Atoms and Atmospheres in Strong Magnetic Fields

Wynn C.G. Ho

School of Mathematics, Southampton

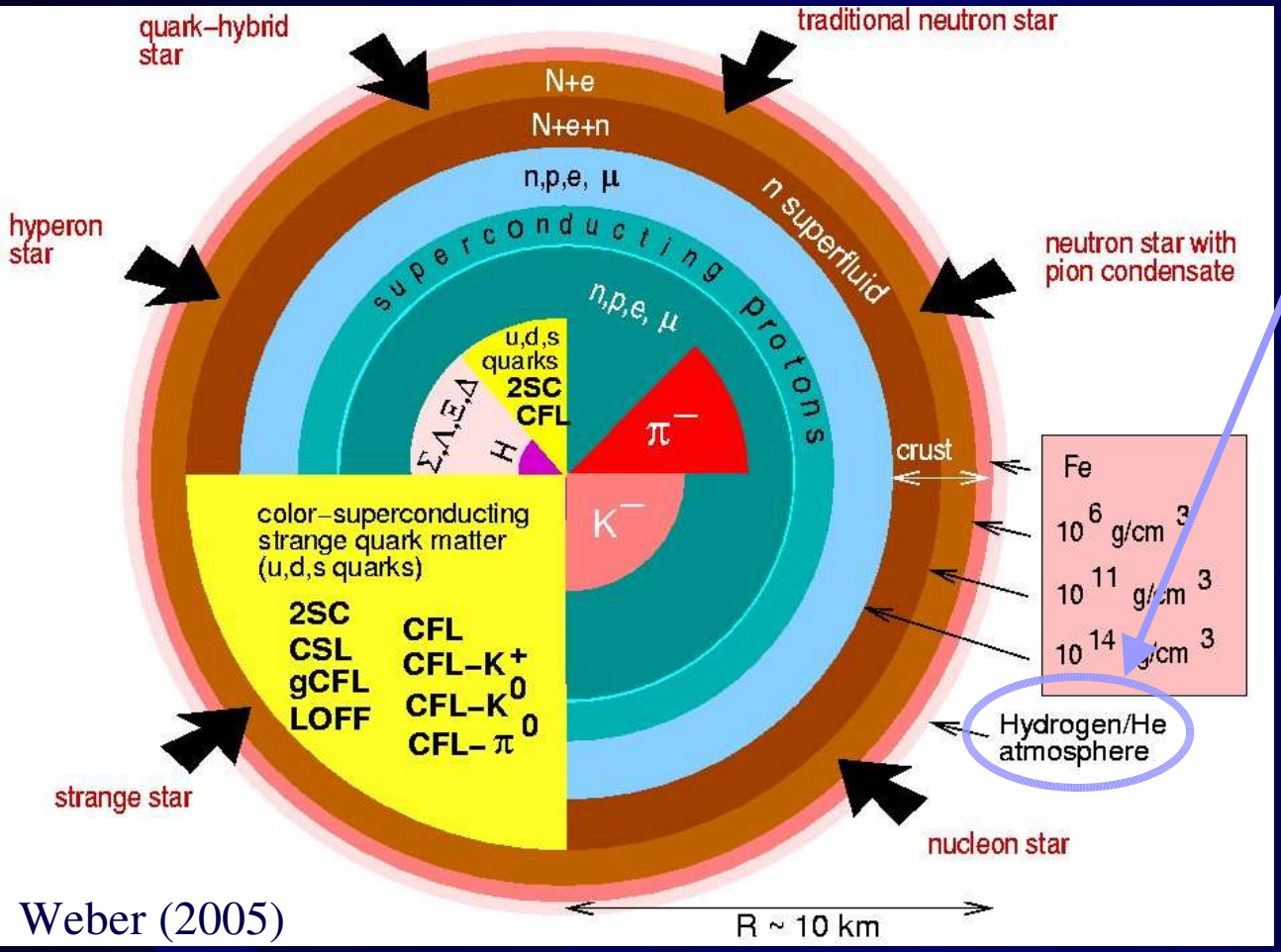
Collaborators

Gilles Chabrier - Ecole Normale Superieure de Lyon, CRAL, France
Philip Chang - University of California, Berkeley, USA
David L. Kaplan – University of California, Santa Barbara, USA
Dong Lai - Cornell University, USA
Kaya Mori – Columbia University, USA
Alexander Y. Potekhin - Ioffe Physico-Technical Institute, Russia
Matthew van Adelsberg – University of California, Santa Barbara, USA

MICRA2009 – 24-28 August 2009

UNIVERSITY OF Southampton
School of Mathematics

Neutron Star Surface Emission



Weber (2005)

- Atmosphere scale height
  $H \sim 1\ \mathrm{cm} \ll R$
- Chemically homogeneous
- Emission is anisotropic and polarized in magnetic field
- Vacuum polarization important at
  $B > B_Q = m_e^2 c^3/e\hbar$
  $= 4.4 \times 10^{13}$ G
- Atomic structure altered by magnetic field
  $\Rightarrow$ bound atoms must be taken into account

Weber (2005)

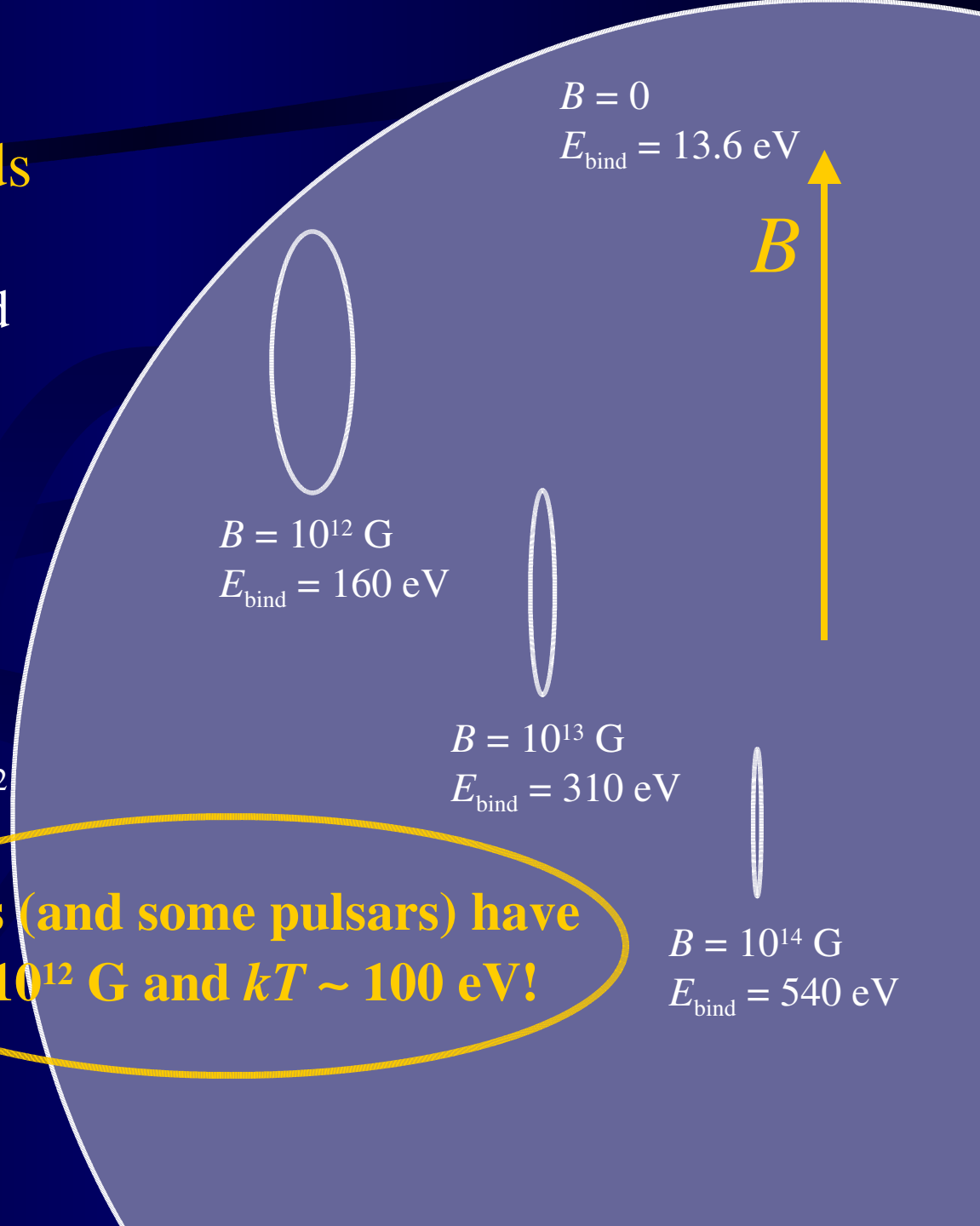
Atoms in Strong Magnetic Fields

- Atomic structure altered by magnetic field when

$$B > B_0 = e^3 m_e^2 c/\hbar^3$$
$$= 2.35 \times 10^9 \text{ G}$$

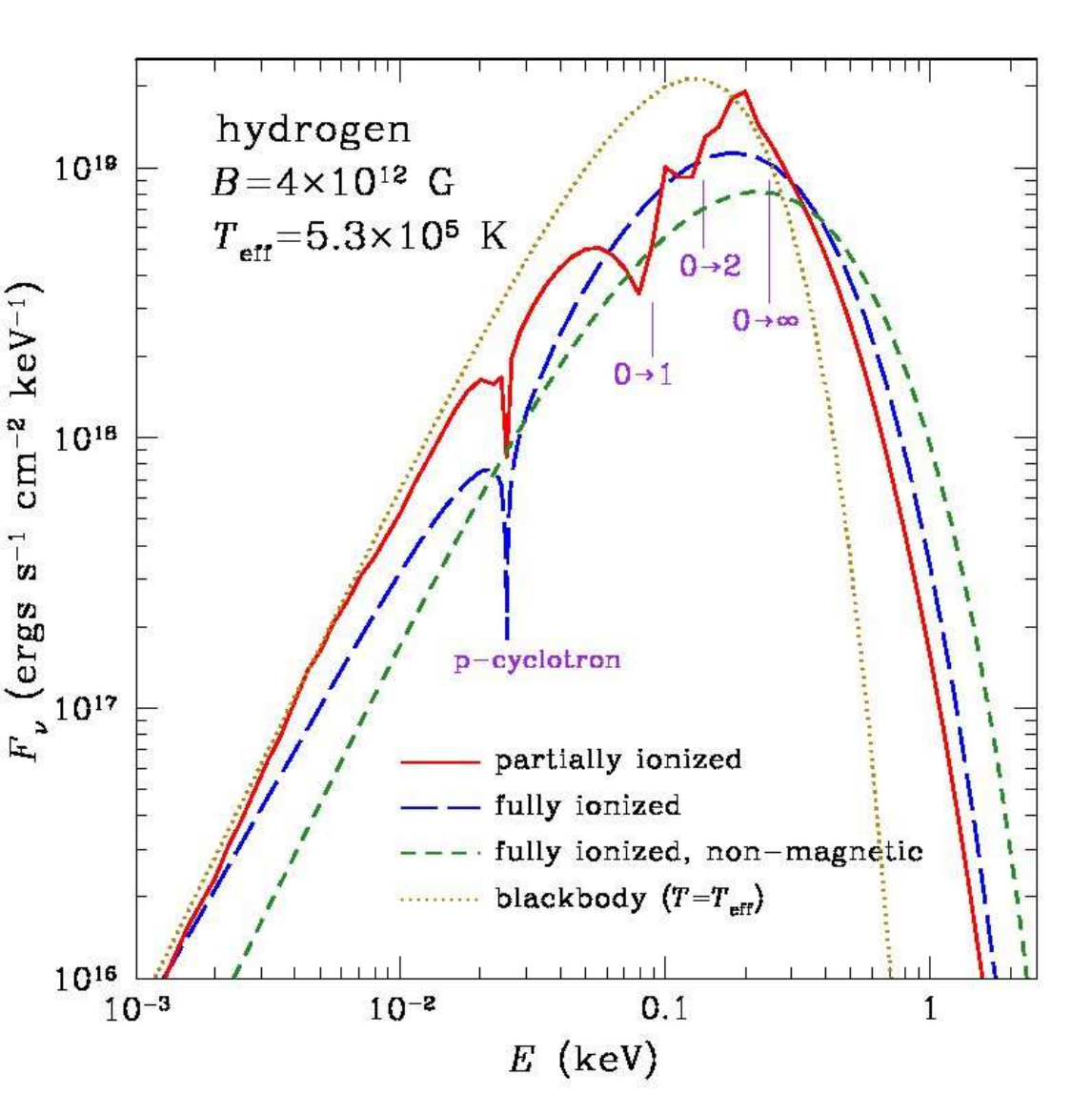
- Binding energy ~ $(\ln b)^2$
- $L_\perp \sim b^{-1/2}$
- $L_z \sim (\ln b)^{-1}$

where $b = (B/B_0)$



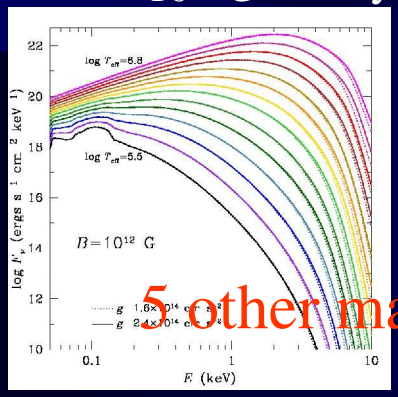
INSs (and some pulsars) have $B > 10^{12}$ G and $kT \sim 100$ eV!

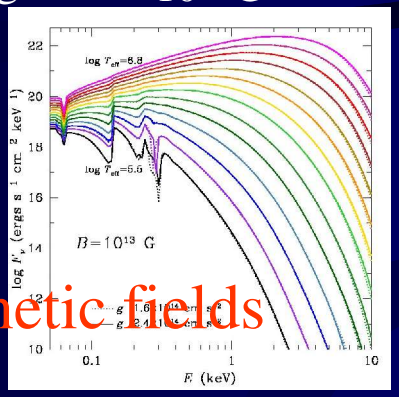
Model Atmosphere Spectra

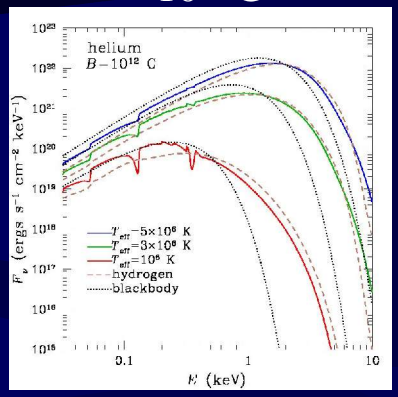


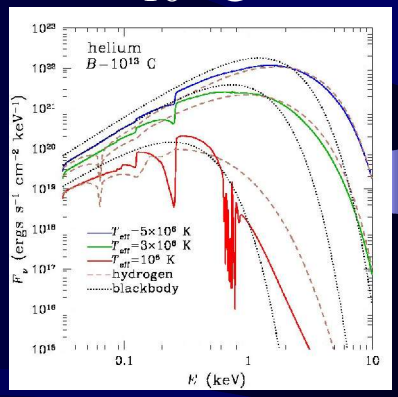
NSMAX (in XSPEC): Magnetic Atmosphere Models

10^{12} G hydrogen 10^{13} G 10^{12} G helium 10^{13} G



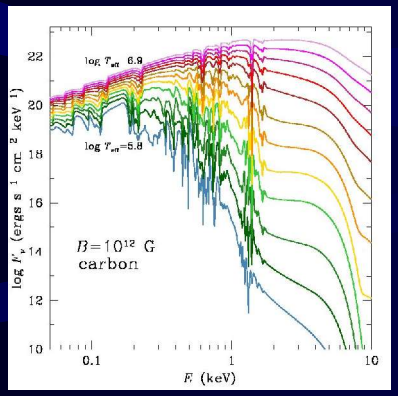


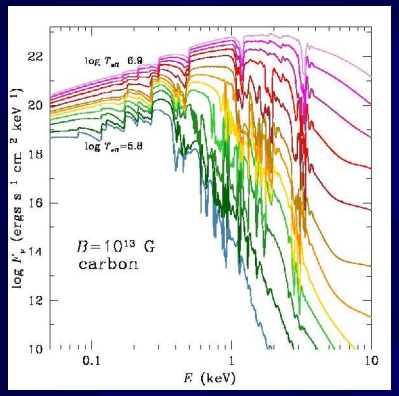


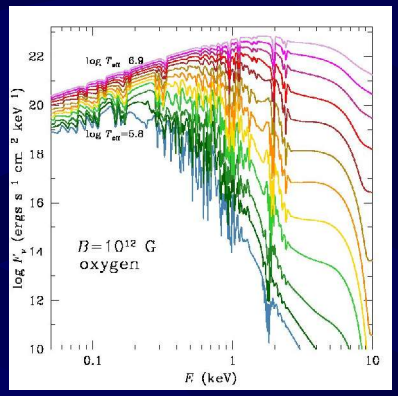


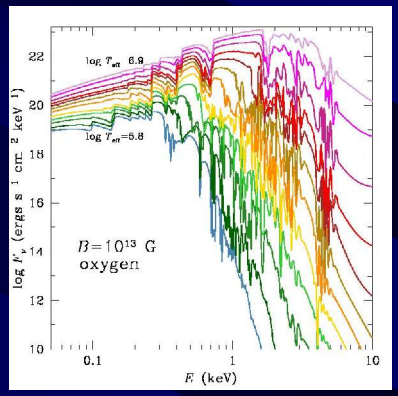
5 other magnetic fields

carbon oxygen

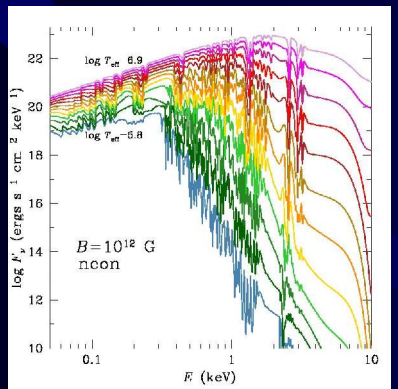


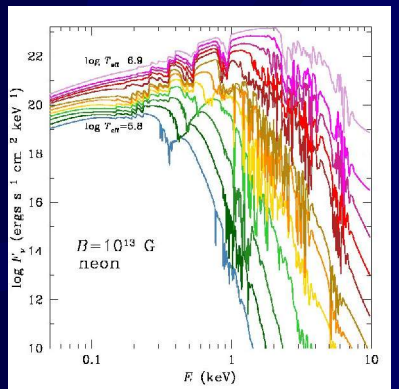


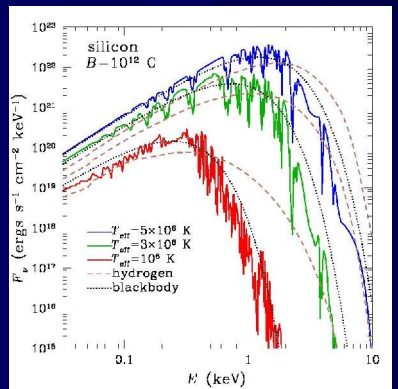


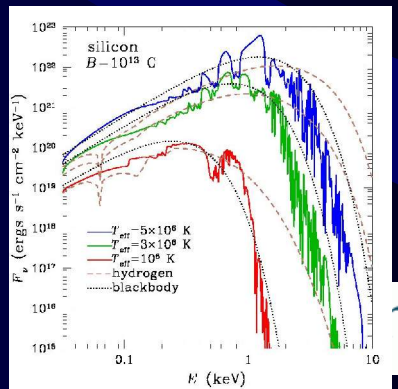


neon silicon

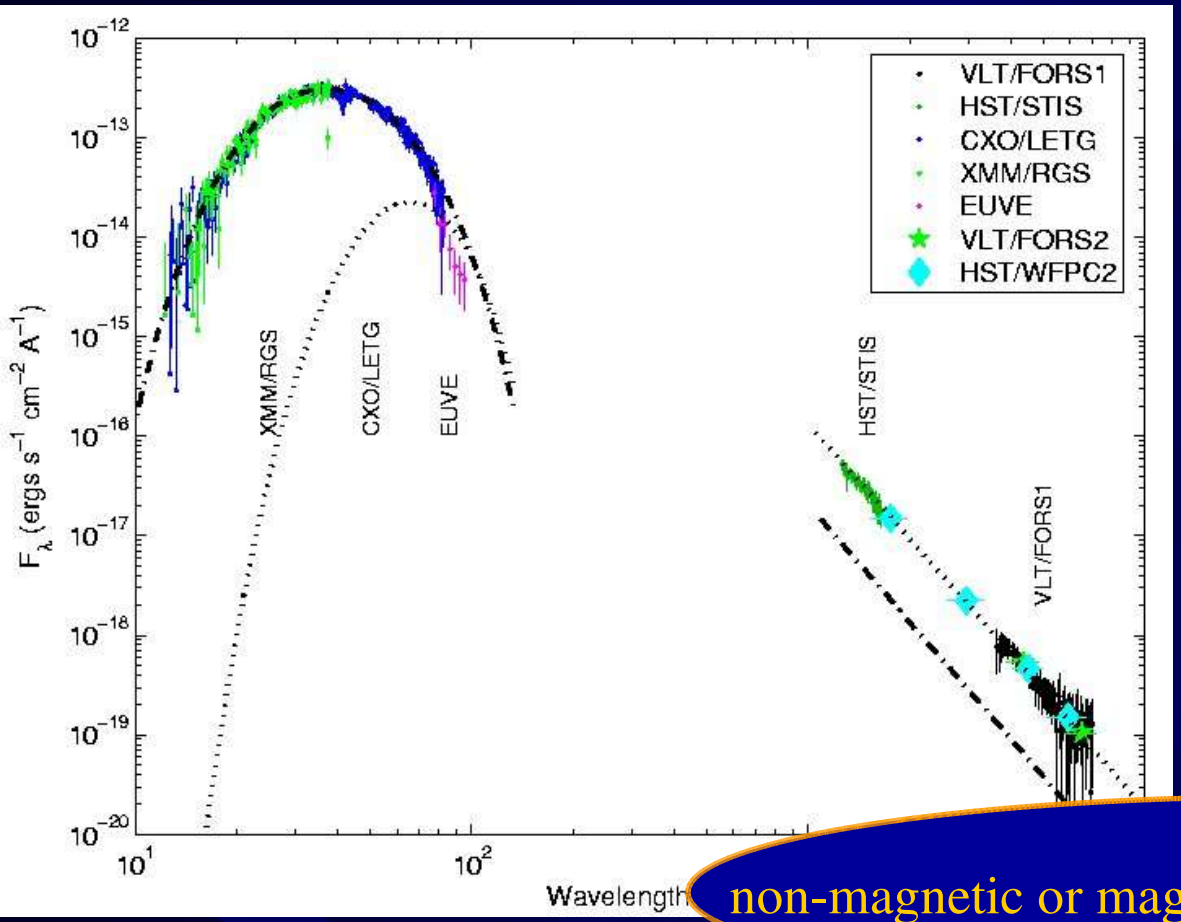








Spectral Models for RX J1856.5-3754



- Dim isolated NSs, aka, "Magnificent Seven"
- Thermal emission

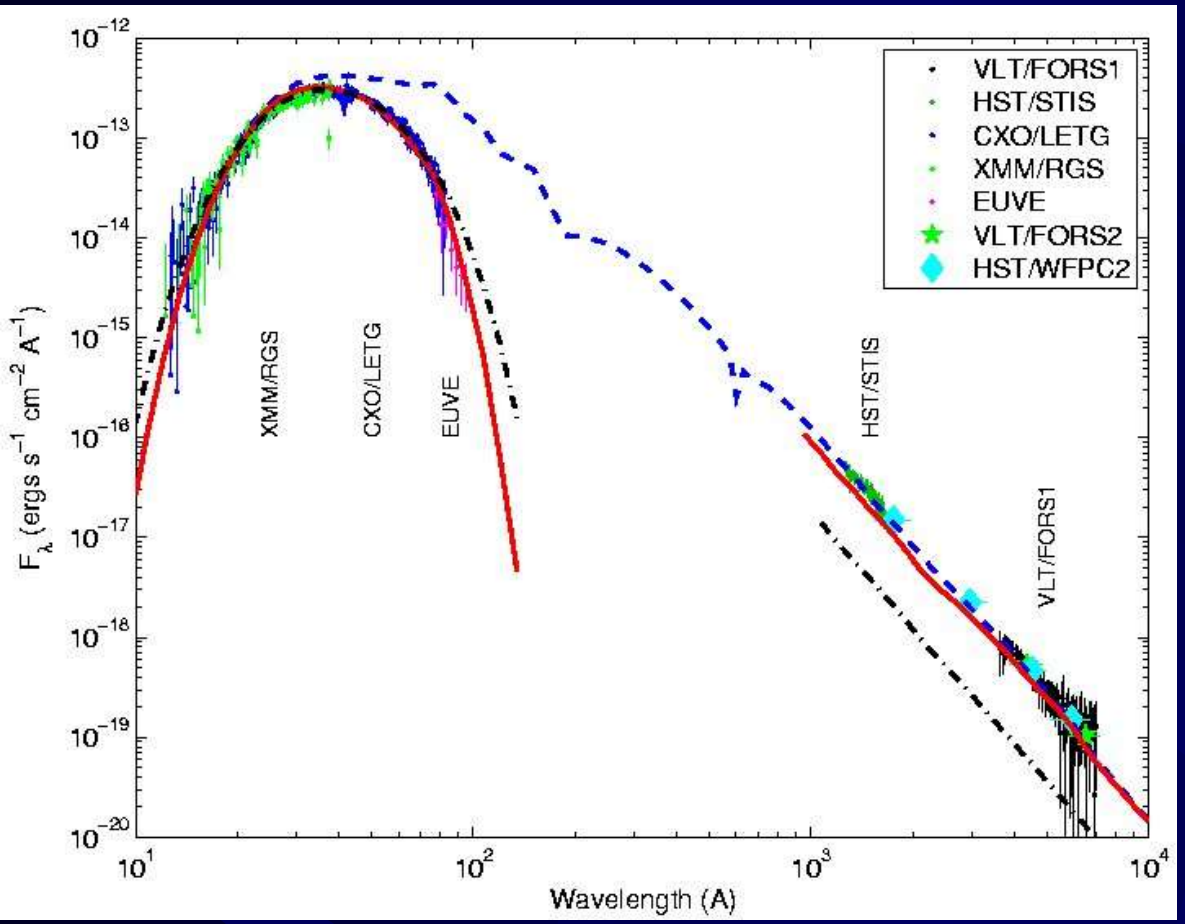
- No spectral features
- One BB underpredicts optical by 7
- Two blackbodies
  - $kT_X^\infty = 63$ eV, $R_X^\infty = 5.1$ km
  - $kT_{opt}^\infty = 26$ eV, $R_{opt}^\infty = 21$ km
- Atmosphere overpredicts » 1
- X-ray pulsations
  - spin period = 7 s
  - pulse fraction ≈ 1%

non-magnetic or magnetic but fully-ionized hydrogen

magnetic partially-ionized hydrogen?

UNIVERSITY OF Southampton
School of Mathematics

Magnetic Hydrogen Atmosphere Model for RX J1856.5-3754

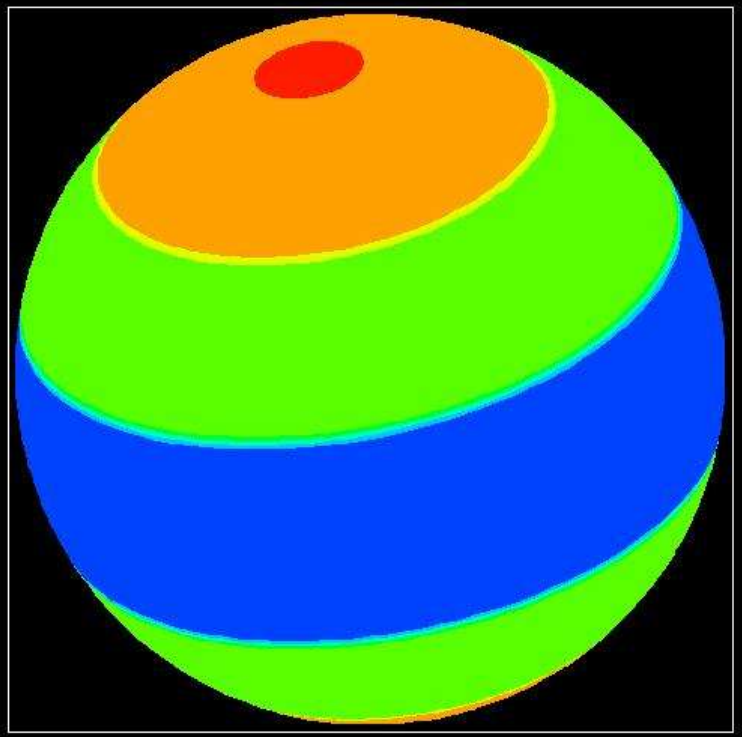


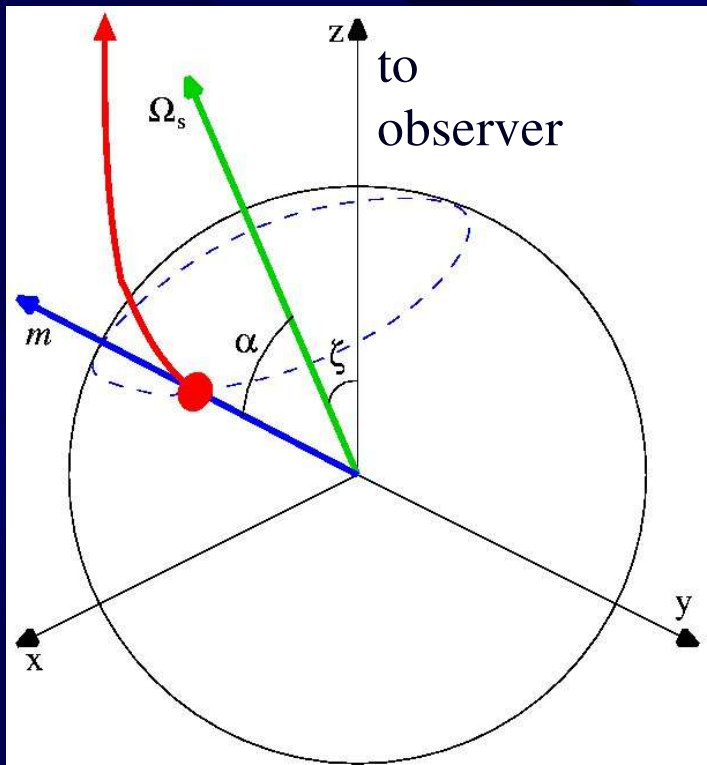
- One BB underpredicts optical by 7
- Two blackbodies
  - $kT_X^\infty = 63$ eV, $R_X^\infty = 5.1$ km
  - $kT_{opt}^\infty = 26$ eV, $R_{opt}^\infty = 21$ km
- Single atmosphere spectrum
  - thin hydrogen atmosphere
  - $B_p \approx (6\text{-}7)\times 10^{12}$ G
  - $kT^\infty = 43$ eV, $R^\infty \approx 17$ km
  - $z_g \approx 0.22$
  - $\Rightarrow R \approx 14$ km
- X-ray pulsations
  - spin period = 7 s
  - pulse fraction $\approx 1\%$

UNIVERSITY OF Southampton
School of Mathematics

Constructing Model of Neutron Star Surface Emission

- Stitch together local patches of atmosphere with different $T_{\rm eff}$ and $\vec{B}$
- Integrate total surface emission, including effect of gravitational light-bending [redshift = $(1 - 2GM/c^2R)^{-1/2}$]
- Resulting emission depends on two angles (α, ζ):
  - α = angle between rotation axis and observer
  - ζ = angle between rotation and magnetic axes

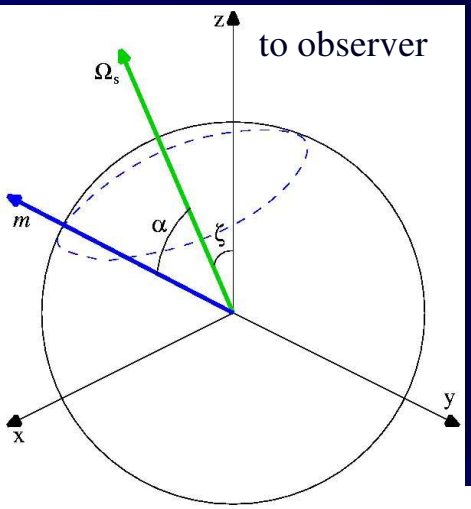


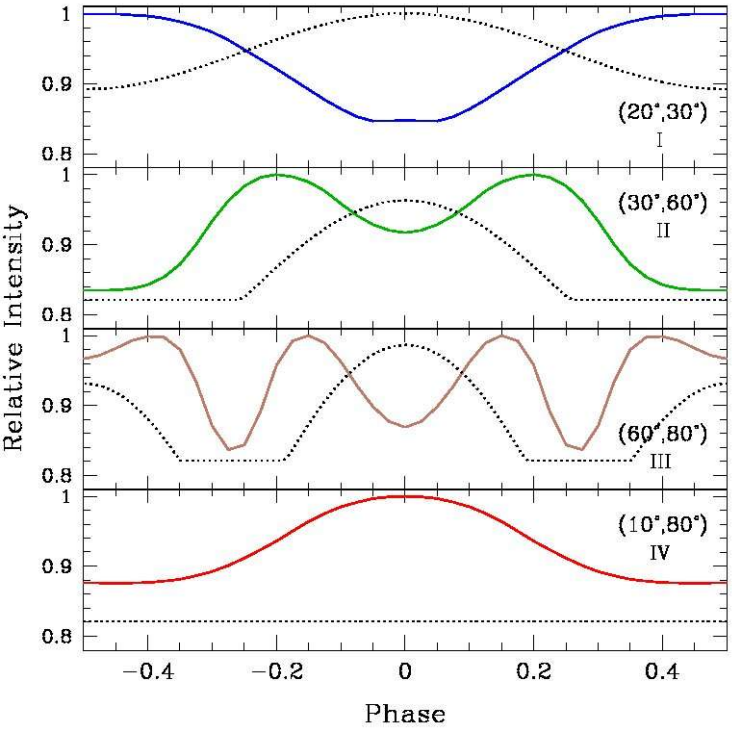


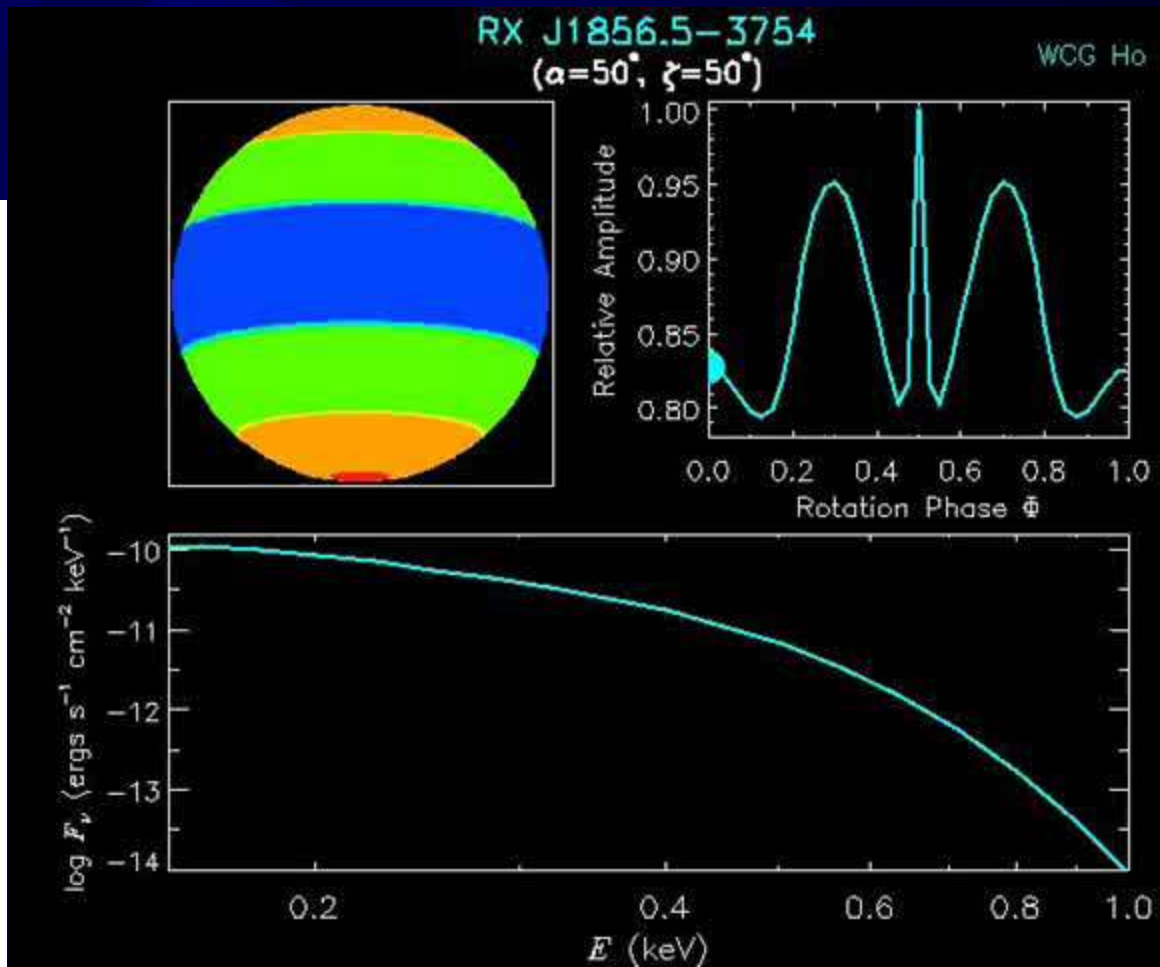
Neutron Star Geometry from Pulse Profiles and Phase-resolved Spectra

- realistic neutron star surface
  - magnetic fields
  - temperatures
  - light bending
- rotating star

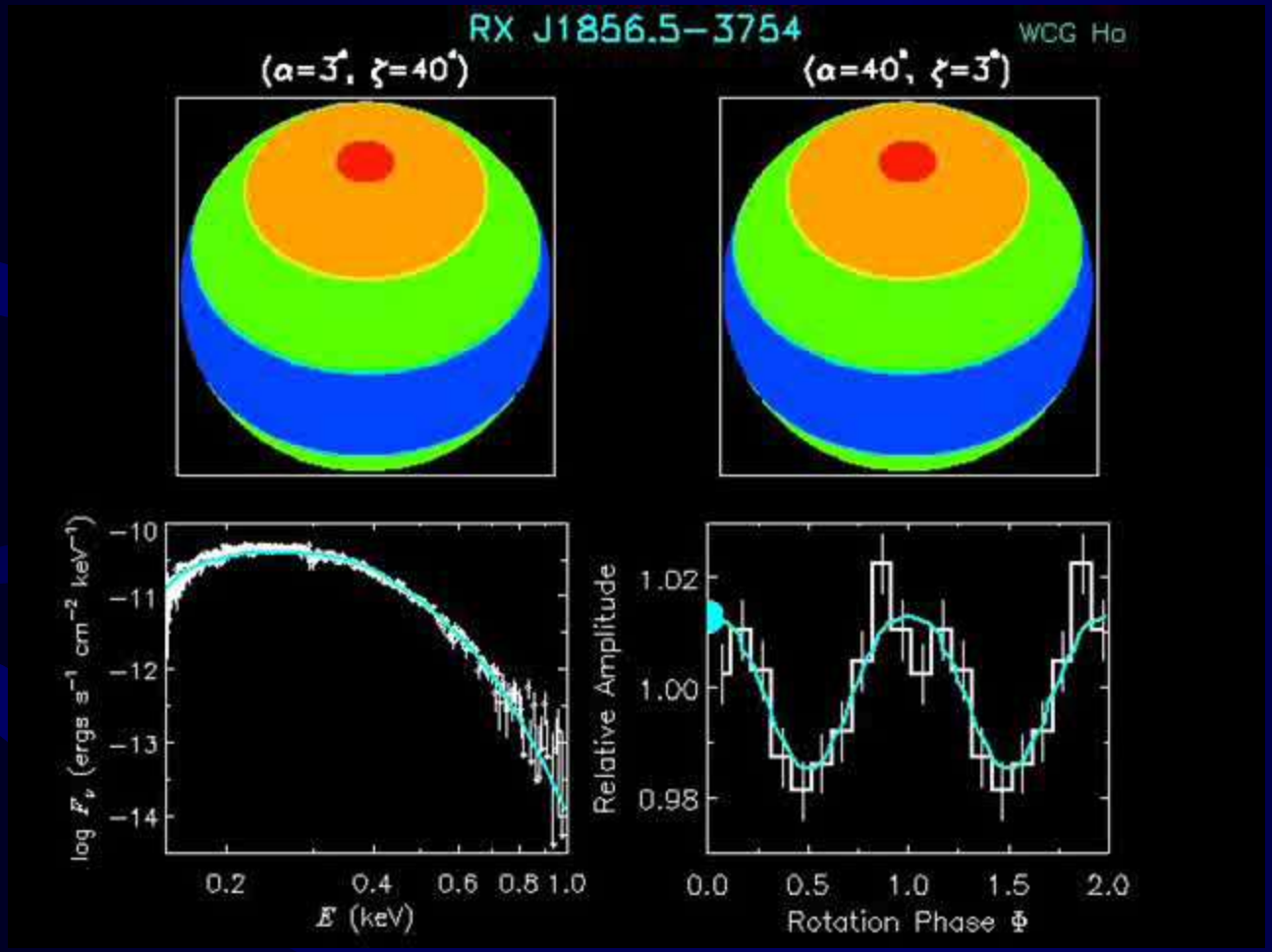
⇒ modulation of brightness and spectrum





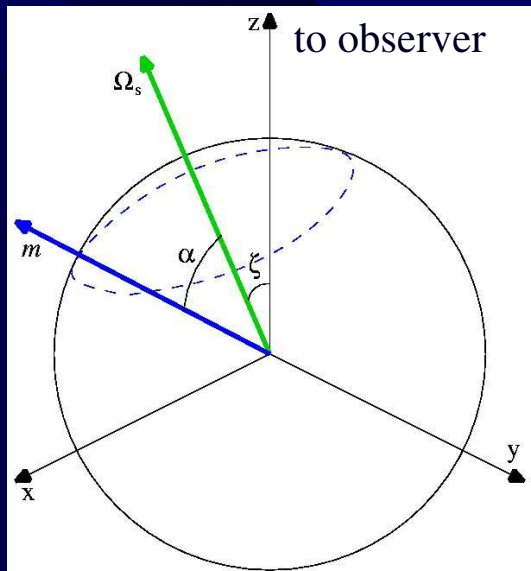


Surface Model for RX J1856.5-3754 and Phase-resolved Spectra

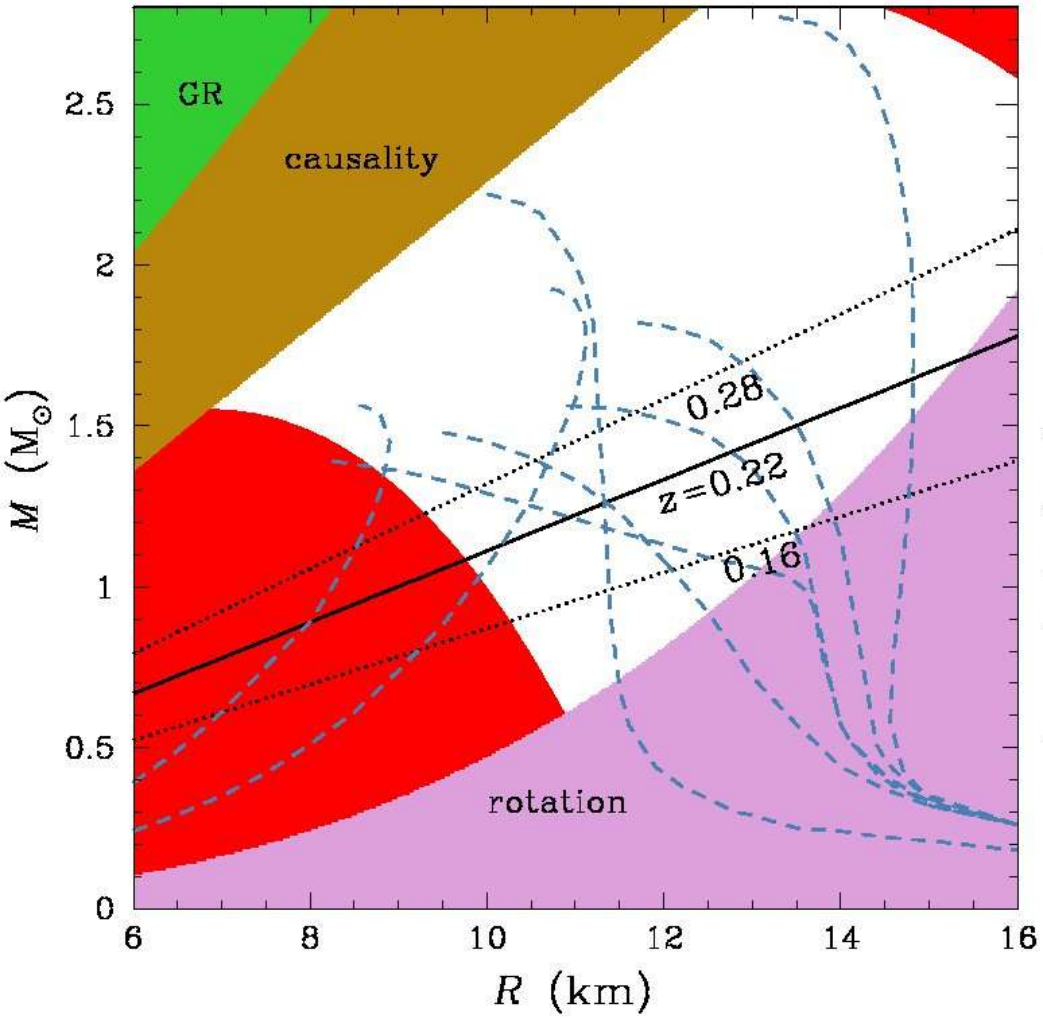


- Emission model with $(T_{\rm eff}, \vec{B}_{\rm p})$-surface distribution and relativistic effects

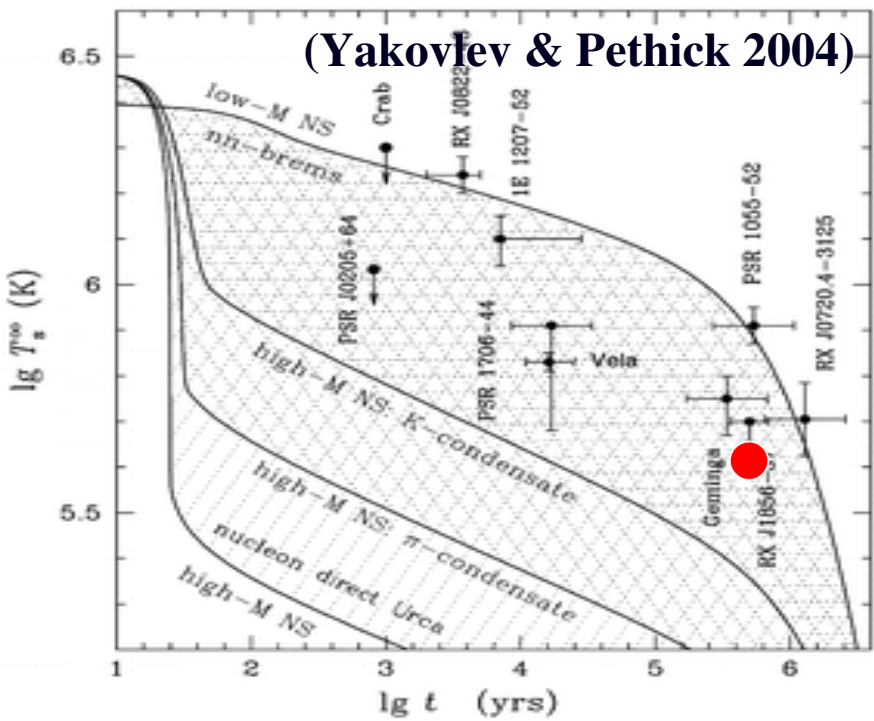
- $B_{\rm p} \approx (6\text{-}7)\times10^{12}$ G
- $kT^{\infty} = 43$ eV
- $R^{\infty} \approx 17$ km
- $z_{\rm g} \approx 0.22$
- α or $\zeta < 6°$
- α or $\zeta \approx 20\text{-}45°$

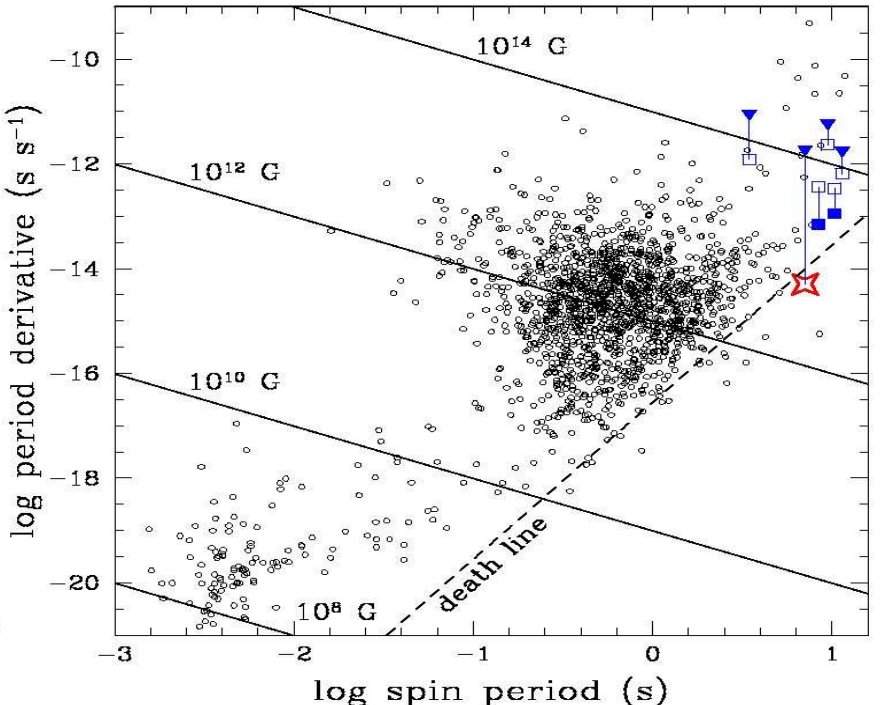


Physics from RX J1856.5-3754

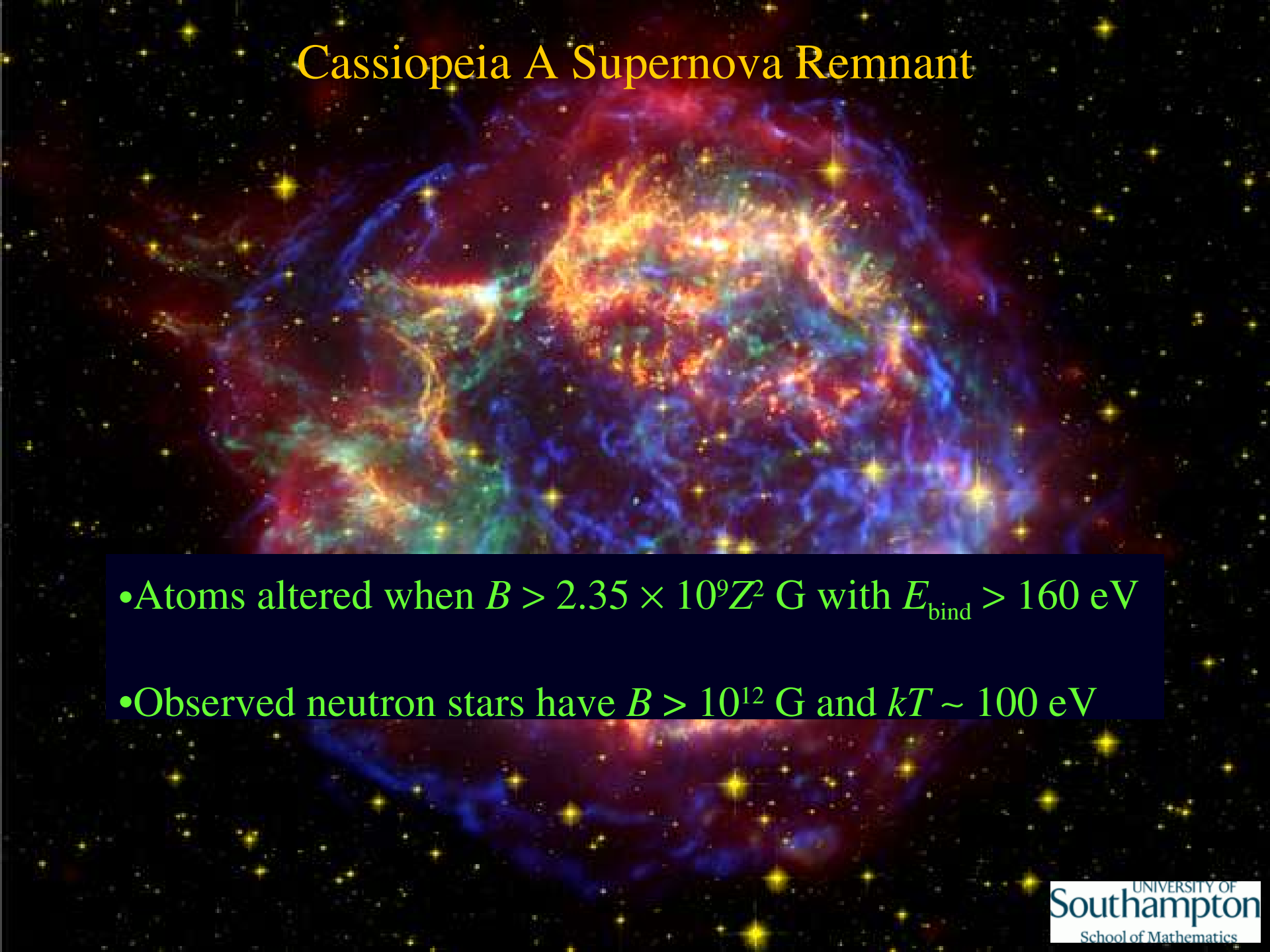


(Yakovlev & Pethick 2004)





Cassiopeia A Supernova Remnant



- Atoms altered when $B > 2.35 \times 10^9 Z^2$ G with $E_{\text{bind}} > 160$ eV
- Observed neutron stars have $B > 10^{12}$ G and $kT \sim 100$ eV

UNIVERSITY OF Southampton
School of Mathematics