XMM-Newton revealed synchronous X-ray and radio-mode changing in a pulsar: a bi-stable emission behaviour requiring global magnetospheric changes

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Outline

- Introduction: pulsar mode switching
- Simultaneous radio and X-ray observations of PSR B0943+10: X-ray results from spatial, timing and spectral analyses
- Dilemma's
- Conclusions

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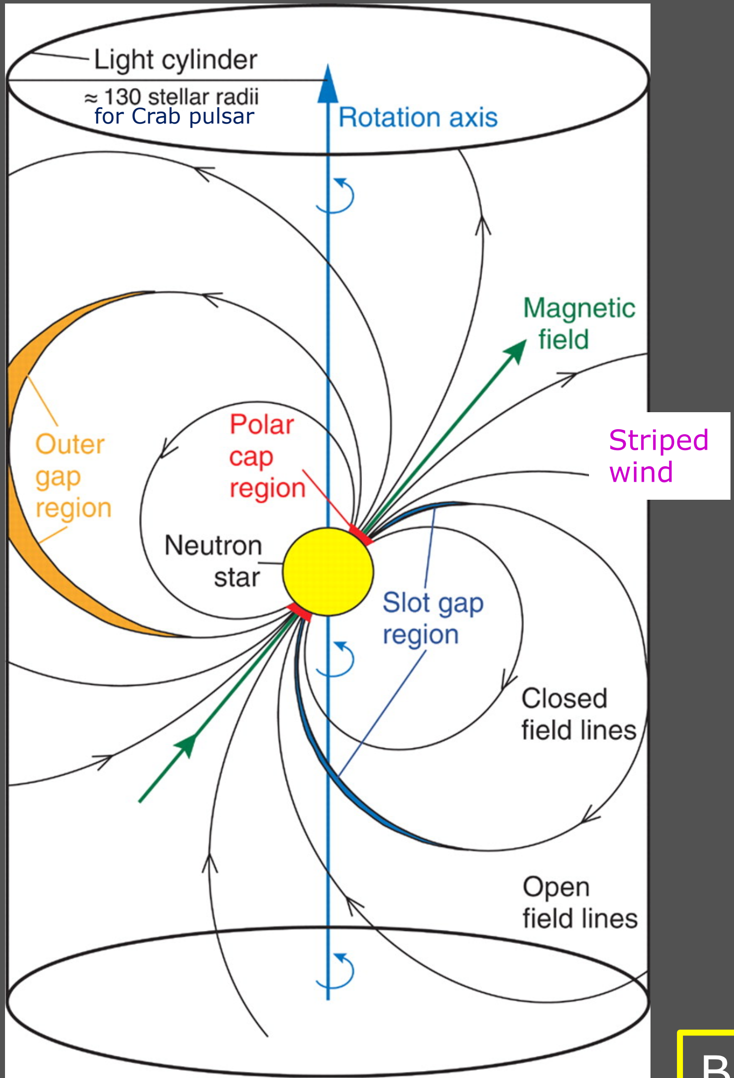
- Introduction: pulsar mode switching

The Problem of Pulsar Radiation

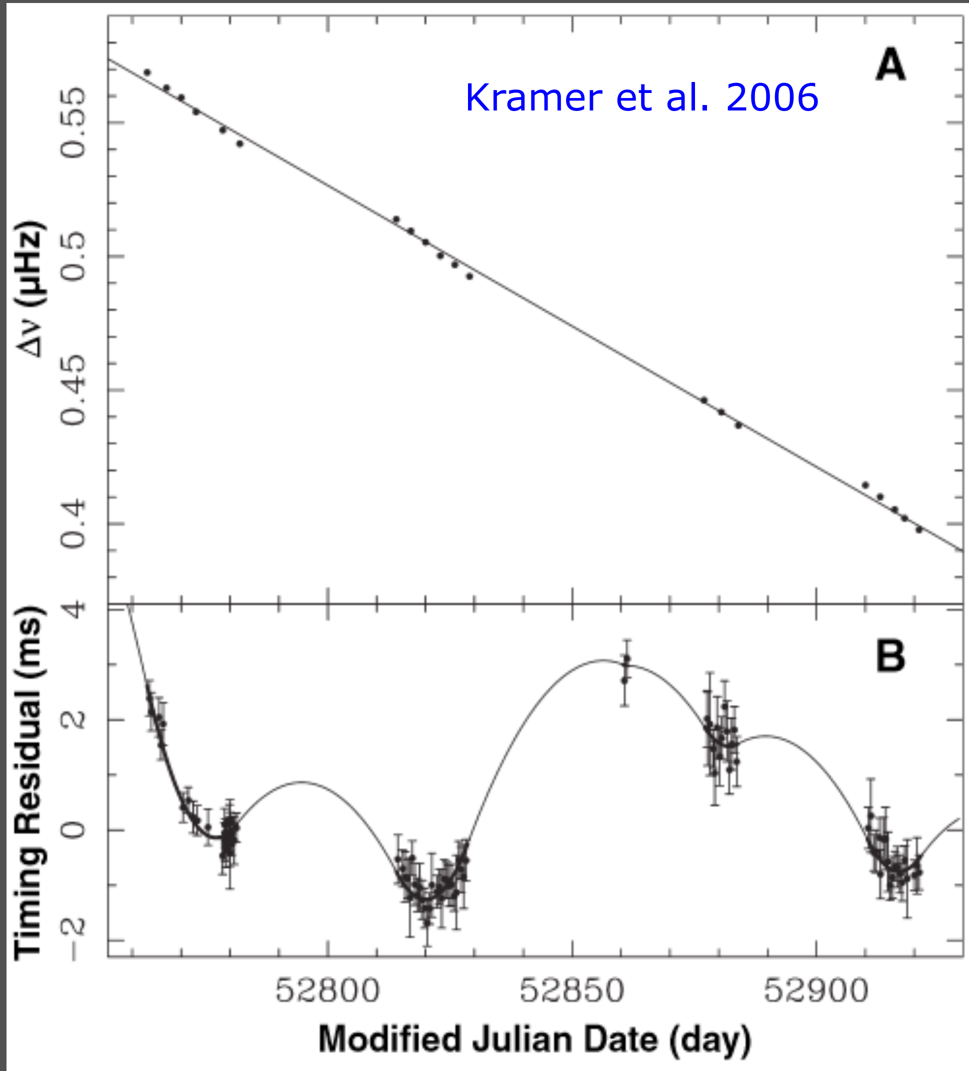


- Radio beams from magnetic poles sweep across the Earth like a lighthouse
- Thermal X-rays from hot surface and/or bombarded hot polar cap
- Non-thermal high-energy emission from Slot Gap, Outer Gap or Striped wind?

But, how, where is radio emission produced?

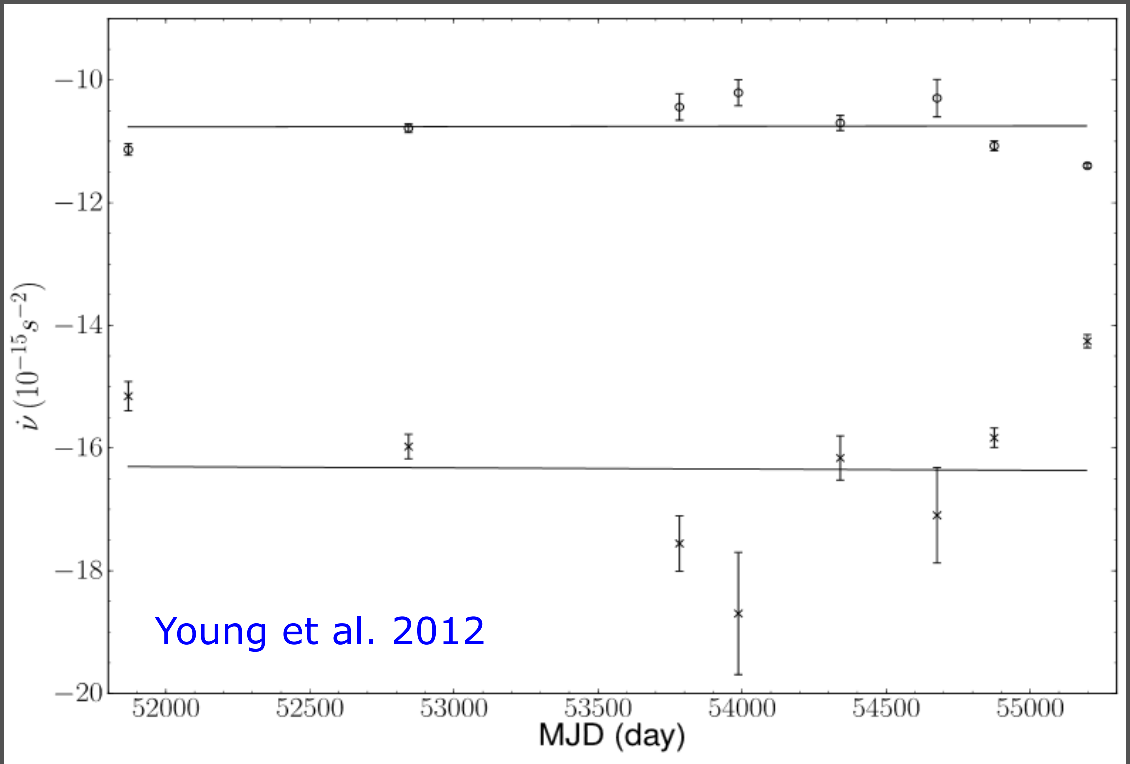
PSR B1931+24, the intermittent pulsar

- **Ceases emitting for tens of days**
- Radio emission "on" → large spin-down.
- Change in spin-down (factor 1.5) caused by a change in the pulsar wind.
- Implied charge density change: ρ_{GJ}
- Radio emission is a probe of drastic changes in the magnetosphere.



PSR B1931+24, the intermittent pulsar

- Young et al. 2012 analysed 13 years of data of PSR B1931+24.
- Spin-down rates in the on/off modes appear to be stable over time: truly bimodal



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Further Evidence for Rapid, Global, Magnetospheric Changes

- Several other pulsars display smaller changes in spin-down rate that correlate with changes in pulse shapes (Lyne et al. 2010).

- Behaviour similar as found for PSR B1931+24 has recently been reported for
  PSR J1841-0500 (Camilo et al. 2012) and
  PSR J1832+0029 (Lorimer et al. 2012)

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- Simultaneous radio and X-ray observations of PSR B0943+10: X-ray results from spatial, timing and spectral analyses

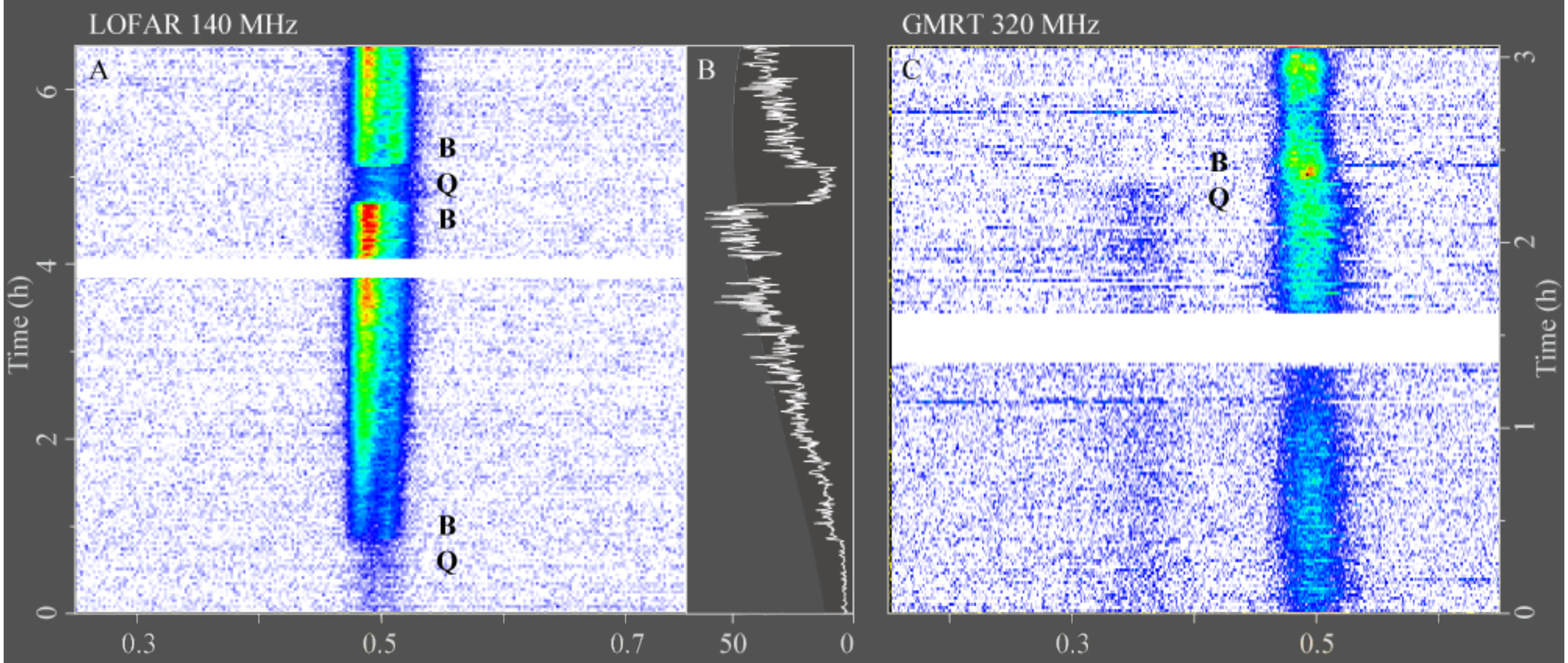
Simultaneous X-ray and radio observations of PSR B0943+10

Characteristics of PSR B0943+10

- $P = 1.10$ s
- $\dot{P} = 3.5 \times 10^{-15}$
- $\dot{E} = 10^{32}$ ergs s^{-1}
- $B_p = 2 \times 10^{12}$ G
- $T = 5 \times 10^{6}$ yr
- mode switching between B(right) and Q(uiet) mode

Zhang et al. 2005: B0943 is weak X-ray source;
Spectrum thermal or non-thermal

PSR B0943+10 mode switching with LOFAR and GMRT



Pulsar phase

Simultaneous X-ray and radio observations of PSR B0943+10

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- mode switching between B and Q mode

6 x 6 hrs
XMM-Newton 0.2-10 keV
LOFAR 140 MHz
GMRT 325 MHz

Aim: to learn about the pulsar inner accelerator by studying any correlation between the X-ray emission characteristics and mode changes in the radio emission

Hermsen et al. 2013 (Science 339, 436)

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XMM-Newton observation times (ks), November – December 2011

Date /CCDs	4/11	6/11	21,22 /11	27,28 /11	1,2/12	4/12*	Mode
PN	15.3	24.2	23.0	20.7	20.8	19.0	Full Frame
MOS-1	21.7	25.9	24.7	22.3	22.5	20.7	Small Window
MOS-2	21.7	25.9	24.7	22.4	22.5	20.7	Small Window

* Too many soft proton flares: data not usable

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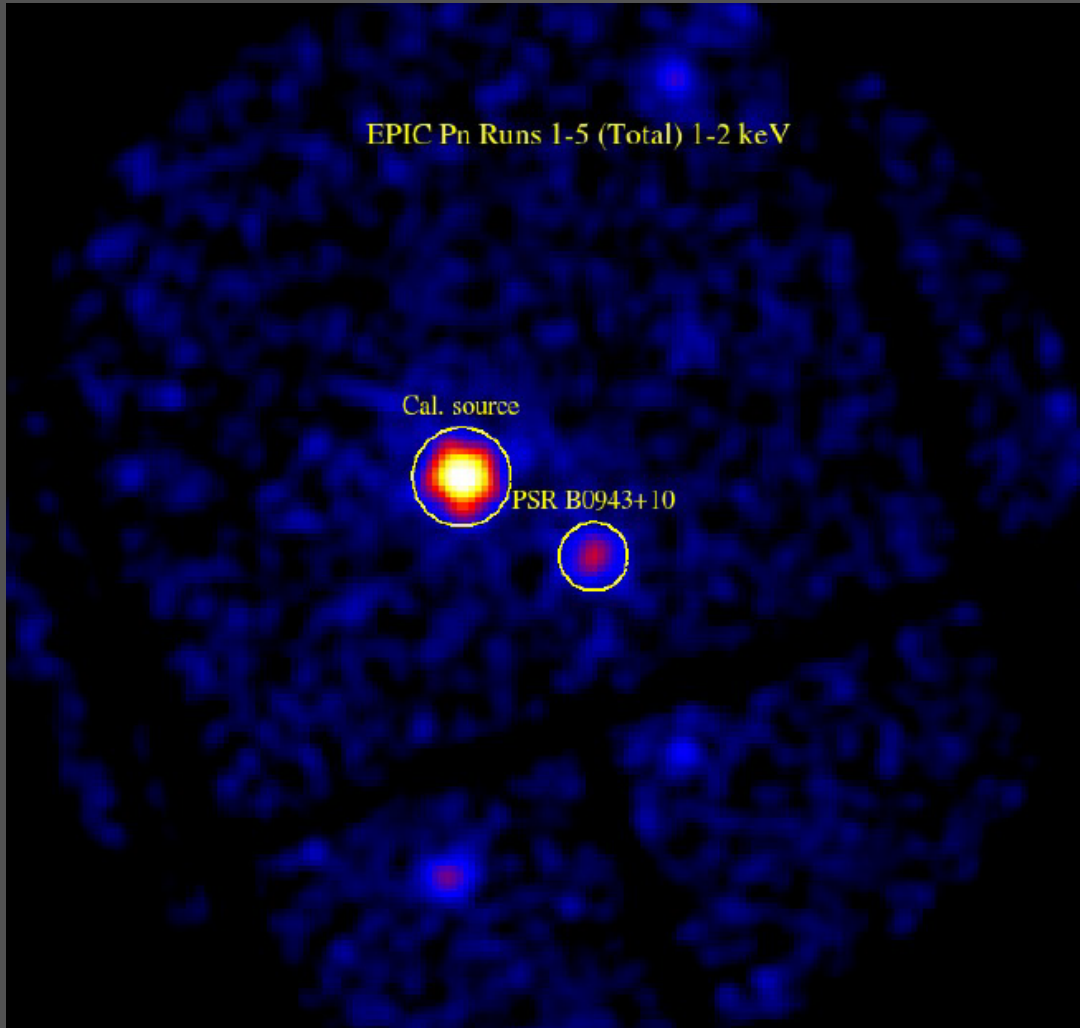
- Spatial analysis

XMM-Newton raw-counts skymap, PN, 104 ks, 1–2 keV



20 σ detection PSR B0943+10

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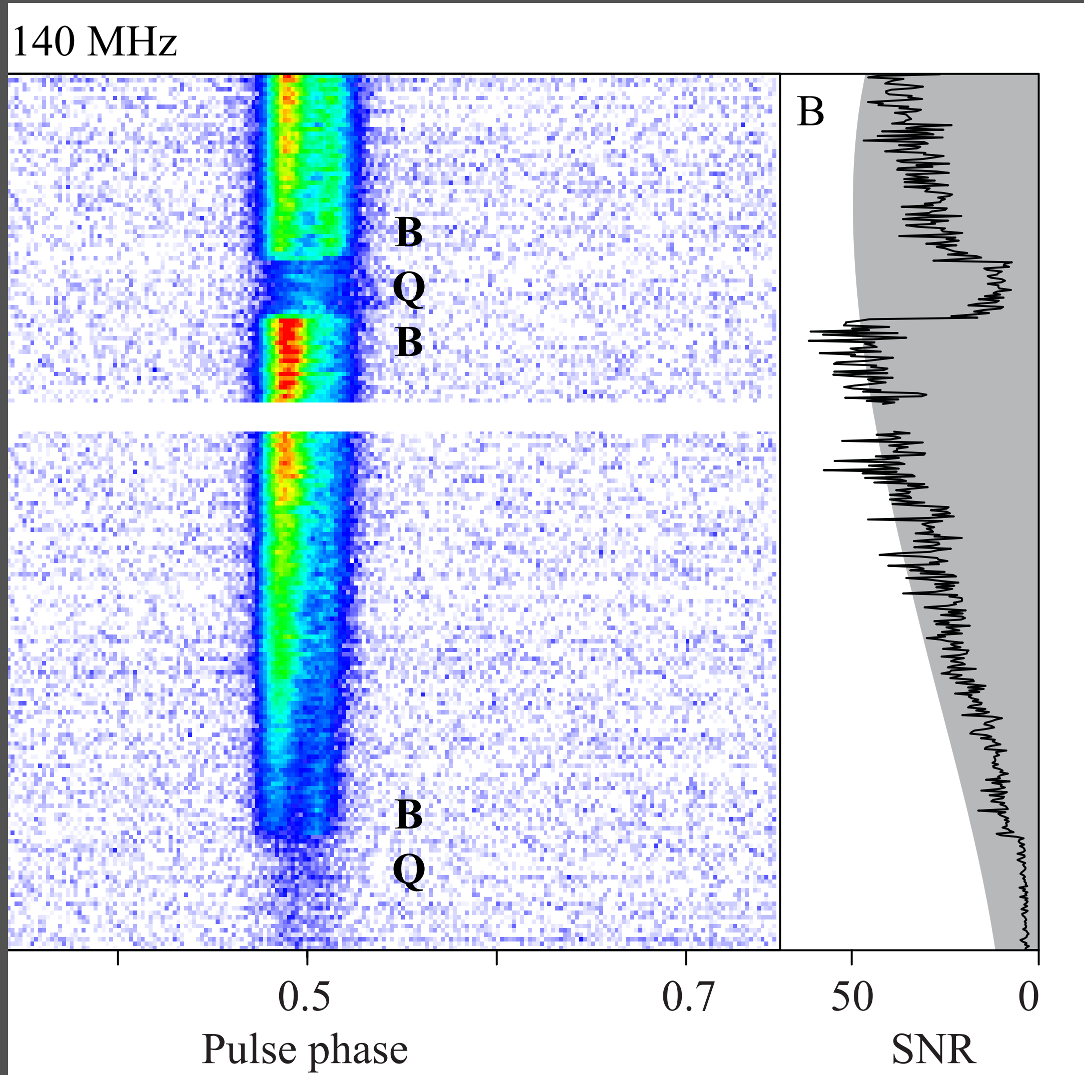
Q-to-B-Mode Transitions in B0943+10

LOFAR

Observation #1

Q- and B-mode time windows can be derived using the LOFAR and GMRT observations taken simultaneously with XMM-Newton



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

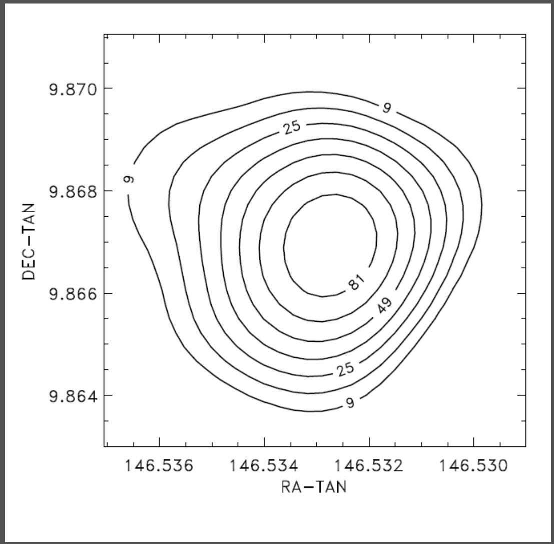
B-mode windows

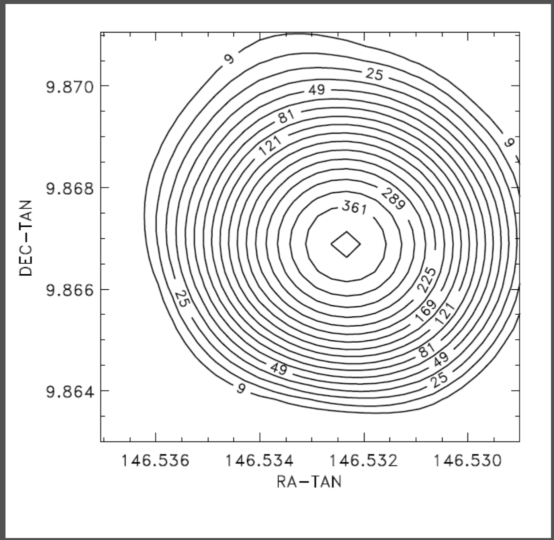
t_{eff} 39.7 ks

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

Correlated Radio – X-ray mode change !
Anti correlation !

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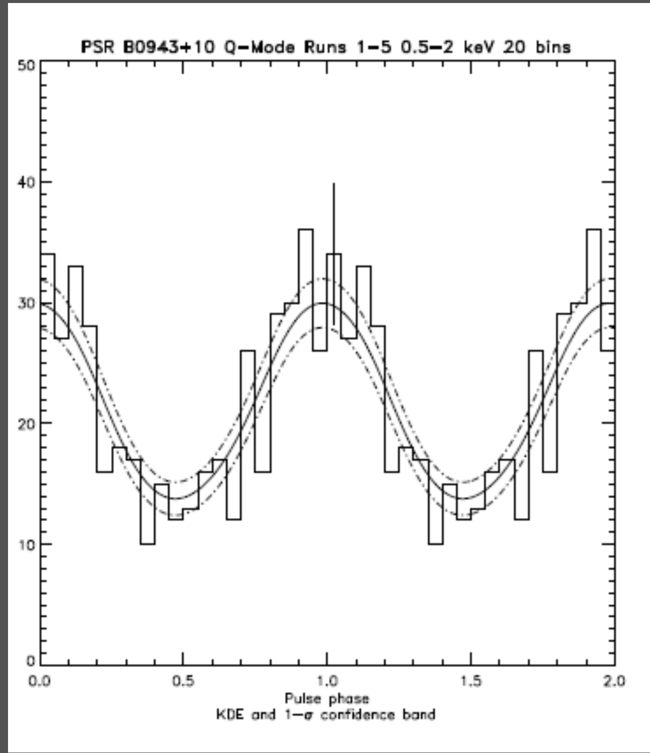
- Timing analysis

Detection of X-ray pulsation in radio Q-mode windows

Phase folding with Jodrell Bank radio ephemeris



6.6 σ detection
0.5 – 2 keV
EPIC PN + MOS-1+MOS-2

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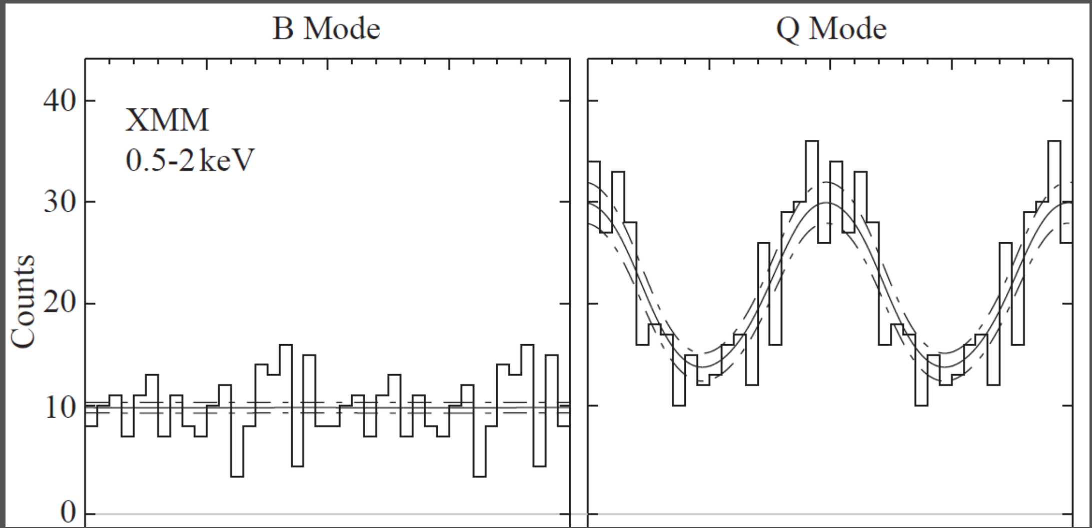
No detection of X-ray pulsation for radio B mode !

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



The difference between X-ray emissions emitted in radio B mode and Q mode is the addition of a pulsed component in Q mode !

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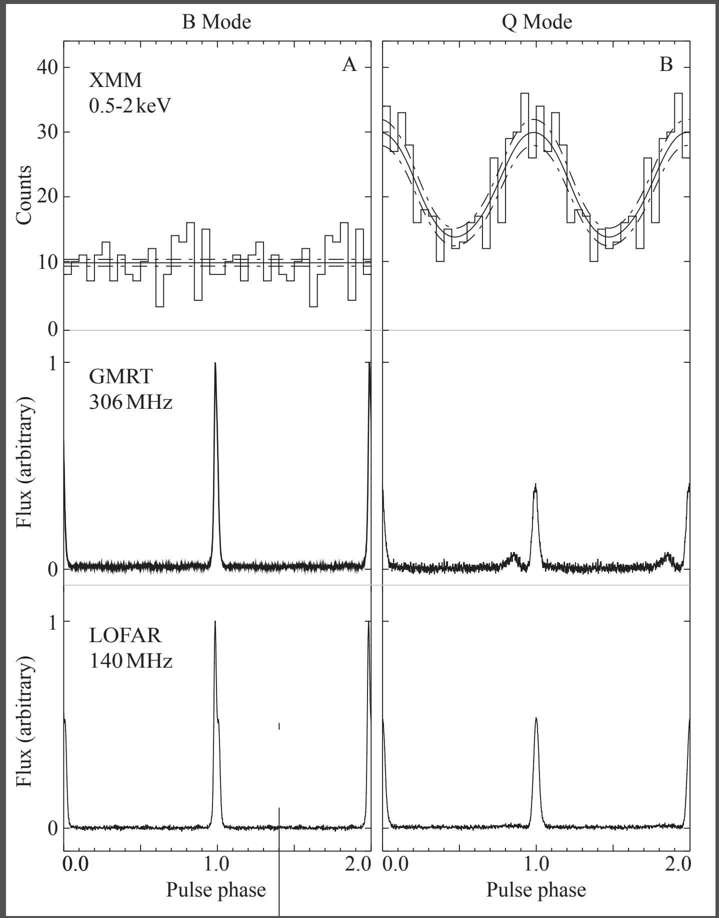
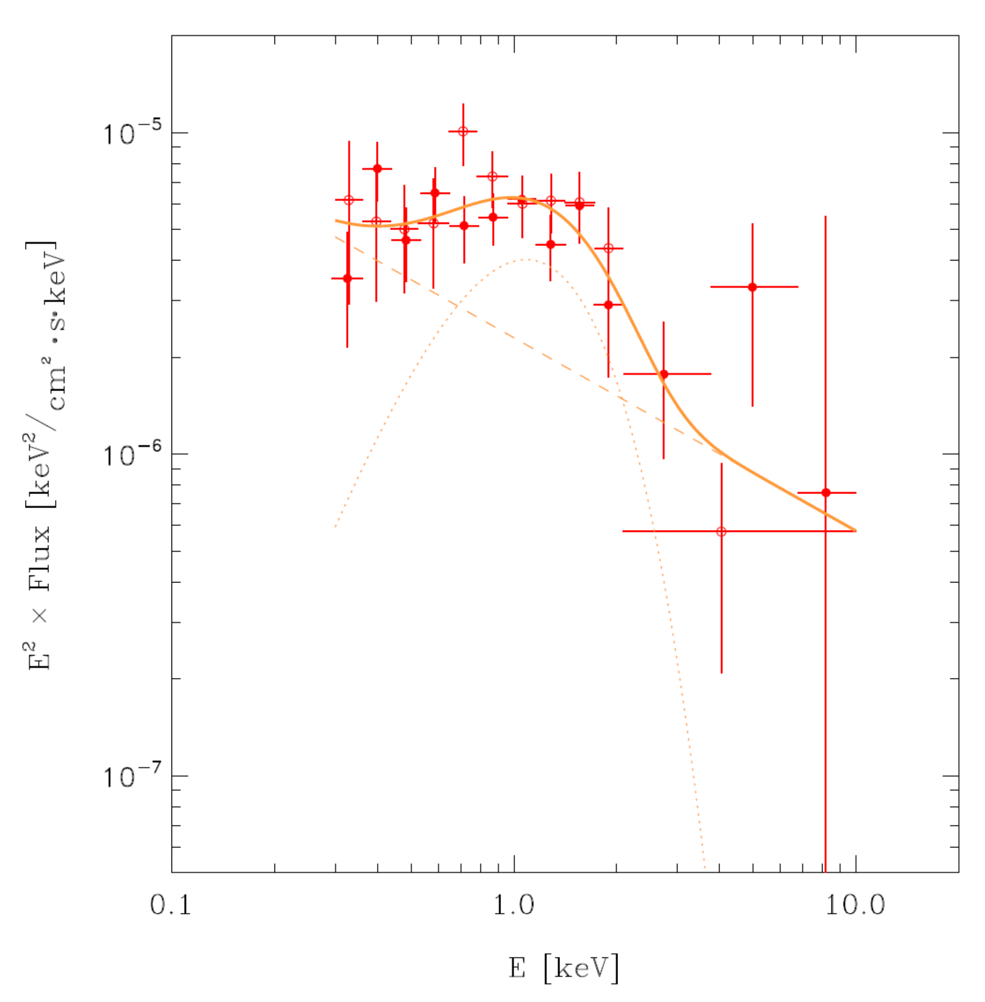
Phase alignement radio v.s. X-ray profiles

- Broad X-ray pulse in **Q-mode** data includes phases of main radio pulse and **precursor**
- Appearance of precursor in Q mode related to pulsed X-ray component?



- Spectral analysis

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



- Maximum Likelihood analysis of skymaps
- EPIC PN: ●
- EPIC MOS-1 + MOS-2: o

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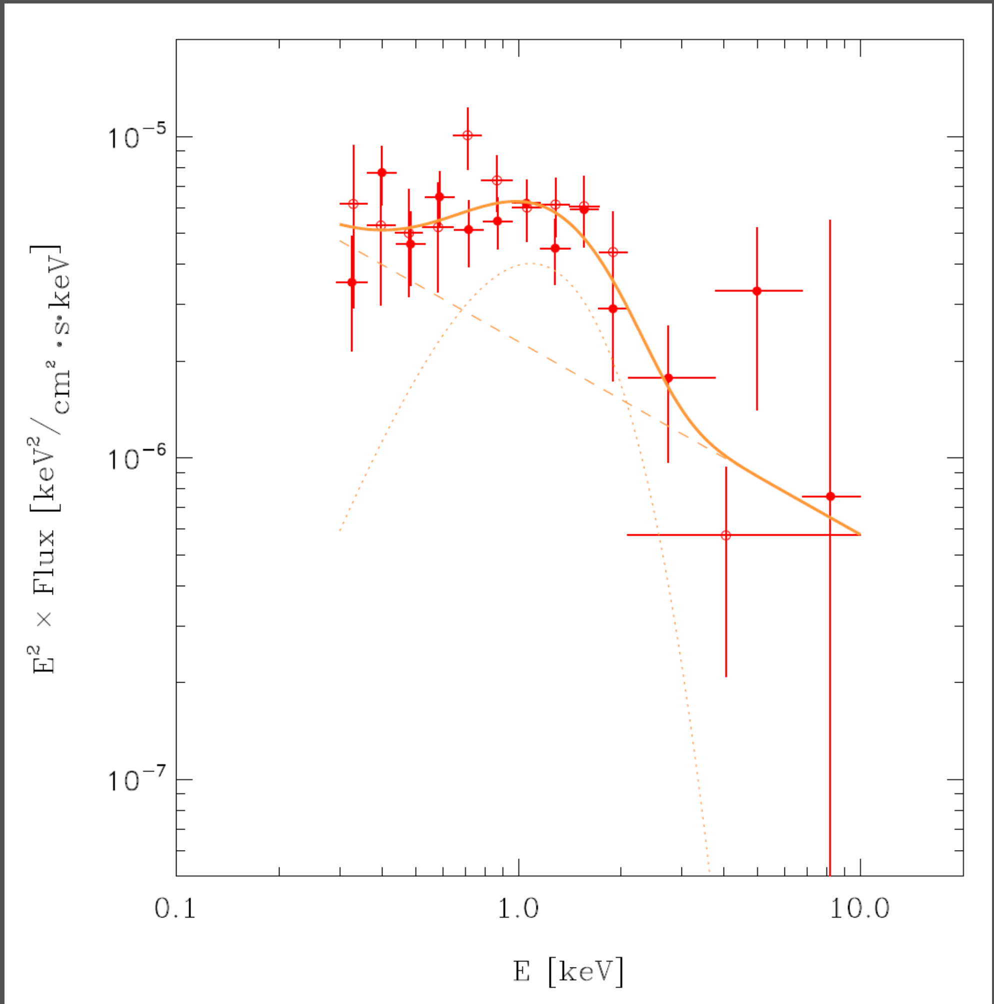
Total emission X-ray spectrum of PSR B0943+10: radio **Q mode**



- **Best fit: BB + PL; χ^2_ν = 0.81**
- N_H = 4.3 x 10^{20} cm^{-2} (fixed)
- BB: kT = 0.277 ± 0.012 keV

  PL: Γ = -2.60 ± 0.34
- F_{BB} (0.5-8 keV)= (7.5 ± 2.2) 10^{-15} erg cm^{-2} s^{-1} (unabsorbed)
- F_{PL} (0.5-8 keV)=(7.6 ± 1.8) 10^{-15} erg cm^{-2} s^{-1} (unabsorbed)
- $R_{hot\ spot}$ ≈ 24 m (d = 630 pc)

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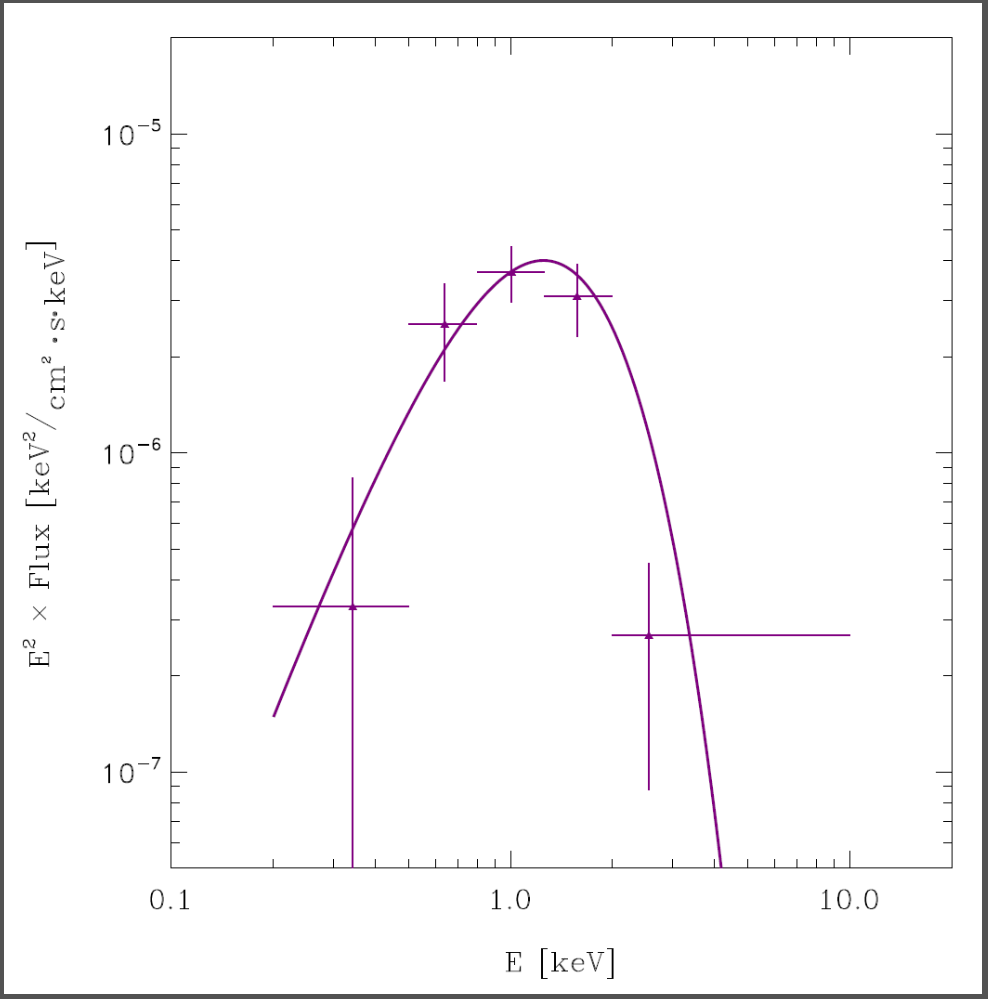
Pulsed emission X-ray spectrum of PSR B0943+10: radio **Q mode**



- **Best fit: BB; χ^2_ν = 1.14/3, 38%**
- 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)

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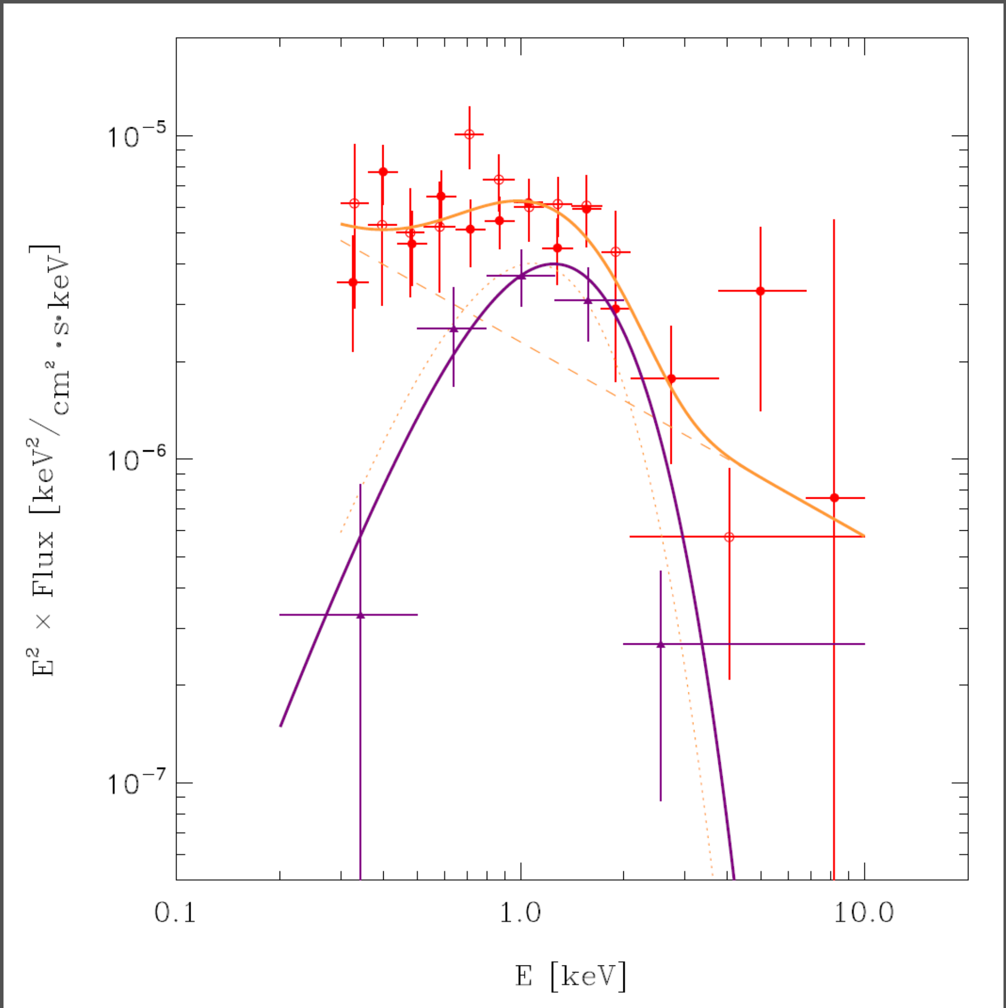
Total + pulsed X-ray spectra of PSR B0943+10: radio Q-mode



BB component in total emission is same component as pulsed BB emission (!)

Δ flux = 0.1 σ
Δ kT = 2.5 σ

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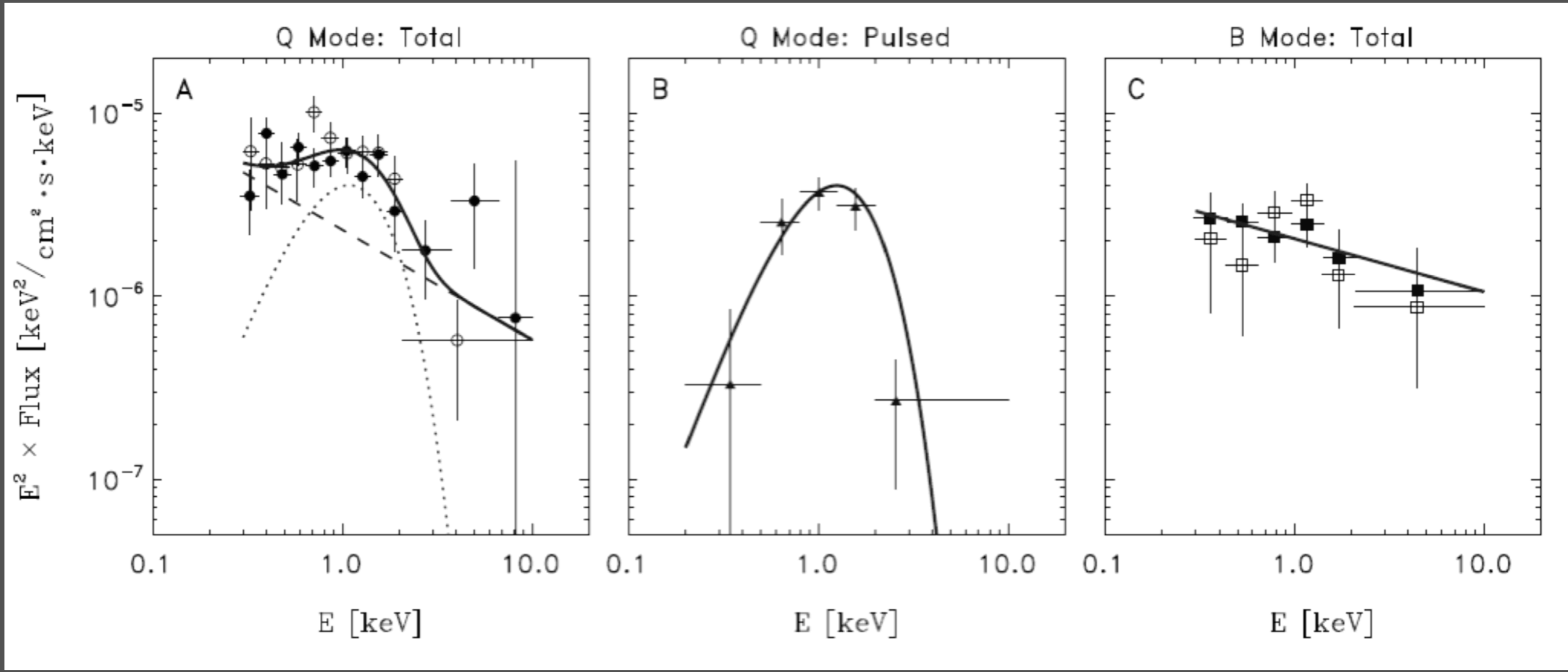
Conclusions on X-ray characteristics



- 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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- Dilemma's

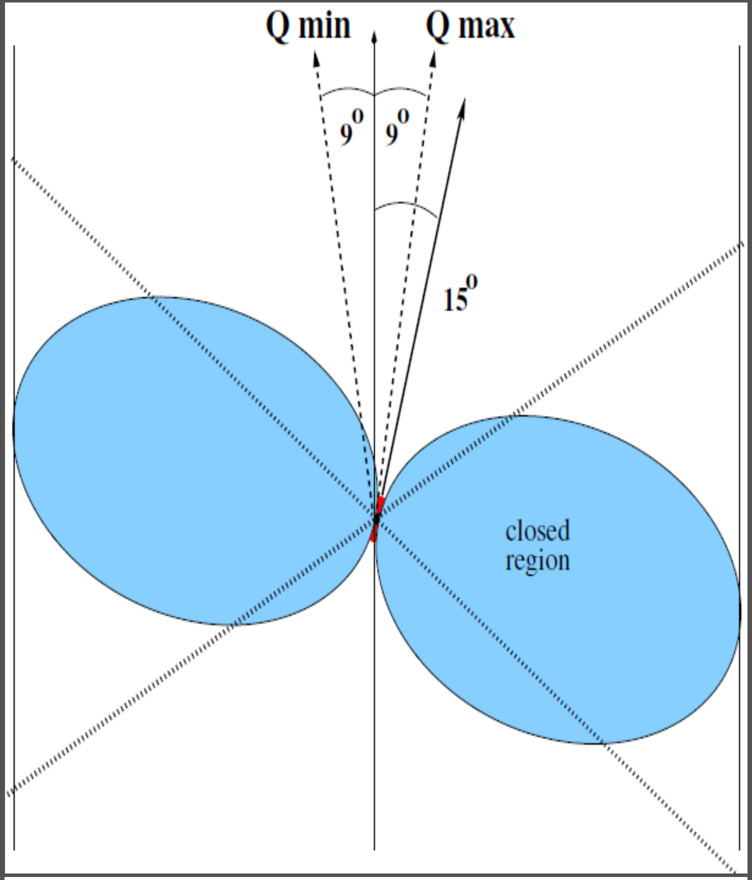
Many unanswered questions, dilemma's:

- Geometry accurately determined with Rotation Vector Model

- The B-mode X-ray emission is non-thermal and unpulsed; no sign of (a) heated hot spot(s)

For old pulsars curverture radiation not important anymore

Inverse Compton scattering and/or Synchrotron emission can explain non-thermal spectrum in B-mode
(Zhang & Harding 2000; Harding & Muslimov 2002)



Improved geometrical model

Then no explanation for thermal emission in Q mode

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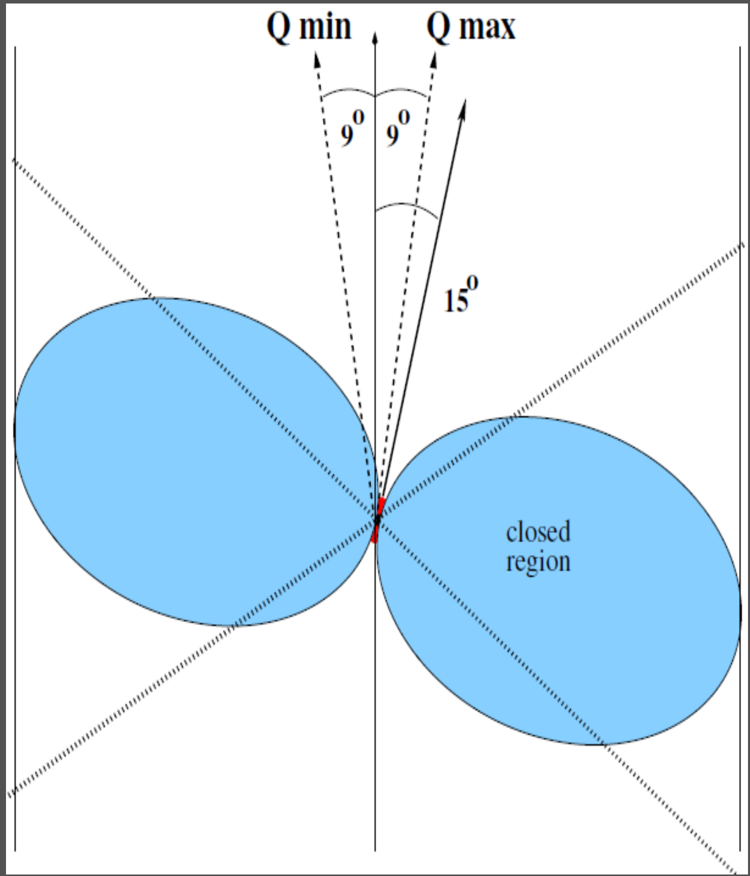
Many unanswered questions, dilemma's:

- Is the pulsed thermal emission in Q-mode related to the radio precursor, produced at higher altitudes?

We do not know a mechanism to produce thermal emission at high altitudes

Thermal emission has to come from a hot spot at the surface, heated by a back flow



Improved geometrical model

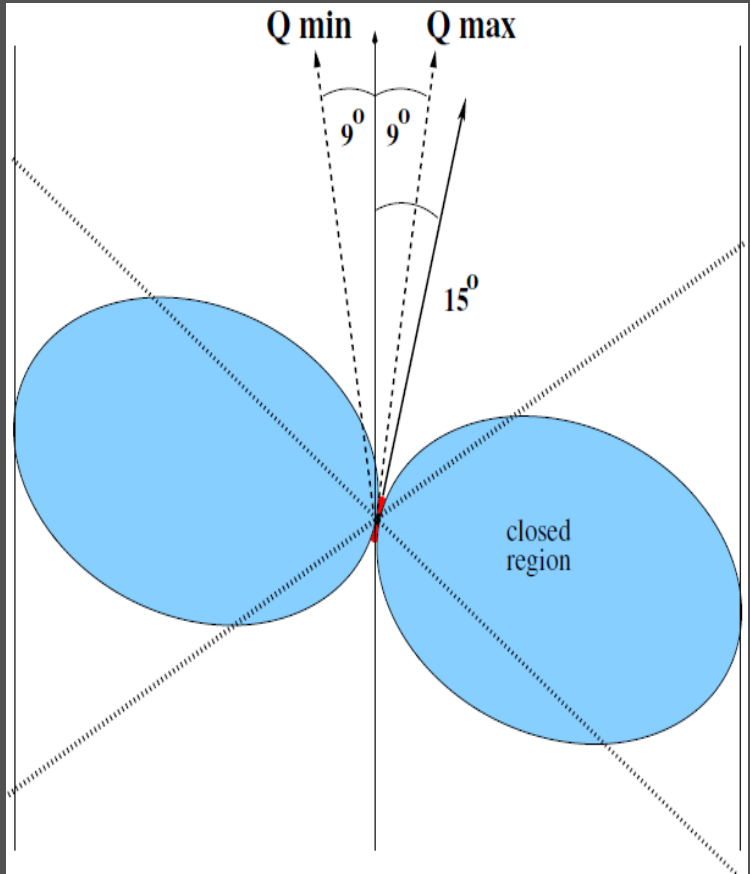
Many unanswered questions, dilemma's:

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

For this slow pulsar, light cylinder radius is 52,000 km

Q min: 10,000 km viewed through closed-field-line region

Q max: 500 km viewed through closed-field-line region



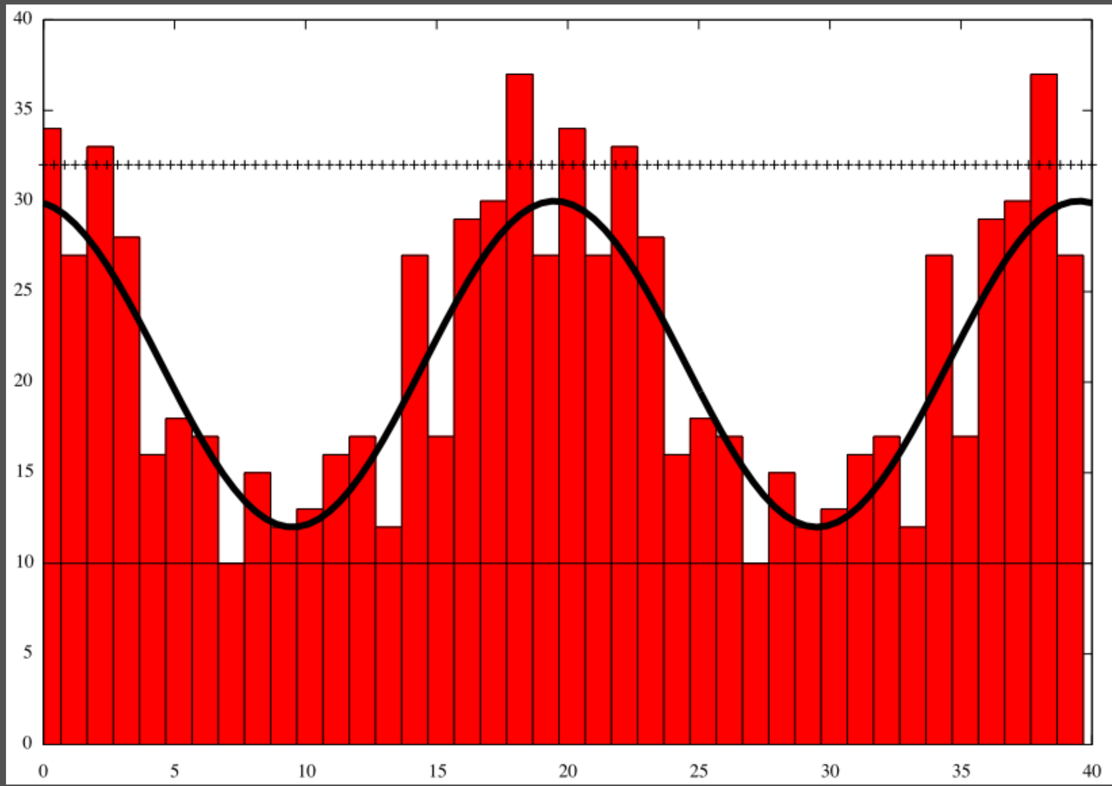
Improved geometrical model

Q mode: scattering in closed-field-line region of thermal emission from hot spot?

e.g. like the synchrotron absorption in PSR J0737-3039 to explain radio modulation during its magnetospheric exlipses
(Lyutikov & Thompson 2005)

- Assume scattering is proportional to distance transferred through closed-field-line region

- Sinusoidal profile can be obtained



Then 100 % absorption required in B mode !?

Or, switch off of back flow in B mode ?

Or, switch on of back flow in Q mode ?

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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 mode switching additional proof of rapid, global, magnetospheric change**

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Conclusions

XMM-Newton revealed:

First-ever correlated mode changes in X-ray and radio pulsar emission

The radio Q and B modes have steady power-law X-ray emission

Above that, the Q mode has pulsed thermal X-ray emission

X-ray modes show the entire magnetic and current configuration changes

Evidence for a Rapid Global Transformation of the Magnetosphere

Hermsen et al. 2013 (Science 339, 436)

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New campaign on PSR B1822-09 in September 2013

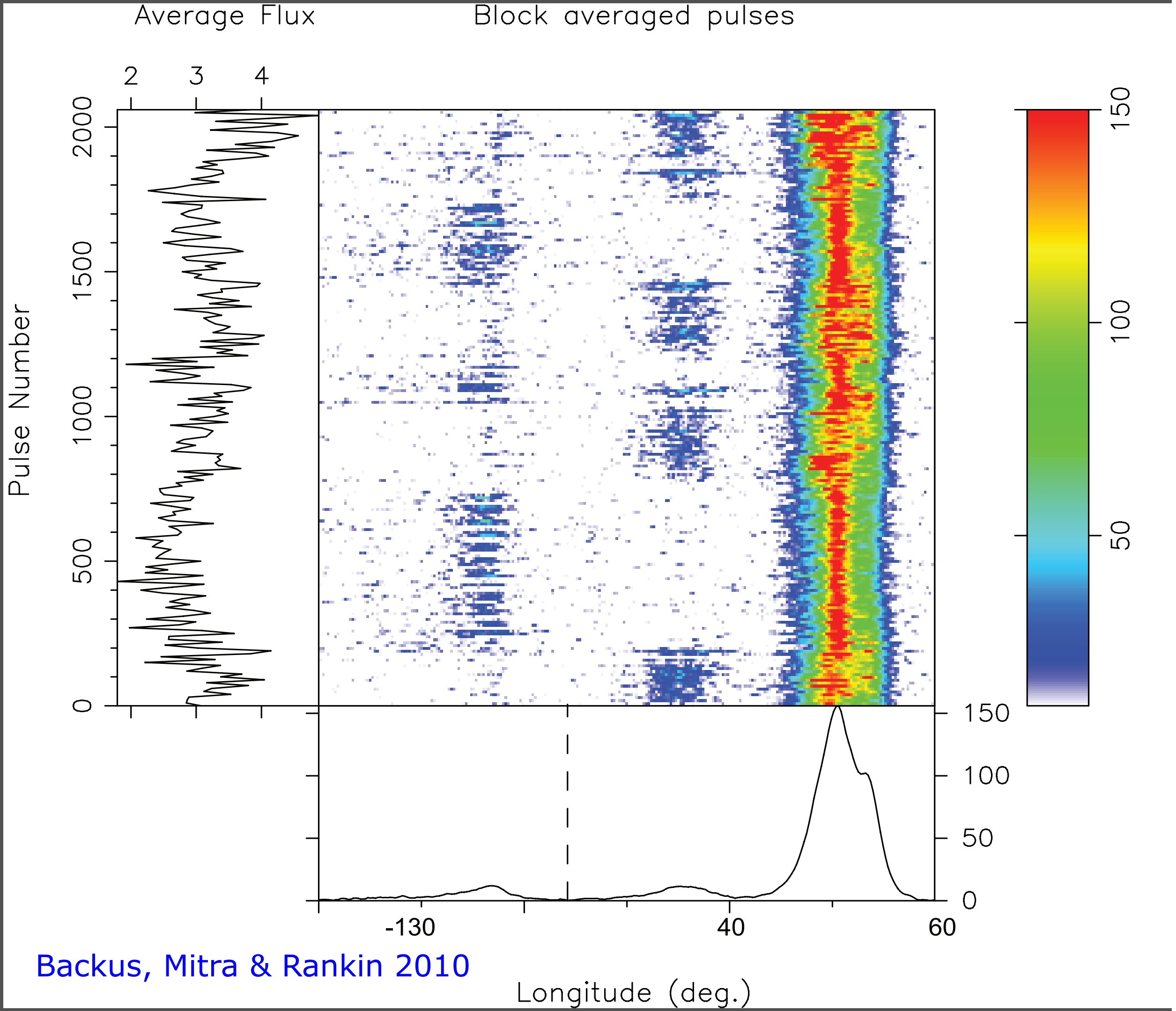
- Nearly orthogonal system
- Radio mode switching of:

  Main pulse, like B0943+10

  Precursor, like B0943+10

  Interpulse shows also mode switching !

  ➔ X-rays ??



Backus, Mitra & Rankin 2010

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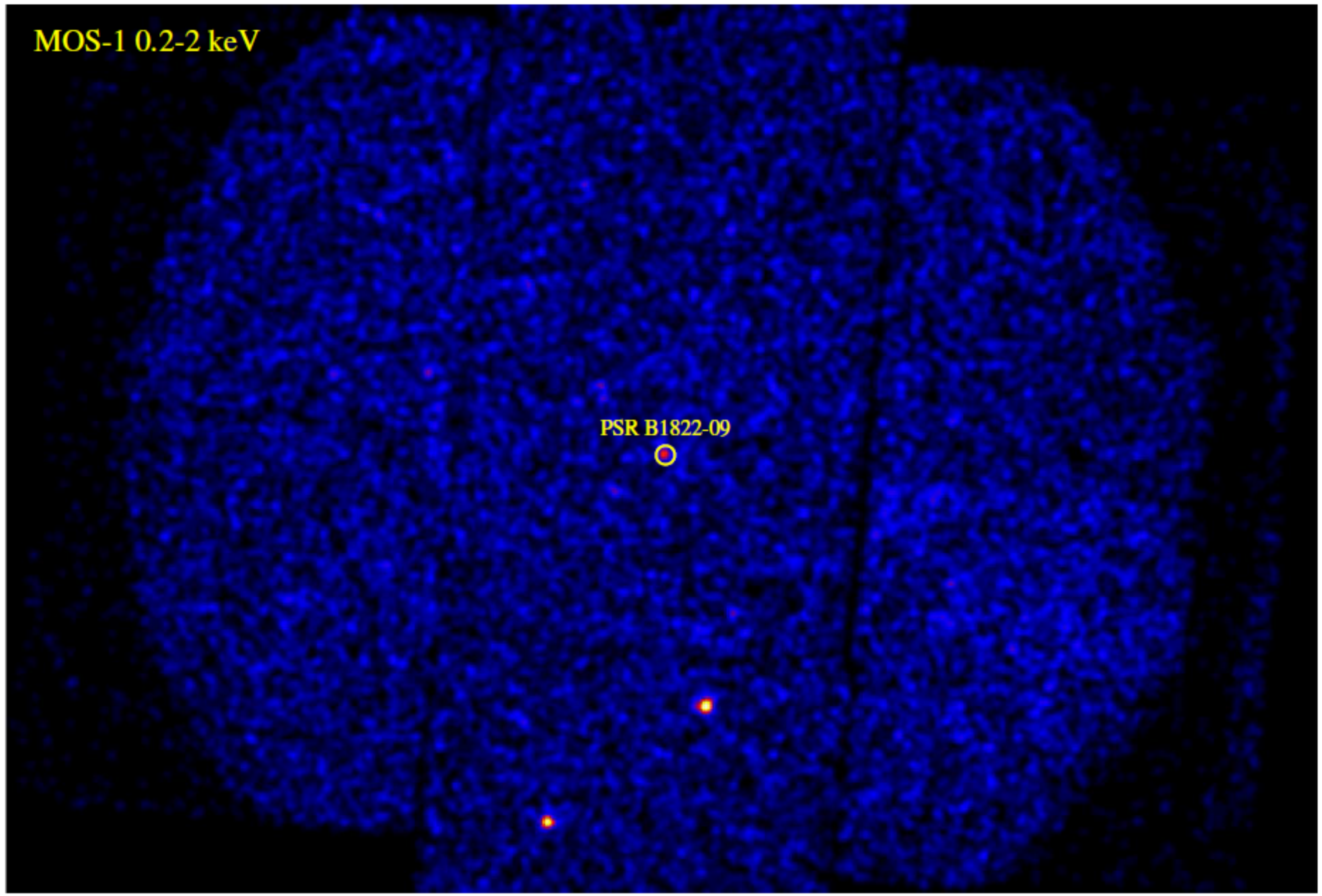
PSR B1822-09 detection in archive XMM-Newton map (5 ks)



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Thank you for listening!