The mystery of simultaneous pulsar moding in the X-ray and radio bands

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Netherlands Organisation for Scientific Research (NWO)

Outline

- Introduction: Discovery of synchronous X-ray and radio-mode switching in pulsar PSR B0943+10. (Hermsen et al. 2013, Science 339, 436)
- New insights (Storch et al. 2014)
  (New long campaign on PSR B0943+10: results under embargo;
  Mereghetti et al. 2016, including authors of Hermsen et al. 2013,
  Mereghetti et al. 2013, MNRAS 435, 2568 & Kevin Stovall +)
- Simultaneous radio and X-ray observations of PSR B1822-09: results
- Conclusions, Next Steps

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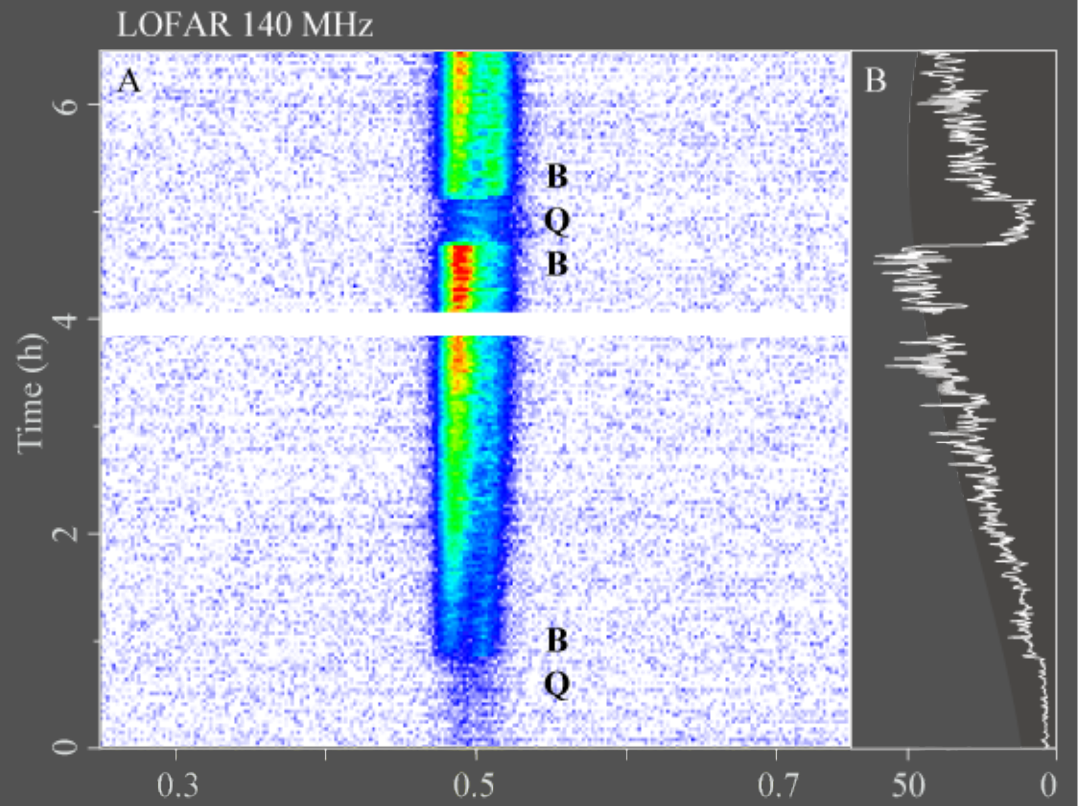
The radio-mode switching PSR B0943+10

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

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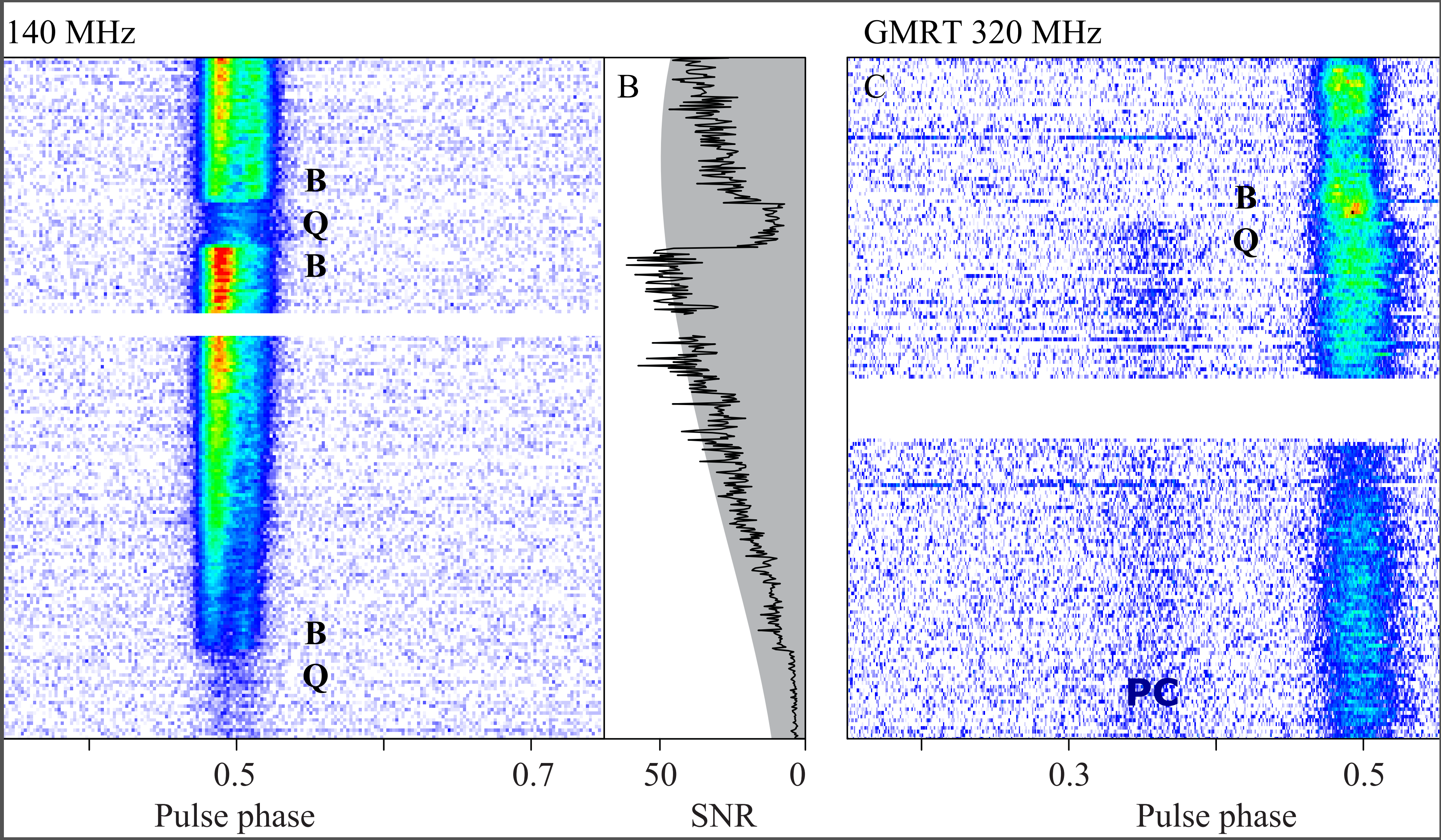
PSR B0943+10: also a moding Precurser (**PC**)



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)

- 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 X-ray emission** is added to the X-ray flux in the B mode.

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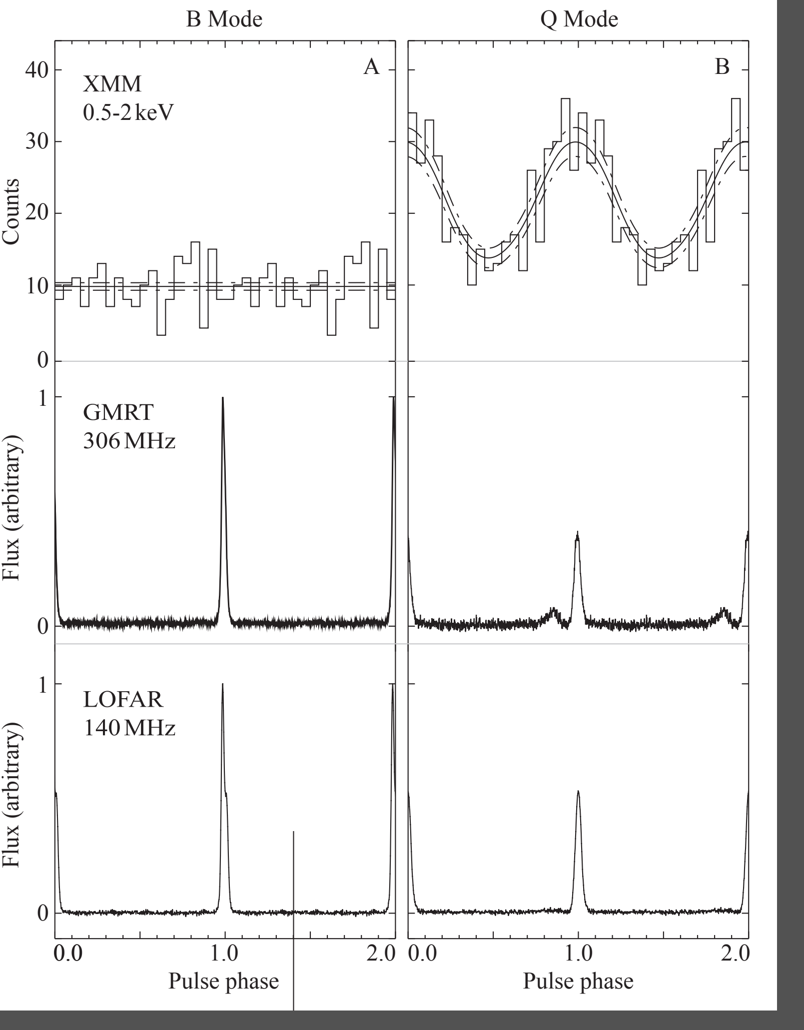
Discovery of Synchronous X-ray and Radio Mode Switches

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



Detection of pulsed X-ray emission in radio Q mode
B mode:3-σ upper limit pulsed fraction 40-50%, Mereghetti et al. 2013

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

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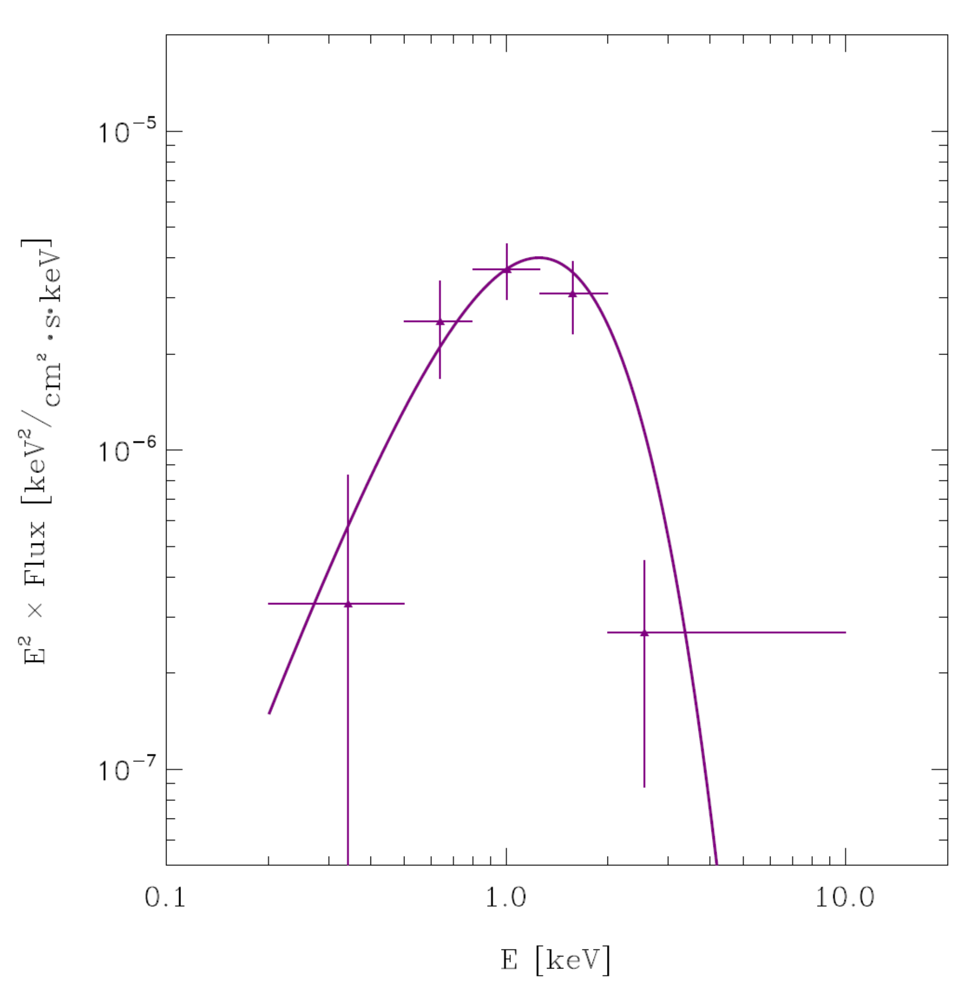
PSR B0943+10: X-ray spectrum **pulsed emission** in radio **Q-mode**



- **Best fit: BB;** $\chi2/\nu$ = 1.14/3, ~78%
- N_H = 4.3 x 10^{20} cm^{-2} (fixed)
- BB: kT = 0.319 ± 0.012 keV
  3.70 ± 0.14 MK
- 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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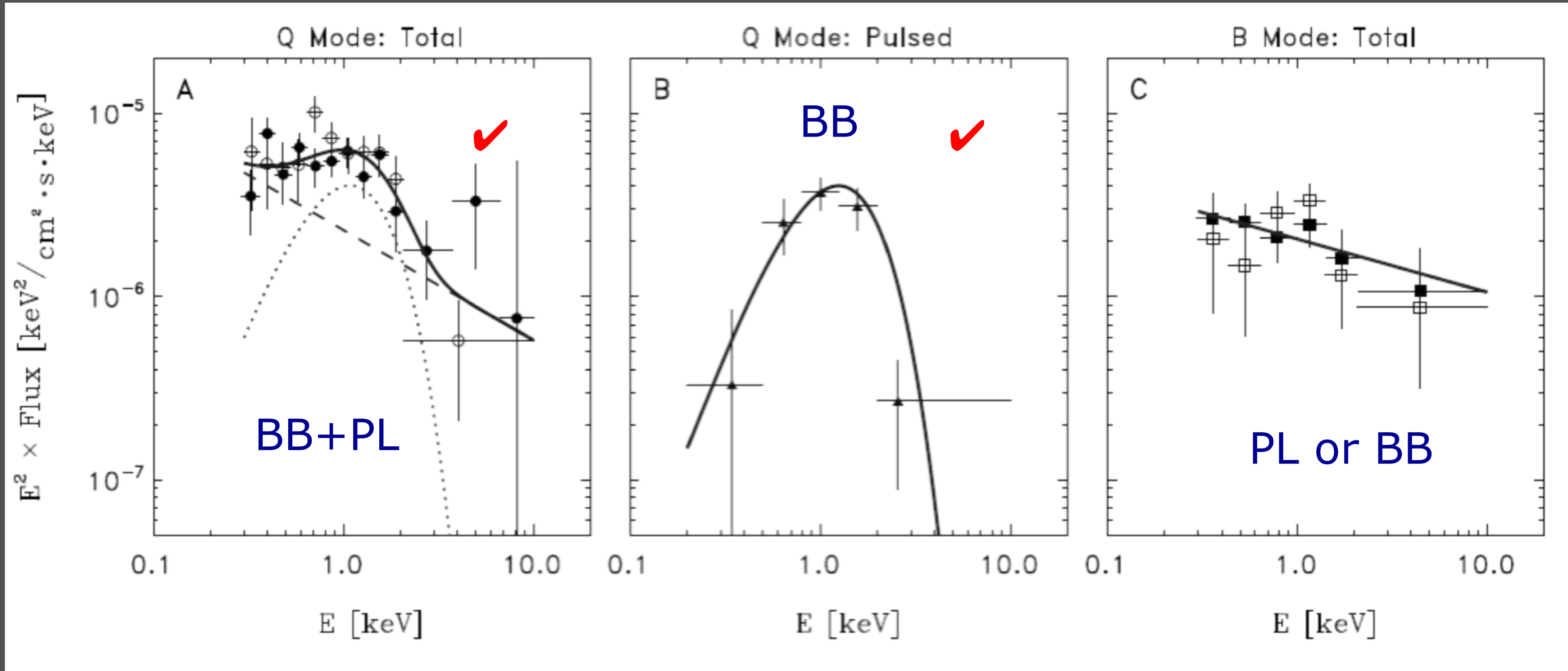
X-ray spectral characteristics

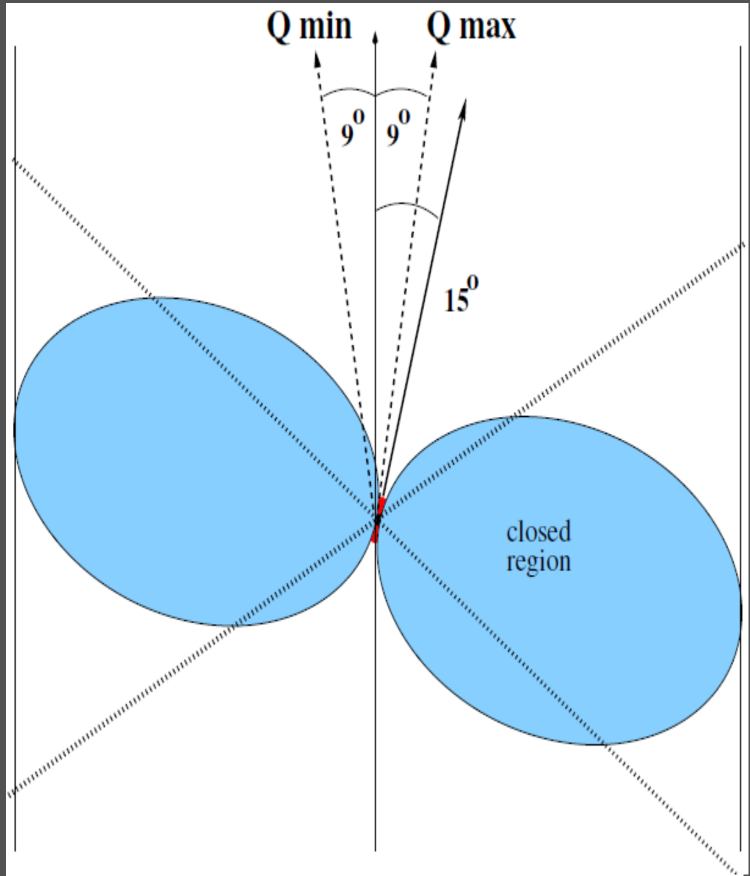


Mereghetti et al. 2013 reanalized our observations and preferred:
pulsed emission non-thermal, unpulsed emission thermal

Unanswered questions, e.g.:

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

- What is causing the simultaneous X-ray radio mode switch?



Geometry as constrained by
Deshpande & Rankin 2001

Geometrical model
PSR B0941+10

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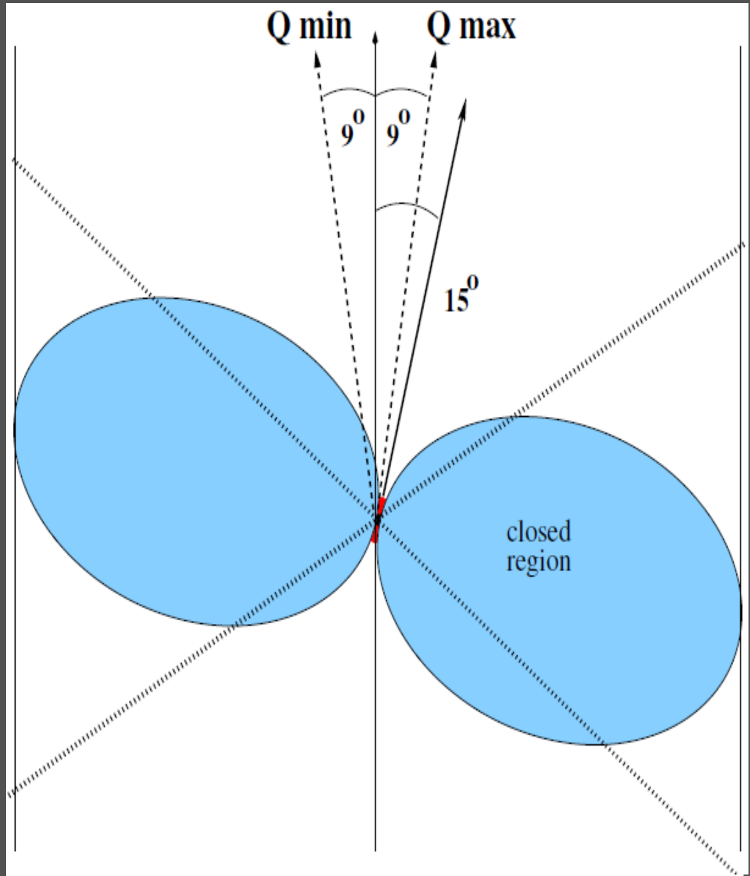
➔ **Magnetic beaming**



Geometry as constrained by Deshpande & Rankin 2001

Geometrical model
PSR B0941+10

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Magnetic beaming

References e.g.

- Pavlov et al. 1995, Rajagopal et al. 1997, Zavlin & Pavlov 2002
- Ho et al. 2003, 2004, Adelsberg & Lai 2006

-- Storch et al. 2014: addressed (in particular) the pulse profile and the high pulsed fraction of PSR B0943+10 in the Q mode.

➔ Magnetic beaming or a displaced dipole geometry

-- PSR B0943+10 is old (5Myr), but $B_p = 2.0 \times 10^{12}$ G is sufficiently strong to cause beaming along the direction of B field

➔ Pencil beam + broad fanlike beam

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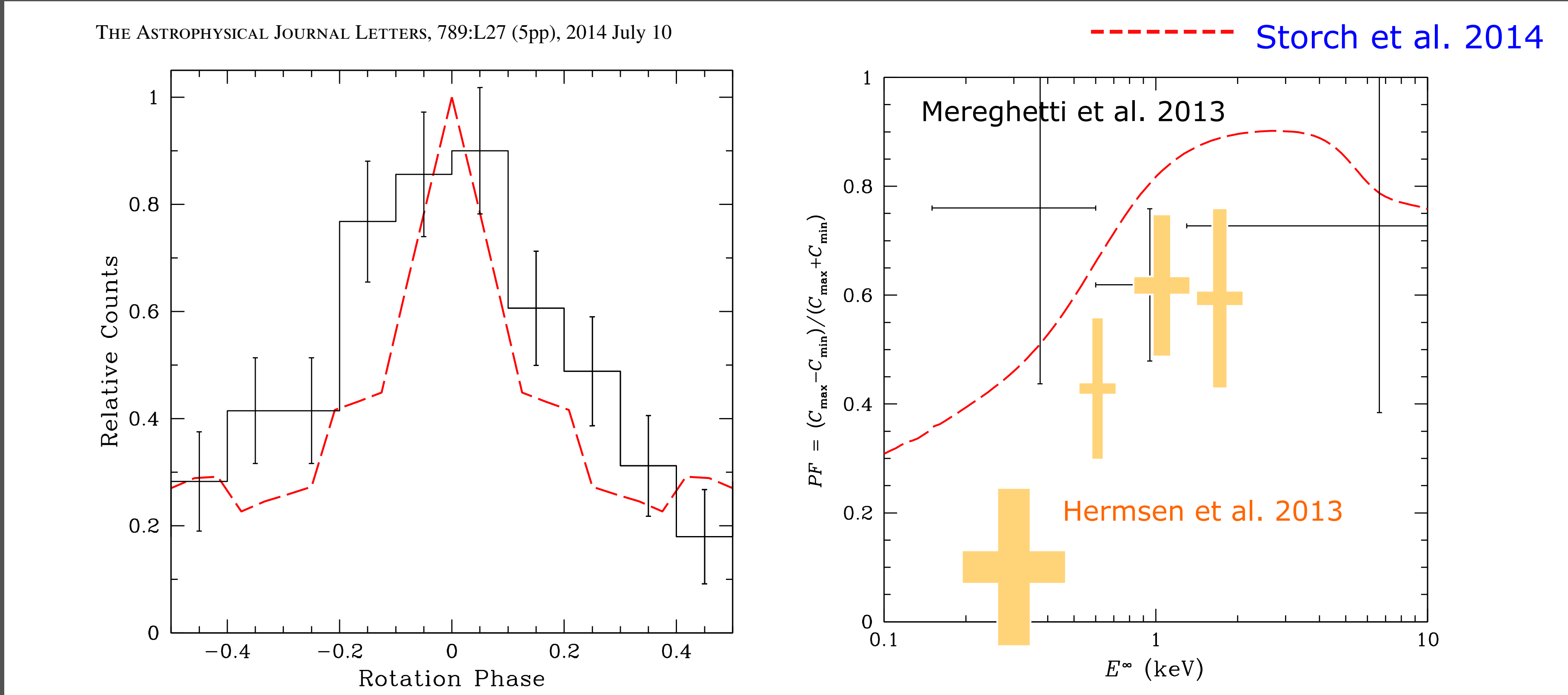
Magnetic beaming for the nearly aligned geometry of PSR B0943+10 (Deshpande & Rankin 2001)



Q-mode

For a magnetized, partially ionized hydrogen atmosphere model (Ho et al. 2008)

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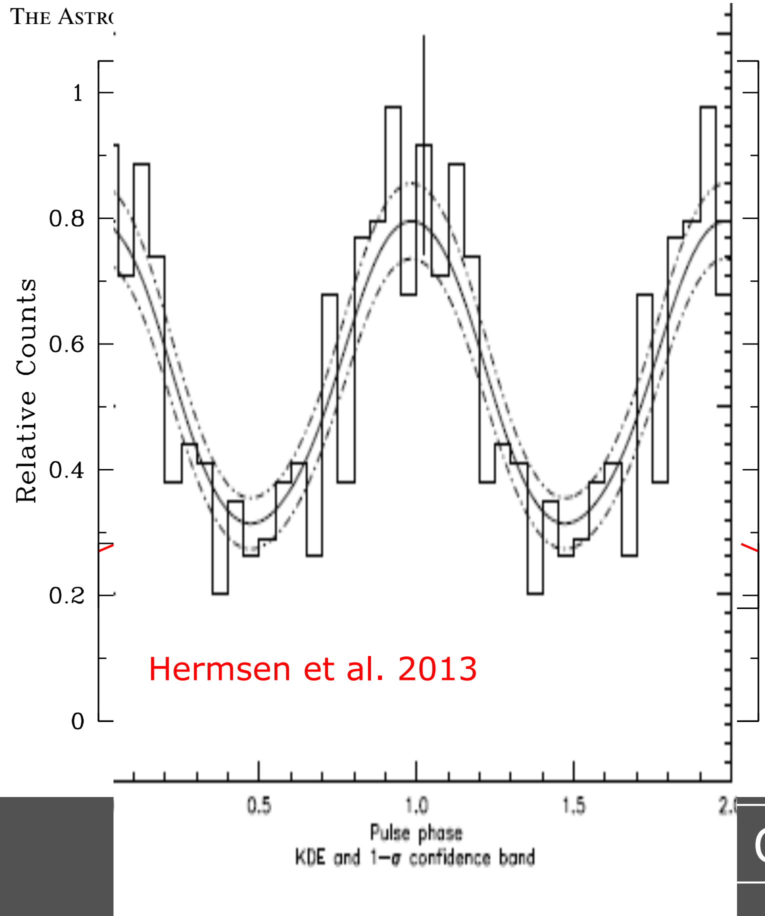
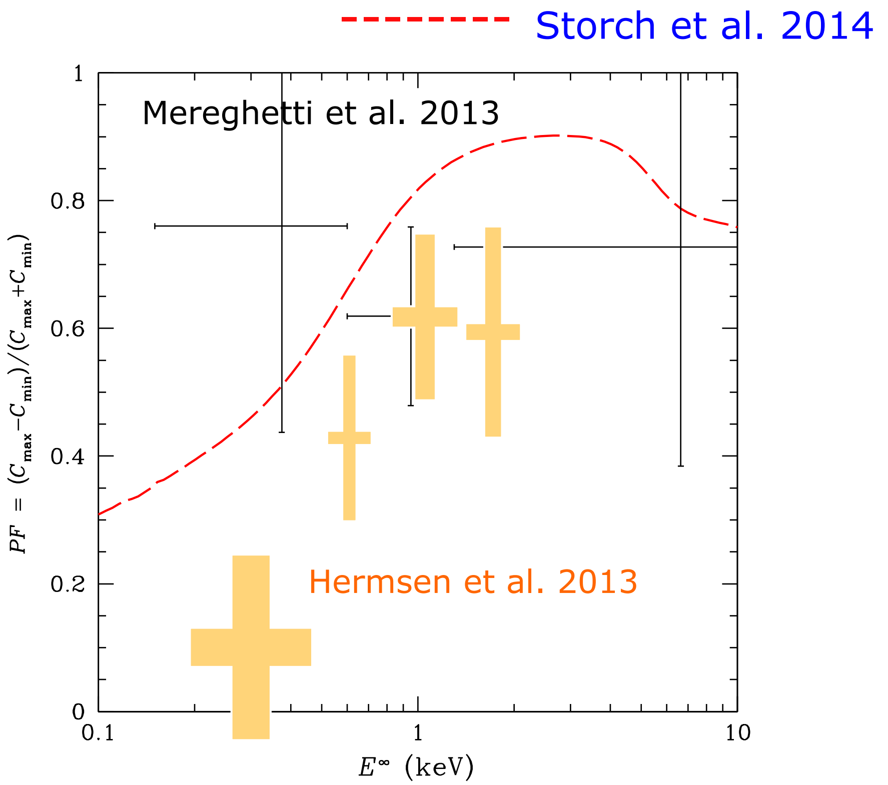


Q-mode



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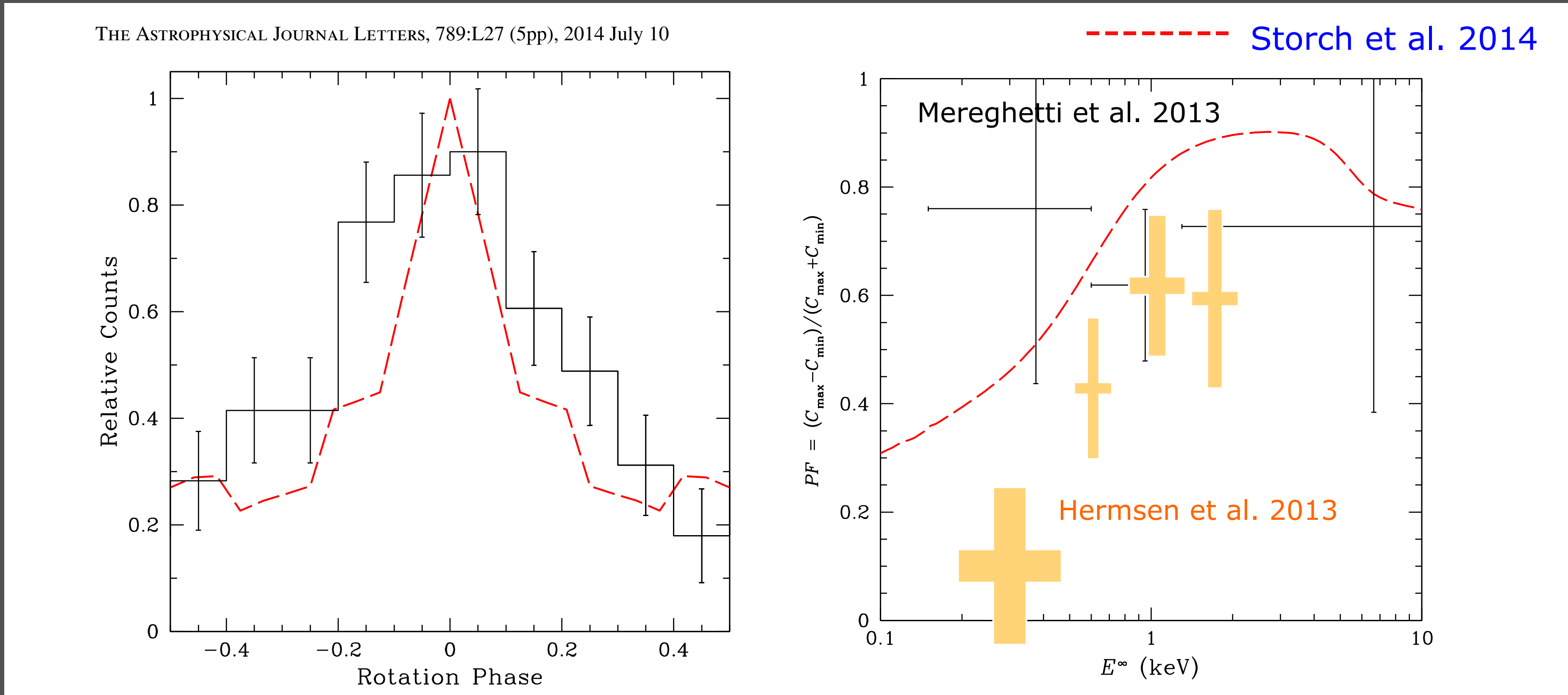


Q-mode

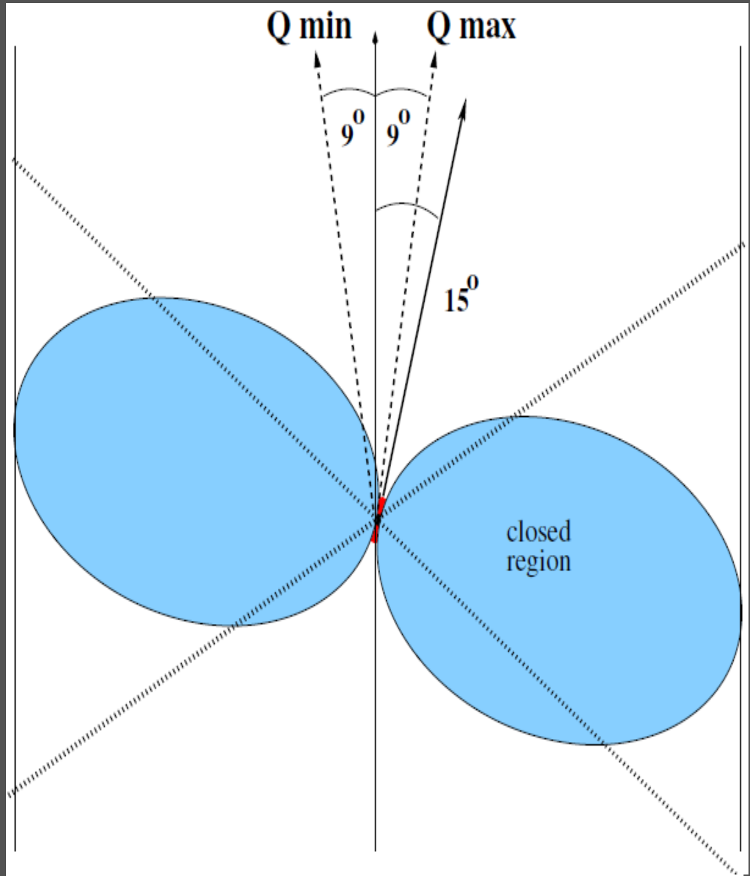
For a magnetized, partially ionized hydrogen atmosphere model (Ho et al. 2008)

Unanswered questions, e.g.:

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

→ **Magnetic beaming**

- **What is causing the simultaneous X-ray radio mode switch?**



Geometrical model
PSR B0941+10

Geometry as constrained by
Deshpande & Rankin 2001

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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)

Local phenomenon:

- Three modes of pulsar inner gap (Zhang et al. 1997)
- Partially Screened Gap model (Gil, Melikidze, Zhang, 2006; Szary, Melikidze, Gil, 2015)

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Theoretical Support for Rapid, Global, Magnetospheric Changes

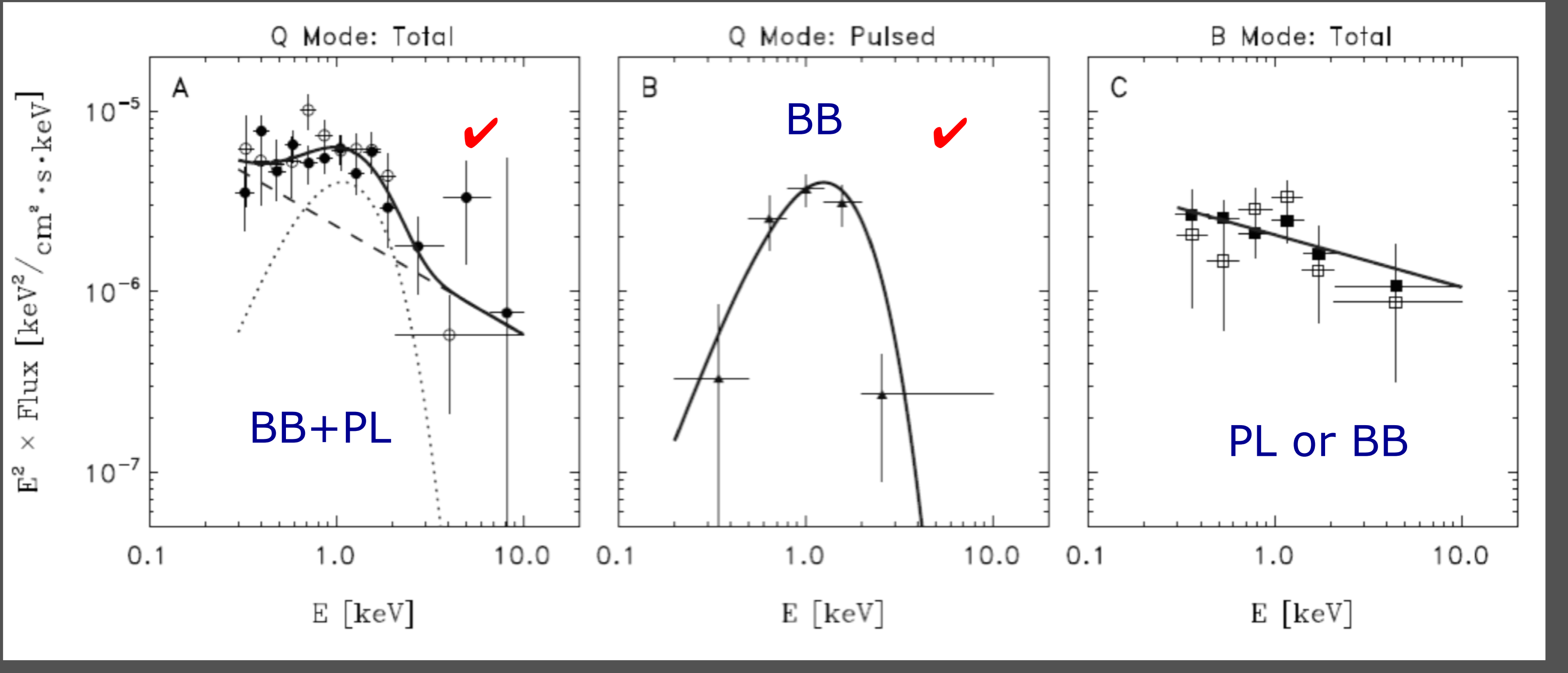
- Mode switching is global: a range of Quasi-stable magnetospheric configurations is expected

  (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 spectral characteristics



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

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)

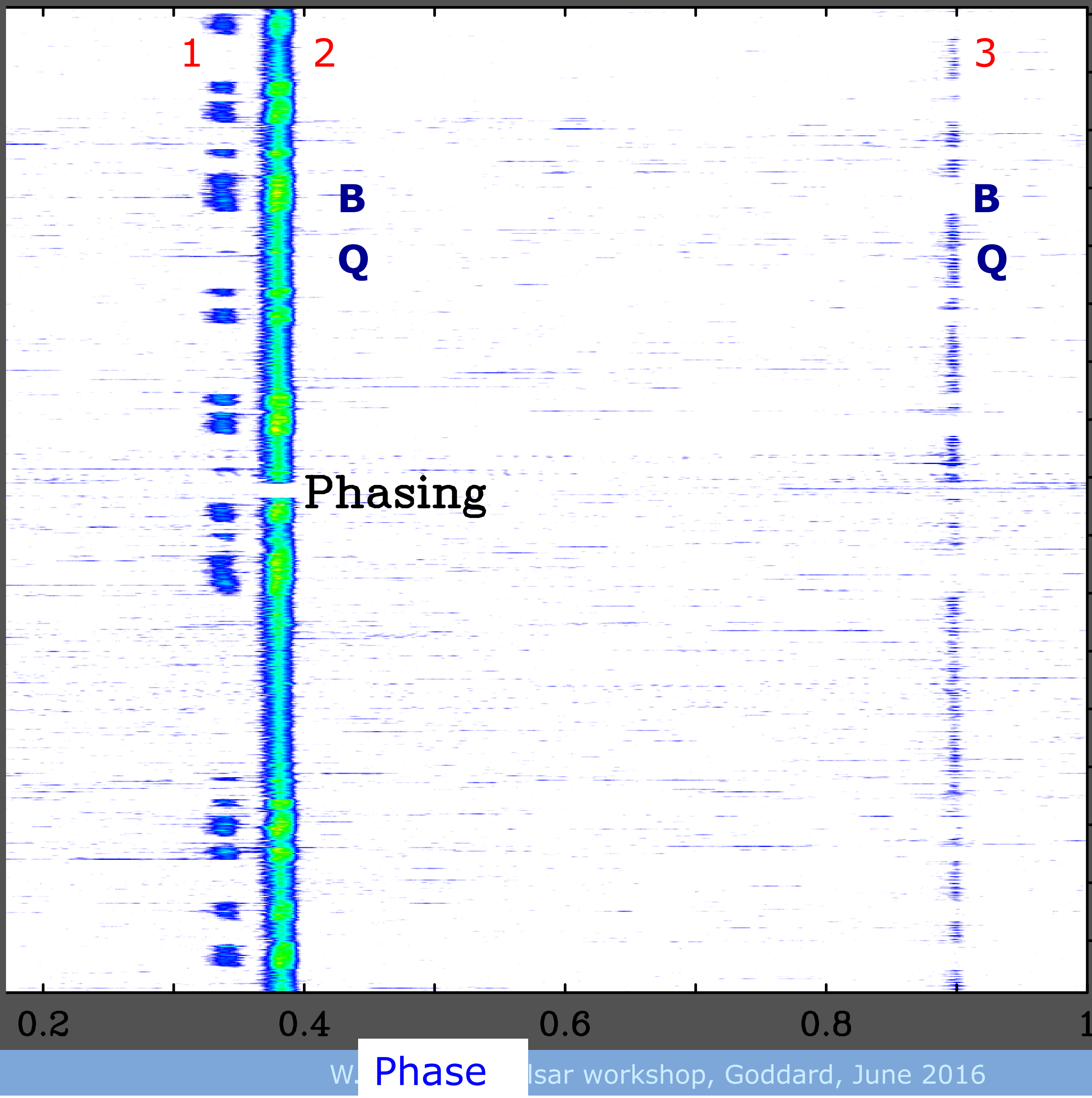
Mode switching

1: Precursor

2: Main pulse

3: Interpulse

Typical mode durations less than 5 minutes



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

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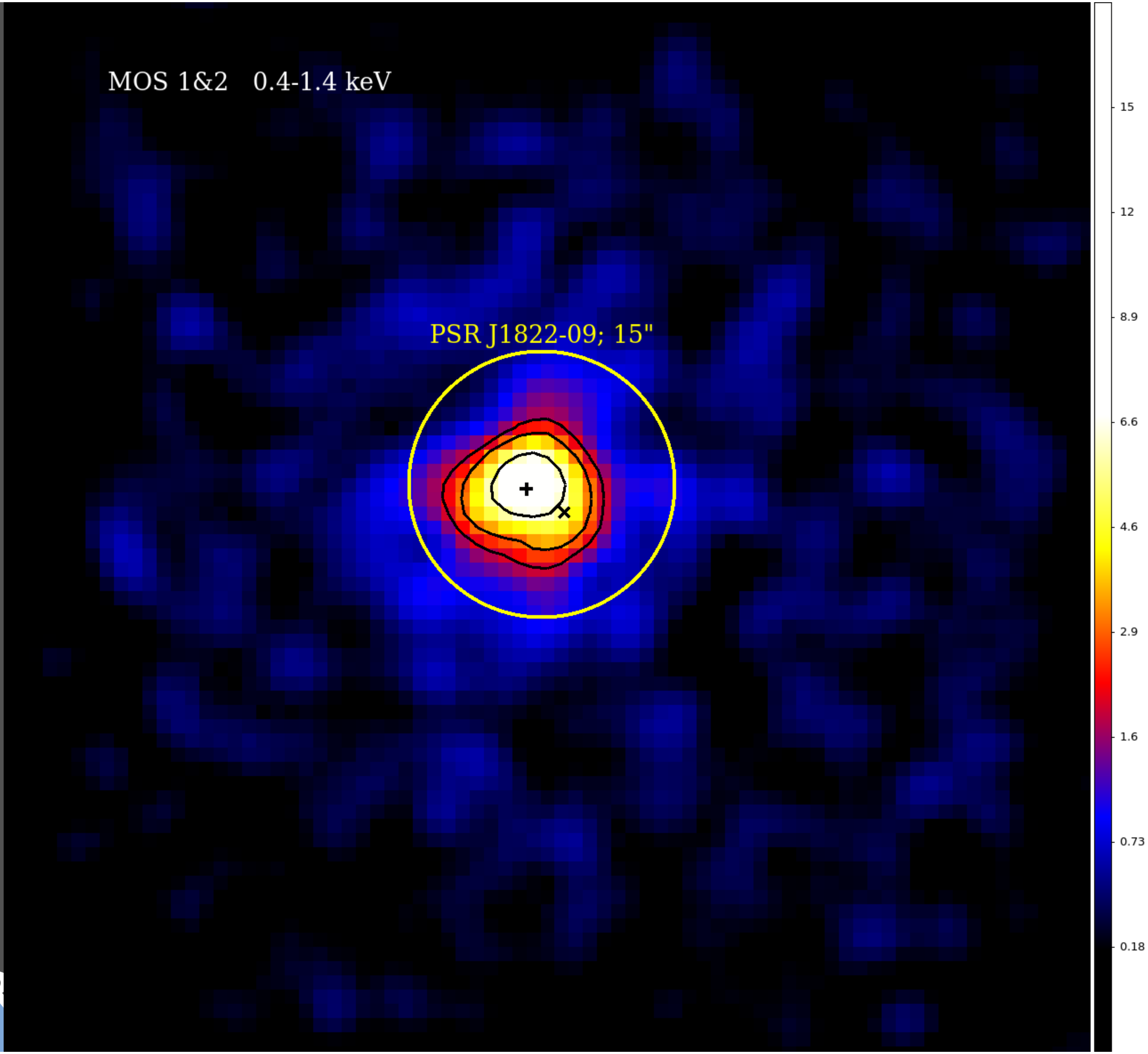
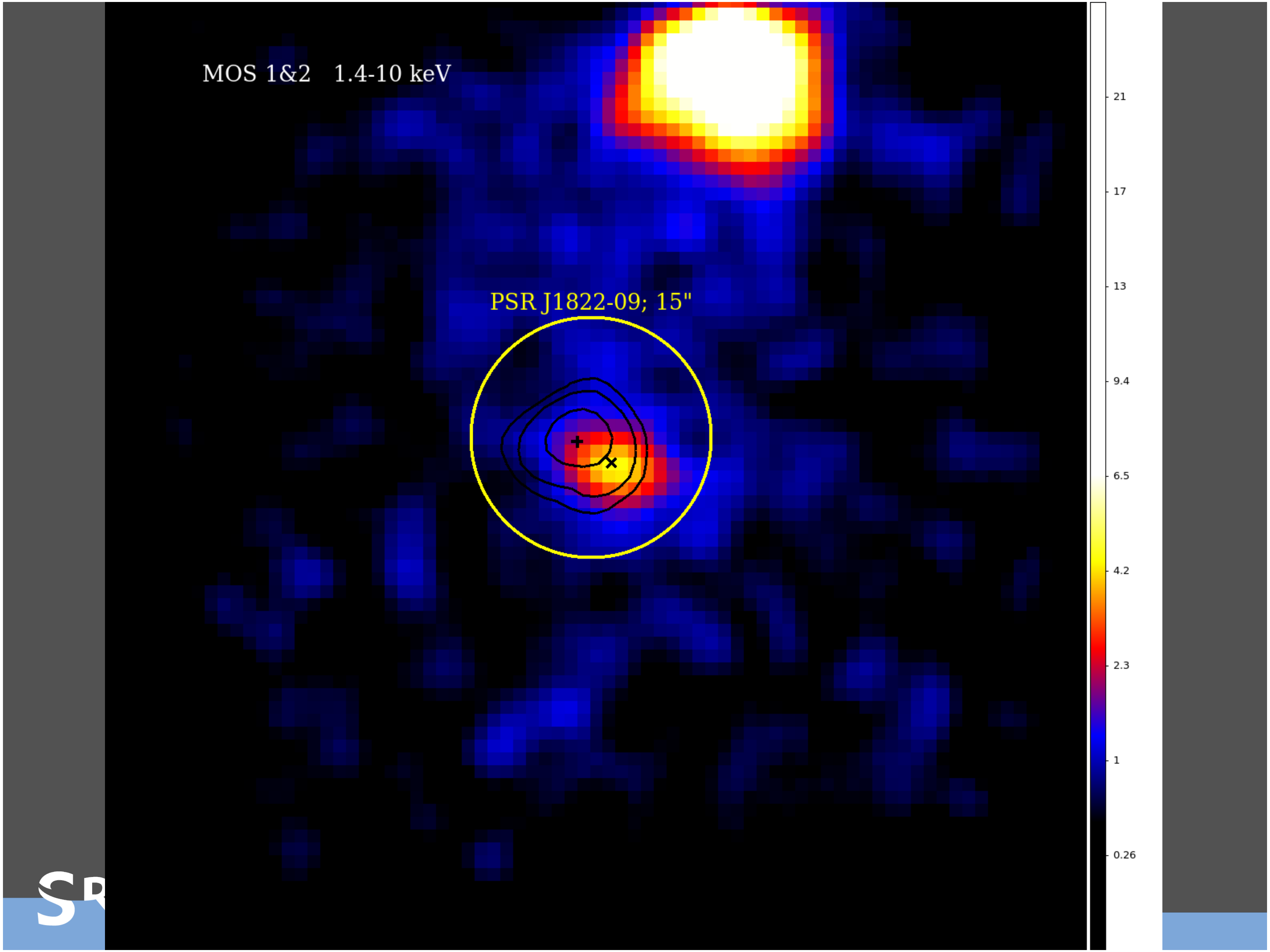
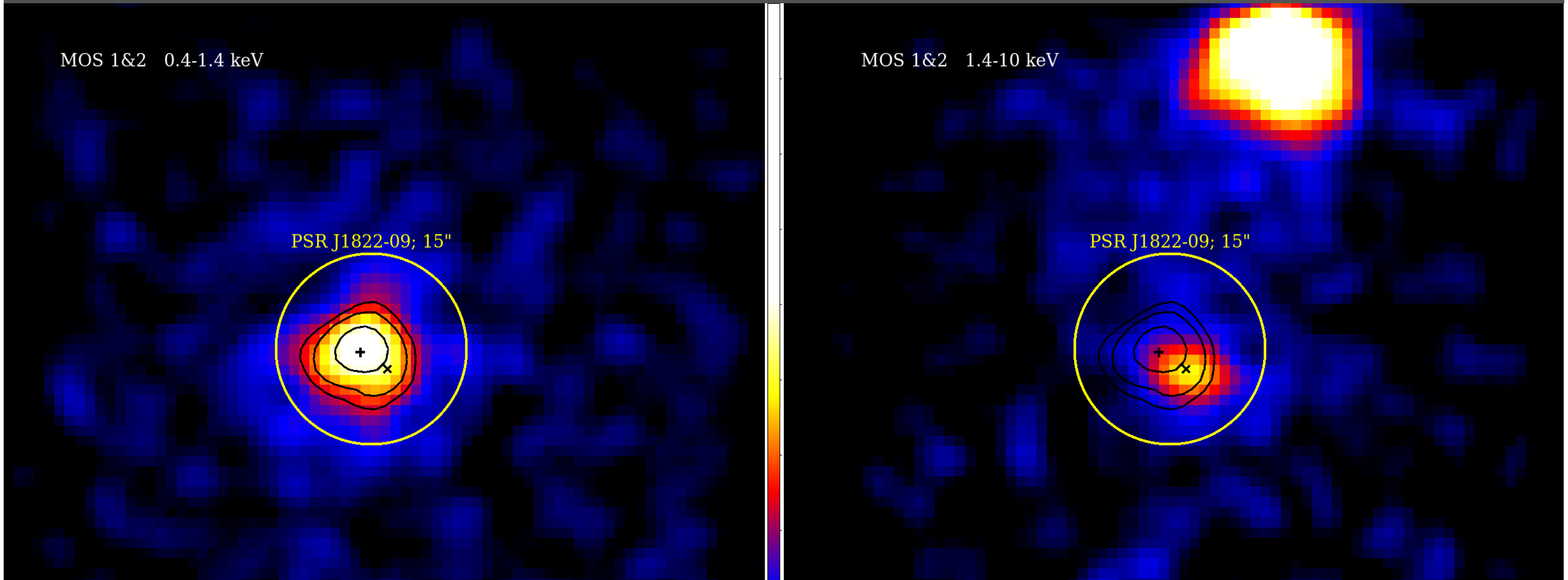

MOS 1&2 0.4-1.4 keV
PSR J1822-09; 15"
15
12
8.9
6.6
4.6
2.9
1.6
0.73
0.18


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 5.1″±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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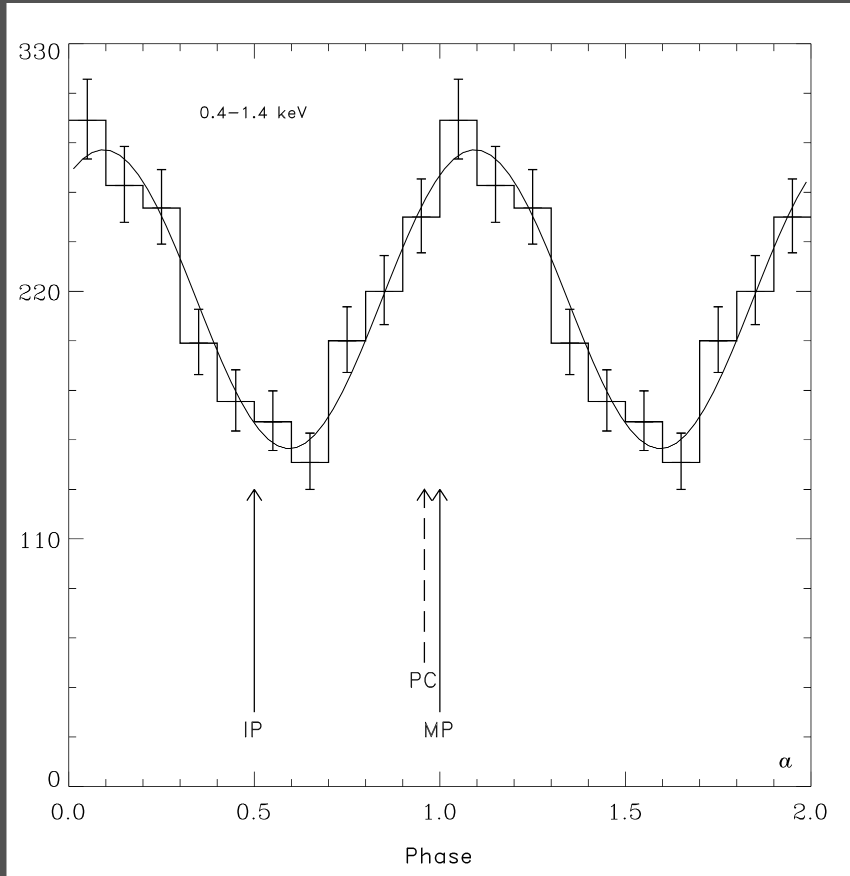
X-ray timing analysis (PN + MOS1&2)

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

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

- Broad sinusoidal X-ray pulse shifted in phase by 0.094 ± 0.017 with respect to radio main pulse (0.0)



9.6 σ detection significance

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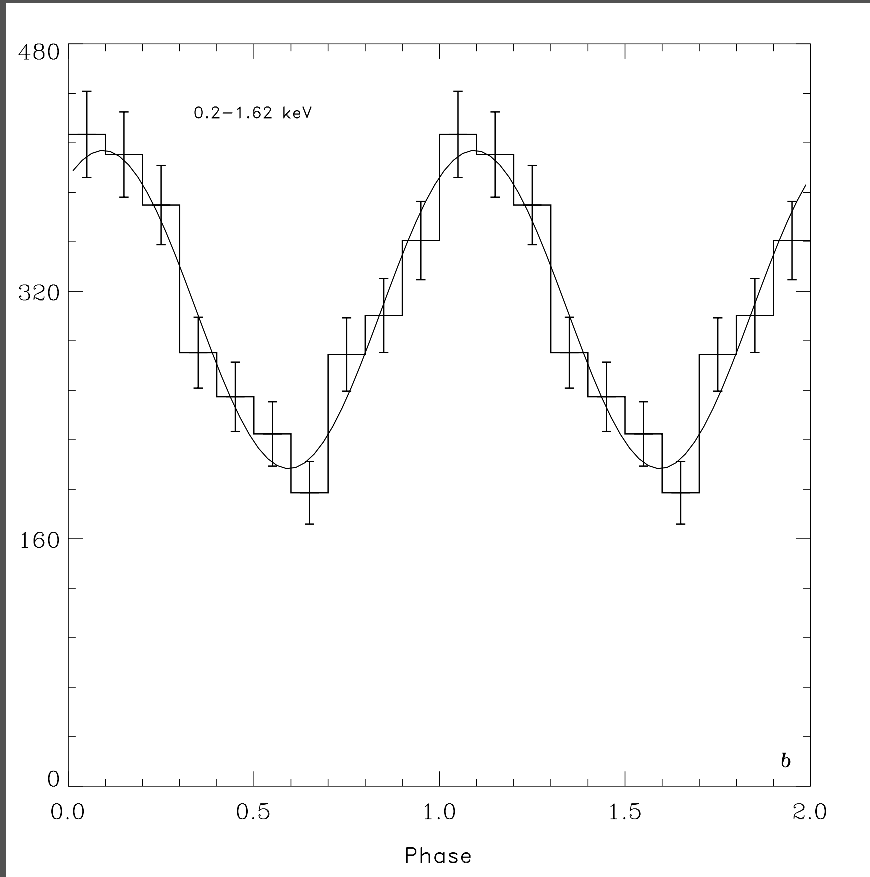
X-ray timing analysis (PN+MOS1&2)

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

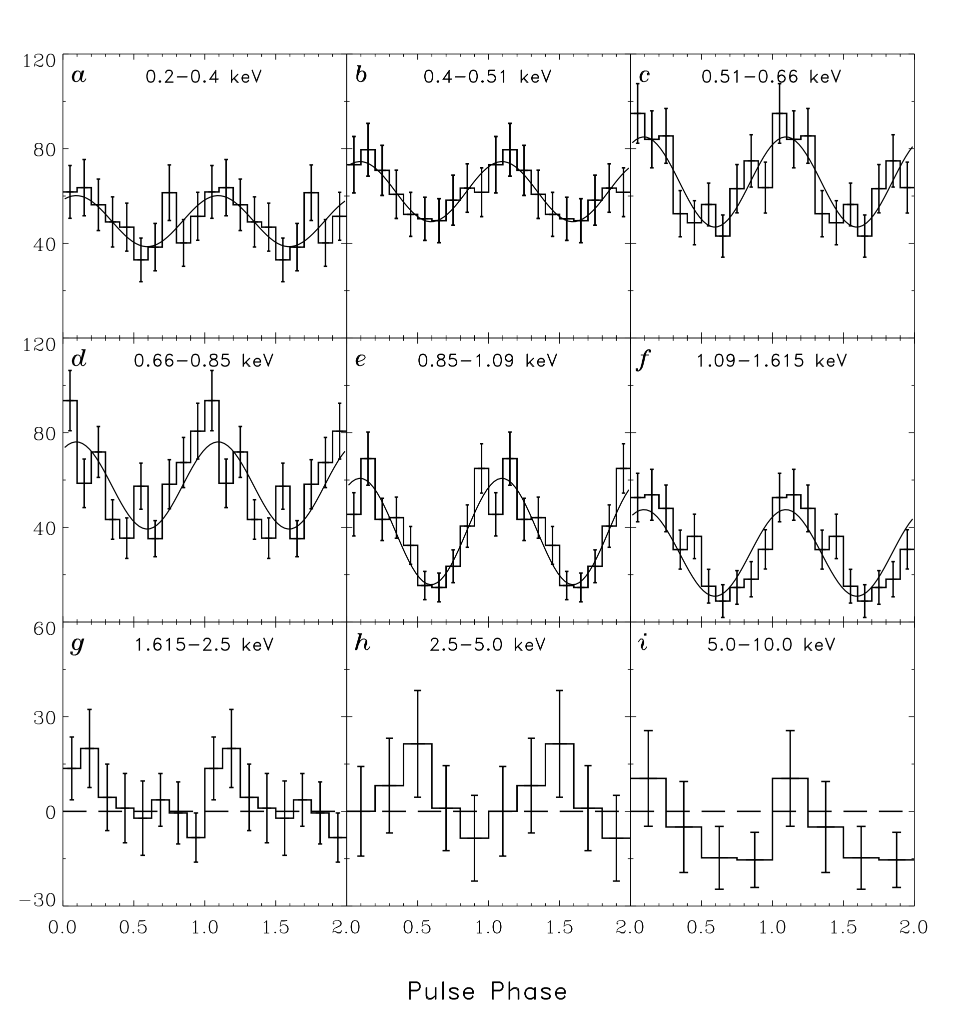


PSR B1822-09

Phase-resolved spatial analysis:
all counts from pulsar

Pulse detections
from 0.2 to 1.6 keV

No evidence for pulse shape
variations over this X-ray band



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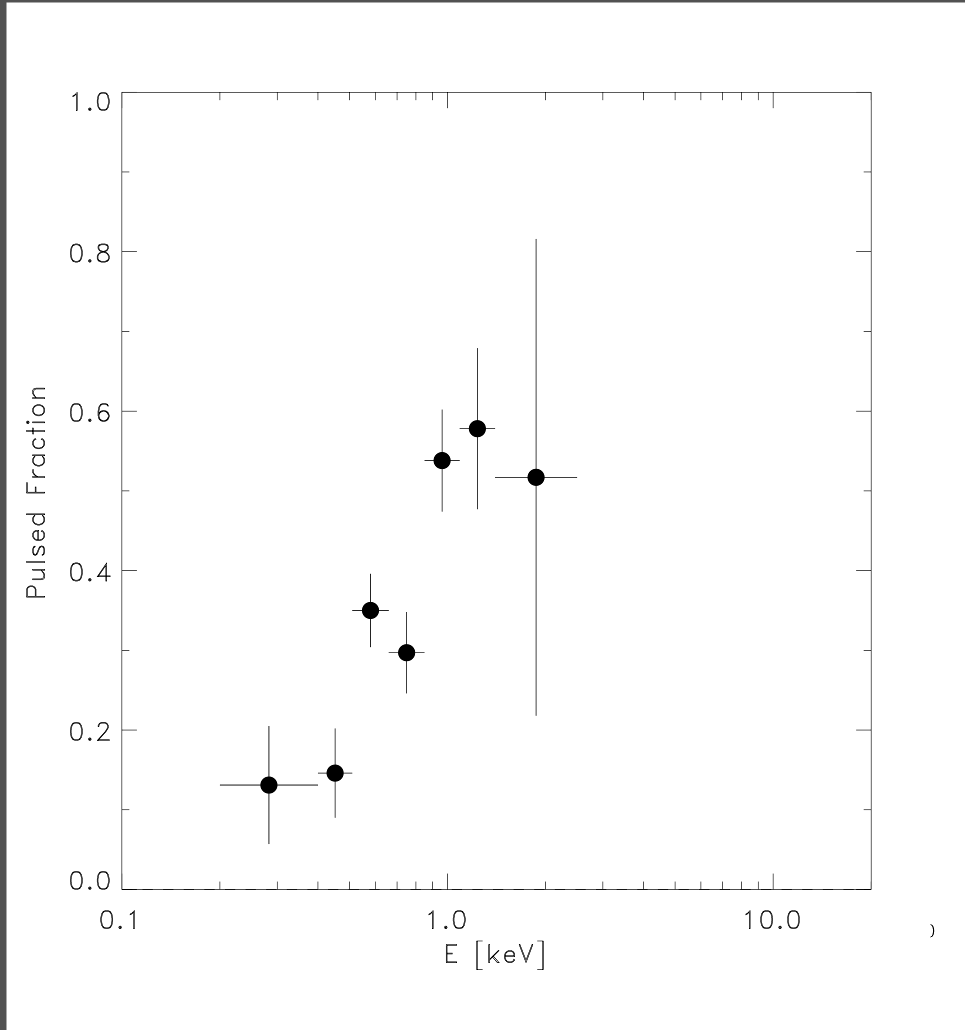
PSR B1822-09

Pulsed fractions determined in 3-dimensional Maximum Likelihood analysis.

Events sorted in 3-D space: two sky coordinates + pulsar phase



Pulsed fraction increasing from ~15% at 2 keV up to ~60% at 1 keV

➔ Spectrum pulsed emission much harder than that of unpulsed emission

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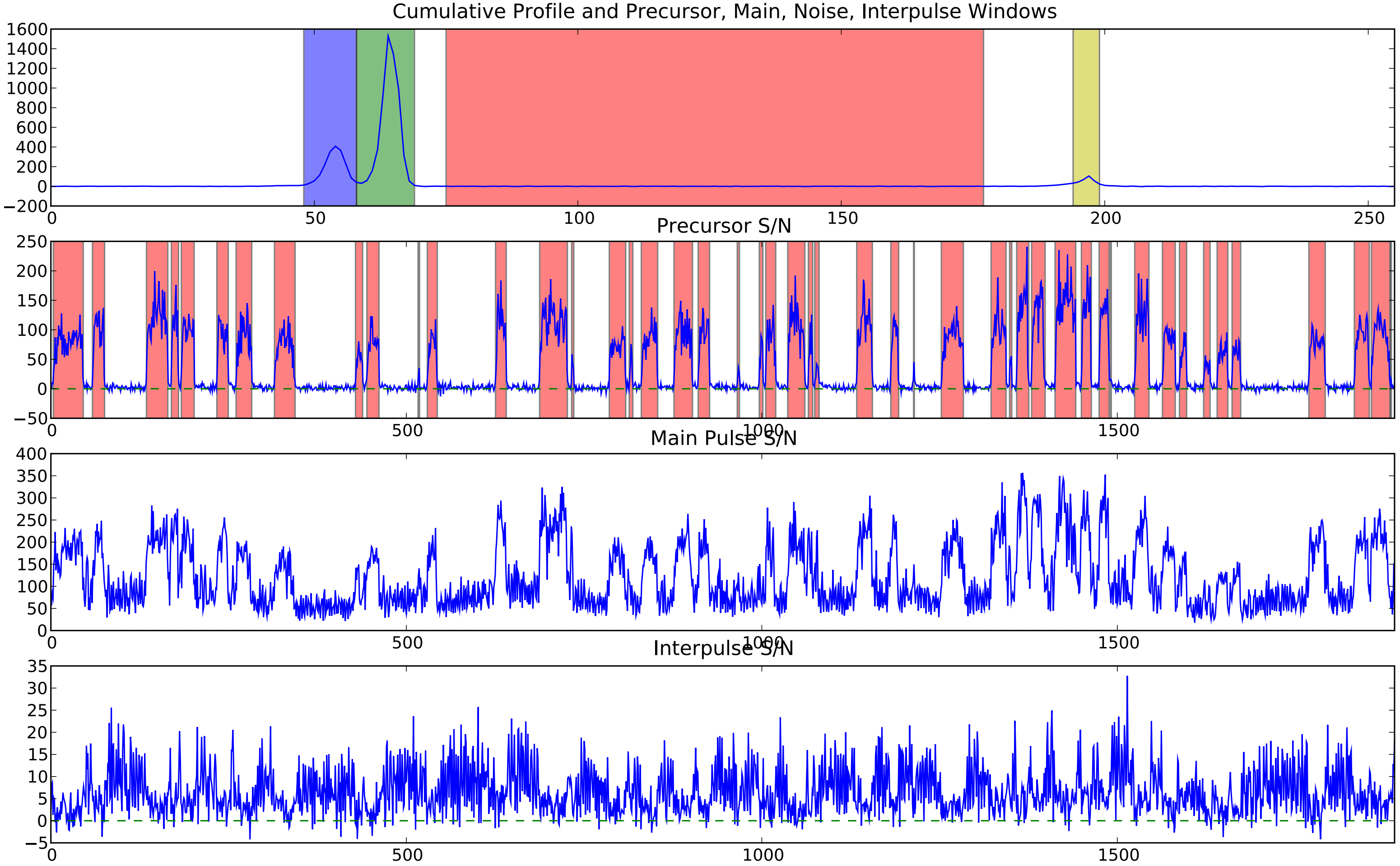
PSR B1822-09: X-ray mode switching ?

PSR B1822-09, 5.55 hrs observing with the WSRT



S/N of detection in bins of 10 s

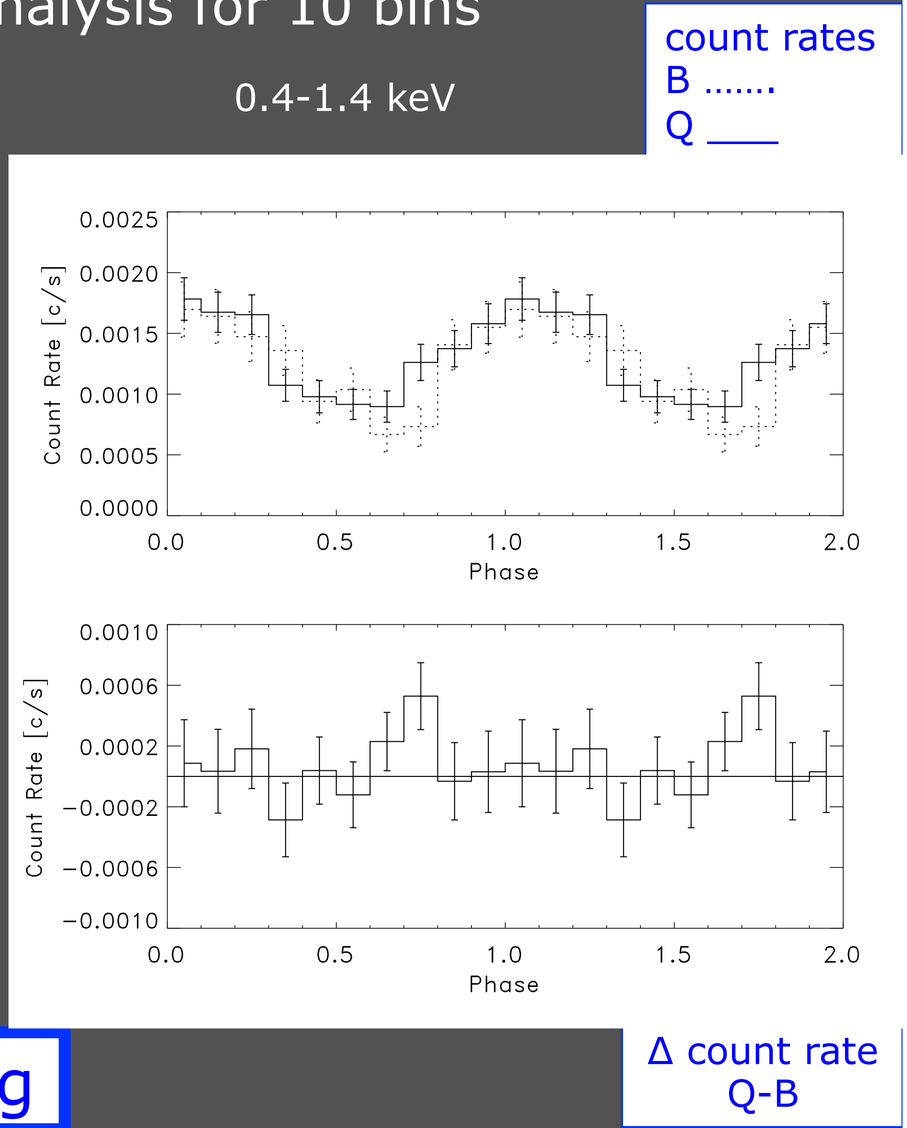
PSR B1822-09: phase distributions for Q and B intervals

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 of pulsed emission
- flux of unpulsed emission



No evidence for mode switching

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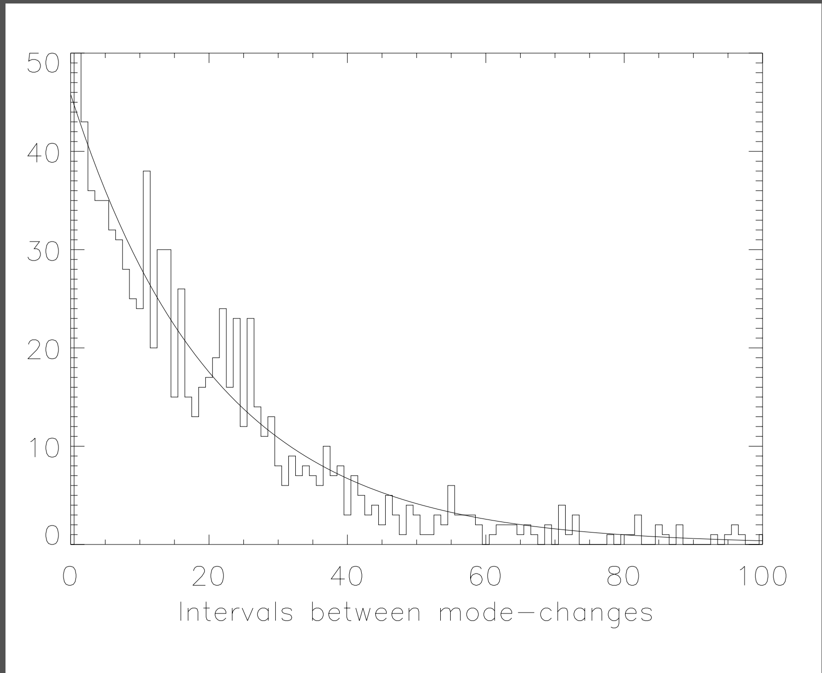
PSR B1822-09, WSRT observations



Duration mode intervals in bins of 10s:
~10 s to ~15 minutes

For PSR B0943+10 we had durations of ~0.5 to ~8 hours

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Spectral analysis

- Distance PSR B1822-09:
  -- Upper limit 1.9 kpc (Johnston et al. 2001),
  before Sagittarius – Carina arm
  -- 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

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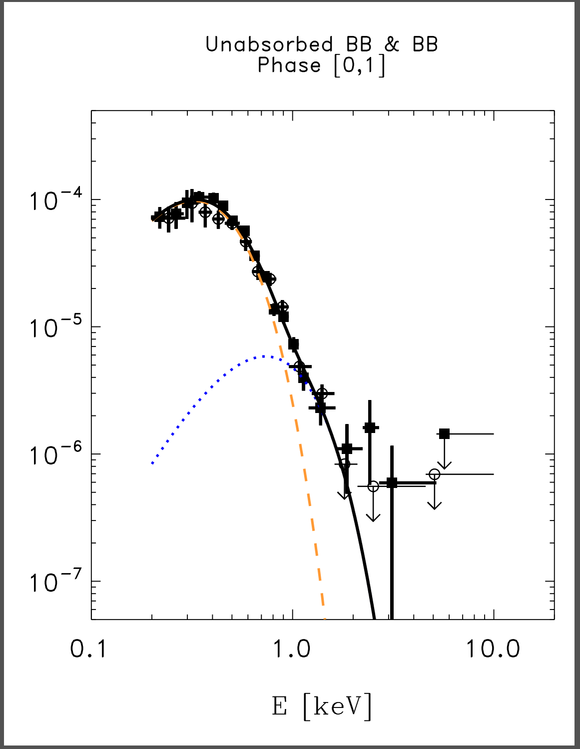
PSR 1822-09: Total-emission spectrum, fit model BB_{cool} + BB_{hot} (BB_1 + BB_2) (unabsorbed)

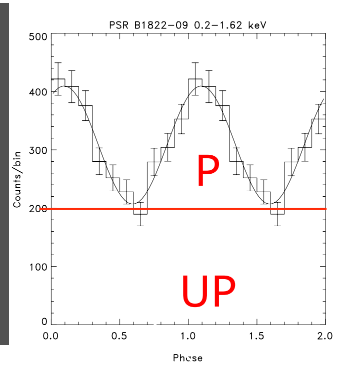
E^2 x Flux [keV^2/ cm^2.s.keV

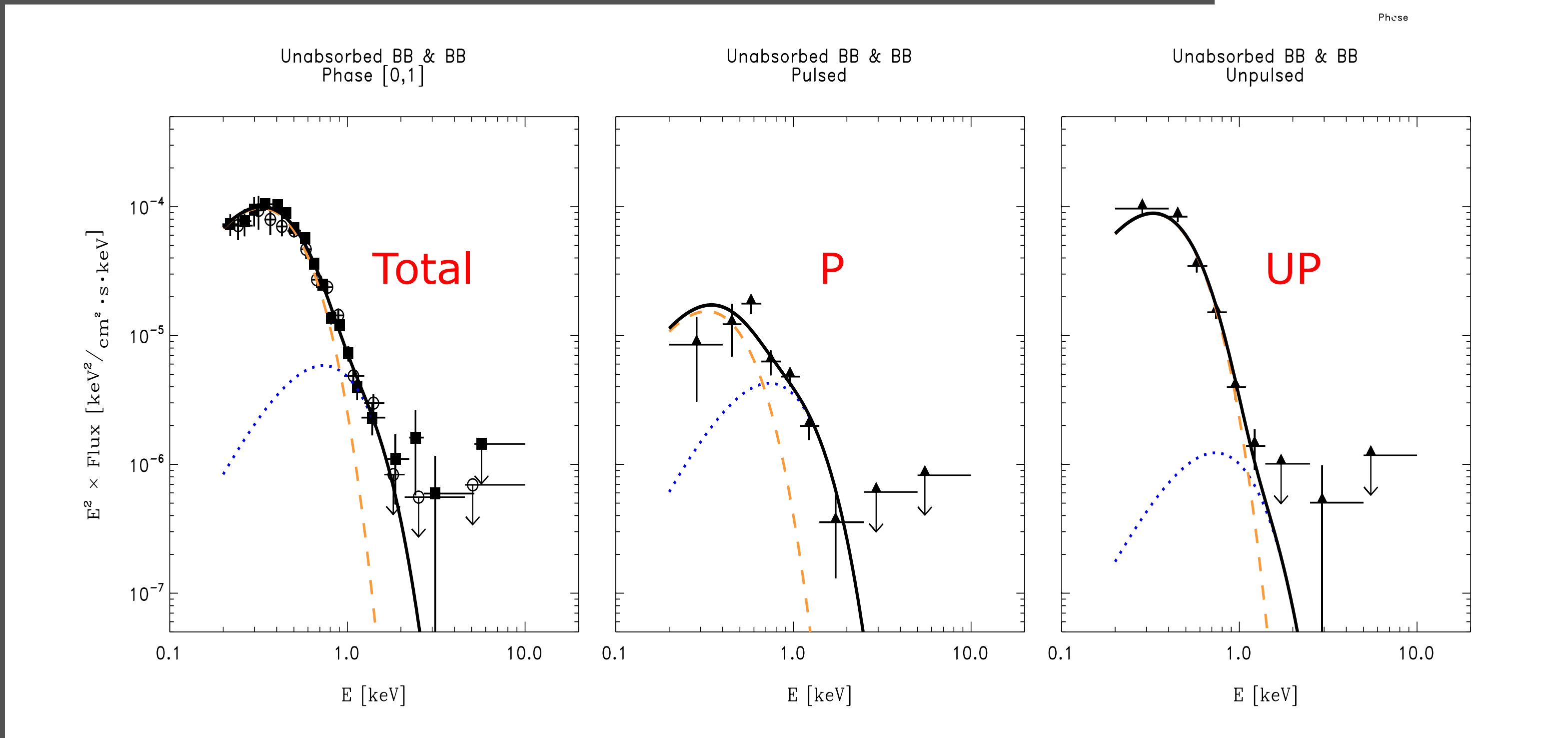


- **Best fit: BB_1 + BB_2; χ_r^2/ν = 1.14/28,**
- $N_H = (2.40^{+0.43}_{-0.41})\ 10^{21}\ cm^{-2}$
- BB_1: kT_1 = 0.083±0.004 keV (T=0.96 MK)
- $R_1 = (2039^{+427}_{-332})$ m (d = 1 kpc)
- F_1 (0.5-2 keV)= (3.2 ± 0.2) 10^{-14} erg cm^{-2} s^{-1} (unabsorbed)
- BB_2: $kT_2 = 0.187^{+0.026}_{-0.023}$ keV (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 1822-09: spectral fits for BB_{cool} + BB_{hot}
unabsorbed spectra





kT_c [keV]	0.083 ± 0.004	0.083	0.083
R_c [m]	2039 ± 380	811 ± 89	1940 ± 290
kT_h [keV]	$0.187^{+0.026}_{-0.023}$	0.187	0.187
R_h [m]	98^{+60}_{-25}	84 ± 5	45 ± 11

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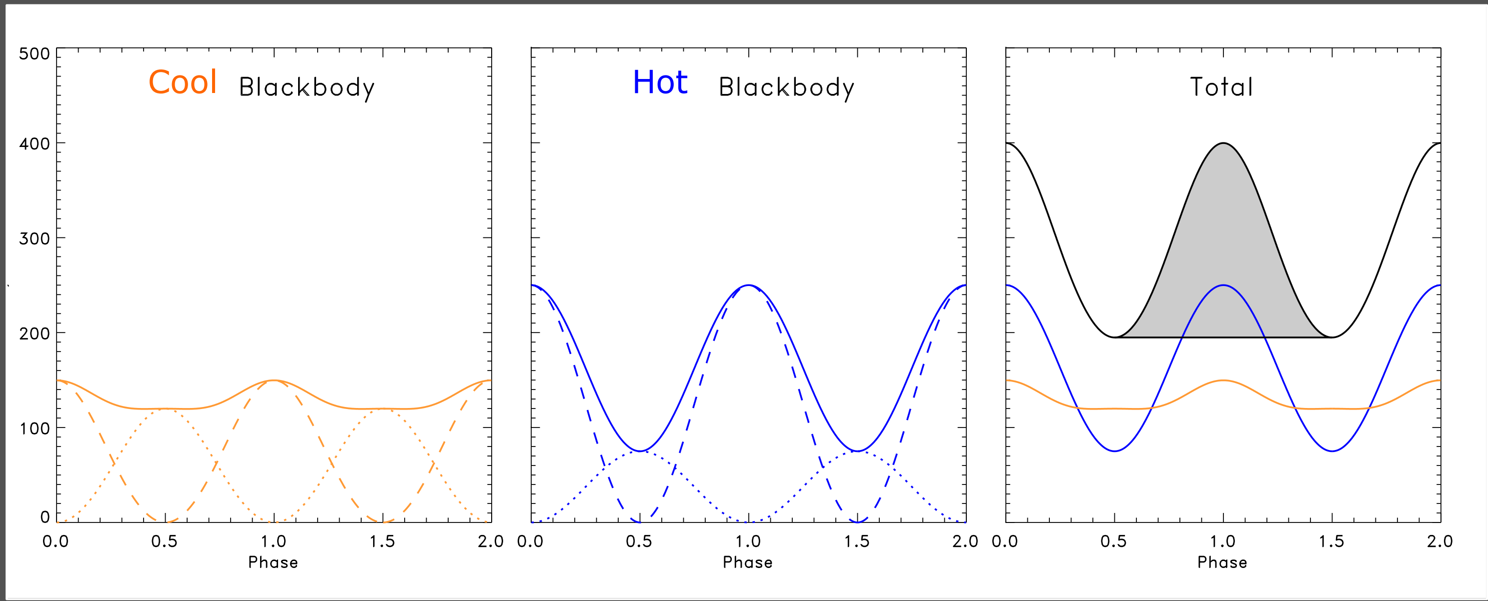
PSR B1822-09: cartoon, consistent with spectral and timing analysis



Broad cool pulses
MP + IP(~75% of M)

kT ≈ 0.083 keV

R ≈ 2000 m

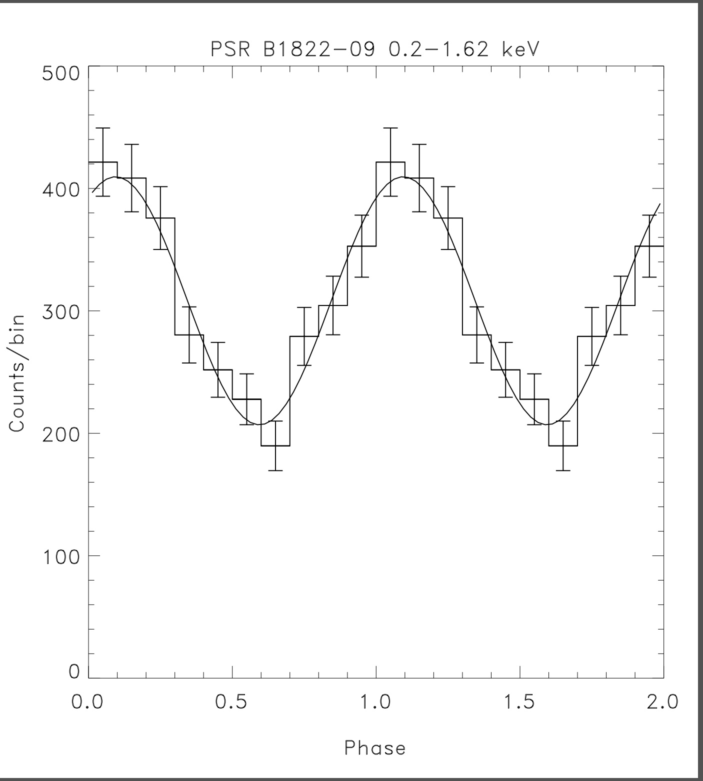
Narrow hot pulses
MP + IP(~15% of M)

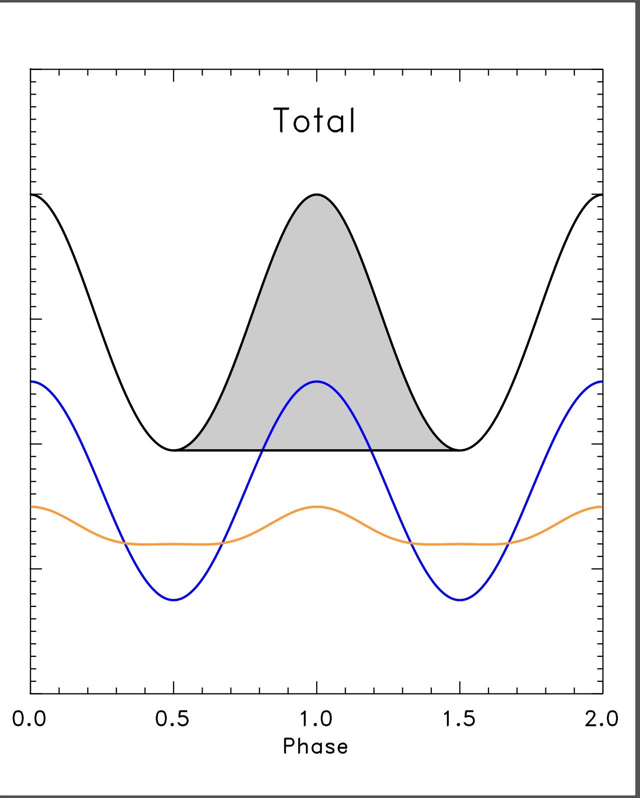
kT ≈ 0.187 keV

R ≈ 90 m

Summed total profile

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


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


Total
Phase
0.0
0.5
1.0
1.5
2.0

Detection of PSR B1822-09 with Fermi LAT?

Fermi 4 August 2008 – 9 December 2015

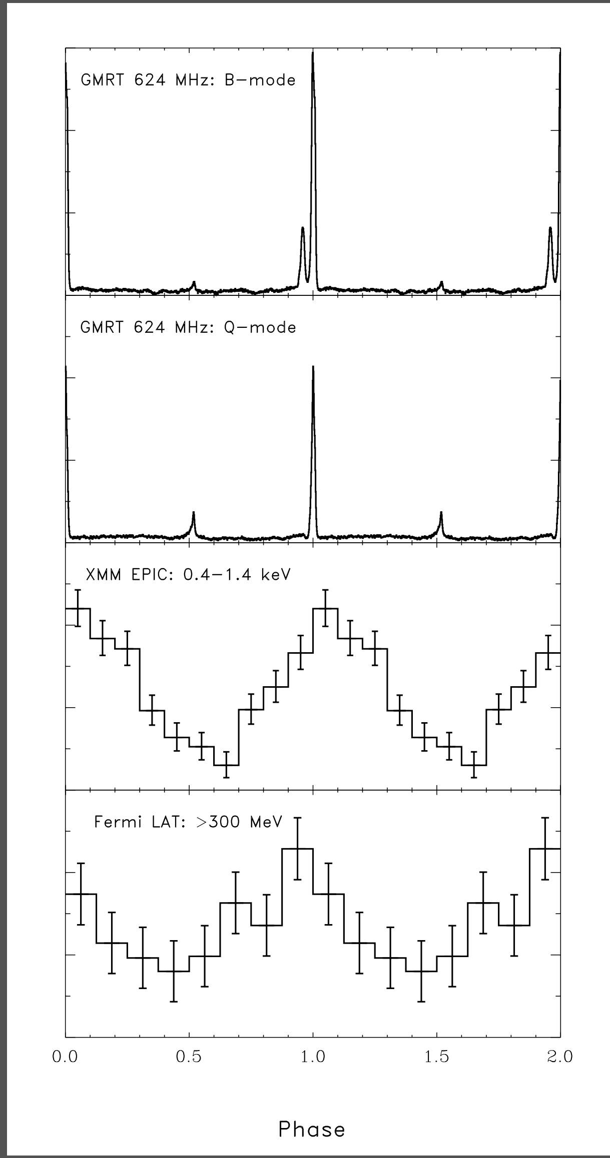
Extended Jodrell Bank ephemris

Energy-dependent aperture (68% source counts)

X-ray maximum at phase 1.094 ± 0.017

2.7σ detection, or 0.66% chance probability

γ-ray maximum at phase 0.92 ± 0.05
shifted 3.3σ w.r.t. X-ray maximum



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How to reconcile X-ray characteristics with an orthogonal geometry as concluded from radio characteristics ?
Impact angle small

- PSR B1822-09 has $B_p = 6.4 \times 10^{12}$ G
- **Magnetic beaming**?

  If so, then:

  -- Hot (2.2 MK) X-ray emission from primary spot (main pulse) beamed in our direction (R ≈ 90 m)

  -- Hot (2.2 MK) X-ray emission from antipodal spot (inter pulse) (mostly) beamed away from us

  -- Cool (0.96 MK) unpulsed emission seen from both poles (R ≈ 2km), but ~30% more from MP than from IP

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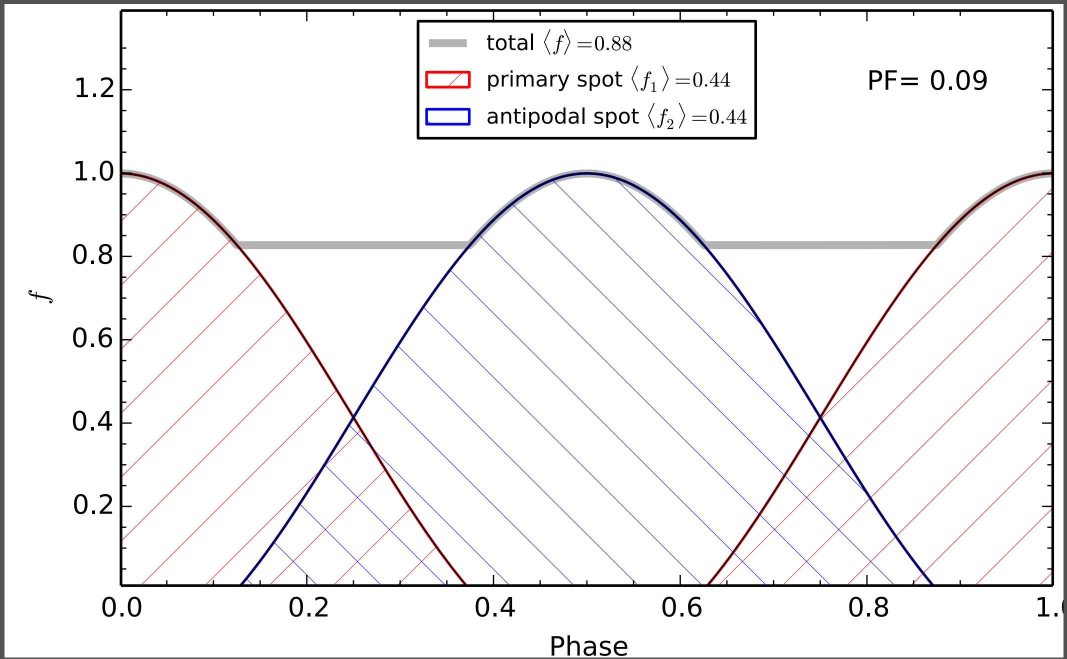
Isotropic thermal emission from both poles?

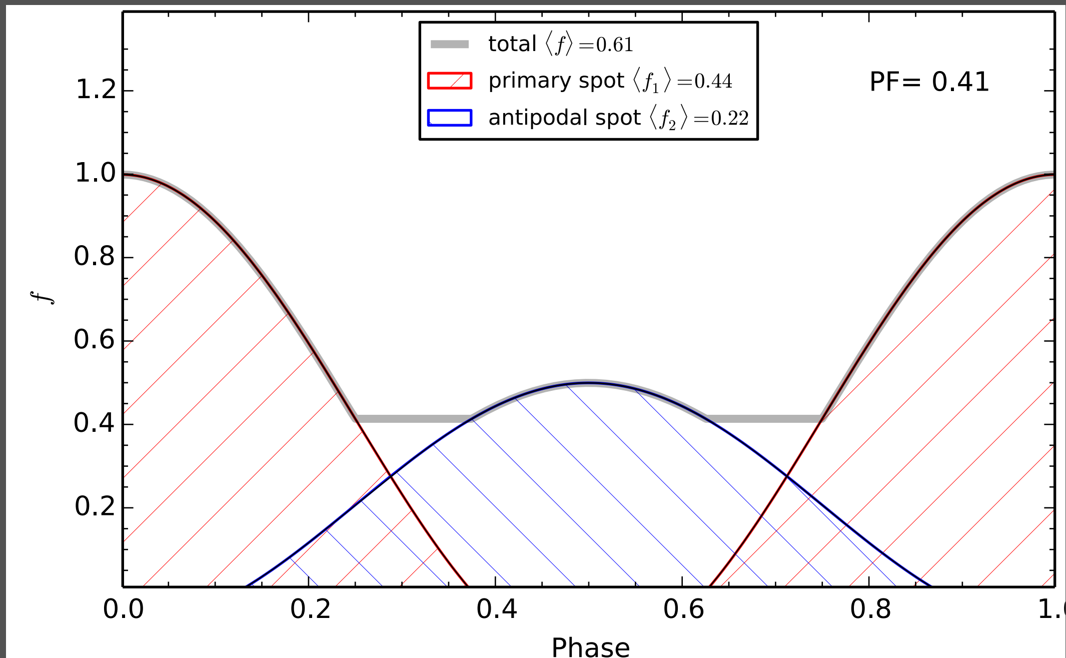
X-ray pulsed fraction 0.8 – 1.6 keV ~60 %
Hot pulse is nearly 100% pulsed



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

Isotropic thermal emission from both poles?

X-ray pulsed fraction 0.8 – 1.6 keV ~60 %
Hot pulse is nearly 100% pulsed



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

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Short summary

- 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.
- For PSR B1822-09 as well as for PSR B0943+10 the X-ray pulse profiles difficult to reconcile with radio-derived geometries: magnetic beaming
- X-ray emission from PSR1822-09 can be explained as emission from opposite poles, each with cool (T≈1MK, R≈2 km) and hot (T ≈ 2.2 MK, R≈100m) components.
- 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 ?)

New campaign: Mode-switching Pulsar PSR B0823+26

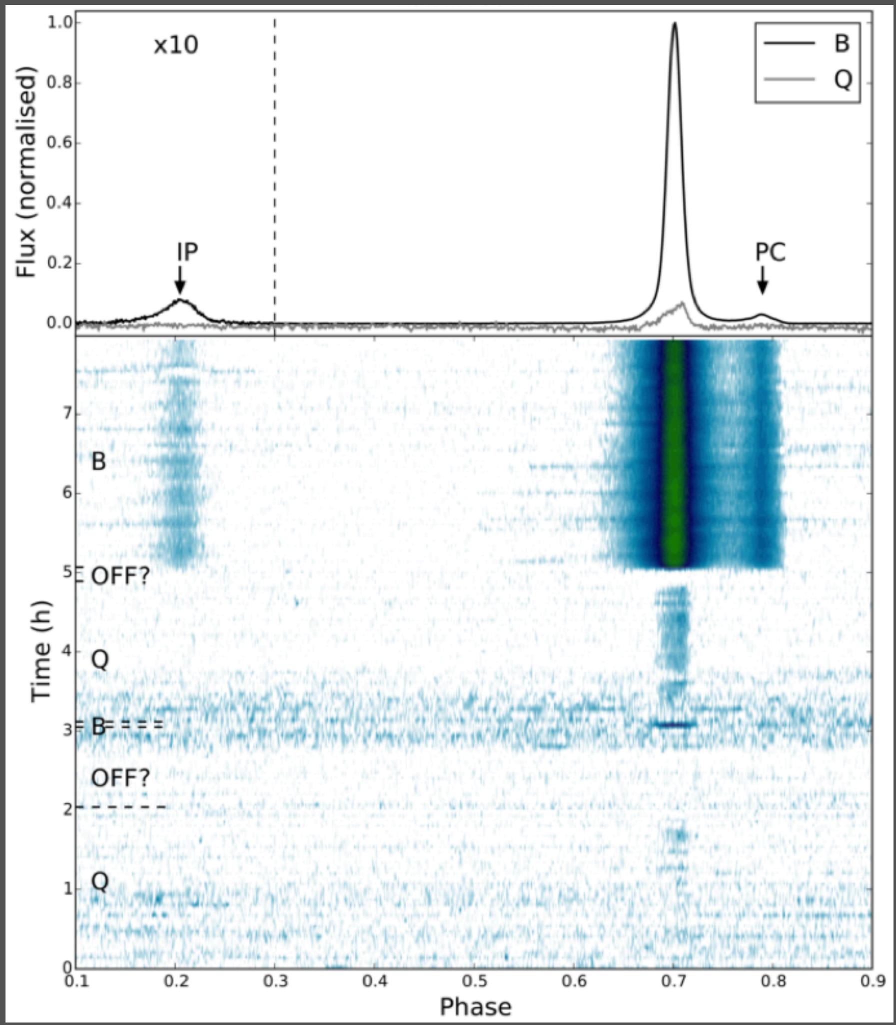
Characteristics: PSR B0823+26

- P = 0.53 s
- B_p = 9.8 x 10^{11} G
- T = 4.9 x 10^6 yr
- Distance ~340 pc

- **orthogonal** rotator ?

- PSR B0823+26 also switches between radio B(right) and Q(uiet) mode (nulling?) Mode durations minutes to several hours

XMM-Newton 150 ks + GMRT



Sobey et al. 2015; LOFAR

SRON

Thank you for listening!