A *Suzaku* View of Cyclotron Line Sources and Candidates

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on behalf of the *MAGNET* collaboration

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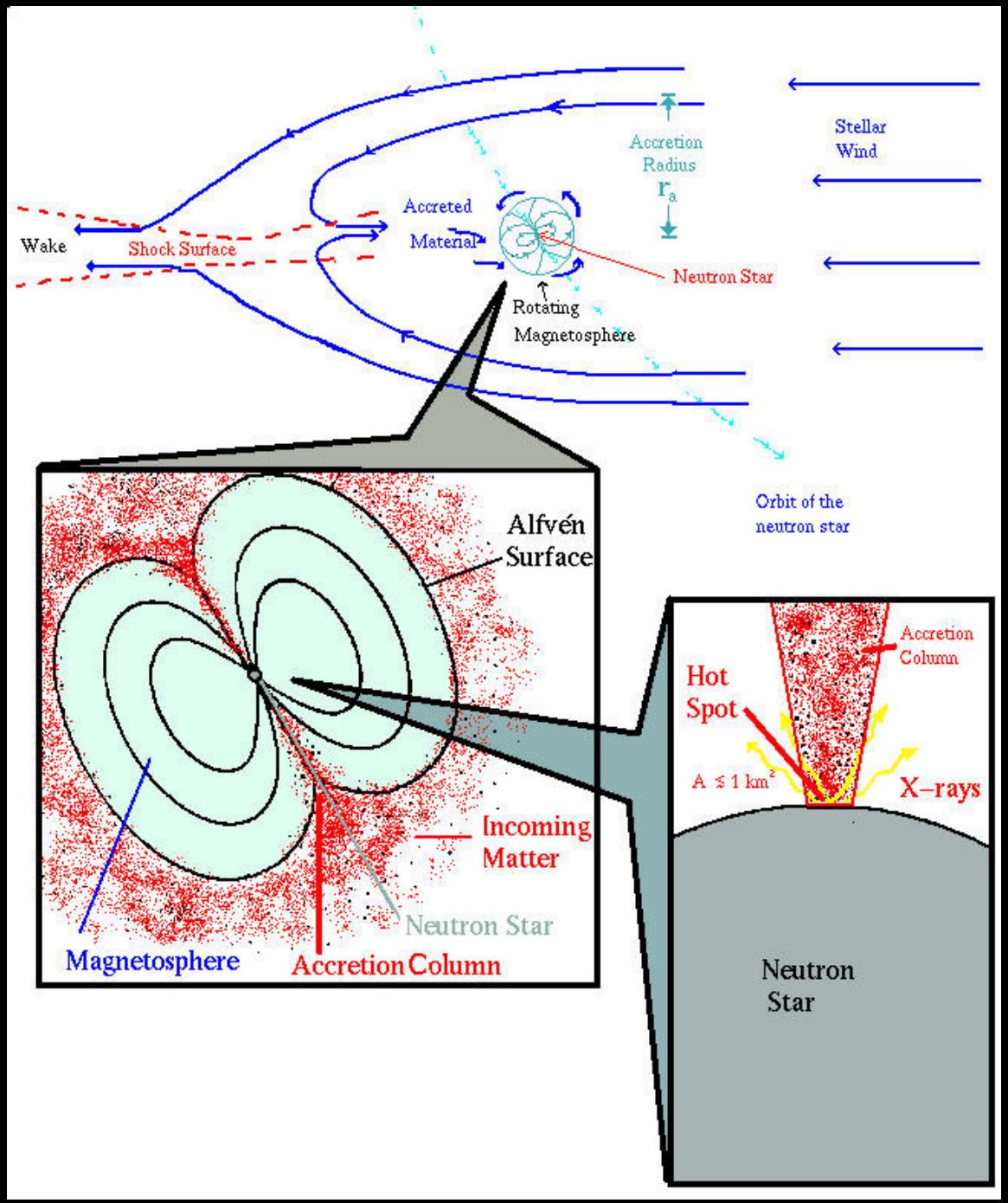
Exploring the X-ray Universe: Suzaku and Beyond, SLAC, July 20-22, 2011

CRESST UMBC NASA



CRSF Sources

mainly HMXBs

accreting pulsars

$\sim$1–5 $\times 10^{12}$ G

$\sim$ 17 sources

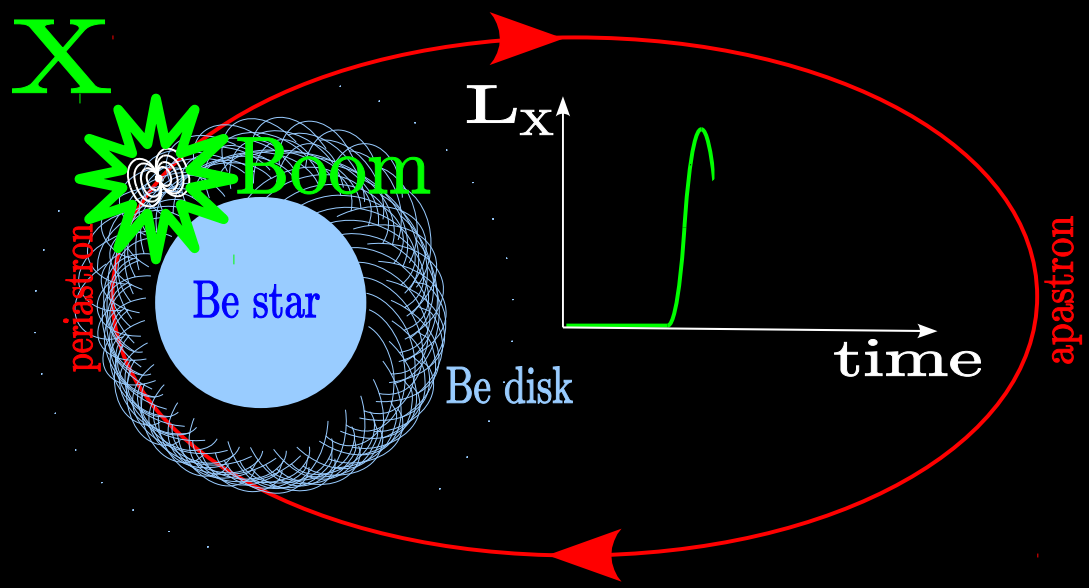
$\sim$ 50% transient

Wind Accretion

generally persistent

dips & flares

Negueruela, based on Davidson & Ostriker (1973)



courtesy Sebastian Müller (Remeis)

CRSF Sources

mainly HMXBs

accreting pulsars

$\sim$1–5 $\times 10^{12}$ G

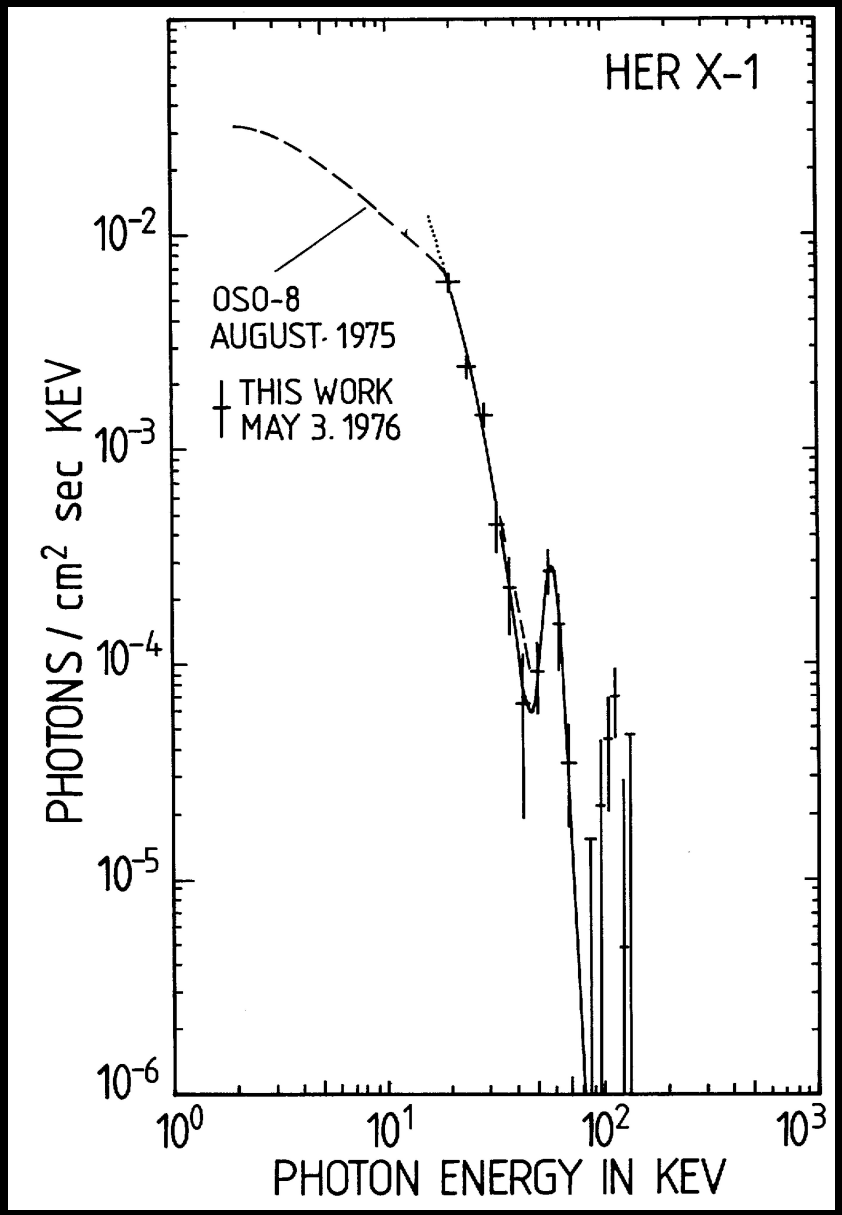
$\sim$ 17 sources

$\sim$ 50% transient

Be Accretion

transient
weeks-long bursts

CRSFs: The First Observation



X-Ray Spectrum

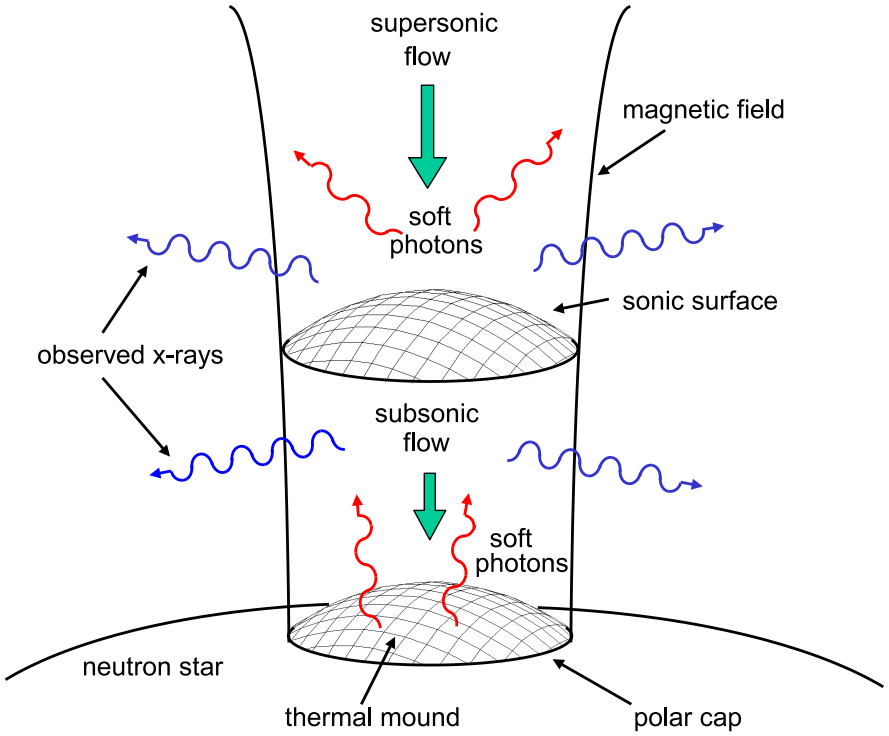
cutoff power law continuum
$\Leftrightarrow$ Compton scattering

often Fe Kα line at 6.4...6.7 keV
$\Leftrightarrow$ fluorescence in circumstellar material

cyclotron line, luminosity & pulse phase dependence
$\Leftrightarrow$ strong, complex B-field

Trümper et al. (1978a)

CRSFs: Principle I

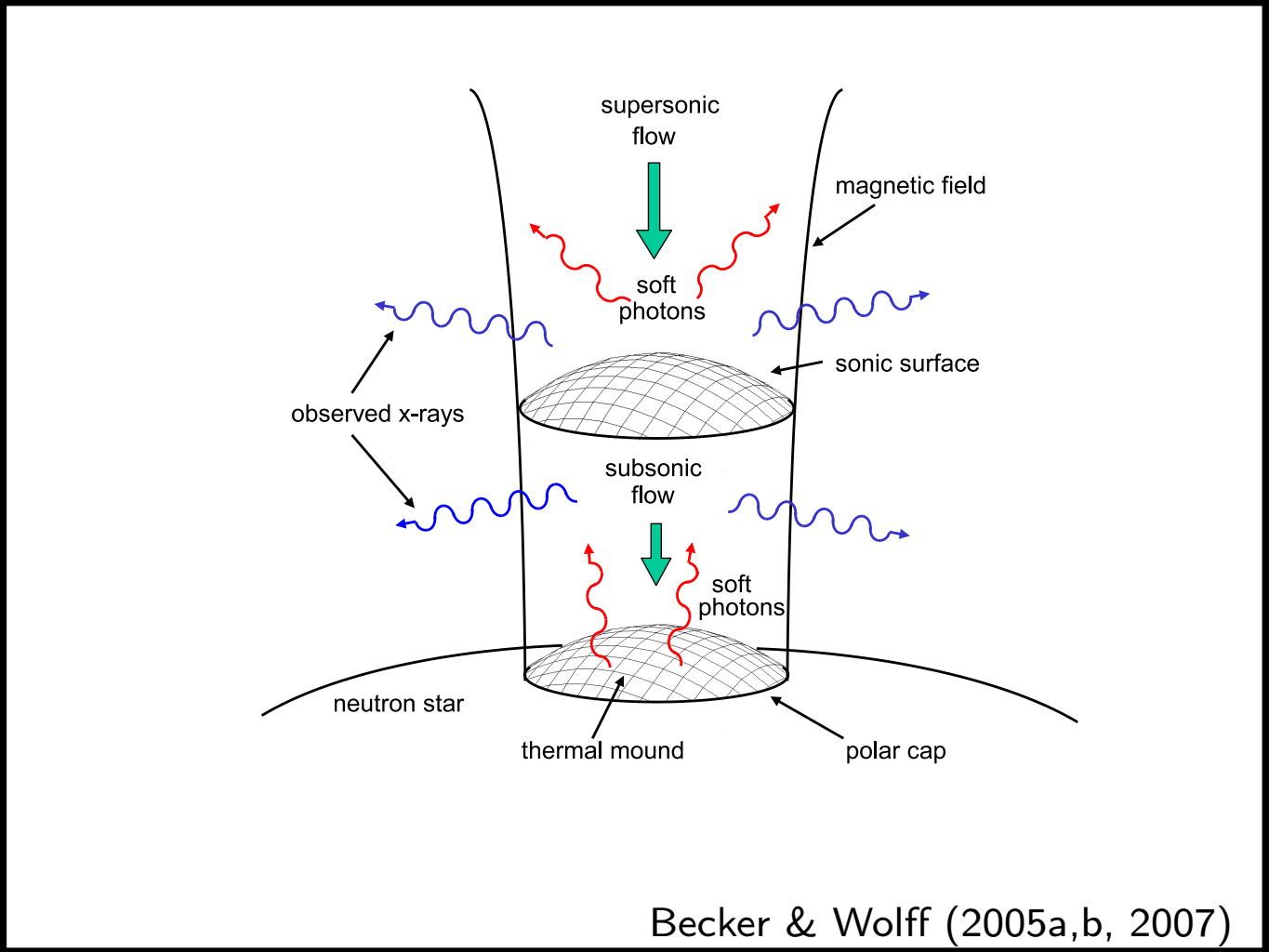


Becker & Wolff (2005a,b, 2007)

Continuum from the Accretion Column

Bulk motion and thermal Comptonization of seed photons (bremsstrahlung, cyclotron, blackbody) from accretion mound in shock.

CRSFs: Principle II



Becker & Wolff (2005a,b, 2007)

Cyclotron Resonant Scattering Features – CRSFs ("Cyclotron Lines")

Quantization of electron energies $\perp$ B-field lines, Landau levels:

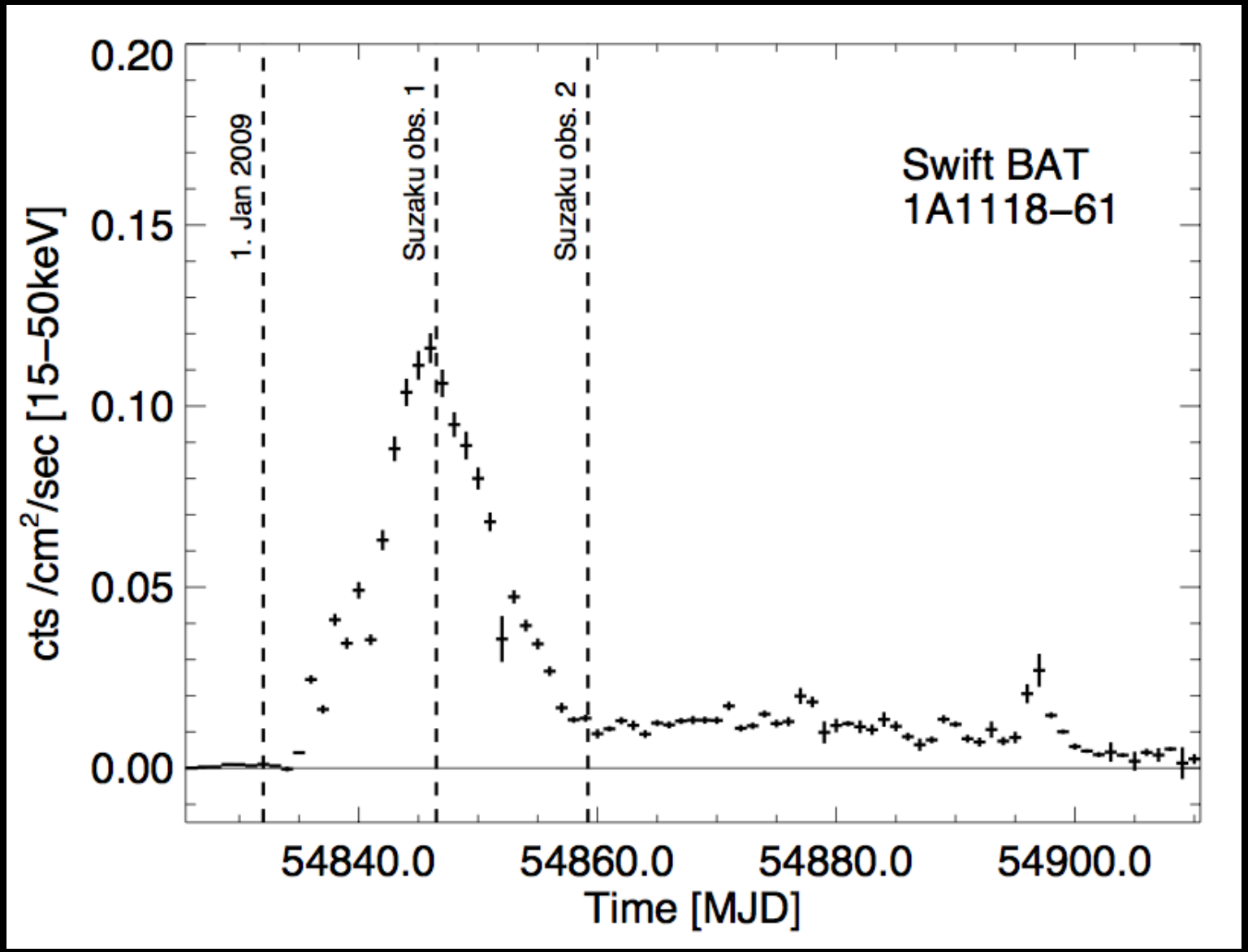
$$E_{\mathrm{cyc,n,obs}} = n \times (1+z)^{-1} \times 11.6\,\mathrm{keV} \times \left(\frac{B}{10^{12}\,\mathrm{G}}\right)$$

	Source	E_{cyc} [keV]	P_s [s]	P_{orb} [d]	type
1	Swift J1626.6−5156	10, 18	15	132.9	T, Be
2	4U 0115+63	14, 24, 36, 48, 62	3.6	24.31	T, Be
3	V 0332+53	27, 51, 74	4.37	34.25	T, Be
4	Cep X-4	28	66.25	>23	T, B1
5	MXB 0656−072	33	160	?	T, O9.7 Ve
6	XTE J1946+274	36	15.8	169.2	T, B0-1 V-IVe
7	A 0535+26	45, 100	105	110.58	T, Be
8	GX 304−1	54	272	?	T, Be
9	1A 1118−616	55	408	24	T, O9.5 IV-Ve
1	4U 1907+09	19, 40	438	8.38	P, B2 III–IV
2	4U 1538−52	20	530	3.73	P, B0 I
3	Vela X-1	25, 53	283	8.96	P, B0.5 Ib
4	X Per	29	837	250.3	P, B0 III–Ve
5	Cen X-3	30	4.8	2.09	P, O6.5 II
6	GX 301−2	37	690	41.5	P, B1.2 Ia
7	4U 1626−67	37	7.66	0.028	P, LMXB
8	Her X-1	39	1.24	1.7	P, A9-B
	EXO 2030+375	11? 63?	42	46.0	T, B0 Ve
	GRO J1008−57	88?	93.7	249.5	T, B0e
	XTE J1739−302		?	51.47	T, O8 Iab
	OAO 1657−415	36?	37.7	10.4	P, B0-B6 Ia-Iab
	4U 1700−377	37?	?	3.4	P, O6.5 Iaf+
	LMC X-4	100?	13.5	1.41	P, O7 IV
	4U 1909+07		604	4.4	P, OB
	IGR 16318−4848		?	?	P, sgB[e]

after Caballero & Wilms, 2011, Proc. 29th Frascati

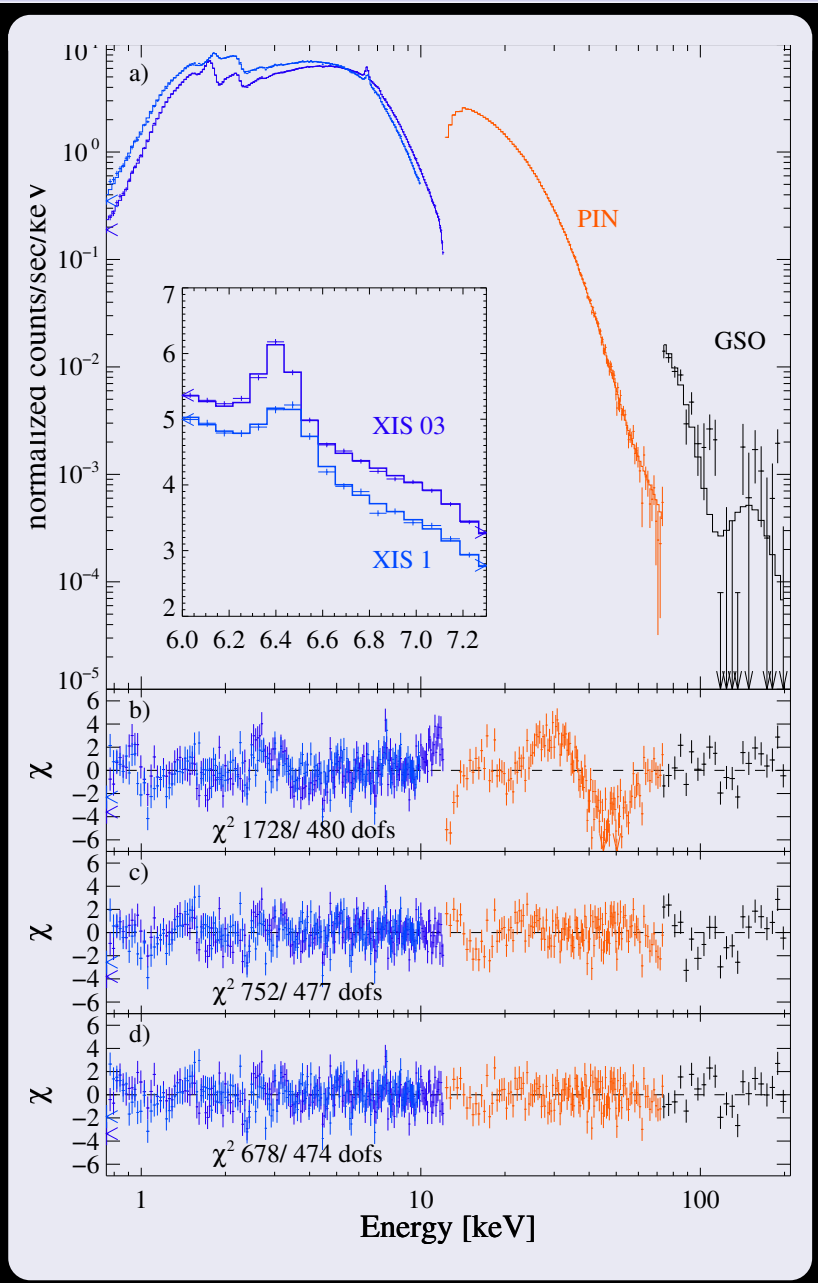
	Source	*Suzaku* Obs.	*Suzaku* References
1	Swift J1626.6−5156	–	
2	4U 0115+63	07/2011 – 2x	waiting for data
3	V 0332+53	–	
4	Cep X-4	–	
5	MXB 0656−072	–	
6	XTE J1946+274	10/2010	work in progress (Marcu)
7	A 0535+26	2005/09/10	Terada/Naik'06'08, Caballero **(prep.)**
8	GX 304−1	08/2010	new line: Yamamoto'11
9	1A 1118−616	01/2009 – 2x	new line: Suchy'11
1	4U 1907+09	05/2006, 04/2007	Rivers'10
2	4U 1538−52	–	
3	Vela X-1	06/2008	Doroshenko'11
4	X Per	–	
5	Cen X-3	12/2008	Naik'11
6	GX 301−2	08/2008, 01/2009	Suchy'11 **(subm.)**
7	4U 1626−67	03/2006, 09/2010	Camero-Arranz **(prep.)**
8	Her X-1	2005/06/08/10	Klochkov **(prep.)**
	EXO 2030+375	05/2007	
	GRO J1008−57	11/2007	Naik'11, Kühnel **(prep.)**
	XTE J1739−302	02/2008	Bodaghee'11
	OAO 1657−415	–	
	4U 1700−377	09/2006	work in progress (Marcu)
	LMC X-4	01/02/04/2008	Hung'10
	4U 1909+07	11/2010	work in progress (Marcu)
	IGR 16318−4848	08/2006	Barragan'09

1A 1118−61: 2009 Outburst



Suchy, Pottschmidt et al., 2011, 733, 15

1A 1118−61: Cyclotron Line Discovery



3rd Outburst in Source History

500 mCrab:

Suzaku: $58.2^{+0.8}_{-0.4}$ keV

RXTE: $55.1^{+1.6}_{-1.5}$ keV

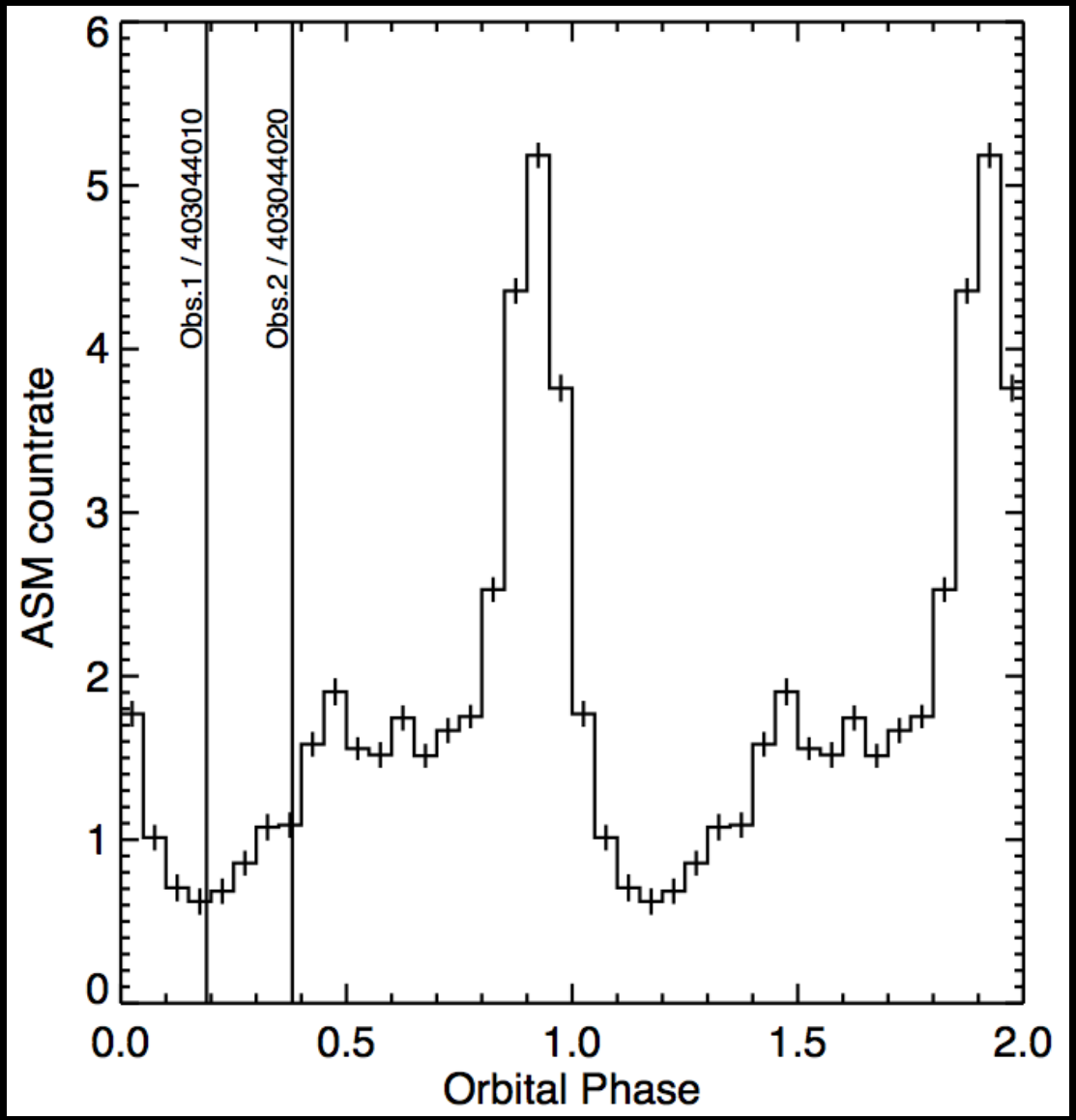
50 mCrab:

Suzaku: $47.4^{+3.2}_{-2.3}$ keV (?)

L dependence important for models.

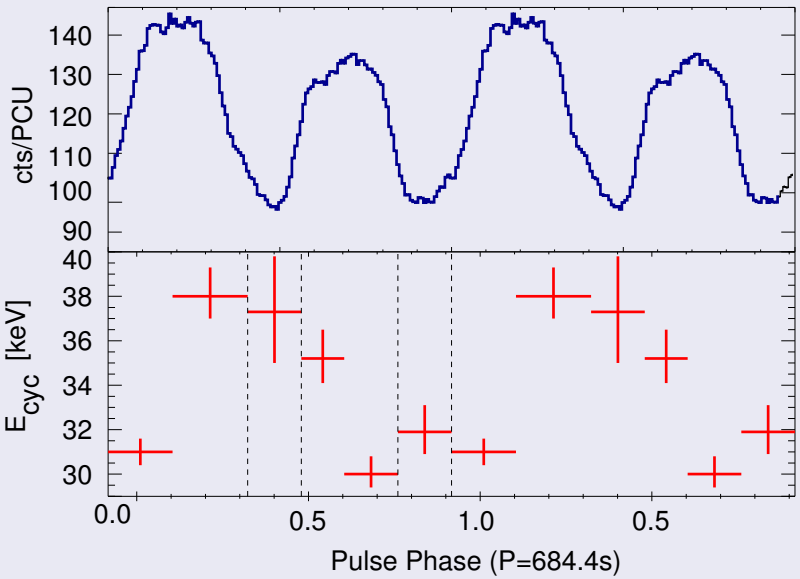
Suchy, Pottschmidt et al., 2011, ApJ, 733, 15
Doroshenko, Suchy et al., 2010, A&A, 515, 1

GX 301−2: 41.5 Day Orbit, Pre-Periastron Flare



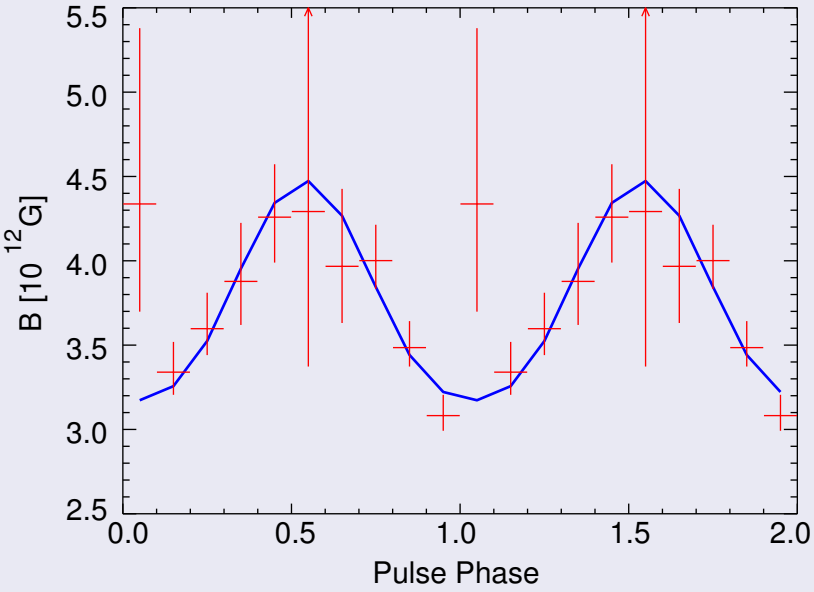
Suchy et al., 2011, ApJ, submitted

GX 301−2: Pulse Phase Resolved Spectroscopy



RXTE, 200 ks, Pre-Periastron Flare

Kreykenbohm et al., 2005, A&A, 427, 975

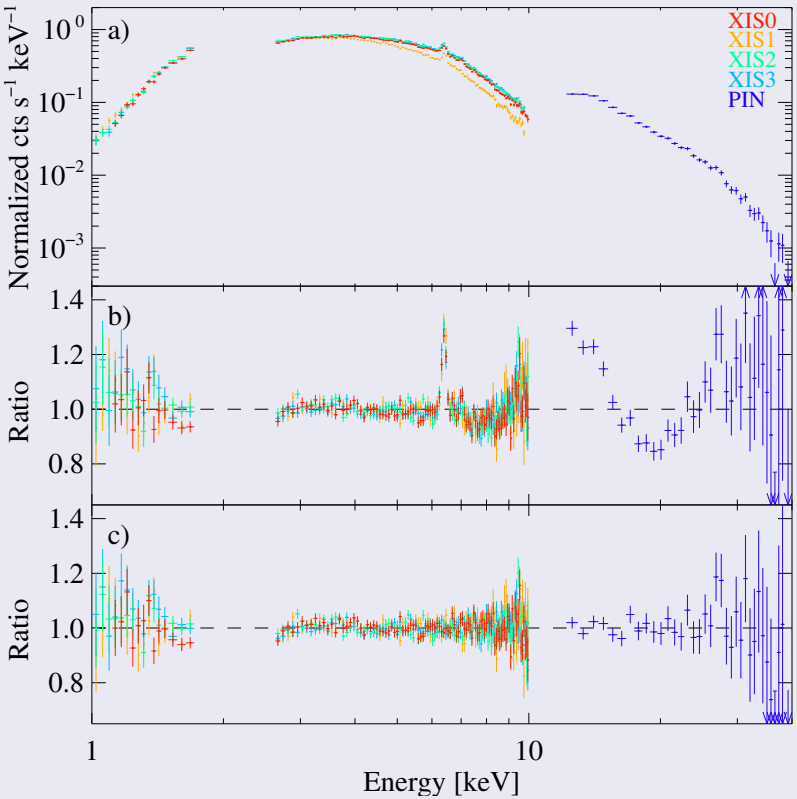


Suzaku, 60 ks

Suchy et al., 2011, ApJ, subm.

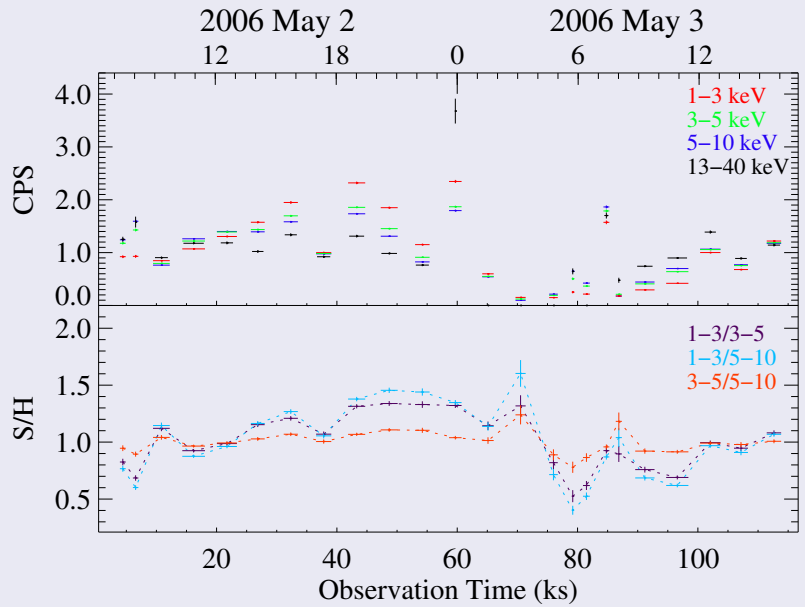
Suzaku confirms CRSF at ∼35 keV varies with pulse phase, finds consistency with dipole B-field, spin axis tilted 15° to LOS.

4U 1907+09: Persistent But Dips & Flares



Suzaku 2006: $E_{\rm cyc} = 18.6^{+0.8}_{-0.7}$ keV

Fritz et al., 2006, A&A, 458, 885:
INTEGRAL, 2.3 Ms: $E_{\rm cyc} = 18.9^{+0.6}_{-0.7}$ keV



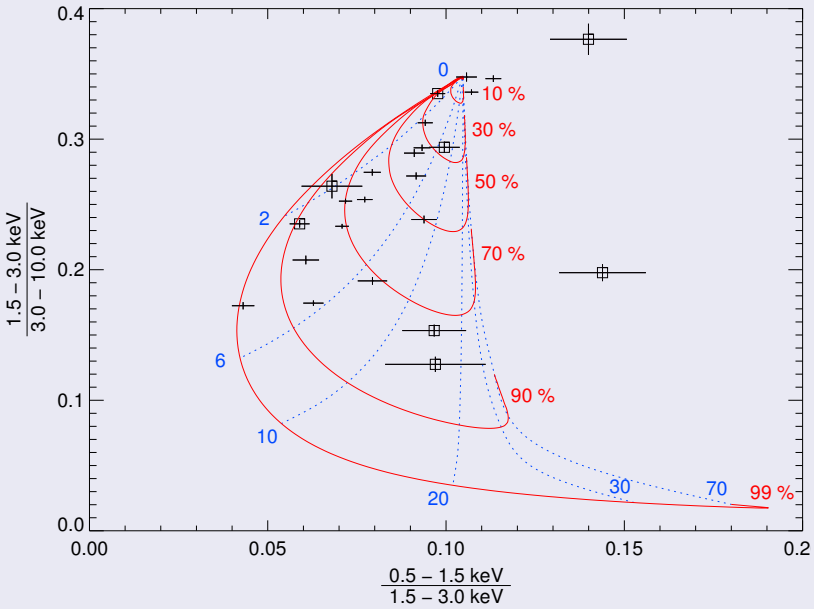
Suzaku 2006: Dips and Flares

Rivers, Markowitz, Pottschmidt et al., 2010, ApJ, 709, 179

Suzaku observations in 2006 (60/30 ks) and 2007 (80/65 ks)

Similar results with *Suzaku* in 2007.

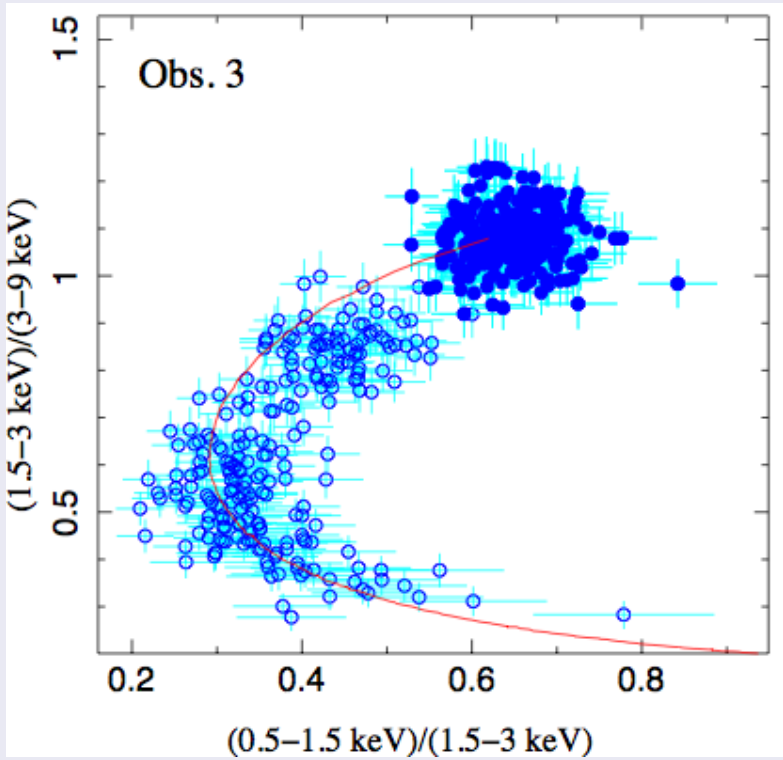
4U 1907+09: Not All Absorption?



4U 1907, 40 mCrab, 90 min bins

Rivers et al., 2010, ApJ, 709, 179

Local, partially covering absorption defines distinct CC tracks.

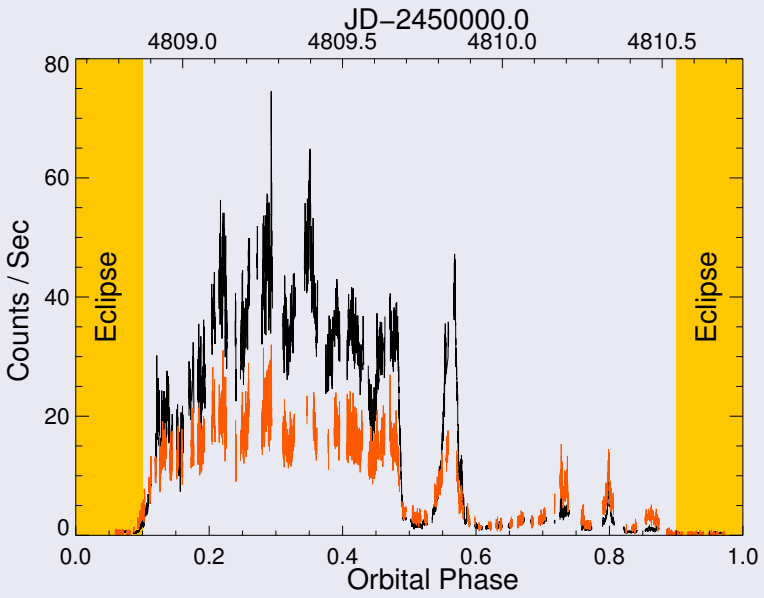


Cyg X-1, 300 mCrab, 16 s bins

Nowak et al., 2011, ApJ, 728, 13

Suzaku observed strong local absorption dips, e.g., for Cyg X-1 (Nowak et al., 2011) and Cen X-3 (Naik et al., 2011) but also increases rare observations of dips due to suppression of accretion, e.g., for Vela X-1 (Doroshenko et al., 2011). 4U 1907+09 seems to show both.

Cen X-3: Iron Lines

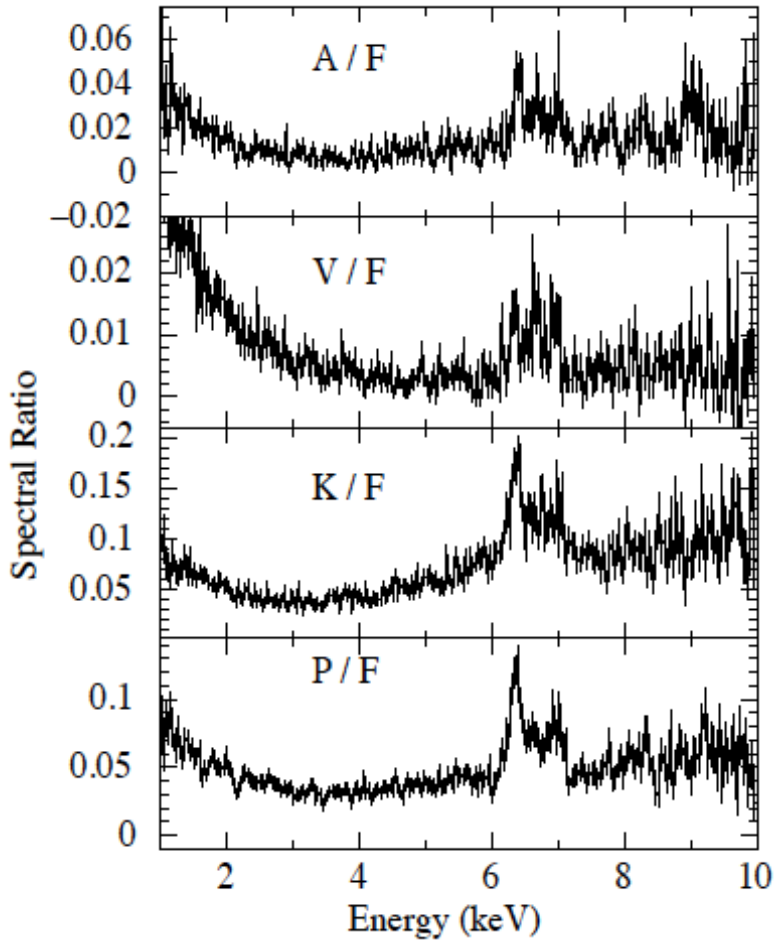


Suzaku 2008: One Cen X-3 Orbit

courtesy Slawomir Suchy (UCSD)

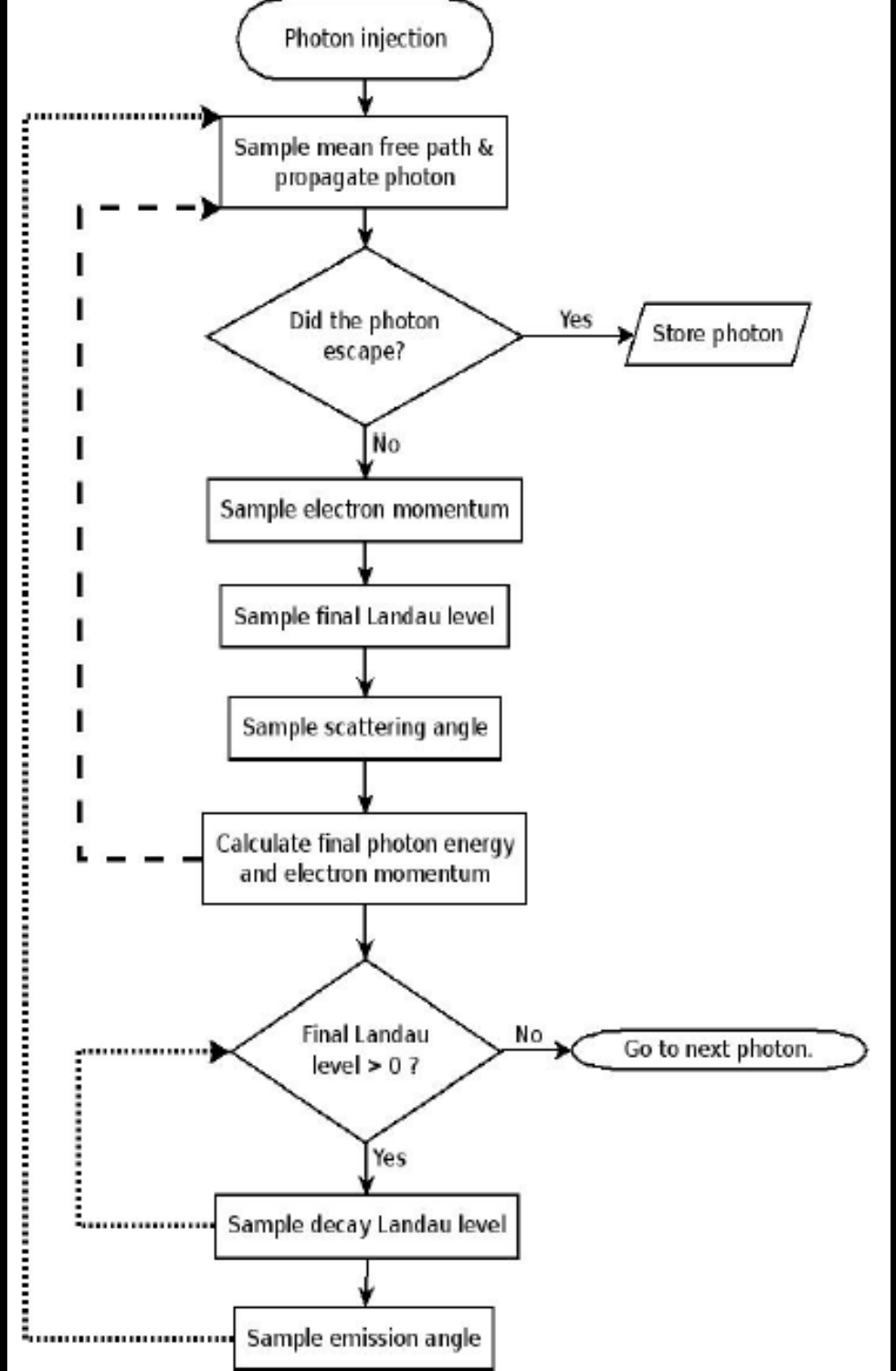
Fe Lines in Dips

– known lines @ 6.4, 6.7, 6.97 keV
– decline less than continuum
– 6.4 keV declines less than others
⇒ absorber in outer accretion disk



Eclipses/Bright (A/F, V/F)
Dips/Bright (K/F, P/F)

Naik et al., 2011, ApJ, in press



CRSF Modeling

Past/Present

empirical profiles
Gaussian/Lorentzian

Present/Future

physical profiles
B, kT_e, τ_{es}, geometry

Monte Carlo Code

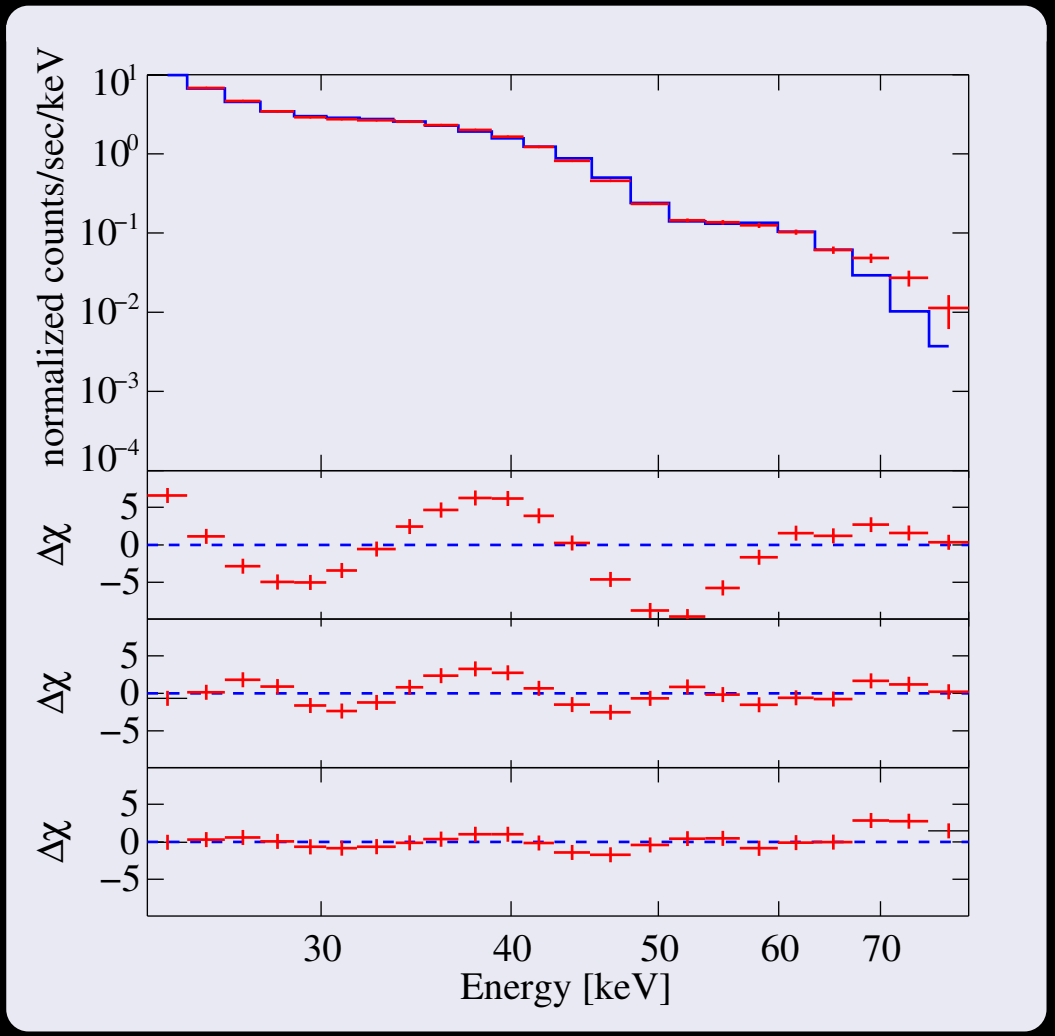
courtesy Fritz-Walter Schwarm (Remeis), after Araya & Harding ('99)

Physical CRSF Models: History & Current Status

- **Original MC code, Araya**: based on Araya & Harding (1999)
- **Schönherr et al. (2007):** added new geometry (bottom illuminated slab); calculated Greens' functions to apply to any continuum; XSPEC model `cyclomc`; emission wings, first harmonic too strong?
- **Schwarm (2010):** mean free path correction; profile functions (cross section, inverse mean free paths) now consistent with Harding & Daugherty (1991) and Nishimura (priv. comm.)
- **Next, Schwarm:** new grid calculations (B, kT_e, τ_{es}, geometry); new Greens' functions for `cyclomc`

`http://www.sternwarte.uni-erlangen.de/new/Arbeiten/2010-09_Schwarm.pdf`

CYCLOMC Example



V0332+53, *INTEGRAL*
Schönherr et al., 2007, A&A, 472, 353

Continuum – `fdcut`

$\Gamma = 0.94$
$E_{\mathrm{cut}} = 12.8\,\mathrm{keV}$
$E_{\mathrm{fold}} = 7.5\,\mathrm{keV}$

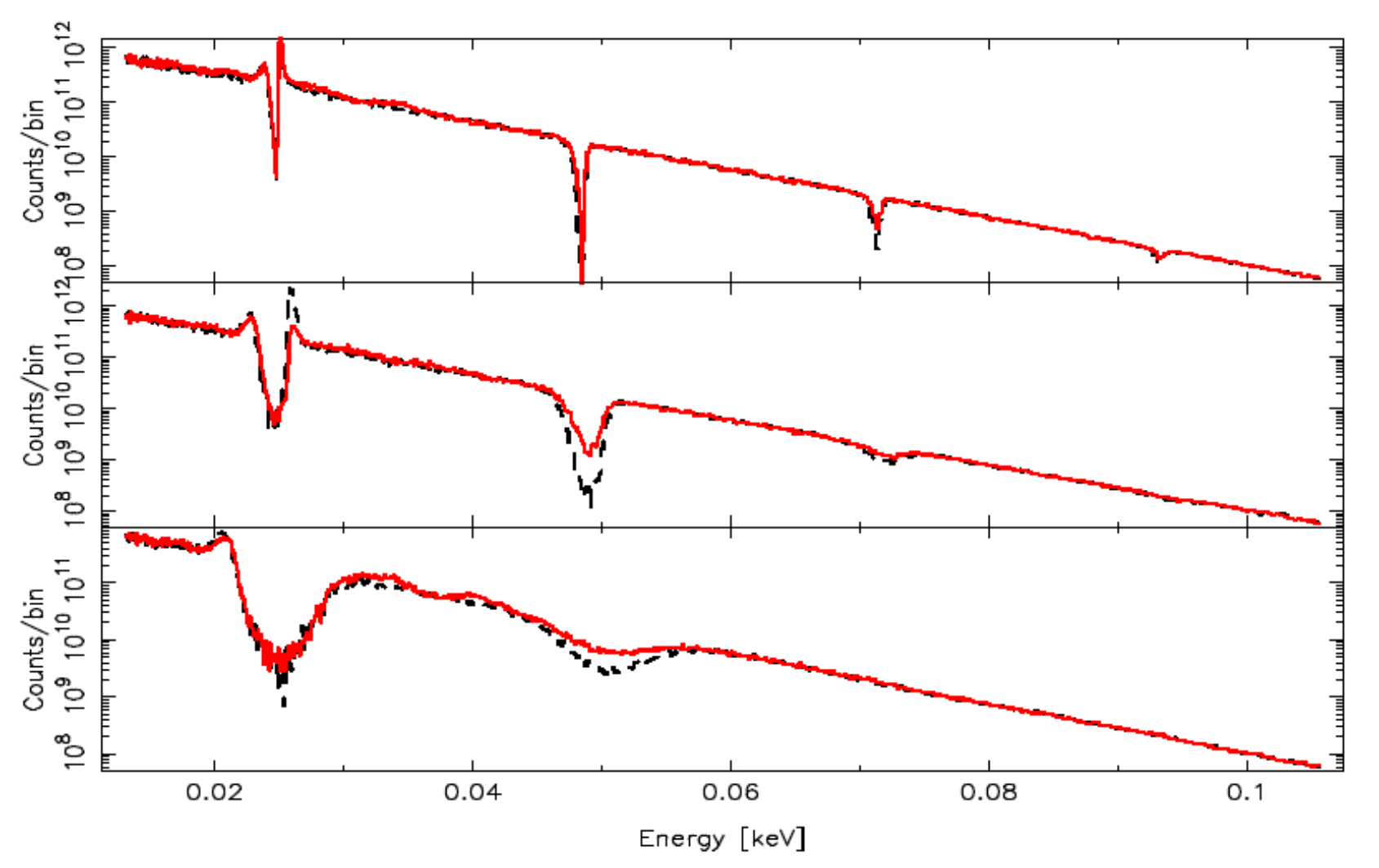
Line Model – `cyclomc`

$B = 3.05 \times 10^{12}\,\mathrm{G}$
$kT_{\mathrm{e}} = 10.2\,\mathrm{keV}$
$\tau_{\mathrm{es}} = 0.003,\ \mu = 0.06$

Reducing Emission Wings

- bottom illuminated slab
- partial covering

Model Spectra Example



Cylinder Geometry, $\mu = 0, 0.3, 0.8$ $B/B_{\mathrm{crit}} = 0.05$, $kT_{\mathrm{e}} = 3\,\mathrm{keV}$, $\tau_{\mathrm{es}} = 10^{-3}$

Schwarm, 2010, diploma thesis

Summary & Outlook

- 11 of 17 CRSF sources have been observed with *Suzaku* at least once.
- Good spectral statistics for comparatively short exposures and weak sources.
- It would be ideal if this strength could be better explored by monitoring observations sampling the spectral evolution with time and L.
- Study of *Suzaku* CRSF observations as a sample will start soon.
- Goal: Apply new `cyclomc` line model.