Neutron Star Binaries

~ Cyclotron Resonances Revisited ~

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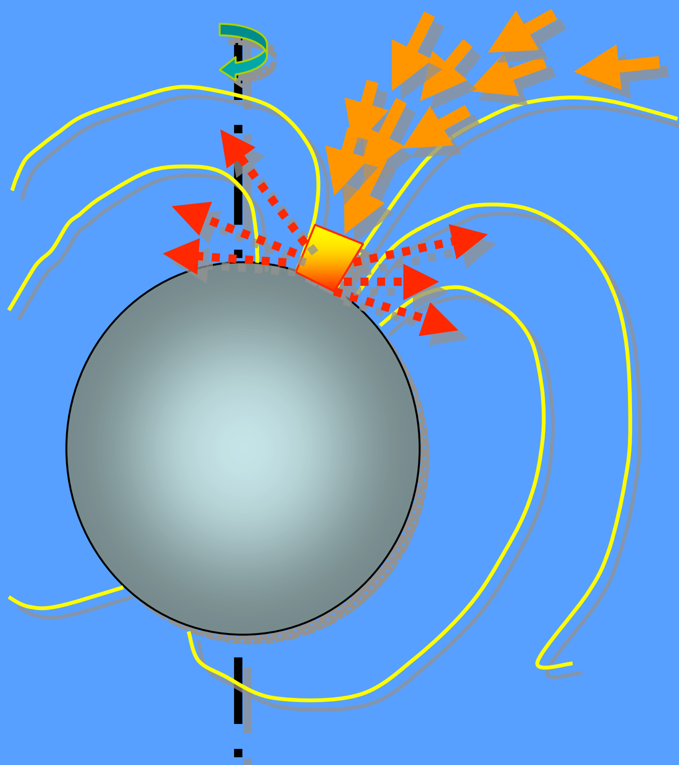
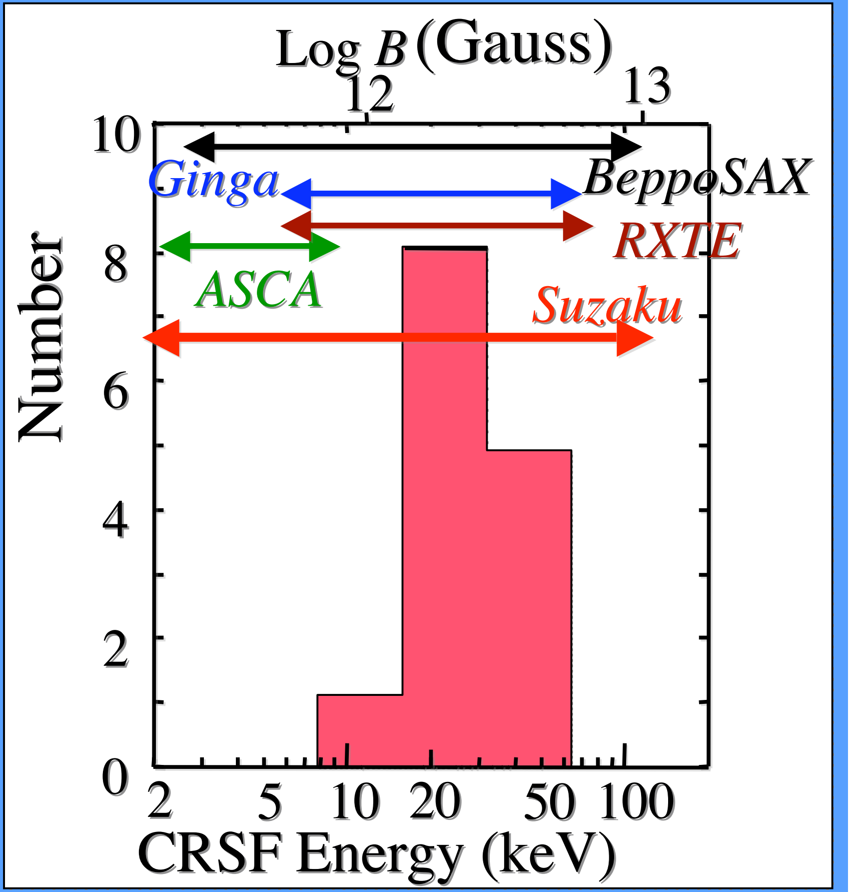


With thanks to T. Enoto (U. Tokyo), M. Nakajima (Nihon U.), T. Kitaguchi (U. Tokyo), T. Mihara (RIKEN), & Y. Terada (Saitama U.)

CRSF *(cyclotron resonance scattering feature)*

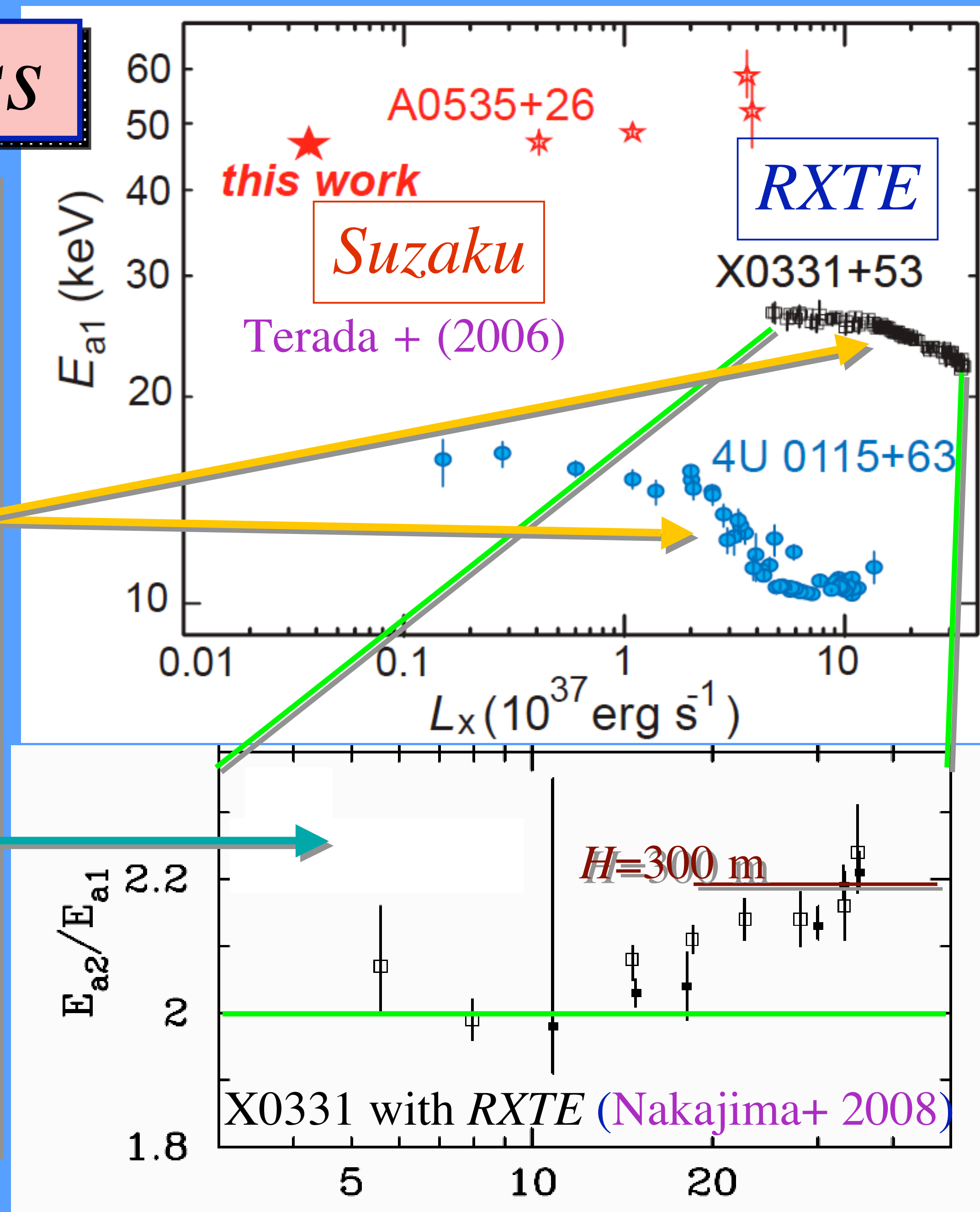
- a spectral feature due to e^- transitions between adjacent Landau levels in a magnetic filed *B*, observed at an energy of $E = 11.6\,(B/10^{12}\mathrm{G})$ keV.
- detected all in absorption from ~15 accreting pulsars, with balloons, *HEAO-1*, *CGRO*, *Ginga* (2 reconfirm., 5 discoveries; Mihara 95), *BeppoSAX*, *RXTE*, *INTEGRAL*, *Swift*, and *Suzaku*.
- provides the most accurate estimates of NS surface magnetic fields, with clean and important fundamental physics.



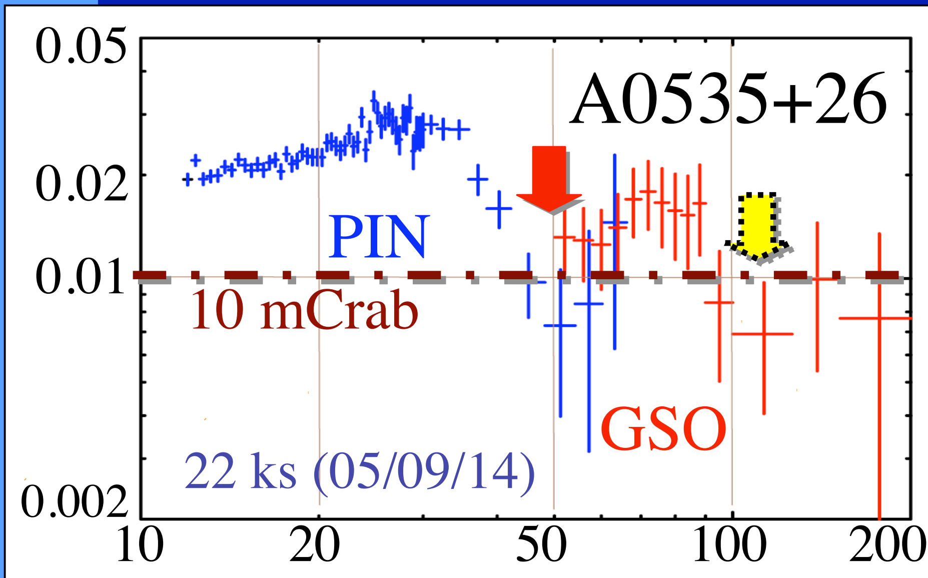
The measured *B* (Makishima + 99);
-concentrated over (1-4)x10^{12} G.
-argue against "field decay" hypothesis.
-suggest "ferromagnetism" in nuclear matter.

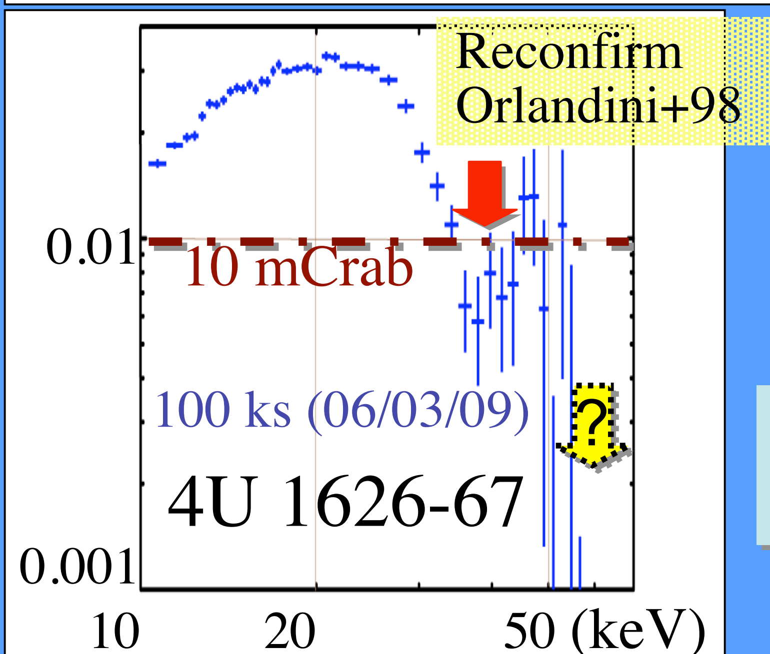
Recent Progress

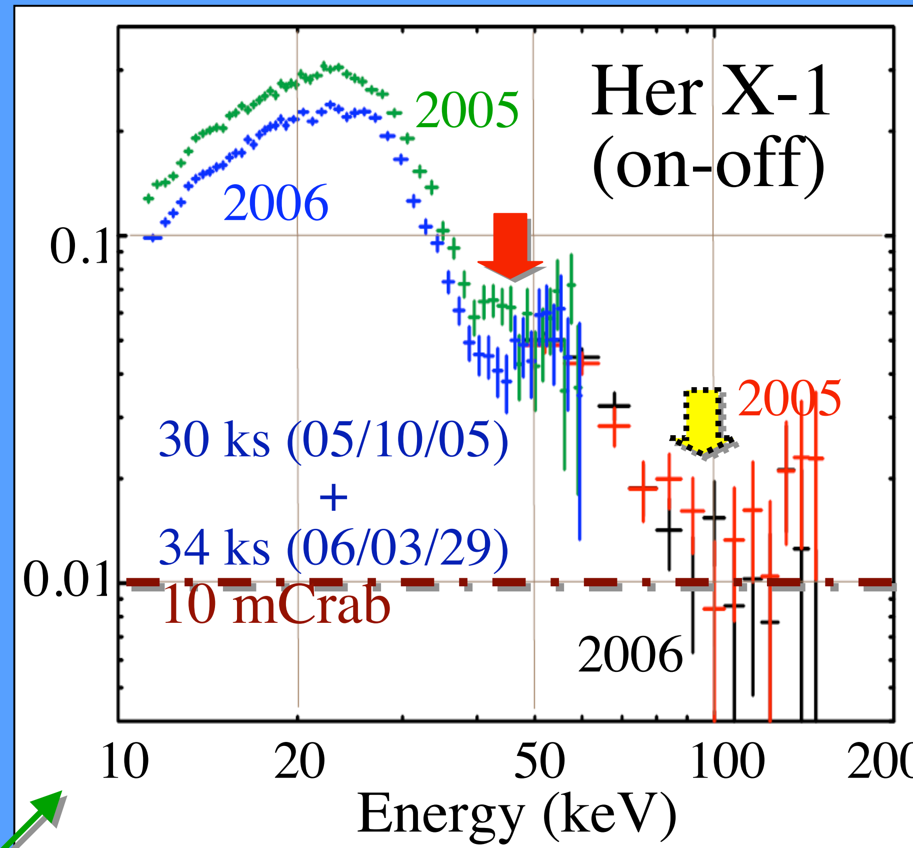
- ✧Three harmonic absorption lines from X0331+53 (Pottschmidt+05), after 4U 0115+63.
- ✧L_x-dependent changes in E_a (Mihara+04; Nakajima +06, 08; Tsygankov +06; Mowlavi+06)--> Column gets taller as L_x increases.
- ✧L_x-dependent change in the E_2/E_1 ratio (Nakajima+08) --> The 2nd harmonic, with a smaller cross section, has a “photosphere” closer to the NS surface.



Suzaku observations of CRSF: Crab ratios







- Terada *et al*. (2006) *ApJL* **648**, L139 (2006)
- Enoto *et al*. *PASJ* 2nd issue, *in press* (2008)

GRO J1008-57 TOO; 2007/11/30

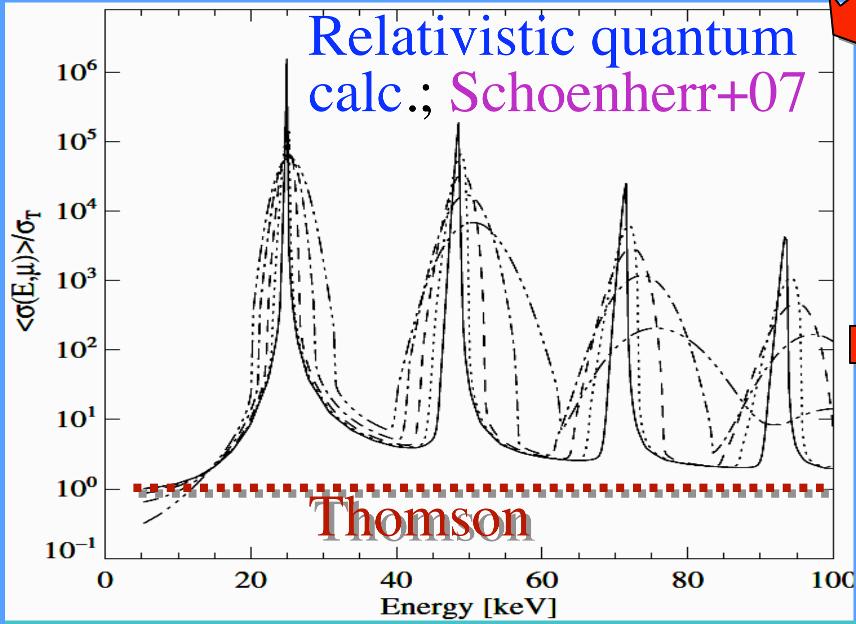
Cyclotron Resonance Profiles

A forced oscillation of an electron in a uniform magnetic field B;

$$m\frac{d\vec{v}}{dt} = -e\vec{v}\times\vec{B} - m\Gamma\vec{v} + \vec{E}_0 e^{i\omega t}$$

Classical scatt. cross section of the incident EM ratdiation;

$$S(E) = D\left(\frac{W}{E_a}\right)^2 \frac{E^2}{(E-E_a)^2 + W^2}$$



The natural width (radiative de-excitation rate of an excited Landau level) is small; $W << E_a$

(1) Use $S(E)$ itself, assuming W gets somehow larger (Clark+ 09)
--> CYAB modeling;

$$CYAB(E) = \exp\{-S(E)\}$$

(2) Assuming thermal Doppler effects dominate, convolve $S(E)$ with a Gaussian
--> Gabs modeling

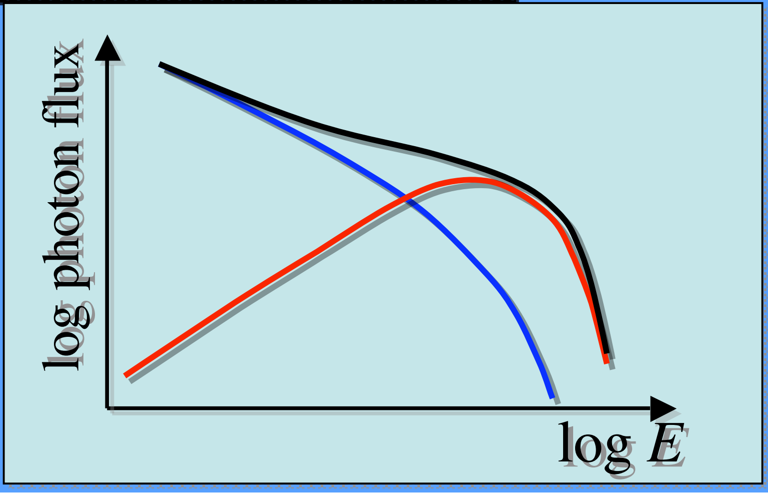
$$Gabs(E) = \exp\left\{-\tau\exp\left(-\frac{(E-Ec)^2}{2\sigma^2}\right)\right\}$$

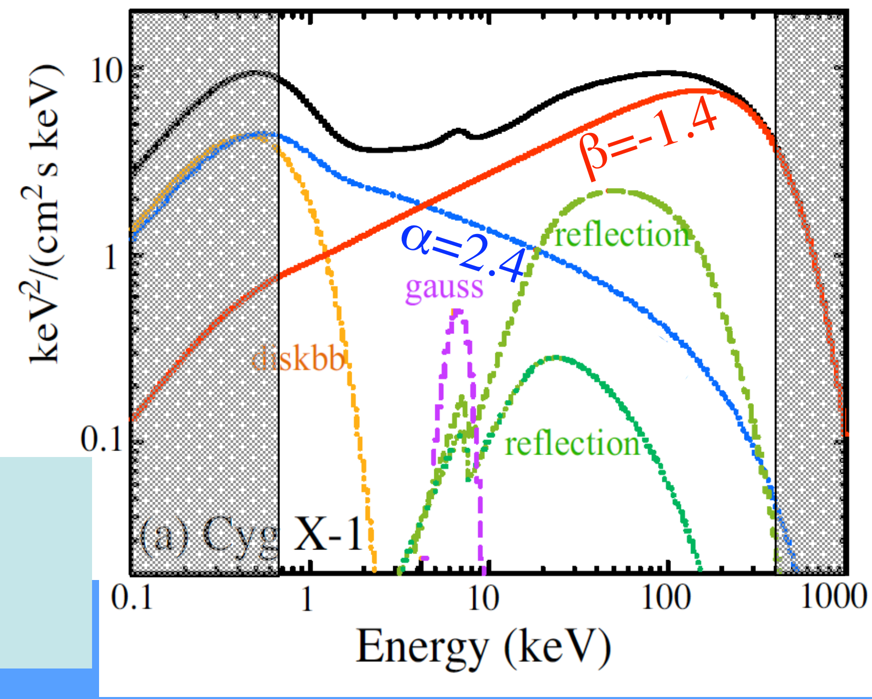
NPEX Continuum Model

- **N**egative & **P**ositieve powerlaws with **Ex**ponetical (Mihara 1995):

$$f(E) = (\underbrace{A^{-}E^{-\alpha}}_{unsaturated} + \underbrace{A^{+}E^{+\beta}}_{saturated})\exp(-E/E_{cut})$$

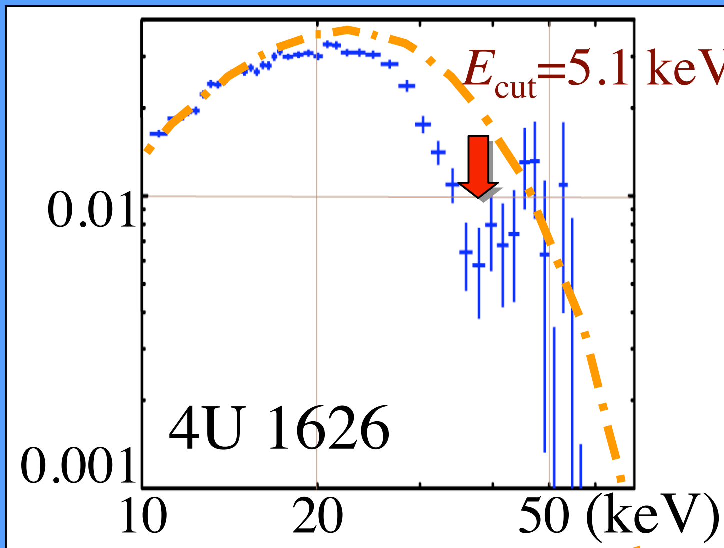
- An approximation to thermal Compton emission with multiple optical depths.
- β=2.0 if in the Wien regime.
- Successful on many accreting pulsar continua (Makishima+ 99).

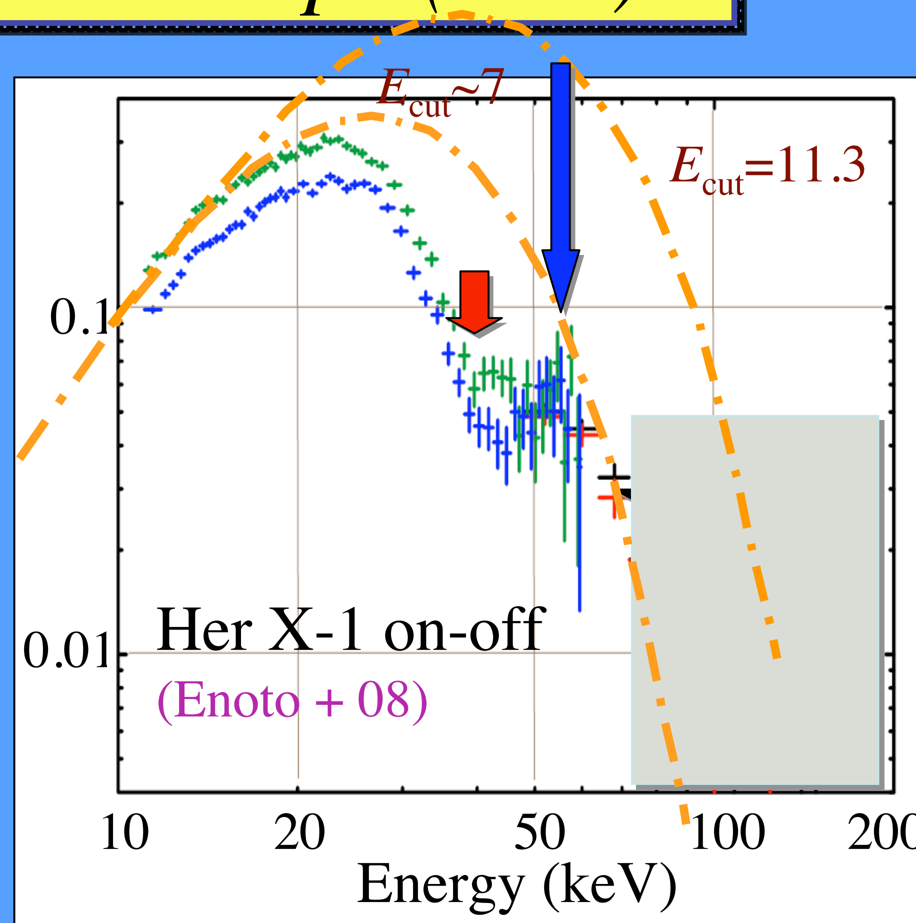


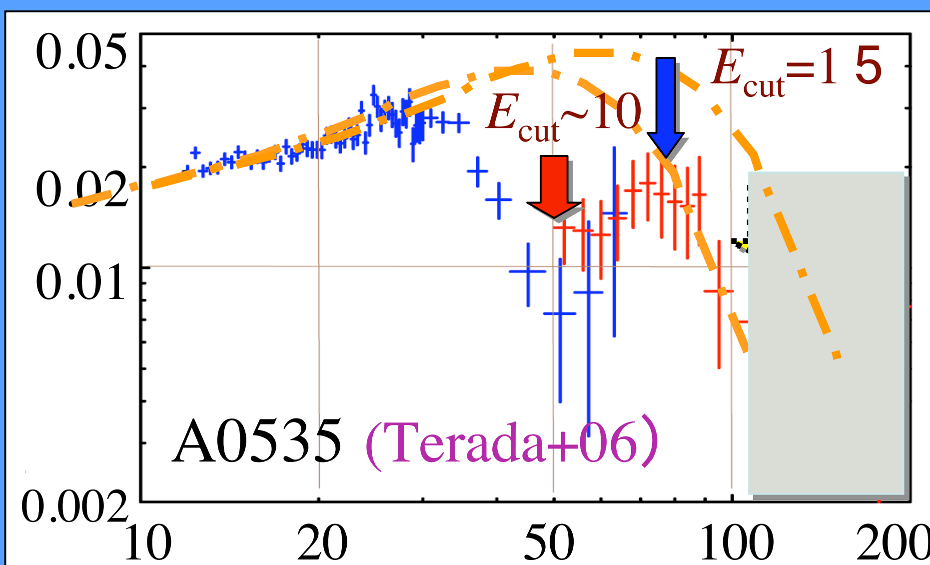


The best-fit double Compton model for Cyg X-1, as determined with *Suzaku* (Makishima + 08, *PASJ*, submitted)

NPEX Continuum Envelope (νFν)



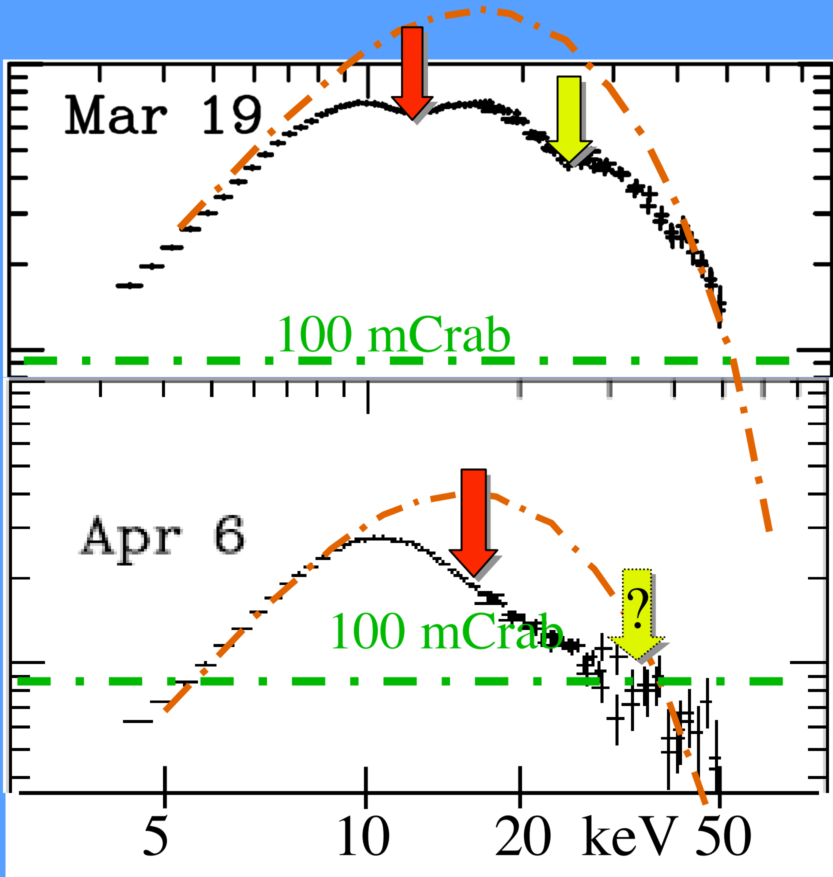




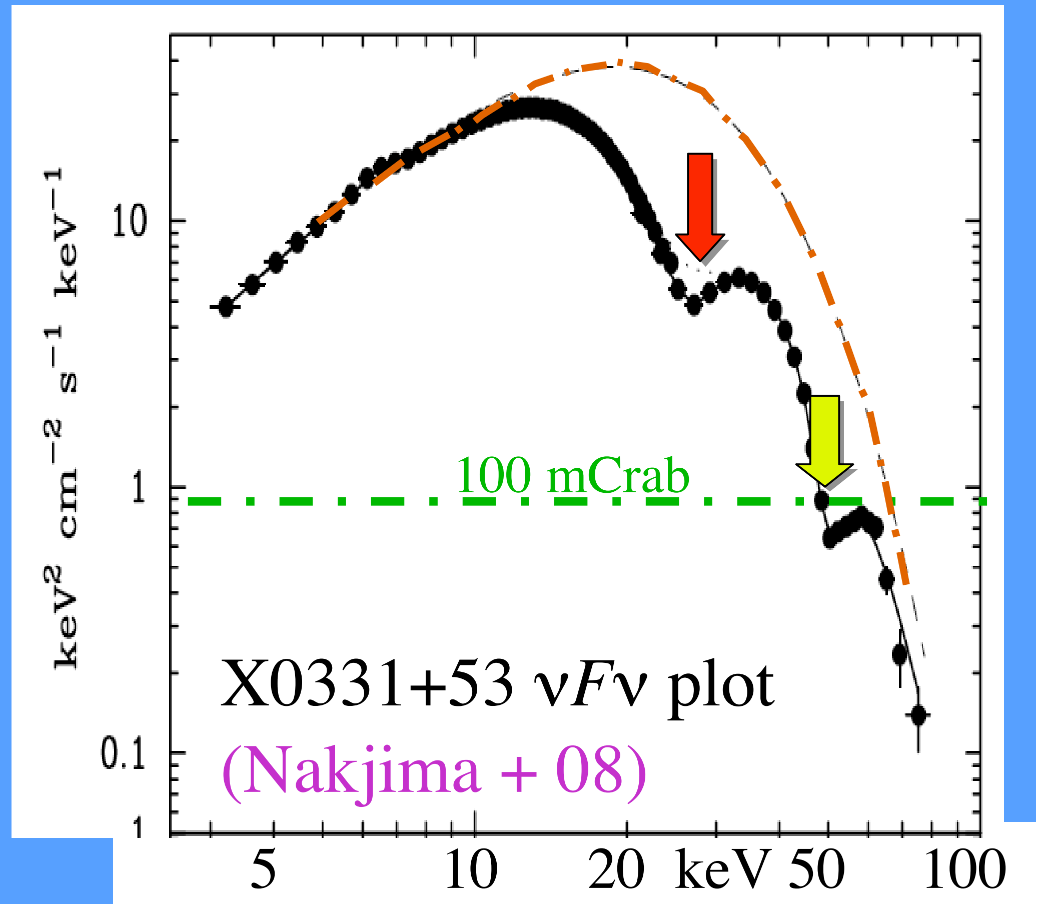
Positive detection at $E > 2E_a$ implies --
- A relatively hard NPEX envelope
- Evidence for the 2nd harmonic
- Strong attenuation between $E_a \sim 2E_a$

Little dependence on the absorption model

Higher-Lx / Lower-field sources with RXTE



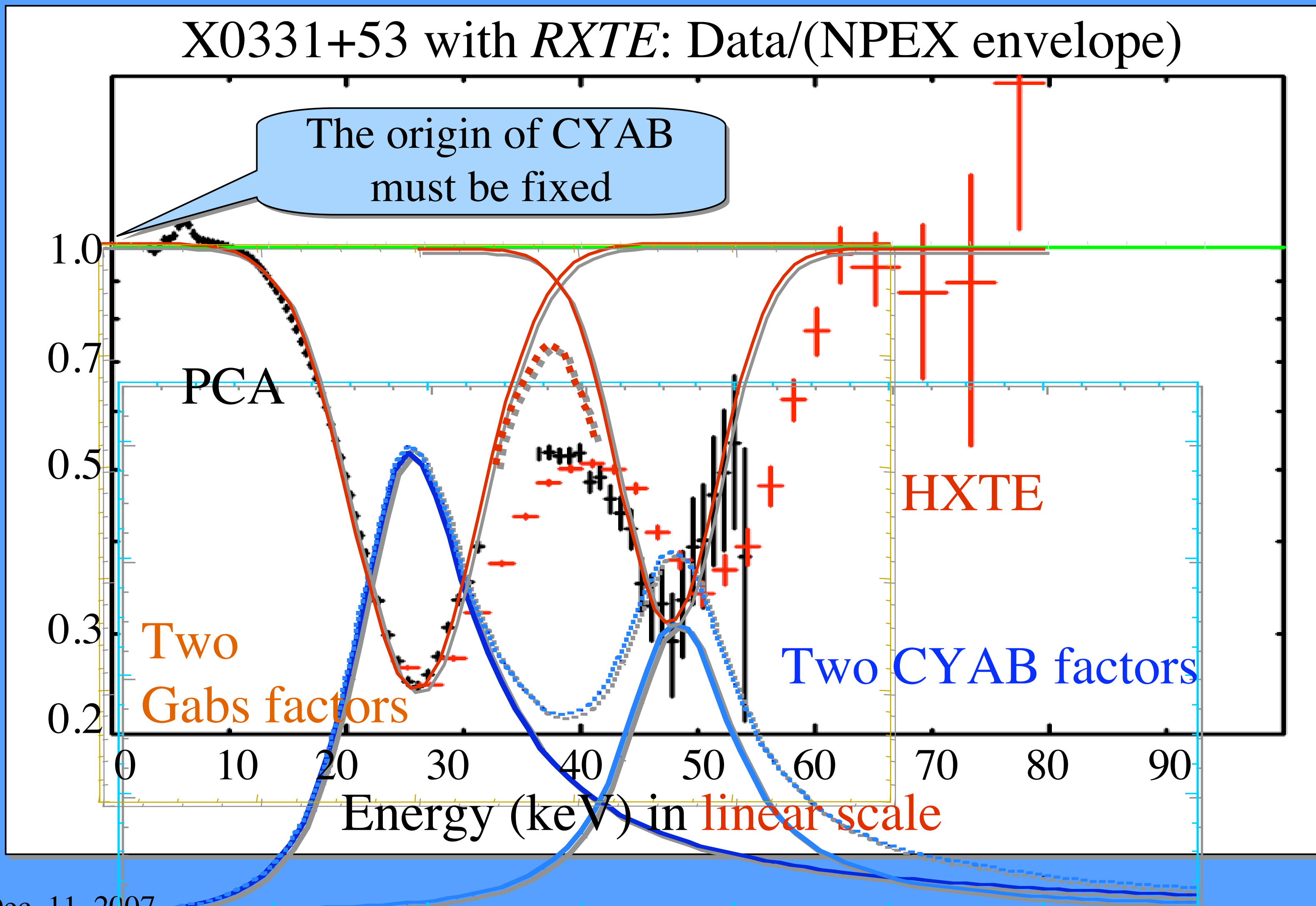
4U 0115+63 Crab ratio
(Nakjima + 06)



The same spectral structure in higher-*L*x and lower-field sources.

Absorption Profile: CYAB or Gabs?

When exp(-*S*) is plotted logarithmically, it directly reveals *S* in linear form



An XSPEC Bug Report

We (Kitaguchi +) found a bug in the Gabs model in Xspec11.3, and reported it to HEASOFT in late November 2007.

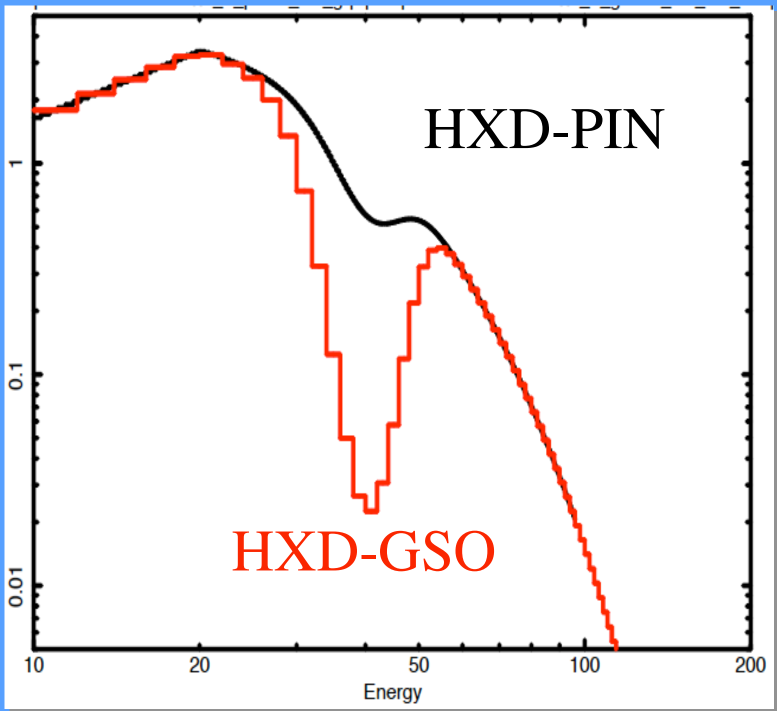
In calculating the multiplicative Gabs model as

$$m=\exp\{-aG\},$$

the current routine utilized the additive Gaussian line model as

$$G= \exp\{-0.5\ (E-b)^2/c^2\},$$

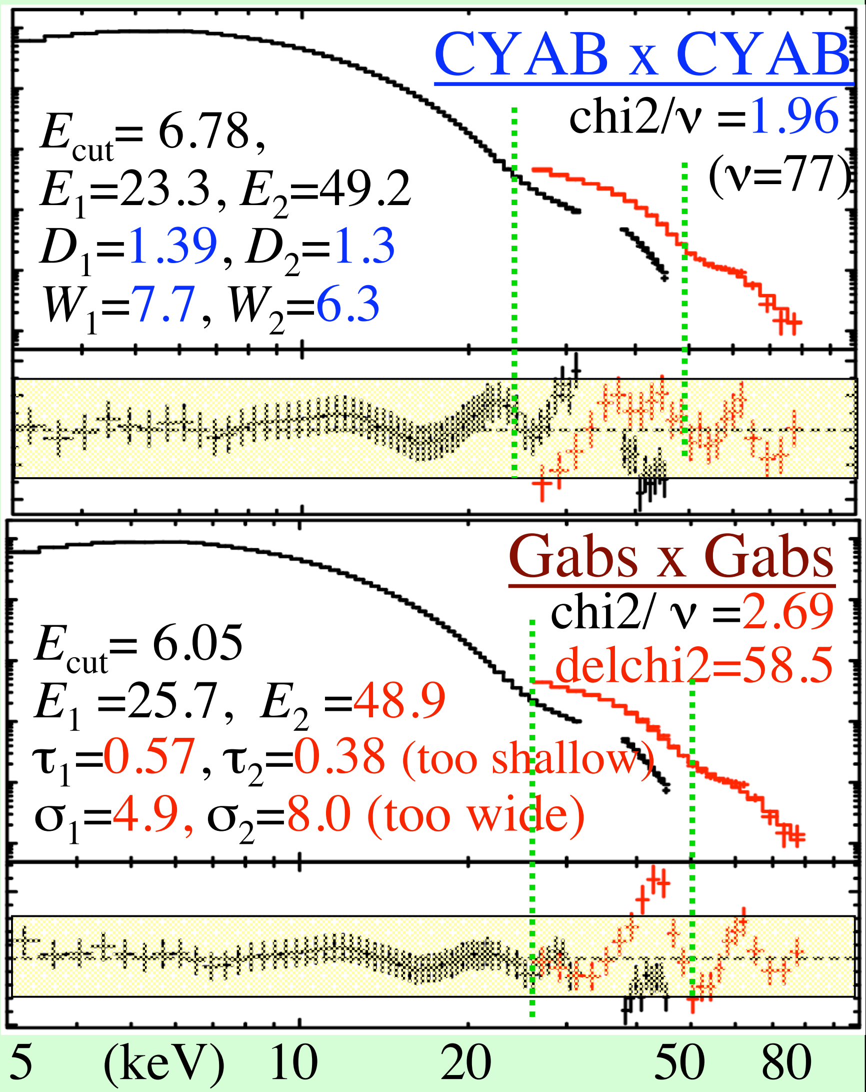
where G is returned in units of photons/cm2/s, instead of photons/cm2/s/keV which should be used in multiplicative models. As a result, G, hence m, became dependent on the bin width.



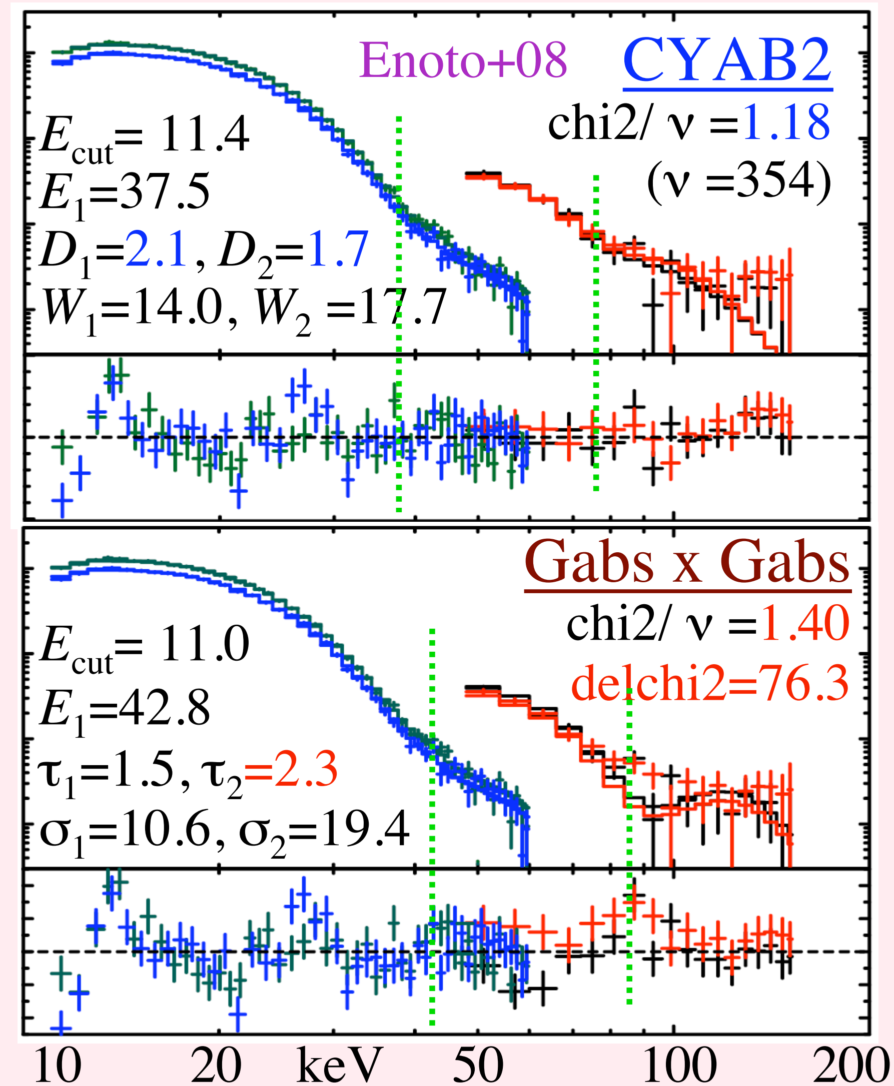
Hereafter, we use a local Gabs model where the bug is fixed.

Fit Results & Goodness

X0331+53 with *RXTE*



Her X-1 (on-off) *Suzaku*



Discussion& Summary

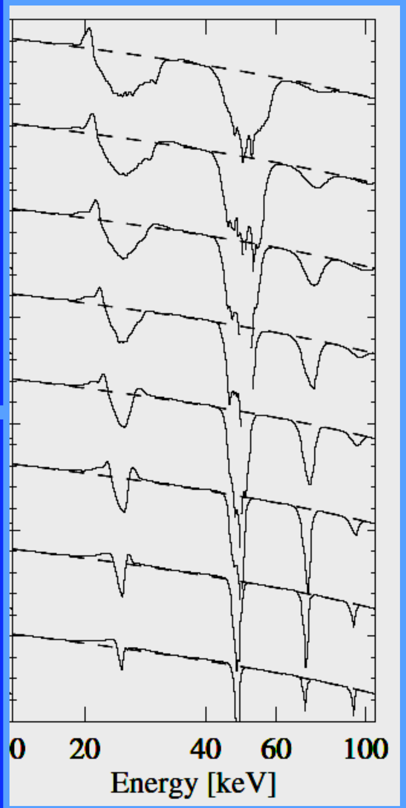
Suzaku observations of dimmer and/or higher-field sources:

- Clear signal detections of at $E > 2E_a$ with HXD-GSO.
- HXD-PIN measurements of the fundamental resonance with good ΔE.

Consequences:

1. The fundamental resonance strong, with D_1=1.3-2.0
2. The 2nd resonance ubiquitous, with $D_2 \sim D_1$.
3. CYAB successful on profile modeling, but Gabs not.
4. Strong flux suppression been E and $2E_a$.
5. Theoretically predicted "red/blue wings" not seen.

Schoenherr+07



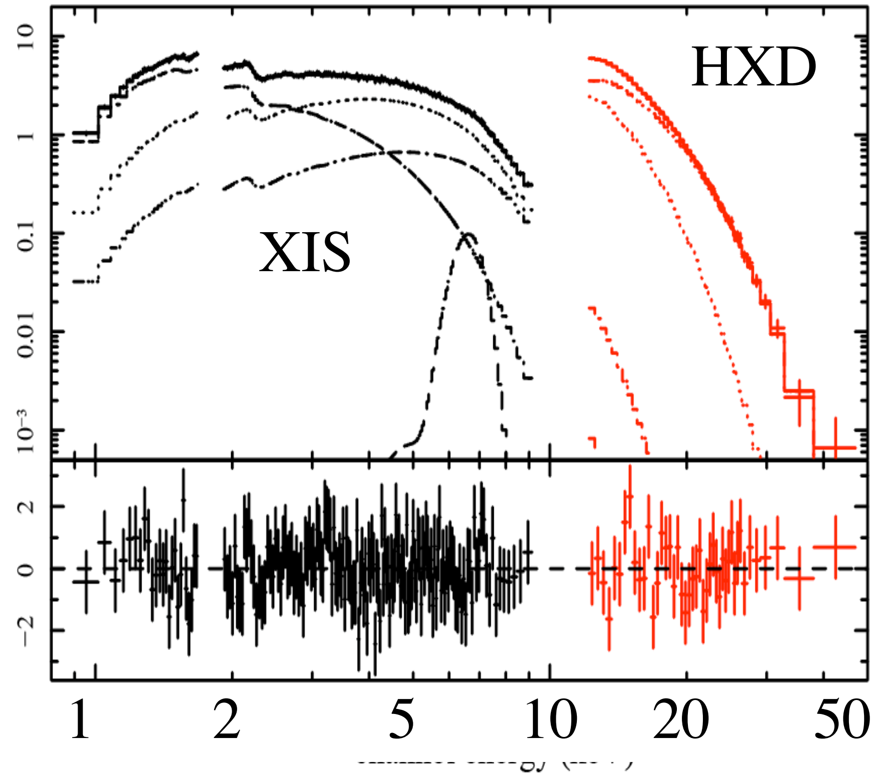
The origin of resonance width :

1. Thermal Doppler-- unlikely to account for 100%.
2. Phase-dependent changes in E_a -- not dominant.
3. Uncertainty principle + unexpectedly short life times of the excited Landau level (Enoto+08) -- Possible?

A Grand Unification of LMXBs

by Hiro Takahashi et al. (Poster B56)

GX 349+2 observed with *Suzaku* in Flaring Branch (2.8 ks)



MCD (T_{in}~1.0 keV, r_{in}~25 km)
BB1 (T~1.6 keV, r~15 km)
BB2 (T~2.7 keV, r~5 km)
Gau (~6.7 keV, σ~0.4 keV, EW~70 eV)