Spectroscopy of Cyclotron Resonance lines

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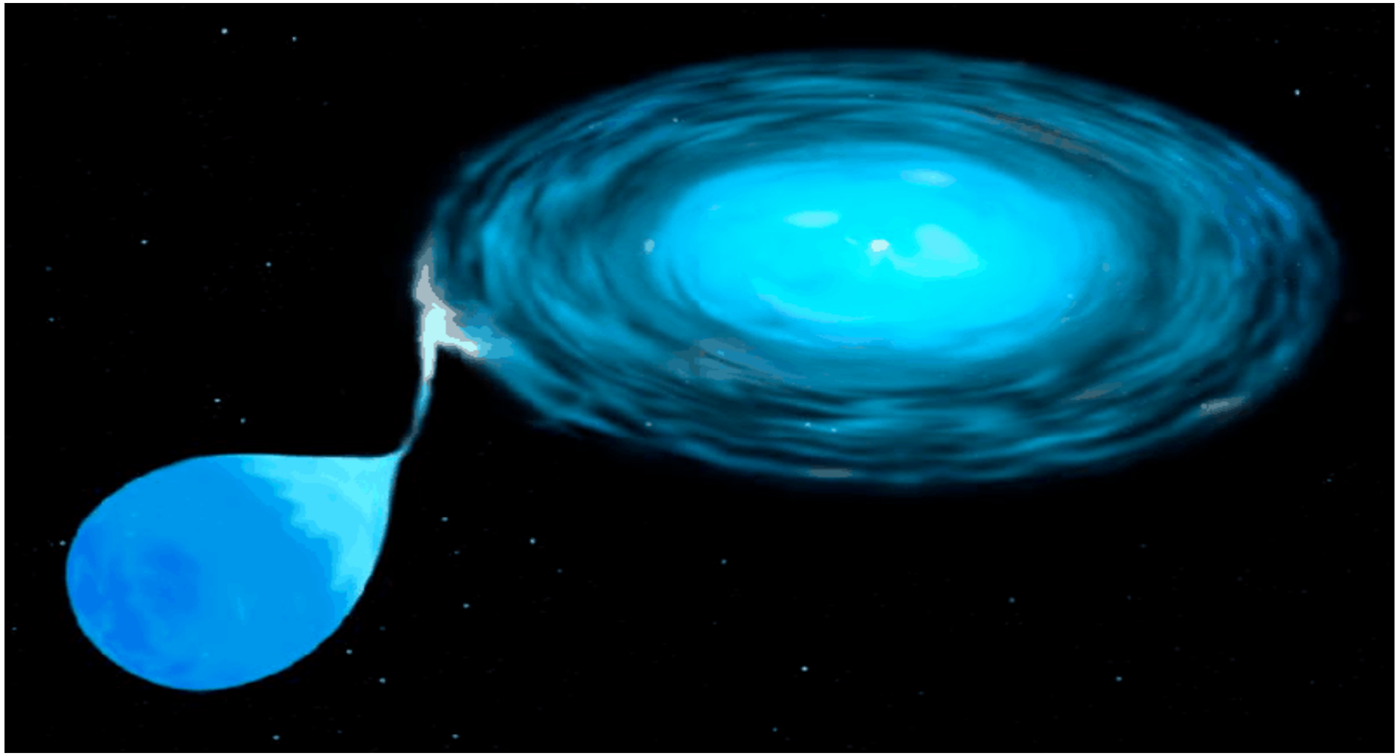
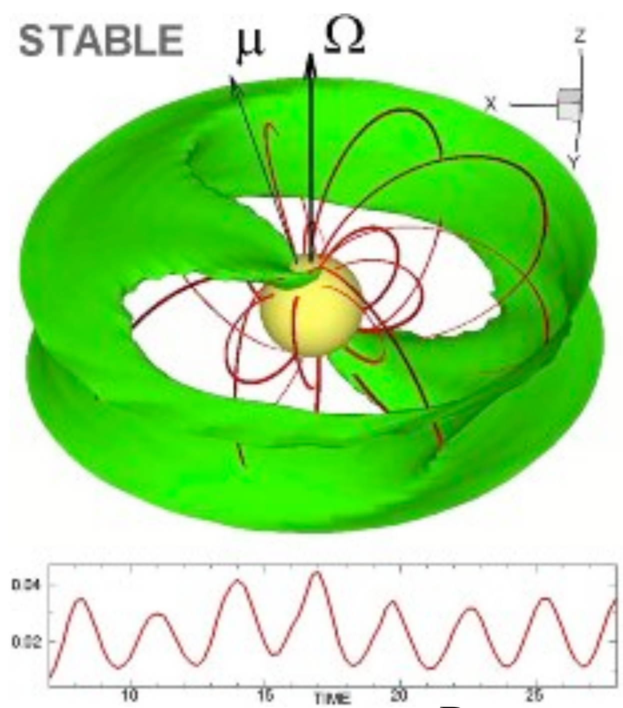
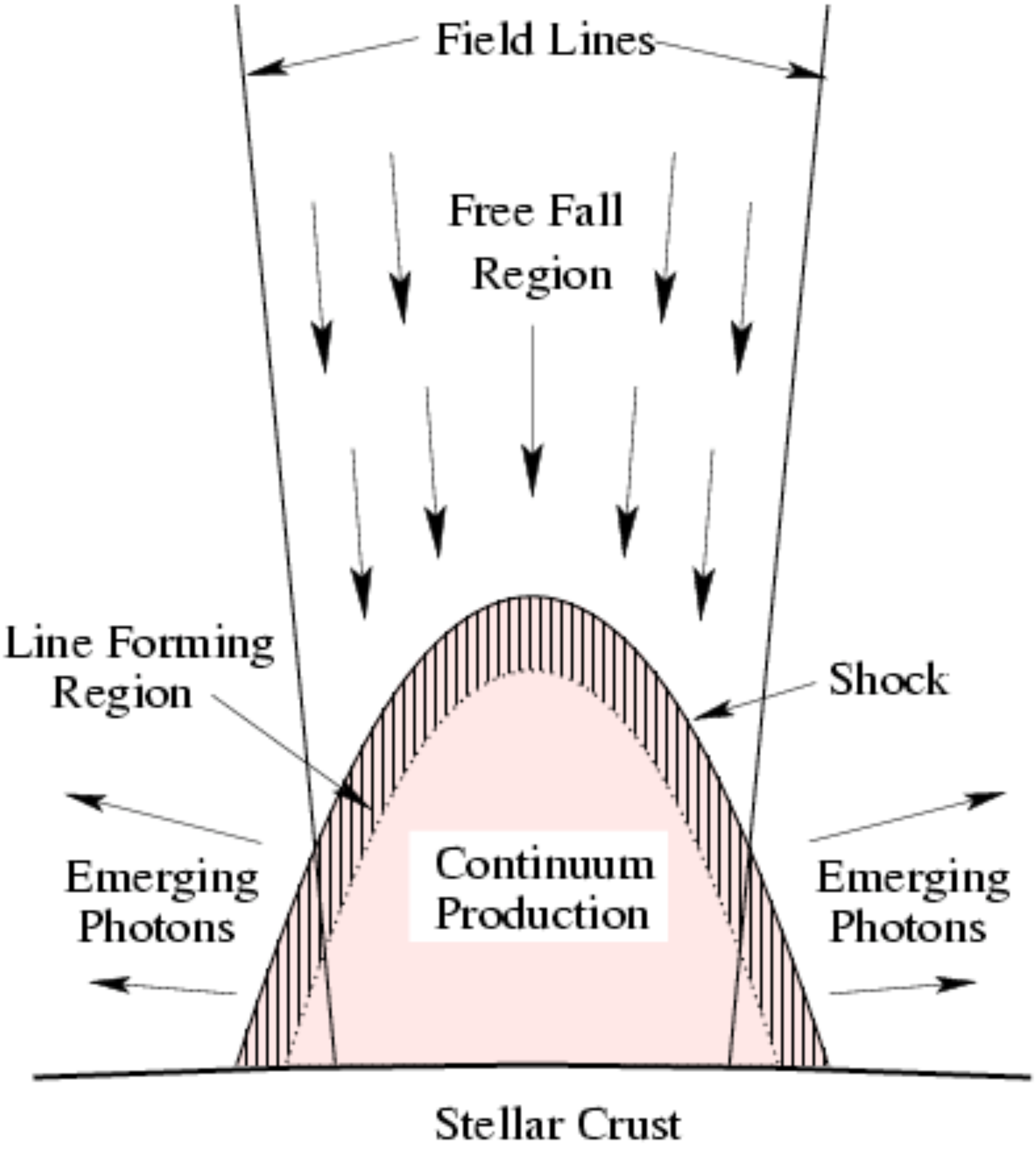


Accretion onto strongly magnetized neutron stars



Romanova, Kulkarni and Lovelace 2008



Heindl et al 2004

Non-relativistic

$$E_{\rm cyc}\,(\text{fund.}) = \frac{\hbar e B}{mc} = 11.6\,B_{12}\ \text{keV}\ (\text{e}^-)$$

$$6.3\,B_{15}\ \text{keV}\ (\text{p}^+)$$

Relativistic

$$E_{\rm cyc} = \frac{mc^2}{\sin^2\theta}\left[\left(1 + 2n\frac{B}{B_{\rm crit}}\sin^2\theta\right)^{1/2} - 1\right]$$

$$B_{\rm crit} = \frac{m^2c^3}{e\hbar} = 4.4\times10^{13}\ \text{G (for e}^-)$$

Observed E_{cyc} will also contain gravitational redshift effect

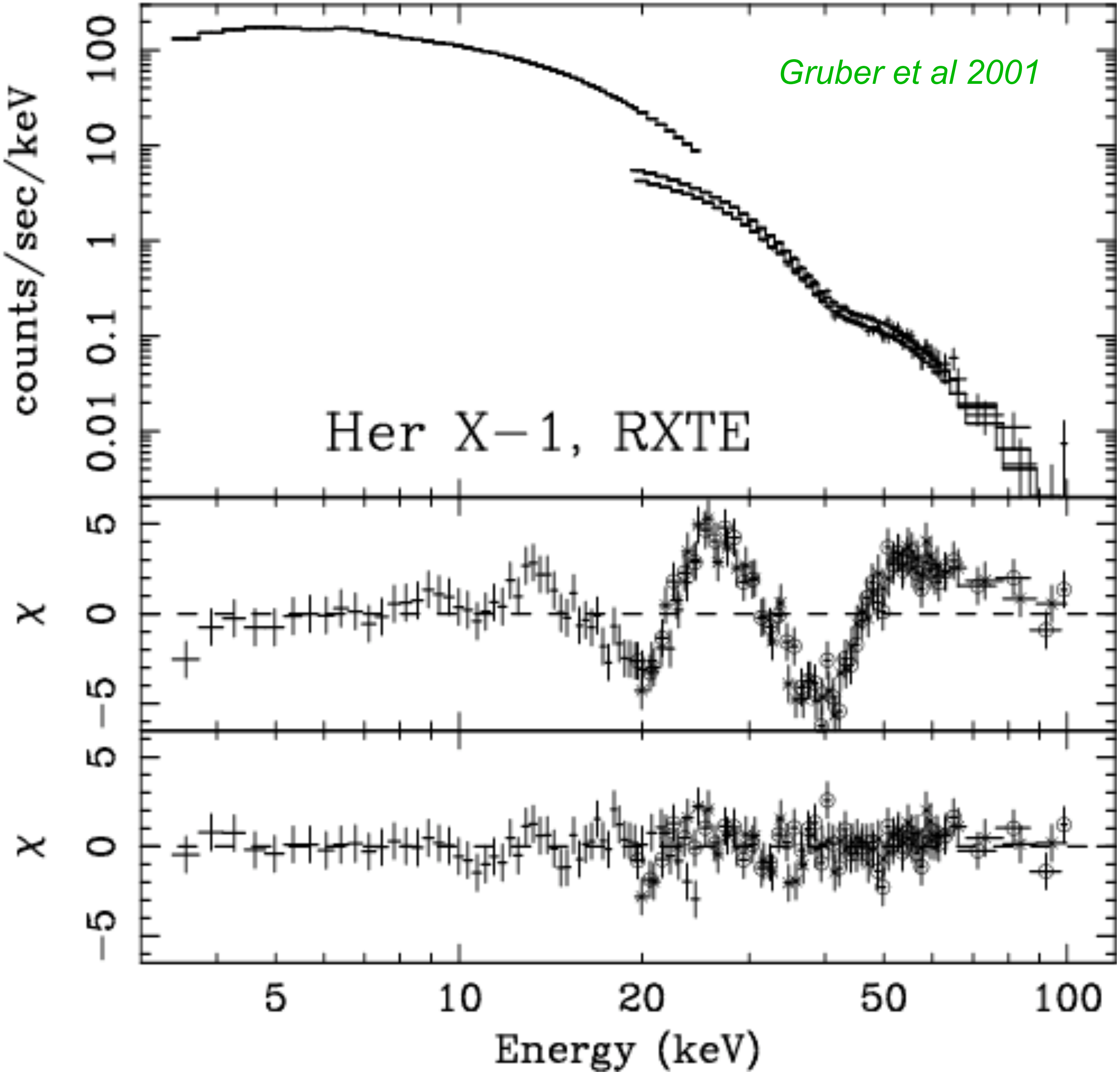
Cyclotron Resonance line Spectroscopy

Detailed study and monitoring of cyclotron lines can determine

- Field distribution at the polar cap
- Long-term and short-term effects of accretion on the stellar magnetic field.

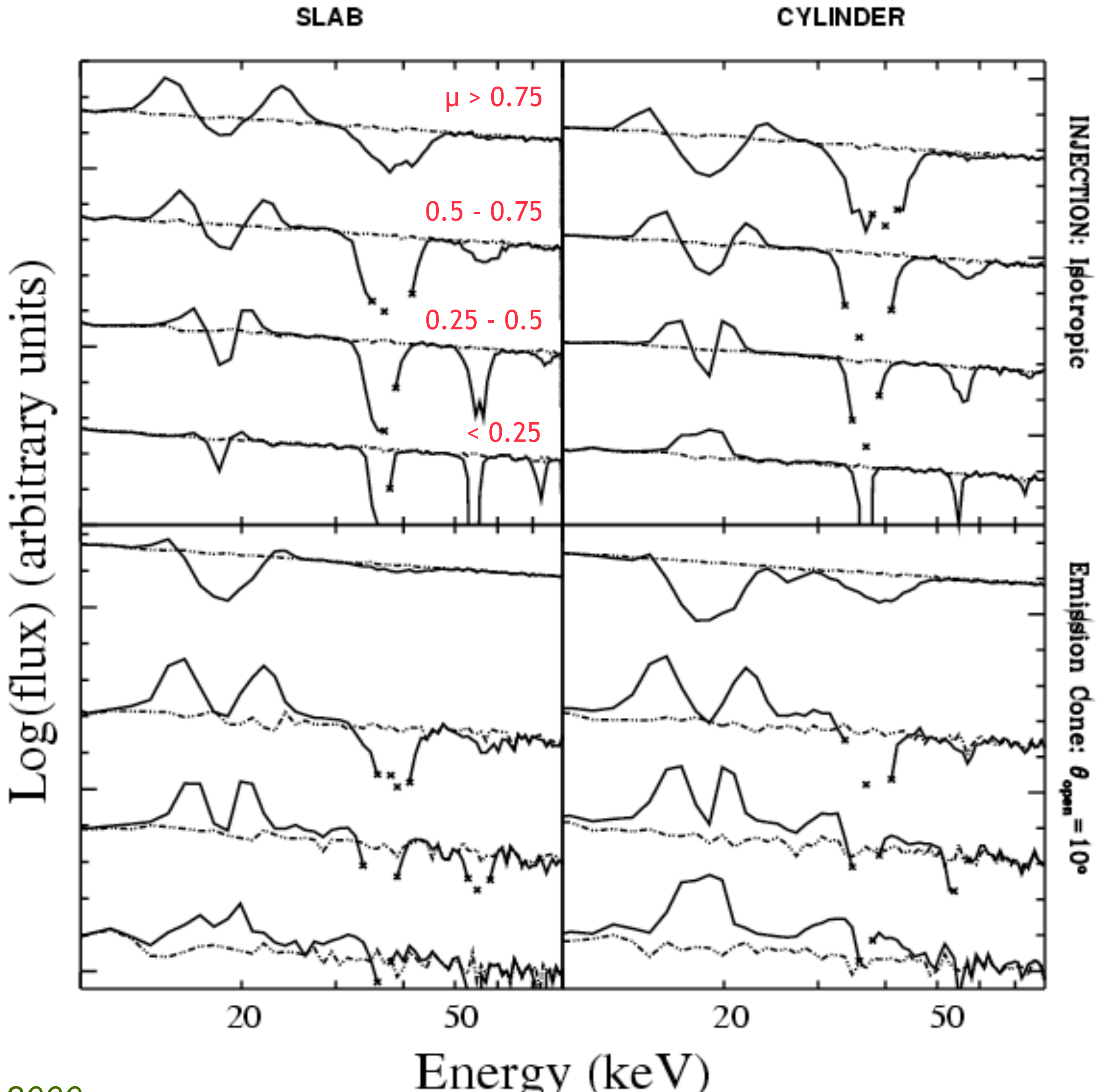
First cyclotron line was detected from the bright X-ray binary Her X-1 using a balloon platform
(Trumper et al 1978)

Her X-1: *Neutron Star with a 2 Msun companion in beginning atmospheric Roche lobe overflow*



Predicted cyclotron line profiles at different angles to the magnetic axis

B = 1.7 TG



Araya-Gochez & Harding 2000

Cyclotron line profile expected to be strongly phase dependent.
Phase averaged spectrum will hide many important features, may even wash out the line.

Phase resolved spectroscopy best way to study CRSF.
Needs high sensitivity (good photon statistics).

Currently, statistics is poor in most of the observed CRSF.
Derived parameters strongly dependent on assumed background continuum spectrum.

Lines picked up from residuals after continuum fitting.

X-ray pulsar continuum models

Most common continuum spectral shapes used:

$$\mathrm{PLCUT}(E) = A\,E^{-b} \times \begin{cases} 1 & E < E_{cut} \\ \exp\left[(E_{cut} - E) / E_{fold}\right] & E > E_{cut} \end{cases}$$

$$\mathrm{NPEX}(E) = A\,(E^{-b} + f.E^{+c}) \times \exp\left[- E / E_{fold}\right]$$

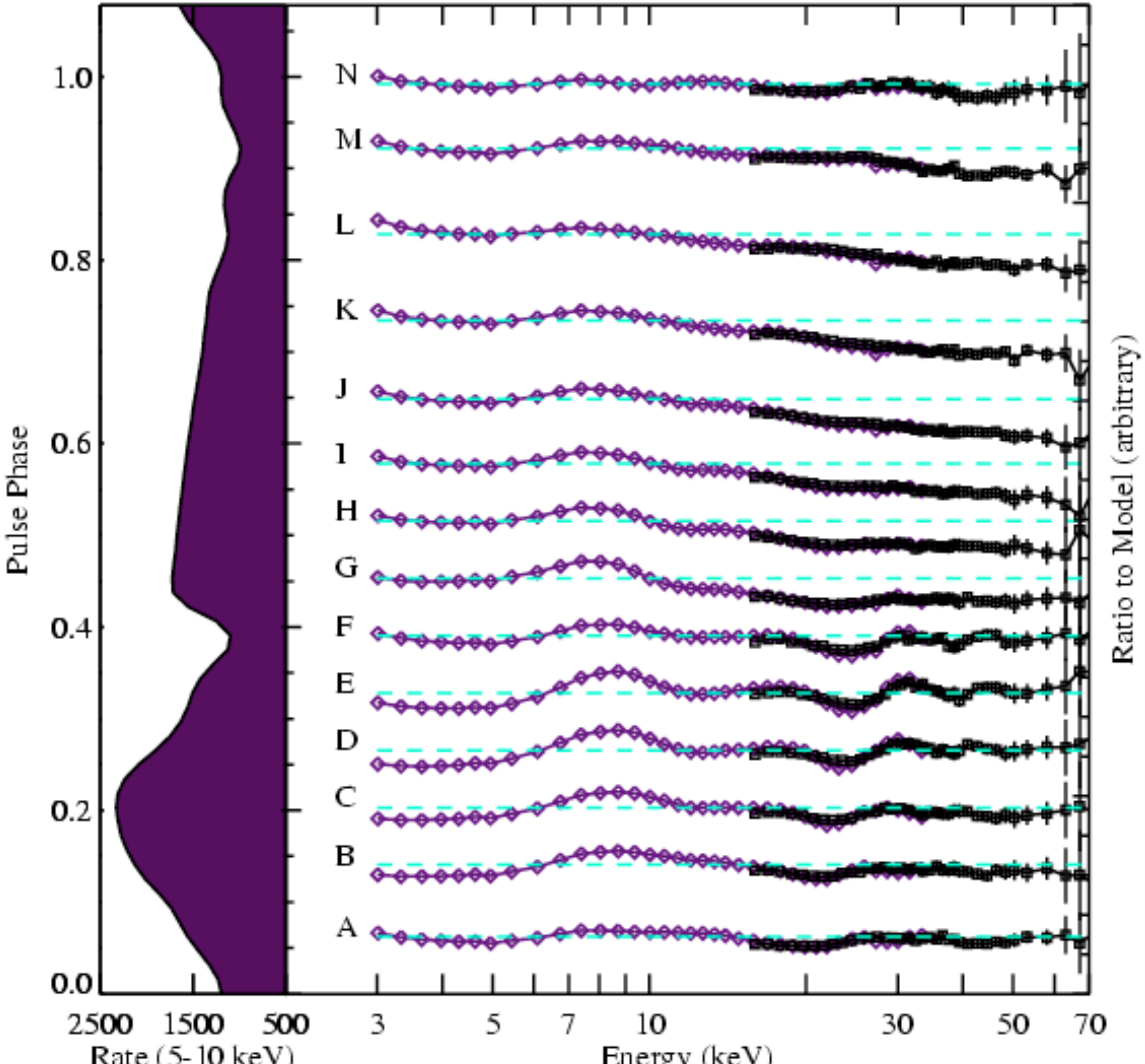
$$\mathrm{FDCUT}(E) = A\,E^{-b}\left\{\exp\left[(E - E_{cut}) / E_{fold}\right] + 1\right\}^{-1}$$

Models are empirical, no strong physical basis.

Line parameters depend on the continuum model used.

Some physical modelling attemped (e.g. Becker and Wolff 2007) but difficult to compute and not widely available

4U0115+63



Heindl et al 2004

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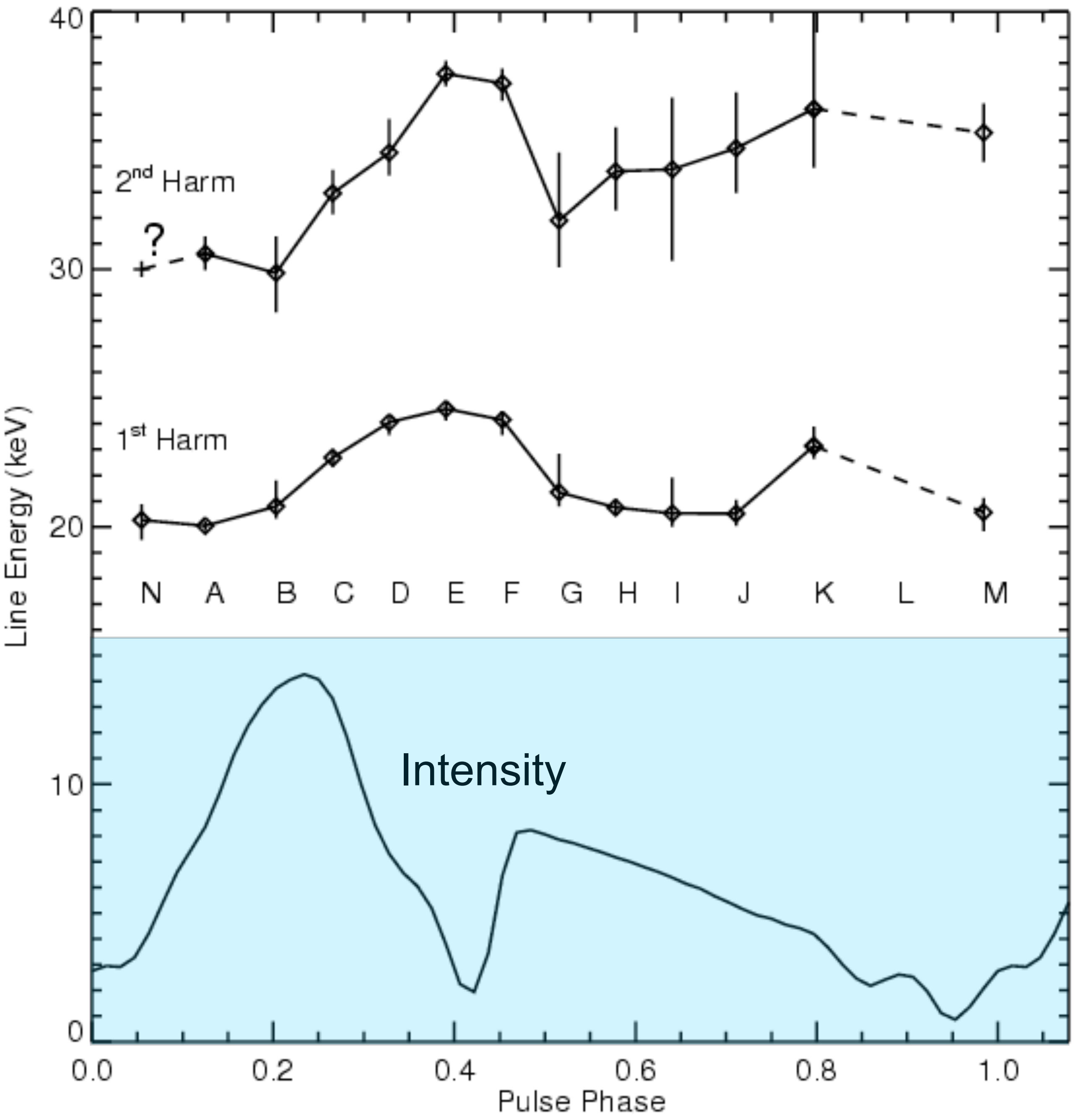
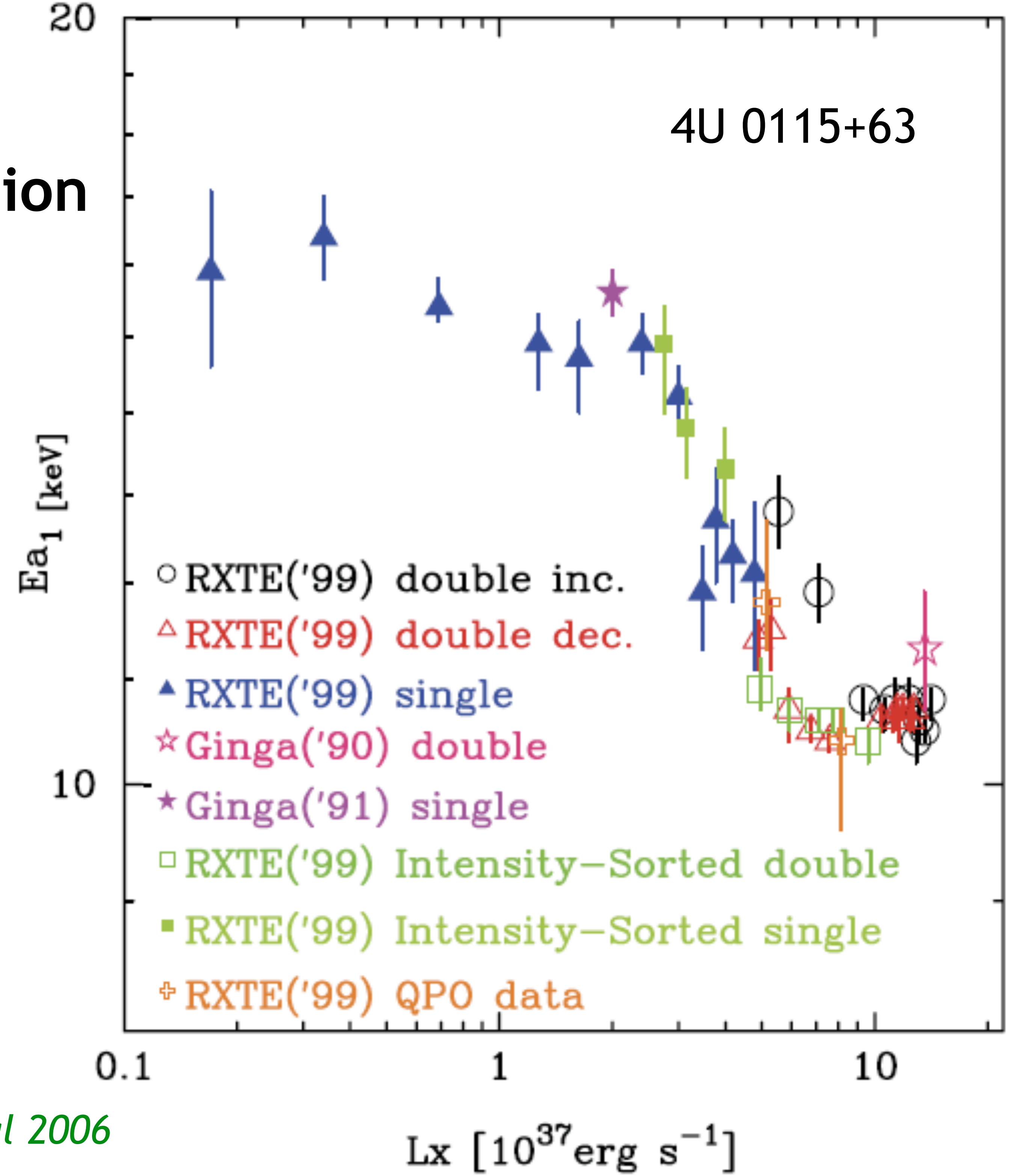


Heindl et al 2004

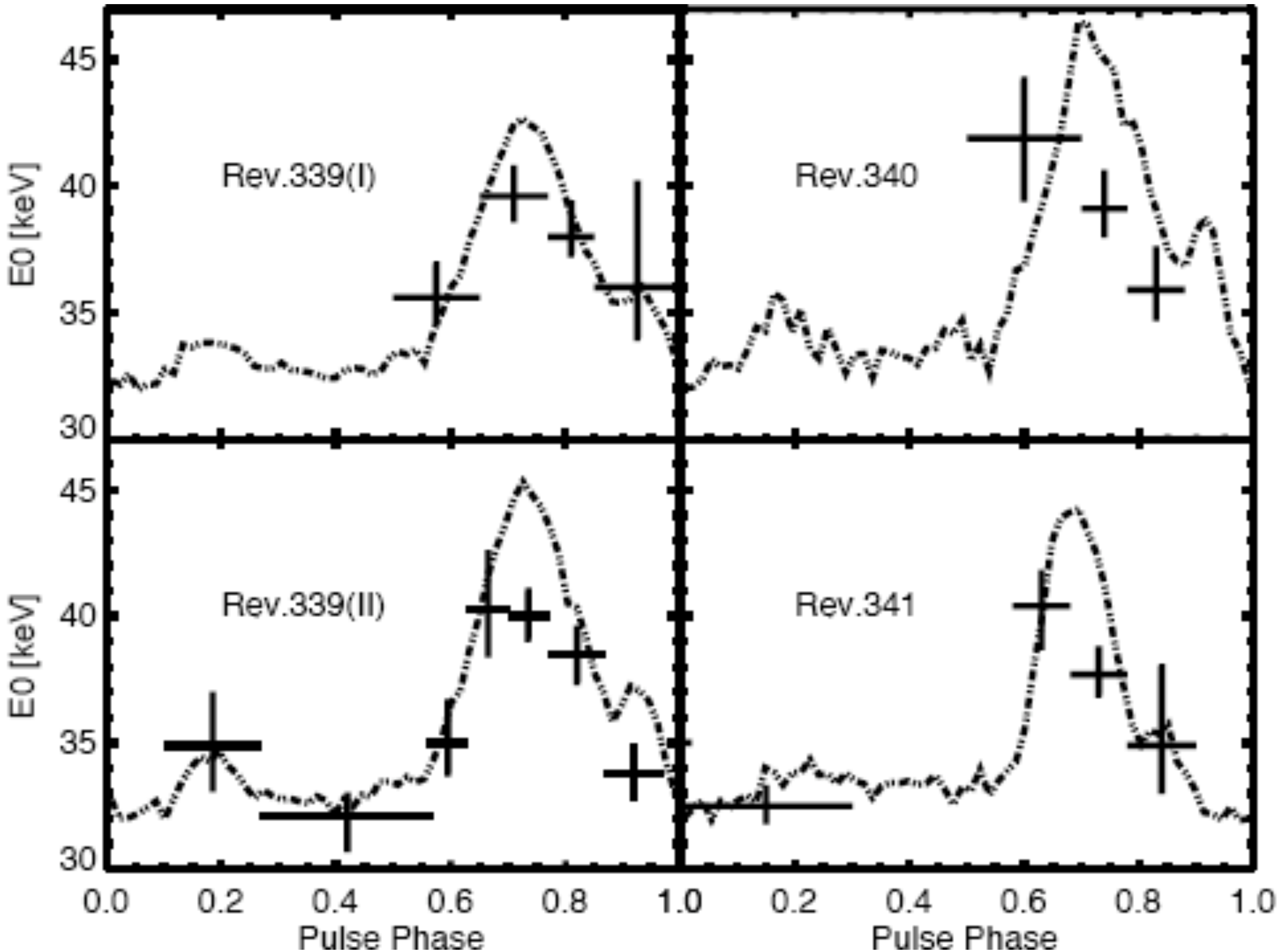
E_{cyc} - L_X correlation



Larger L_X
=> more accretion
=> higher mound
=> line formation further away from the star
=> smaller local field strength
=> lower E_{cyc}

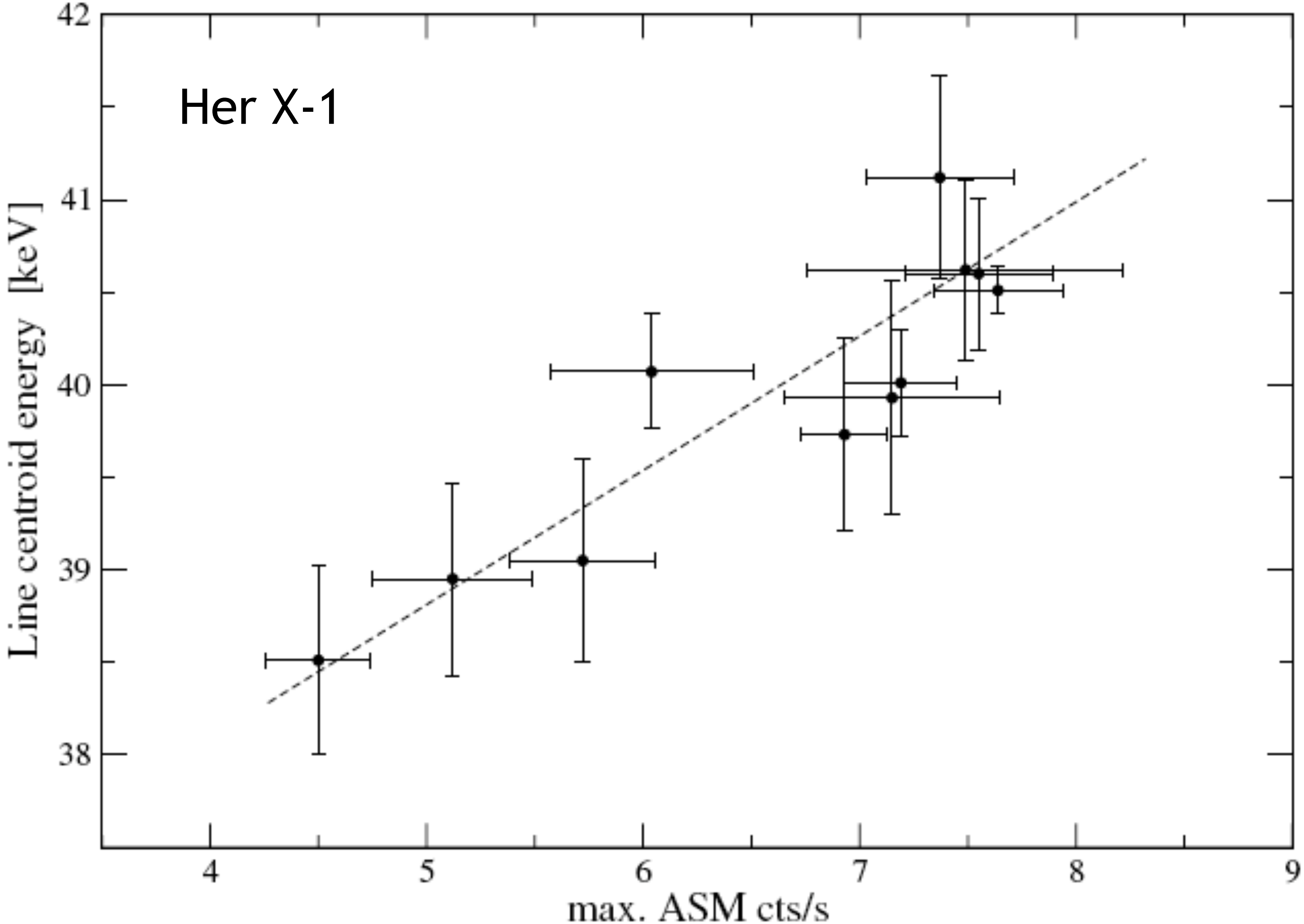
Nakajima et al 2006

INTEGRAL observations of Her X-1 CRSF



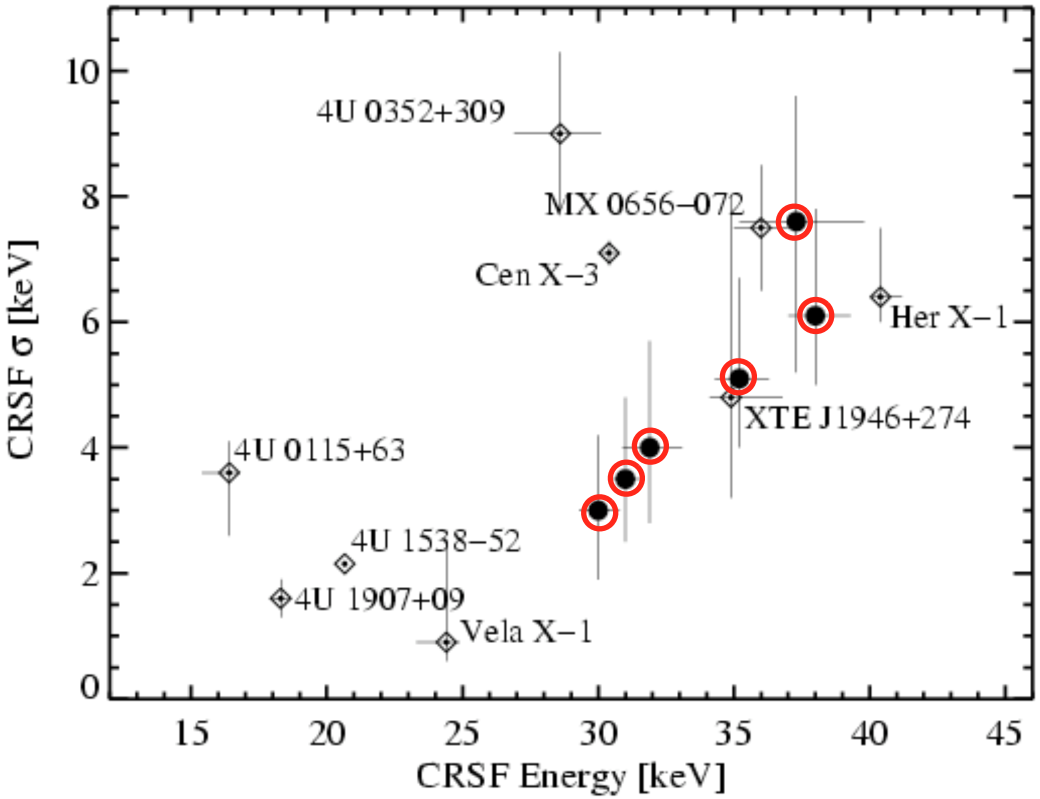
Klochkov et al 2007

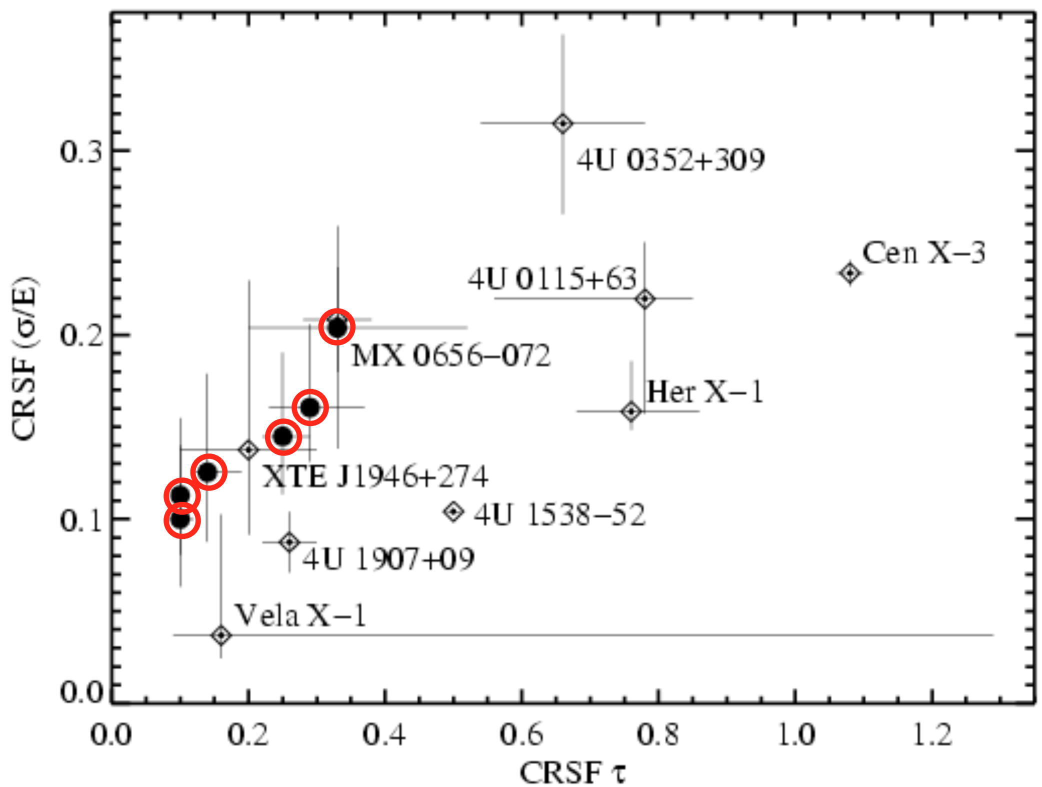
E_{cyc} - L_X correlation



Staubert et al 2007

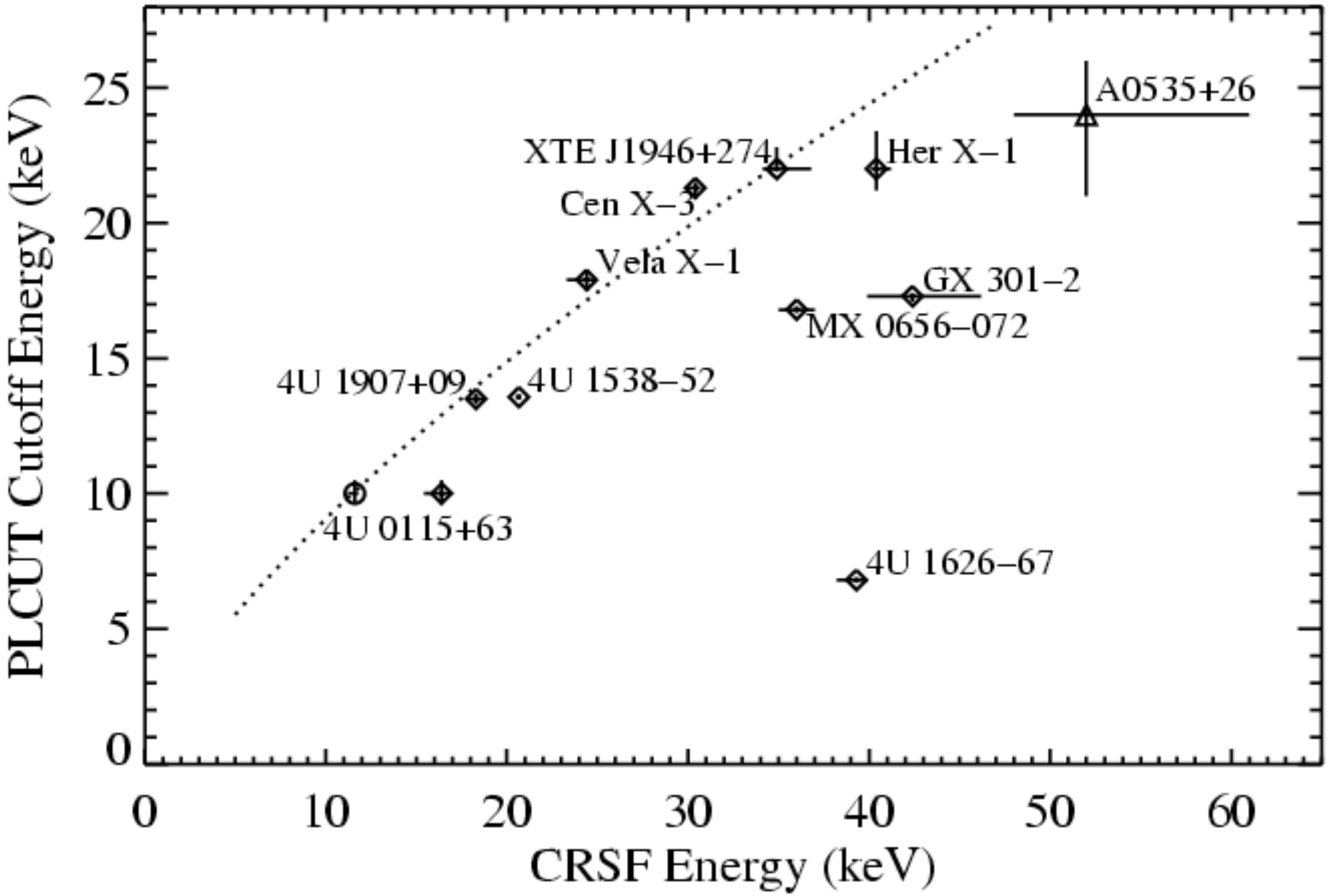
Correlations in CRSF characteristics





Phase resolved CRSF in GX 301-2 ○

Kreykenbohm et al 2004



Coburn et al 2002

INTEGRAL observations of LMXB pulsar GX 1+4:

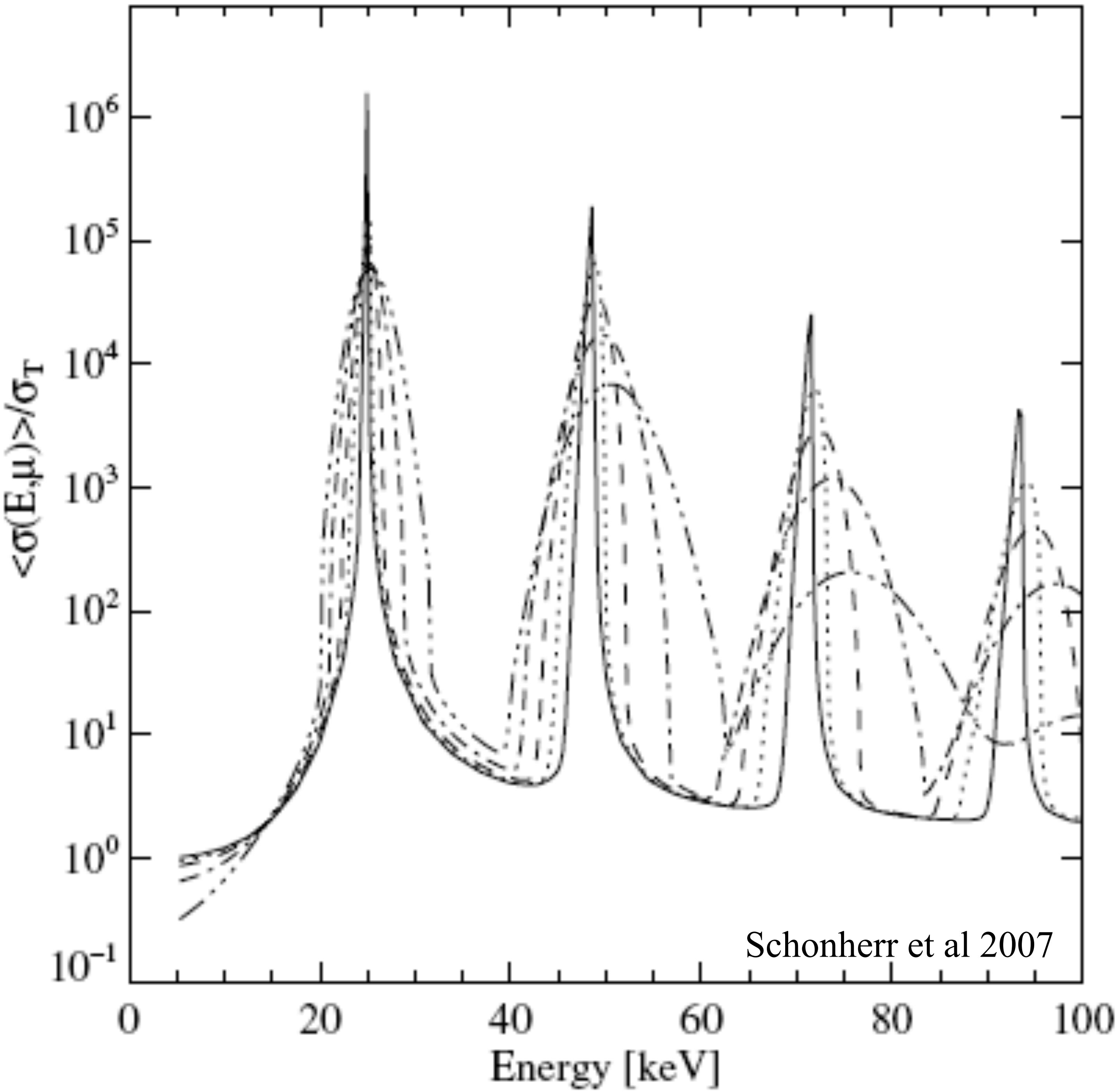
- ~34 keV CRSF at certain pulse phases

  (may have been seen with BeppoSAX: Naik et al '05)

- No CRSF in phase averaged spectrum
- Implied B ~ 3 x 10^{12} G ....*lower* than that inferred from spin-up rate

Ferrigno et al 2007

Modelling cyclotron spectra



Cross sections:

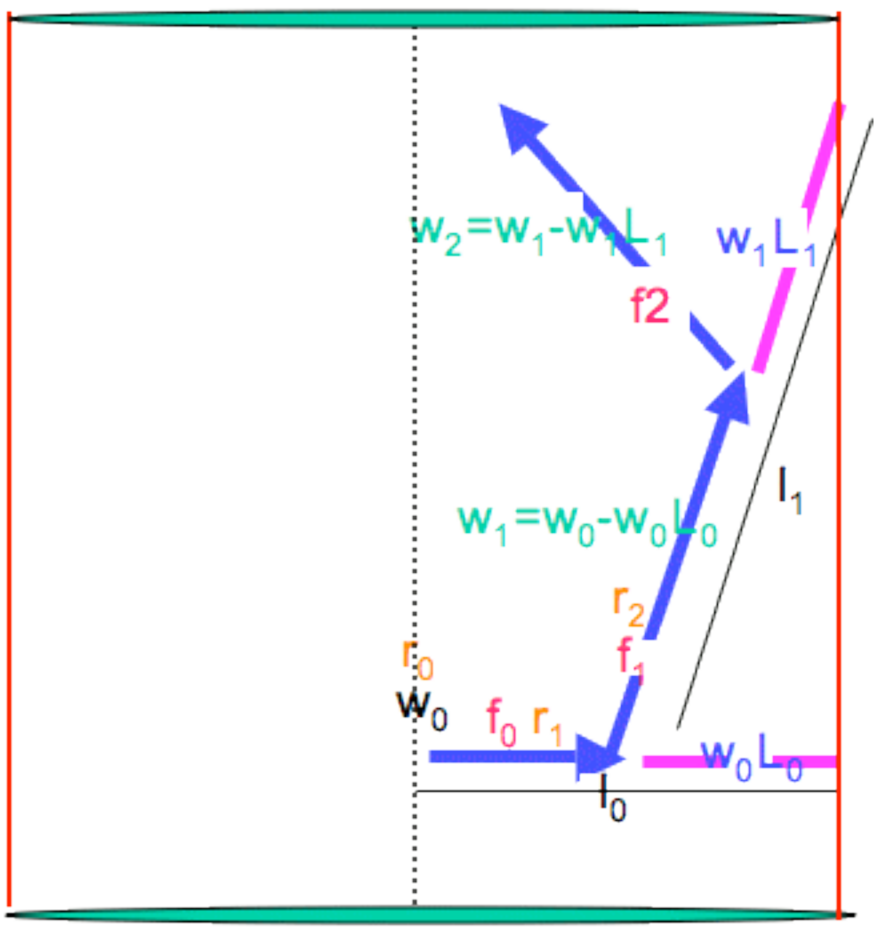
Derived from RQM
(Araya-Gochez and Harding 2000)

Depend on angle, polarization and electron momntum

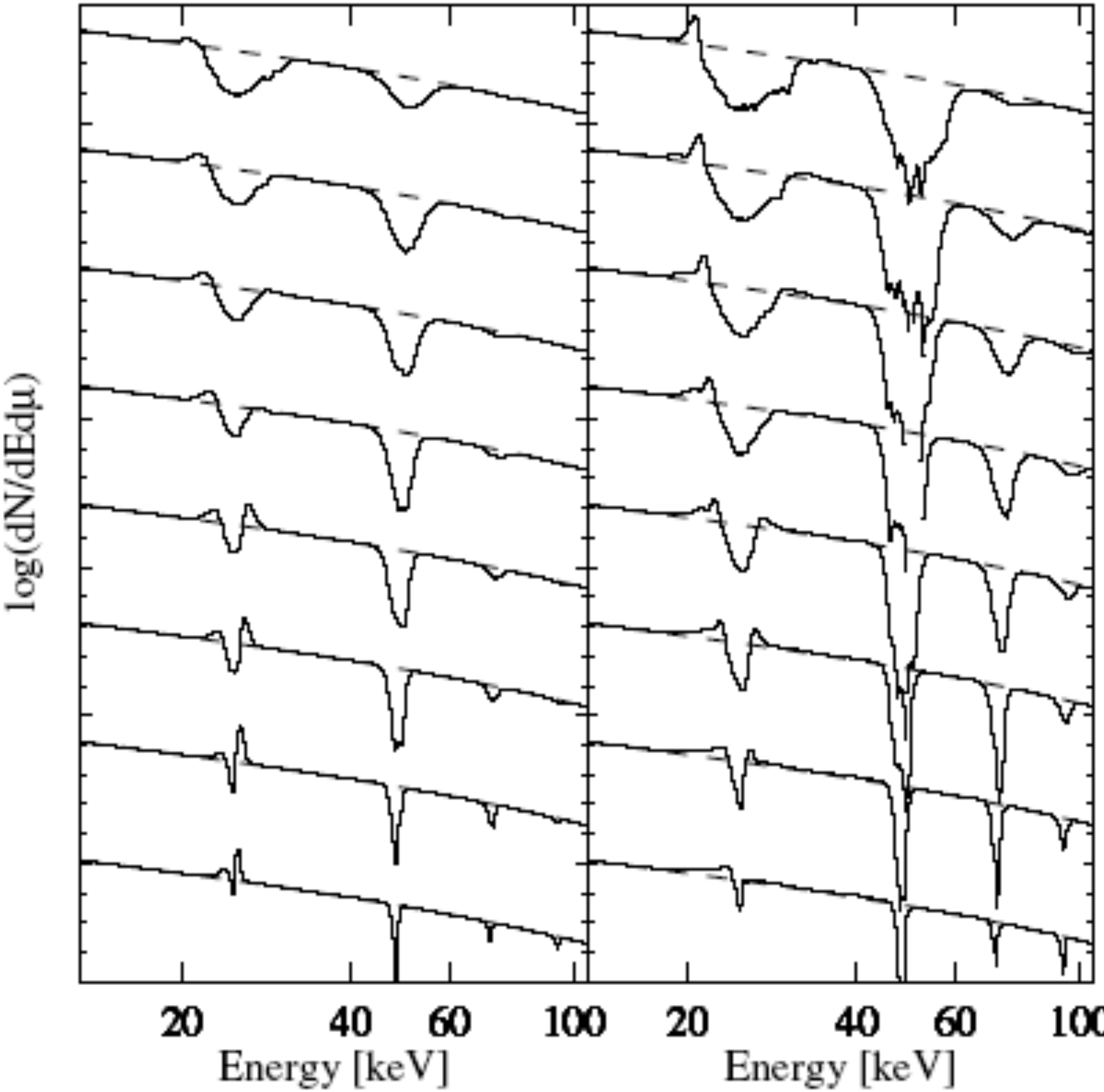
Need to compute at every step

Modelling cyclotron spectra

Monte-Carlo simulation with weights

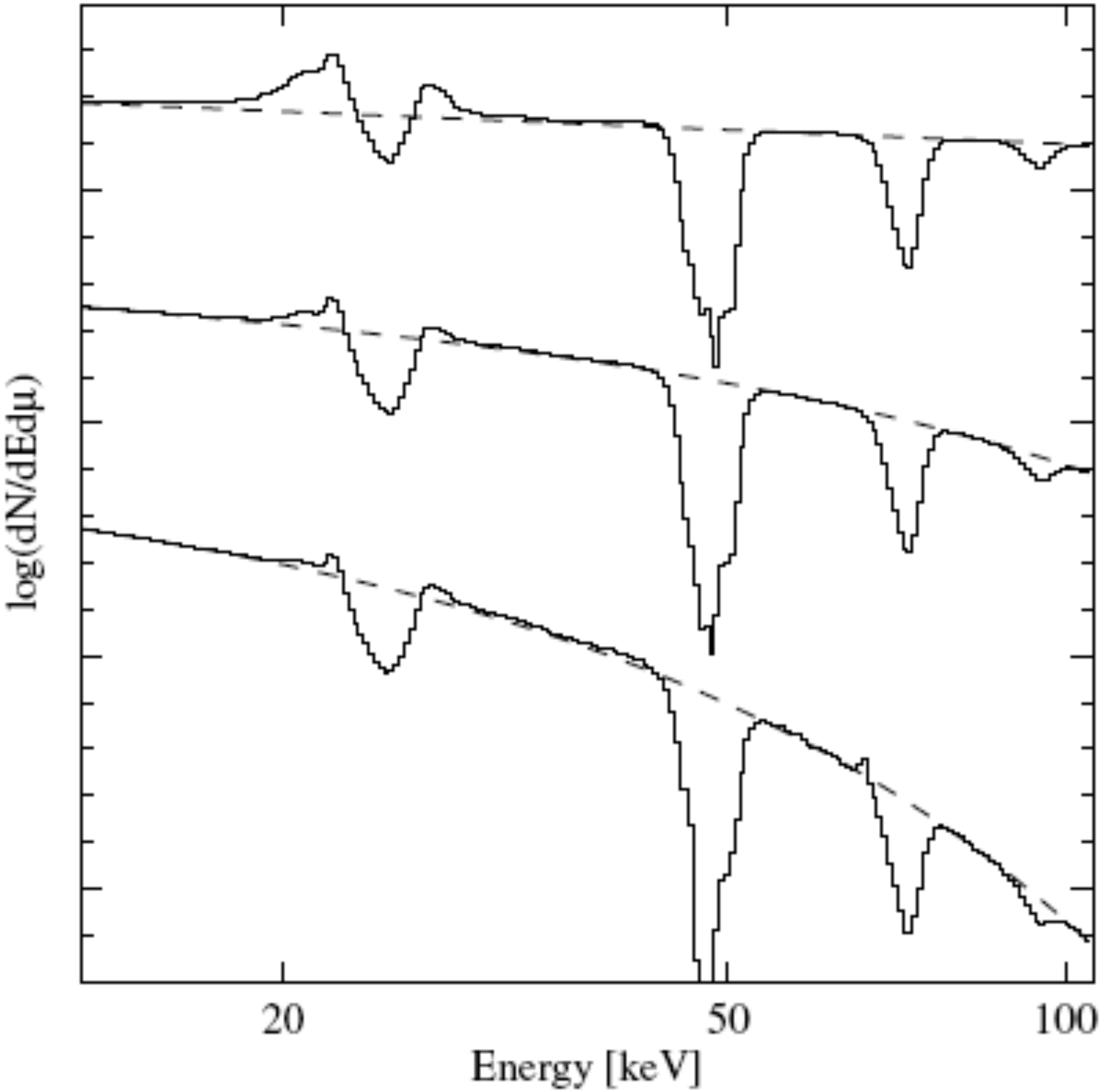


Sandeep Kumar 2009



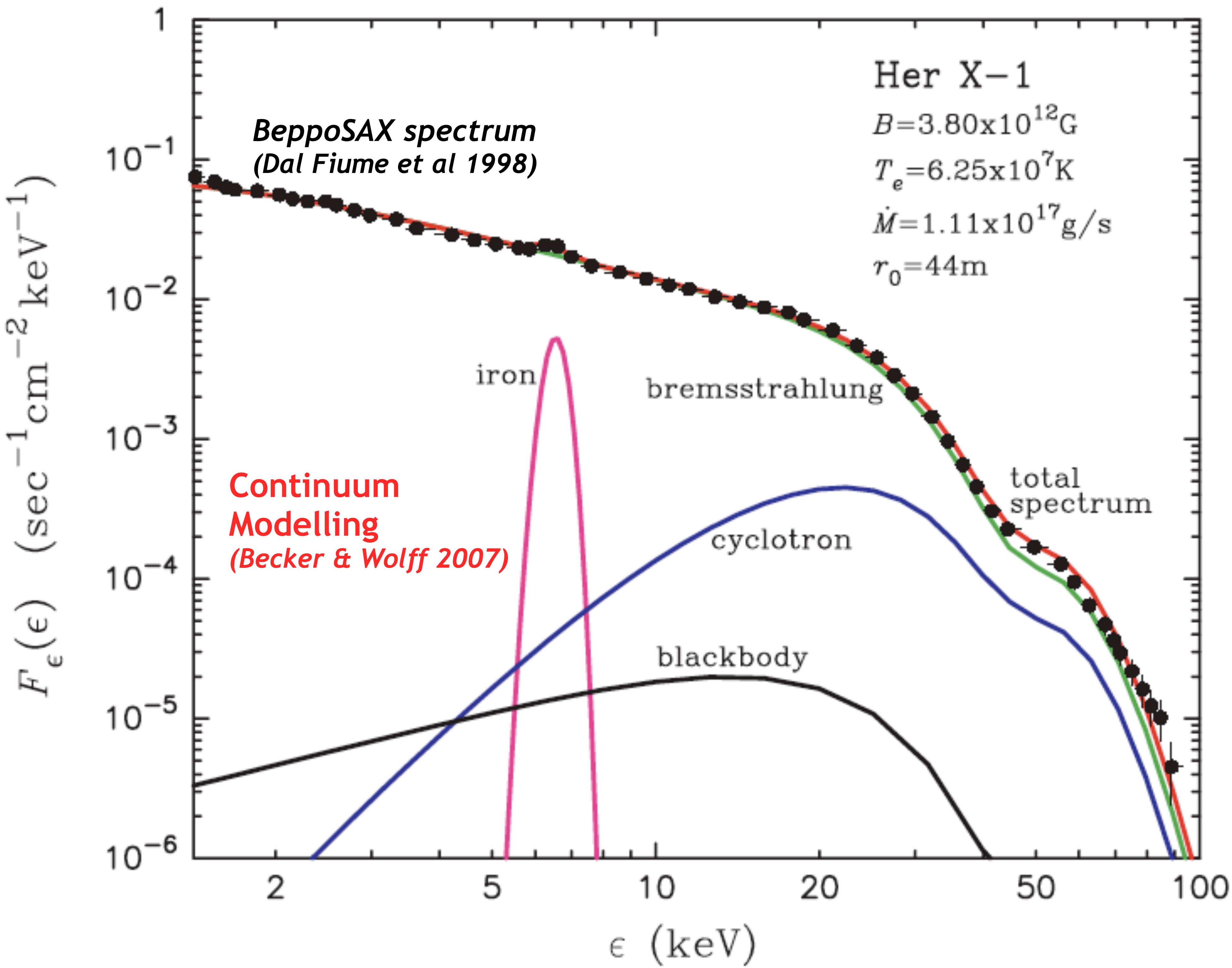
Angle Dependence

Schonherr et al 2007



Continuum Dependence

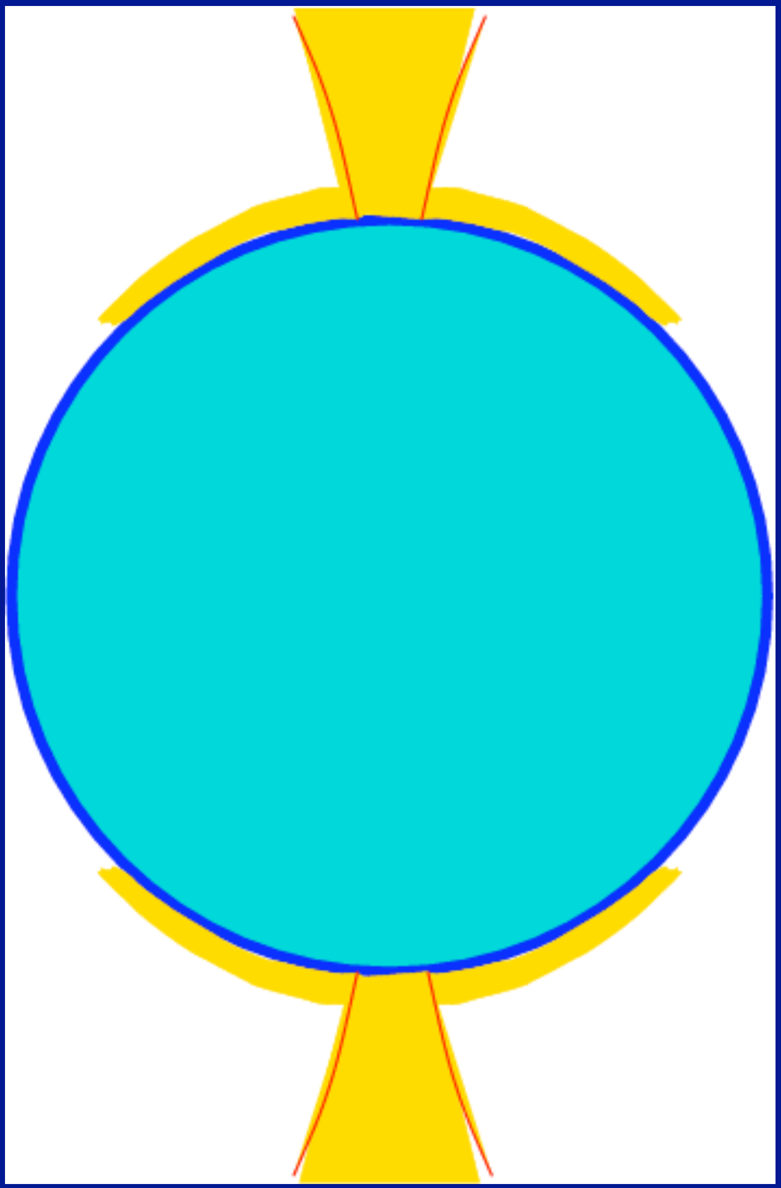
Schonherr et al 2007



BeppoSAX spectrum
(Dal Fiume et al 1998)
Her X−1
B=3.80x10^12G
T_e=6.25x10^7K
Ṁ=1.11x10^17g/s
r_0=44m
iron
bremsstrahlung
total spectrum
cyclotron
blackbody
Continuum
Modelling
(Becker & Wolff 2007)
F_ε(ε) (sec^−1cm^−2keV^−1)
ε (keV)
1
10^−1
10^−2
10^−3
10^−4
10^−5
10^−6
2
5
10
20
50
100

Secular Evolution of Neutron Star Magnetic Fields

What role does accretion play?

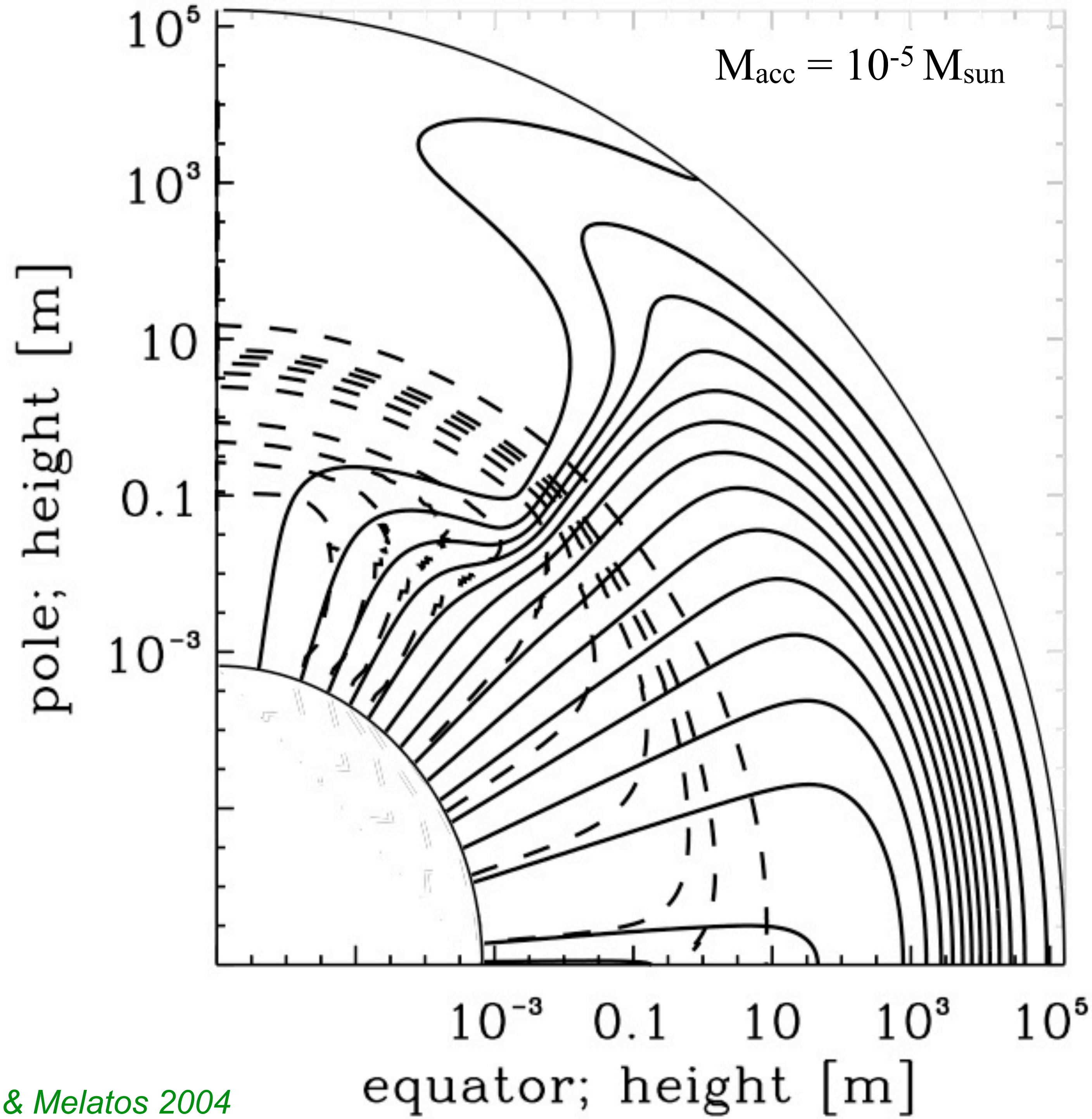


Diamagnetic screening of magnetic field by accreted matter?

Matter accreted on magnetic poles must spread on the neutron star surface

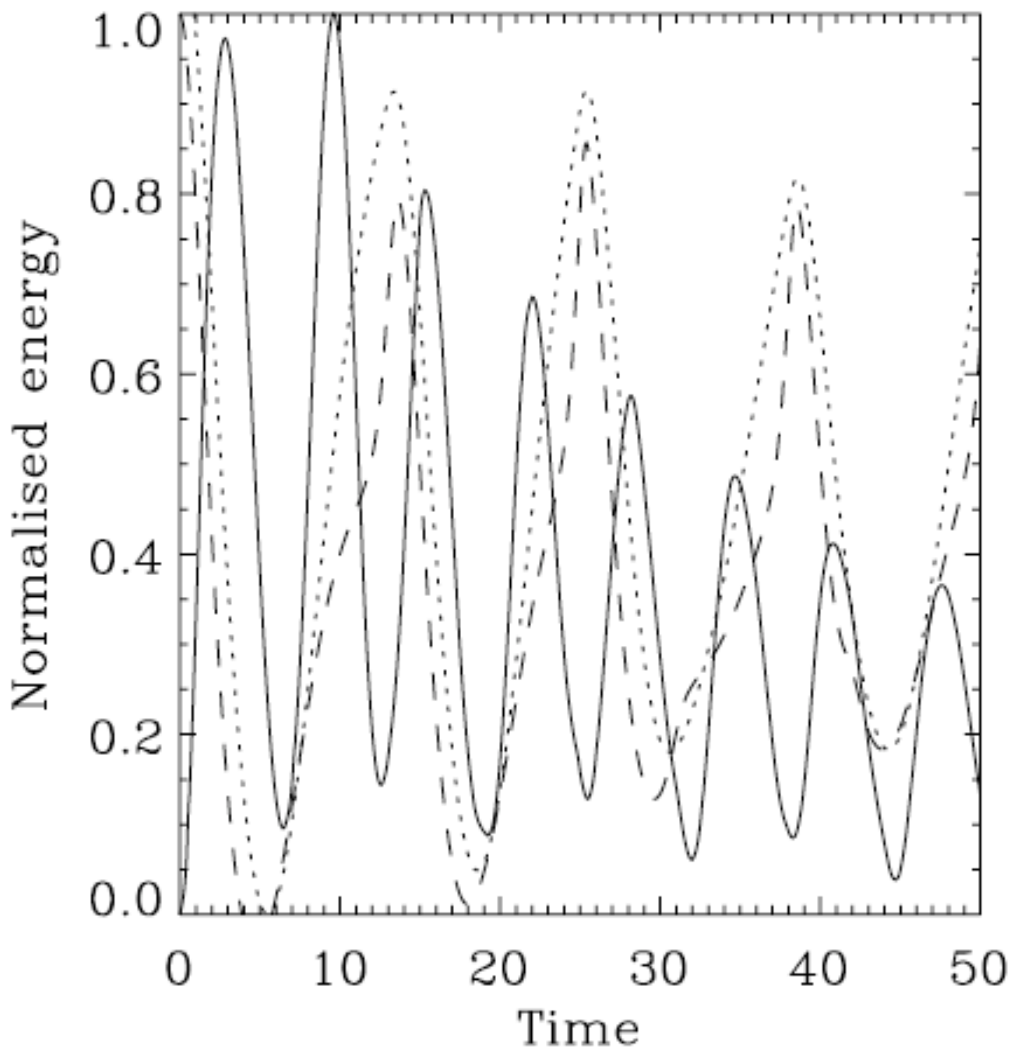
Does the matter drag the field and bury it?

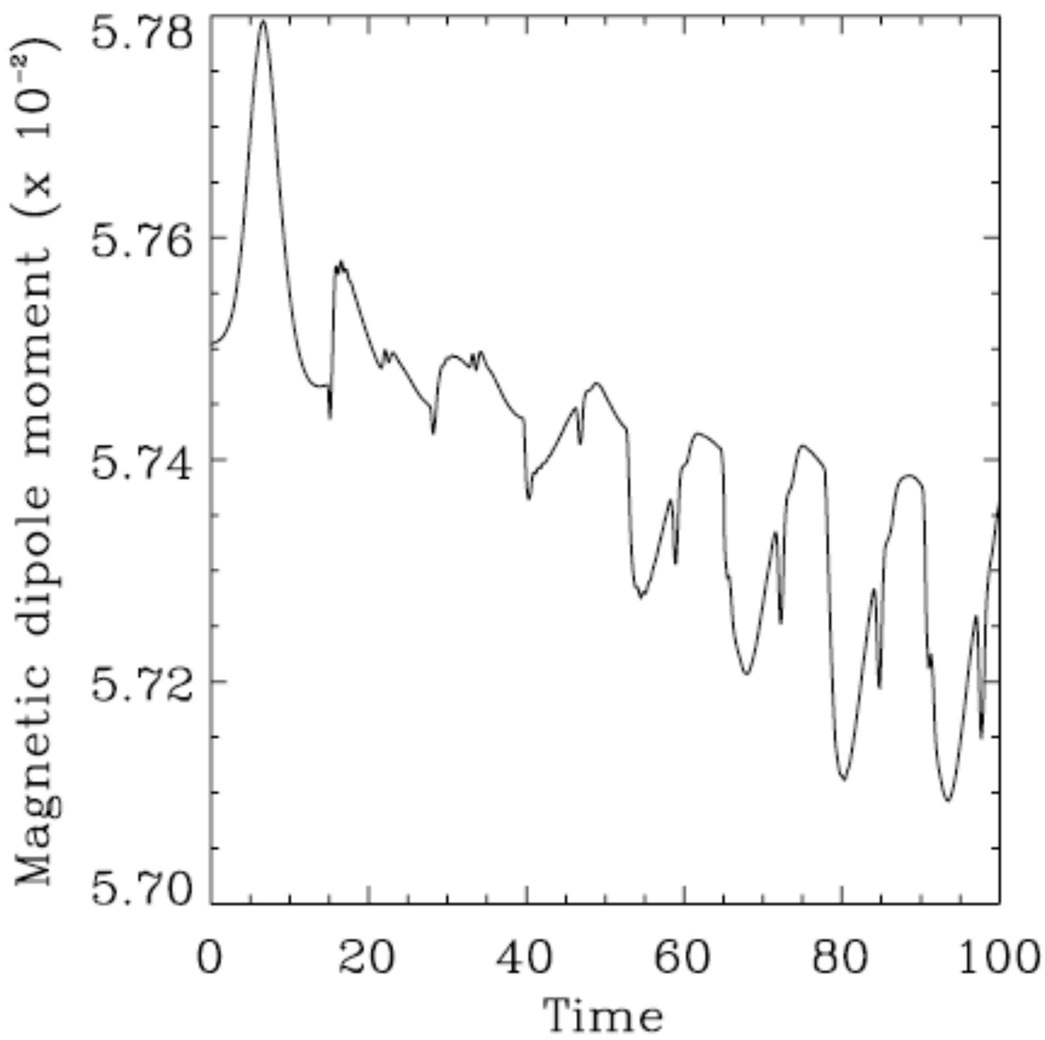
Bisnovatyi-Kogan & Komberg 1978
Romani 1990,1993
Litwin, Brown & Rosner 2001
Melatos & Phinney 2001
Choudhuri & Konar 2002
Payne & Melatos 2004,2007



Payne & Melatos 2004

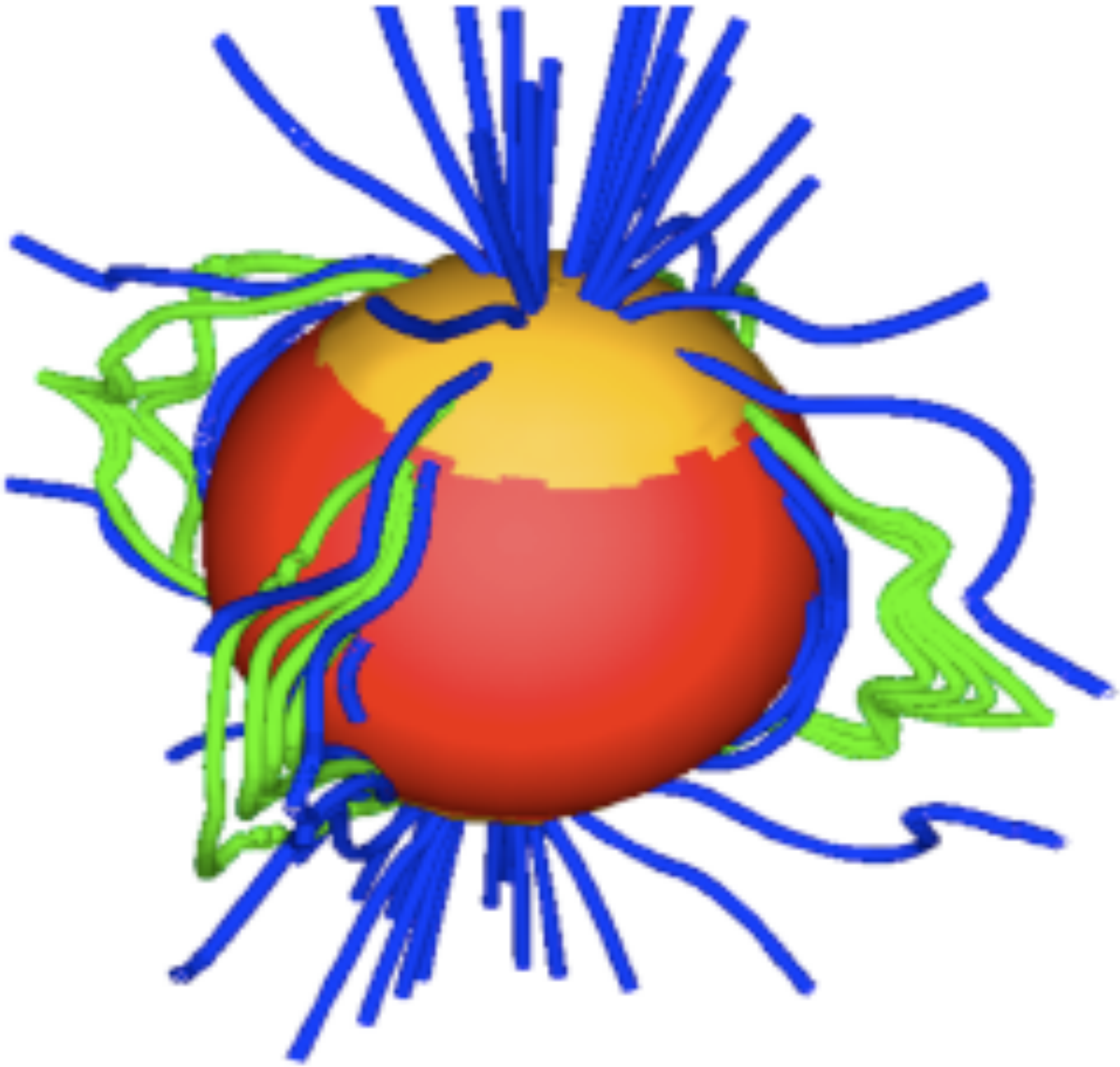
Plasma instabilities would be rife in the accretion column





ZEUS 3D results of Parker mode hydromagnetic oscillations

Payne & Melatos 2007

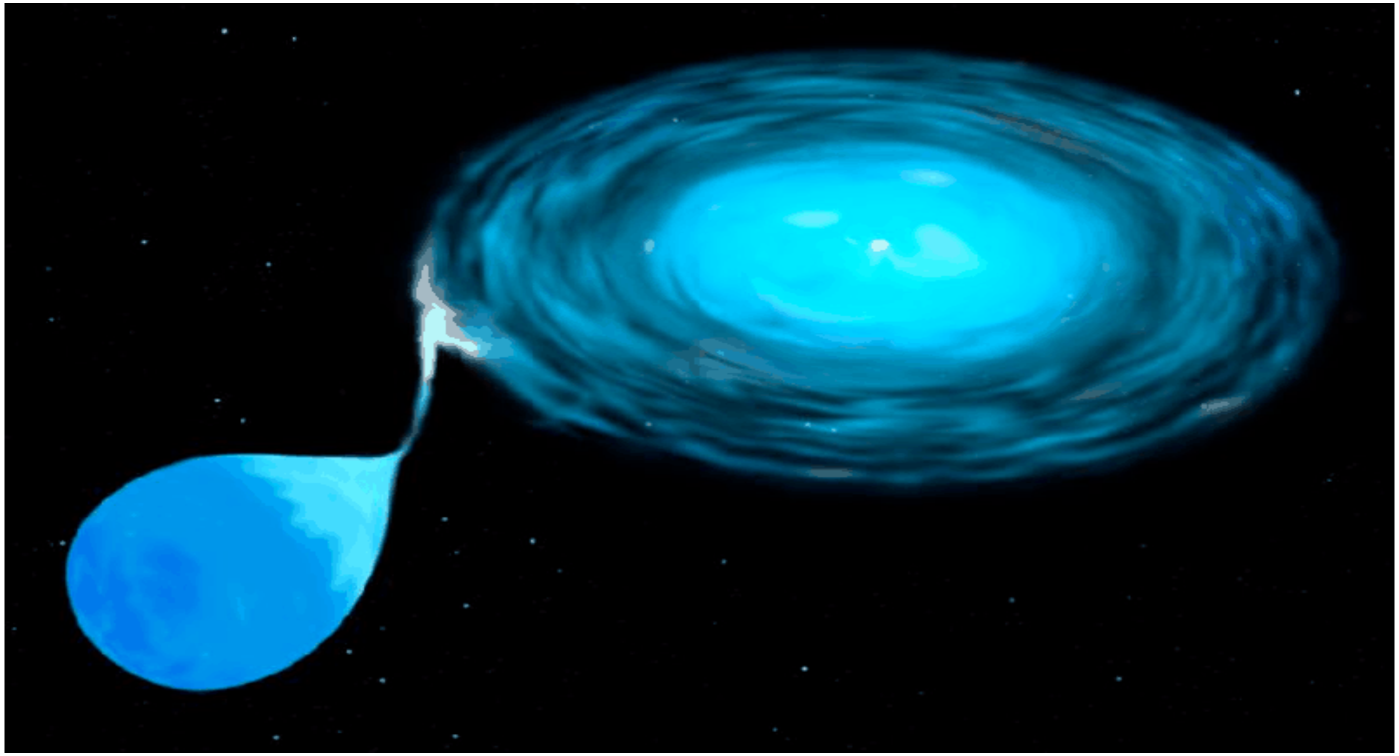


Vigelius and Melatos 2008

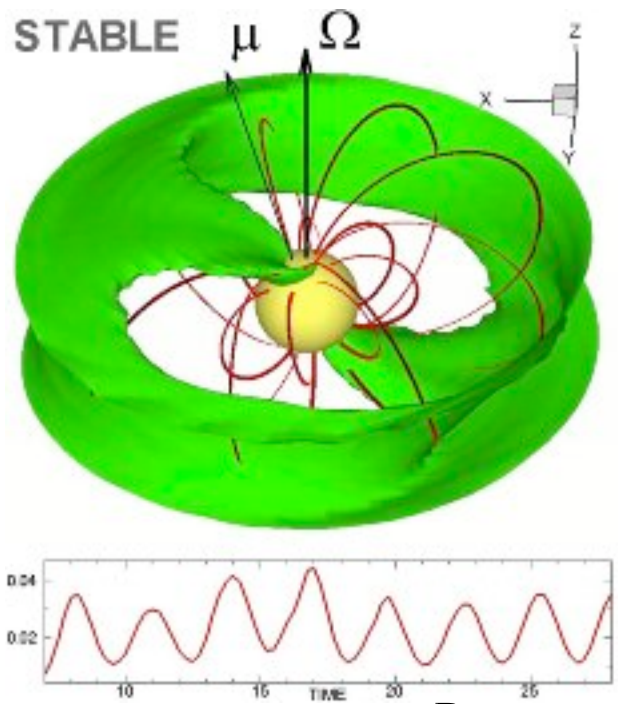
Polar cap of an accreting neutron star

Cross-field plasma transport due to fluting and ballooning instability

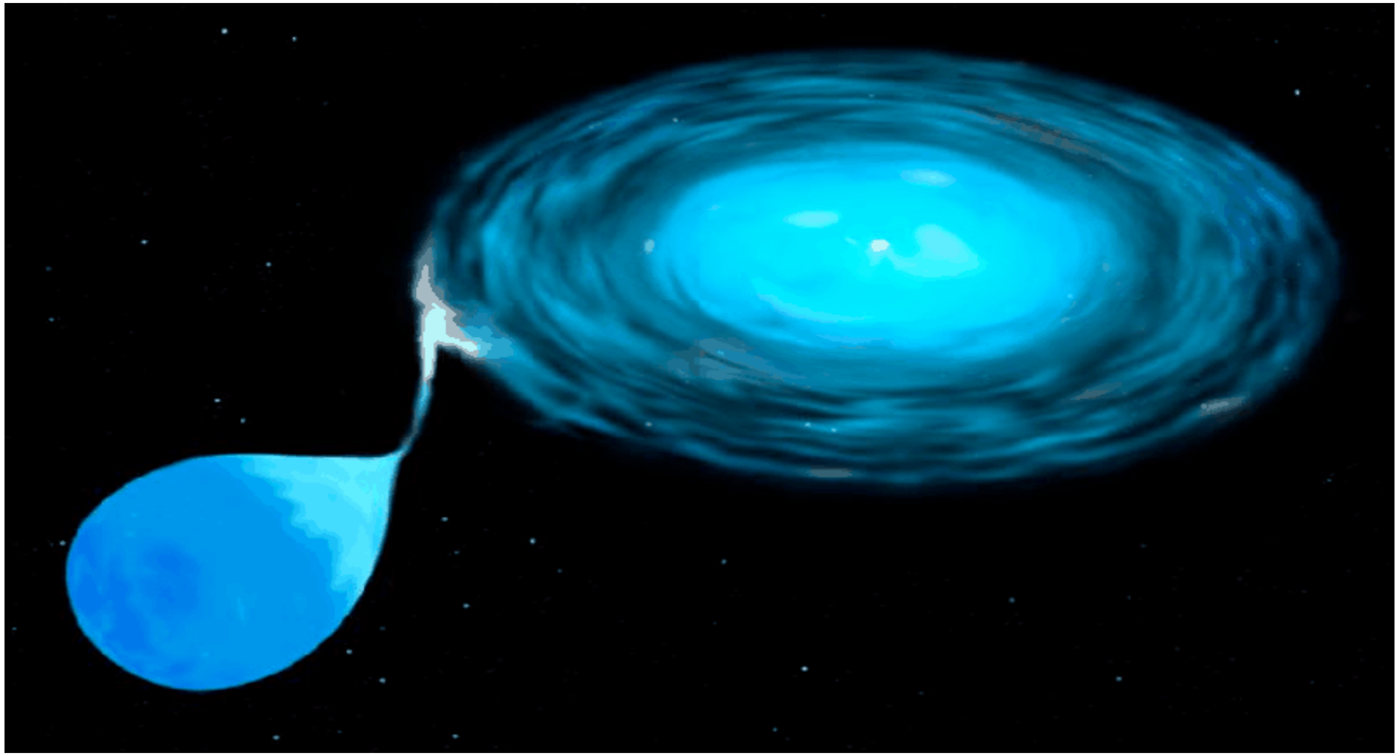
Phase resolved cyclotron line spectroscopy can probe such magnetic distortions



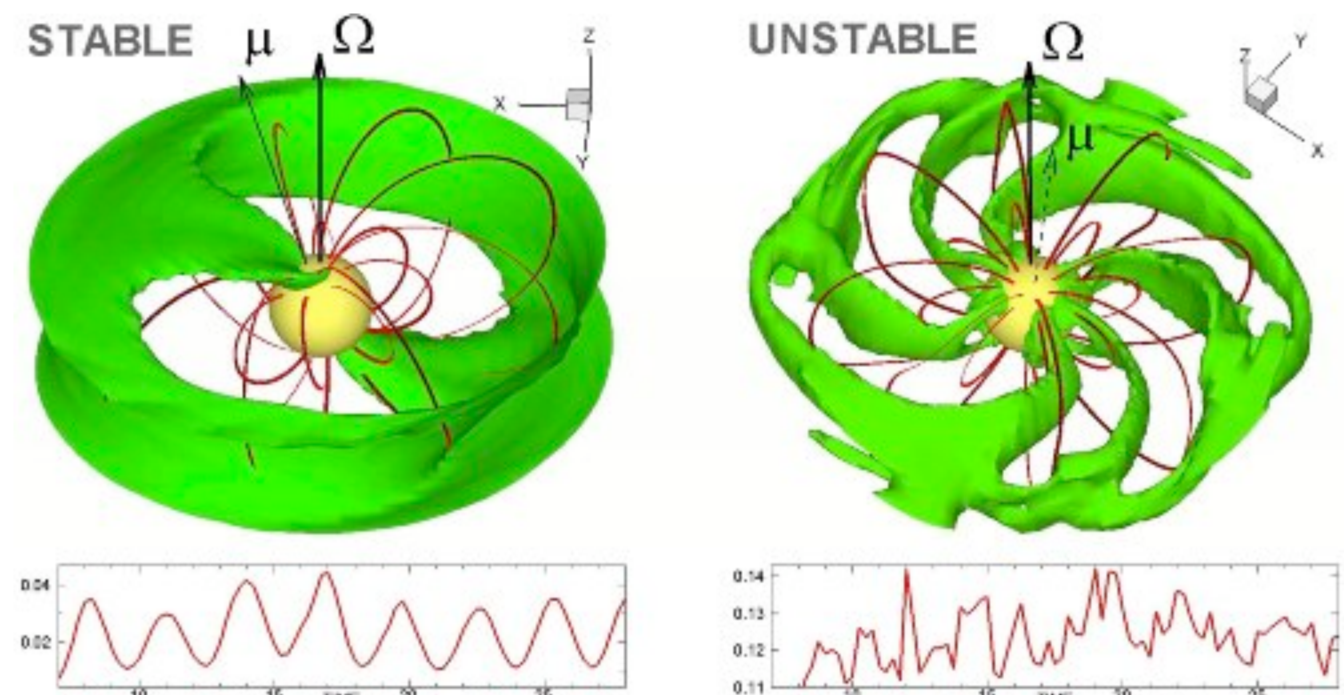
Accretion onto strongly magnetized neutron stars



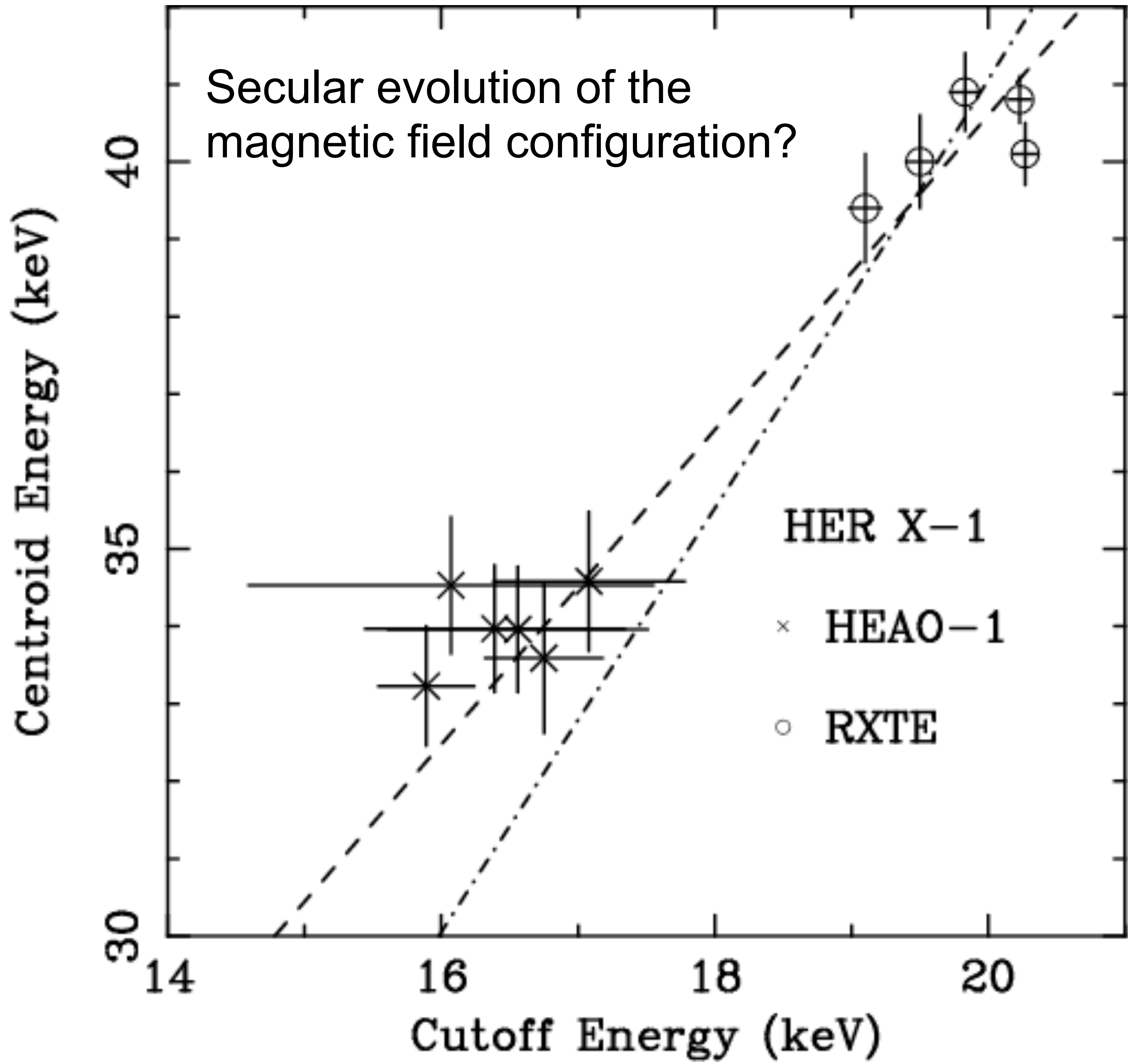
Romanova, Kulkarni and Lovelace 2008



Accretion onto strongly magnetized neutron stars

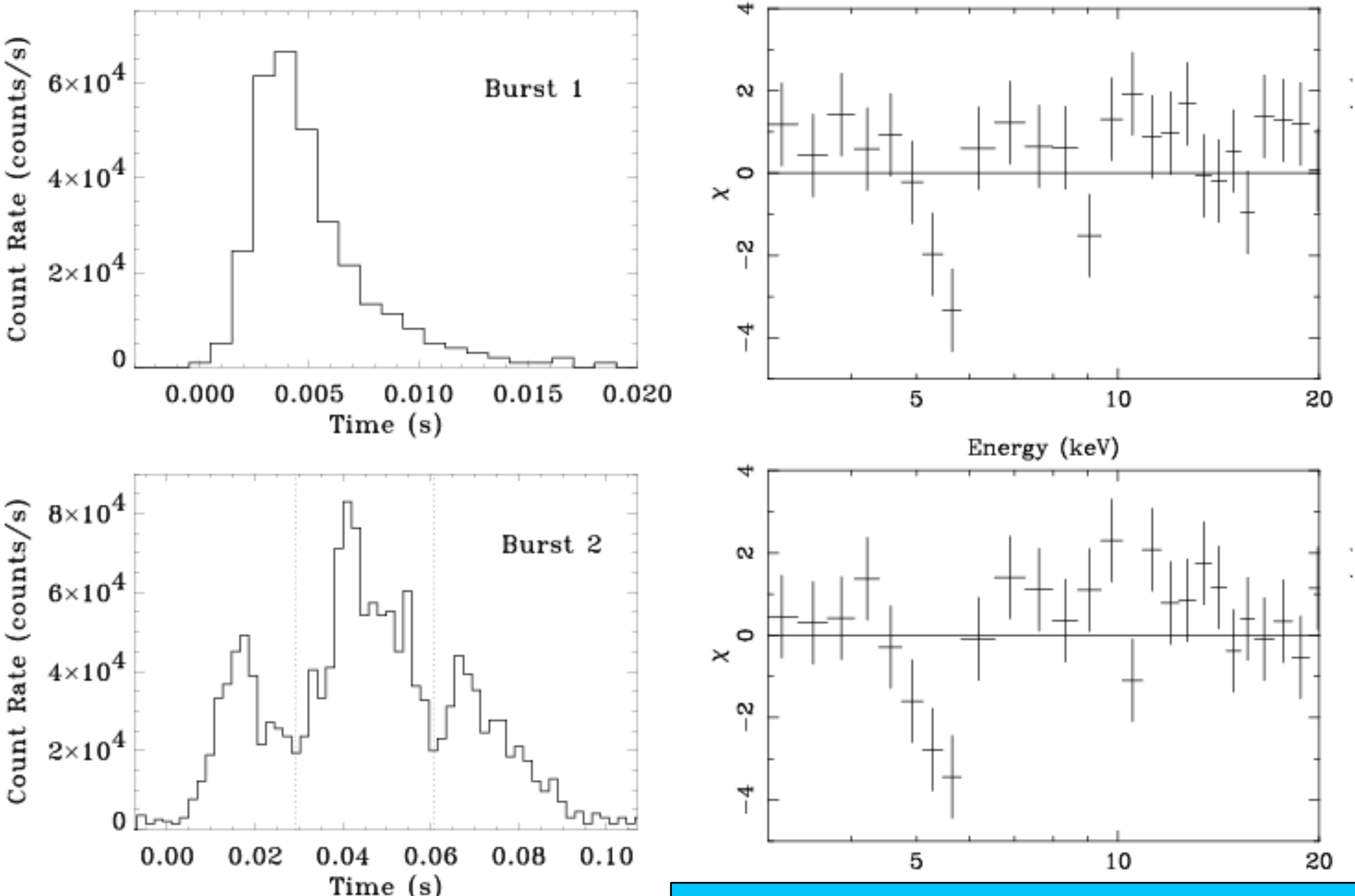


Romanova, Kulkarni and Lovelace 2008



Gruber et al 2001

SGR 1806-20: *5 keV absorption feature* : proton cyclotron line?



Ibrahim et al 2002

Seen in 5 out of a sample of 56 burst peaks in RXTE

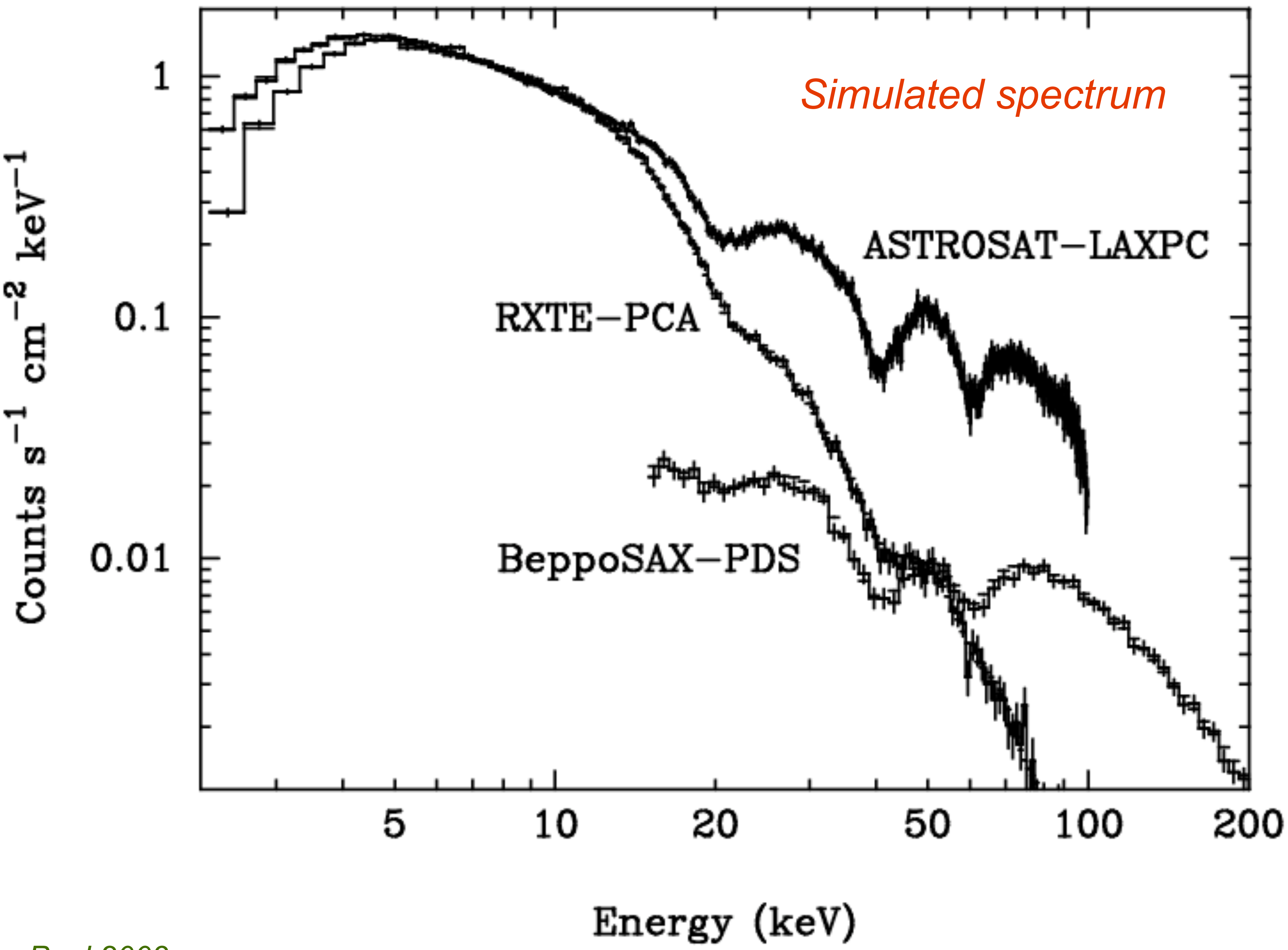
Cyclotron Resonance lines with ASTROSAT

Targets: Accreting X-ray Pulsars
Magnetars in outburst

ASTROSAT will have excellent sensitivity for Cyclotron lines from typical accreting X-ray pulsars:

- The lines are expected in hard X-ray bands (~ 10 — 80 keV)
- Large effective area of LAXPC in hard X-rays
- LAXPC spectral resolution adequate
- Excellent spectral resolution of CZTI for bright sources with CRSF

- ***Need good calibration of spectral response***


Simulated spectrum
ASTROSAT−LAXPC
RXTE−PCA
BeppoSAX−PDS
Counts s^{-1} cm^{-2} keV^{-1}
1
0.1
0.01
5
10
20
50
100
200
Energy (keV)

Paul 2003

Cyclotron line key projects with ASTROSAT

Rotation Phase resolved spectroscopy of accreting X-ray pulsars

Different orbital phases and luminosity states to be probed

Sample size: 15 objects, total exposure ~1.5 Mega second

Search for CRSF in other bright X-ray pulsars

Sample size: ~5 objects, time required ~0.5 Ms

Search for proton cyclotron features in bright SGR/AXP outbursts

Sample size: ~5 objects, time required ~0.5 Ms, TOO

CRSF search in INTEGRAL hard X-ray pulsars

Sample size: ~10 objects, time required ~1 Ms

CRSF search in transient (Be) HMXBs

TOO

Timing study of these objects can be carried out simultaneously

Cyclotron line pulsars known	Bright X-ray pulsars for CRSF search	IGR sources (from)
4U 0115+63		06253+7334
4U 1907+09	SMC X-1	11215-5952
4U 1538-52	LMC X-4	11435-6109
Vela X-1	2S 0114+650	13020-6359
V 0332+53		15479-4529
Cep X-4		16320-4751
Cen X-3		16358-4726
X Per		16393-4643
GX 1+4	SGR/AXP	15418-4532
XTE J1946+274		17088-4008
MX 0656-072	1806-20	17252-3616
4U 1626-67	1900+14	17303-0601
GX 301-2	1810-197	18027-2016
Her X-1	164710.2	18410-0535
A 0535+26	1627-41	21335+5105