Concluding Remarks II

Joachim Trümper

Max-Planck-Institut für extraterrestrische Physik

Garching / Germany

Isolated Neutron Stars:

From the Interior to the Surface

April 24 – 28, 2006

London

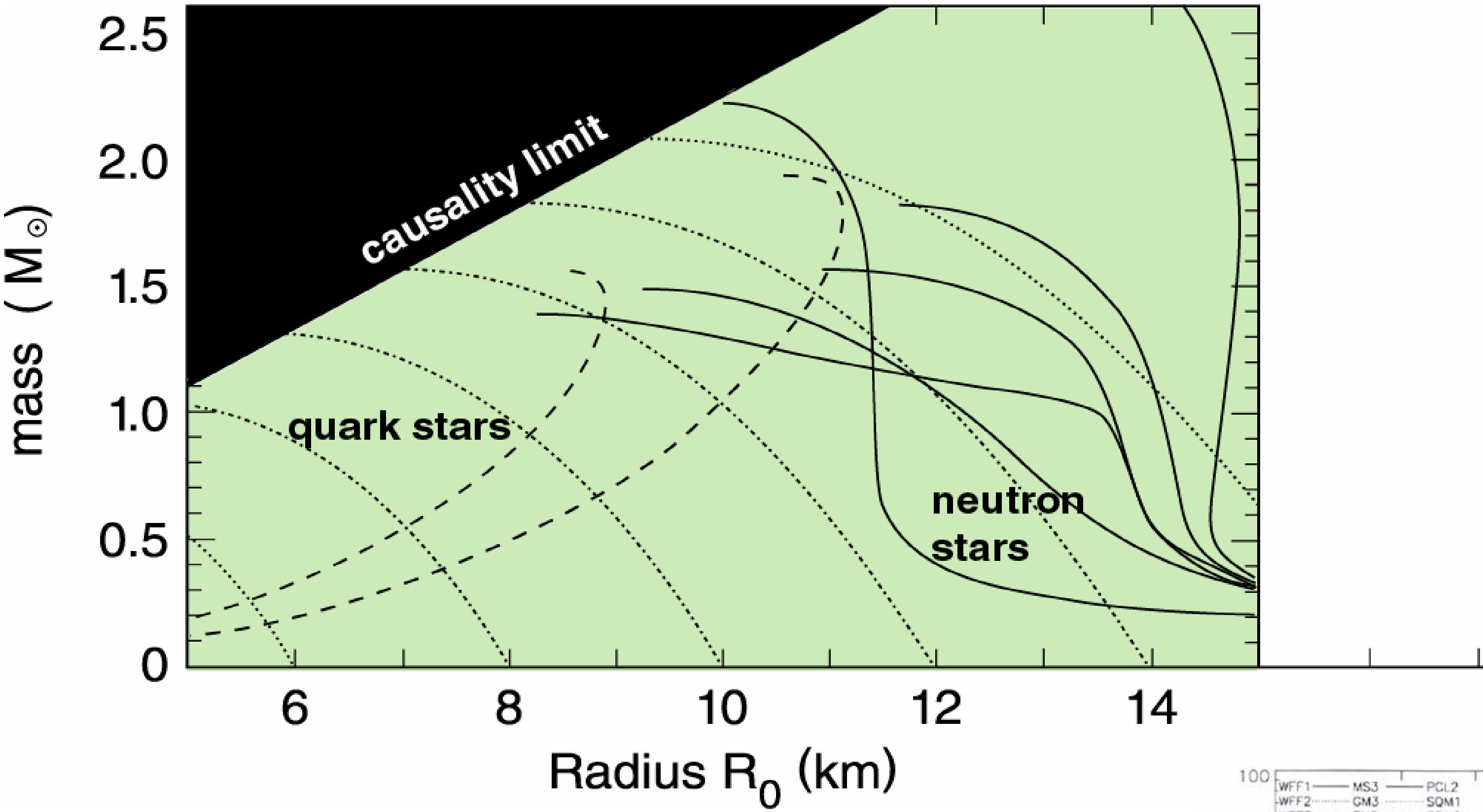
UK

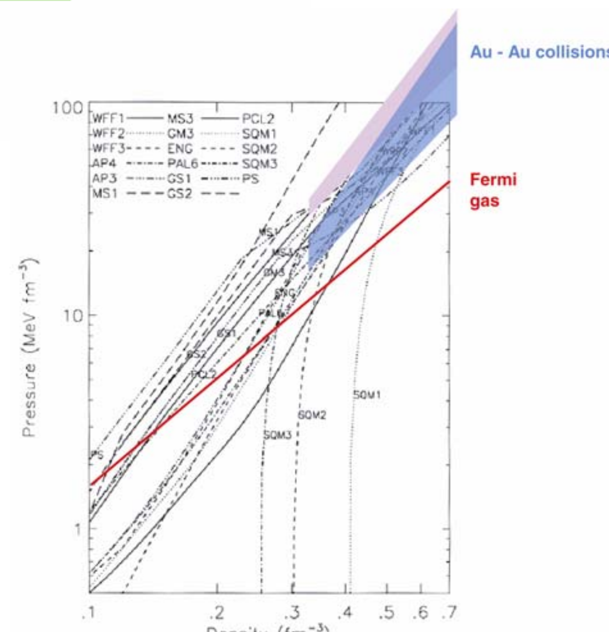
Outline

- **EOS and M-R relations**
- **Precession**
- **X~~D~~INS XBINS alias Magnificent Seven**
- **RRATS**
- **Future observational capabilities**

The equation of state of nuclear matter

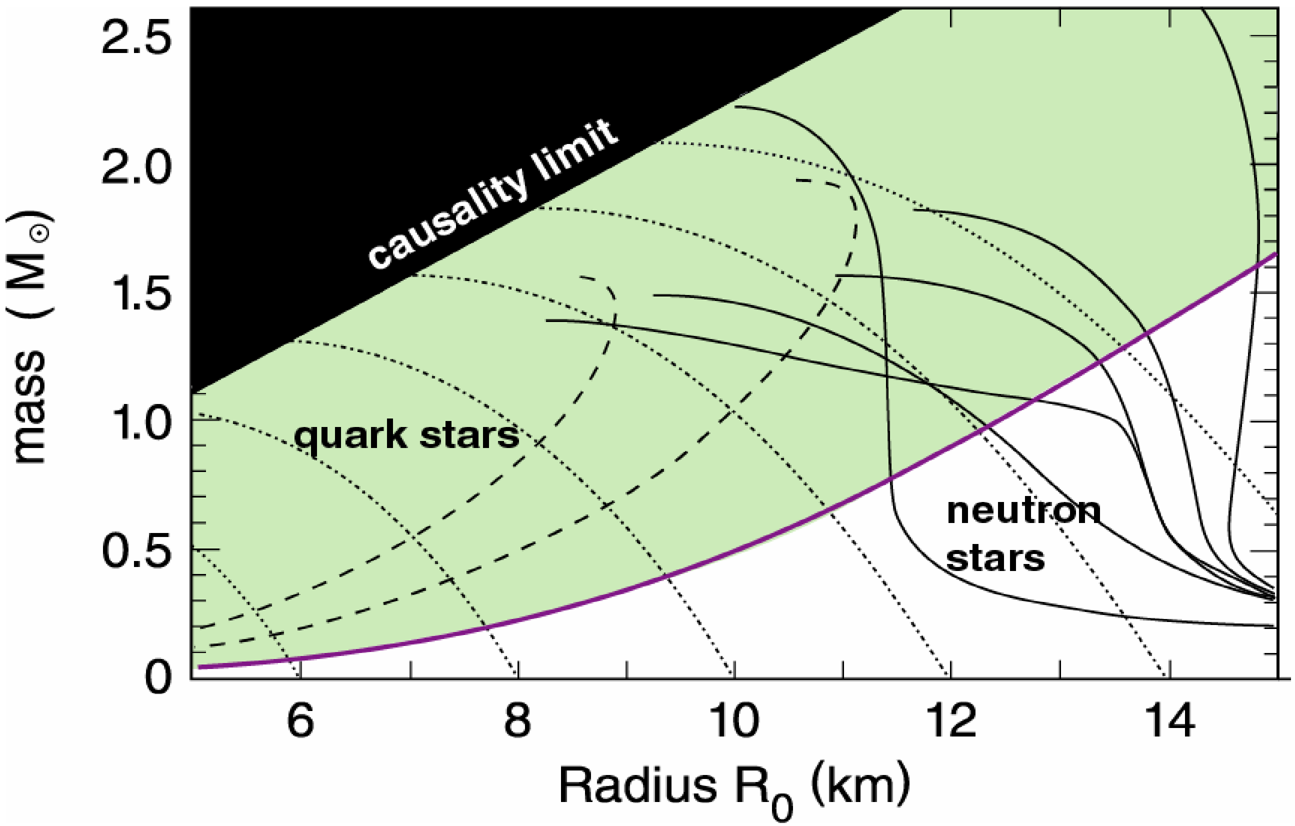
- is of fundamental importance for NS astrophysics
- There are many theoretical EOS models.
- A determination of the EOS can only come from nuclear collision experiments and NS observations.
- There has been great progress in the last 15 years.

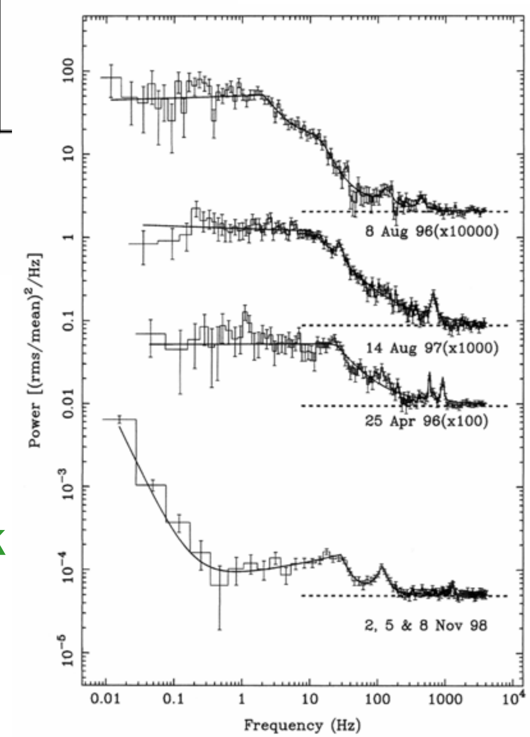




M-R relations for different equations of state

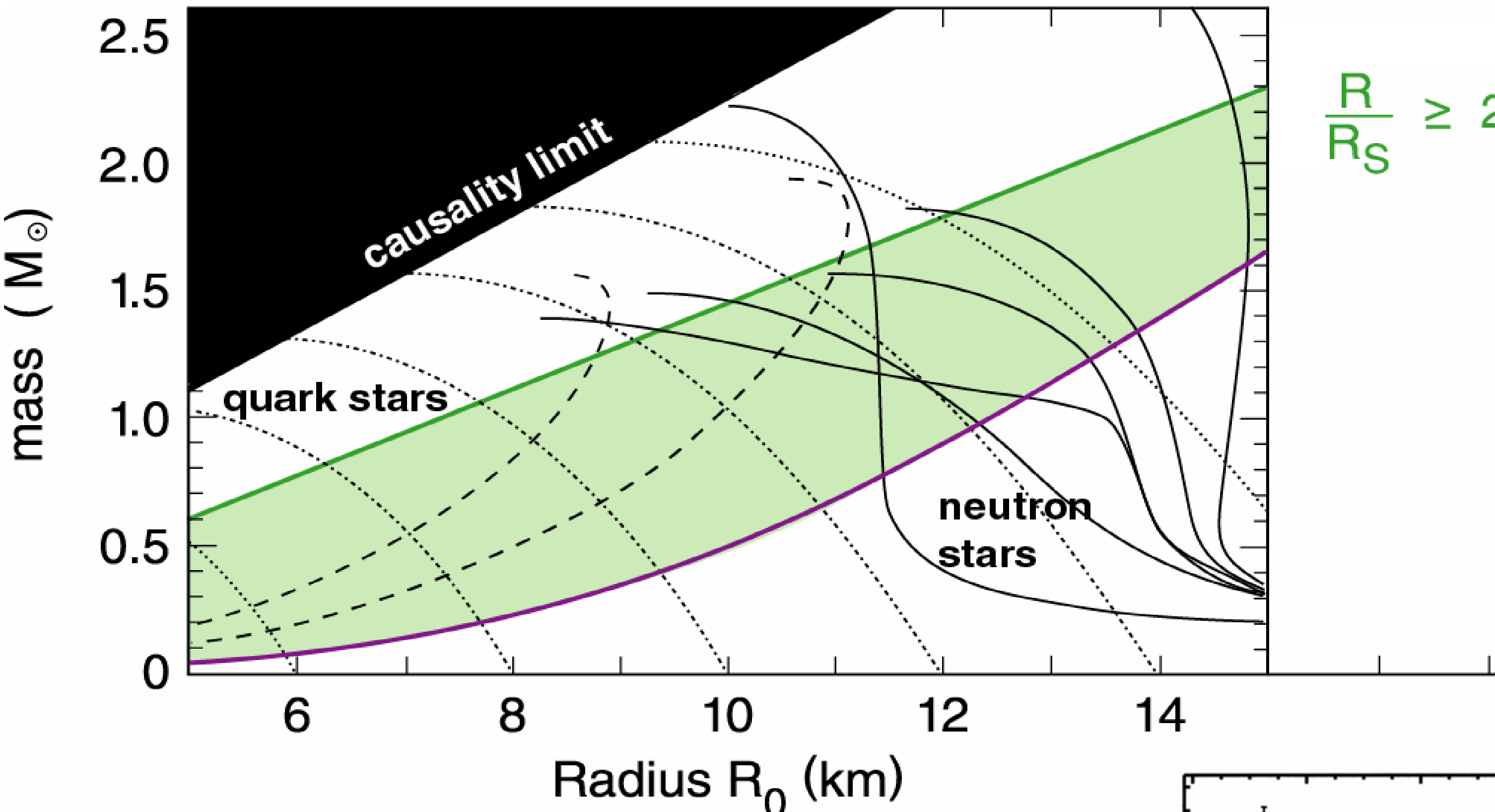
(Lattimer & Prakash 2001)





Upper QPO freqency is the orbital frequency of circulating gas at the inner edge (R_i) of the accretion disk

4U 0614+091 (Miller 2003). $R_i > R_{NS}$

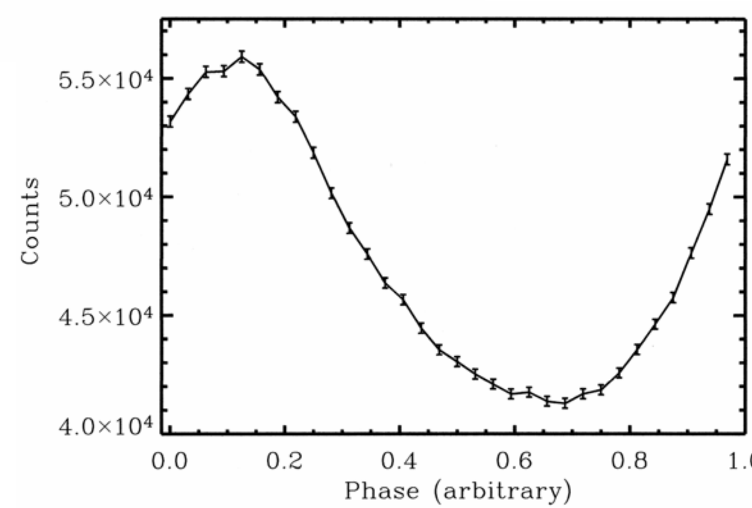


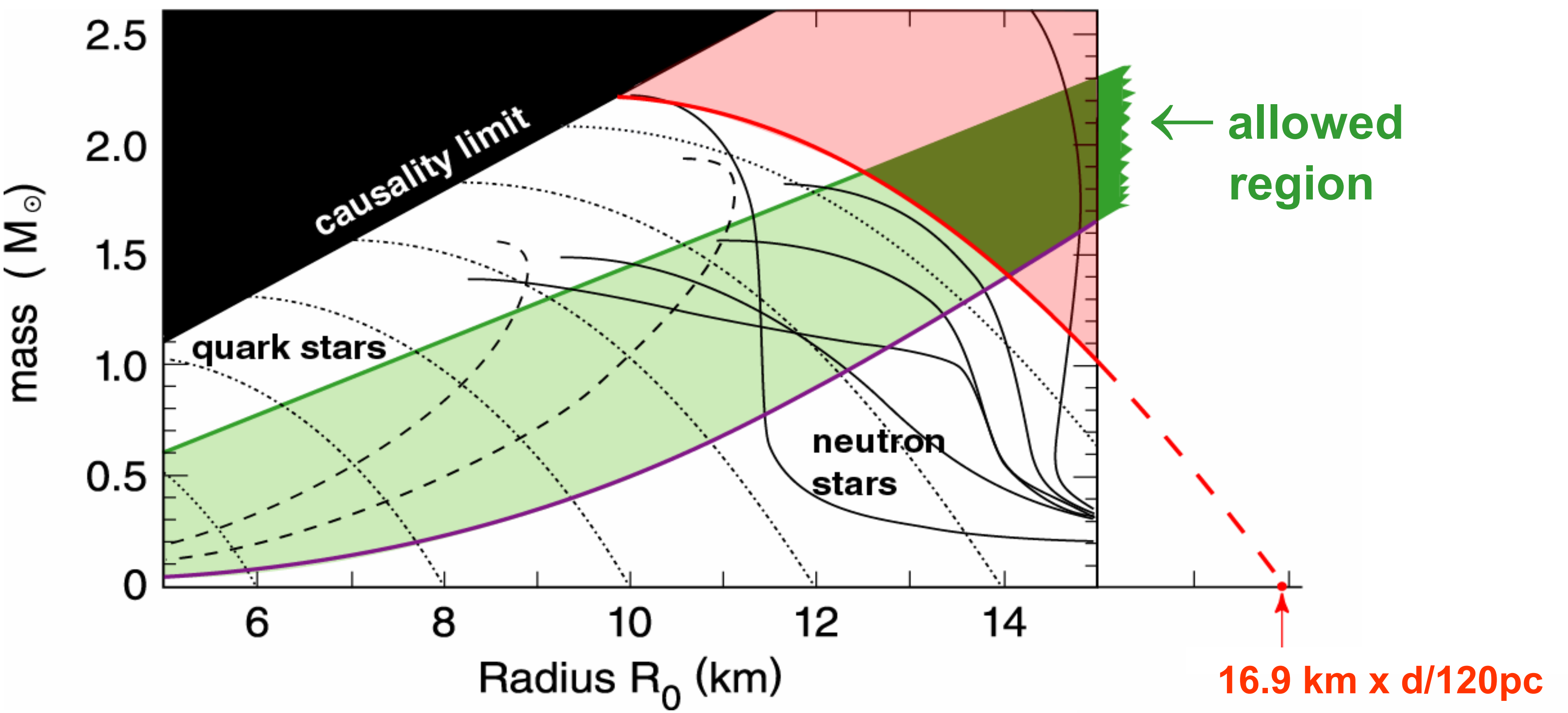
$$\frac{R}{R_S} \geq 2.1$$

Light curve of coherent burst oscillations

4U 0614+091 (Bhattarcharyya et.al. 2005)

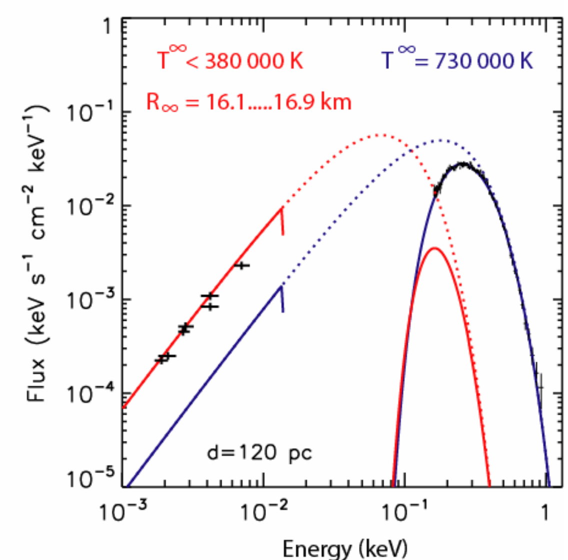
Similar constraints from Poutinen





Radiation radius of the radio-quiet isolated neutron star RX J1856-3754

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



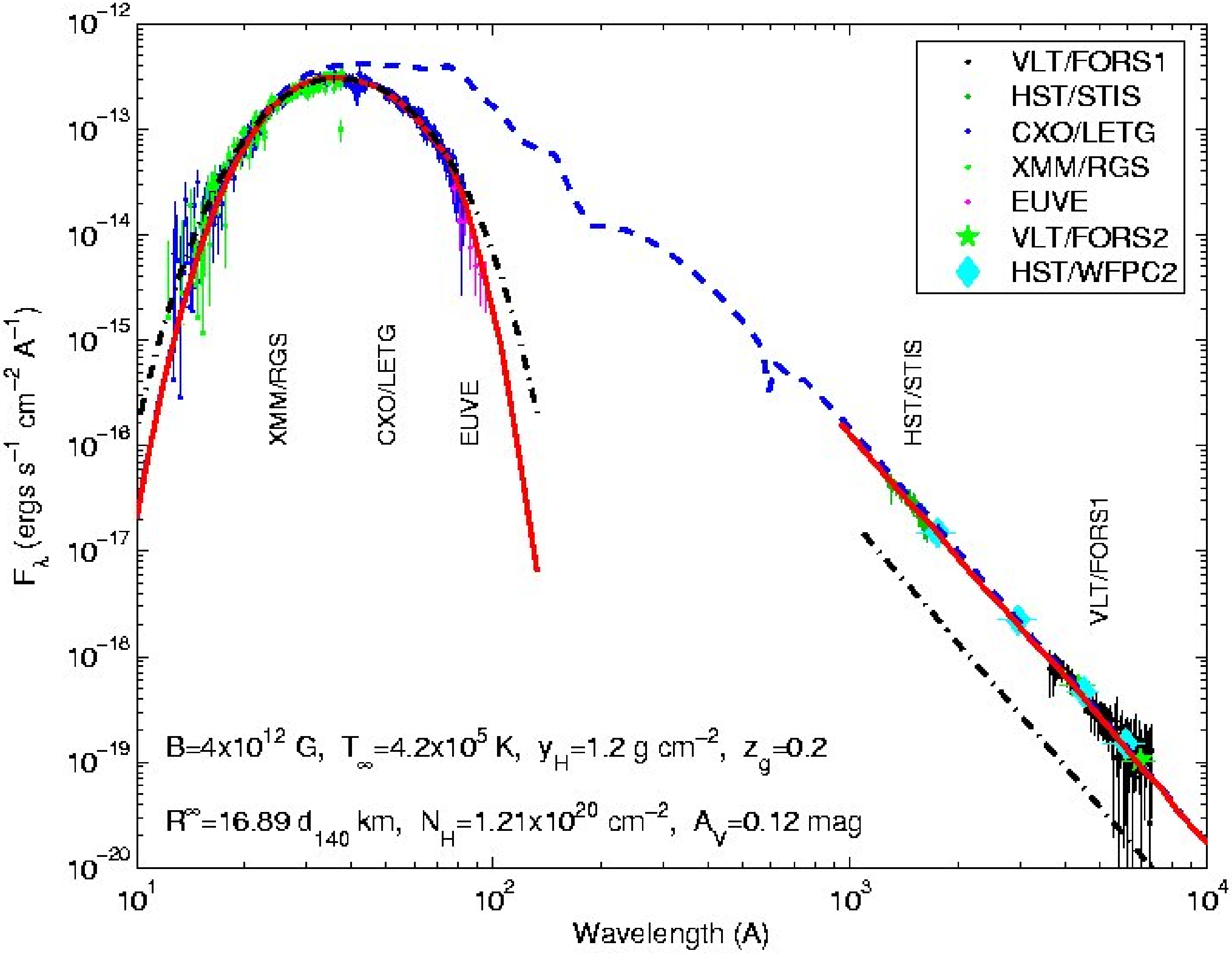
Beyond blackbody:

Two qualitative steps:

- A thin hydrogen layer on top of a blackbody boosts 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)

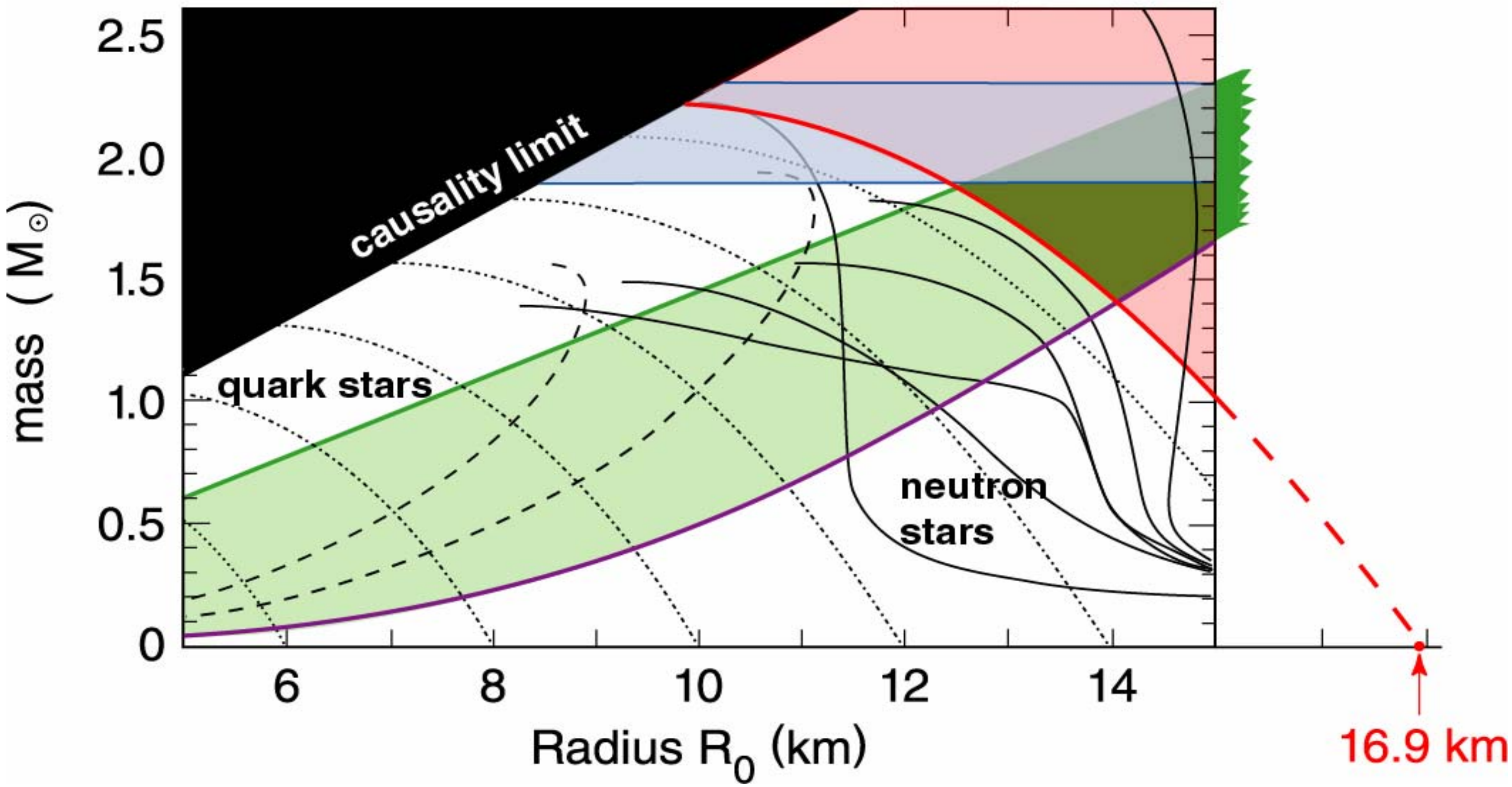
Two quantitative steps:

- Distance of RXJ1856 120 → >140 pc (Kaplan 2004)
- A thin strongly magnetized hydrogen layer, partially ionized, on top of a condensed matter (Fe) surface (Wynn Ho)



VLT/FORS1
HST/STIS
CXO/LETG
XMM/RGS
EUVE
VLT/FORS2
HST/WFPC2
XMM/RGS
CXO/LETG
EUVE
HST/STIS
VLT/FORS1
$B=4\times10^{12}$ G, $T_\infty=4.2\times10^5$ K, $y_H=1.2$ g cm^{-2}, $z_g=0.2$
$R^\infty=16.89\, d_{140}$ km, $N_H=1.21\times10^{20}$ cm^{-2}, $A_V=0.12$ mag
F_λ (ergs s^{-1} cm^{-2} A^{-1})
Wavelength (A)

Wynn Ho



Wynn Ho: 16.89 km x d_{140}

Mass of the pulsar PSR 0751+1807 in a white dwarf binary

(Nice et al. 2005)

Precession

is another important probe of the NS interior –

complementary to glitches, cooling (Dany Page),

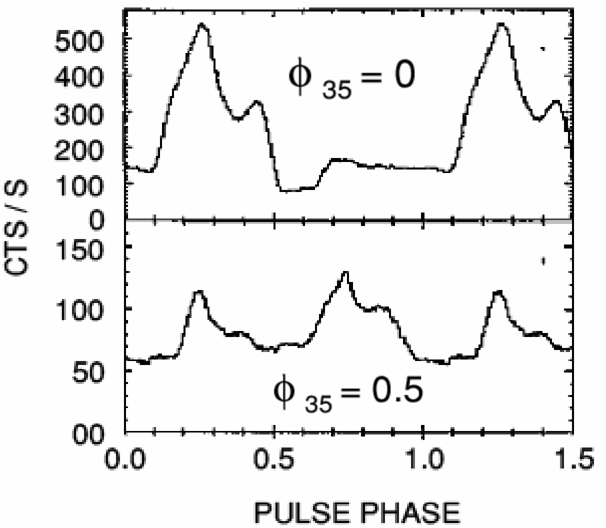
M - R relations

also:

- crust seismology (Anna Watts),
- maximum spin frequency of NS (Jim Lattimer),
- spin down of very young NS (Pawel Haensel),
- etc.

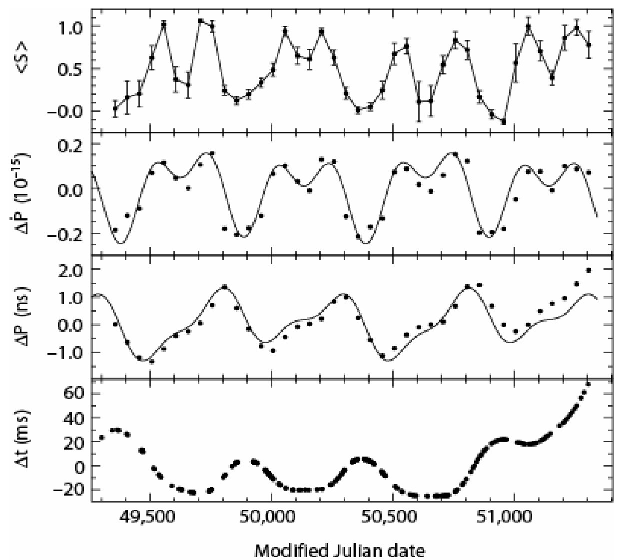
There is strong evidence for long period precession, e.g. in

Her X - 1



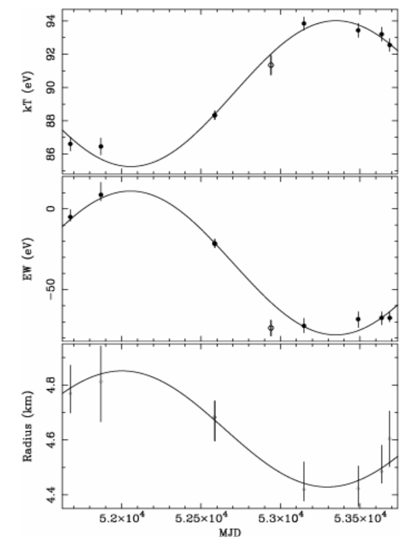
Trümper et al. 1986

PSR 1828 - 11



Stairs et al. 2000

RX J0720 - 31



Haberl et al. 2006

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)

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

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

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

Why do not all NS precess?

- In single stars the damping time of precession (Ali Alpar 2005) may be shorter than the time between excitations (glitches etc.)
- Her X-1 is a special case: the NS and disk precessions are coupled

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} (X-ray dim isolated neutron stars)
- Constant X-ray flux on time scales of years
- No obvious association with SNR
- No radio emission (but: RBS1223, RBS1774: talk by Malofeev)
- 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 (see poster A7)	

(*) 1RXS J130848.6+212708 (**) 1RXS J214303.7+065419

Frank Haberl

Large proper motions, log N – log S → cooling, not accreting

nearby, born in close star forming regions (Christian Motch)

detection limited by interstellar absorption (Bettina Posselt)

high magnetic fields (few x 10^{13} G)

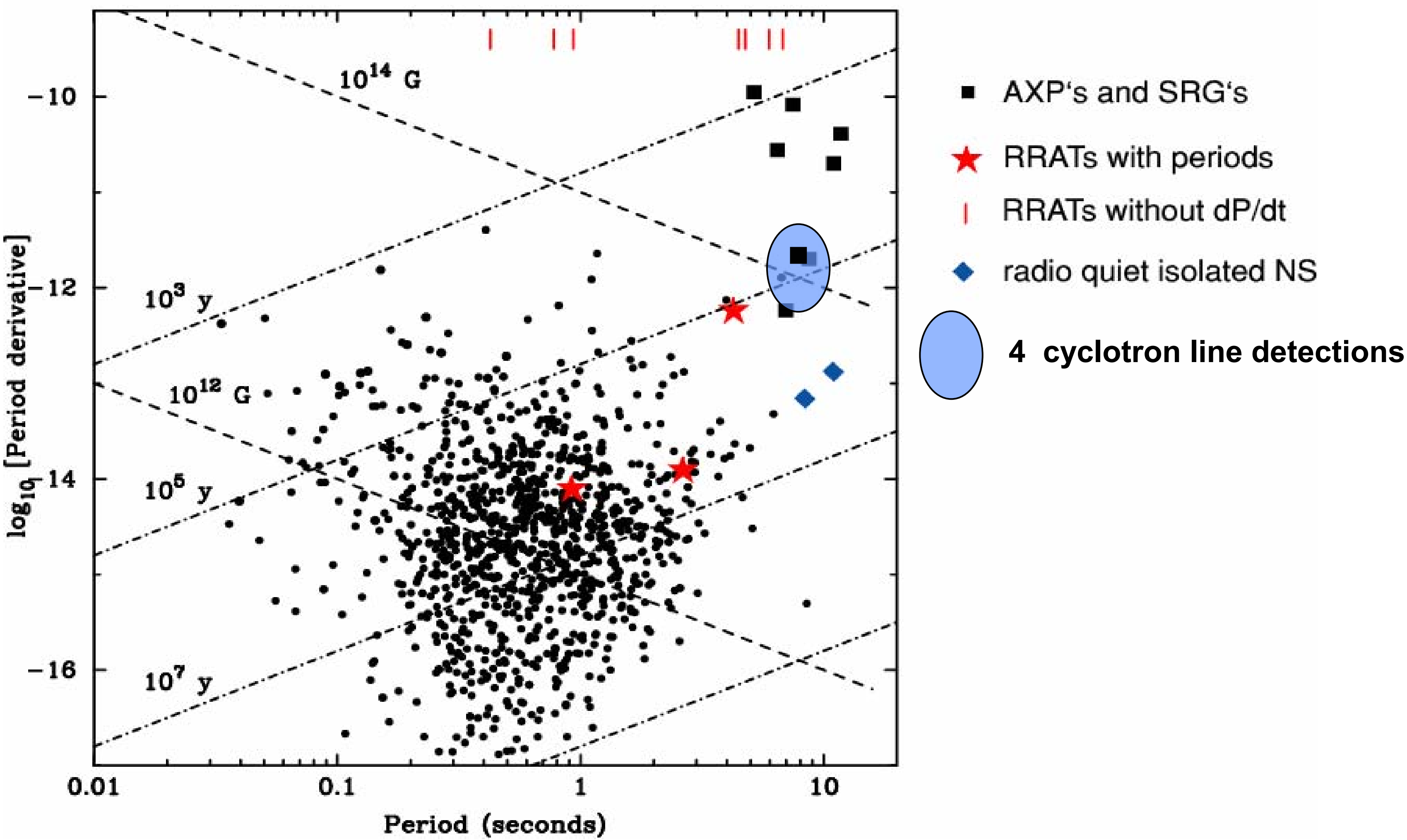
- proton cyclotron lines (Frank Haberl)

  restricted to fundamental frequency (George Pavlov)

- atomic lines (Marten van Kerkwijk)
- molecular lines (Alexander Turbiner)
- condensed matter surfaces (Wynn Ho, Joseph Pons)

Rotating Radio Transients (RRATs)

Mc Laughlin et al. 2005



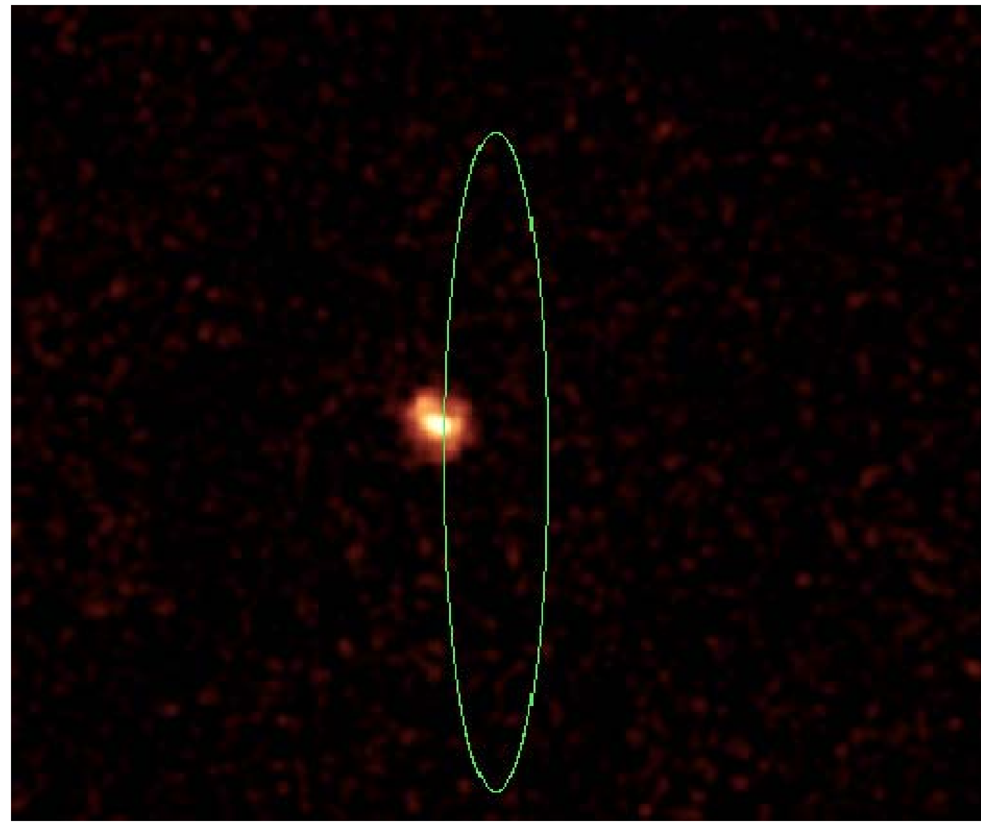
X-ray Detection of J1819-1458

- 30 ks *Chandra* ACIS obs. of SNR G15.9+0.2 in May 2005

- RRAT J1819-1458 falls 11’ from aimpoint

- Clear detection of bright unresolved X-ray source within error circle

- Probability < 10^{-4}



Reynolds et al. (2006)

Bryan Gaensler

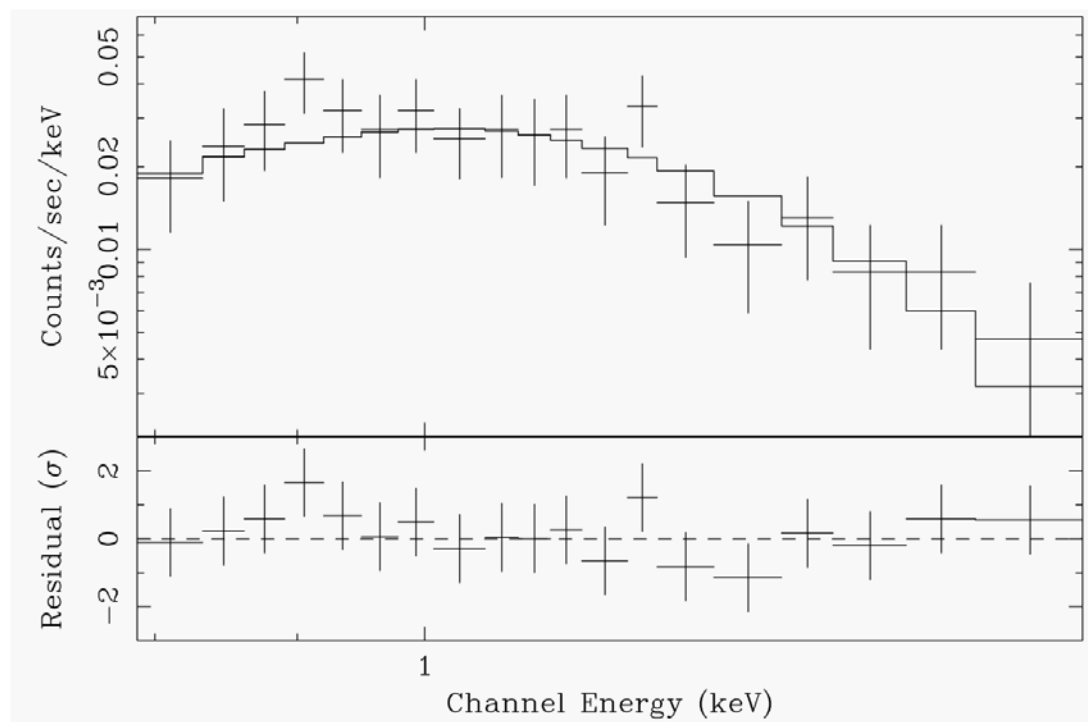
Spectrum & Variability

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

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

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

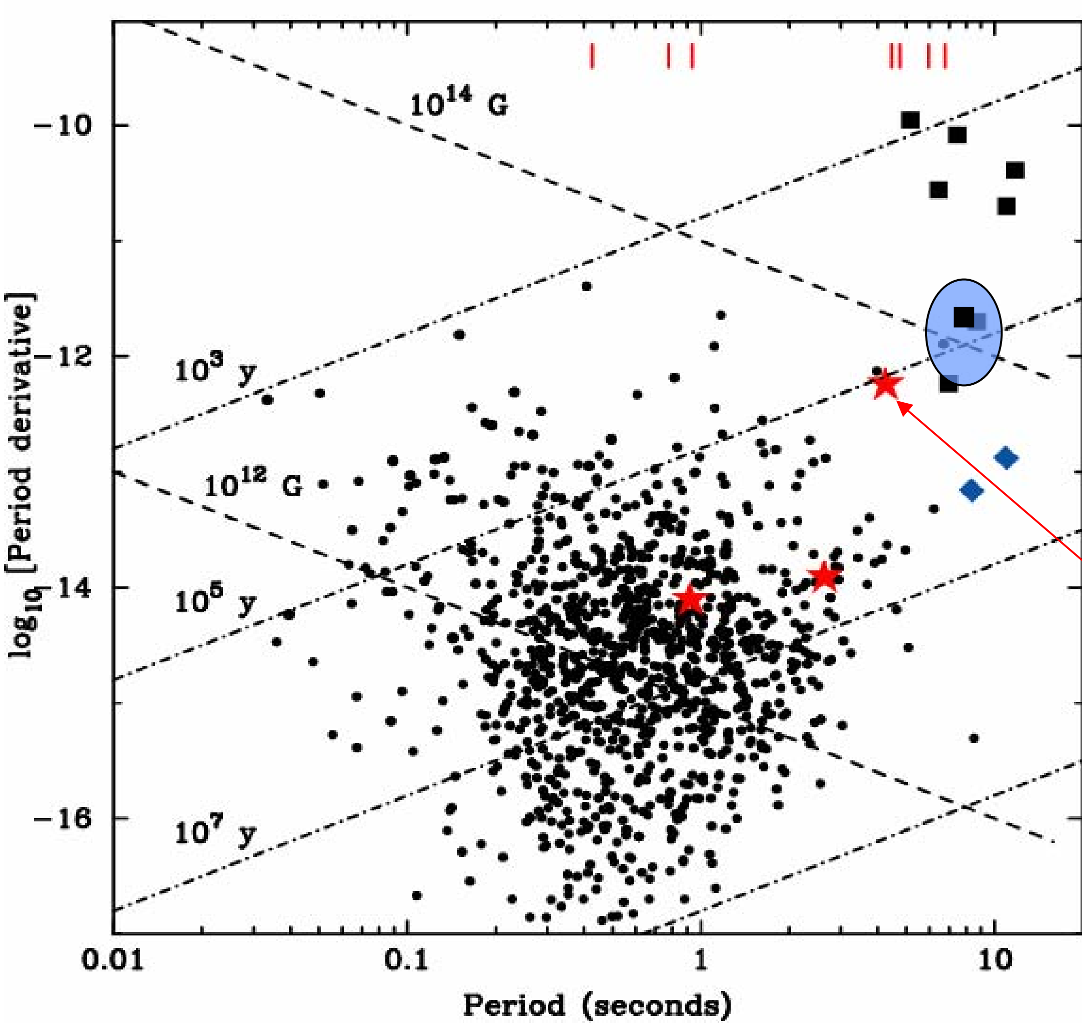


Reynolds et al. (2006)

Bryan Gaensler

Rotating Radio Transients (RRATs)

Mc Laughlin et al. 2005



- ■ AXP's and SRG's
- ★ RRATs with periods
- | RRATs without dP/dt
- ◆ radio quiet isolated NS

4 cyclotron line detections

Chandra detection (Bryan Gaensler)

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

Recent progress has been achieved by investigating about a dozen key objects.

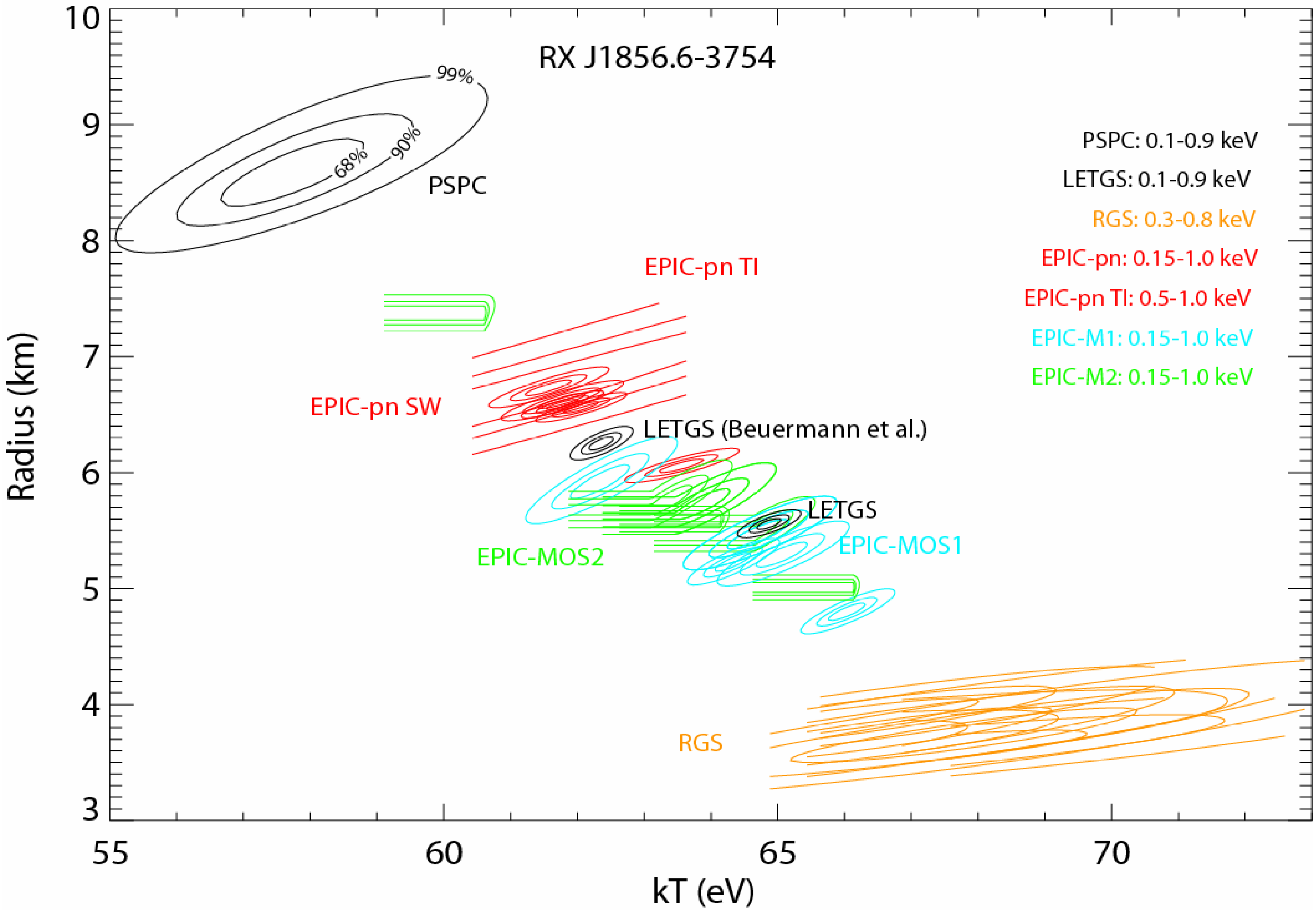
Further progress requires

- **More and better spectroscopic X-ray and optical-UV data**
- **Better absolute calibration of instruments (from ~15% to ~5%)**
- **Improved astrometry**
- **More key objects**

Calibration issues

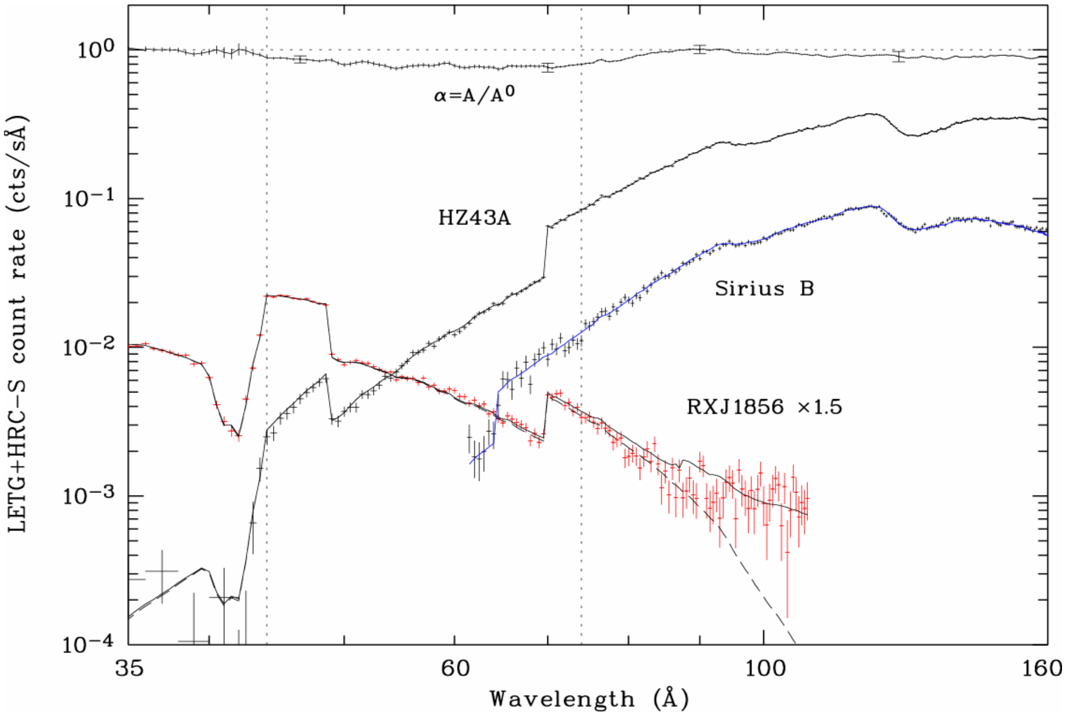
Frank Haberl

Systematic differences between different instrument
due to different energy band passes and spectra responses



The difficult problem of calibration at low energies

It is dangerous to use theoretical spectra of astrophysical objects to calibrate satellite instruments. E.g. hot white dwarfs with pure hydrogen atmosphere spectra have been used to „recalibrate“ the ROSAT PSPC, EUVE Short Wave Spectrometer, Chandra LETG+HRC-S at long wavelengths.



Beuermann et al. 2006 submitted to A&A

Simultaneous fits of RX J1856, HZ 43 Her, and Sirius B in the wavelength band marked by the dotted lines:

- **The ROSAT PSPC ground calibration is confirmed (≤ few %)**
- **The EUVE ground calibration is confirmed as well.**
- **The LETG effective area (A) is ≤ 25% smaller than A in the Nov. 2004 release.**

Stability of Instruments

Chandra LETG HZ 43

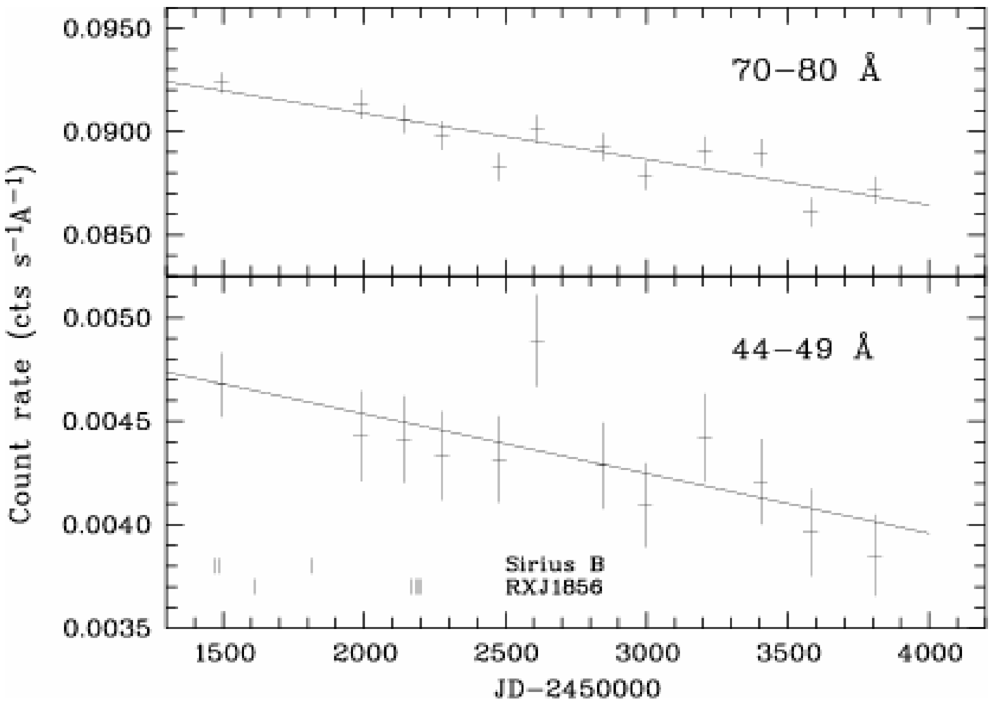


Fig. 1. Long-term variation of the integrated level 2.0 LETG+HRC count rates of HZ43 A for two spectral intervals. The two sets of tick marks indicate the times when the LETG+HRC spectra of Sirius B and RX J1856 were taken.

5.6% in 6 yrs

15% in 6 yrs

WD cooling predict ~ 10^4 times smaller drifts!

These drifts are within the advertised calibration errors, but may affect accurate measurements, e.g. of Neutron Star radiation radii

c. f. Beuermann et al. 2006, submitted to A&A

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 (Martin Weisskopf, talk and after dinner talk).

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 Gamma Ray imager (Lucien Kuiper)

But what about the near future?

- GLAST, AGILE

- Spectrum Röntgen-Gamma, reincarnation 2006

- Einstein Probes ??

The baseline configuration

M. Pavlinsky 2006

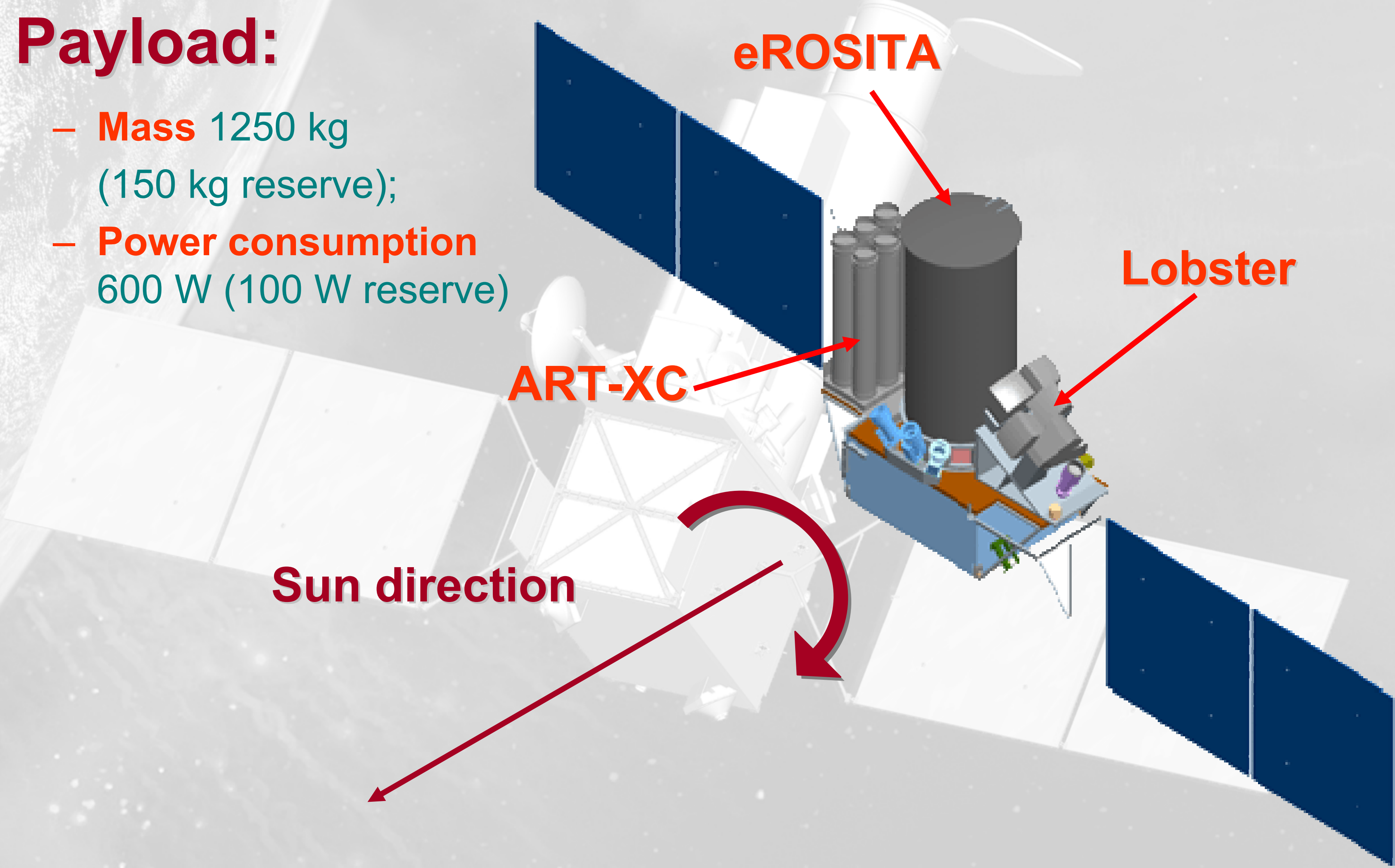
- Launch in the 2010-2011 timeframe by Soyus-2
- Two launch options, 600 km circular orbit:
  - Kourou – inclination ≤5°
  - Baikonur – inclination ≤ 30° as a fallback
- Medium size spacecraft:
  - Yamal (two S/C in operation since 1999 and two since 2003)
  - Navigator (under development)
- Payload:
  - eROSITA (MPE, Germany), X-ray mirror telescopes
  - Lobster (LU, UK), wide field X-ray monitor
  - ART (IKI, Russia), X-ray concentrator based on Kumakhov optics or coded-mask X-ray telescopes as a fallback
  - GRB (IKI, Russia), gamma ray burst detector

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

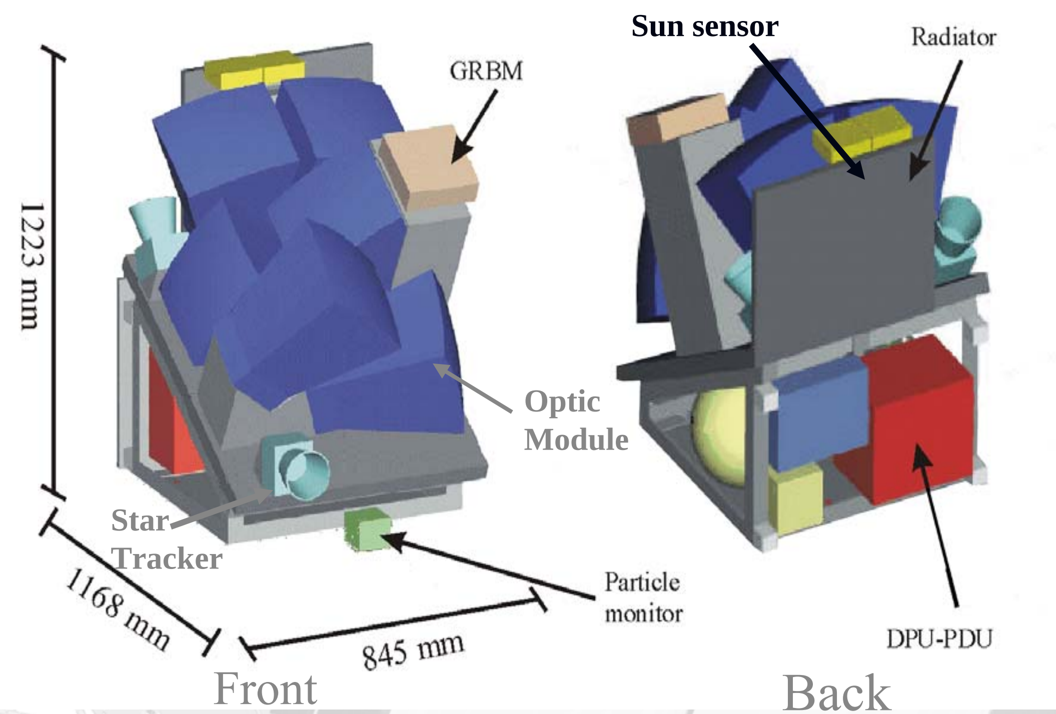
Payload:

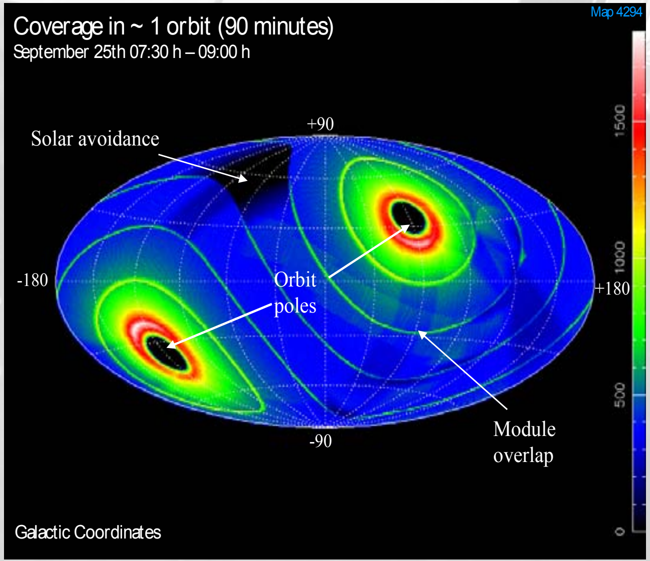
- **Mass** 1250 kg (150 kg reserve);
- **Power consumption** 600 W (100 W reserve)



Lobster (LU, UK)

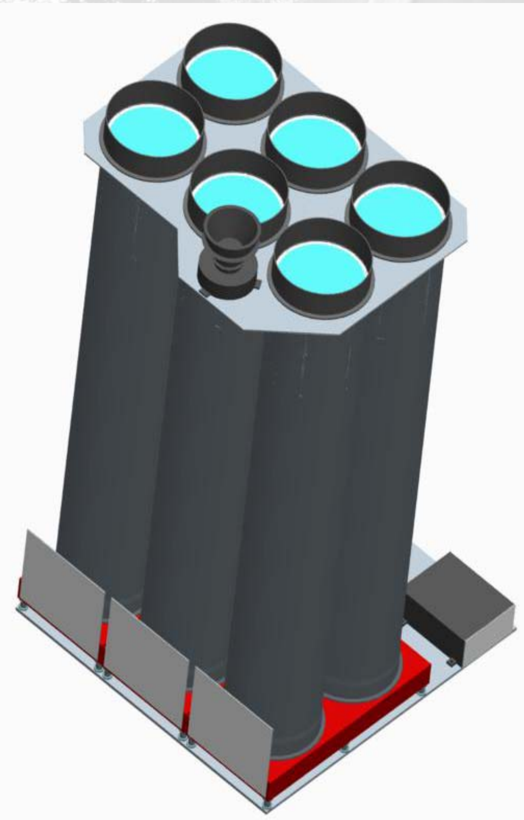
- Wide field X-ray monitor, 6 modules, FOV 22.5°×162°
- 0.1 - 4.0 keV (TBD)
- Angular resolution 4′ (FWHM)
- Energy resolution ΔE/E ~20%
- a grasp ~10^4 cm^2 deg^2 at 1 keV
- 0.15 mCrab for day





- Consortium: UK (hardware) LU and MSSL, (scince) Southampton. Finland U of Helsinki, Switzerland ISDC, Netherland SRON, Italy (GRBM), Spain?

ART-XC (6 units), main characteristics:



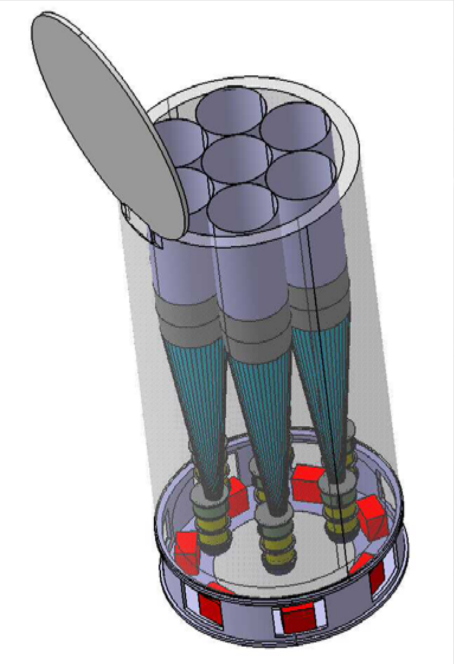
- Energy range — 5-80 keV
- FOV — $46'_{5\ keV}$ - $2.8'_{80\ keV}$
- Effective area of optics — ~1150 cm^2 $_{30\ keV}$
- CZT geometrical area — ≤4 cm^2
- Energy resolution — ≤1 keV $_{60\ keV}$
- Grasp — ~150 deg*cm^2 $_{10\ keV}$

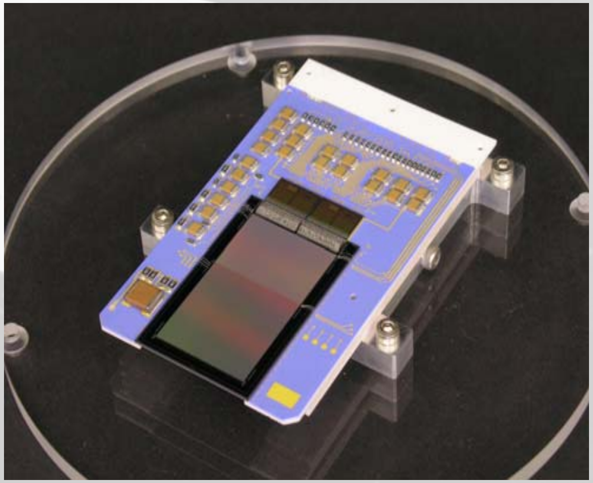
Follow-up, point sources, timing, spectroscopy

eROSITA (MPE, Germany)

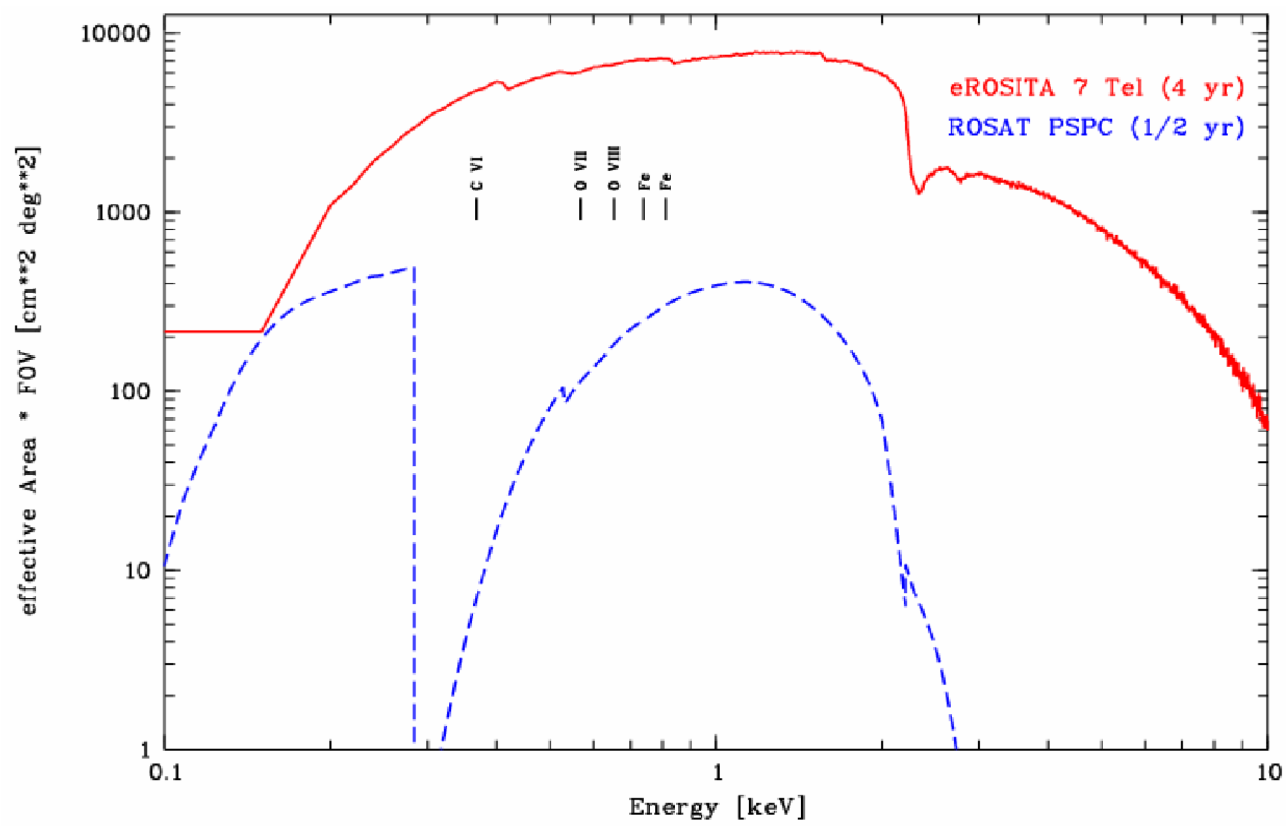
G. Hasinger, P. Predehl, L. Strüder

- 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...

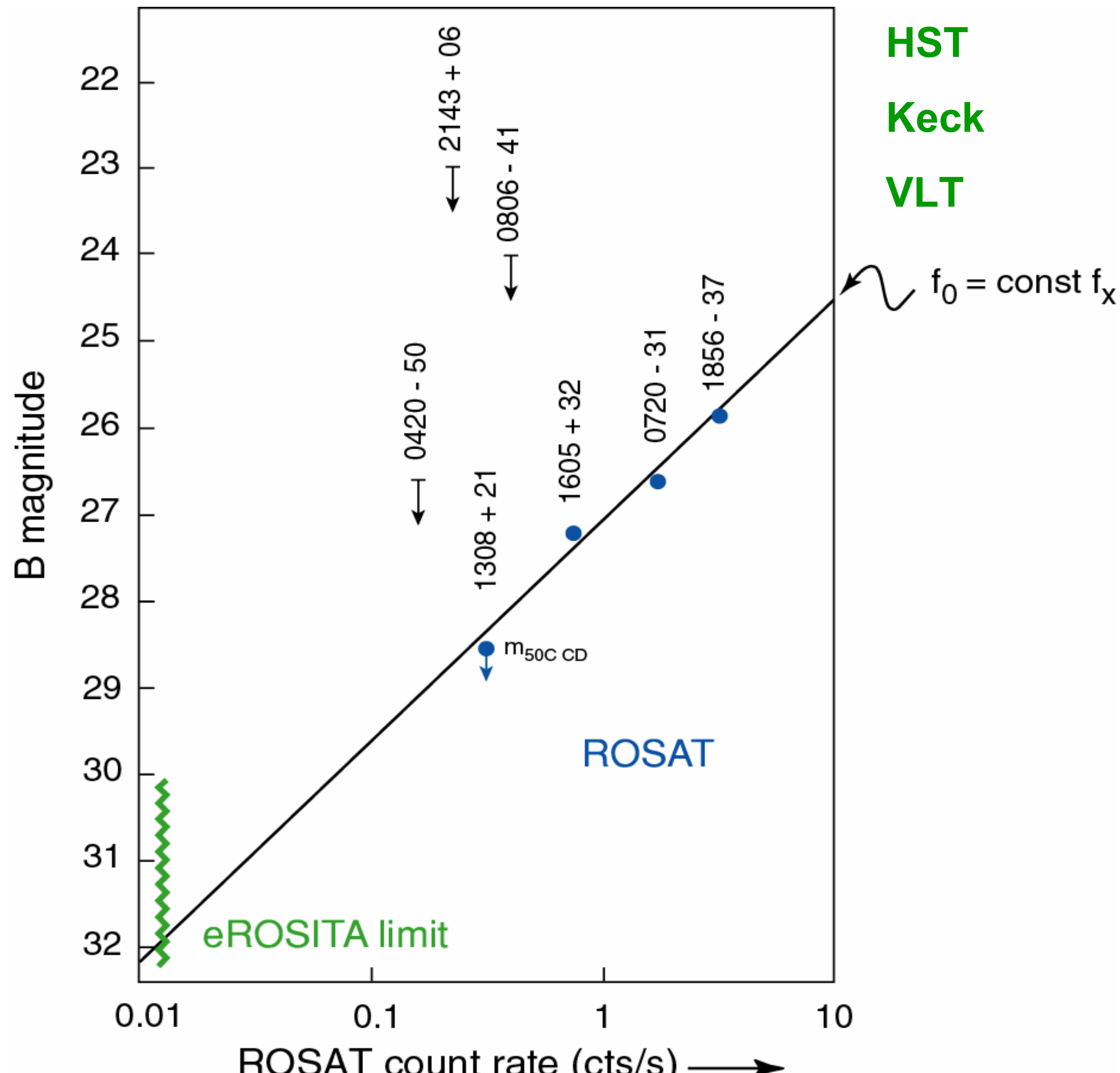
Gain in sensitivity: factor of 10

Mag Seven → ~ $7x10^{3/2}$ ~ 200

% absorption effects (Bettina Posselt)

James Webb ST;

30–50m telescopes



New classes of objects? (Aldo Treves)

Thank you !

Many thanks

to *Silvia Zane* and *Roberto Turolla*

for organizing this exciting

meeting!

and proving that Downtown London is an excellent alternative to Mediterranian beaches