X-ray properties of the mode-switching pulsar PSR B0943+10

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Outline

- Introduction

- PSR B0943+10: an X-ray variable pulsar !

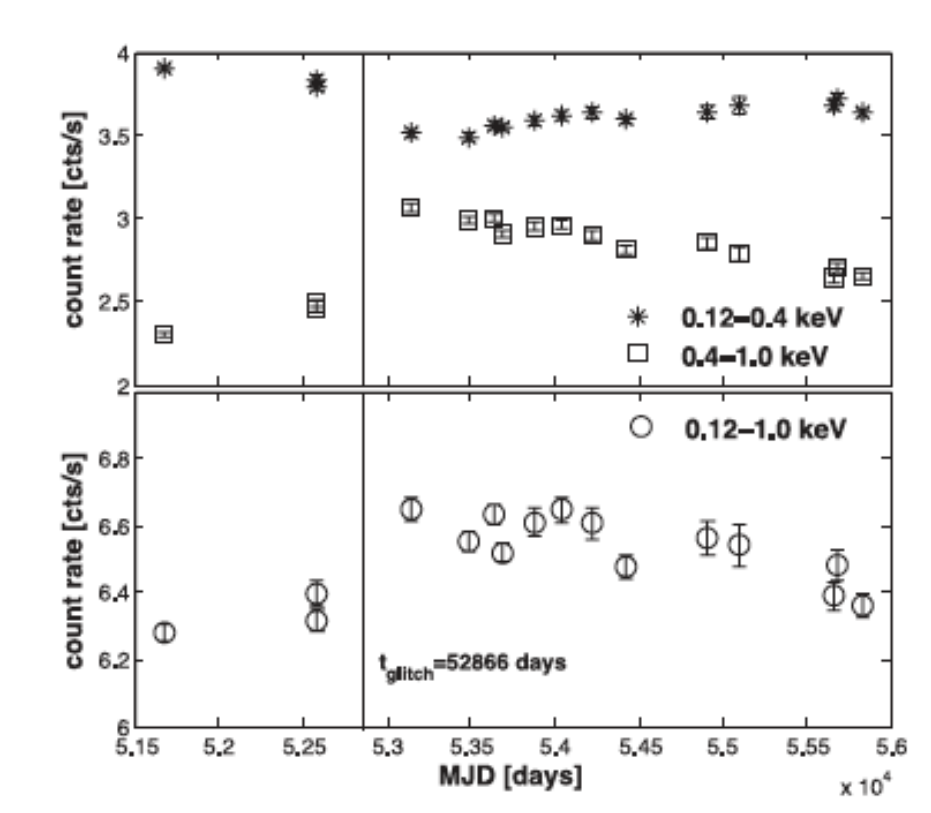
- Summary of previous X-ray observations
  (Hermsen+ 2013, Mereghetti+ 2013)

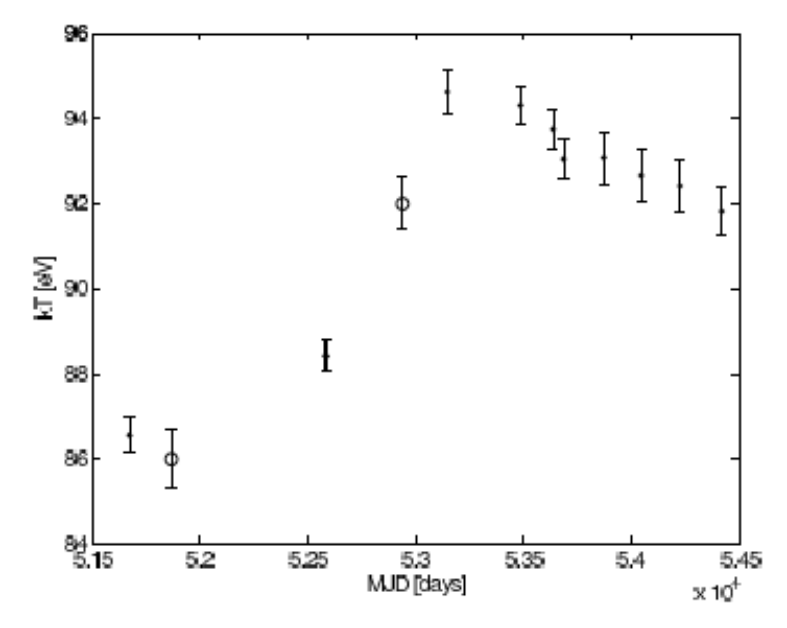
- Results of new X-ray/radio campaign of Nov 2014
  (Mereghetti+ 2016)

Rotation-powered (radio) pulsars have always been thought to be constant sources in X-rays

- **A few exceptions can be ascribed to ''magnetar-like'' activity:**

- Long term variations in some X(D)INS
  (e.g. RXJ0720 Hole+ 2009, 2012) …old magnetars ?

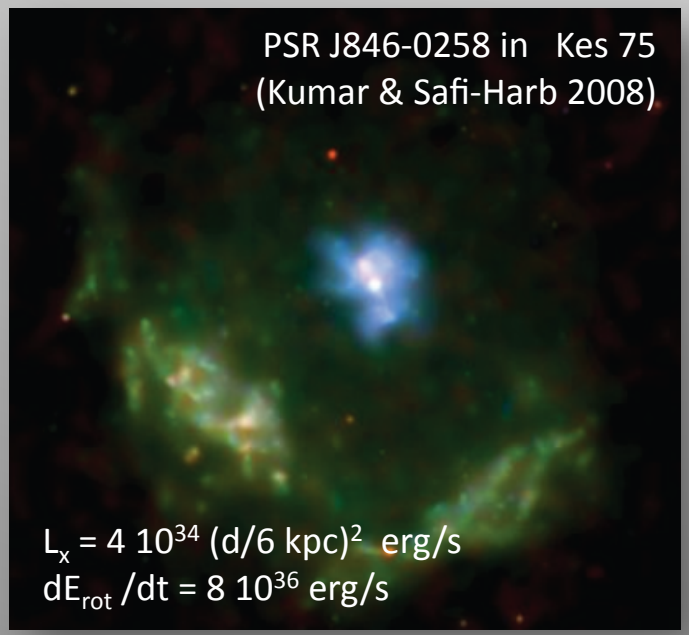


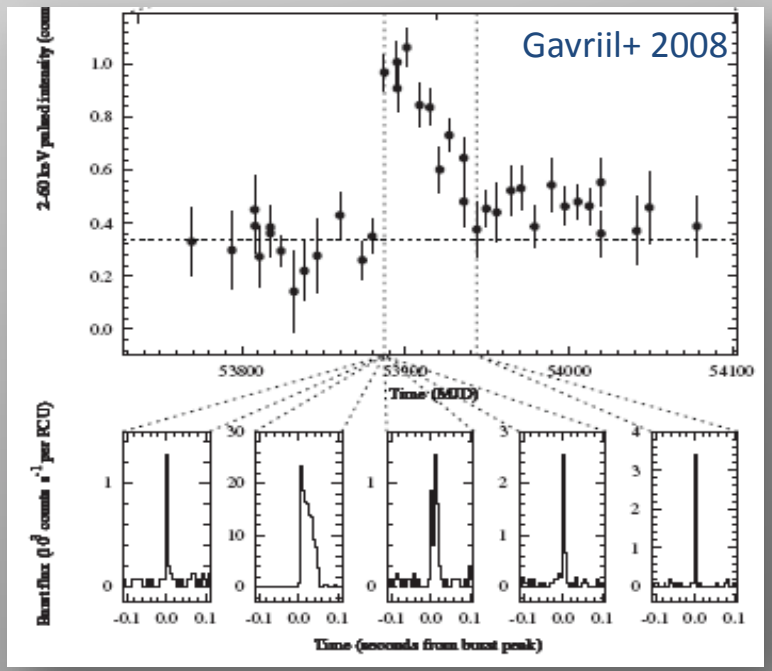


Rotation-powered (radio) pulsars have always been thought to be constant sources in X-rays

- **A few exceptions can be ascribed to "magnetar-like" activity:**

- Long term variations in some X(D)INS
  (e.g. RXJ0720 Hole+ 2009) …old magnetars ?
- Bursts in two young pulsars with high B
  (J1846-0258, J1119-6127, Gavriil+ 2008, Archibald+ 2016)

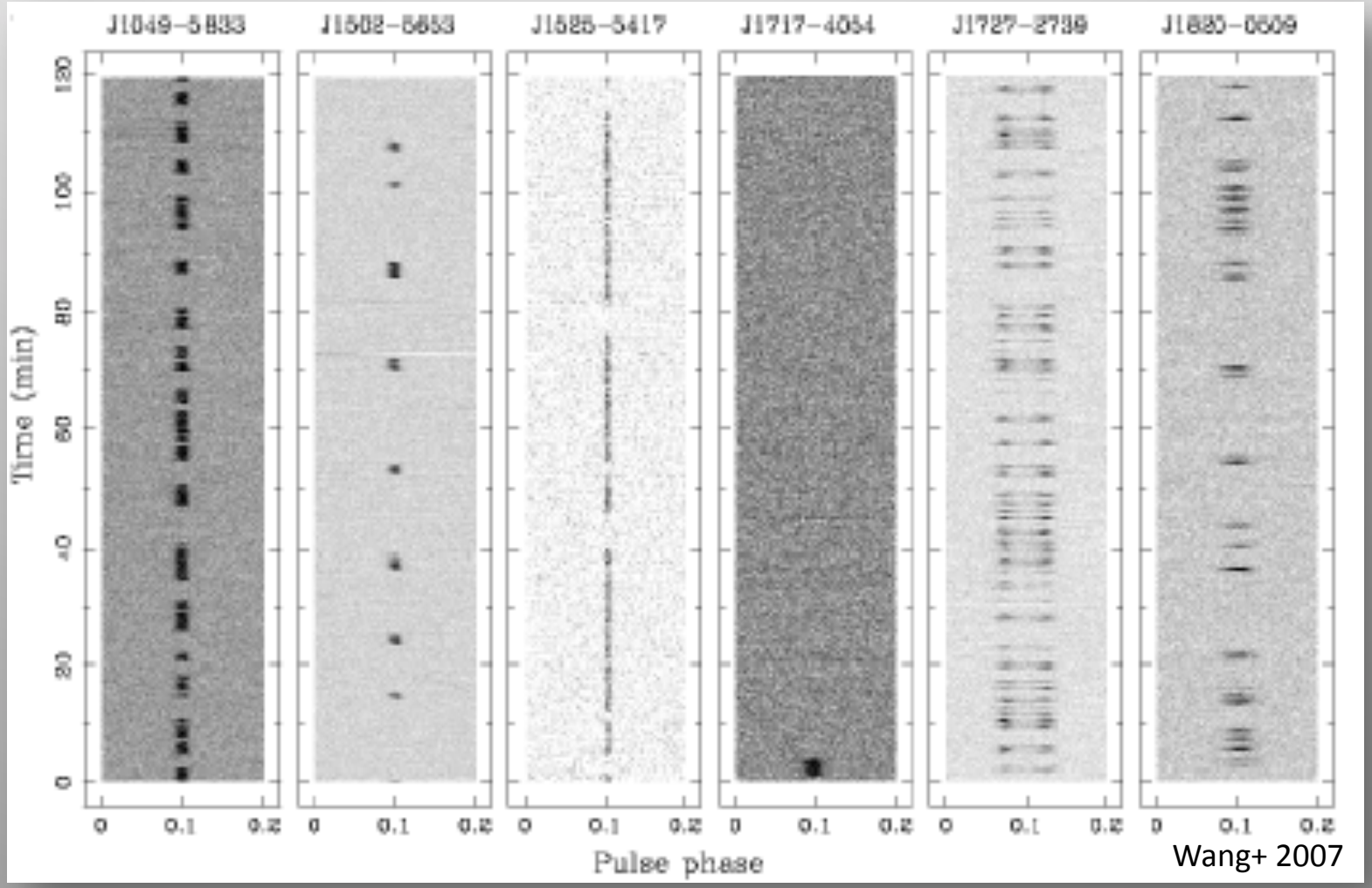




Many pulsars show variability in the radio band

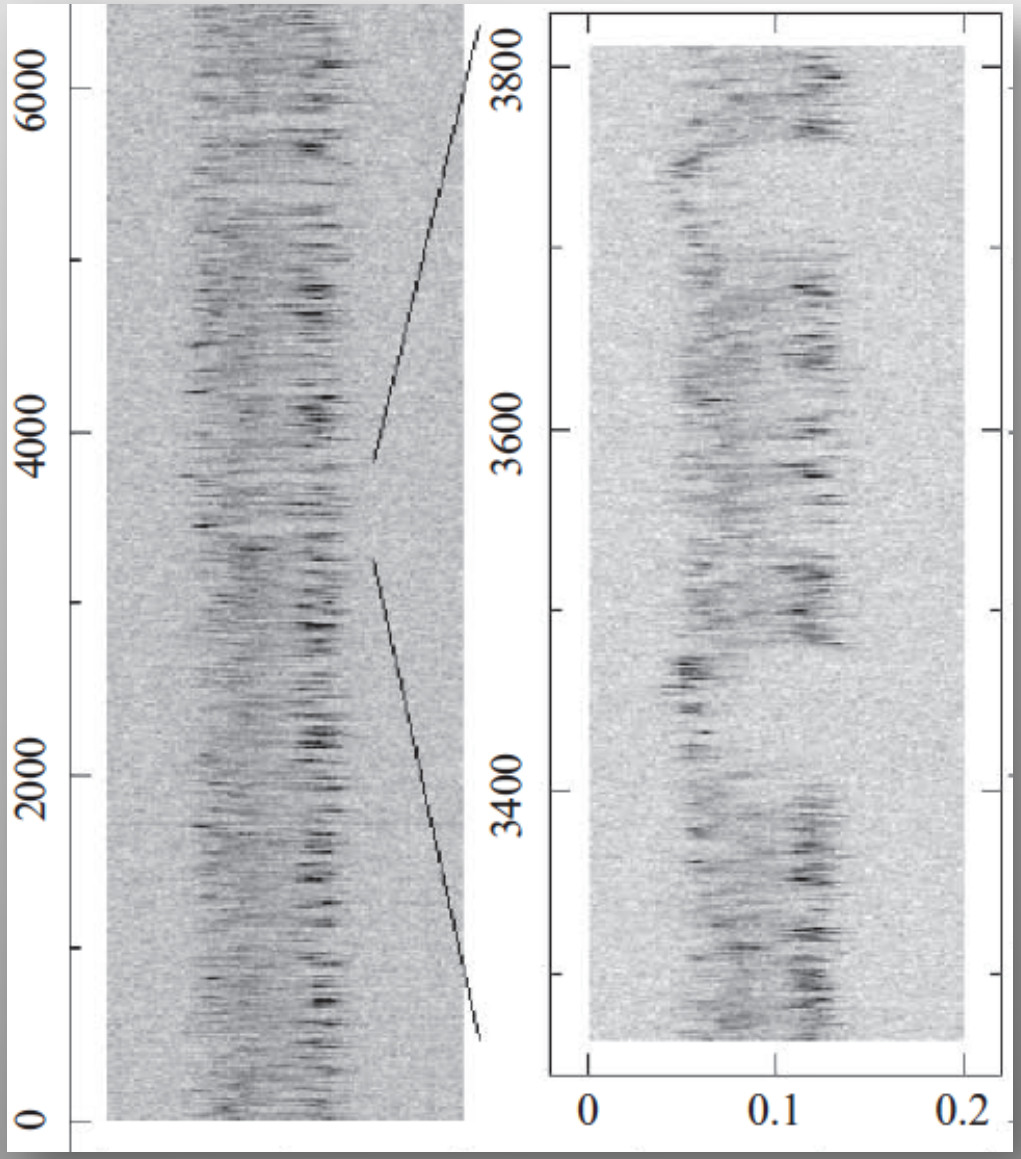
- Different *(but likely related)* phenomena :
  - giant radio pulses
  - nulling
  - bi-states and multi-states
  - RRATs
  - variable spin-down

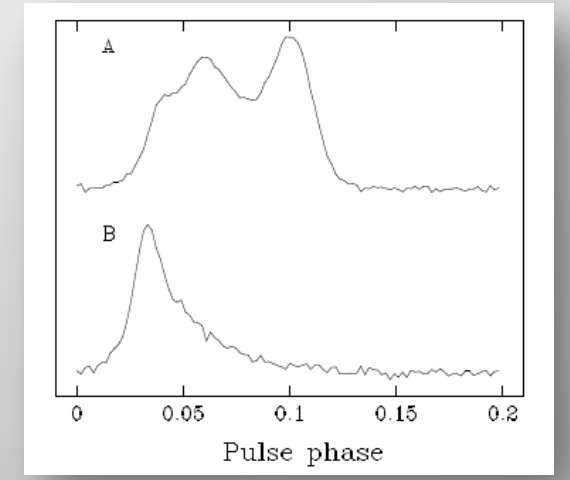
Examples of pulsars showing "nulling''



Wang+ 2007

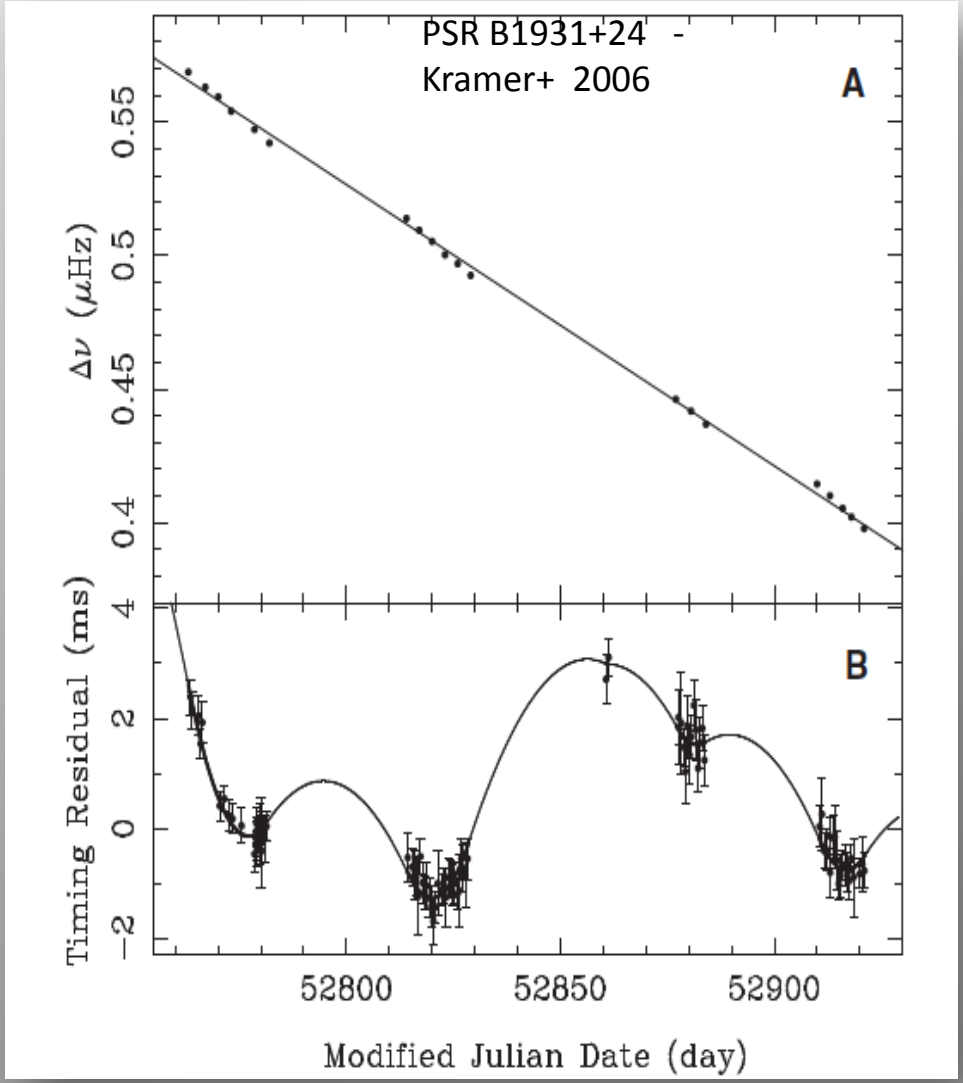
Example of a “mode-switching’’ pulsar





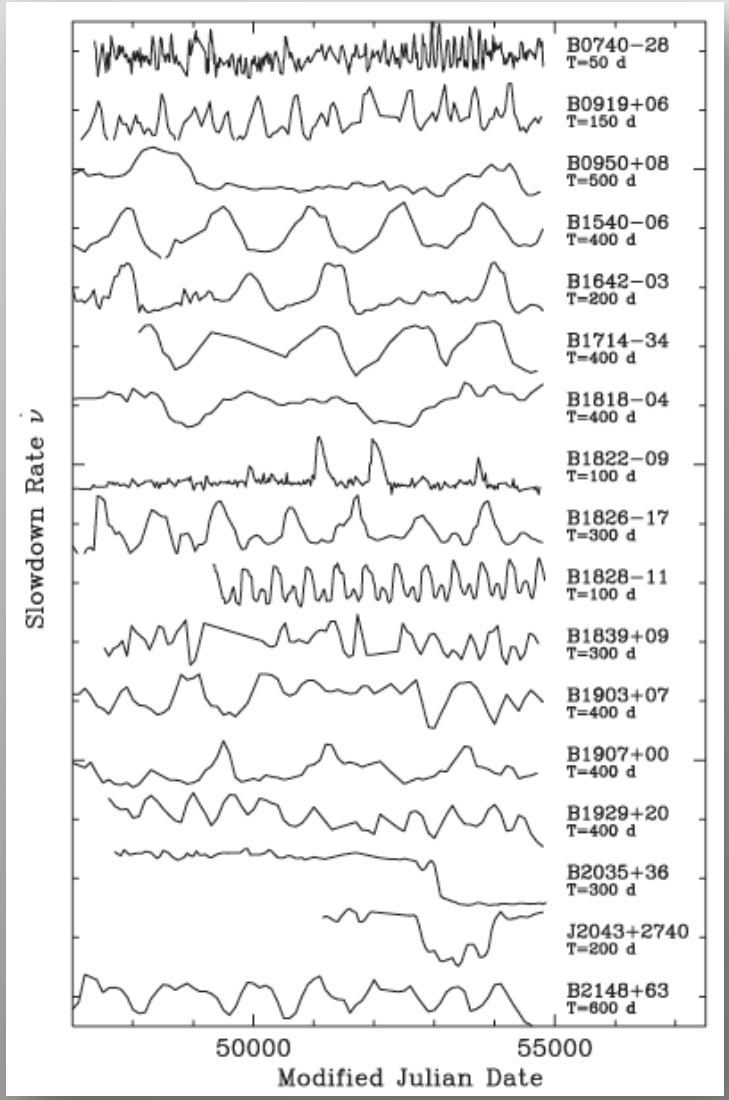
PSR J1326-6700 - Wang+ 2007

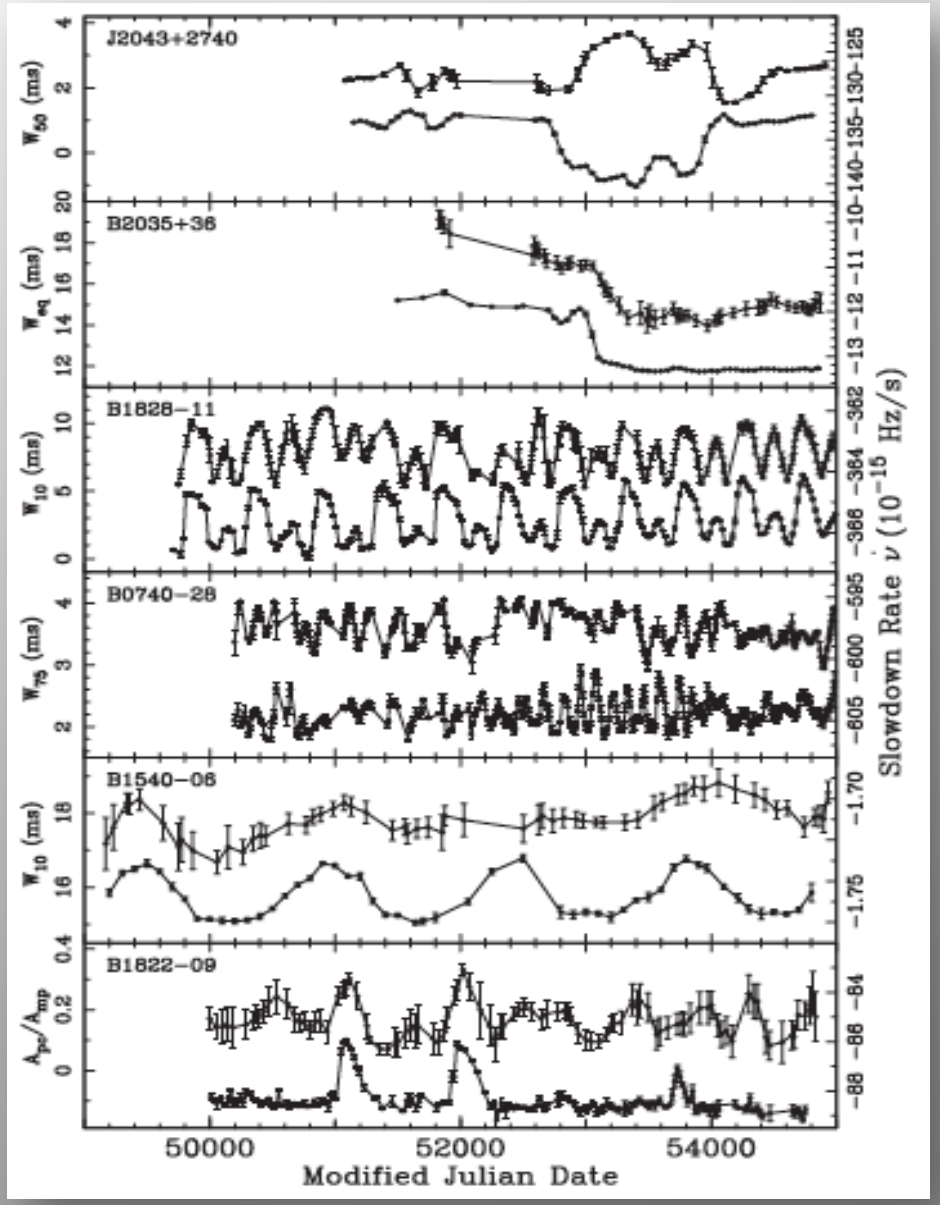
Some PSRs alternate long (days) ON and OFF states
Spin-down ~50% larger when radio emission is ON



Bimodal spin-down rate correlated with pulse profile changes

Lyne+ 2010





What causes the (radio) variations ?

Small-scale changes at sites of particle acceleration ??

or

global changes in the whole magnetosphere ??

Can X-rays help to answer this question ?

PSR B0943+10: the only X-ray variable pulsar

- P = 1.1 s $\dot{P} = 3.5\ 10^{-15}$ s/s
- $\tau \sim 5$ Myr, $B_{dip} = 4\ 10^{12}$ G , $\dot{E}_{rot}=10^{32}$ erg/s

- **A "mode-switching" PSR**: radio emission alternates between B (bright) and Q (quiescent) modes every few hours (or less)

  (Suleymanova & Izvekova 1984; Rankin & Suleymanova 2006)

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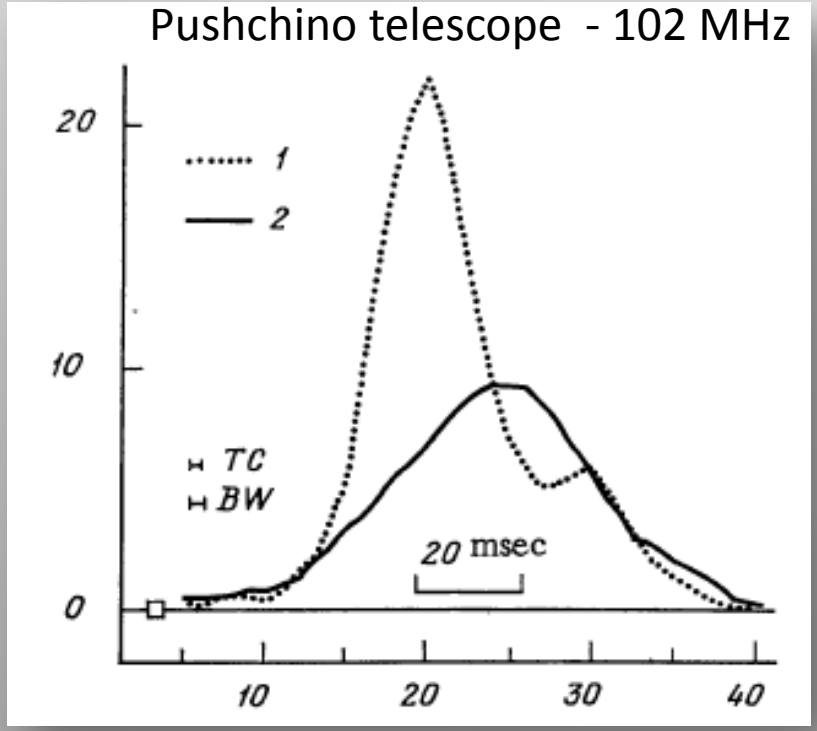
  (Suleymanova & Izvekova 1984; Rankin & Suleymanova 2006)

Pushchino telescope - 102 MHz



Drifting sub-pulses only in B-mode

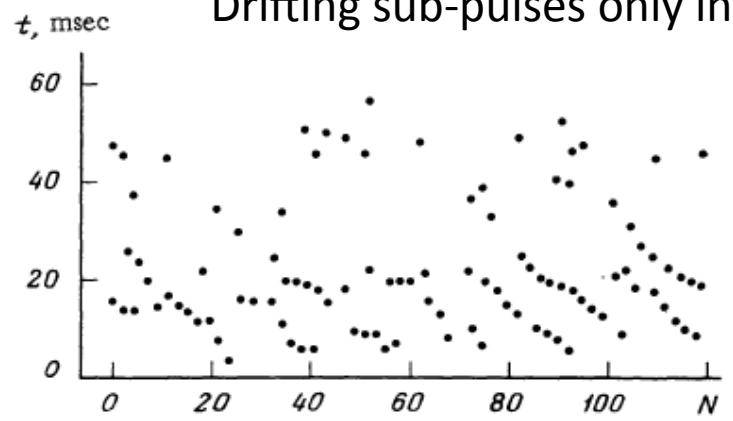
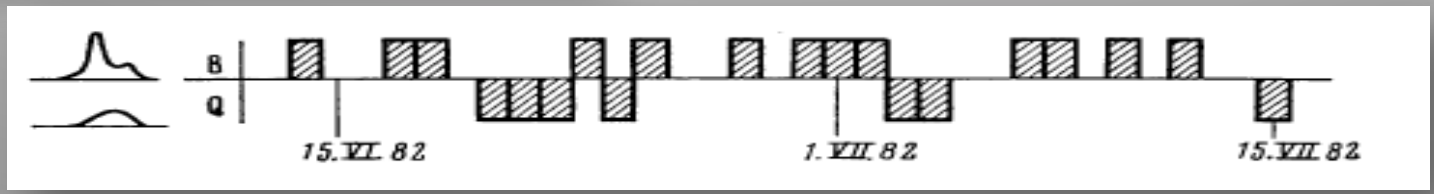
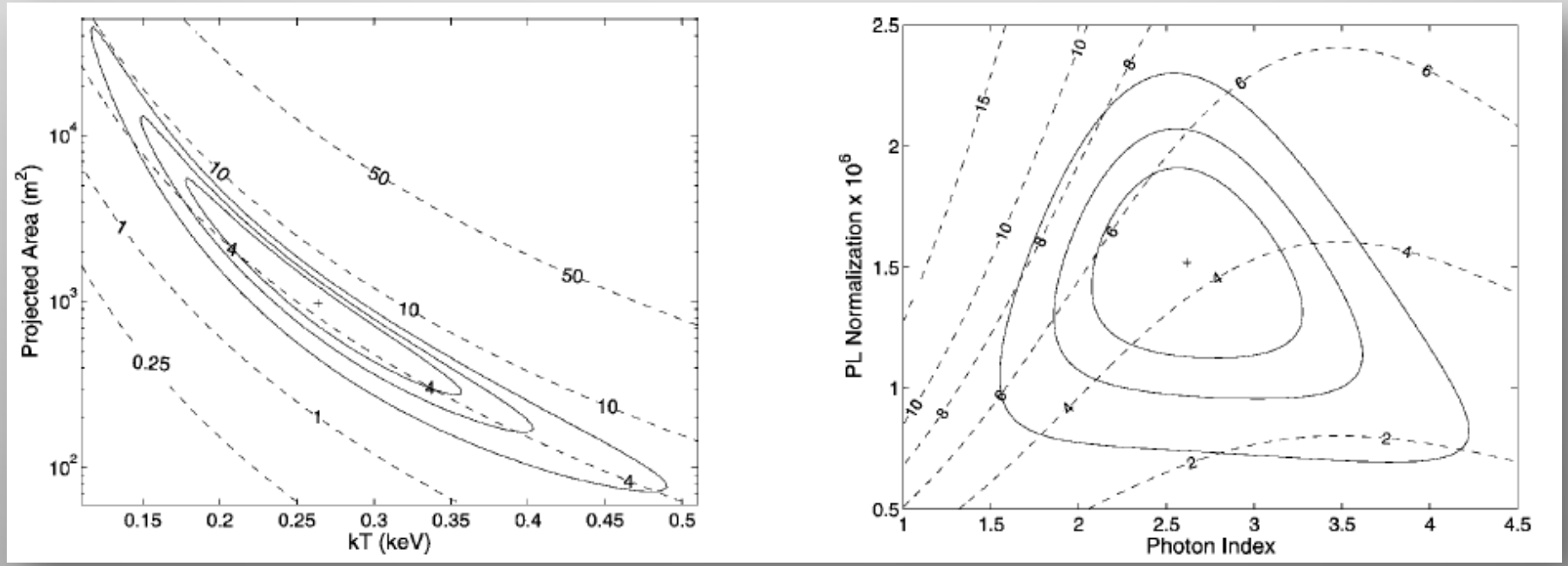


FIG. 6. The subpulse position—pulse number diagram. N, pulse number; t, time.

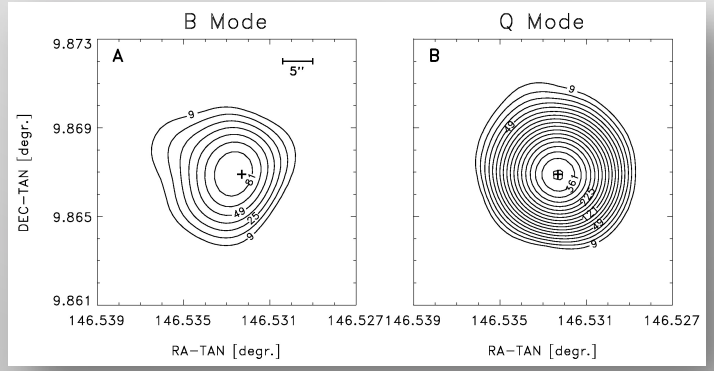


- **X-rays discovered with XMM in 2003** (Zhang, Sanwal & Pavlov 2005)



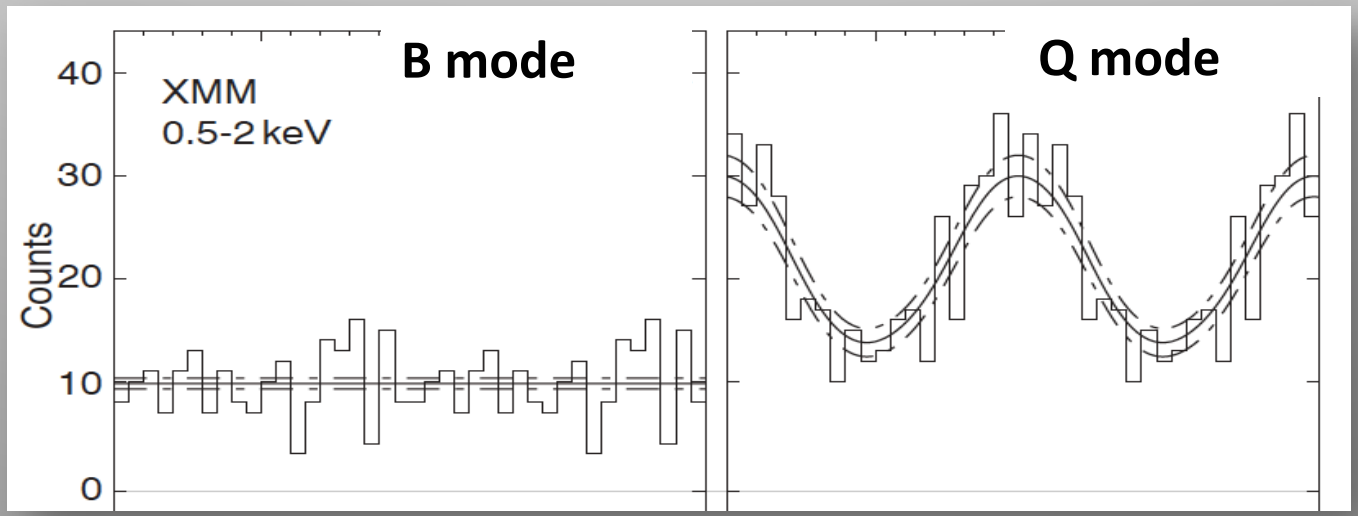
Faint source : too few X-ray photons to detect pulsations
and to constrain the spectrum

- **2011 XMM + <u>radio observations</u>:** discovery of factor ~2 X-ray variability anti-correlated with radio mode (Hermsen+ 2013, Science)



Faint X-ray source !
Best analyzed with ML methods

Pulsations visible only in Q mode



Spectrum in Q-mode
(when X-ray brighter) **is a PL+BB**

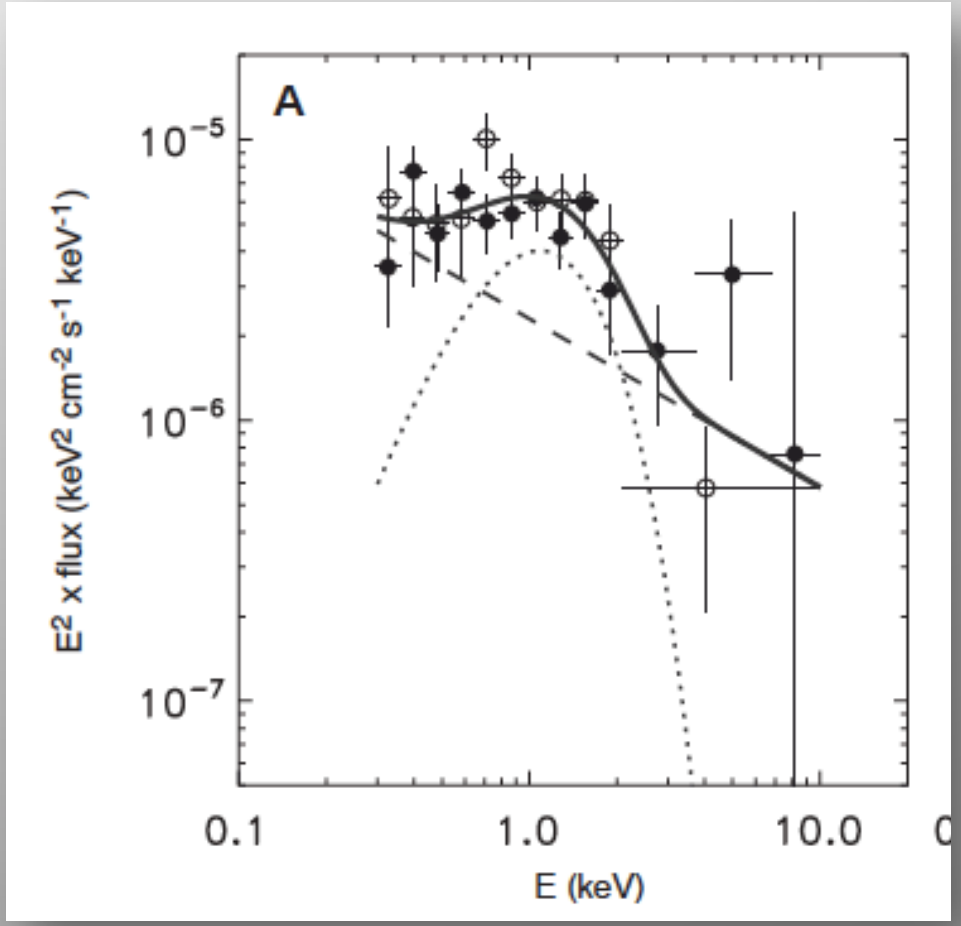
(Hermsen+ 2013)

kT = 0.28 +/- 0.01 keV

Γ = 2.6 +/- 0.3

F_{BB} = (7.5 +/- 2.2) 10^{-15} erg/cm^2/s
F_{PL} = (7.6 +/- 1.8) 10^{-15} erg/cm^2/s

(0.5-8 keV, unabs, N_H=4.3 10^{20} cm^{-2})



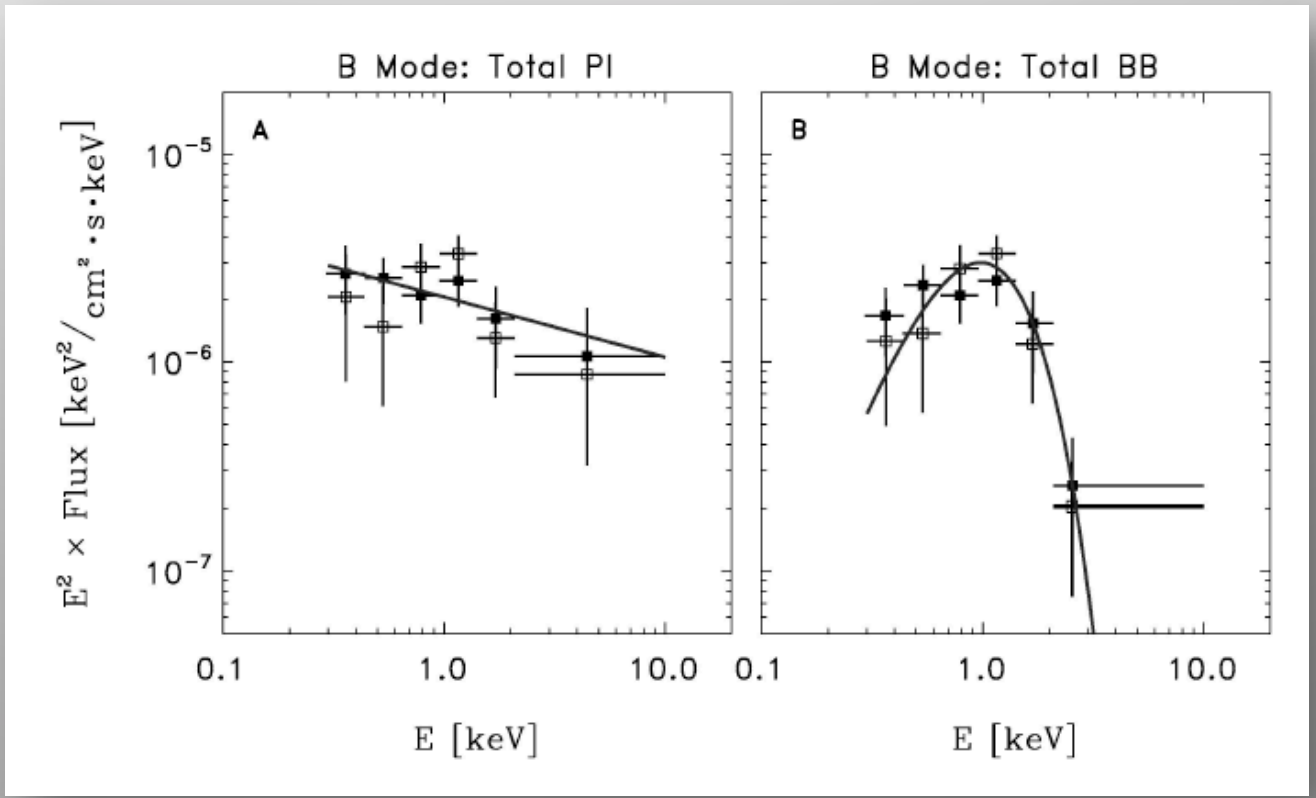
Spectrum in B-mode (when X-ray fainter) **was poorly constrained: either a PL or a BB**

(Hermsen+ 2013)

Γ = 2.3 +/- 0.2
F_{PL} = (7.7 +/- 1.0) 10^{-15} erg/cm^2/s

or

kT = 0.25 +/- 0.01 keV
F_{BB} = (5.4 +/- 0.8) 10^{-15} erg/cm^2/s

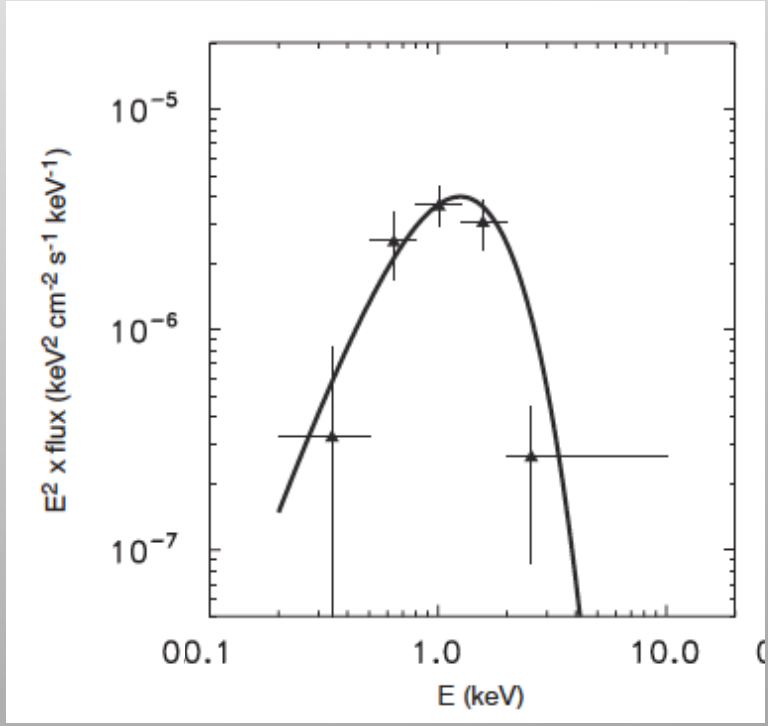


Q-mode pulsed spectrum is a blackbody

kT = 0.32 +/- 0.01 keV

F_{BB} = (7.8 +/- 1.6) 10^{-15} erg/cm^2/s

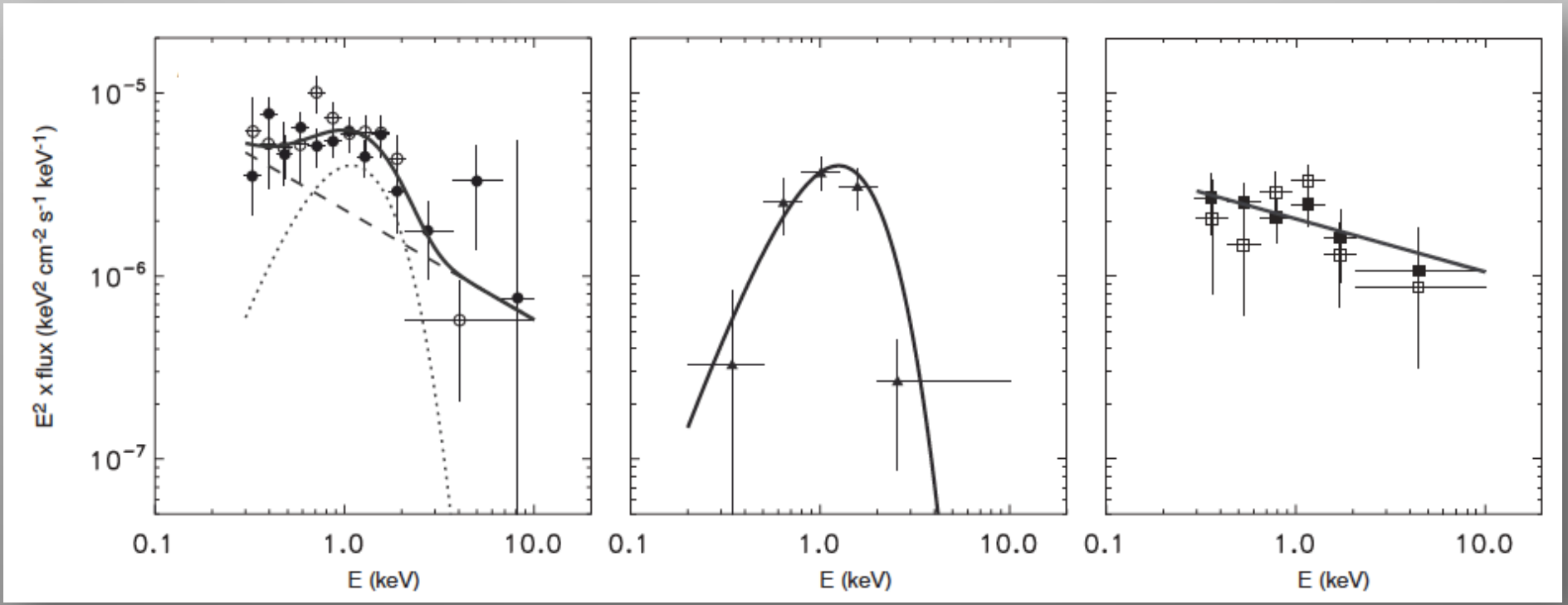
(Hermsen+ 2013)



The power law fitting the B-mode (apparently unpulsed) **and the black-body fitting the pulsed flux are equal** (within the errors) **to the two components** (PL+BB) **that fit the total Q-mode spectrum**

B-mode → Q-mode = appearance of a 100% pulsed blackbody over a constant power law always present

Q-mode: BB + PL **Q-mode pulsed:** BB **B-mode:** PL



B-mode → Q-mode = appearance of a 100% pulsed blackbody over a constant power law always present

...?!

PSR B0943+10 is a nearly aligned rotator seen almost pole-on

(Deshpande & Rankin 2001)

How can a hot polar-cap <u>always visible</u> produce a 100% modulation ?

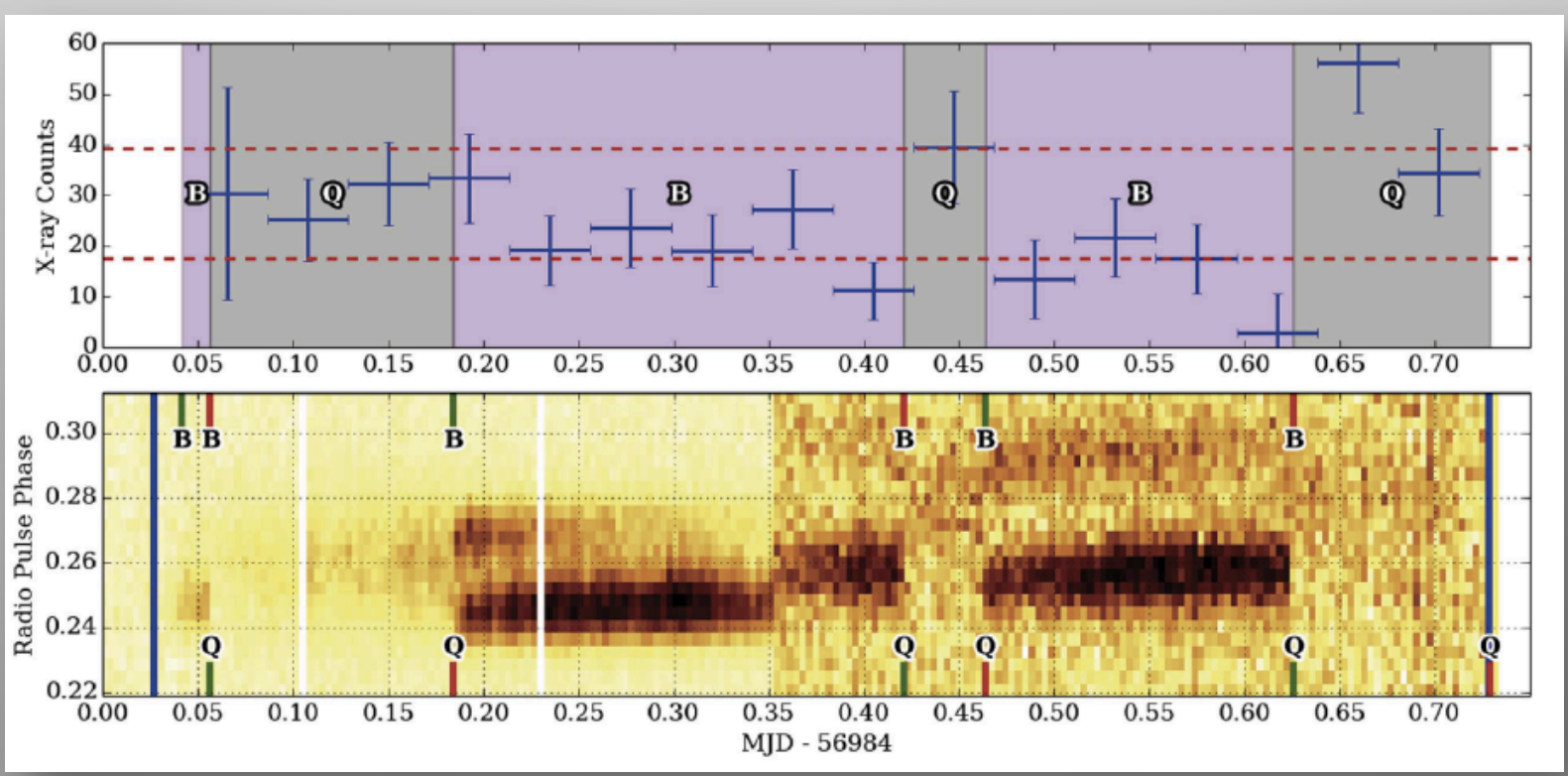
How can its thermal emission disappear in B-mode ?

(see Mereghetti+ 2013, Storch+ 2014)

New data with XMM-Newton Large Program in November 2014

7 XMM observations of ~18 hr with simultaneous radio coverage with LOFAR (150 MHz), LWA (60 MHz), and Arecibo (330 MHz)

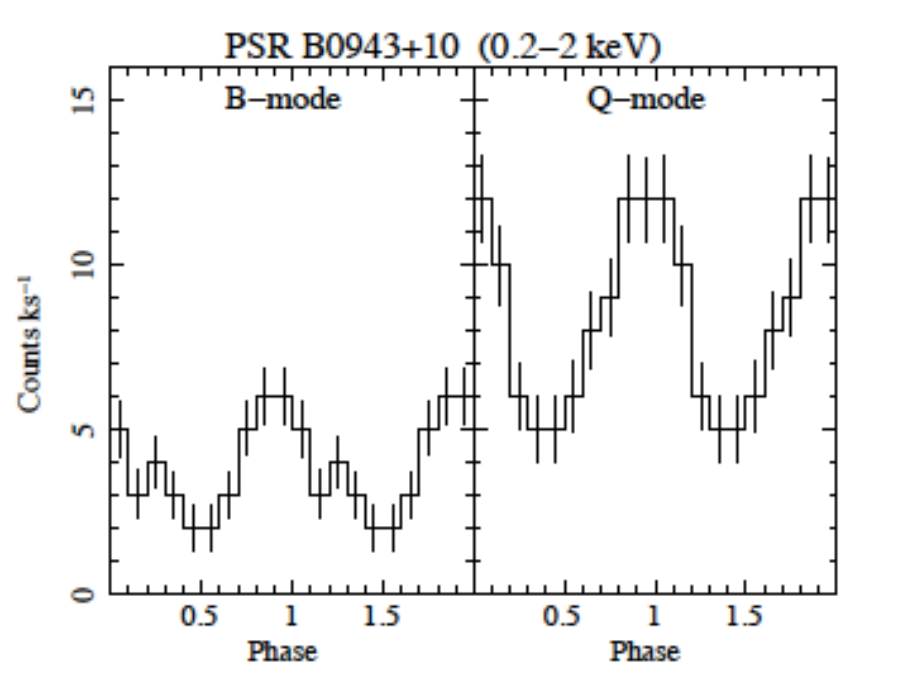
→ 113 ks in Q-mode / 163 ks in B-mode
(wrt ~50 ks for each mode in 2011 data)

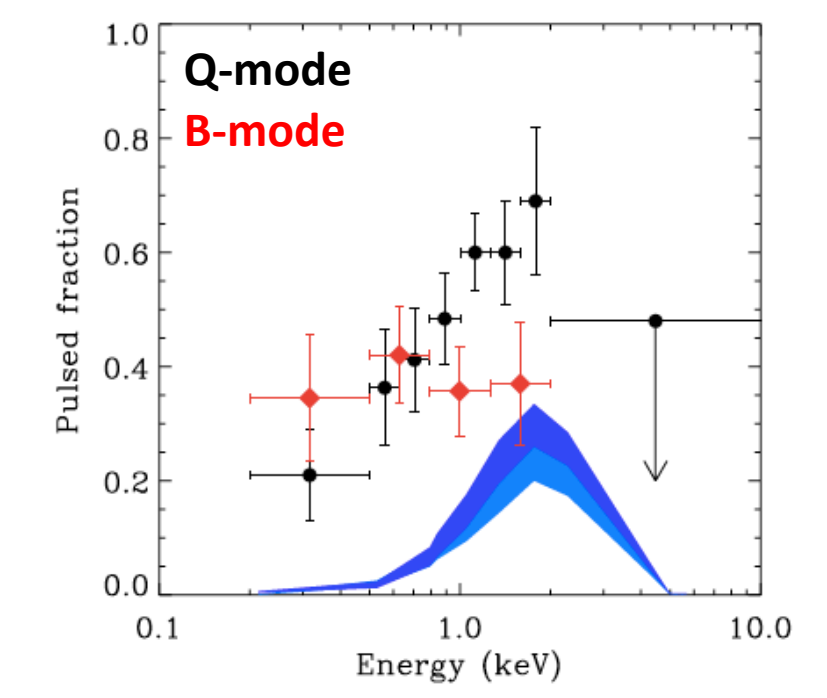


2014 campaign – Timing results

(Mereghetti+ 2016)

X-ray pulsations detected also during the (fainter) B-mode





2014 campaign – Spectroscopy results

Q-mode

- **BB + PL**
  Γ = 2.4 +/- 0.2
  kT = 0.27 +/- 0.04 keV
  R = 21 m

or

- **BB + BB**
  kT_1 = 0.11 +/- 0.02 keV
  R_1 = 153
  kT_2 = 0.34 +/- 0.03 keV
  R_2 = 19 m

B-mode

- **Single power law ruled out**

- **BB**
  kT = 0.24 +/- 0.01 keV

- **BB + PL**
  Γ = 2.3 +/- 0.5
  kT = 0.24 +/- 0.03 keV
  R = 24 m

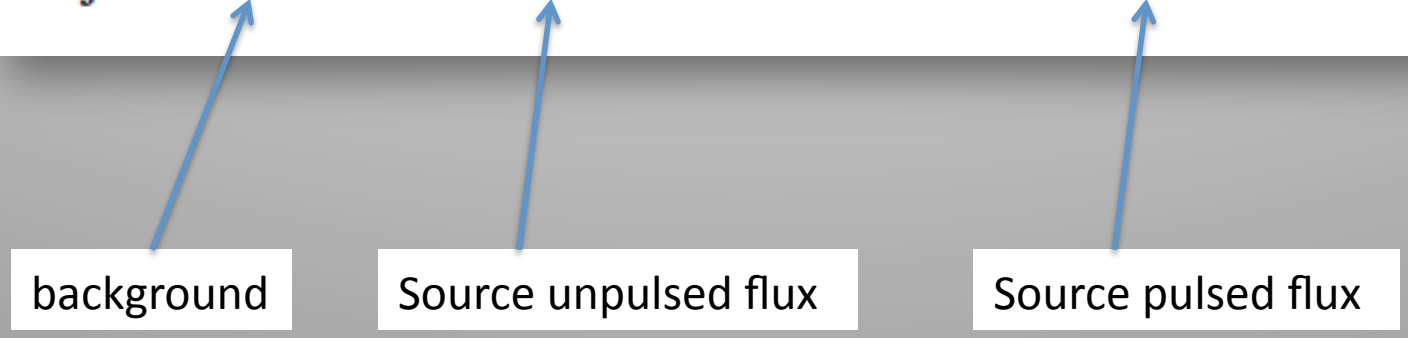
2014 campaign – joint spectral/timing with 3-D ML

3D – Maximum Likelihood

(introduced by Hermsen+ 2017 for PSR B1822-09)

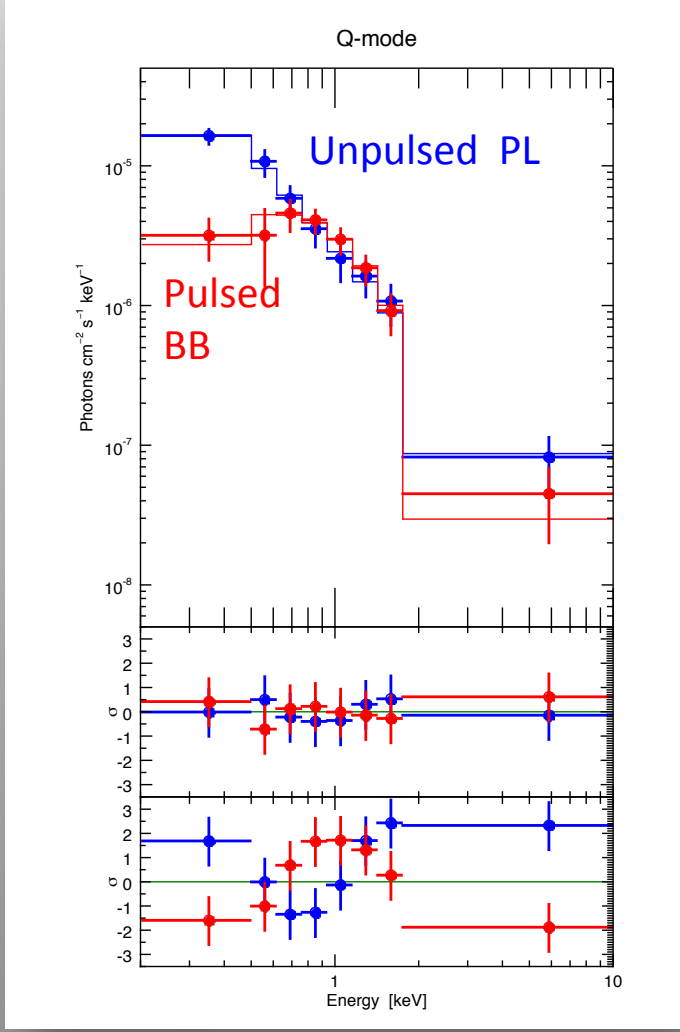
Expectation value fpr data binned in spatial coordinates and phase :

$$\mu_{ijk} = \beta + \sigma_u \times \mathrm{PSF}_{ij} + \sigma_p \times \mathrm{PSF}_{ij} \times \Phi_k.$$

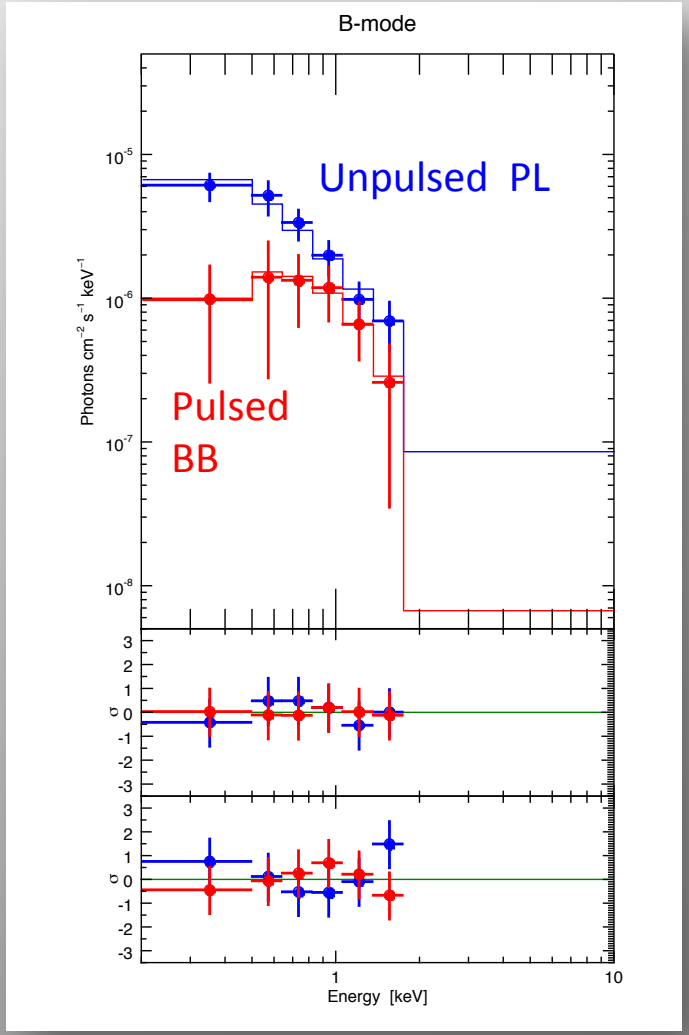


2014 campaign – joint spectral/timing with 3-D ML

Q: Pulsed flux is BB
Unpulsed flux is PL
(the opposite ruled out !)

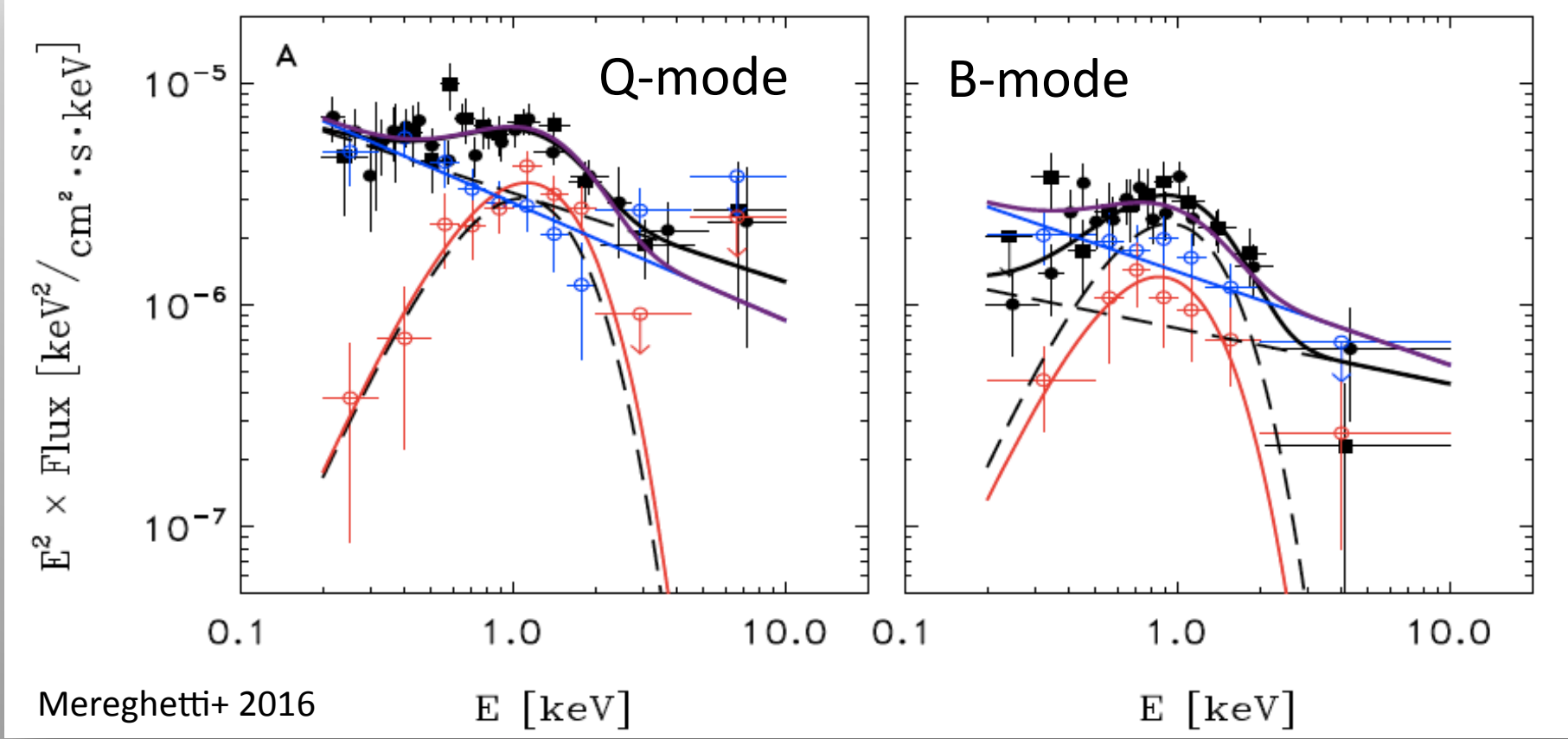


B: Both pulsed and unpulsed
equally fit by either PL or BB
(impossible to distinguish)



A plausible interpretation

pulsed BB + unpulsed PL are present in both modes



Mereghetti+ 2016

BLACK = TOTAL SPECTRUM: BB + PL

RED = PULSED SPECTRUM: BB

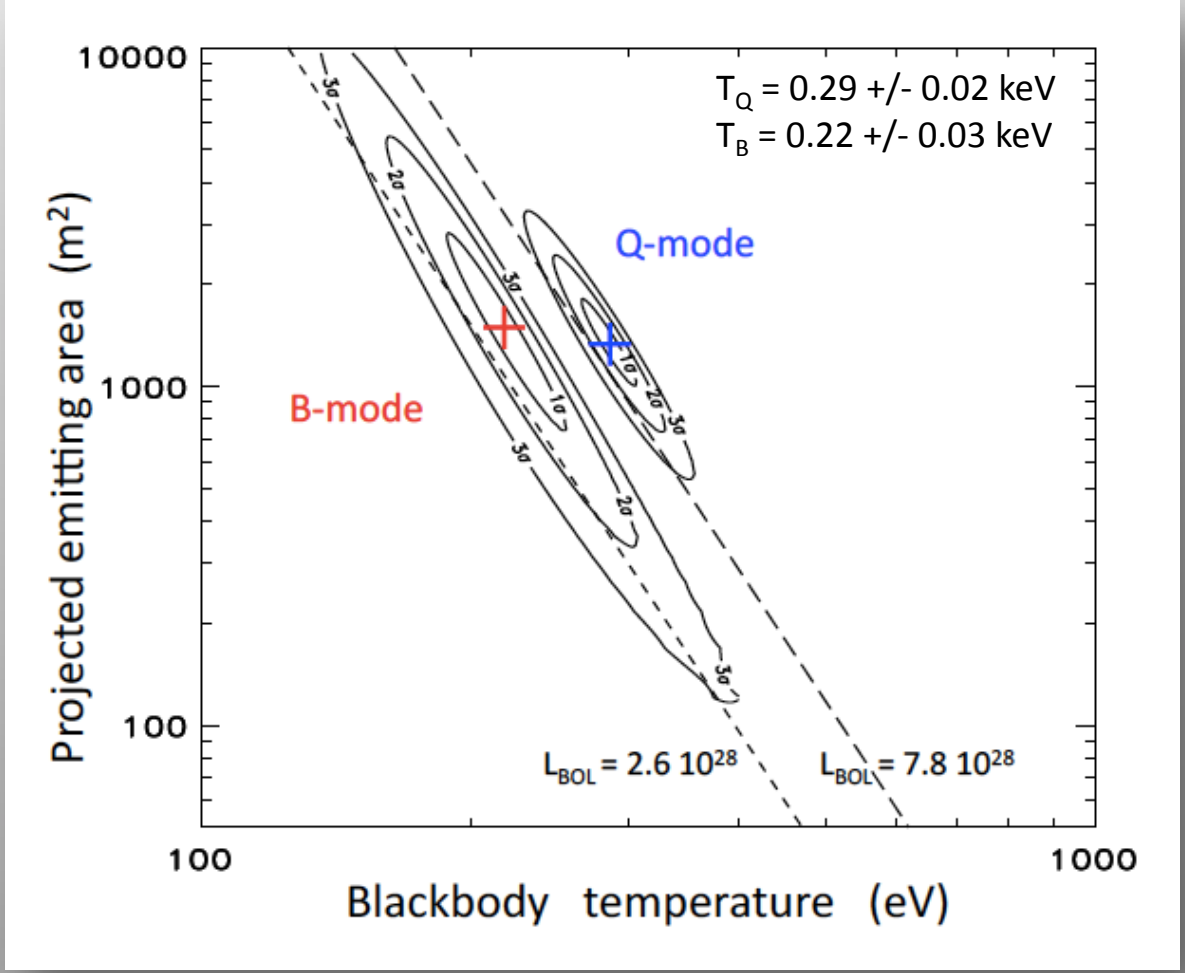
BLUE = UNPULSED SPECTRUM PL

Temperature and emitting area of blackbody component in the two modes

Very small hot spots:

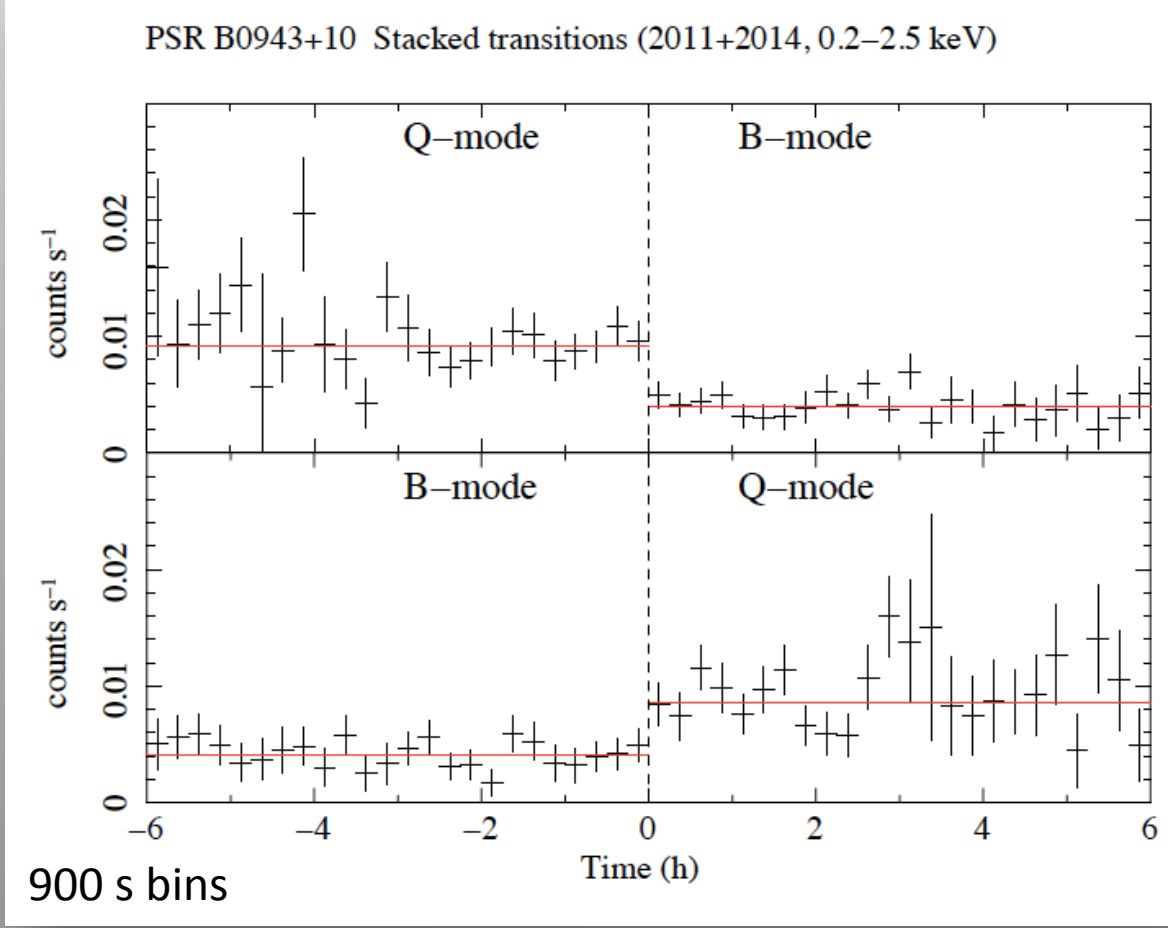
R_Q = 21 +/- 3 m
R_B = 22 +/- 8 m

<< R_{PC} ~ 140 m



Transition between modes

Sharp transitions between the modes
(X-ray change in <~ 15 min)

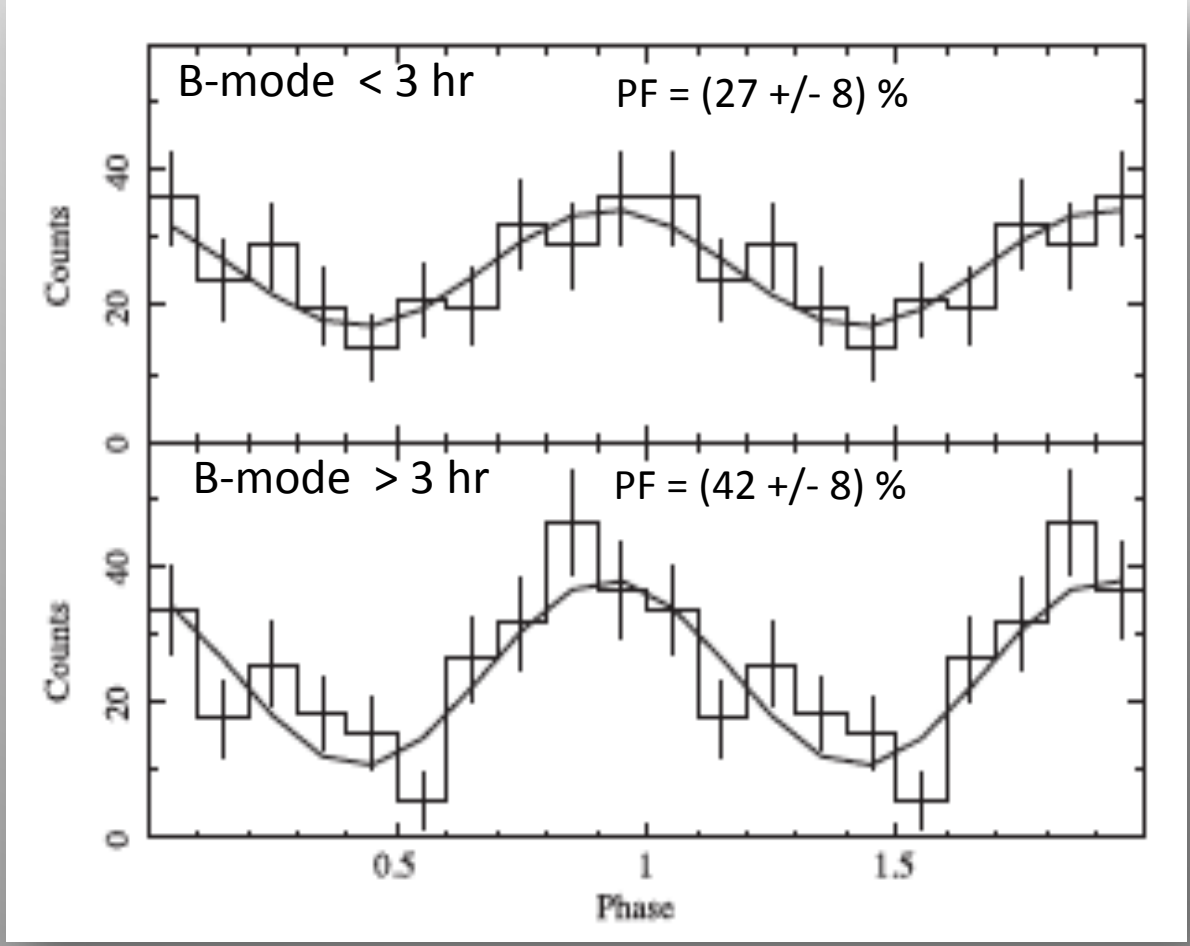


900 s bins

Sum of 15 Q→B transitions

Sum of 12 B→Q transitions

2014 campaign – possible evolution during B-mode



Hint (~2σ) of pulsed fraction increase during the B-mode

CONCLUSIONS

Rotation-powered pulsars can show variability
(unrelated to "magnetar-like" activity)
X-ray variability is a **new tool** to understand radio PSRs
→Next talk by W.Hermsen

PSR B0943: pulsed thermal and unpulsed non-thermal X-rays present in both modes, with different flux

Correlation between thermal and non-thermal X-rays suggests causal relation
(e.g. NS surface heating by backward accelerated particles)

no simple switch on/off of a single spectral component
rapid **global** magnetospheric rearrangement not required ?