Observations of Neutron Stars and the Equation of State of Nuclear Matter

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GSI Kolloquium

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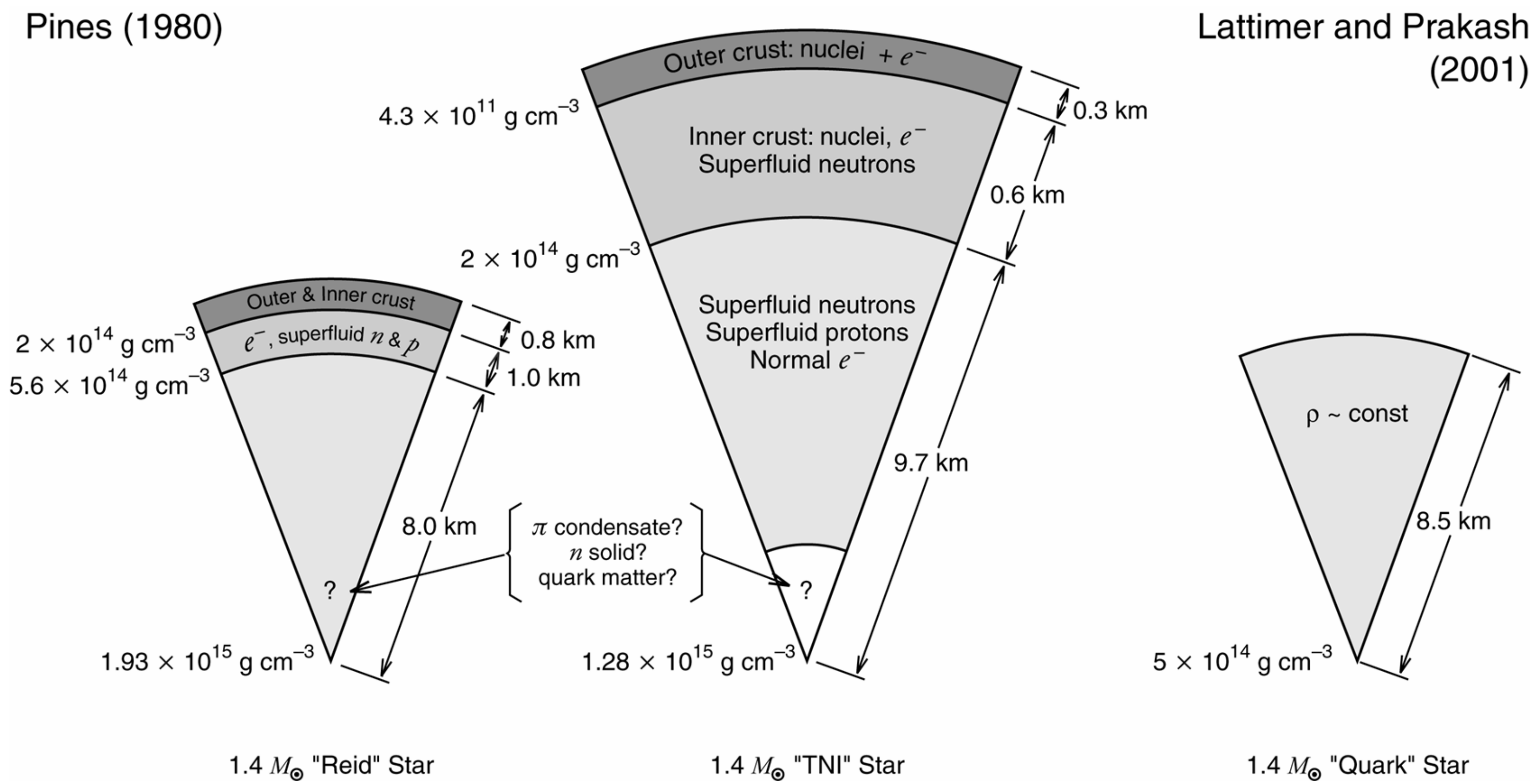
Neutron Star Models



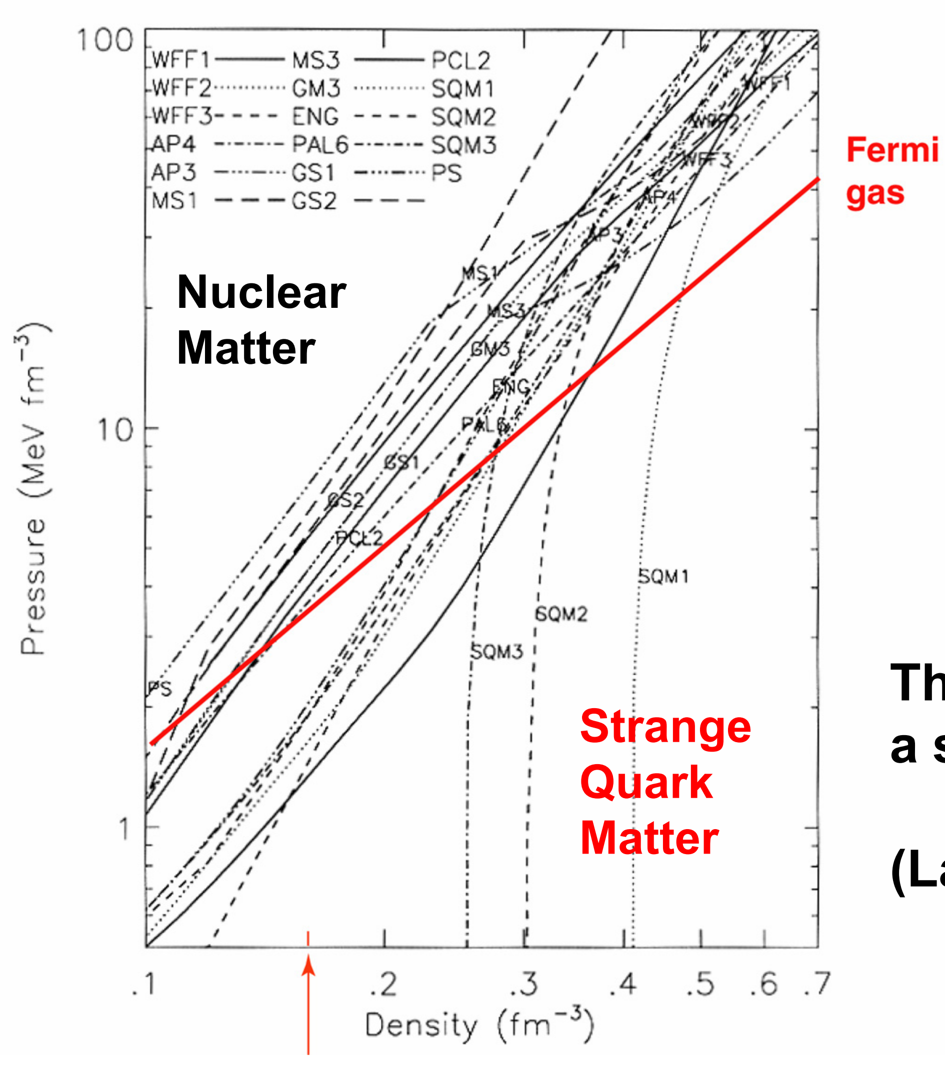
Normal Nuclear Matter (u, d quarks)

Strange Nuclear Matter (u, d, s quarks) (hypothetical)

OUTLINE

- The Equation of State (EOS) of Nuclear Matter
- Accelerator Experiments : Au-Au collisions
- Observations of Neutron Stars
  - Coherent Pulsations in X-Ray Burst Sources
  - Quasi-periodic Pulsations in Low Mass X-Ray Binaries
  - Radiation Radii of Pulsars
  - Radiation Radii of Isolated Neutron Stars
- Conclusions and Outlook

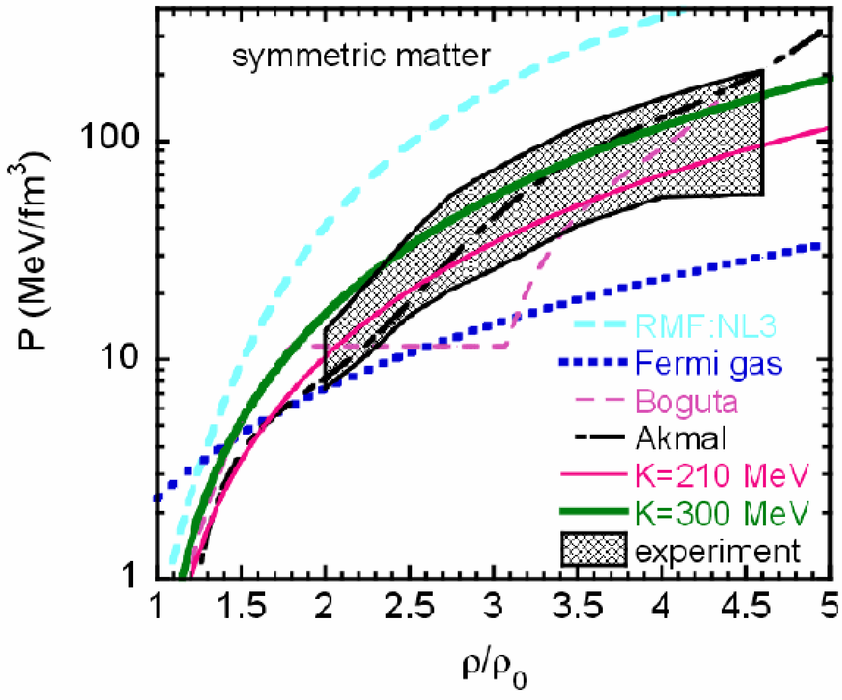
Theoretical EOS models



The pressure - density relations for a selected set of equations of state.

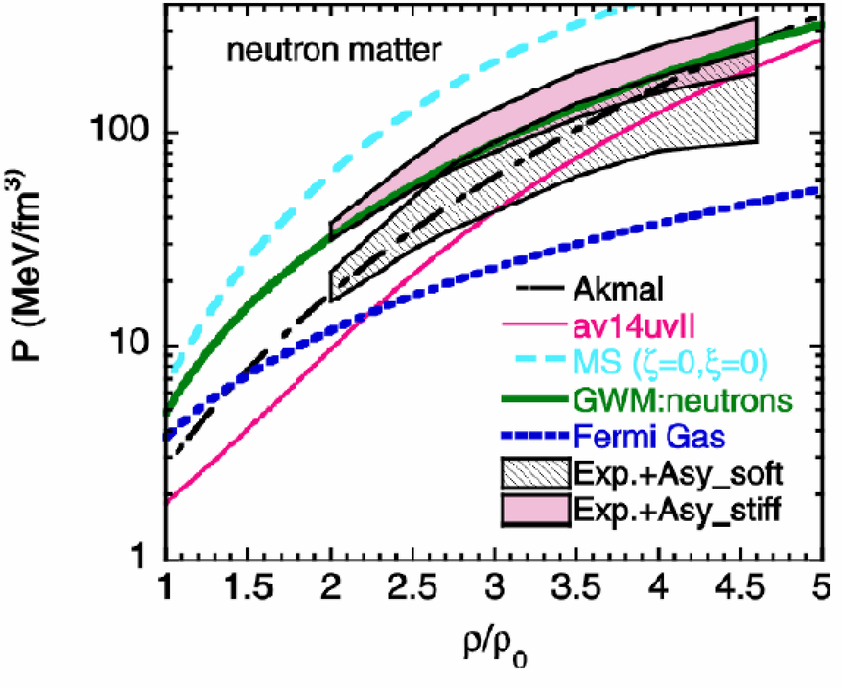
(Lattimer and Prakash 2001)

Nuclear saturation density $\rho_0 = 2.7 \times 10^{14}$ g cm^{-3}



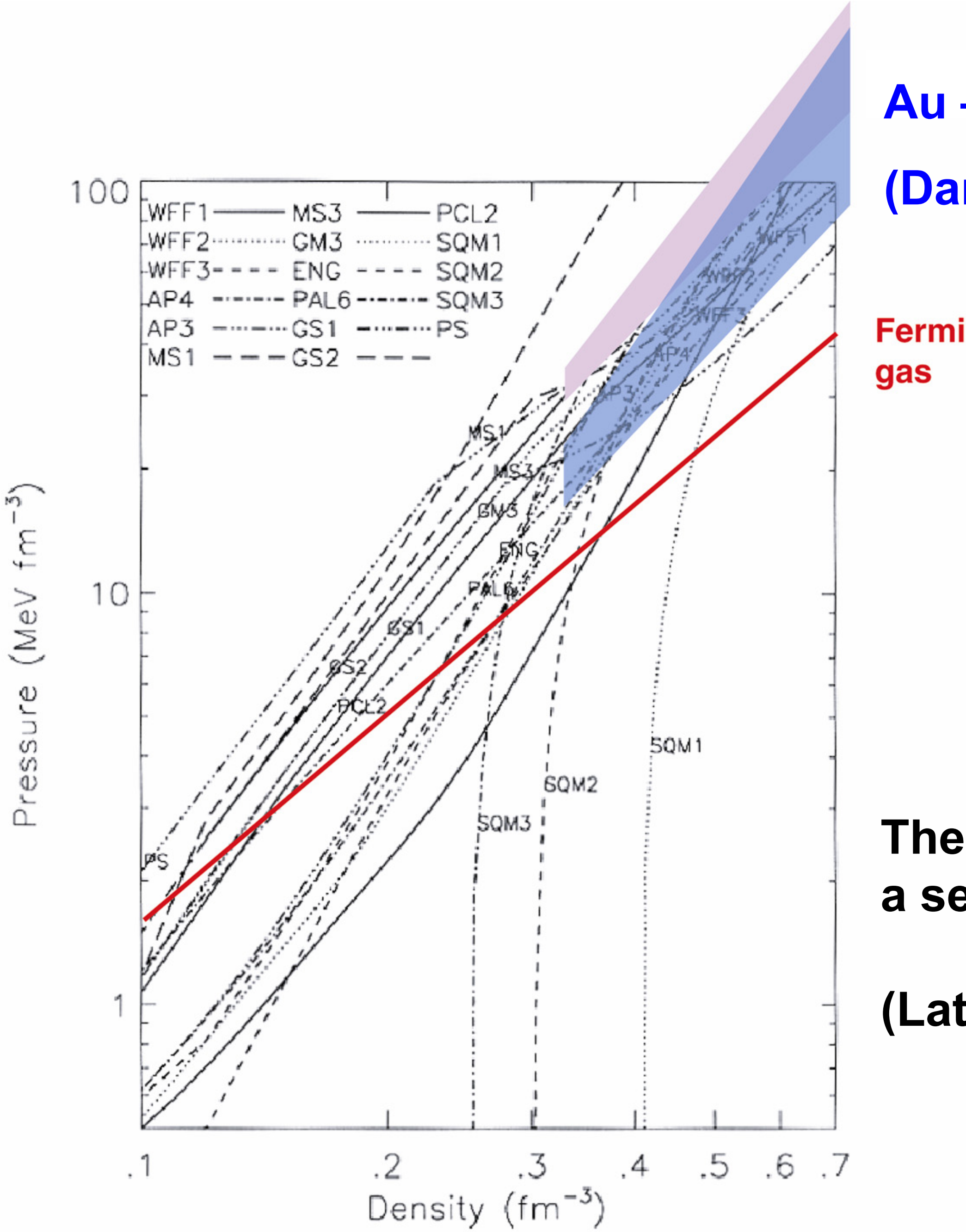
Zero-temperature EOS for „symmetric“ nuclear matter based on Au–Au collisions at 394 GeV (2 GeV/nucleon).

(Experiment E 895 at the AGS Brookhaven National Laboratory)



Zero-temperature EOS for neutron matter,derived from symmetric matter EOS by asymmetric corrections with strong and weak density dependencies.

(Danielewicz, Lacey and Lynch, Science 2002)



Au – Au collisions

(Danielewicz et al. 2002)

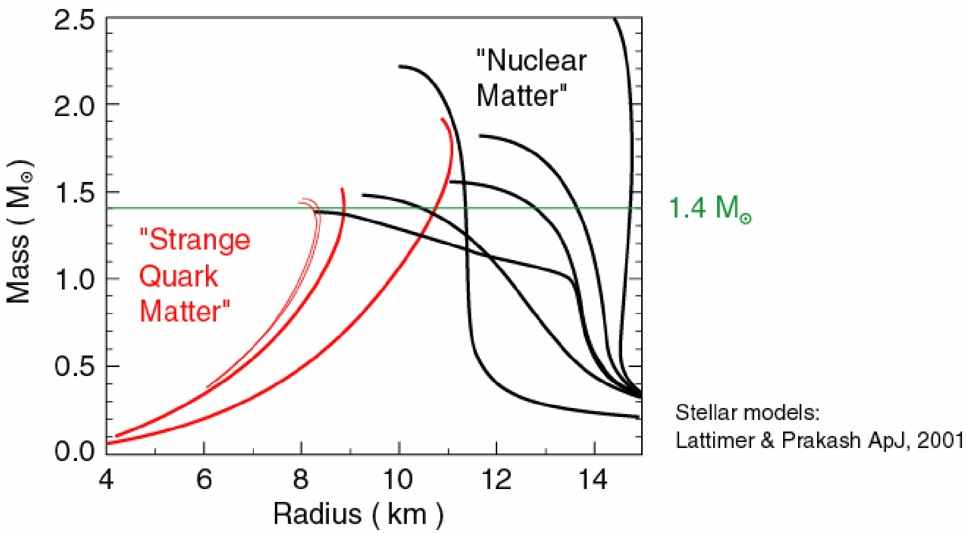
The pressure - density relations for a selected set of equations of state.

(Lattimer and Prakash 2001)

Observations of Neutron Stars

yield informations on M, R, M/R, M/R^2

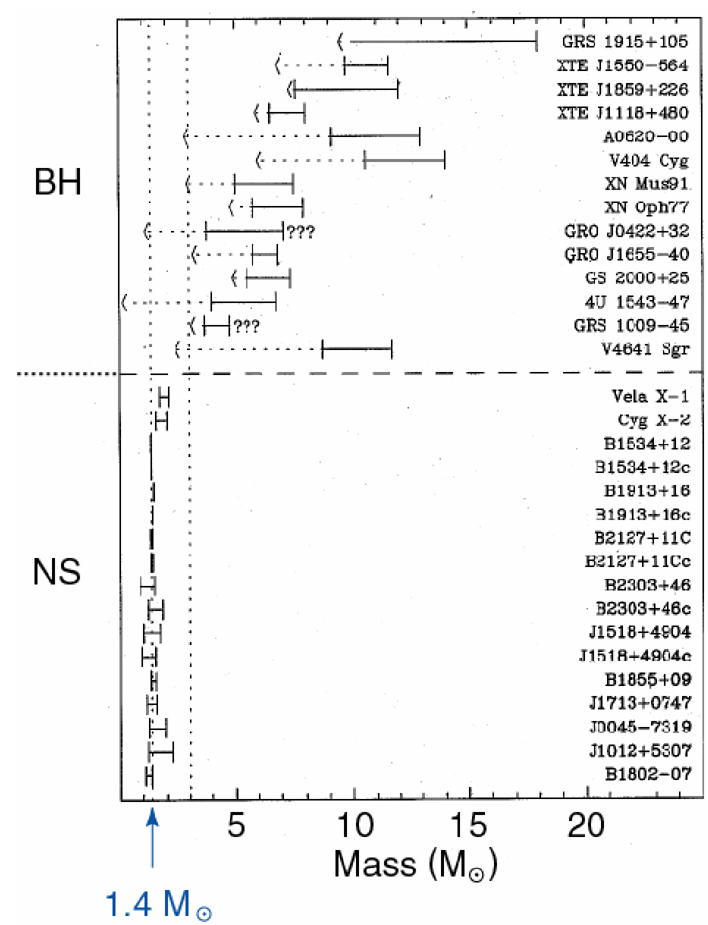
mass-radius relation

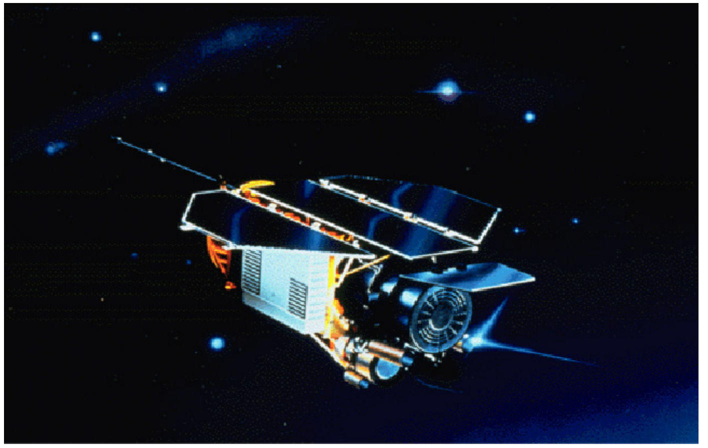


M – R curves cross each other:

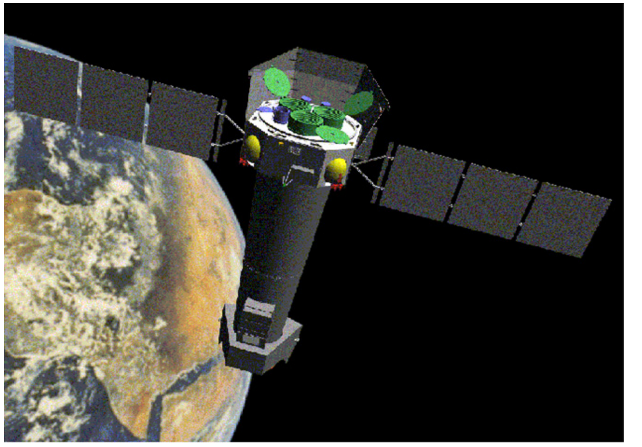
A unique determination of the EOS requires observations of neutron stars with different M and R.

measured neutron star masses

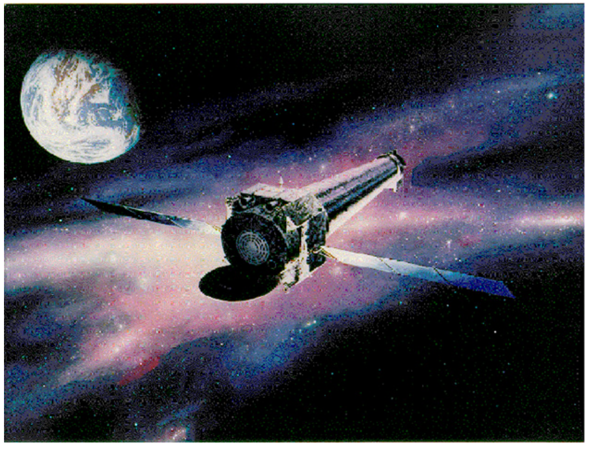




ROSAT (G, UK, USA) 1990 - 1999
0.1 - 2.5 KeV, 4 arcseconds
All Sky Survey + Pointings
200 000 Sources



XMM - Newton (ESA) 1999
0.2 – 20 KeV, 15 arcseconds
Large collecting power,
High resolution spectroscopy

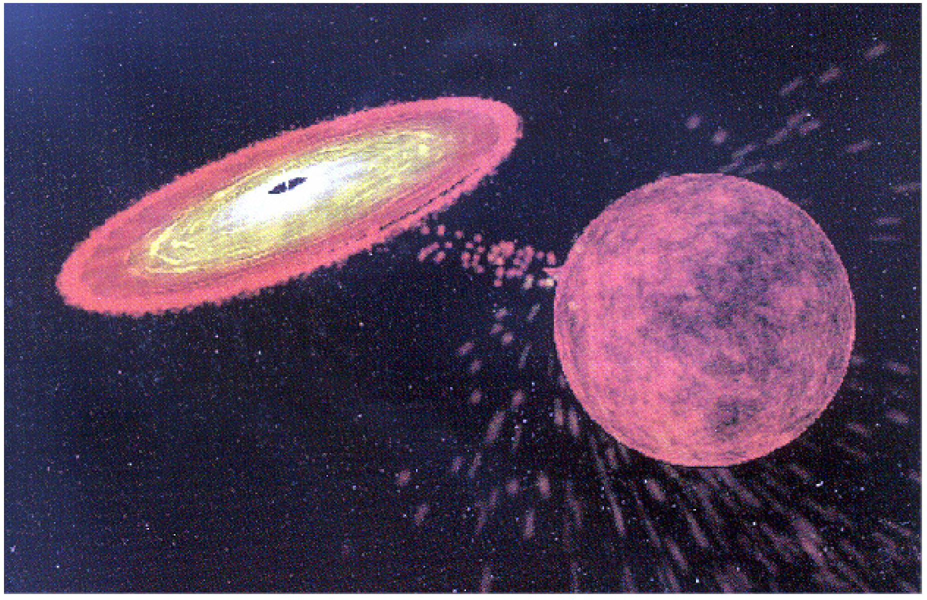


Chandra (NASA) 1999
0.5 – 5 KeV, 0.5 arcseconds
High angular resolution
High resolution spectroscopy

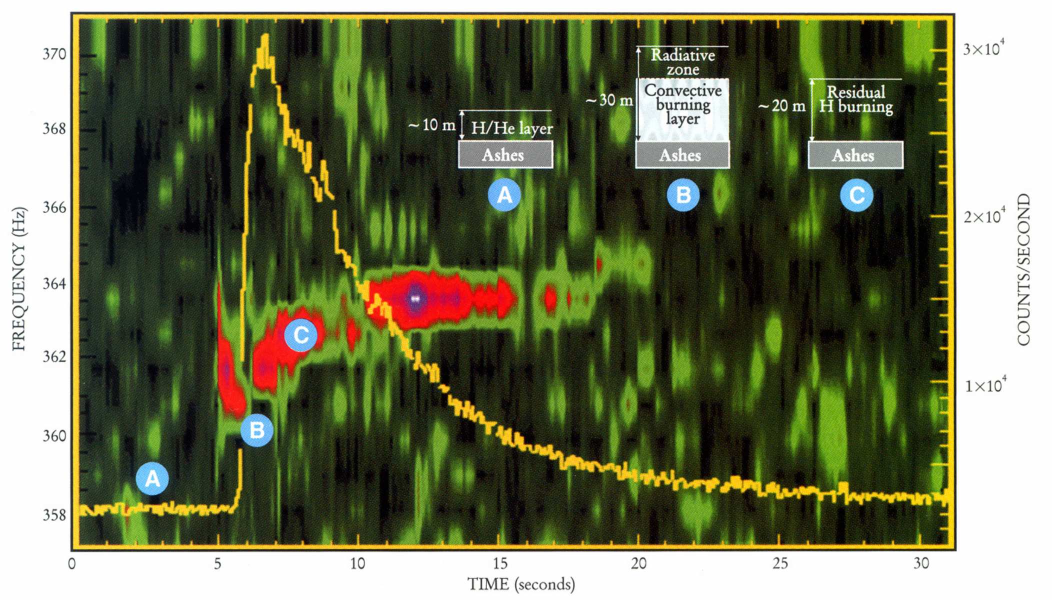
Rossi X-ray Timing Explorer 1995
2 – 250 KeV, 1 degree
Large collecting power
High time resolution

X-Ray Burst Oscillations I (seen in more than a dozen objects):

X-ray Bursts in Low Mass X-ray Binaries
= Thermonuclear Explosions on Neutron Stars



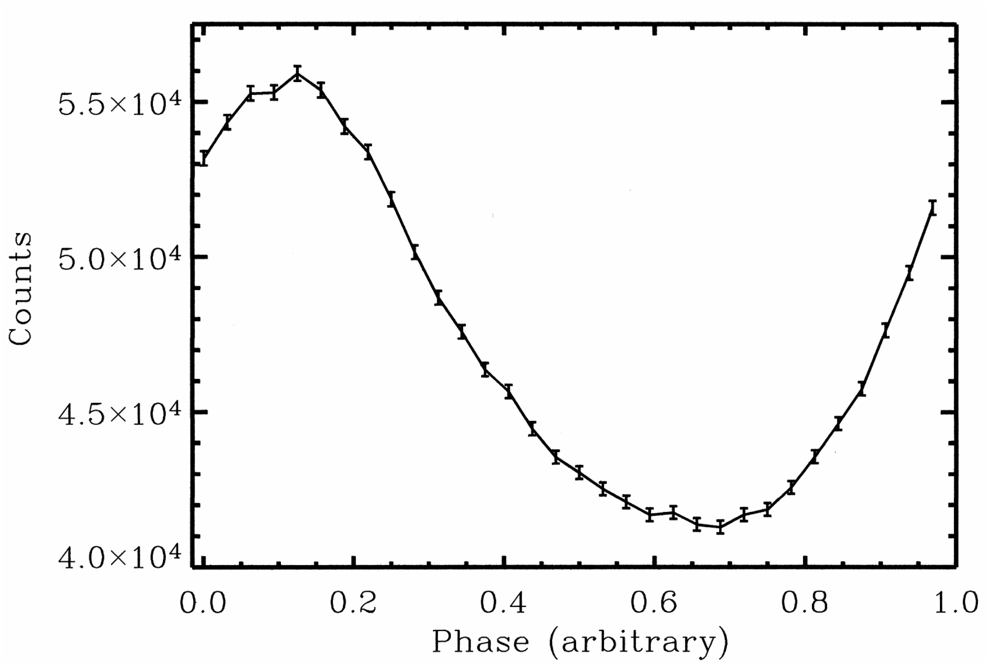
Low Mass X-ray Binary



X-ray burst and burst oscillations in 4 1728-34 at a frequency of 364 Hz (thought to be the spin period of the neutron star)

X-Ray Burst Oscillations II:

Modelling the 314 Hz Light Curve of XTE J1814-338 (Bhattacharyya et al., 2004, similar work by Poutanen, 2004)



The fully added light curve of 22 bursts

model parameters:

- stellar radius
- latitude of the hot spot
- angular size of the hot spot
- beaming $I(\psi) \sim \cos^n \psi$ in the neutron star rest frame
- inclination of the spin axis vs. line of sight

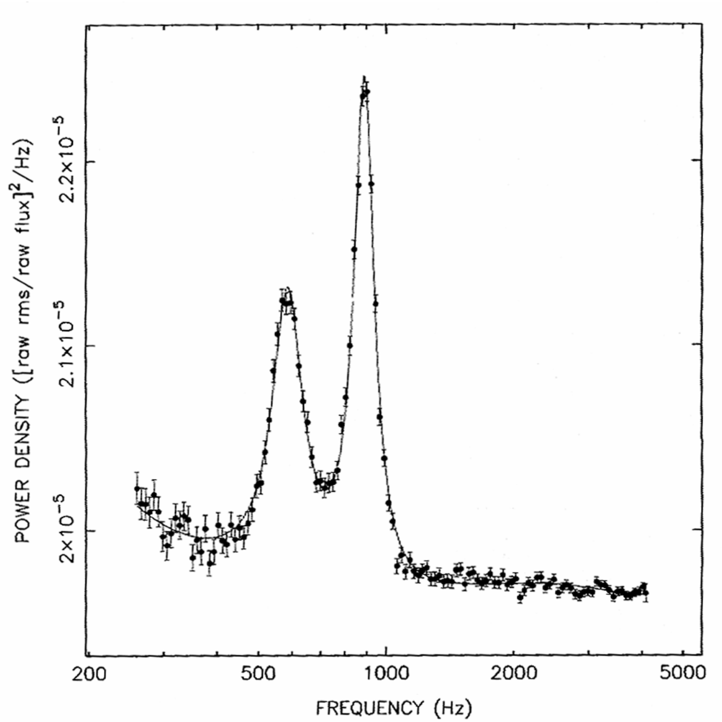
effects considered:

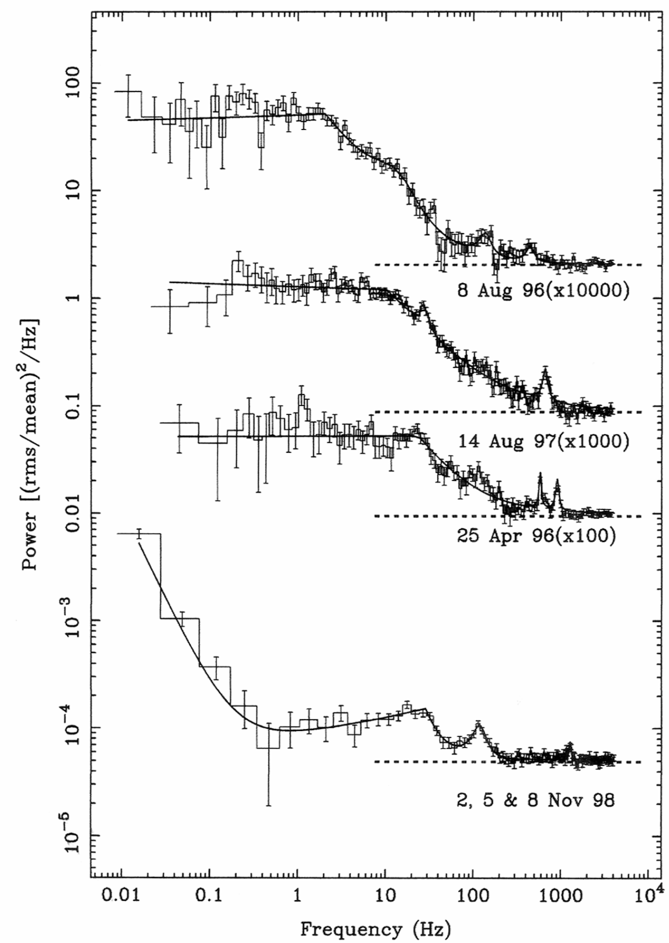
- G.R. light bending,
- frame dragging

$$\Rightarrow \quad \frac{GM}{R\,c^2} = \frac{R_S}{2\,R} \leq 0.24$$

$$\Rightarrow \quad R > 8.7 \text{ km for } M = 1.4\, M_\odot$$

Quasiperiodic Oscillations (QPO) at High Frequencies in LMxB's





Power density spectrum of Sco X-1 (van der Klis 1997)

The highest QPO frequency (at 1330 Hz) ever observed in 4U 0614+09 (van Straaten et al. 2000)

High Frequency QPO

The origin of the high frequency QPO must be in the boundary layer between the accretion disk and the neutron star surface.

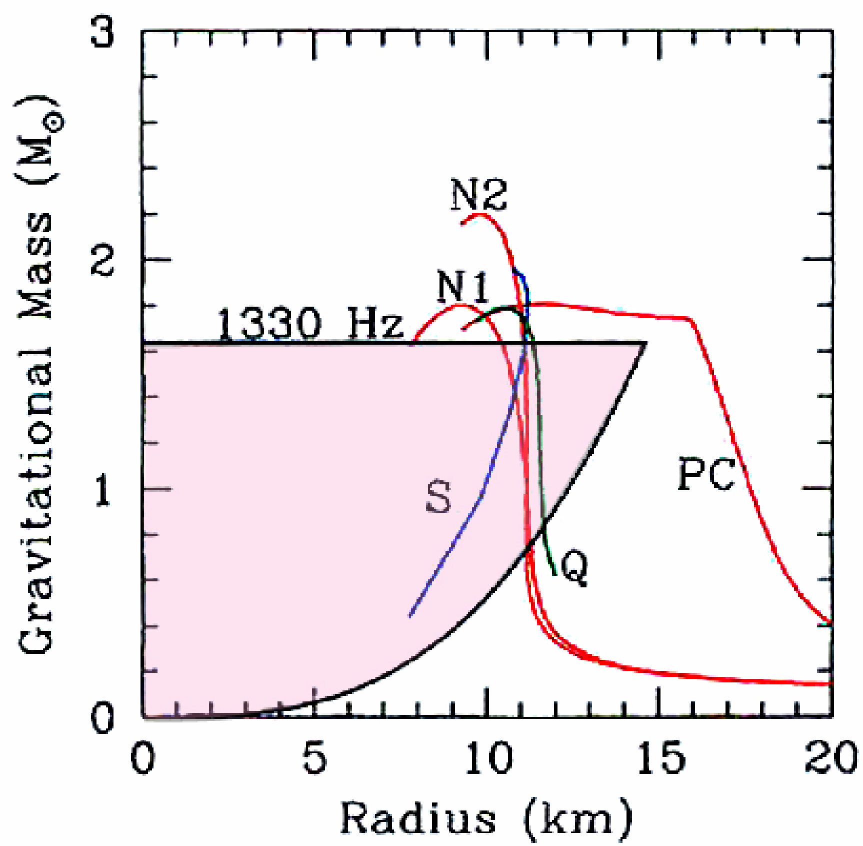
In a popular class of models (e.g. Miller 2003)

ν (QPO) $\approx$ ν (orbit of accreting gas)

Since $R_{orbit} > R_{NS}$ and R_{ISCO} (innermost stable circular orbit):

$M < 2.2\ M_{\odot}$ (1 kHz / ν_{orbit}) (1+0.75j)

$R < 19.5$ km (1 kHz / ν_{orbit}) (1+0.2j)



Limits to M, R for a nonrotating star (j = 0)

$$j = \frac{cJ}{GM^2}$$ **= dimensionless spin parameter**

Thermal Radiation from Hot Neutron Stars

- gravitational redshift of lines or edges $\Rightarrow$ M / R
  problem: line/edge identification, requires knowledge of the magnetic field

Iron K_α	: E	= 6.4 KeV
B = 10^{12} G	: E_{cycl}	~ 11.6 KeV

$\Rightarrow$ this is not a reliable method

- photometric radius $\Rightarrow$ R
  problem: requires knowledge of the distance

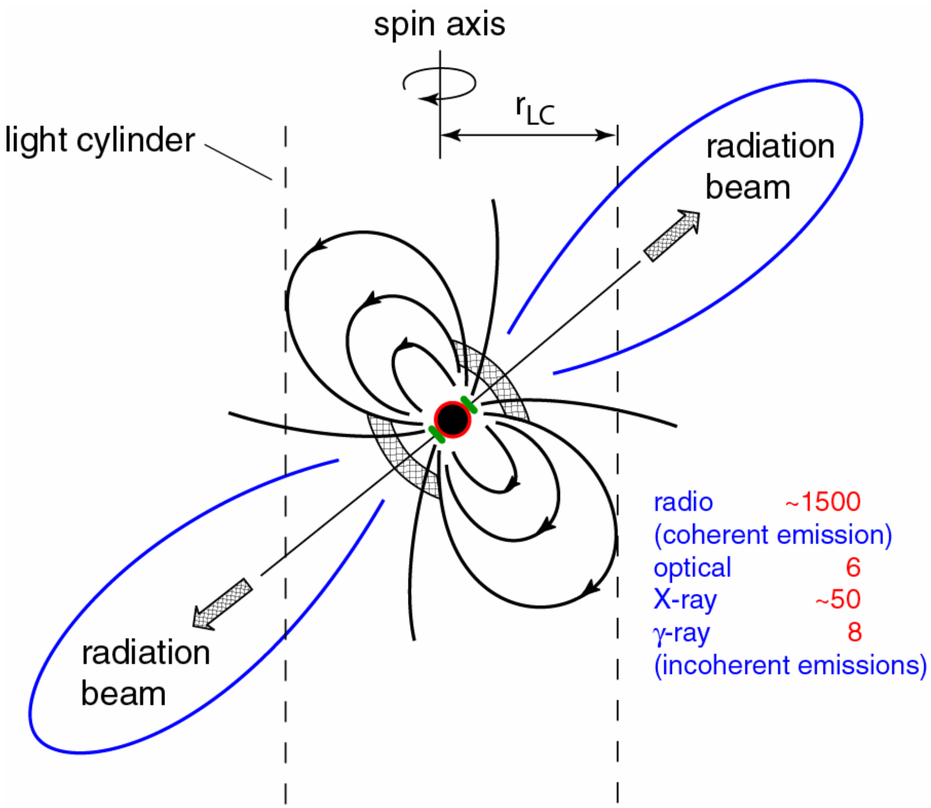
  - blackbody models $\rightarrow$ R_{bb}

  - atmospheric models without or with magnetic fields $\rightarrow$ R $>$ 2 R_{bb} (H, He)
    $\gtrsim$ R_{bb} (Fe)

Application to Pulsars and Isolated Neutron Stars $\Rightarrow$

X-RAY EMISSION FROM PULSARS

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

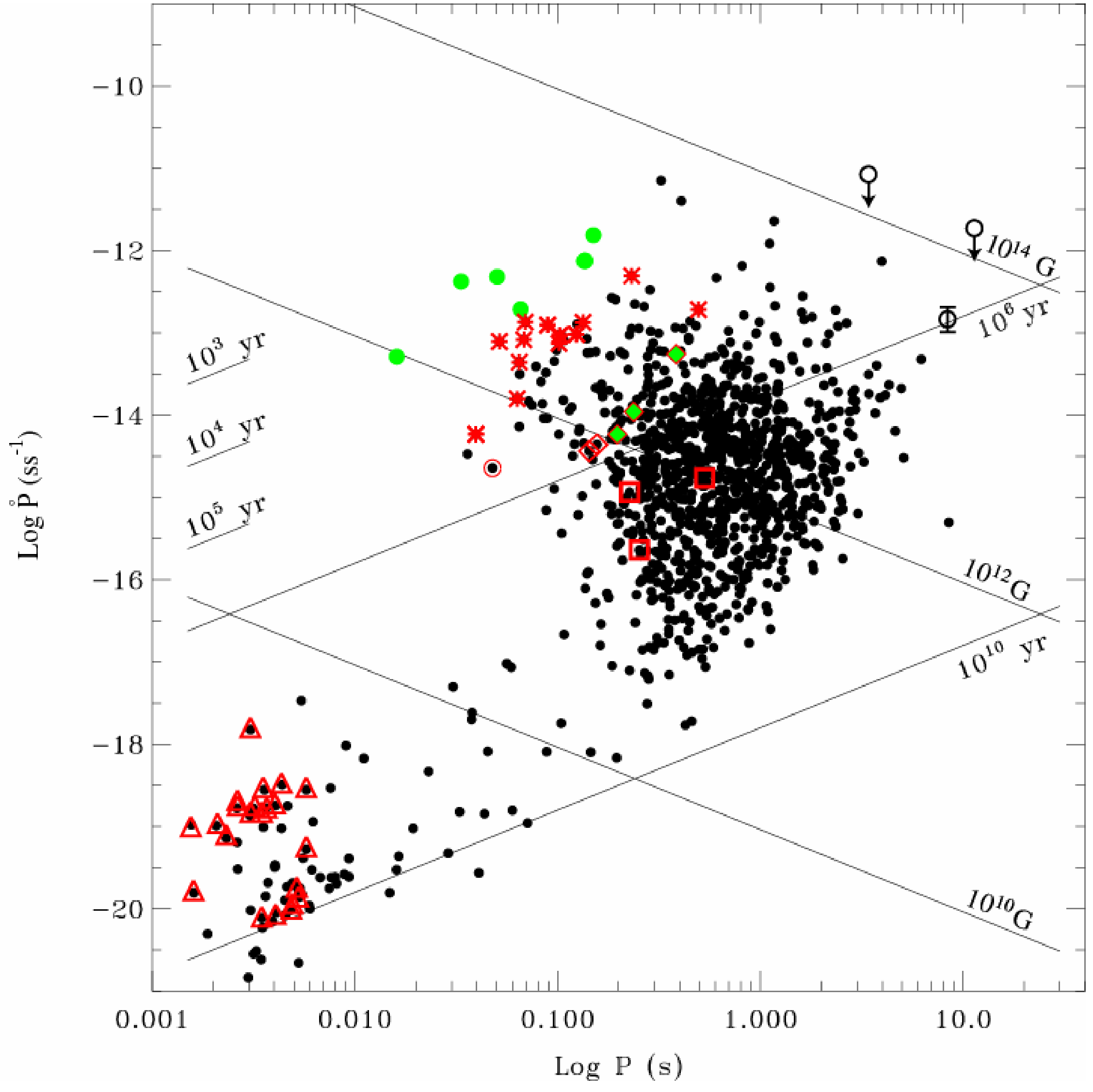


- Photon Emission from extremly high energetic electrons
  (Synchroton radiation, inverse Compton effect)

- 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

Radio Pulsars



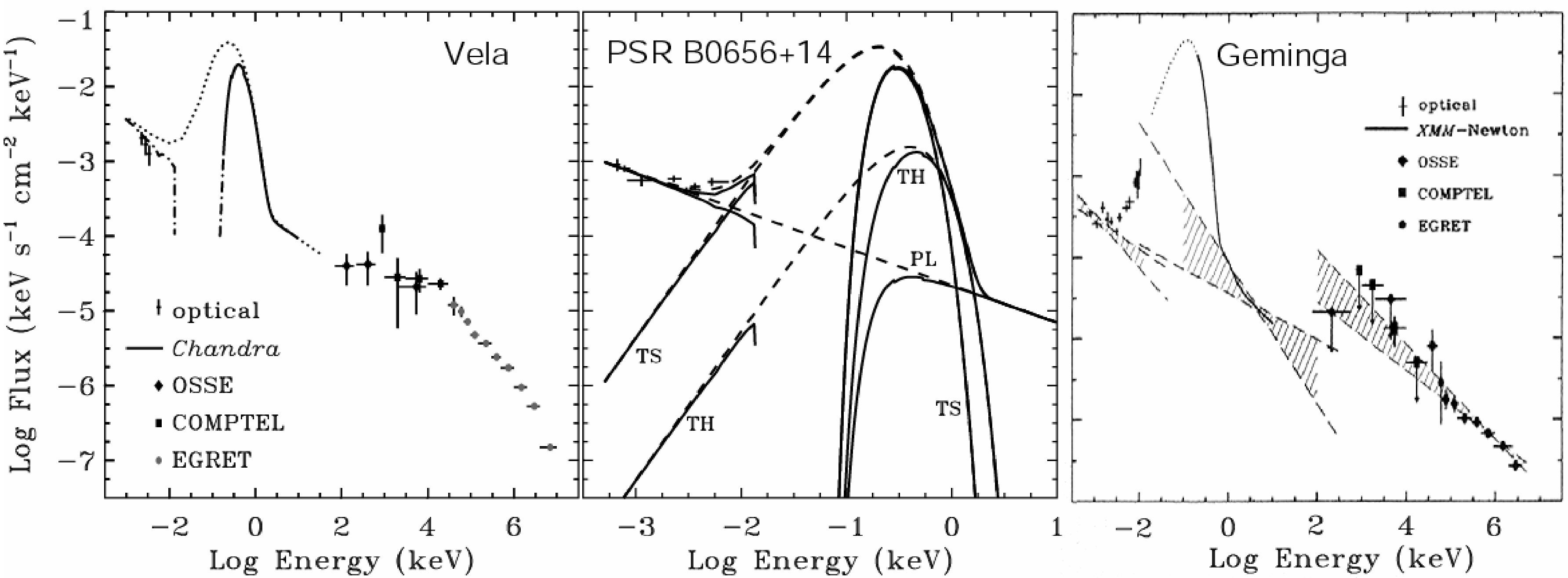
red symbols: X-ray detections

green symbols: γ-ray and X-ray detections

magnetic dipole braking: age = $P / 2\dot{P}$, $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$

Radiation Radii of Pulsars having measured Distances

PAVLOV & ZAVLIN 2003 **Kargaltsev et al 2005**



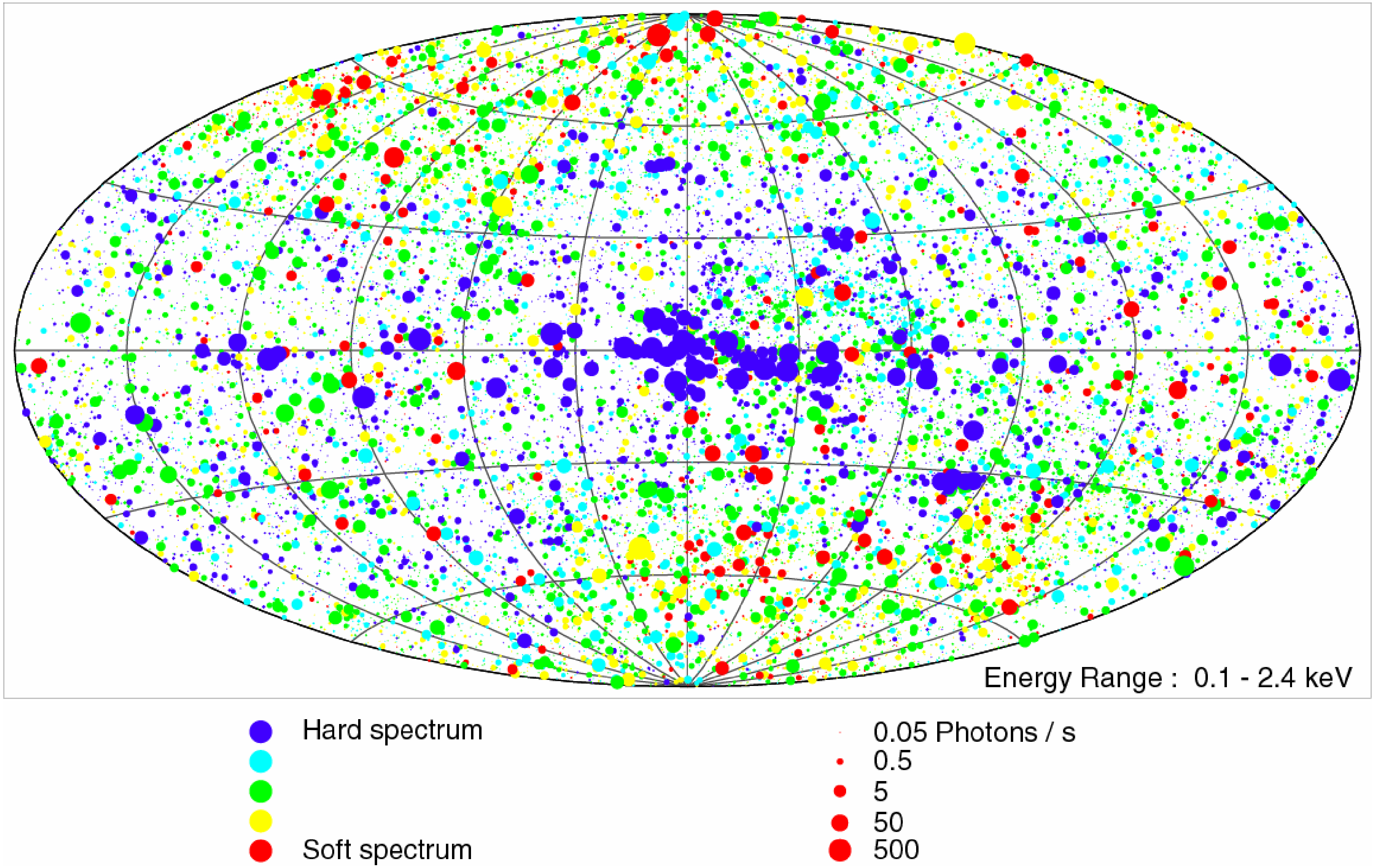
VLBA : 290 pc	VLBA : 288 pc	HST : 157 pc
(Dodson et al. 2003)	(Brisken et al. 2003)	(Caraveo et al. 1996)
R = 17 - 20 km	R = 13 - 20 km	R_{bb} ~ 10 km
		R $\gtrsim$ 20 km

These Neutron Star Radii appear to be large

(but uncertain because of the presence of nonthermal components).

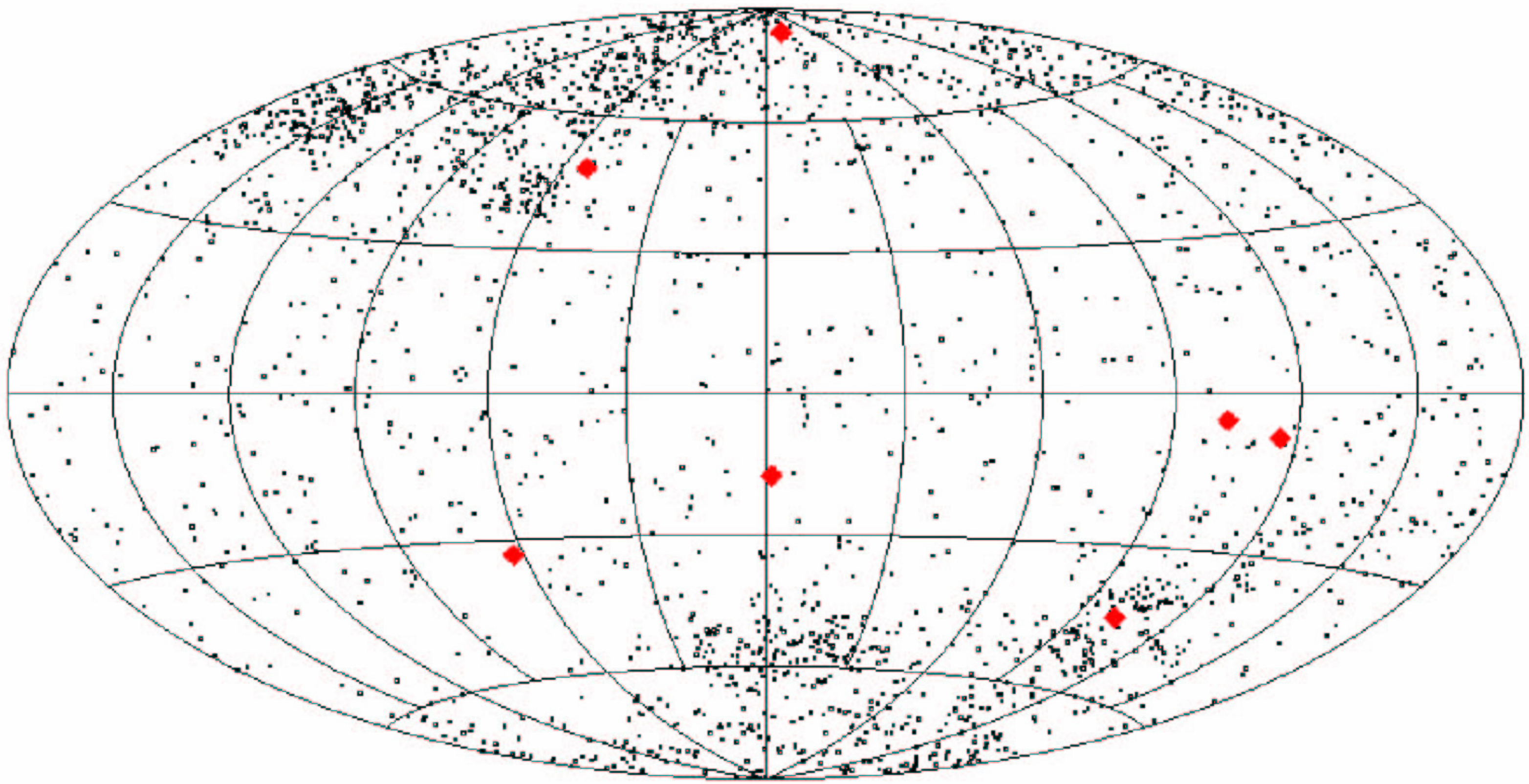
Radio-quiet Neutron Stars in the ROSAT Survey

Distribution of the ~ 20 000 Brightest RASS Sources



How to find them ?

Soft X-ray spectrum + faint in optical



Radio-quiet Isolated Neutron Stars

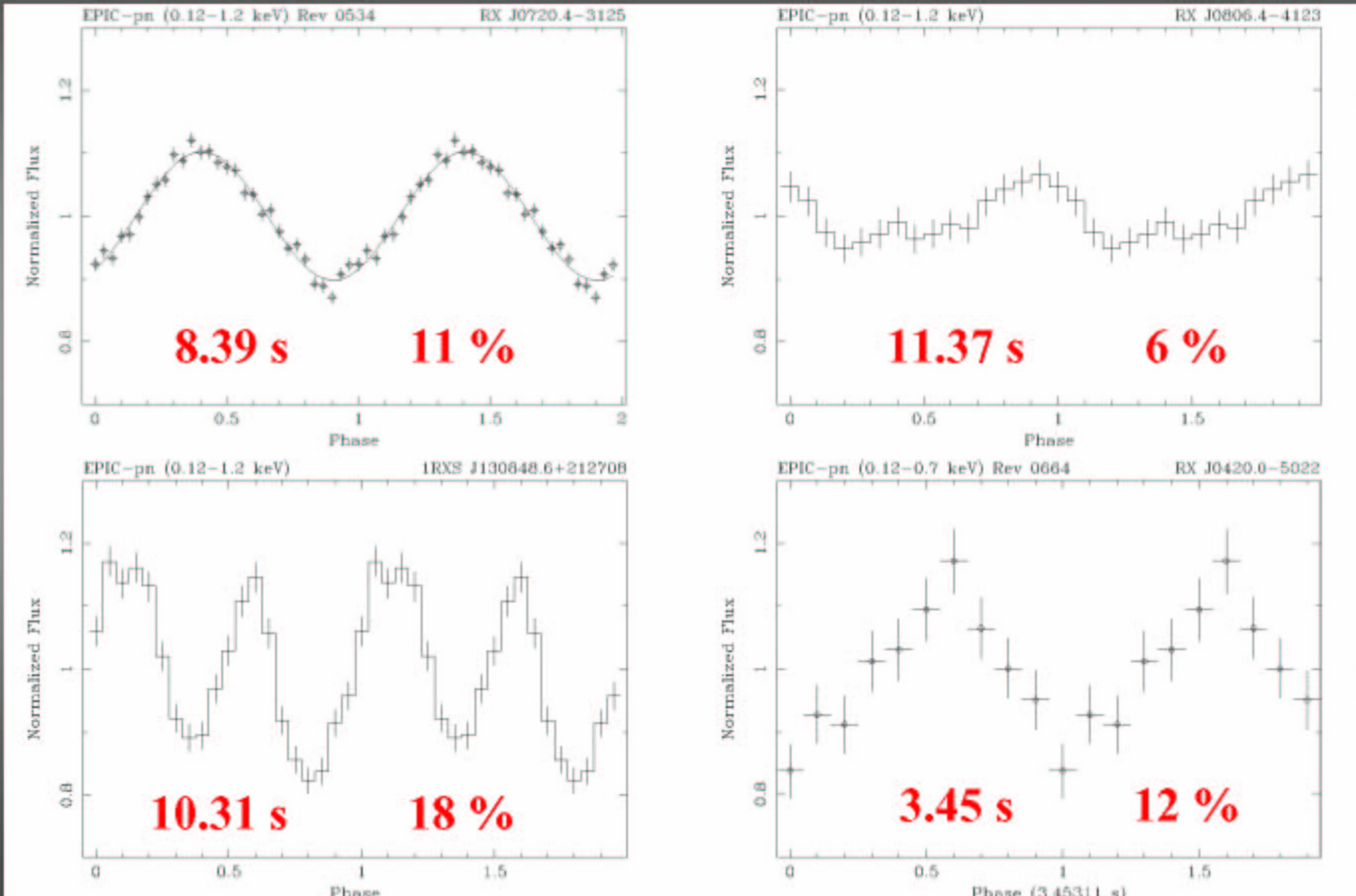
- Soft X- ray sources in ROSAT survey
- Blackbody-like X- ray spectra, no non - thermal hard emission
- Nearby: low absorption ~10^{20} H cm^{-2}, large proper motion, RX J1856.5-3754: 117pc
- Low luminosity ~10^{31} erg s^{-1}
- Constant X- ray flux on time scales of years
- No obvious association with SNR
- No radio emission
- Optically faint
- X- ray pulsations

Object	kT/eV	P/s	Optical	
RX J0420.0-5022	44	3.45	B = 26.6	—
RX J0720.4-3125	85-95	8.39	B = 26.6	PM = 97 mas/y
RX J0806.4-4123	96	11.37	B > 24	—
RX J1308.5+2127	86	10.31	m_{50ccd} = 26.6	—
RX J1605.3+3249	96	—	B = 27.2	PM = 145 mas/y
RX J1856.5-3754	60	—	V = 25.7	PM = 332 mas/y
RX J2143.0+2127	100	9.43	R > 23	—

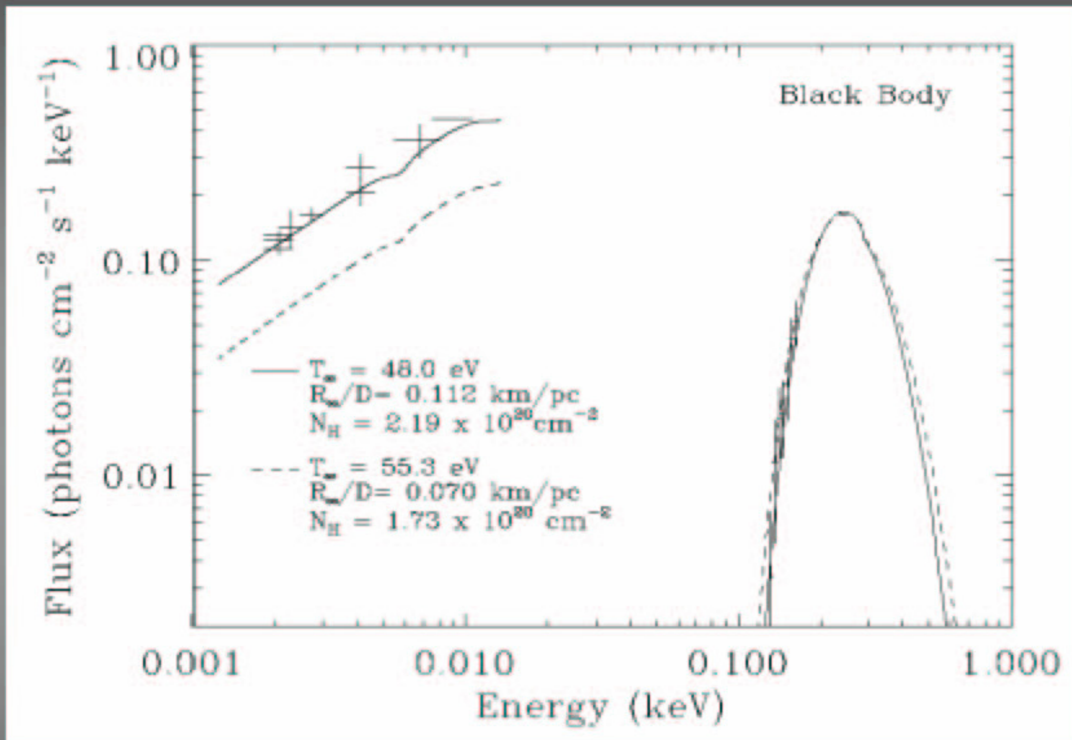
" The Magnificent Seven"

Evidence for an anisotropic temperature distribution

X-ray pulsations



Optical to X-rays



RX J1856.5-3754

In optical a factor ~3 brighter than extrapolation from X-rays (from ROSAT PSPC)

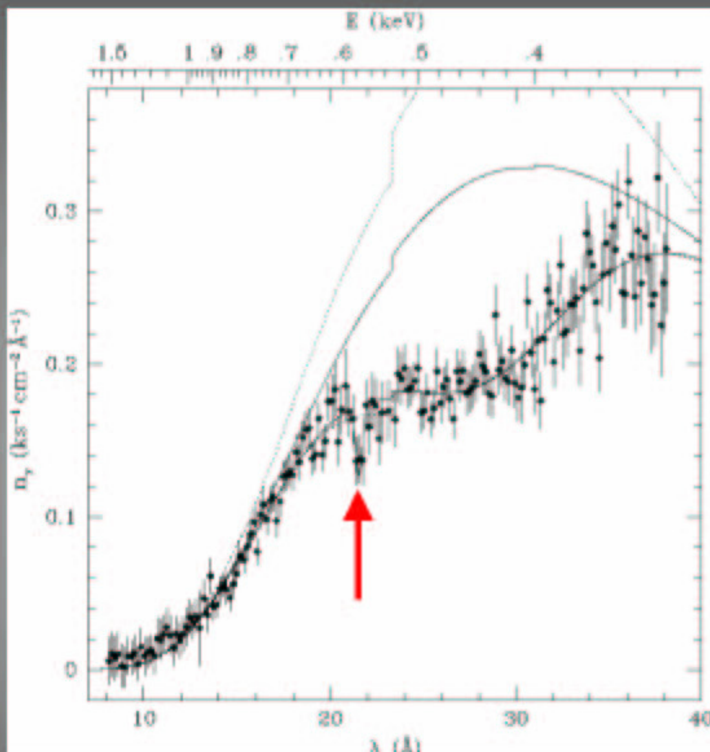
Pons et al. (2002)

(Factor 5-7 if LETG spectrum is used)

RX J0720.4-3125	RBS1223	RX J1605.3+3249	RX J0420.0–5022
Factor ~5	Factor <5	Factor ~14	Factor <12
Motch & Haberl (1998)	*Kaplan et al. (2001)*	*Motch et al. (2004)*	*Haberl et al. (2004)*

X-ray spectral survey: absorption feature

RX J1605.3+3249



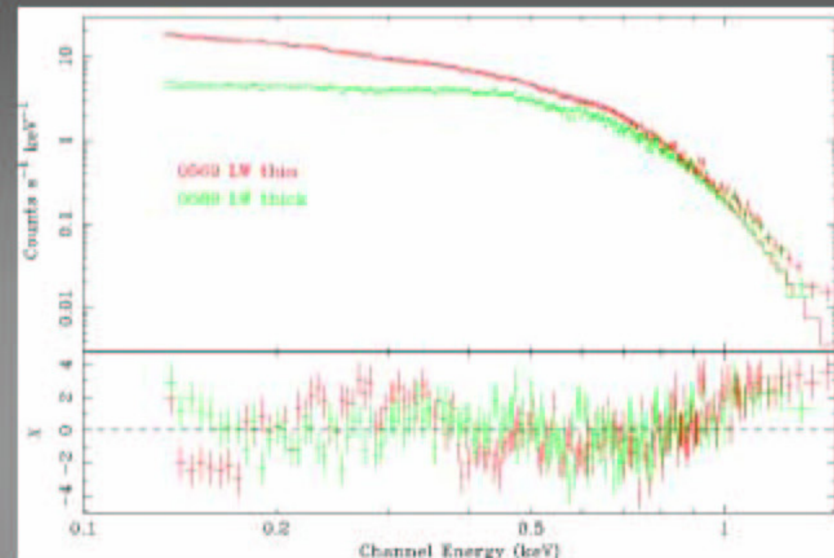
RGS

kT = 95 eV

N_H = 0.8 x 10^{20} cm^{-2}

E_{line} = 450 – 480 eV

Van Kerkwijk et al. (2003) submitted



EPIC

kT = 92 eV

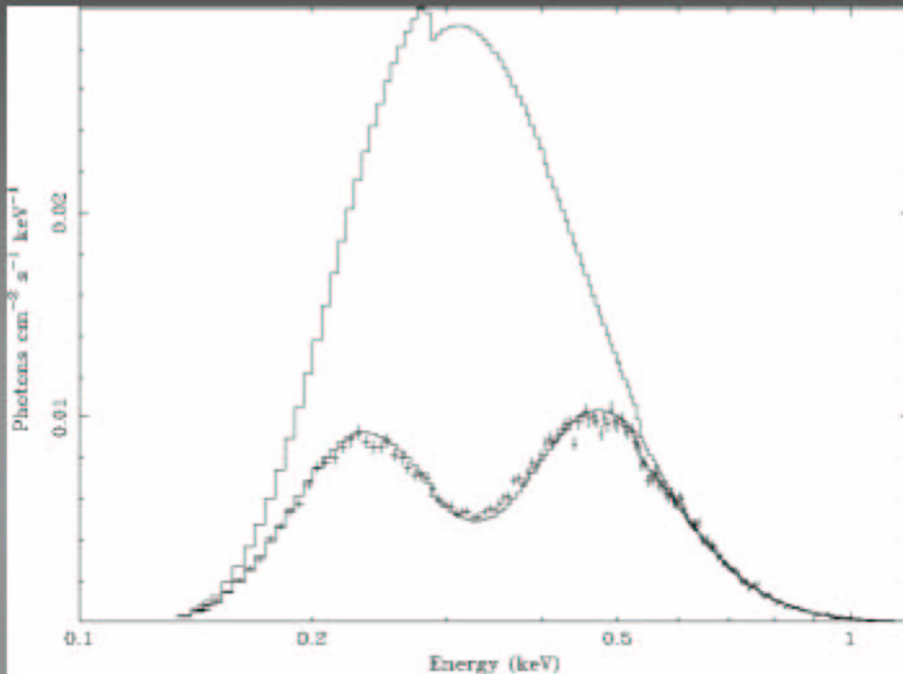
N_H = 1.0 x 10^{20} cm^{-2}

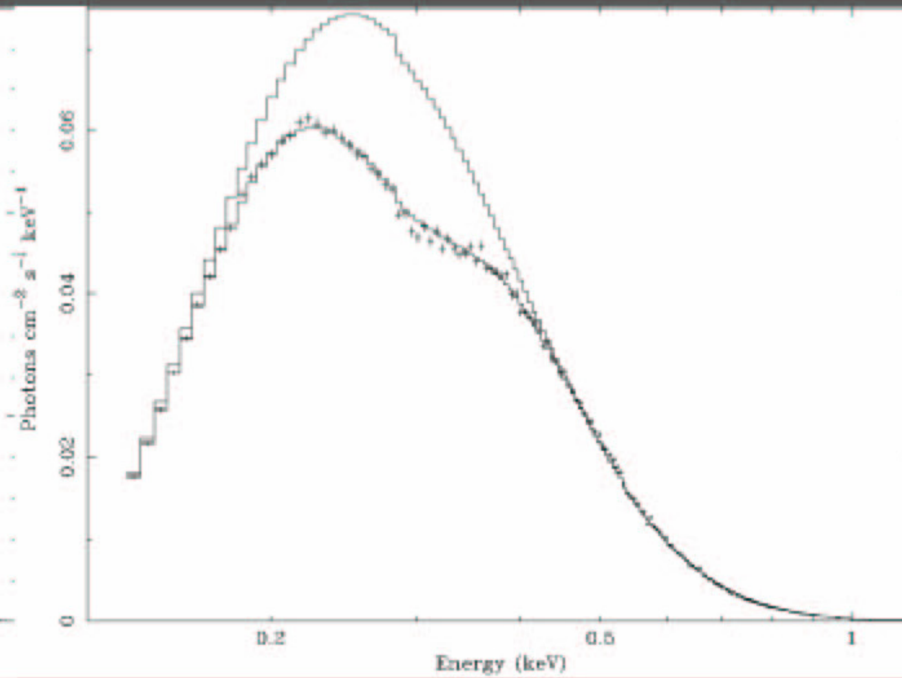
E_{line} ~ 450 eV

σ ~ 70 eV

EW = 37 eV

X-ray spectral survey: absorption feature





RBS1223
EW = 150 eV

RX J0720.4-3125
EW = 40 eV

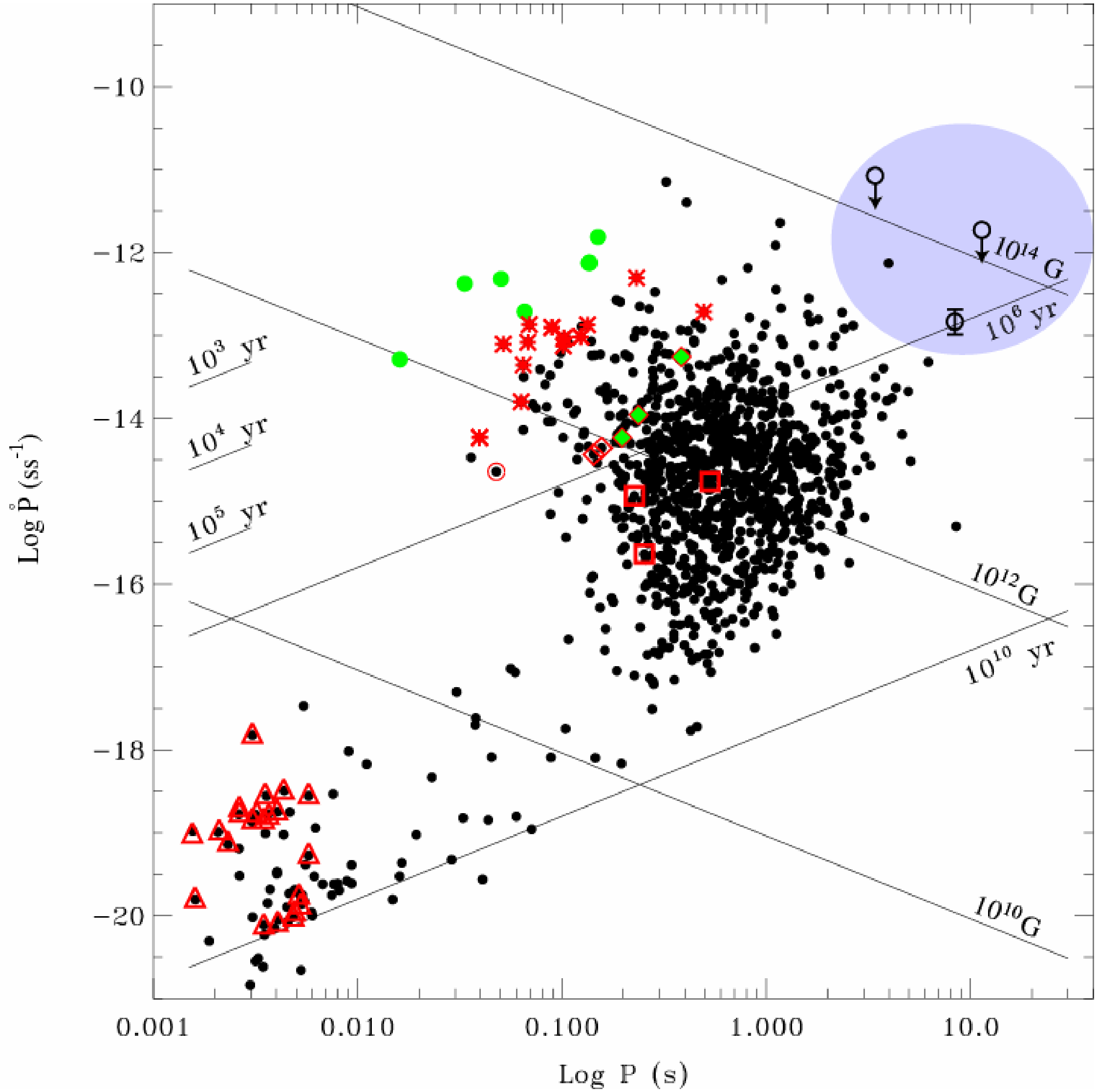
Magnetic Fields

- Magnetic dipole braking $\rightarrow B_{db} \approx 3.2 \times 10^{19} (P\times dP/dt)^{1/2}$
  Spin - down rate (P, dP/dt)
- Proton cyclotron absorption $\rightarrow B_{cyc} \approx 1.6 \times 10^{11} E_{cyc}(eV)/(1\text{-}2GM/c^2R)^{1/2}$

Object	P [s]	Ampl. [%]	dP/dt $[10^{-13} ss^{-1}]$	E_{cyc} [eV]	B_{db} $[10^{13}G]$	B_{cyc} $[10^{13}G]$
RX J0420.0-5022	3.45	13	< 92	330	< 18	6.6
RX J0720.4-3125	8.39	8-15	0.698	260	2.4	5.2
RX J0806.4-4123	11.37	6	< 18	—	< 14	—
1RXS J130848.6+212708	10.31	18	< 9	100-300	< 10	2-6
RX J1605.3+3249	—	—	—	450-480	—	9.1-9.7
RX J1856.5-3754	—	< 2	—	—	~1*	—
1RXS J214303.7+212708	9.43	4	—	~700	—	~14

* derived from the spin-down luminosity to power the H_α nebula and from the age of the neutron star ($\lesssim 10^6$ yrs)

Radio Pulsars



radio quiet
isolated Neutron Stars

red symbols:
X-ray detections

green symbols:
γ-ray and X-ray detections

magnetic dipole braking: age = $P / 2\dot{P}$, $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$

The likely nature of the radio quiet isolated NS

– periods ~ 10s ⇒ old pulsars

why no radio emission?

- INS are located beyond the death line
- radio beam (if it existed) would be very narrow (few degrees) because of their long periods.

– strong magnetic fields ($B \gtrsim 10^{13}$G)

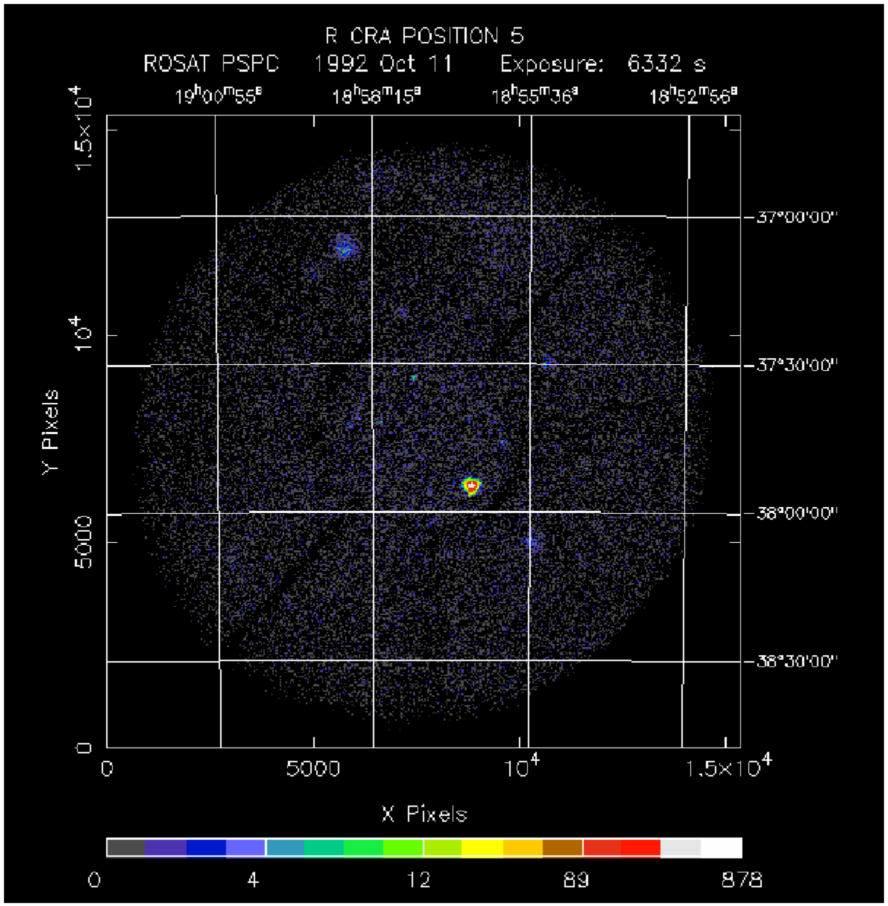
based on $\dot{P}$ and proton cyclotron lines

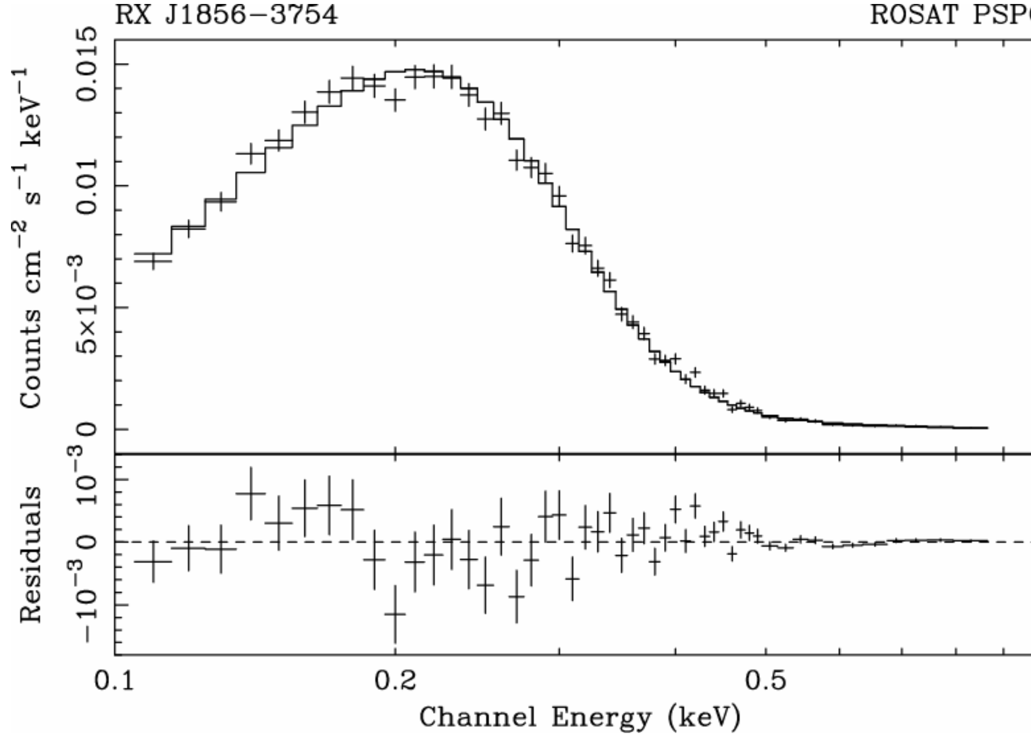
- Such strong magnetic fields are required to make the spin down time ($\propto P^2 B^{-2}$) shorter than their cooling time (~ 10^6 yrs).

⇒ isolated neutron stars may have been normal pulsars when they were young

Discovery of the Bright Isolated Neutron Star RX J1856-3754 in front of the R. Coronae Australis molecular cloud

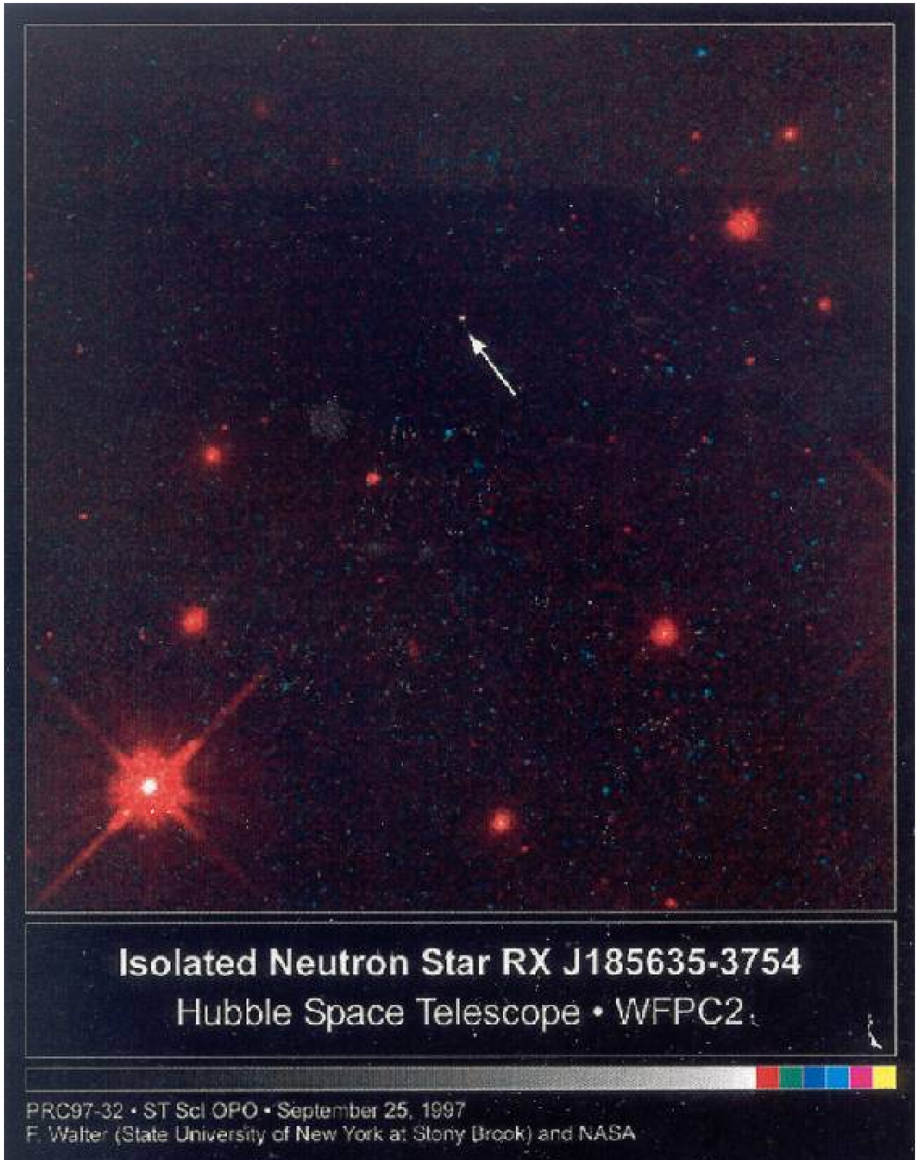
(Walter, Wolk & Neuhäuser, 1996)





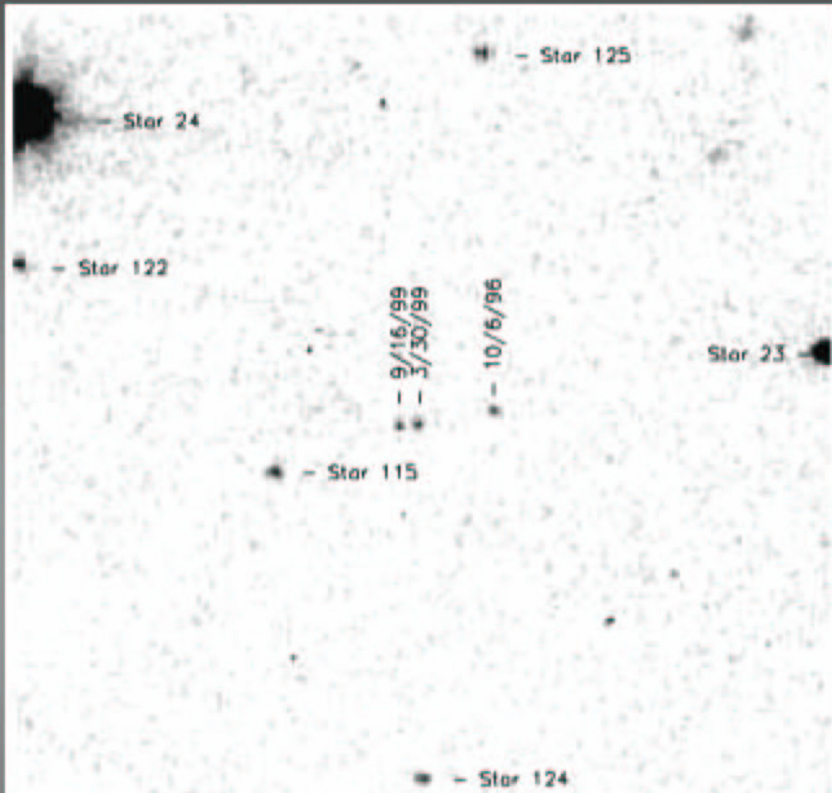
ROSAT – PSPC Spectrum
with blackbody fit ($T \approx 6 \times 10^5$ K)

Optical Identification of the Neutron Star RX J1856-3754



- **A very faint and blue star (*V* = 25.6, U= 24.4) detected by the HST WFPC2 (Walter & Matthews, 1997)**
- **$F_x / F_{opt} \approx 75000$**
- **The source is located in front of a molecular cloud: *d* ≤ 130 *pc***

Optical identifications RX J1856.5-3754

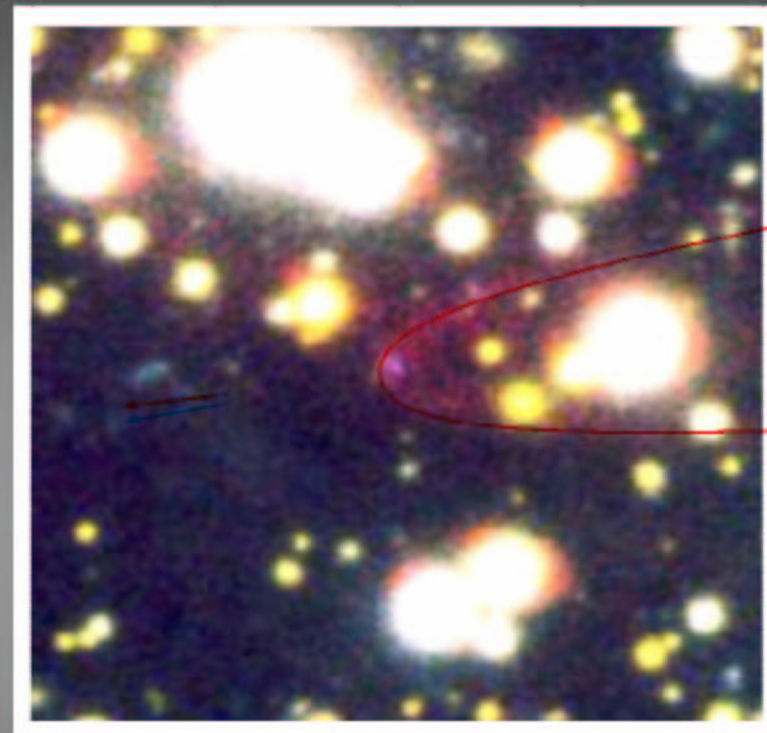


Distance 117 ± 12 pc HST

Proper motion 332 mas y $^{-1}$

Tangential space velocity 185 km s $^{-1}$

Walter (2001); Walter & Lattimer (2002)



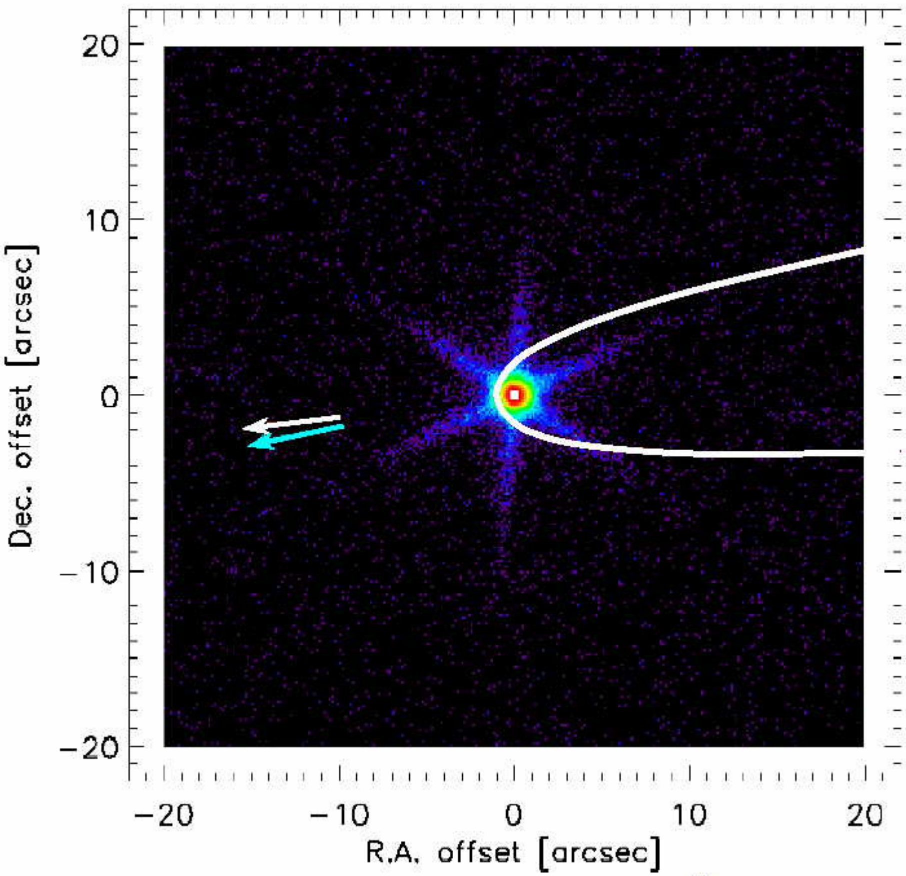
Bowshock Nebula VLT

Kerkwijk & Kulkarni (2001)

High proper motion:
Not heated by accretion of ISM !!

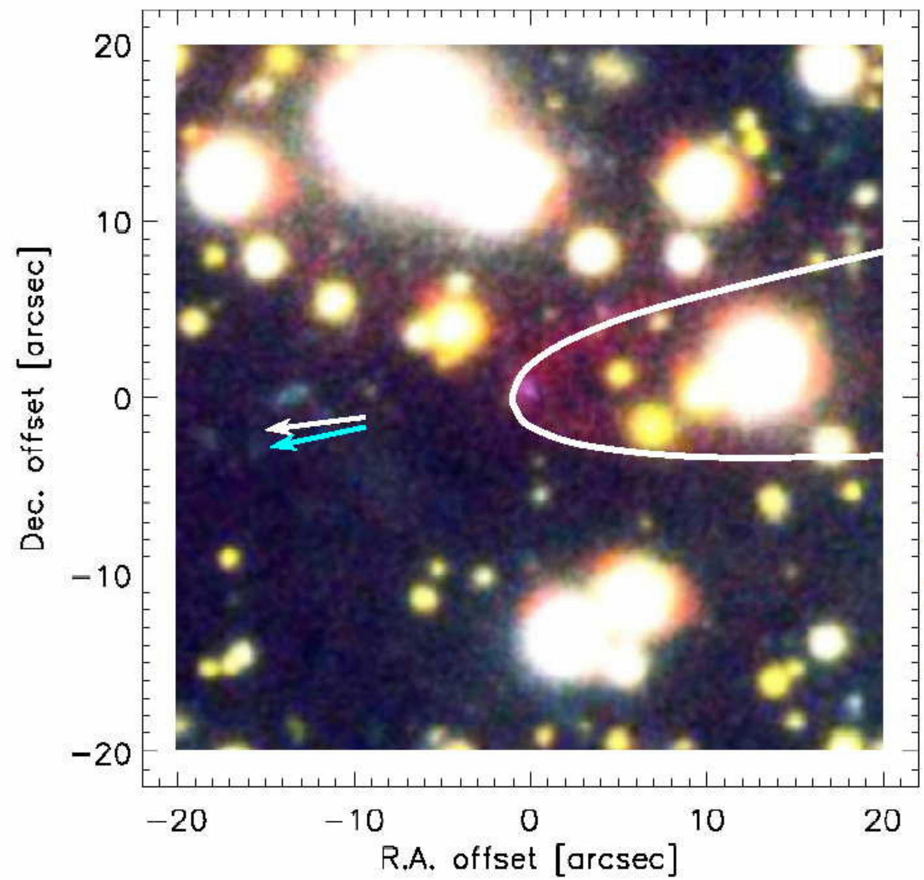
RX J1856.5-3754: Hα bow shock nebula

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



VLT: combined B, Hα and R images

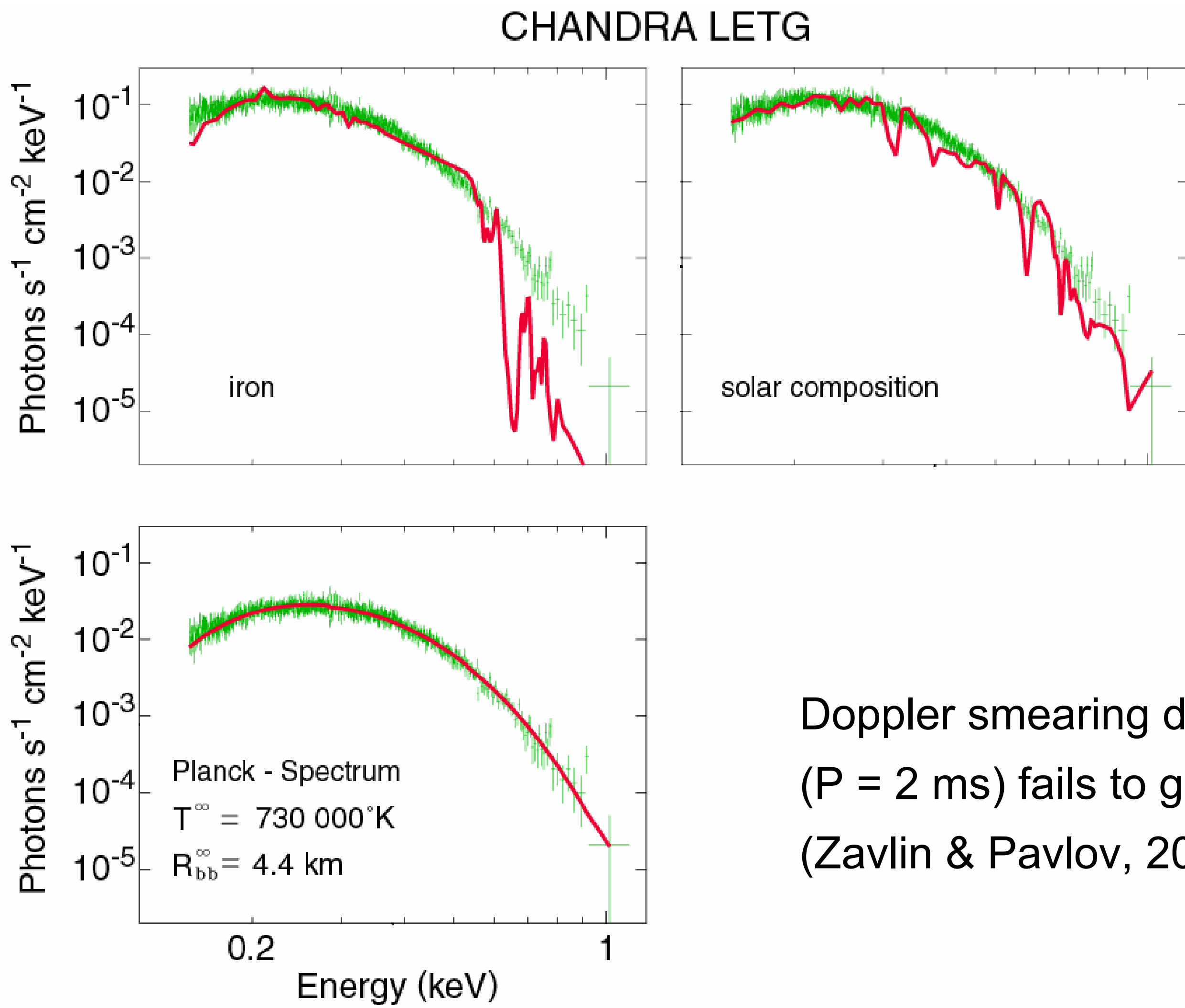
Kerkwijk & Kulkarni 2001 A&A 380, 221

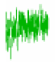


Vadim Burwitz (MPE)

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

HIGH RESOLUTION CHANDRA LETG SPECTRUM OF RX J1856-3754





$\frac{\Delta E}{E} < 1\%$!

Observation time ~ 6 days!

⇒ Featureless spectrum

(Burwitz et al. 2003)

Doppler smearing due to fast rotation

(P = 2 ms) fails to give an acceptable fit

(Zavlin & Pavlov, 2002)

Why no spectral features?

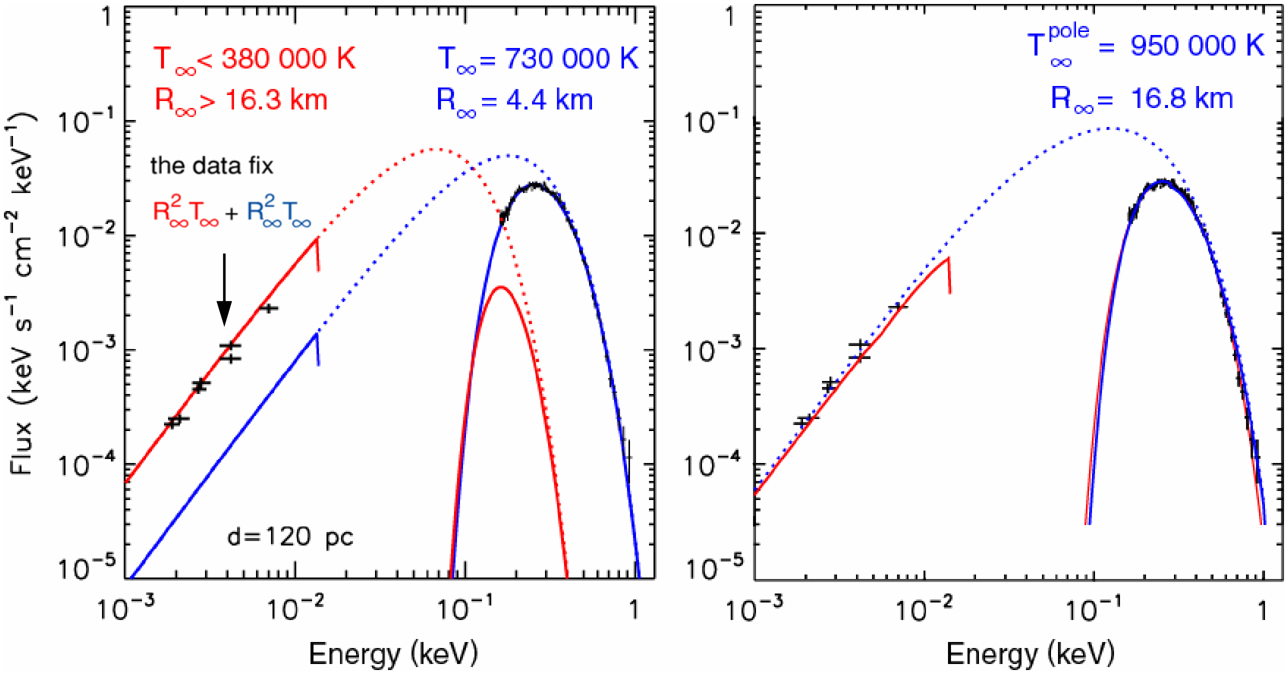
- **No photosphere, but condensed matter surface? (Burwitz, Trümper et al. 2003, Zane et al. 2003, based on early work of Lenzen & Trümper 1978, Brinkmann 1980).**

  - But: Condensation requires B $\gtrsim 10^{14}$ G for hydrogen at kT ~ 60 eV, condensation of iron is highly uncertain (Lai, 2001)!

- **Line smearing in strong magnetic fields (B ~ 10^{13} G) is probably working.**

  - Variations of dipolar magnetic field strength of a factor ~ 2 across the photosphere!

The Spectrum of RX J1856-3754 is blackbody-like in the Optical and X-rays



Trümper, Burwitz

Haberl & Zavlin, 2004

Two temperature model:

- **hot polar cap**
- **cooler surface**

$\Rightarrow R_\infty \geq 16.9 \text{ km} \times d_{120}$

Temperature distribution:

$$T = T_{pole} \left(\frac{1}{1 + (\theta/\theta_0)^2}\right)$$

$\Rightarrow R_\infty = 16.8 \text{ km} \times d_{120}$

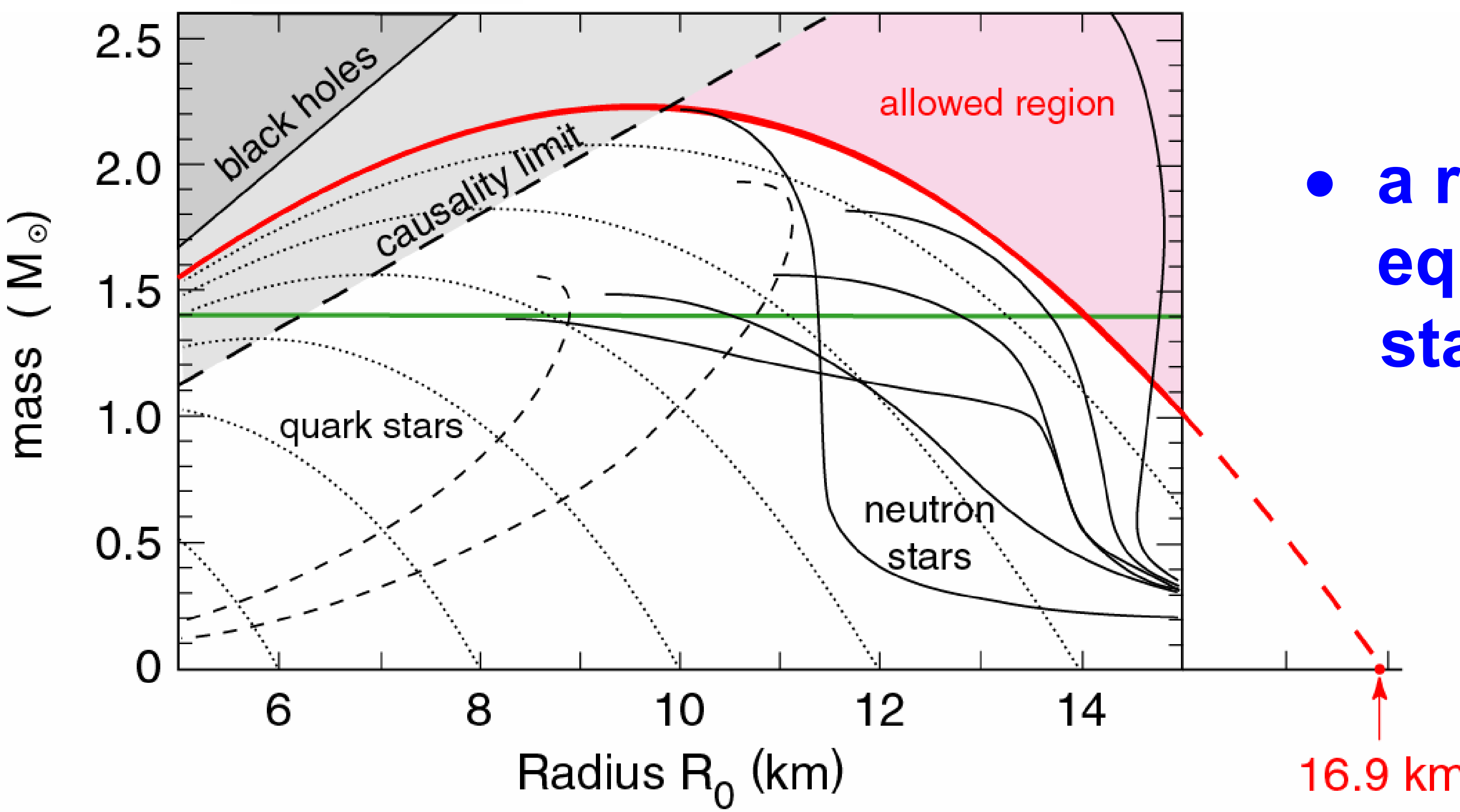
This is a conservative limit because any real photosphere will have a lower emissivity than the assumed blackbody.

Constraints on mass and radius of RX J1856-3754 for a distance of 117 pc

$$R_\infty = R_0 \left(1 - R_s / R_0\right)^{-1/2} \qquad R_s = \frac{2\,GM}{c^2}$$

$R_\infty = 16.9$ km

Trümper et al., 2004

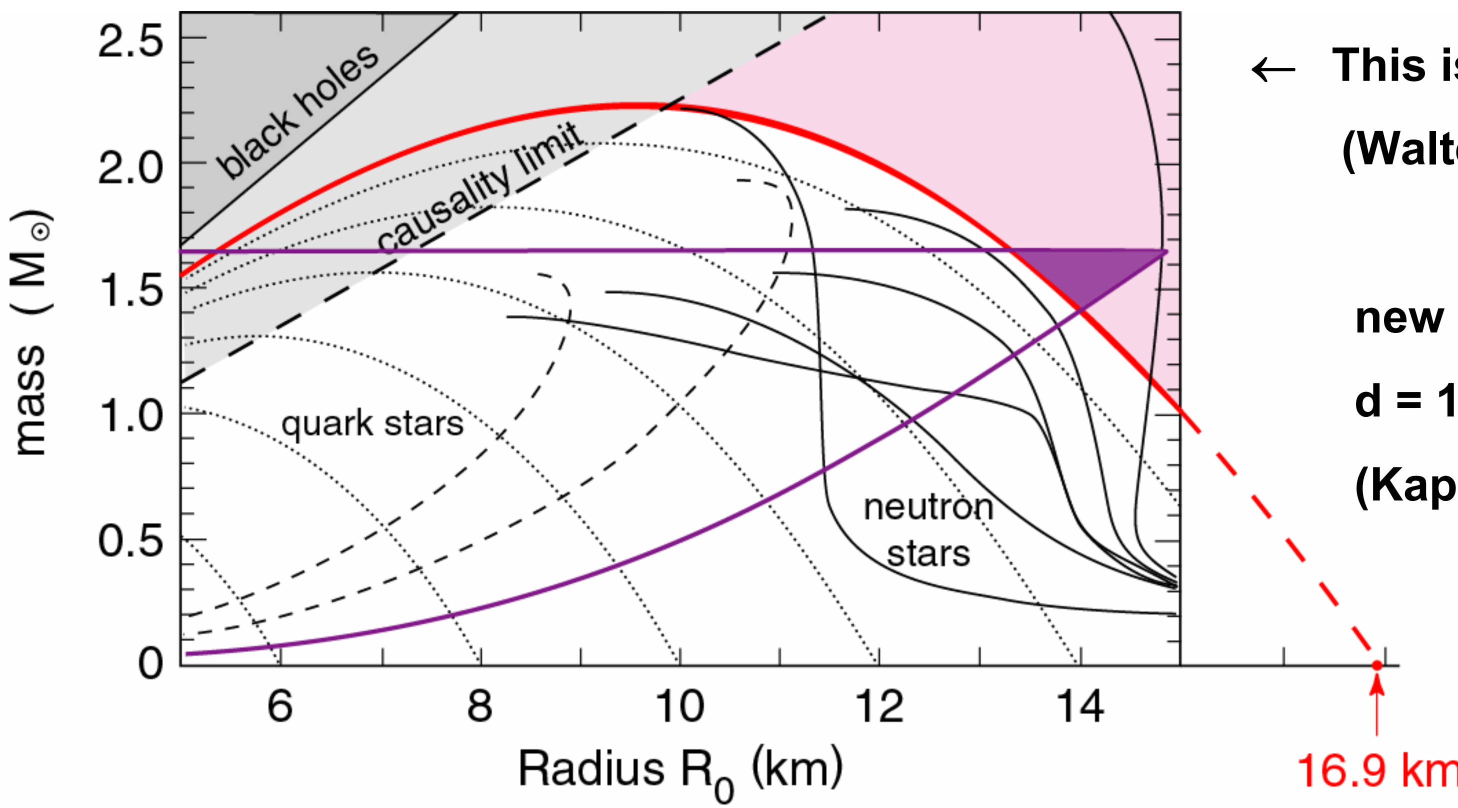


- **a rather stiff equation of state is required**

CONCLUSION

Photospheric Spectra ⇒ lower bound on M, R (this work)

High frequency Oscillations ⇒ upper bound on M, R (Miller 2003)



← This is for d = 120 pc (Walter & Lattimer 2002)

new data suggest d = 140 – 170 pc (Kaplan 2004, 2005)

The data require definitely a stiff equation of state

OUTLOOK

Future requirements:

- **More sources: Sensitive sky surveys in X-rays (e.g. ROSITA)**
  optical telescopes of the 30 – 100 m class
  (e.g. CELT, OWL)

- **More/better absolute distances**

- **Better data on timing and spectroscopy**
  (10 m^2 X-ray Detector, XEUS)

- **Progress in physics of heavy atoms/condensed matter**
  in superstrong magnetic fields

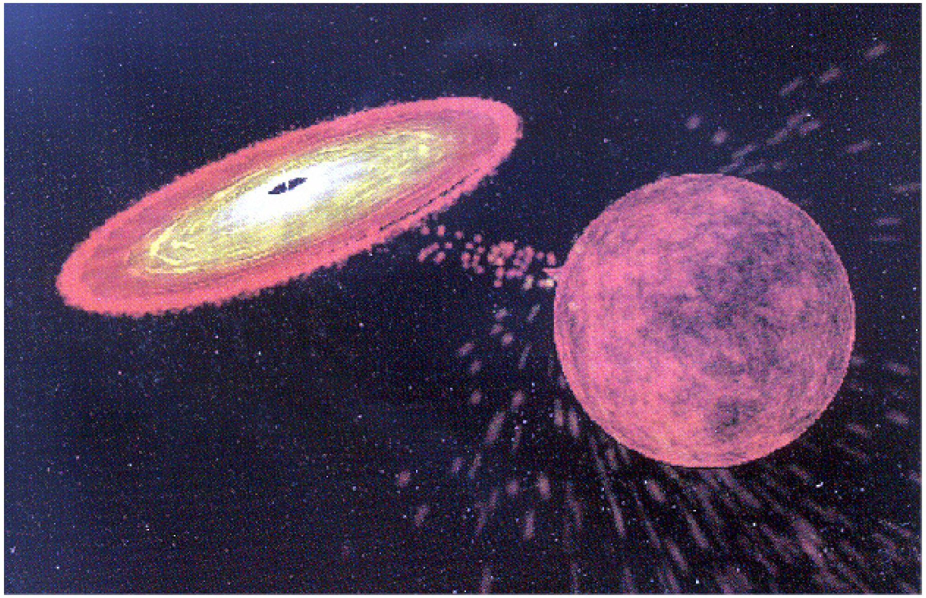
Spectral Fits - Temperatures and Radii

(e.g. Pavlov & Zavlin et al., 1996.....2004)

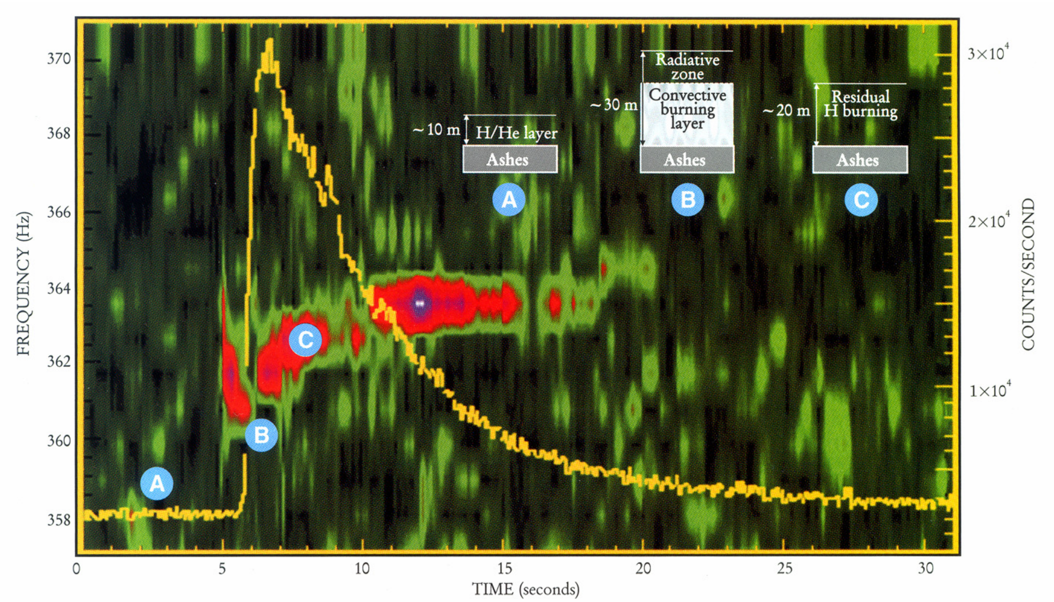
Blackbody models	$f_x = \frac{R_{bb}^2}{d^2} \cdot \sigma T_{bb}^4$	T_{bb}^{∞} , R_{bb}^{∞}/d
nonmagnetic H, He photospheric models		$T^{\infty} \sim (0.3\text{-}0.7)\, T_{bb}^{\infty}$ $R^{\infty} \sim (2\text{-}7)\, R_{bb}^{\infty}$
magnetic H, He photospheric models (B ~ 5×10^{12} G)		The parameters are between the nonmagnetic and blackbody cases
Fe photospheric models		$T^{\infty} \lesssim T_{bb}^{\infty}$ $R^{\infty} \gtrsim R_{bb}^{\infty}$
magnetic Fe photospheric models		only crude models exist based on energy levels and oscillator strengths calculated in Hartree-Fock approximation (c.f. Rajagopal, Romani, Miller 1997)

X-Ray Burst Oscillations (in more than a dozen objects)

X-ray Bursts in Low Mass X-ray Binaries
= Thermonuclear Explosions on Neutron Stars

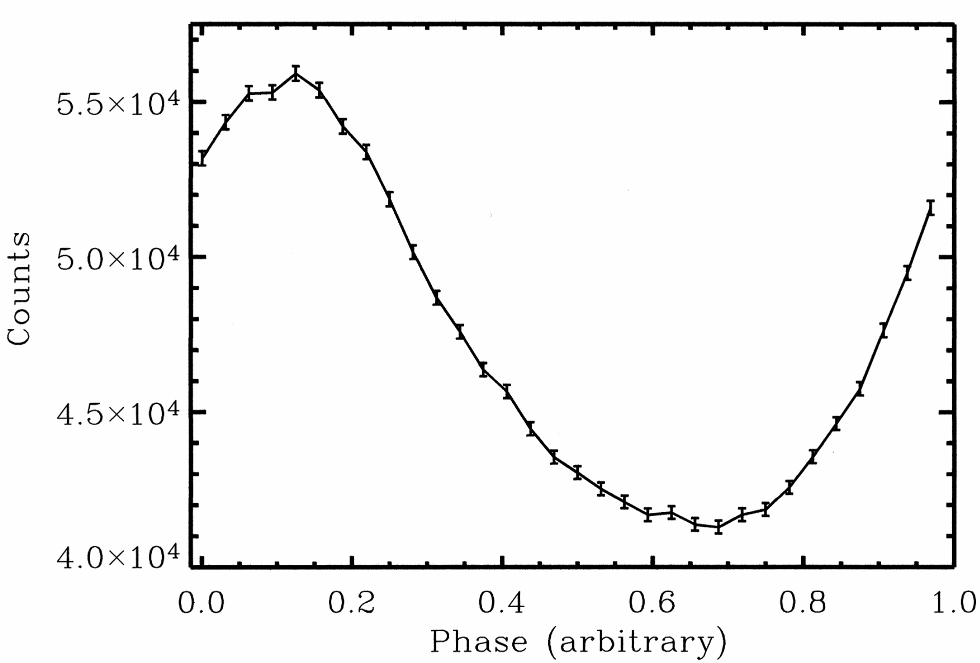


Low Mass X-ray Binary



X-ray burst and burst oscillations in 4 1728-34 at a frequency of 364 Hz (thought to be the spin period of the neutron star)

Modelling the 314 Hz Light Curve of XTE J1814-338
(Bhattacharyya et al., 2004, similar work by Poutanen, 2004)



The fully added light curve of 22 bursts

model parameters:

- **stellar radius**
- **latitude of the hot spot**
- **angular size of the hot spot**
- **beaming $I(\psi) \sim \cos^n \psi$ in the neutron star rest frame**
- **inclination of the spin axis vs. line of sight**

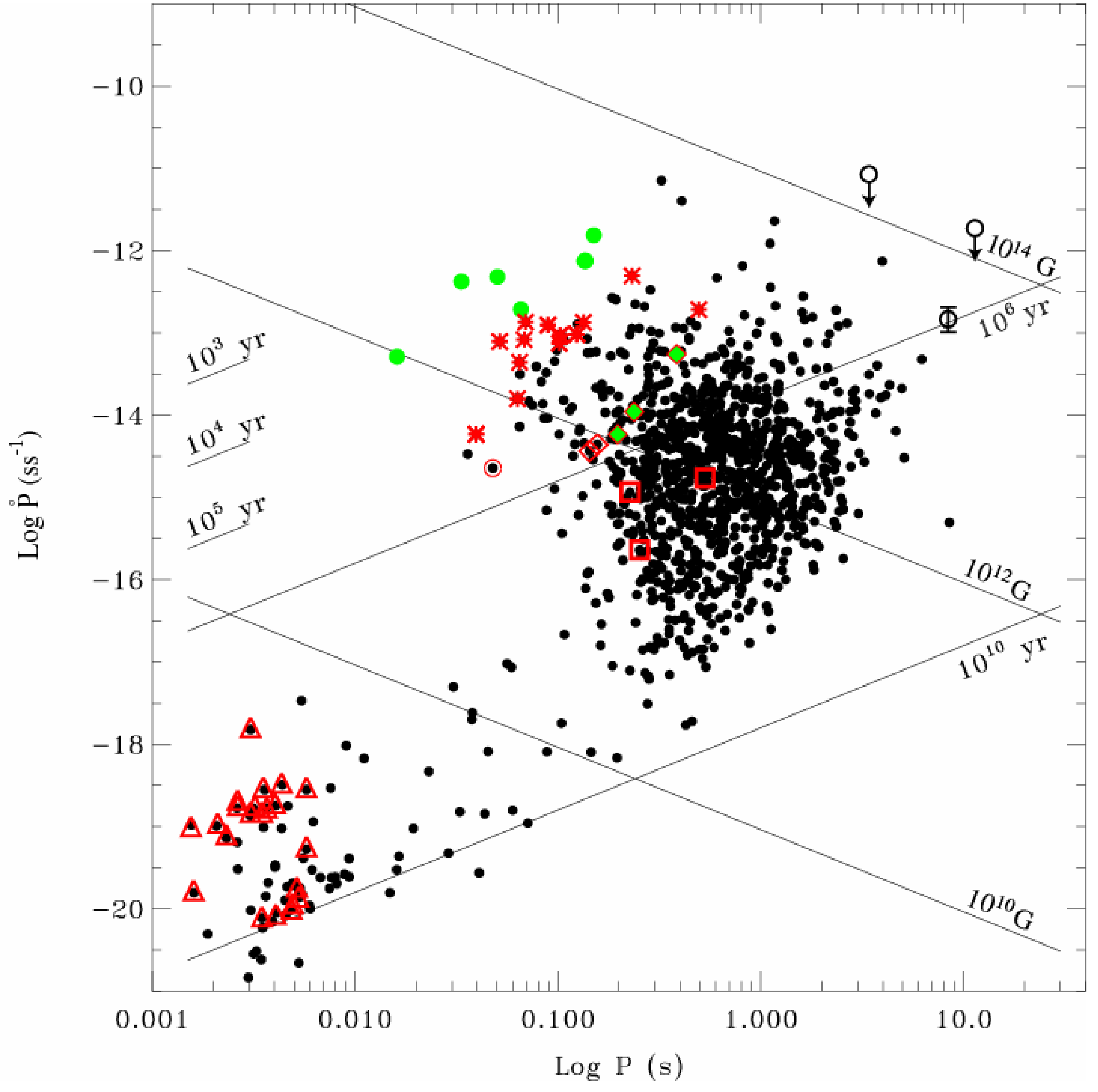
effects considered:

- **G.R. light bending,**
- **frame dragging**

$$\Rightarrow \quad \frac{GM}{R\,c^2} = \frac{R_S}{2\,R} \leq 0.24$$

$$\Rightarrow \quad R > 8.7 \text{ km for } M = 1.4\, M_\odot$$

Radio Pulsars



red symbols:
X-ray detections

green symbols:
γ-ray and X-ray detections

magnetic dipole braking: age = $P / 2\dot{P}$, $B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$

The likely nature of the dim isolated NS

– periods ~ 10s ⇒ old pulsars

why no radio emission?

- INS are located beyond the death line
- radio beam (if it existed) would be very narrow (few degrees) because of their long periods.

– strong magnetic fields ($B \gtrsim 10^{13}$G)

based on $\dot{P}$ and proton cyclotron lines

- Such strong magnetic fields are required to make the spin down time ($\propto P^2 B^{-2}$) shorter than their cooling time (few 10^6 yrs).

⇒ dim isolated neutron stars have been normal pulsars when they were young