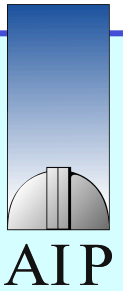


The magnetic field of neutron stars:

What cyclotron lines can tell us

Gabriele Schönherr (Astrophysical Institute Potsdam)

– on behalf of the MAGNET collaboration –

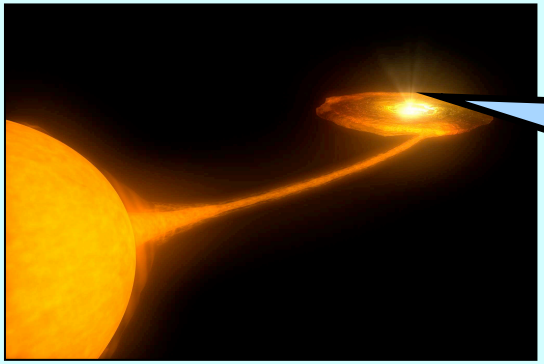
J. Wilms, I. Kreykenbohm (FAU, Germany), P. Kretschmar (ESAC,Spain), R.E. Rothschild, S. Suchy (UCSD, USA), K. Pottschmidt (Goddard, USA), V. McBride (Univ. Southampton, UK), I. Caballero (CEA Saclay), C. Ferrigno (IAAT & ISDC, Switzerland), D. Klochkov, A. Santangelo, R. Staubert (IAAT, Germany), et al.

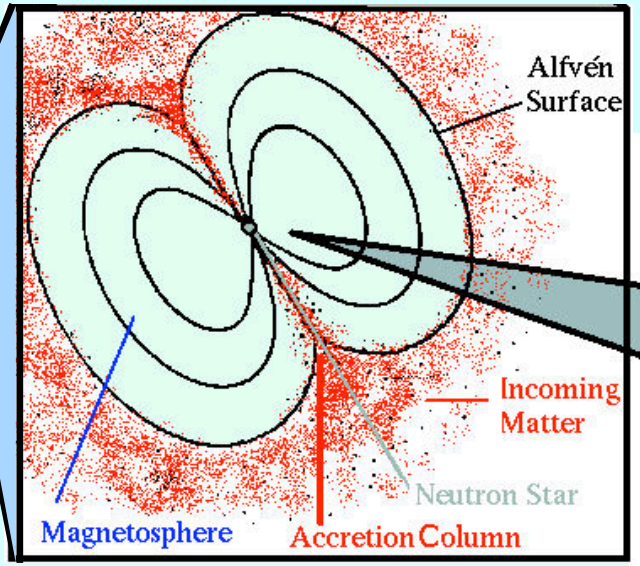
X-ray astronomy 2009, Bologna, September 2009

Magnetic fields

AIP

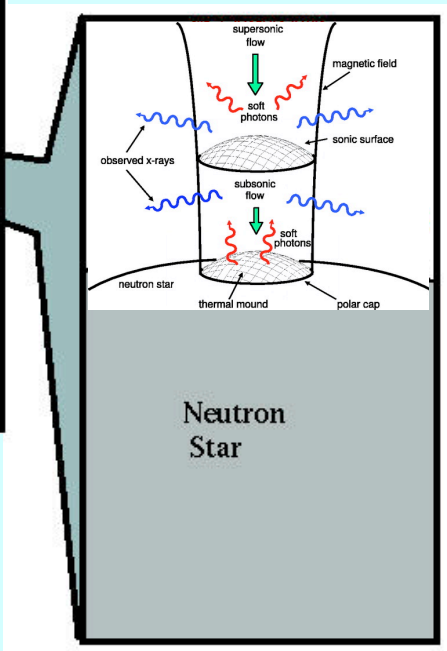
- Extremely strong magnetic fields are encountered in the universe.
- Onset of „new“ physics.
- Accreting X-ray pulsars have magnetic fields of the order of 10^{12} Gauss dominating the processes of accretion.





(I. Negueruela)

(Becker & Wolff 2007)



Accretion types

- wind accretion
- Be wind accretion
- Roche lobe overflow

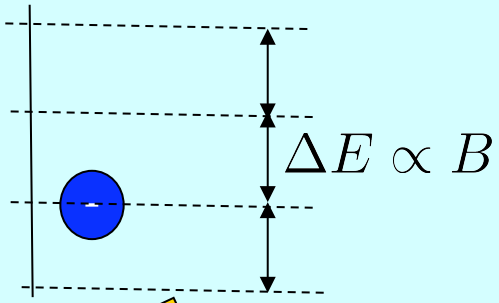
$$B \sim 10^{12}\,\mathrm{G}$$

Cyclotron Resonant Scattering Features

AIP

- Scattering of X-ray photons with quantized electrons in a strong magnetic field
- Electron perpendicular momentum/energy restricted to Landau levels
- Photons induce - -transitions: „12-B-12 rule“:

$$\Delta E \approx 11.6\,\mathrm{keV}\, B_{12}^{(*)}$$



- Resonant cross sections
  - →Photons at $n\Delta E$ can‘t escape the line forming region
  - →Lines form in absorption

$$(*)\begin{cases} E_n = m_e c^2 \sqrt{1 + \left(\frac{p}{m_e c}\right)^2 + 2n\frac{B}{B_{\mathrm{crit}}}} \\ B_{\mathrm{crit}} = (m^2 c^3)/(\hbar e) = 44.14 \times 10^{12}\,\mathrm{G} \end{cases}$$

Quasi-harmonic features

The power of cyclotron lines

AIP

- Measure the magnetic field (structure) of a neutron star: only direct method!

$$\Delta E \approx 11.6\,\mathrm{keV}\, B_{12}$$

- Constrain the physical conditions in the accretion column

SHAPE matters

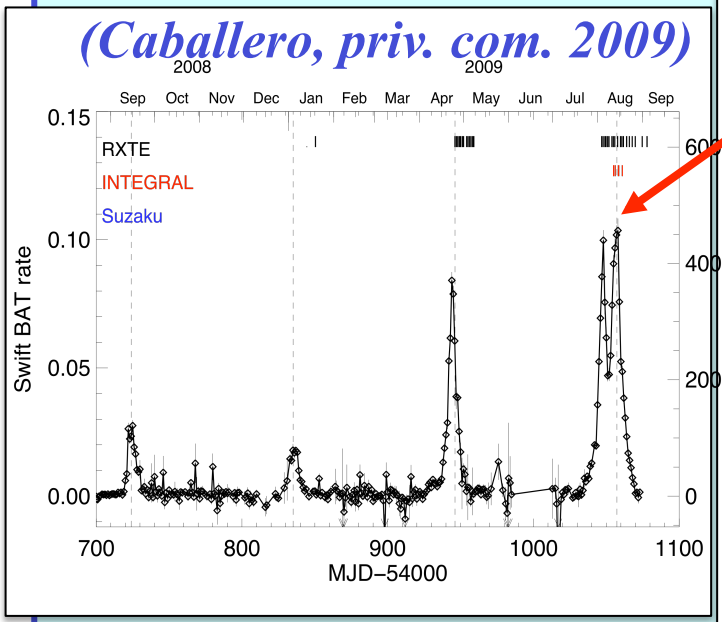
High-quality data

Example: the Be/X-ray binary A0535+26

…in outburst again: August 2009

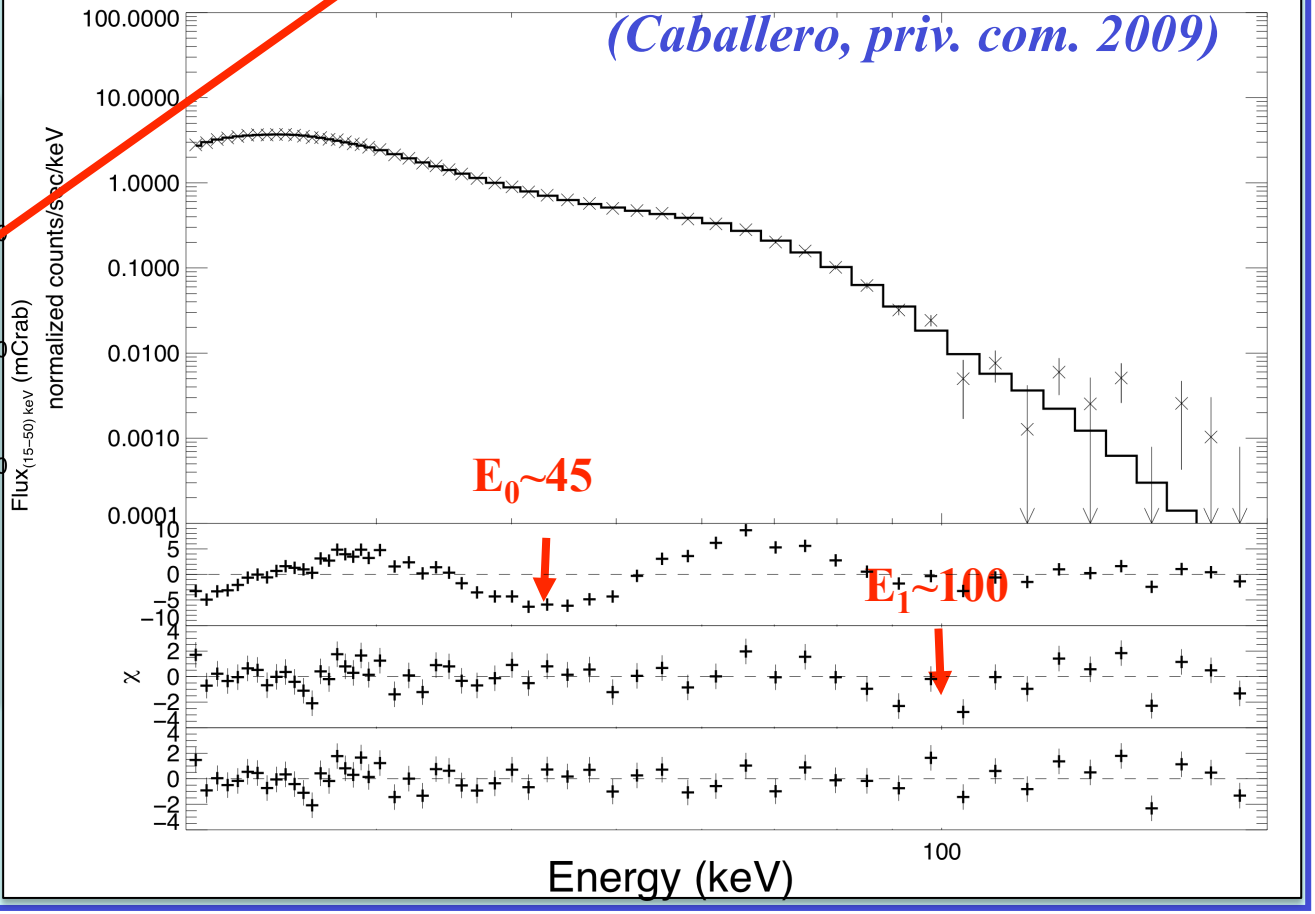
Swift-BAT light curve

(Caballero, priv. com. 2009)



INTEGRAL IBIS (ISGRI) spectrum

(Caballero, priv. com. 2009)



See poster no. 4.59 ☺ !!

Observational sample and findings

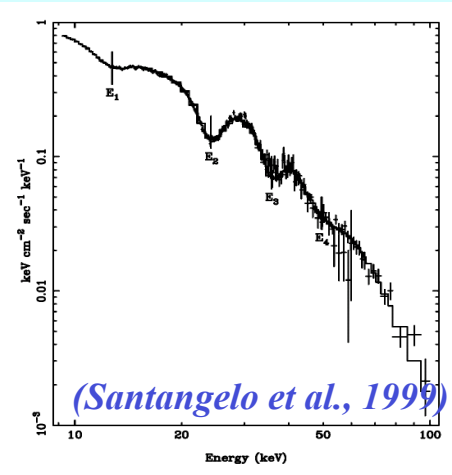
AIP

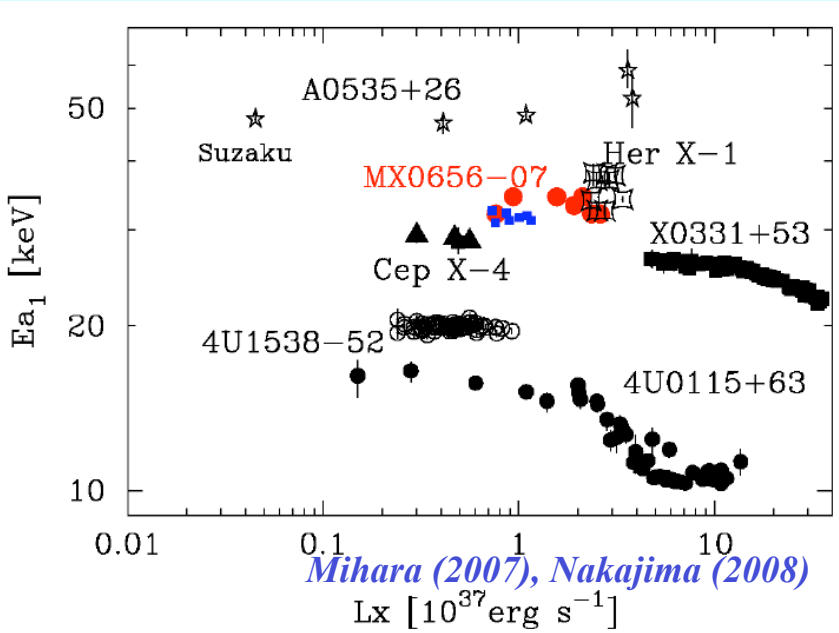
- ~15 sources with confirmed cyclotron resonance scattering features have been observed by *BeppoSax, RXTE, INTEGRAL, Suzaku*, etc.

- Detection of several harmonics in several sources → up to 5 lines detected! (in 4U 0115+63)

- Significant variability of line-parameters with phase, over time, etc.

- Parameter correlations: Energy-Luminosity dependence





cyclomc XSPEC fitting model

AIP

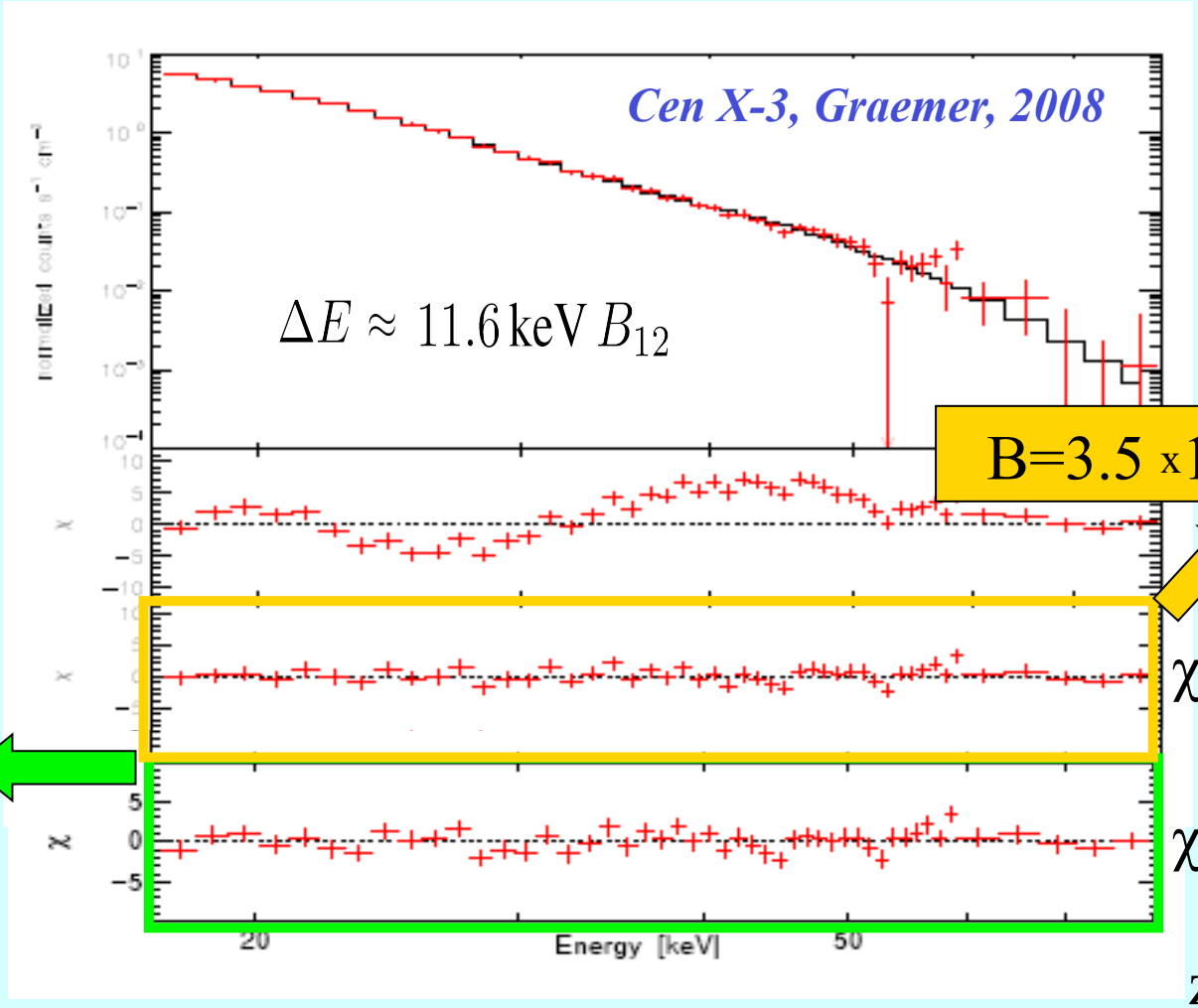
Numerical model:

Cyclomc

(Schönherr, Wilms)

- B=3.6 x10^{12} G
- T_e=6.6 keV
- τ_{Thom}= 2.9 x 10^{-3}
- μ= 0.93

bottom illuminated slab geometry



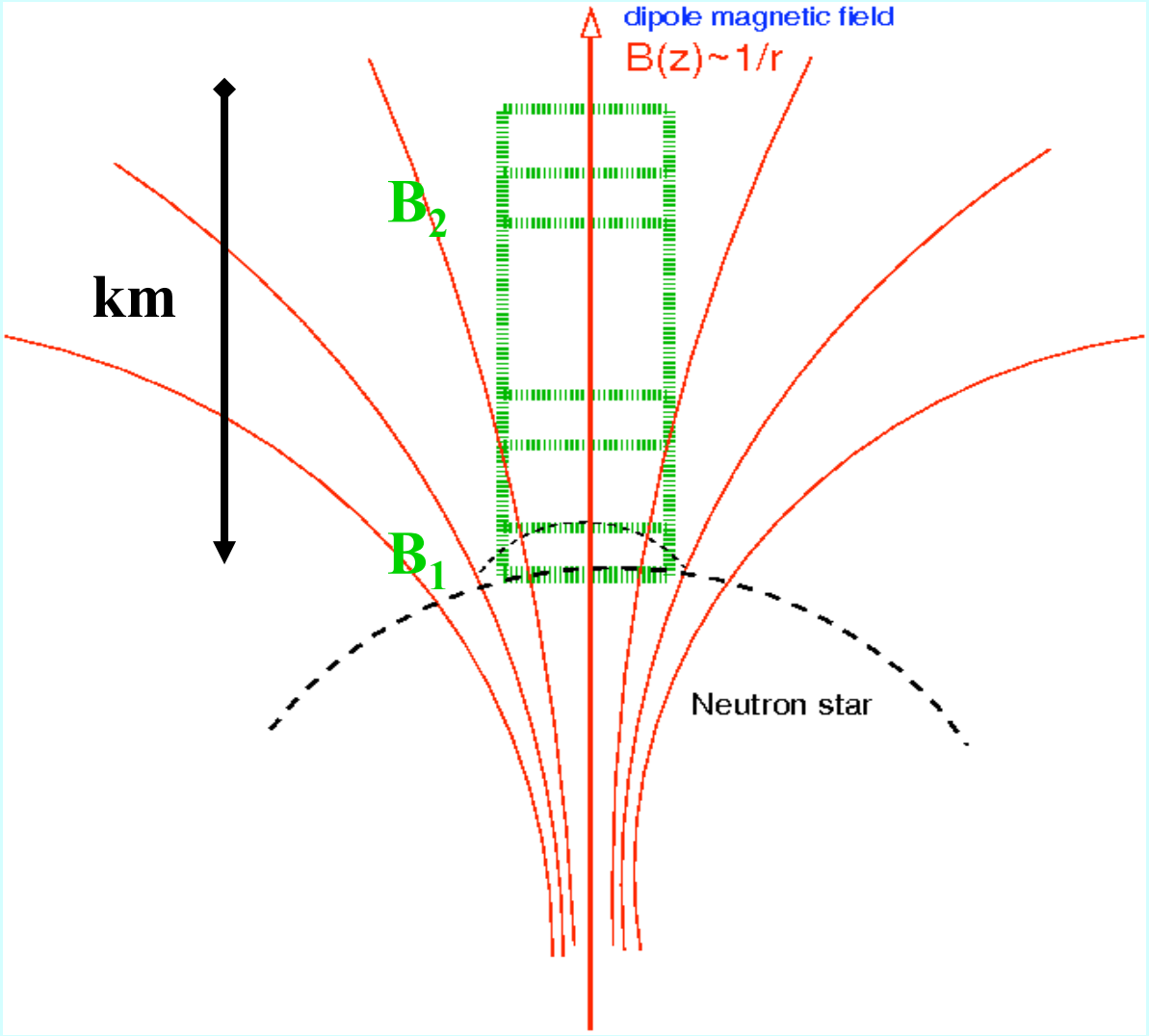
B=3.5 x10^{12} G

χ^2=1.3

χ^2=1.7

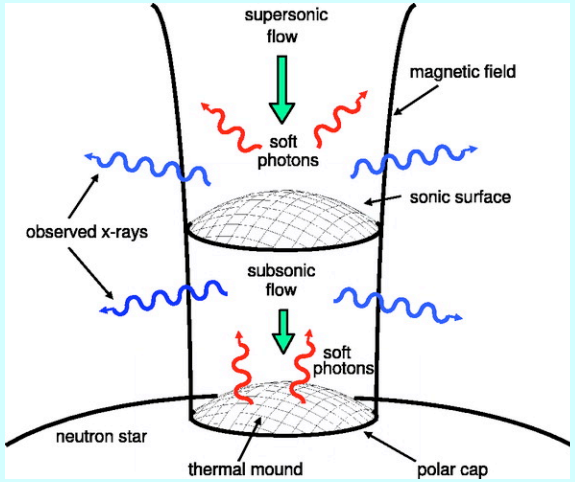
z=0.3

Parameter interpretation: what? Where?

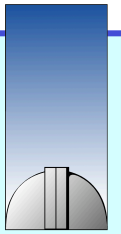


Location, size/geometry of line-forming region

(Becker & Wolff 2007)



Location and geometry of line-forming region



- Her X-1: ***Staubert et al. 2007***: Line forming region now at different height than years before (due to change of luminosity regime)

Secular change of cyclotron line energy (associated B-field)

- GX 301-2: ***Doroshenko et al. 2009*** (submitted): Line-forming region / observed X-rays from 10-20 km above the surface

B-field determined from timing much stronger than B-field from cyclotron lines

- 4U 0115+63: ***Ferrigno et al 2009***: lines form close to the NS surface, cyclotron cooling occurs at 1.7 km above

different B as fit result from continuum radiation model (cyclotron emission) than from absorption line energies

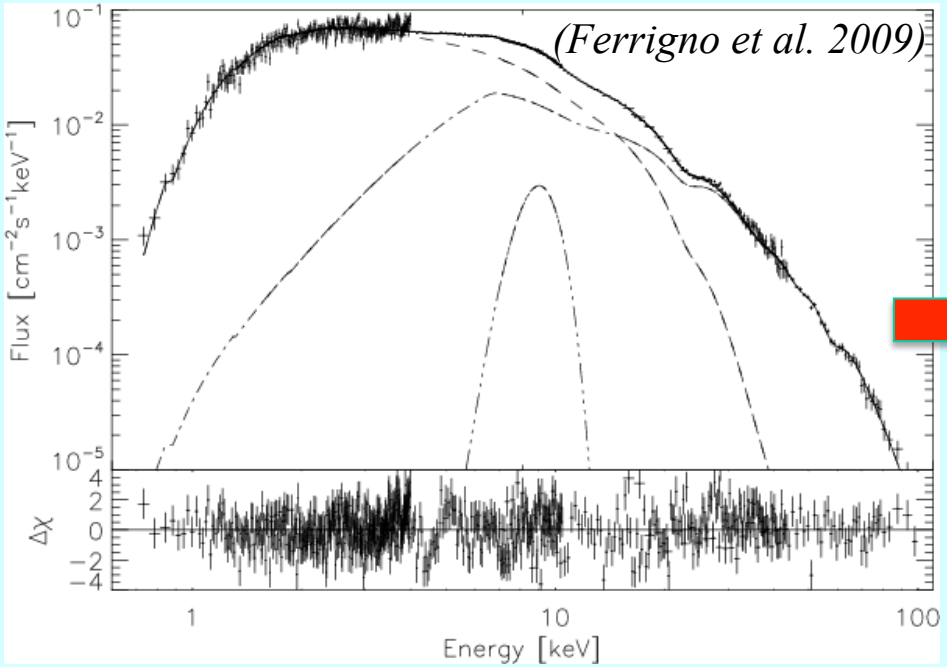
For studies of the Energy-Luminosity correlation, see also, e.g., Mihara (1998,2007), Gruber (2001), Mowlavi (2006), Tsygankov (2006), Nakajima (2006,2008)

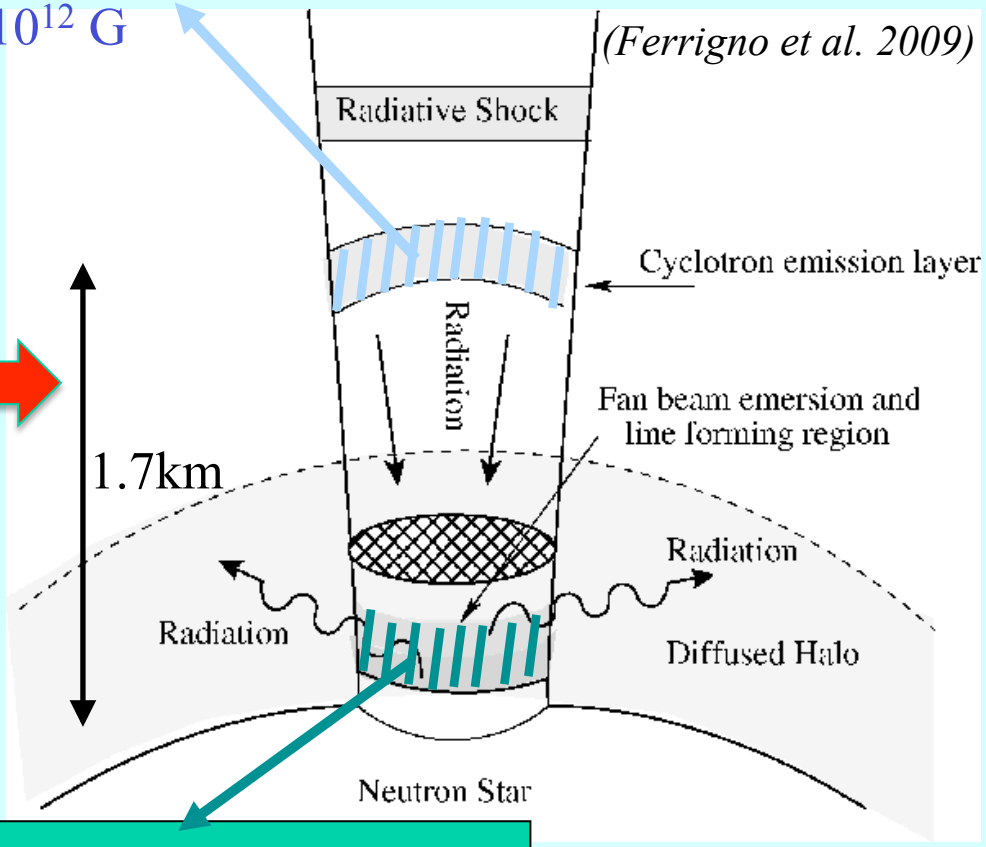
Line-forming region (*Ferrigno 2009*)

AIP

Cyclotron emission/cooling:

B=0.6 x10^{12} G





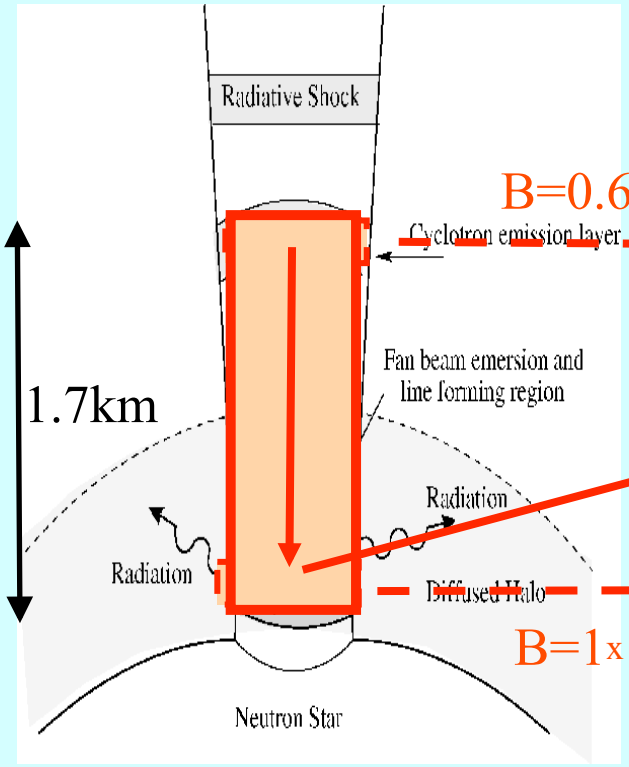
Need separate parameter B for good fit of the continuum

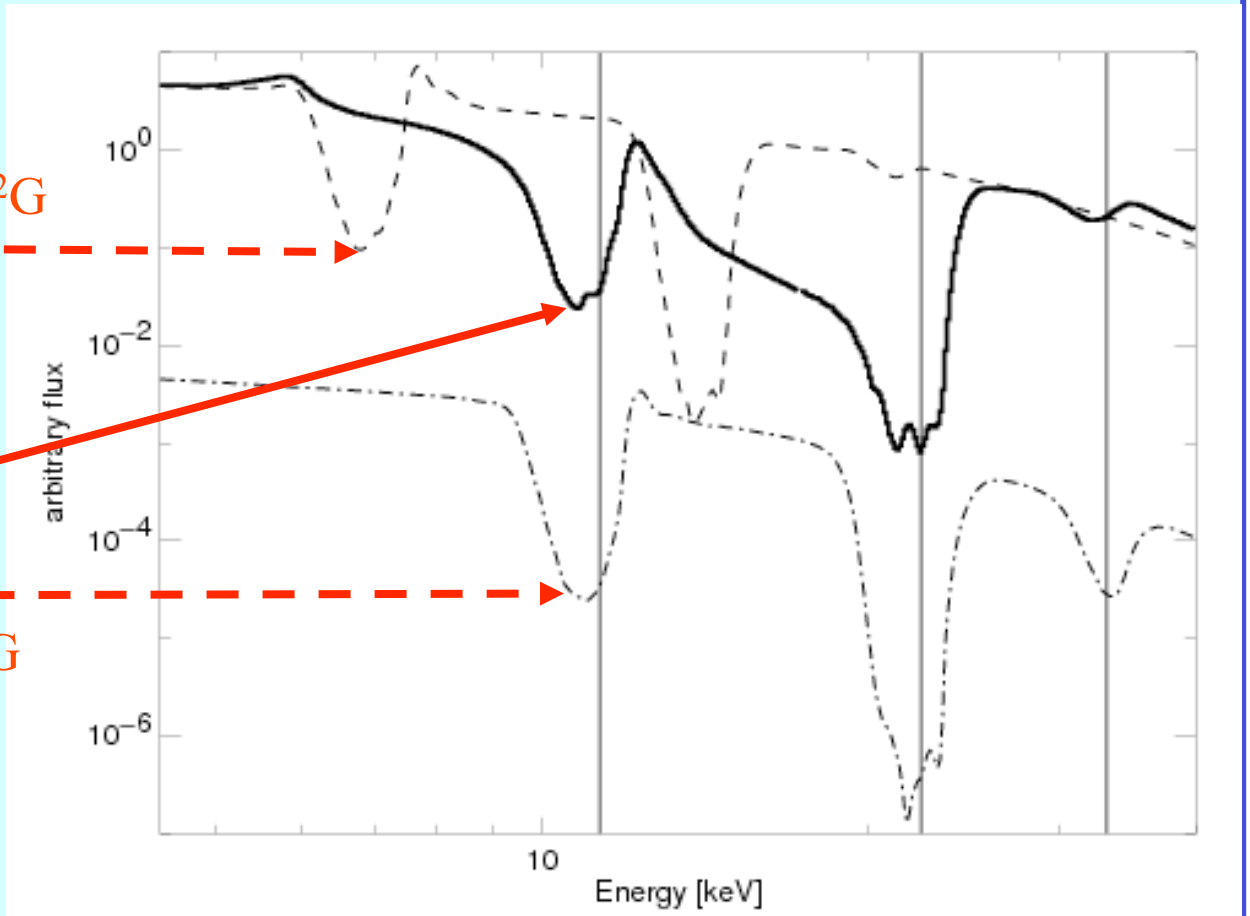
Cyclotron scattering/absorption

B=1x10^{12} G

A possible scenario for 4U 0115+63 (cyclomc)

AIP



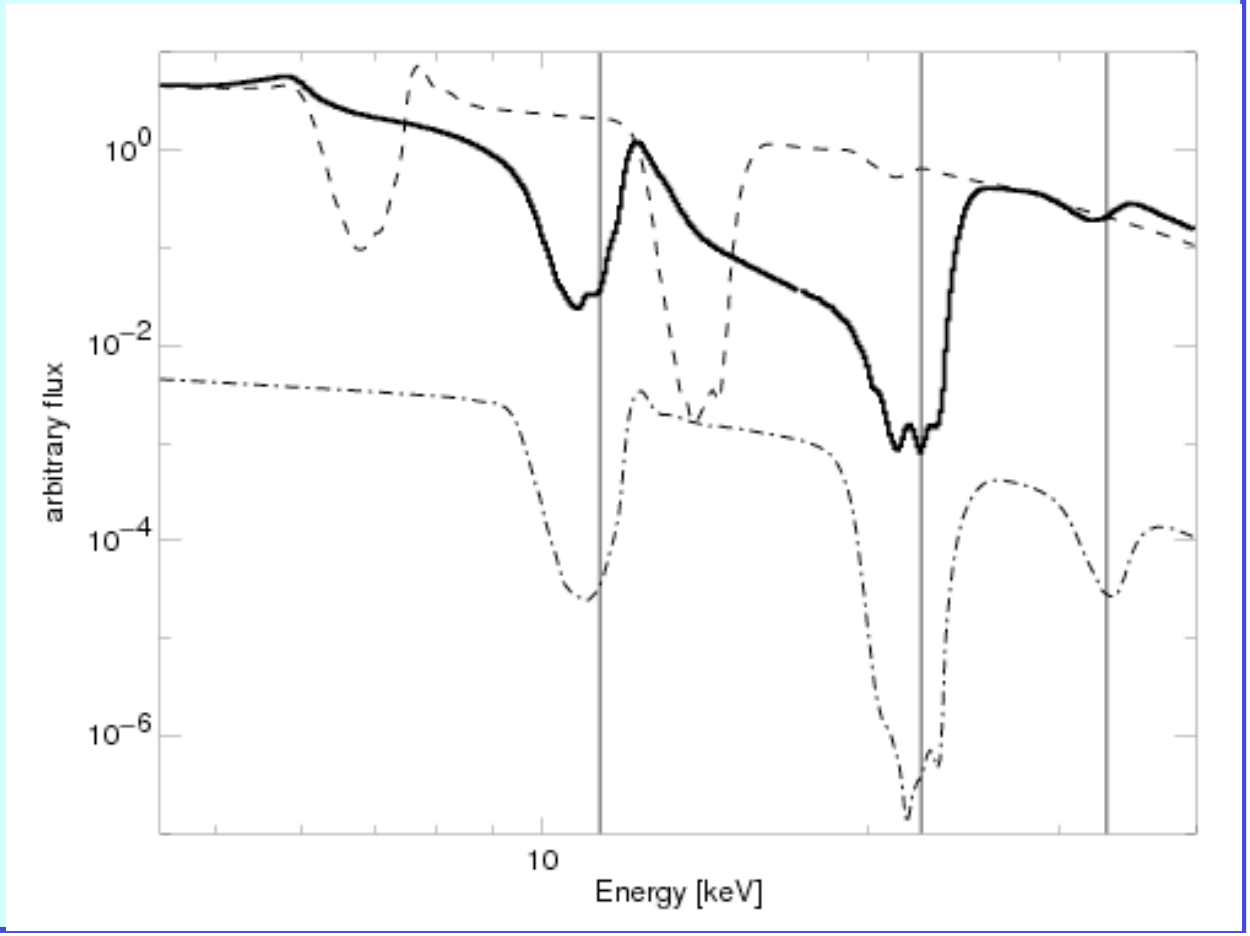


A possible scenario for 4U 0115+63 (cyclomc)

AIP

explains different findings at once:

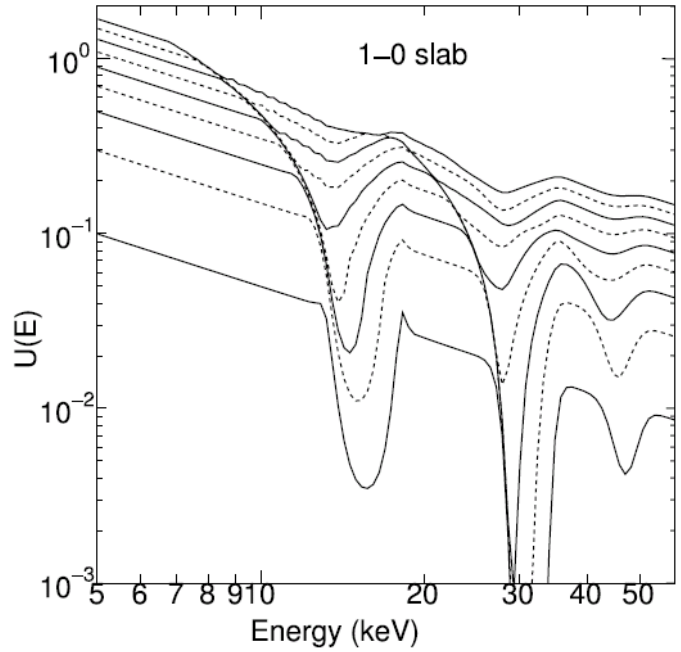
- differences in emission B and absorption B (*Ferrigno 2009*)
- Special line ratios of the source (e.g., *Heindl 1999 Santangelo 1999*)
- lines are broader and shallower than simulations (for constant B), e.g., *Ferrigno 2009*



Mechanism to produce broad and shallow lines

AIP

(*Nishimura 2008*)



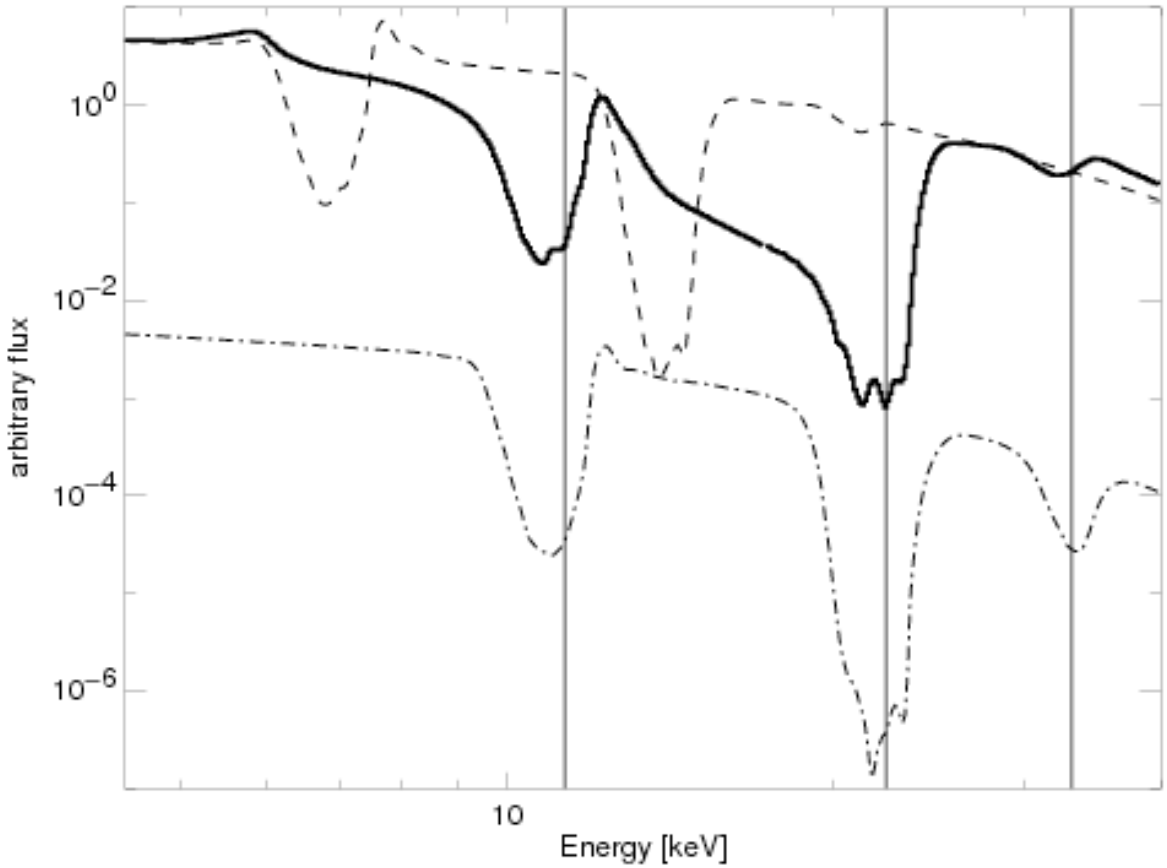
- Different geometrical settings
- (fundamental) line(s) disappear
- Very broad and shallow profiles

Shape matters

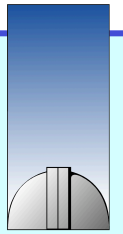
AIP

- Line peak „remembers“ the last encountered B-field
- Line shape reflects the B-field structure along the photon path

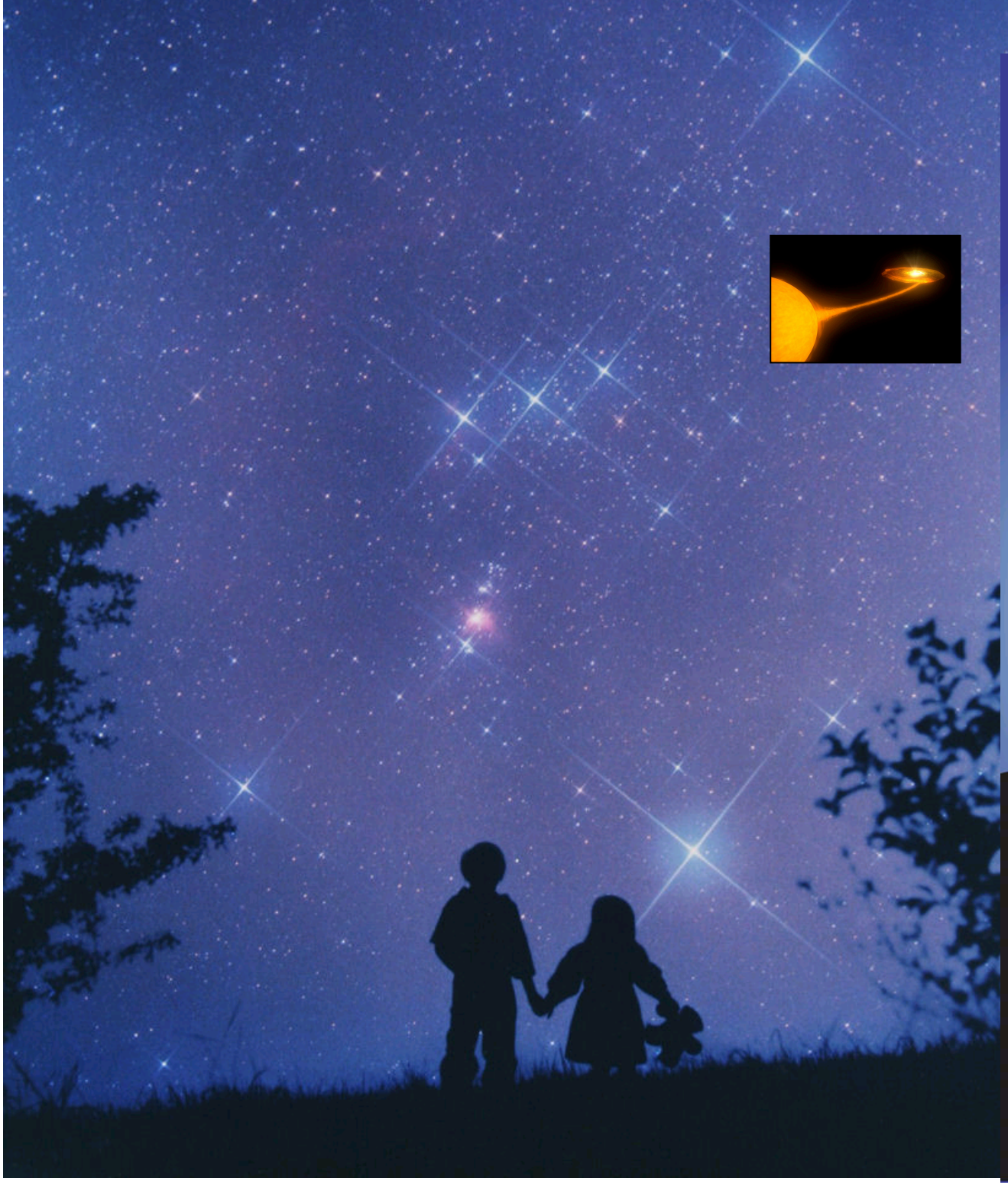
(for a smoothly increasing or decreasing field)



Conclusions



- Cyclotron lines can probe the complex magnetic field structure in detail
- Physics-based fitting models are available now for quantitative analysis of observed lines (Schönherr 2007) and interpretation of the continuum radiation processes (Becker&Wolff 2007, Ferrigno 2009) in the accretion column
- With progress in X-ray instrumentation, improved energy resolution → in-depth analysis of shape
- Complete approach (continuum+lines) for ~~complete~~ better ☺ picture of the accretion column



THE UNIVERSE
YOURS TO DISCOVER

INTERNATIONAL YEAR OF
ASTRONOMY
2009