

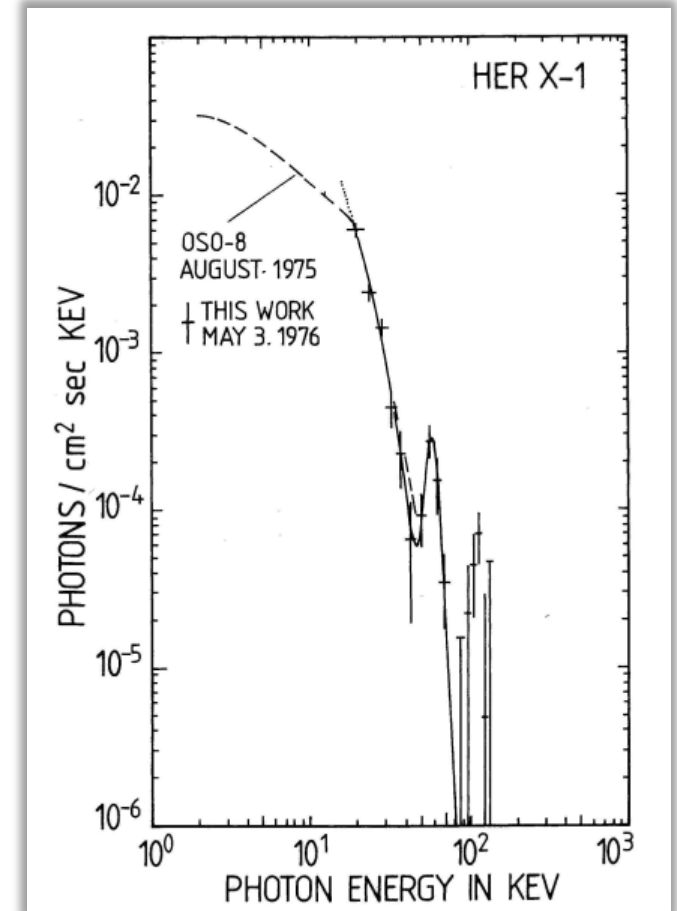
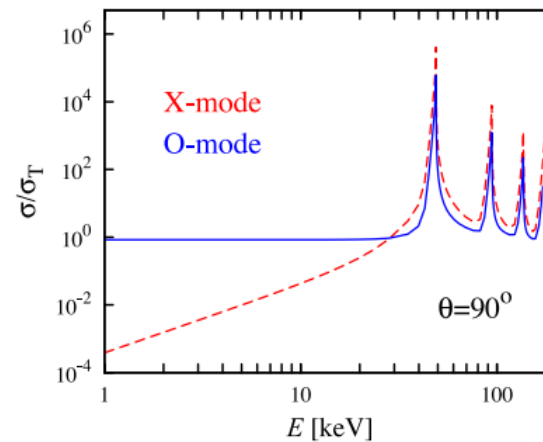
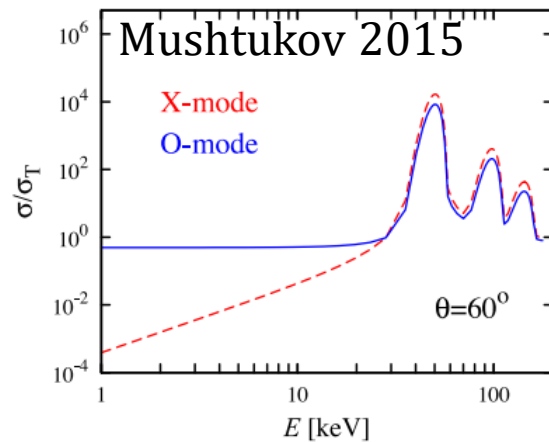
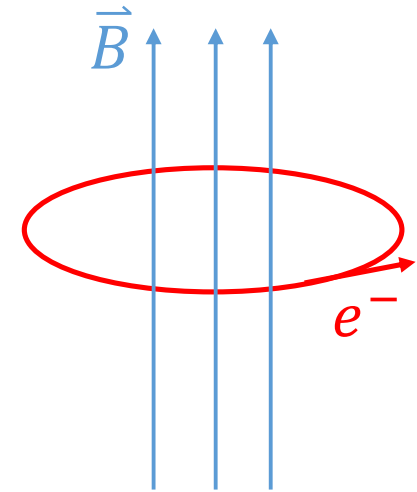


# The evolution of cyclotron resonant scattering features

Long Ji (纪龙)

# Background

CRSFs (cyclotron resonant scattering features), also known as cyclotron lines, are absorption features in the X-ray spectra of highly magnetized neutron stars.



“12- $B_{12}$ -rule”:

$$E_{ce} = \hbar\omega_{ce} = \hbar \frac{eB}{m_e c} = 11.577 B_{12} \text{ keV}$$

First detection of a cyclotron line in 1976 (Trümper et al. 1977, 1978)

# Background

The CRSF energy is found to vary with:

- 1, pulse phase;
- 2, luminosity;
- 3, time
- 4, phase of the super-orbital period

⇒ changes of the line-forming region

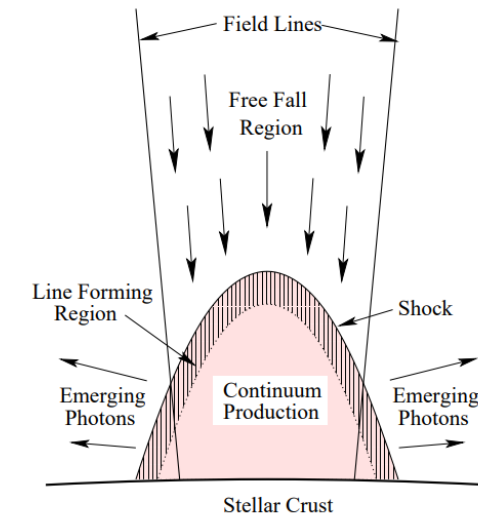
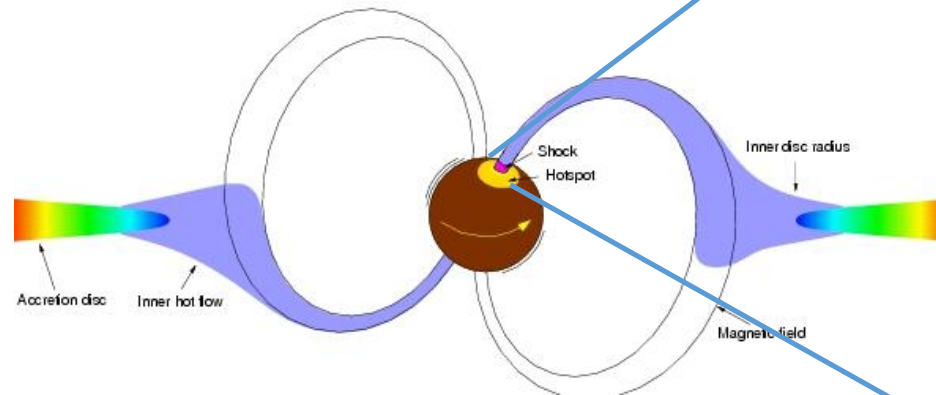
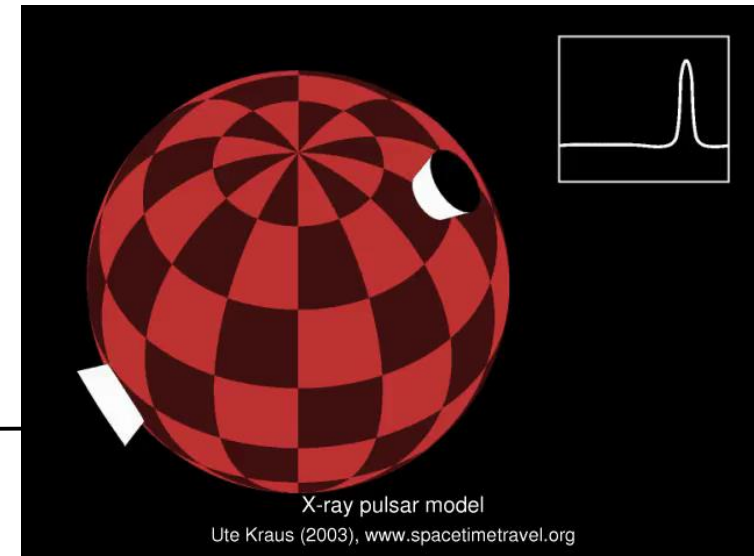
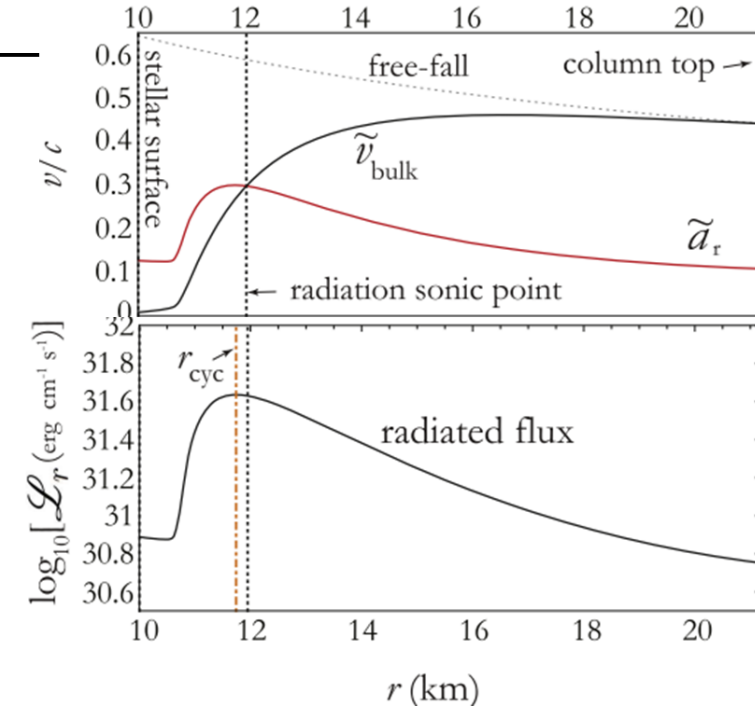
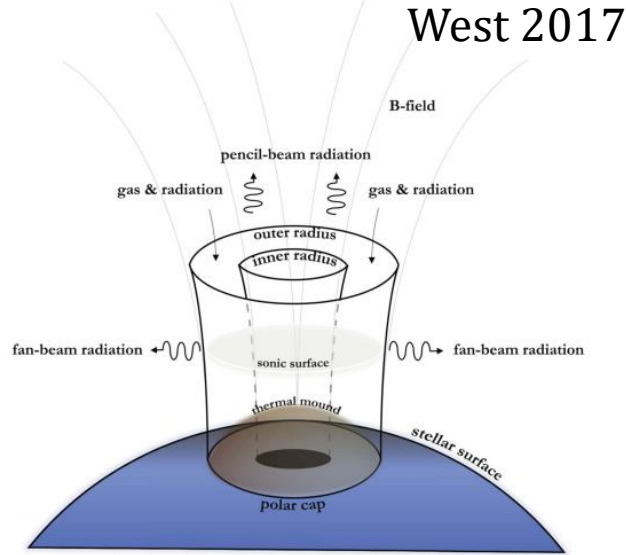
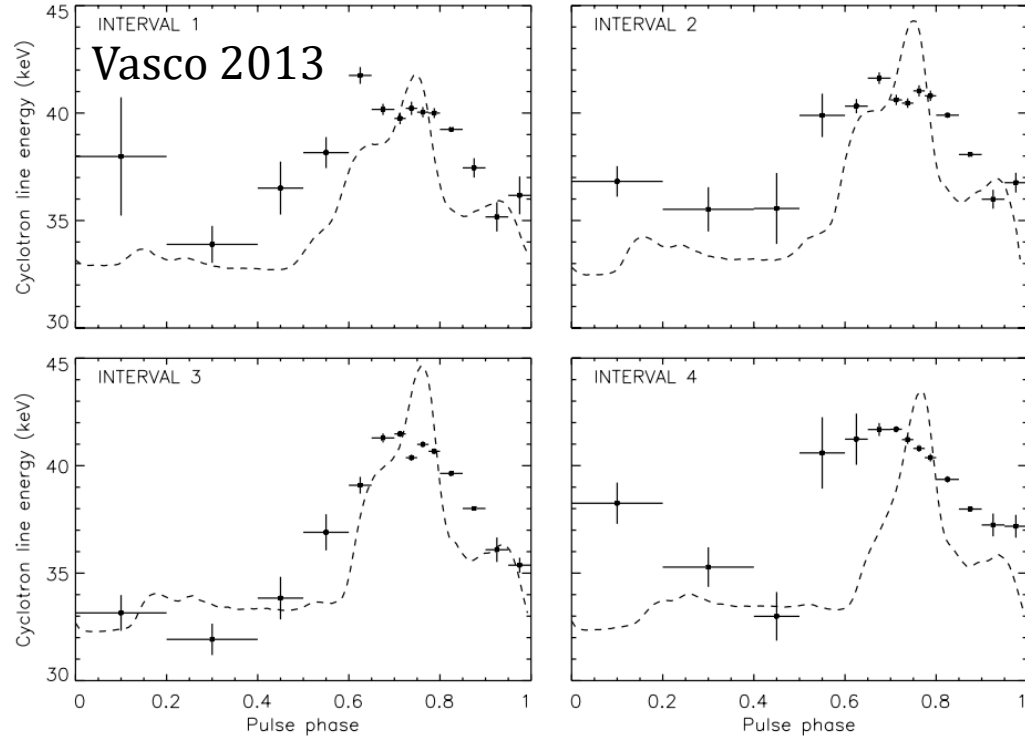


FIGURE 1. Schematic diagram of the “accretion mound” showing the line-forming region as a discrete layer covering the continuum production zone.

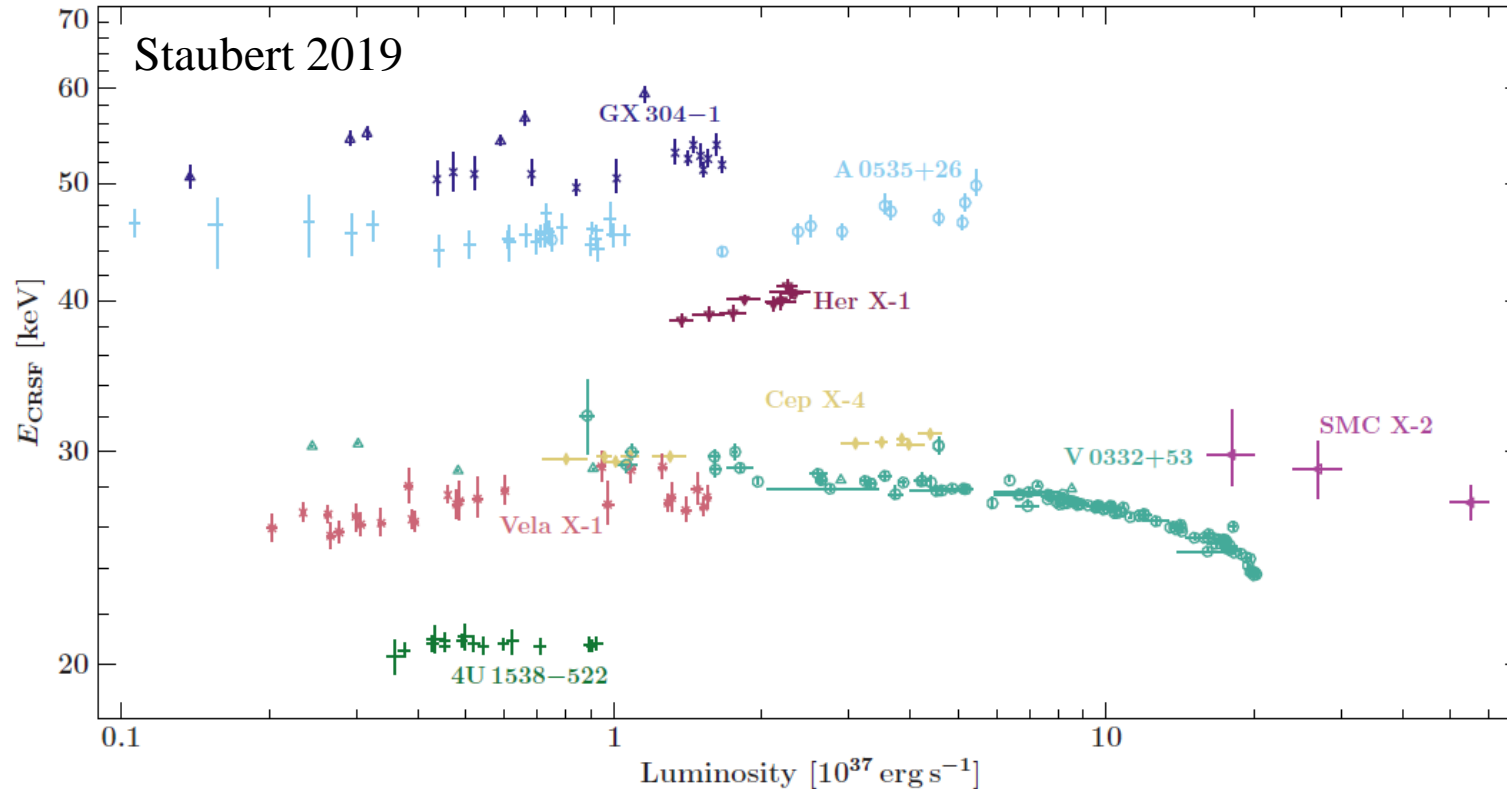
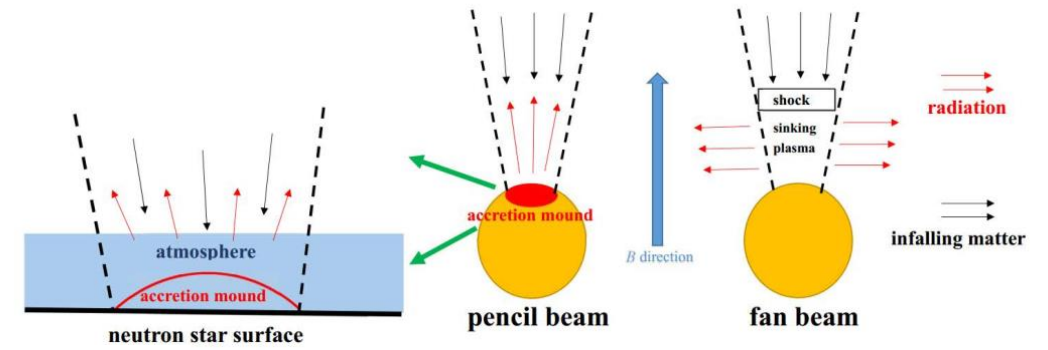
Heindl 2004

# Pulse-phase-dependent $E_{cyc}$

- appear in almost all objects



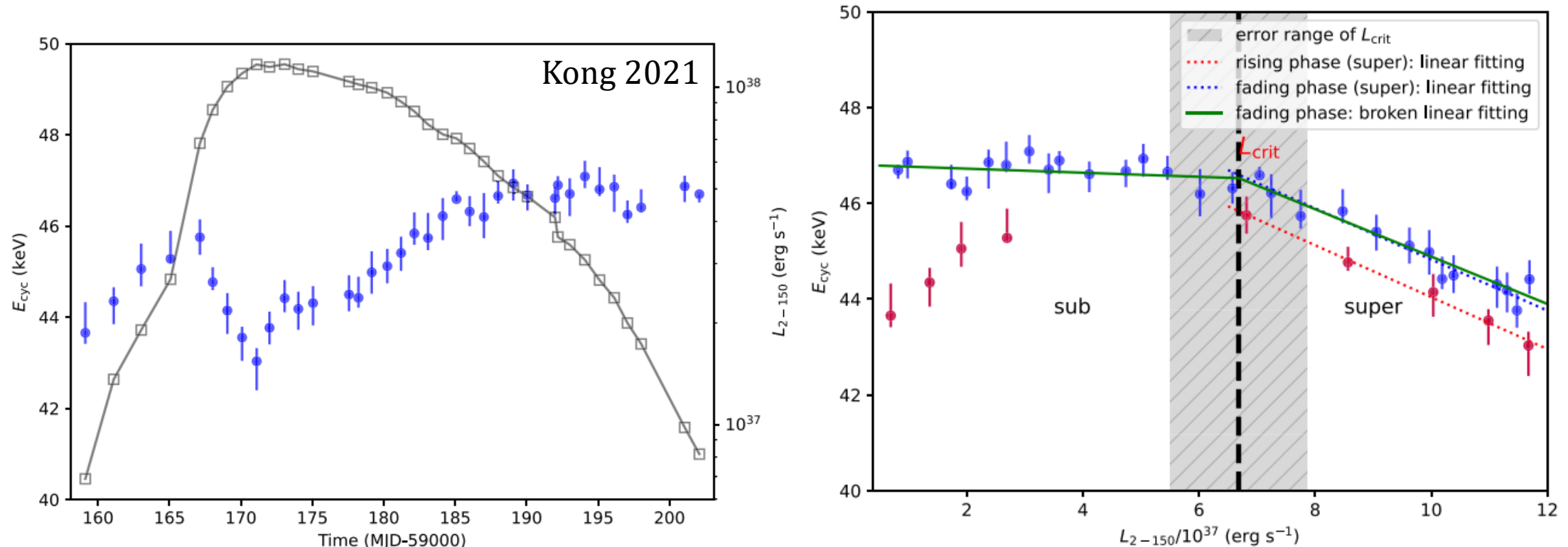
# Luminosity-dependent $E_{\text{cyc}}$



Different luminosity ( $L$ ) states:  
 Low  $L$ : positive  $L - E_{\text{cyc}}$  correlation  
 High  $L$ : negative  $L - E_{\text{cyc}}$  correlation

$$L_{\text{crit}} = 1.49 \times 10^{37} \text{ erg s}^{-1} \left( \frac{\Lambda}{0.1} \right)^{-7/5} w^{-28/15} \\ \times \left( \frac{M_*}{1.4 M_{\odot}} \right)^{29/30} \left( \frac{R_*}{10 \text{ km}} \right)^{1/10} \left( \frac{B_*}{10^{12} \text{ G}} \right)^{16/15}.$$

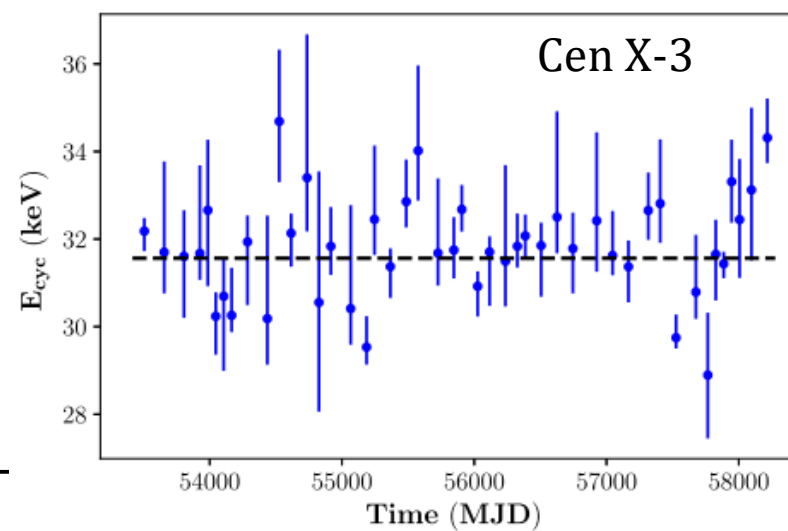
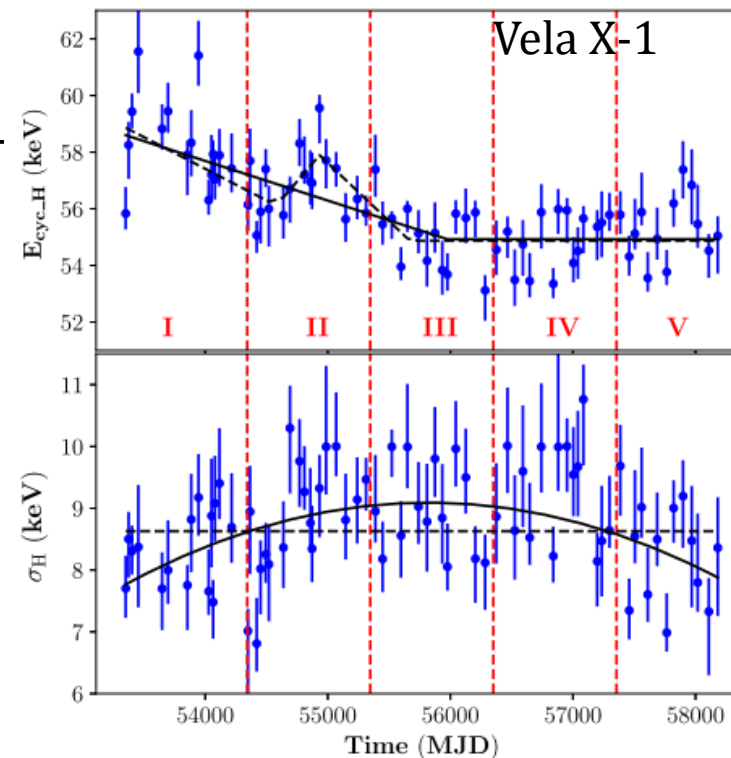
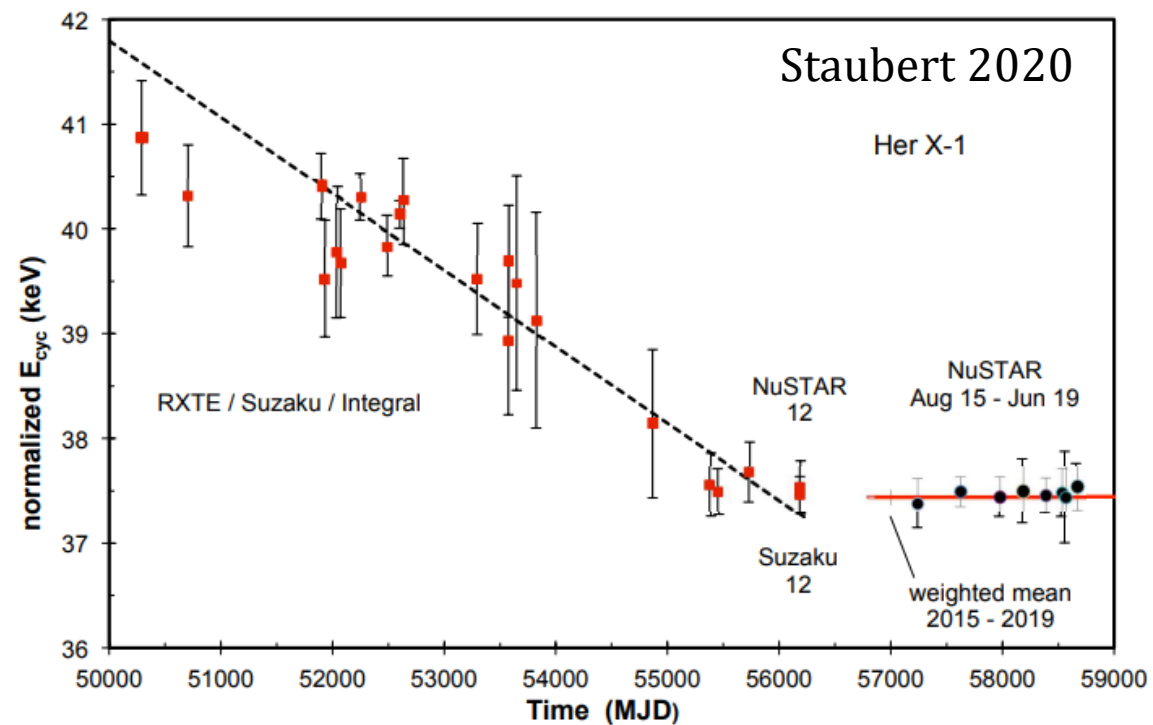
# Luminosity-dependent $E_{cyc}$



New discovery in A 0535+26:

- 1, evidence for the transition between accretion regimes
- 2, hysteresis pattern, i.e., significant differences between rising and fading phases

# Time-dependent $E_{cyc}$

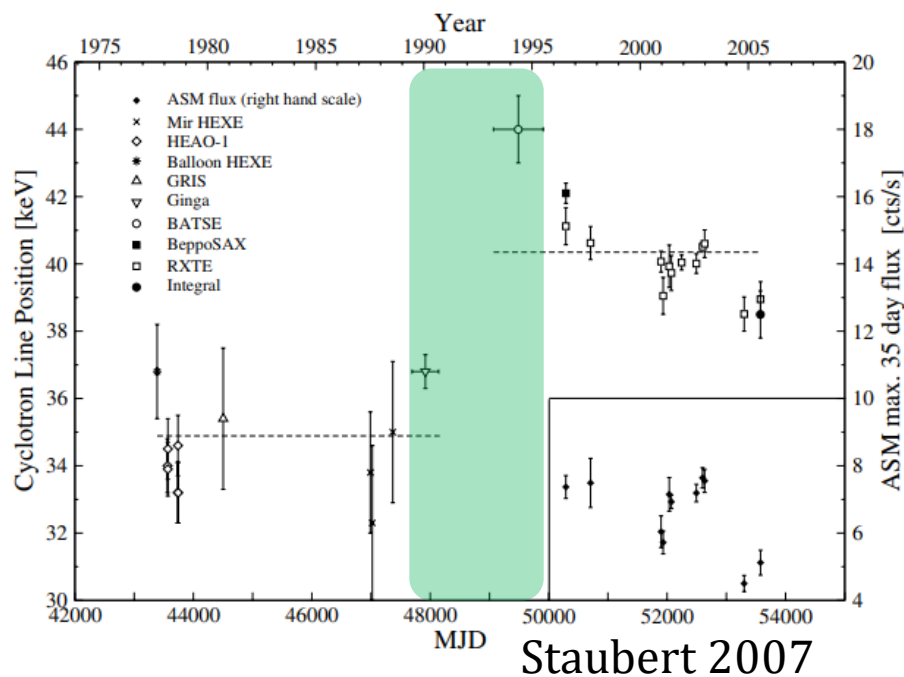


Ji 2019

# Time-dependent $E_{cyc}$

Why?

- a geometric displacement of the line-forming region?
- a physical change in the magnetic field configuration at the polar cap?
- quadrupole field?

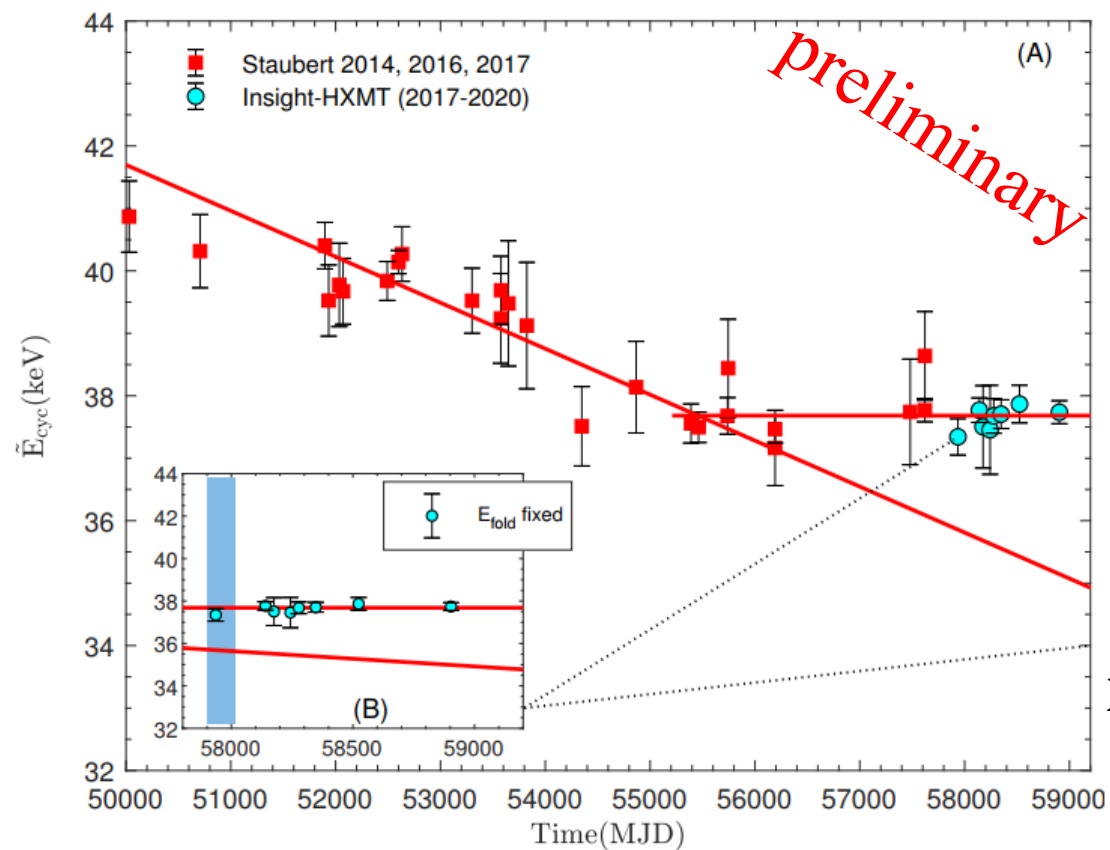


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Monitoring campaign with HXMT/NuSTAR/INTEGRAL/AstroSAT

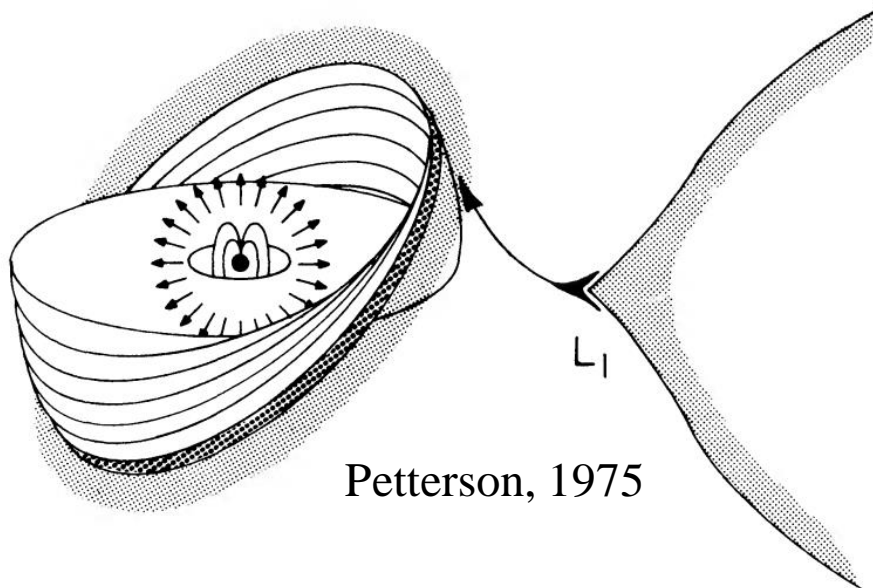
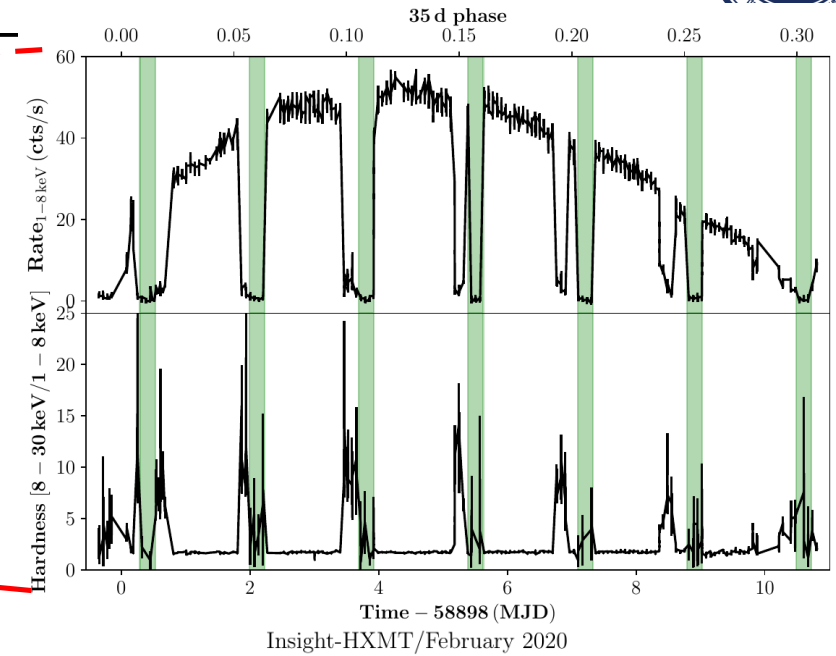
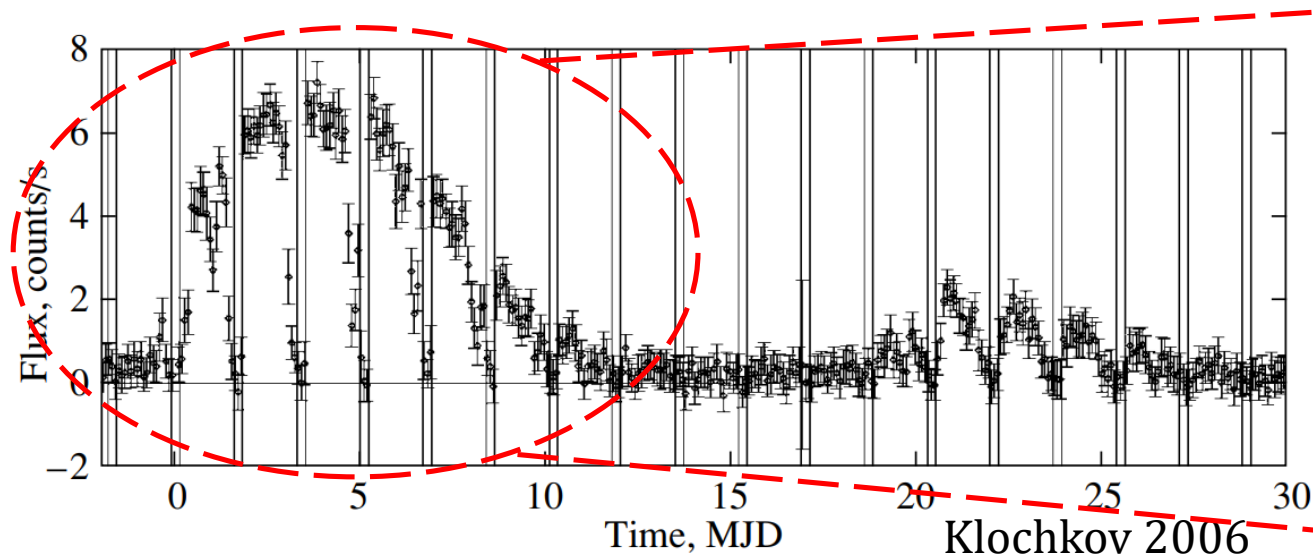


# Time-dependent $E_{cyc}$

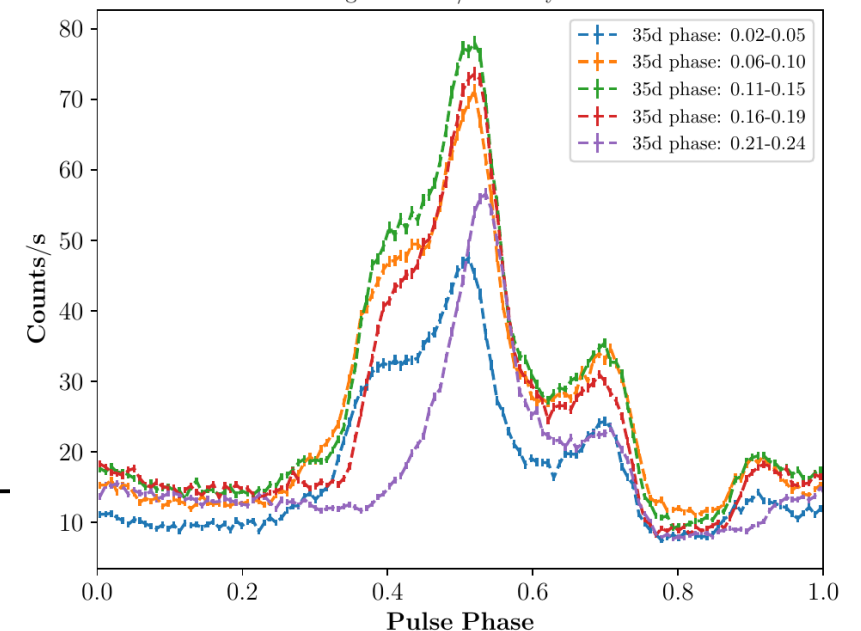


Xiao 2022, in preparation

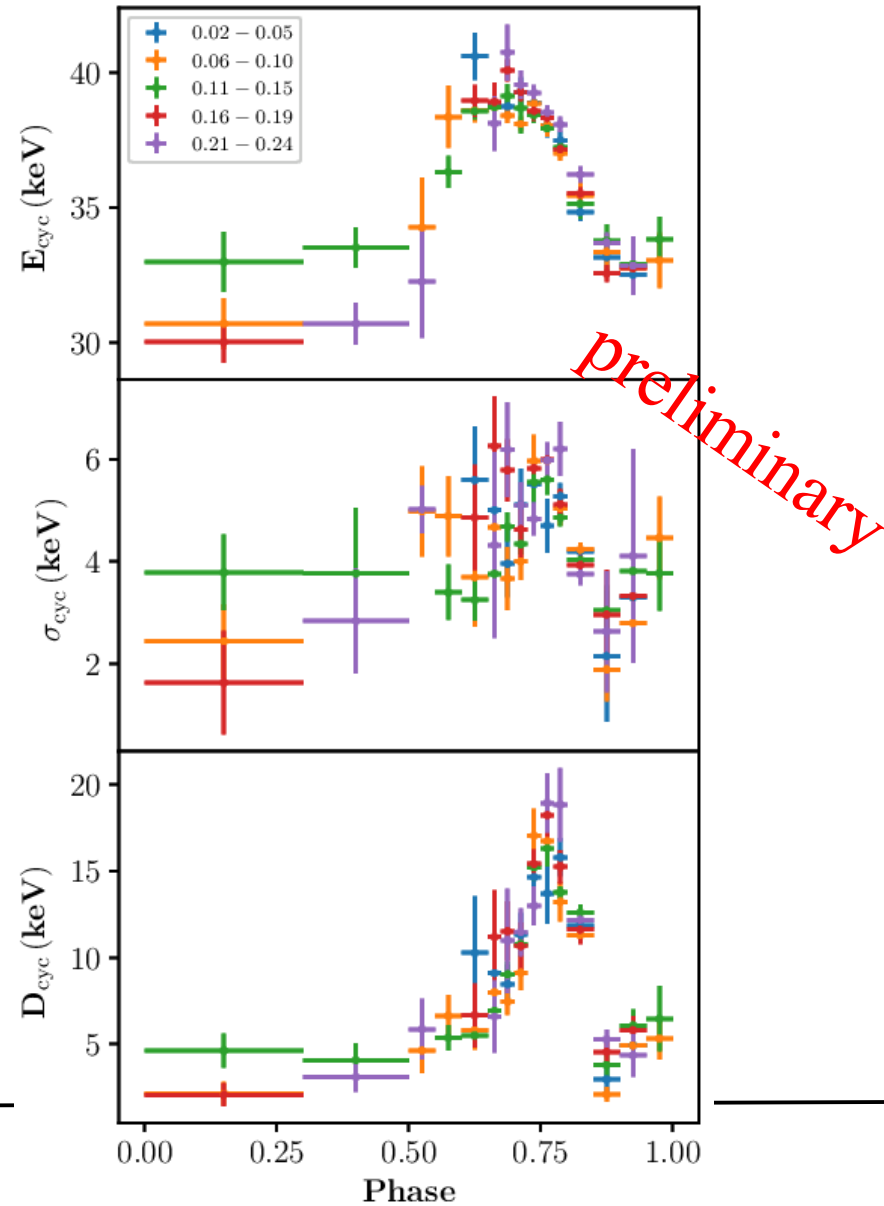
# $E_{cyc}$ and superorbital modulation



Peterson, 1975



# $E_{\text{cyc}}$ and superorbital modulation





# Future and Prospects

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- Self-consistent CRSF and continuum model
- More negative  $L - E_{\text{cyc}}$  cases
- Long-term  $E_{\text{cyc}}$  evolution
- various  $E_{\text{cyc}}$  with polarization states

*Thank you!*