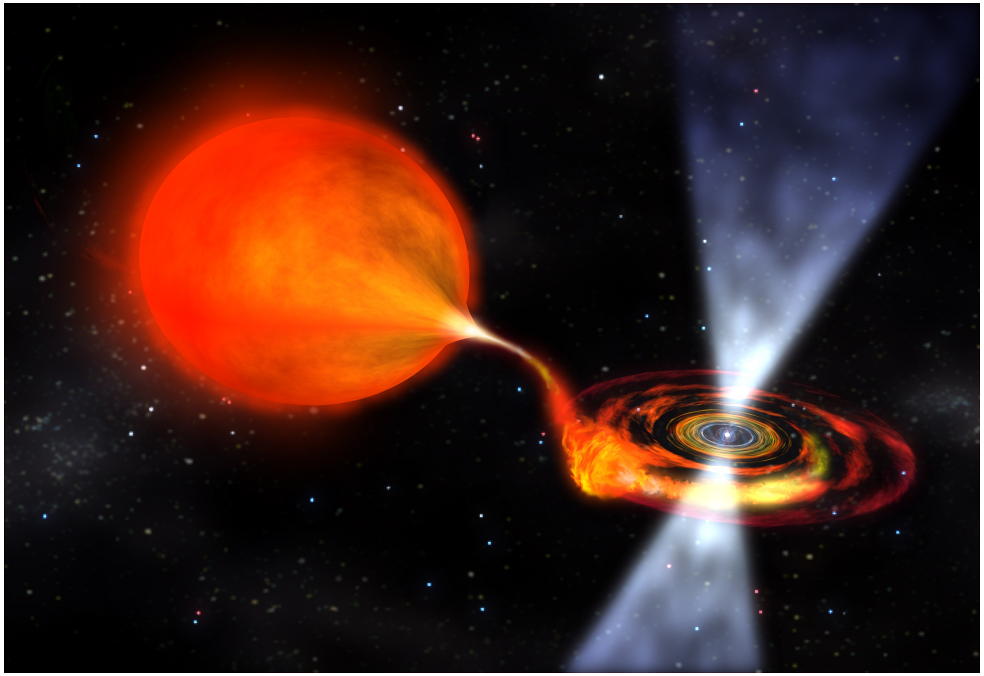
ACCRETING MILLSECOND PULSARS

IDEAL TEST BEDS FOR THEORIES OF ACCRETION ONTO FAST MAGNETIZED ROTATORS



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Outline

Accreting ms Pulsars: long sought progenitors of rotation powered ms PSRs

Where to search for accreting millisecond pulsars?

The NS-LMXB spin distribution

Spin evolution of AMSPs during outbursts

Timing noise

Orbital evolution

The X-ray spectra

Broad iron lines as a probe of the magnetospheric radius

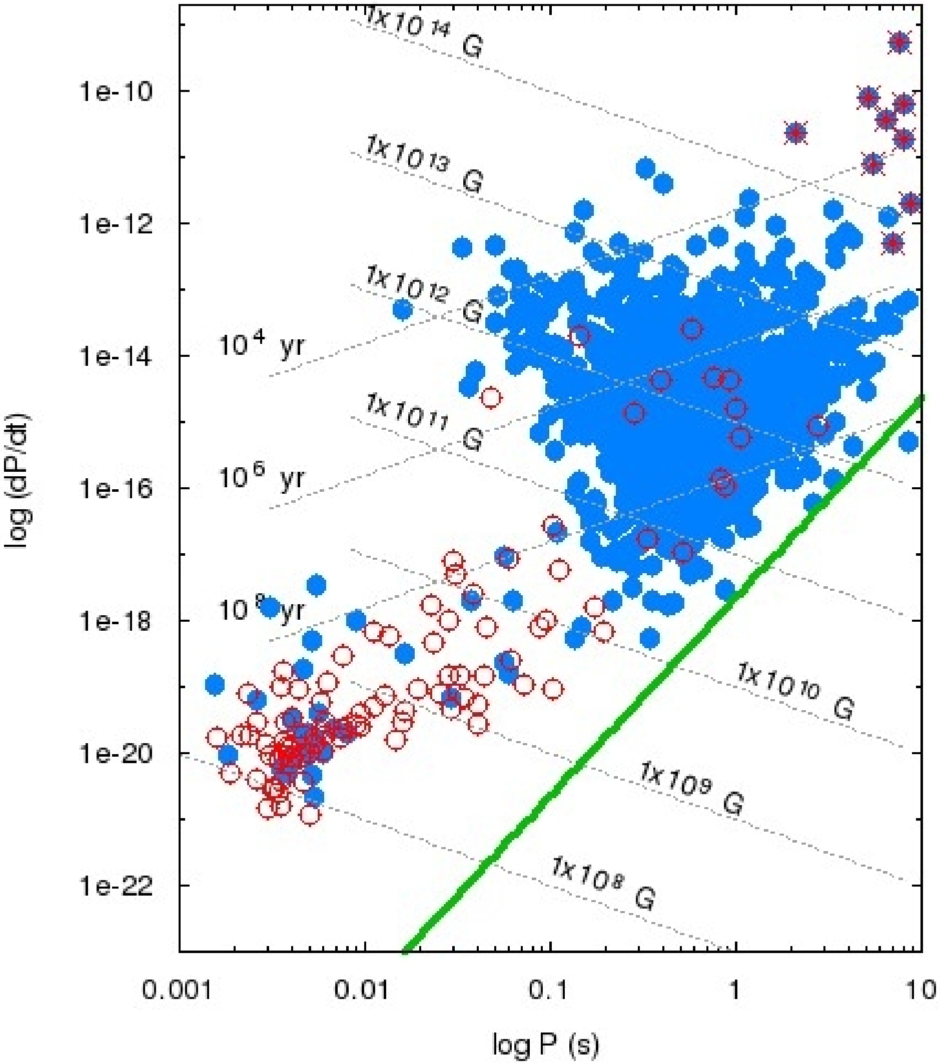
AMSP & THE RECYCLING SCENARIO

Discovery of rotation powered ms PSRs
(Backer et al. 1982)

- Usually in binary systems
- Low NS magnetic field (10^8-10^9 G)

Accretion induced spin up in low field NS of Low Mass X-ray Binary
(Alpar et al. 1982,
Radhakrishnan & Srinivasan 1982)

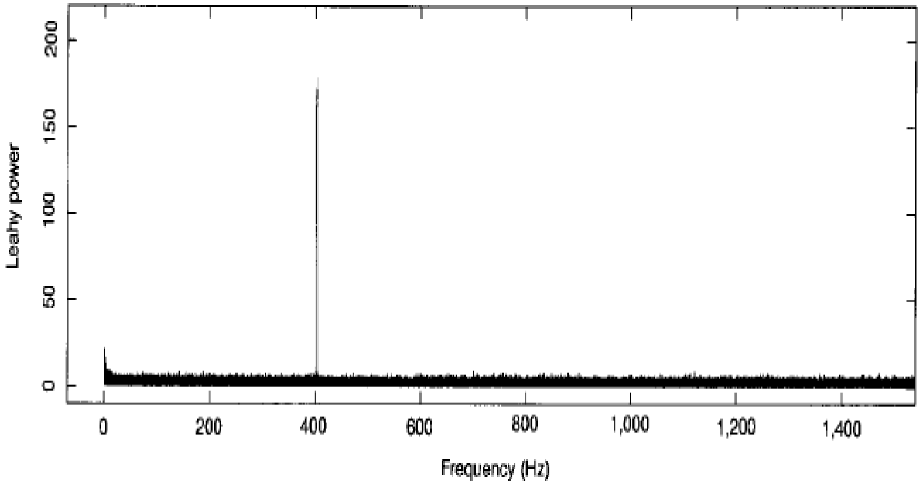
Search for progenitors unsuccessful until the RXTE era

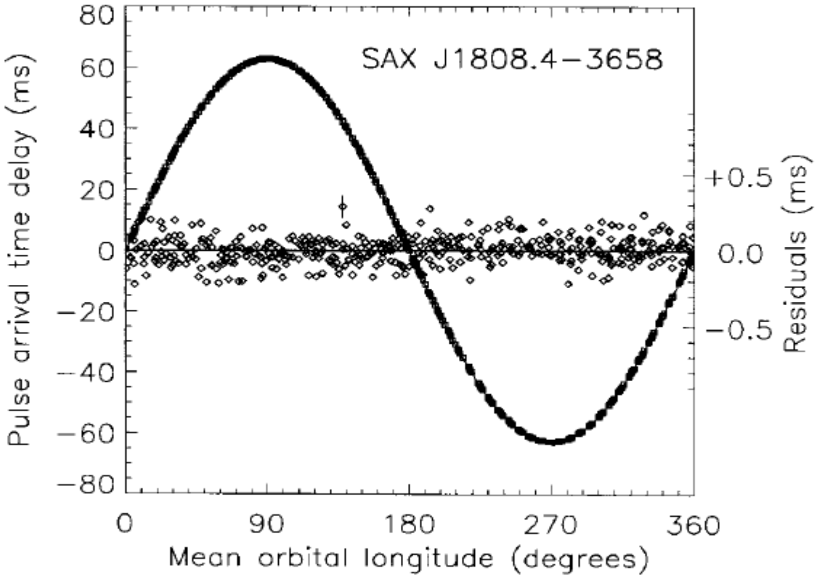


DISCOVERY OF AN AMSP

2.5 ms pulses faint XRT SAX J1808.4-3658
(Wijnands & van der Klis 1998)

Ideal progenitor of msPSRs (B≃~10^8-10^9G)



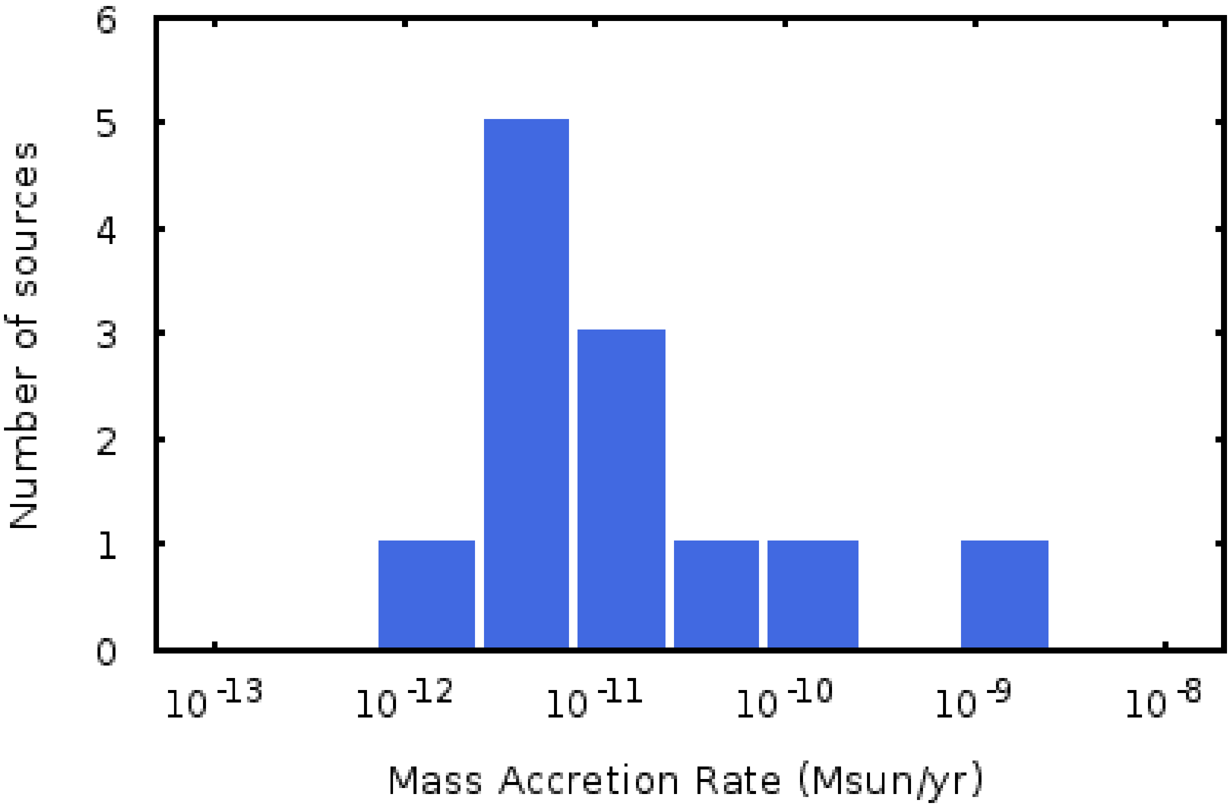


2hr binary system; companion mass < 0.18 M_{sun}
(Chakrabarty & Morgan 1998)

AMSP: A CENSUS

- 13 sources discovered so far (~ 1 yr $^{-1}$)
- All faint X-ray transients (average accretion rate 10^{-4} - 10^{-3} $\dot{M}$edd)

A large accretion rate buries the field under the NS surface
(Cumming et al. 2001)



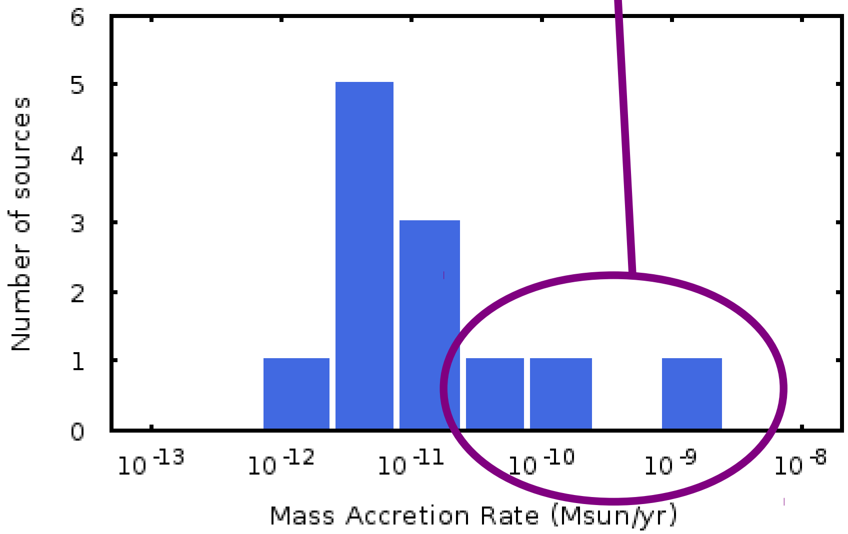
AmsP: a census

- Intermittent pulsators
  (Galloway et al. 2007, Altamirano et al. 2008, Riggio et al. 2010)

- What about Aql X-1 (Casella et al. 2008) ?
  duty cycle ‹ 0.03 %, accretion powered pulses?

- Searches in very faint NS-LMXB did not found pulses
  (Patruno et al. 2010)

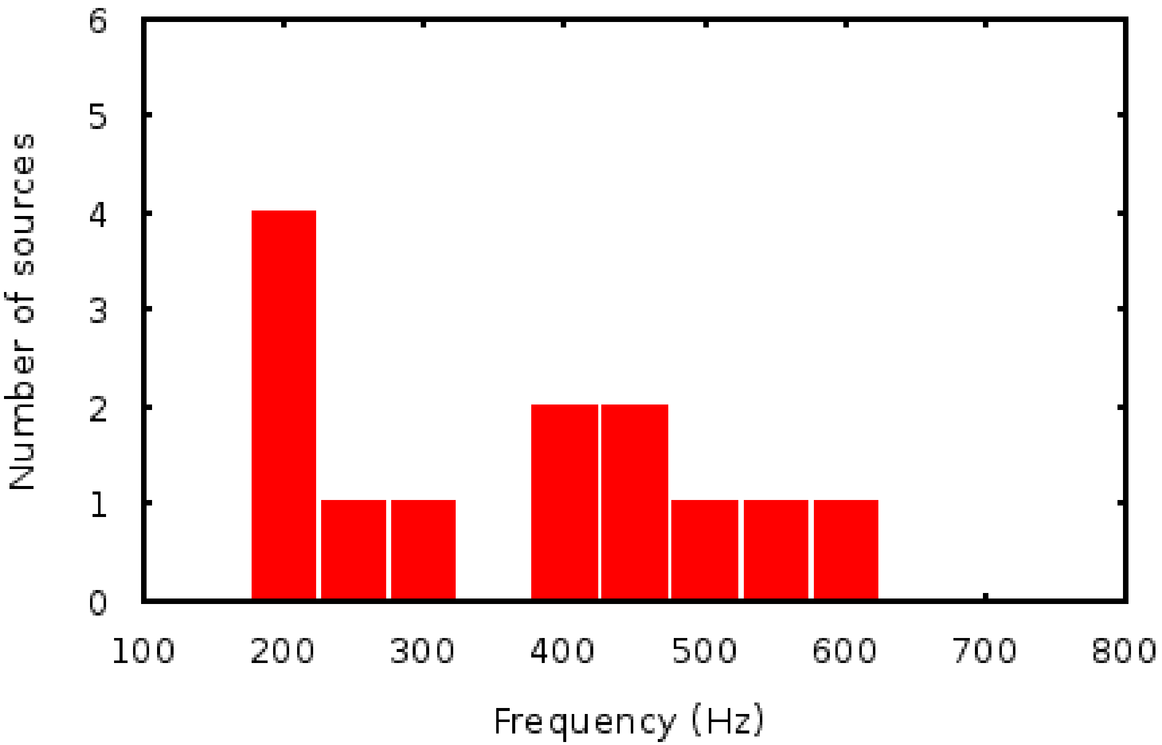
- Other models to explain pulse appearence/disappearance:
  scattering in a hot corona (Titarchuk et al. 2002)
  magnetic-spin axes alignement (Lamb 2008),
  MHD instabilities (Kulkarni et al. 2008)



AMSP SPIN DISTRIBUTION

- Search for sub-ms pulsars
- Most EoS predict a break up frequency › 1000 Hz

  ...but the fastest AMSP discovered so far spins at ~600 Hz

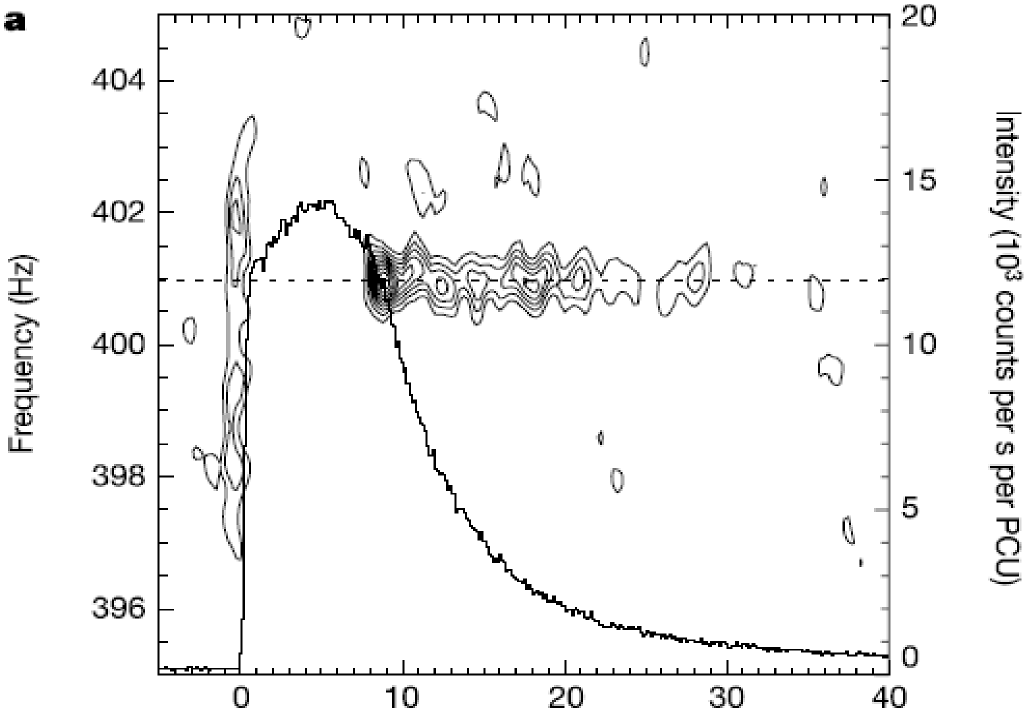


COHERENT & BURST OSCILLATIONS

- Burst oscillation detected from SAX J1808.4-3658 at a frequency within few Hz from the spin frequency
  (Chakrabarty et al. 2003)

- Same for other four ASMP
  (Watts et al. 2008,2009; Altamirano et al. 2010)

- The frequency of burst oscillations is the frequency of the NS

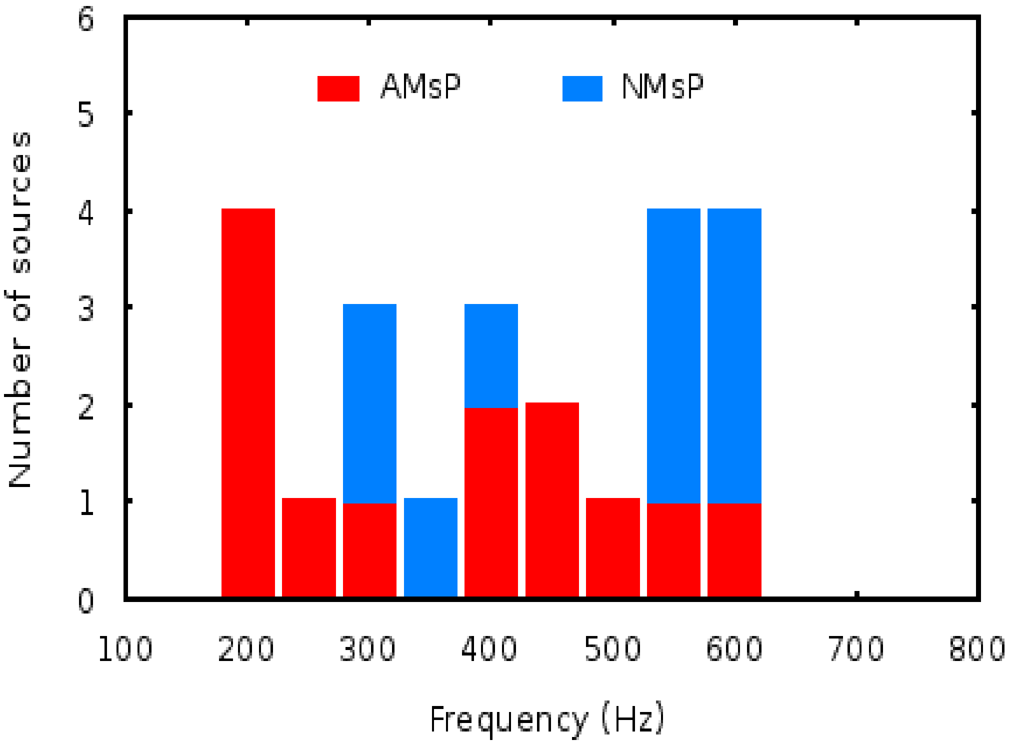


SPIN DISTRIBUTION OF AMSP+NMSP

- 10 NmsPs + 13 AMsPs

- A uniform distribution up to a cut off indicates a maximum frequency of 730 Hz (95% c.l.; Chakrabarty et al. 2003,
Patruno et al. 2010)

- Possible explanations:
  - Magnetic spin equilibrium
  - GW emission
  - Propeller effect

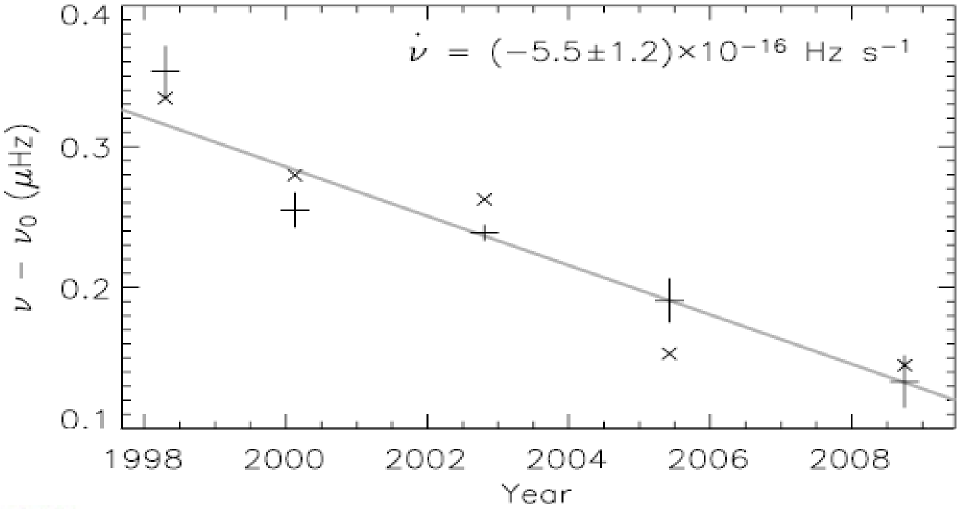


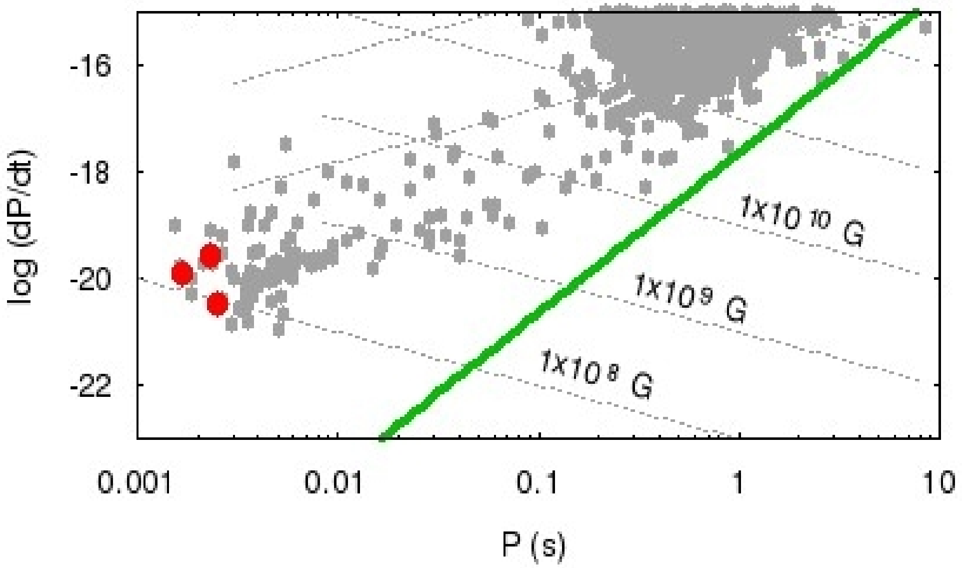
LONG TERM SPIN EVOLUTION

- Spin down of SAX J1808.4-3658
  (Hartman et al. 2008, 2009)

- Magneto dipole spin down
  B=1.5(2) x 10^8 G

- Similar estimates in other two cases
  (Patruno et al., Hartman et al., Papitto et al.,, Riggio et al. 2010)

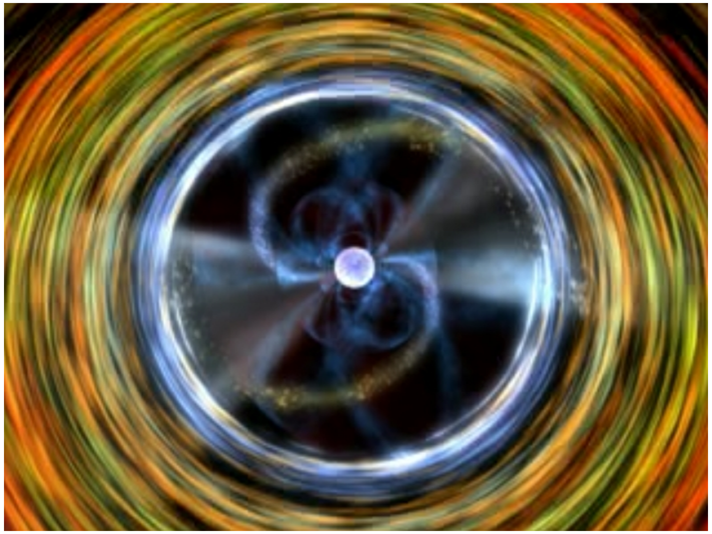




- The long terms spin down of AMSPs is explained by magneto dipole torques

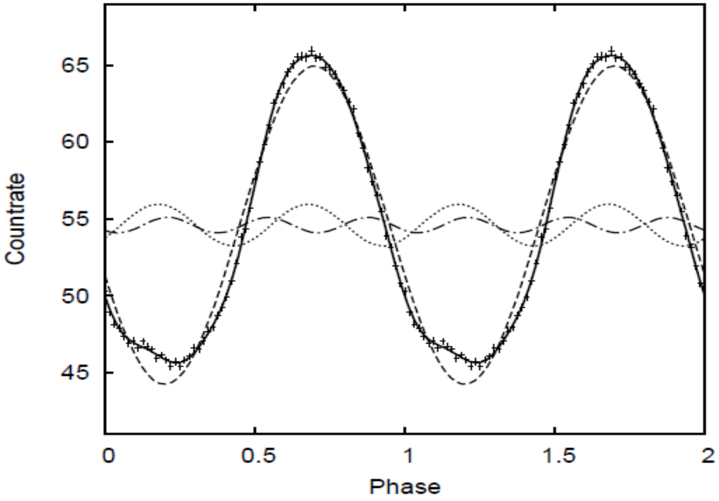
- AMSPs are not strong GW emitters

SHORT TERM SPIN EVOLUTION



Study the spin up torque while it is in action

Key parameters:
    mass accretion rate and magnetic field

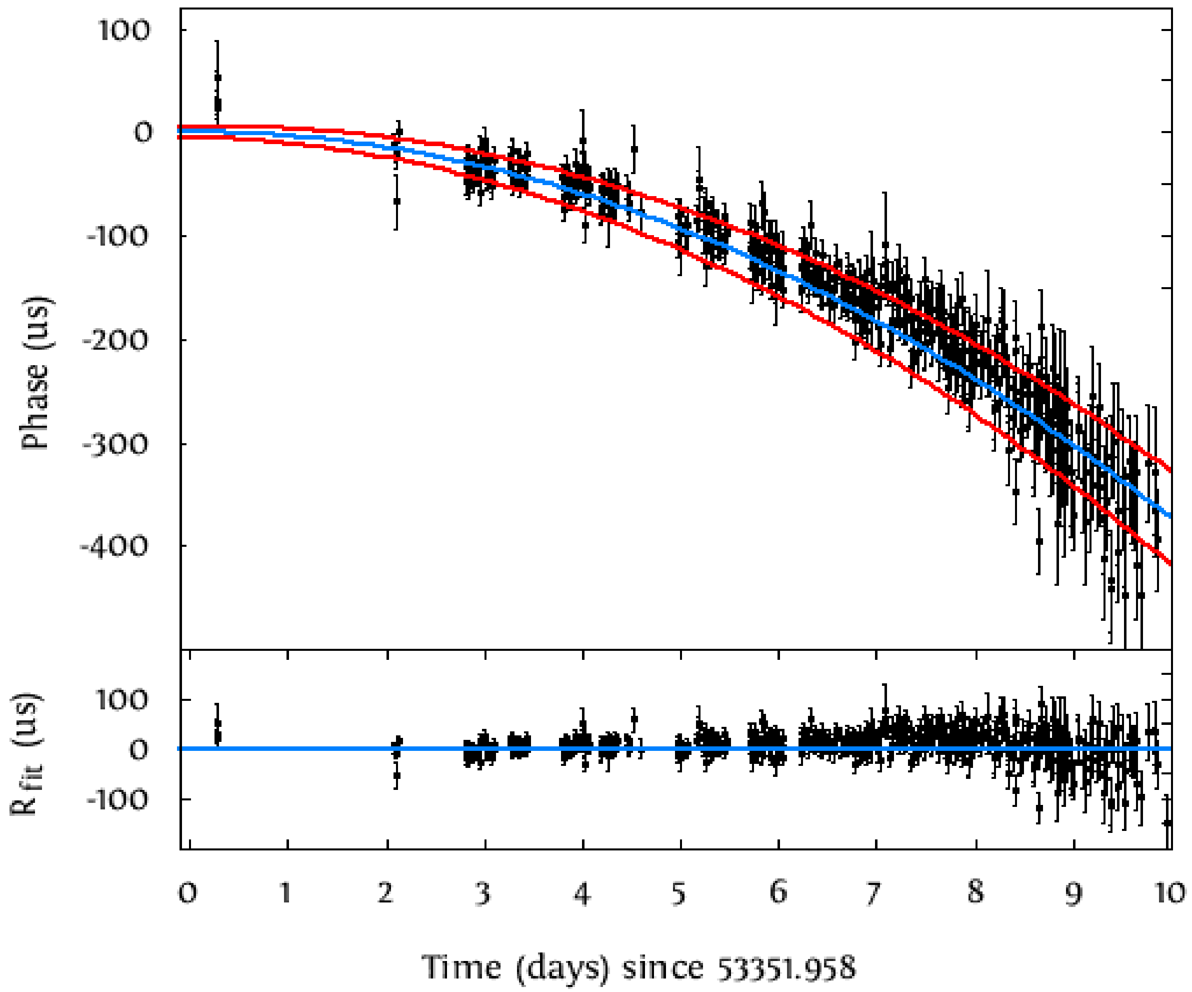


Pulse profile reconstruction

Timing analysis:
follow the evolution of the phases

ACCRETION TORQUES

The fastest AMSP known, IGR J00291+5934, just one harmonic,



- 2004 outburst
  Spin up
  $\langle d\nu/dt \rangle=(6.0\pm0.3)\times10^{-13}$ Hz/s
  (Falanga et al. 2005; Burderi et al. 2007; Papitto et al. 2010)

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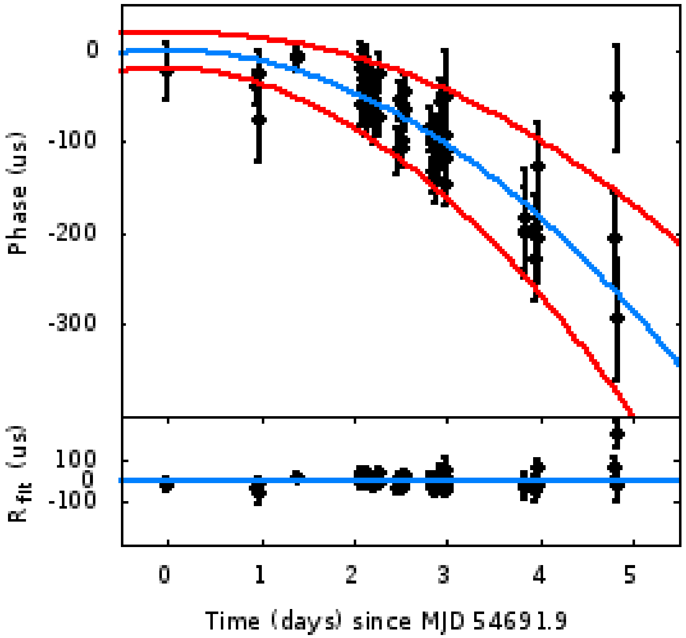
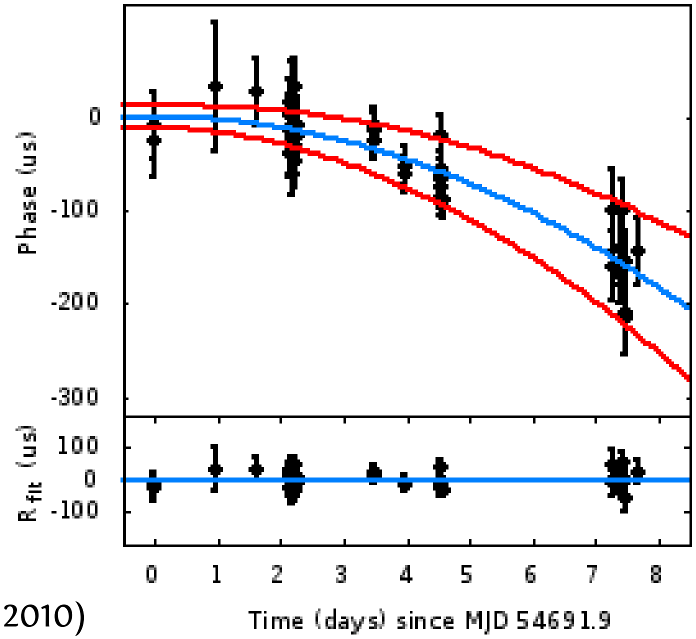


2008 August
Spin up upper limit
$\langle dv/dt \rangle < 2 \times 10^{-12}$ Hz/s
(Papitto et al. 2010, Hartman et al. 2010)

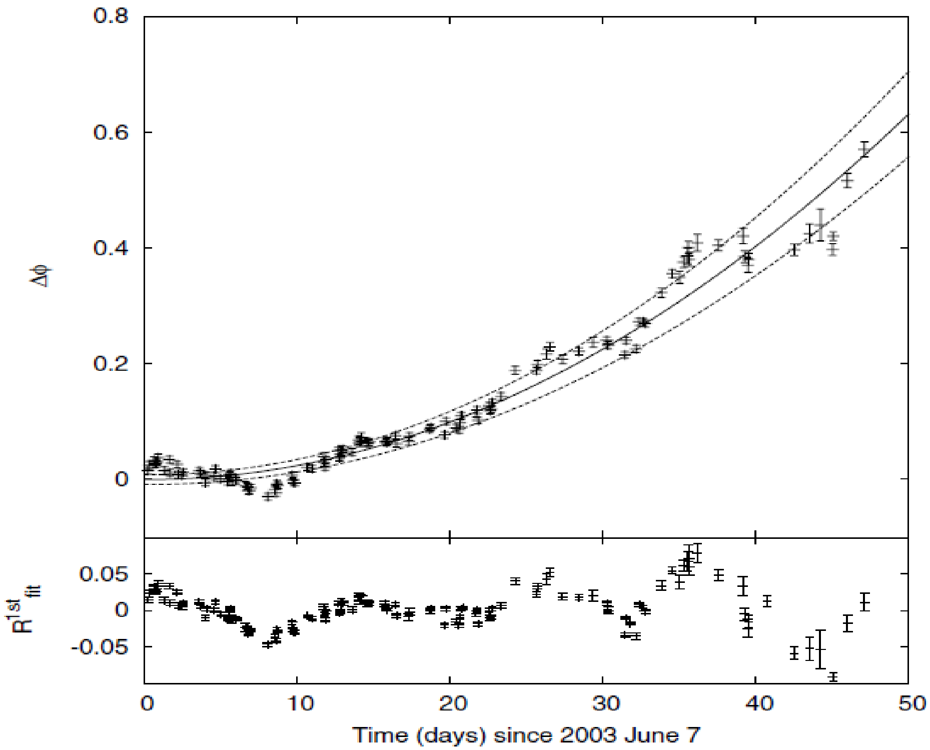


- September 2008
  spin up
  $\langle dv/dt \rangle = (4.4 \pm 1.2) \times 10^{-13}$ Hz/s
  (Papitto et al. 2010, Hartman et al. 2010)

TIMING NOISE IN AMSP

- 3 other sources show smooth phases (Di Salvo et al. 2007, Papitto et al. 2008)

- The majority of AMSPs is affected by a timing noise
  - Measuring the spin derivative is more problematic



- Phase anticorrelate with flux

e.g. XTE J1814-338 (Papitto et al. 2007)

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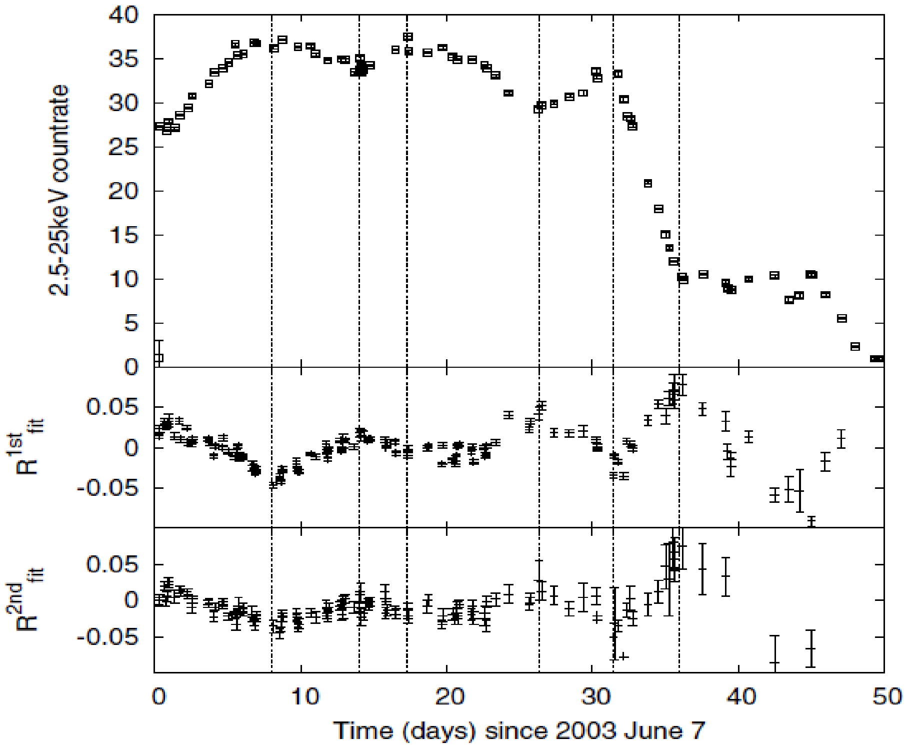

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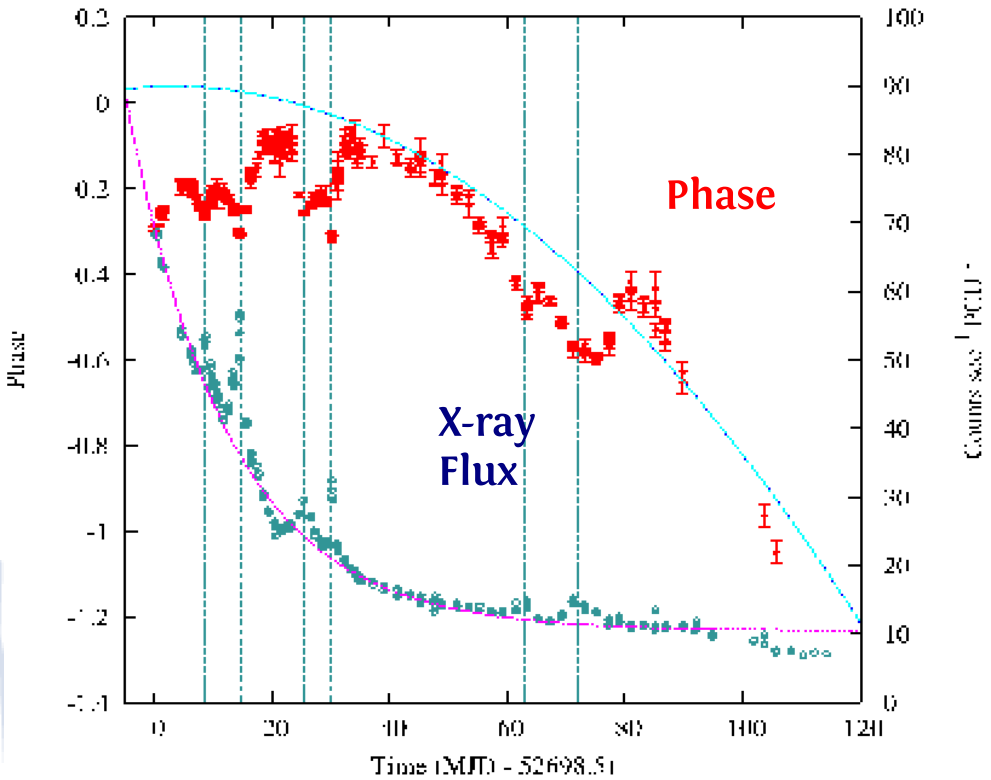

- Phase anticorrelate with flux

e.g. XTE J1807-294 (Riggio et al. 2008)

TIMING NOISE IN AMSP

- Only 3 sources show 'well' behaving phases (Di Salvo et al. 2007, Papitto et al. 2008)

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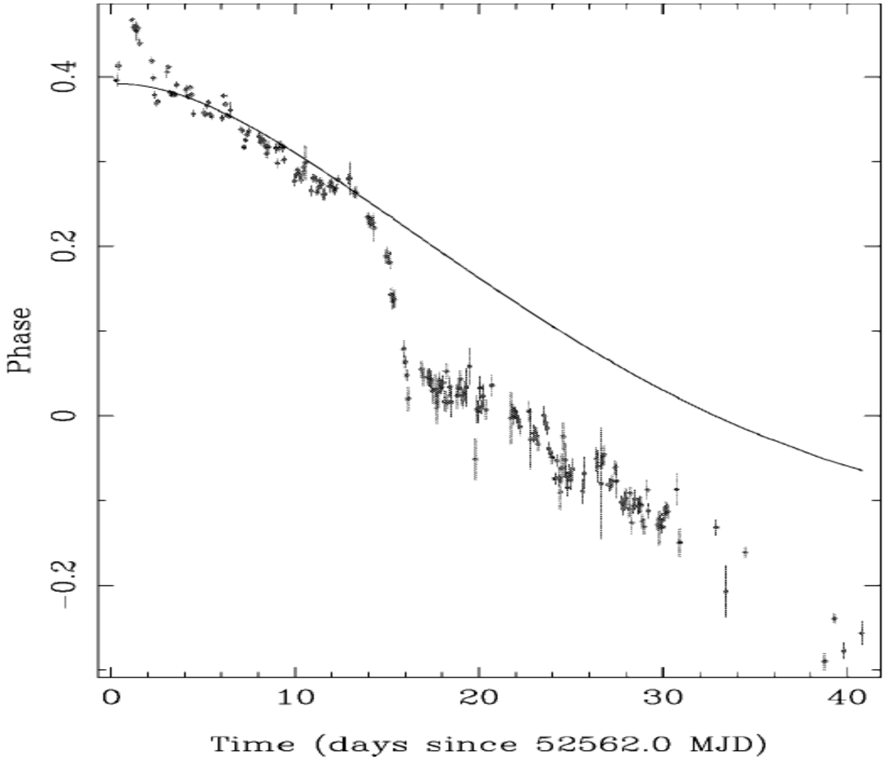

- Phase anticorrelate with flux

e.g. XTE J1807-294 (Riggio et al. 2008),
XTE J1814-338 (Papitto et al. 2007)

- Phase jumps in the 1st harmonic without contemporary changes in the 2nd

e.g. SAX J1808.4-3658 (Burderi et al. 2002),
SWIFT J1749.4-2807 (Papitto et al. in prep.)

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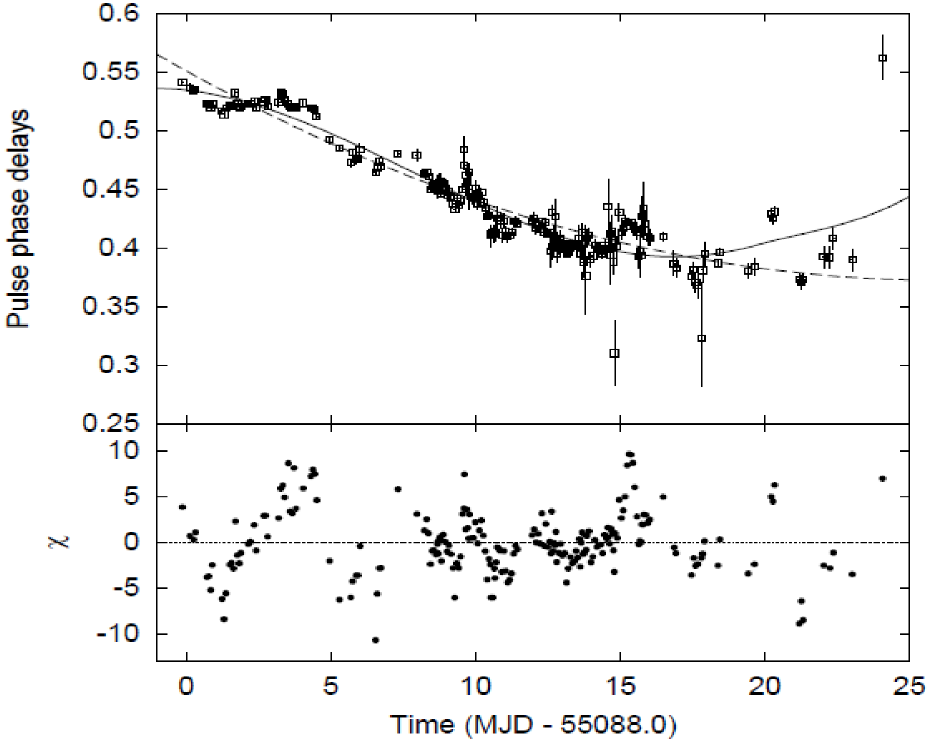

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  e.g. SAX J1808.4-3658 (Burderi et al. 2002),
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- Chaotic patterns
  e.g. IGR J17511-3057 (Riggio et al. 2010),
  SAX J1808.4-3658 (Hartman et al. 2008)

TIMING NOISE IN AMSP

Pulse shape variability

How to mitigate it ?

- Chose the least varying harmonic (Burderi et al. 2006)
- Weigh harmonics differently (Hartman et al. 2008)
- Assume a phase-flux correlation law (Patruno et al. 2009)

How to interpret it?

- Hot spots movements correlated with X-ray flux
  - Nearly aligned field (Lamb et al. 2008)
  - MHD instabilities (Kulkarni et al. 2008)

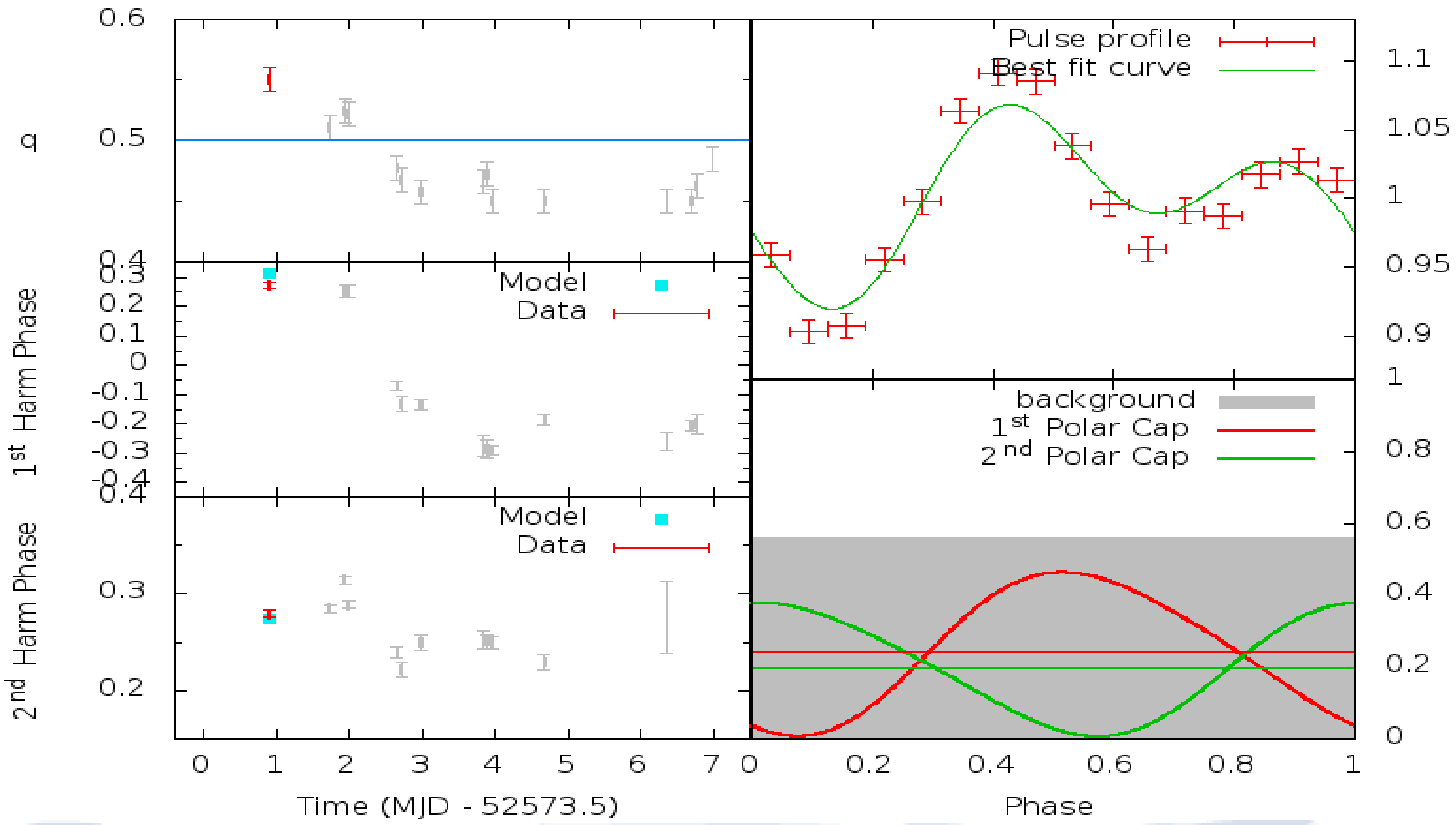
- Variation of the flux received from the antipodal spot,
  - Disc occultation (Poutanen et al. 2009)
  - Small variation of the mass accreted by the spots (Burderi et al. 2008, Riggio et al. In prep.)

Apart from 'well' behaving cases, the interpretation of timing data usually needs preliminary assumptions on the noise nature (and the weaker ones should be preferred...)

TIMING NOISE IN AMSP

The eclipsing AMSP, SWIFT J1749.4-2807 (Markwardt et al. 2010, Belloni et al. 2010, Ferrigno et al. 2010)

Second harmonic often stronger than first, and more stable in time
Model predicts variations of 10% of the mass accreted by the two spots
(Papitto, Riggio et al. 2010 in prep.)

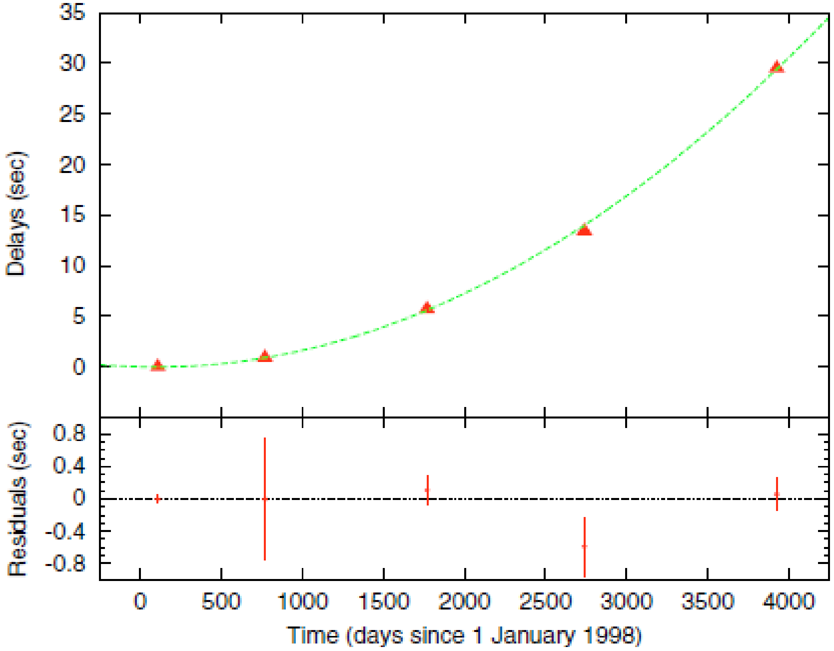


ORBITAL EVOLUTION

SAX J1808.4-3658

dPorb/dt = (3.89 +/- 0.15) x 10^{-12} s/s
(Di Salvo et al. 2008, Burderi et al. 2009; Hartman et al. 2009)

Too large rate for conservative evolution



Non conservative evolution:

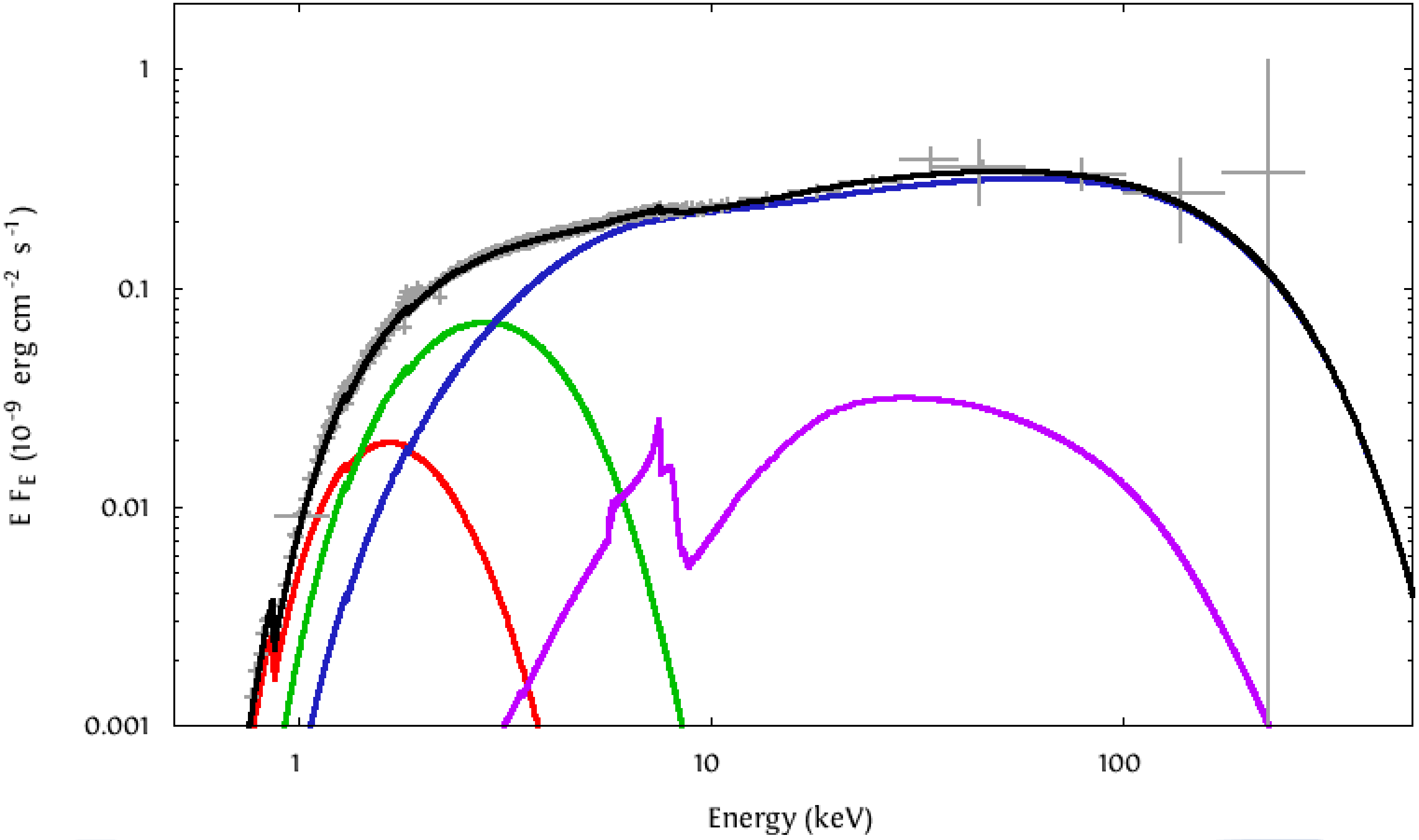
During quiescence mass and angular momentum is lost by the system

Link with Black Widown PSR ?

THE X-RAY SPECTRUM OF AMSP

Spectral analysis provides crucial info on the geometry of the system

- Quite similar spectral properties
- XMM-Newton + RXTE spectrum of IGR J17511-3057 (Papitto et al. 2010)

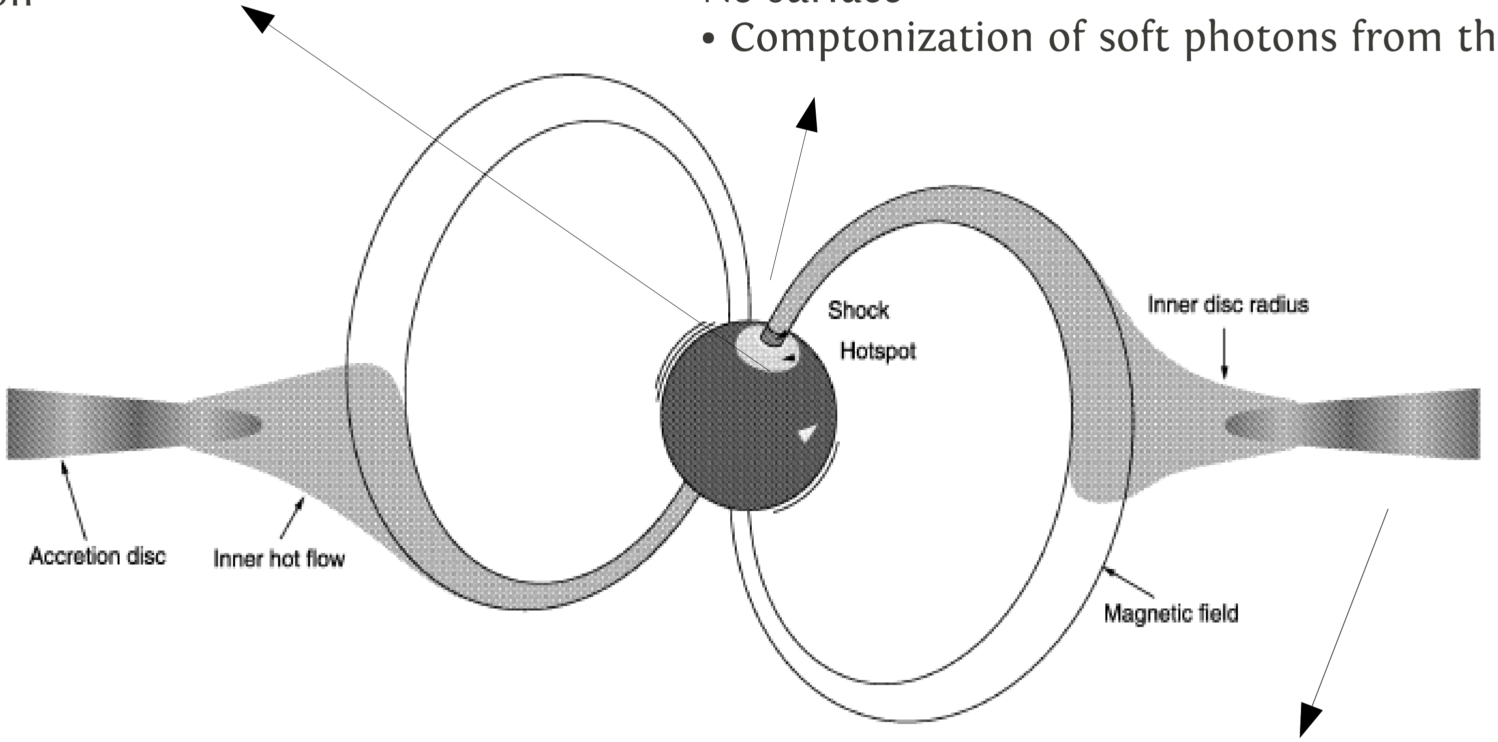


AMSP CONTINUUM

Hot spots – Reprocessing of the Irradiating hard photons into thermal radiation

Accretion Column – Accreting plasma heated above NS surface

- Comptonization of soft photons from the surface



Disk emission

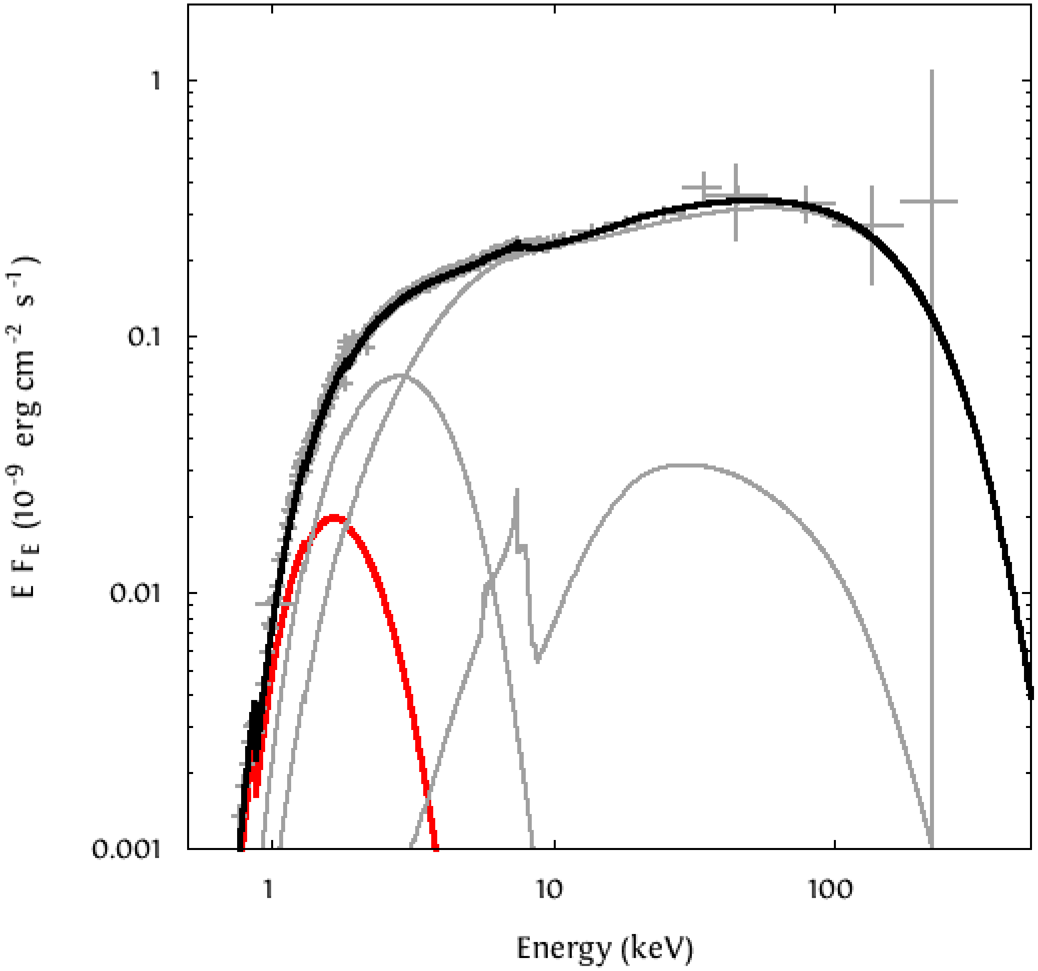
Gierlinski, Done & Barret 2002
Gierlinski & Poutanen 2005

AMSP CONTINUUM

Disk Black Body

kT_{in} =0.2 - 0.4 keV

Rin $(\cos i)^{1/2} \simeq$ 10-20 km



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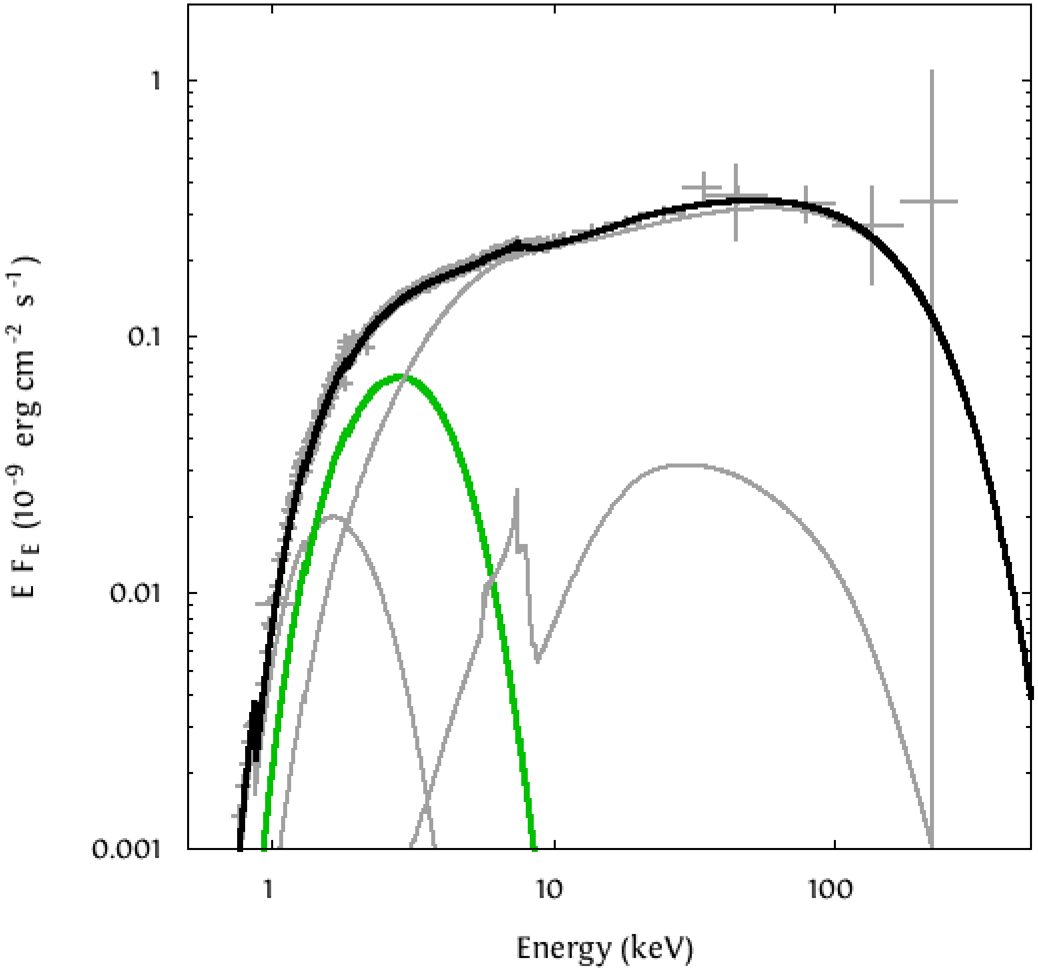
Rin (cos i)$^{1/2}\simeq$ 10-20 km

Single T Black Body –

KT= 0.4 - 1.0 keV

R_{BB}=5 - 10 km



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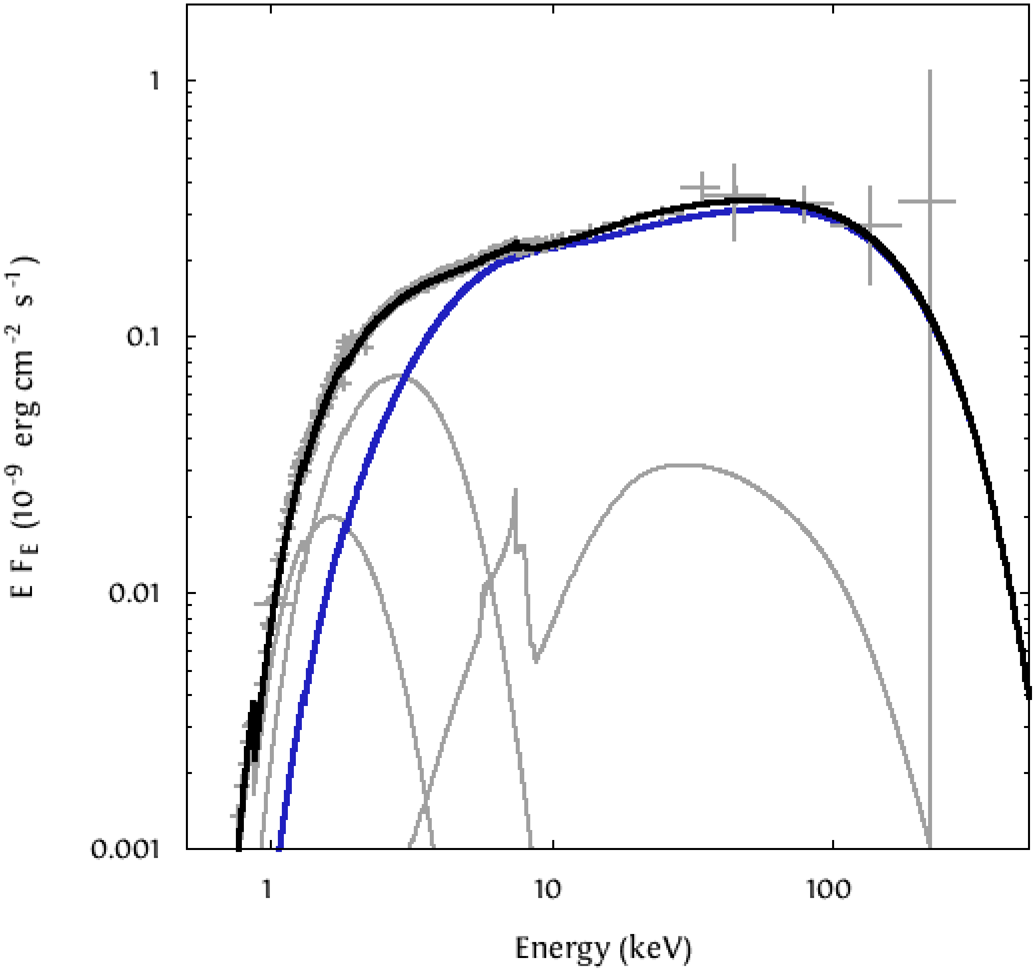
Comptonization

α = 1.8 - 2.1

KT_e= 20-60 keV

$\tau \sim$ 0.7 - 2.5



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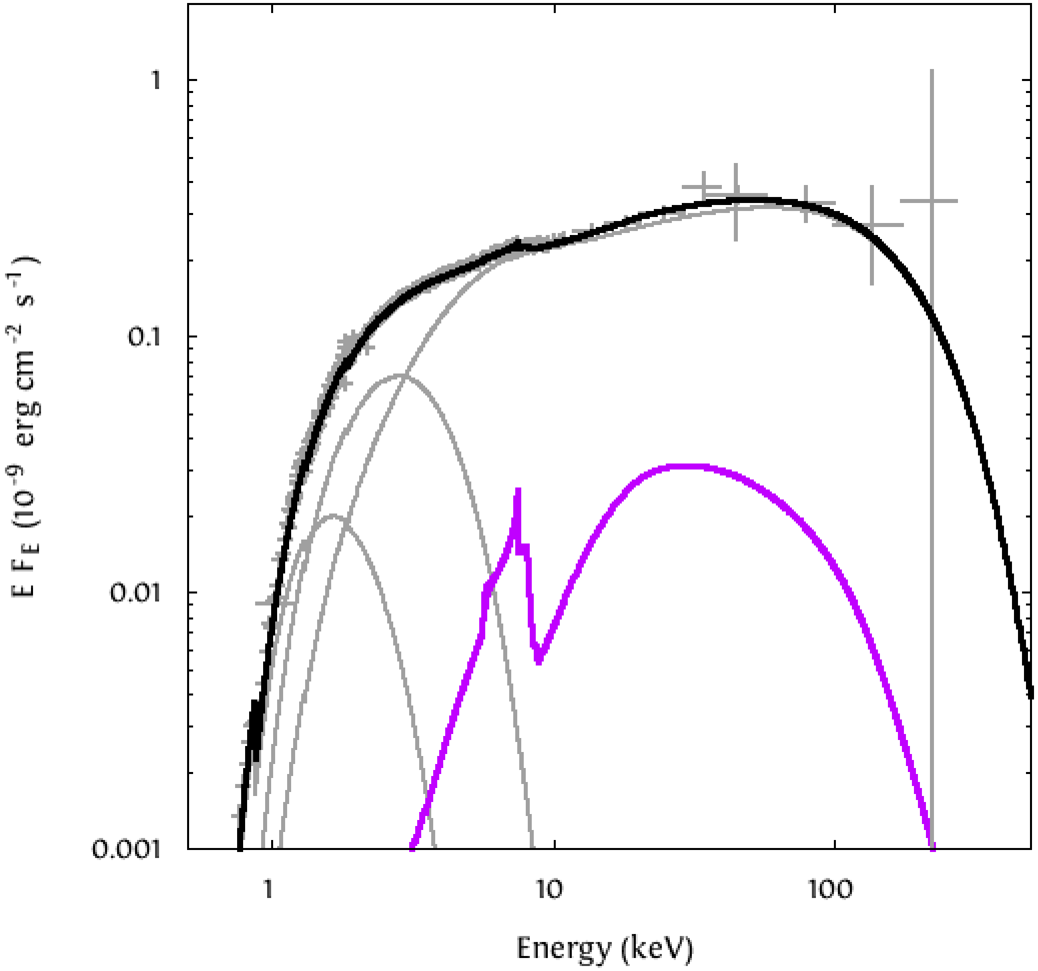
Reflection of the hard emission on the disc
Iron Kα feature
R ~ 0.1-0.5

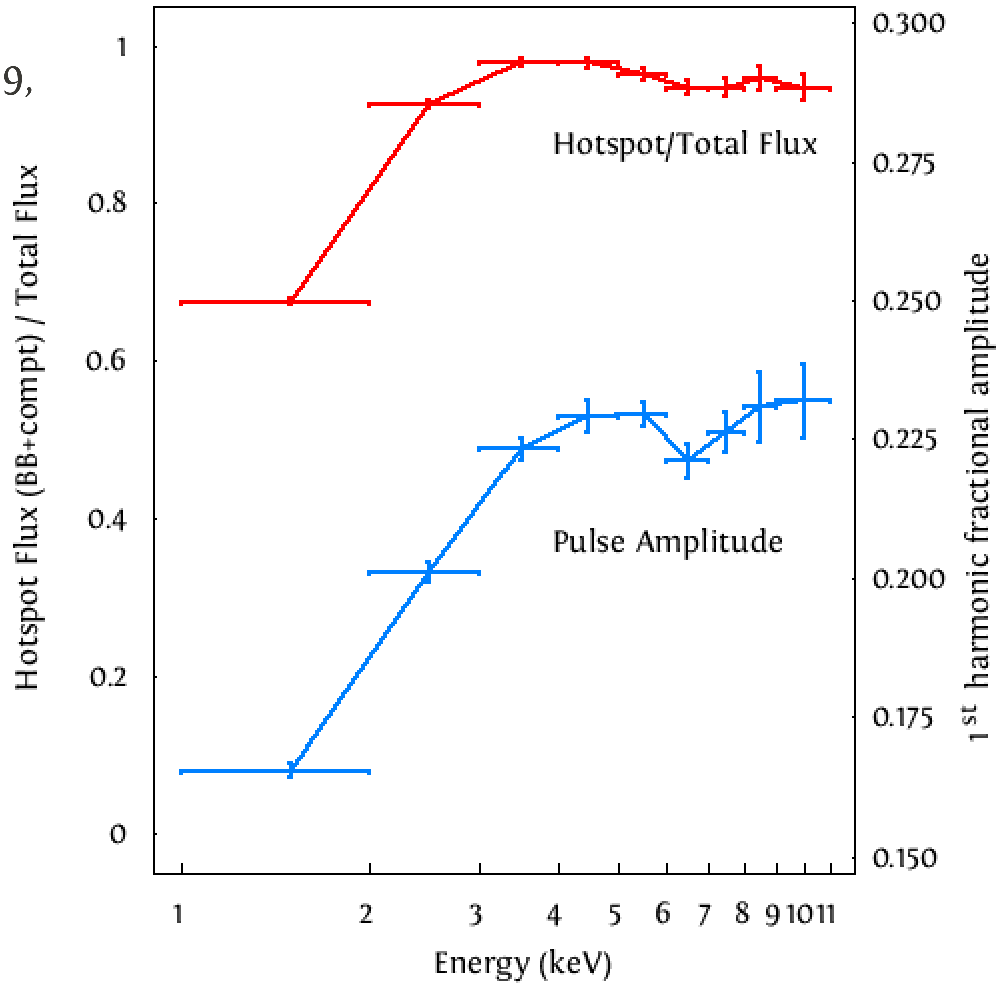


ENERGY DEPENDENCE OF PULSES

- Pulsed fraction decrease at soft energies (Gierlinski & Poutanen 2005, Patruno et al. 2009, Papitto et al. 2010)

- Influence of the disc emission

- BB+comptonization are originated near the hotspots



PHASE LAGS

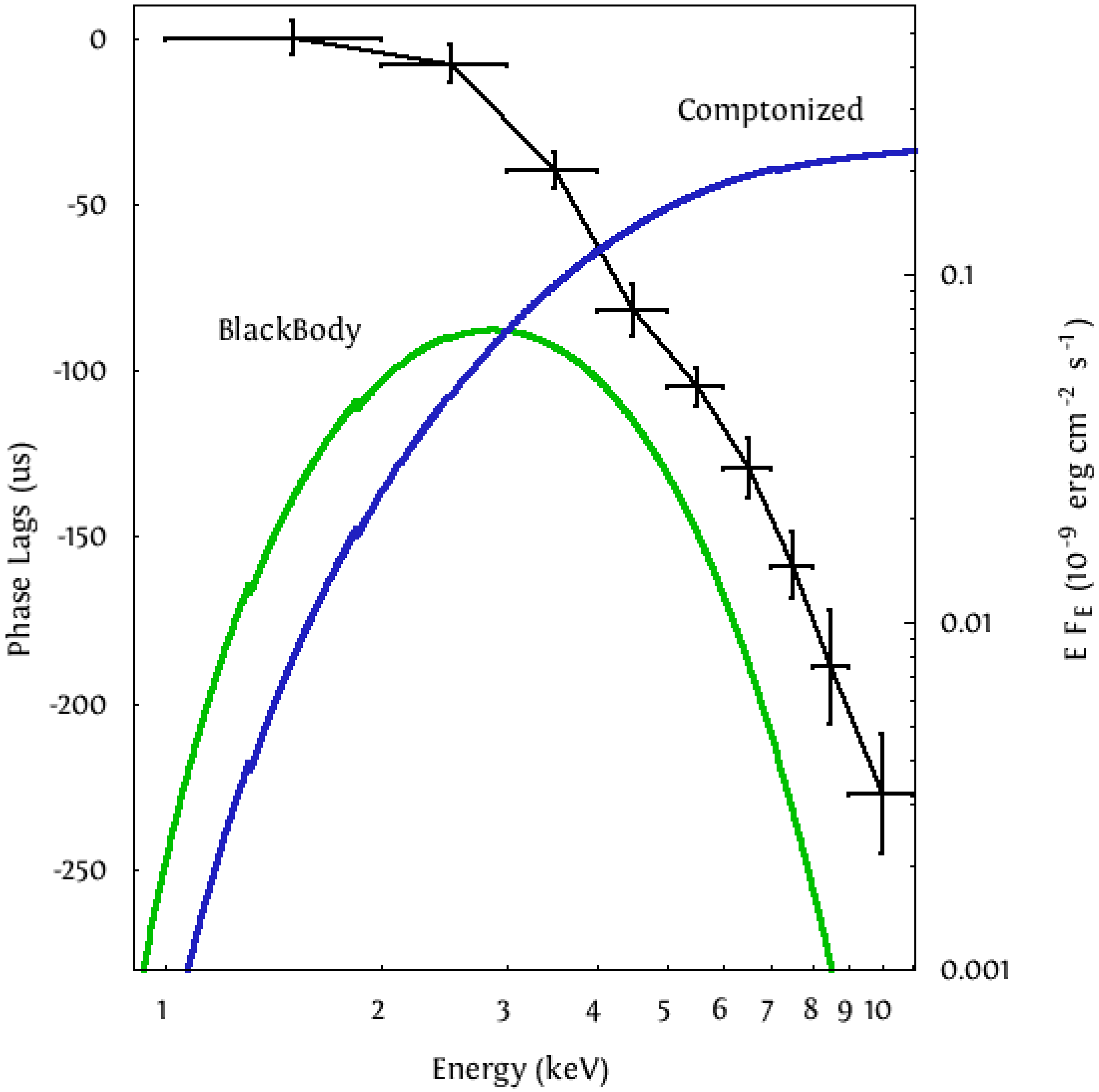
- Phase Lags

  Harder photons arrive earlier

- Correlation with the weight of the two main spectral components

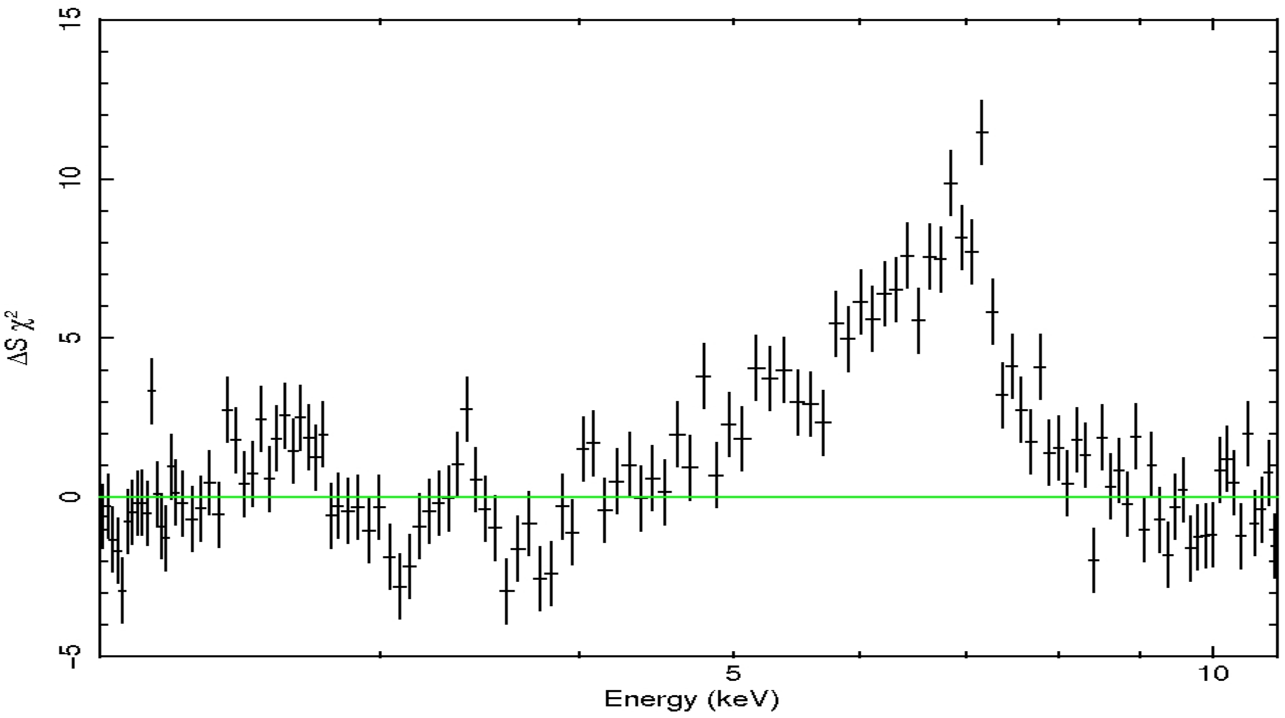
- Comptonized & BB photons have different angular distribution

  (Gierlinski, Done & Barret 2002; Poutanen & Gierlinski 2003)



IRON LINE IN SAX J1808.4-3658

45 ks XMM-Newton observation during the last outburst of the source



- FeKα line **strongly required** **(10 sigma excess)**

E_K = 6.43 (8) keV σ = 1.1 (2) keV
broadness & extended red wing suggest a disk origin

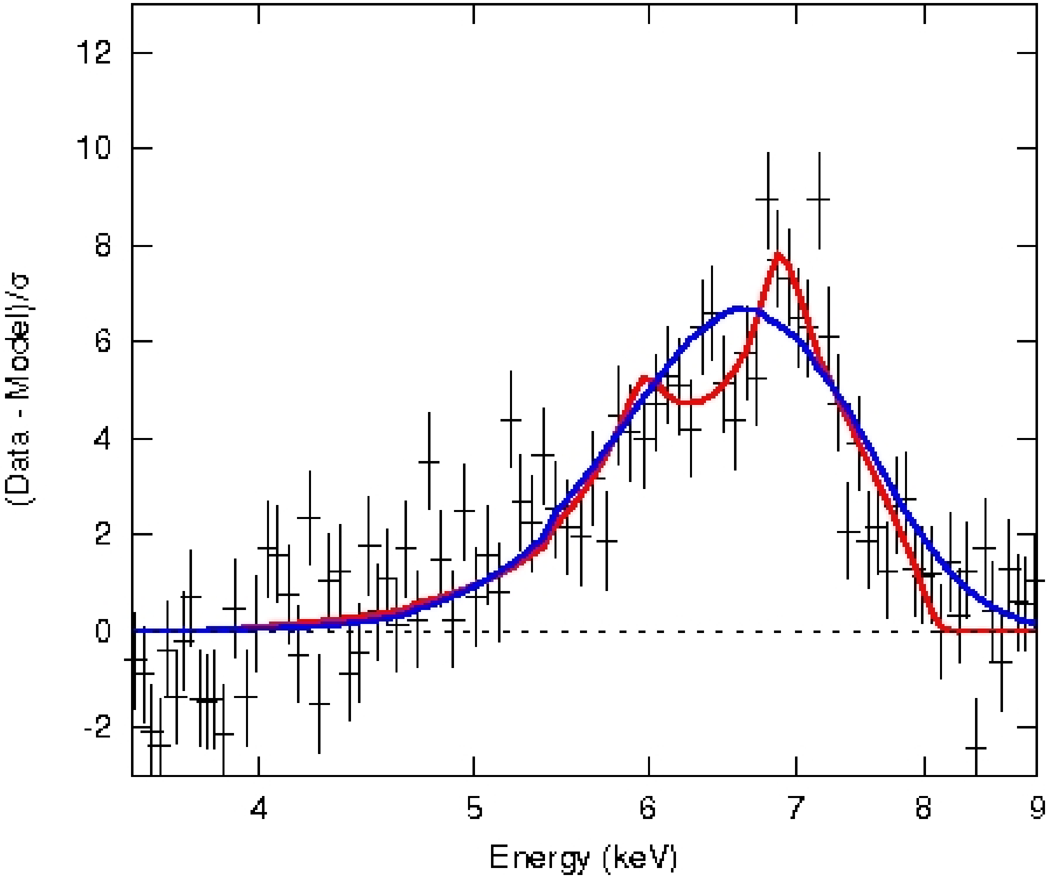
RELATIVISTIC DISK LINE

Diskline model (Fabian et al. 89)

Best Fit parameters:

• Line Energy	6.47(7) keV
• Inner disc radius	$8.7^{+3.7}_{-2.7}$ R_g
• Inclination	> 60°
• Emissivity index	-2.3(3)

Slightly large inclination, still compatible with the estimate from Deloye et al. 2008 (36°-67°)



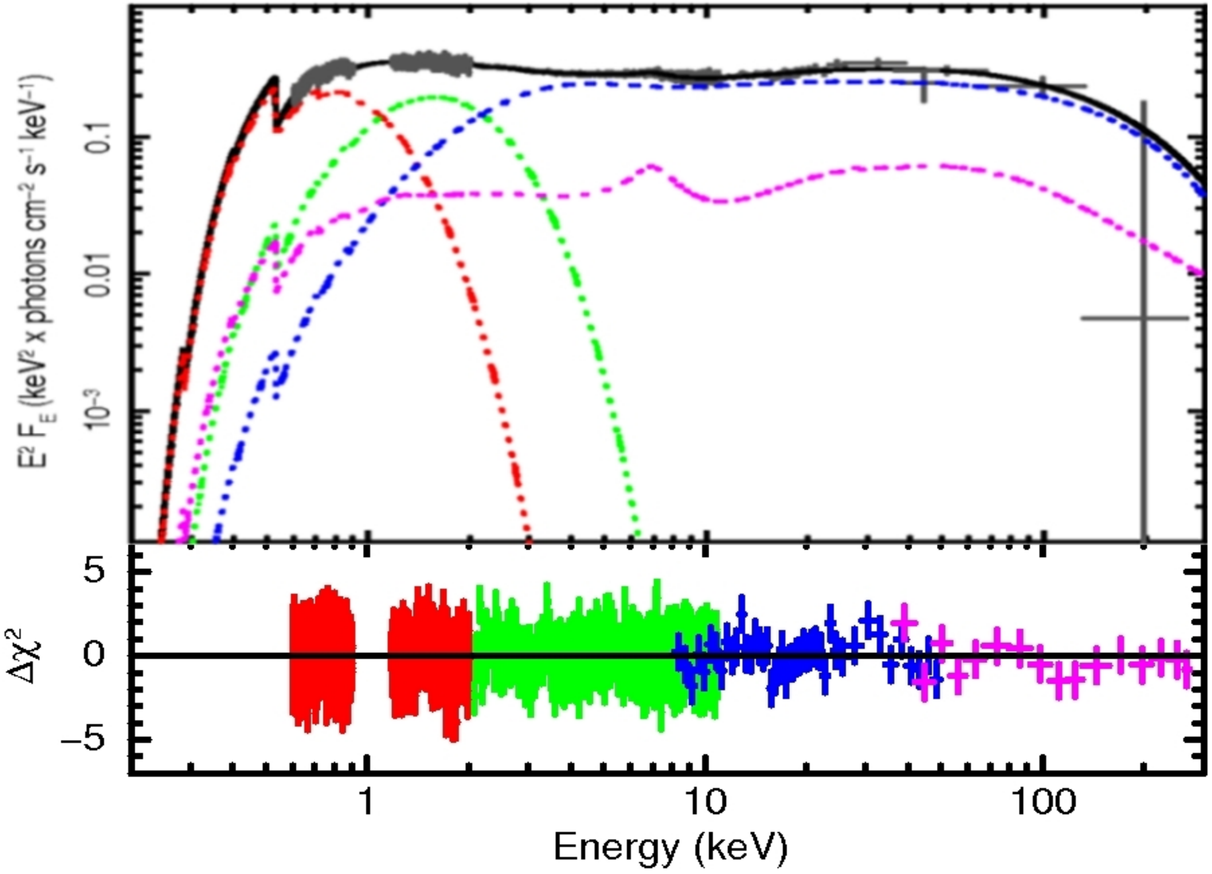
Alternatives?

Broadening in a corona is unlikely for kTe>35 keV, τ~2 (Gierlinski,Done,Barret 02)

DISC REFLECTION

XMM-Newton – RXTE combined spectrum

Reflection fraction= 0.32(4) consistent with previous estimates (Ibragimov et al. 2009 & Cackett et al., 2010)



Rin < 15 Rg

The inner disc radius is compatible with the PN estimate !

THE INNER DISC RADIUS

- For the first time in a pulsar, the inner disc radius from Fe line broadening
  - **R_{in} = 18.0$^{+7.6}_{-5.6}$ $m_{1.4}$ km**

- For a 2.5 ms pulsar accreting at $\dot{M}$=5.6 x 10^{-10} $D_{3.5}^{2}$ M_{sun}/yr, with B=(1-5)x10^8 G:
  - **R_{in} ~ 12 - 26 km** (Ghosh & Lamb 79) -- well in accord with our estimate

- **Our upper limit of 25.6 km is well within the corotation radius** **(31 km)**, and fits perfectly in the small zone around the pulsar where accretion is possible, thus giving an important **confirmation of accretion theories on fast rotators**

IRON FEATURES IN AMSPS

Other AMSPs:

HETE J1900.1-2455

Broad line at E = 6.7-6.97 keV with EW ≃ 120 eV (Cackett et al. 2010)
Inner disc radius dependent upon reflection modelling
Need for observations at larger statistics

IGR J17511-3057

Moderately broad line et E = 6.7--6.97 keV (EW ≃ 45eV) (Papitto et al. 2010)
A ionized reflector is indicated also by the reflection continuum ($\log\xi \simeq 3$)
Rin = 18 – 33 Rg

Tight upper limits (EW ‹ 25eV) for **XTE J1751-305 & XTE J1807-334**
A disc truncated far from the NS? (Gierlinski & Poutanen 2005)

No Line detection simultaneous to a kHz QPO

CONCLUSIONS

Accreting ms Pulsars have to be searched in faint transients

Some mechanism prevents accreting pulsars to reach sub-ms periods

- AmsPs evolution in quiescence is explained by magneto-dipole emission

Both spin ups and spin downs observed during outbursts

- ...but phase fluctuations sometimes observed

Orbital evolution suggests a link with BWP

Broad emission lines observed also in AmsPs

- A spectral insight on the inner region of the accretion disc