X-Ray Observations of Neutron Stars and the Equation of State of Nuclear Matter

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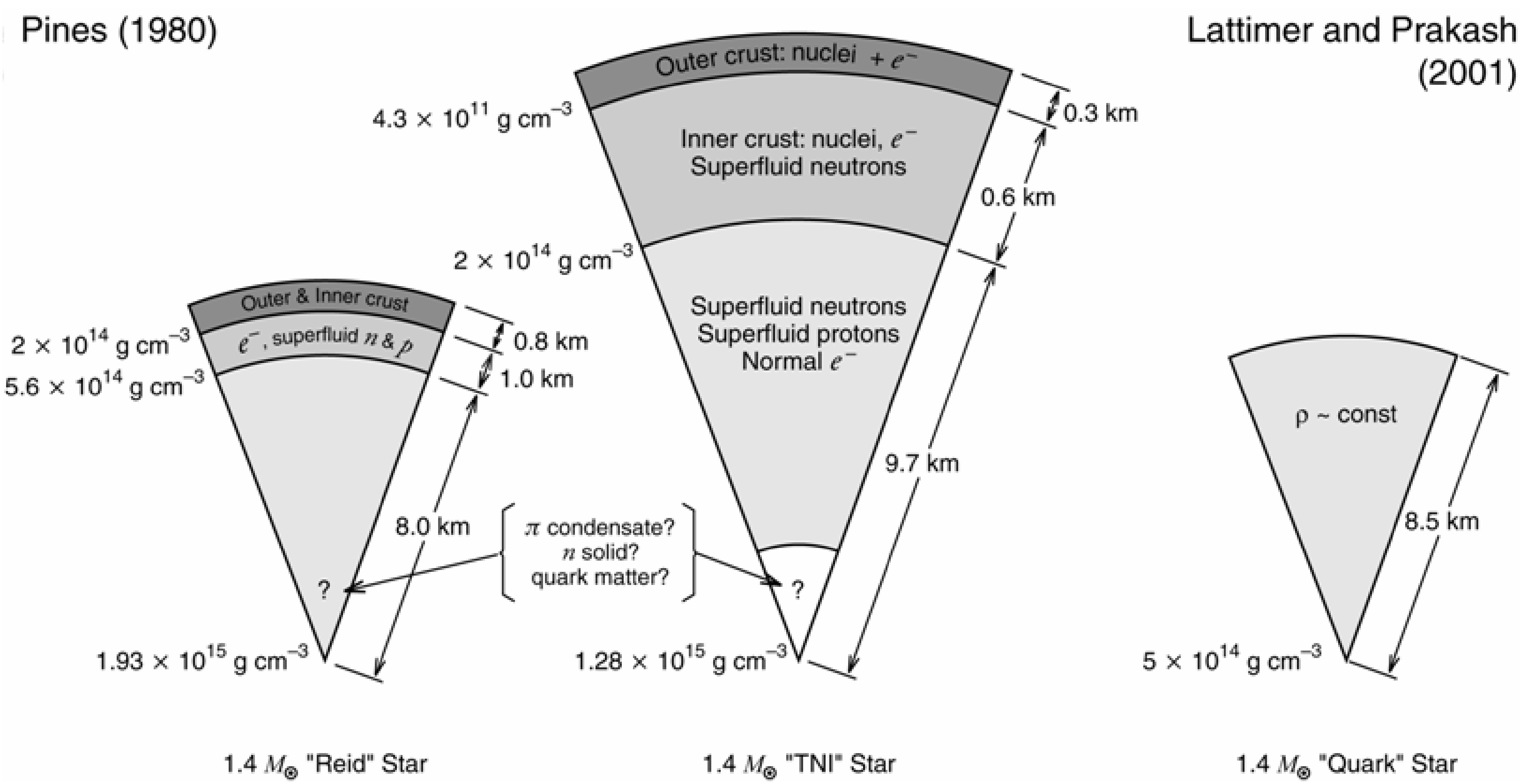
OUTLINE

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

Neutron Star Models



Normal Nuclear Matter (u, d quarks)

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

Talks by Fridolin Weber and Jürgen Schaffner-Bielich

The Equation of State of Nuclear Matter

- is of fundamental importance for NS astrophysics.
- There is an inflation of theoretical EOS models.
- A determination of the EOS can only come from

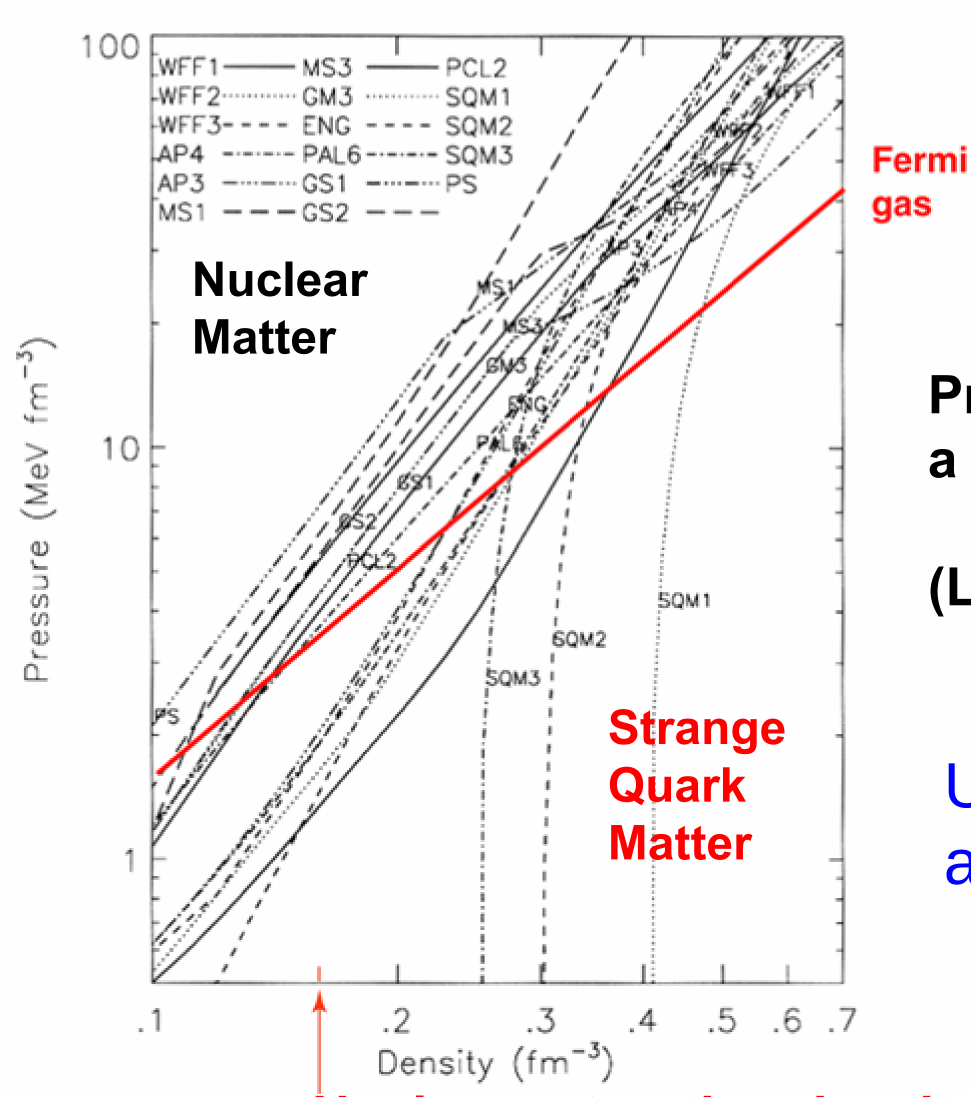
  nuclear collision experiments and NS observations.
- There has been great progress in the last 15 years;

  we have reached a point where NS observations really

  become constraining EOS models

There exist many observations and claims -- I will try to restrict myself to the most constraining & reliable results

Theoretical EOS models

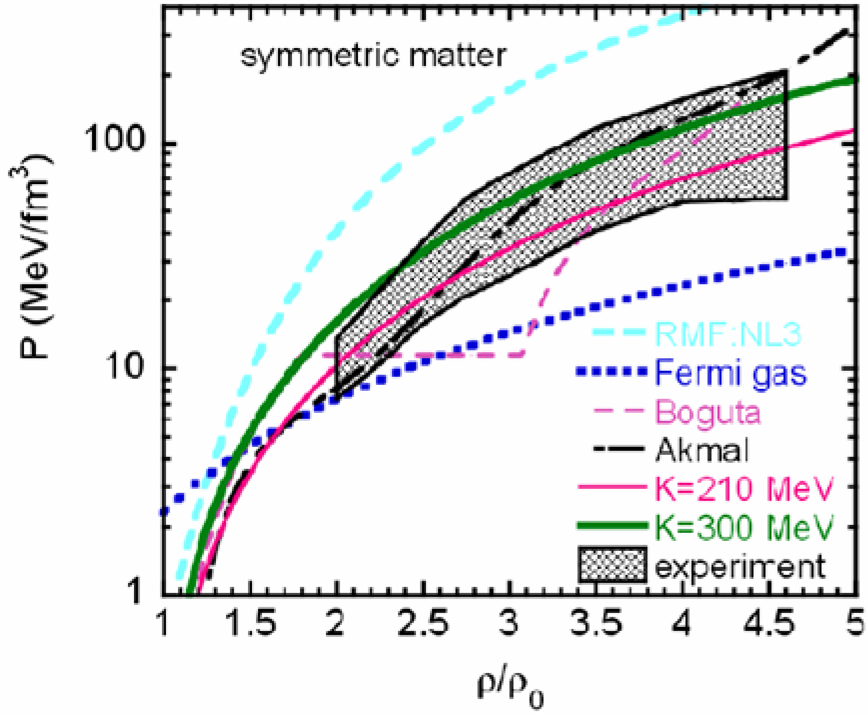


Pressure - density relations for a selected set of equations of state.

(Lattimer and Prakash 2001)

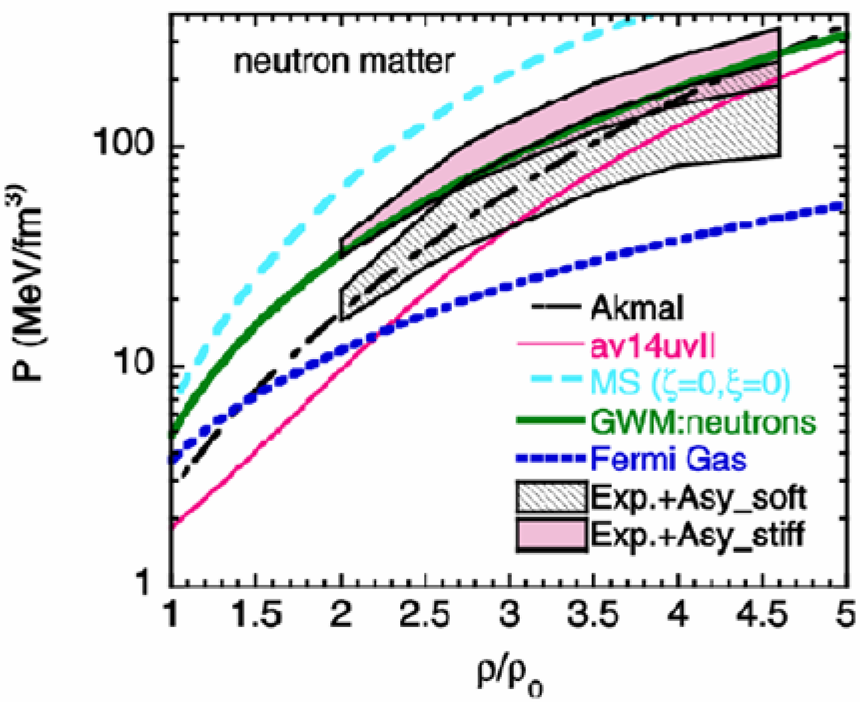
Uncertainty in pressure ~ factor 6 and more (SQM) !

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



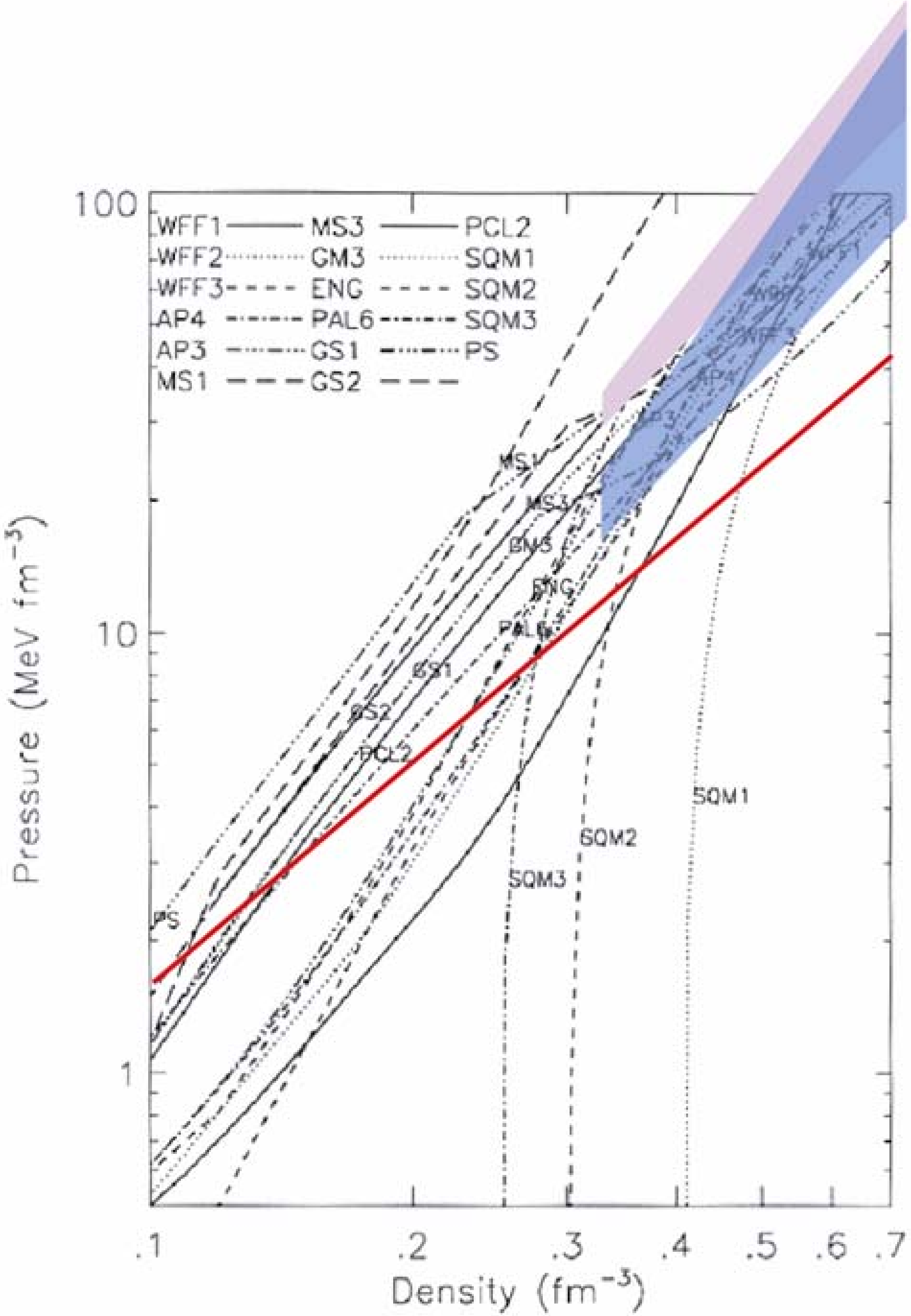
Zero-temperature EOS for „symmetric" nuclear matter based on Au–Au collisions at 394 GeV (2 GeV/nucleon).

(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

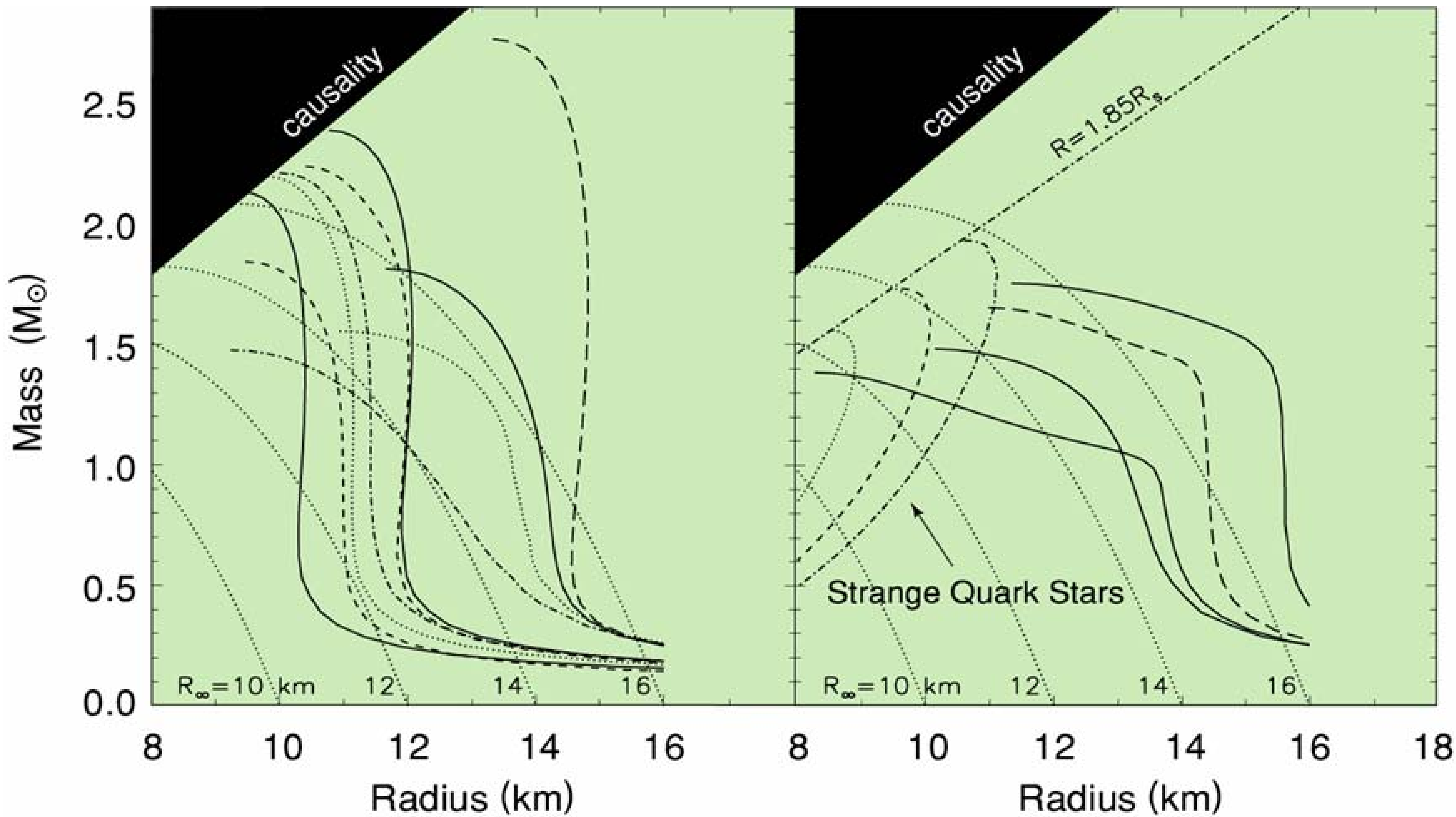
(Danielewicz et al. 2002)

Pressure - density relations for a selected set of equations of state.

(Lattimer and Prakash 2001)

M-R Relations for Different Equations of State

(Lattimer & Prakash 2001)

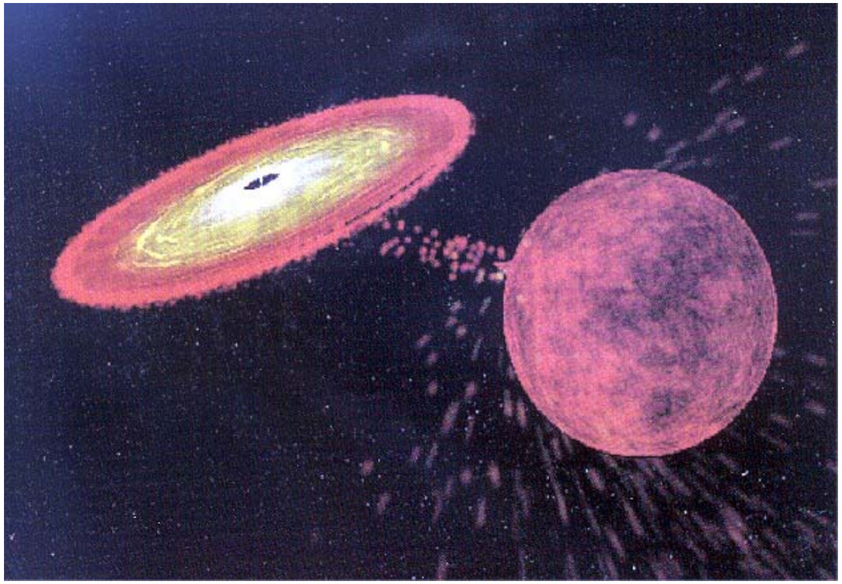


nucleon / hyperon stars

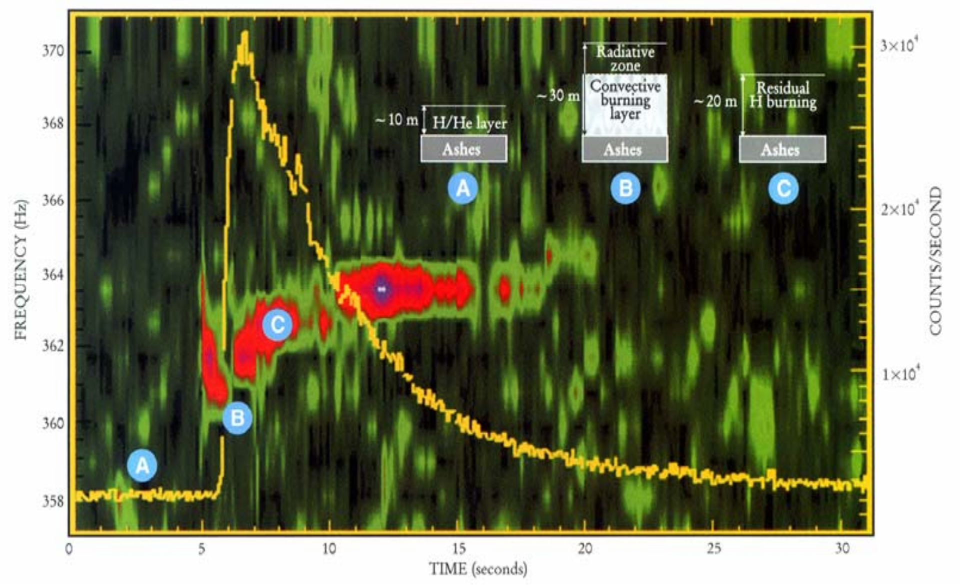
kaon condensates strange quark stars

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



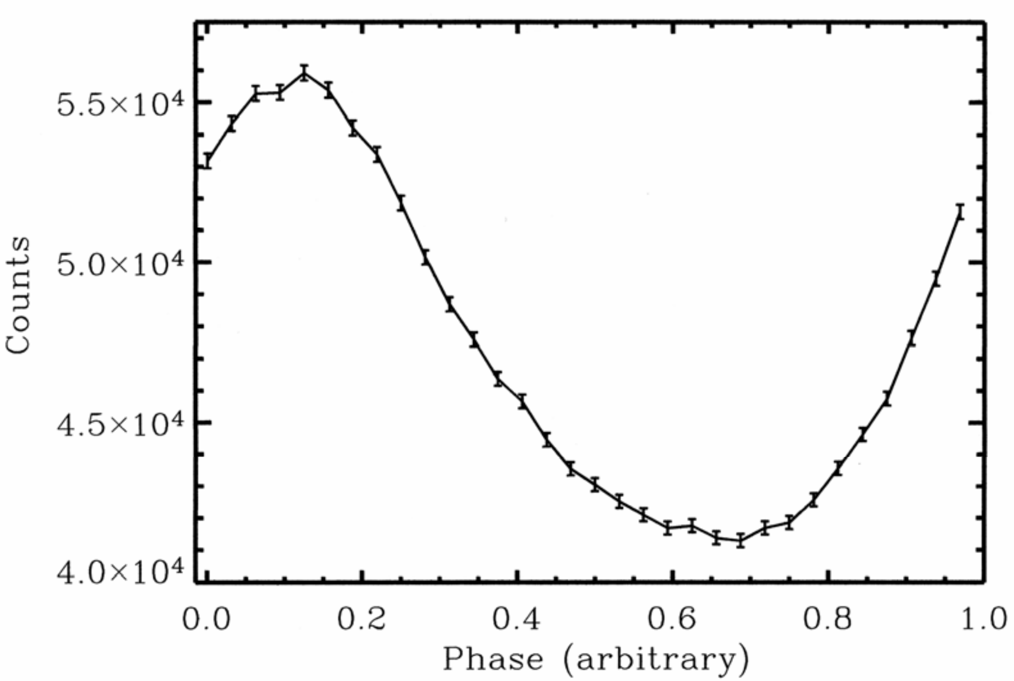
Low Mass X-ray Binary



X-ray burst and burst oscillations in XTE J1318-338 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 (ψ) ~ $\cos^n \psi$ in the neutron star rest frame**
- **inclination of the spin axis vs. line of sight**

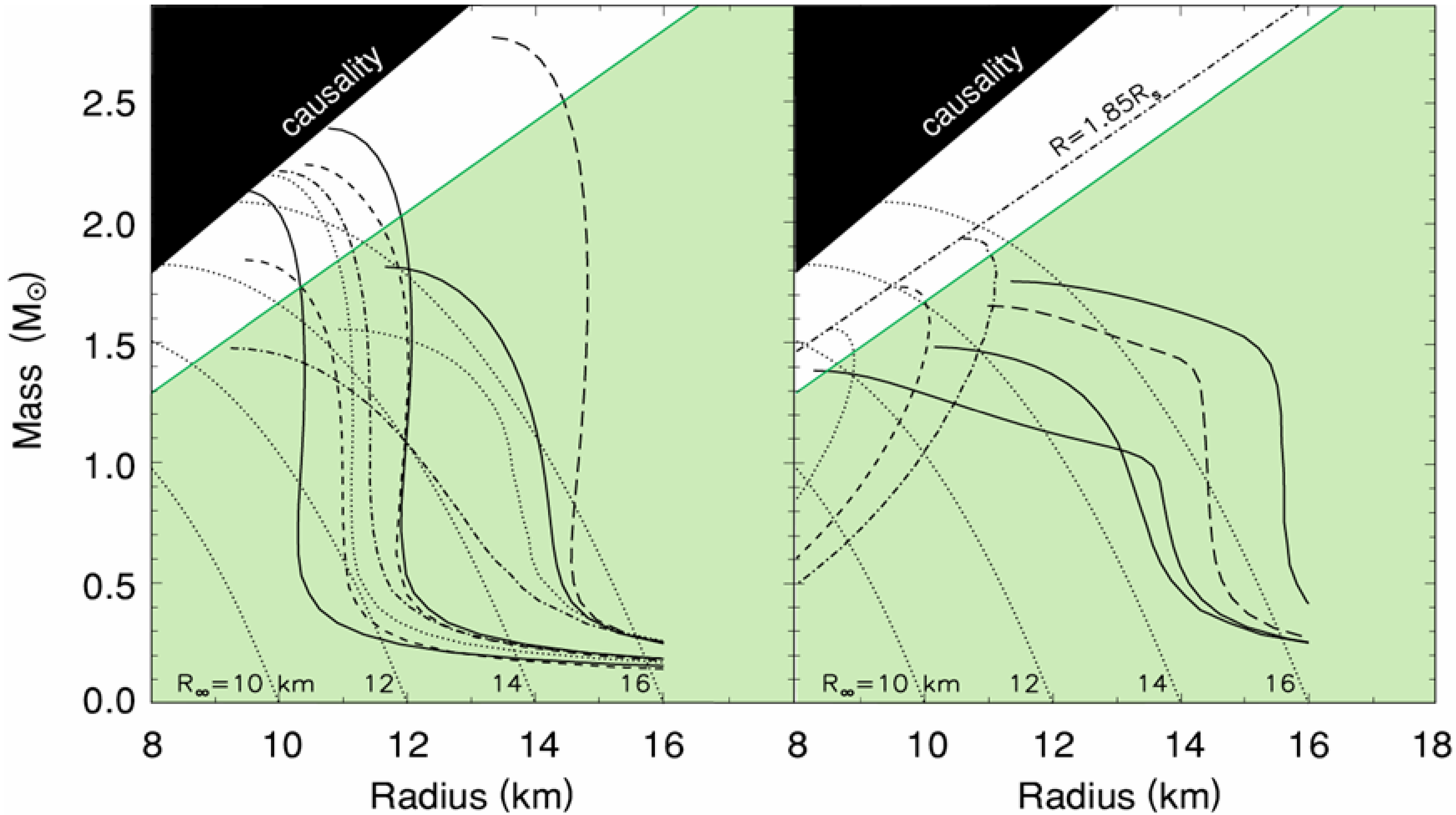
effects considered:

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

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

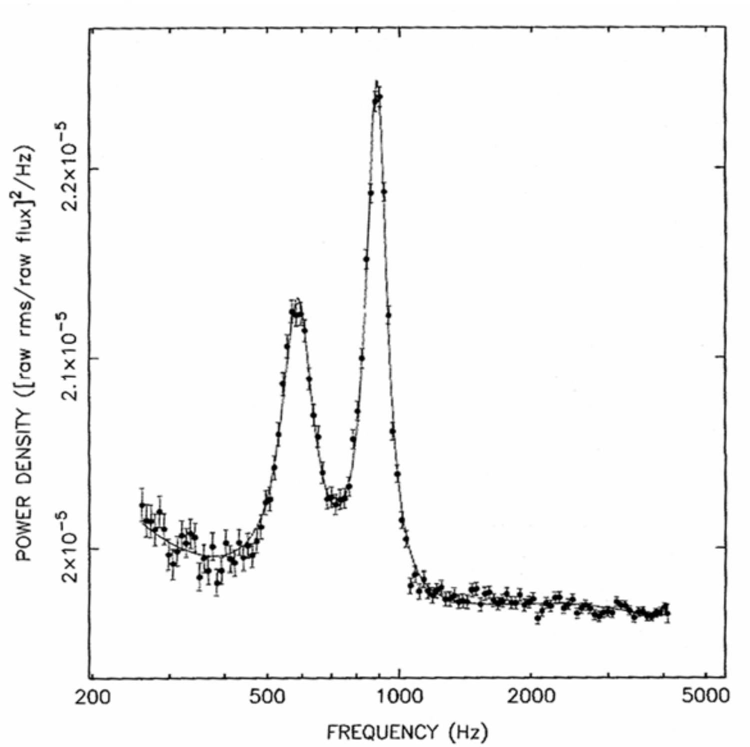
$$\Rightarrow R > 8.7 \text{ km for } M = 1.4 M_\odot$$

Talk by Denis Leahy

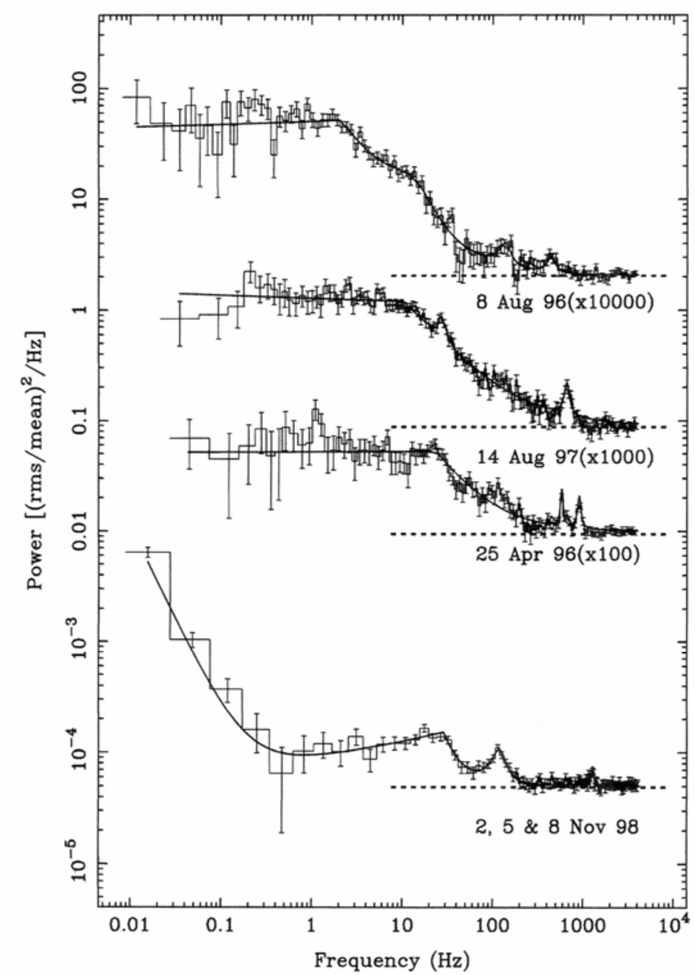


Light curve of coherent burst oscillations of 4u 1728-34 : $R / R_S > 2.1$ (Bhattarcharyya et.al. 2005)
Similar constraints from Poutanen 2004

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)

$R_{orbit} > R_{NS} \rightarrow R < [GM/4\pi^2\nu^2(orb)]^{1/3}$

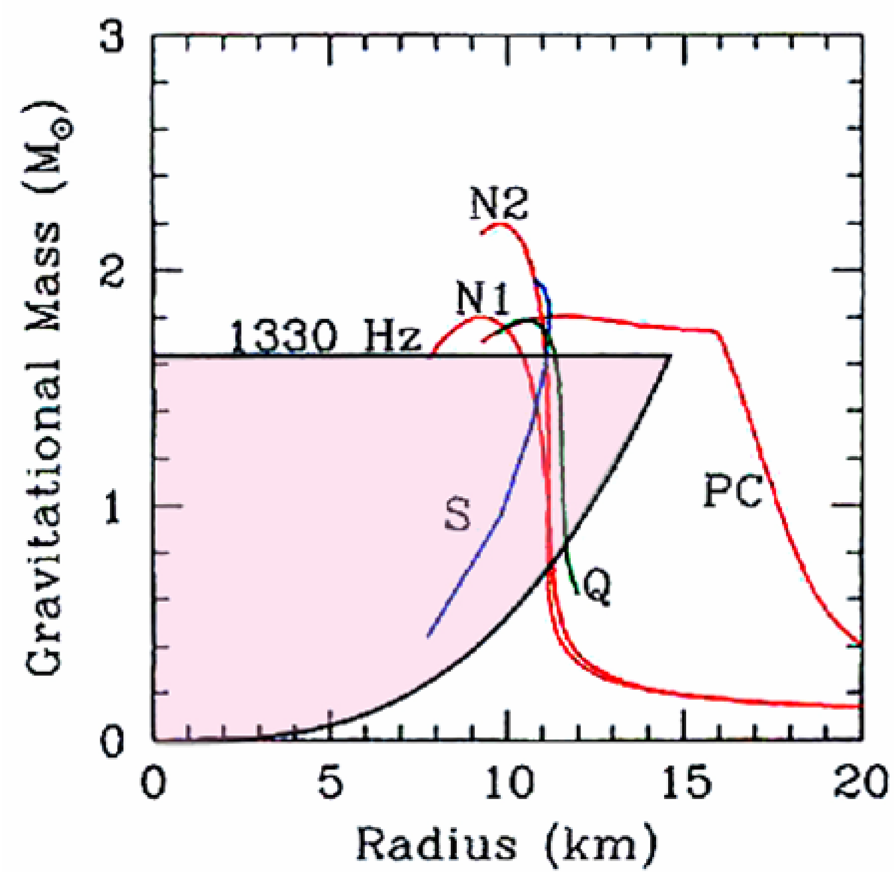
If the QPO came from the innermost stable circular orbit:

$M < 2.2\ M_{sun}\ (1\ \text{kHz} / \nu_{orbit})\ (1+0.75j)$

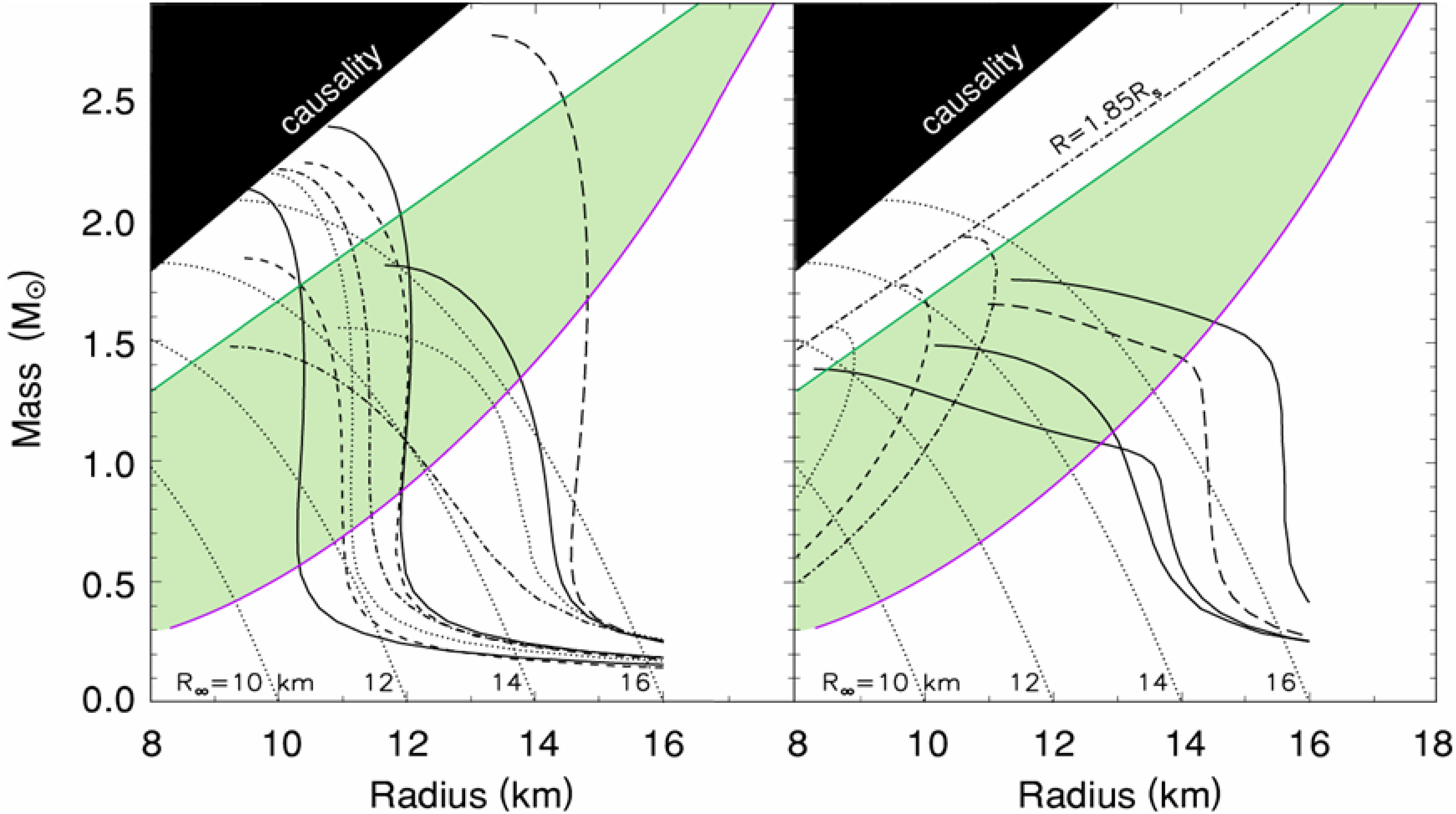
$R < 19.5\ \text{km}\ (1\ \text{kHz} / \nu_{orbit})\ (1+0.2j)$

(has not been reliably observed yet)

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



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



Upper QPO frequency (1330 Hz) of 4u 0614+091
= orbital frequency at the inner edge of the accretion disk
($R_{QPO} > R_{NS}$) **(Miller 2003)**

Thermal Radiation from Hot Neutron Stars

- gravitational redshift of lines or edges $\Rightarrow$ M / R

  problem: the line/edge identification requires
  an accurate knowledge of the magnetic field

  Iron K_α : E = 6.4 KeV
  B = 10^{12} G : $E_{cycl} \sim 11.6$ KeV
  $\Rightarrow$ this has not been a reliable method yet
  however, EXO 0748-676 may be an interesting candidate
  if the atomic lines which XMM-RGS may have detected were
  confirmed (Cottam et al. 2002, Oezel 2006)

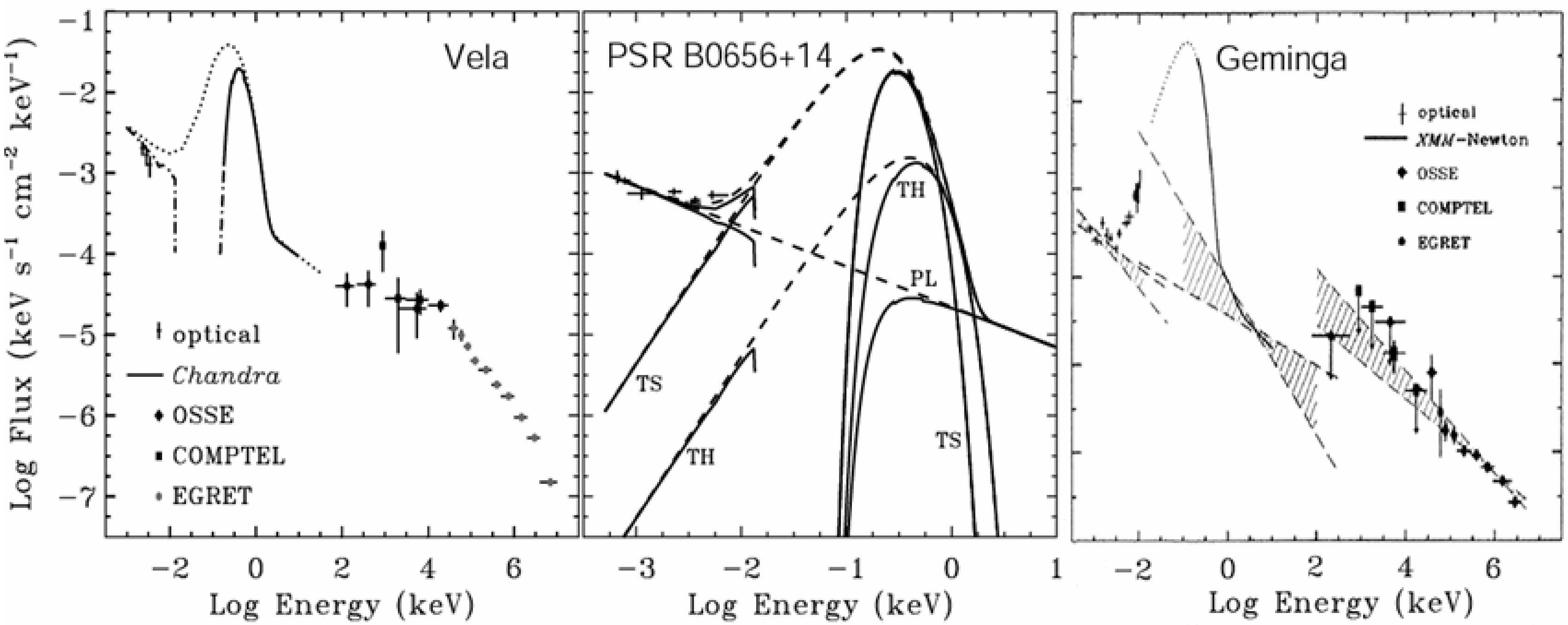
- photometric radius $\Rightarrow$ R/D
  problem: requires an accurate knowledge of the distance D

  - blackbody models $\rightarrow$ R_{bb}

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

Radiation Radii of Pulsars having measured Distances

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



VLBA : 290 pc
(Dodson et al. 2003)
R = 17 - 20 km

VLBA : 288 pc
(Brisken et al. 2003)
R = 13 - 20 km

HST : 157 pc
(Caraveo et al. 1996)
R_{bb} ~ 10 km
R ≳ 20 km

~250 pc !

These neutron star radii appear to be large

(but the spectra are not well constrained in the optical-UV because of the presence of nonthermal components).

Thermal, radio-quiet isolated neutron stars

- **Soft X-ray sources in ROSAT survey**
- **Blackbody-like X-ray spectra, No non-thermal hard emission**
- **Low absorption ~10^{20} H cm^{-2}, nearby (parallax for RX J1856.5-3754)**
- **Luminosity ~10^{31} erg s^{-1}**
- **Constant X-ray flux on time scales of years**
- **No obvious association with SNR**
- **No radio emission (but: RBS1223, RBS1774 ?)**
- **Optically faint**
- **Some (all?) are X-ray pulsars (3.45 – 11.37 s)**

best candidates for „genuine“ INSs with undisturbed emission from stellar surface

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	
RBS 1223 (*)	80-92	10.31	m_{50ccd} = 28.6	
RX J1605.3+3249	96	6.88?	B = 27.2	PM = 145 mas/y
RX J1856.5–3754	62	–	V = 25.7	PM = 332 mas/y
RBS 1774 (**)	102	9.44	B > 26	

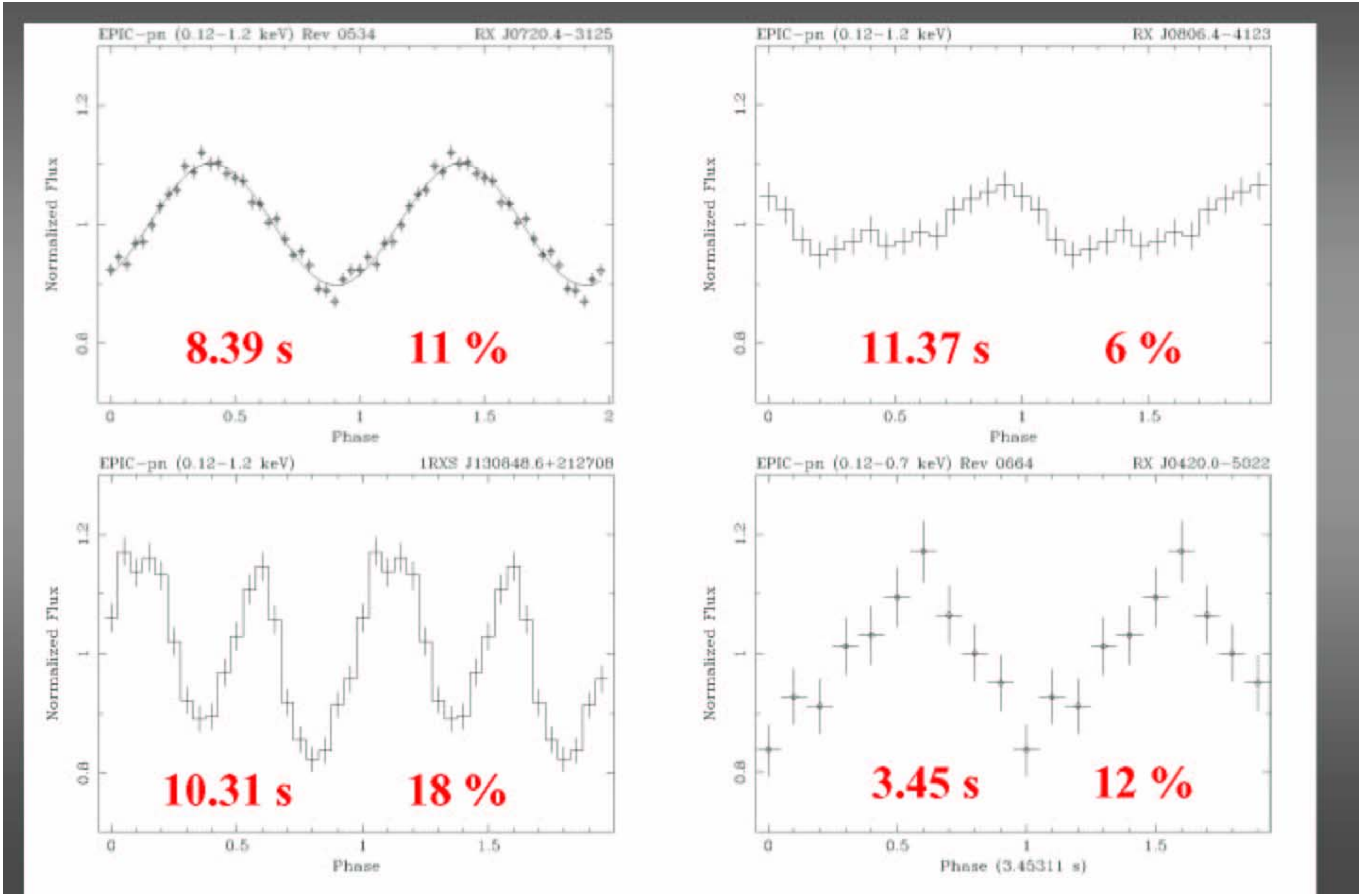
The Magnificent Seven

F.Haberl 2006

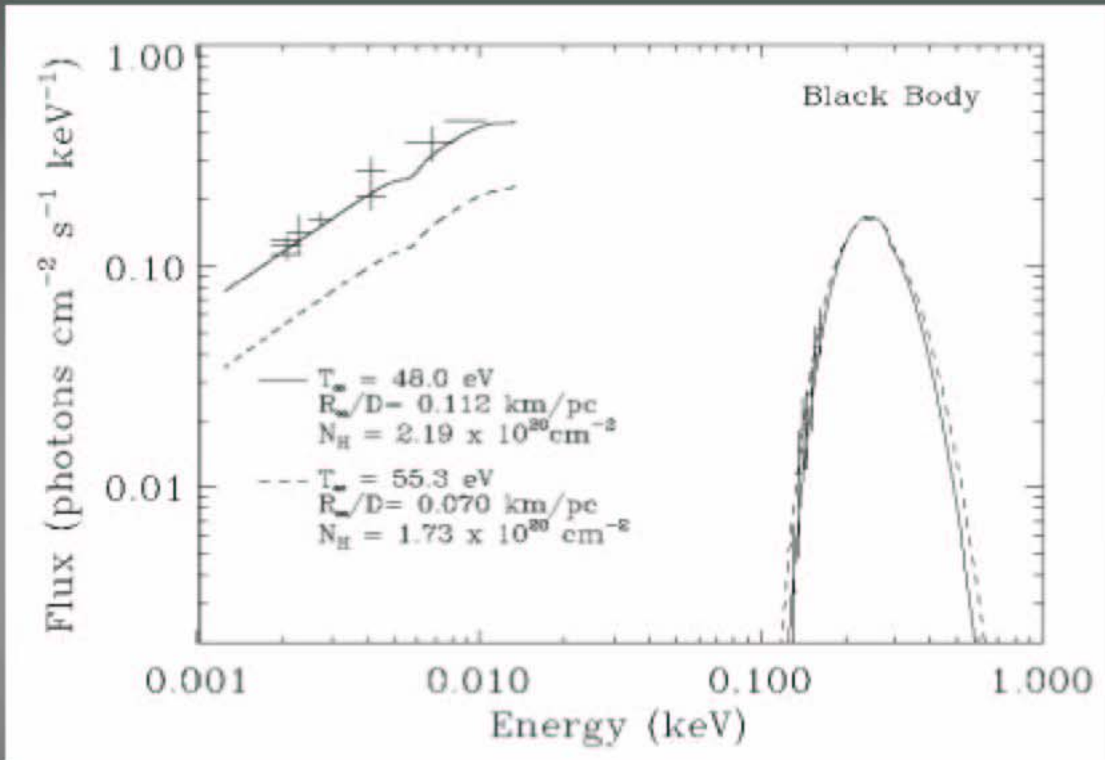
Roberto Turolla & Frank Haberl talks

Evidence for an anisotropic temperature distribution

I. Pulsations



Evidence for an anisotropic temperature distribution
II. Optical Excess



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)***

Magnetic fields

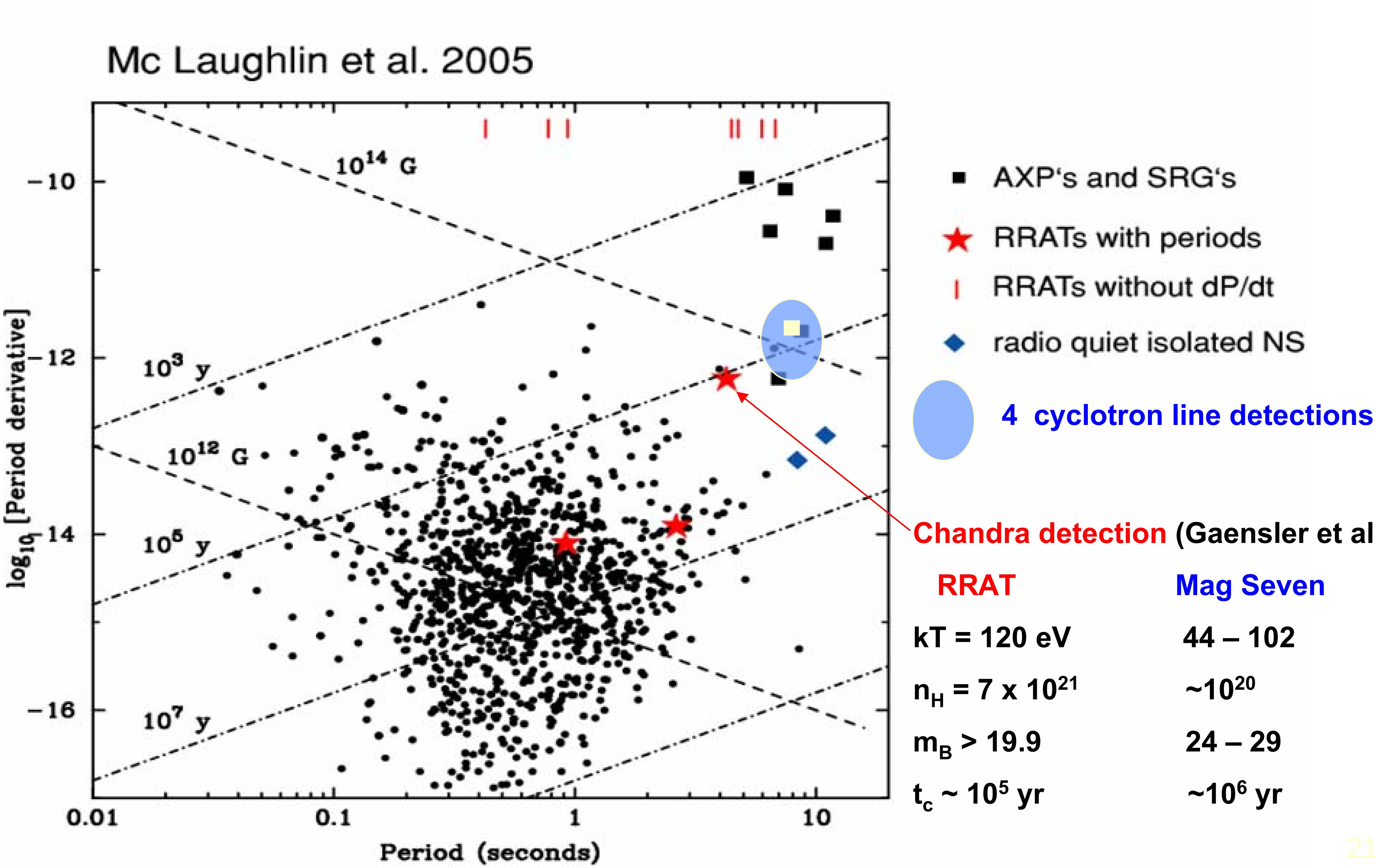
- Magnetic dipole braking → **$B = 3.2 \times 10^{19} (P \times dP/dt)^{1/2}$**
  Spin-down rate (P, dP/dt)
  Spin-down luminosity required to power the Hα nebula (dE/dt, τ)
- Proton cyclotron absorption →**$B = 1.6 \times 10^{11}\ E(eV)/(1\text{-}2GM/c^2R)^{1/2}$**

Object	P [s]	Semi 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	?	< 18	
RX J0720.4–3125	8.39	8-15%	0.698(2)	280	2.4	5.6
RX J0806.4–4123	11.37	6%	< 18	430/306[a]	< 14	8.6/6.1
1RXS J130848.6+212708	10.31	18%	1.120(3)	300/230[a]	3.4	6.0/4.6
RX J1605.3+3249				450/400[b]		9/8
RX J1856.5–3754				–	~1[c]	
1RXS J214303.7+065419	9.43	4%	<60[d]	750	< 24[d]	15

a) Spectral fit with single line / 2 lines at E and 2*E
b) Sepctral fit with single line / three lines at 400 eV, 600 eV and 800 eV
c) Estimate from Hα nebula assuming that it is powered by magnetic dipole breaking
d) Radio detection: Malofeev et al. 2006, ATEL 798

F. Haberl 2006

The Magnificent Seven and Company



RRAT	Mag Seven
kT = 120 eV	44 – 102
$n_H = 7 \times 10^{21}$	$\sim 10^{20}$
$m_B > 19.9$	24 – 29
$t_c \sim 10^5$ yr	$\sim 10^6$ yr

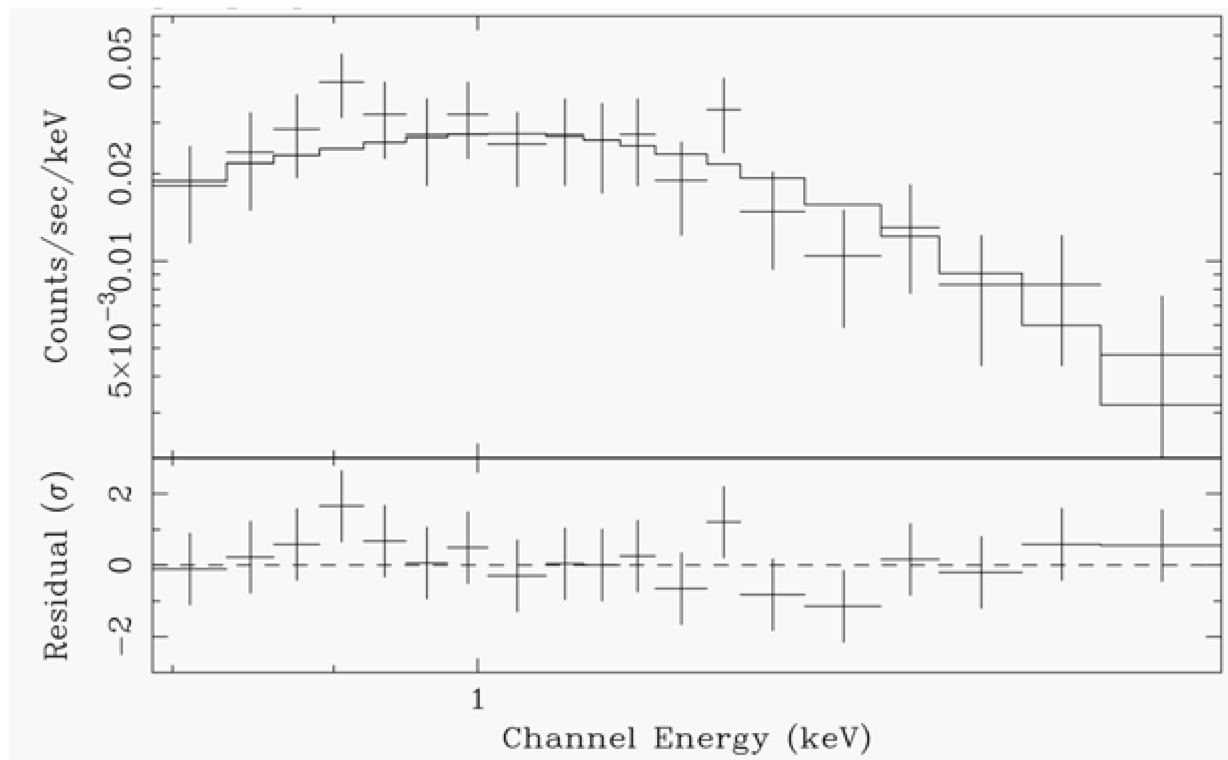
Spectrum & Variability

- 524 ± 24 counts
- Poor spectral fit to PL, good fit to blackbody ($R_{BB,\infty} \approx 20d_{3.6}$ km)

$N_H = 7\ (+7,-4) \times 10^{21}$ cm^{-2} $\quad kT_{\infty} = 120 \pm 40$ eV

$f_{X,unabs} \approx 2\mathrm{x}10^{-12}$ ergs/cm^{-2}/s $\quad L_X \approx 3.6d^2_{3.6}\mathrm{x}10^{33}$ ergs/s (0.5-8 keV)

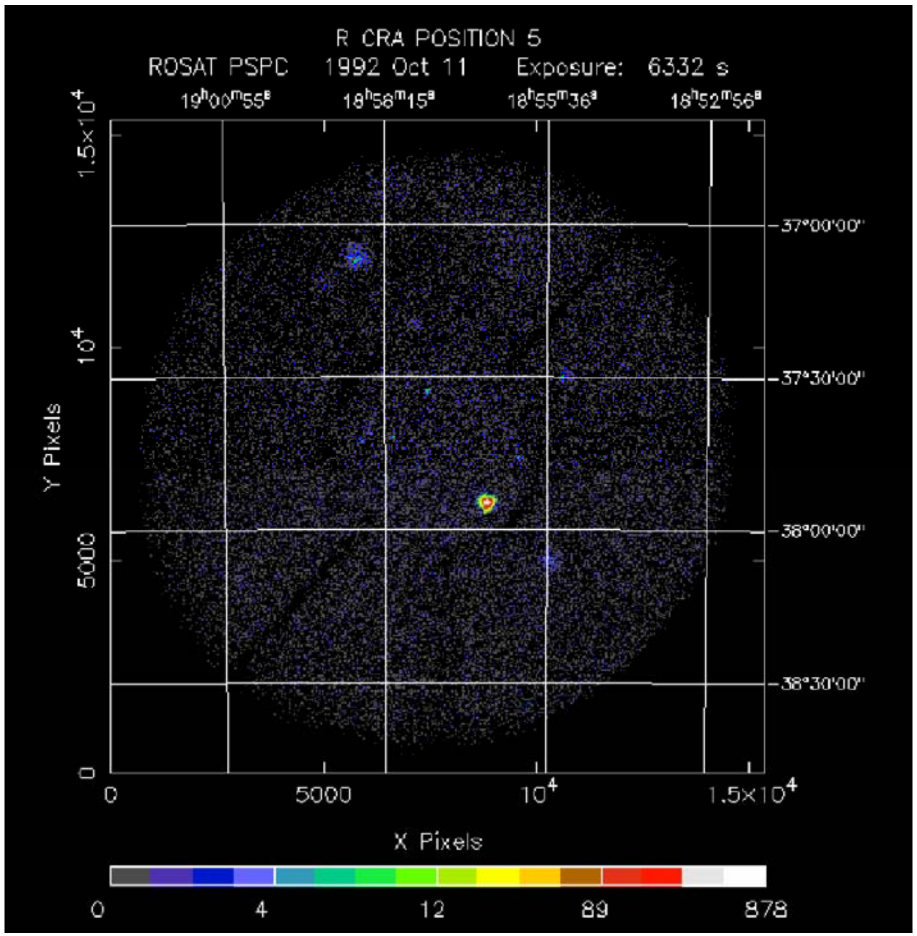
- No X-ray bursts, $E_{\mathrm{burst}} < 10^{36} \times d^2_{3.6}$ ergs
- No variability seen on scales 3.2 sec to 5 days
- No (aliased) pulsations, $f < 70\%$ for sinusoid

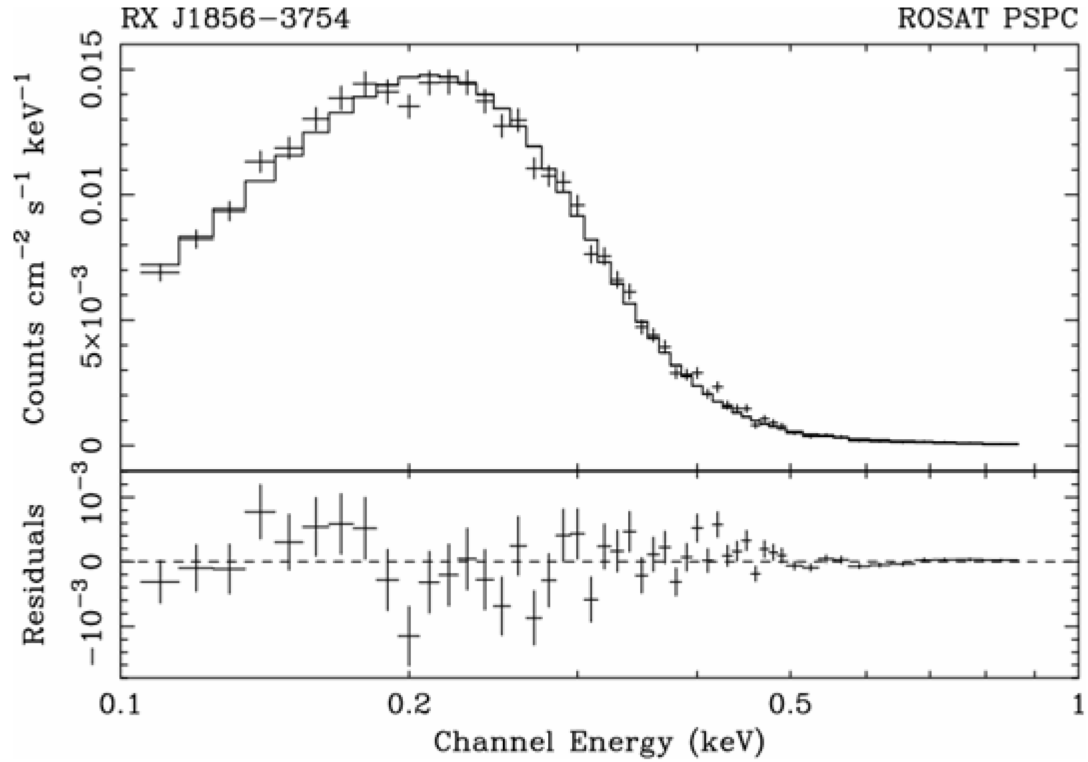


Reynolds et al. (2006)

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

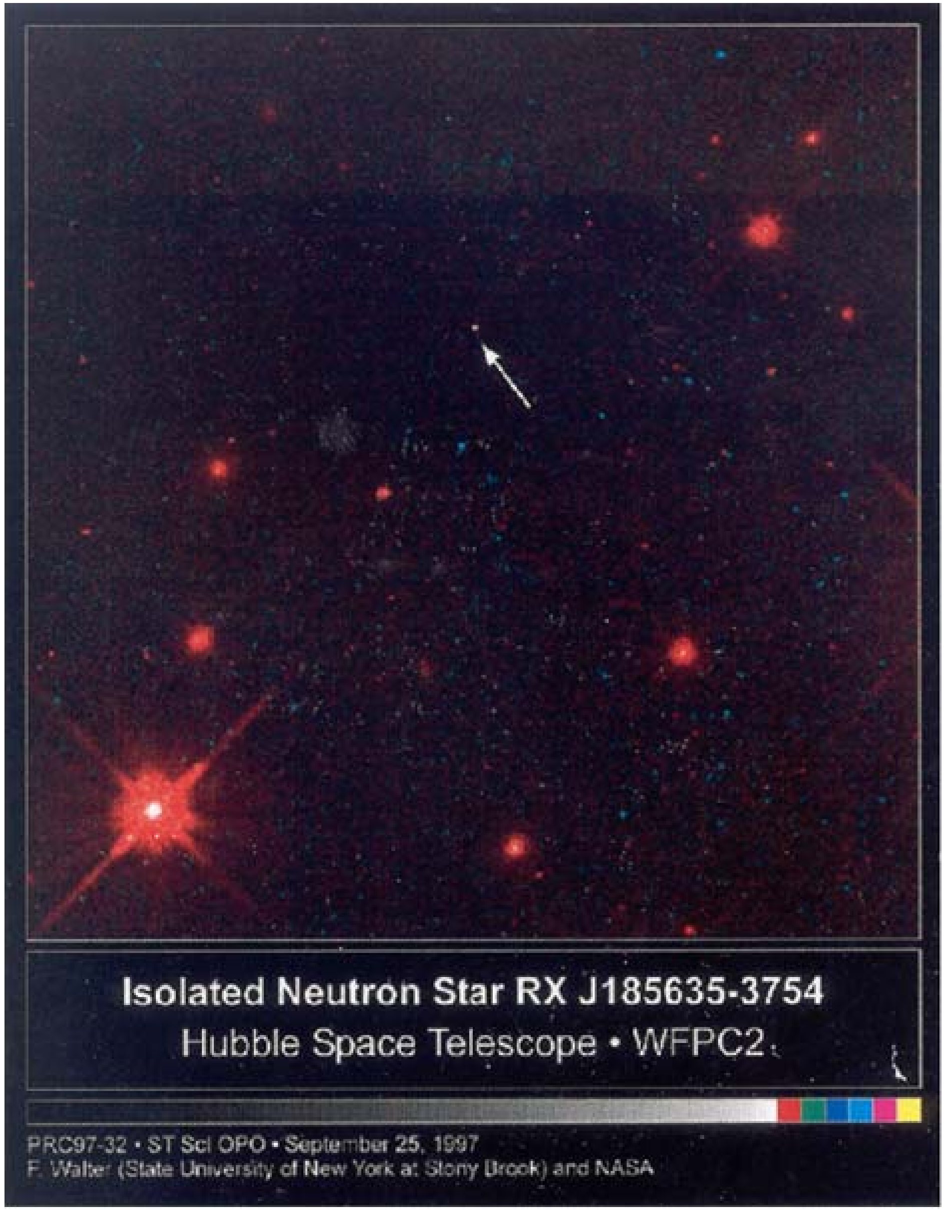
(Walter, Wolk & Neuhäuser, 1996)





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

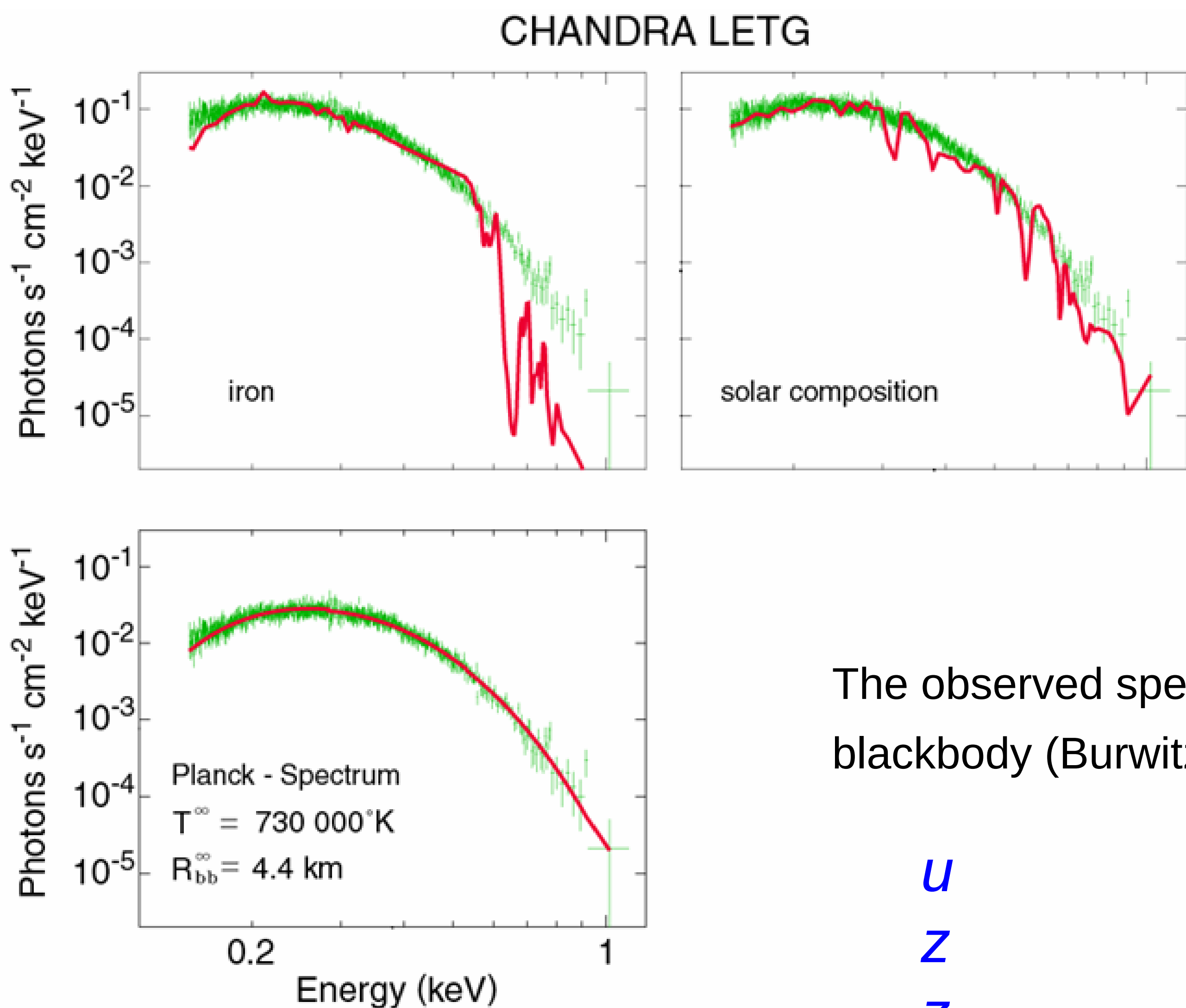
Optical Identification of the Neutron Star RX J1856-3754



- 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: $d \leq 130$ *pc*

HIGH RESOLUTION CHANDRA LETG SPECTRUM OF RX J1856-375

(observation time 6 days!)



CHANDRA LETG-DATA $\frac{\Delta E}{E} < 1\%$!

Expected atmospheric features are not seen!

The observed spectrum looks like a perfect blackbody (Burwitz et al. 2001, 2003)

u

z

z

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).

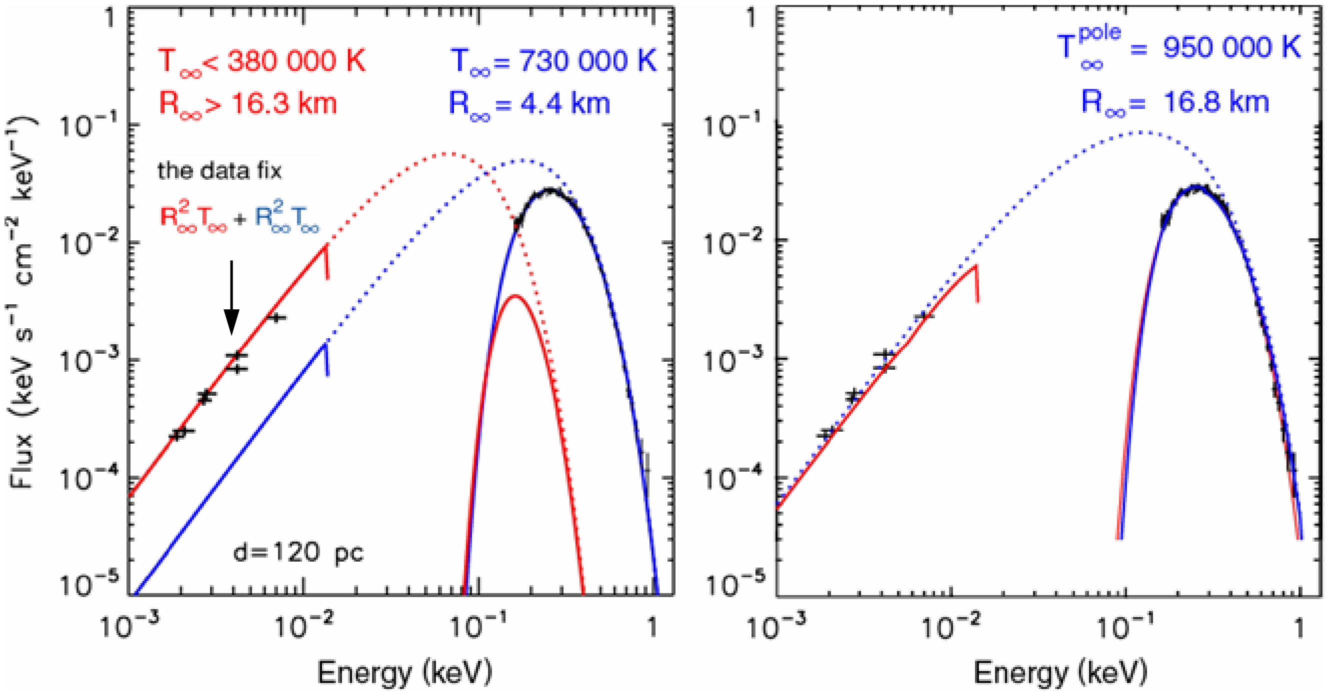
  - But: Condensation requires $B > 10^{14}$ G for hydrogen at kT ~ 60 eV, condensation of iron is uncertain (Lai, 2001), but may be possible because of cohesive forces (Lai, 2006)

- **Atomic line smearing in strong magnetic fields?**
  ($B \sim 10^{13}$ G)

  - A dipolar magnetic field strength varies by a factor of ~ 2 across the photosphere!

Talk by Roberto Turolla

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**

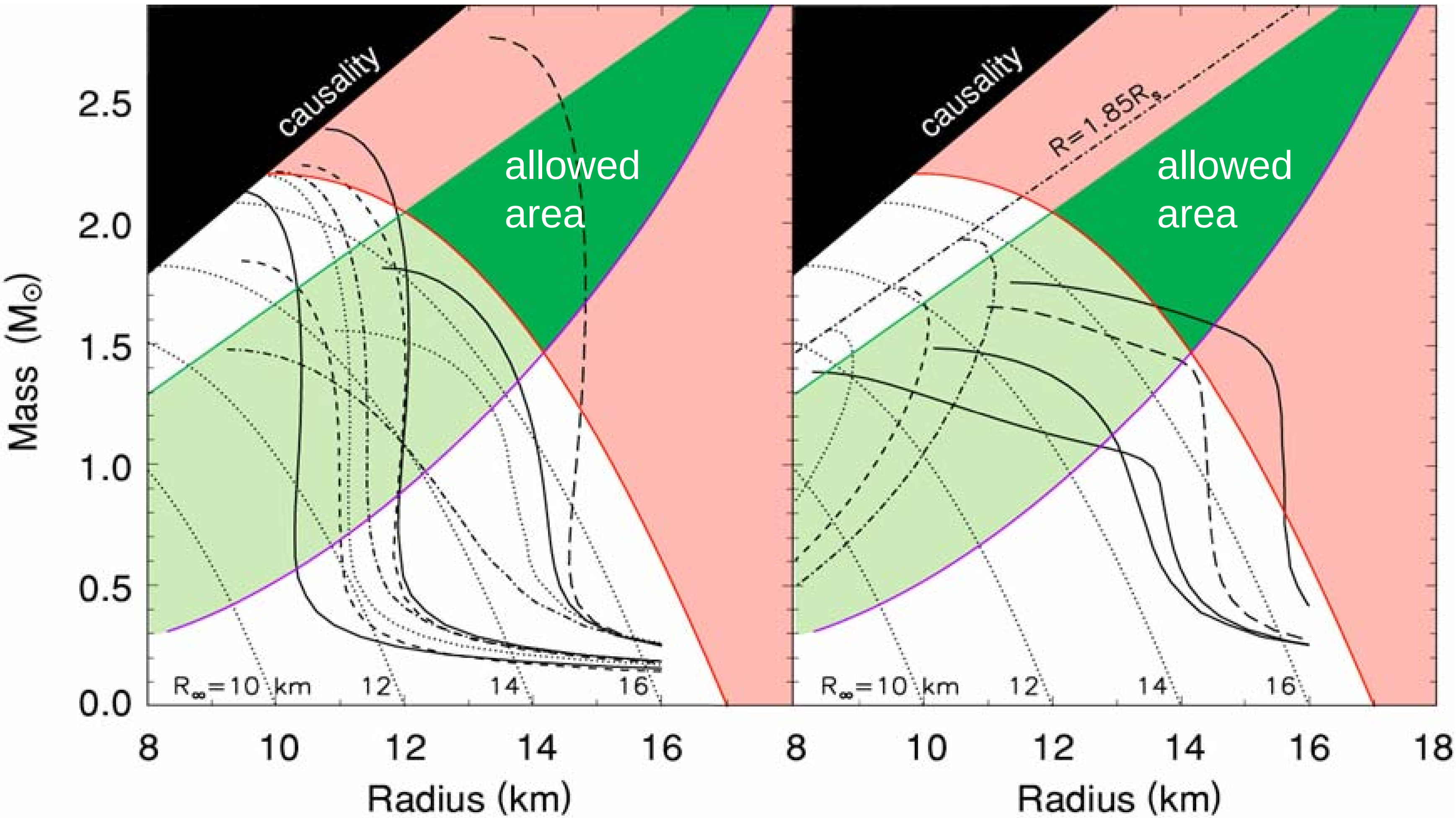
$\Rightarrow R_\infty \geq 16.9$ km $\times\, d_{120}$

Temperature distribution:

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

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

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



The radiation radius of the radio-quiet isolated neutron star RX J1856-3754 is large: R ~17 km

(Walter & Lattimer 2002, Braje & Romani 2002, Pons et al. 2002, Burwitz et al. 2003, Trümper 2005, Ho 2006)

Beyond blackbody:

A thin hydrogen layer on top of a blackbody increases the optical / UV flux (Motch, Zavlin & Haberl 2003)

Condensed matter surface emission is close to blackbody (Burwitz et al. 2001, 2003; Turolla, Zane & Drake 2004; van Adelsberg et al. 2005) Turolla talk

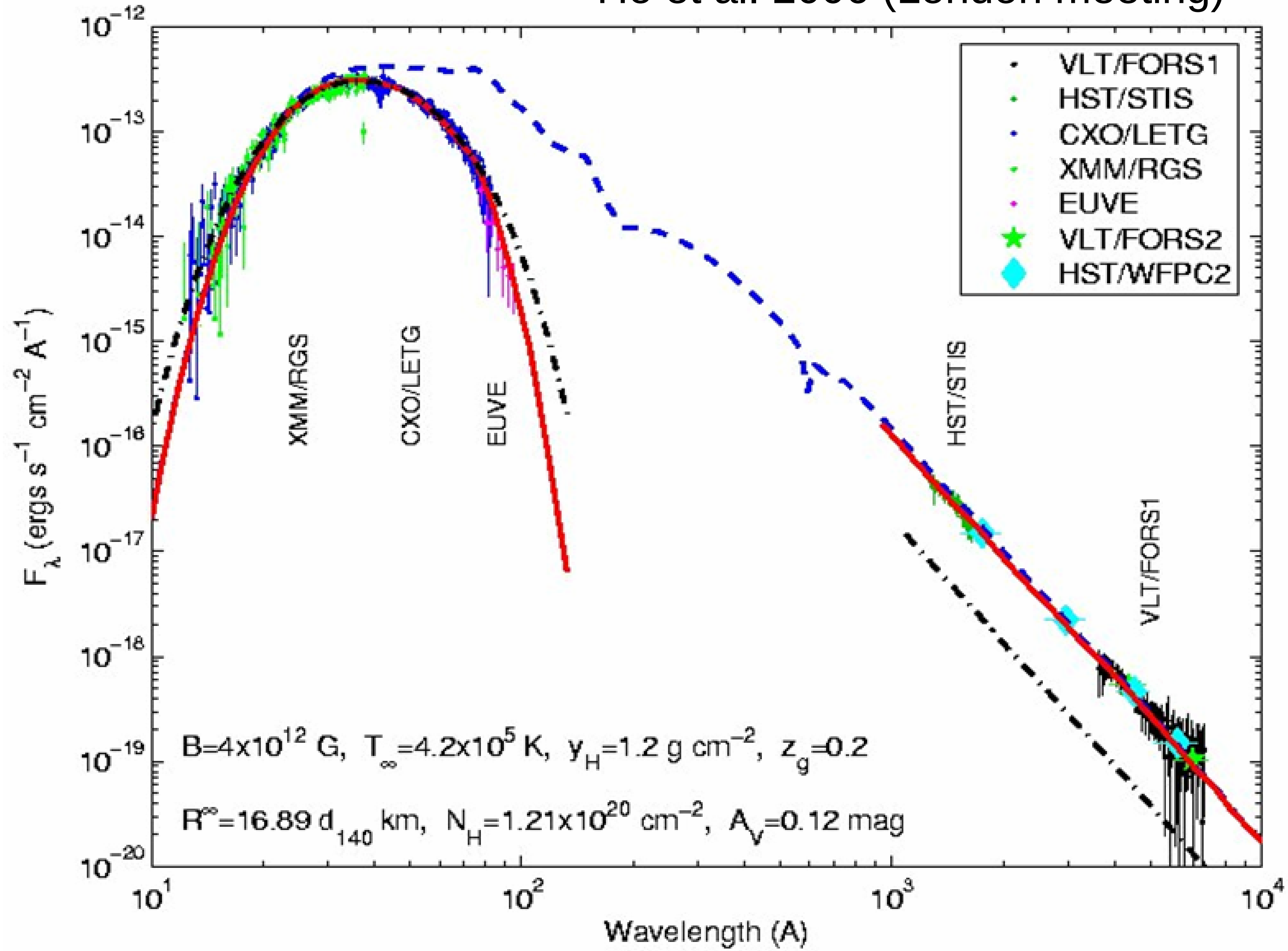
-- Distance of RXJ1856 : 120 → >140 pc (Kaplan 2004)

Radiative transfer in a thin strongly magnetized hydrogen layer, which is on top of a condensed iron surface (Ho et al. 2006)

Influence of magnetospheric processes ??

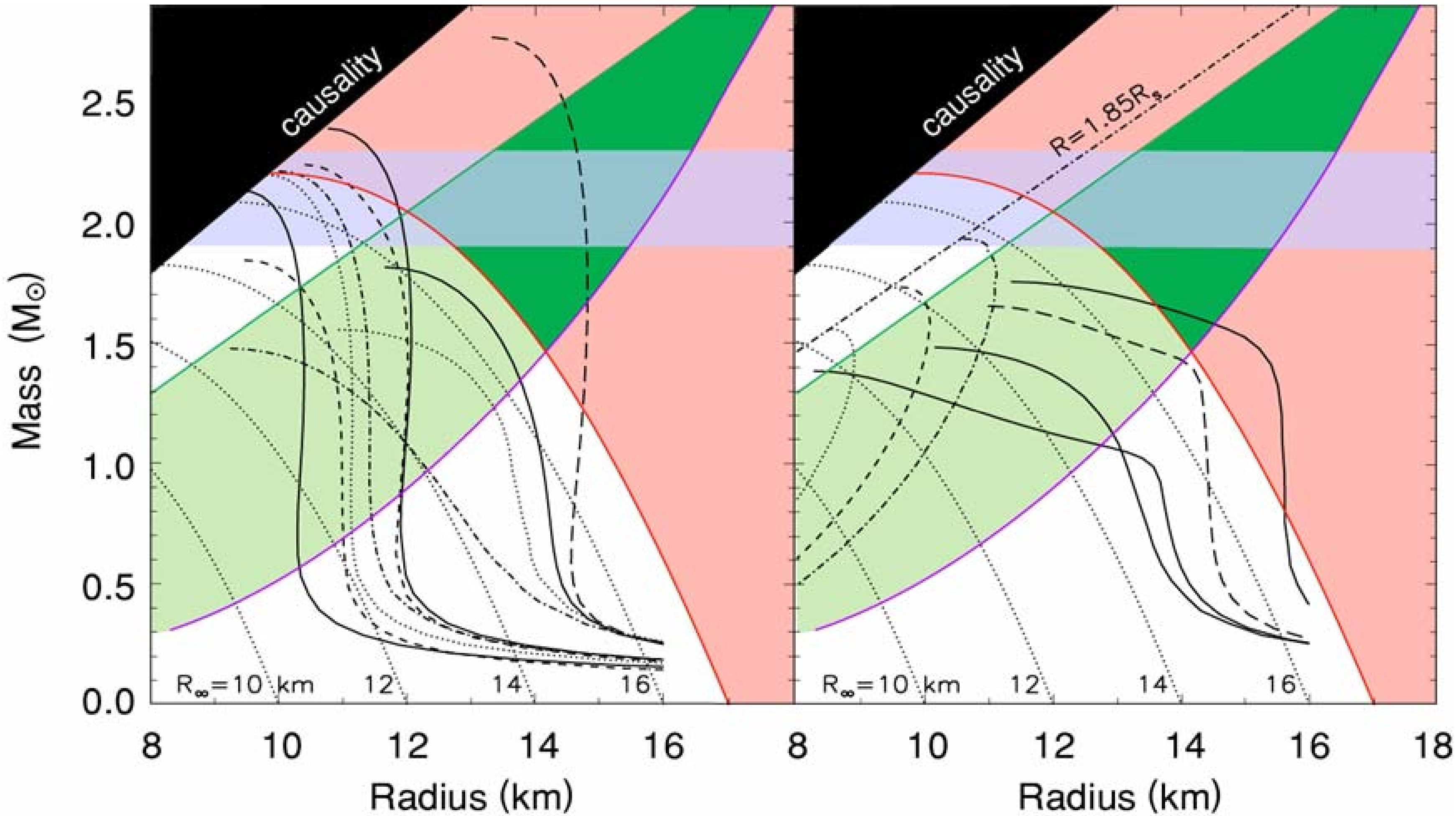
Magnetized hydrogen layer on top of a condensed iron surface

Ho et al. 2006 (London meeting)



This is not a fully realistic model yet: Magnetic field and temperature constant !

Quality of the fit??? E-mail from Wynn Ho, yesterday: R = 17.00 km



The pulsar PSR 0751+1807 in the white dwarf binary system has a mass of 2.1 + 0.2 M (Nice et al.2005)

All data require a stiff equation of state !

Cooling and Precession

are another important probes of the NS interior –

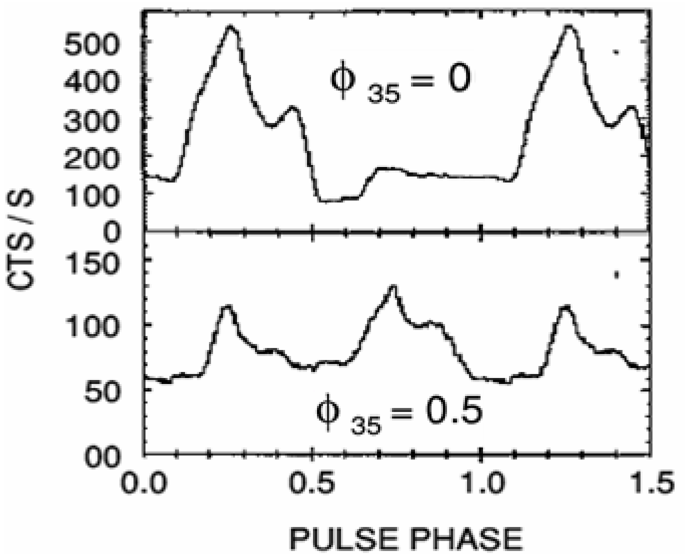
complementary to M - R relations

Cooling depends not only on EOS, condensates, superfluidity etc.,but also on magnetic field structures, e.g. on magnetic blankets provided by toroidal fields (Dany Page talk).

Separating both effect is difficult!

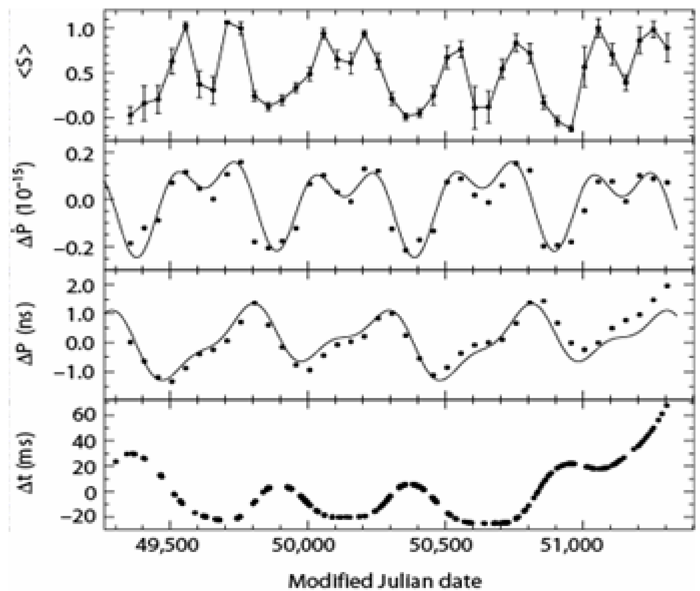
There is evidence for long period precession in NS, e.g. in

Her X - 1



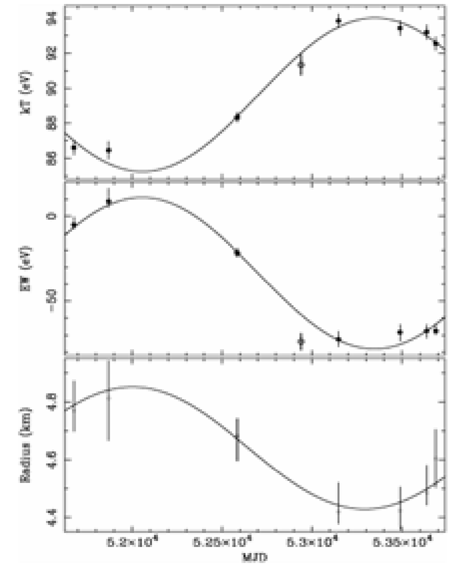
Trümper et al 1986

PSR 1828 - 11



Stairs et al. 2000

RX J0720 - 31



Haberl et al. 2006

	Her X - 1	PSR 1828 - 11	RX J0720 - 31
P (s)	1.24	0.405	8.39
P_{pr} (d)	34.858	~1000	~2600
P/P_{pr}	4.1×10^{-7}	1.3×10^{-9}	3.7×10^{-8}

accreting NS
clock: precessing NS
which synchronizes a sloppy disk
(Shakura, Staubert et al. 2000, 2004)
Poster D. Klochkov

radio pulsar

radio quiet
isolated NS

Long period precession requires solid body rotation

$$\frac{P}{P_{pr}} = \frac{\Delta I}{I \sin \alpha}$$

I = moment of inertia
α = wobble angle

problem with superfluid components of the NS interior

At the London conference:

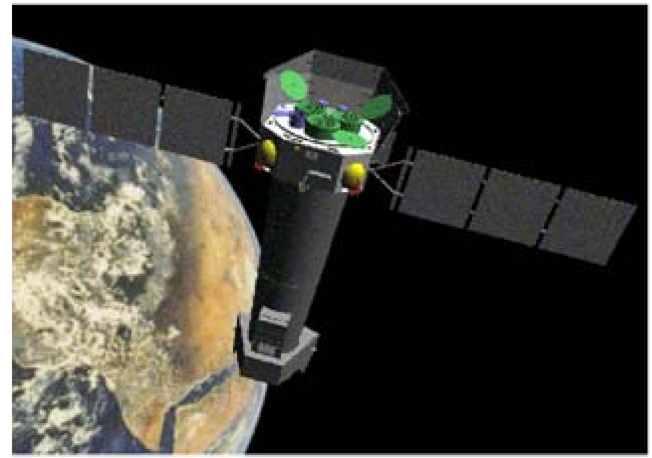
Bennett Link: - Superconducting type I protons (instead of type II) required
or
neutrons are normal in the outer core
(consequences for NS cooling)

Ali Alpar: - precession also works for type II superconducting protons

Ongoing e-mail discussion – no agreement yet!

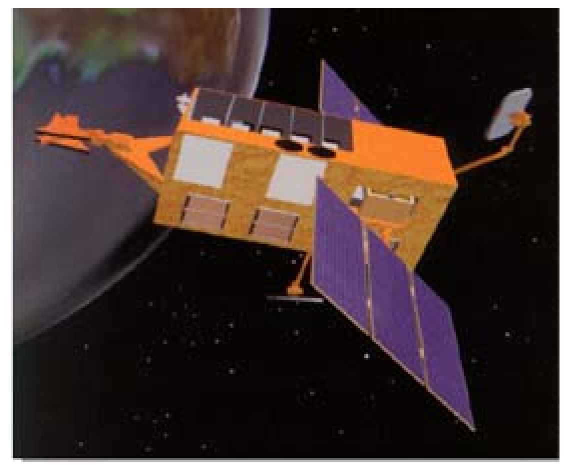
Why do only a few NS precess? Need glitches which are rare events; damping times of precession ~ a few hundred P_{prec}

ROSAT (G, UK, USA) 1990 - 1999
0.1 - 2.5 KeV, 4 arcseconds
All Sky Survey + Pointings
200 000 Sources
3.333 ref. papers / 84.085 citations



XMM - Newton (ESA) 1999
0.2 – 20 KeV, 15 arcseconds
Large collecting power,
High resolution spectroscopy
1.270 ref. papers / 18.160 citations

Chandra (NASA) 1999
0.5 – 5 KeV, 0.5 arcseconds
High angular resolution
High resolution spectroscopy
2.266 ref. papers / 41947 citations



Rossi X-ray Timing Explorer 1995
2 – 250 KeV, 1 degree
Large collecting power
High time resolution
762 ref. papers / 11.153 citations

The Future

The last 15 years have been called the „Golden Age of X-ray Astronomy“. They have been golden for gamma-ray astronomy as well.

90’s: ROSAT, ASCA, BeppoSAX, Compton GRO, RXTE
00’s: Chandra, XMM-Newton, Integral, SWIFT, Suzaku

On the long run (>2015) there will be hopefully Super-Observatories like XEUS, Constellation-X and the Gamma Ray Imager

But what about the near future?

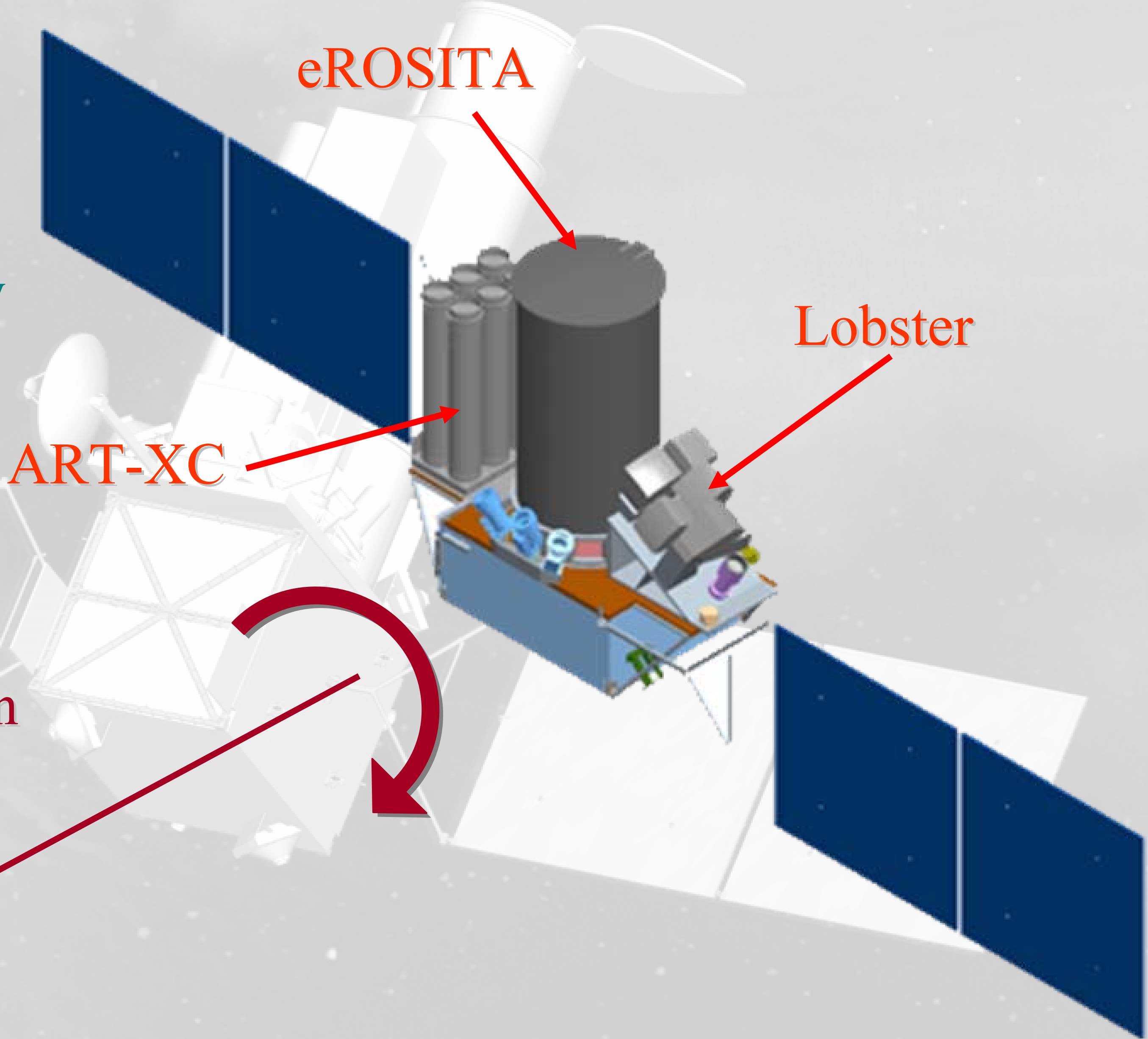
GLAST, AGILE
Spectrum Röntgen-Gamma, a reincarnation in 2006
Einstein Probes ??

Scientific goals

- First all sky (≤12 keV) survey with record sensitivity, energy and angular resolution
  - Systematic registration of all obscured accreting Black Holes in nearby galaxies and many (~million) new distant AGN
  - Registration of hot interstellar medium in ~ 100 thousand galaxy clusters and groups (Large scale structure of Universe)
  - X-ray and optical follow-up of selected sources
- Study of physics of galactic X-ray source population (transient, binaries, SNR, stars, et. al.) and gamma-ray bursts

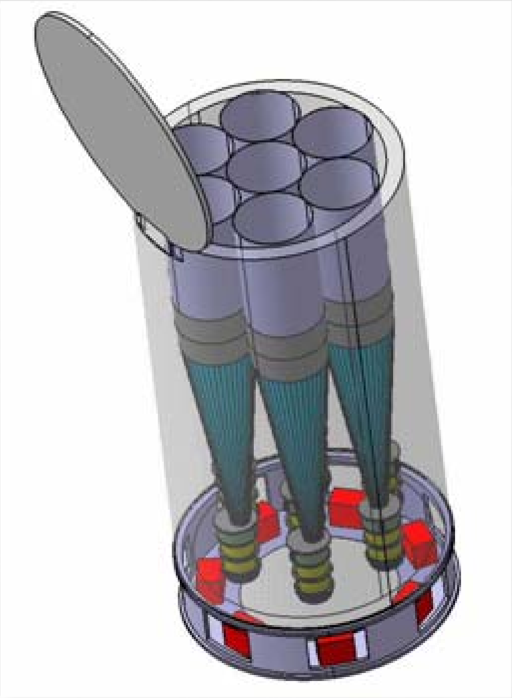
Payload:

- Mass **1250 kg**
  (150 kg reserve);
- Power consumption **600 W**
  (100 W reserve)

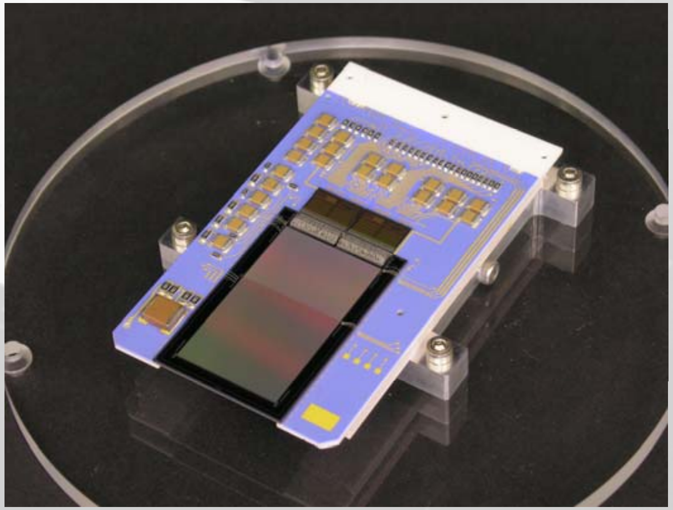


eROSITA (MPE, Germany)

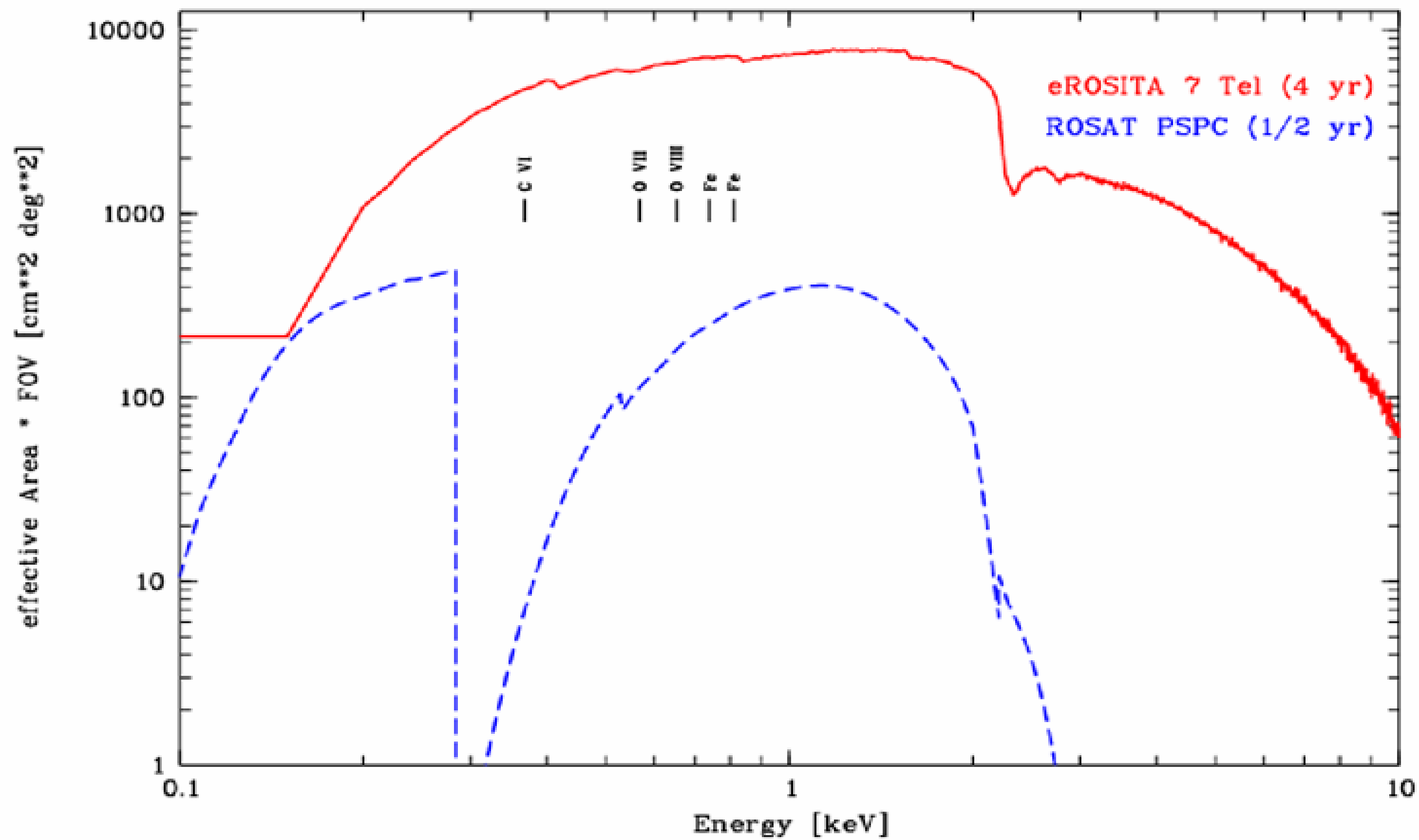
G. Hasinger, P. Predehl, L. Strüder



- 7 mirror systems (∅ 35 cm each)
- energy range 0.2 - 12.0 keV
- PSF ~20″ (FOV averaged) and ~15″ on axis
- energy resolution 130 eV at 6 keV
- effective area 2500 cm^2
- a grasp of ~700 cm^2 deg^2 at 1 keV



Grasp of eROSITA compared with RASS



point source location better than ROSAT ASS
energy resolution ~ 4 × ROSAT PSPC

This will be an extremely powerful instrument!

eROSITA will detect >> 10^6 X- ray sources, among them many pulsars and radio quiet isolated neutron stars...

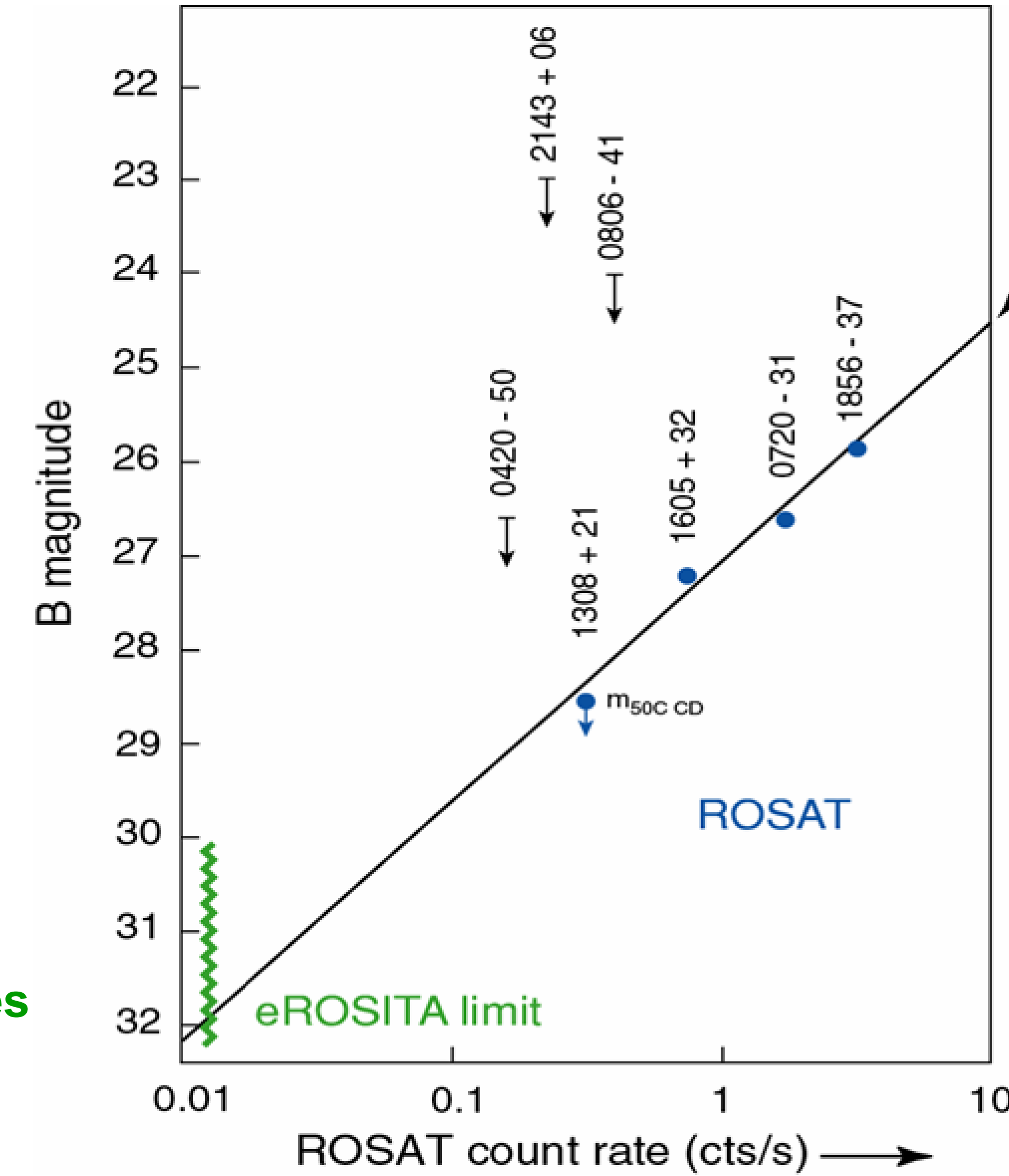
Gain in sensitivity: factor of 10

Mag Seven → ~ $7 \times 10^{3/2}$ ~ 200

% absorption effects

James Webb ST;

30–50m telescopes



HST

Keck

VLT

$f_0 = \text{const } f_x$

M. Gries poster

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An unbiased survey will turn up new classes of objects!

Conclusion

Observations suggest that the EOS is rather stiff and we are dealing with normal neutron stars. Strange quark stars may exist, but have not been convincingly detected.

Wish-list for the Future

-- Statistical errors have become small, and often systematic errors dominate (e.g. Chandra LETG ~15%, XMM-RGS is even worse). It would be very important to cut down systematic errors for previous, present and future missions. There is room for improvements!

-- There has been progress in radiation models (atmospheric and condensed matter), but they are not fully selfconsistent. Also the atomic and condensed matter physics of high Z elements in superstrong magnetic fields is only known in crude approximations. There is a need for more theoretical work!

-- In summary, we need more and better data and further progress in theory!

Thank you!