# Study of cyclotron line sources, the present and the future.

# Outline

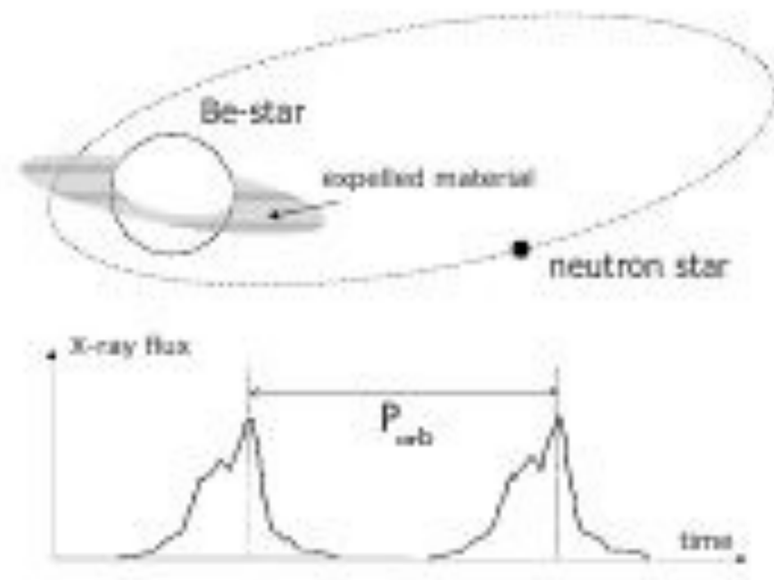
- A quick summary
- A theoretical study on the origin of cyclotron line energy flux dependency
- New INTEGRAL determination of a positive flux-centroid energy in GX 304-1
- IGR J18179-1621: a new cyclotron source ?
- RX J0440.9+4431: a new cyclotron line source.
- Prospects for future missions.

# High B-field: an ubiquitous phenomenon

- Low mass X-ray binaries normally associated with low-B ($10^{8-9}$ G) neutron star (old systems). An exception is, e.g., Her X-1
  - Roche lobe overflow -> accretion disk
  - transient or persistent

- High mass X-ray binaries are normally young systems, where NS has a high B-field ($10^{12-13}$ G)
  - wind-fed systems but with formation of transient accretion disk
  - transients or persistent

- Be-Xray binaries are very important, as they become very bright during outbursts and give high S/N




$$\frac{L_X^{outburst}}{L_X^{quiescence}} \sim 10^3$$

# Some famous sources

## Be-binaries

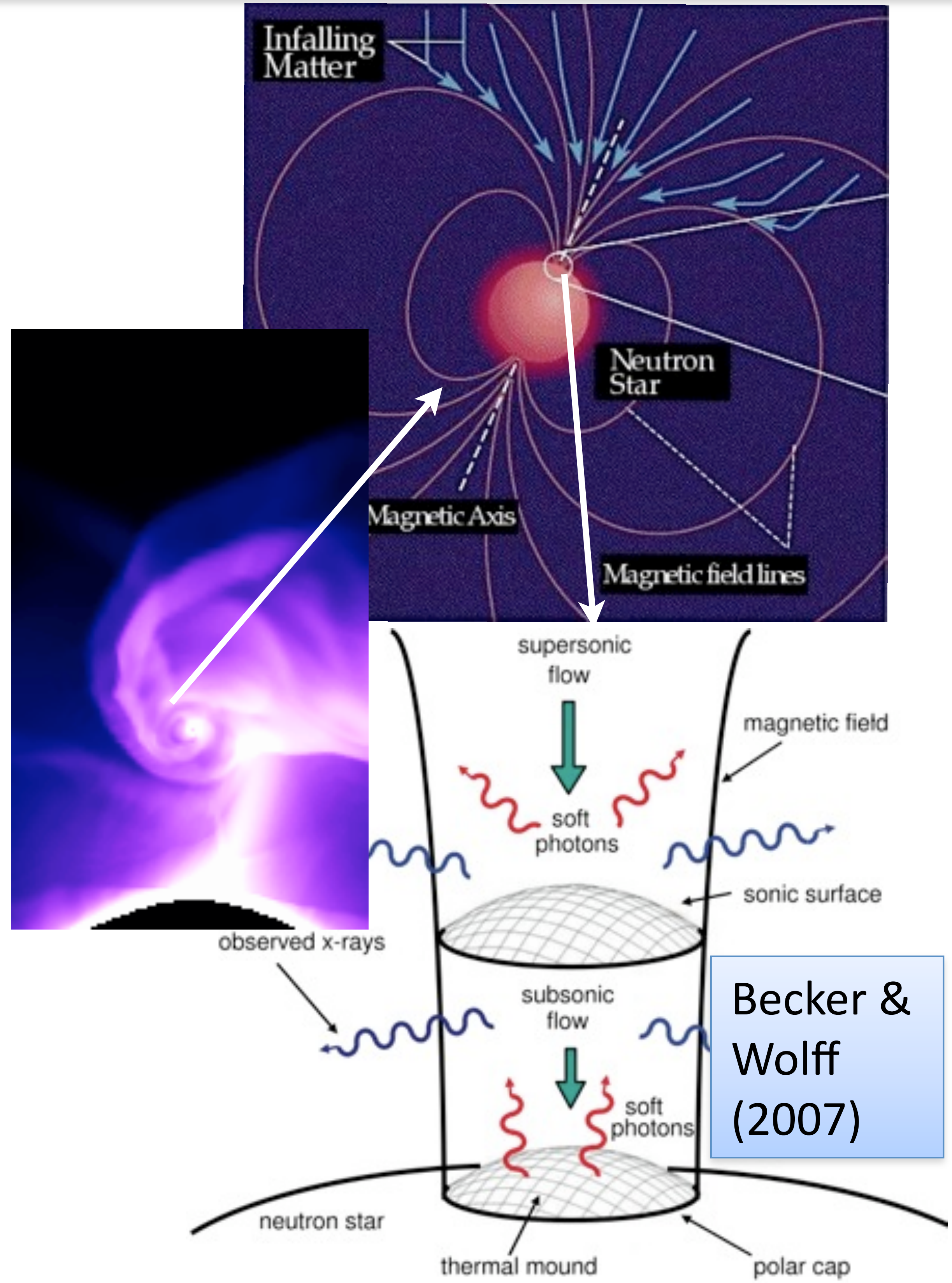
- 4U 0115+63:
  - B ~ $10^{12}$ G, the lowest
  - Fundamental cyclotron line plus 5 higher harmonics detected
  - $P_{spin}$=3.6 s. Spectrum is highly variable with spin phase.
- V 0332+53:
  - B ~ $2x10^{12}$ G, 3 harmonics
  - $P_{spin}$=4.4 s not very variable with spin phase
- A 0535+262:
  - B ~ $5x10^{12}$ G, 2 harmonics
  - $P_{spin}$= 103 s

## Roche lobe overflow

- Her X-1:
  - B ~ $4x10^{12}$ G
  - Fundamental cyclotron line plus 1 higher harmonic
  - $P_{spin}$=1 s. Spectrum is highly variable with spin phase and superorbital modulation

# Emission mechanisms in a high magnetic field

- Accreting matter acquires a high kinetic energy v~c/2 which is partially dissipated close to the compact object surface and emitted in the form of X and Gamma-rays.
- If the neutron star has a considerable magnetic field, the accreting matter is channeled at the magnetic poles along the field lines and accretes on the poles.
- For high accretion rates, radiation dominates: a radiative shock and accretion column form.
- Seed photons coming from thermal mound and electron breemstrahlung, in the high B-field, are Compton scattered.




Becker & Wolff (2007)

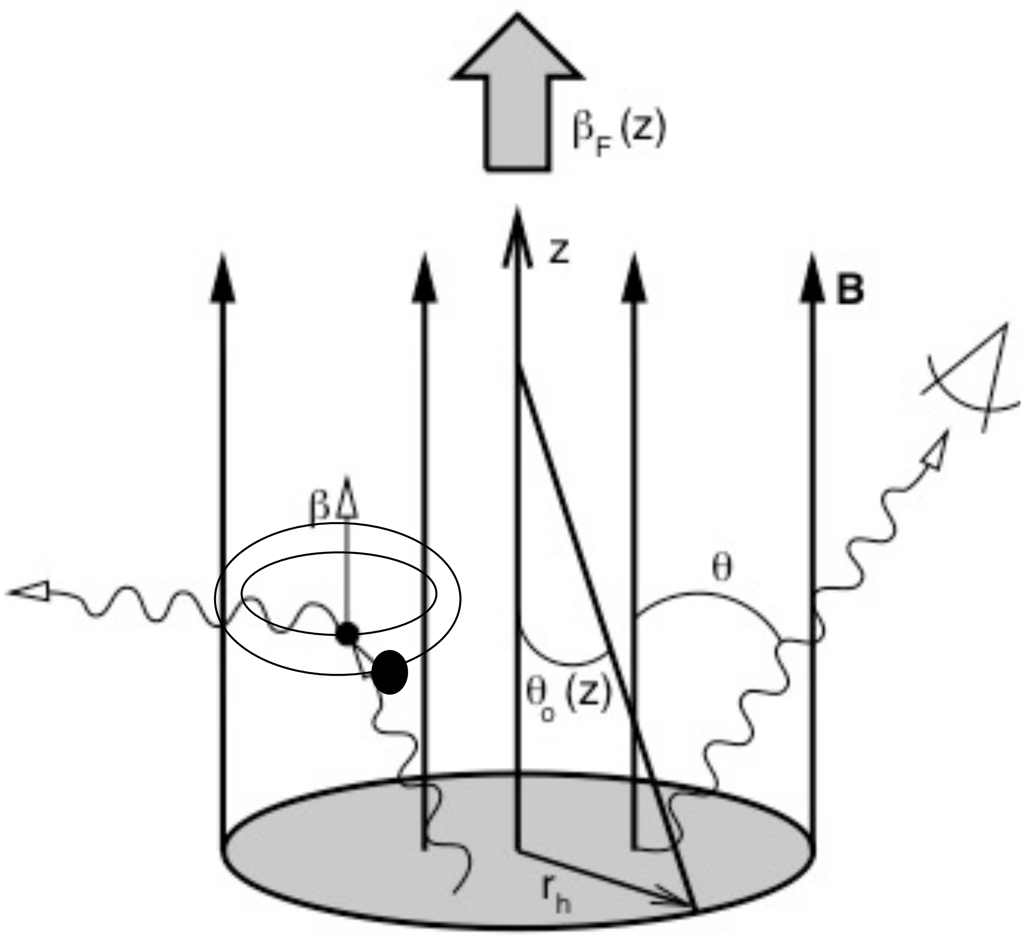
# Cyclotron scattering absorption features

- Electrons are exited to the first Landau level and then re-emit
- To be observed in the X-ray domain, a B-field of $10^{12\text{-}13}$ G is required.

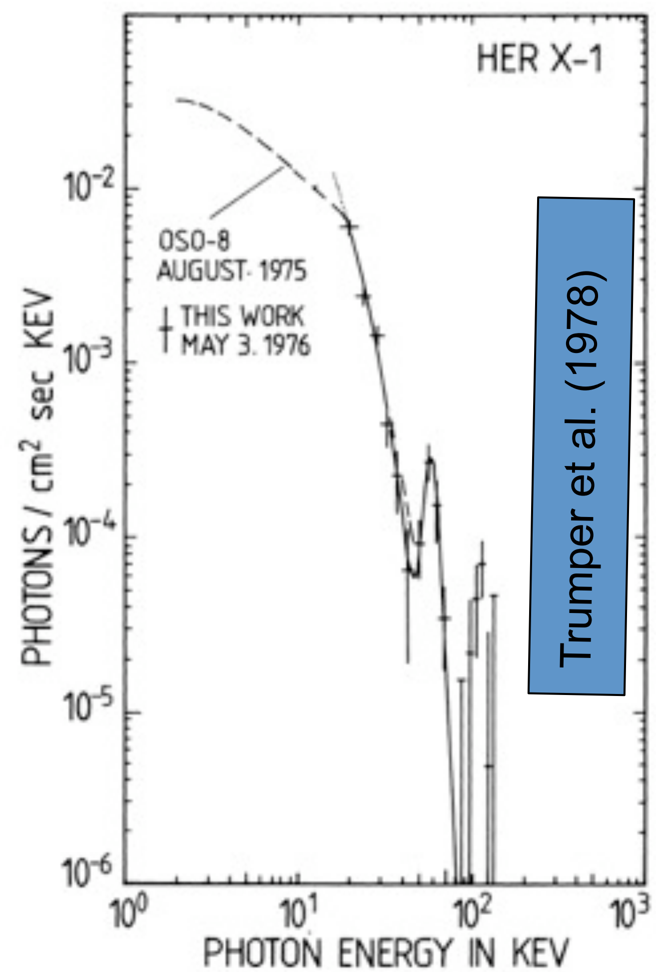
$$E_n = m_e c^2 \frac{\sqrt{1 + 2n(B/B_{\rm crit})\sin^2\theta} - 1}{\sin^2\theta}\frac{1}{1+z},$$

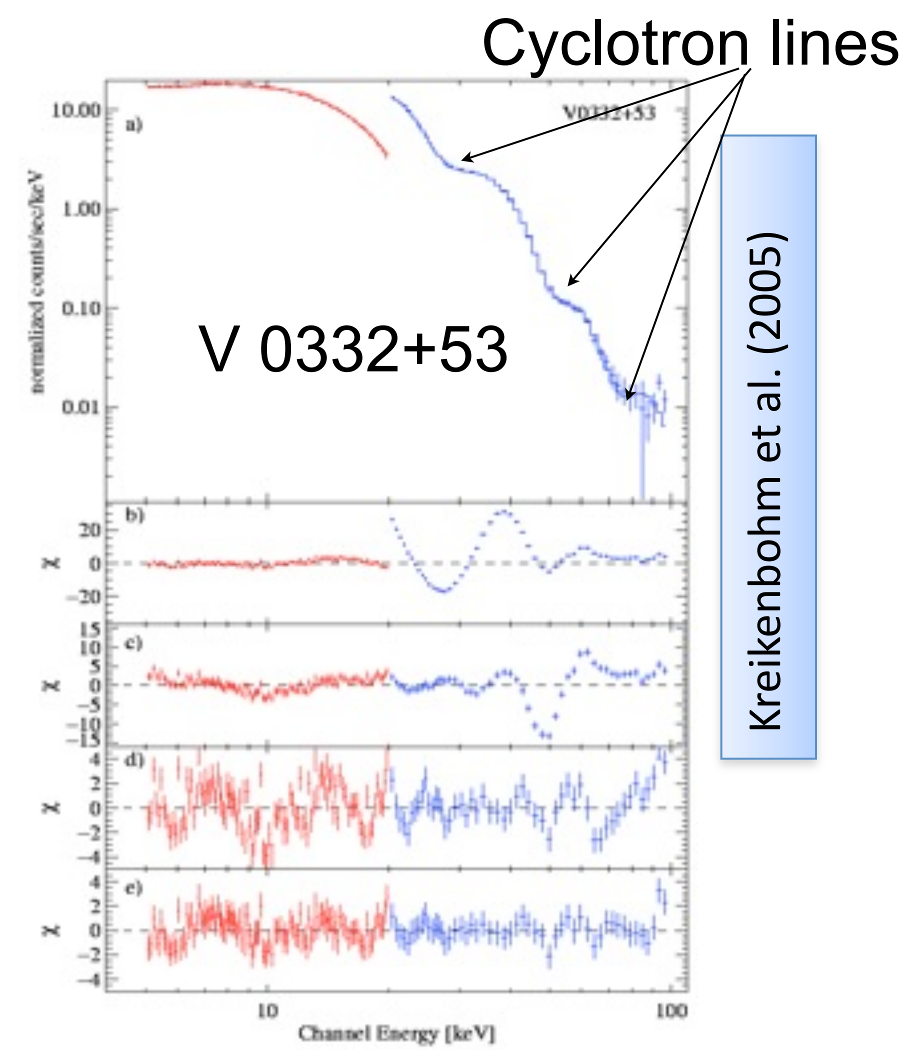
$4.4\times10^{13}$G

- Discovered on the spectrum of Her X-1 (Trumper 1977, 1978)



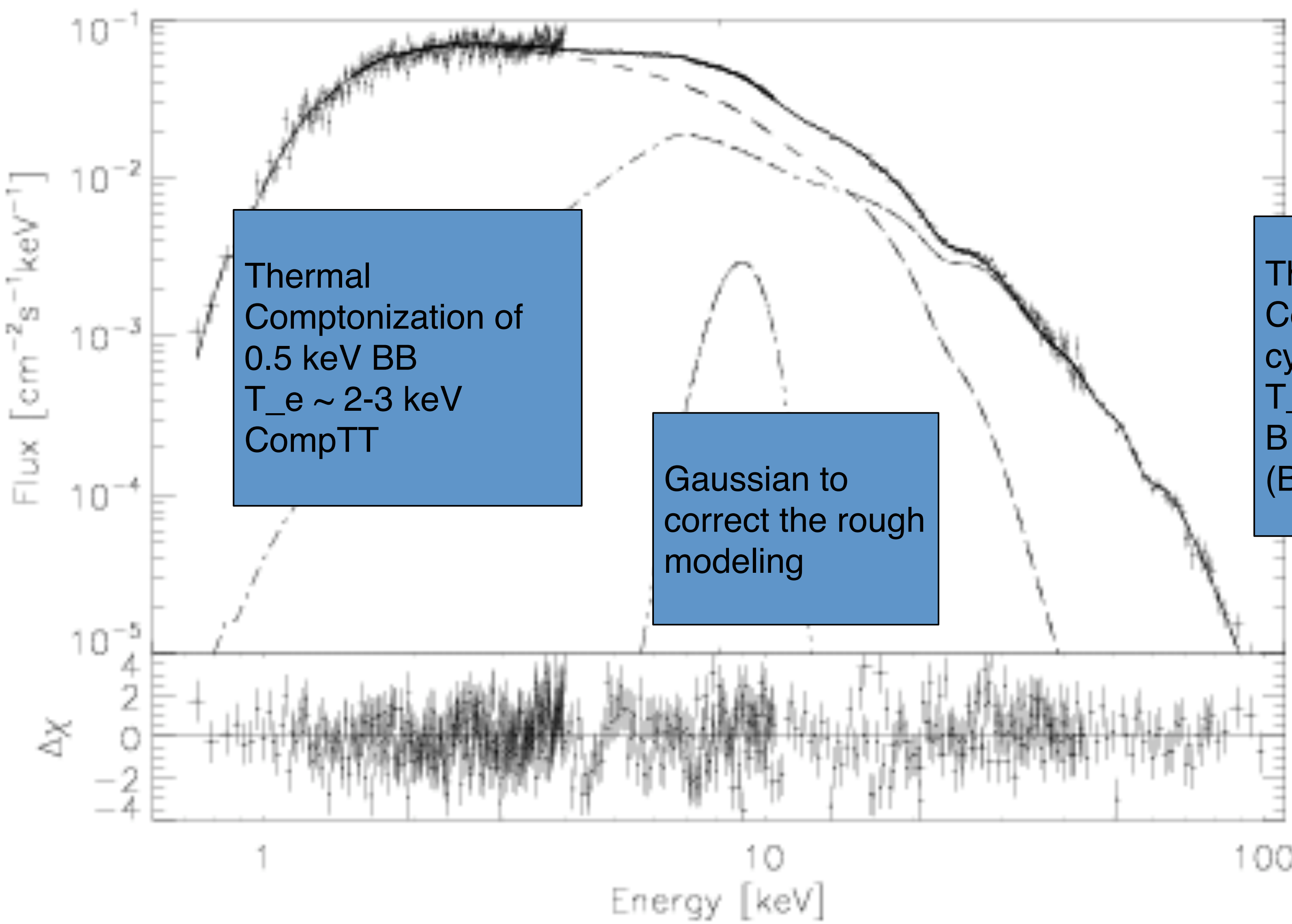

Isenberg et al. (1998)



# Continuum physical model

- One long BeppoSAX observation in 1999. We introduced the cyclotron emission model, and added a lower energy Comptonization component. Satisfactory description of the properties of 4U 0115+634.



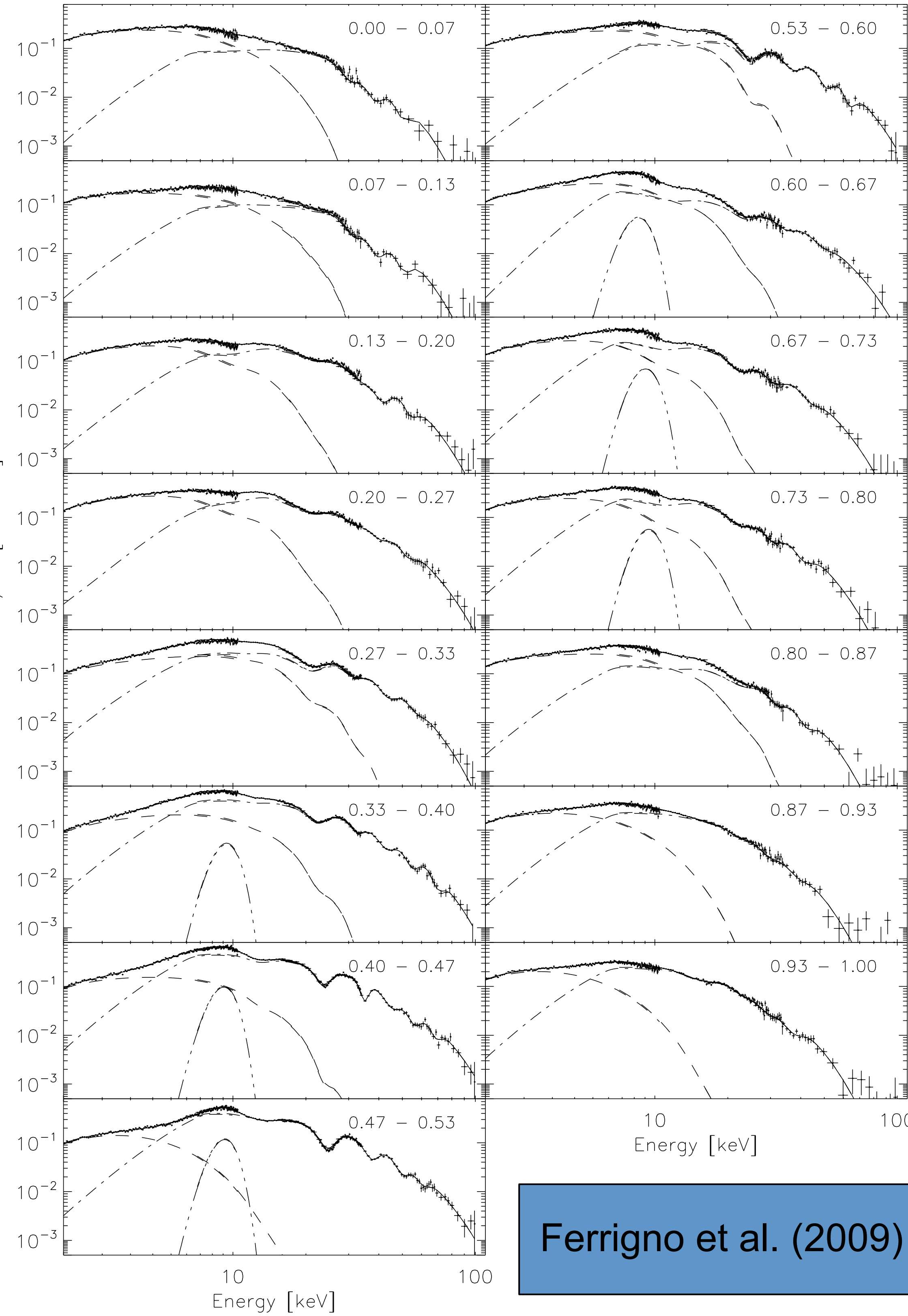

Thermal Comptonization of 0.5 keV BB
T_e ~ 2-3 keV
CompTT

Gaussian to correct the rough modeling

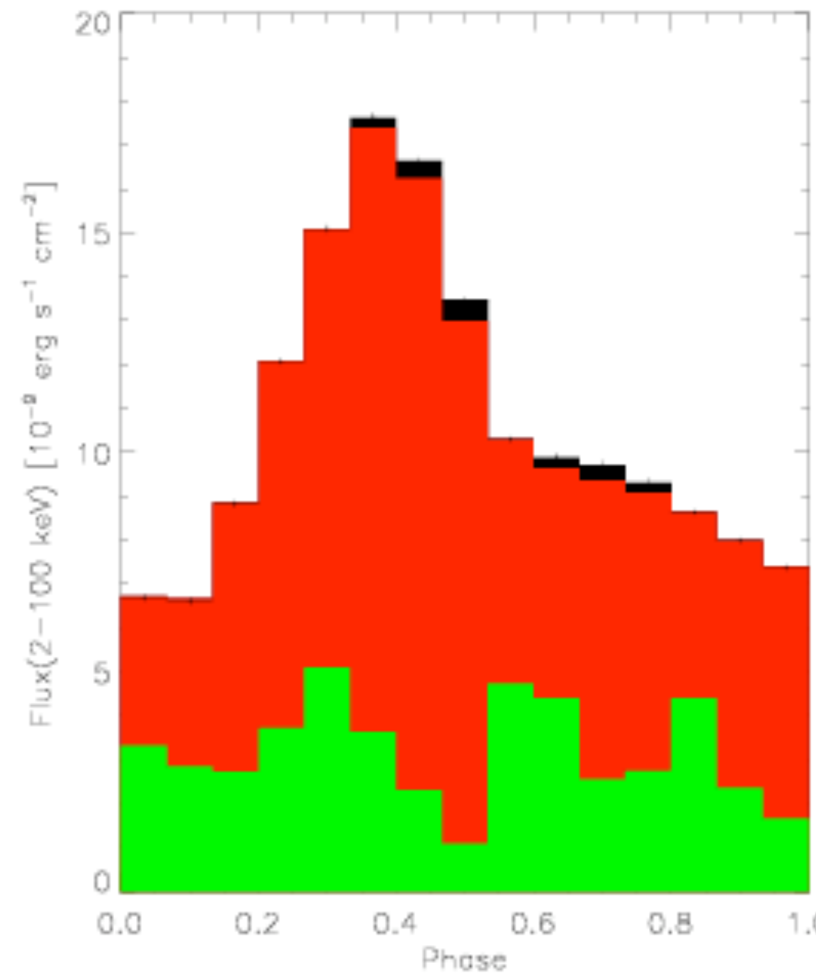
Thermal and bulk Comptonization of cyclotron emission.
T_e ~ 6-10 keV
B ~ 0.6-0.8 $10^{12}$ G
(Becker & Wolff, 2007)

Ferrigno et al. (2009)

# Soft scattering halo?

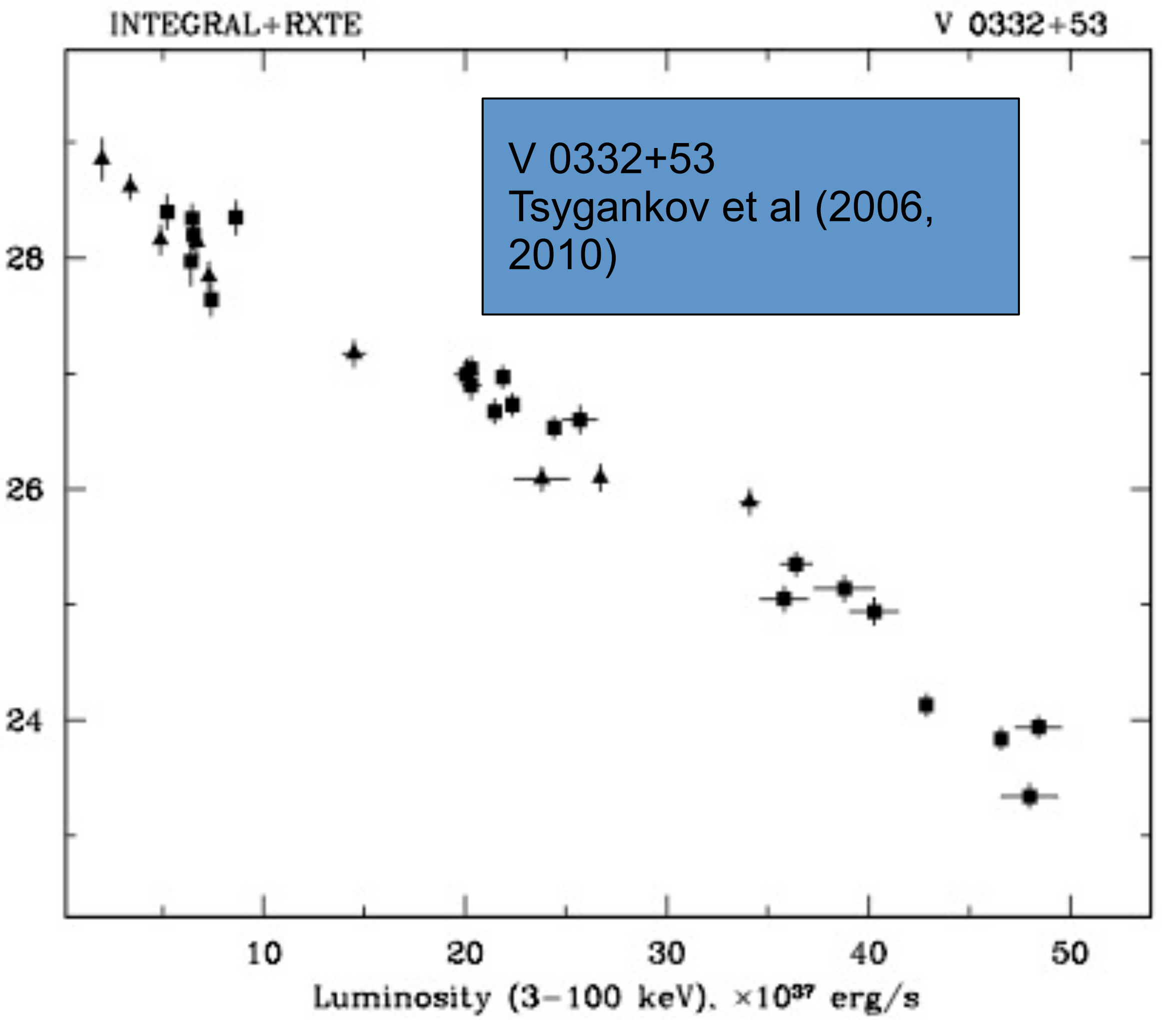


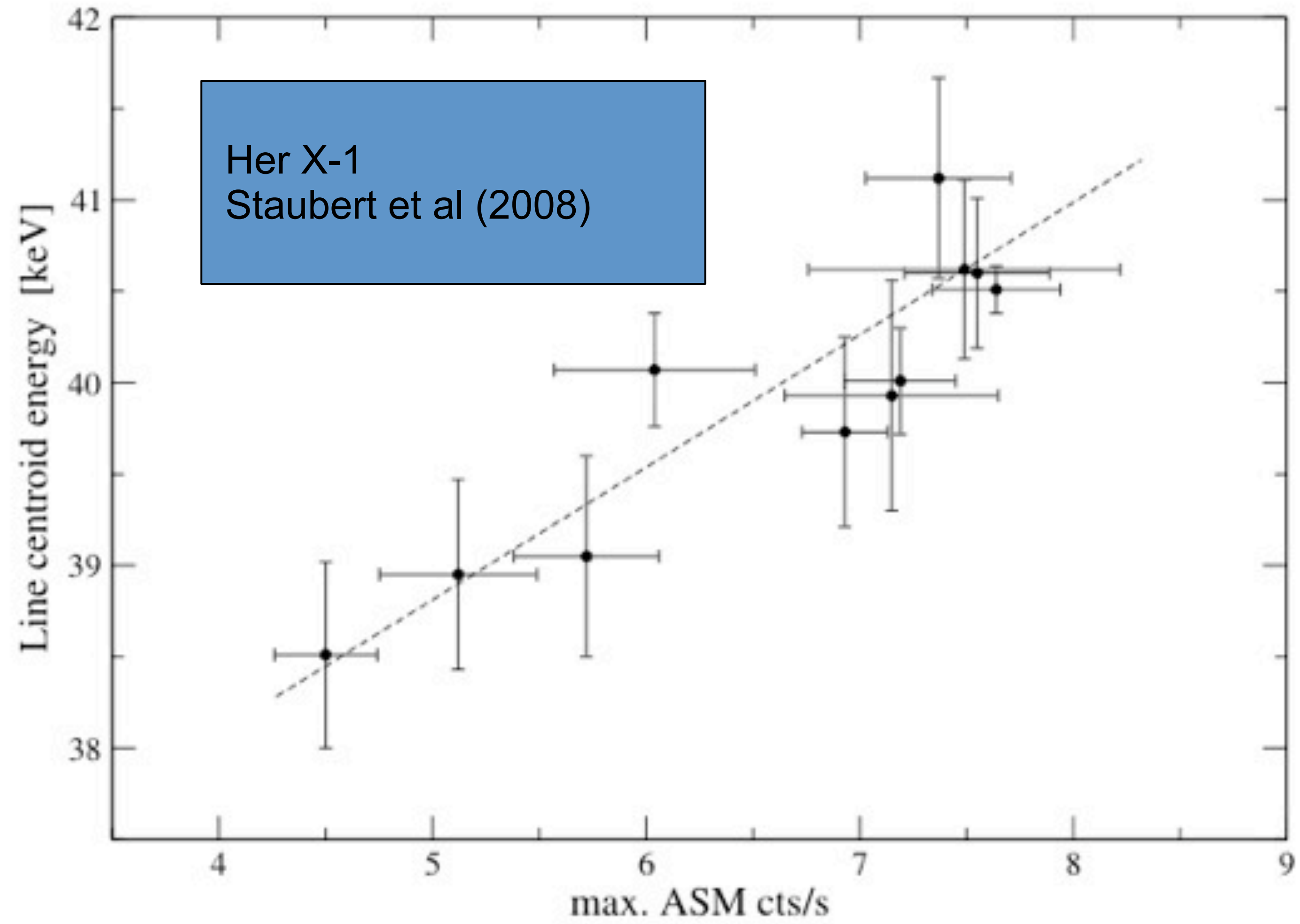

Ferrigno et al. (2009)




- Pronounced phase variations of continuum and lines.
- Hard component prominent in the peak, soft component spread in phase: a scattering halo?

# Luminosity dependent $E_{cyc}$



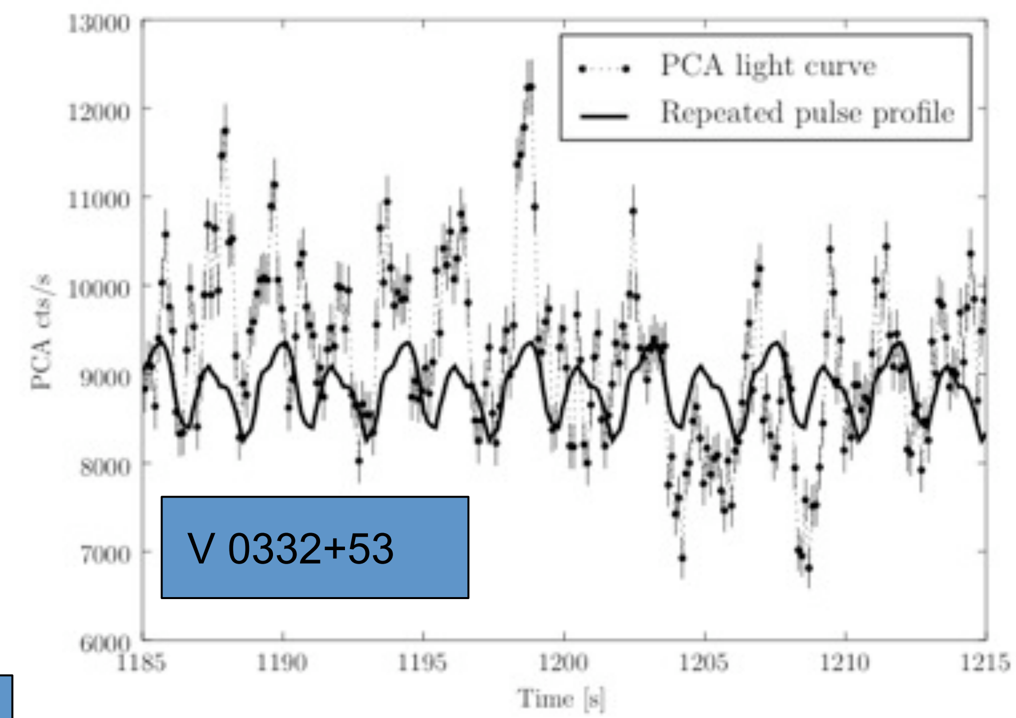




- RXTE/INTEGRAL data in 3-100 keV band
- Anti correlation with luminosity
- Radiation enlarges the column

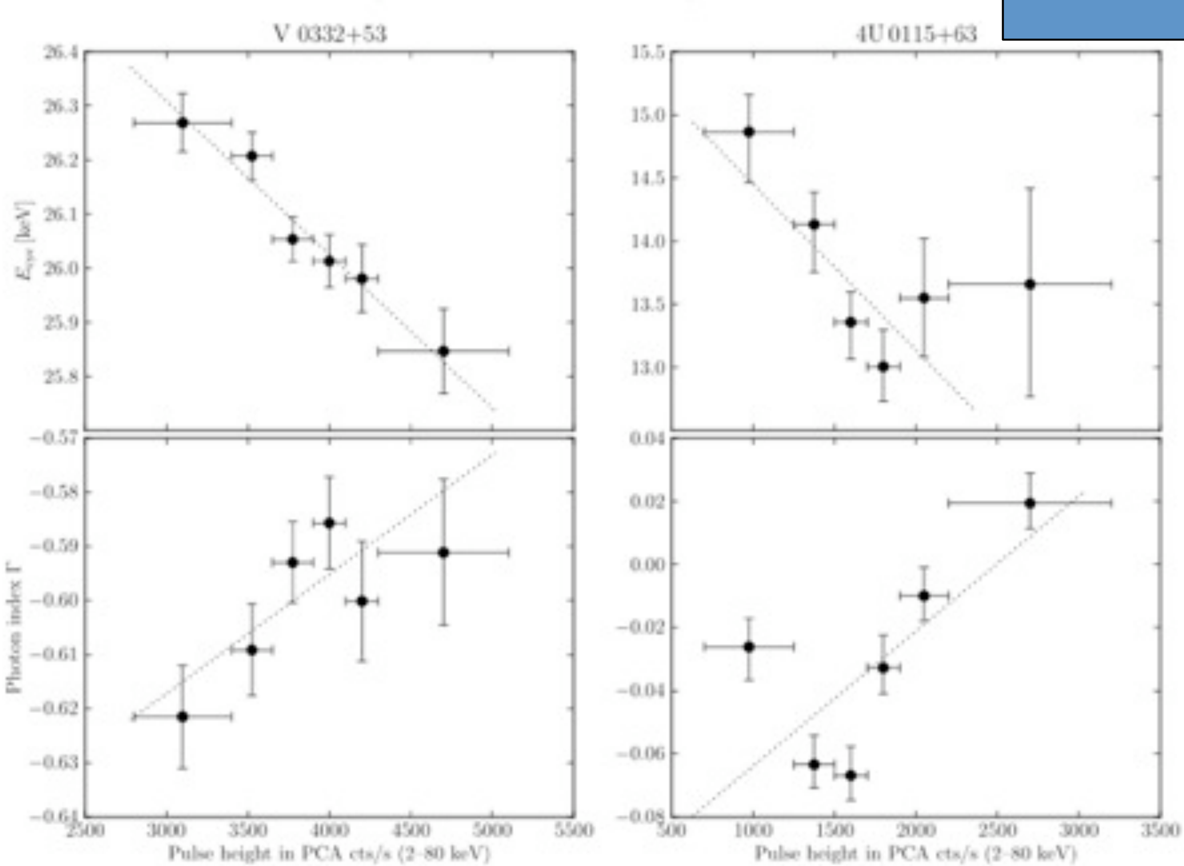
- RXTE data of main-on (obscuration from disc)
- Correlation with luminosity
- Accretion squeezes the column

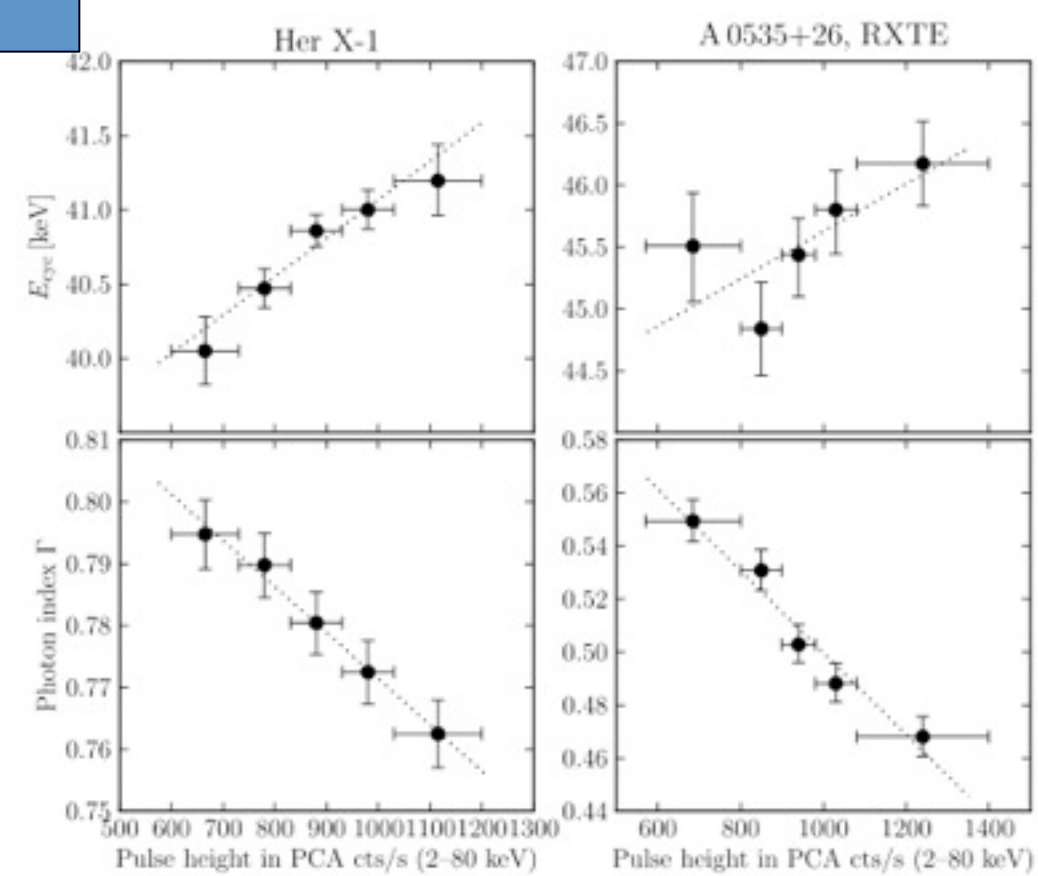
# Pulse to Pulse Variability

- During the bright phase (!) of an outburst
- Rate resolved spectroscopy reveals trend !
- Evidence of different accretion regimes in four bright sources

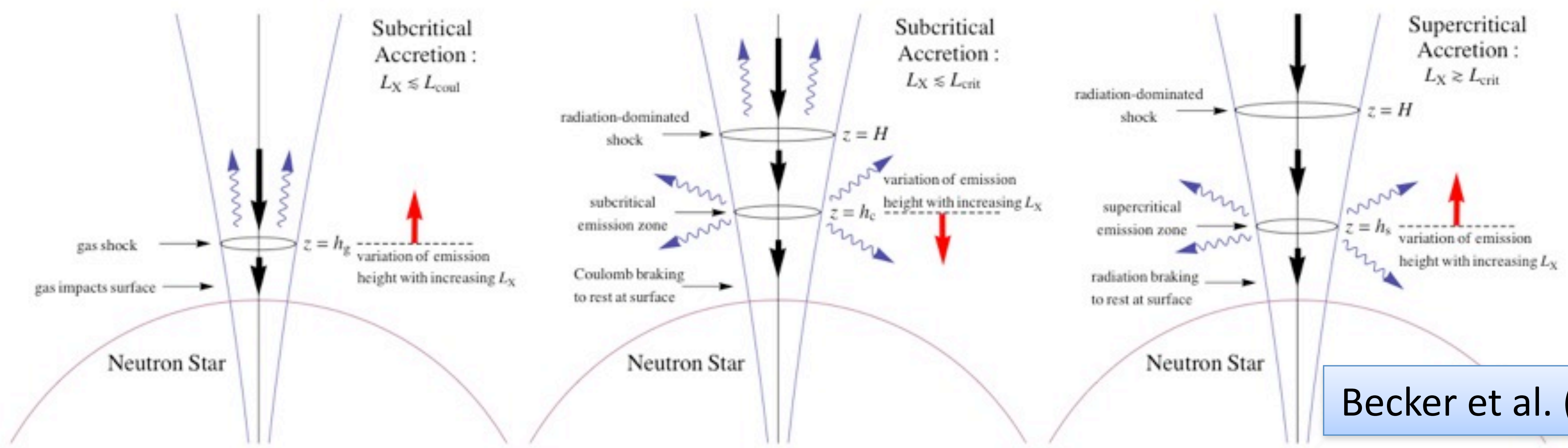



Klochkov et al (2011)



# Different accretion regimes




Becker et al. (2012)

- Column is a region magnetically confined
- Depending on its width and amount of accretion, radiation can play an important role.
- Eddington limit must be adapted for the geometrical and cross section effects

Radius of the column

$$L_{\rm Edd} = \frac{4\pi G M_* m_{\rm p} c}{\sigma_{\rm T}}, \longrightarrow L^*_{\rm Edd} = L_{\rm Edd}\frac{\sigma_{\rm T}}{\sigma_{||}}\frac{\pi r_0^2}{4\pi R_*^2} = \frac{G M_* m_{\rm p} c}{\sigma_{||}}\frac{\pi r_0^2}{R_*^2},$$

Cross section parallel to B-field

# A critical luminosity

$$L_{\rm crit} = \frac{GM_* m_{\rm p} c}{\sigma_{||}} \frac{\pi r_0^2}{R_*^2} \left( \frac{R_*}{49H} + 1 \right) . \qquad (9)$$

Height of the radiative shock

Our goal is to express the parameters $r_0$, $\sigma_{||}$, and $H$ appearing on the right-hand side of Eq. (9) in terms of observable quantities.

- Equation is derived following Basko & Sunyaev (1977) by:
  - assuming a strong radiative shock ($L > L_{Edd}$)
  - free-fall velocity ($v_{ff}$) upstream and $v_{ps}$= 1/7 $v_{ff}$ downstream
  - constant deceleration below the shock $$a = \frac{v_{\rm ps}^2}{2H} = \frac{GM_*}{49R_* H} .$$
  - radiation braking $$a = \left( \frac{L_{\rm X}}{L_{\rm Edd}^*} - 1 \right) \frac{GM_*}{R_*^2} .$$

Becker et al. (2012)

# Comparison to data

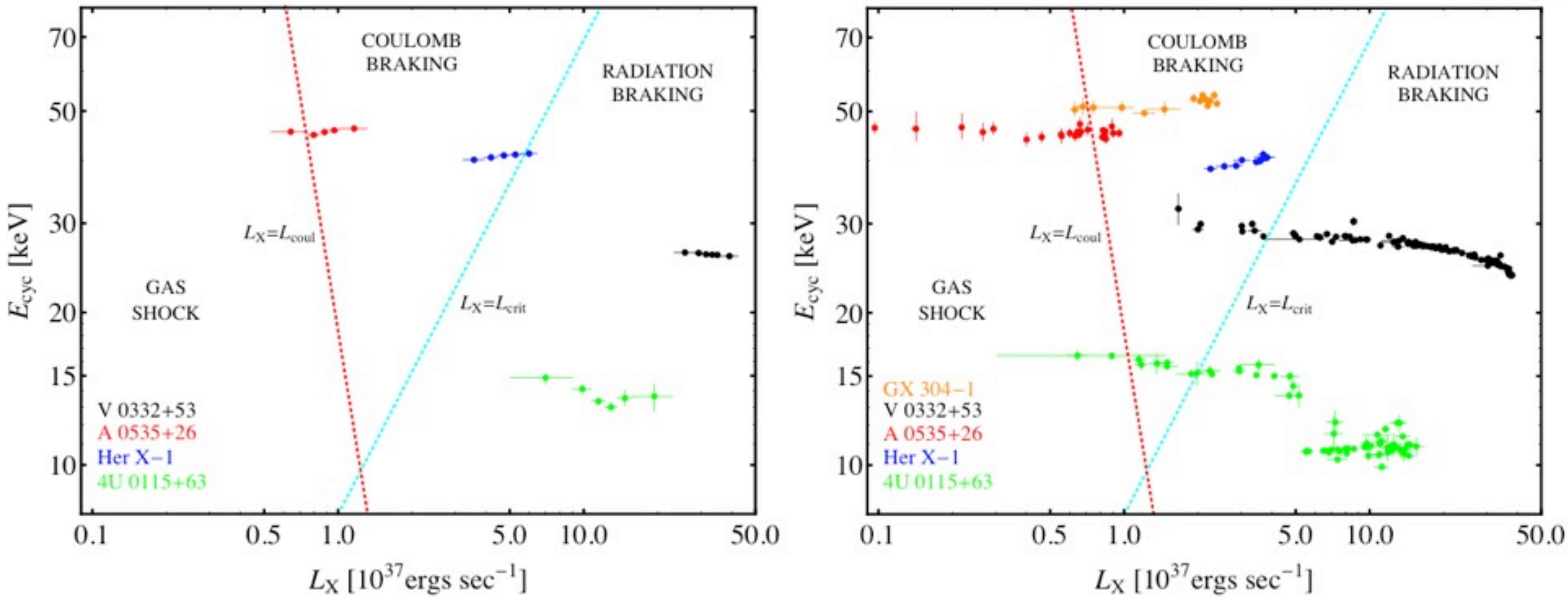


- Use the surface magnetic field and assume a dipole structure, a variation of the emission height translates into a variation of the observed cyclotron scattering centroid energy

$$E_* = 11.58\ \mathrm{keV}\left(\frac{B_*}{10^{12}\mathrm{G}}\right) \qquad \frac{E_{\mathrm{cyc}}}{E_*} = \left(\frac{R_* + h}{R_*}\right)^{-3}$$

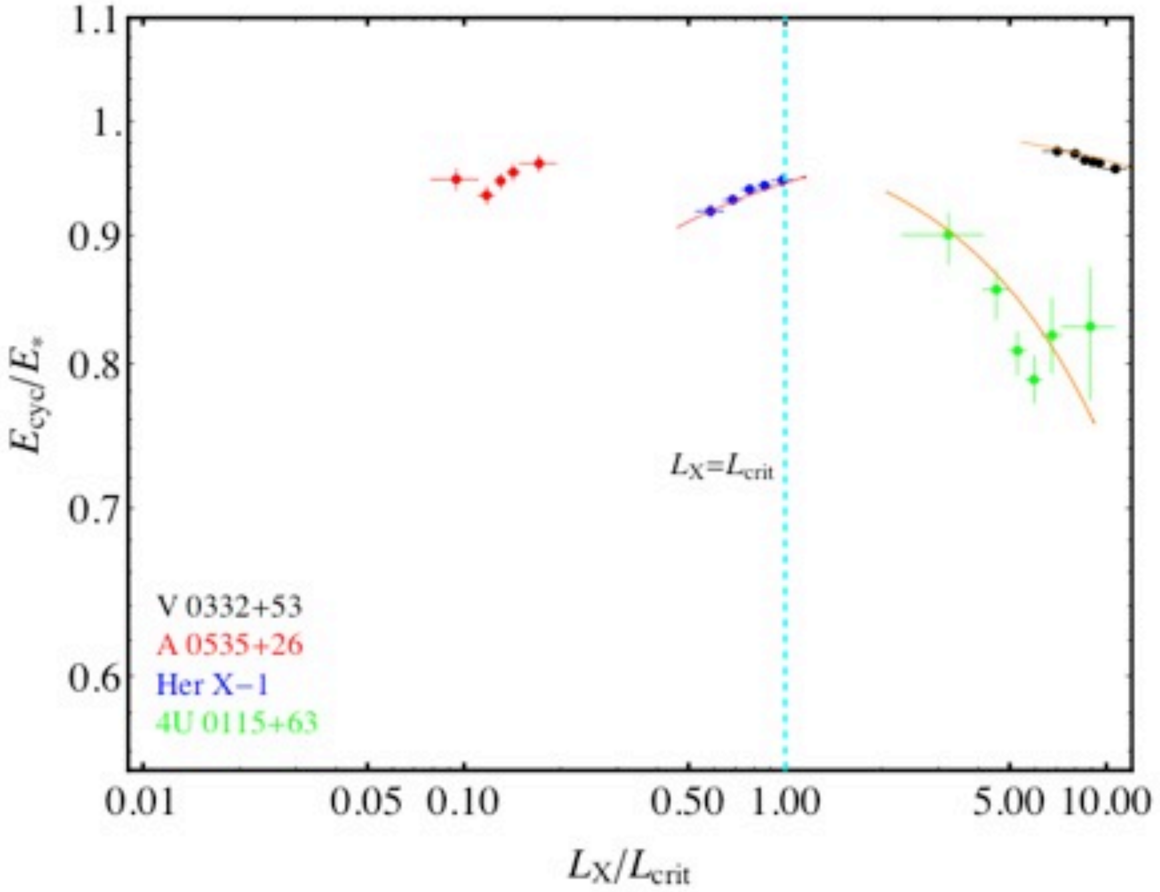
- where h is $h_s$ or $h_c$ in the two regimes

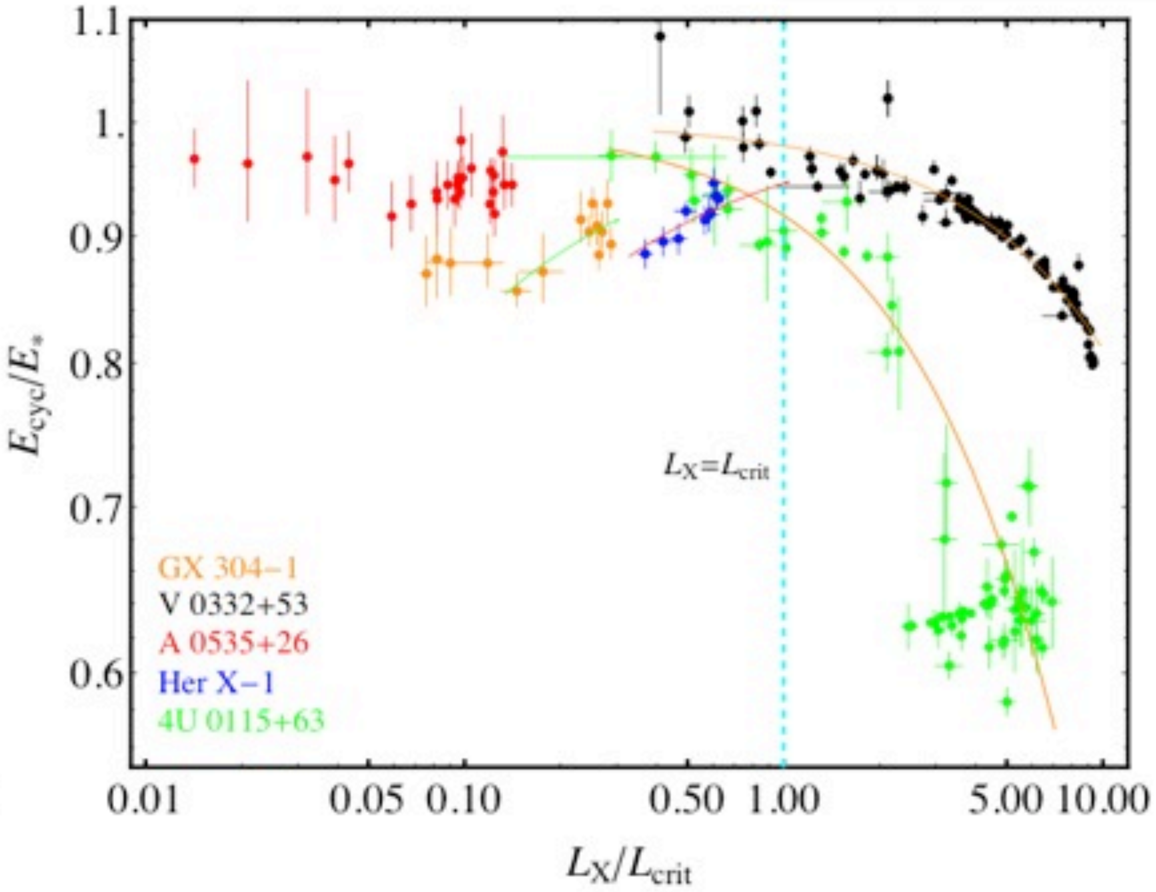
Becker et al. (2012)



# Comparison to data

Becker et al. (2012)

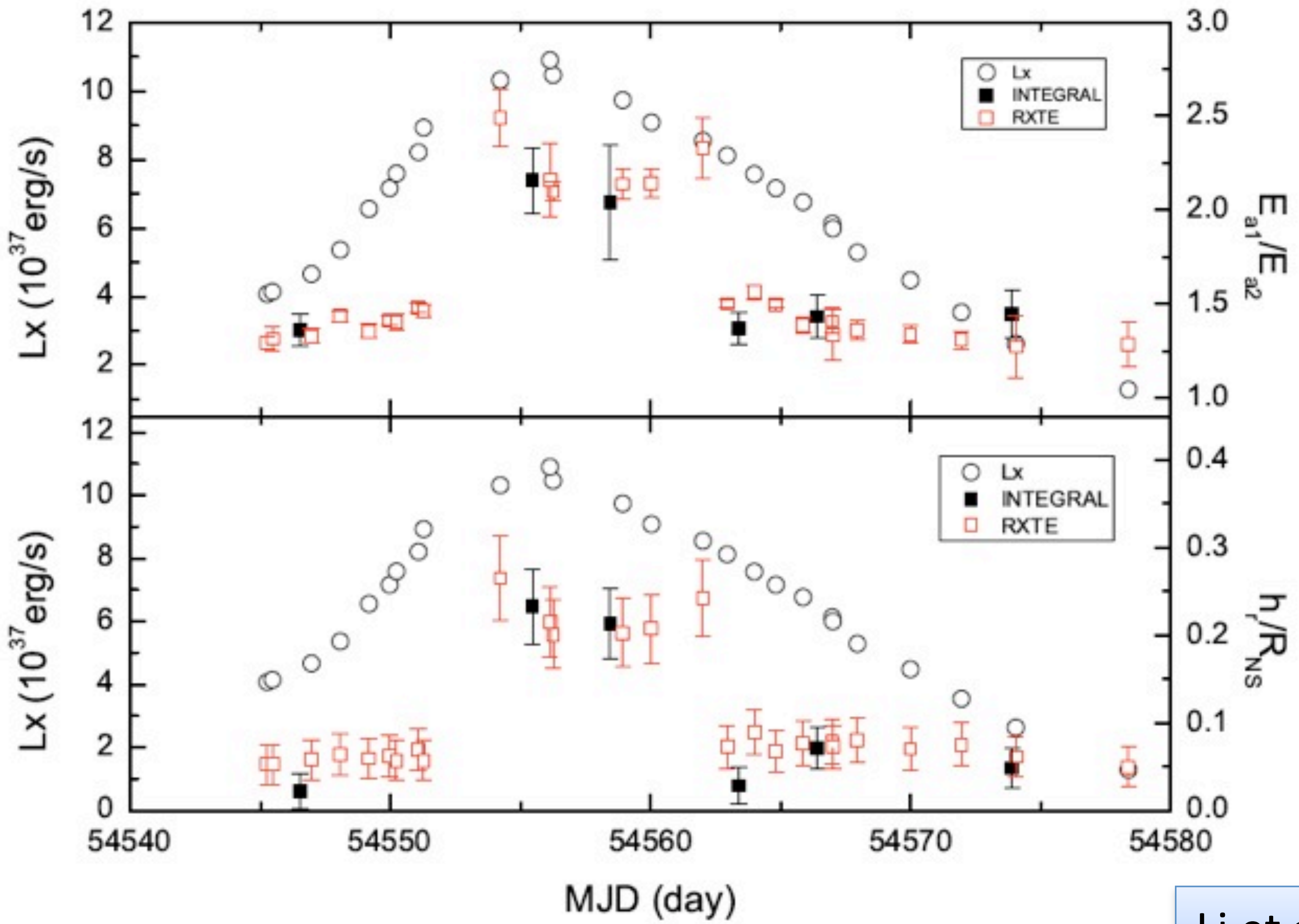



| Source | Long-term $\xi$ | Long-term $E_*$ [keV] | Long-term $L_{crit}$ [$10^{37}$ erg sec$^{-1}$] | Pulse-pulse $\xi$ | Pulse-pulse $E_*$ [keV] | Pulse-pulse $L_{crit}$ [$10^{37}$ erg sec$^{-1}$] |
|---|---|---|---|---|---|---|
| 4U 0115+63 | $5.72 \times 10^{-2}$ | 17.0 | 2.24 | $2.14 \times 10^{-2}$ | 16.5 | 2.17 |
| V 0332+53 | $7.86 \times 10^{-3}$ | 29.7 | 4.06 | $1.43 \times 10^{-3}$ | 27.0 | 3.67 |
| Her X-1 | - | 43.5 | 6.11 | - | 43.5 | 6.11 |
| A 0535+26 | - | 48.0 | 6.78 | - | 48.0 | 6.78 |
| GX 304-1 | - | 58.0 | 8.30 | - | - | - |

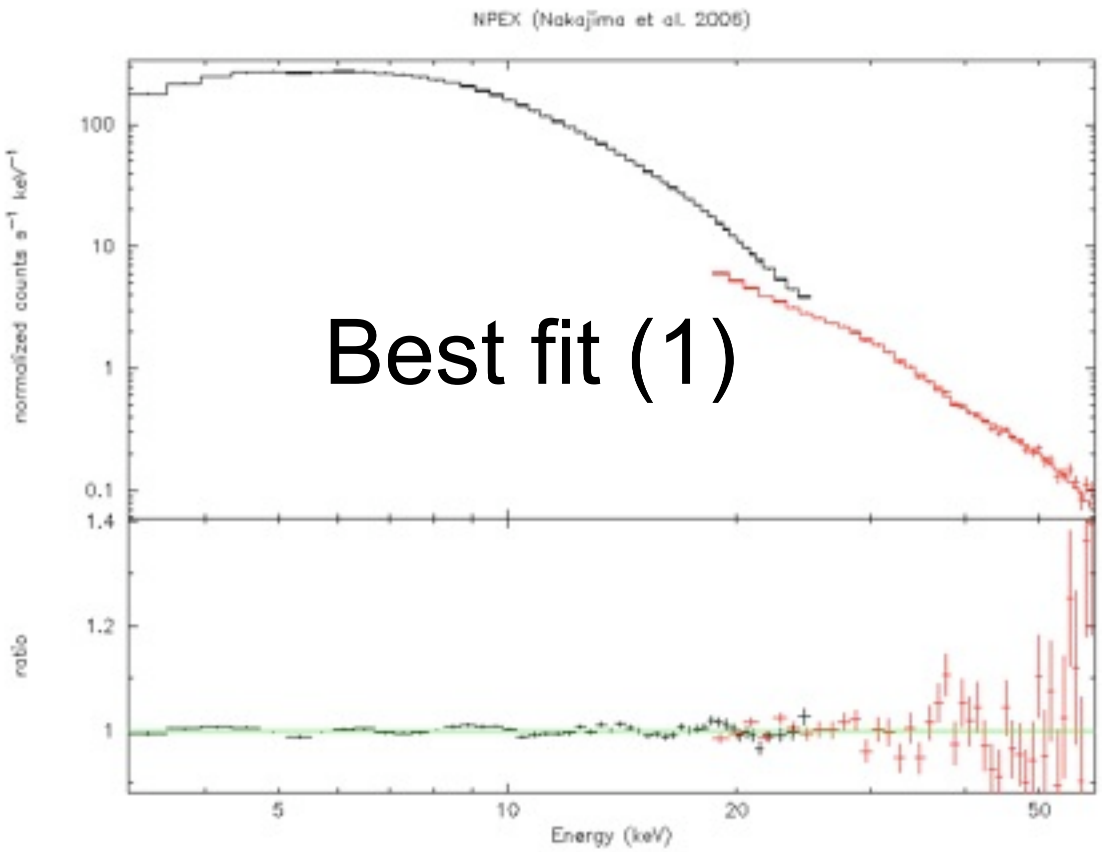
# 4U 0115+63, is the line variation real?

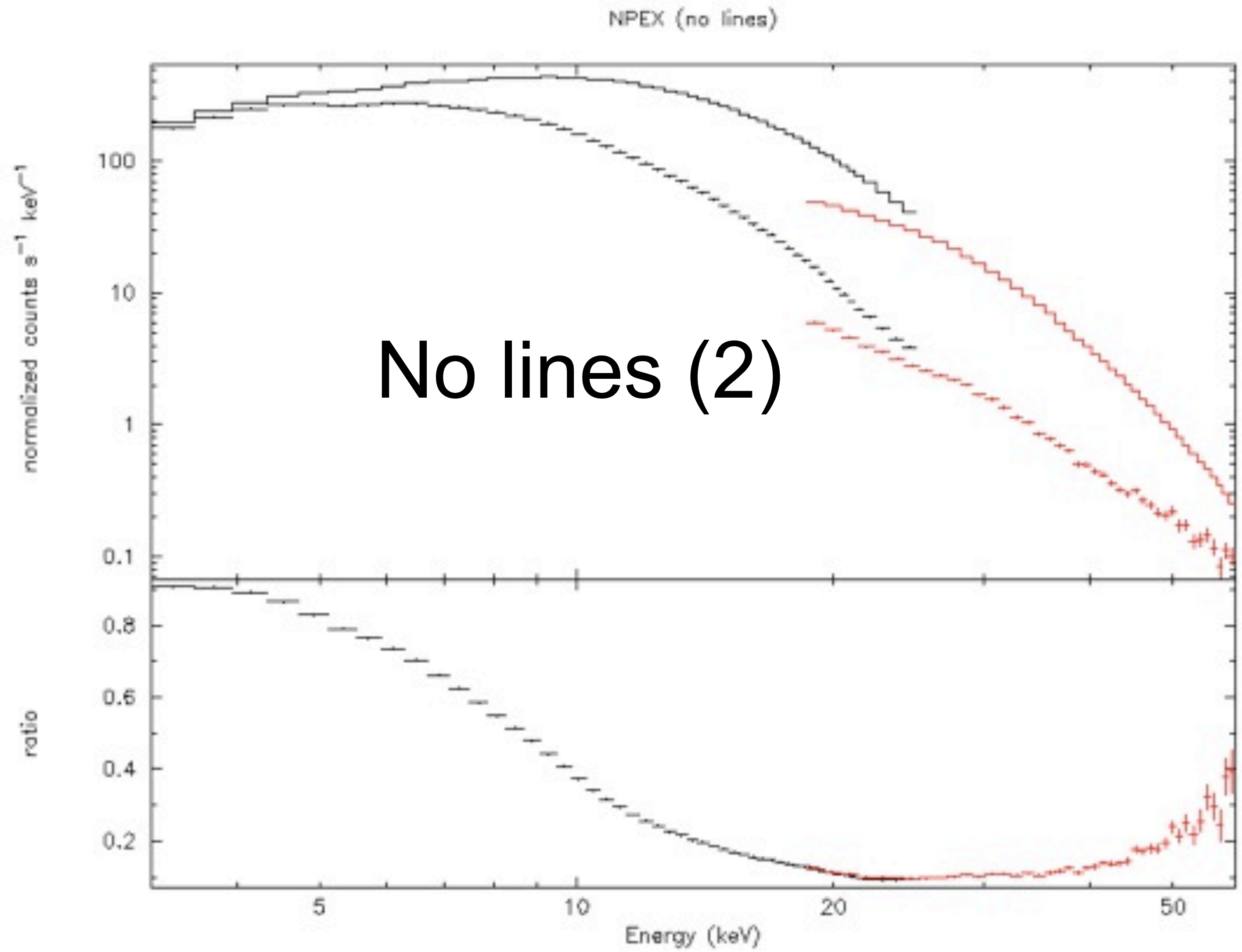
- Only the fundamental shows a variation, the higher harmonics are stable !! -> fit is wrong  (2008 outburst using NPEX continuum model)




Li et al. (2012)

# NPEX

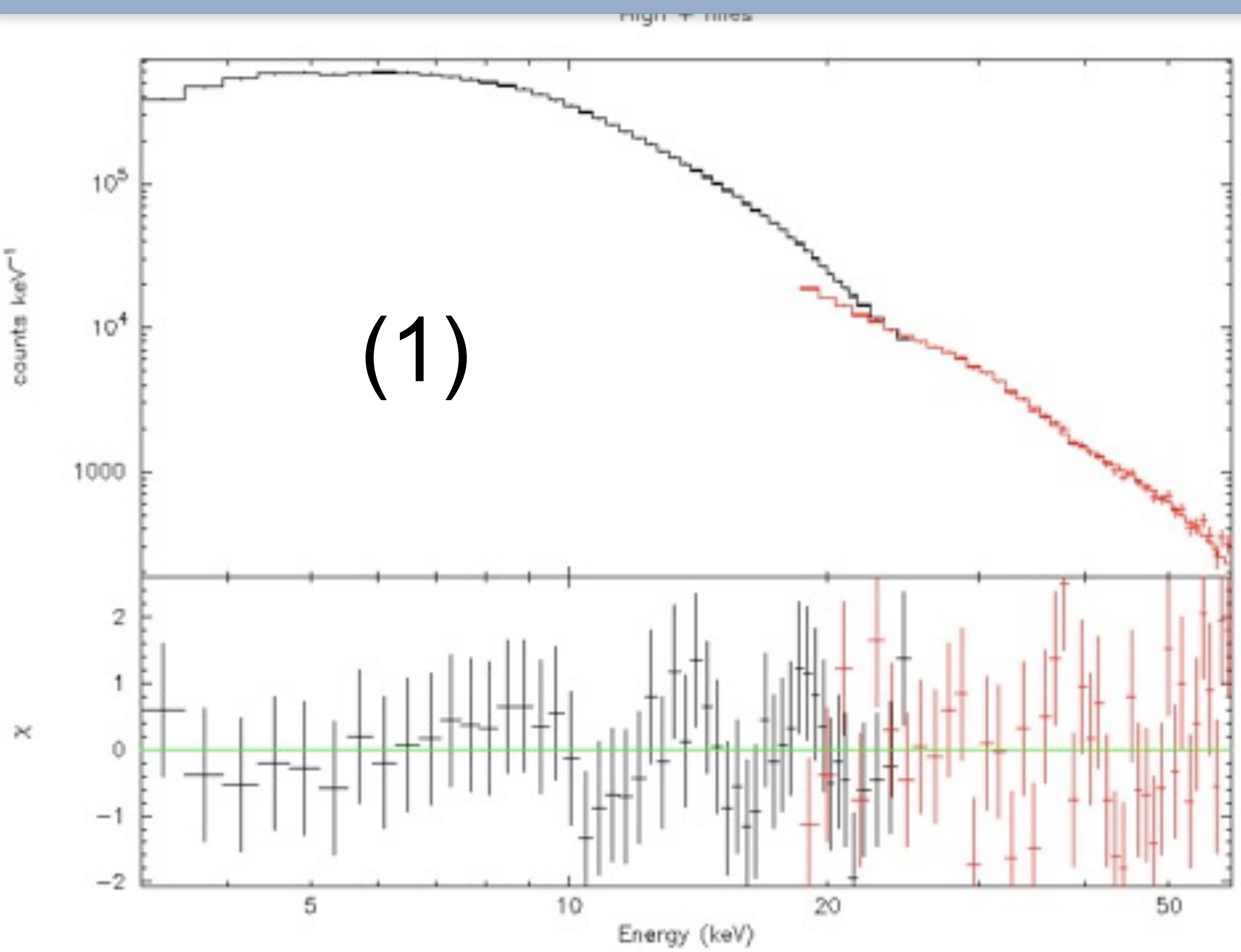


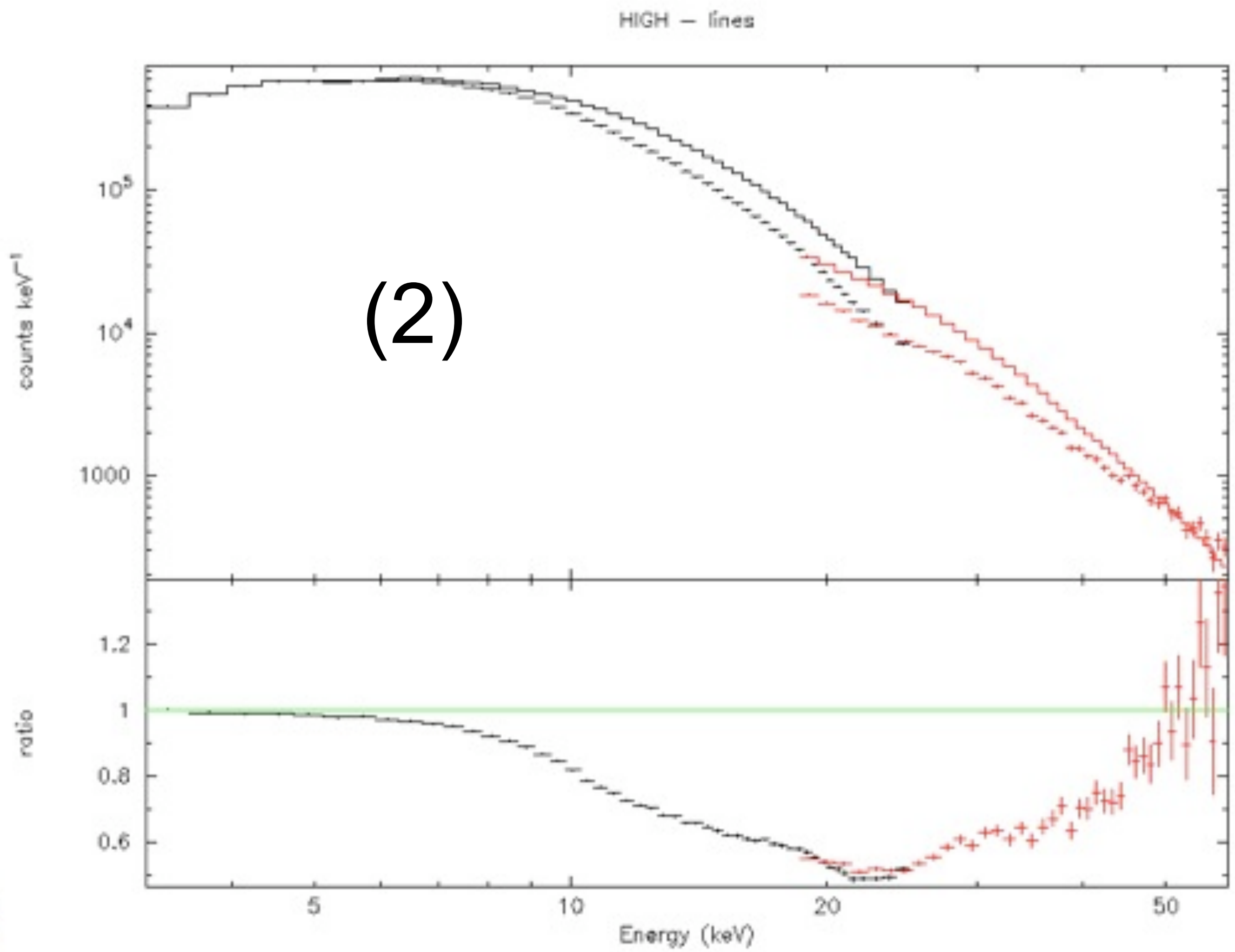




- I call it Wrong !!!!!
- Large sigma in Gaussian or width in Lorentzian lines.

$$\mathrm{NPEX}(E) = (A_1 E^{-\alpha_1} + A_2 E^{+\alpha_2}) \exp\left(-\frac{E}{kT}\right),$$

# High energy cut-off PL

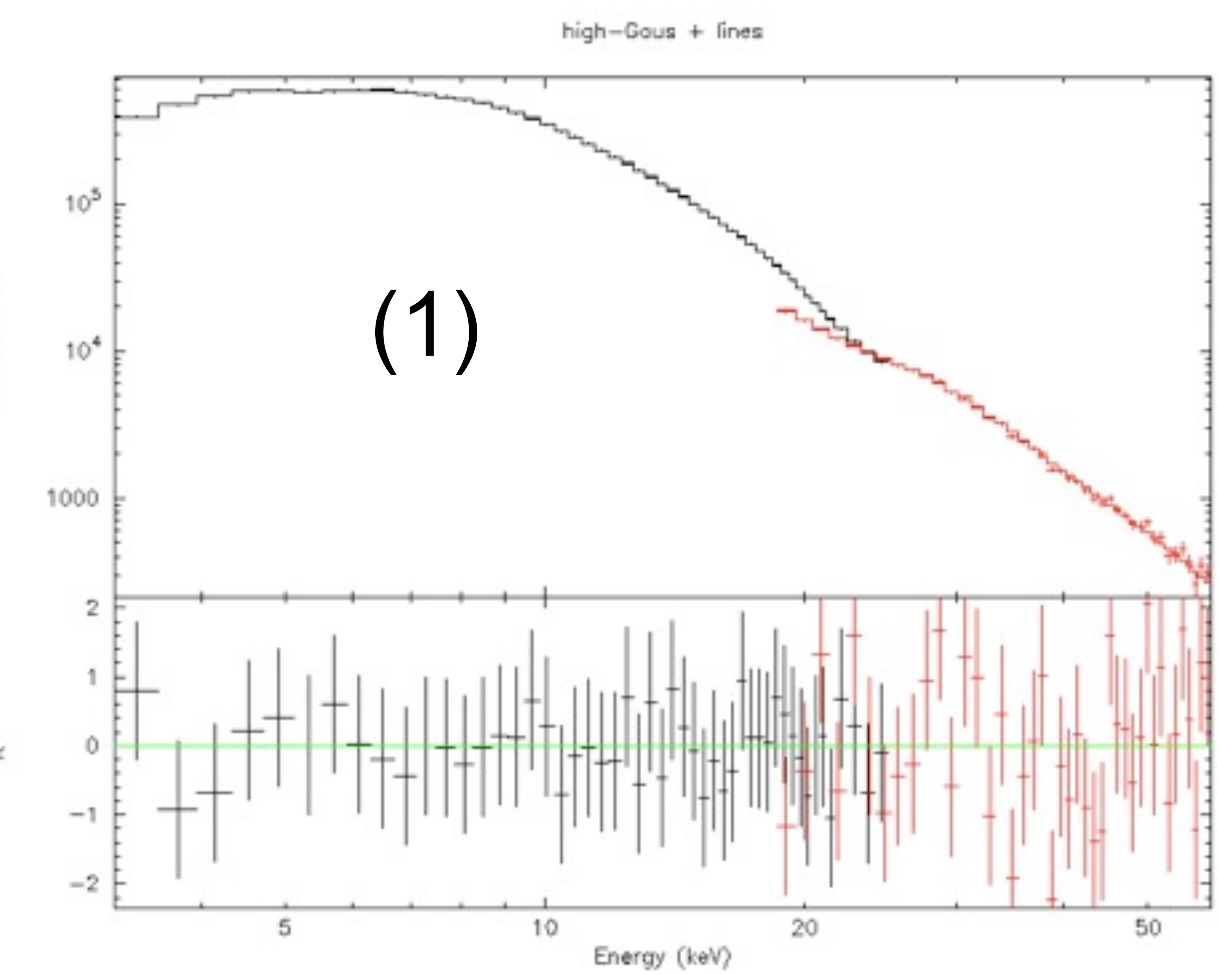


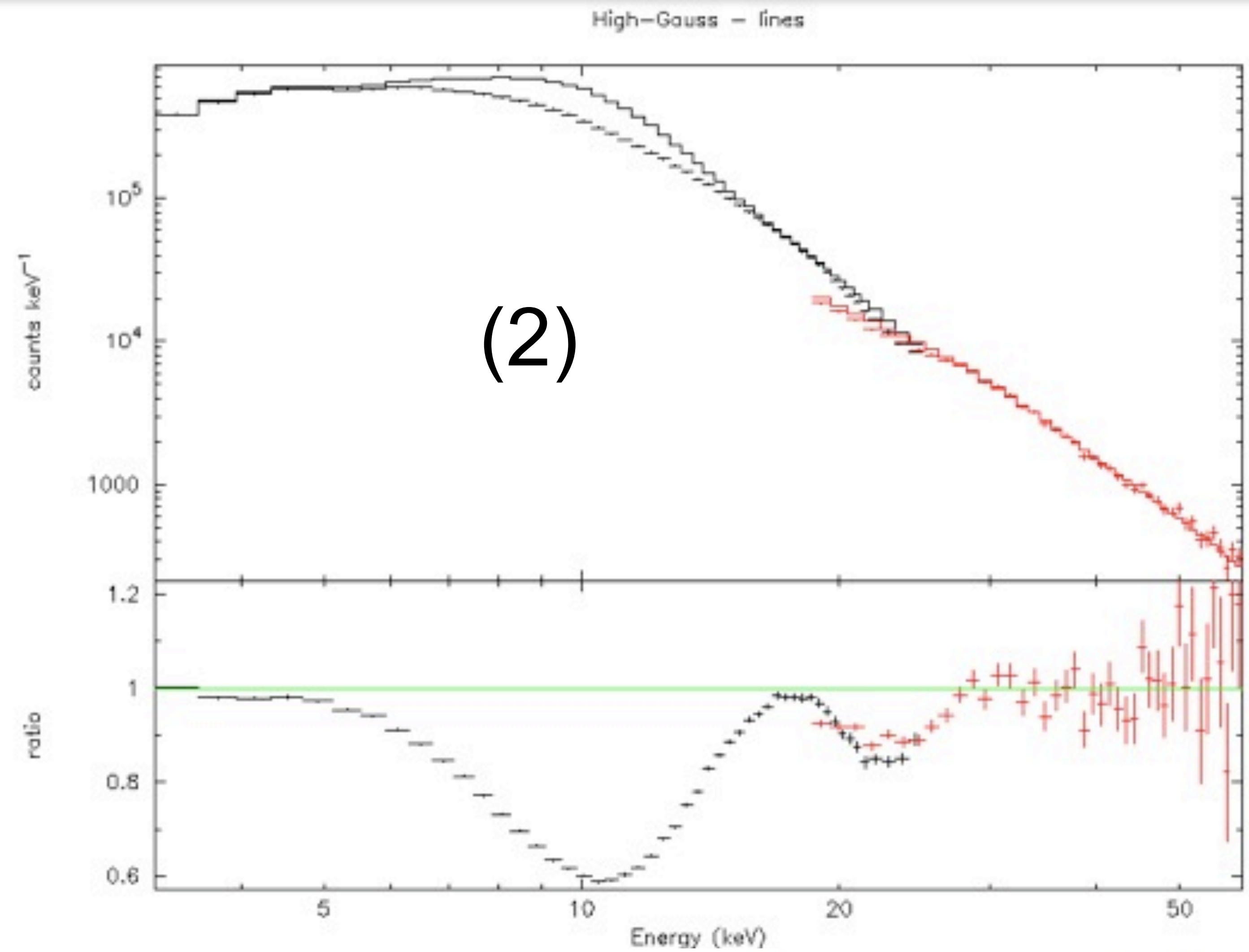



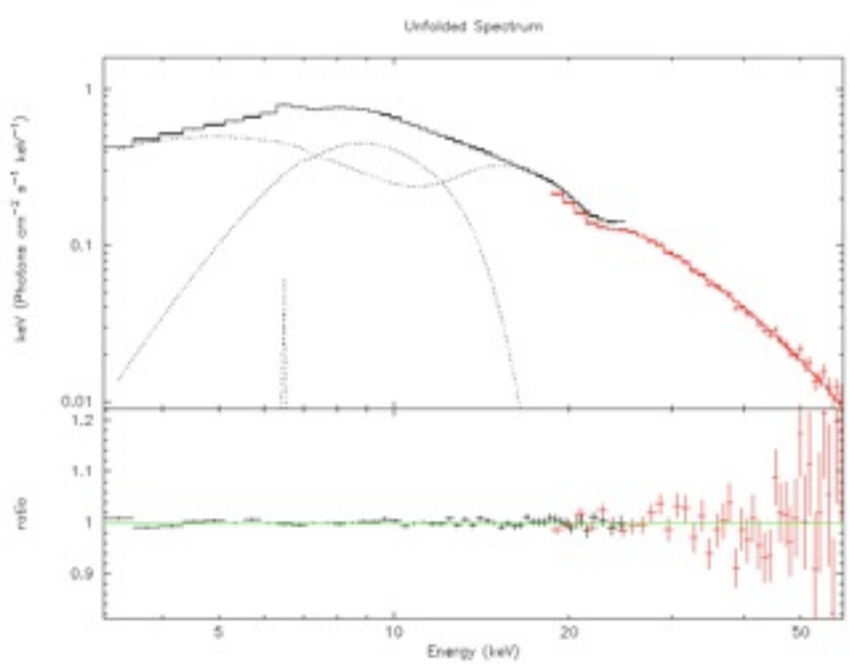

$$I_{\rm cont} = K \cdot \begin{cases} E^{-\Gamma}, & \text{if } E \le E_{\rm cutoff} - \Delta E \\ E^{-\Gamma} \cdot \exp\left(-\frac{E-E_{\rm cutoff}}{E_{\rm fold}}\right), & \text{if } E > E_{\rm cutoff} + \Delta E \\ AE^3 + BE^2 + CE + D, & \text{if } E_{\rm cutoff} - \Delta E < E < \\ & < E_{\rm cutoff} + \Delta E, \end{cases}$$

- Still artificial suppression of continuum

# High-E cut-off PL+ 9 keV Gaussian



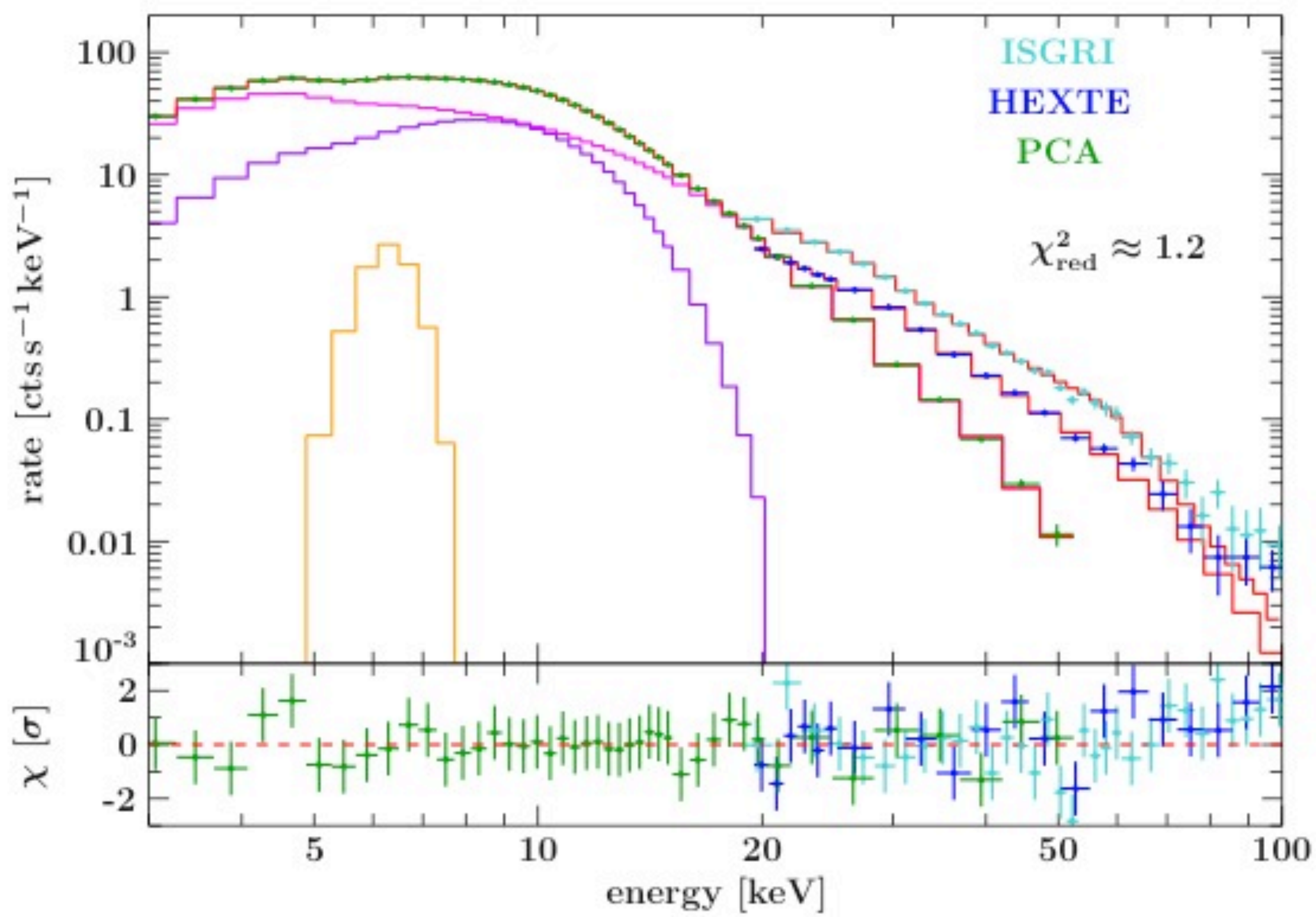




$$I_{\mathrm{Model\,I}} = I_{\mathrm{cont}} + K_{\mathrm{bump}} \exp\left\{-\frac{(E - E_{\mathrm{bump}})^2}{2\sigma_{\mathrm{bump}}^2}\right\},$$

- More correct

# Continuum variations !

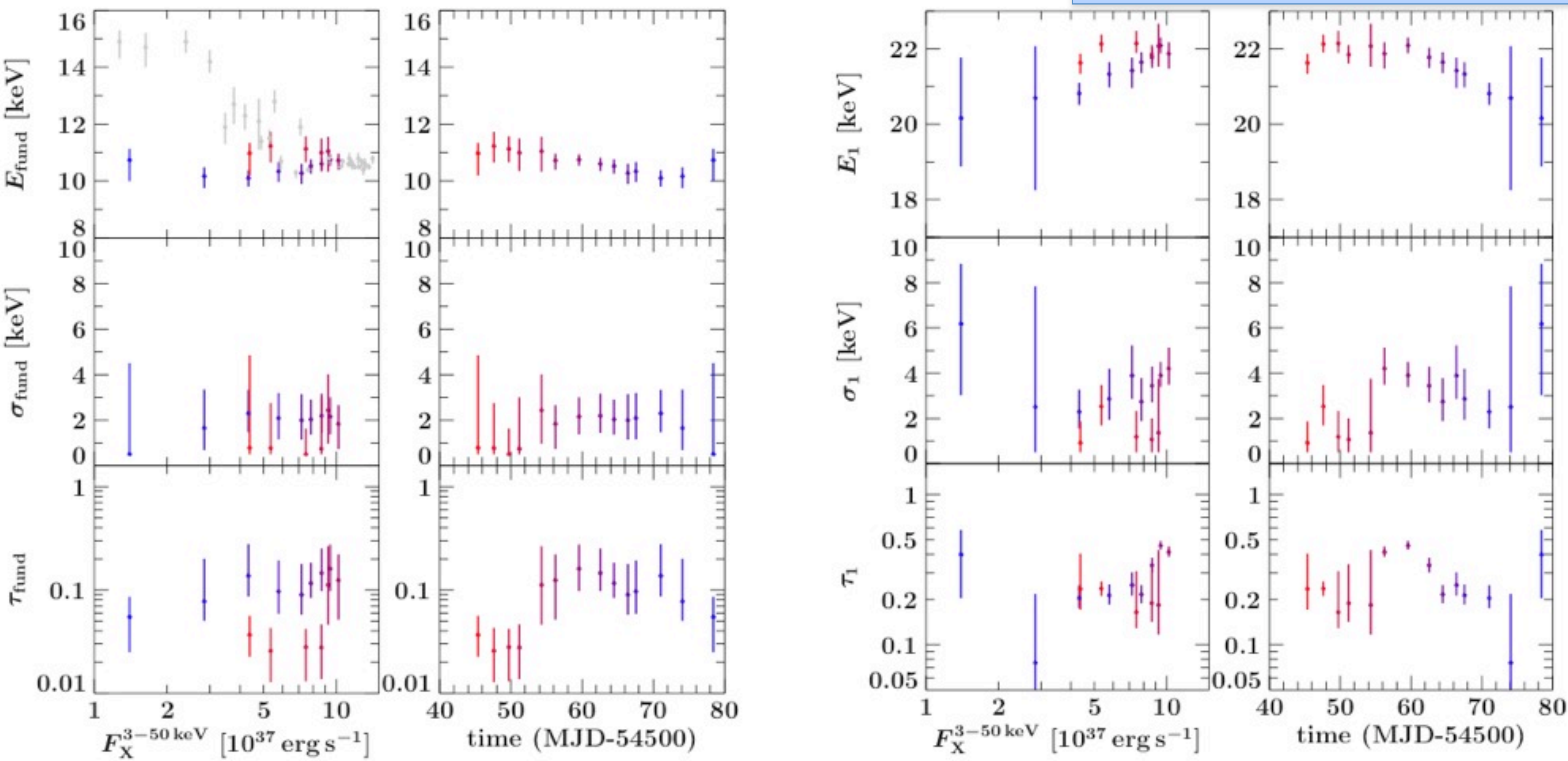



Mueller, Ferrigno et al. (in prep)

- Adopt a more complex continuum, so that the lines do not fudge the continuum itself

# Luminosity dependency vanishes

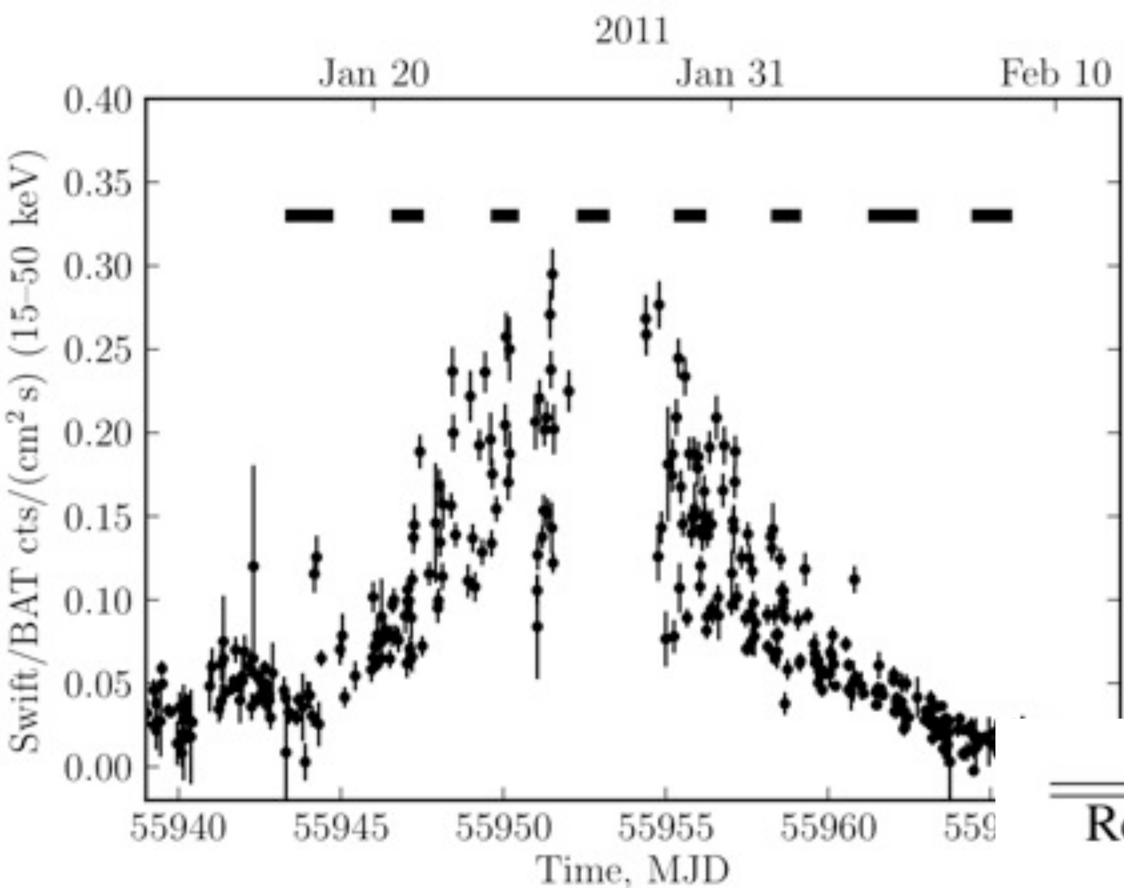
Mueller, Ferrigno et al. (in prep)




- Coherent fundamental and first harmonic non-variation

# INTEGRAL observations of GX 304-1

- Outburst in 2011 when it reached Crab-like flux

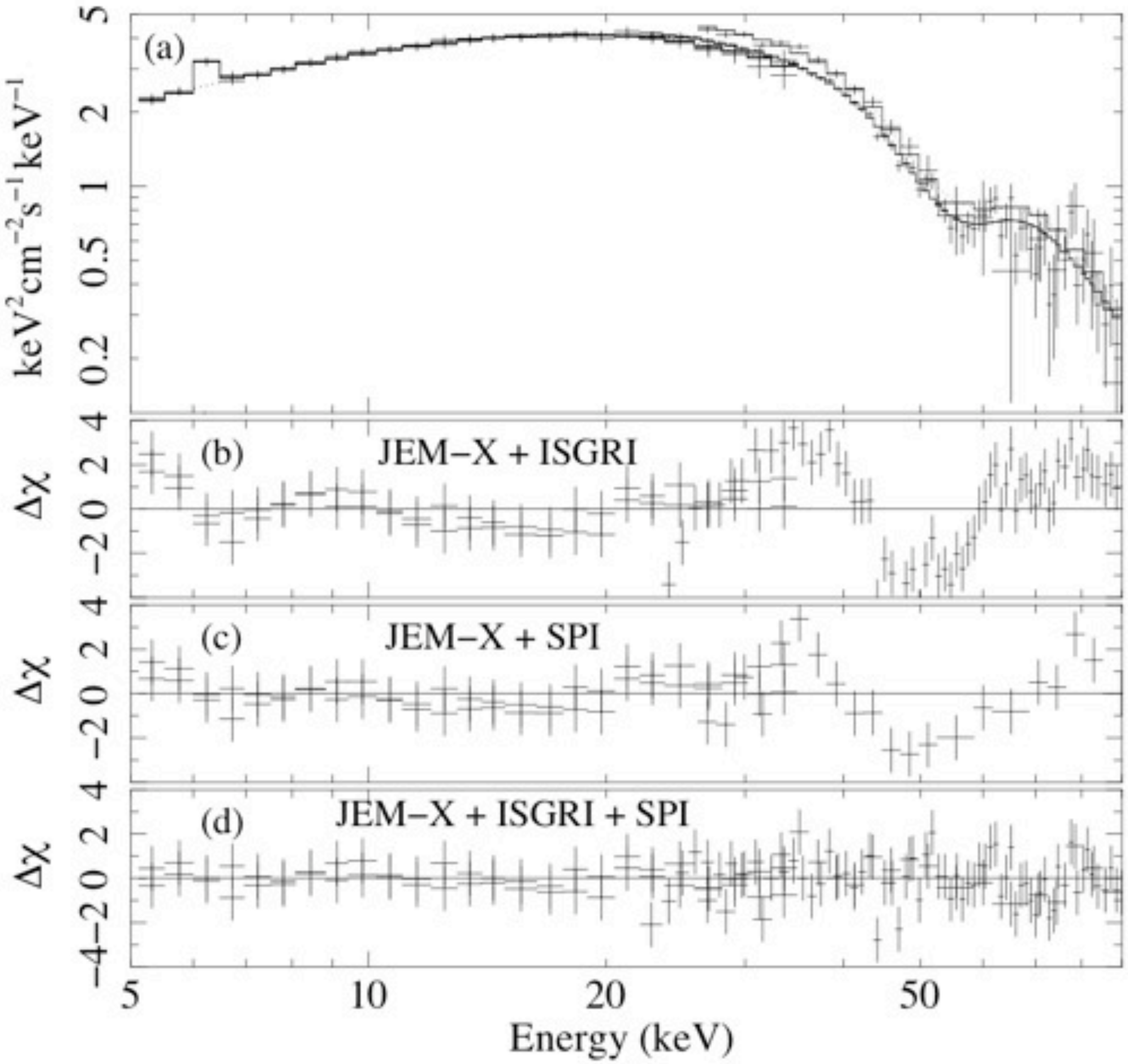


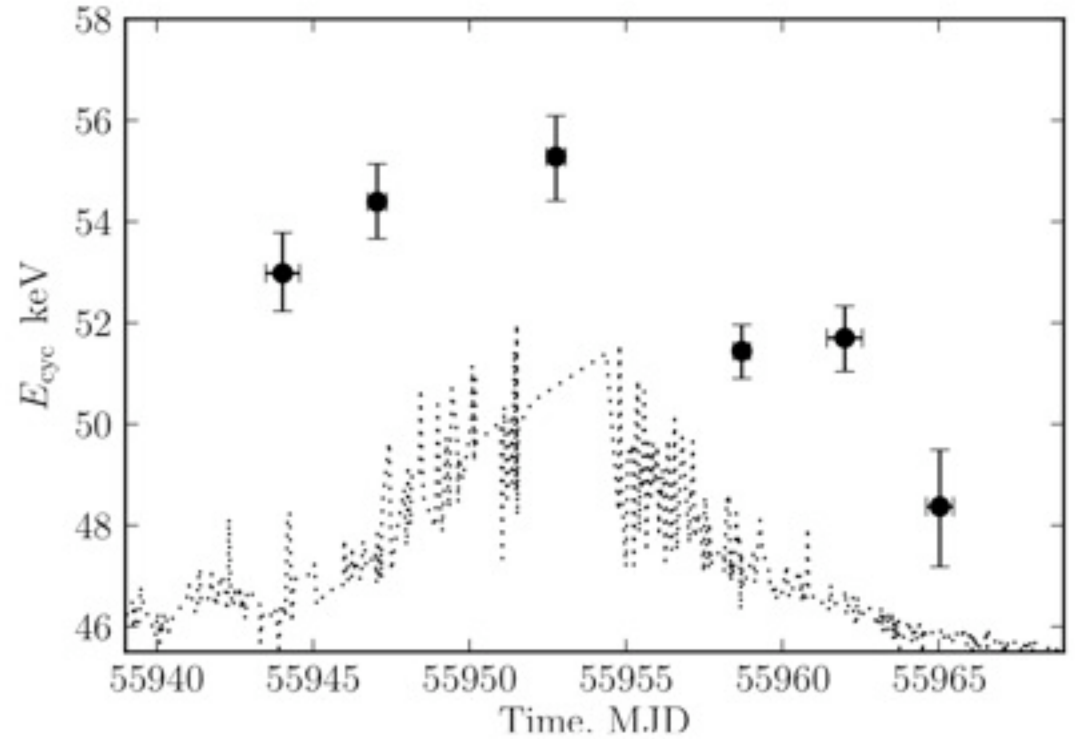

Klochkov et al. (2012)

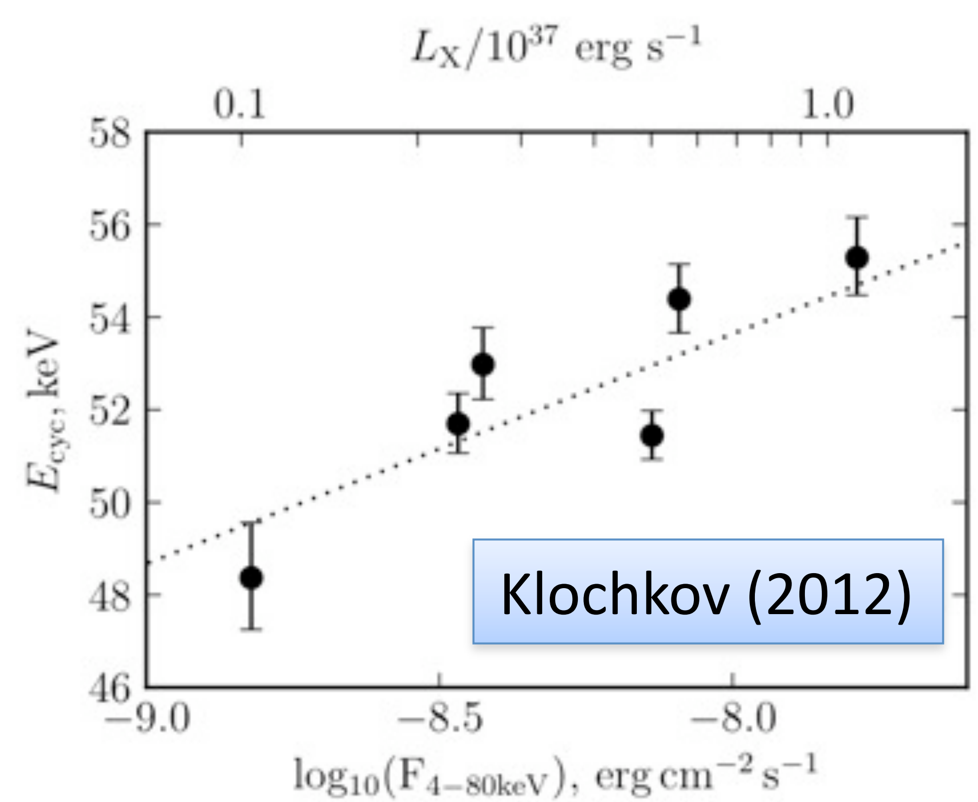
- A flux-cyclotron line positive correlation has been reported during previous outbursts using Suzaku and RXTE

| Rev. | Obs. ID | Mid. MJD | Exposure [ksec] | | |
|---|---|---|---|---|---|
| | | | JEM-X | IBIS | SPI |
| 1131 | 09400230006 | 55944.0 | 64.6 | 42.7 | 68.6 |
| 1132 | 09400230007 | 55947.0 | 42.4 | 31.9 | 36.6 |
| 1133 | 09400230008 | 55950.0 | – | – | 10.7 |
| 1134 | 09400230009 | 55952.8 | 7.3 | 25.4 | 37.8 |
| 1135 | 09400230010 | 55955.7 | – | 6.7 | 25.1 |
| 1136 | 09400230011 | 55958.7 | 36.9 | 28.1 | 32.9 |
| 1137 | 09400230012 | 55962.0 | 78.1 | 59.7 | 78.4 |
| 1138 | 09400230013 | 55965.0 | 60.7 | 45.2 | 52.3 |

# Positive correlation

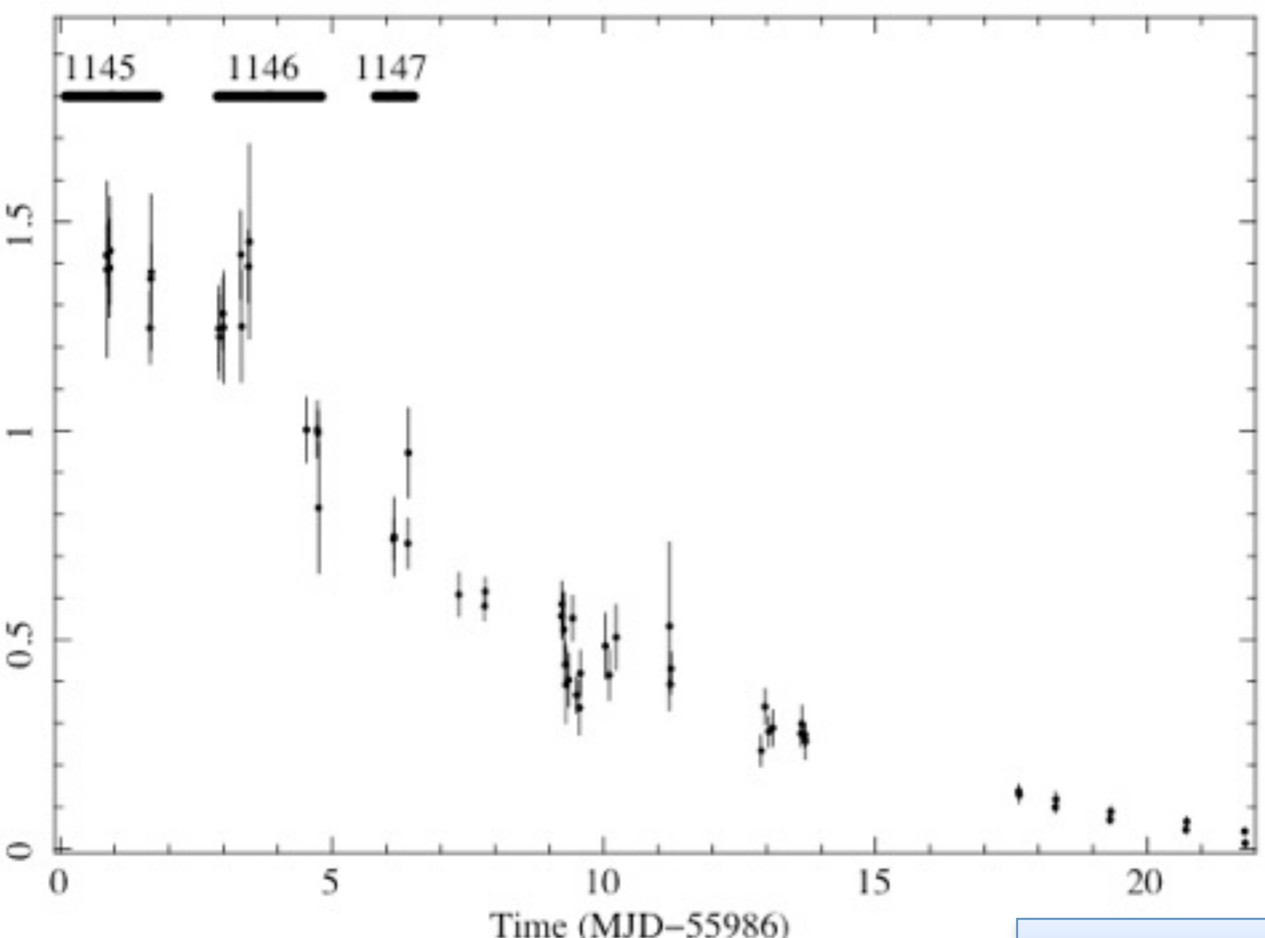


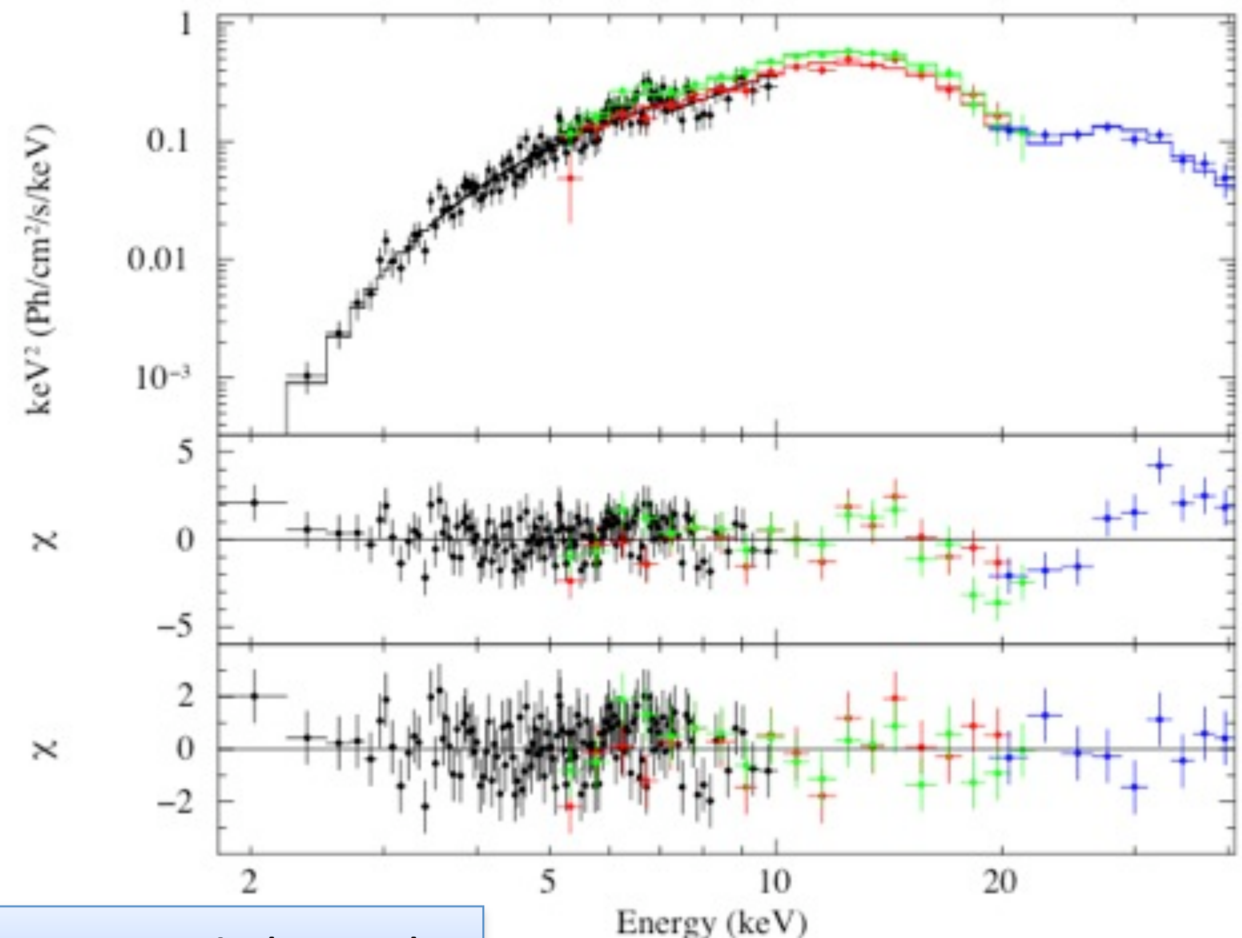




- Beautiful measures of another subcritical system

# A new cyclotron source ?



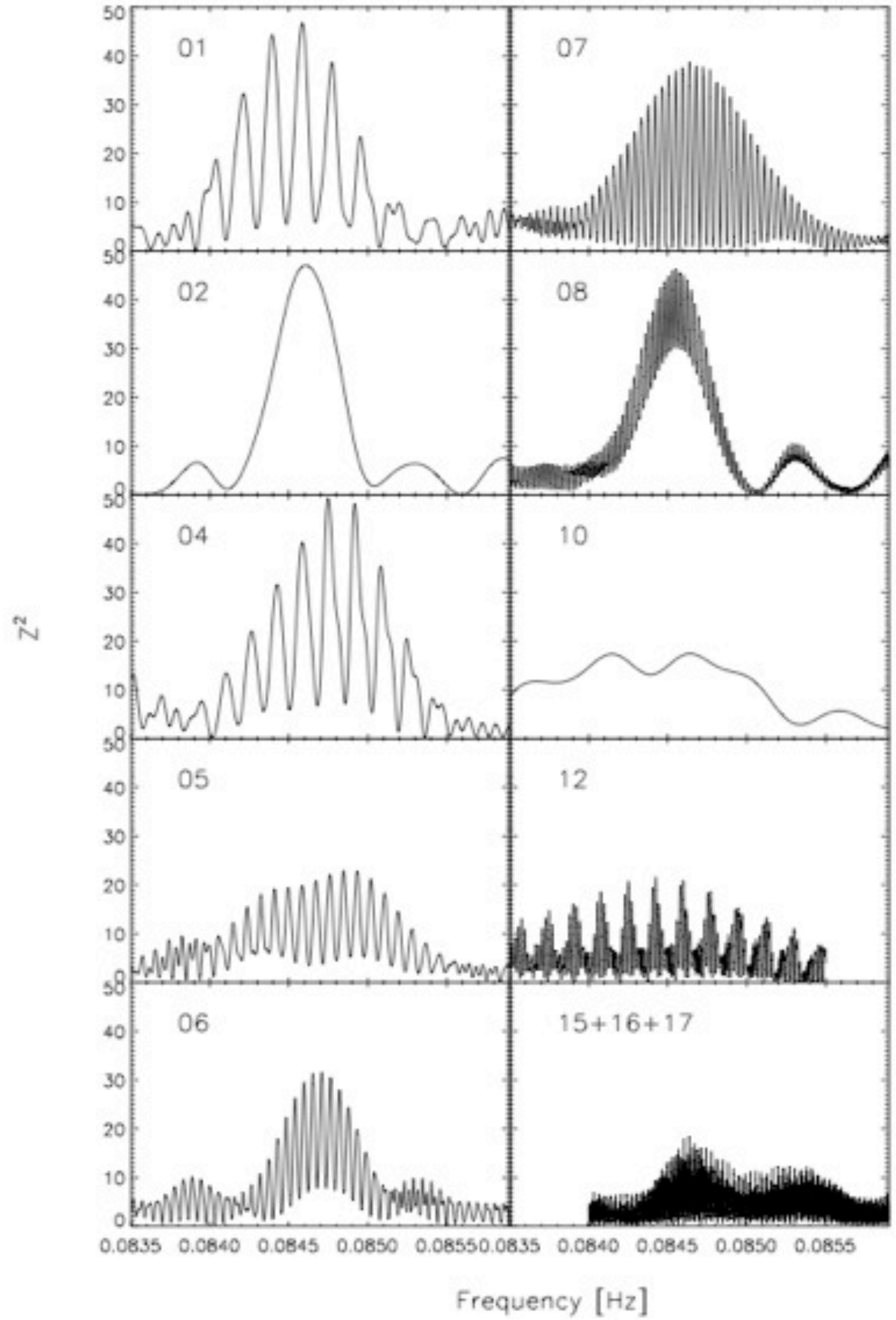




Bozzo, Ferrigno et al. (2012)

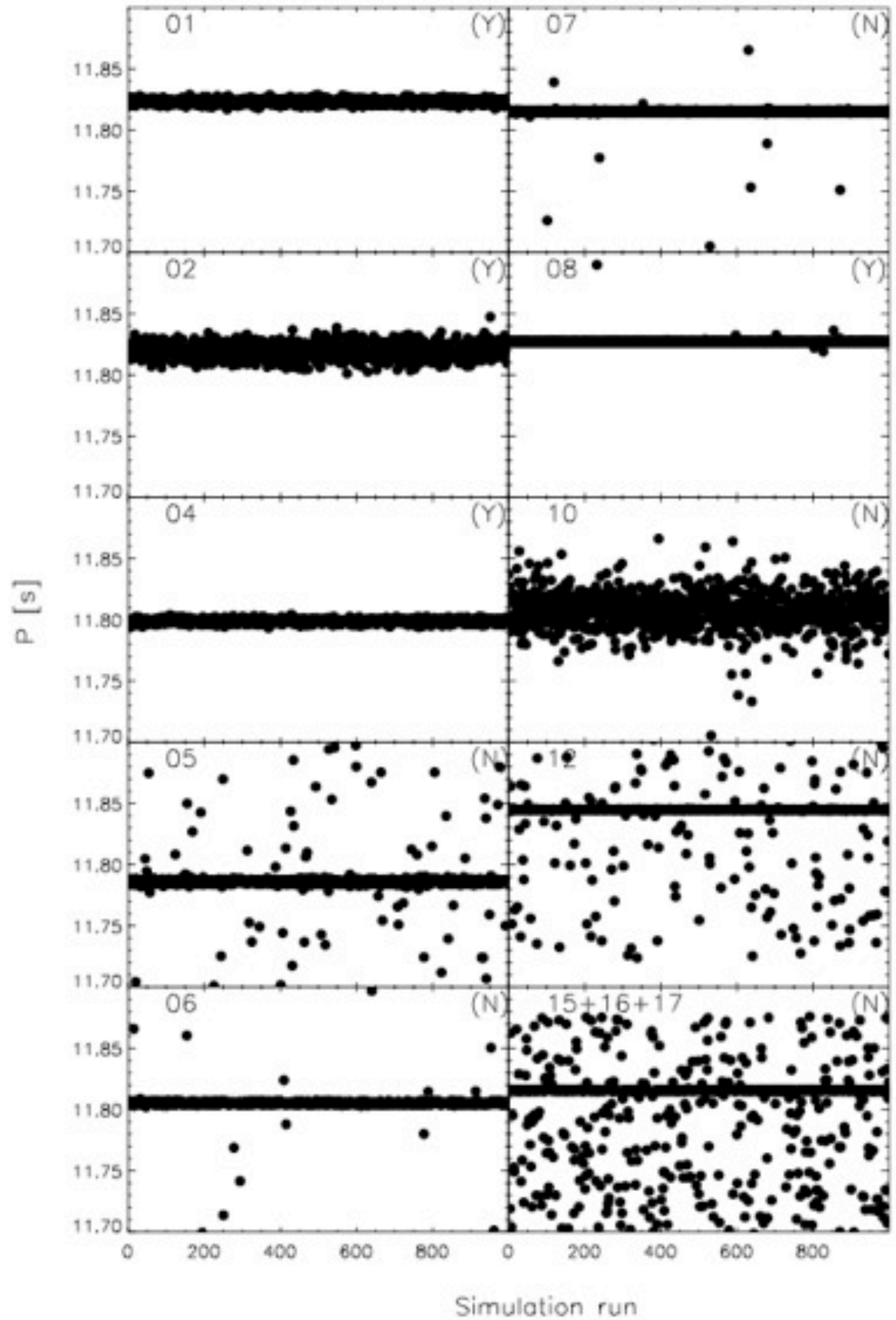
- IGR J18179-1621 discovered during quick-look (ATeL #3947)
- Observed by INTEGRAL serendipitously
- Swift/XRT follow-up campaign
- Strong indication of a cyclotron line a ~20 keV

# Difficult timing study

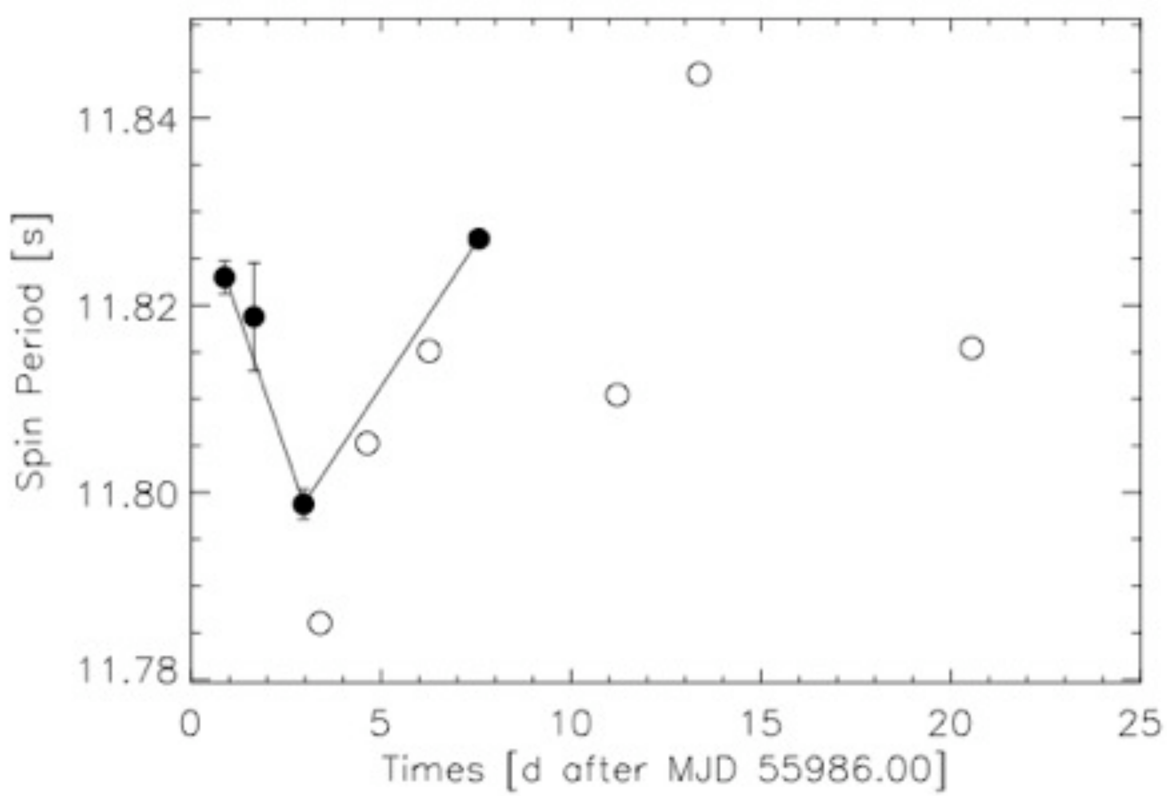
## Data




## Simulations



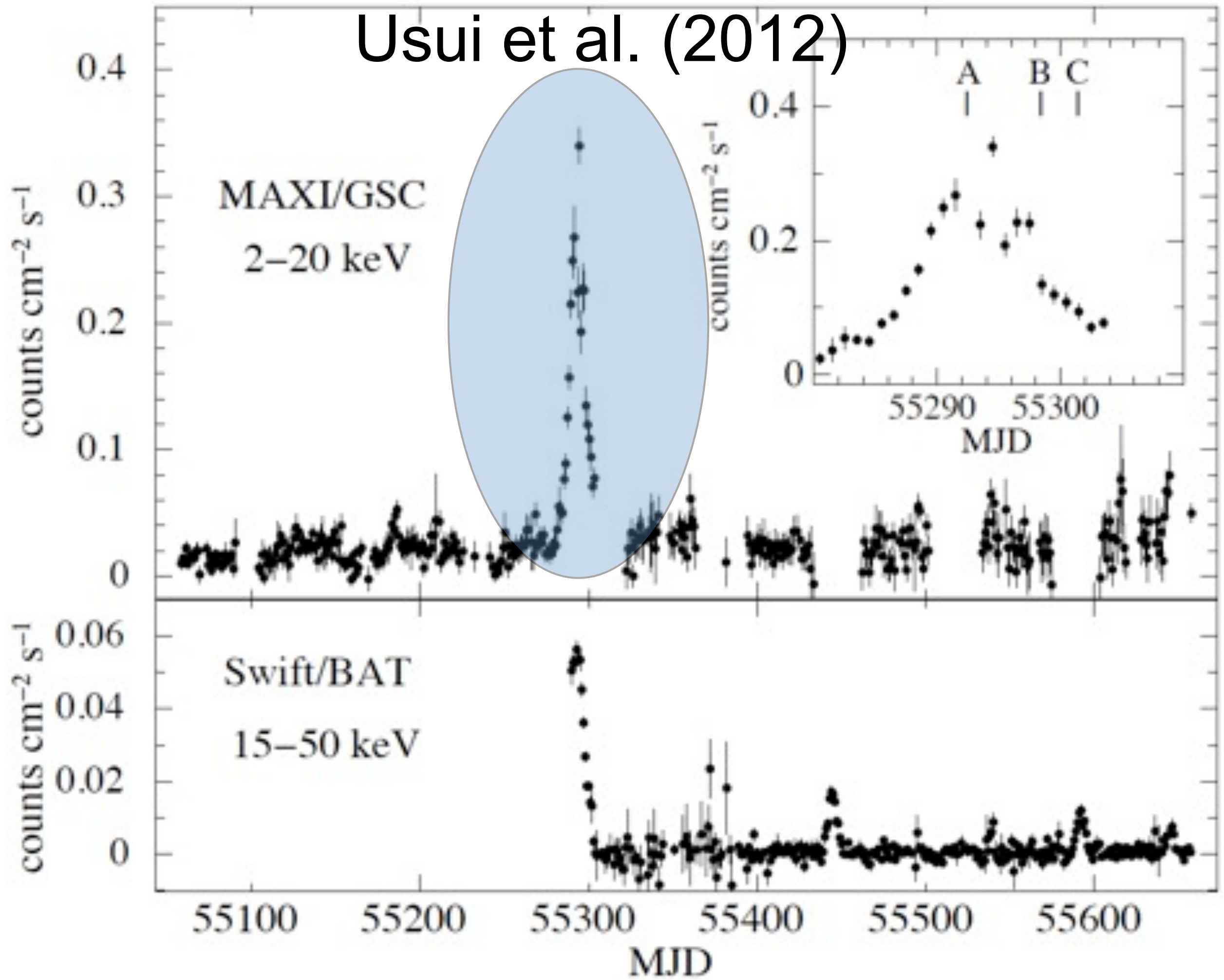
# Timing results

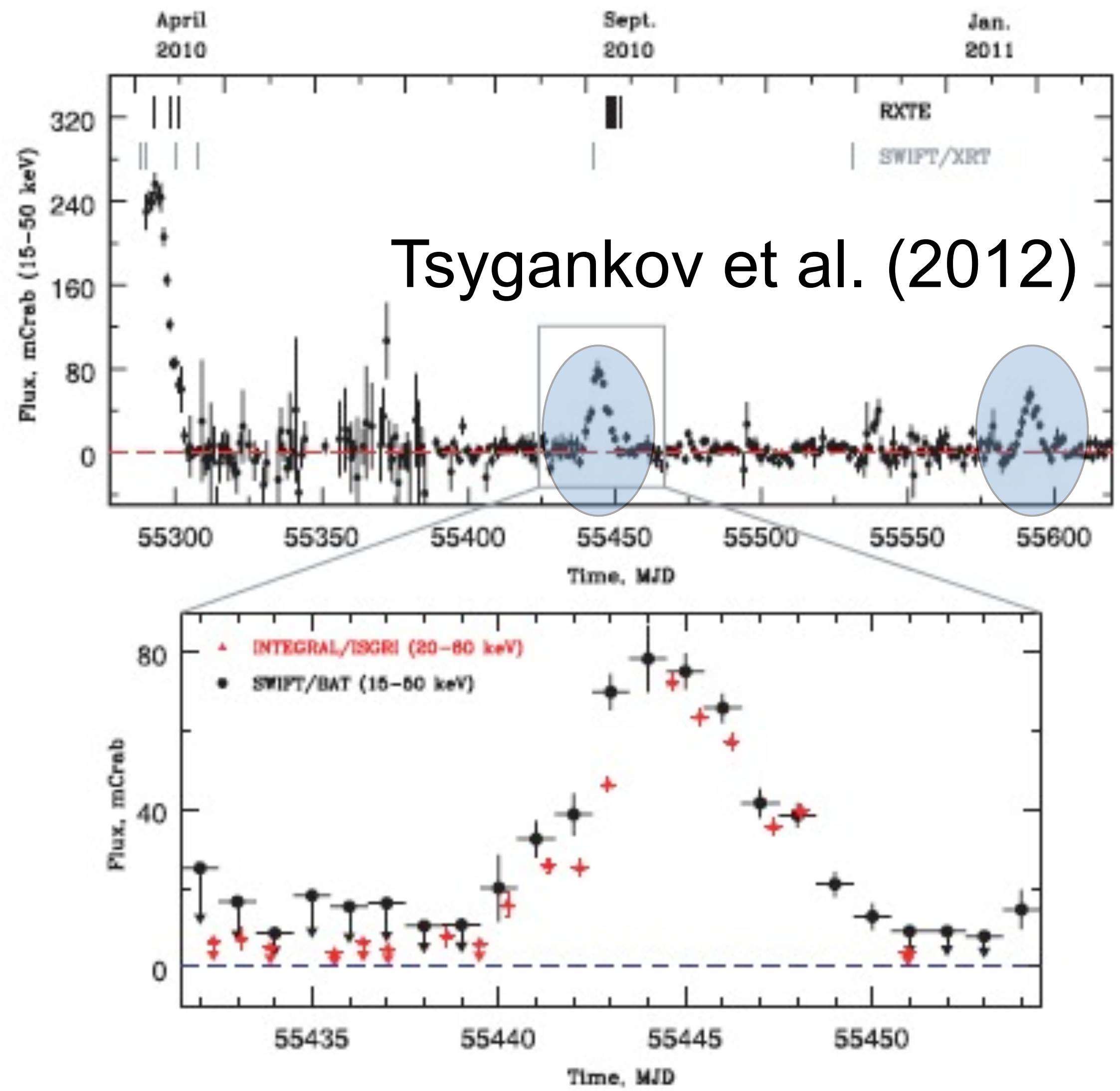



Bozzo, Ferrigno et al. (2012)

- Estimate confidence of determination using MC simulation and $Z^2$ statistics technique
- At 99% c.l., we can retain just 4 out of 9 determinations

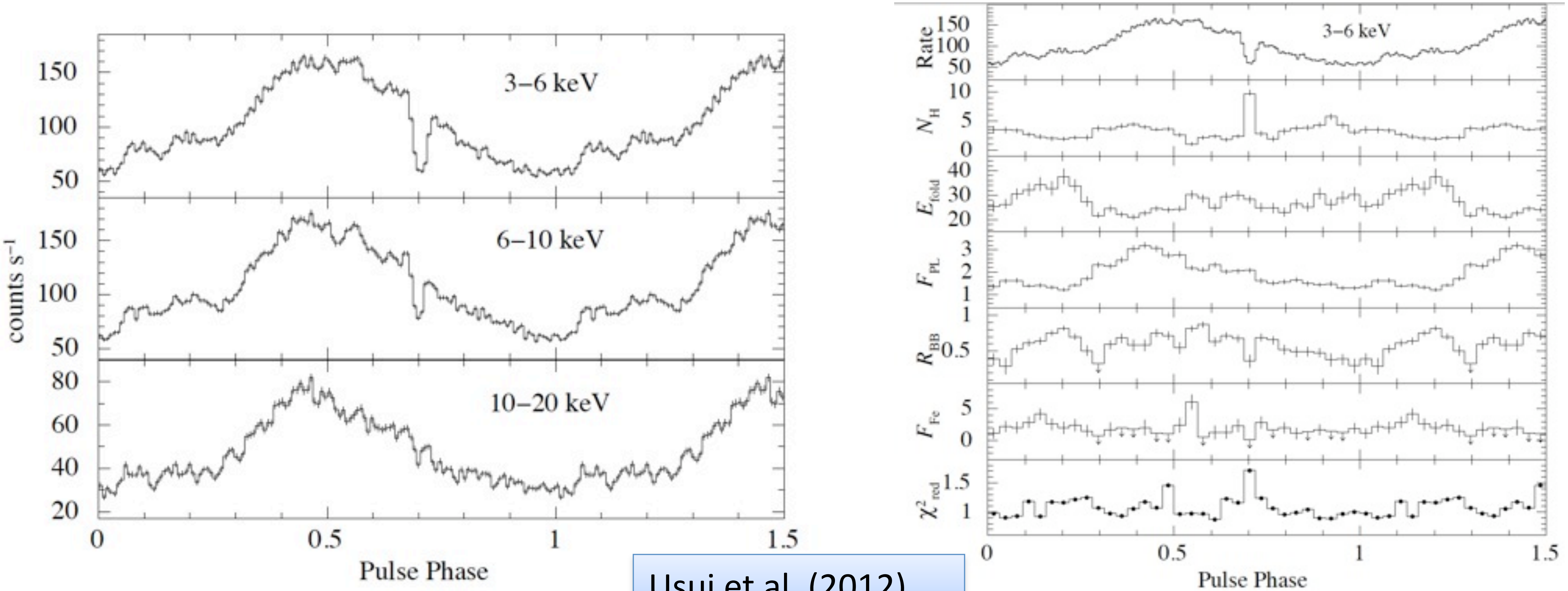
# RX J0440.9+4431= LS V +44 17




- Classified as persistent Be/X-ray binary at 3.3 kpc distance
- Series of flares separated of ~155 days in 2010-2011
- Three papers published and one in preparation

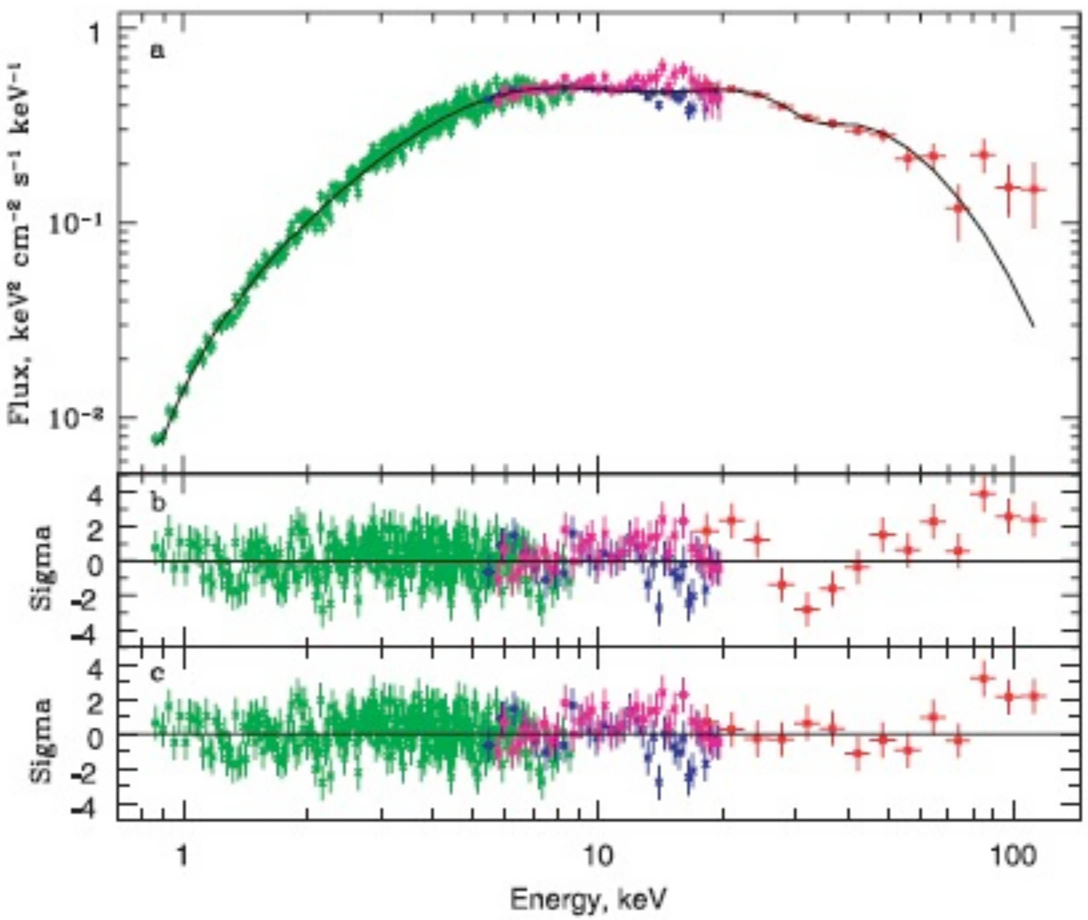
# A dip-like structure at high L



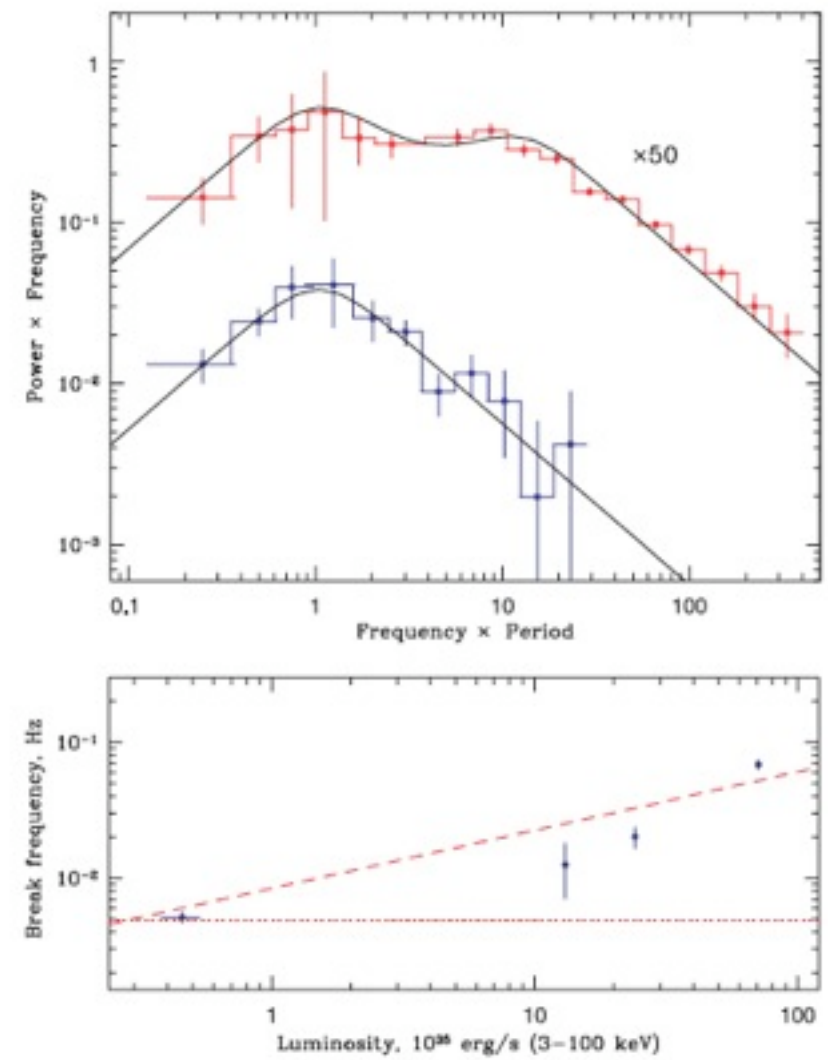

Usui et al. (2012)

- A dip-like structure appeared during the first outburst at soft X-rays
- Interpreted as due to occultation from the accretion stream
- Introduced a very soft BB for a better fit (the accretion stream?)

# A cyclotron absorption in INTEGRAL



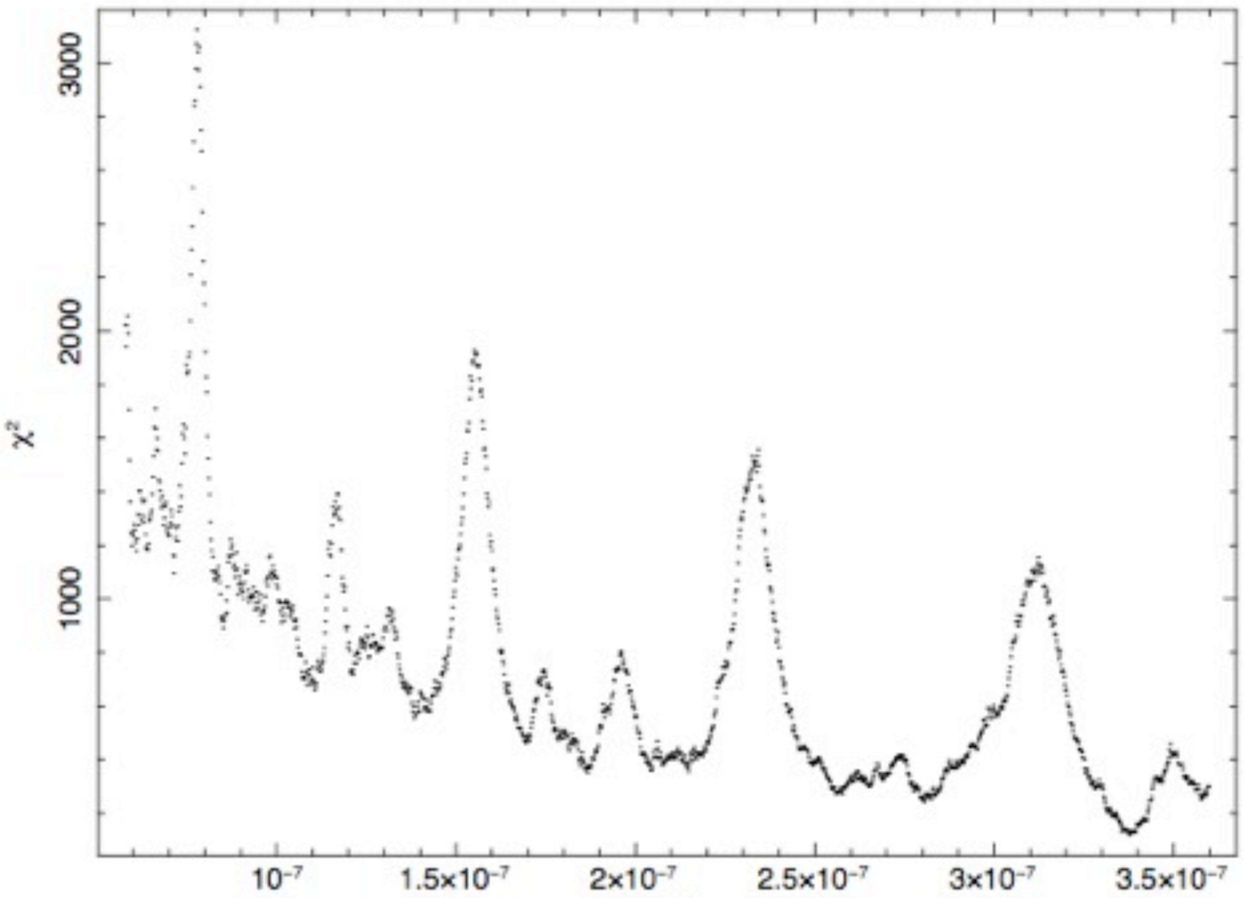

Tsygankov et al. (2012)



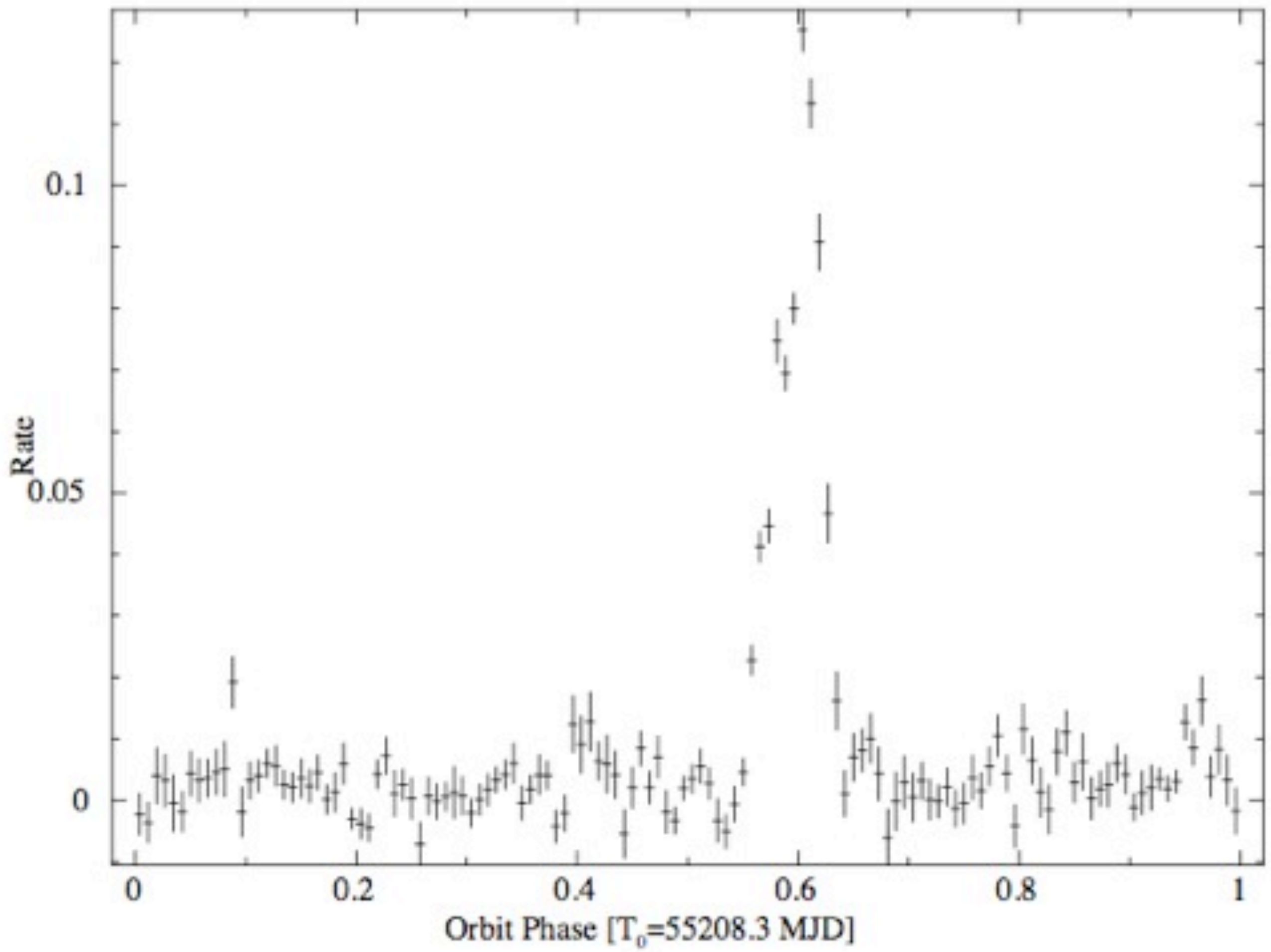

- Hard X-ray coverage by INTEGRAL of second outburst
- Discovery of an absorption feature due to cyclotron scattering
- Magnetic field strength confirmed by PSD analysis.

# RXTE-Swift/XRT follow-up



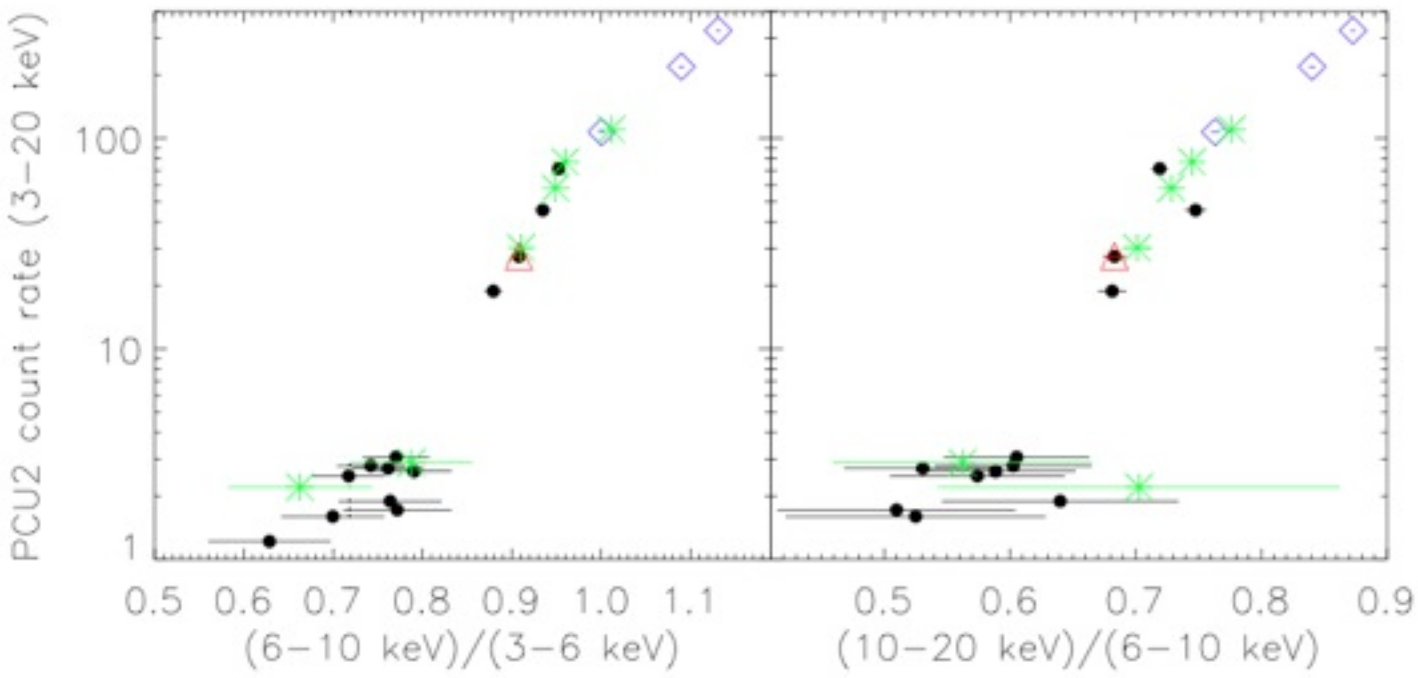



Ferrigno et al. (in prep.)

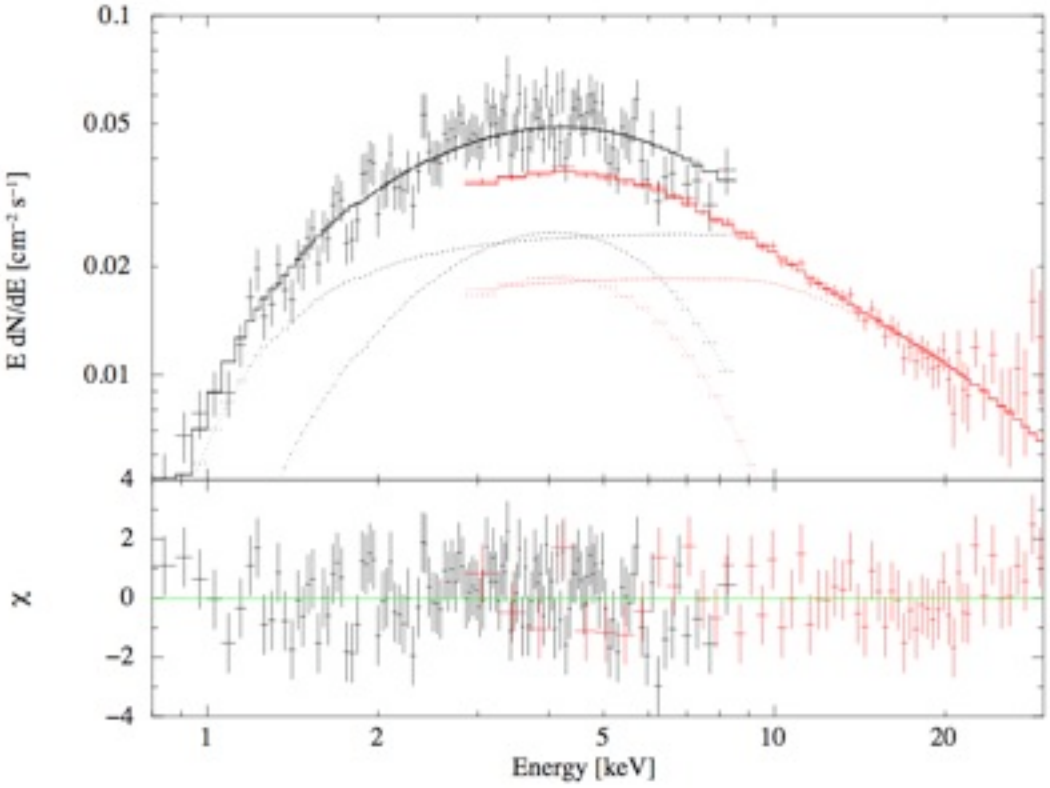



- Analysis of Swift/BAT data confirms periodicity and gives a typical Be/X-ray binary orbital light curve $P_{orb}$=(147.9+/-0.3)

# RXTE-Swift/XRT follow-up

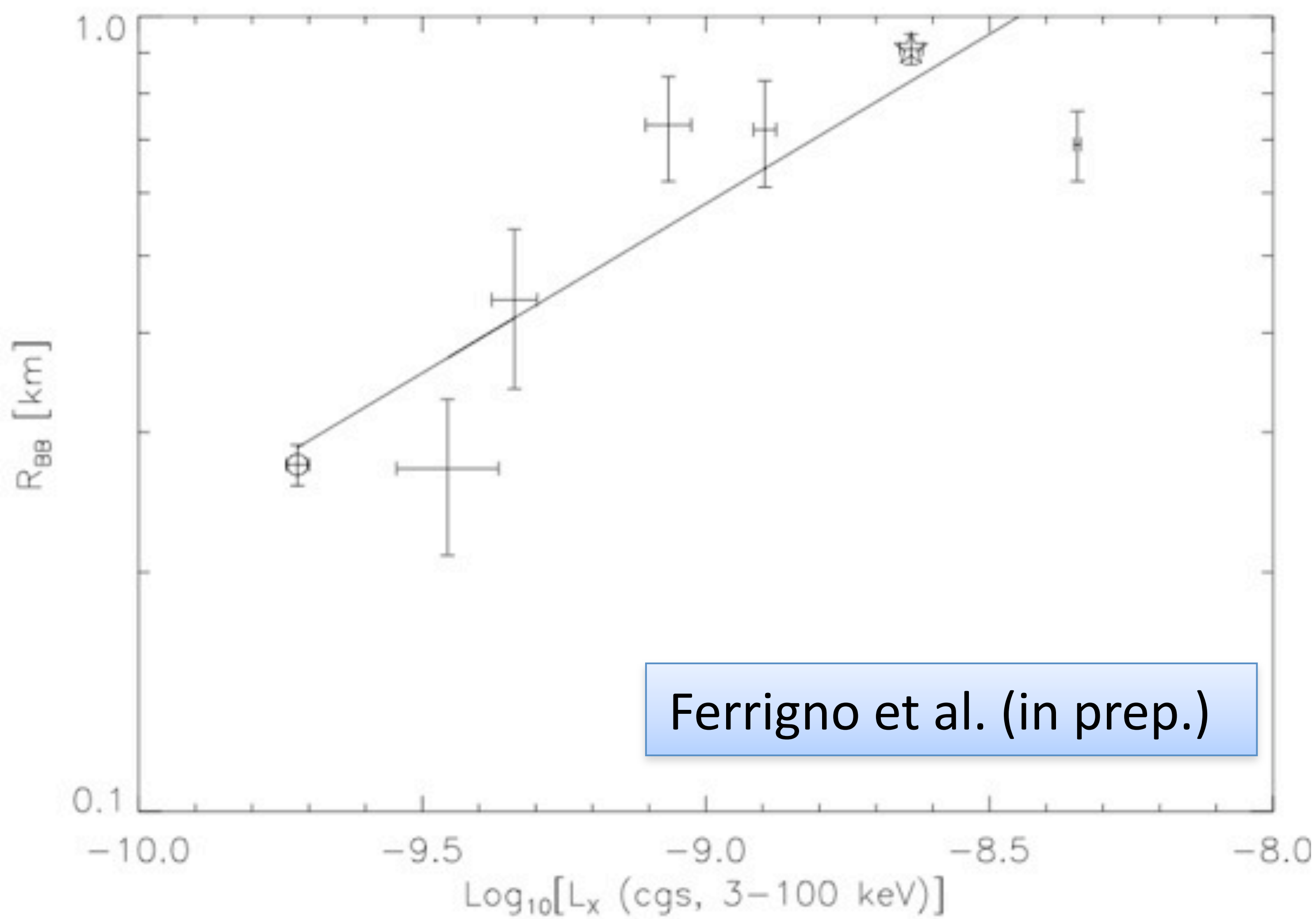


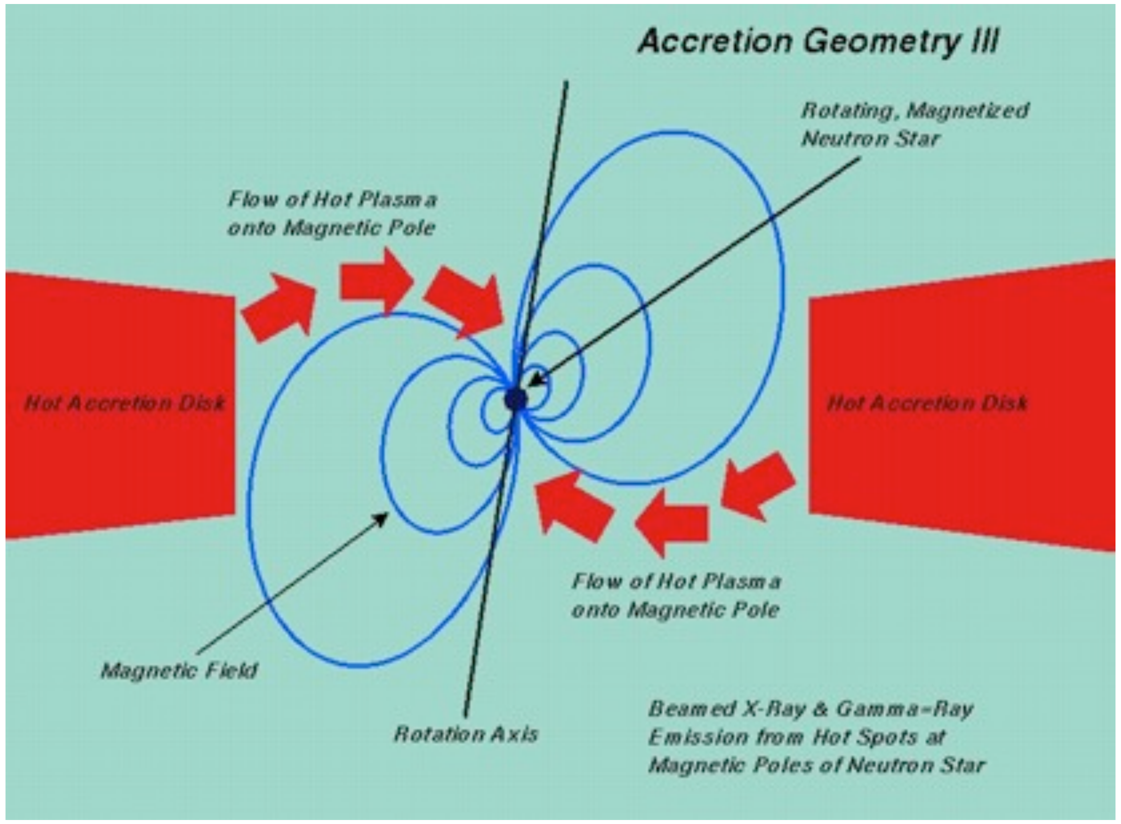

Ferrigno et al. (in prep.)




- Spectral hardening as function of luminosity, the same in three outbursts, due to high $E_{cut}$ and larger BB area
- Spectrum is combination of BB+cutoffPL with low absorption $N_H$~$0.7x10^{22}$ $cm^{-2}$
- BB not detectable at low luminosity with RXTE but detected in quiescence by XMMM-Newton (La Palombara et al., 2011)

# BB radius and luminosity



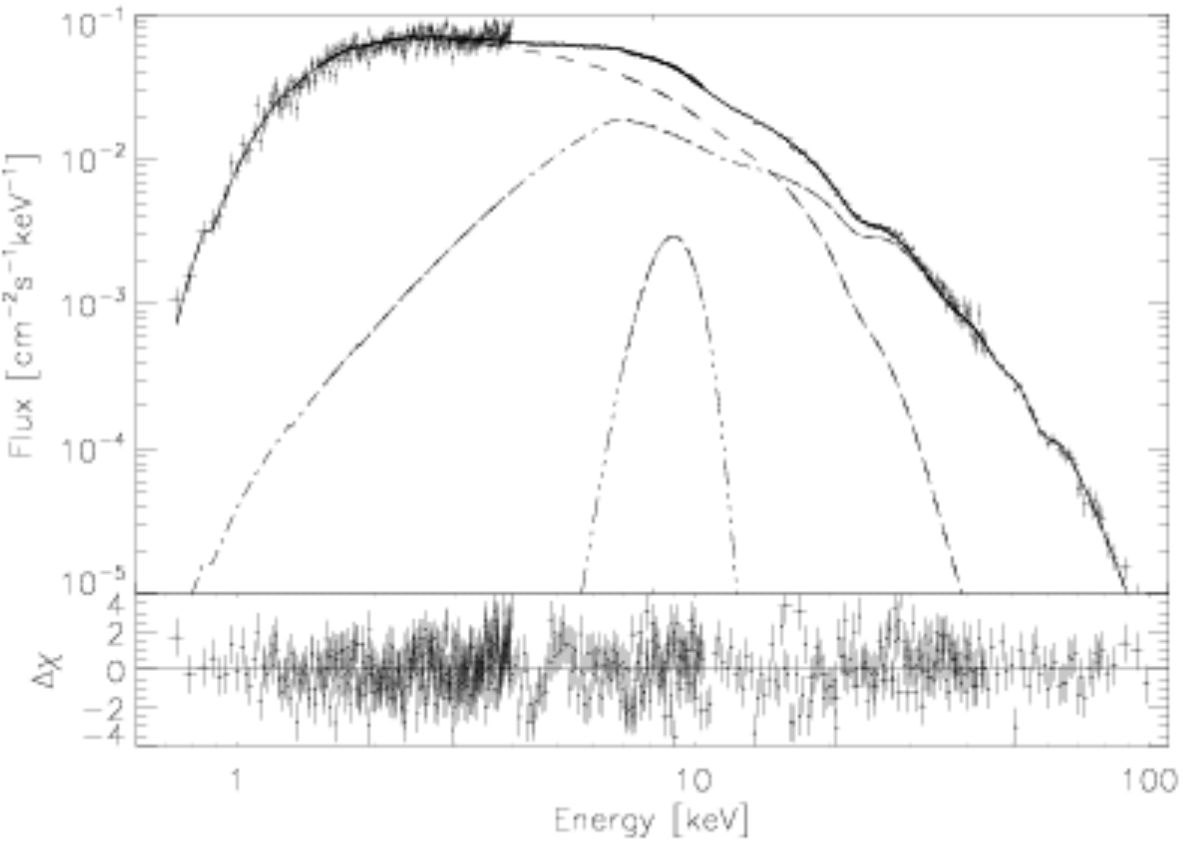




$$r_0 = 1.93\times10^5\,\mathrm{cm}\left(\frac{\Lambda}{0.1}\right)^{-1/2}\left(\frac{M_*}{1.4M_\odot}\right)^{-1/14}\left(\frac{R_*}{10\,\mathrm{km}}\right)^{11/14}\times\left(\frac{B_*}{10^{12}\mathrm{G}}\right)^{-2/7}\left(\frac{L_X}{10^{37}\mathrm{erg\,sec^{-1}}}\right)^{1/7}$$

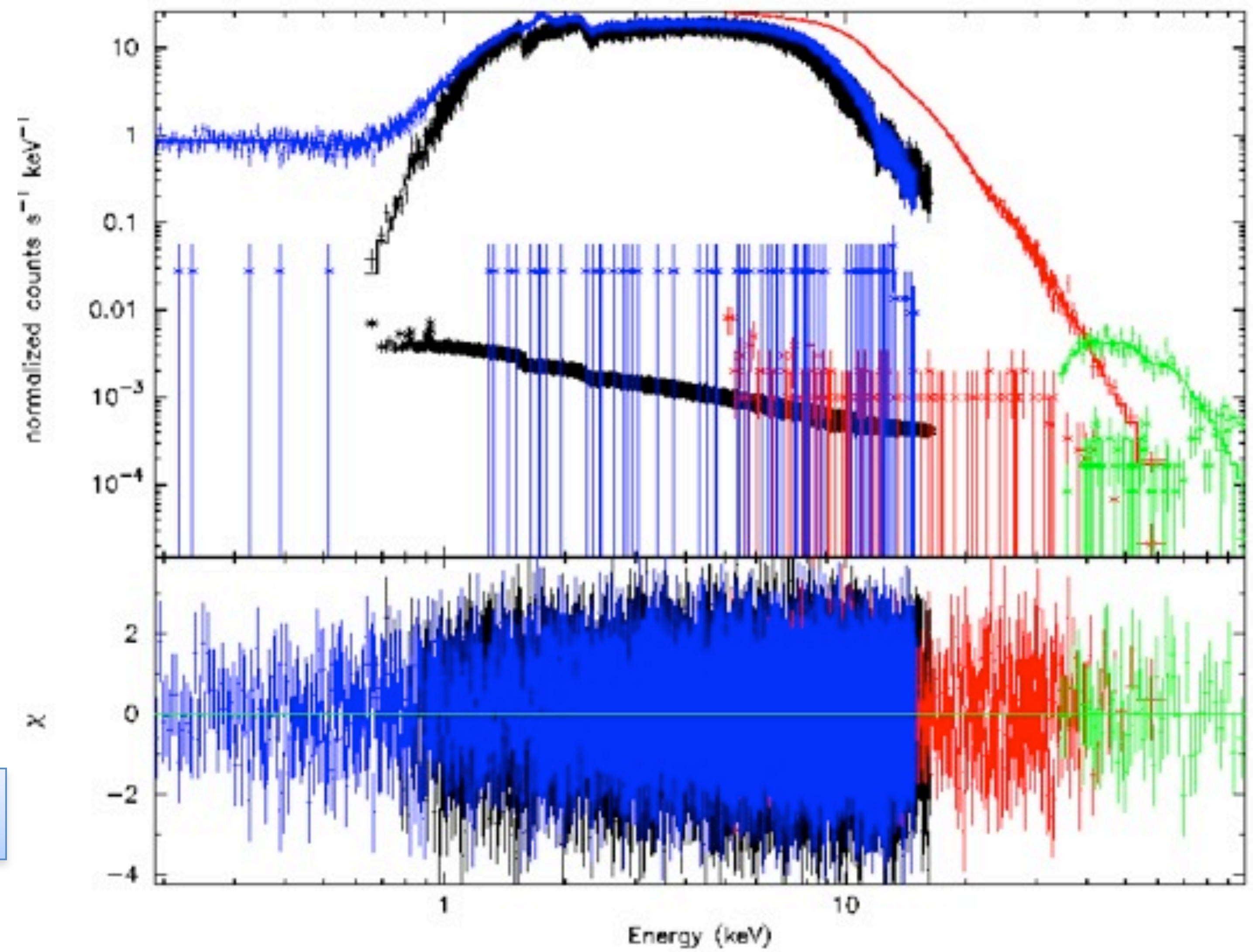
- BB radius increases with L, as expected in disk-fed systems
- slope is steeper than expected if BB radius is coupled with magnetospheric radius
- At highest luminosity, decrease ?

# Future

# Astro-H potential

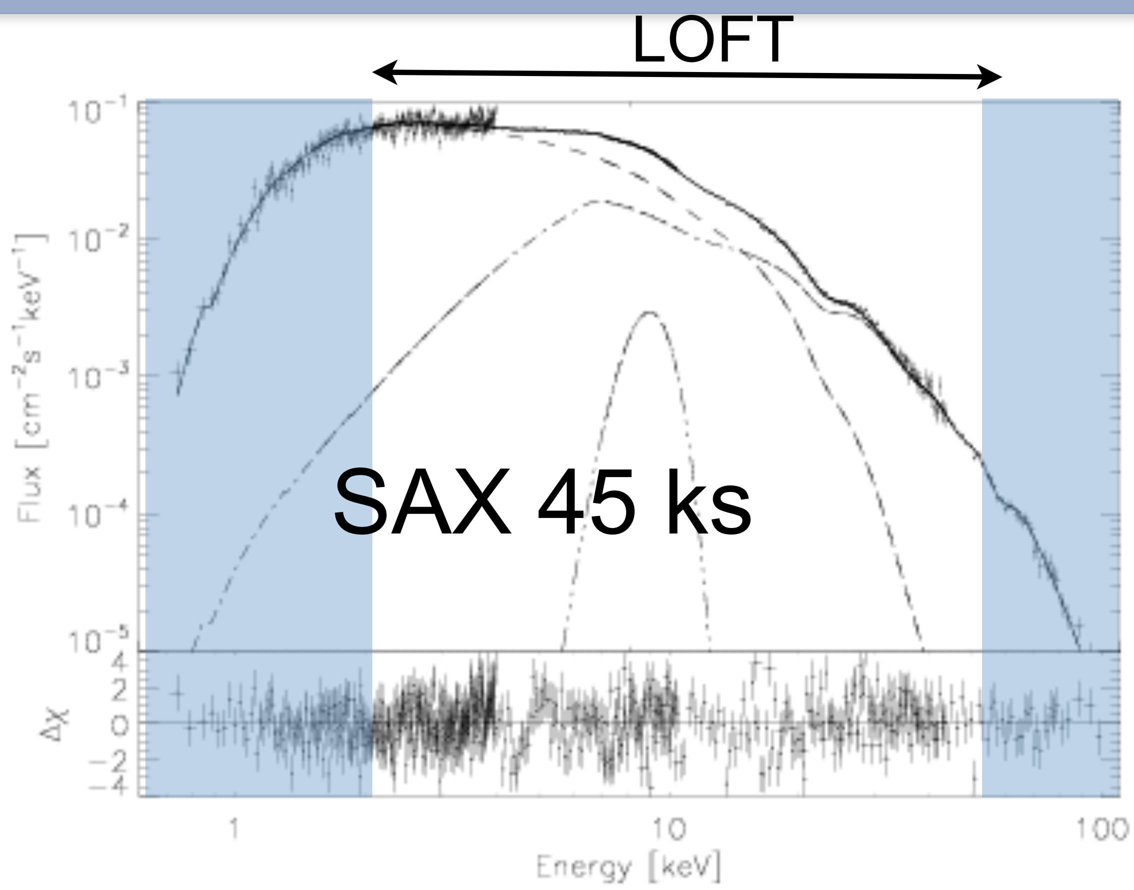


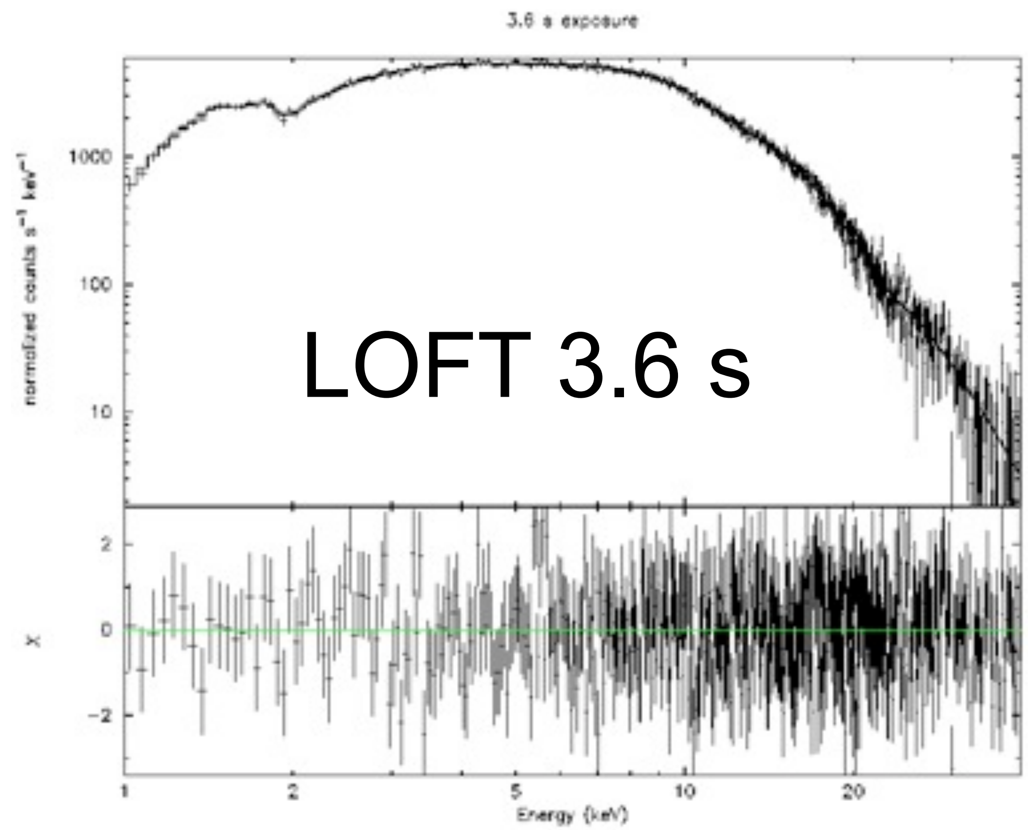

Ferrigno et al. (2009) SAX




- 4U 0115+63 in outburst, fit with a complex model using Beppo-SAX broad-band data (45 ks)
- Astro-H will provide in 10 ks a better constraints on relevant parameters (line width at 0.2 keV) and a slightly larger band !

# LOFT




- Smaller band prevents continuum study, but large effective area provides spectral ability on one pulse time-scale.
- Line centroids at better than 1 keV in 3.6s exposure !
- Variability study at pulse time scale -> trace accretion.

# Conclusions

- The presented theoretical study furnishes a robust understanding of the cyclotron line flux dependency in different sources with different trend.
- We also demonstrated that in the case of 4U 0115+63, the observational result is doubtful.
- The use of archive data is limited and it would be important to discover more sources showing this effect.
- It is essential to use a facility with high-energy coverage as INTEGRAL and Suzaku (Astro-H and LOFT in the future).
- However, Suzaku normally does not provide extended coverage of an outburst as INTEGRAL.