What can QED tell us about neutron stars and vice versa?

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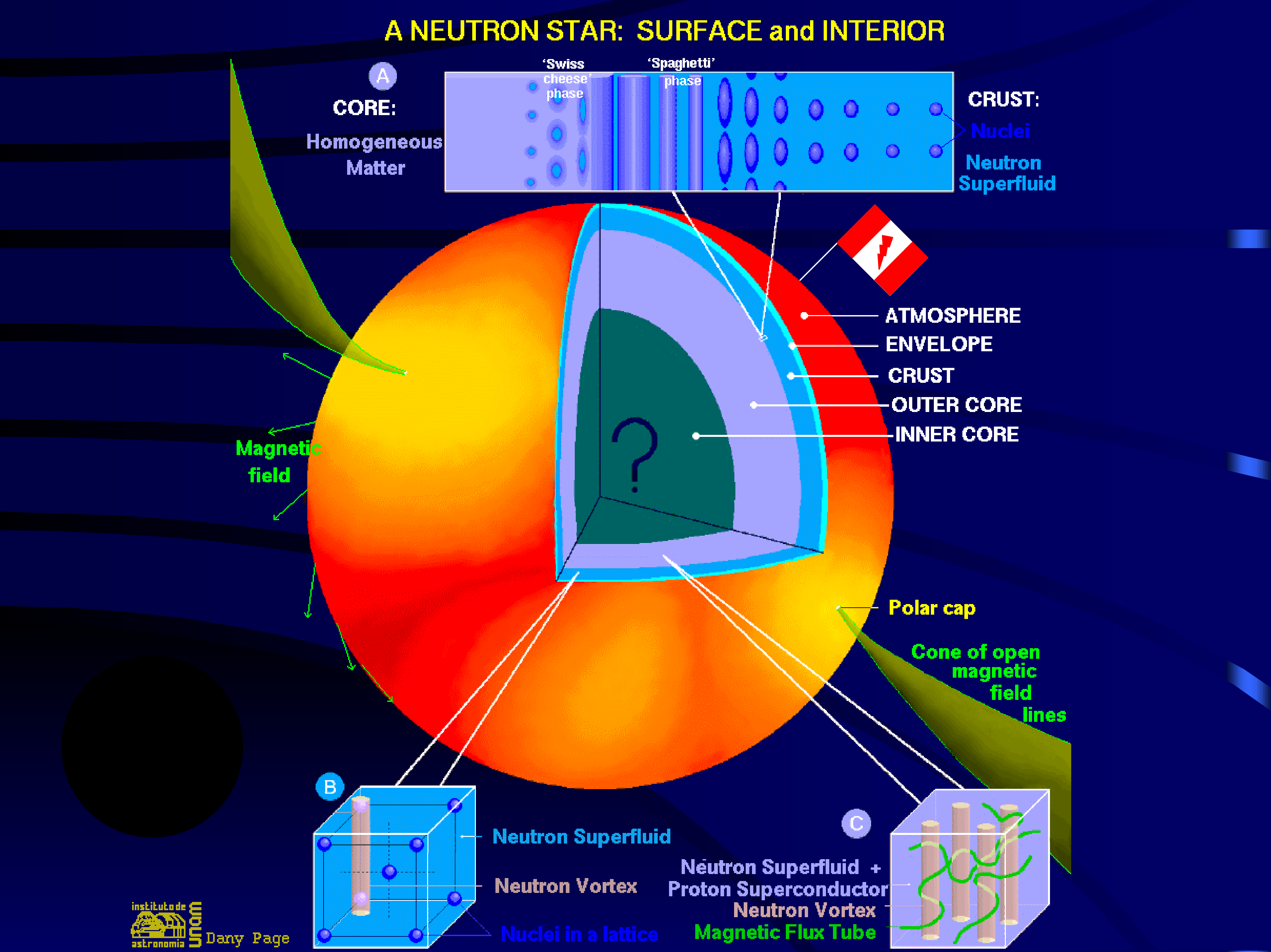
Introduction

- The structure, cooling and observations of neutron stars probes all four forces in regimes inaccessible to Earthbound experiments. Neutron stars uniquely probe:
  - Strong-field general relativity
  - Nuclear and neutrino physics at supernuclear densities
  - QED in ultrastrong magnetic fields


A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube
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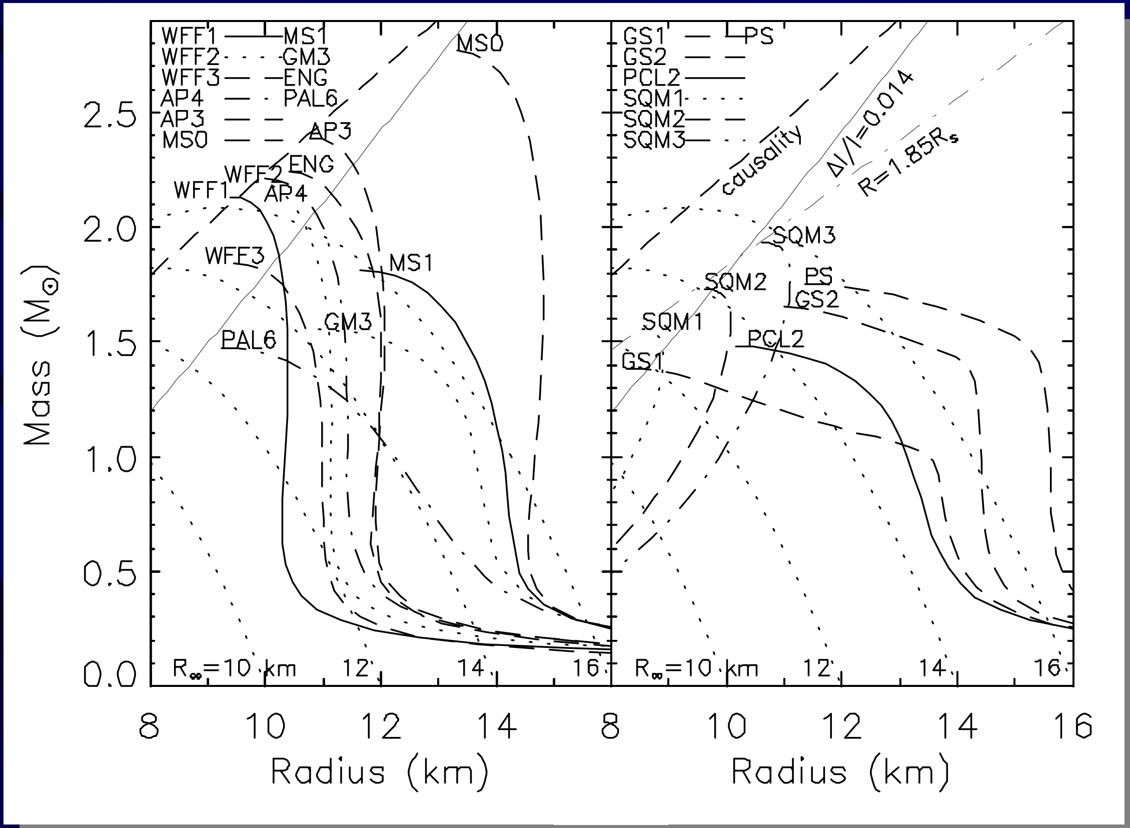
The Nuclear Equation of State

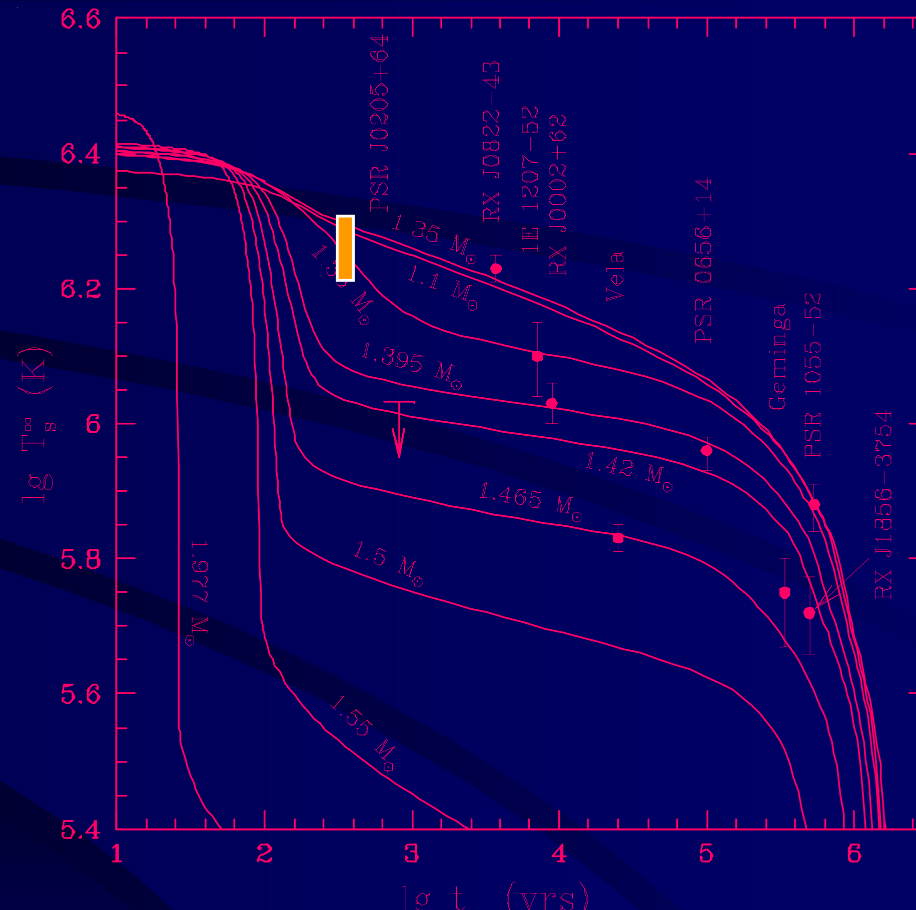
- Softer equations of state result in more compact stars.
  - Relativistic effects
  - Higher surface gravity
- Heat capacity and emissivity depends the composition of the core.



Lattimer & Prakash '01

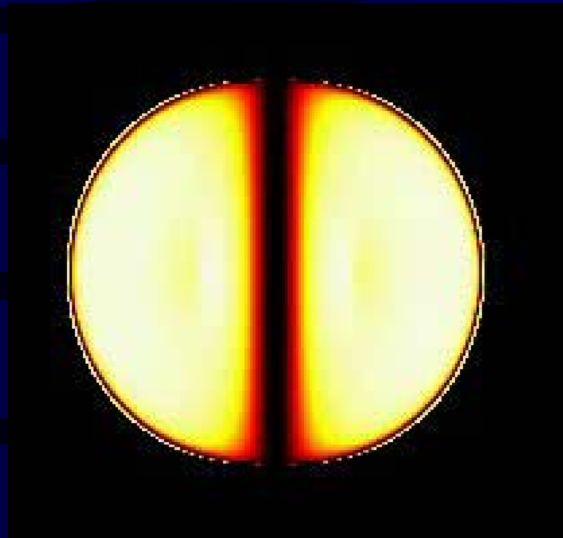
Young Cooling Neutron Stars

- The luminosity of young cooling neutron stars is a direct probe of the physics of ultradense matter.
- Is there a quark-gluon phase transition at high chemical potential?

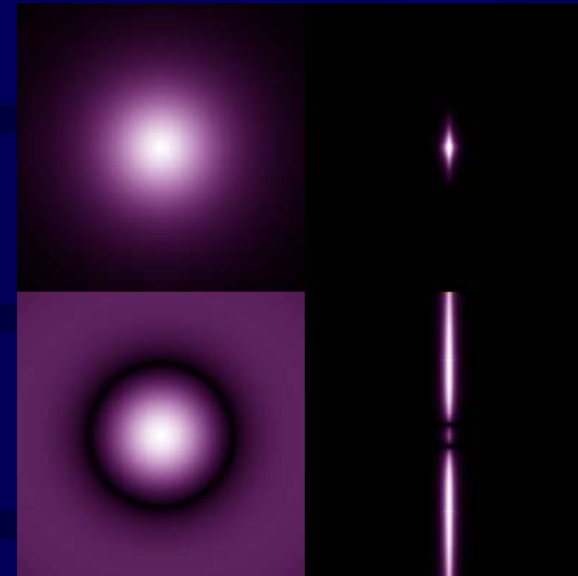


Yakovlev et al. ‘02

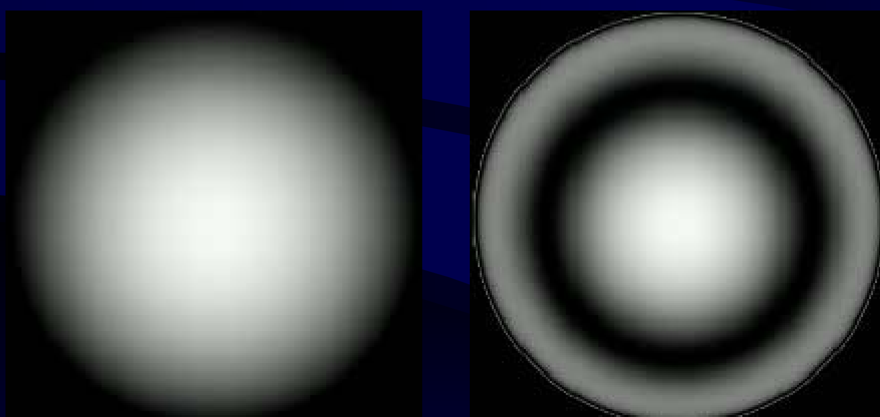
Chakrabarty et al. ‘01



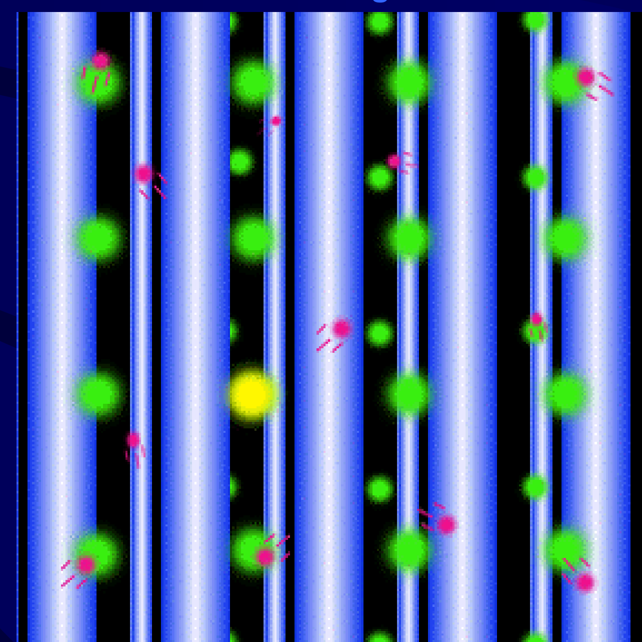
MAGNETOSPHERE: Magnetic Lensing



ATMOSPHERE: Magnetic Atoms



MAGNETOSPHERE: Gravitational Lensing



ENVELOPE: Anisotropic Heat Conduction

JSH, Hernquist; Shaviv, JSH, Lithwick '99

Polarized Light near Neutron Stars

- The thermal radiation from the surface of neutron stars is slightly to fully polarized.
- How strongly polarized is the radiation that we could observe and what can it tell us?
- *c.f.* Pavlov & Zavlin

with Nir Shaviv (CITA) and Don Lloyd (CfA)

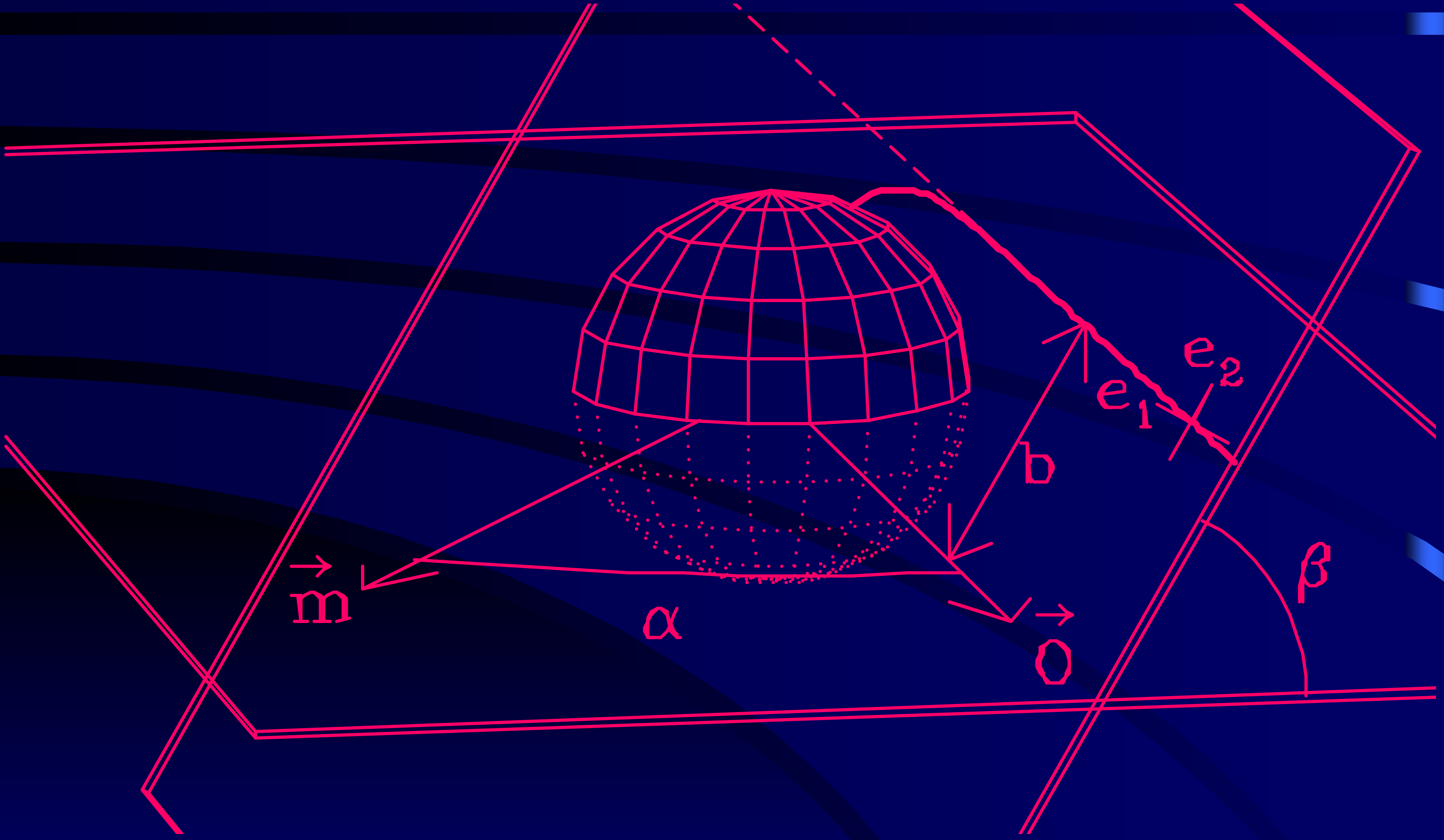
Contents

- Neutron Stars:
  - – What happens to photons as they pass through neutron star magnetospheres?
  - – How does this affect what we see?
    - Ionized hydrogen atmosphere
  - – How can we verify that this happens (with today's instruments)?

Neutron Star Atmospheres

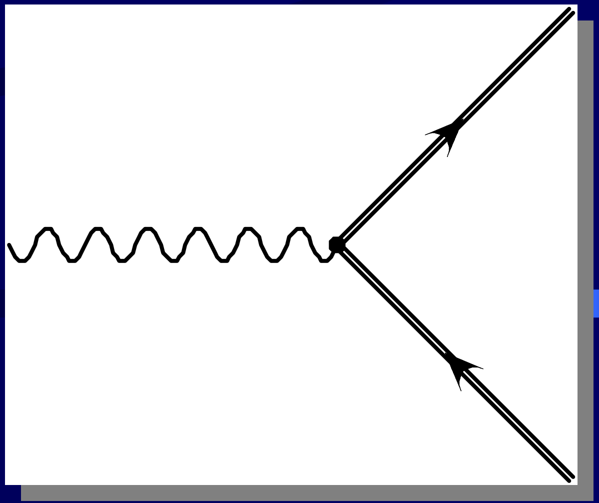
- In the atmosphere of a magnetized neutron star, the opacity of photons in the two propagating modes may vary by several orders of magnitude.
  - $\kappa_{\parallel} \sim (E_\gamma/E_{cyl})\, \kappa_{\perp}$
- The emergent radiation is polarized perpendicular to the local magnetic field.
- How does it all add up?

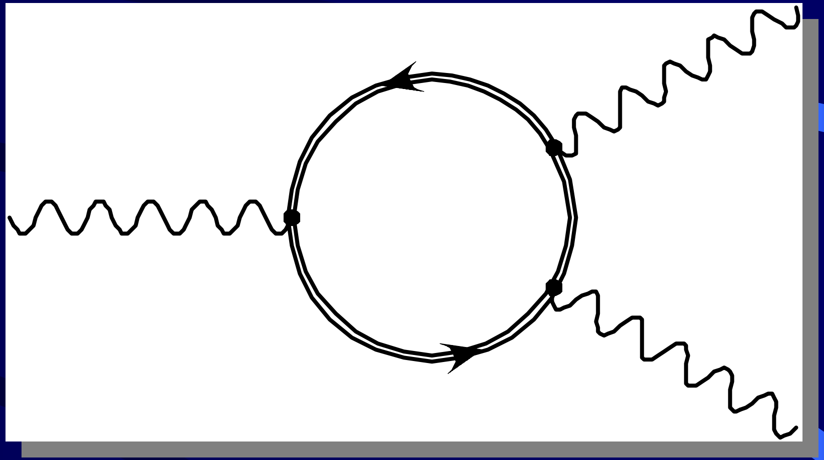
The Photon Trajectory

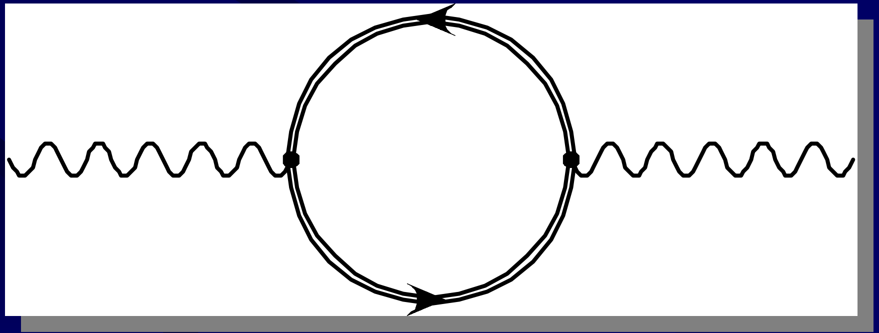


Strong-field QED

- In the magnetic field near a neutron star, many process may become important that we cannot otherwise probe.
- Tracers of these processes are generally polarized.







What happens to the polarization of photons near neutron stars?

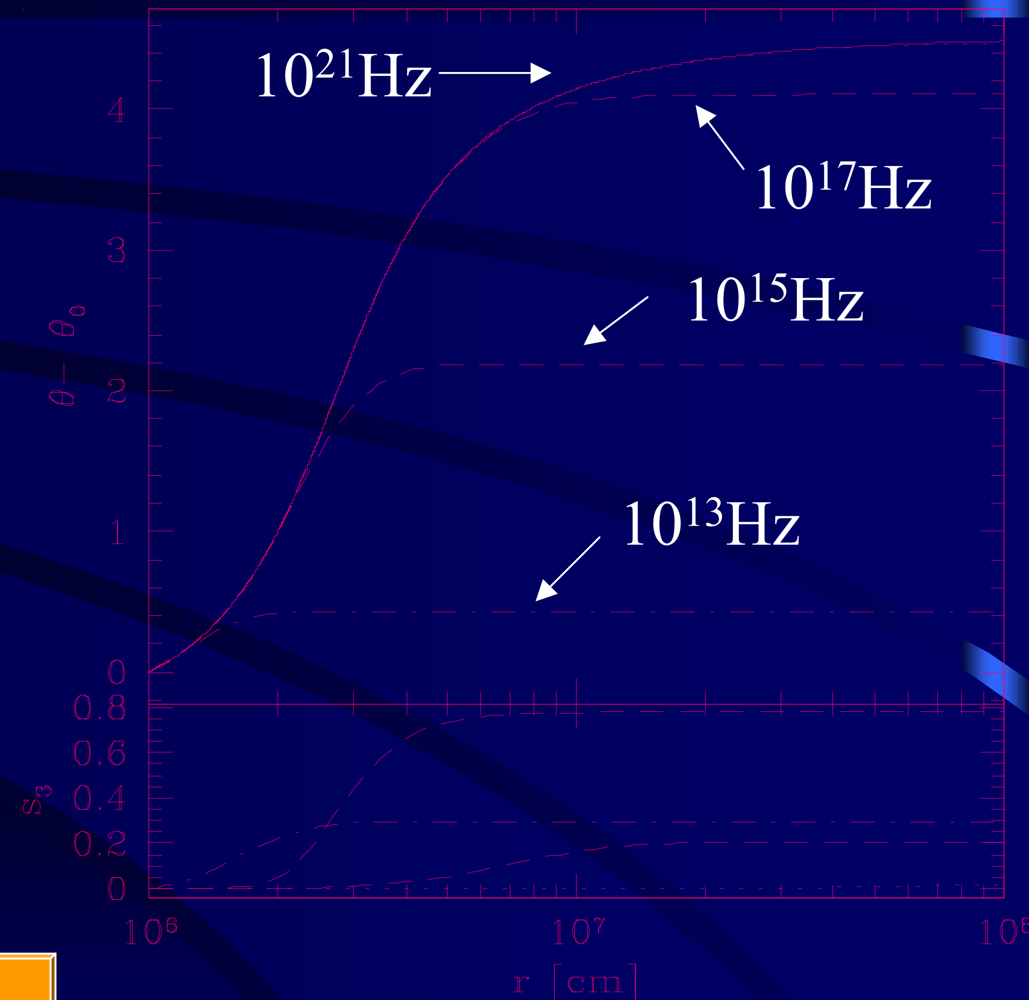
- The polarization of light travelling through a transparent medium evolves as:

$$\frac{d\vec{s}}{dl} = \vec{\Omega} \times \vec{s}$$

  - *s* is the normalized Stokes polarization vector
  - Ω is the birefringent vector which for QED points in the direction of the projection of the magnetic field onto the Poincaré sphere.

Polarization-Limiting Radii

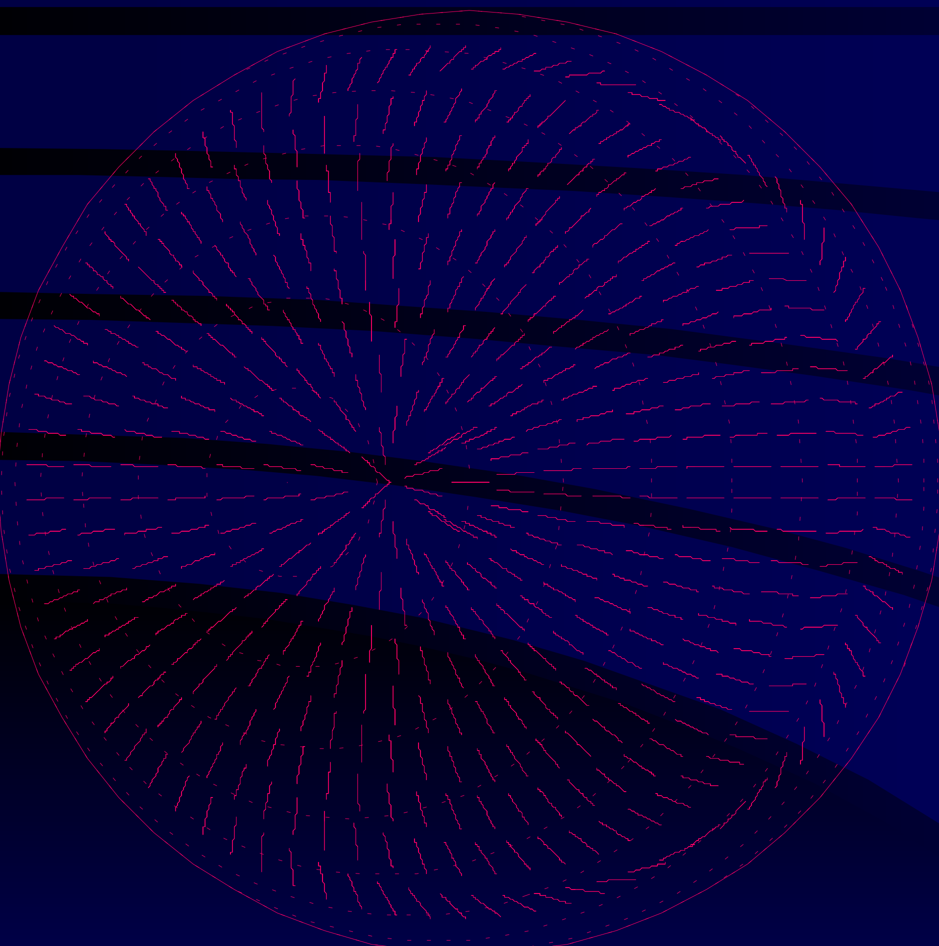
- The polarization modes of high-energy photons couple further from the stellar surface than those of low-energy photons.
- Also, if the direction of the magnetic field changes appreciably during coupling we get a circular component.



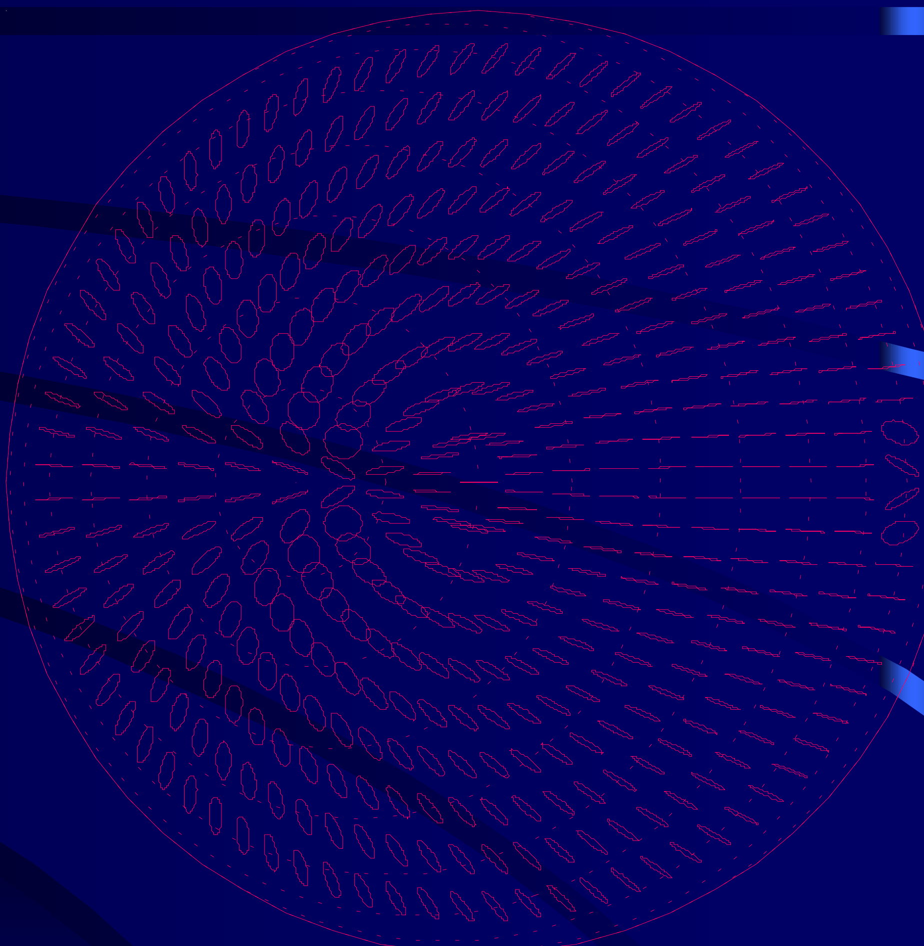
Why Is This Important?

- Cheng and Ruderman exploited the plasma-induced low-energy PL radius to explain the high net polarization of pulsars in the radio.
- We can do the same here!   Except:
  - We understand the emission in detail.
  - The emission comes from the surface.
  - Plasma birefringence is familiar; vacuum birefringence is unprobed.

Low-Energy Polarized Images

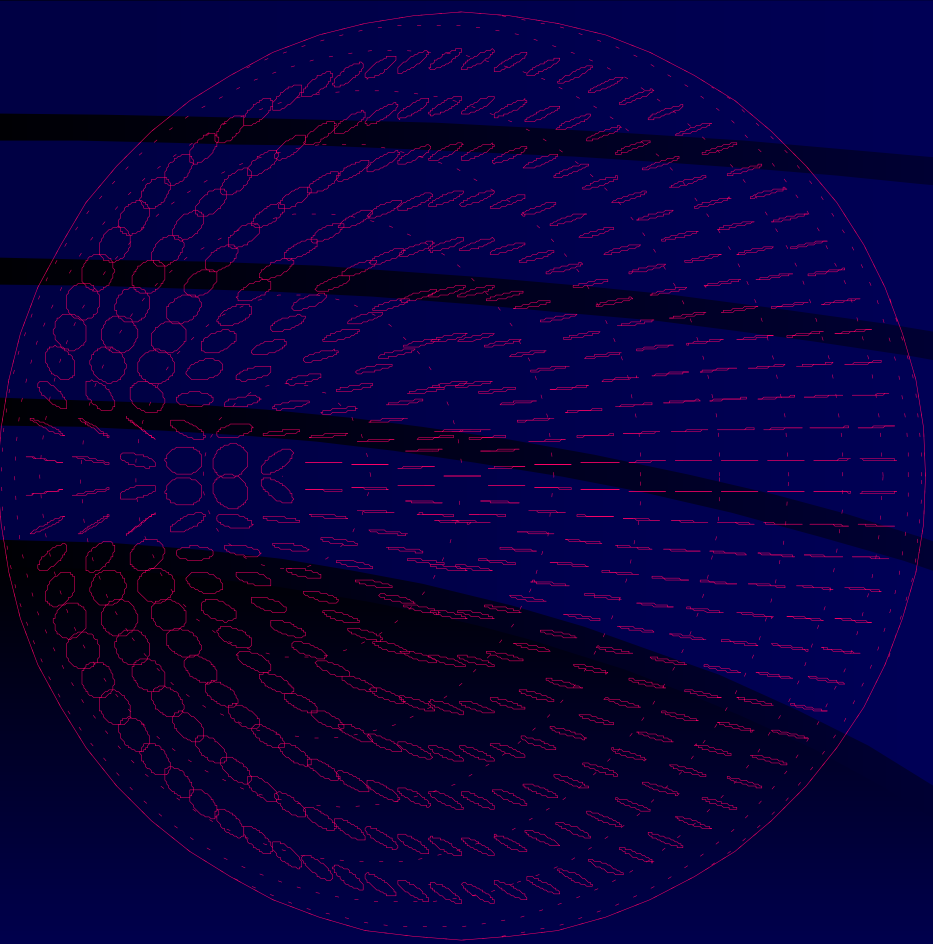


Zero Hz - QED neglected

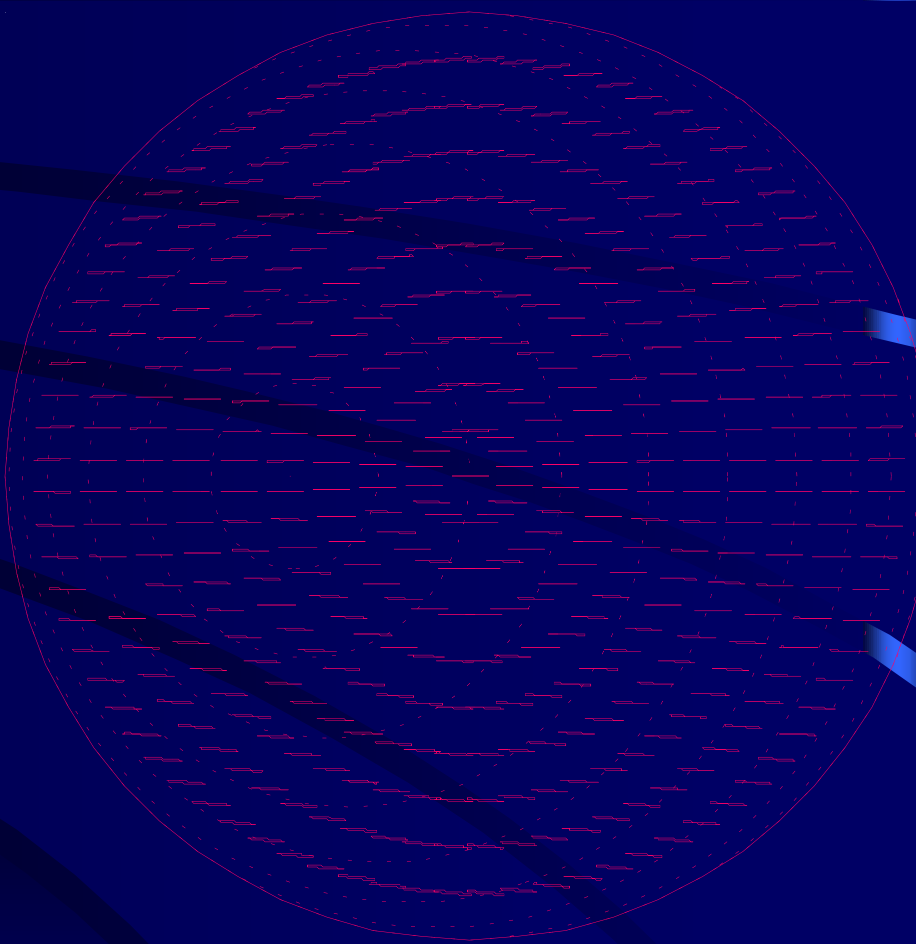


10^{15} Hz - Optical/UV

High-Energy Polarized Images

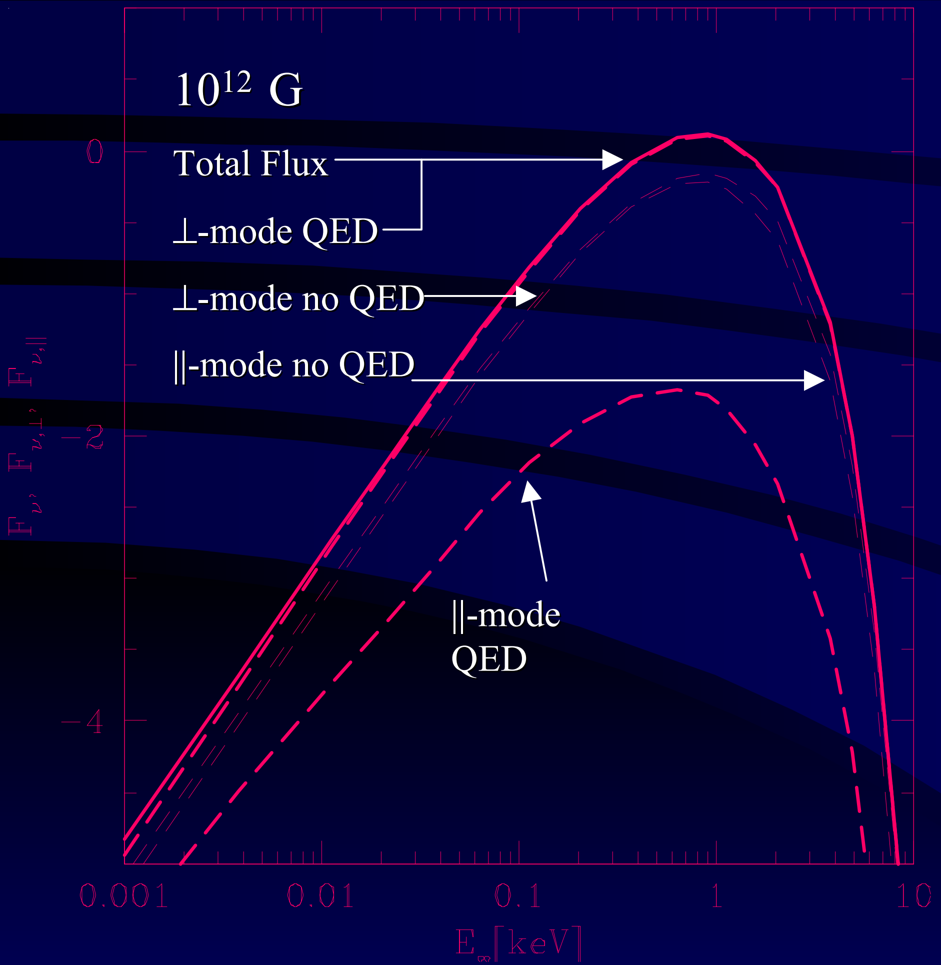


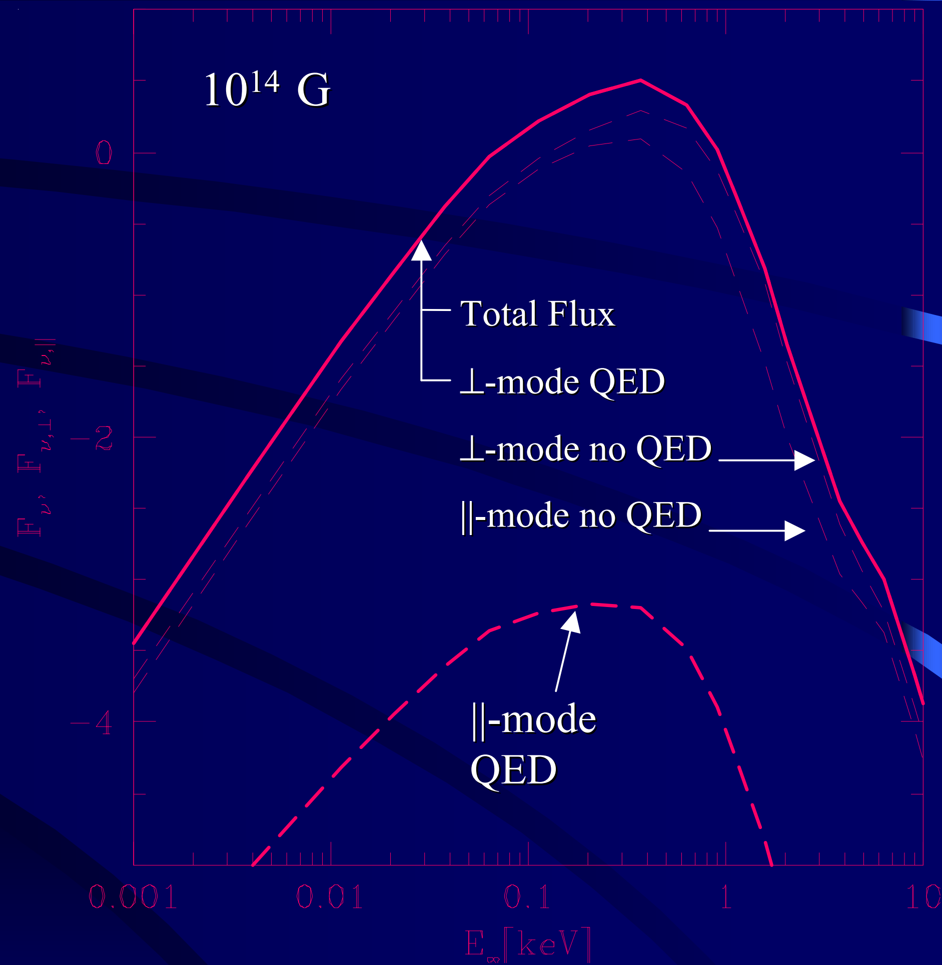
10^{17} Hz - Soft X-Ray



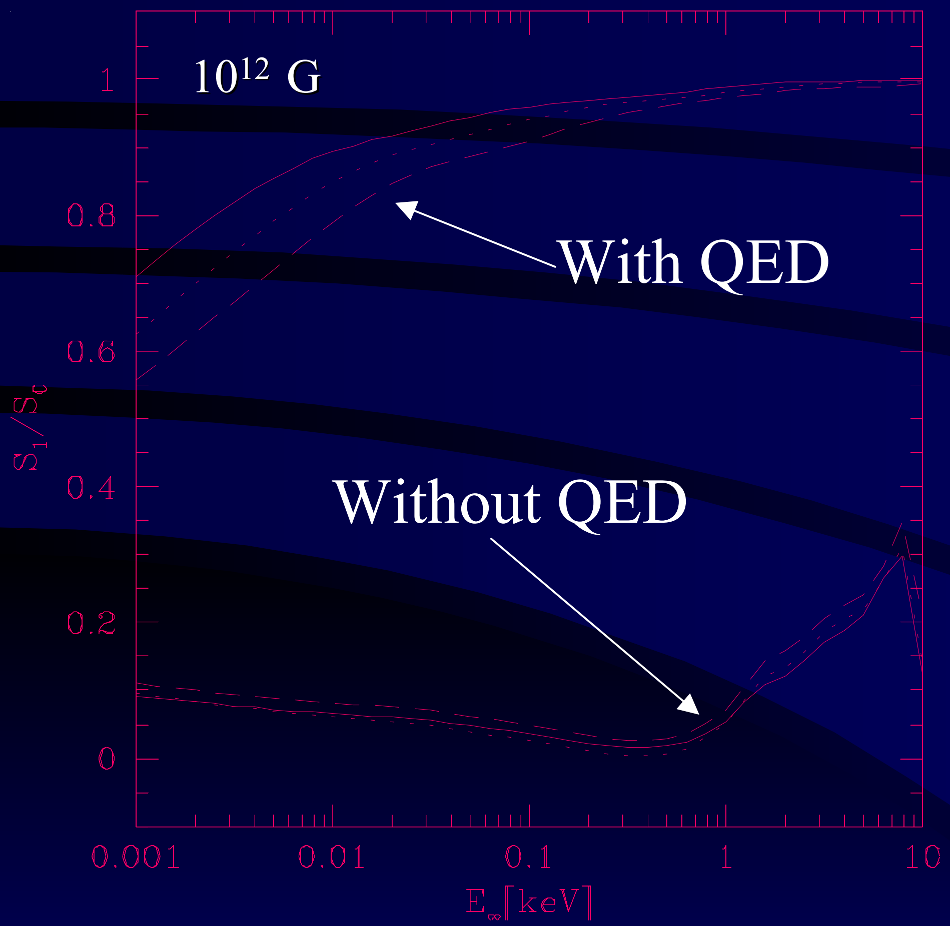
10^{21} Hz - Gamma-Ray

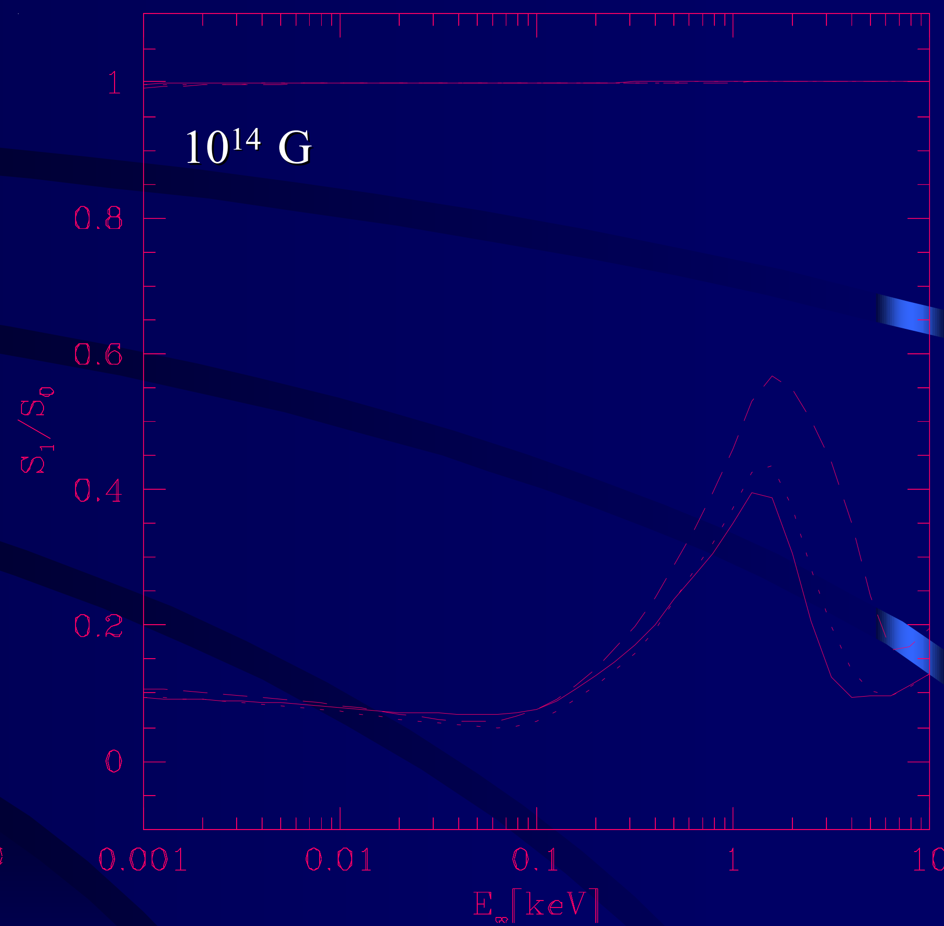
Polarized Spectra from Neutron Stars





Polarized Fractions

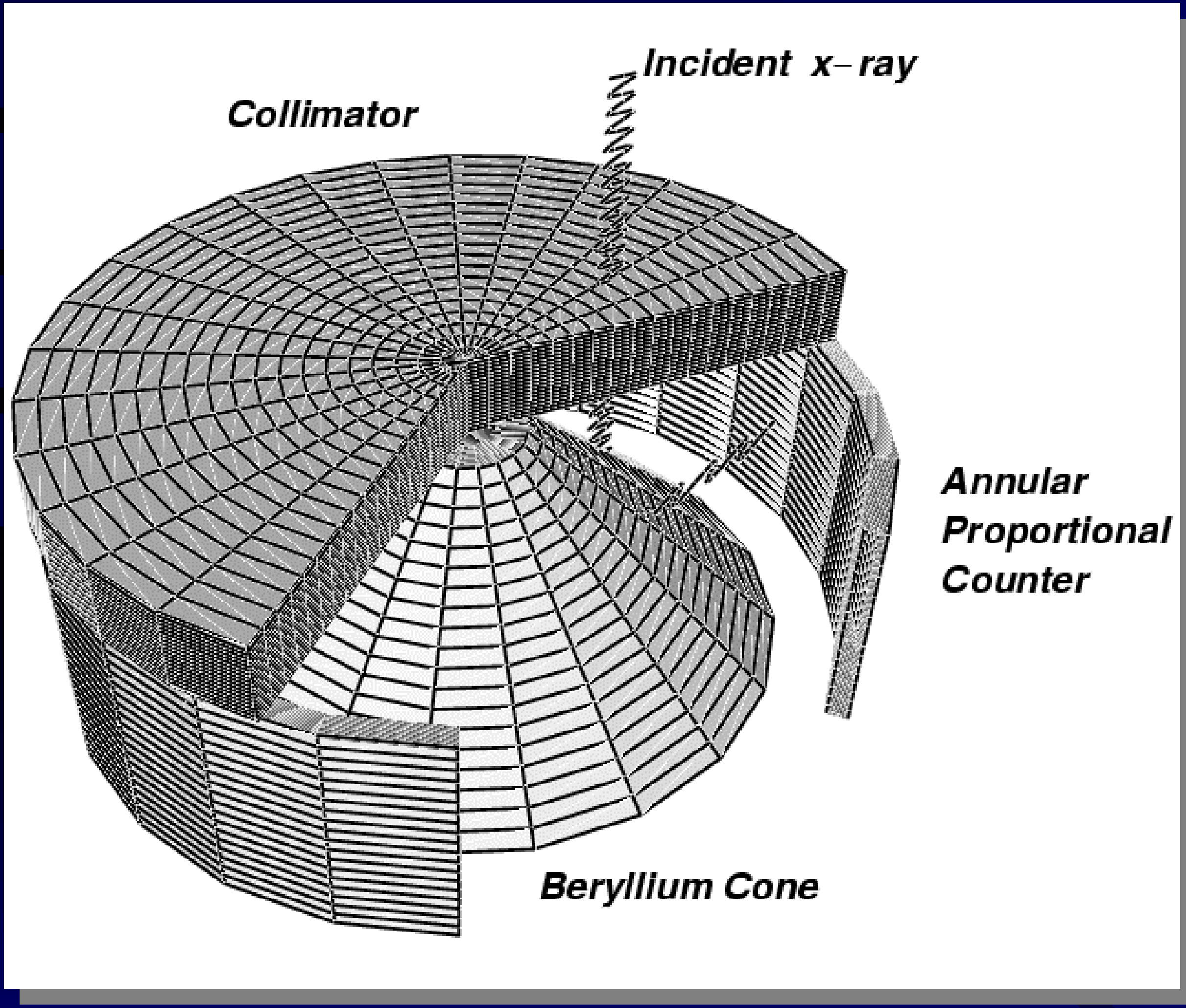




Implications

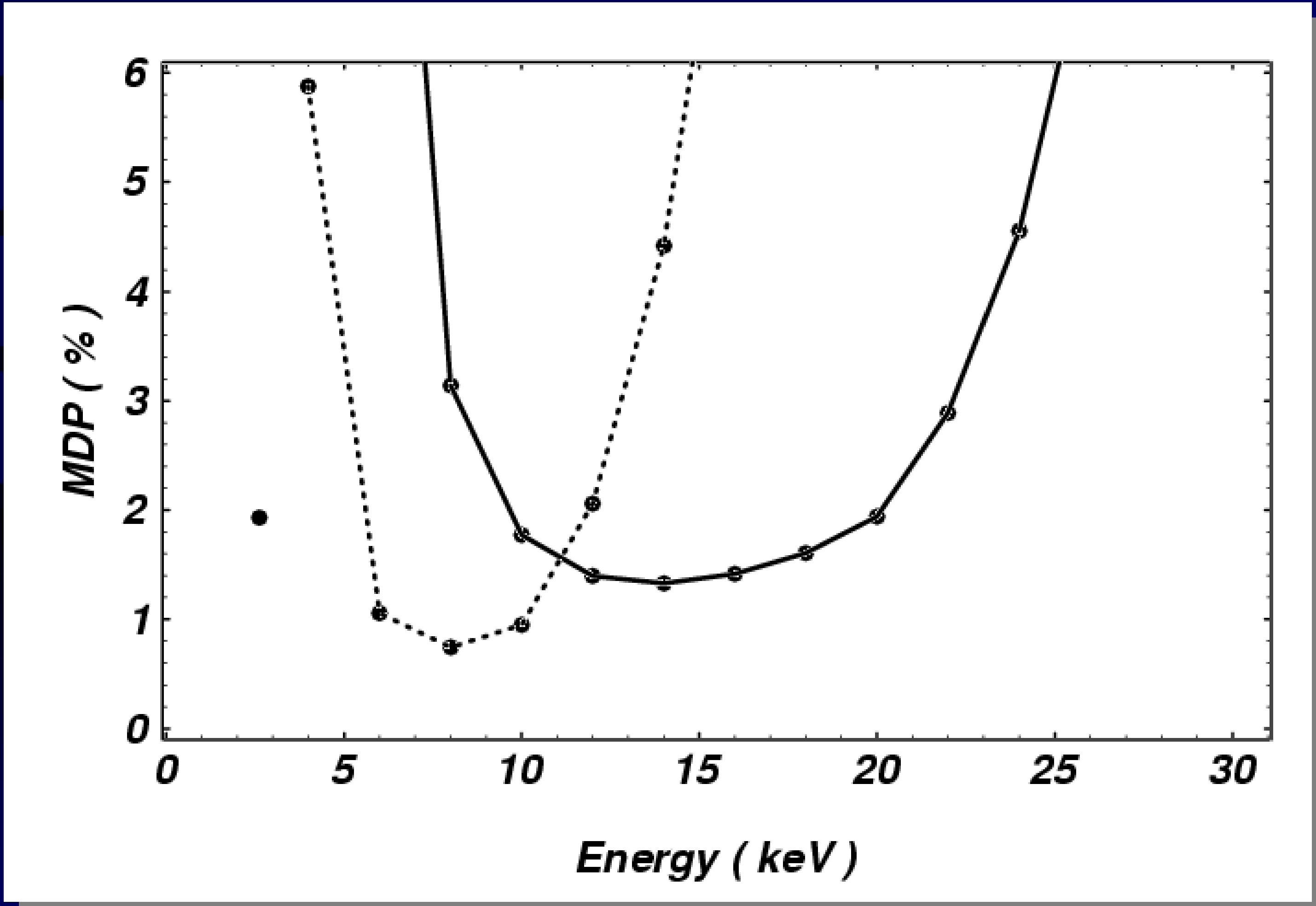
- The best diagnostics for understanding NS structure are in optical/UV not X-ray!
- A detection of the polarized thermal radiation at any energy from a NS will verify the birefringence of the magnetic vacuum!
- The polarized fraction depends strongly on geometry and field strength.

X-ray Prospects



- XPE SMEX for the current NASA AO

Sensitivitiy



Let's Do It!

- Optical/UV emission originating from the stellar surface has been detected from:

RXJ 1856.5-3754	*U*=24.4	36ks
RXJ 0720-3125	*B*=26.6	120ks
PSR B0656+14	*B*=24.98	210ks
PSR B0950+08	*F(130LP)*=27.1	900ks
Geminga	*V*=25.3	90ks

Polarizer for ACS is only 15% efficient at 2500Å

- Performing the observations as far into the UV as possible reduces the contamination from synchrotron emission plus the objects are brighter and more polarized in the UV.

Optical Prospects

- Ground-based polarimeters achieve higher throughput. Prism analyzers can achieve nearly fully transmission.
- 24ks on Keck in *B* would detect 20% polarization from RXJ 0720-3125.
- Polarimetry of these objects is possible (although one would need a generous TAC) using HST or 8-meter telescopes!