Simultaneous XMM-Newton Radio Observations of the Mode-switching Radio Pulsar PSR B1822-09

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Outline

- Introduction: XMM-Newton revealed synchronous X-ray and radio-mode changing in pulsar PSR B0943+10.
  (Hermsen et al. 2013, Science 339, 436)
- Simultaneous radio and X-ray observations of PSR B1822-09: results
- Conclusions / Dilemma's

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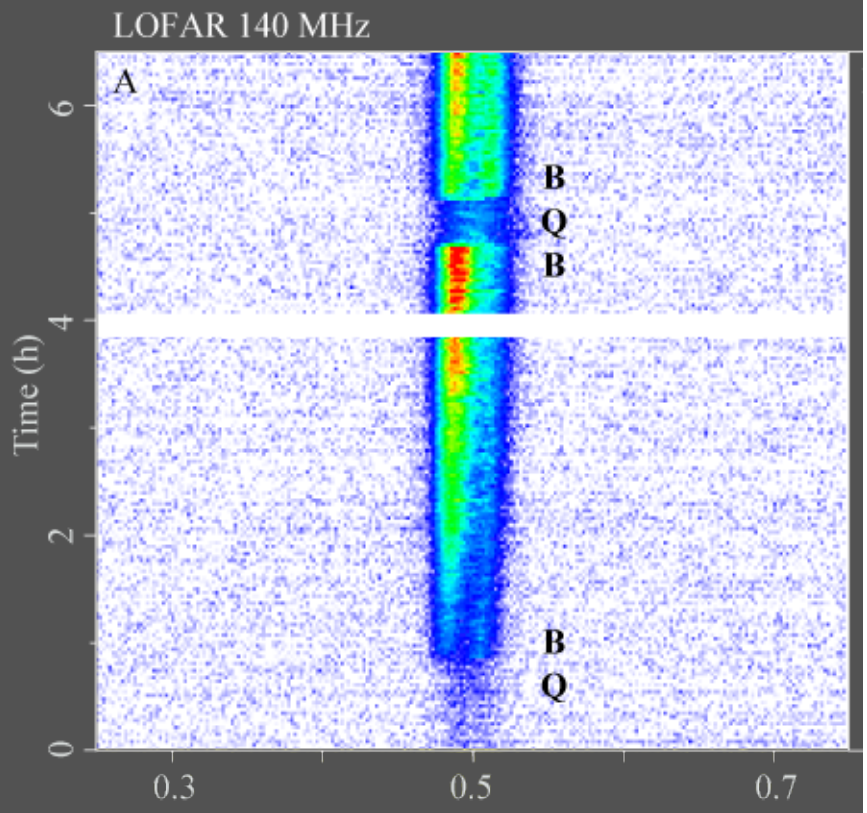
PSR B0943+10; 6x6 hrs of simultaneous XMM-Newton X-ray and GMRT/LOFAR radio observations

Characteristics of PSR B0943+10

- $\dot{P}$ = 1.10 s
- $\dot{P}$ = 3.5 x 10^{-15}
- $\dot{E}$ = 1.0 x 10^{32} ergs s^{-1}
- B_p = 2 x 10^{12} G
- T = 5.0 x 10^6 yr
- Nearly aligned rotator



- mode switching between radio B(right) and Q(uiet) modes

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XMM-Newton **PN**, Maximum-Likelihood Maps, 0.2-10 keV

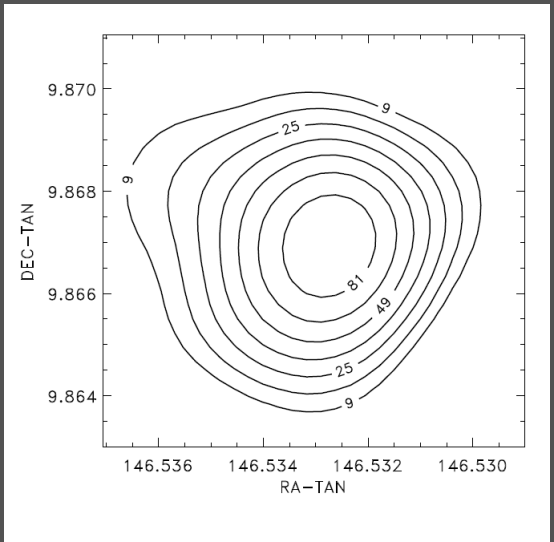
B-mode windows

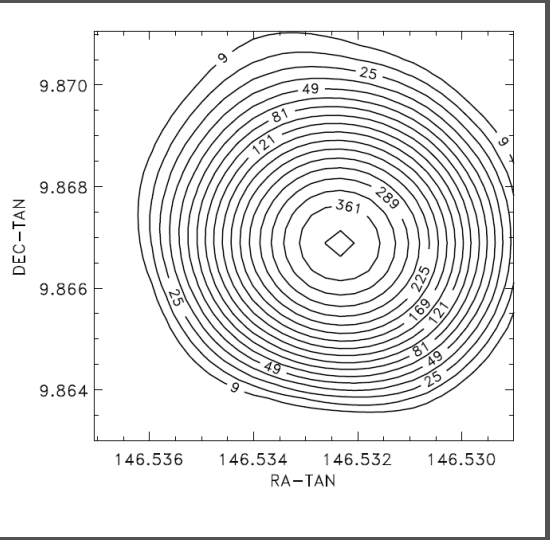
t_{eff} 39.7 ks

9.9 σ detection

174 ± 36 cnts

(0.44 ± 0.07) 10^{-2} cnts/s





Q-mode windows

t_{eff} 43.5 ks

20 σ detection

470 ± 33 cnts

(1.08 ± 0.08) 10^{-2} cnts/s

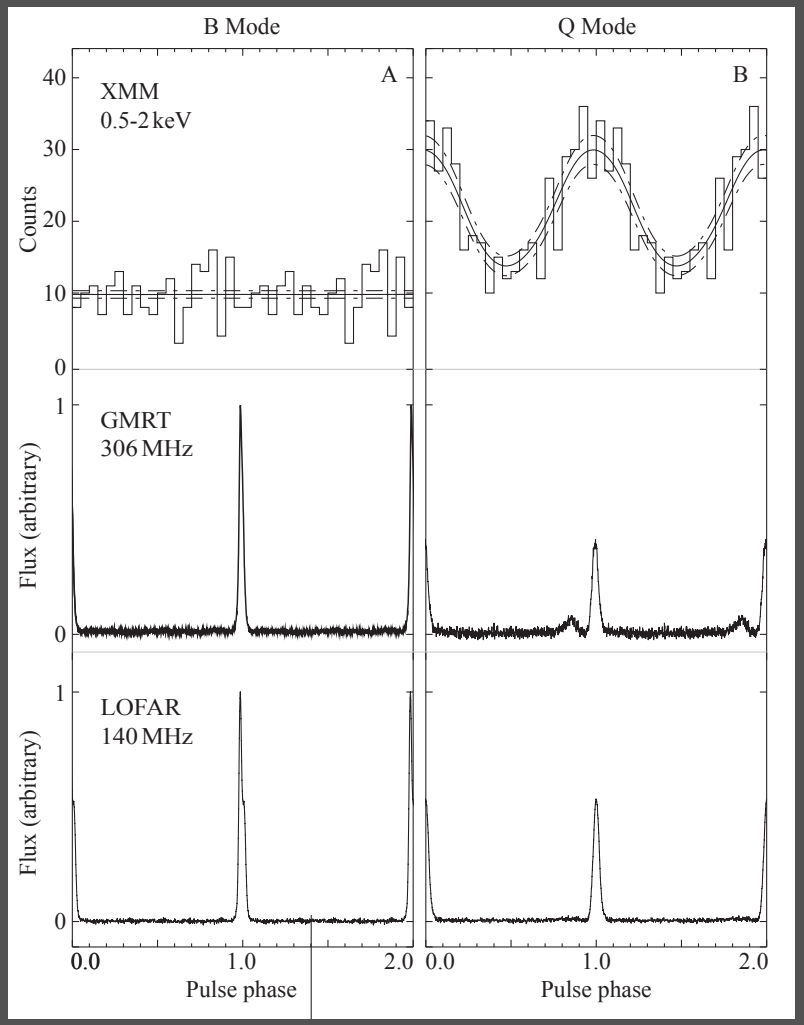
Discovery of correlated Radio – X-ray mode changes
Anti correlation !

Discovery of X-ray pulsation only in radio Q mode intervals !

XMM-Newton
EPIC PN + MOS-1
+ MOS-2

Difference between X-ray emissions in radio B and Q mode is addition of a pulsed X-ray component in Q mode !

X-ray pulse aligned with radio main pulse with precursor

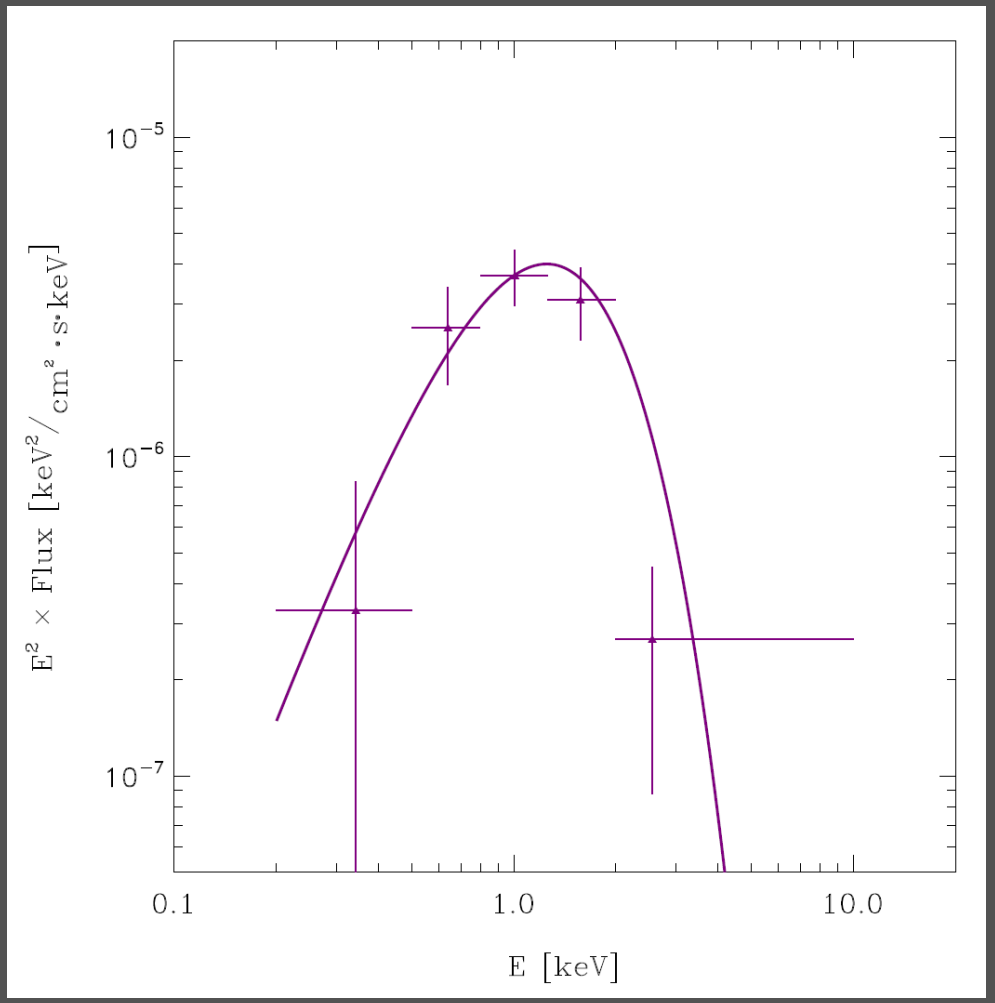


Pulsed fractions

. Pulsed fractions of PSR B093+10 as a function of energy, defined as the ratio of the flux in the pulse profile over the total flux of the point source measured in the sky maps. Errors are 1 σ.

Energy interval keV	Pulsed fraction
0.2 - 0.5	0.10 ± 0.15
0.5 - 0.8	0.44 ± 0.16
0.8 - 1.3	0.62 ± 0.14
1.3 - 2.0	0.60 ± 0.17
2.0 - 10	0.72 ± 0.53

Pulsed emission X-ray spectrum of PSR B0943+10: radio **Q-mode**



- **Best fit: BB; χ2/v = 1.14/3, ~78%**
- N_H = 4.3 x 10^{20} cm^{-2} (fixed)
- BB: kT = 0.319 ± 0.012 keV
- F_{BB} (0.5-8 keV)= (7.8 ± 1.6) 10^{-15} erg cm^{-2} s^{-1} (unabsorbed)
- $R_{hot\ spot}$ ≈ 18 m (d = 630 pc)

PL fit; χ^2/ v= 9.50/3, ~2.3%

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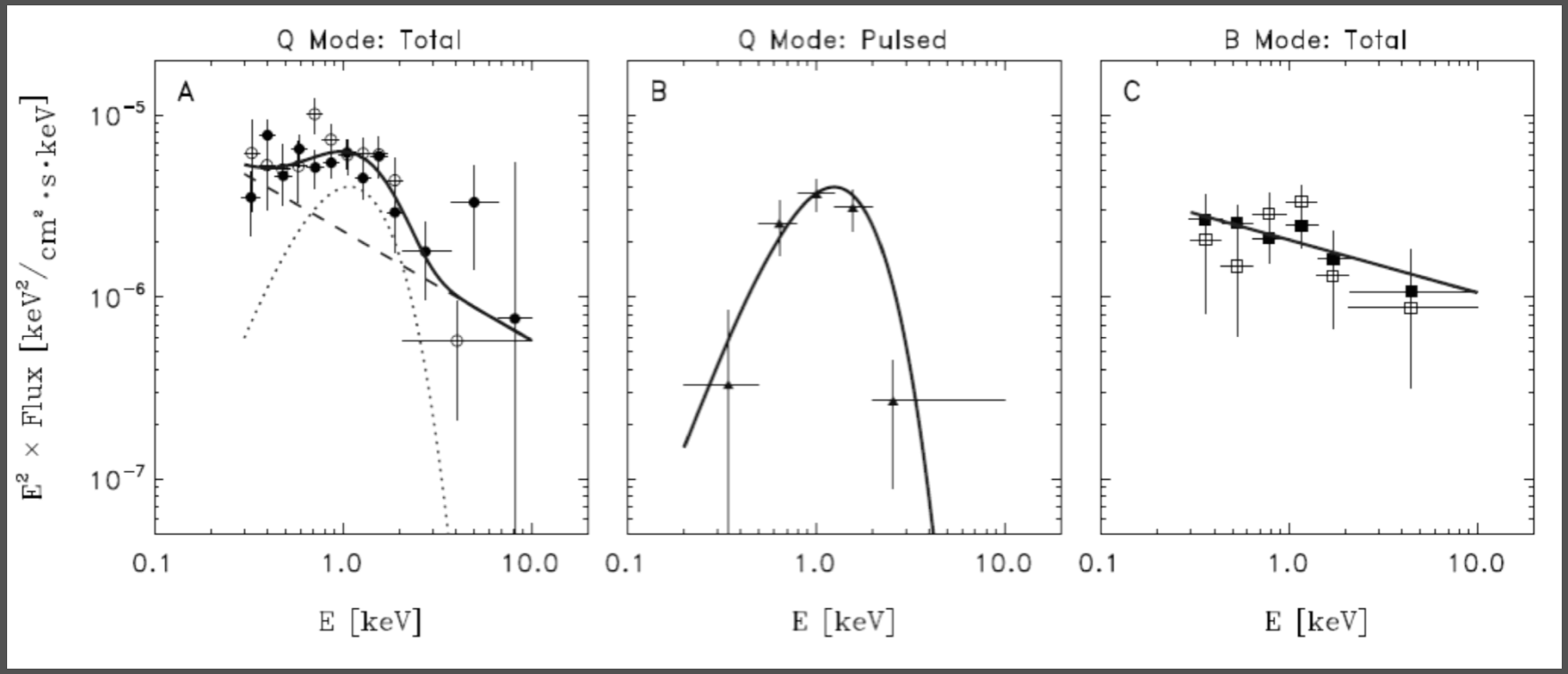
Conclusions on X-ray spectral characteristics



- Radio B mode: unpulsed, non-thermal emission (index and normalization within 1 σ the same as for power-law component in Q mode)

- Radio Q mode: same unpulsed non-thermal emission plus pulsed thermal emission

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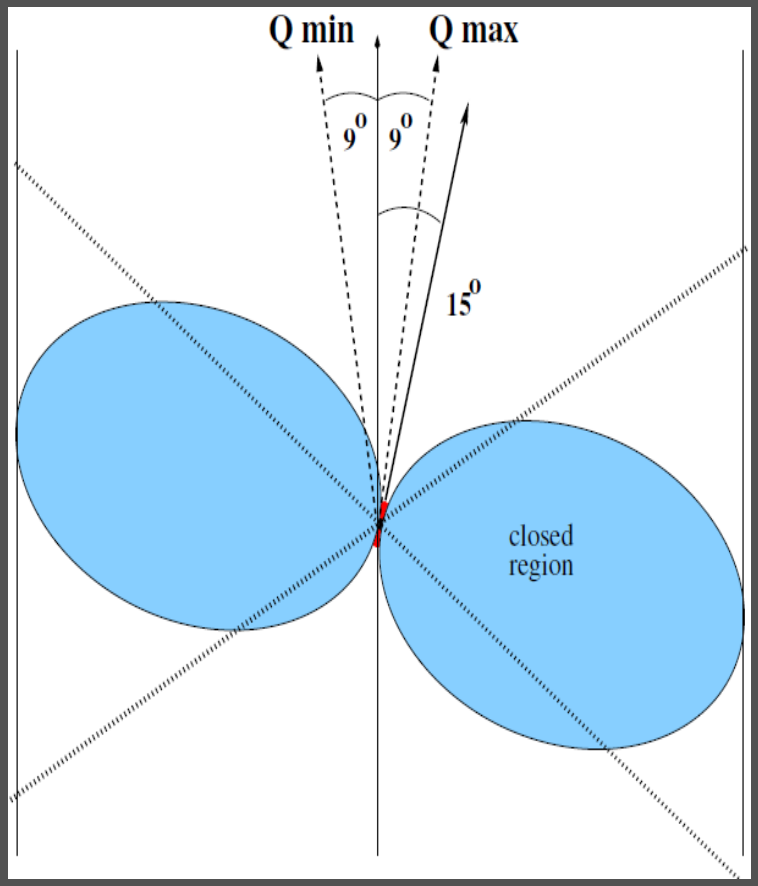
Many unanswered questions, dilemma's:

- The polar cap region is viewed continuously: how to produce a 100%-pulsed thermal component in the Q mode?

- How to switch off a thermal X-ray component in the B mode while the radio emission becomes bright and ordered.

etc., etc, ……



Improved geometrical model

New X-ray and radio campaign on PSR B1822-09

Characteristics:	PSR B0943+10	PSR B1822-09
•	P = 1.10 s	0.77 s
•	$\dot{P} = 3.5 \times 10^{-15}$	5.2×10^{-14}
•	$\dot{E} = 1.0 \times 10^{32}$ erg s^{-1}	4.5×10^{33} erg s^{-1}
•	$B_p = 2.0 \times 10^{12}$ G	6.4×10^{12} G
•	T = 5.0×10^{6} yr	2.3×10^{5} yr
•	nearly **aligned** rotator	nearly **orthogonal** rotator

(but, Malov & Nikitina 2011, 2013: aligned rotator)

- Both pulsars mode switching between radio B(right) and Q(uiet) mode

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PSR B1822-09
@ 624 MHz
(GMRT)

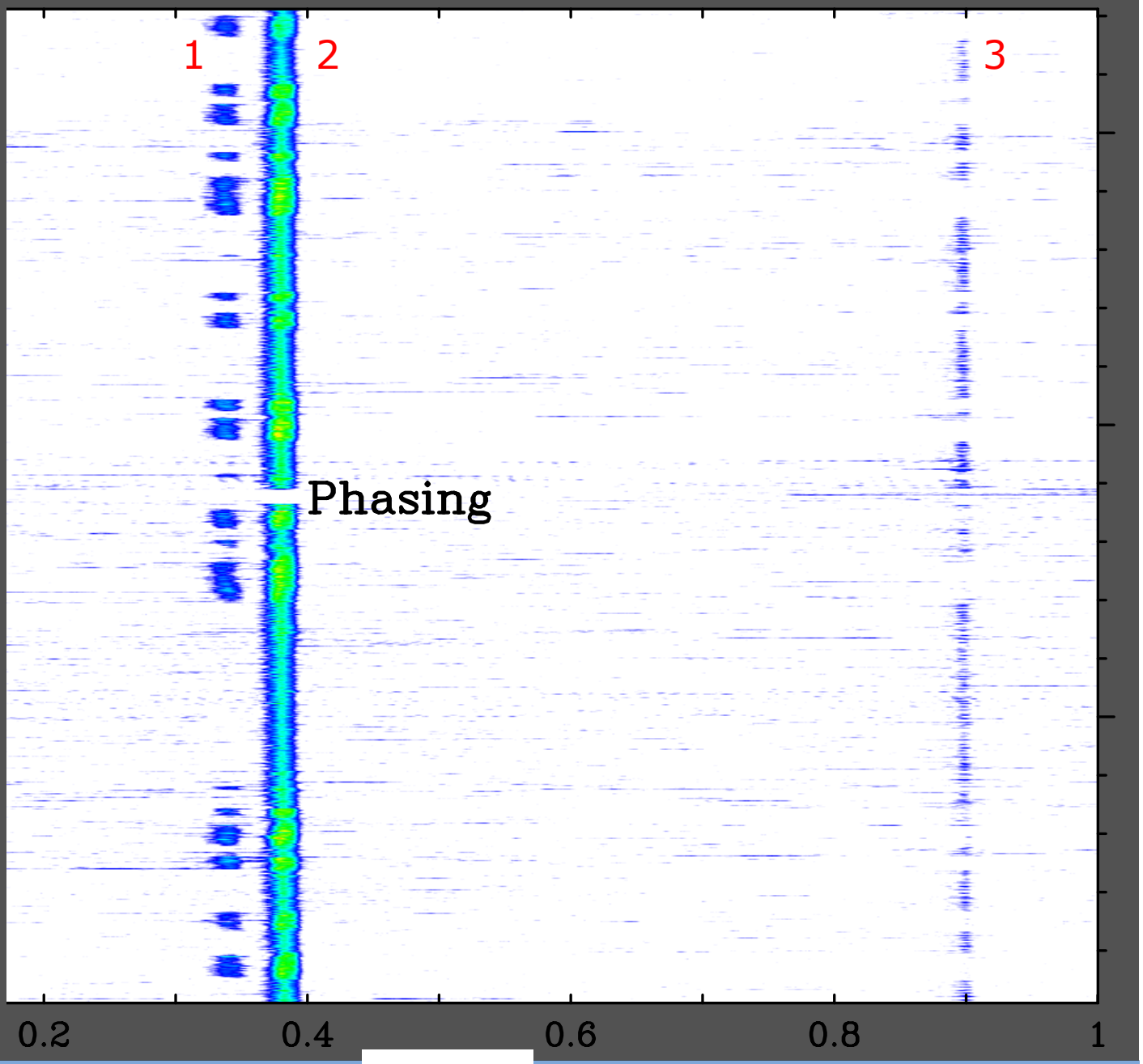
Mode switching

1: Precursor

2: Main pulse

3: Interpulse

Typical mode durations less than 5 minutes



XMM-Newton observation times (ks) in September, October 2013, and March 2014

Date /CCDs	10/09 2013	18/09 2013	22/09 2013	28/9 2013	30/09 2013	06/10 2013	10/03 2014	12/03 2014	Mode
PN	23.1	21.1	24.8	21.1	27.9	21.1	21.1	34.1	Large Window
MOS-1	24.8	22.8	26.5	22.8	29.6	22.8	22.8	35.8	Small Window
MOS-2	24.8	22.8	26.5	22.8	29.6	22.8	22.8	35.8	Small Window

Simultaneous radio observations with the WSRT, Lovell and GMRT

Total XMM-Newton PN 194.3 ks
MOS-1 209.3 ks
MOS-2 209.3 ks

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X-ray spatial analysis of skymaps

- **Maximum Likelihood Analysis**
- Two sources are detected separated by 5.3”±0.5”
- A soft-spectrum source at the position of PSR J1822-09, dominating below 1.4 keV
- A hard-spectrum source dominating above 1.4 keV

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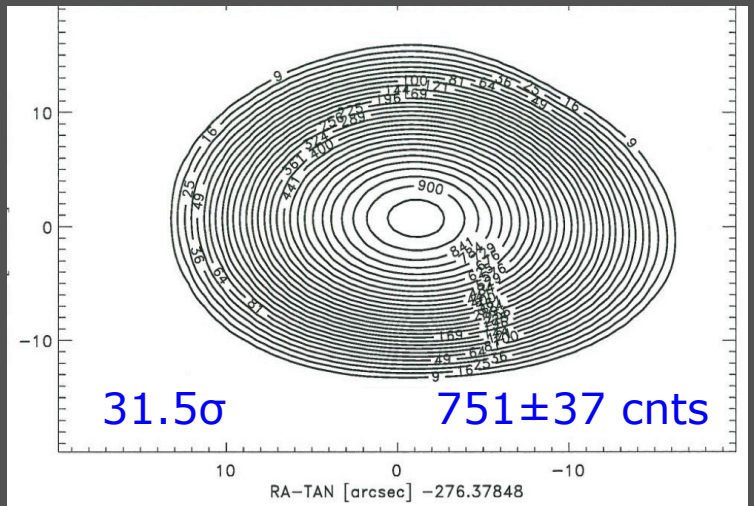
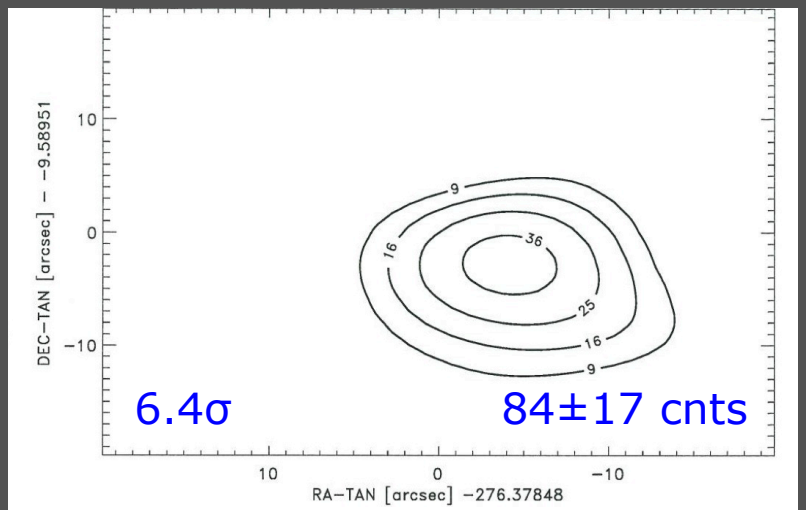
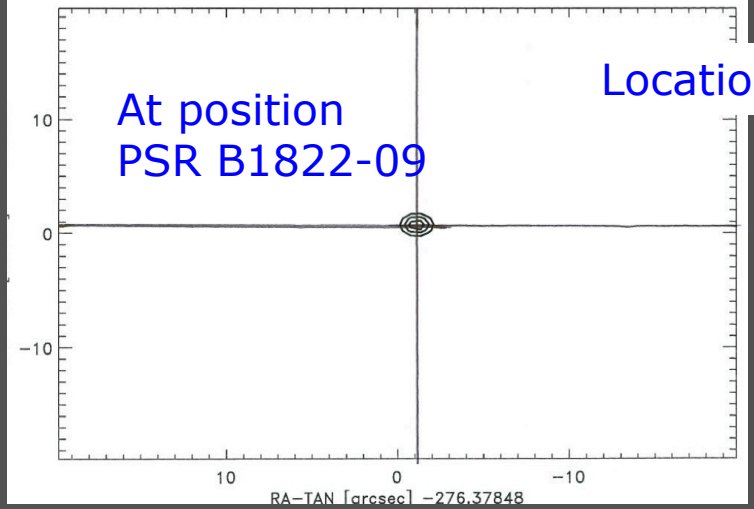
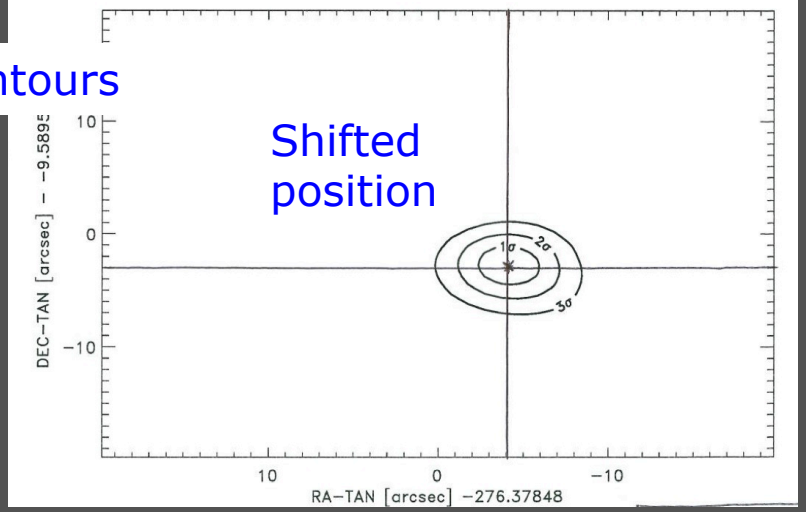
Example Maximum Likelihood maps PN detector, Runs 1-3





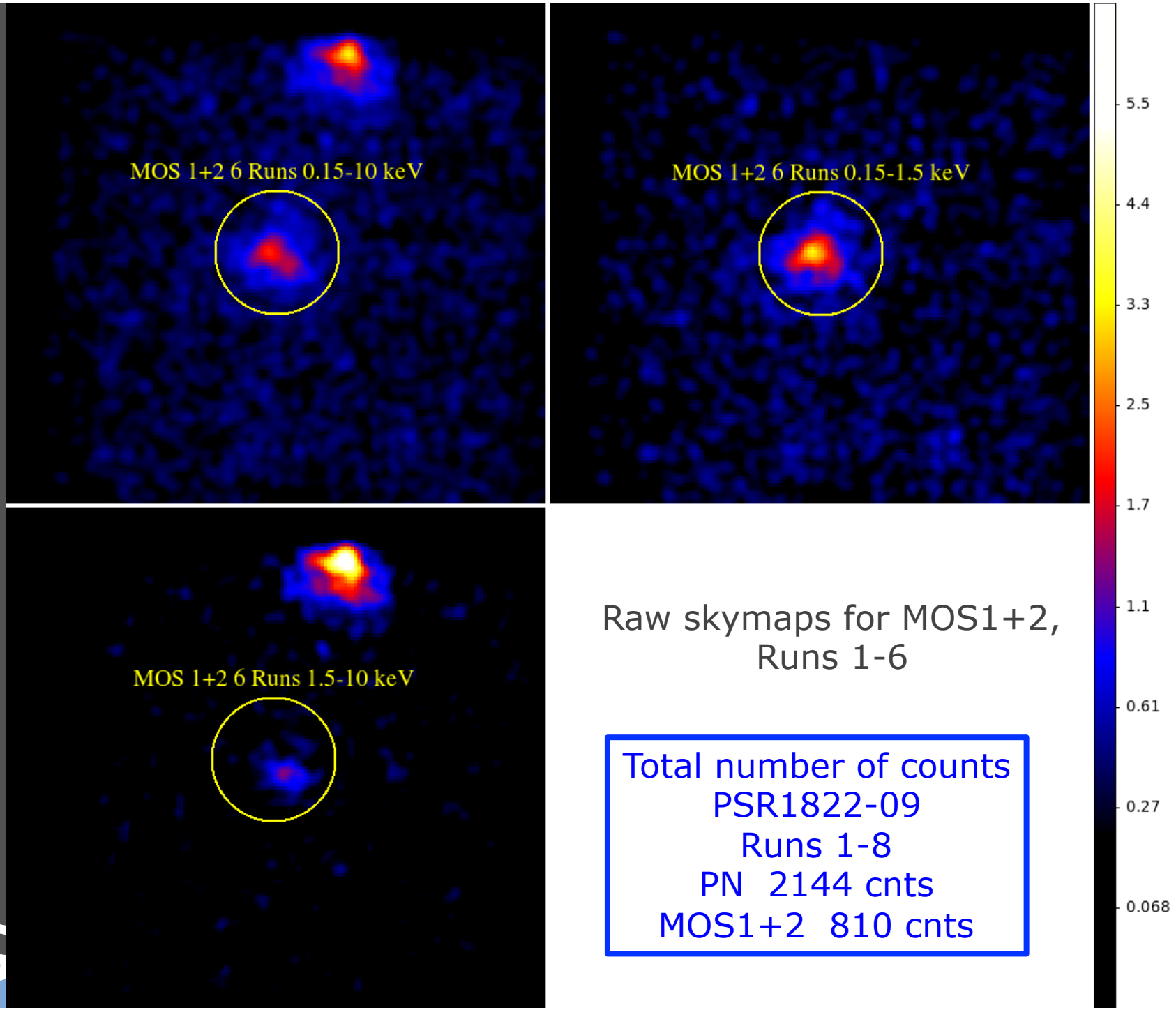


Location contours



0.3 – 2 keV

2-10 keV



Raw skymaps for MOS1+2, Runs 1-6

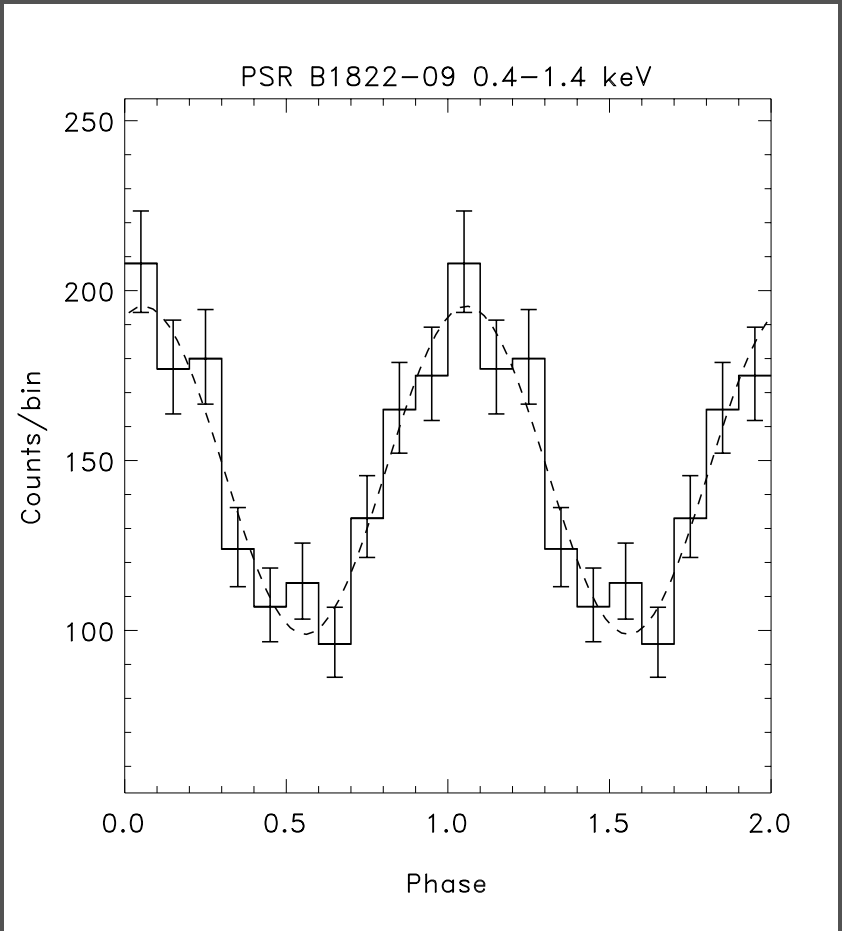
Total number of counts
PSR1822-09
Runs 1-8
PN 2144 cnts
MOS1+2 810 cnts

X-ray timing analysis (Runs 1-8, PN+MOS1+2)

Detection of X-ray pulsation in energy band 0.4-1.4 keV

Phase folding with ephemeris from Jodrell Bank

- Broad sinusoidal X-ray pulse shifted by ~0.07 in phase with respect to radio main pulse (0.0)
- No indication for X-ray pulse from radio interpulse
- Pulsed fraction ~35%



9.8 σ detection significance

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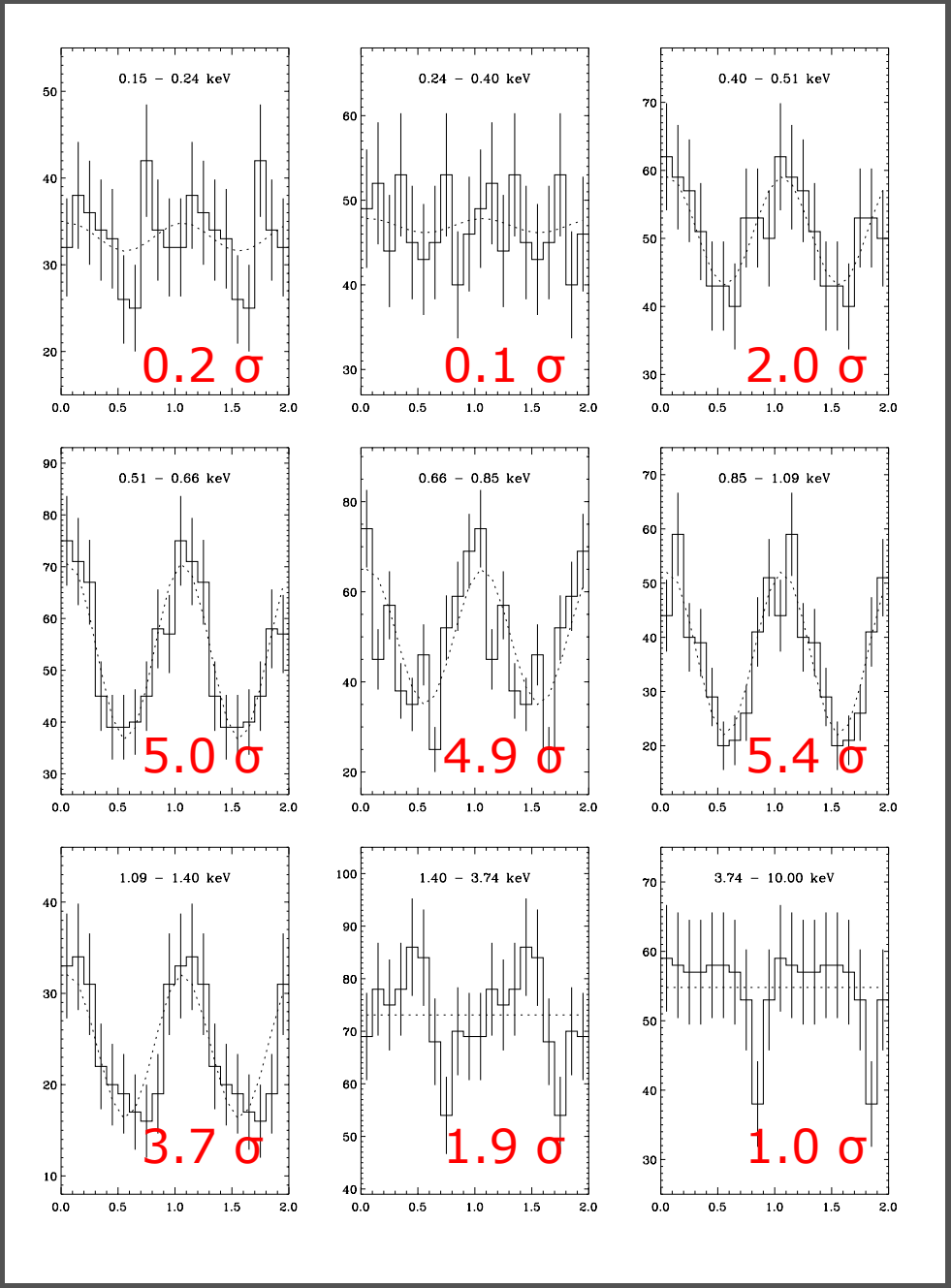
X-ray timing analysis

Profiles in differential energy bands: pulse detections only between 0.4 and 1.4 keV (z_1^2 statistic)

Dashed profiles are fits with profile shape for integral energy band 0.4-1.4 keV at fixed phase.



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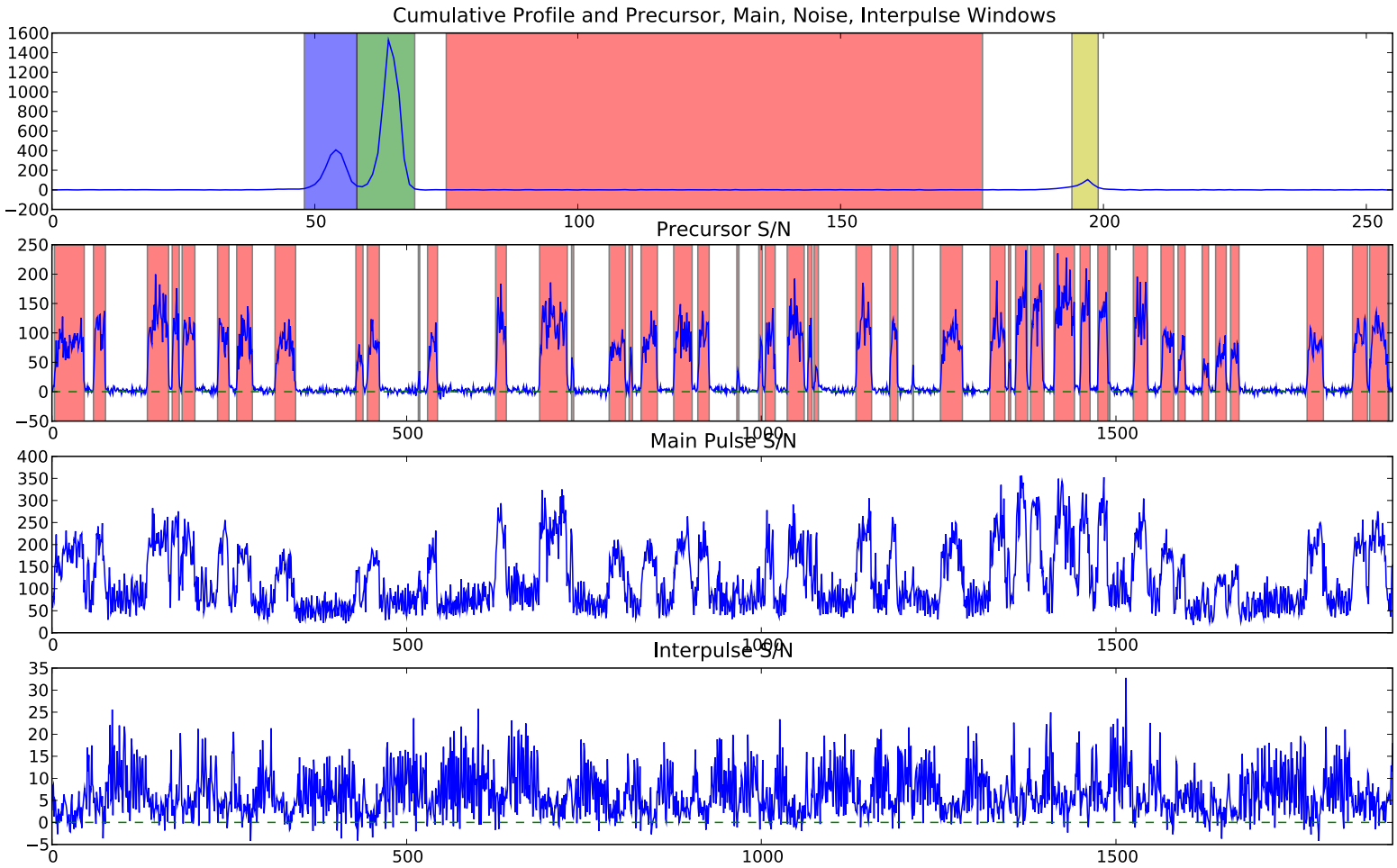
X-ray mode switching ?

PSR B1822-09, 5.55 hrs observing with the WSRT



S/N of detection in bins of 10 s

X-ray mode switching? Preliminary result for runs 1-6

Q-mode 85.5 ks and B-mode 50.4 ks

- Skymap analysis with Maximum Likelihood Method of count maps separately for PN and MOS1+2 detectors and ΔE:
  - 0.15-0.4 keV & 0.4-1.4 keV fitting 1 source (PSR B1822-09)
  - 1.4-10 keV fitting 2 sources

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X-ray mode switching? Preliminary result for runs 1-6

Q-mode 85.5 ks and B-mode 50.4 ks

Count rates total emission PSR B1822-09

ΔE	0.15 – 0.4 keV	0.4 – 1.4 keV	1.4 – 10 keV
No mode selection	(2.52±0.21)x10-3	(8.97±0.34)x10^{-3}	(0.73±0.27)x10^{-3}
B-mode	(2.67±0.35)x10-3	(7.98±0.53)x10^{-3}	(0.96±0.44)x10^{-3}
Q-mode	(2.41±0.27)x10-3	(9.60±0.44)x10^{-3}	(0.57±0.34)x10-3
Δ B-Q modes	0.6 σ	-2.4 σ	0.7 σ

➔ only 2.4 σ hint for X-ray mode switching in 0.4-1.4 keV band, which contains pulsed signal

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X-ray mode switching? Preliminary result for runs 1-6

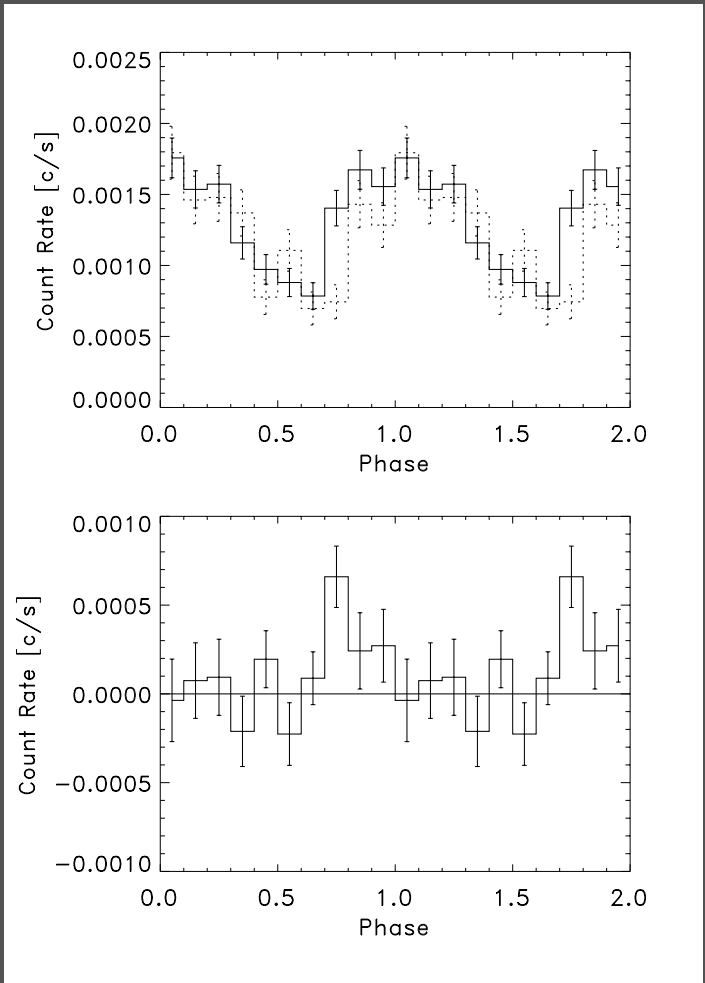
Q-mode 85.5 ks and B-mode 50.4 ks

- Timing/phase resolved imaging for 10 phase bins

Upper figure shows source count rates: broken lines B mode, solid line Q mode

Lower figure: count rate difference (Q-B) as a function of phase

KS-test: 30% chance probability that both distributions are drawn from same parent distribution



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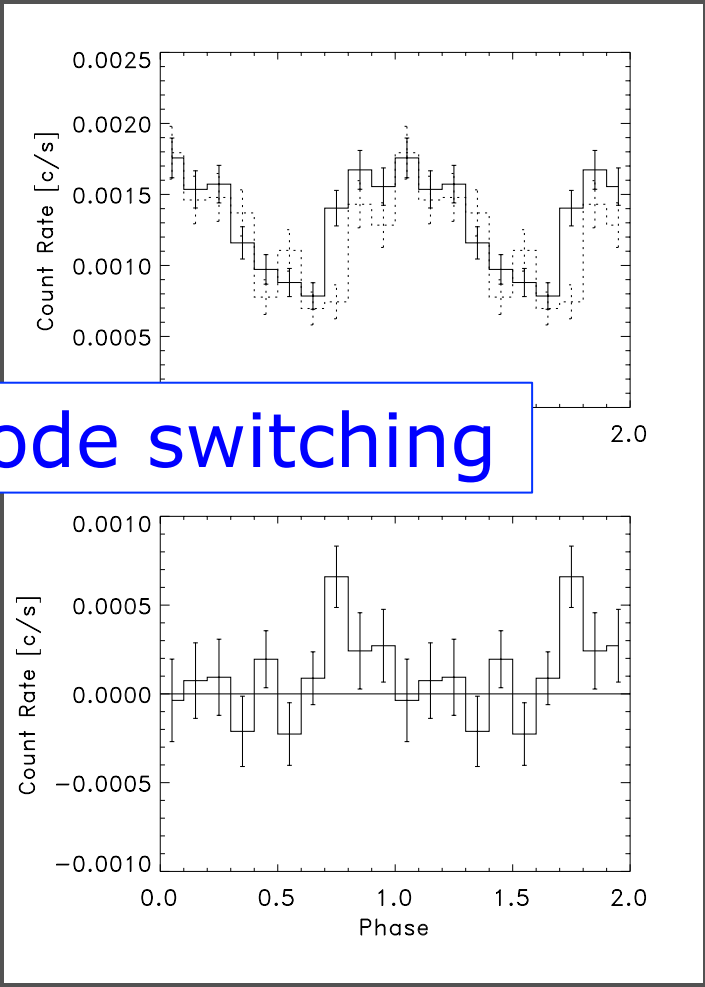

No significant evidence for mode switching

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Spectral analysis

- Distance PSR B1822-09:
  Upper limit 1.9 kpc (Johnston et al. 2001),
  often quoted d~1 kpc (e.g. Zhou et al. 2005).

- N_H at ~1.9 kpc is ~3 10^{21} cm $^{-2}$

- N_H is in initial analysis treated as free parameter

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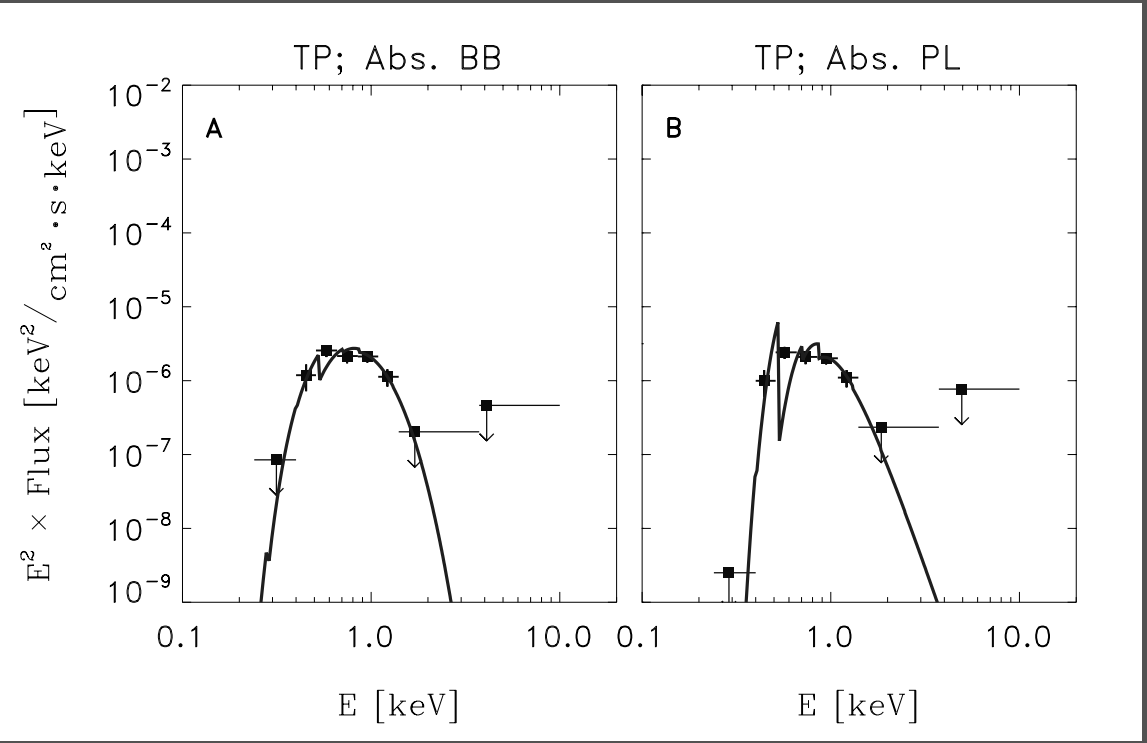
Pulsed emission X-ray spectrum of PSR B1822-09: 'absorbed'



- BB fit: χ^2_ν =1.14 (d.o.f. 6)
- N_H = ($2.03^{+0.35}_{-0.30}$) 10^{21} cm^{-2}
- BB_{norm} = 0.0047±0.0007
- kT = $0.138^{+0.003}_{-0.004}$ keV

- PL fit: **χ^2_ν = 1.11 (d.o.f. 6)**
- N_H = ($9.28^{+0.36}_{-0.30}$) 10^{21} cm^{-2}
- α = (1.85±0.28) 10^{-5} ph cm^{-2} keV^{-1} at 1 keV
- Γ = $-9.5^{+0.5}_{-0.4}$

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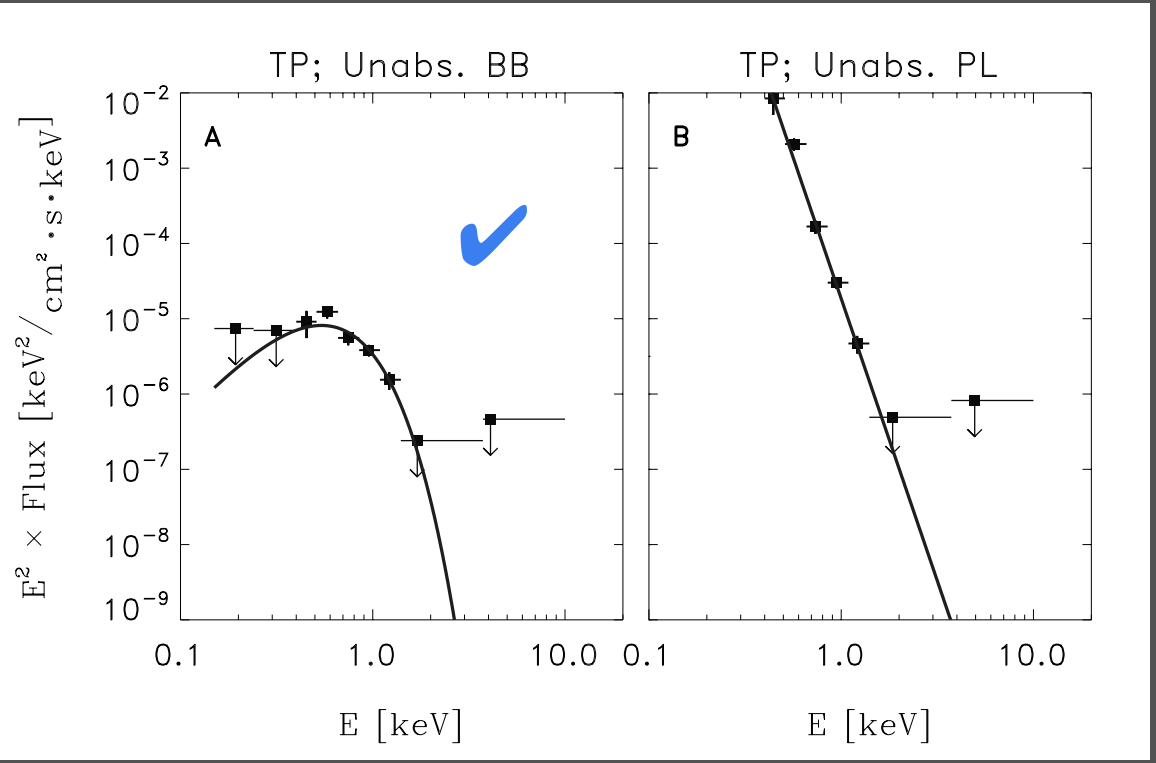
Pulsed emission X-ray spectrum of PSR B1822-09 ('unabsorbed')



- BB fit: χ^2_ν =1.14 (d.o.f. 6)
- $N_H = (2.03^{+0.35}_{-0.30}) \, 10^{21}$ cm^{-2}
- BB: kT = $0.138^{+0.003}_{-0.004}$ keV
- $R_{hot\ spot} \approx 213$ m (d = 1 kpc)

- PL fit: χ^2_ν = 1.11 (d.o.f. 6)
- $N_H = (9.28^{+0.36}_{-0.30}) \, 10^{21}$ cm^{-2}
- $\Gamma = -9.5^{+0.5}_{-0.4}$

➔ Values for NH and Γ in PL fit are not acceptable/realistic

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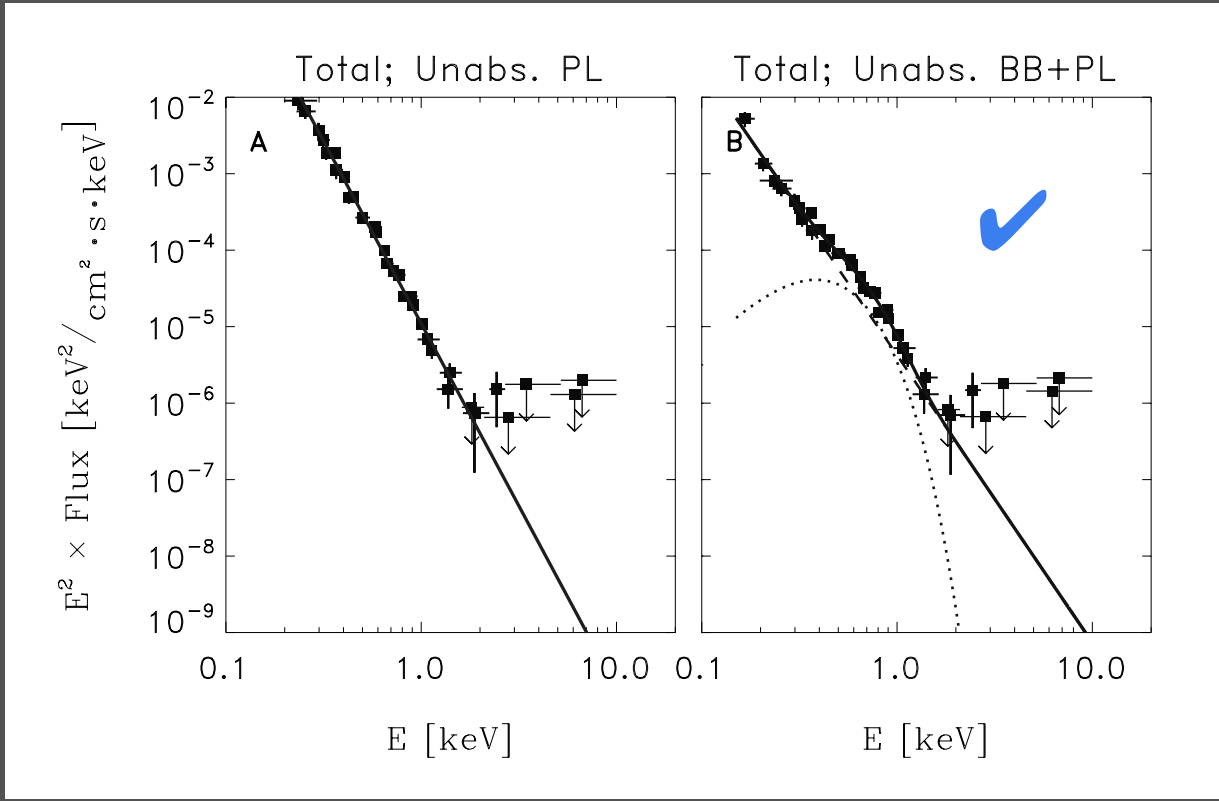
Total emission X-ray spectrum of PSR B1822-09 ('unabsorbed')



- PL fit: χ^2_v = 1.65 (d.o.f. 32) **~1% prob.**
- N_H = (4.15±0.05) 10^{21} cm^{-2}
- Γ = -6.77± 0.07
- BB fit : χ^2_v = 1.60 (d.o.f. 32) **~1-2% prob.**

- BB+PL fit: χ^2_v =1.43 (d.o.f. 30) **~7.5% prob.**
- N_H = (2.85±0.08) 10^{21} cm^{-2}
- BB_{norm} = 0.093±0.010
- kT = 0.098±0.002 keV
- $R_{hot\ spot}$ ≈ 948 m (d = 1 kpc)
- α = (1.85±0.28) 10^{-5} ph cm^{-2} keV^{-1} at 1 keV
- Γ = -5.76± 0.15

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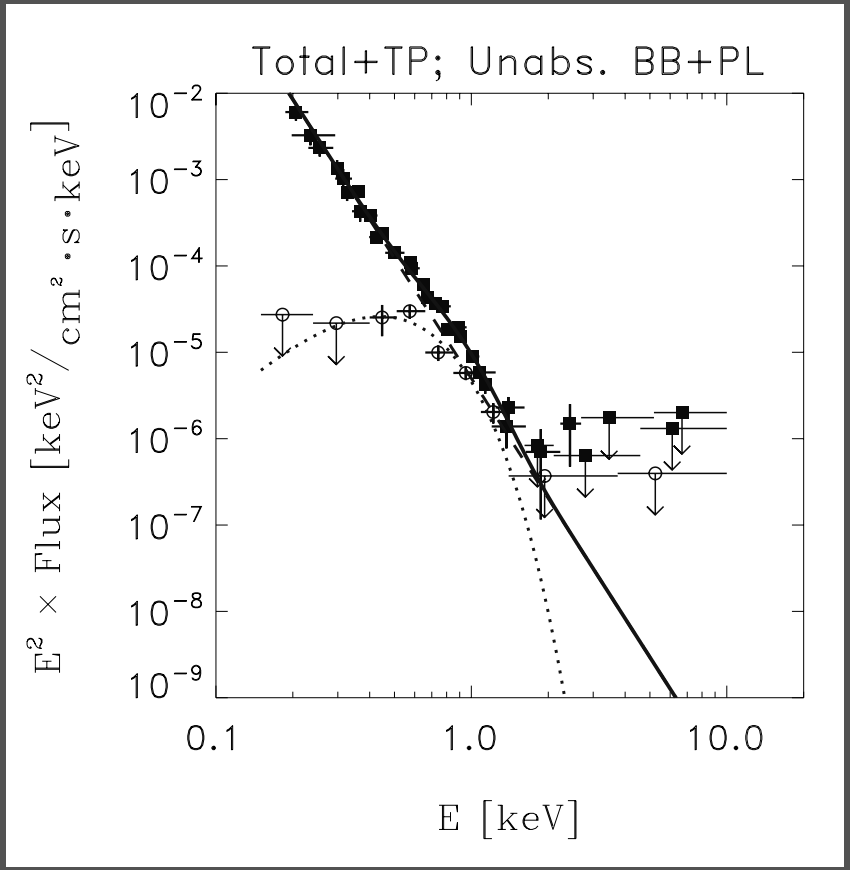
JOINT FIT TO TOTAL AND PULSED SPECTRA OF PSR B1822-09

Assuming that:

- pulsed emission is a BB and equals BB component in total spectrum.
- Unpulsed emission has a PL shape



- BB+PL fit: χ^2_ν =1.40 (d.o.f. 39) **~5% prob.**
- N_H = (3.39±0.08) 10^{21} cm^{-2}
- BB_{norm} = 0.0345±0.0046
- kT = 0.112±0.002 keV
- $R_{hot\ spot}$ ≈ 578 m (d = 1 kpc)

- α = (5.0±0.4) 10^{-6} ph cm^{-2} keV^{-1} at 1 keV
- Γ = -6.62± 0.13

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Conclusions / Dilemma's

- PSR B1822-09 has been detected with XMM-Newton with a pulsed fraction of ~35% in the energy band 0.4-1.4 keV
- The pulse profile is sinusoidal; maximum within 0.1 phase from the peak of the radio main pulse; no pulse detected at the phase of the weak radio inter pulse.
- There is no significant evidence for simultaneous X-ray-radio mode-switching by PSR B1822-09. What causes this difference with PSR B0943+10?
- The spectrum of the total emission is best fitted with a thermal BB-component plus a non-thermal PL component.
- The spectrum of the pulsed component is best fitted with a thermal component, consistent with a heated polar cap passing through our line-of-side for an orthogonal rotator. But, what about a non-thermal unpulsed component?
- The X-ray-radio characteristics of PSR B1822-09 do not shed more light on the interpretation of the X-ray/radio characteristics of PSR B0943+10

SRON Etc .etc….. Many open questions

Thank you for listening!

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