Simultaneous X-ray Radio Observations of Mode-switching Radio Pulsars PSR B0943+10 and PSR B1822-09

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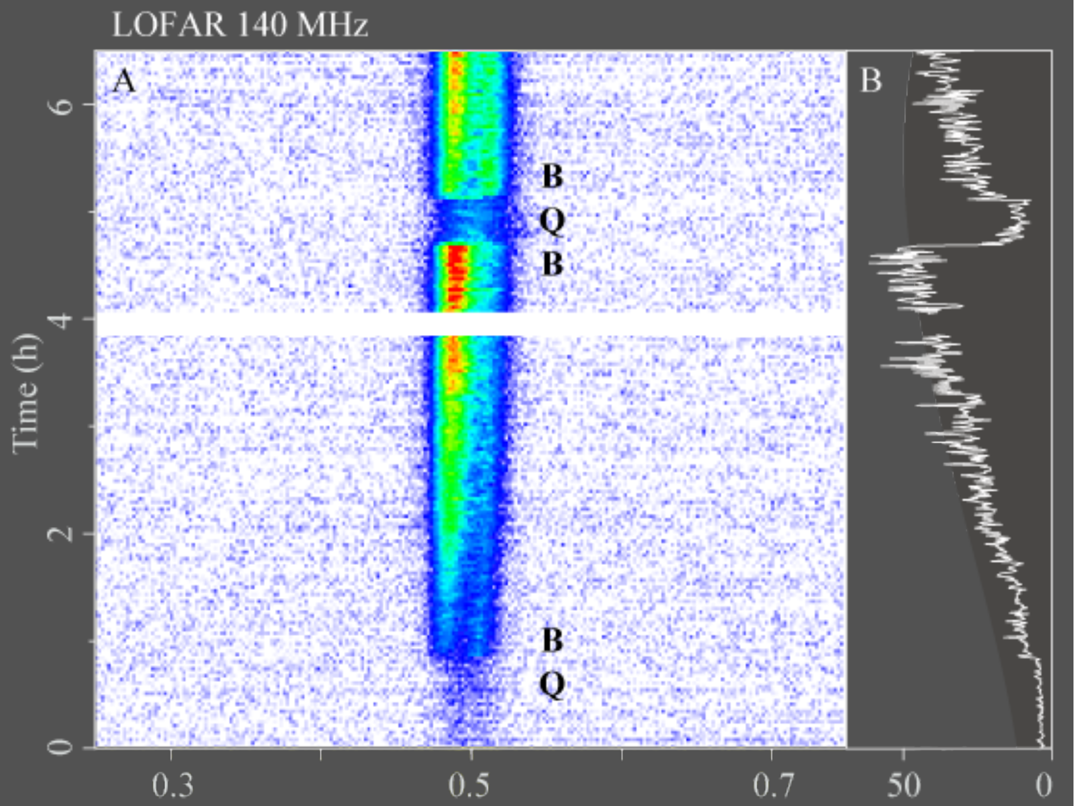
Outline

- Introduction: Discovery of synchronous X-ray and radio-mode switching 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

The radio-mode switching PSR B0943+10

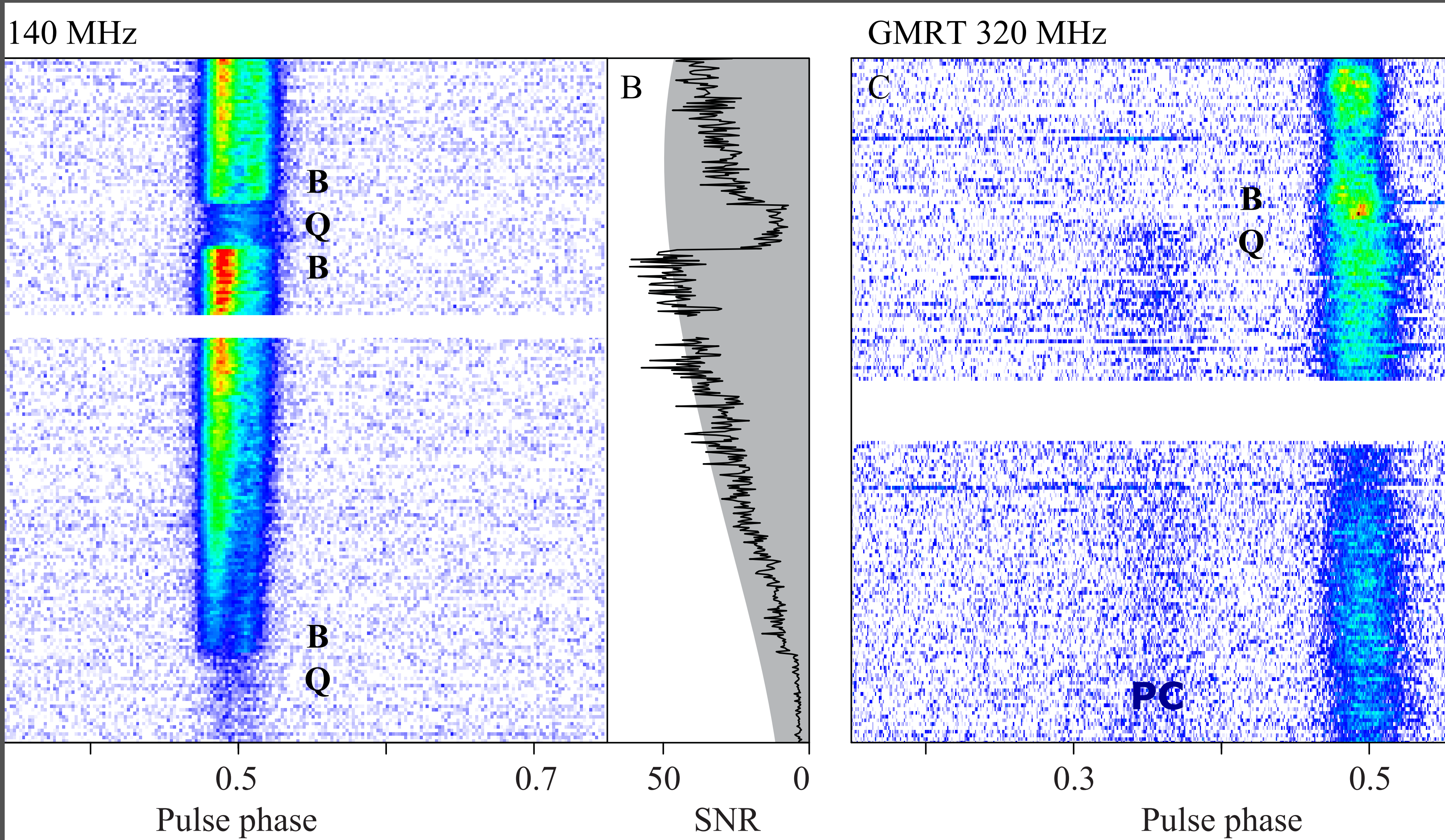
Characteristics

- $P = 1.10$ s
- $\dot{P} = 3.5 \times 10^{-15}$
- $\dot{E} = 1.0 \times 10^{32}$ erg s^{-1}
- $B_p = 2.0 \times 10^{12}$ G
- $T = 5.0 \times 10^{6}$ yr
- nearly **aligned** rotator



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

PSR B0943+10: also a moding Precurser (**PC**)



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Radio-mode switching a local or global phenomenon ?

Observational Evidence for Rapid, Global, Magnetospheric Changes:

- Mode switching and correlated $\dot{\nu}$ changes for PSR B1931+2421
  (Kramer et al. 2006, Science 312, 549)

- Similar behaviour for PSR J1841-0500 and PSR J1832+0029
  (Camilo et al. 2012; Lorimer et al. 2012)

- Mode changing, nulling, profile-shape changes likely due to change in magnetospheric particle current flow
  (Lyne et al. 2010, Science 329, 408)

Theoretical Support for Rapid, Global, Magnetospheric Changes

- Mode switching is global: a range of Quasi-stable magnetospheric configurations is expected
  (Goodwin et al. 2004, Timokhin 2006)

- The non-linear system is proposed to suddenly switch between specific states, each having a specific emission beam and spin-down rate
  (Timokhin 2010)

X-ray – Radio campaign on PSR B0943+10

- Simultaneous observations for ~140 ks in November/December 2011: **XMM-Newton** with **LOFAR, GMRT and Lovell**

- **Discovery of Synchronous X-ray and Radio Mode Switches**

  (Hermsen et al. 2013, Science 339, 436)

- When PSR B0943+10 switches from the radio B(right) mode to the radio Q(uiet) mode the X-ray flux (in **anti correlation)** more than doubles (times 2.45)!

- In the radio Q mode **thermal pulsed emission** is added to the X-ray flux in the B mode.

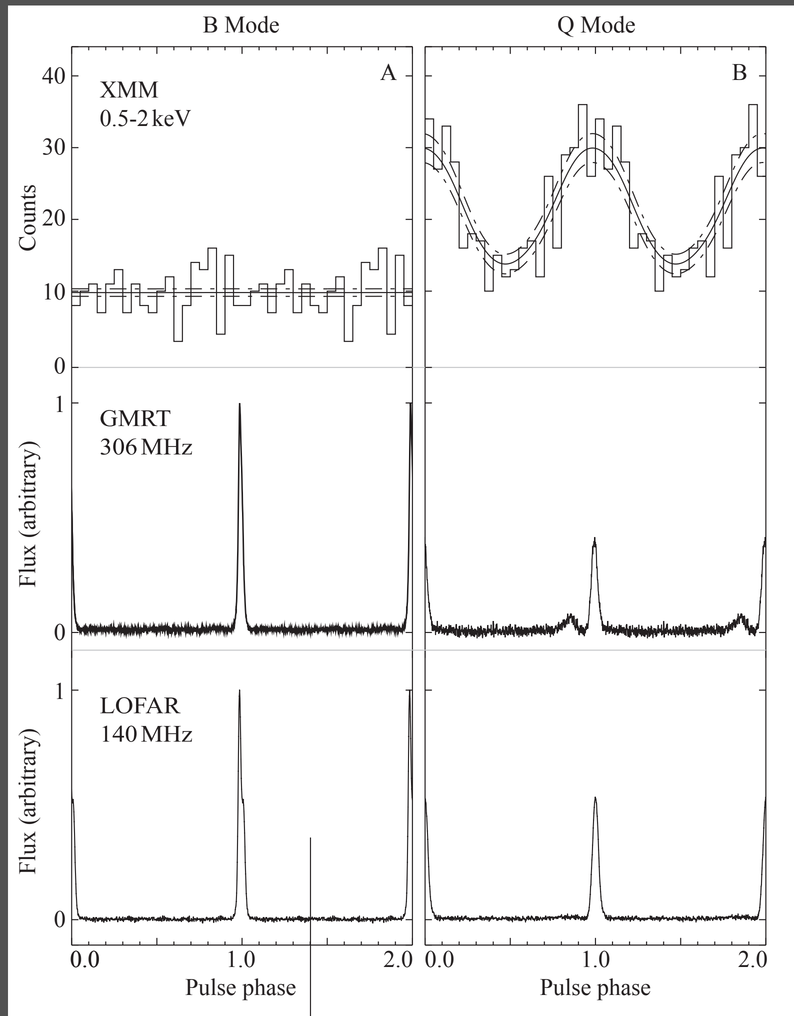
Discovery of Synchronous X-ray and Radio Mode Switches

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

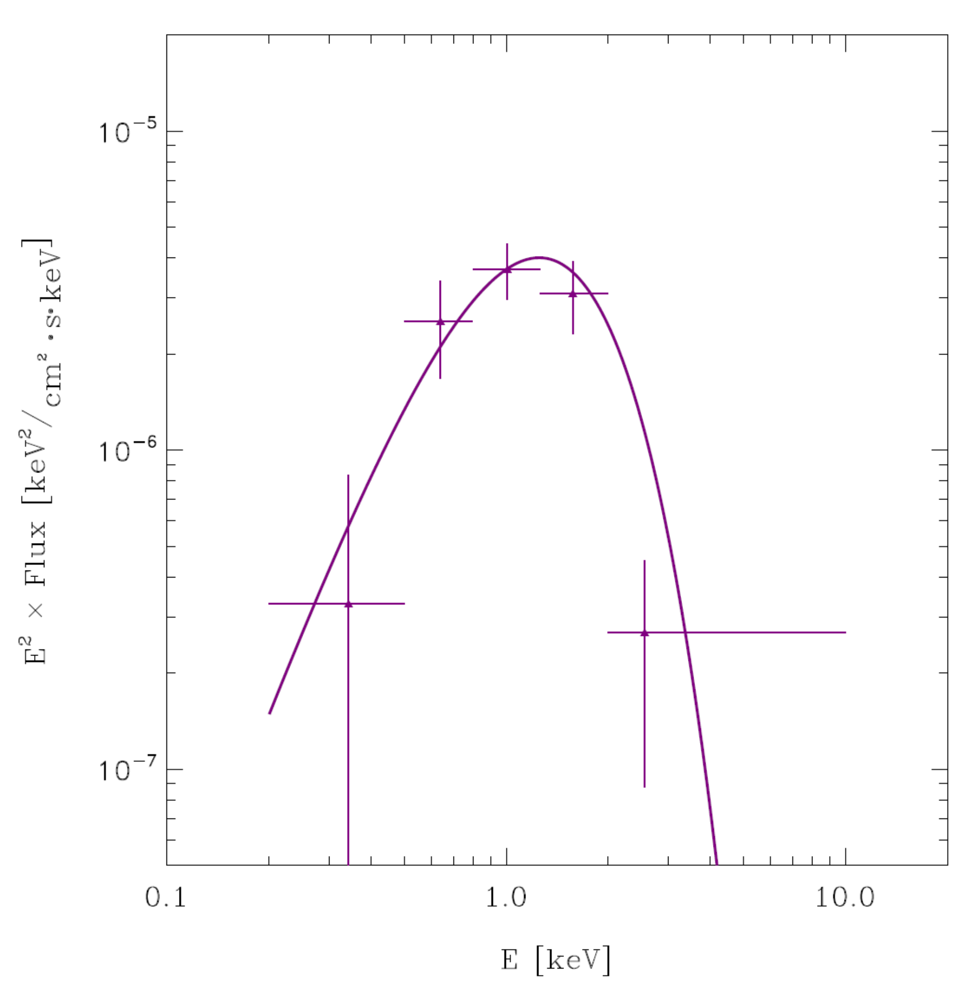
Detection of pulsed X-ray emission in radio Q mode

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

X-ray pulse is aligned with radio main pulse with precursor



PSR B0943+10: X-ray spectrum **pulsed emission** in radio **Q-mode**



- **Best fit: BB;** $\chi 2/\nu$ = 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)

Thermal pulsed emission

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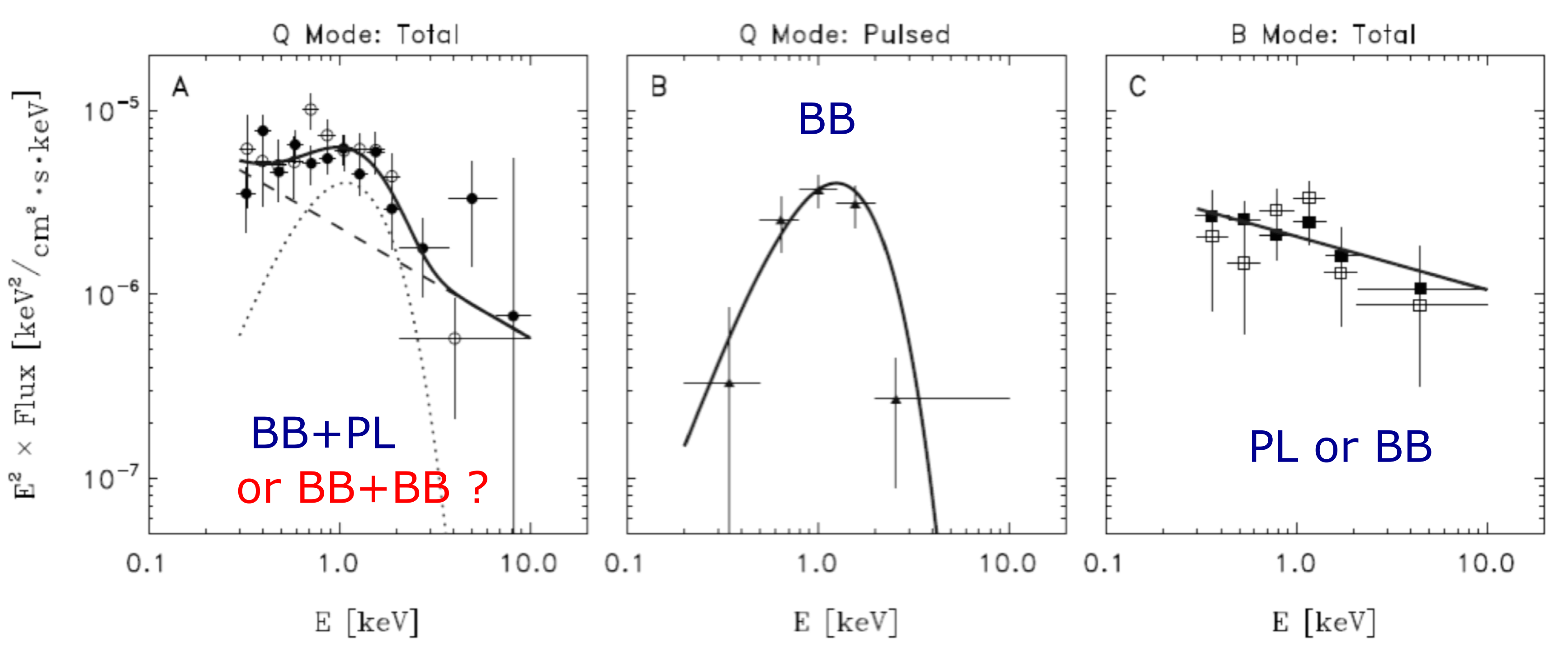
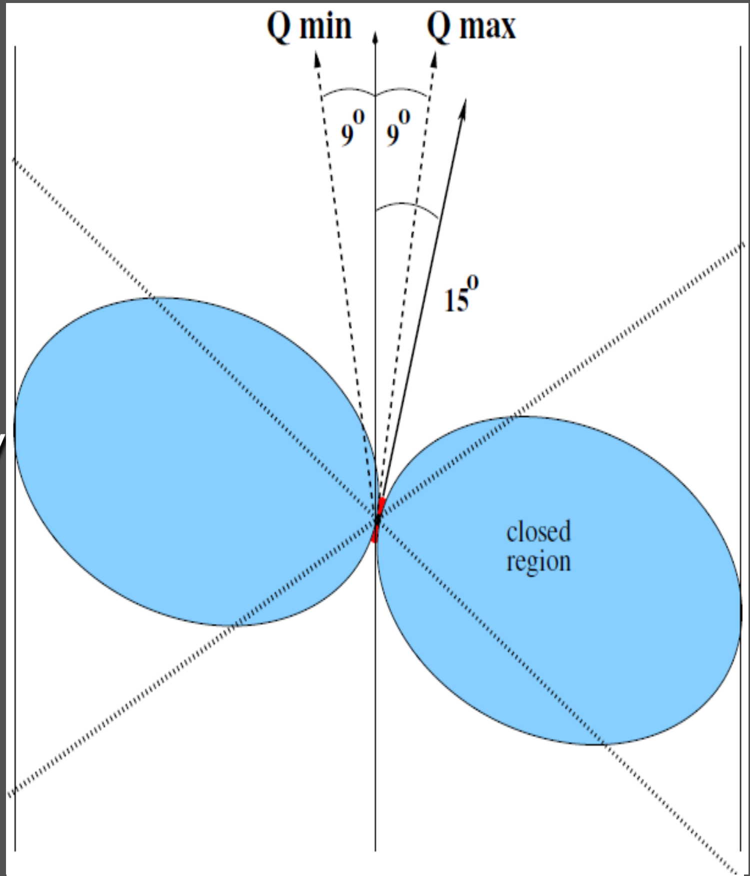
X-ray spectral characteristics



Data from a new long X-ray – radio campaign on PSR B0943+10 is being analysed

Many unanswered questions, e.g.:

- The polar cap region is viewed continuously: how to produce a 100% pulsed thermal component in the Q mode ?
- What causes disappearance (or largely suppresses) a thermal X-ray pulse switching from weak chaotic radio Q to bright ordered B mode ?



Geometrical model
PSR B0941+10

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New campaign: Mode-switching Pulsar **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
•	$T = 5.0 \times 10^{6}$ yr	2.3×10^{5} yr
•	nearly **aligned** rotator	nearly **orthogonal** rotator, or nearly aligned? (Malov, Nikitina 2011)

- PSR B1822-09 also switches between radio B(right) and Q(uiet) mode

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PSR B1822-09
@ 624 MHz
(GMRT)

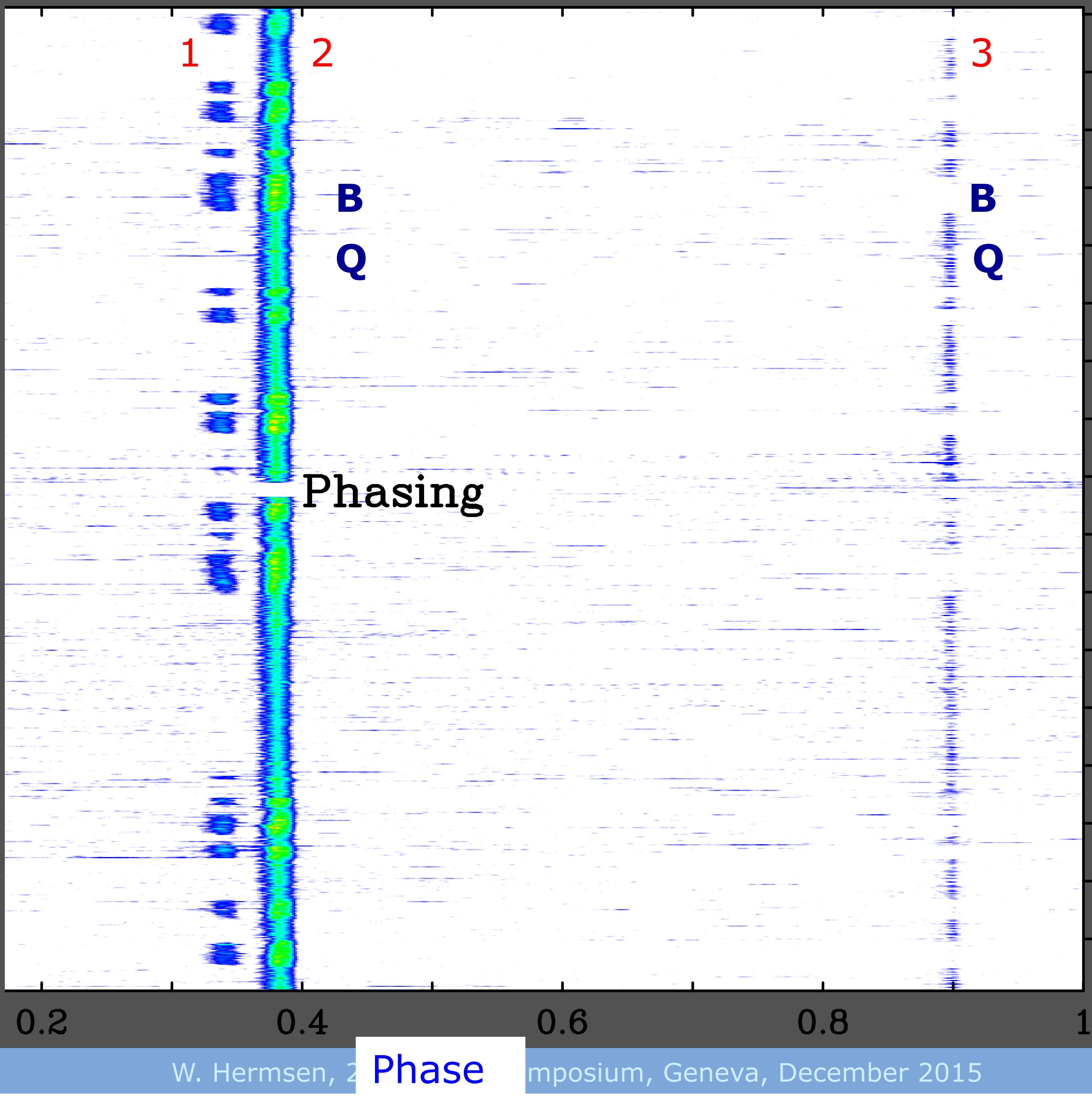
Mode switching

1: Precursor

2: Main pulse

3: Interpulse

Typical mode durations less than 5 minutes



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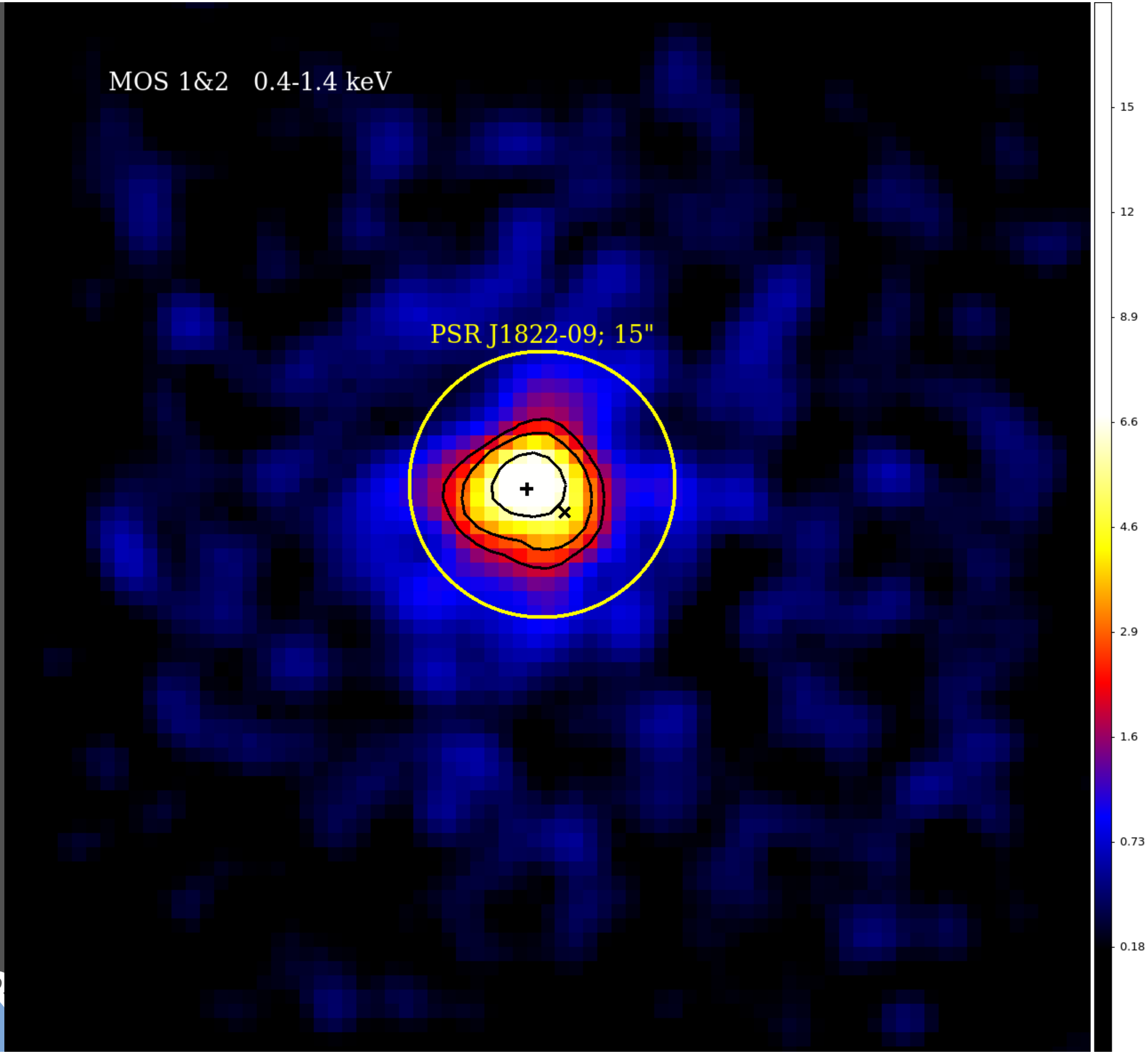
PSR B1822-09: XMM-Newton observation times (ks) September, October 2013, and March 2014

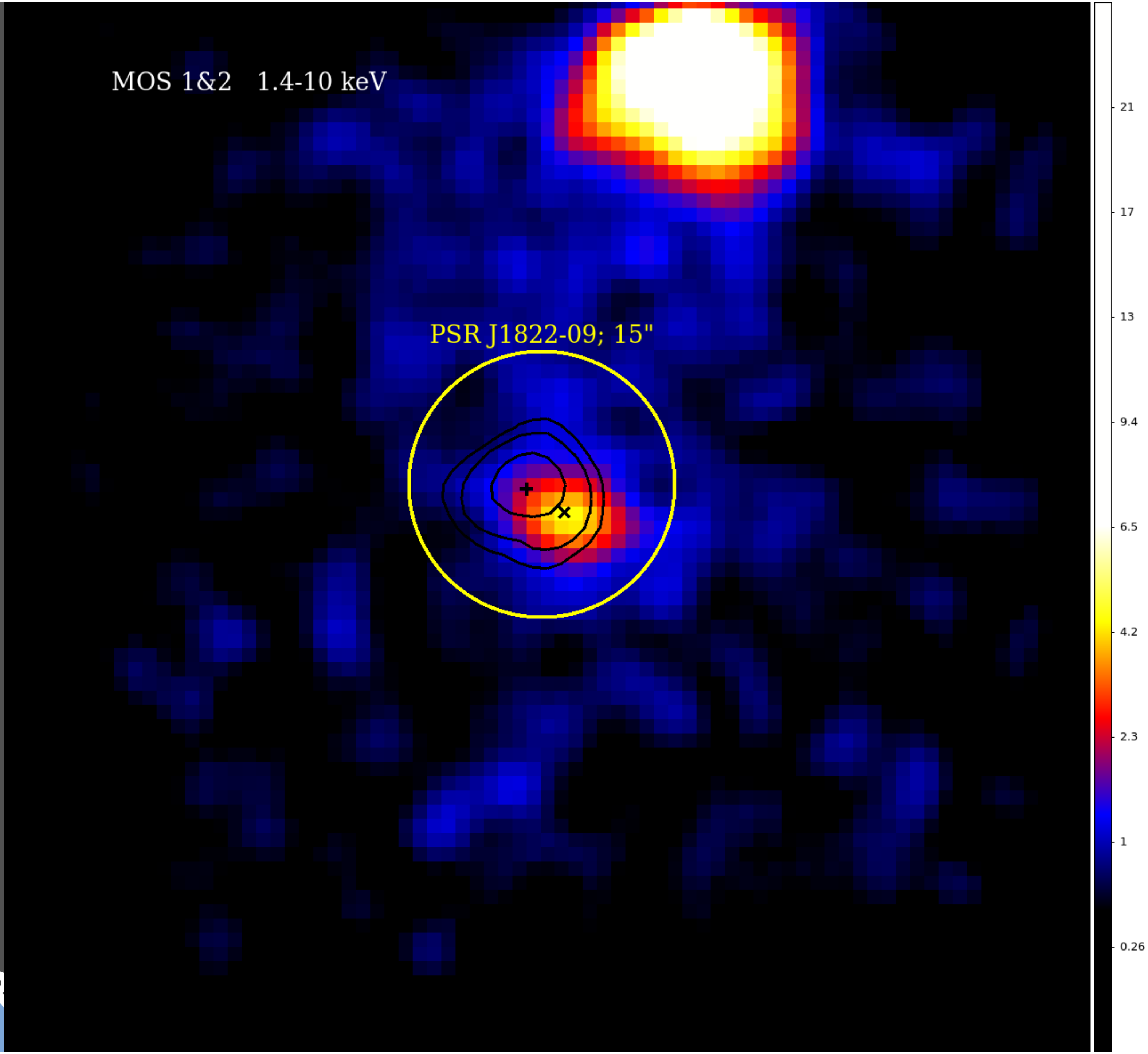
Date /CCDs	10/09 2013	18/09 2013	22/09 2013	28/9 2013	30/09 2013	06/10 2013	10/03 2014	12/03 2014	Mode
PN	23.1	21.1	24.8	21.1	27.9	21.1	21.1	34.1	Large Window
MOS-1	24.8	22.8	26.5	22.8	29.6	22.8	22.8	35.8	Small Window
MOS-2	24.8	22.8	26.5	22.8	29.6	22.8	22.8	35.8	Small Window

Simultaneous radio observations with the WSRT and partly Lovell and GMRT

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

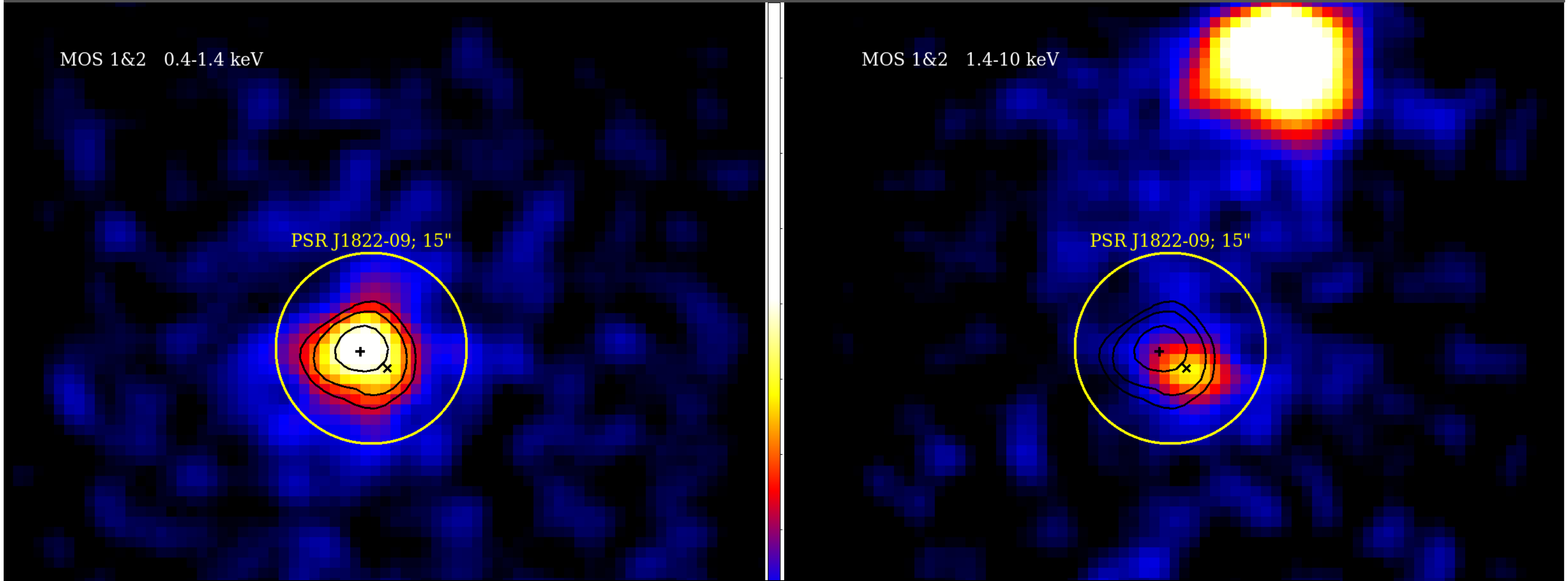


MOS 1&2 0.4-1.4 keV
PSR J1822-09; 15"
15
12
8.9
6.6
4.6
2.9
1.6
0.73
0.18


MOS 1&2 1.4-10 keV
PSR J1822-09; 15"
21
17
13
9.4
6.5
4.2
2.3
1
0.26

Maximum likelihood analysis of X-ray skymaps:

Two sources are detected separated by 5.3″±0.5″



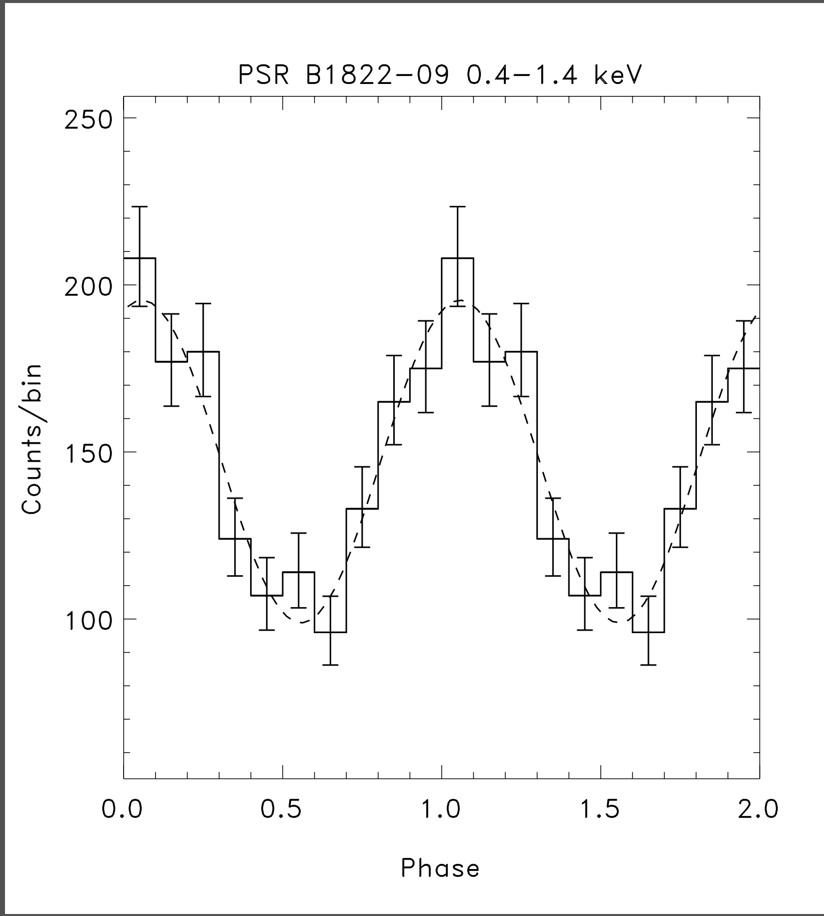
- A soft-spectrum source at the position of PSR J1822-09, dominating below 1.4 keV
- A hard-spectrum source dominating above 1.4 keV

X-ray timing analysis (PN + MOS1&2)

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

Phase folding with ephemeris from Jodrell Bank: events selected with 15″ from pulsar position

- Broad sinusoidal X-ray pulse shifted in phase by 0.094 with respect to radio main pulse (0.0)



9.8 σ detection significance

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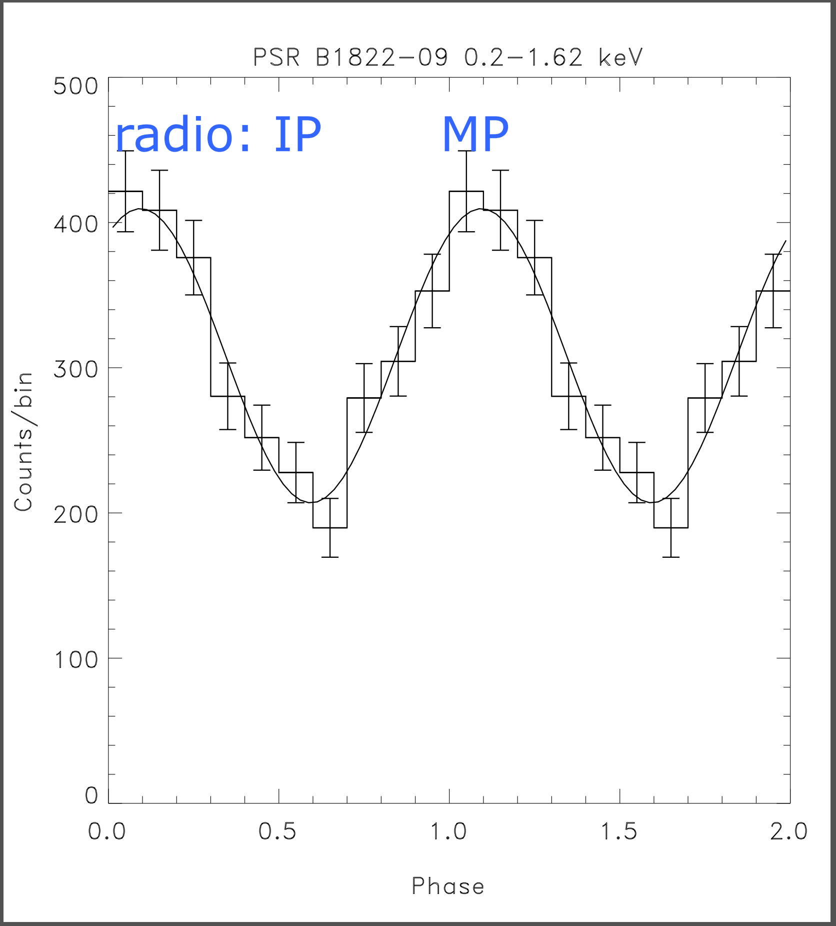
X-ray timing analysis (PN+MOS1&2)

Phase-resolved spatial analysis: background subtracted profile



- Pulsed fraction for 0.2-1.6 keV: ~35%
- No indication for X-ray pulse from radio interpulse

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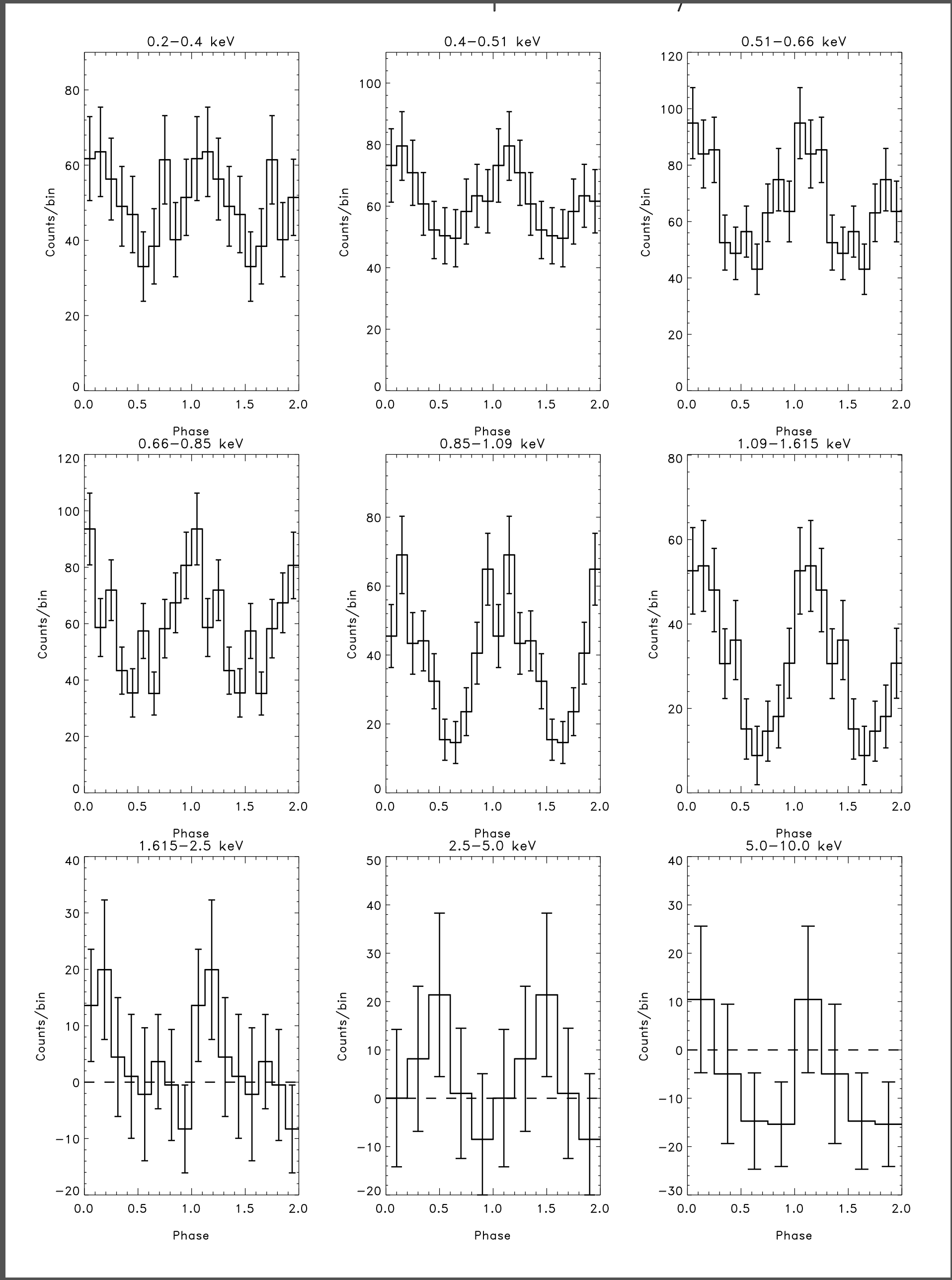
PSR B1822-09

Phase resolved spatial analysis:
all counts from pulsar

Significant pulse detections
for 0.5-1.6 keV

Pulsed fraction 0.85-1.6 keV:
60-65% !

➔ Spectrum pulsed emission much harder than that of unpulsed emission



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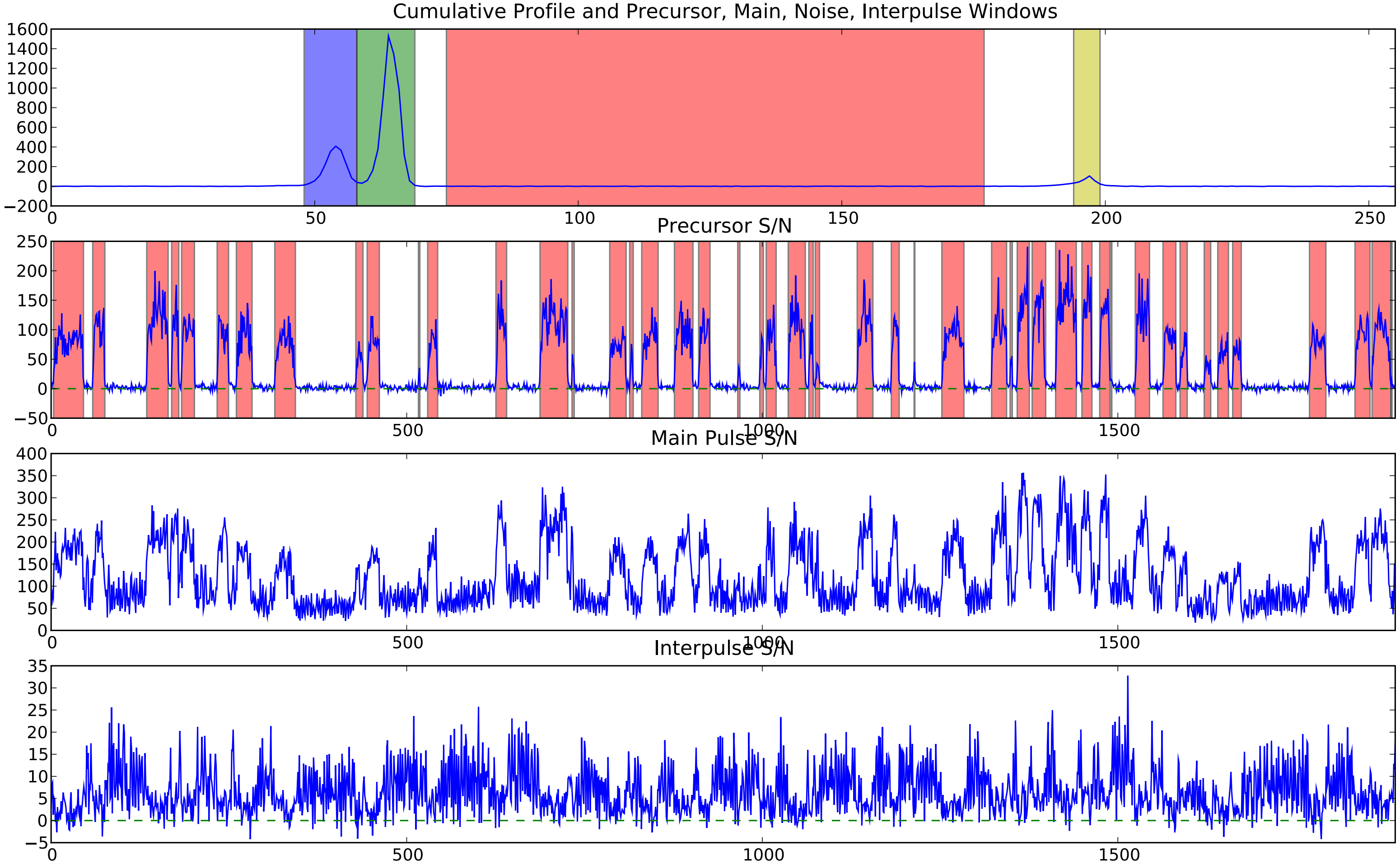
PSR B1822-09: X-ray mode switching ?

PSR B1822-09, 5.55 hrs observing with the WSRT



S/N of detection in bins of 10 s

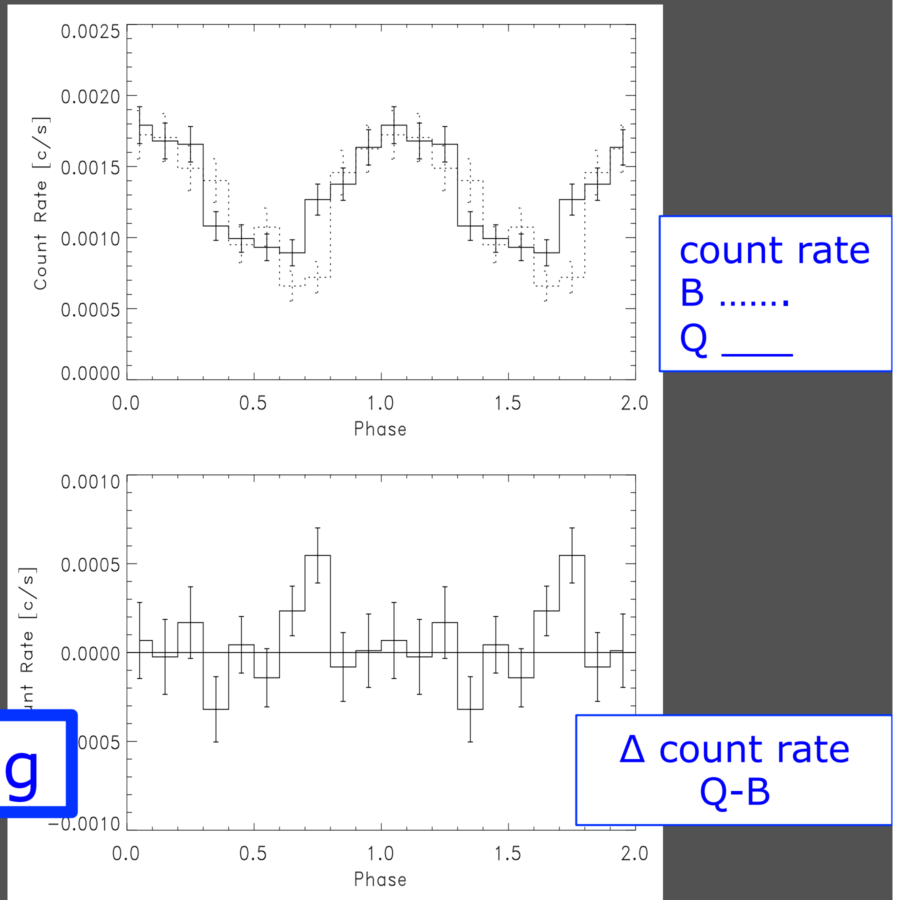
PSR B1822-09: phase distributions for Q and B intervals
Phase-resolved spatial analysis for 10 bins

Kolmogorov-Smirnov test: probability that the two profiles are drawn from the same parent distribution is 97%

No significant difference in:

- pulse shape and flux
- flat level of unpulsed emission

0.4-1.4 keV



No evidence for mode switching

Spectral analysis

- Distance PSR B1822-09:
  -- Upper limit 1.9 kpc (Johnston et al. 2001),
  -- DM = 19.9 pc cm^{-3}, N_H = 6.1 x 10^{20} cm^{-2}
  -- 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

PRELIMINARY

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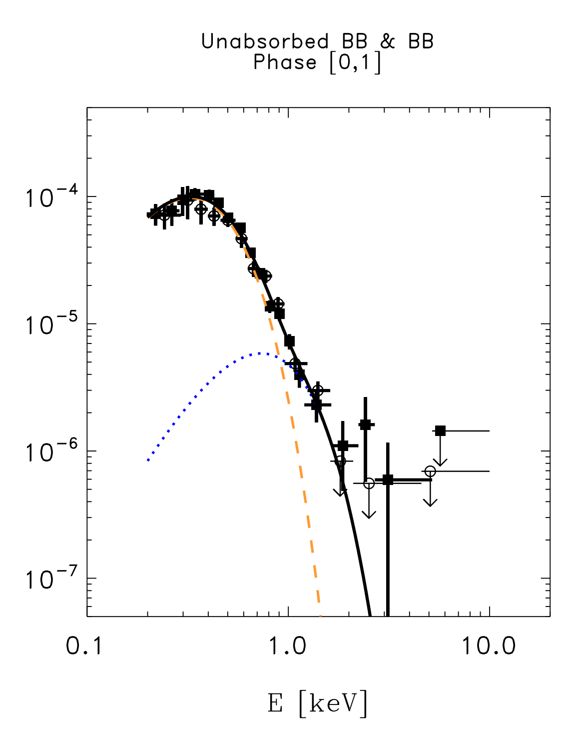
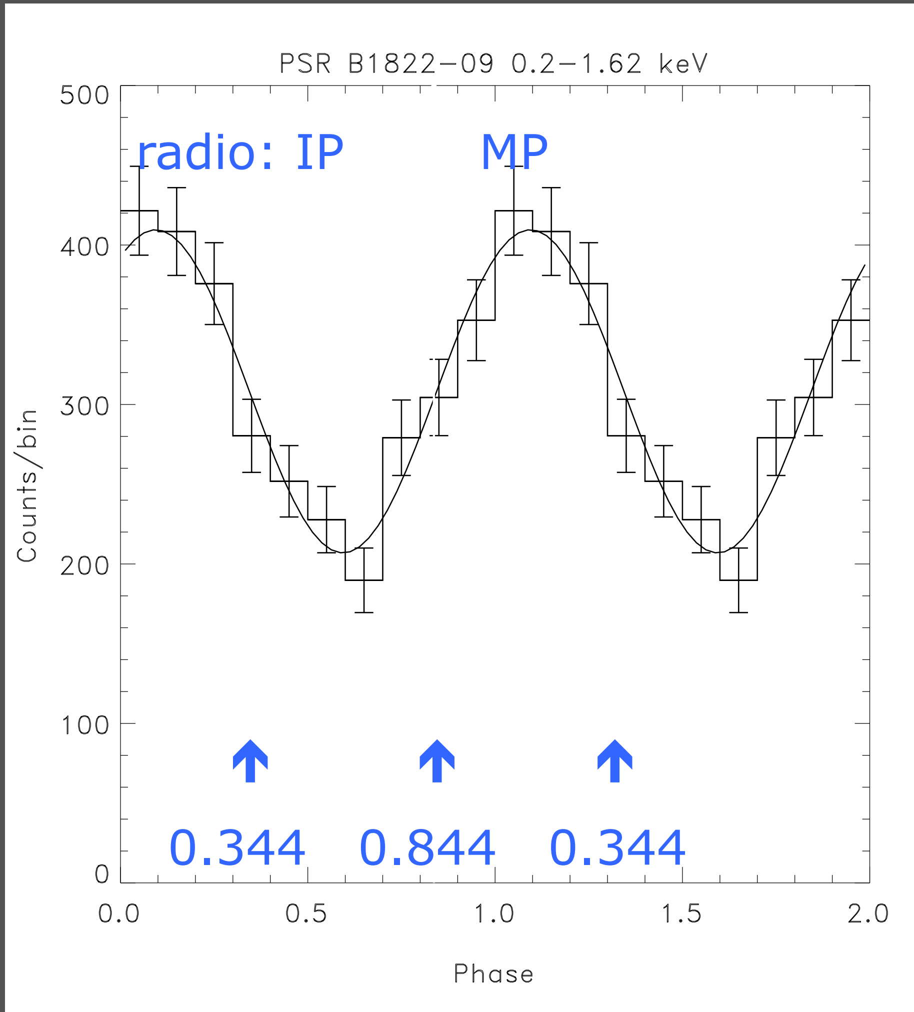
PSR 1822-09: Total-emission spectrum, fit model BB_{cool} + BB_{hot} (BB_1 + BB_2)

E² x Flux [keV²/ cm².s.keV



- **Best fit: BB_1 + BB_2; χ_r^2/ν = 1.14/28,**
- $N_H = (2.40^{+0.43}_{-0.41})\ 10^{21}\ cm^{-2}$
- BB_1: kT_1 = 0.083±0.004 keV (T=0.96 MK)
- $R_1 = (2039^{+427}_{-332})$ m (d = 1 kpc)
- F_1 (0.5-2 keV)= (3.2 ± 0.2) 10^{-14} erg cm^{-2} s^{-1} (unabsorbed)
- BB_2: $kT_2 = 0.187^{+0.026}_{-0.023}$ keV (T=2.2 MK)
- $R_2 = (98^{+59}_{-25})$ m (d = 1 kpc)
- F_2 (0.5-2 keV)= (6.5 ± 1.1) 10^{-15} erg cm^{-2} s^{-1} (unabsorbed)

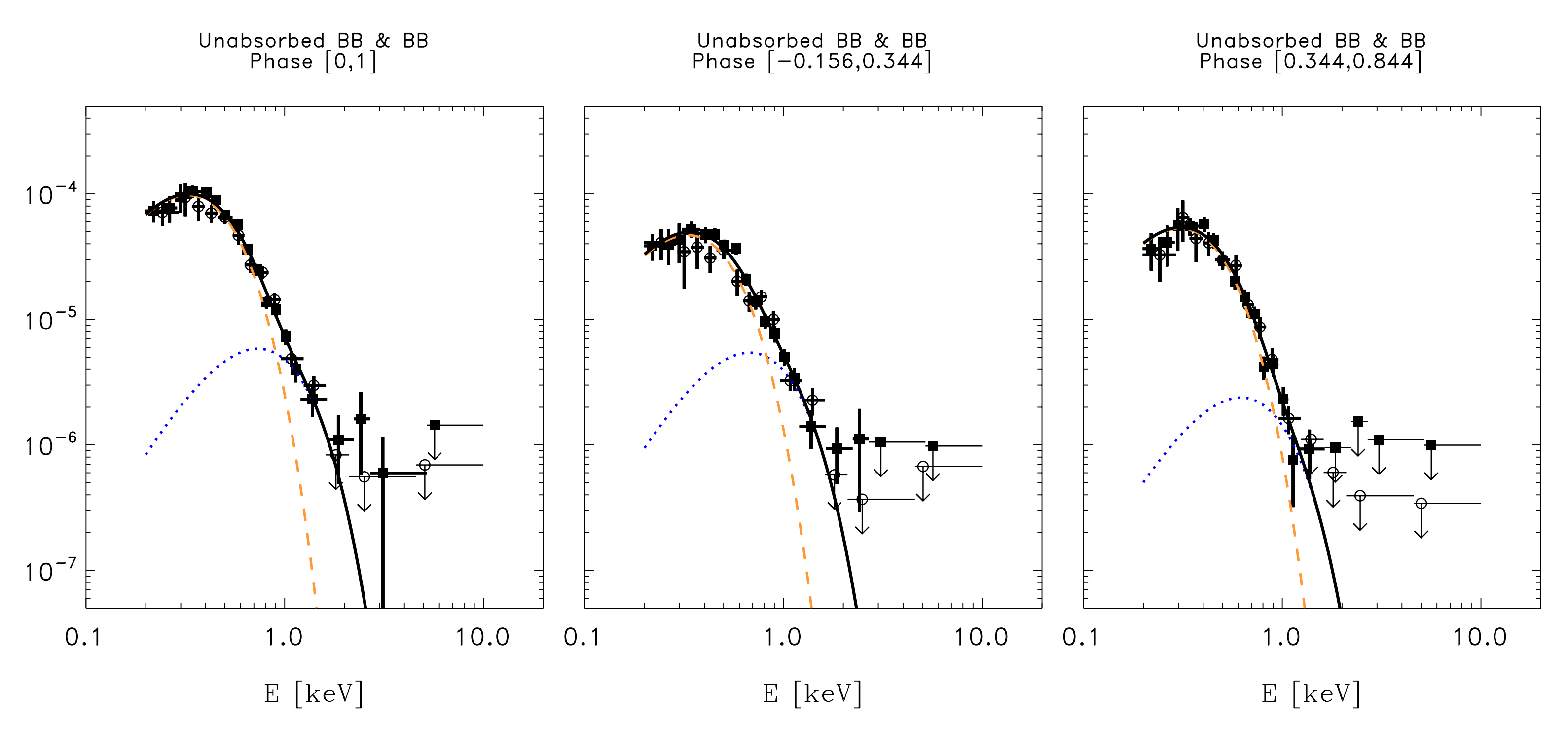
Similar BB-fits three musketeers: Geminga, PSR B0656+14 & PSR B1055-52


PSR B1822−09 0.2−1.62 keV
radio: IP
MP
Counts/bin
Phase
0.344
0.844
0.344
0
100
200
300
400
500
0.0
0.5
1.0
1.5
2.0

PSR 1822-09: spectral fits for BB_{cool} + BB_{hot} ($BB_1 + BB_2$)

Total emission | Main Pulse | Inter Pulse

E² x Flux [keV²/cm².s.keV]



	Total emission	Main Pulse	Inter Pulse
kT_1 [keV]	0.083 ± 0.004	0.084 ± 0.005	0.078 ±0.005
R_1 [m]	2039^{+427}_{-332}	1380^{+399}_{-242}	1700^{+532}_{-316}
kT_2 [keV]	$0.187^{+0.026}_{-0.023}$	$0.172^{+0.043}_{-0.038}$	$0.158^{+0.043}_{-0.029}$
R_2 [m]	98^{+59}_{-25}	112^{+52}_{-26}	88^{+121}_{-33}

Within statistics same cool and same hot BB components

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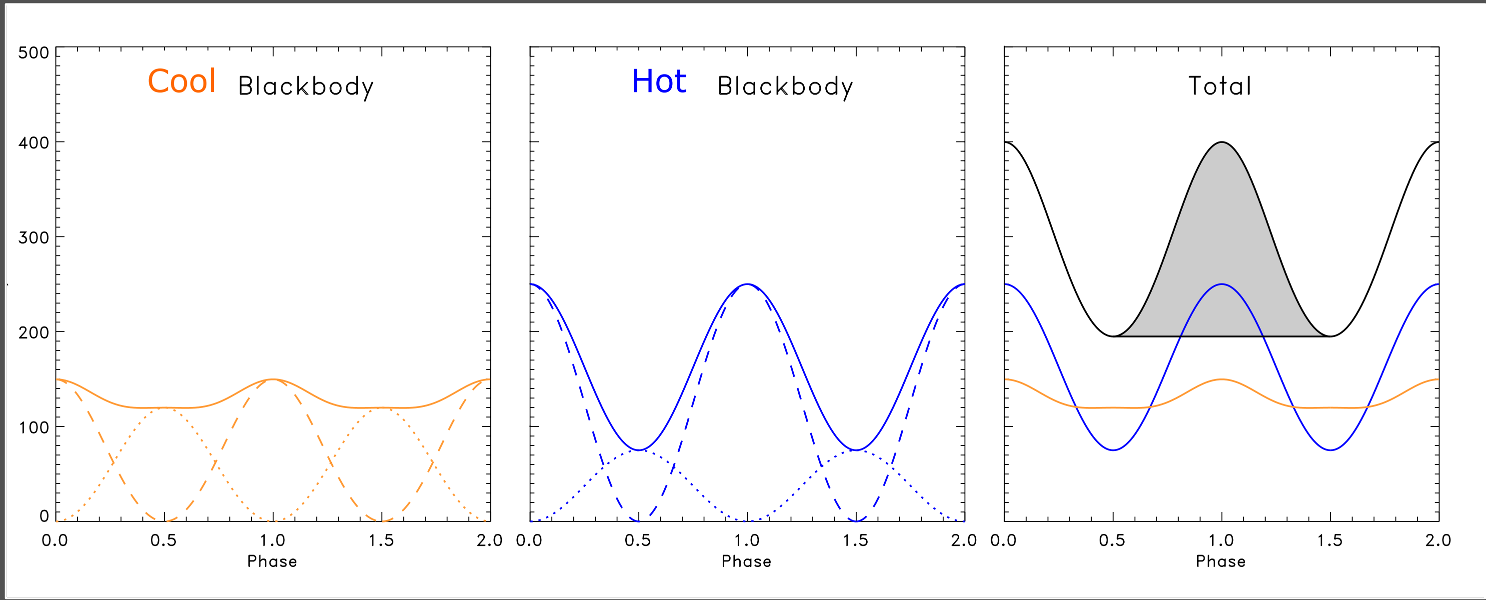
PSR B1822-09: cartoon, consistent with spectral and timing analysis



Broad cool pulses
MP + IP

kT ≈ 0.080 keV

R ≈ 1700 m

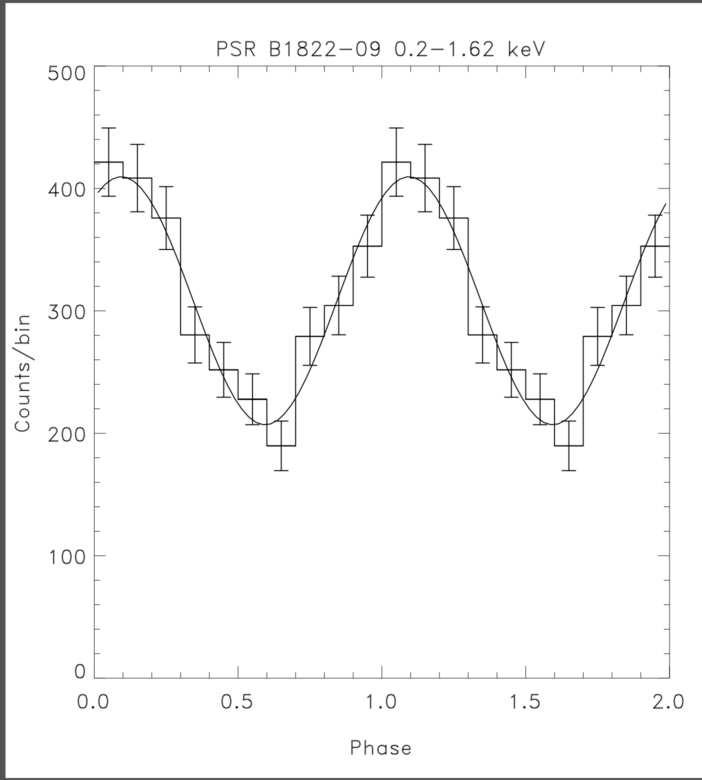
Narrow hot pulses
MP + IP

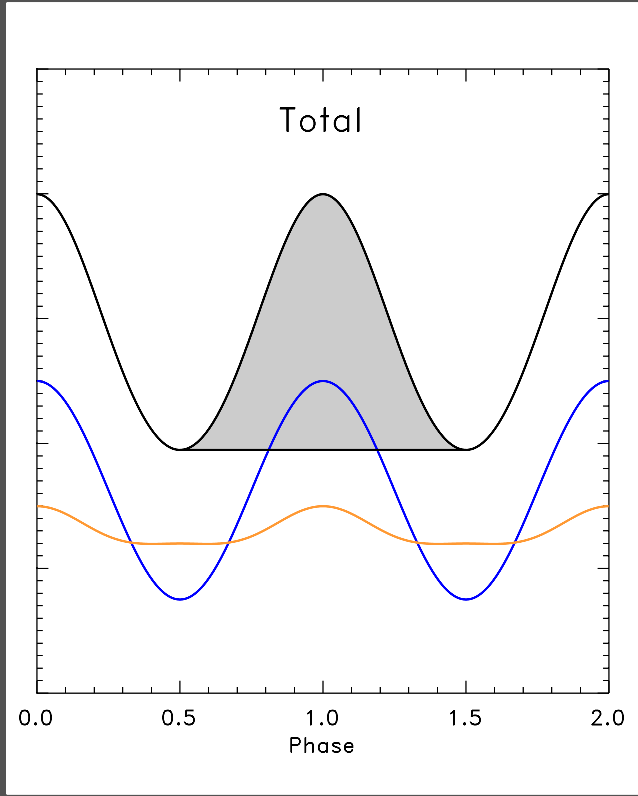
kT ≈ 0.180 keV

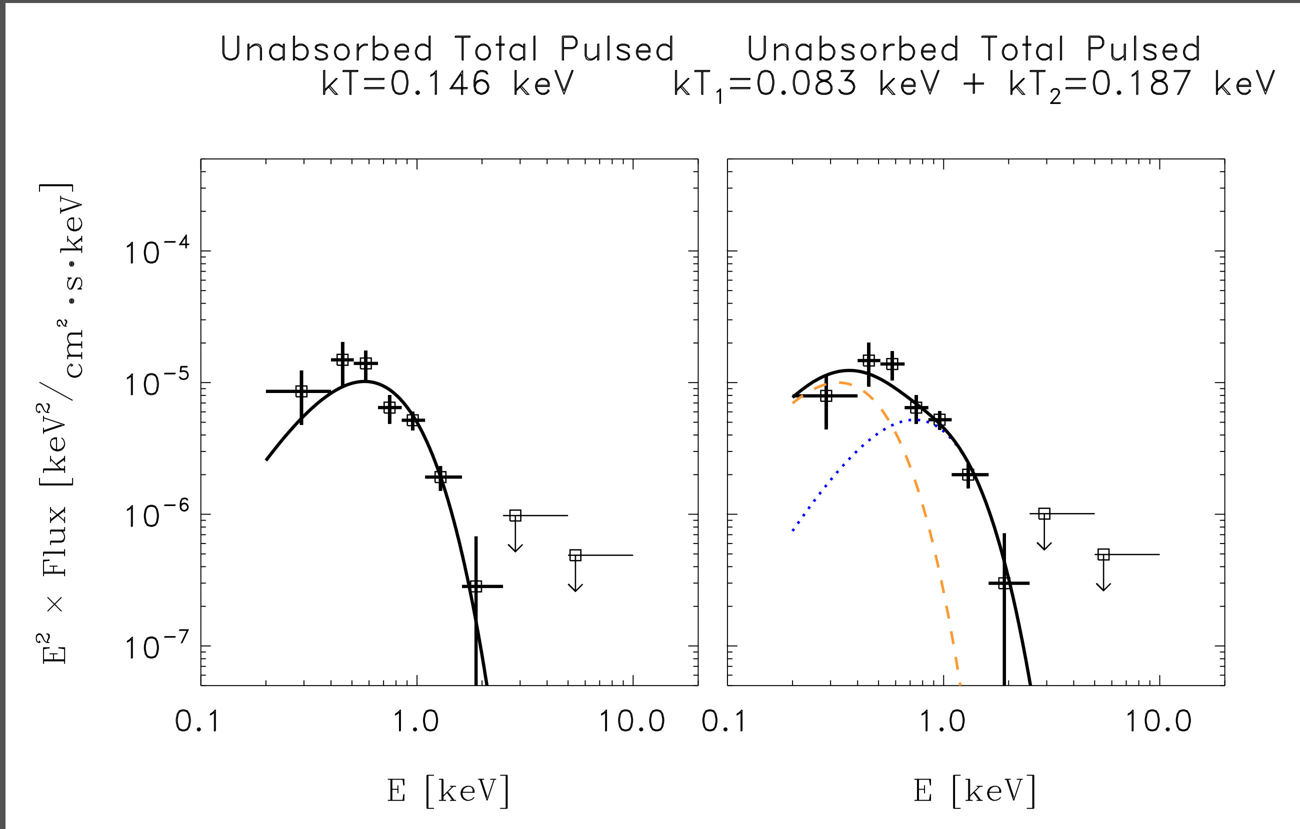
R ≈ 100 m

Summed total profile

Shaded area is detected pulse above flat 'unpulsed' level (should contain contributions of underlying cool and hot pulses)


PSR B1822−09 0.2−1.62 keV
Counts/bin
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
Phase


Total
0.0
0.5
1.0
1.5
2.0
Phase



Left: Spectrum pulsed emission can be well fitted with single BB with kT in between that of the cool and hot components of the total emission.

Right: Pulsed spectrum can also be explained as the sum of a cool and hot component with temperatures fixed at the values of the total emission.

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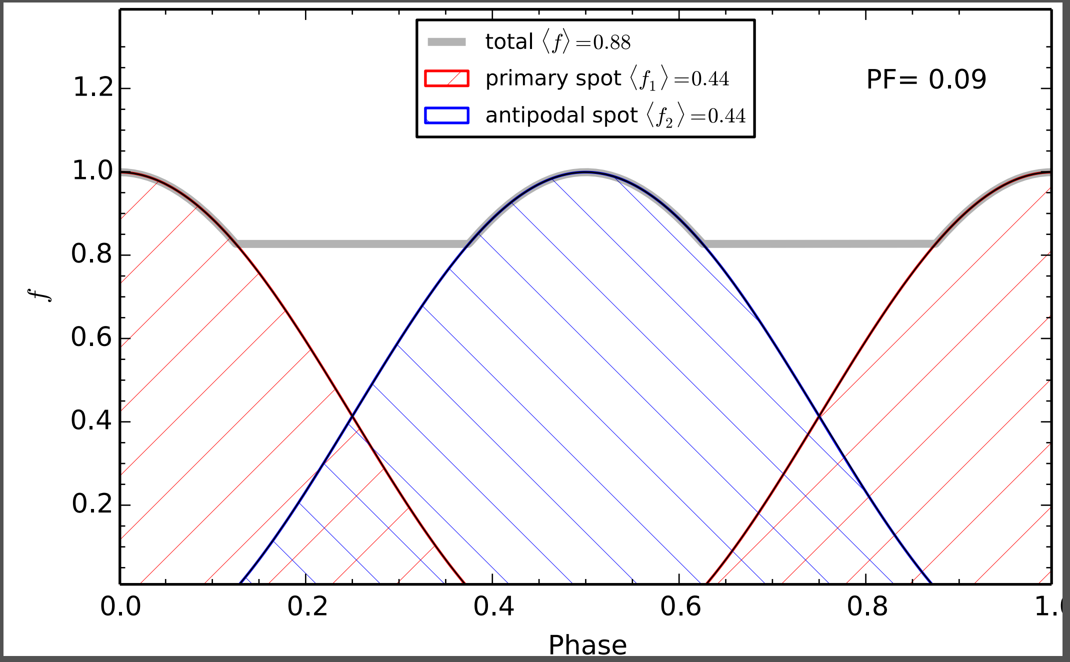
Dilemma: X-ray results contradict radio-derived geometry ?

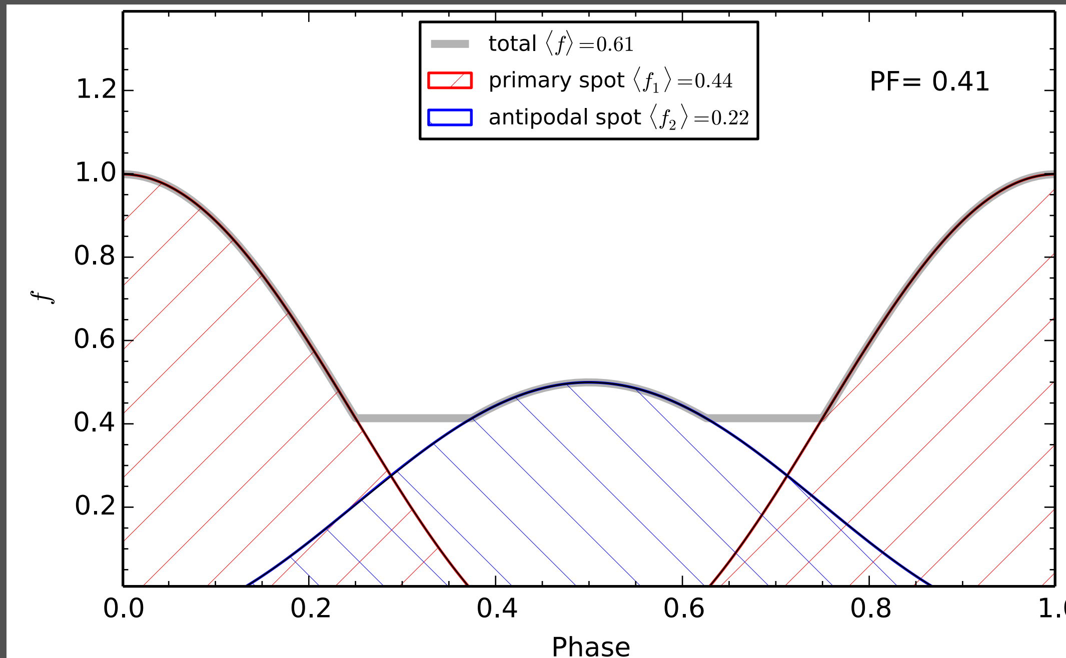
Radio: nearly orthogonal rotator, impact angle small
but
X-ray pulsed fraction 0.8 – 1.6 keV 60-65% !



If luminosities primary and antipodal spots equal: pulsed fraction ~9%

Dilemma: X-ray results contradict radio-derived geometry ?

Radio: nearly orthogonal rotator, impact angle small
but
X-ray pulsed fraction 0.8 – 1.6 keV 60-65% !



If luminosity antipodal spot half of luminosity primary pole:
pulsed fraction ~41%

- For nearly aligned rotator
- hot X-ray pulse is excluded (but PSR B0943+10?)

Conclusions

- PSR B1822-09 has been detected with XMM-Newton with average pulsed fraction ~35% (0.4-1.4 keV), and 60-65% for 0.85-1.6 keV
- The pulse profile is sinusoidal; maximum at ~0.1 phase from the peak of the radio main pulse.
- X-ray emission from PSR1822-09 can be explained as emission from opposite poles, each with cool ($T \approx 1MK$, $R \approx 2$ km) and hot ($T \approx 2.2$ MK, $R \approx 100m$) components.
- For PSR B1822-09 as well as for PSR B0943+10 the X-ray pulse profiles difficult to reconcile with radio-derived geometries.
- There is no evidence for simultaneous X-ray-radio mode-switching by PSR B1822-09. What causes this difference with PSR B0943+10?
- We still do not know what causes X-ray mode switching seen for PSR B0943+10 (local vs global ? More insight from new long campaign on PSR B0943+10 ?)

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Thank you for listening!