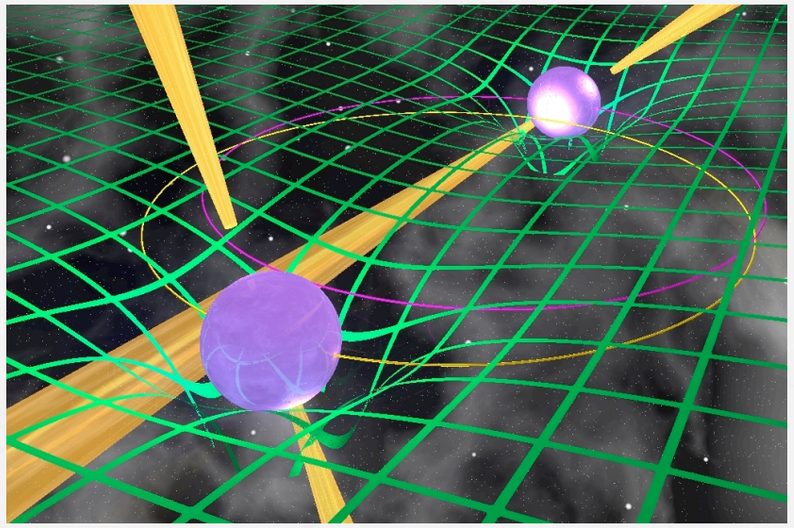
Spectral Analysis of the Double Pulsar PSR J0737-3039 with XMM-Newton



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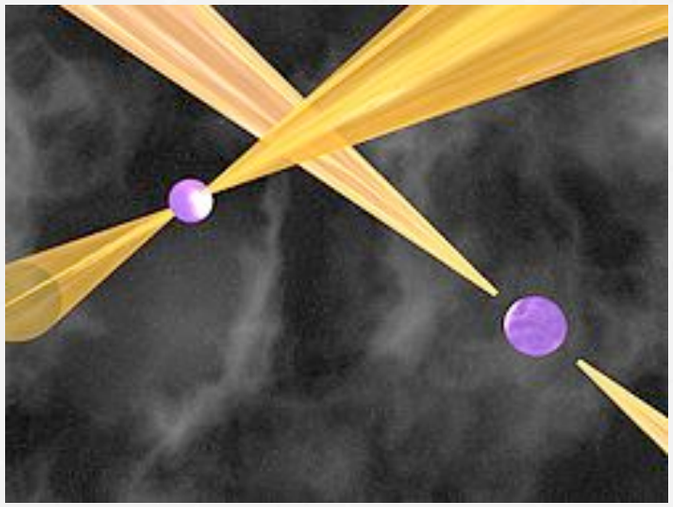
Physics of Neutron Stars 2014, St Petersburg

A fantastic system

- Double neutron star (DNS) systems are rare... less than 10 systems
- PSR J0737-3039 is **unique** since **both NSs are radio pulsars**



- 2.4 hours orbital period, high orbital velocities ~ 1 million km/h !!!

  The most relativistic system ever discovered

The double-radio pulsar

- Discovered 10 years ago (Burgay et al. 2003, Lyne et al. 2004)

PSR A

Fast, mildly recycled, old pulsar

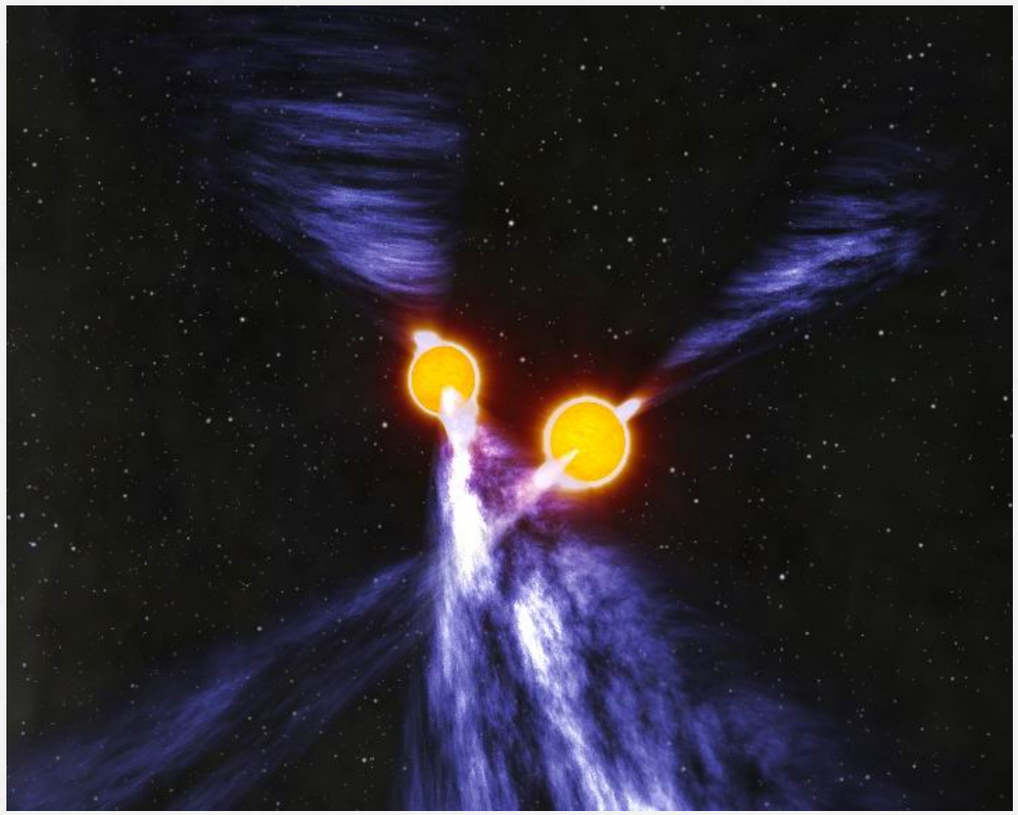
P = 22.7 ms

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

$B = 6.3*10^{9}$ G

$\mathbf{\dot{E}_{rot}=5.9*10^{33}\ erg/s}$

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

$\mathbf{\dot{E}_{rot}=1.7*10^{30}\ erg/s}$

Age = 50 Myr

A unique laboratory

- **Best timing test for GR in strong field regime** (Kramer et al. 2006)
- **Observed pulse arrival times modified by relativistic effects**

=> 5 post-Keplerian parameters very well-determined

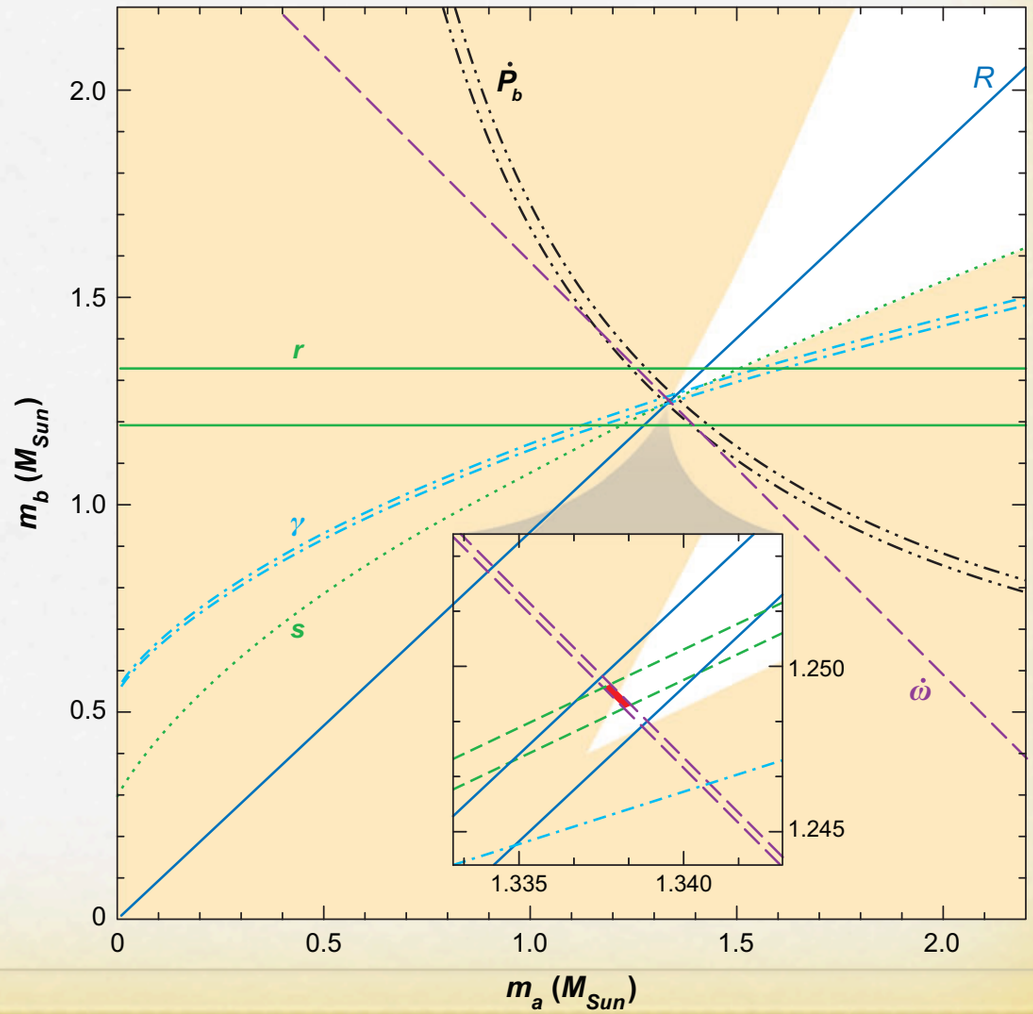
- **Most precise measurement of masses**

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

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

Confirmation of prediction of GR within 0.05% !!!

Kramer et al. 2008

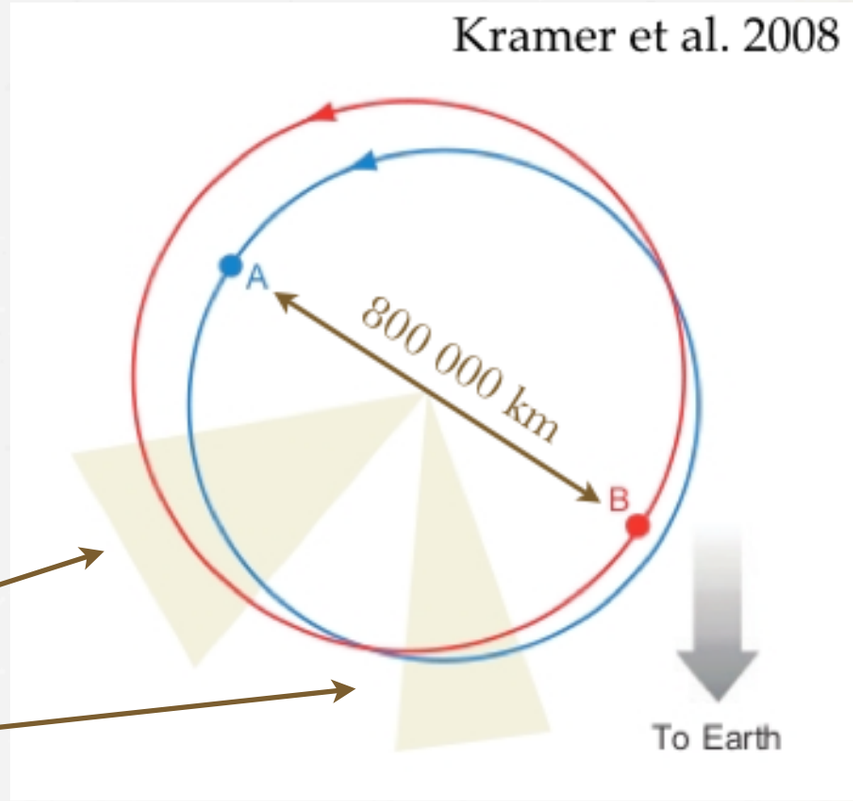


Radio properties

- **PSR A : stable pulse profile**

- **PSR B : changes in the pulse profile and not visible since 2008**

Orbital phases where PSR B was strongly detected in radio

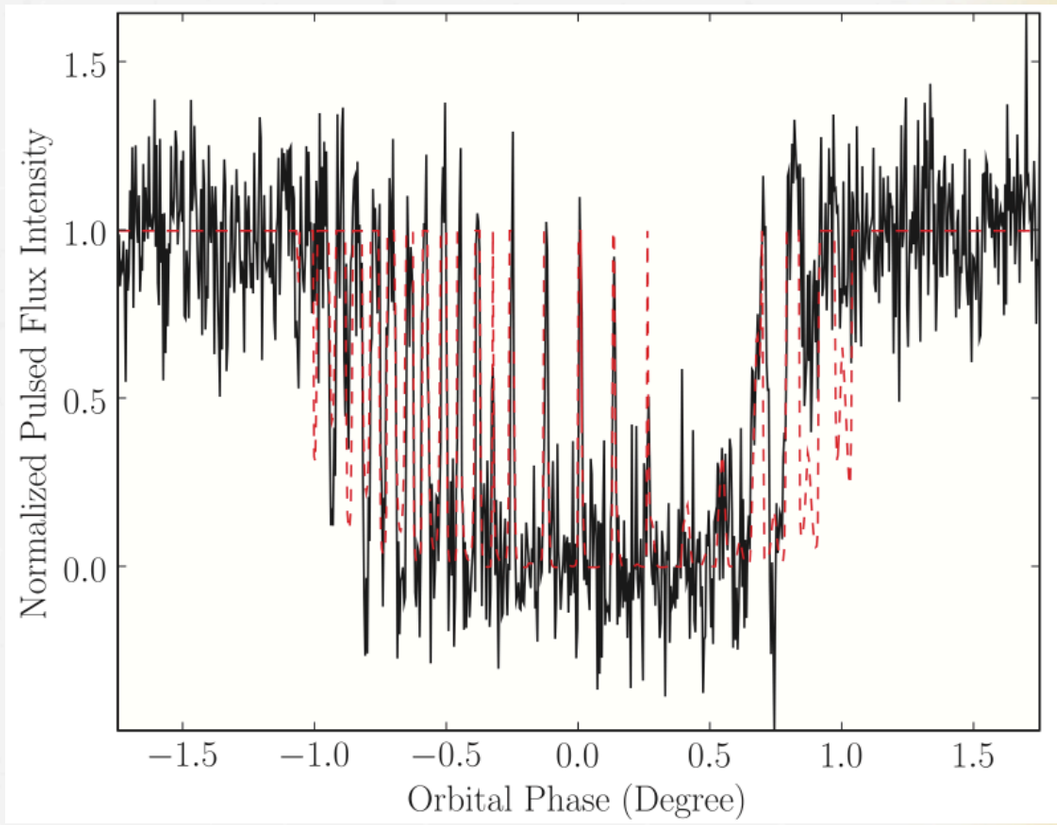


Radio properties

- **Radio eclipses of PSR A**

System observed nearly **edge-on** !

Breton et al. 2008



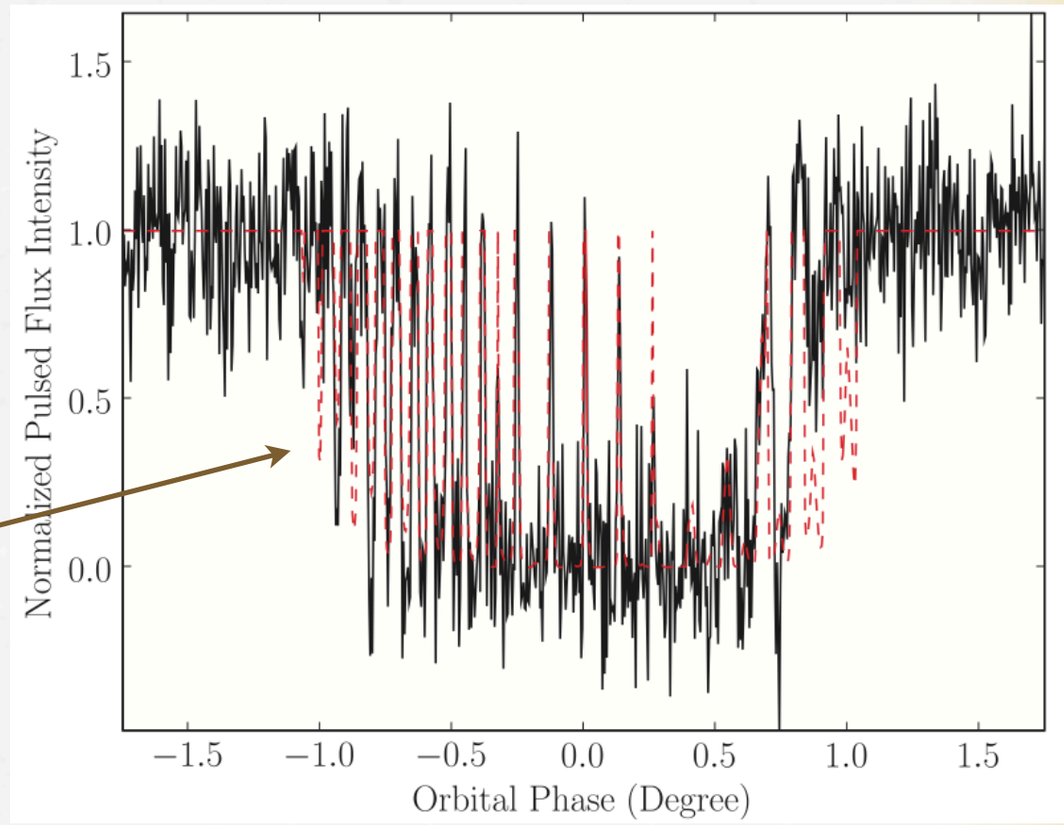
Radio properties

- **Radio eclipses of PSR A**

System observed nearly **edge-on** !

Modulation consistent with
PSR B′ rotation period

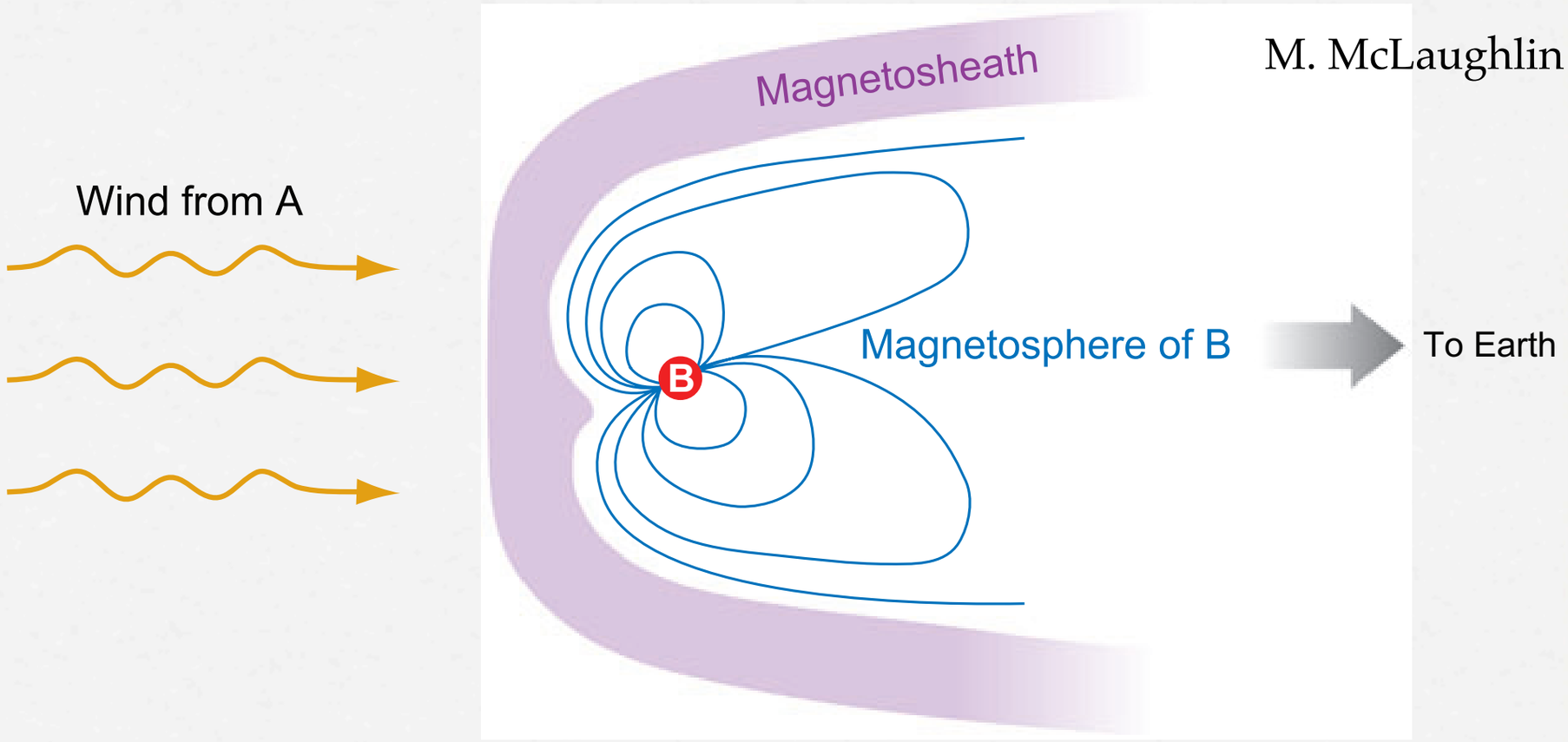
Breton et al. 2008



=> Unusual magnetospheric interactions between the 2 pulsars

X-rays

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



- Deformation of the magnetosphere of PSR B caused by the wind of PSR A

Two large programs with XMM-Newton

- **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
PN	small window	5.67 ms
MOS	small window	0.3 s

=> timing + spectral analysis of the Double Pulsar

(Pellizzoni et al. 2008, Iacolina et al. 2014, Iacolina et al. in prep, Egron et al. in prep)

Spectral models

- **PL + BB :** magnetospheric emission from PSR A (synchrotron/ICS), thermal emission from PSR A or B (polar cap?) / shock?

- **BB + BB :** thermal emissions from PSR A and B

- **PL + BB +BB :** thermal emissions from PSR A and/or B / shock?

=> Applied on 2011 data, then comparison with 2006 data (Pellizzoni et al. 2008)

=> Results perfectly in agreement

Results of the two large programs

- **PL + BB :** $\Gamma = 3.2 +/- 0.2$ => no shock
  $kTbb = 160 +/- 15$ eV;
  $\chi^2/dof = 533/520$ (=1.02)
  Flux 0.2-3 keV $\approx 9 \times 10^{-14}$ erg/cm^2/s

- **BB + BB :** NH not constrained
  $kTbb1 = 105 +/- 5$ eV; $kTbb2 = 270 +/- 15$ eV
  $\chi^2/dof = 551/520$ (=1.06)

- **PL + BB +BB :** NH not constrained
  $\Gamma = 2.4 +/- 0.6$ => shock ?
  $kTbb1 = 110 +/- 20$ eV; $kTbb2 = 230 +/- 30$ eV
  $\chi^2/dof = 525/518$ (=1.01)

Where do X-rays originate?

PSR A: non-thermal

PSR A: thermal

PSR B

shock ?

- Comparison with the results of the **timing analysis**
- Black-body emission radii consistent with polar cap radii ?
- Luminosity of each component => % $\dot{E}_{rotA}$, $\dot{E}_{rotB}$

=> PSR B powered by PSR A's spin-down energy

Timing analysis

- **PSR A : very stable pulse profile, consistent with radio ephemeris** (Kramer et al. 2006)

  Unpulsed flux : orbital flux variability

  Pulsed fraction => 60% of the total source flux

- **PSR B : X-ray pulsations, slight shift w.r.t radio**

  BUT not visible in radio since 2008 (Perera et al. 2010)

  Pulsed flux and profile variations with the orbital phase

  16% of the total flux

=> X-ray emission region far from PSR B's surface...

From an interface layer / shock at about 1 sec-light ?

Pellizzoni et al. 2008; Iacolina et al. 2014; Iacolina et al. in prep

Where do X-rays originate?

- **PL + BB :** no shock, 85% emission from the PL => PSR A's magnetosphere

  but flux overestimated (pulsed-flux PSR A)

  R_{BB} compatible with the polar cap radius of Pulsar B (100m)

- **BB + BB :** R_{BB} compatible with the polar cap radii of PSR A (1km) and PSR B

  Hot BB: Pulsar B, and Cold BB: Pulsar A

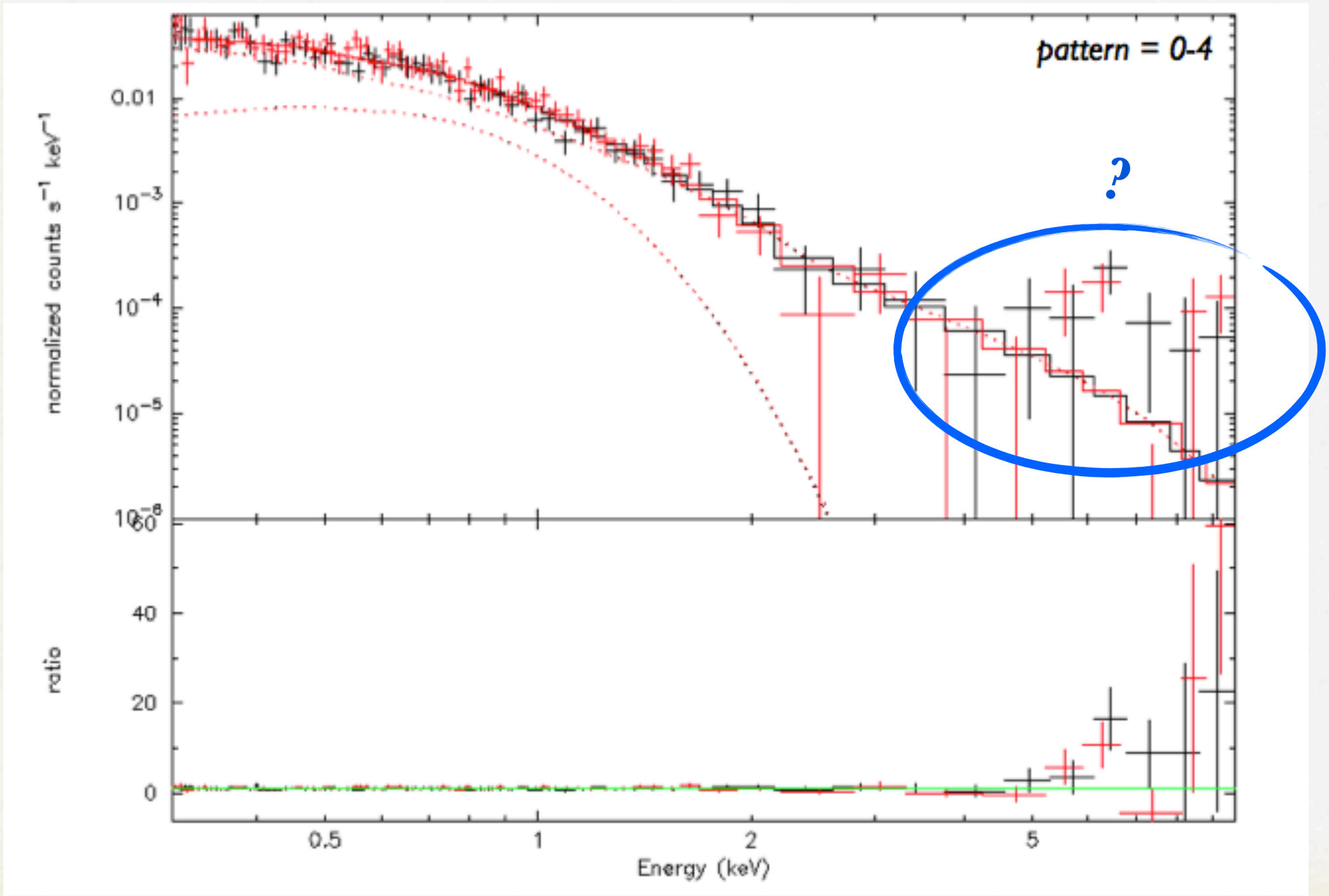
- **PL + BB +BB :** possible shock

=> Nature of the X-ray emission associated to PSR B ?

Work in progress...

Last but not least...

An intringuing feature in the 2006 data



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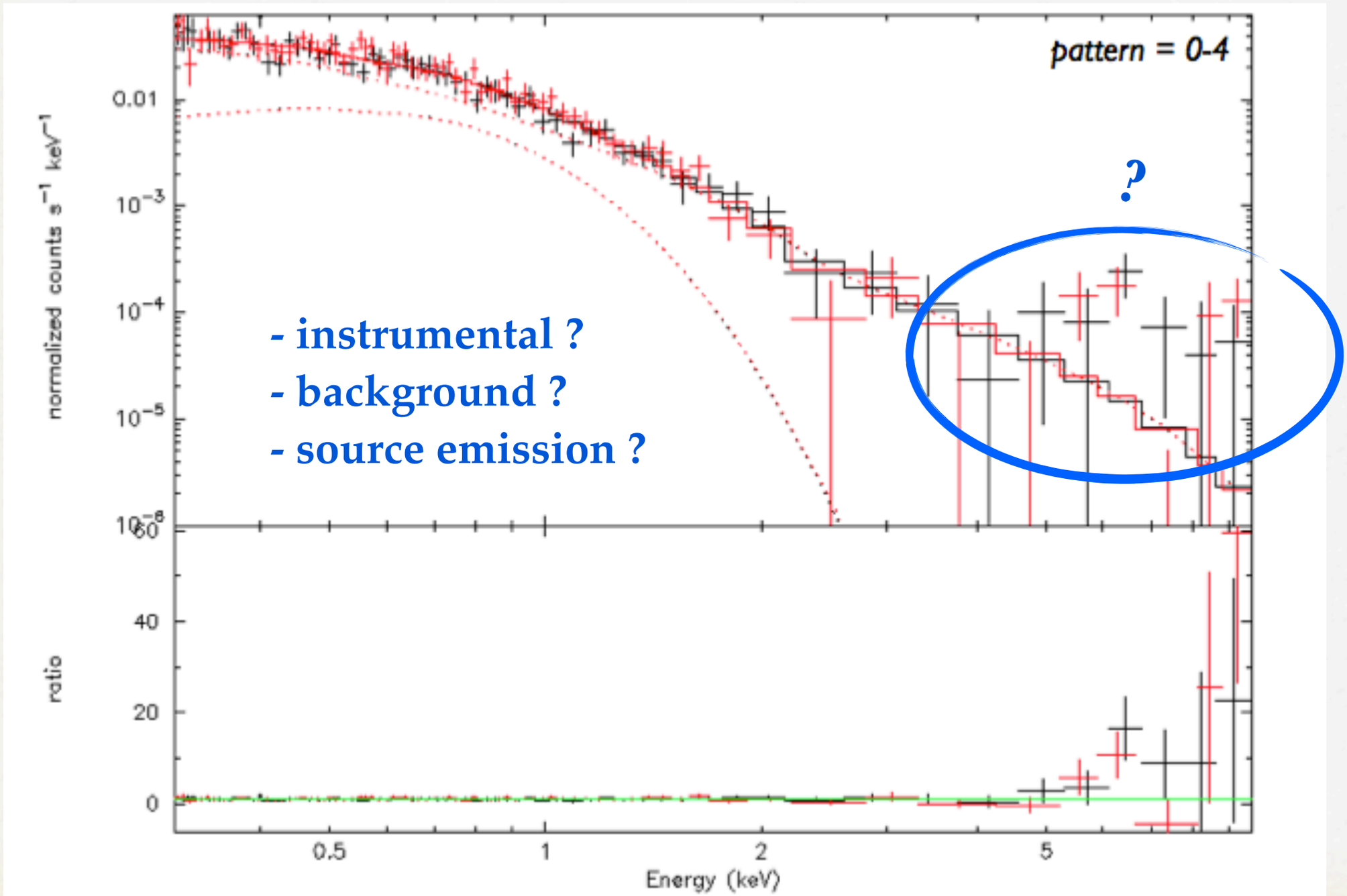


Emission from the Double Pulsar ?

- **Spatial model (4 < E < 8 keV) applied by A. Pollock**

  * Combined likelihood detection statistic : lnL = 15.04

  * 157 photons detected in about 400 ks

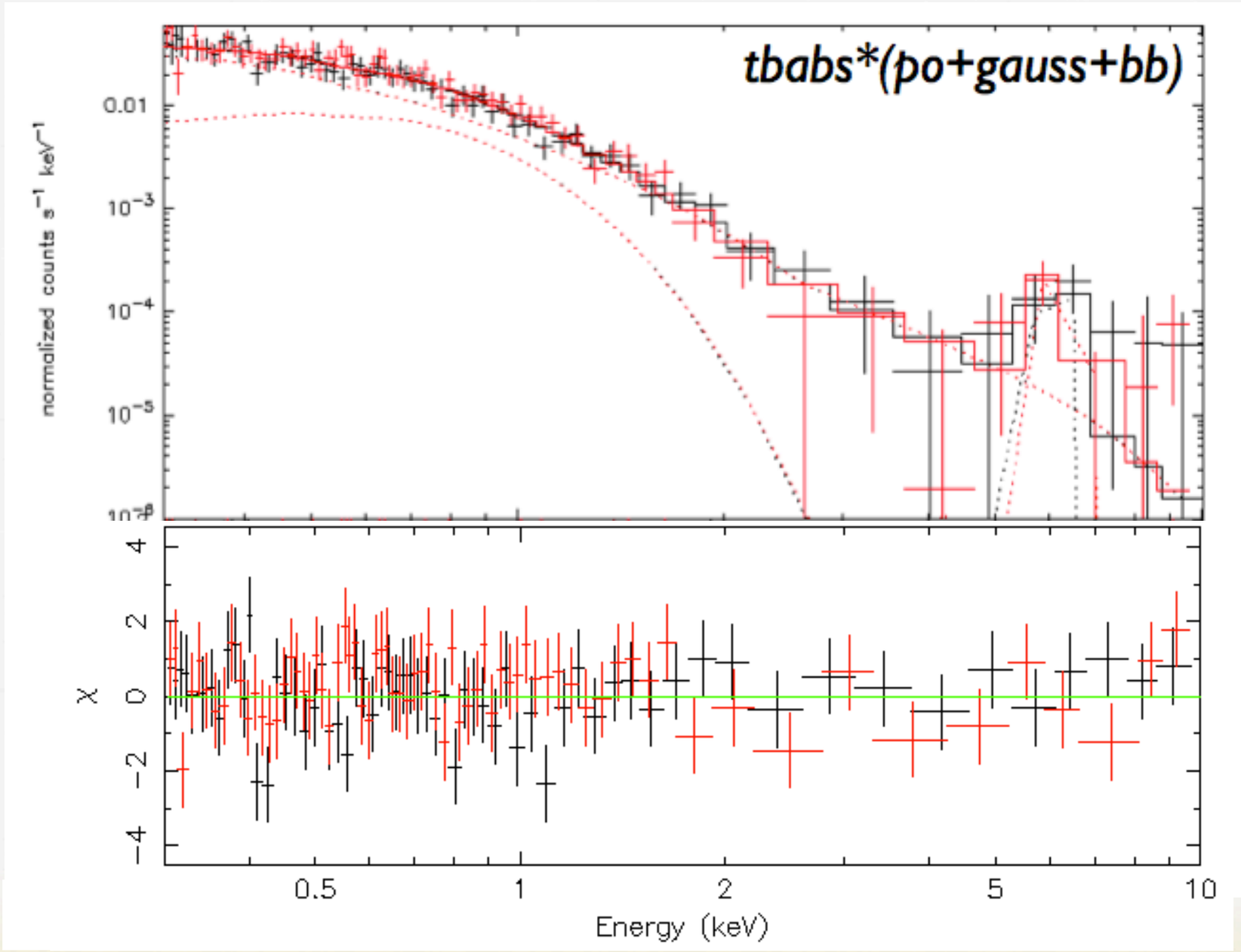
  * 1 high-energy photon every 44 minutes

- **Confirmation that the detection at high energy comes from the source !!!**

- **Above 8 keV: background dominates**

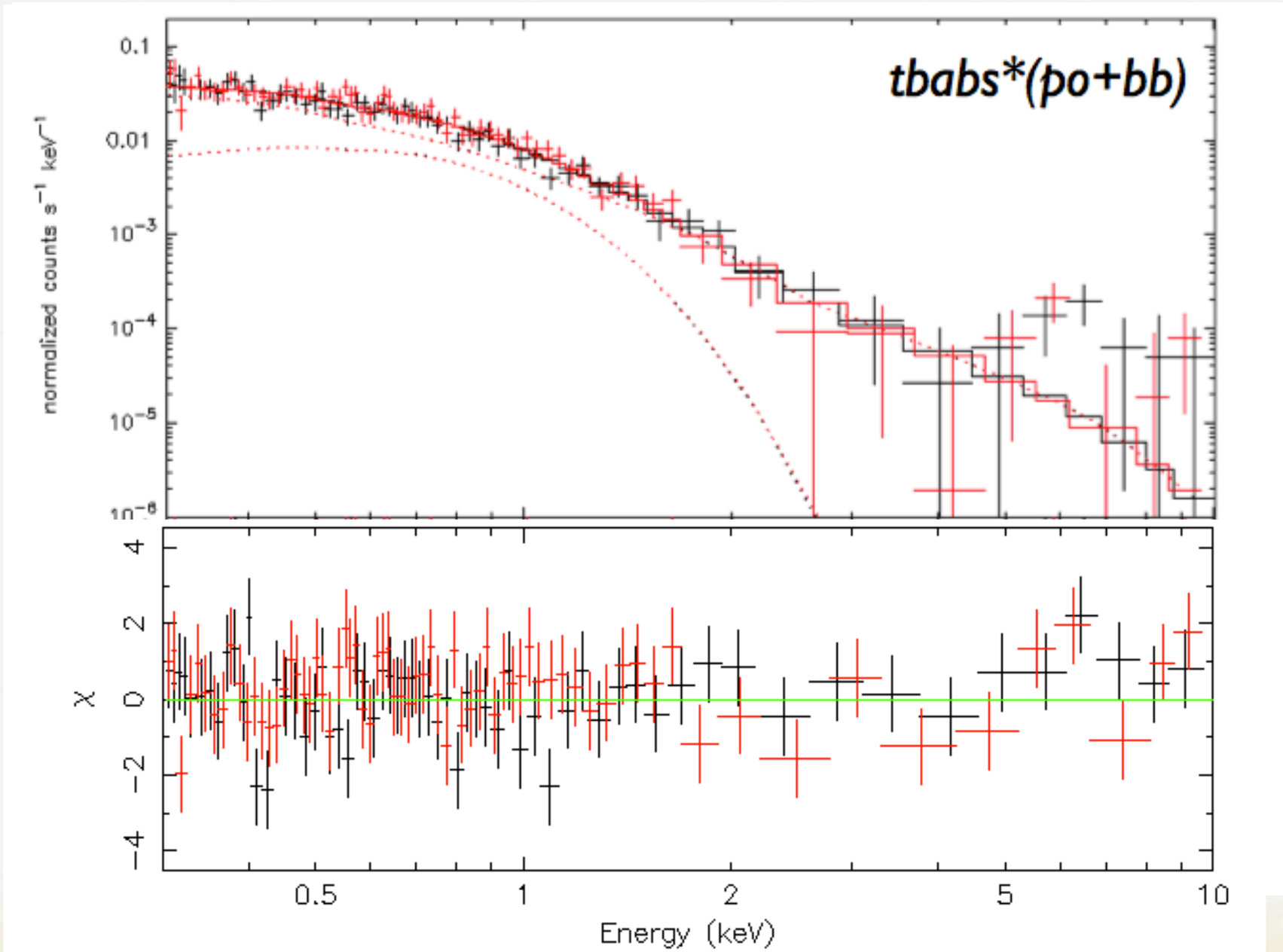
2006 data

- **Addition of a Gaussian at 6.2 +/- 0.2 keV**



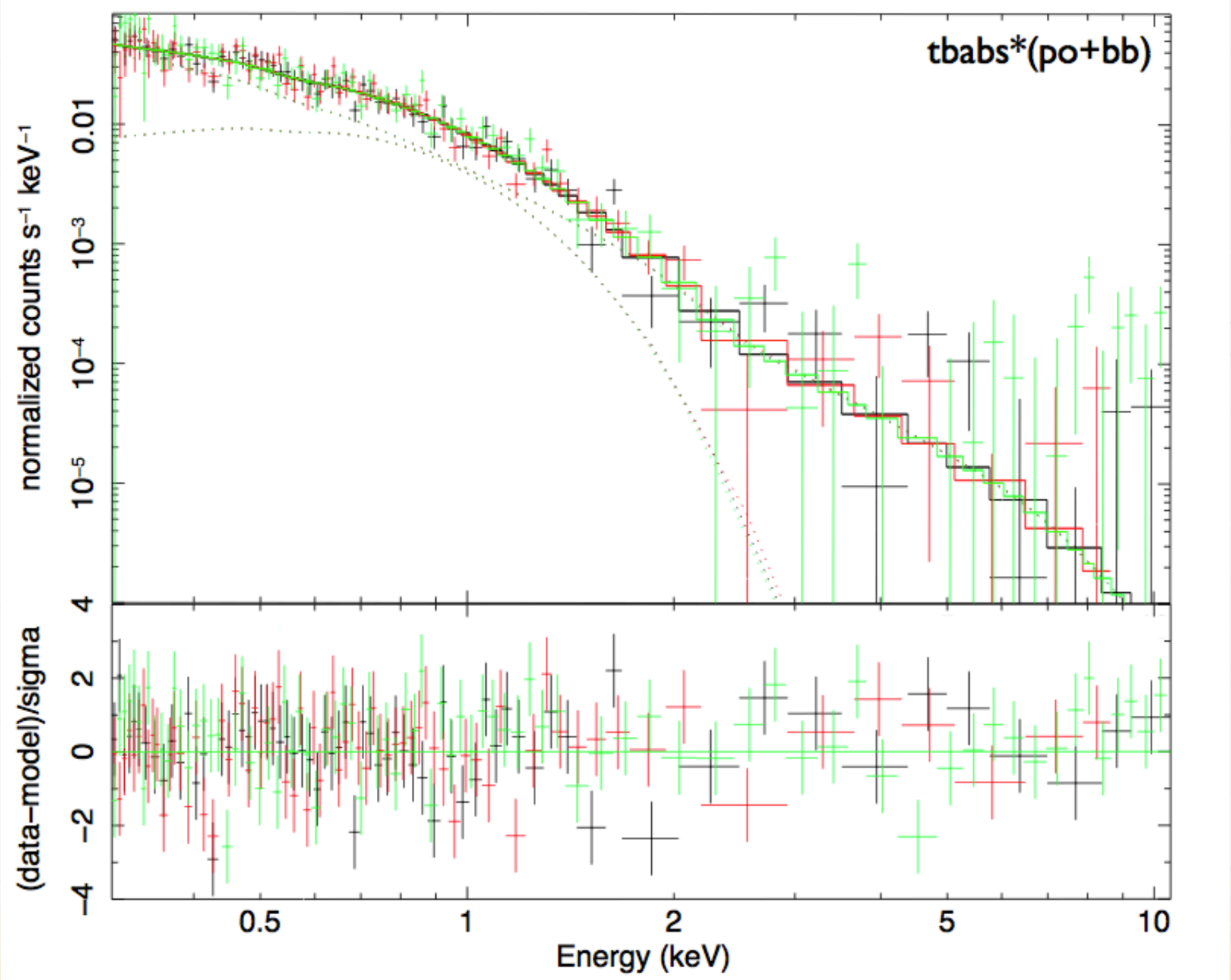
2006 data

- **Without the Gaussian**



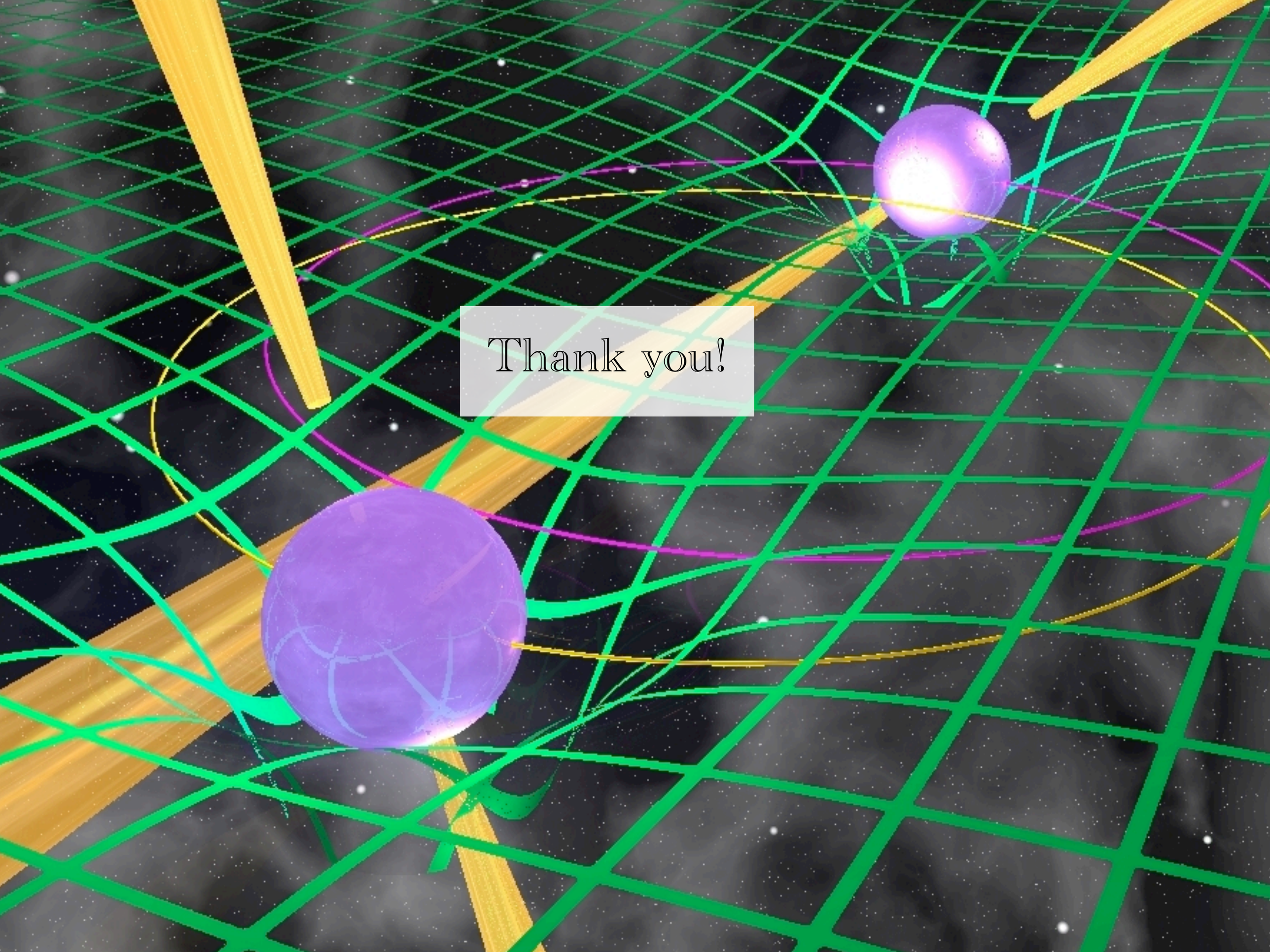
2011 data

- A bit more complex...



Conclusions

- **Double Pulsar : amazing but very complex pulsar interactions**
- **Most of the X-ray emission : PSR A**
- **Emission of PSR B's : further from the NS surface** (Iacolina et al. in prep)
- **Evidence of high-energy photons above 4 keV => NuSTAR**
- **2006 data : 5-8 keV => Fe line ? relic disk ? matter trapped between A and B ? atmosphere (but line shifted...) ?**
- **Shock ?** as suggested by Lyutikov et al. 2004, Arons et al. 2005
- **Work in progress :** pulse phase resolved spectra
  spatial/spectral analysis


Thank you!

A unique laboratory

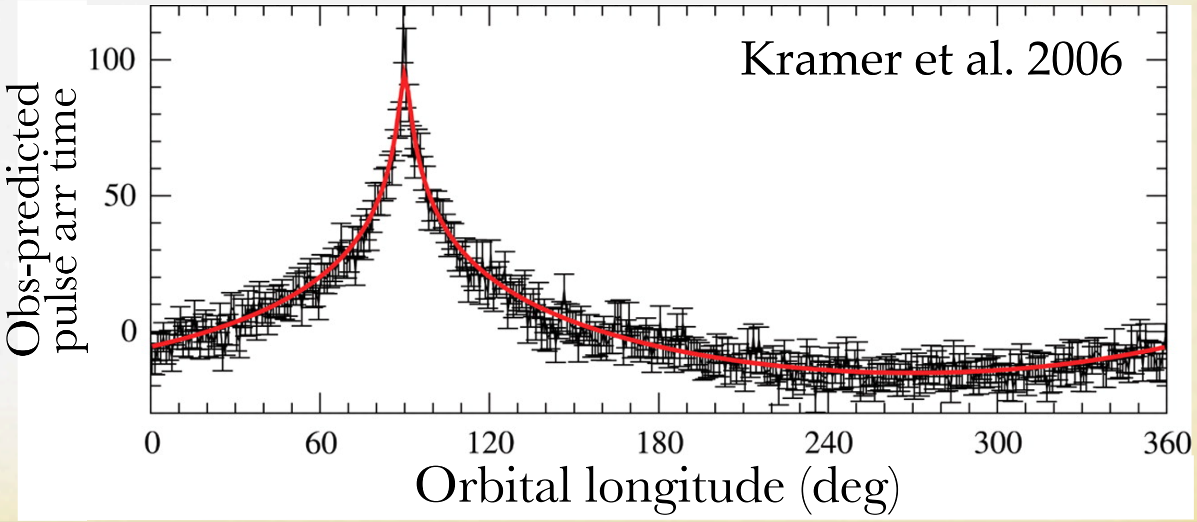
- **Best timing test for GR in strong field regime** (Kramer et al. 2006)

- **Observed pulse arrival times modified by relativistic effects**

=> 5 post-Keplerian parameters very well-determined

- Advance of periastron: $\dot{\omega}$ = **17°/yr**
- Orbital shrinking: **7 mm/day**
  System expected to merge in **85 Myr** (Burgay et al. 2003)
- Shapiro delay: pulses demonstrate the **curvature of space-time**

Confirmation of prediction of GR within 0.05% !!!



X-ray observations

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

  => Lx = $2*10^{30}$ erg/s, about 10^{-4} E_{rotA} (assuming d=0.5 kpc)

  => spectrum poorly constrained, quite soft (McLaughlin et al. 2004)

- **XMM-Newton** : 50 ks, **800 photons**

  (Pellizzoni et al. 2004, Campana et al. 2004)

  => confirmation soft spectrum

  => single component : PHABS*PL or PHABS*BB

- **Chandra** : 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