# The Puzzles of RXJ 1856-3754

# Neutron Star or Quark Star?*

*Joachim Trümper*

*MPE*

- Neutron Stars & Quark Stars
- X-ray Emission from Neutron Stars
- The Spectrum of RXJ 1856-3754
  - condensed matter surface emission
  - photospheric emission
- The Radius of RXJ 1856-3754

Bonn Pulsar Workshop

April 2003

* to be published
(Trümper, Burwitz, Haberl, Zavlin)

# Strange stars suggest new kind of matter

April 10, 2002 Posted: 11:41 AM EDT (1541 GMT)

(NASA/SAO/CXC/DRAKE ET AL)

RXJ1856 burns at 1.2 million degrees F (700,000 degrees C) and has a diameter of 7 miles (11.3 km).

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By Richard Stenger
CNN

**(CNN) -- Two rogue stars have failed to live up to scientific expectations, compelling puzzled astronomers to consider the likelihood that they possess a new and exotic form of matter.**

If confirmed, the discovery would warrant a new class of objects, quark stars, which fall somewhere in between neutron stars and black holes in density.

"It would change the family tree a bit and put a new member in it," University of Chicago astronomer Michael Turner told reporters Wednesday.

Neutron stars are the vestiges of immense supernova explosions, collapsed stars with extremely compact cores, denser than all known objects except black holes. A teaspoonful of a neutron star would weigh one billion tons, as much as all the cars and trucks on Earth.

At least, until astronomers using the Chandra X-ray Observatory spied two presumed neutron stars, RXJ1856 and 3C58. Based on the known laws of physics, the former appeared much smaller and the latter much colder than they should.

The strange traits of RXJ1856 and 3C58 suggest that the pair are not neutron stars at all. They could be composed of quarks, or crystals of sub-nuclear particles rather than neutrons.

"Both of these objects have properties which seem to contradict what we know about matter," said Harvard-Smithsonian astronomer Jeremy Drake.

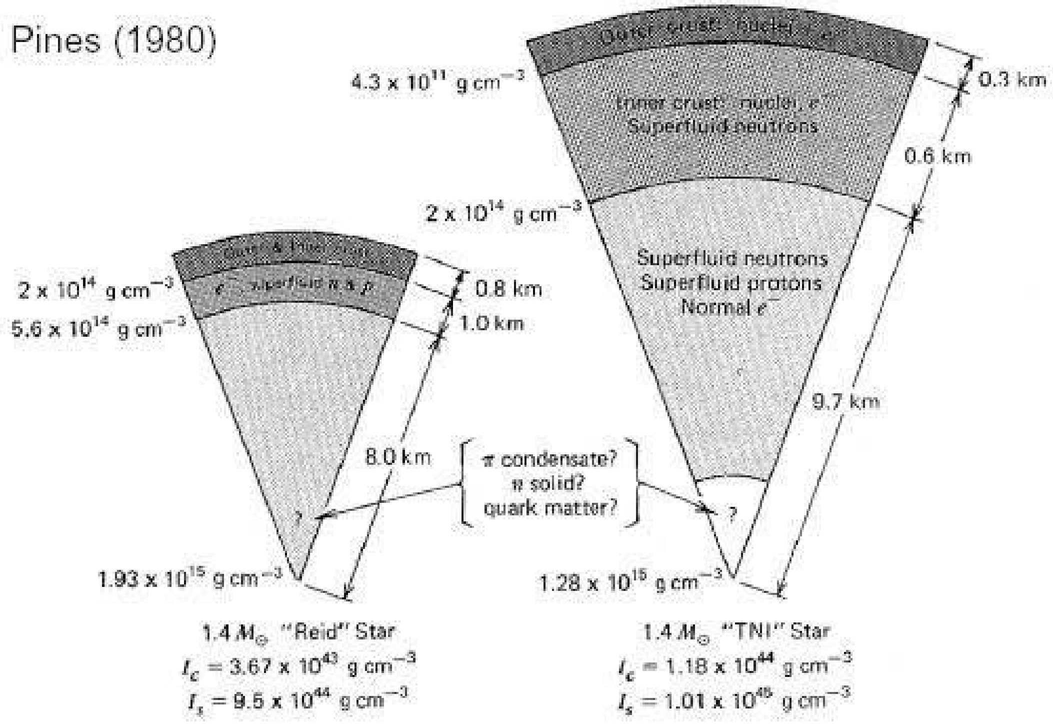
Quarks are thought to be the fundamental building blocks of matter. They combine to make the basic subatomic particles, protons and neutrons.

But quarks have remained fleeting, appearing for a fraction of a second in a handful of laboratories when atomic nuclei smash into one another at incredible speeds.

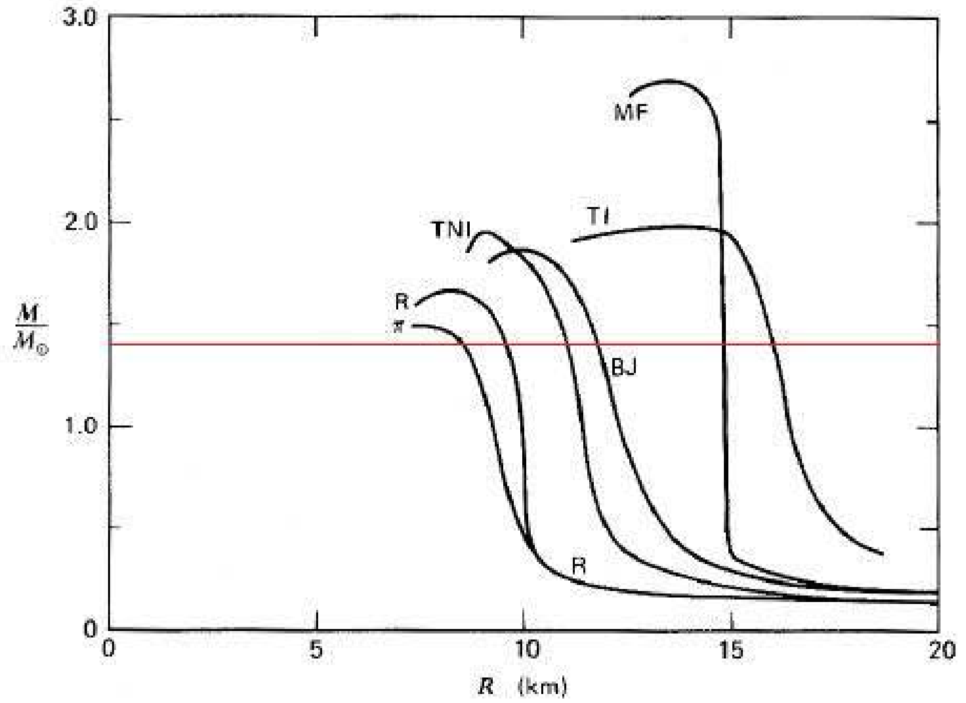
The quarks that make up conventional matter are called "up" and "down" quarks. Physicists theorize that even

# Neutron Star Models

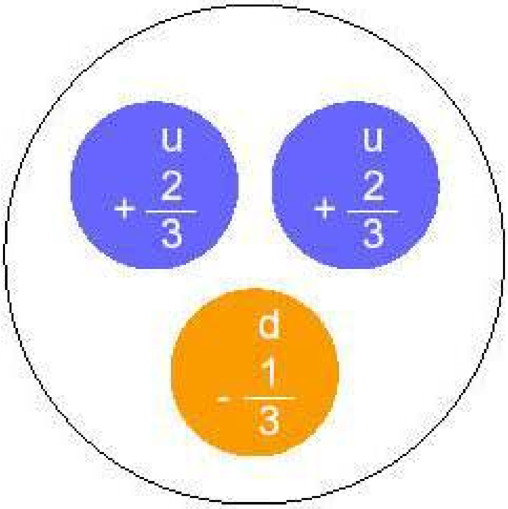
Pines (1980)



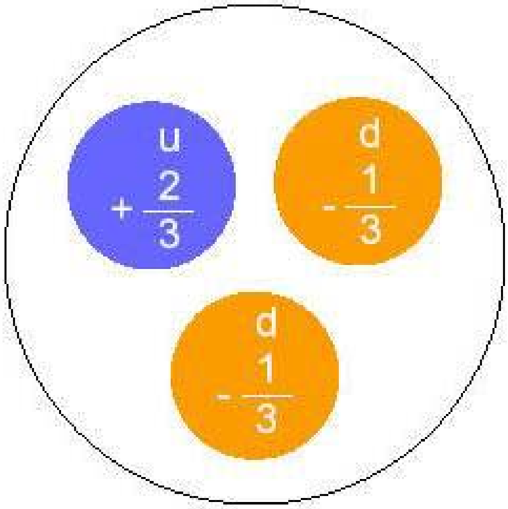

Baym and Pethick (1979)



# Normal Nuclear Matter consists of Quark:




PROTON
charge = + e

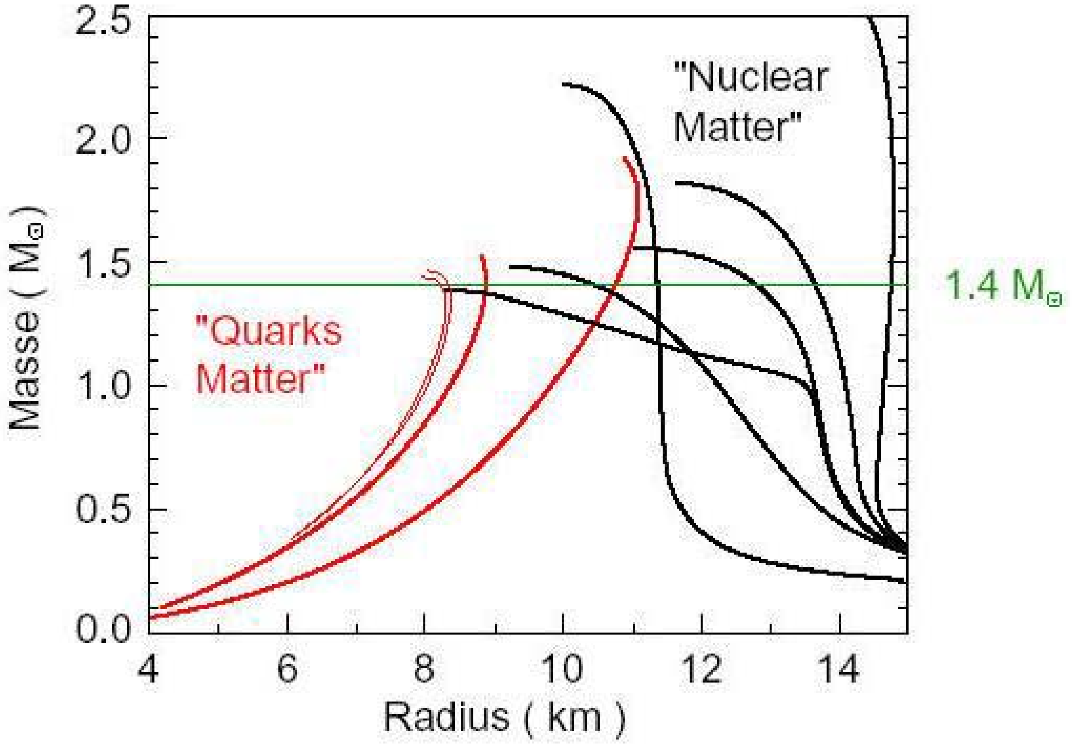



NEUTRON
charge = 0

| | families | | | electr. charge | st | em | weak | grav |
|---|---|---|---|---|---|---|---|---|
| **Quarks** | **u** | **c** | **t** | 2/3 | x | x | x | x |
| | **d** | **s** | **b** | -1/3 | x | x | x | x |
| **Leptons** | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | 0 | - | - | x | ? |
| | **e** | $\mu$ | $\tau$ | -1 | - | x | x | x |

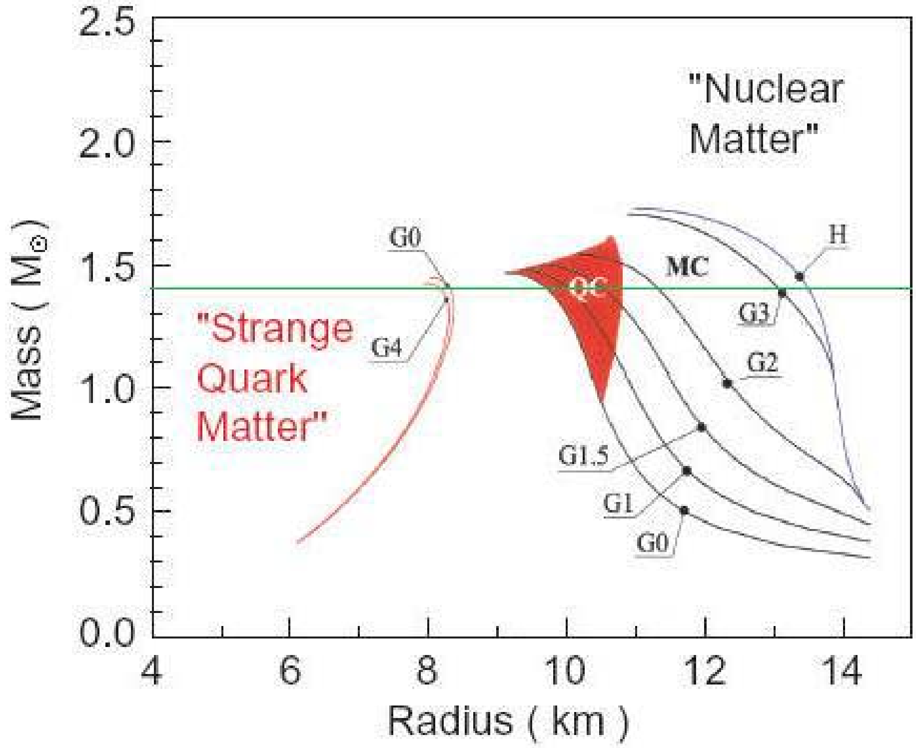
E. Witten's hypothesis (1984) :

Matter consisting of u, d and s quark (SQM) could be more stable than normal nuclear matter. This would mean that nuclear matter is transformed into SQM when it gets into contact with SQM nuggets.




Stellar models: Lattimer & Prakash ApJ, 2001

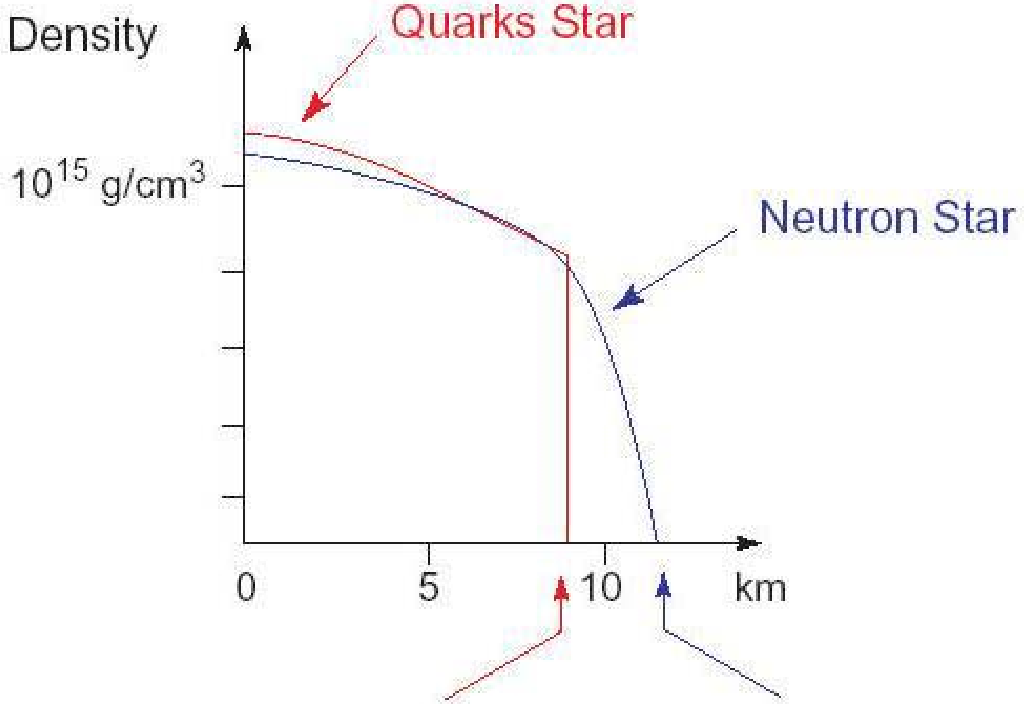
# IF SQM IS LESS STABLE THAN NUCLEAR MATTER IT MAY EXIST IN THE CORES OF NEUTRON STARS




Stellar models: Schertler et al. Nuclear Phys. A (1998, 2000)

# Radial Density Profiles

$M = 1.4\ M_{\odot}$




Thickness of the surface layer $10^{-13}$ cm !

Thickness of the atmosphere ~ 0.1 cm

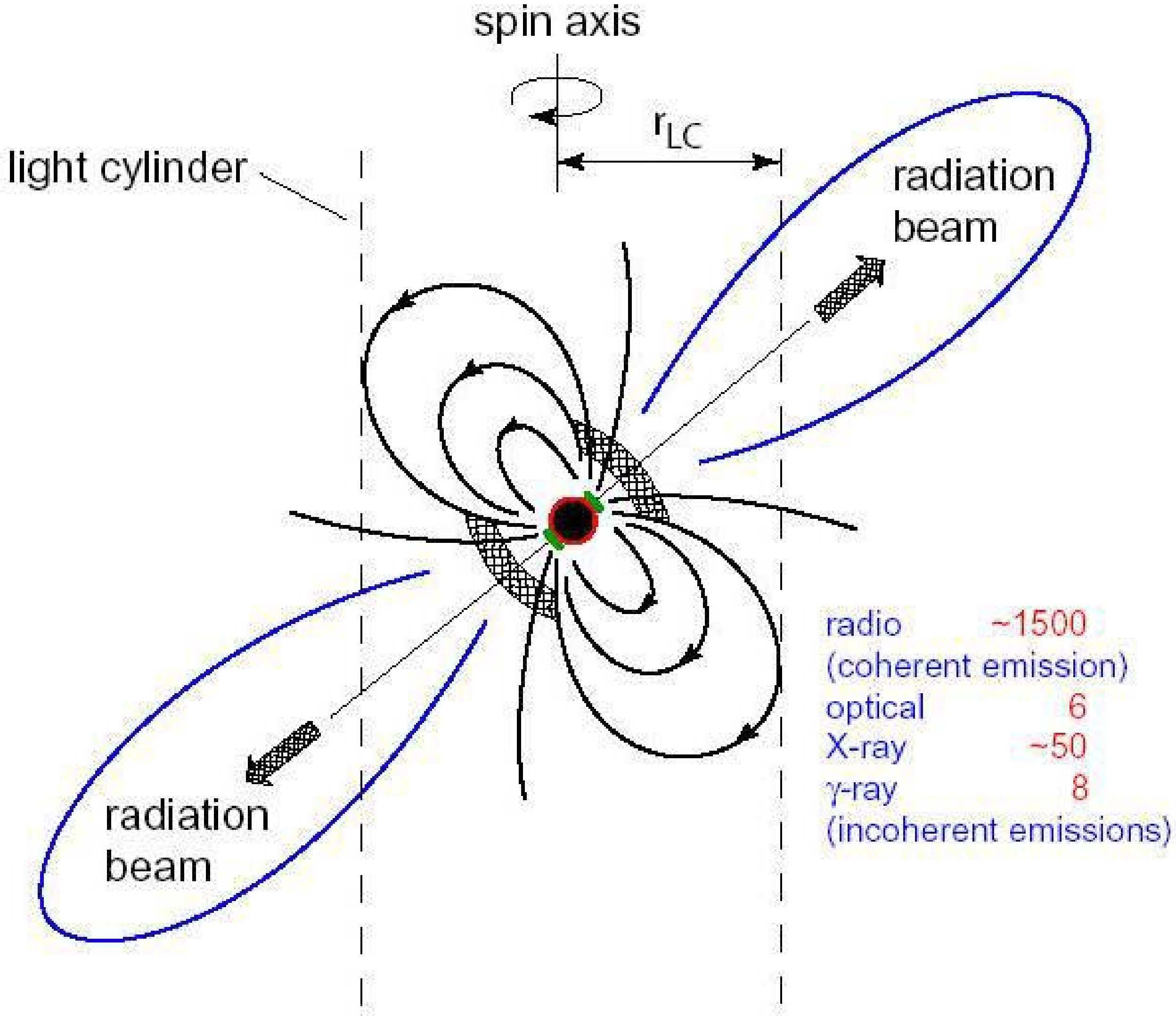
$\hbar\omega_p \sim 20$ MeV :

( ~ T )

NO SOFT X-RAY EMISSION POSSIBLE!
(CHMAI et al., USOV)

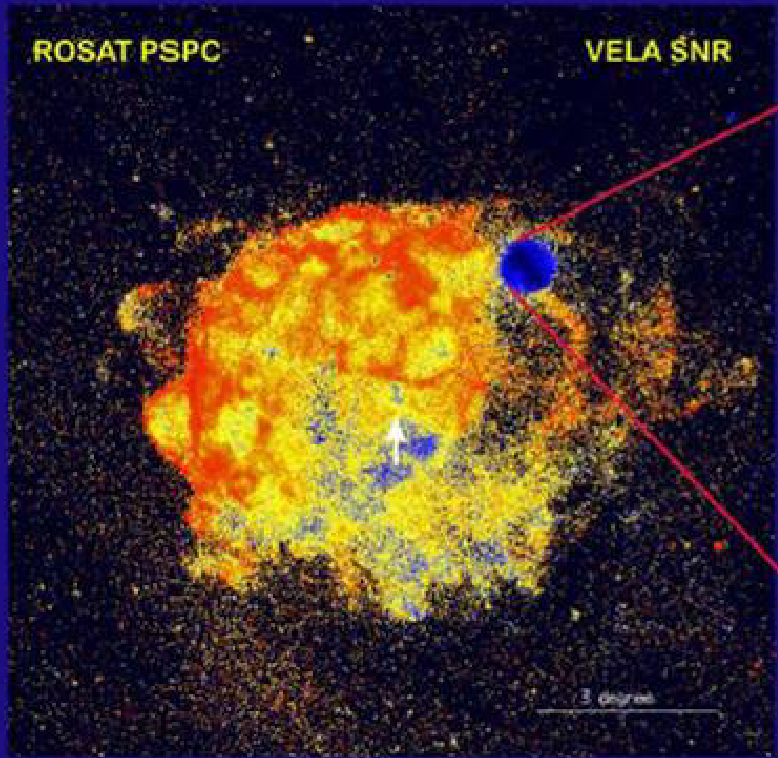
# X-RAY EMISSION FROM PULSARS

P = 1.6 ms.......5 s



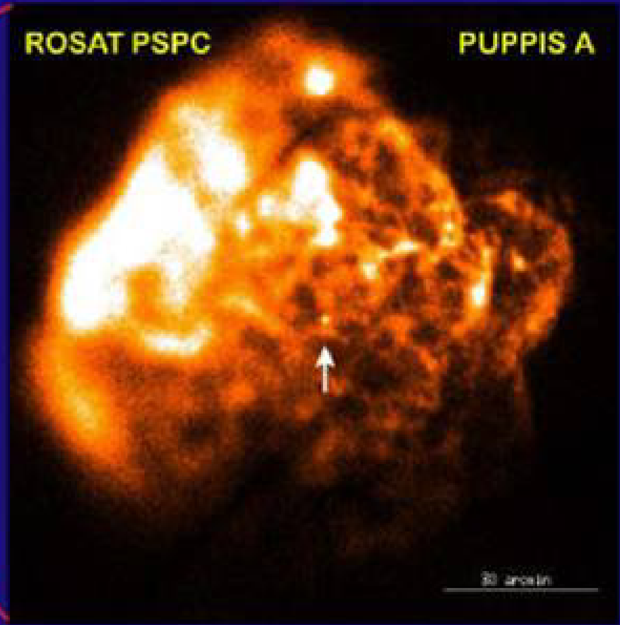

- Photon Emission from extremly high energetic electrons
( Synchroton radiation, inverse Compton effect )
- Thermal Emission from the hot surface T ~ $10^6$ K
- Hot polar cap (T ~ few $10^6$ K) heated by
  - internal friction or
  - particle bombardment

# *SUPERNOVAE and NEUTRON STARS*




*Pulsar*

*(radio, optical, X-ray, Gamma-ray)*



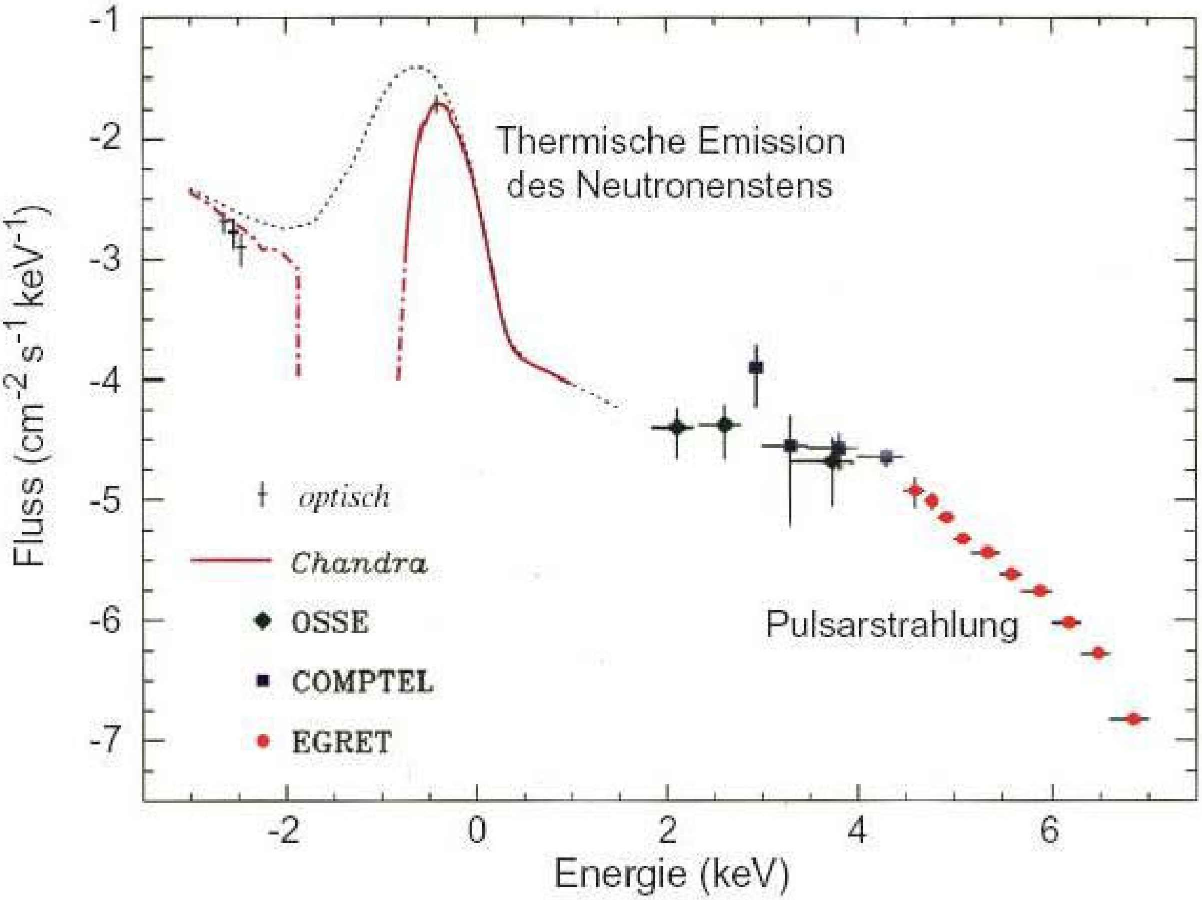

*cooling neutron star*

*T~ 1.5 million degrees*

Werner Becker
MPE-Garching

# VELA PULSAR

P = 89 ms



# *X-ray Dim Isolated Neutron Stars (XDINS)*

- Bright, soft X-ray sources in ROSAT survey
- Blackbody-like spectra, no non-thermal hard emission
- Low absorption, nearby
- Constant X-ray flux
- No radio emission ?
- No obvious association with SNR
- Some are X-ray pulsars (8.39 – 11.37 s)

| Object | kT/eV | $L_x$/erg $s^{-1}$ | d/pc | Opt. | Comment |
|---|---|---|---|---|---|
| RX J0420.0–5022 | 46 | $2.7 \times 10^{30}$ | 100 | B > 25.5 | |
| RX J0720.4–3125 | 85 | $2.6 \times 10^{31}$ | 100 | B = 26.6 | |
| RX J0806.4–4123 | 96 | $5.7 \times 10^{30}$ | 100 | B > 24 | |
| 1RXS J13048.6+212708 | 86 | $5.1 \times 10^{30}$ | 100 | $m_{50ccd}$ = 28.6 | RBS1223 |
| RX J1605.3+3249 | 96 | $1.1 \times 10^{31}$ | 100 | B > 27 | RBS1556 |
| RX J1856.5–3754 | 60 | $1.5 \times 10^{31}$ | 117 | V = 25.7 | |
| 1RXS J214303.7+065419 | (90) | $1.1 \times 10^{31}$ | 100 | R > 23 | RBS1774 |
| RX J1836.2+5925 ? | (43) | $5.4 \times 10^{30}$ | 400 | V > 25.2 | variable ? |

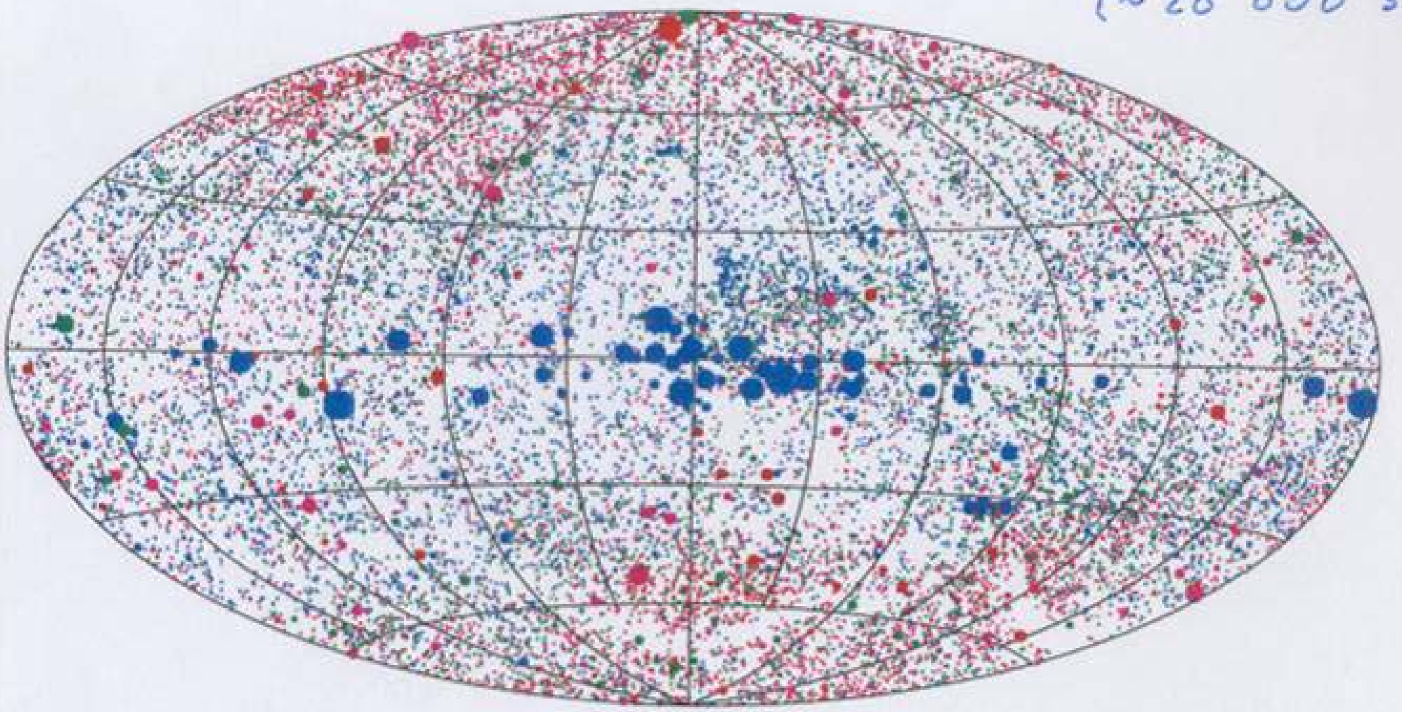
*Frank Haberl*

*MPIfR / MPE Pulsar Meeting – 24-25 April 2003 – MPIfR Bonn*

VOGES et al. 1996 WEB/ A+A

# The ROSAT All-Sky Survey Bright Source Catalogue

(~ 20 000 sources)



HR1 = (−1.0,−0.5)

HR1 = (−0.5, 0.0)

HR1 = ( 0.0,+0.5)

HR1 = (+0.5,+1.0)

0.05 counts $s^{-1}$

0.5 counts $s^{-1}$

5 counts $s^{-1}$

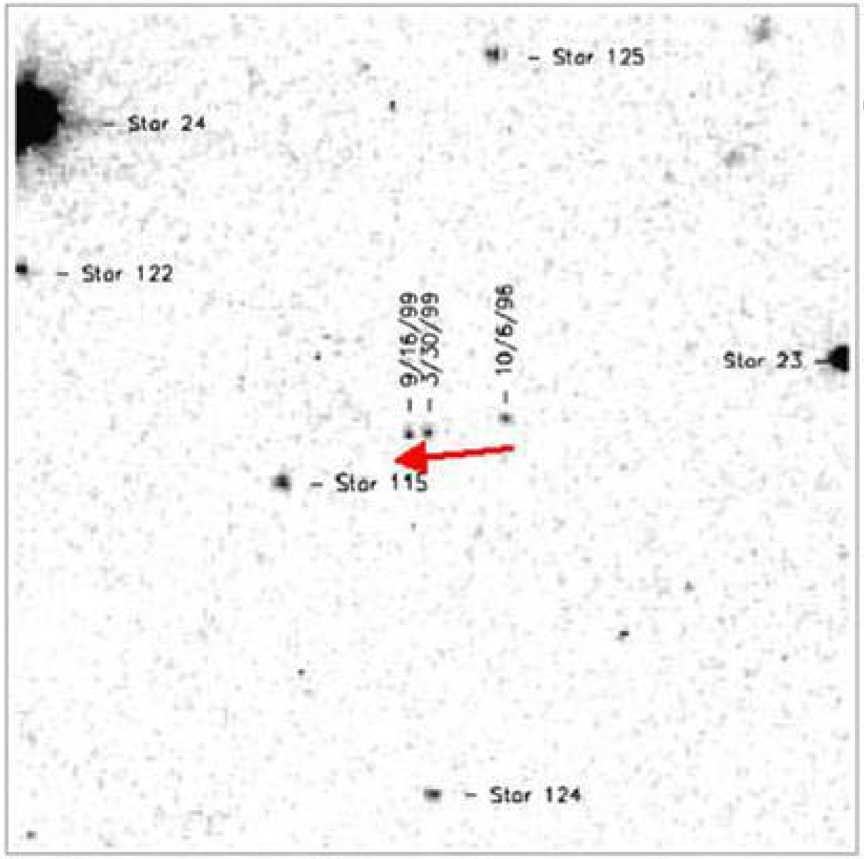
50 counts $s^{-1}$

ROSAT: Total number of Sources ~ 250 000

# RXJ1856-3754


- Thermal ($T \simeq 6 \times 10^5\ K$) spectrum (Walter, Wolk, & Neuhäuser, 1996)
- A very faint and blue star ($V = 25.6, U = 24.4$) detected by the HST WFPC2 (Walter & Matthews, 1997)
- Optical flux close to the RJ extrapolation of the ROSAT BB
- $F_x/F_{opt} \simeq 75000$
- $d \leq 130\ pc$

# Proper Motion and Parallax of RX J1856.5-3754




## HST Observations

Walter & Lattimer 2002, ApJ 576, 145

Proper motion

332.3 ± 0.4 mas / year

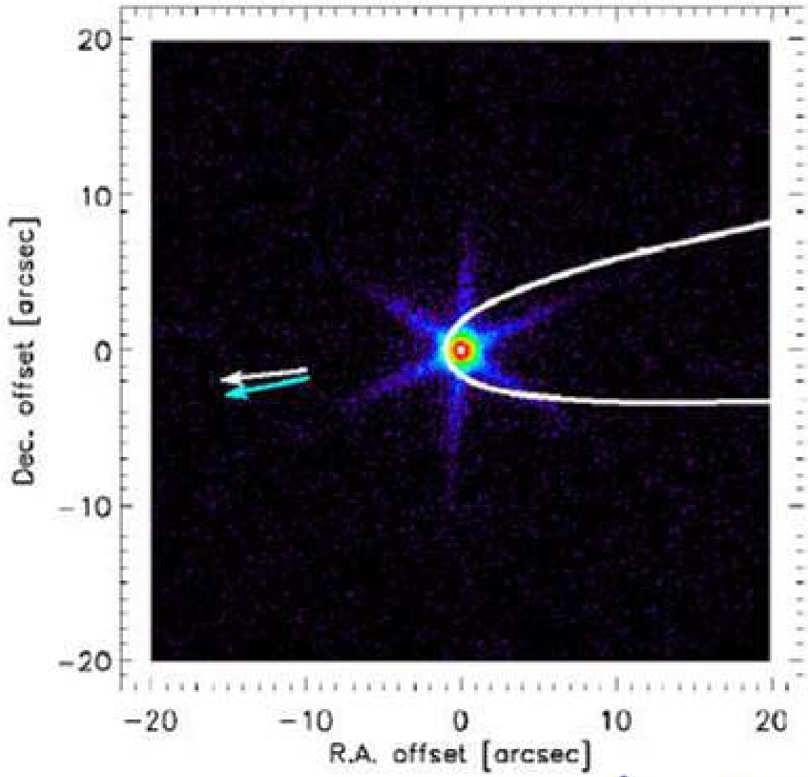
Parallax Distance

8.5 ± 0.9 mas 117 ± 9 pc

Origin in Upper Sco OB association
Age ~ 0.5 million years

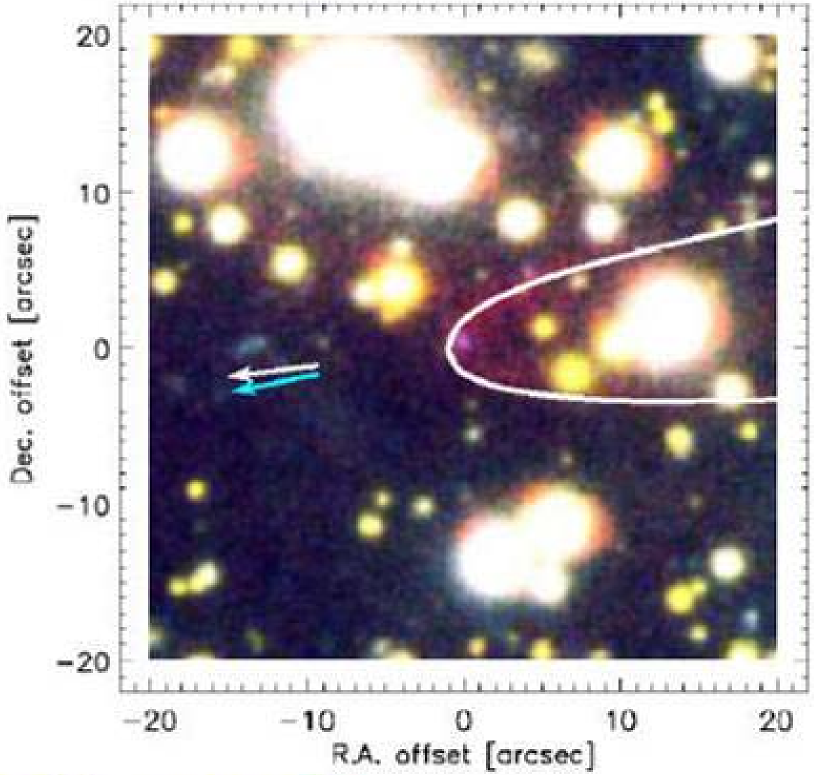
# RX J1856.5-3754: Hα bow shock nebula

Chandra LETGS (GTO +DDT)
502 ksec 0th order image



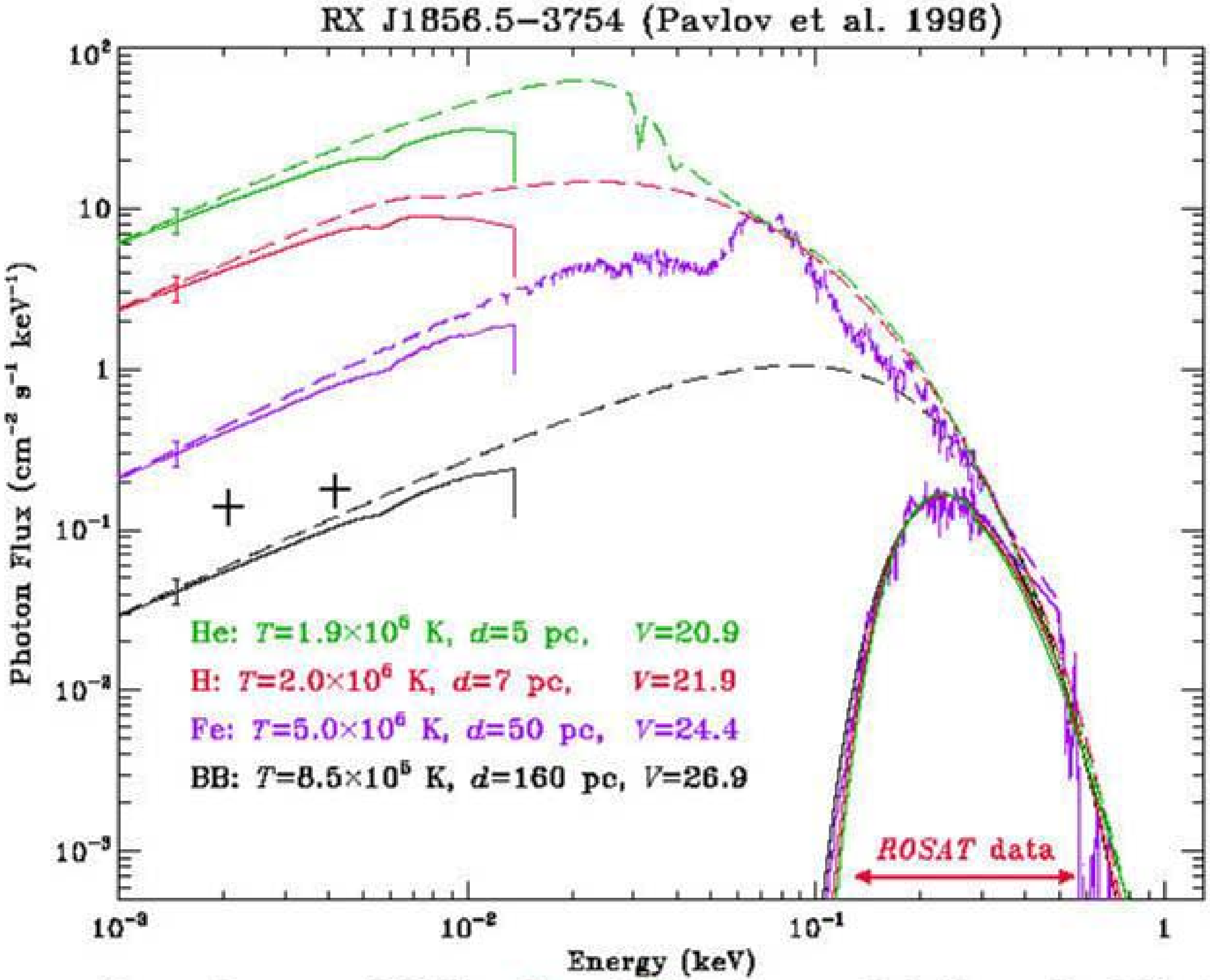

VLT: combined B, Hα and R images

Kerkwijk & Kulkarni 2001 A&A 380, 221




Vadim Burwitz (MPE)

$\dot{E} \sim 2 \times 10^{32}$ erg/sec
T ~ 0.5 million yrs
} B ~ $10^{13}$ G !



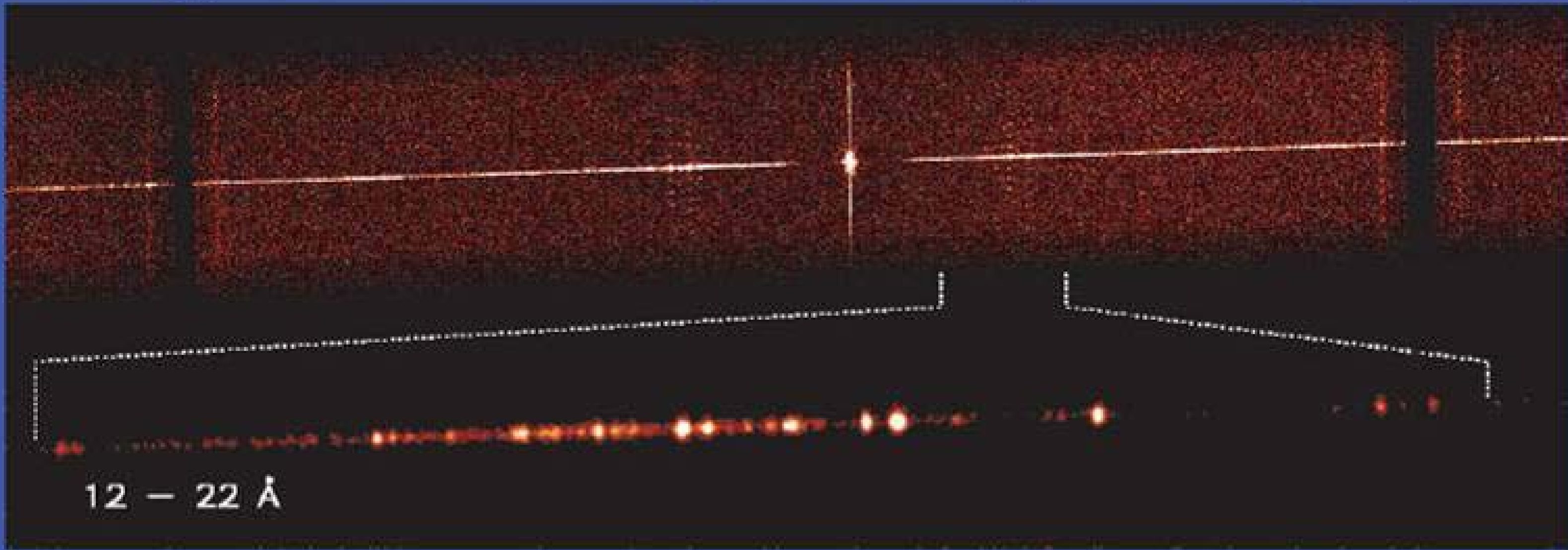

Atmosphere model fits, H and He, overpredict the optical flux!

# *Chandra* and *XMM-Newton* : Overview

- *Chandra* (NASA)
  - Launch: July 1999 (STS-93)
  - Orbit: 64 hours
- 1 Telescope
  - 1100 $cm^2$, 0.5"
- Detectors
  - ACIS, HRC
- Gratings
  - LETG (MPE), HETG

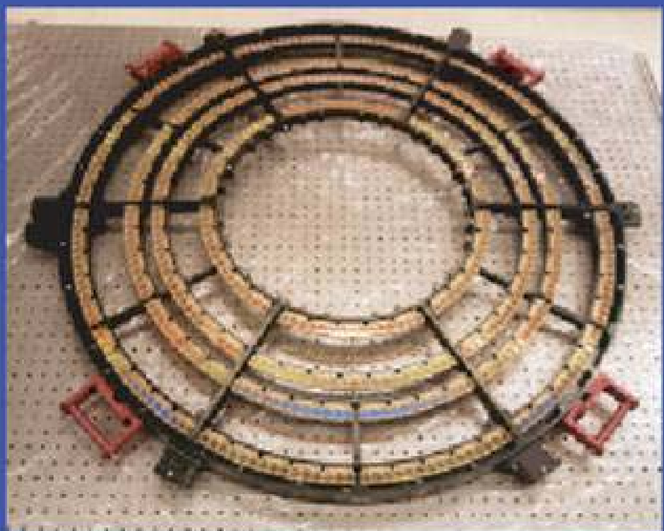
- *XMM-Newton* (ESA)
  - Launch: Dec.1999 (Ariane 5)
  - Orbit: 48 hours
- 3 telescopes
  - 6000 $cm^2$, 15" (MPE)
- Detectors
  - EPIC-pn (MPE), -mos
  - Gratings
  - RGS

# Low Energy Transmission Grating + HRC-S: Capella first light spectrum

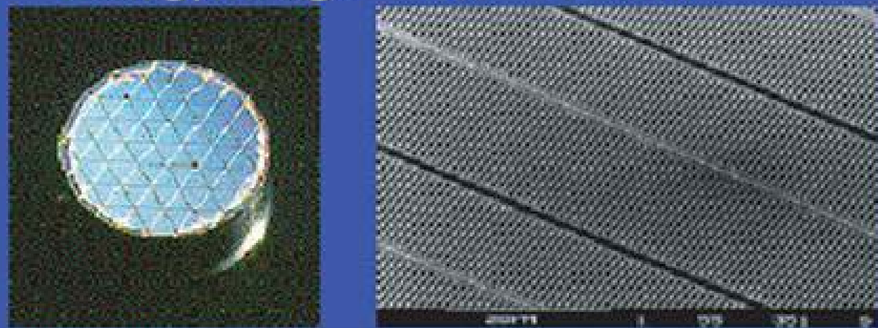



Freestanding Gold Wires

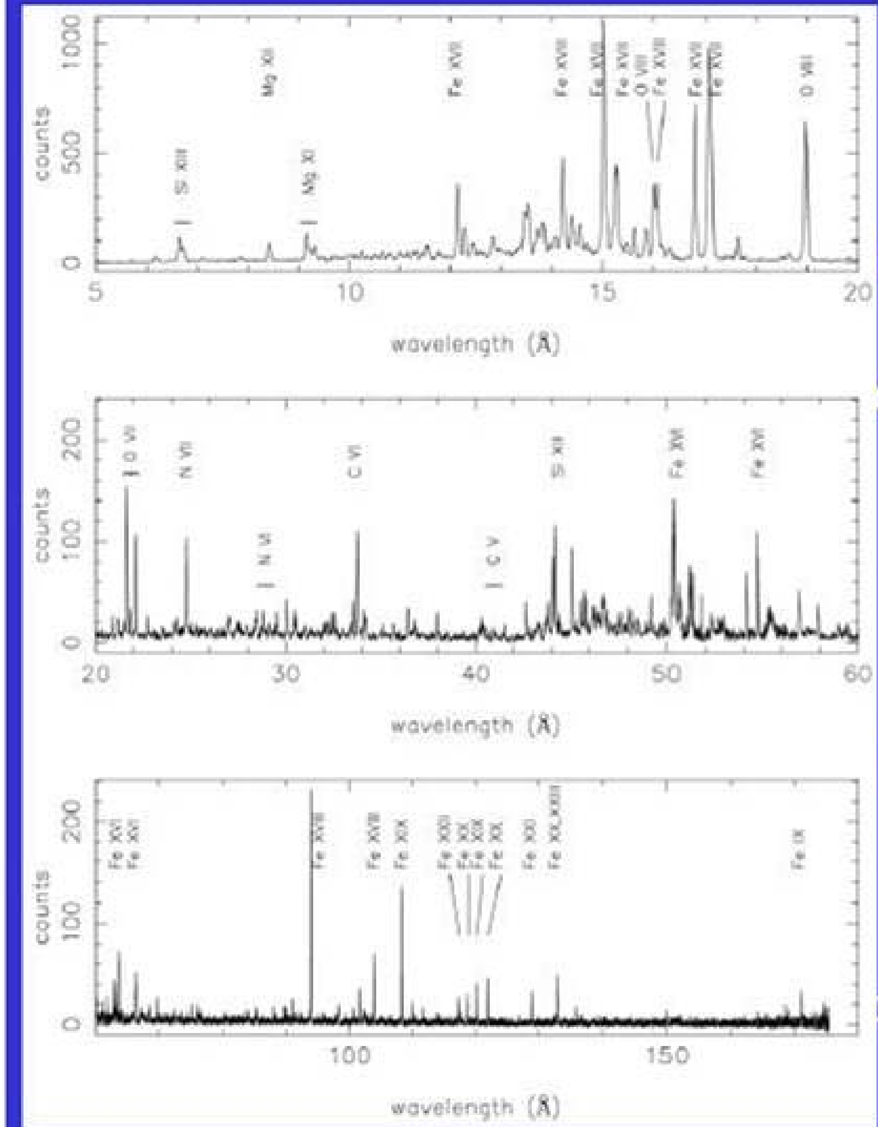
| | |
|---|---|
| Grating Period | 1008 lines/mm |
| E/ΔE | ~2000 @ 0.1 keV |
| Energy Range | 0.07 - 10 keV |



↑ Mounting structure SRON ↑



↑ Gratings elements MPE ↑




# *Chandra* LETGS: Capella spectrum

**Brinkman, et al.,2000, ApJ 530, L111**

first high resolution spectrum of Capella

0.06 Å FWHM

150 lines identified

95 ksec *Chandra* LETG+HRC-S

5-175 Å (2.5-0.07 keV)

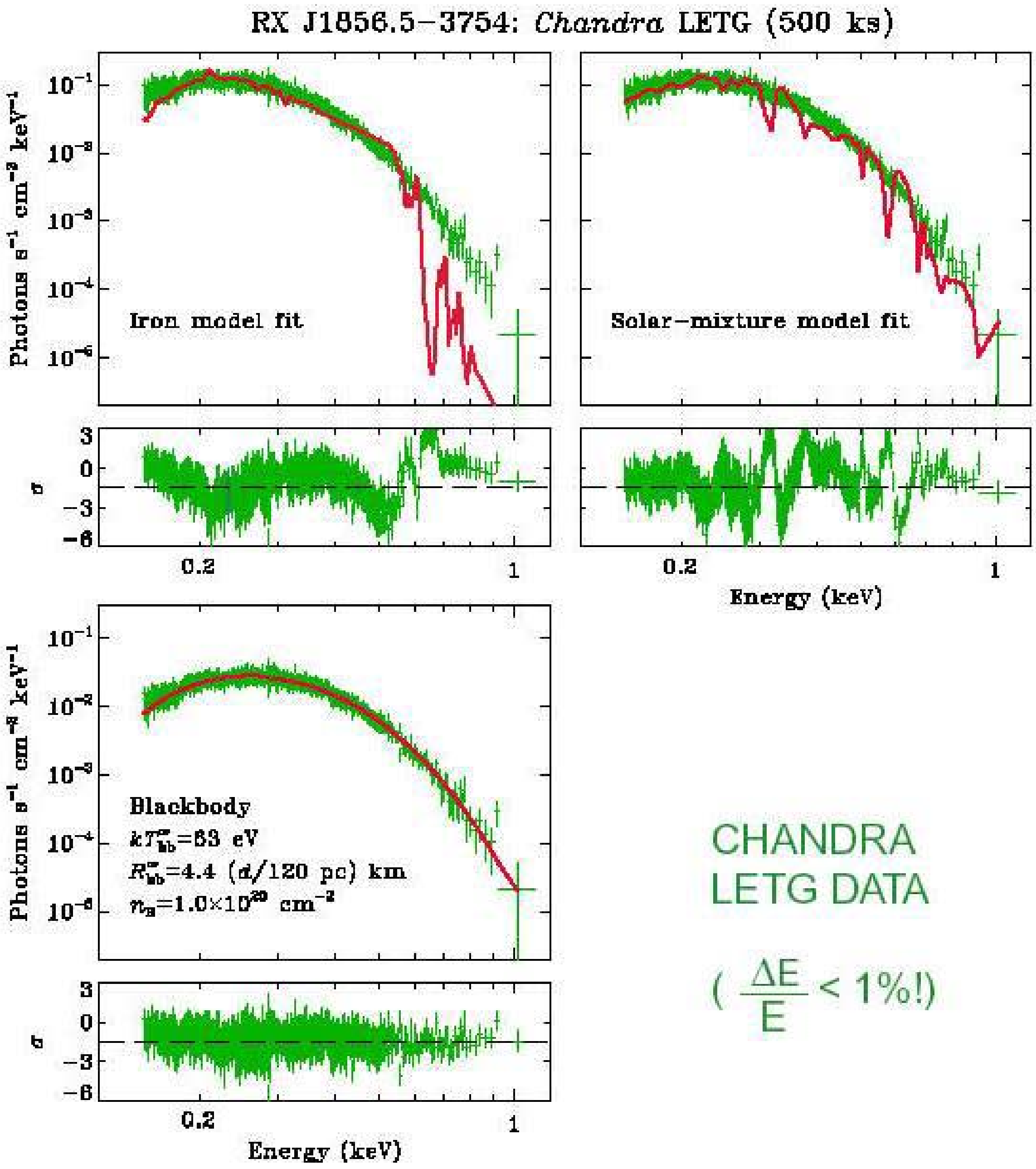
**Ness et al. 2001, A&A 367, 282**

218.5 ksec *Chandra* LETG+HRC-S

Detailed analysis of OVII, NVI, CV triplets for density diagnostics.

Info: distance 12.9 pc, binary with (G1+G8) giants with $P_{orb}$ = 104 days

# ATMOSPHERIC MODEL (nonmagnetic)



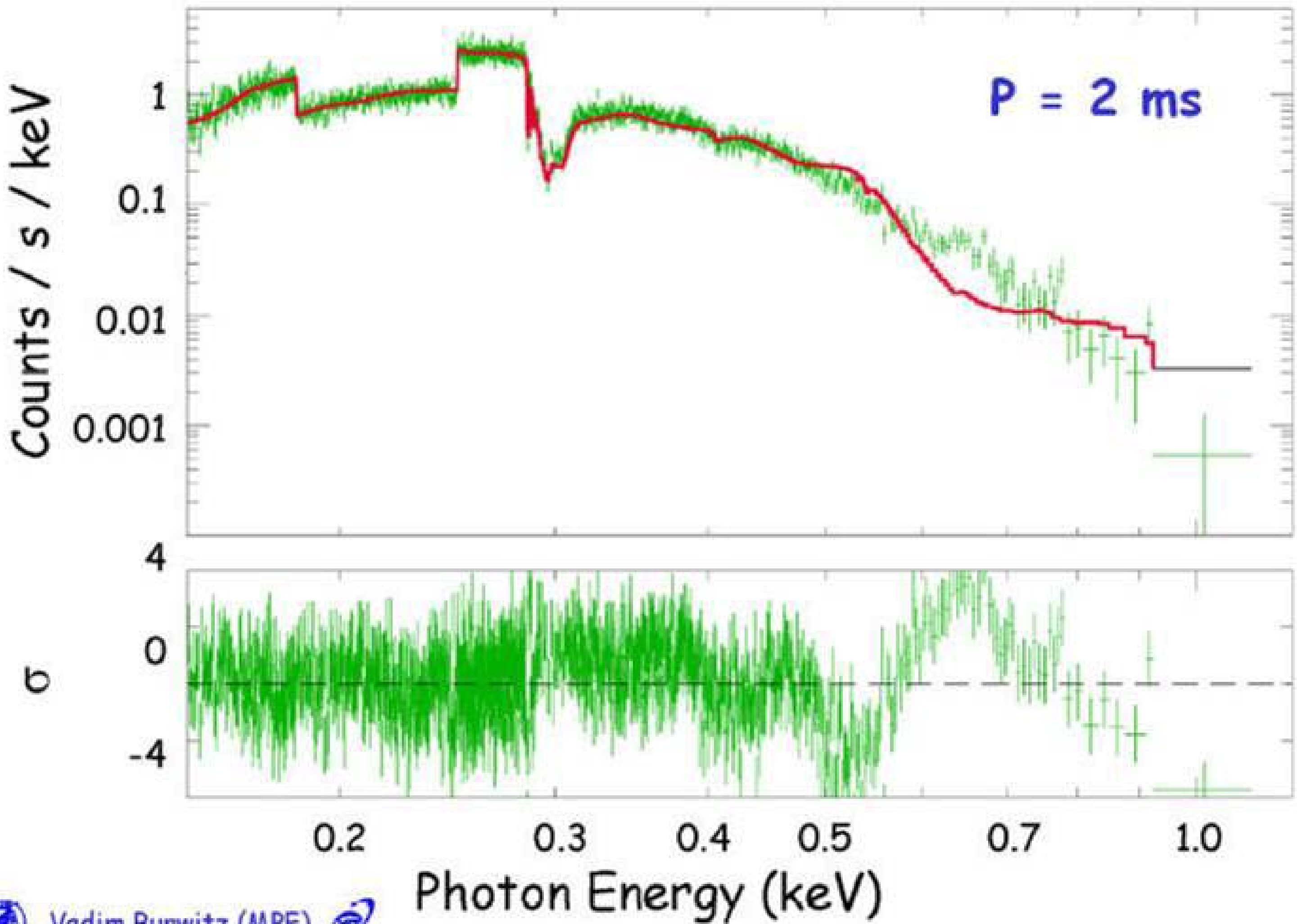

CHANDRA
LETG DATA

$\left( \frac{\Delta E}{E} < 1\%! \right)$

# Why no spectral features?

- Doppler broadening due to fast rotation? ($P < 10$ ms?)
- No photosphere, but condensed matter surface?
- Effects of very strong magnetic fields ($B \sim 10^{13}$ G)?

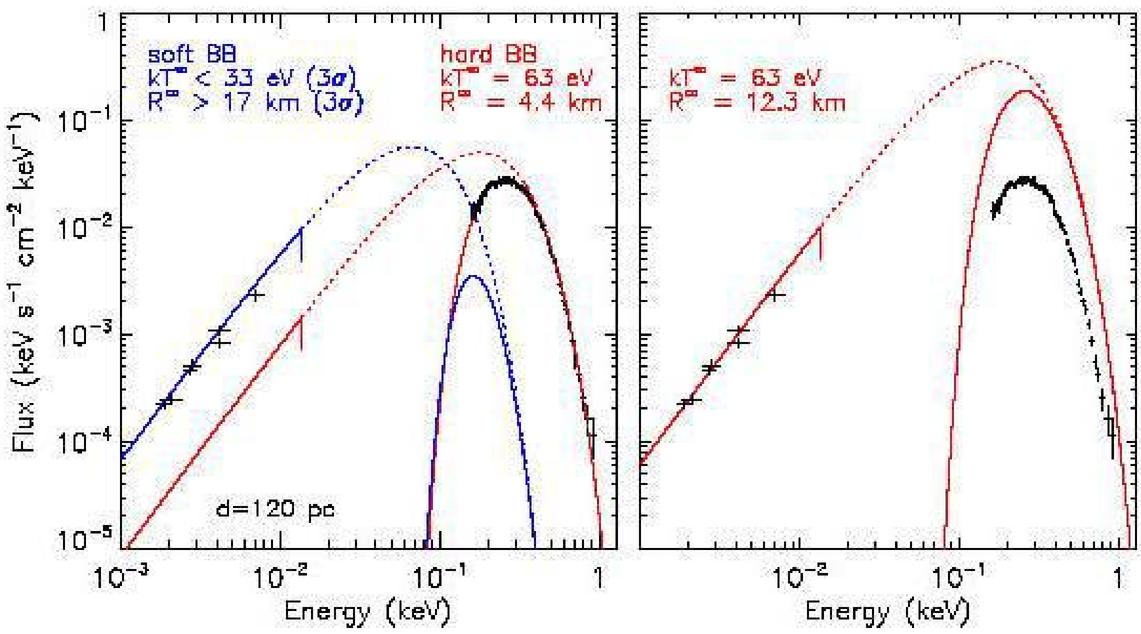
# rotationally broadned lines: Solar mixture spectrum




Vadim Burwitz (MPE)

# RXJ 1856.5-3754: modeling X-ray & optical data

Burwitz et al. 2002, A&A, in press (astro-ph/0211536)

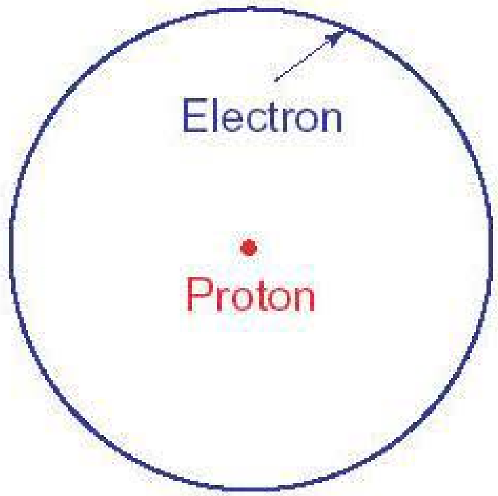


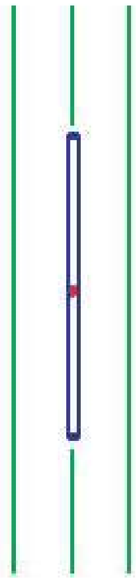

problems:

- XMM-Newton
  pulsed fraction < 1.3 %
- requires a reflective surface

(P ≥ 10 ms)

# Hydrogen Atom



Magnetic field ≈ 0

Magnetic field
$= 5 \times 10^{12}$ Gauss
$= 5 \times 10^{8}$ Tesla

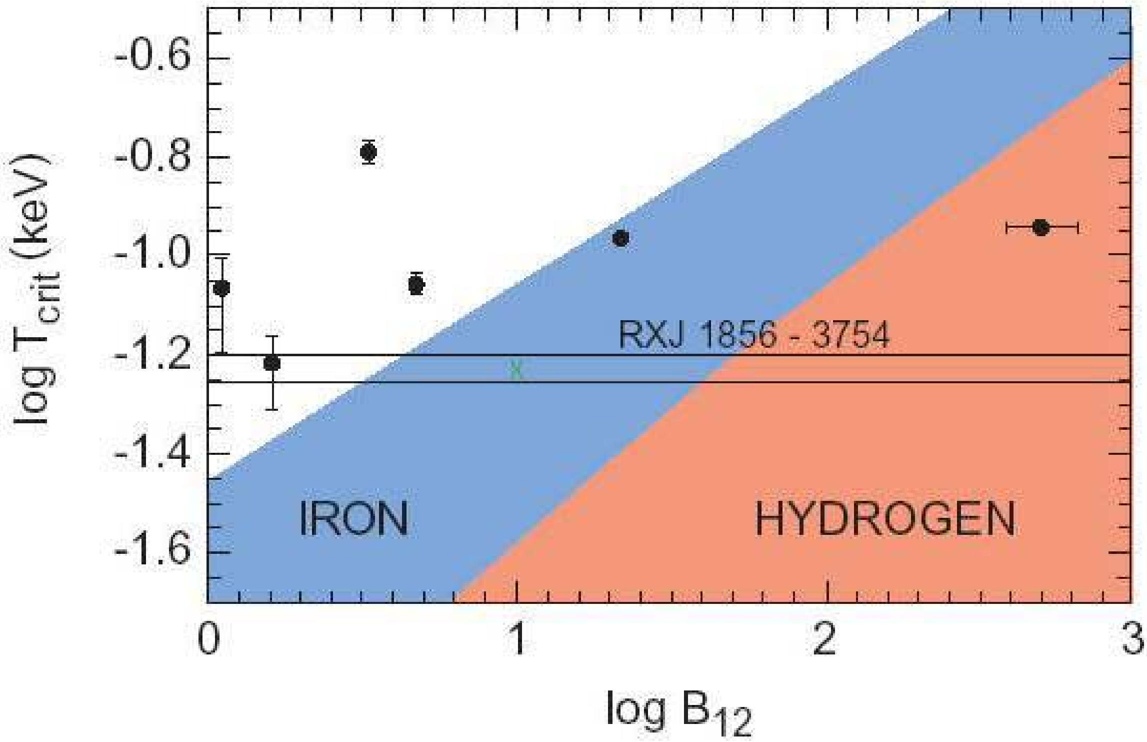
Lorentz force >>
Coulomb force

$$\rho_s = 561\ \mathrm{g/cm^3} \times \left(\frac{B}{10^{12}\mathrm{G}}\right)^{6/5} \quad \text{for hydrogen}$$

→ high electron density (~ $B^{6/5}$)
→ high plasma frequency (~ $B^{3/5}$)
→ reflecting surface

R. Lenzen + J. Trümper, Nature 1978
W. Brinkmann, A&A 1980, Turolla et al 2003

Lai 2001

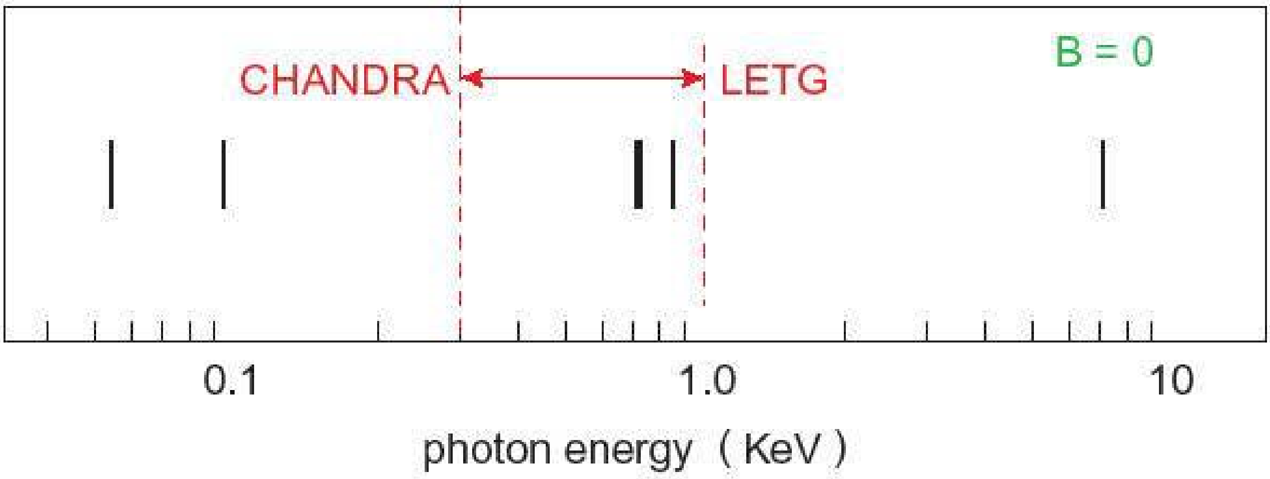



$T_{crit}$ for magnetic condensation:

- certain for hydrogen
- uncertain for iron

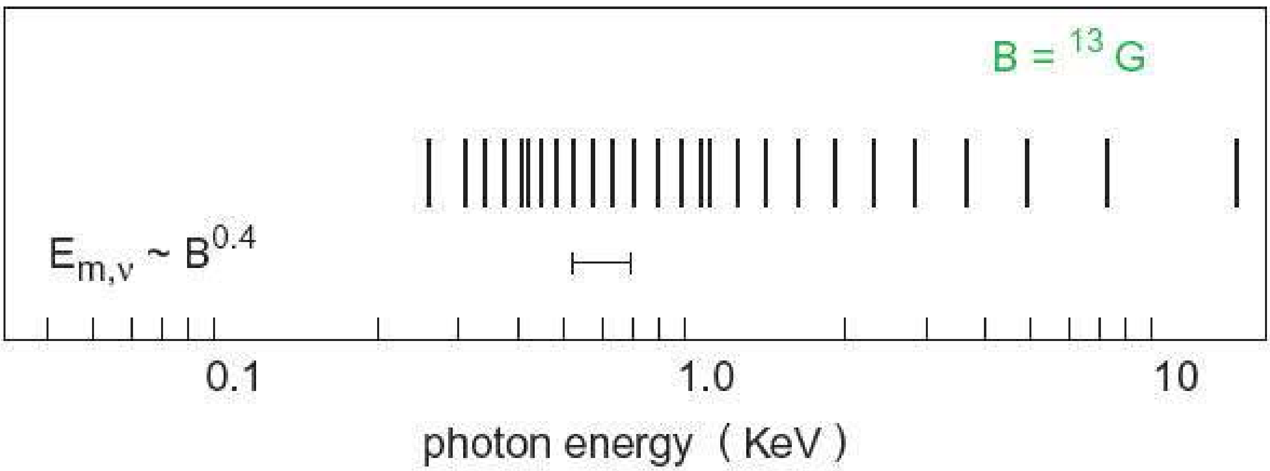
  - may be possible (Lai 2001)
  - impossible (Neuhauser, Koonin and Langanke 1987)

# Atomic Energy Levels
# Iron




size of the pulsar wind nebula
age of the neutron star

} B ≳ 13 G!




(Neuhauser, Koonin and Langanke 1987)

# Why no spectral features?

- Doppler broadening due to fast rotation? ($P < 10$ ms?)

  - is not sufficient !

- No photosphere, but condensed matter surface?

  - too low effect on reflectivity
  - Fe condensation uncertain

- Effects of very strong magnetic fields ($B \sim 10^{13}$ G)?

  - probably works

In principle two possibilities exist:

1) RXJ 1852-3754 is a ms pulsar

pros:
- pulsar wind nebula typical for ms pulsars
- large hot spot size

2:2

cons:
- old age, incompatible with origin in the Upper SCO Region
- absence of line features

2) RXJ 1852-3754 has a magnetic field of ~ $10^{13}$ G

pros:
- $\dot{E}$ (pulsar wind nebula), $t = 5 \times 10^5$ yrs
- absence of line features
- similarity with 0720-3125 $B \geq 10^{13}$ G $(P, \dot{P})$
  RBS 1223 high B !
  ($J_X \sim E \times$ blackbody, $J_o / J_X \sim 4 - 6$)

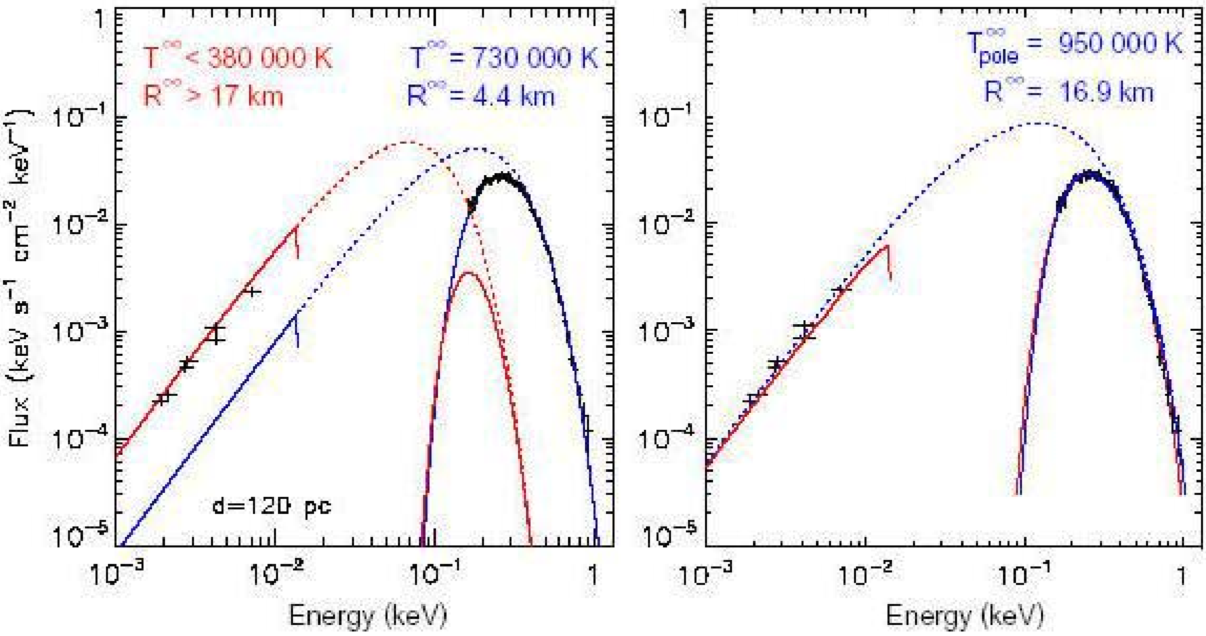
3:1

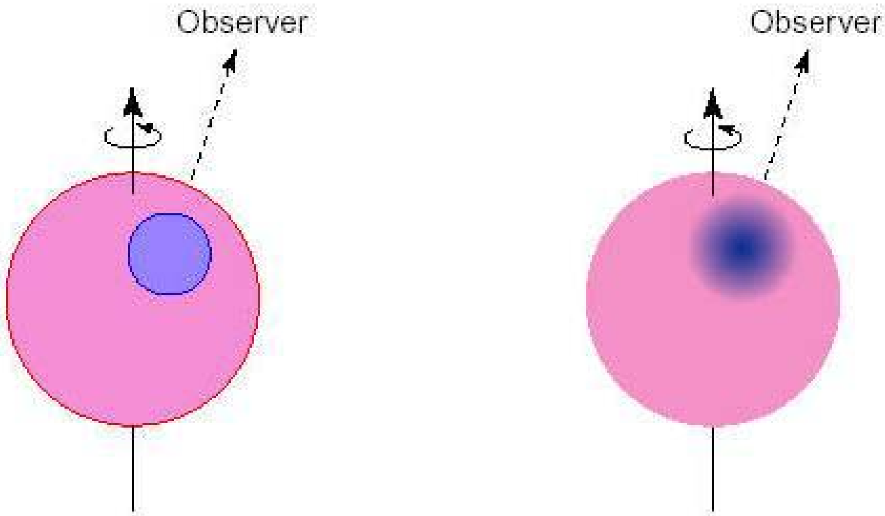
cons:
- large hot spot size

Test: Search for ms pulsations ($P < 10$ ms)

BUT : Independent of all that........

# The Spectrum of RXJ 1856 - 3754




$$T^{\infty} = \frac{T^{\infty}_{pole}}{1+\left(\frac{\theta}{40^{\circ}}\right)^2}$$

$T_{equator}$ = 150 000 K

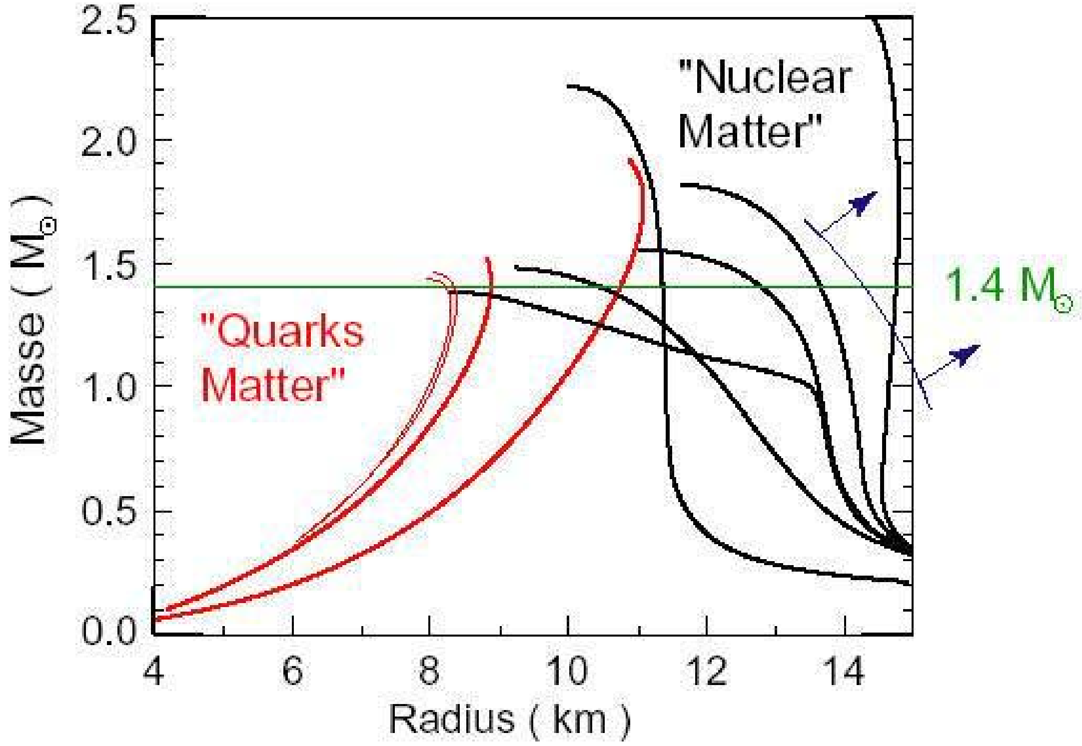
# The Radius of RXJ 1856-3754

Blackbody radius $R_{bb}^{\infty} = 16.9$ km

→ Real radius $R^{\infty} > 16.9$ km

→ Local stellar radius $R$

$$R_{\infty} = R\,(1-2\,GM/Rc^2)^{1/2}$$




RXJ 1856 - 3754 is not a quark star but a neutron star with a rather stift equation of state