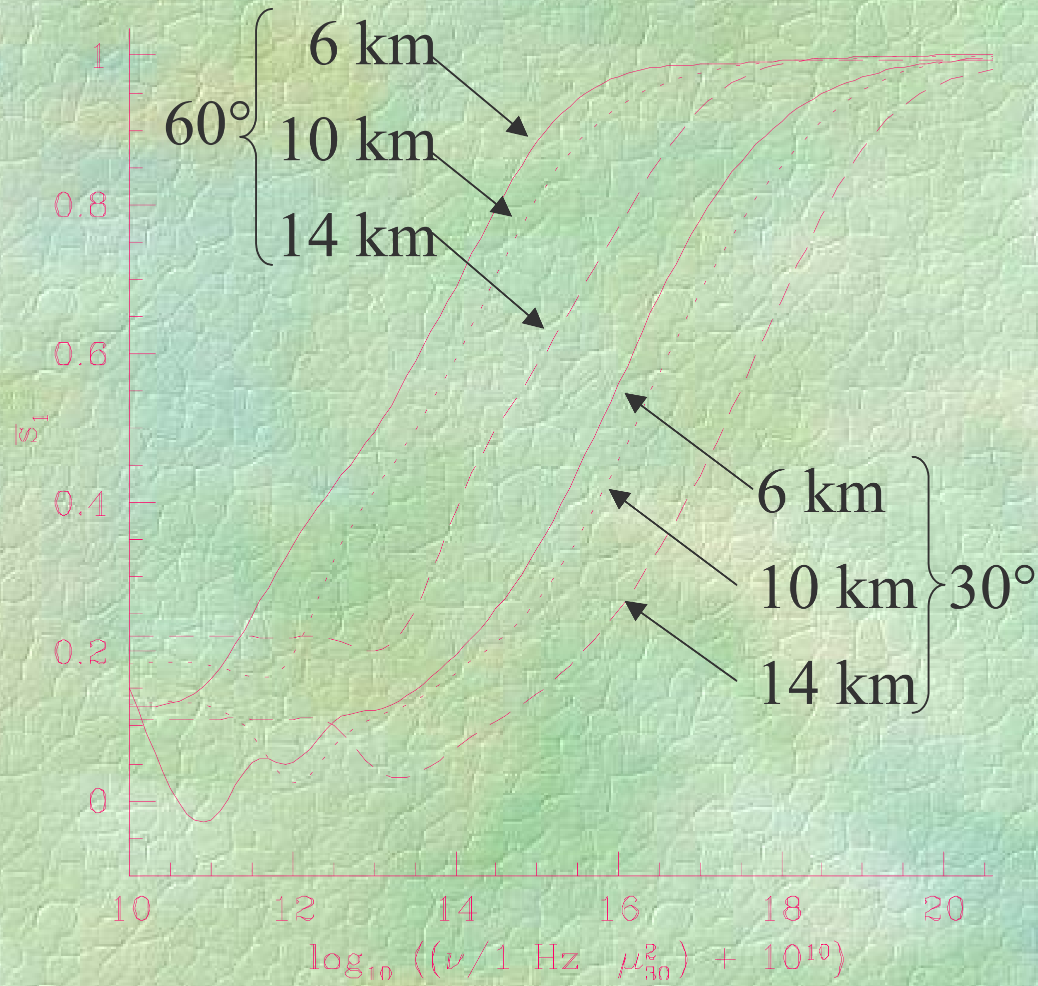


10^{17} Hz - Soft X-Ray

10^{21} Hz - Gamma-Ray

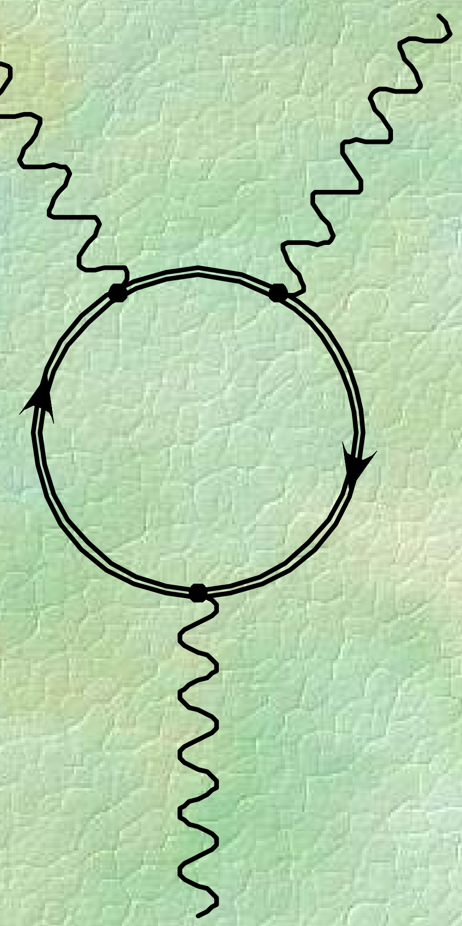
Big Trends

- 330 images,
  105 rays/image (HS02)
- $\nu\uparrow$ $s_1\uparrow$
- $\mu\uparrow$ $s_1\uparrow$
- $\alpha\uparrow$ $s_1\uparrow$
- $R\uparrow$ $s_1\downarrow$ for $\nu>10^{14}$ Hz
- $R\uparrow$ $s_1\uparrow$ for $\nu<10^{14}$ Hz



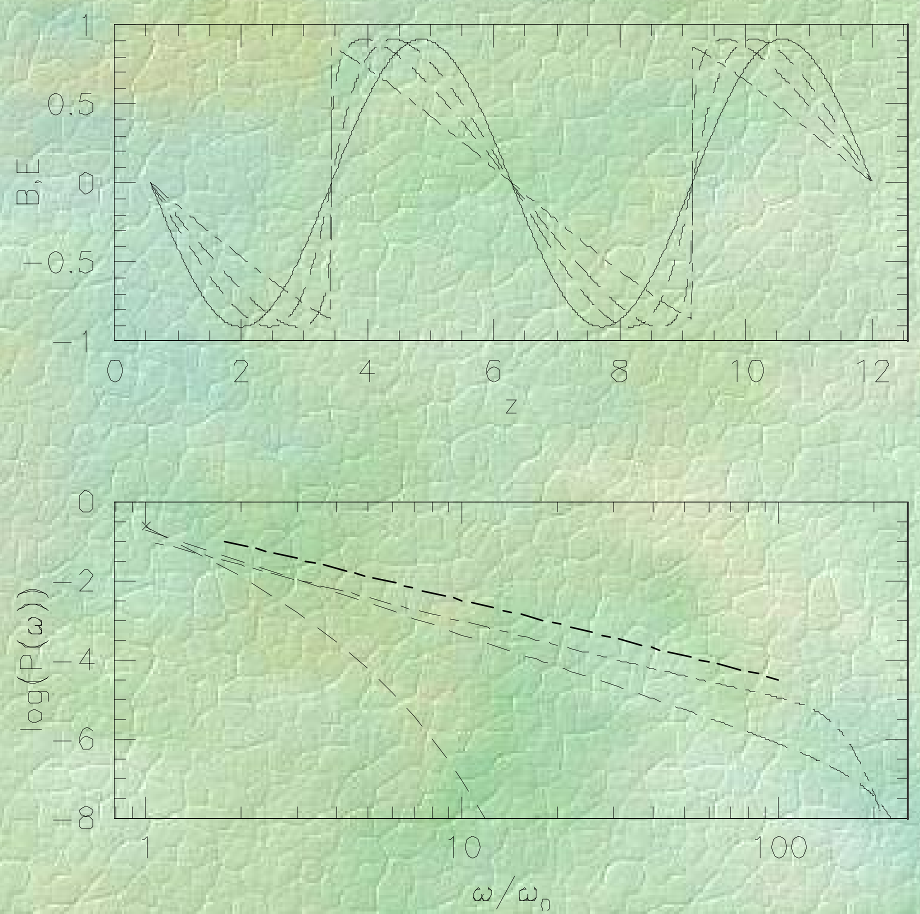
Photon Splitting/Merging

- Photon splitting may be important in SGRs (see works by Baring); however, the emission from GRBs originates in a weak-field region.
- The inverse process may be important for the dynamics of the plasma.



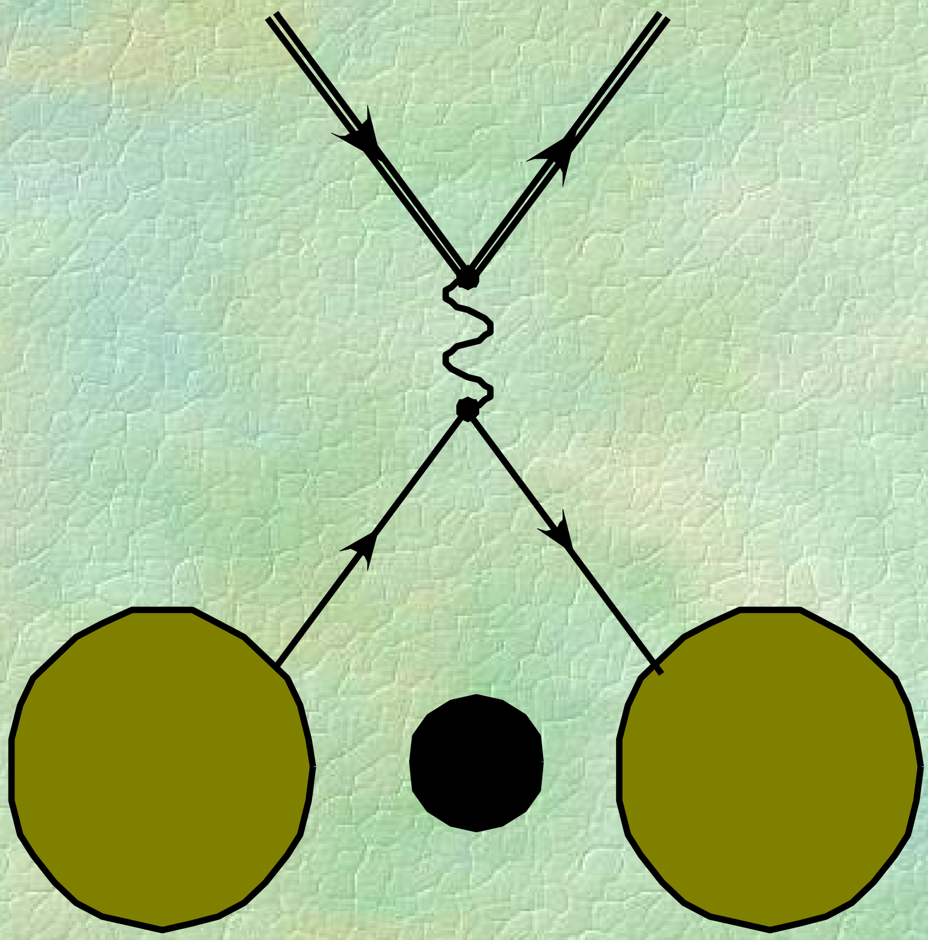
QED/MHD Shocks

- A fast mode travelling through a strong magnetic field will shock in $3\alpha^{-1}(\Delta B/B)^{-1}$ wavelengths (HH99).
- The non-linear interactions tend to sharpen density gradients. Shocking may occur too early.



Neutrino Production/Annihilation

- Neutrinos can drive a polar outflow.
- The accretion flow may be neutrino-dominated.



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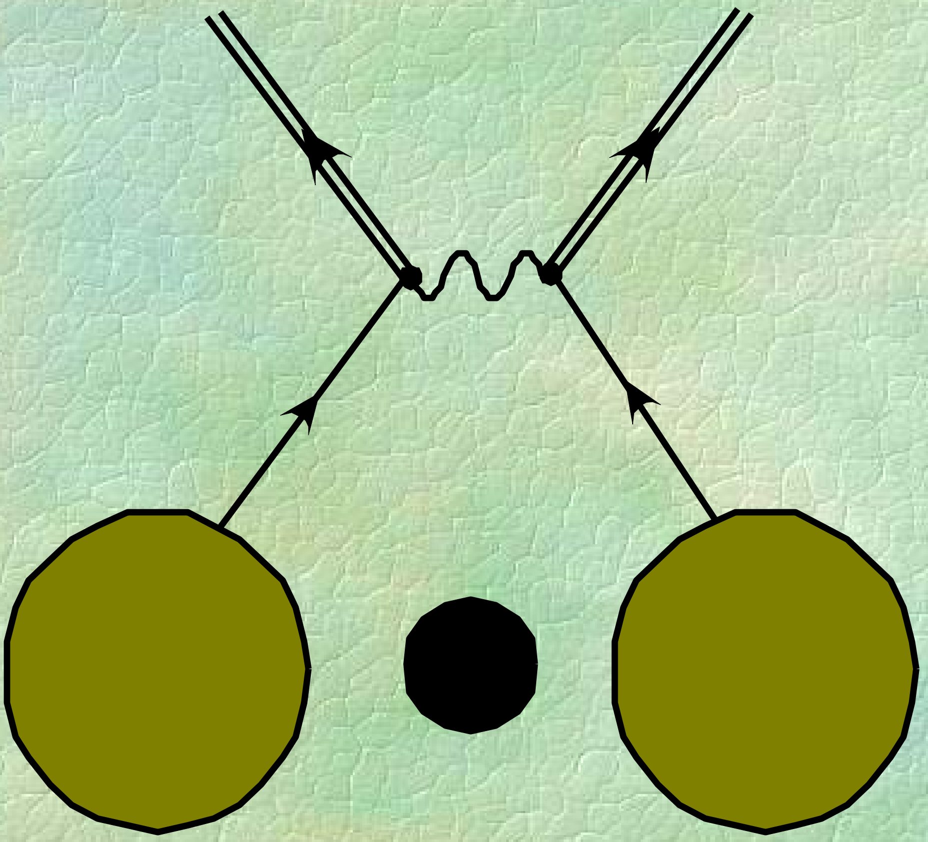
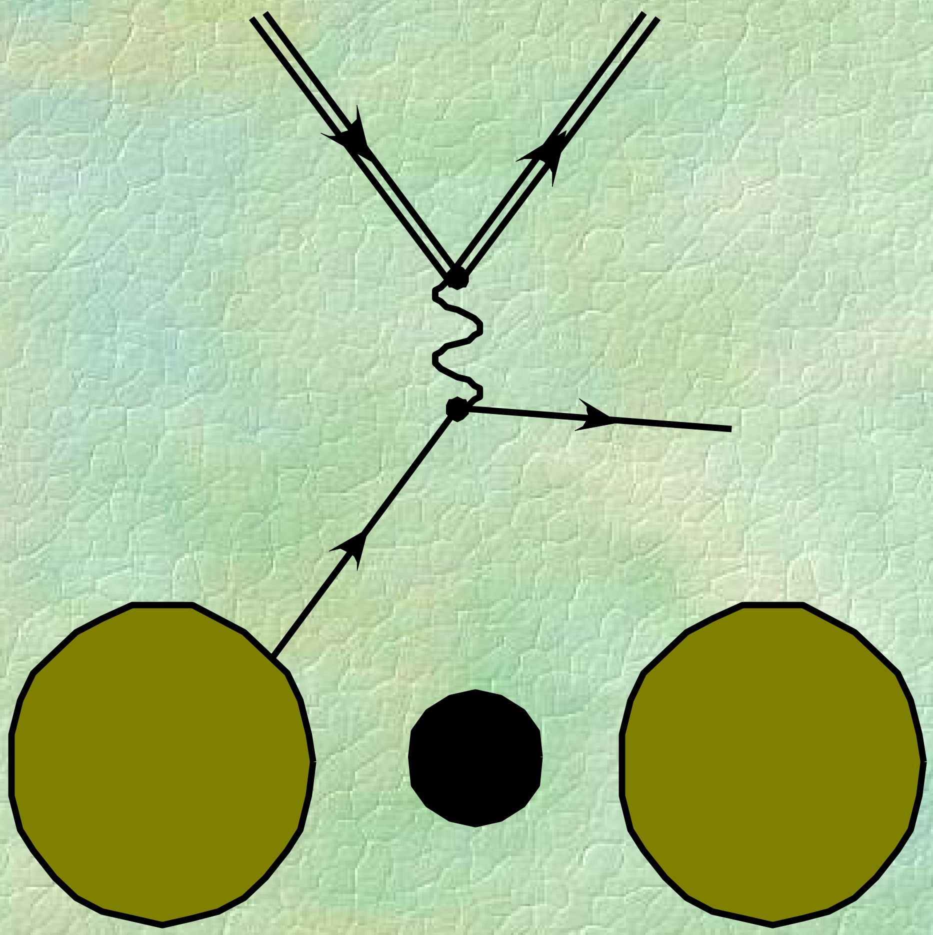
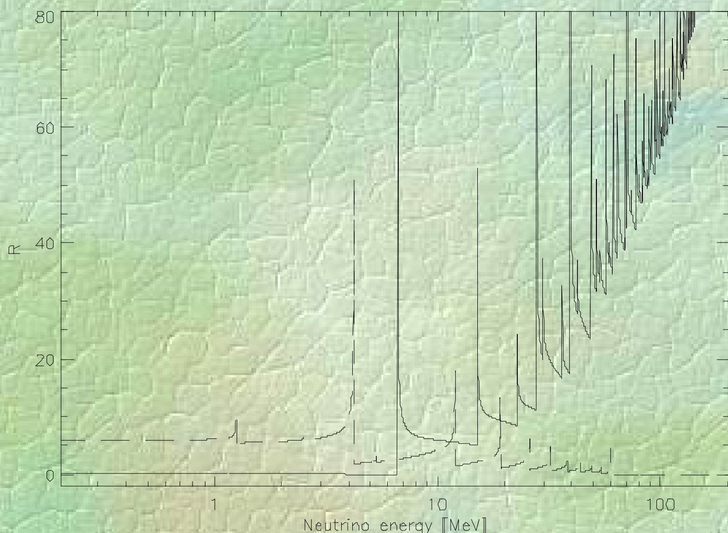


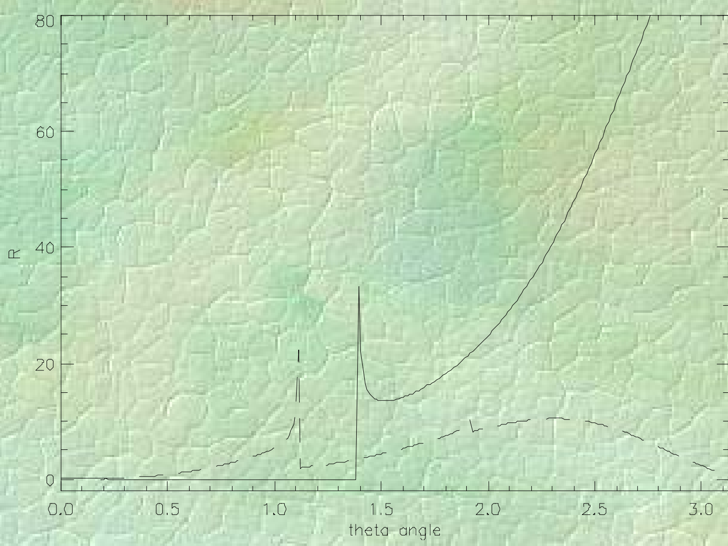
Neutrino Production/Annihilation

- Neutrinos can drive a polar outflow.
- The accretion flow may be neutrino-dominated.
- In analogy to the photon case, the strong magnetic field opens new reaction channels (Hardy & Thoma '00)



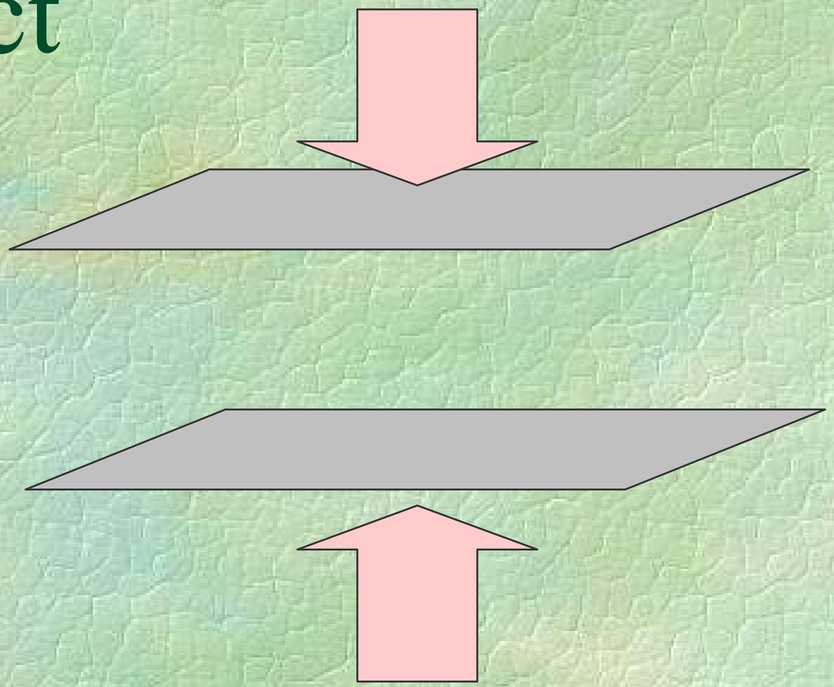
New Neutrino Channels





- A single neutrino can emit or absorb an electron-positron pair.
- A single electron can emit or absorb a neutrino pair.
- The neutrino rates increase with magnetic field and strongly depend on the field direction.

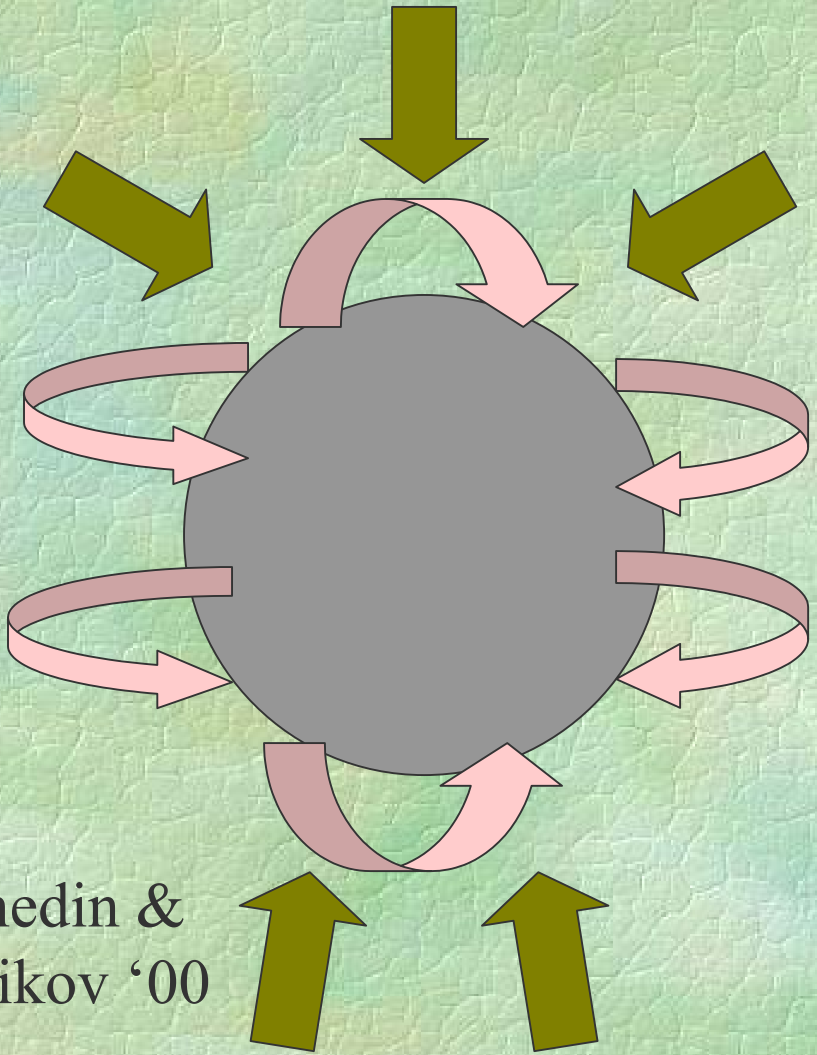
The Casimir effect



- The Casimir effect results from the difference in vacuum energy between two regions with different indices of refraction.
- The classic example is the slight attraction between two closely spaced metal plates.
- Accounting for the Casimir force is crucial in designing nanotechnology.

The Casimir effect - Neutron Star

- Material quickly accretes onto a strongly magnetized neutron star pushing the magnetic field loops against the star.
- The collapse of a loop quickly releases the energy of the cavity:
  $\sim 10^{49}$ erg $R_6^{\,3}\, B_{16}^{\,6}$



Gnedin & Kiikov '00

The Casimir effect in water

- Schwinger ‘92 proposed this as an explanation for the emission of light and X-rays from water driven with ultrasound.
- Here ~100 Hz accretion instabilities crush loops creating the GRB time structure.
- This might sound crazy, but who would have thought that some massive stars explode by shooting an ultrarelativistic jet through their envelopes.

Summary

- The presence of a strong magnetic field dramatically alters the interaction of light and matter.
  - Some corrections are small (index of refraction).
  - New processes become possible (photon splitting, one-photon pair production, etc.)
  - Processes that are sensitive to the structure of electron phase-space can be dramatically affected (neutrino emission and absorption).