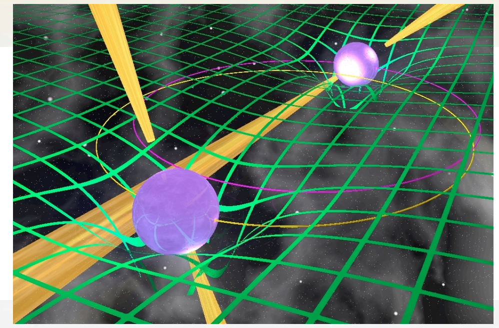
OAC Osservatorio Astronomico di Cagliari



INAF ISTITUTO NAZIONALE DI ASTROFISICA

# X-ray Spectral Analysis of the Double Pulsar PSR J0737-3039 using XMM-Newton Data

by Elise Egron

in collaboration with Alberto Pellizzoni, Maria N. Iacolina et al.

*Project financed by the RAS 'Regione Autonoma della Sardegna'*

ESAC Madrid
*May 21, 2013*

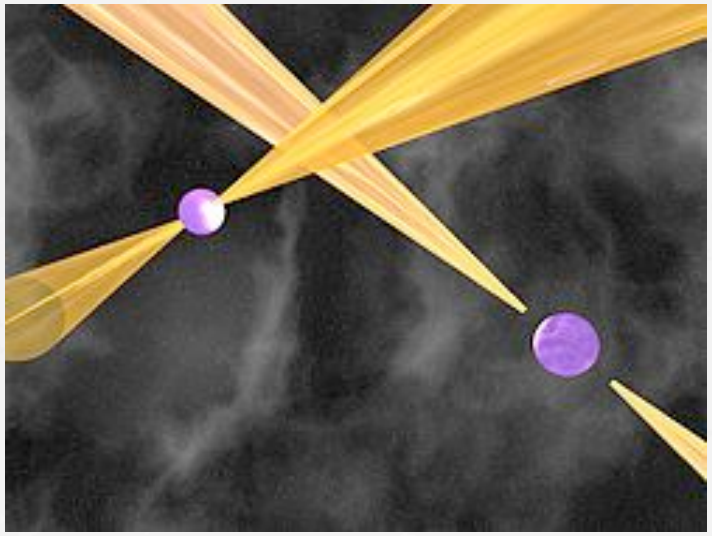
# Outline

- I. PSR J0737-3039
- II. Multi-wavelength observations
- III. 2006: First large XMM-Newton program
- IV. 2011: Second large XMM-Newton program
- V. Analysis of the 2006 + 2011 data
- VI. Different possible interpretations...

# I. PSR J0737-3039

# A fantastic system!

- Binary neutron star systems are rare... only 6 systems
- PSR J0737-3039 is amazing since both neutron stars are radio pulsars



- High orbital velocities

  => the most relativistic system ever found

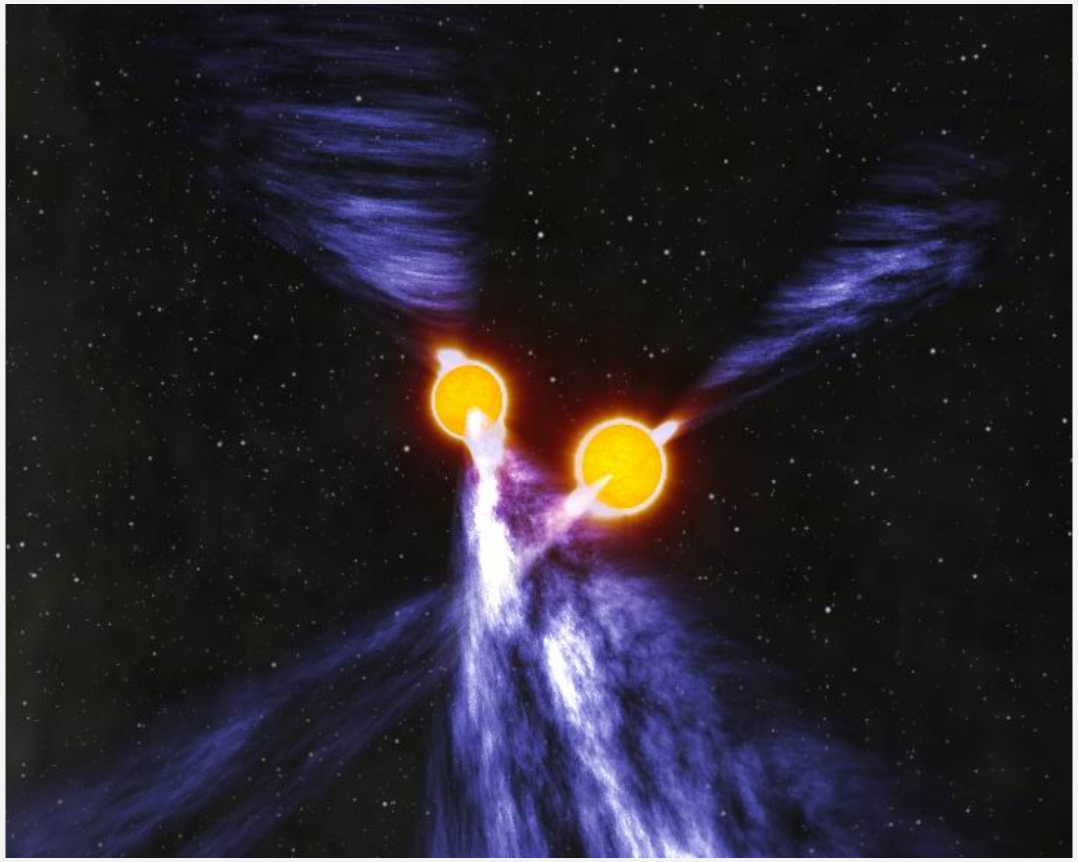
# The double-radio pulsar

- Discovered in 2003 (Burgay et al. 2003, Lyne et al. 2004)

## PSR A

Fast, mildly recycled, old pulsar

P = 22.7 ms
M = 1.3381(7) $M_{sol}$
B = $6.3 * 10^9$ G
$E_{rot} = 5.9 * 10^{33}$ erg/s
Age = 210 Myr



## PSR B

Slower, young, «lazy» pulsar

P = 2.77 s
M = 1.2489(7) $M_{sol}$
B = $1.2 * 10^{12}$ G
$E_{rot} = 1.7 * 10^{30}$ erg/s
Age = 50 Myr

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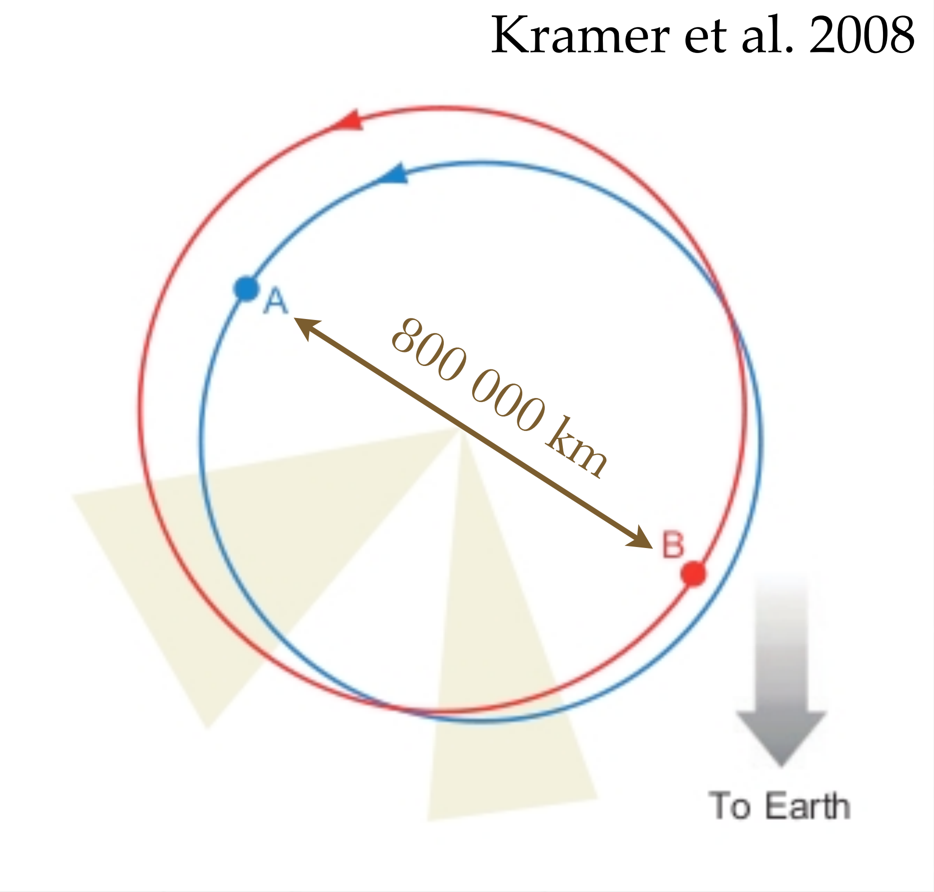


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Age = 50 Myr

Low orbital period: 2.4 hours
Eccentricity e = 0.088

# (Un)usual formation?

- Different scenarios are proposed for the formation of DNSs

  *(Smarr & Blanford 1976, Bhattacharya & van den Heuvel 1991)*

- The double pulsar shows different properties

  => low mass of PSR B, low eccentricity, etc

  => Probably a different evolution

- PSR B progenitor : possibly an electron-capture supernova onto an O-Ne-Mg core, low kick velocity

  *(Ferdman et al. 2013)*

**Mildly recycled**
pulsars (P = 20-60 ms, B<10[11] G)

⇩

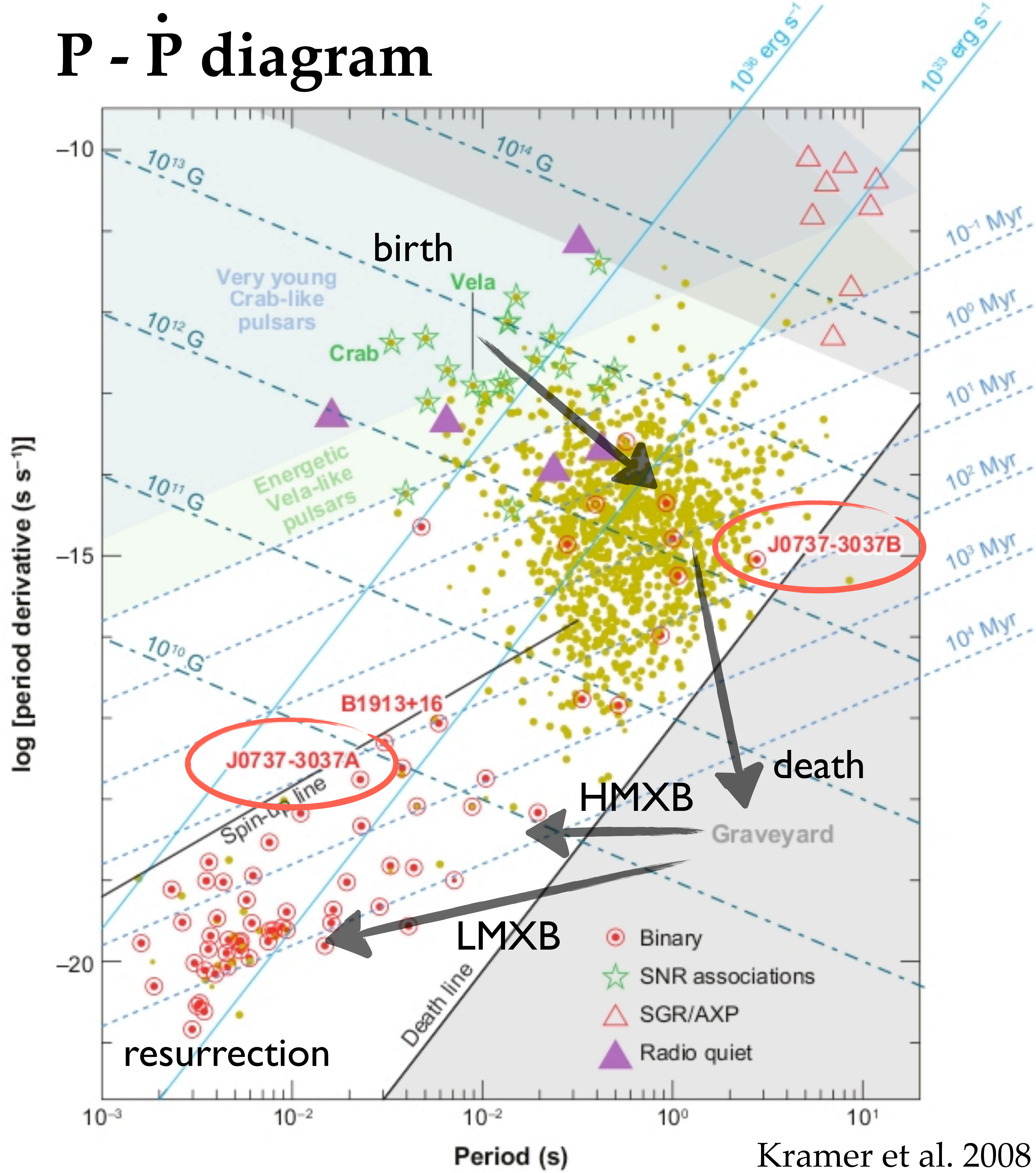
HMXB progenitors

**Fully recycled**
pulsars (P < 20 ms)

⇩

LMXB progenitors

# P - Ṗ diagram



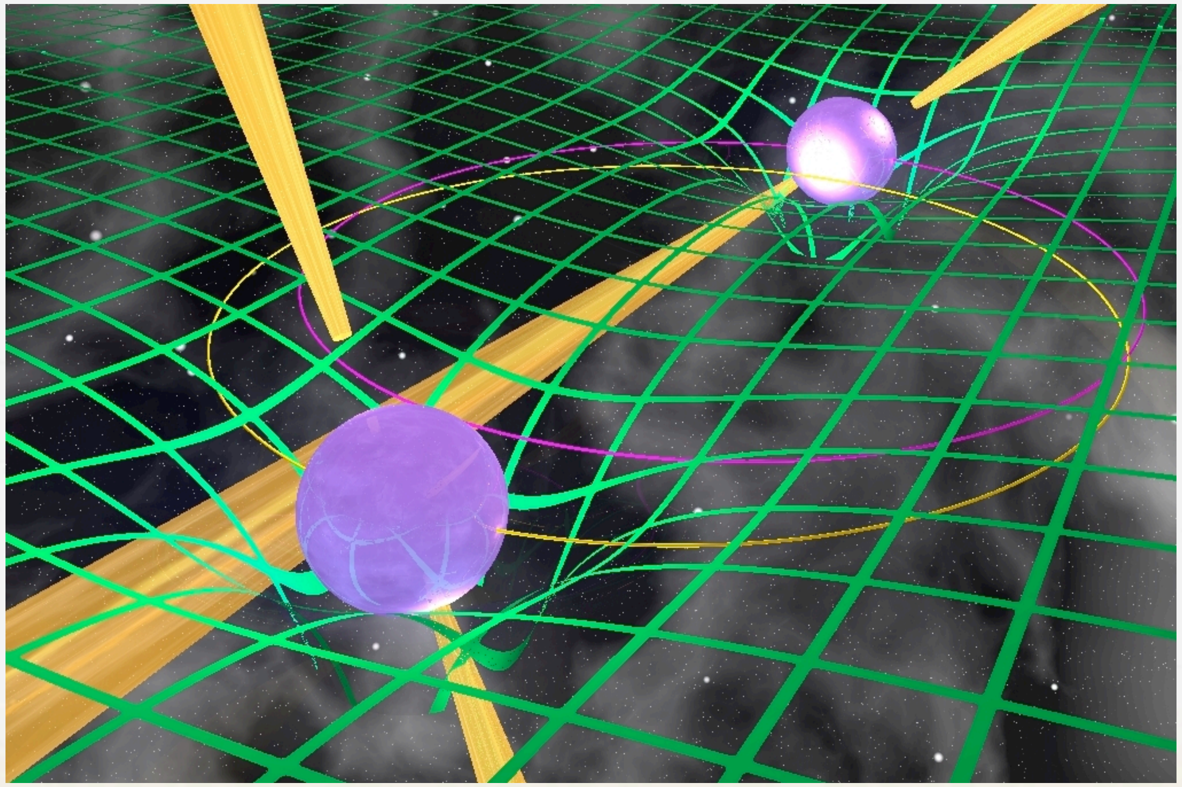

Kramer et al. 2008

# A unique laboratory

- Best timing test for general relativity in strong gravitational fields *(Kramer et al. 2006)*

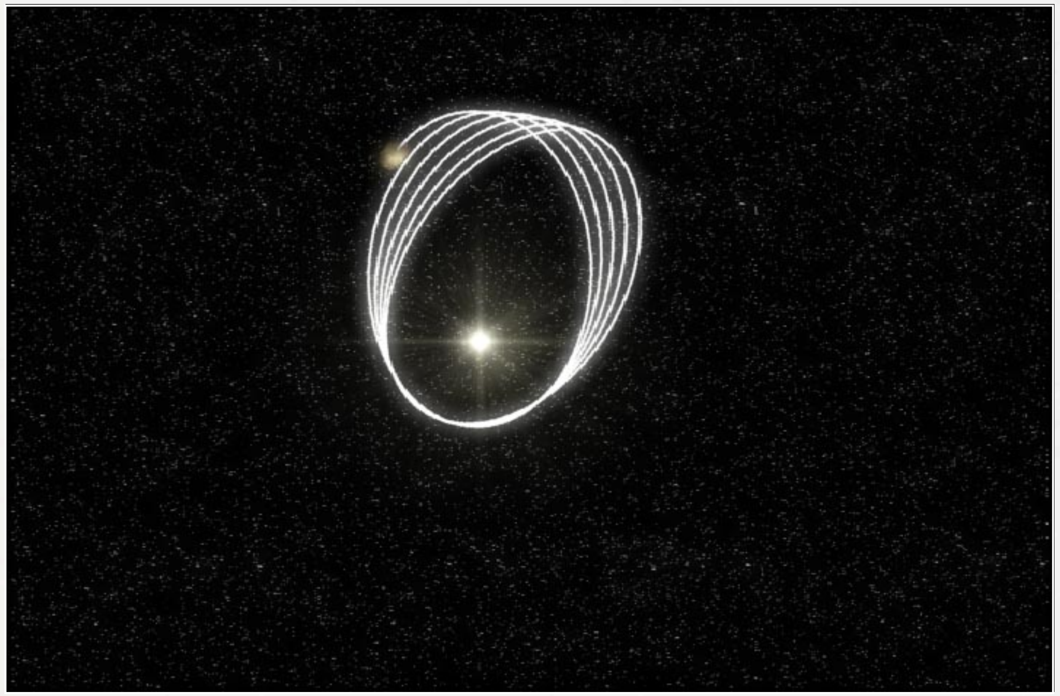
- Observed pulse arrival times modified by relativistic effects

=> 5 post-Keplerian parameters very well-determined



# Post-Keplerian parameters

1) Periastron precession



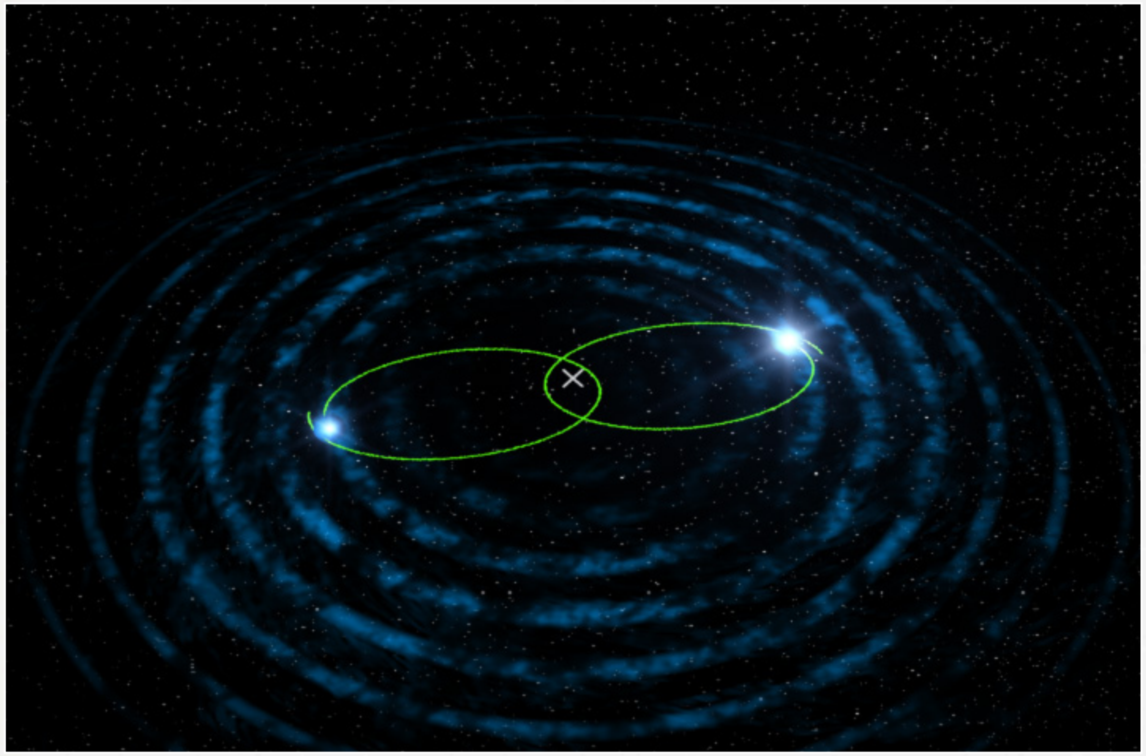
Changes in the orbit's orientation

Advance of periastron:
$\dot{\omega} = 17^\circ/\mathrm{yr}$

$$\dot{\omega} = 3\left(\frac{P_\mathrm{b}}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}$$

# Post-Keplerian parameters

2) Orbital decay



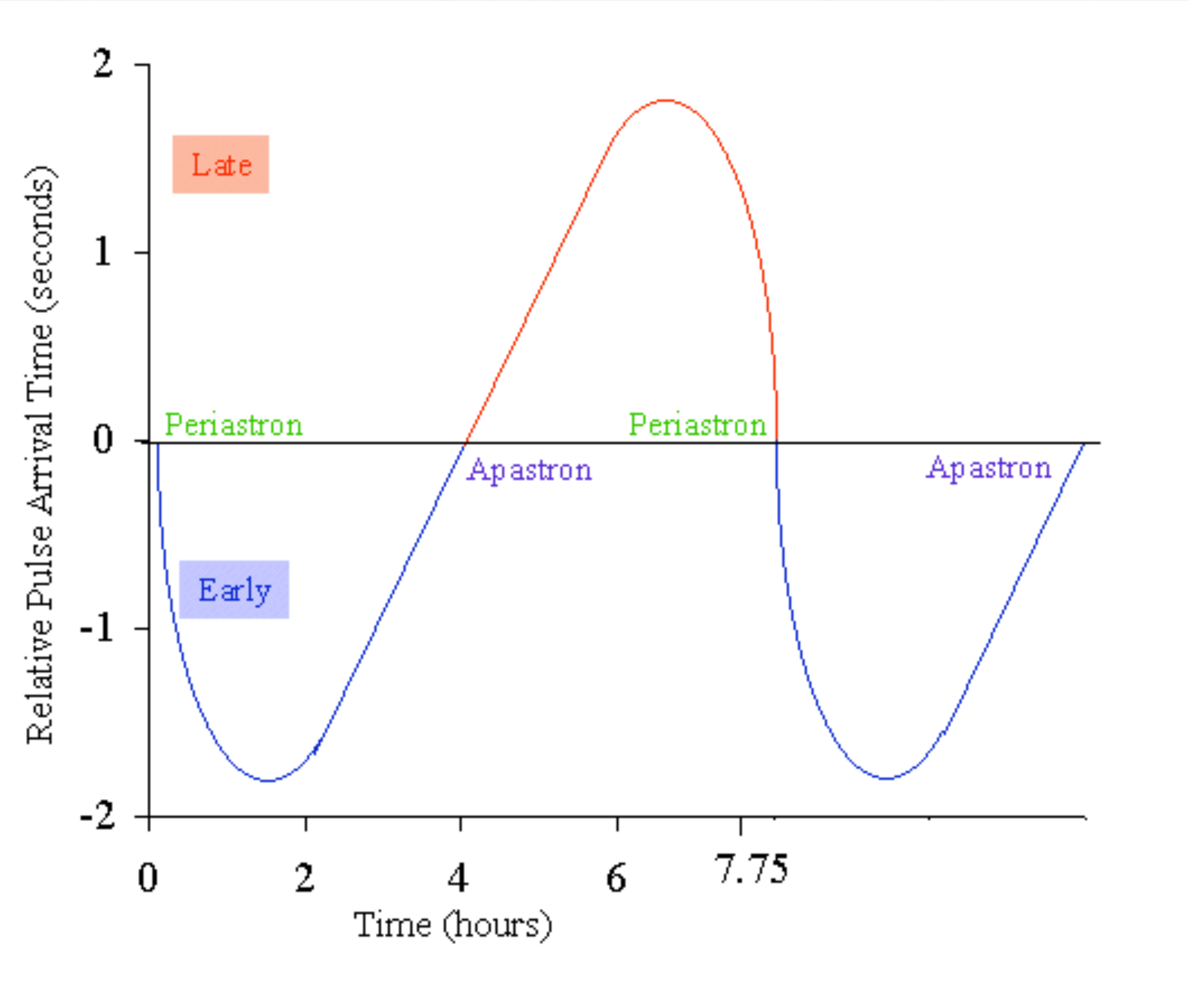
Rotational period derivative:
Orbital shrinking 7 mm/day

=> system expected to merge in 85 Myr (Burgay et al. 2003)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}T_\odot^{5/3}m_A m_B M^{-1/3}$$

# Post-Keplerian parameters

3) Gravitational redshift and time delay

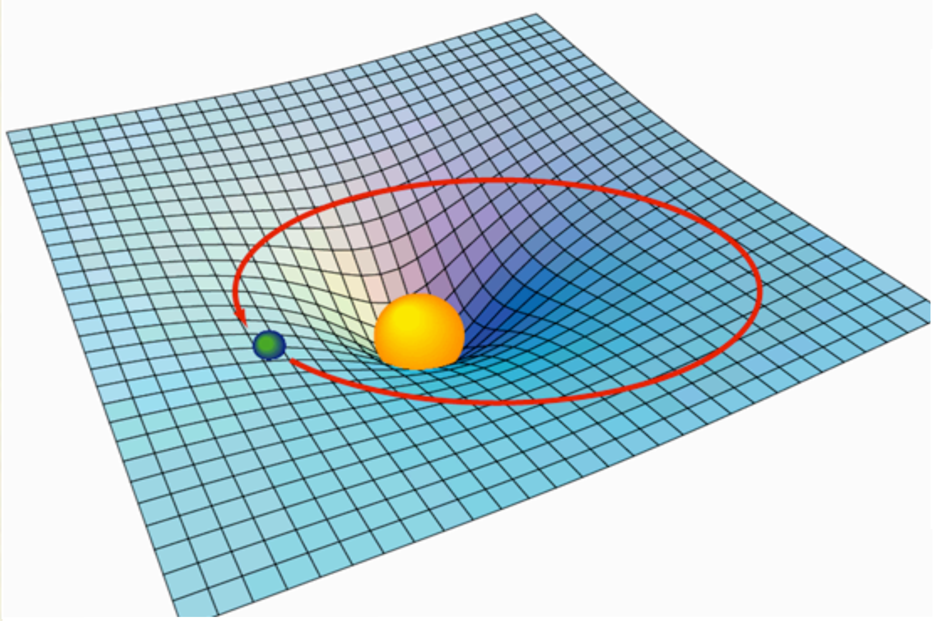


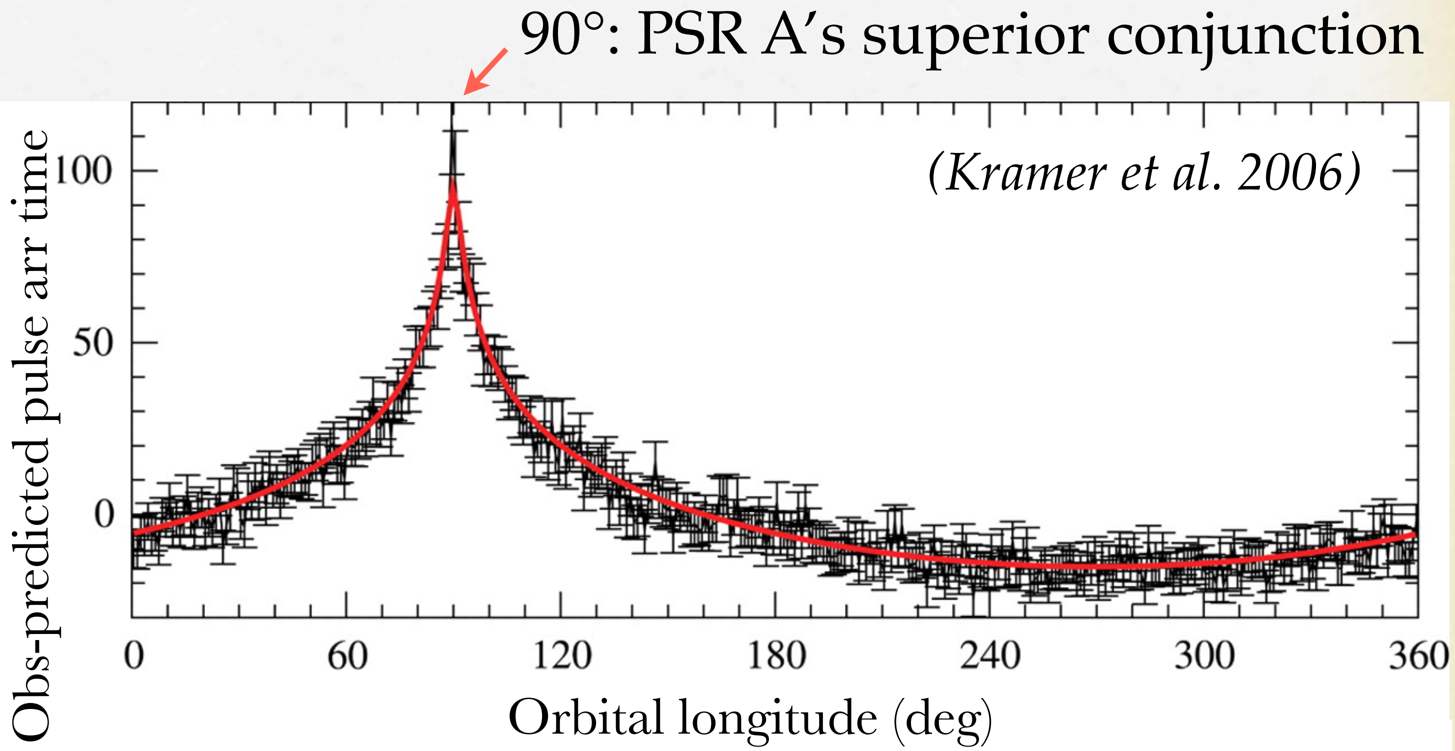

Measure the range relative to the center of mass of the binary

$$\gamma = e\left(\frac{P_\mathrm{b}}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_B(m_A + 2m_B)$$

# Post-Keplerian parameters

4-5) Shapiro Delay






Pulses => Demonstrate the curvature of space-time

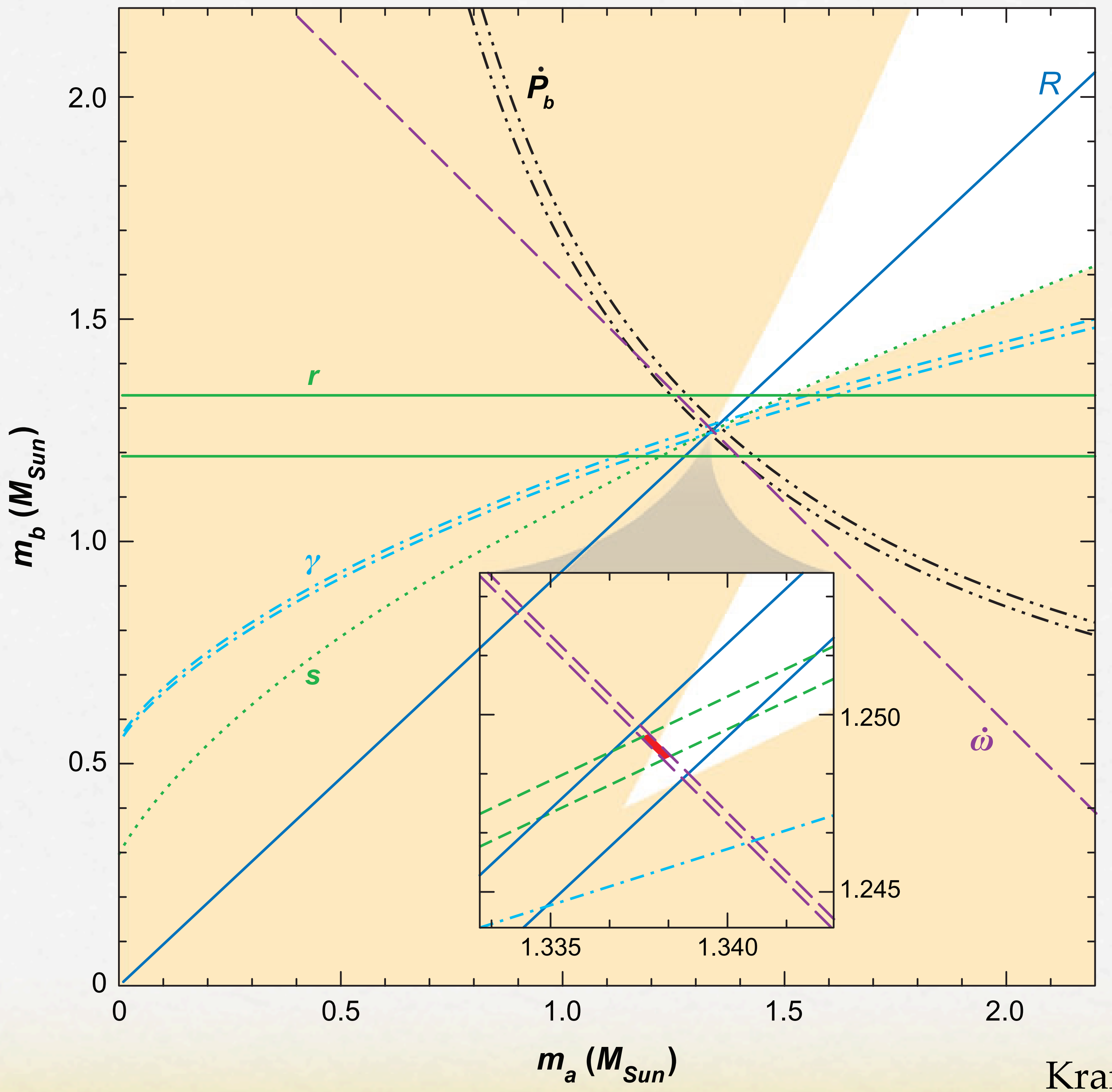
$$r = T_{\odot} m_B$$

$$s = x \left( \frac{P_b}{2\pi} \right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_B^{-1}$$

# Most precise measurement of the masses

$M_A = 1.3381(7)\ M_{sol}$

$M_B = 1.2489(7)\ M_{sol}$



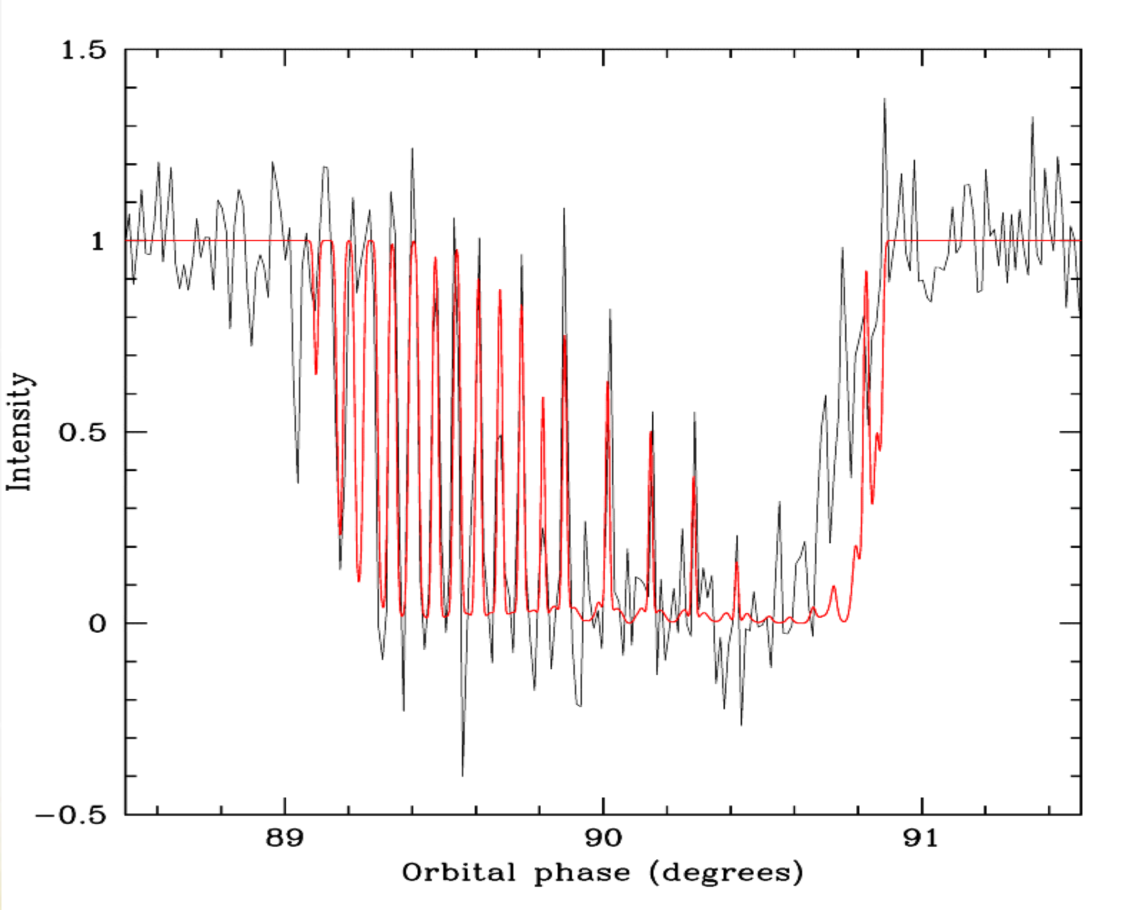

Kramer et al. 2008

# A unique laboratory

- Equation of state of superdense matter
- Interactions between the magnetospheres and relativistic winds of the two pulsars
- Orbital inclination angle i = 89° => edge-on

- eclipses of 30 sec

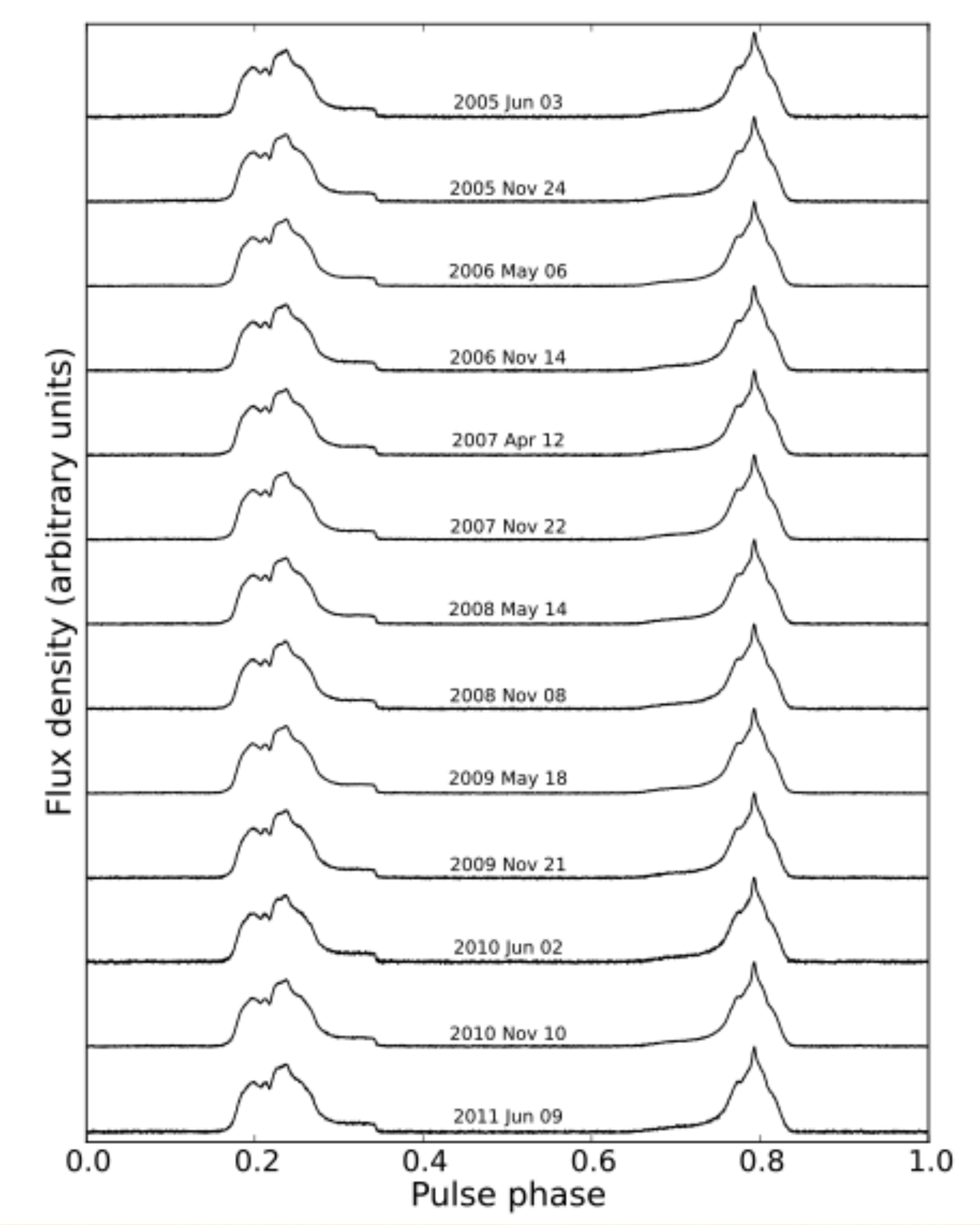
- Shapiro delay



# II. Multi-wavelength observations

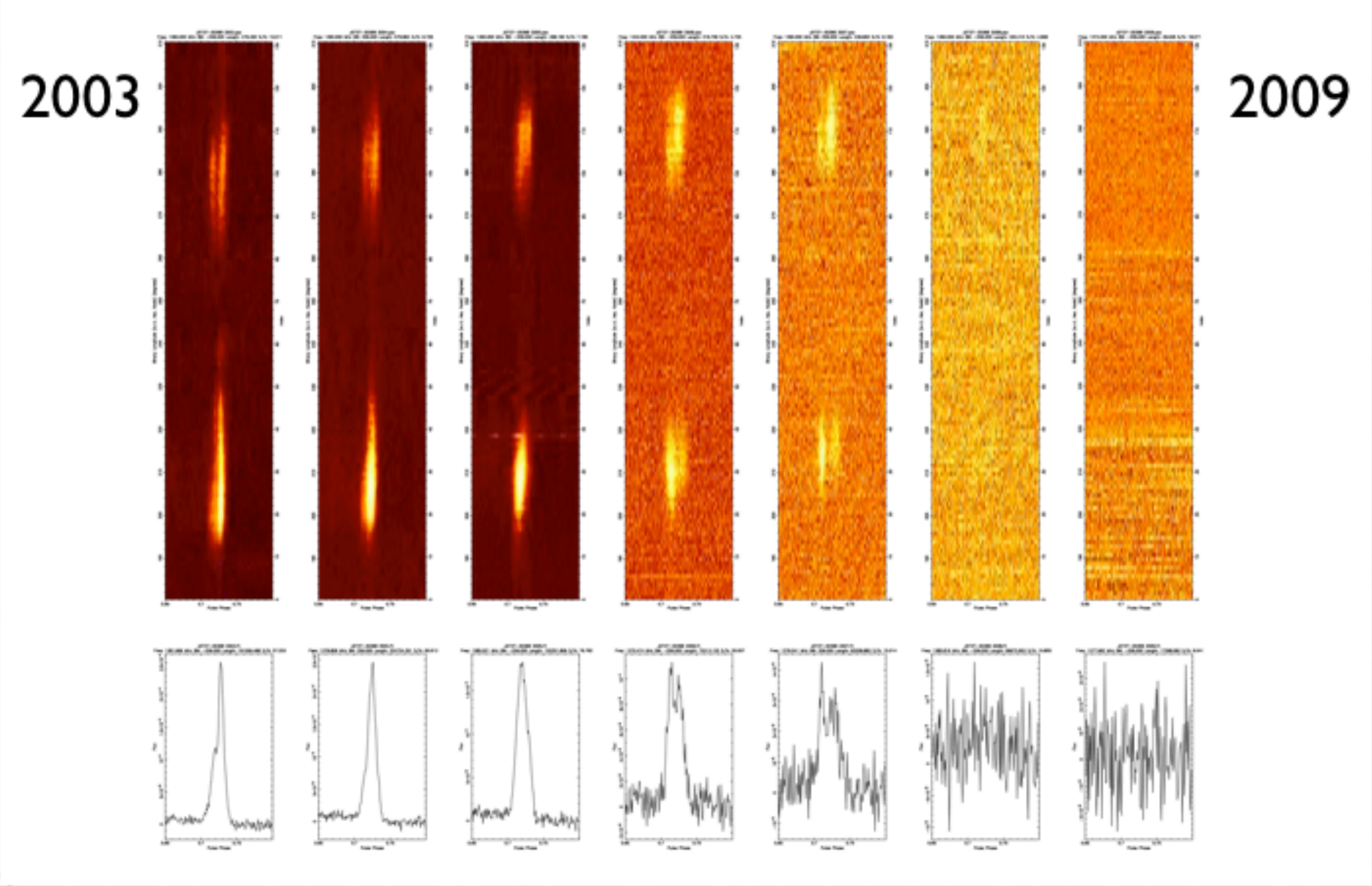
# Radio

- PSR A: a double signal, always visible *(Ferdman et al. 2013)*



# Radio

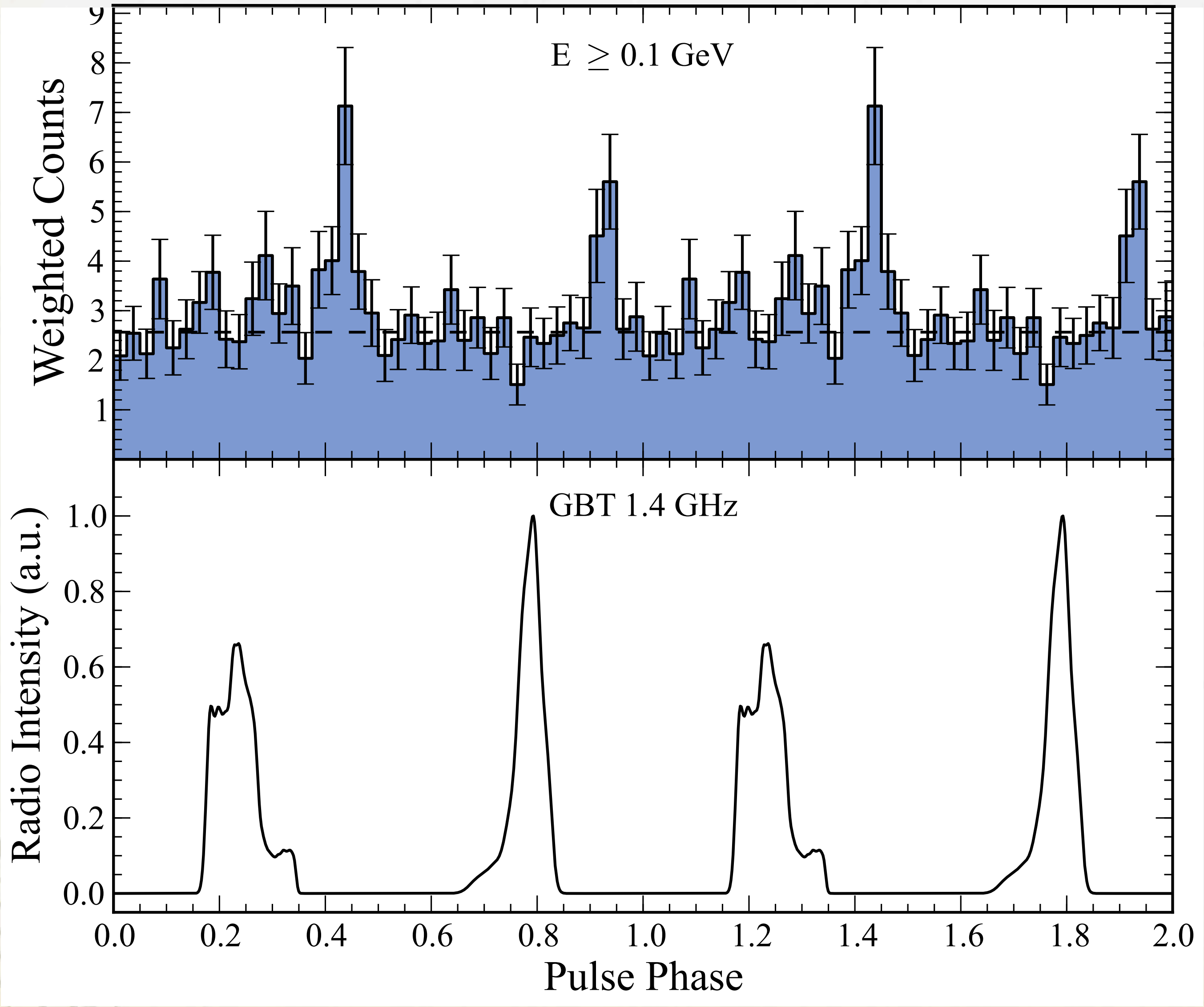
- PSR B: disappears in 2008... *(Perera et al. 2008)*



# Gamma-rays

- Fermi LAT: gamma-ray pulsations from PSR A *(Guillemot et al. 2013)*

=> first mildly recycled ms pulsar detected in GeV



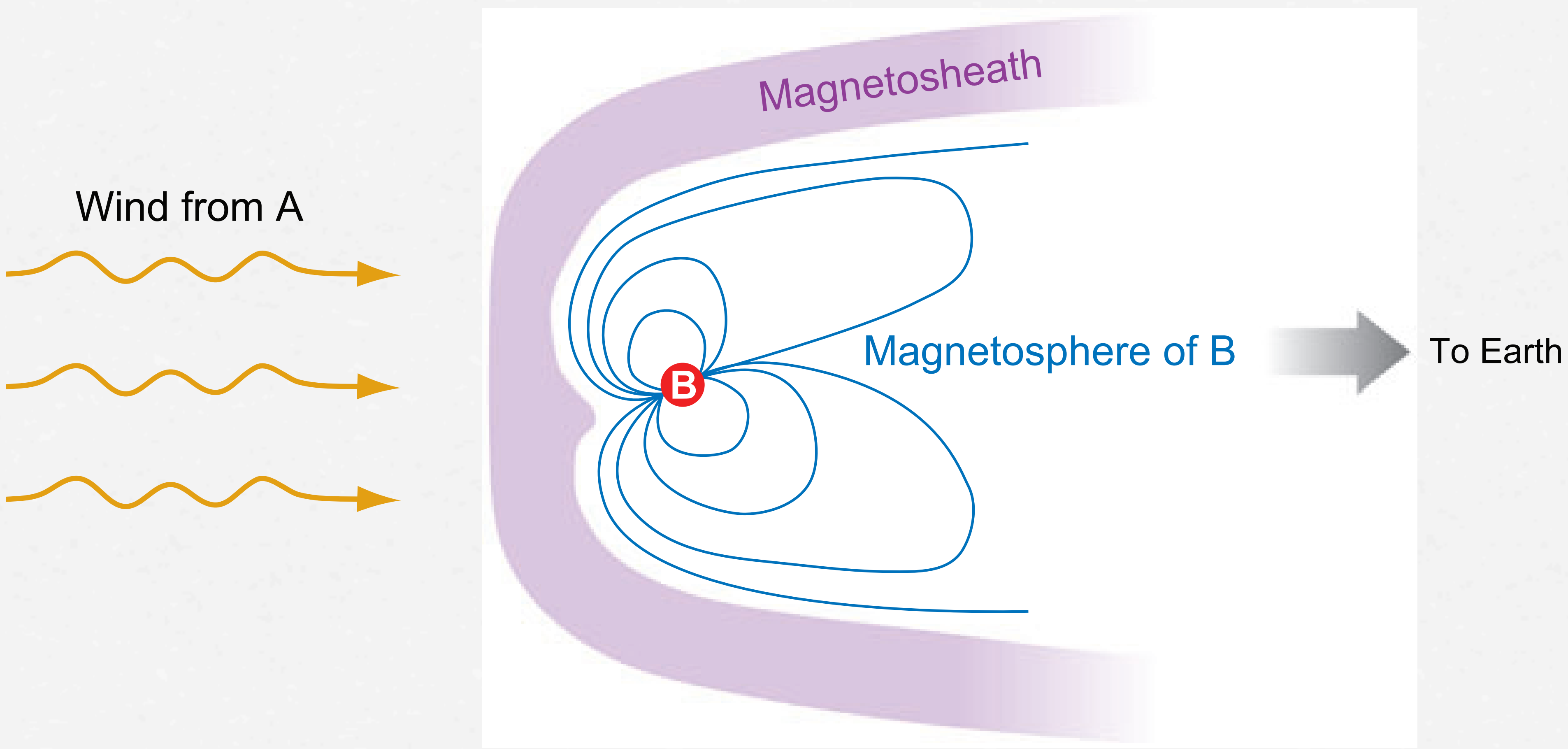

Different origin from radio emission ?

=> slot/outer gap?

shift in freq, phase?

# X-rays

- To understand the physics of the magnetospheric emissions and their interactions




*M. McLaughlin*

# X-ray observations

- **Chandra** : first X-ray observation, 10 ks, 80 photons

  => spectrum poorly constrained, quite soft

- **XMM-Newton** : 50 ks, 800 photons *(Pellizzoni et al. 2004, Campana et al. 2004)*

  => confirmation soft spectrum : PHABS*PL or PHABS*BB

  => first timing analysis

- **Chandra** : HRC-S in timing mode + ACIS-S, 90 ks + 80ks, 400 + 500 photons

  *(Chatterjee et al. 2007, Possenti et al. 2008)*

  => double-peaked pulses at the PSR A period, similar to radio pulses

  => very soft spectrum dominated by the pulsed emission from PSR A

# Two large XMM-Newton programs

- **2006 : 26 revolutions** of the binary system (120 ks + 115 ks) => 235 ks
  *(Pellizzoni et al. 2008)*

- **2011 : 41 revolutions** (130 ks + 130 ks + 107 ks) => 367 ks

- **Cameras'characteristics**

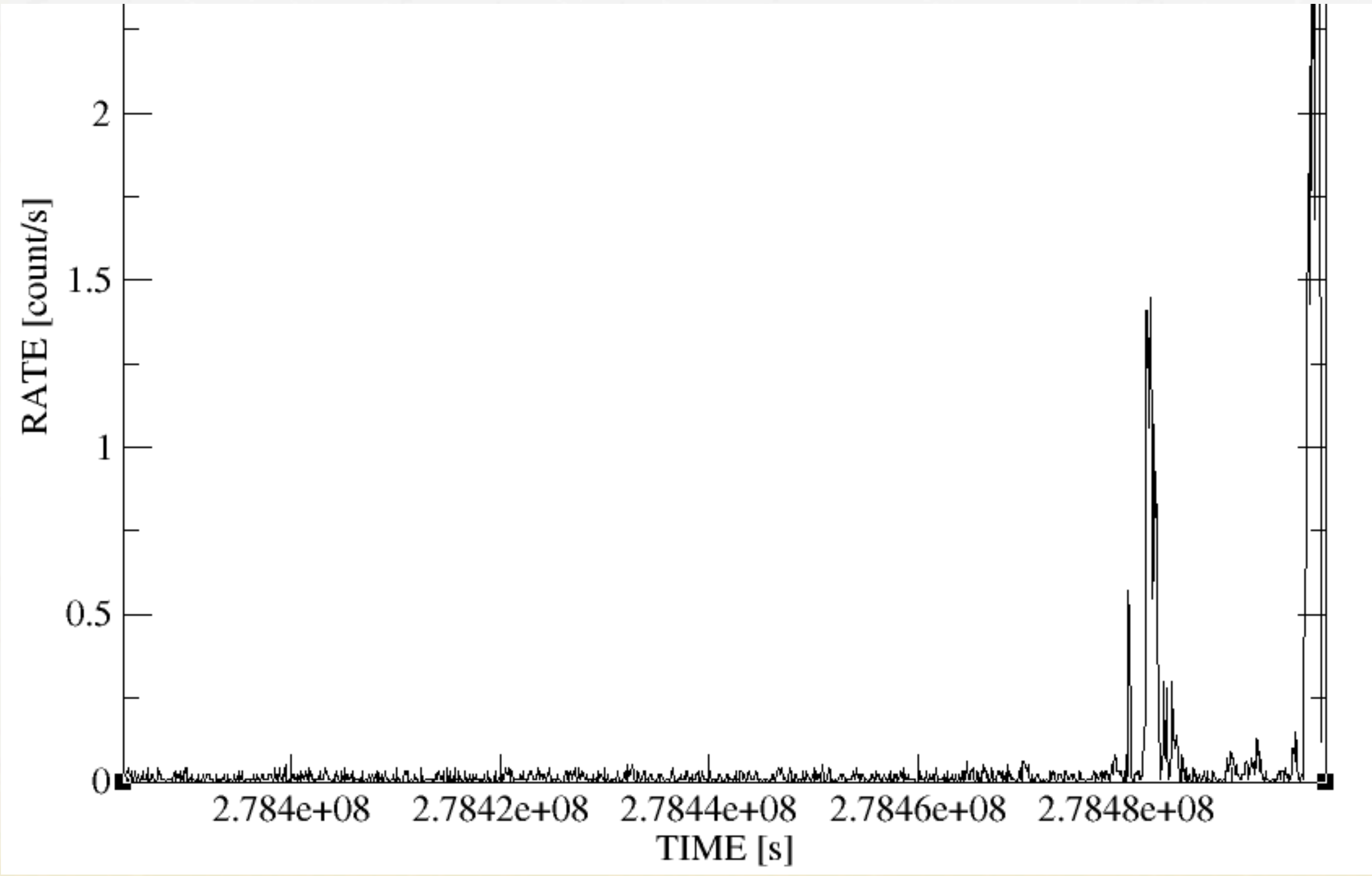
| | Mode | Time res | Filter |
|---|---|---|---|
| PN | small window | 5.67 ms | medium (2006)<br>thin (2011) |
| MOS | small window | 0.3 s | medium (2006)<br>thin (2011) |

# III. 2006: First large XMM-Newton program

# Data reduction

- EPIC/pn pattern = 0 (single events) for the spectral analysis
- High particle background screening : soft proton flares

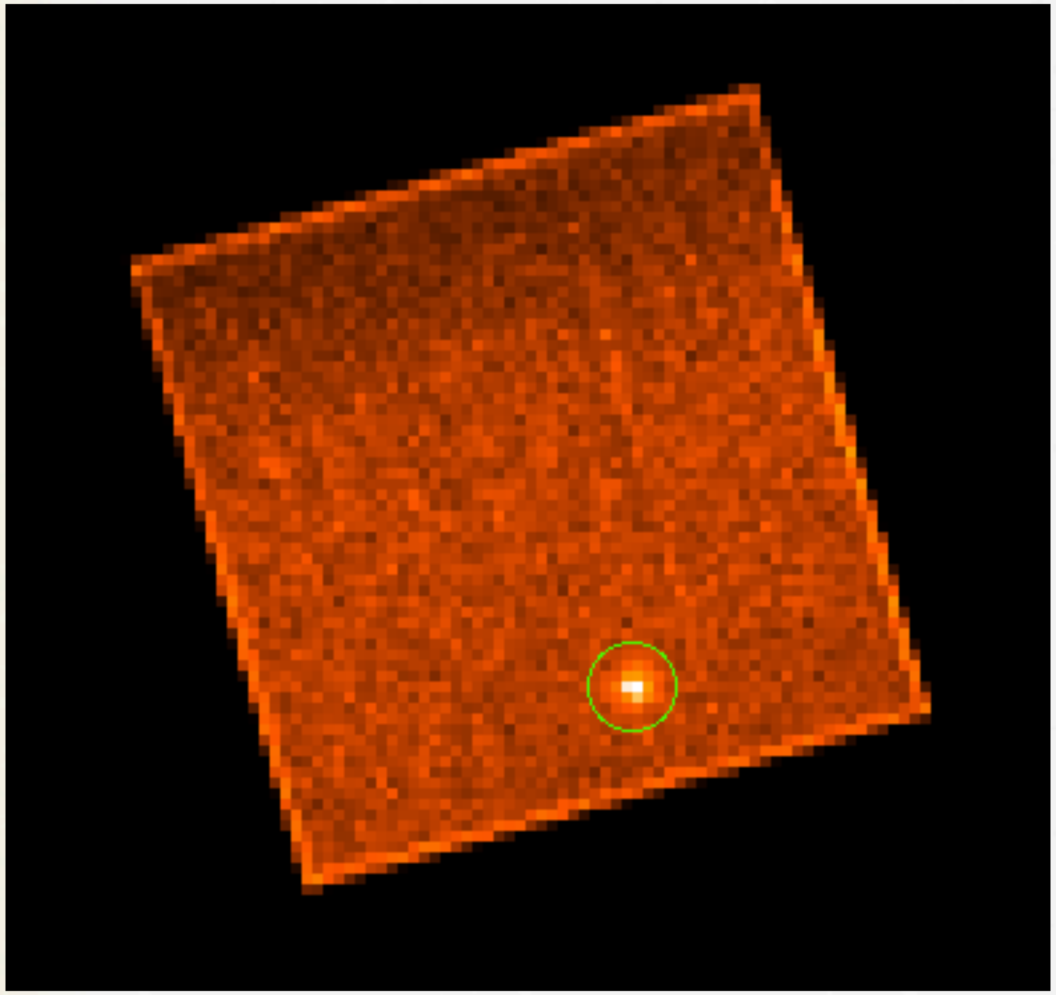
=> threshold at 5 sigma from the quiescent rate *(De Luca & Molendi 2004)*




light curve 10-12 keV

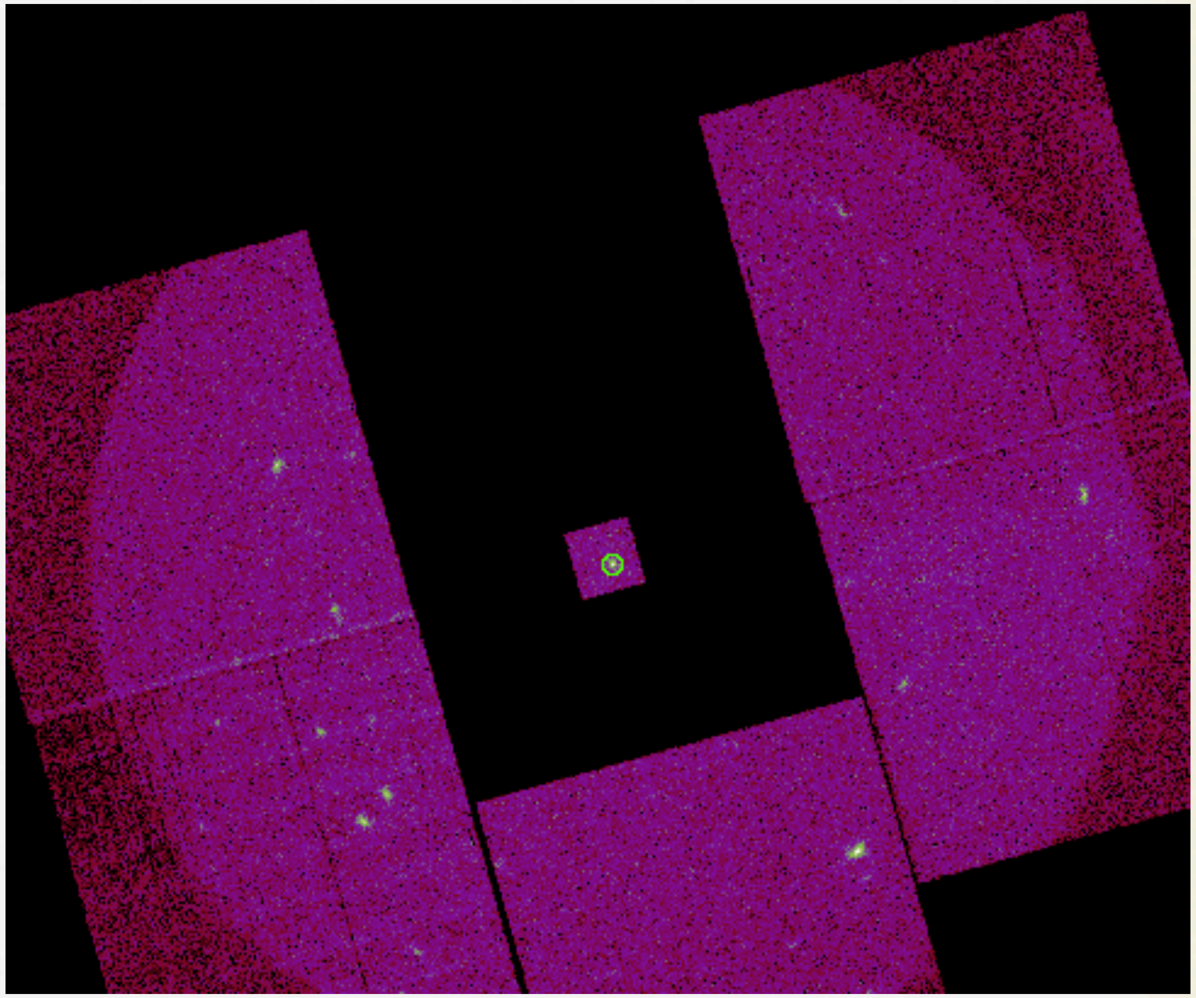
# Data reduction

- EPIC/PN



Source extraction radius: 18″

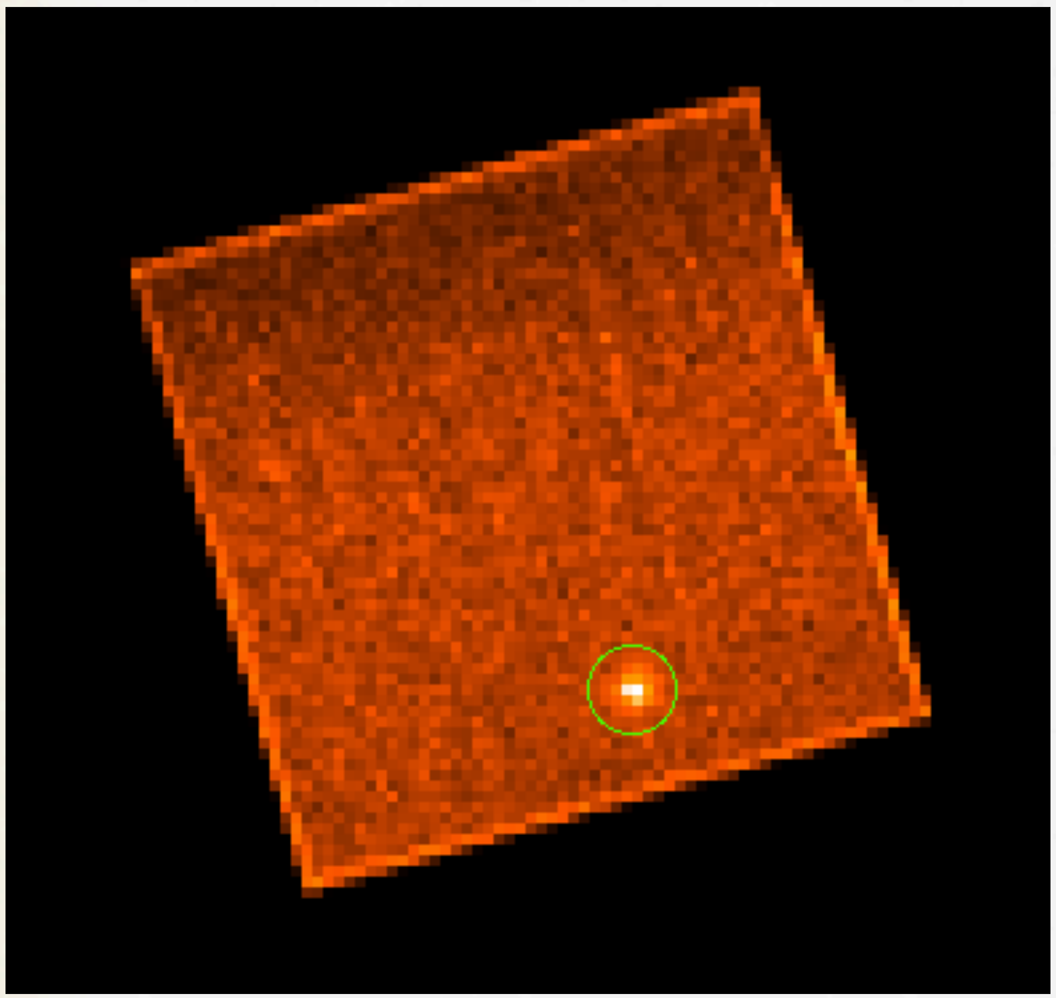
- EPIC/MOS



Source extraction radius: 15″

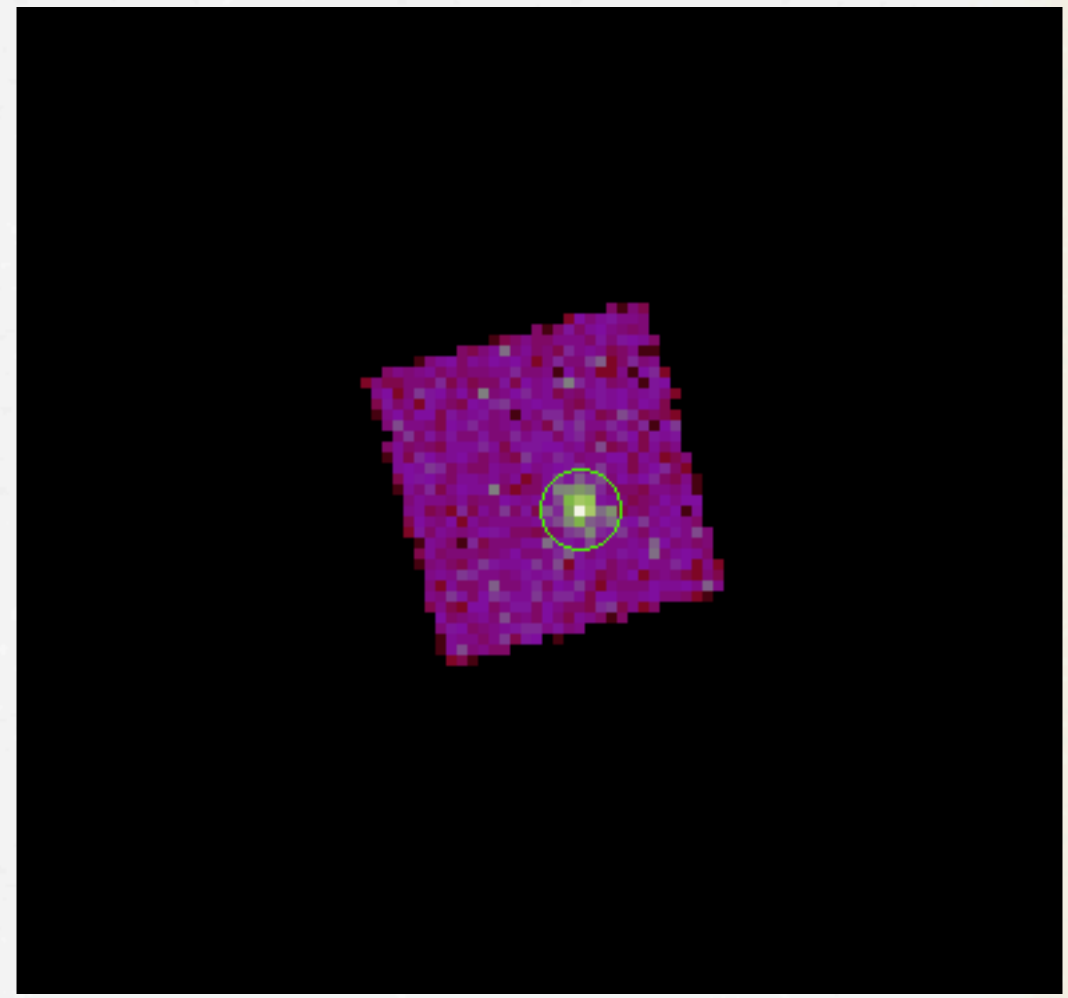
# Data reduction

- EPIC/PN



Source extraction radius: 18″

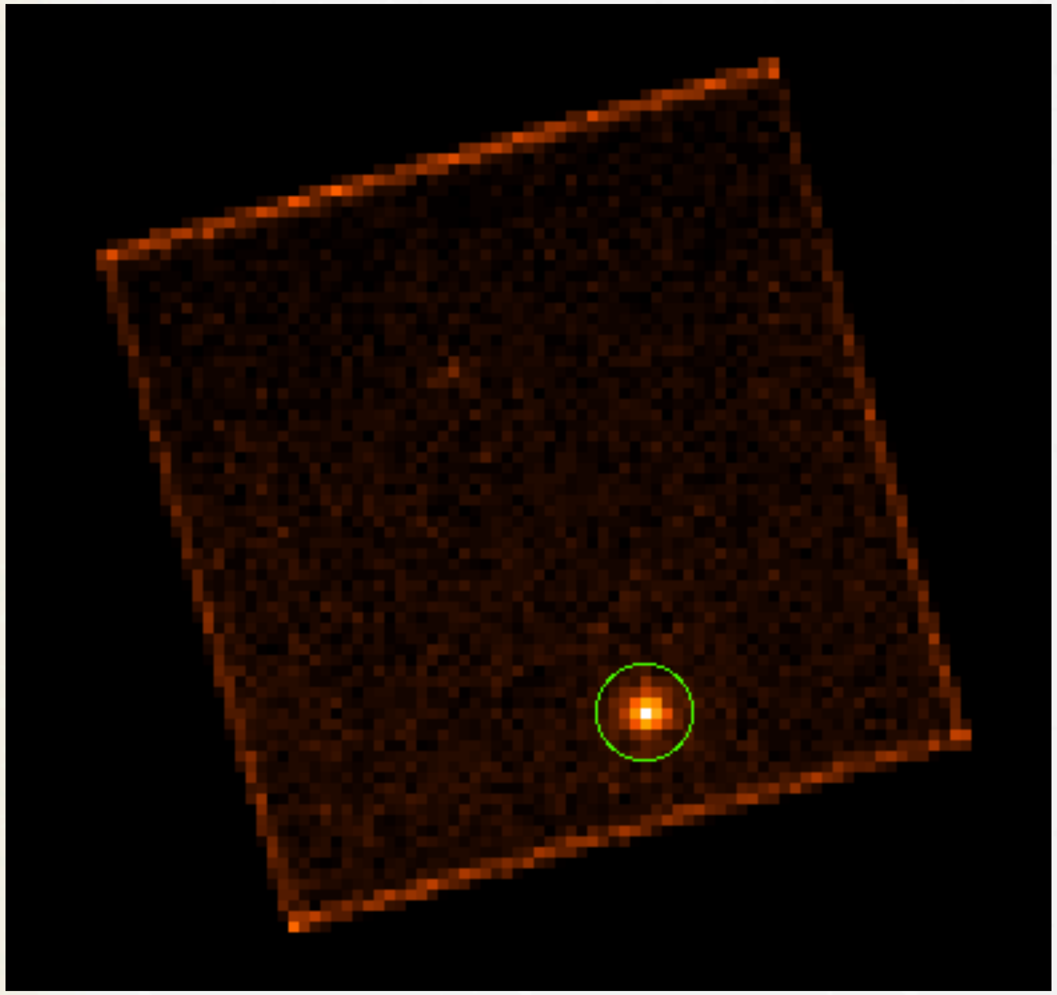
- EPIC/MOS



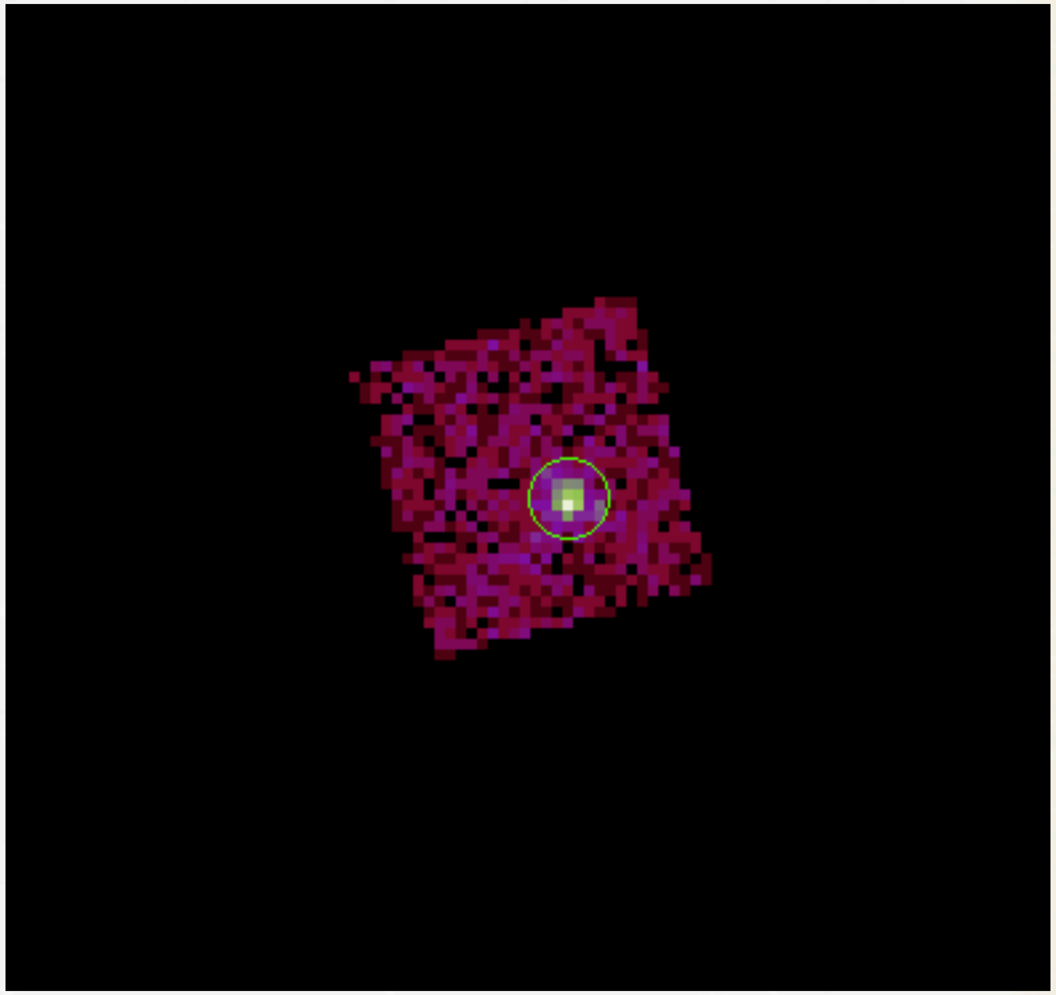
Source extraction radius: 15″

# Data reduction

- EPIC/PN
- EPIC/MOS



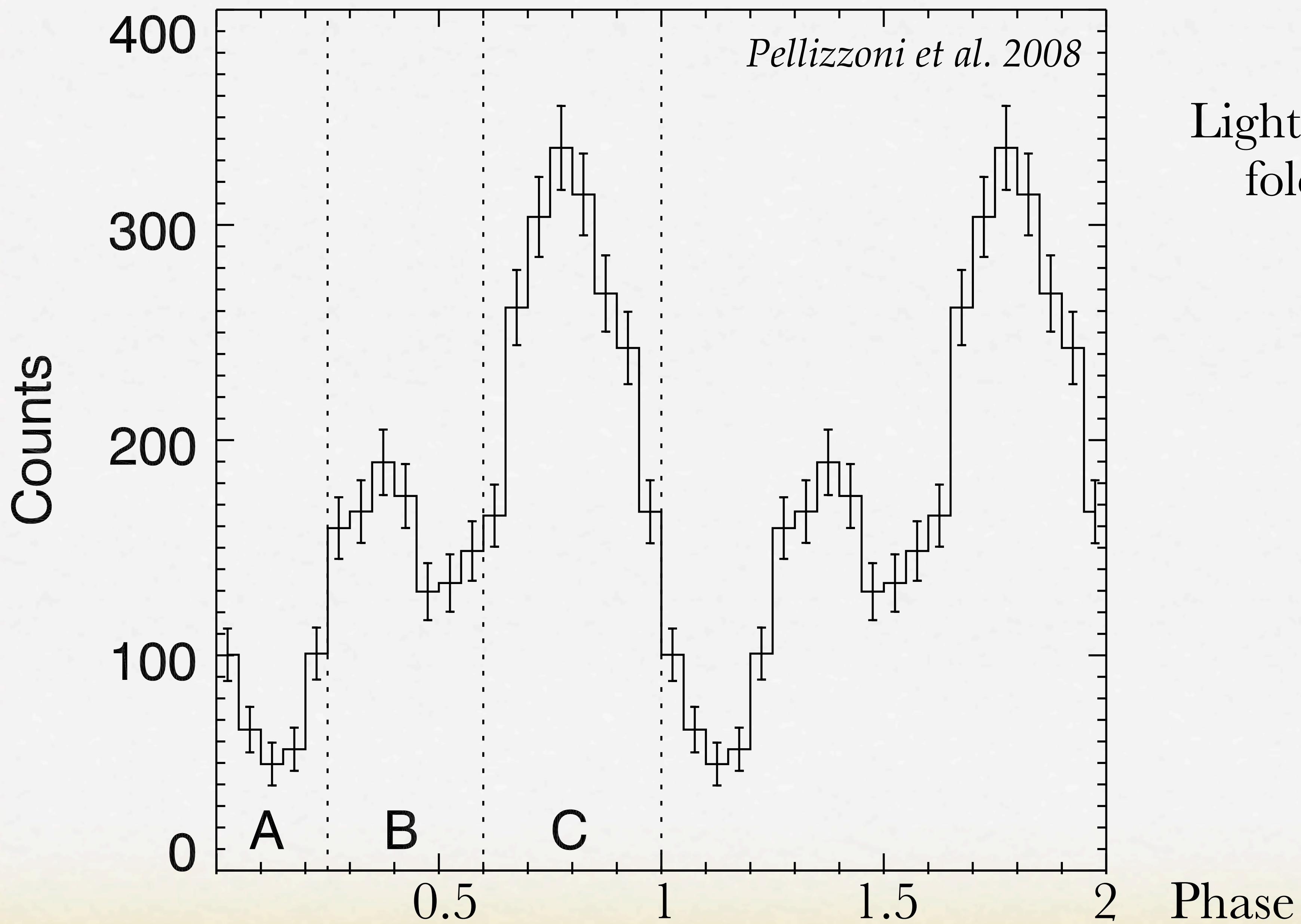
pattern = 0
threshold 5 sigma



pattern = 0-12
threshold 5 sigma

# Timing analysis

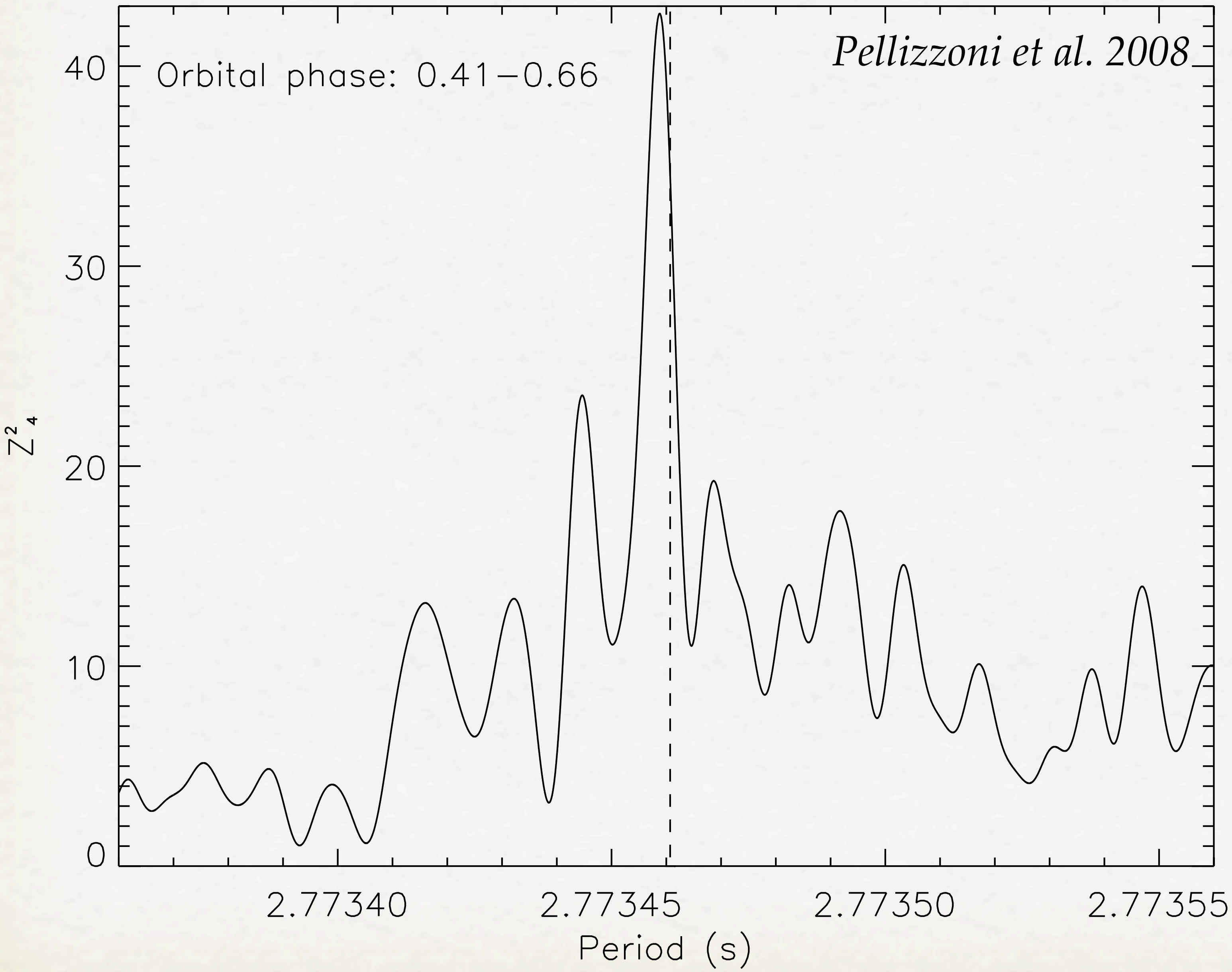
- Pulsations from PSR A: P = 22.6993787(5) ms




Light curve 0.15-4 keV folded at period P

# Timing analysis

- Pulsations from PSR B




Distribution of the $Z^2$ statistics for the pn data

Dashed line: PSR B period from radio ephemeris => small shift

# Spectral analysis

- Different models were tested (modified by the photoelectric absorption):

  - 1 single component: PL or BB => failure

  - 2 components (PL + BB) or (BB + BB)

    => (PL + BB) $\quad \mathrm{Chi}^2_r = 0.92$ (96)

    $\Gamma = 3$, $kT_{BB} = 150 \pm 20$ eV, $R_{BB} = 80 \pm 30$ m

    => (BB + BB) $\quad \mathrm{Chi}^2_r = 1.00$ (96)

    $kT_{BB} = 290 \pm 40$ eV, $R_{BB\_1} = 20 \pm 8$ m

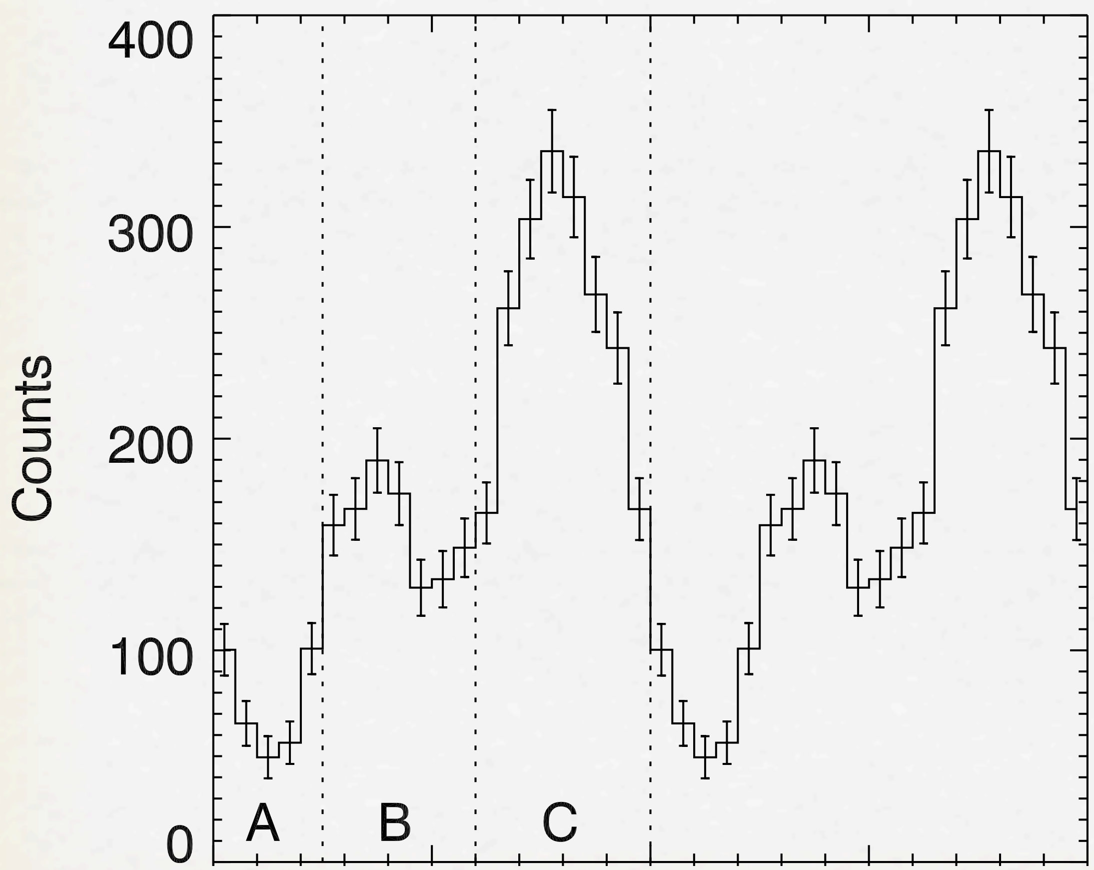
    $kT_{BB} = 114 \pm 10$ eV, $R_{BB\_2} = 210 \pm 40$ m

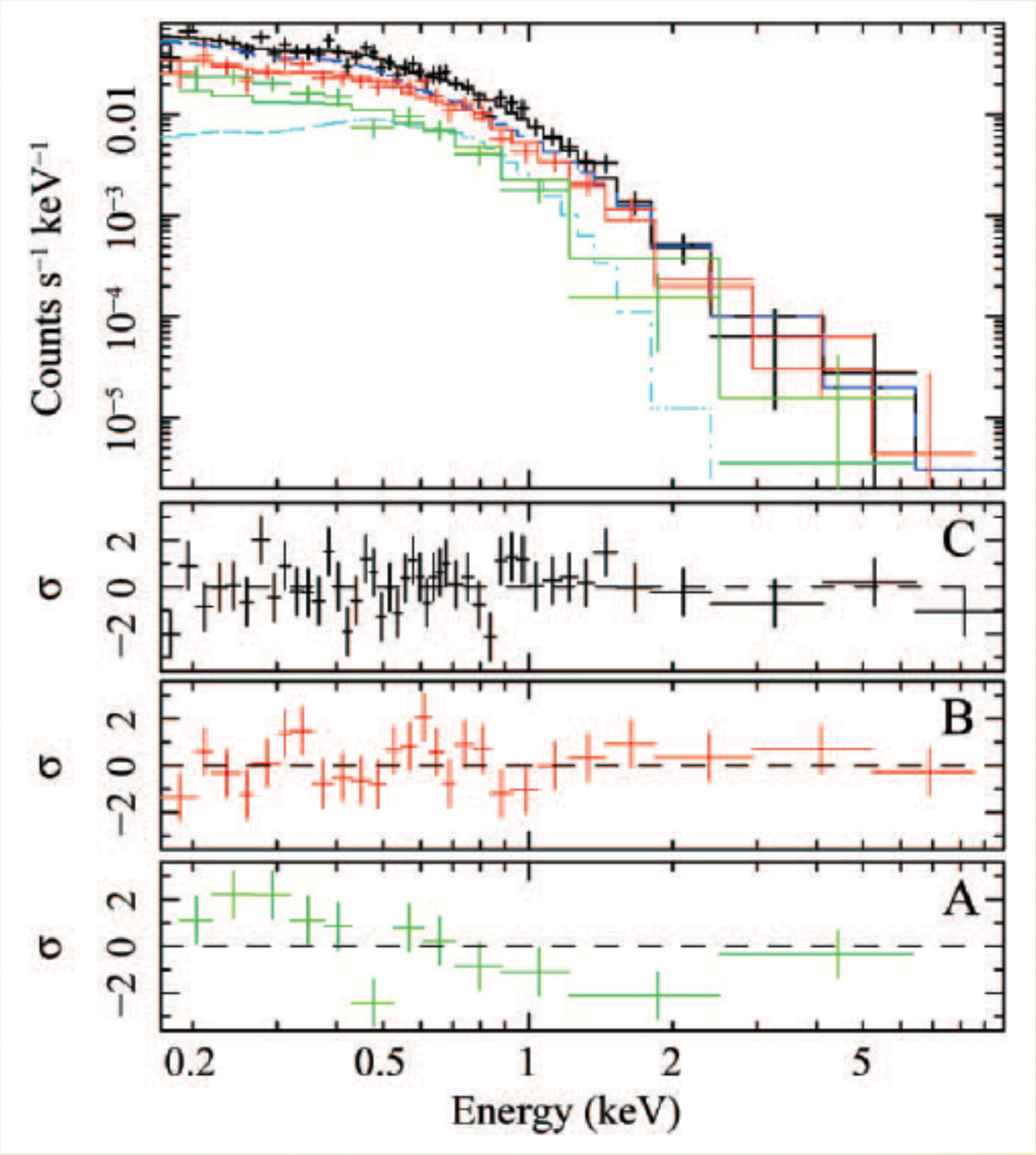
# Spectral analysis

- 3 pn phase-resolved spectra

  model: PHABS*(PL + BB)

*Pellizzoni et al. 2008*



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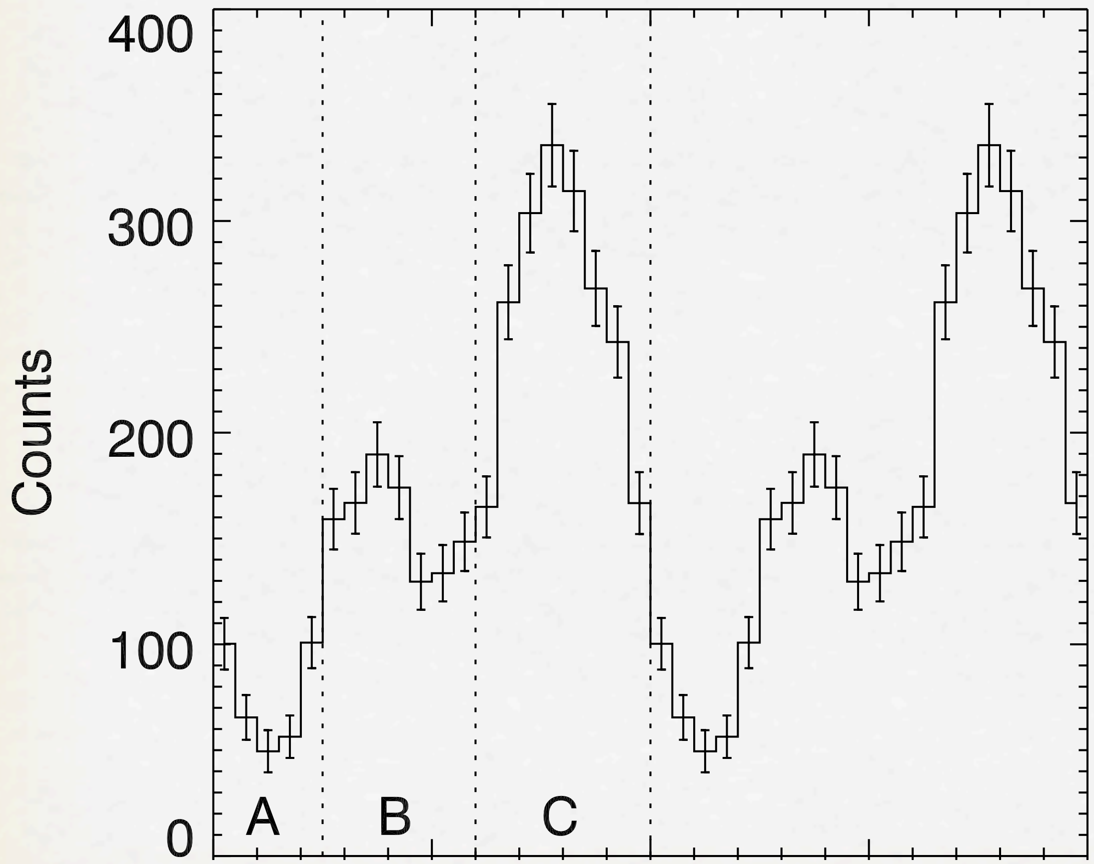
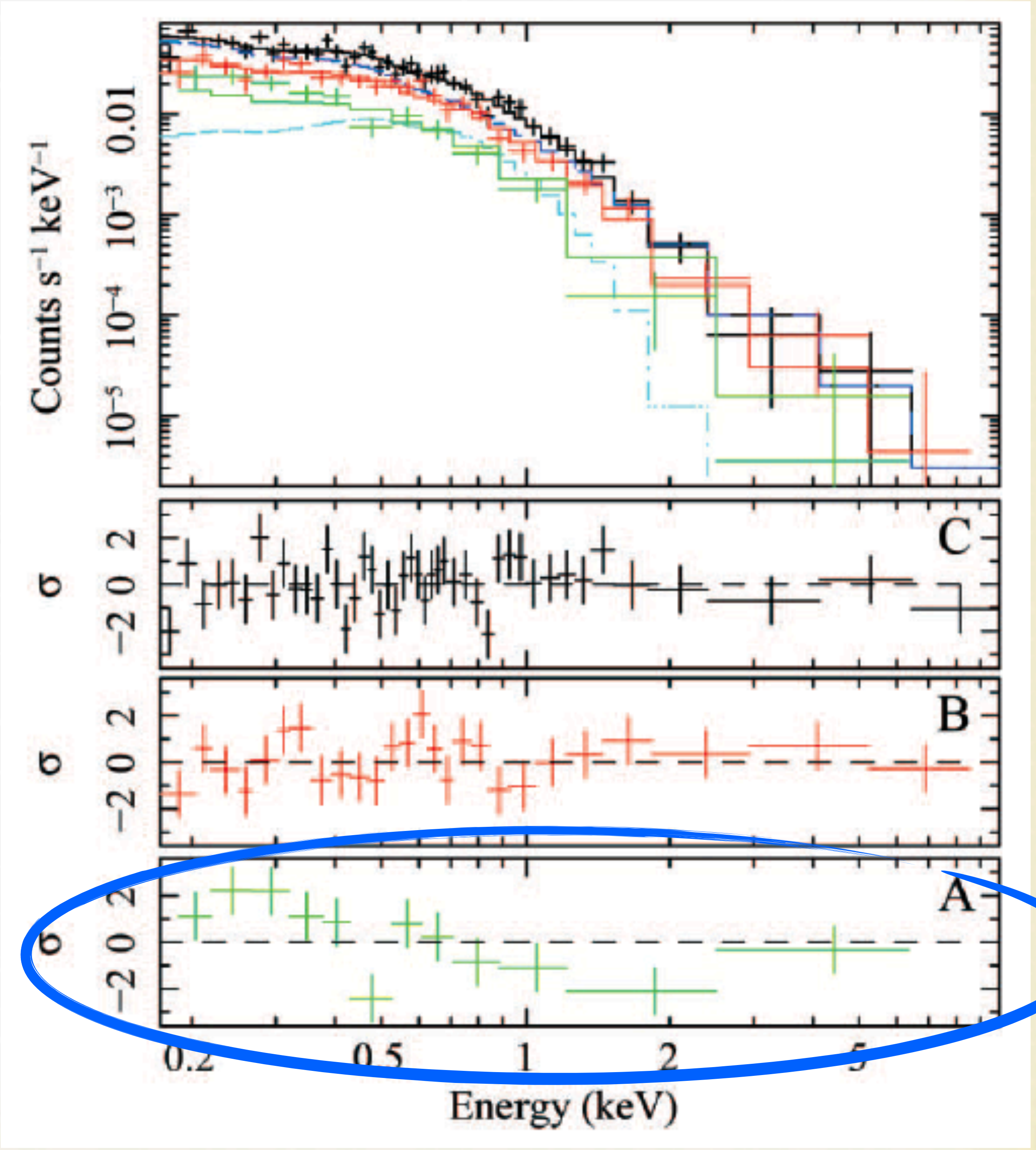
*Pellizzoni et al. 2008*



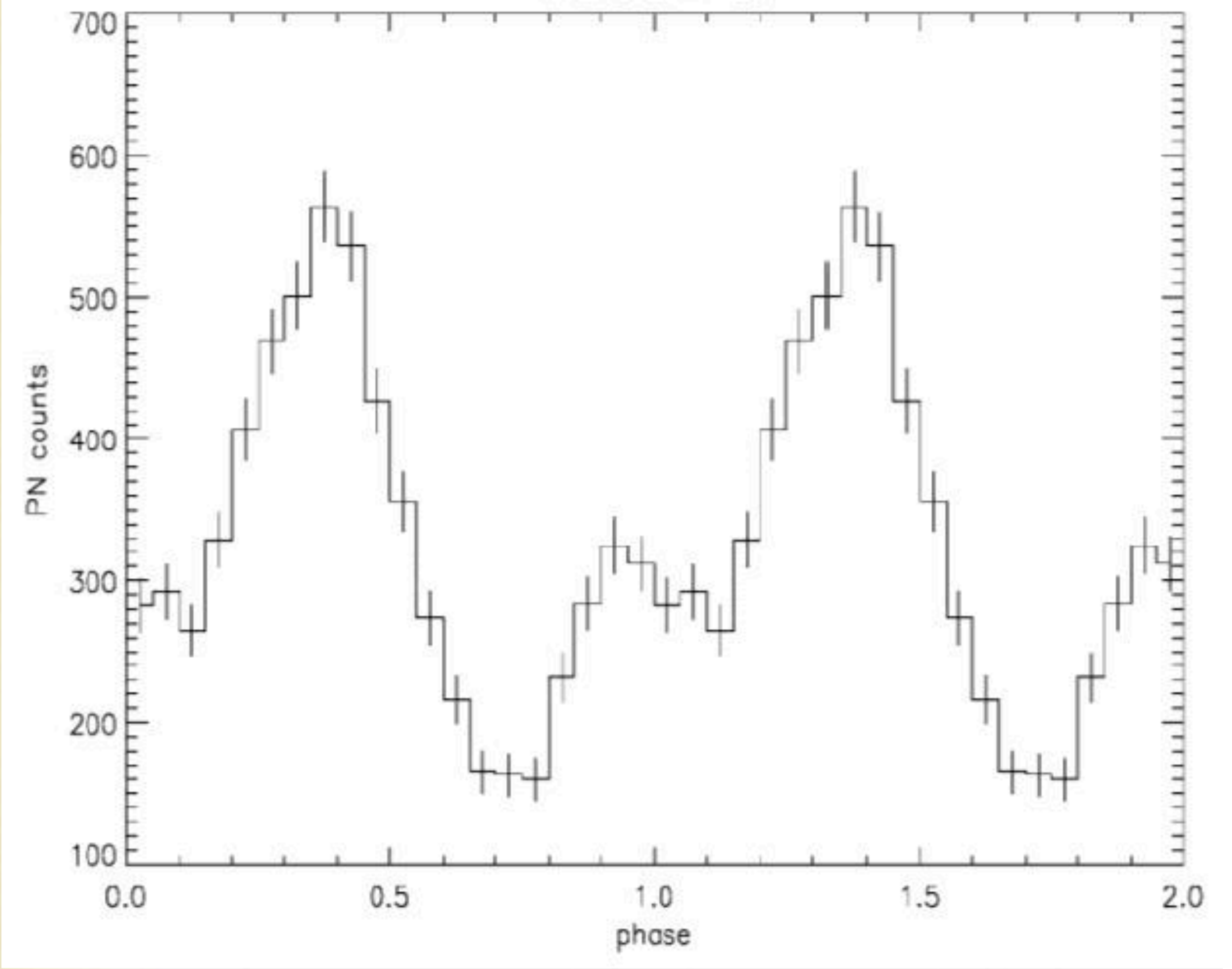




Off-pulse spectrum is different

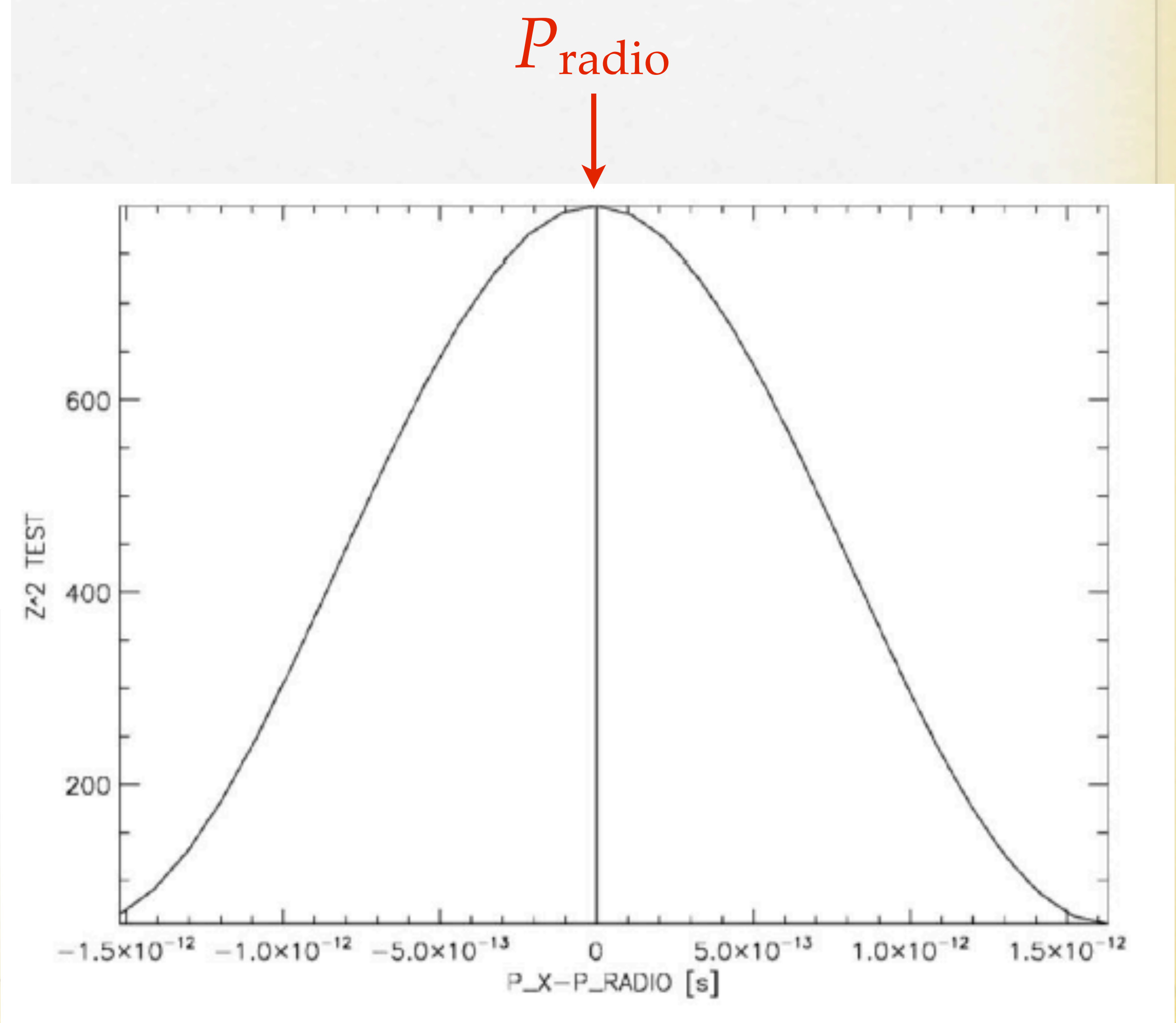
# IV. 2011: Second large XMM-Newton program

# Timing analysis

- Pulsations from PSR A: P = 22.6993787(5) ms



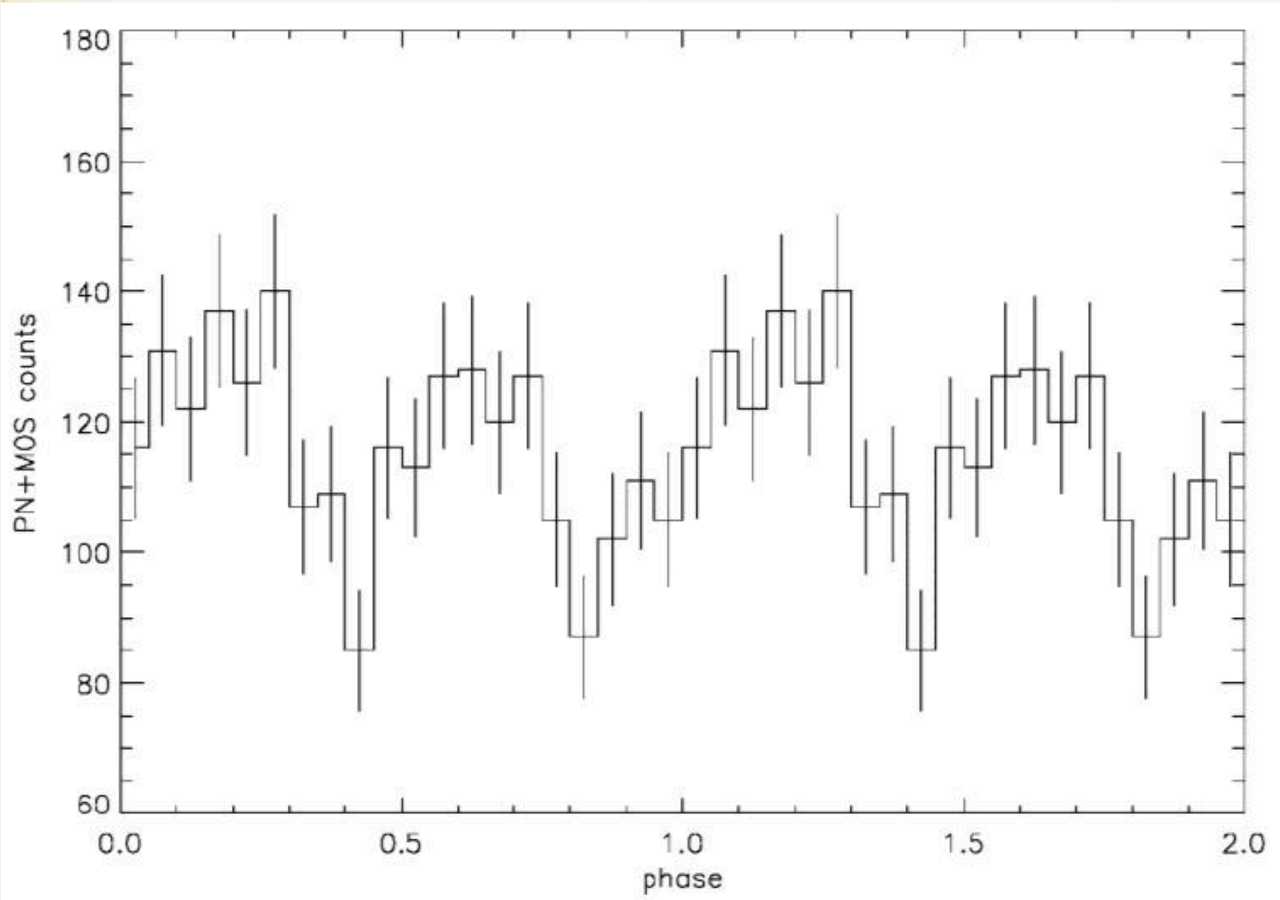

*Iacolina et al., in prep*



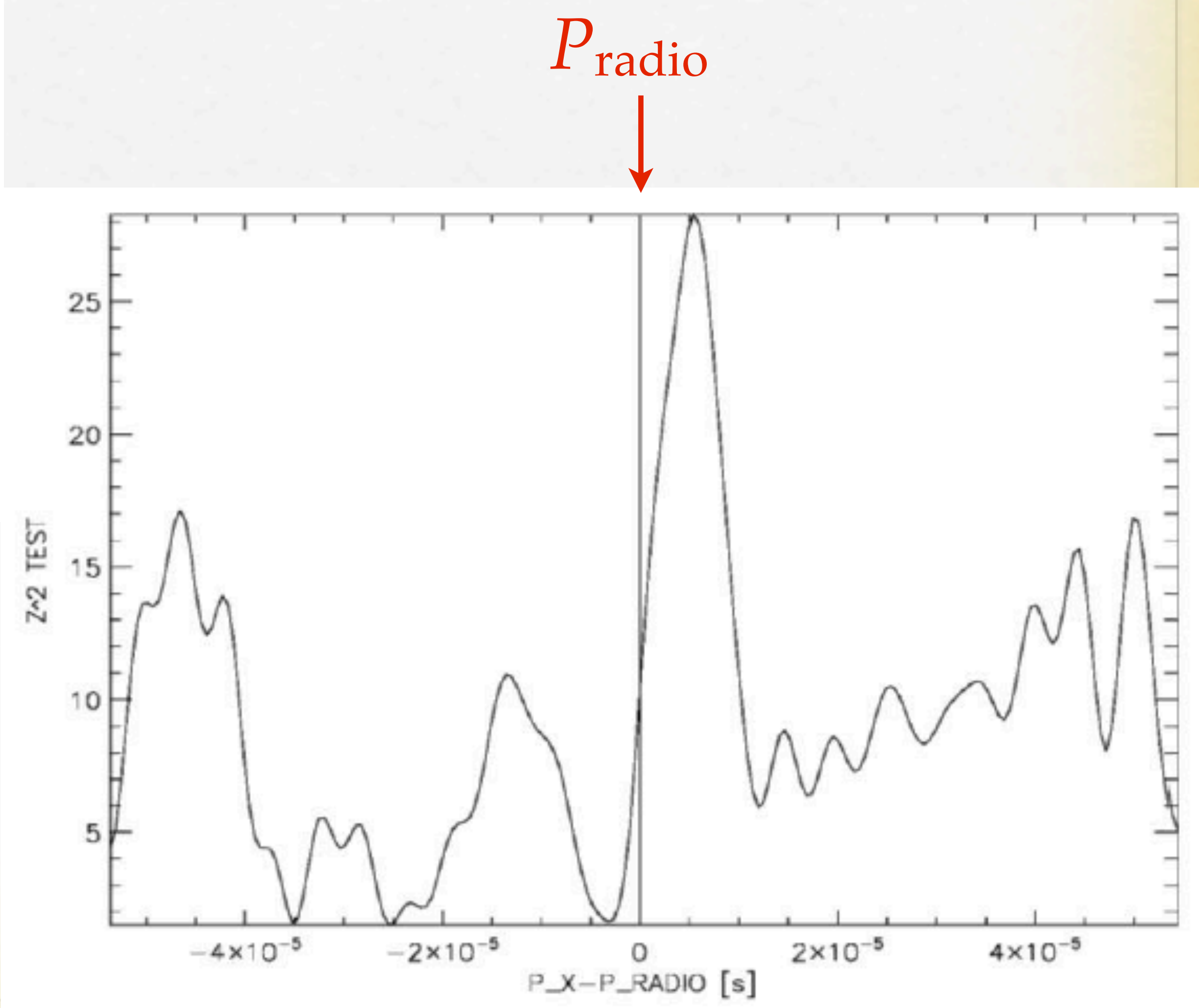

- $Z^2$ test peaks at the radio spin period

# Timing analysis

- Pulsations from PSR B, $P_{radio}$: 2.7734607024(7) s




*Iacolina et al., in prep*




- $Z^2$ test : shift ($6*10^{-6}$) with respect to the radio spin period

# Spectral analysis

- Two component models fit well the data (pn + mos)

  - PHABS*(PL + BB) => $Chi^2_r$ = 1.06 (325 dof)

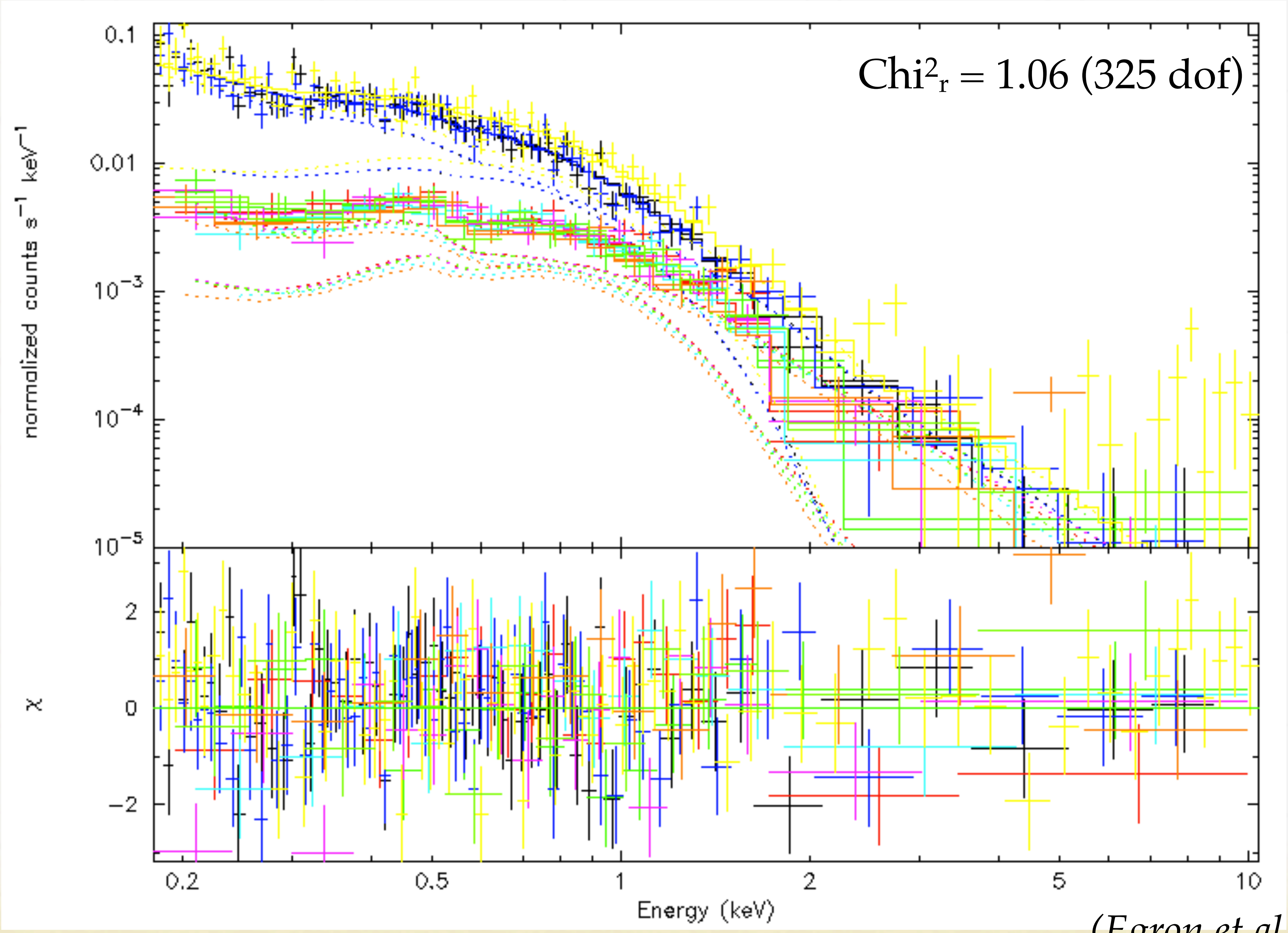
  - PHABS*(BB + BB) => $Chi^2_r$ = 1.10 (325 dof)

- Values very similar to those obtained in 2006

- Error bars slightly smaller

# EPIC/pn + mos

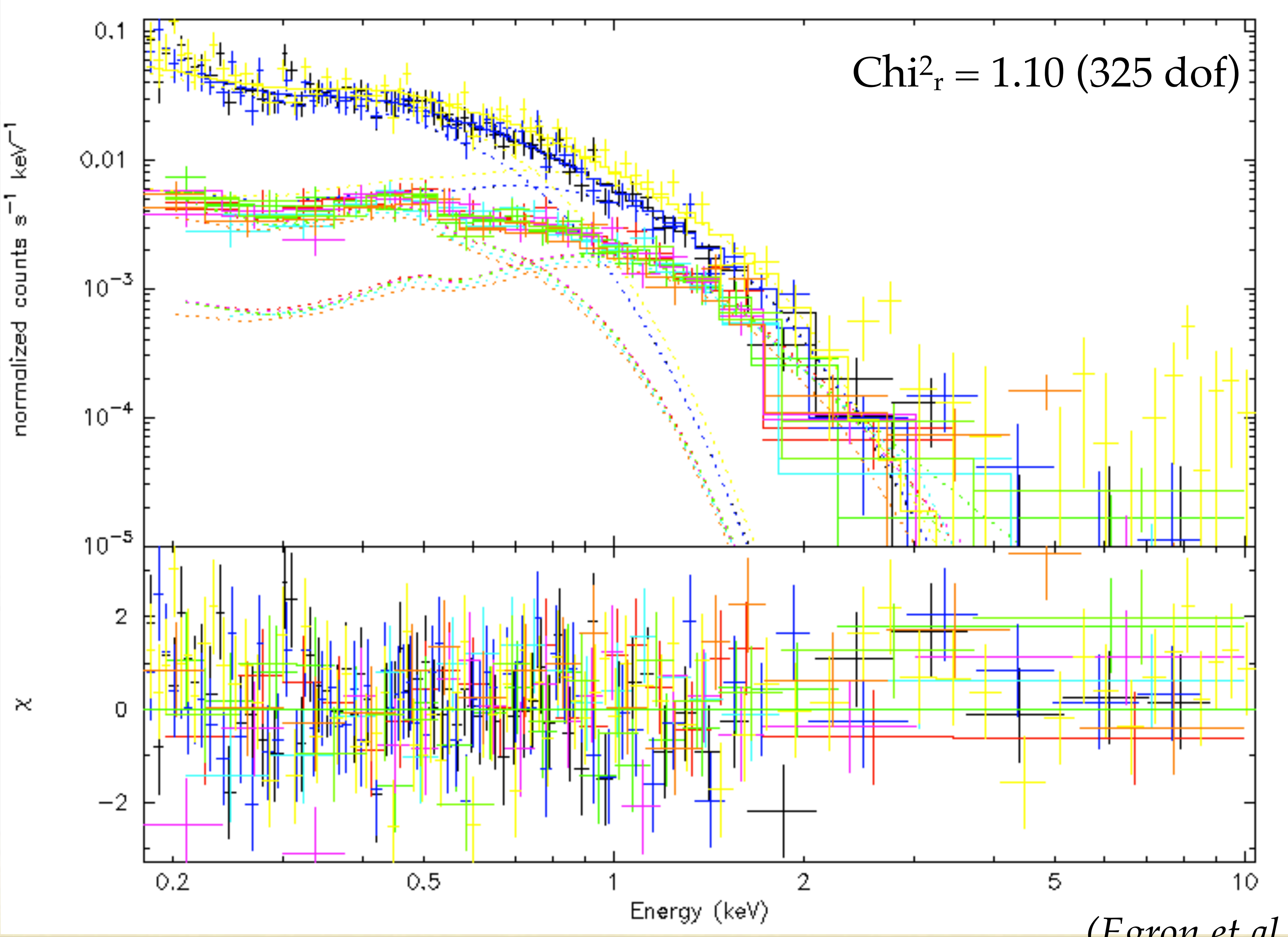
PHABS*(PL + BB)




*(Egron et al., in prep)*

# EPIC/pn + mos

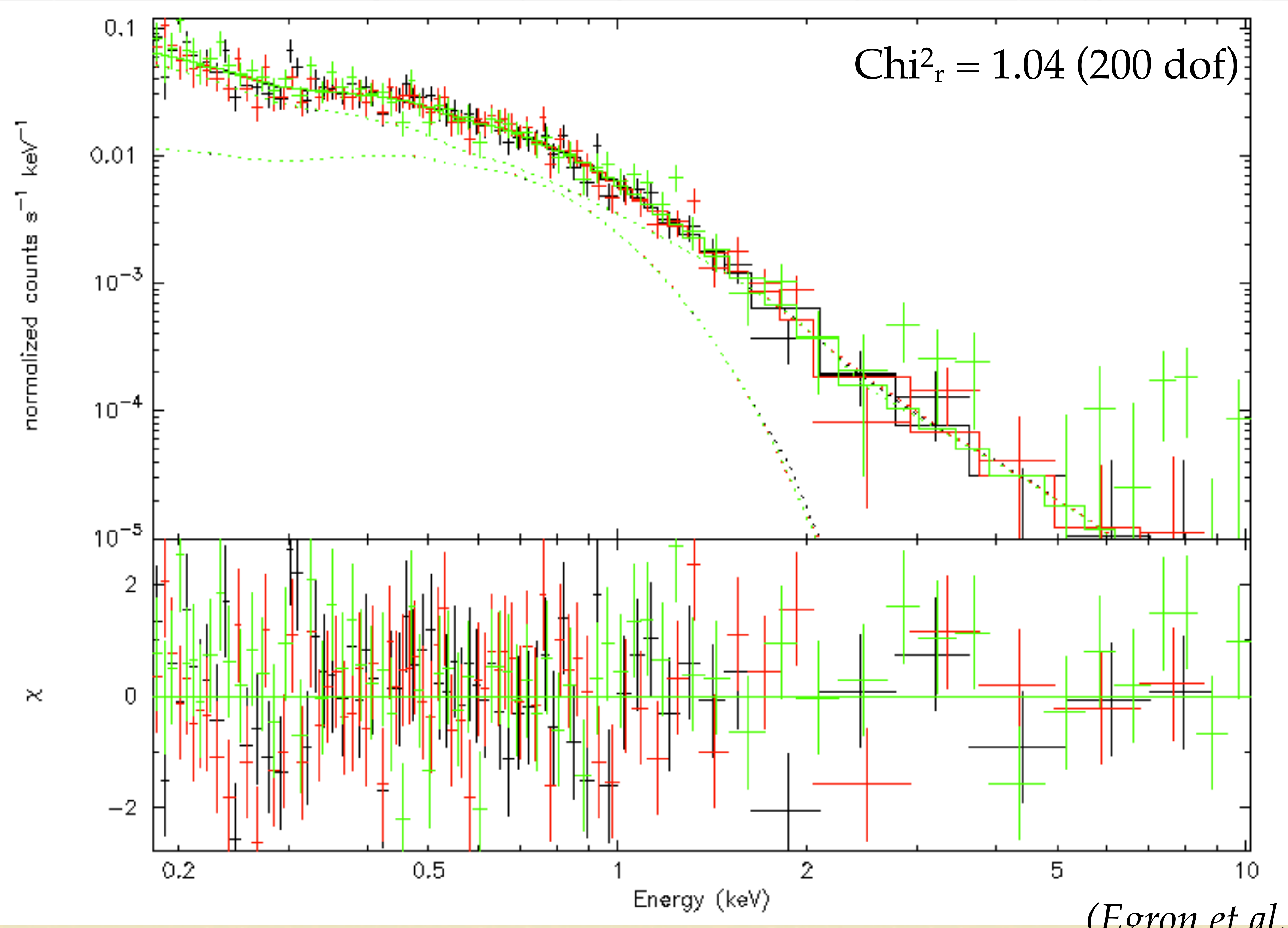
PHABS*(BB + BB)




*(Egron et al., in prep)*

# EPIC/pn

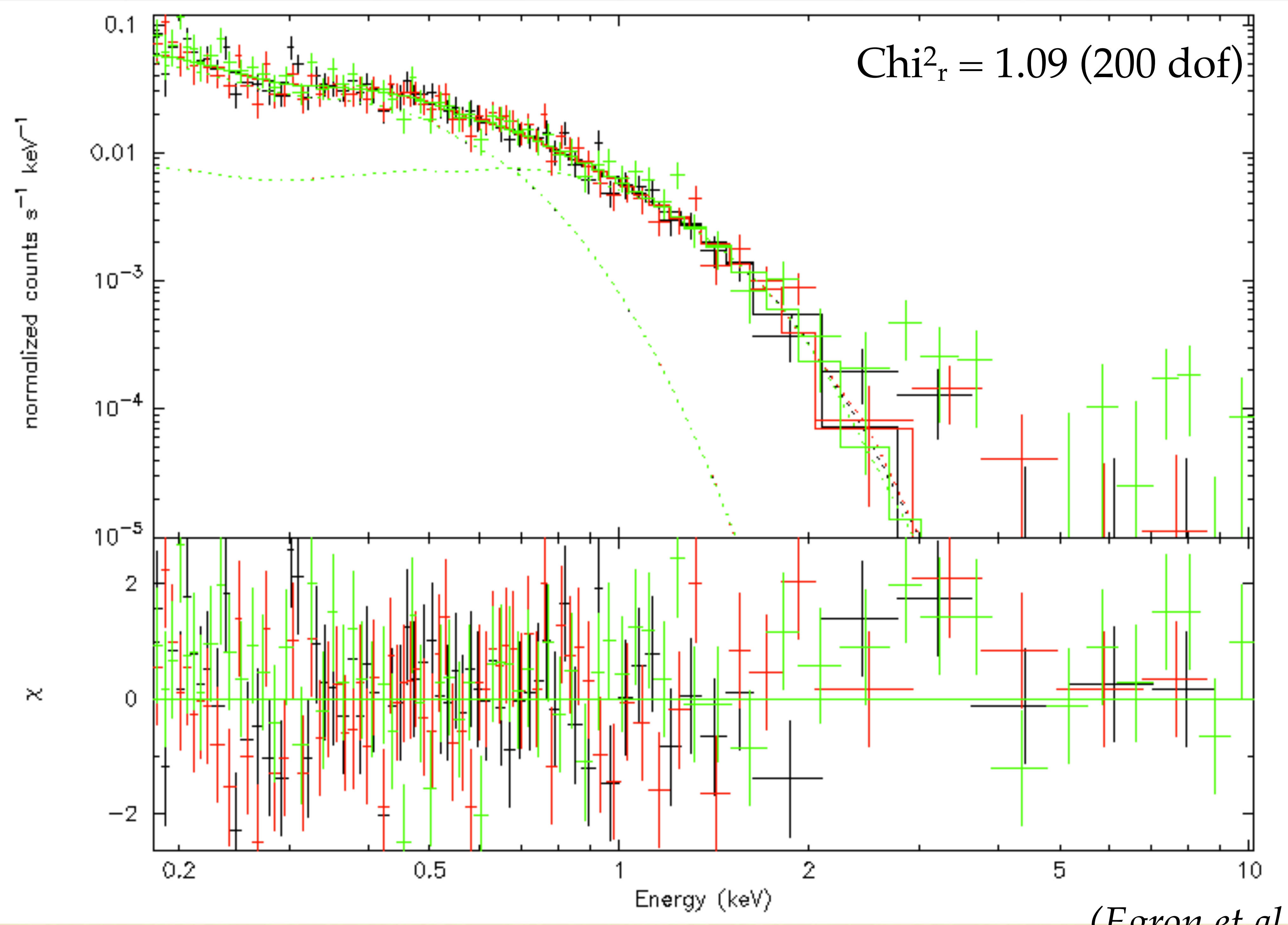
PHABS*(PL + BB)




*(Egron et al., in prep)*

# EPIC/pn

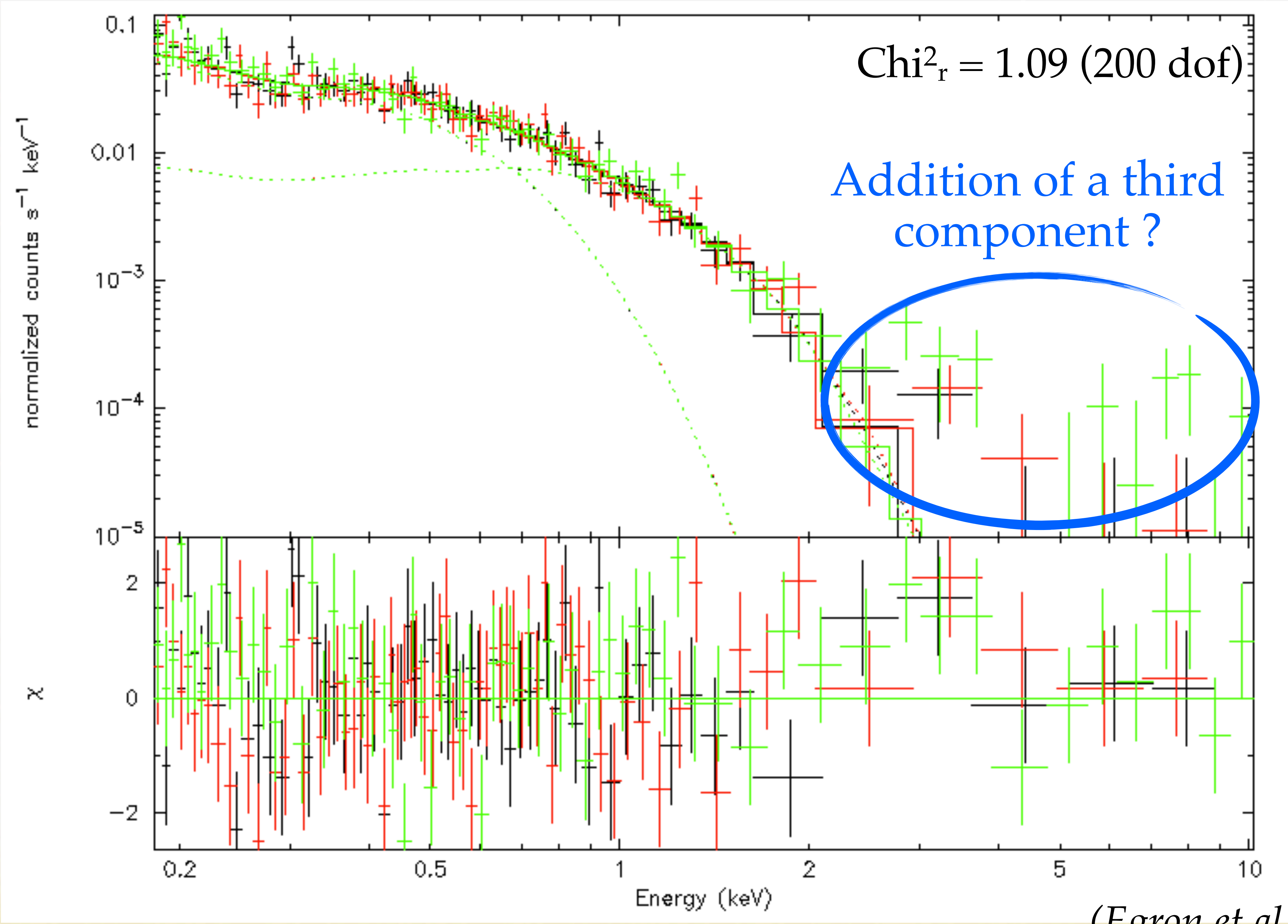
PHABS*(BB + BB)




*(Egron et al., in prep)*

# EPIC/pn

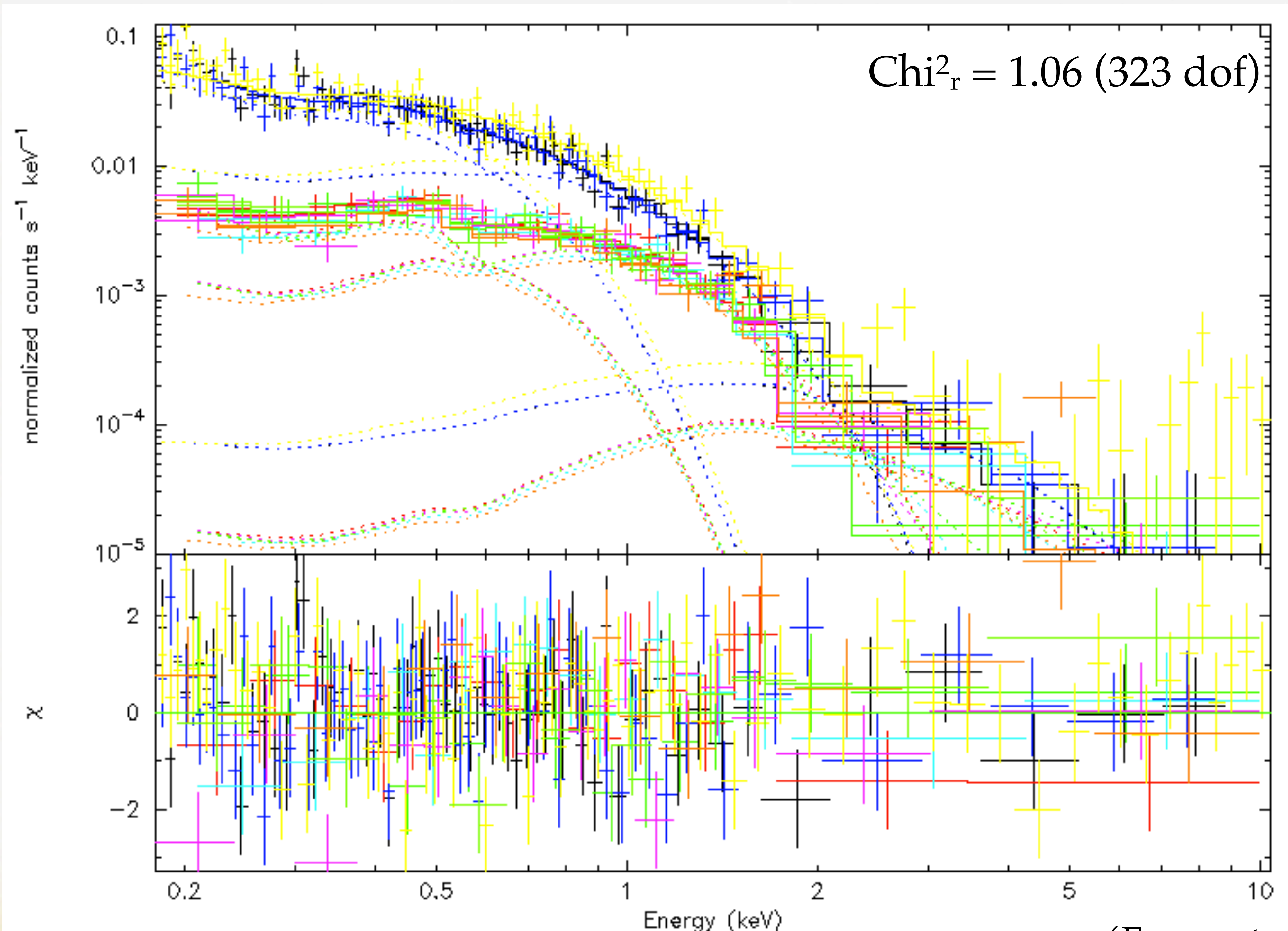
PHABS*(BB + BB)




*(Egron et al., in prep)*

# EPIC/pn + mos

PHABS*(BB + BB + BB)




*(Egron et al., in prep)*

# Spectral analysis

- A three-component model ?

  - PHABS*(BB + BB + BB) => $Chi^2_r$ = 1.06 (323 dof)

    $kT_{BB\_1}$ = *97 +/- 10 eV*, $R_1$ = *270 (+54 -35) m*

    $kT_{BB\_2}$ = *221 +/- 30 eV*, $R_2$ = *1.2 (+2.6 -0.8) m*

    $kT_{BB\_3}$ = *883 (+1010 - 370) eV*, $R_3$ = *42 (+20 -11) m*

- Comparison with PHABS*(BB + BB) : F-test = $6*10^{-4}$

# V. Analysis of the 2006 + 2011 data

# Spectral analysis

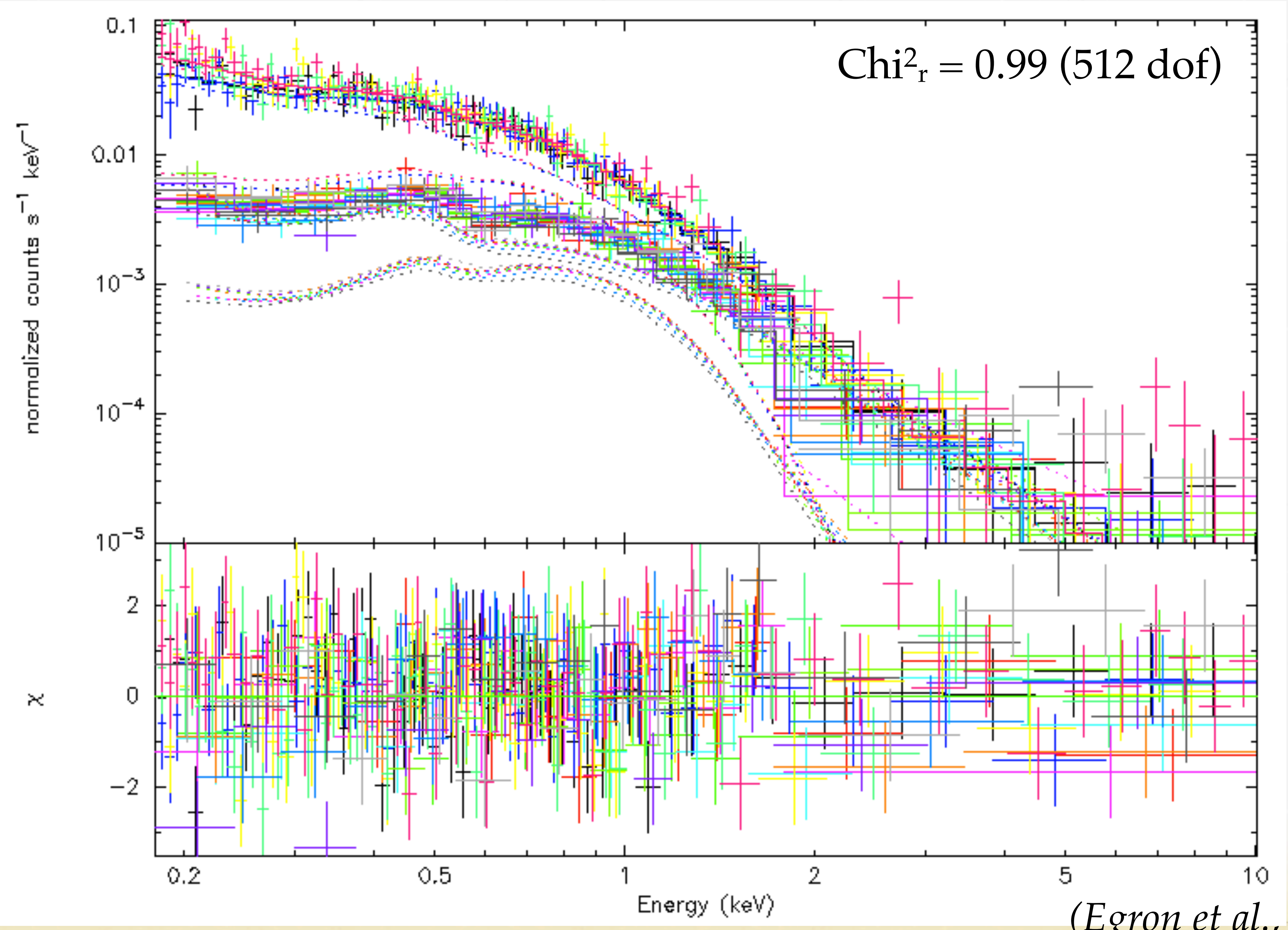
- The data of 2006 + 2011 are well fitted with a two-component model modified by phabs:

  - PHABS*(PL + BB) => $Chi^2_r$ = 0.99 (512 dof)

  - PHABS*(BB + BB) => $Chi^2_r$ = 1.02 (512 dof)

**pn + mos (15 spectra)**

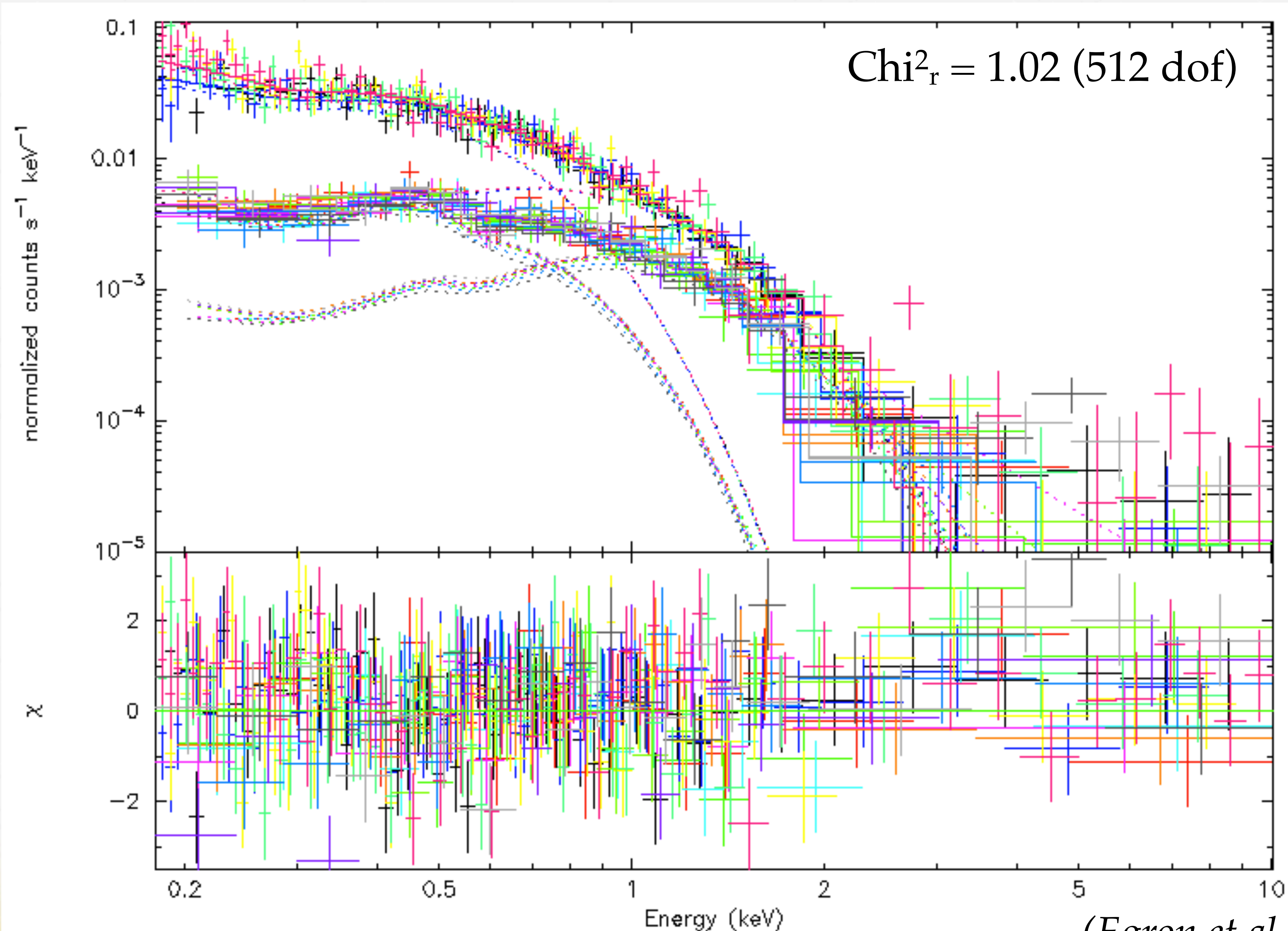
PHABS*(PL + BB)




*(Egron et al., in prep)*

# pn + mos (15 spectra)

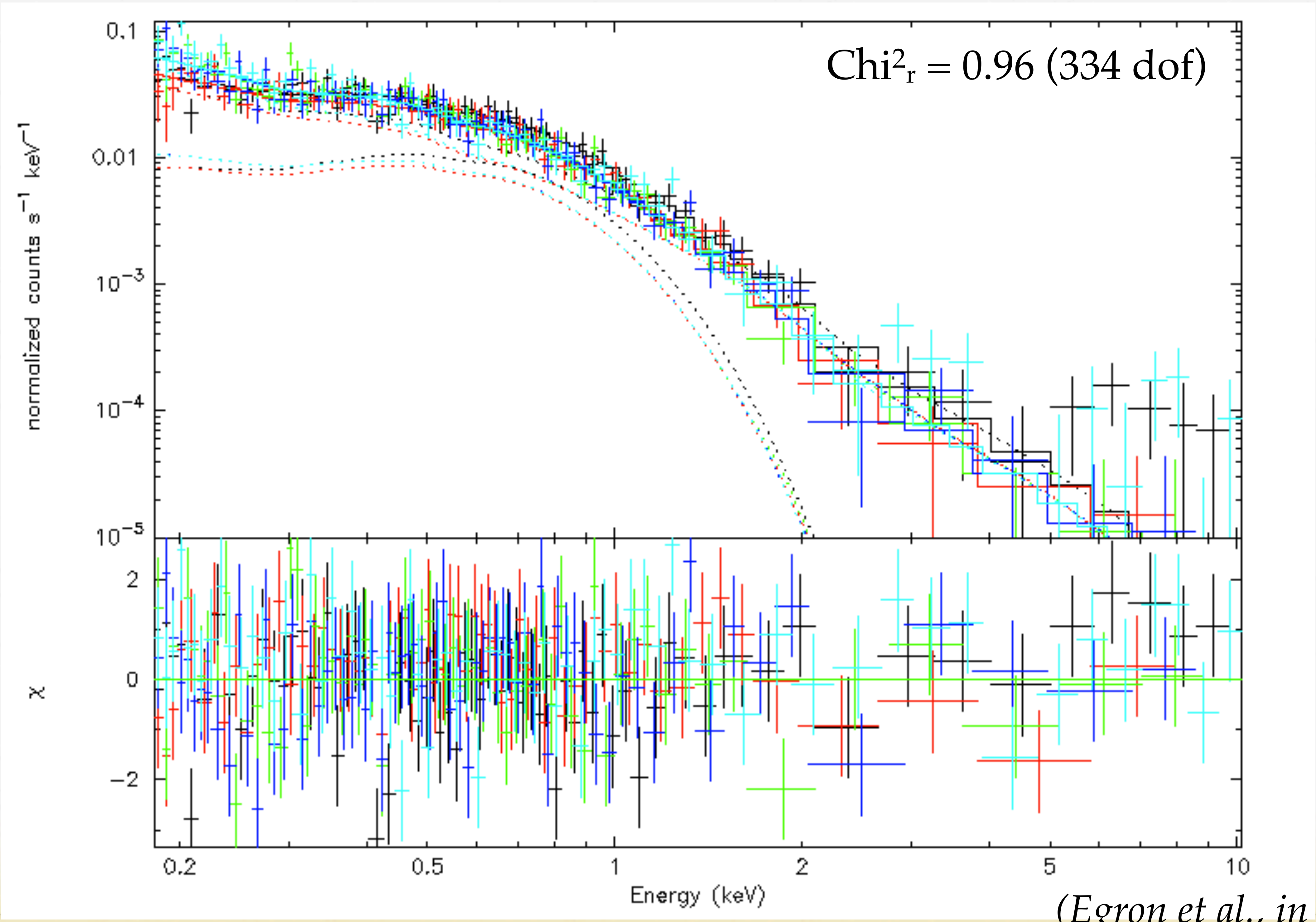
PHABS*(BB + BB)




*(Egron et al., in prep)*

## pn (5 spectra)

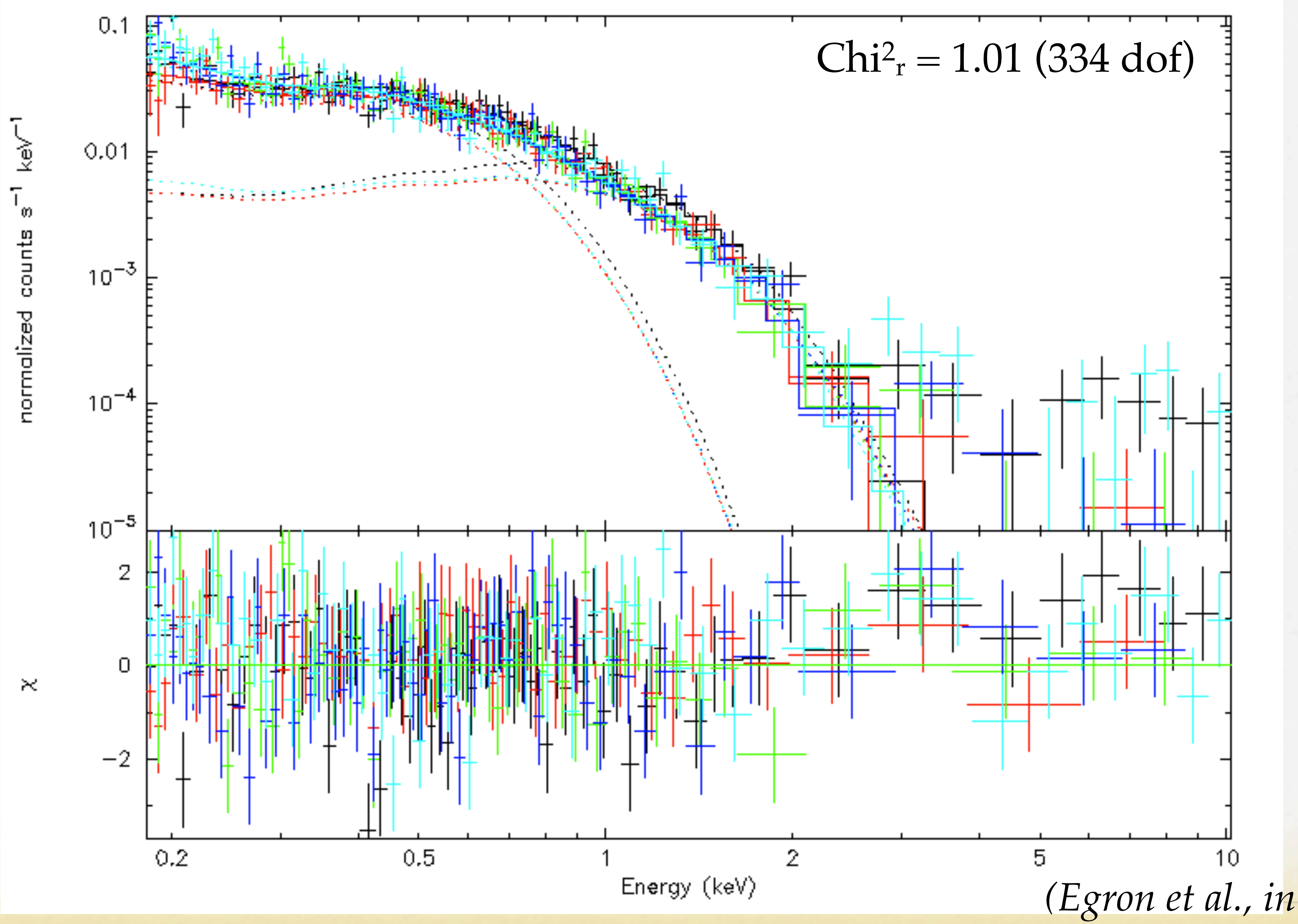
PHABS*(PL + BB)




*(Egron et al., in prep)*

**pn (5 spectra)**

PHABS*(BB + BB)

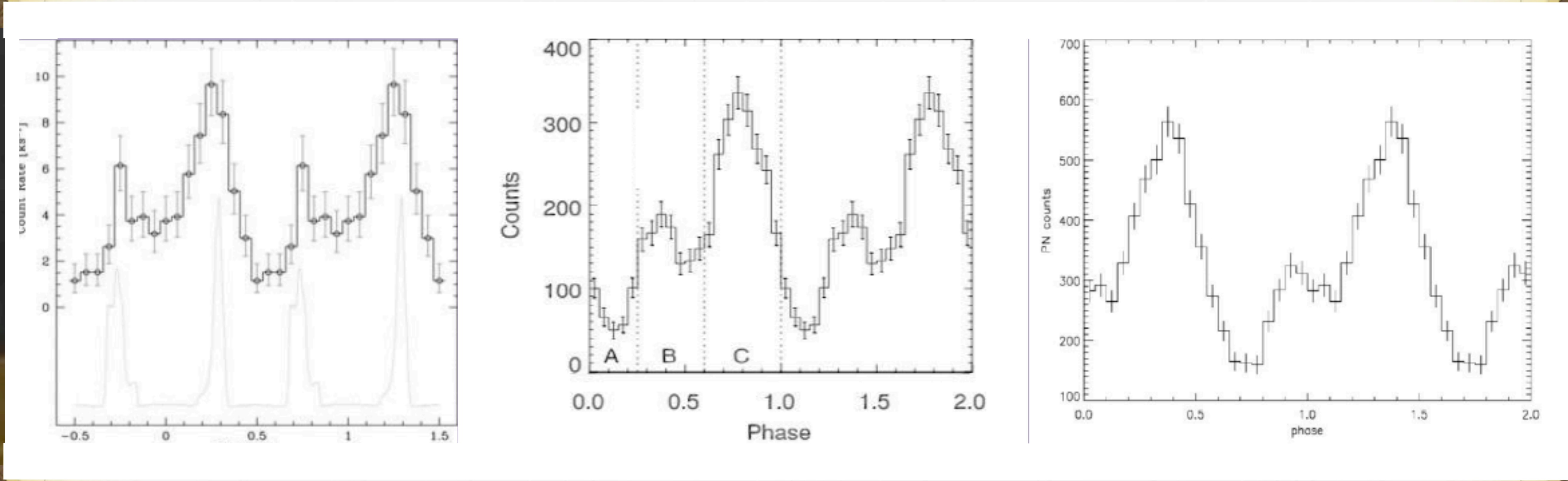



*(Egron et al., in prep)*

# VI. Different possible interpretations...

# PSR A in X-rays

- Does the pulse profile change at high energy?



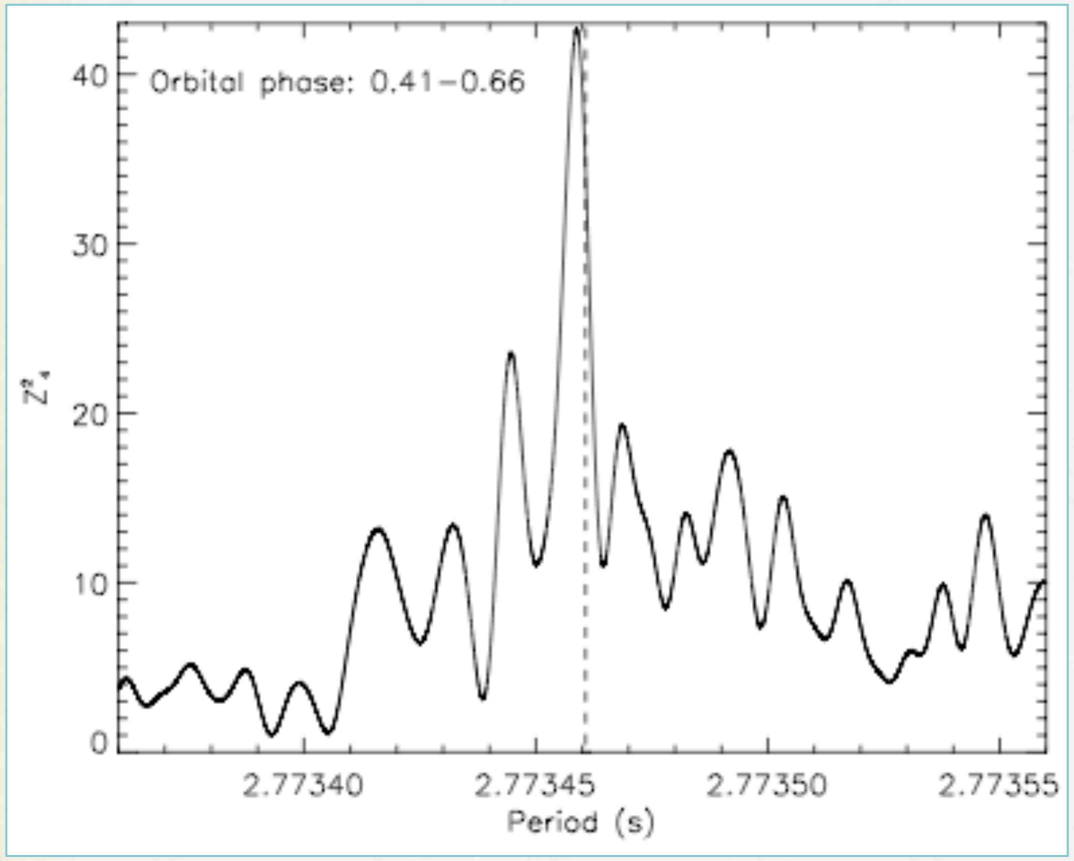

February 2006
Chandra
*(Chatterjee et al. 2007)*

October 2006
XMM-Newton
*(Pellizzoni et al. 2008)*

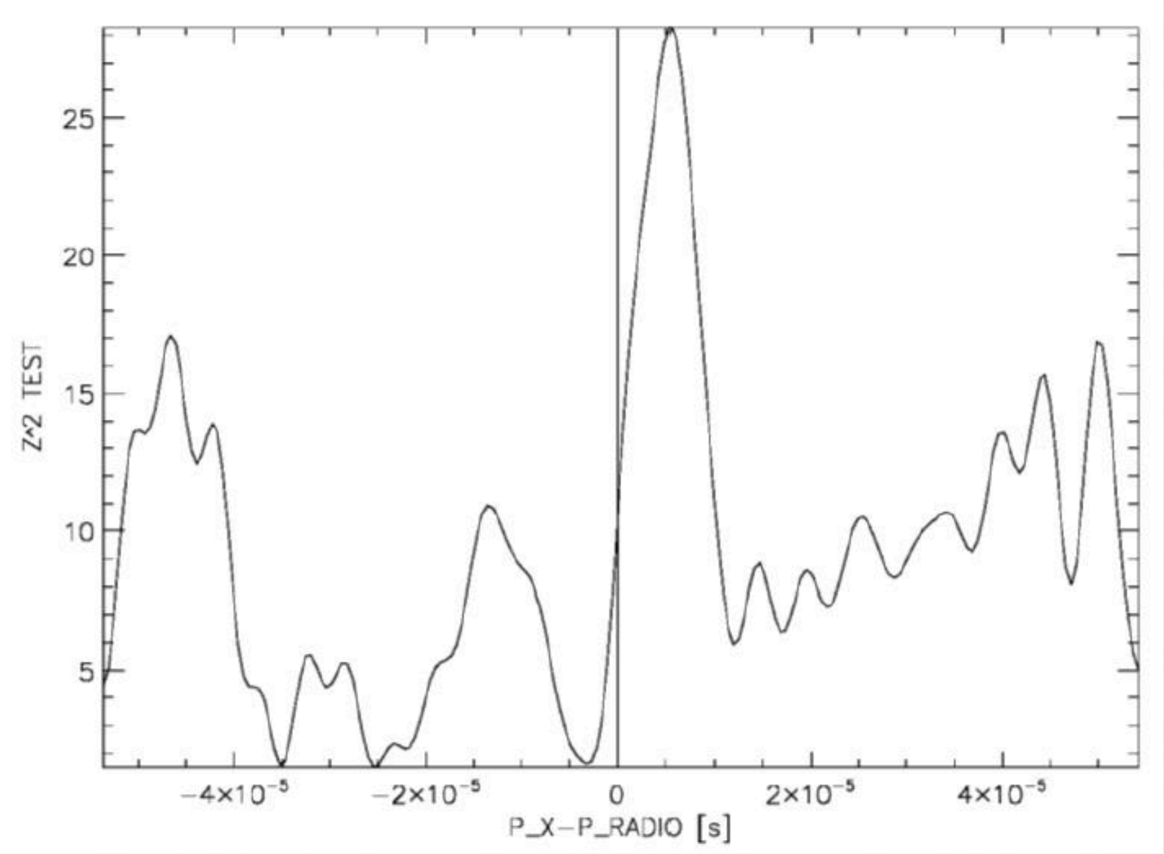
October 2011
XMM-Newton
*(Iacolina et al., in prep.)*

# PSR B in X-rays

- Shift observed with respect to radio




October 2006
XMM-Newton
*(Pellizzoni et al. 2008)*




October 2011
XMM-Newton
*(Iacolina et al., in prep)*

# From Timing analysis...

- PSR A: - Radio, X-ray => double profile

  - Gamma-rays => double profile, shifted with respect to radio

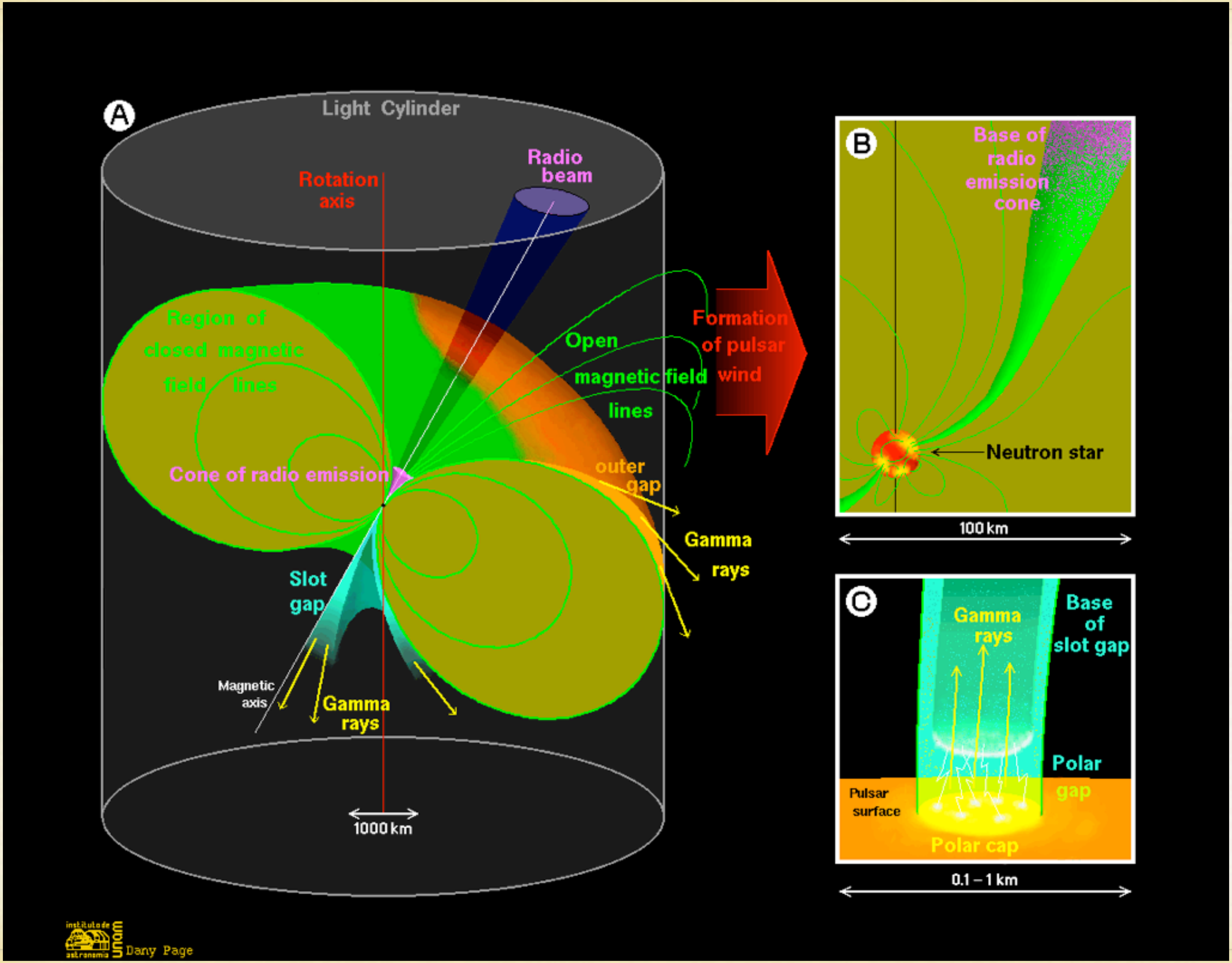
- PSR B: - Radio: disappears since 2008

  - visible in X-rays, but shifted with respect to radio

# Origin of the emissions

- **PSR A**: radio, X-rays => polar cap?
- Double profile => two poles? two zones in the polar cap?
- Gamma-rays => outer gap?

- **PSR B**: cannot emit X-rays by itself
- Radio: precession of the spin axis ? P = 71 yr
- X-rays : shift => from interaction between the PSR A's wind and the PSR B's magnetosphere?


A
Light Cylinder
Rotation axis
Radio beam
Region of closed magnetic field lines
Open magnetic field lines
Formation of pulsar wind
Cone of radio emission
outer gap
Gamma rays
Slot gap
Magnetic axis
Gamma rays
1000 km
B
Base of radio emission cone
Neutron star
100 km
C
Gamma rays
Base of slot gap
Polar gap
Pulsar surface
Polar cap
0.1 – 1 km
Dany Page

# From Spectral analysis...

- Multi-component models able to fit the data
- Thermal and/or non thermal emissions?
- Cooler BB => PSR B powered by PSR A’s wind heating PSR B’s surface
- Hotter BB => backflowing particles heating polar caps of PSR A
- Non-thermal magnetospheric emission?
- Formation of a bow shock expected but not visible...

# From Spectral analysis...

About the lines...

- Narrow absorption line at 0.4 keV ?
- Emission line at 2.4 keV ?
- Component at E > 5 keV ? Fe line ? Residuals from accretion disk?

# Conclusion

- Complex X-ray phenomenology
- Mutual interactions of the two pulsars at high energies
- No evidence of a shock for the moment...

- Next steps:

  - Study the spectral variations with the orbital phase
  - Phase-resolved spectral analysis
  - Do we see some changes?

# Other observations

- Study of other double neutron star systems:

  - J1537+1155

  - J1756-2251

  - J1915+1606

  - J2130+1210

- Comparison of the data (X-ray spectra, soft component)

- evolved Laser Interferometric Space Antenna (eLISA/NGO)
  => detection of gravitational waves...

# Sardinia Radio Telescope

*www.srt.inaf.it*

*Thank you !*