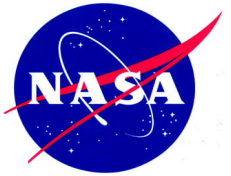
NuSTAR's view of accreting Galactic binaries

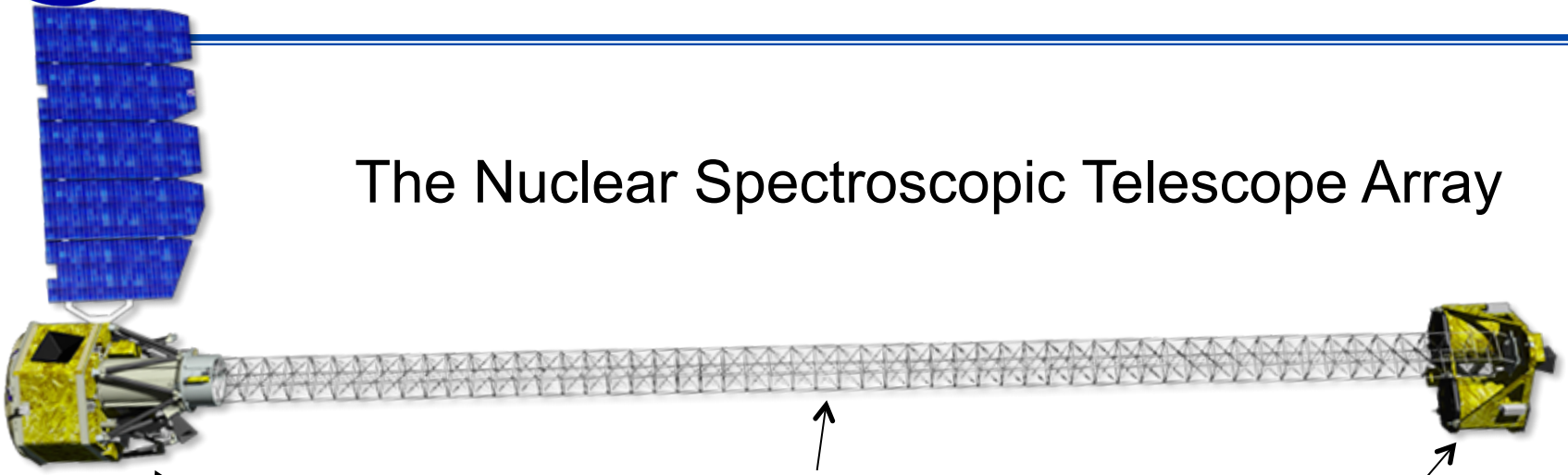
(or some highlights thereof)

Felix Fürst

California Institute of Technology



The Nuclear Spectroscopic Telescope Array



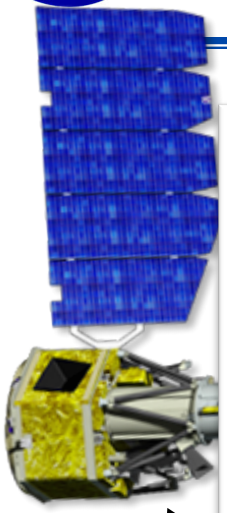
10m extendable mast

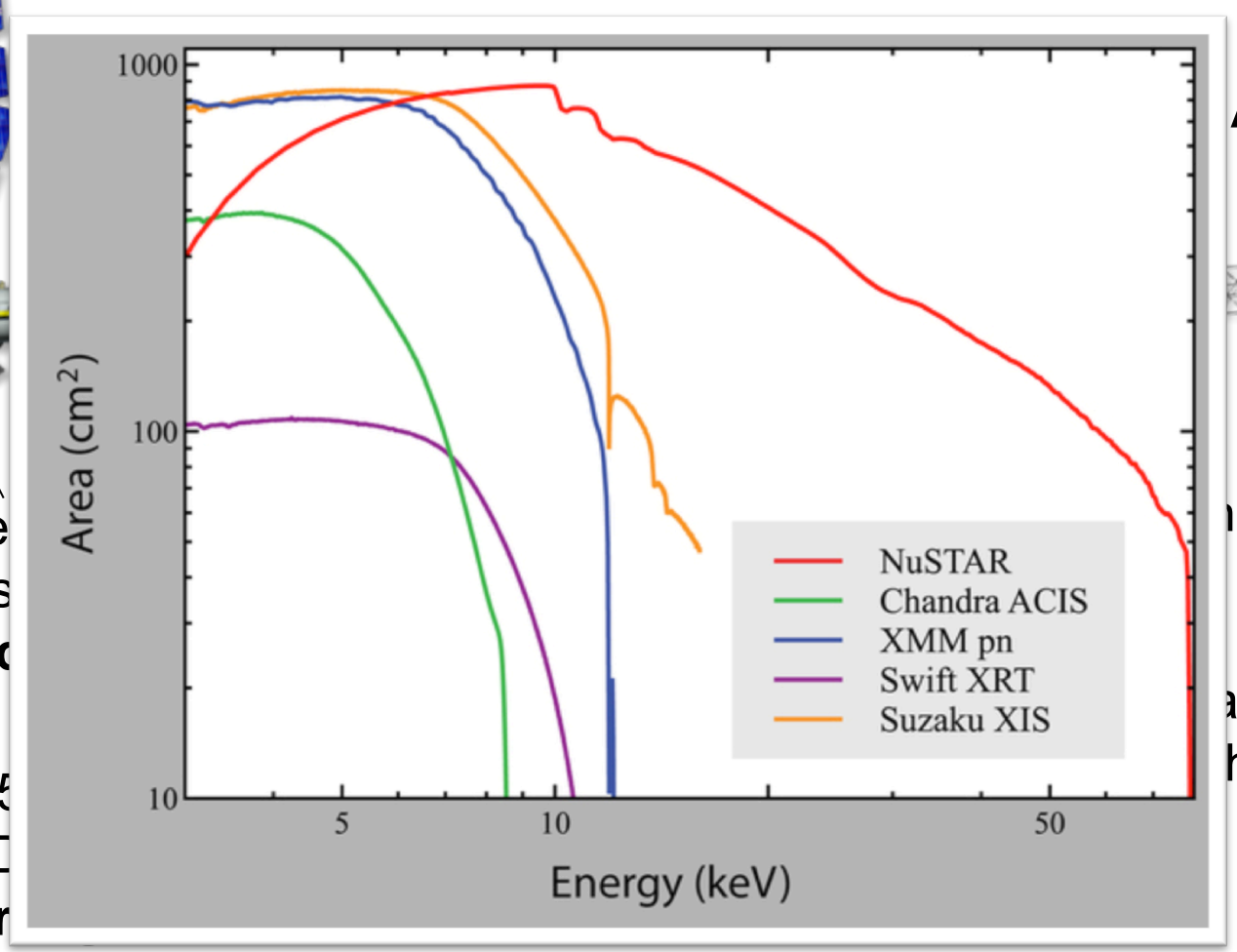
Two independent CZT detectors, with 64x64 **triggered** pixels each.

Two depth-graded, multilayer, gracing incidence, Wolter approximation, focusing optics, with 133 shells each

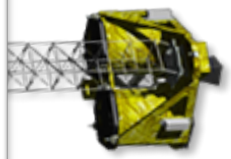
FoV: 12.5’ x 12.5’
PSF HPD: 58”
Energy range: 3-79 keV
Energy resolution: 0.5keV @ 6keV, 1keV @ 60keV
Sensitivity: μCrab in 1Ms (10-40keV)

NuSTAR





Array



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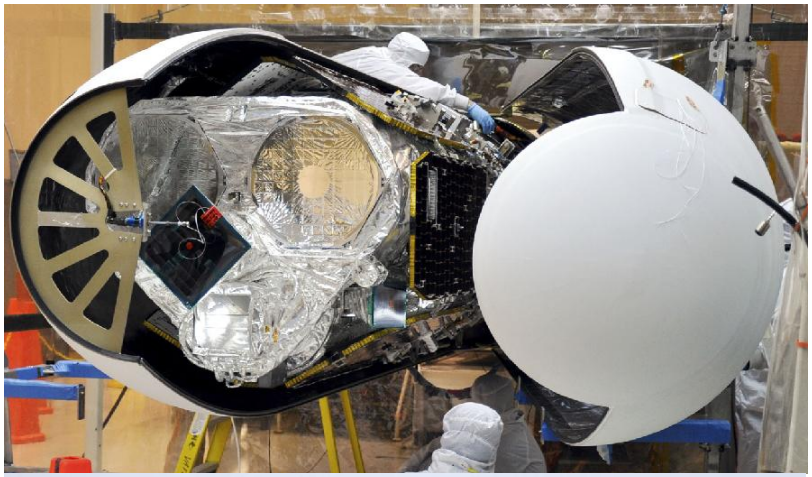
NuSTAR launch



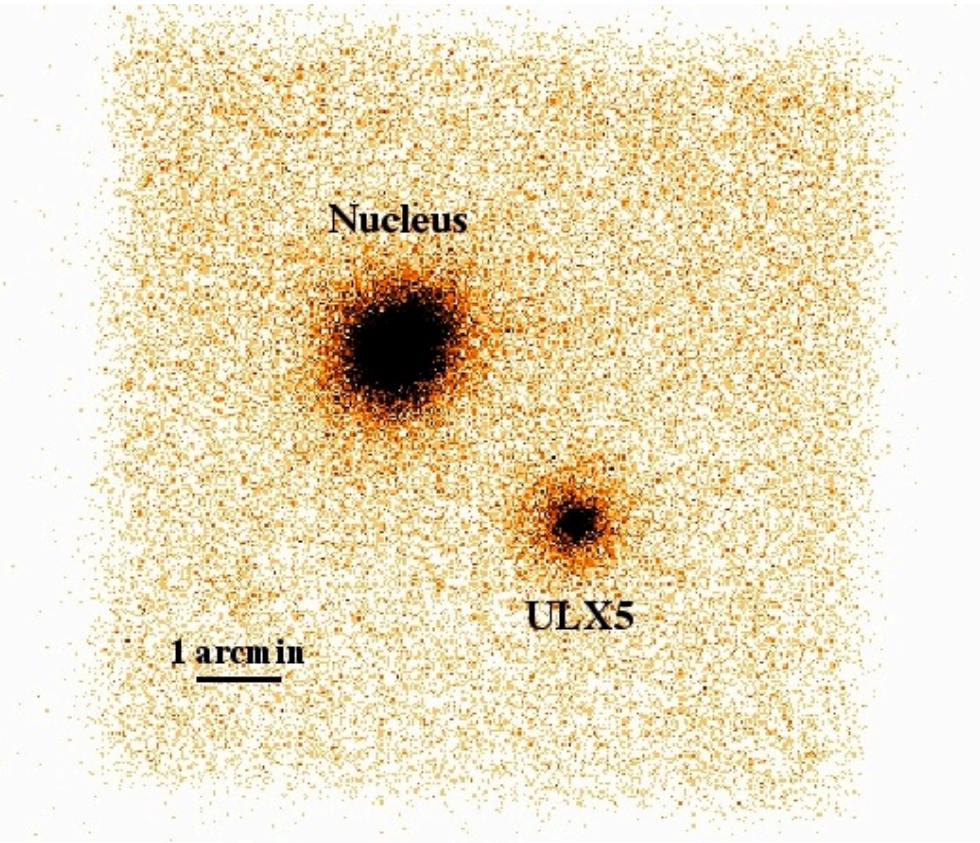
- Launched on June 13 2012 from the Reagan Test Site, Kwajalein Atoll
- Entered stable 630km low Earth orbit with only 6º inclination
- Orbital lifetime ~10 years
- No expendables on board, so mission could last as long as the orbit
- first 2 years are team-led base-line mission, then GO program
- GO program to start in fall 2014 (senior review proposal submitted to NASA)

NuSTAR images

Cassiopeia A

Grefenstette et al. (2013), Nature, in press

Circinus Galaxy and ULX



Walton et al. (2013), ApJ in press, astro-pH:1310.2633

Galactic Binaries

Compact object \ Optical companion	High-mass ($M > 10M_\odot$)	Low-mass ($M < 1M_\odot$)
Neutron Star ($M \sim 1.4M_\odot$)	Persistent, slow pulsar $L_x \sim 10^{36}$ erg/s Strong B-field (10^{12} G), Cyclotron lines	Persistent (pulsar) X-ray bursts B-field ($\leq 10^{11}$ G), Accretion disk
Black hole ($M > 3\text{-}4M_\odot$)	Rare, persistent systems $L_x \sim 10^{37}\text{-}10^{39}$ erg/s Reflection spectrum Broad iron lines	Transient systems State change follows q-shape Broad iron lines

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Vela X-1

Ser X-1

Cyg X-1

GX 339-4

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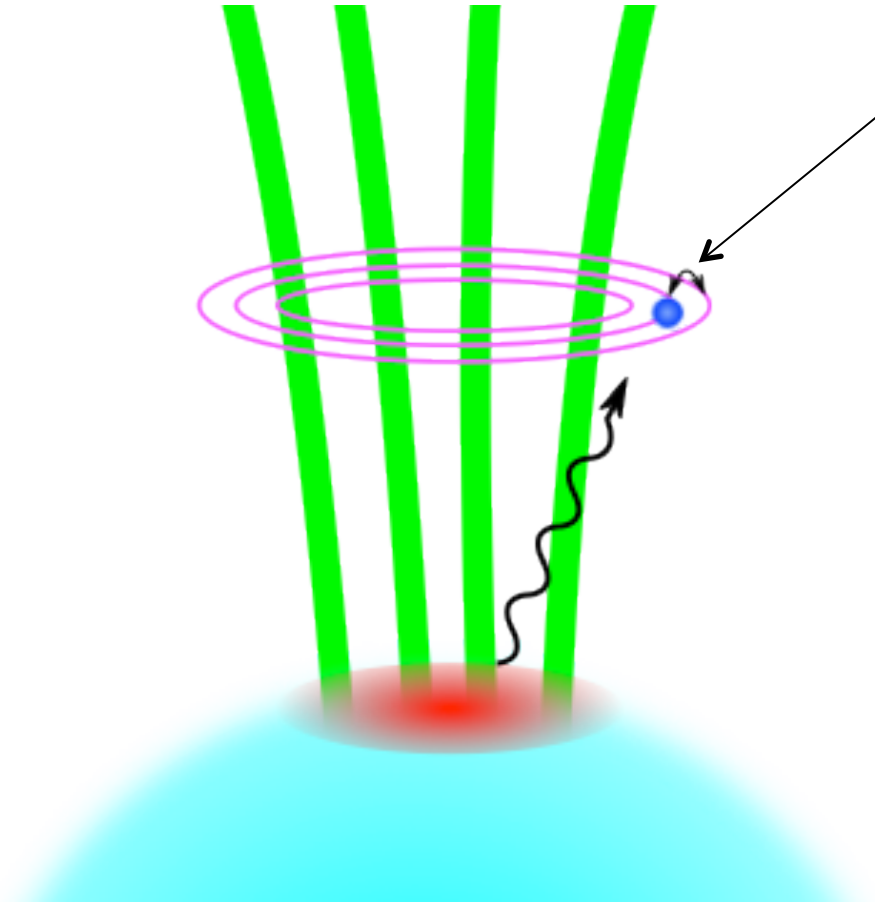
GX 339-4

CRSF production

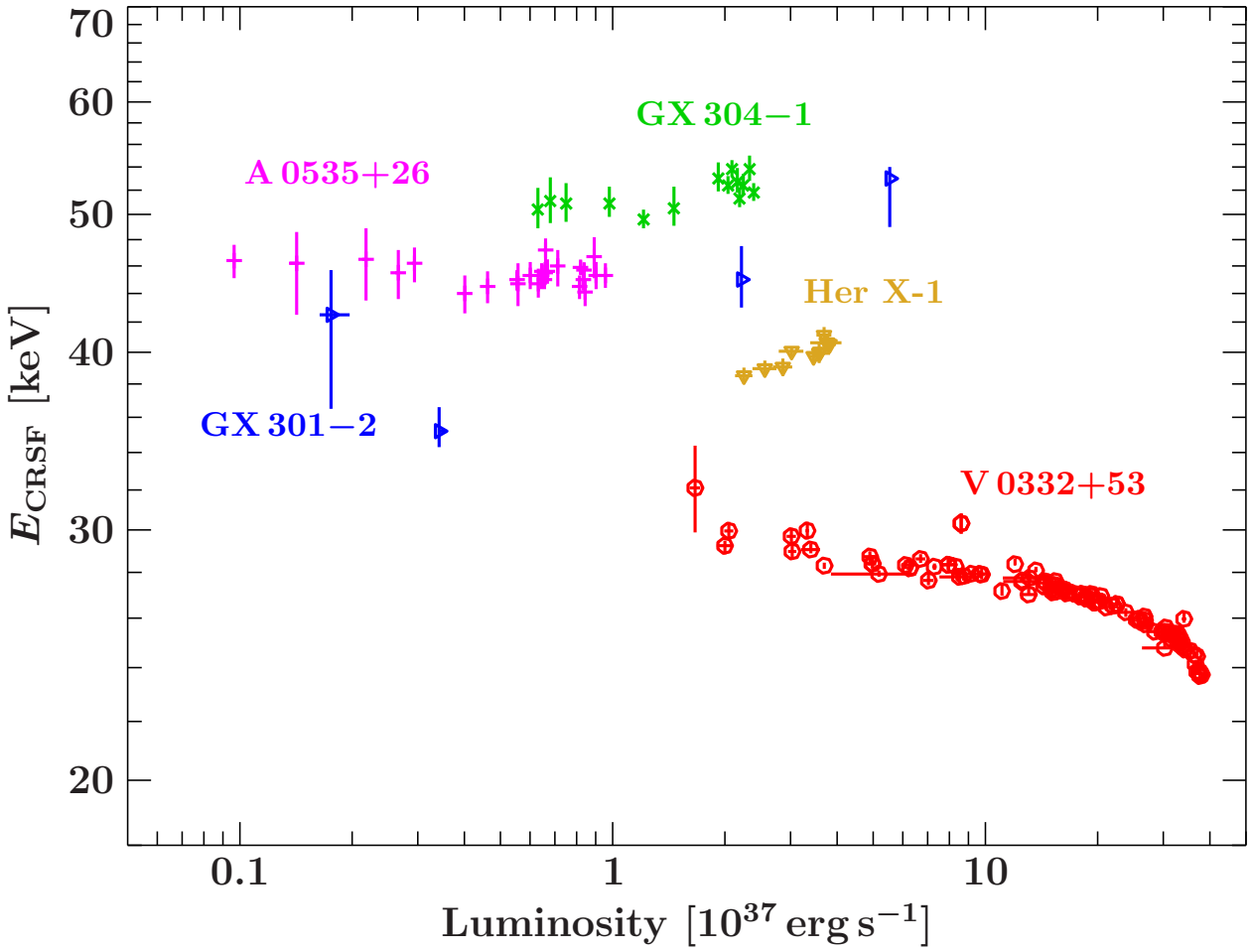


Electrons quantized to Landau-levels perpendicular to the magnetic field.

⇒ resonant scattering removes photons at the Landau-level-energies from the observed spectrum

$E_{CRSF} \approx 12 \times B_{12}$ keV
(B_{12} is B-field in 10^{12} G)

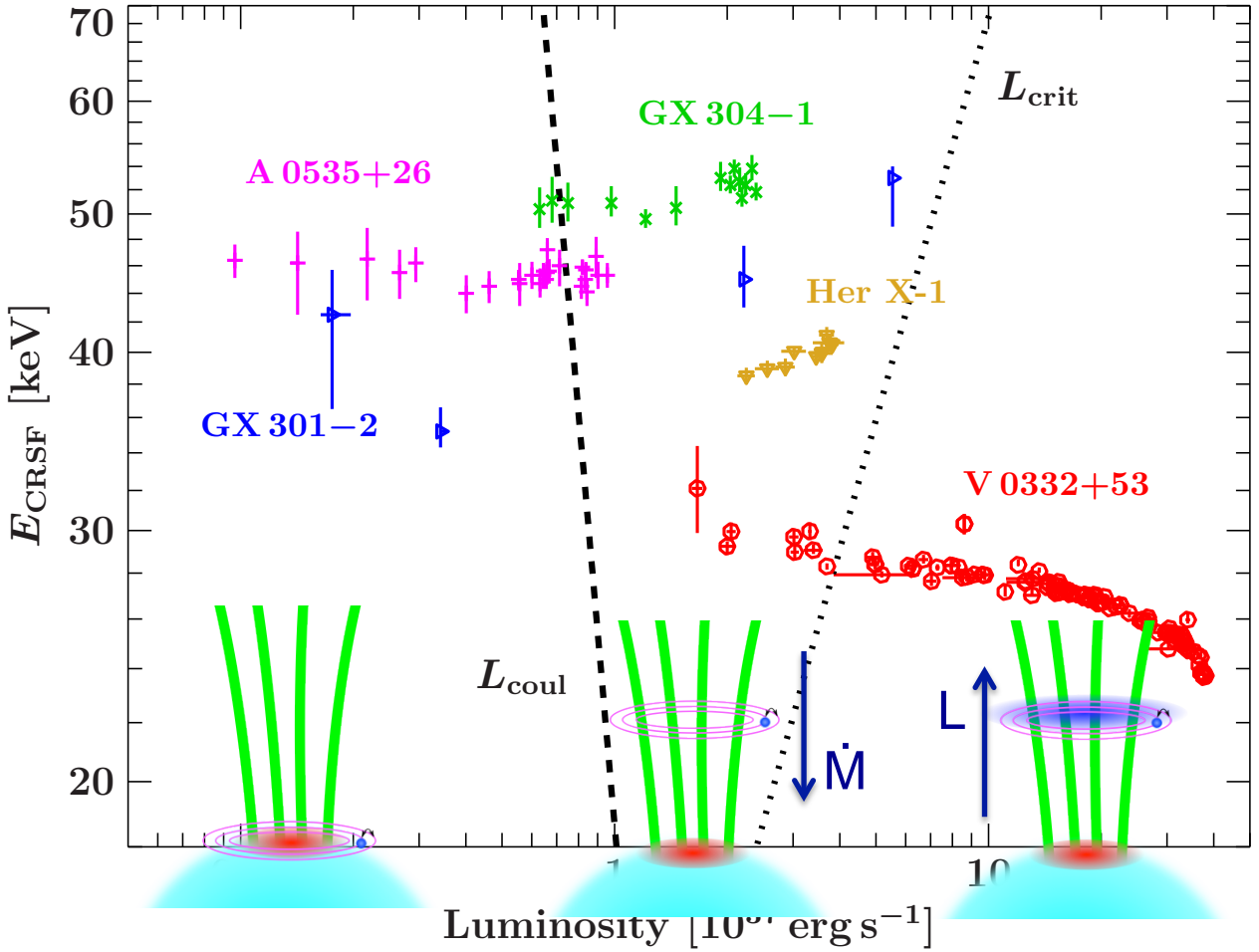
E_{CRSF}-L_x-correlation



A 0535+26: Caballero et al. (2007), V 0332+53:Tsygankov,

Lutovinov & Serber (2010), Her X-1 : Staubert et al. (2007),
GX 304−2: Yamamoto et al. (2011).

E_{CRSF}-L_x-correlation



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After Becker et al. (2012)

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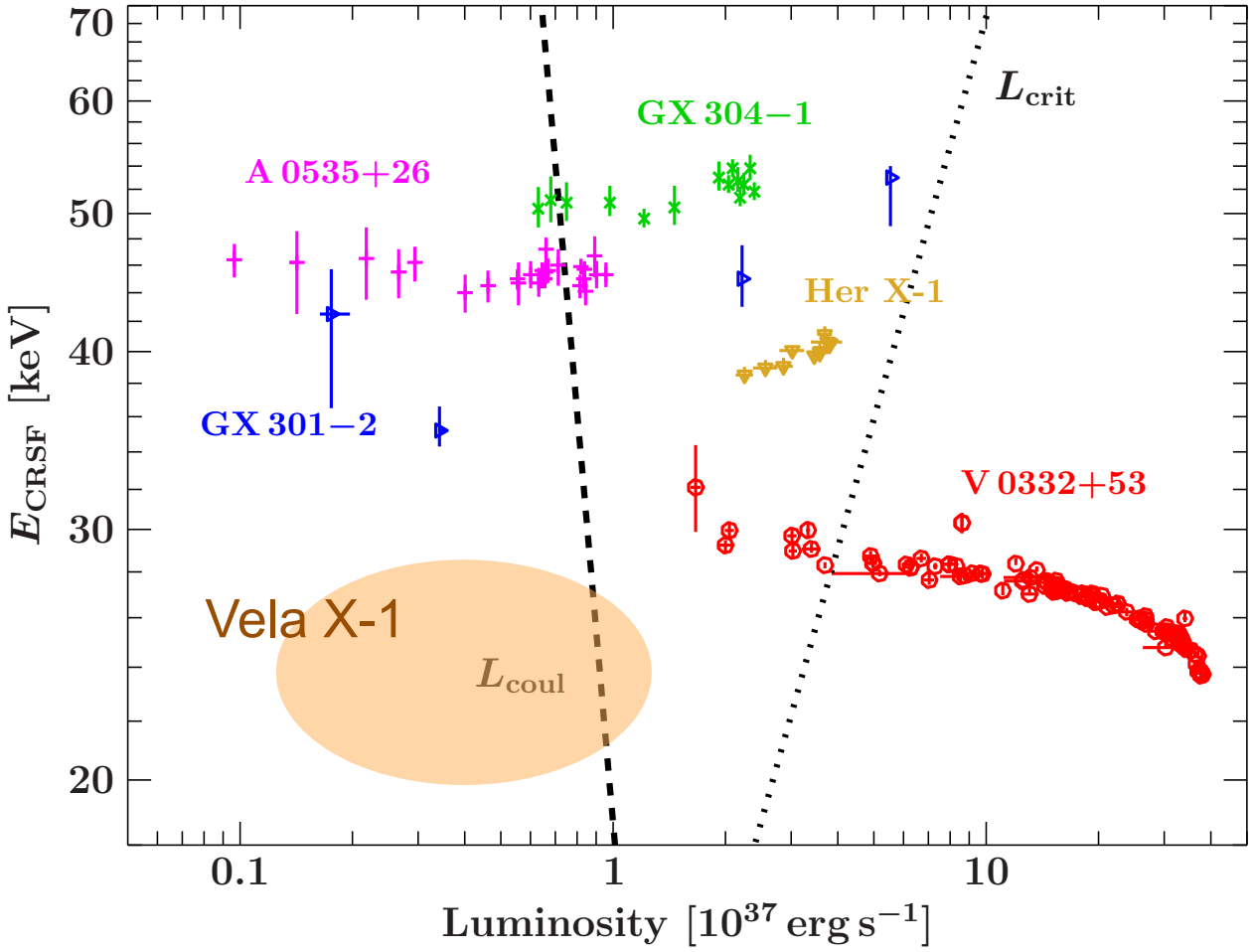

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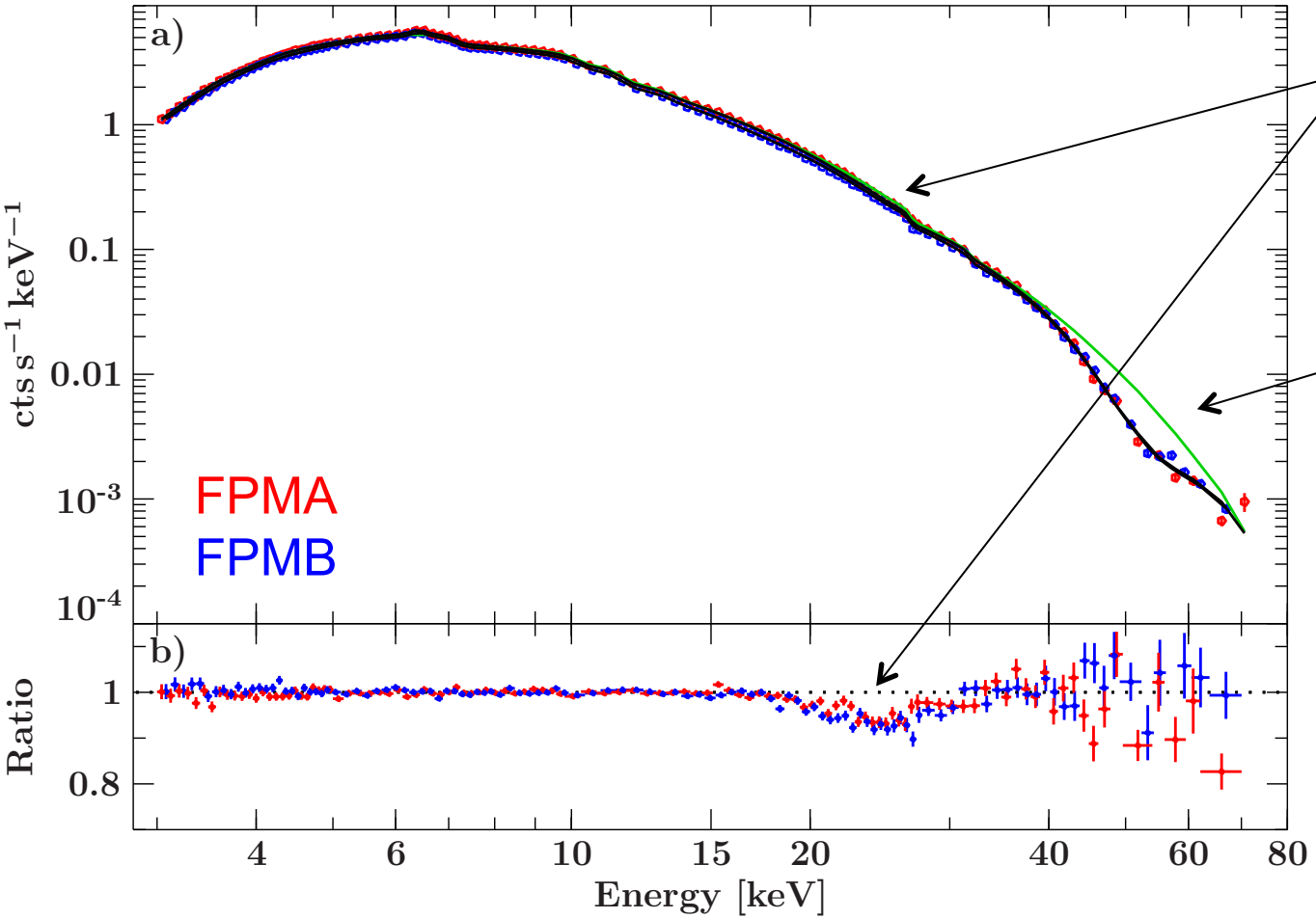
Vela X-1 spectrum

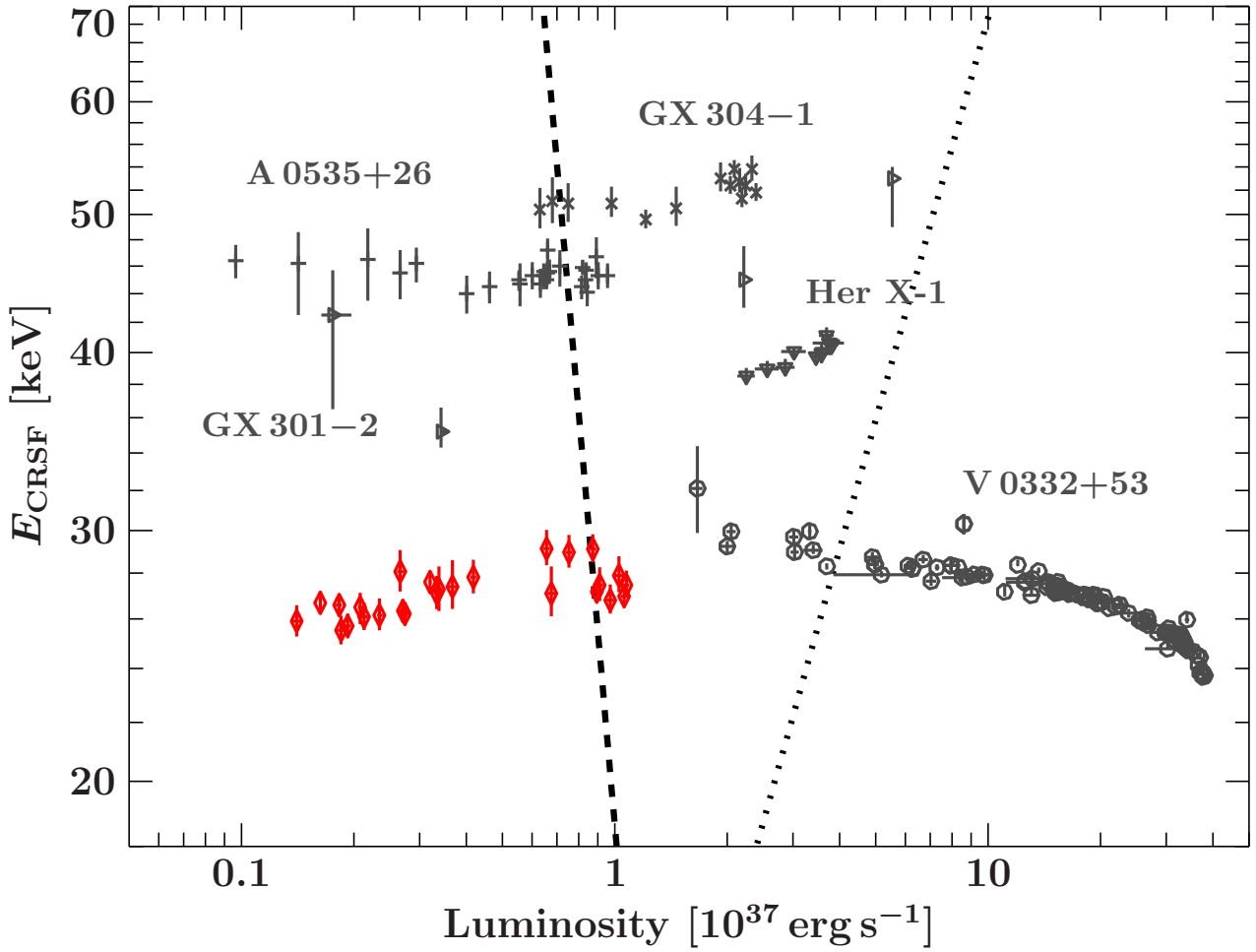


Fundamental line at 27keV

Harmonic line at 55keV

Fürst et al., 2014, ApJ 780, 133

E_{CRSF}-L_x-correlation w/ Vela X-1

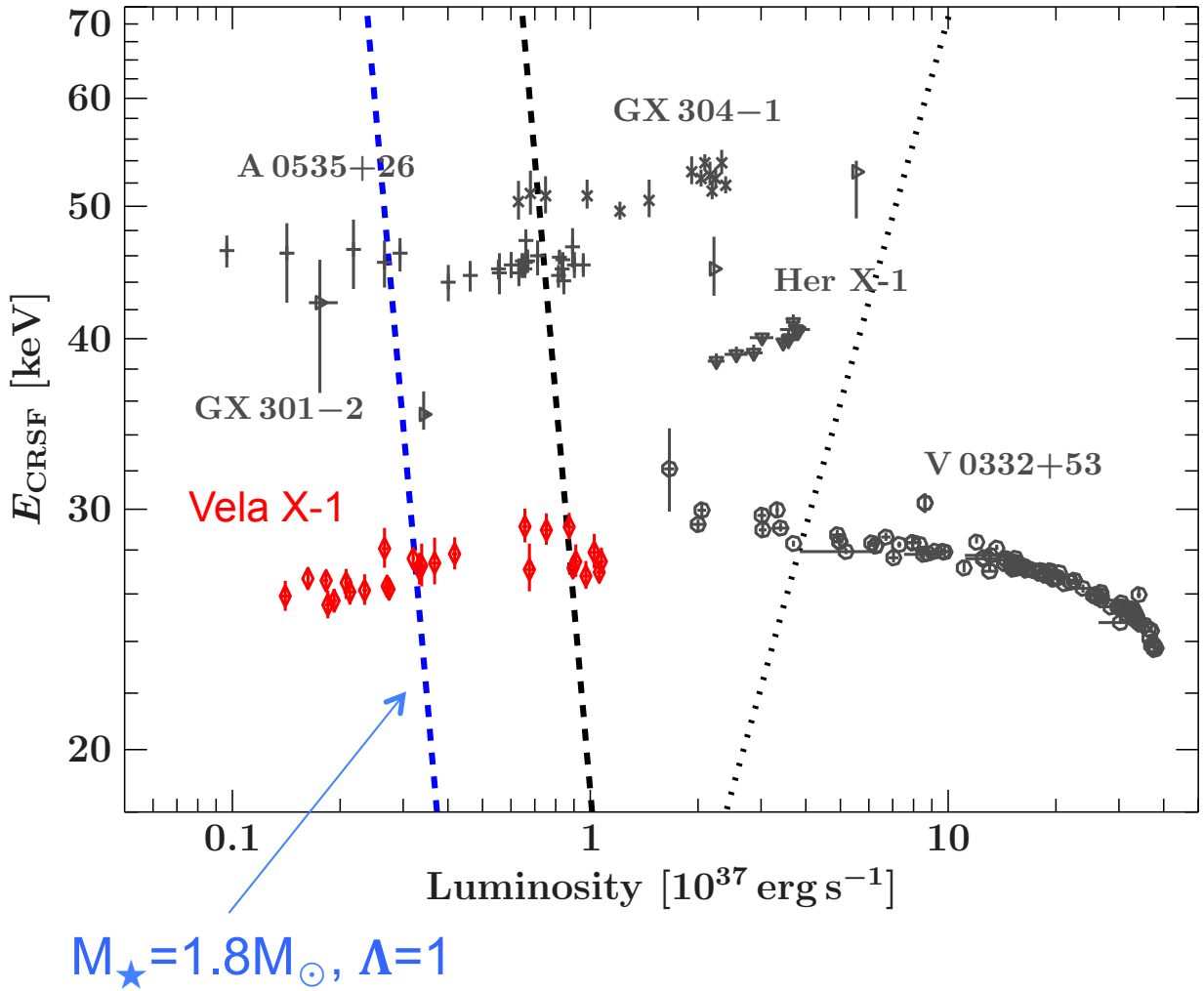


Harmonic line, divided by 2

Clear **positive** correlation visible in **low flux** regime!

Fürst et al., 2014, ApJ 780, 133

Summary Vela X-1



$M_{\star}=1.8M_{\odot}$, $\Lambda=1$

- Accretion column narrow (**r=0.4km**)
- Pushing Vela to **Coulomb interaction dominated** regime
- Can be investigated for other wind accreting, persistent neutron stars with high sensitivity of *NuSTAR*

Fürst et al., 2014, ApJ 780, 133

Galactic Binaries

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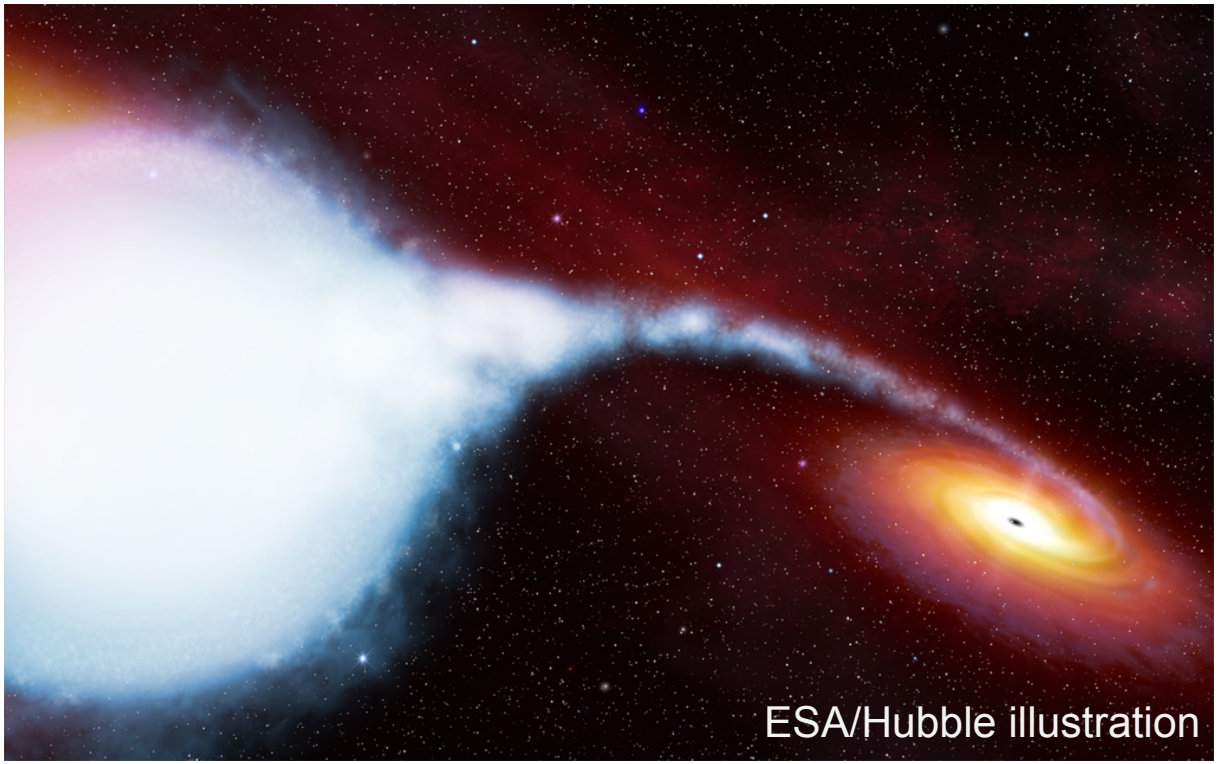
Vela X-1

Ser X-1

Cyg X-1

GX 339-4

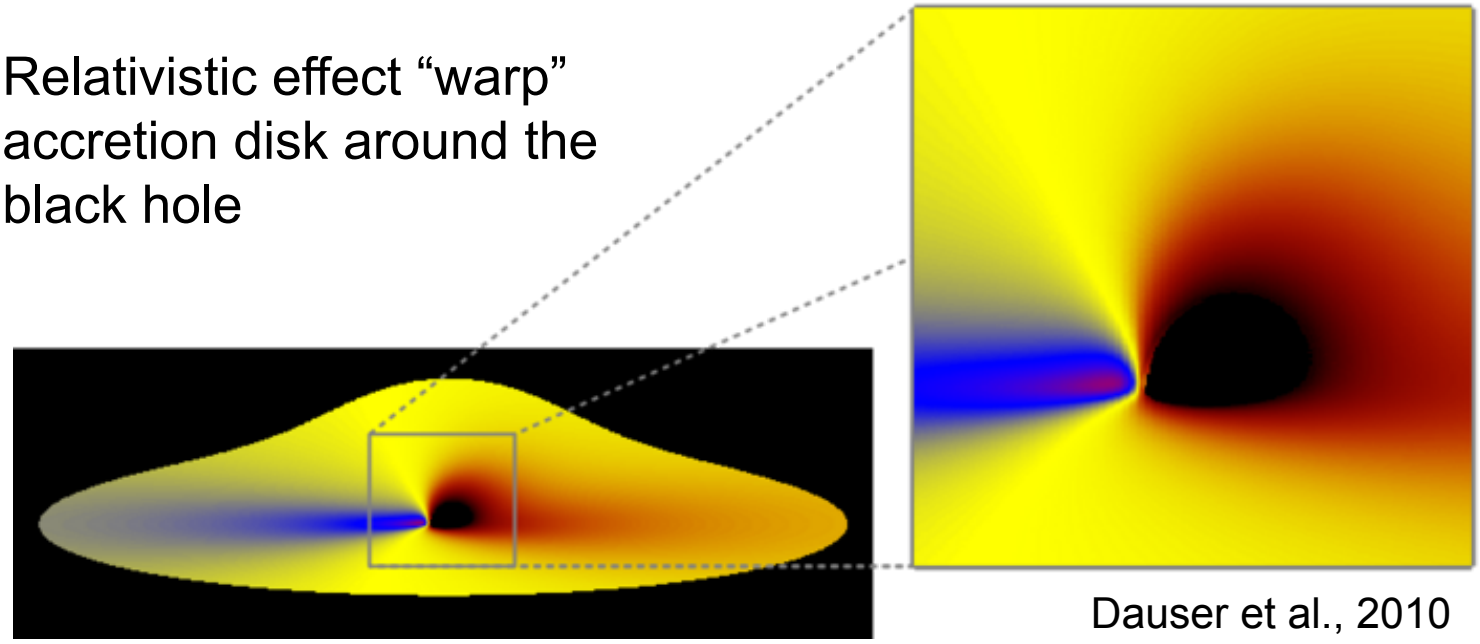
Cyg X-1



Black hole mass = 14.8 ±1.0$M_\odot$, companion ~ 20$M_\odot$
First confirmed black hole binary system
Spectrum described by power-law and reflection of the accretion disk

Strong gravity

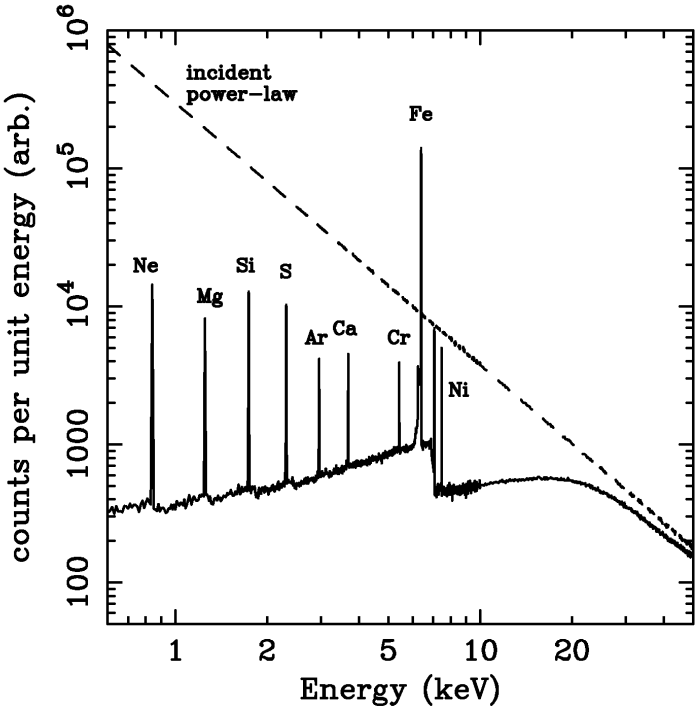
Relativistic effect “warp” accretion disk around the black hole



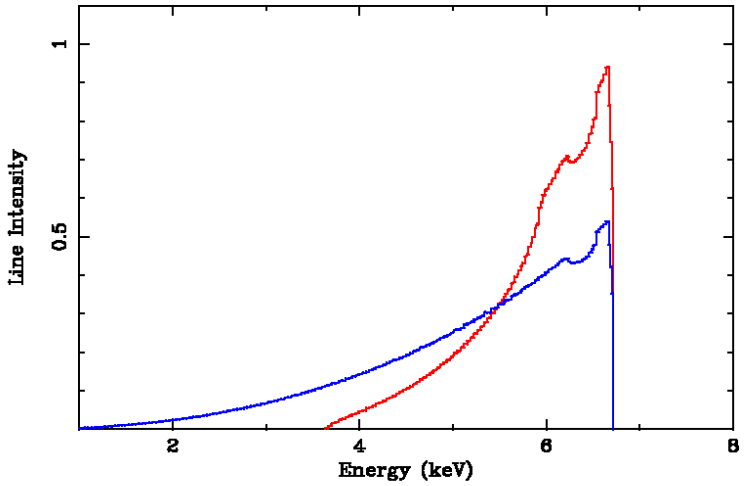
Dauser et al., 2010

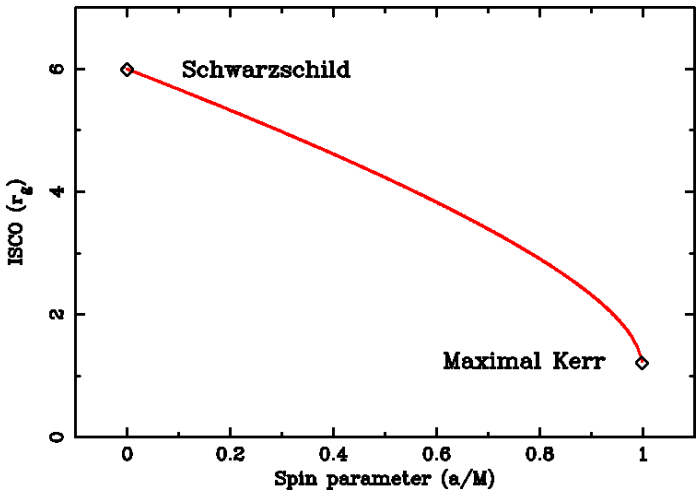
Gravitational redshift changes shape of the reflected spectrum

Reflection intro



Reynolds & Nowak 2003; Reynolds 1996



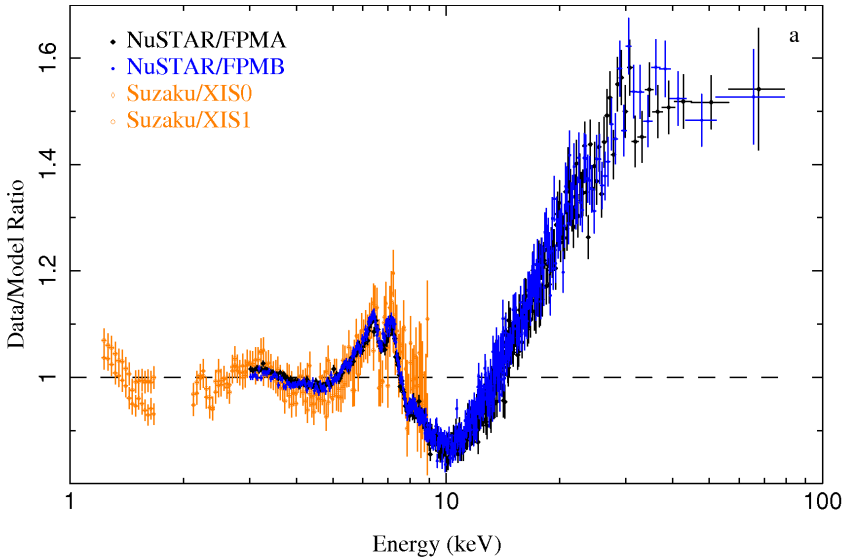


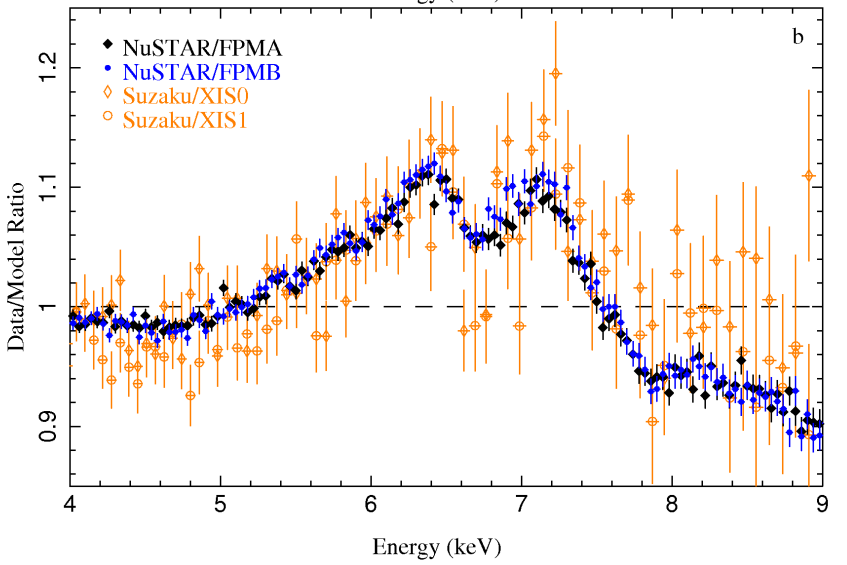
Miller et al. 2007; Fabian et al. 1989

- Modeling of the *NuSTAR* spectra has largely used reflionx_hc (Ross & Fabian, 2005)
- Custom modifications by Michael Parker and Andy Fabian

Cyg X-1 reflection component

- Simultaneous ~30 ks *NuSTAR* and *Suzaku* observation
  - *NuSTAR*: Source rate is 25-1000x background for all energy bins up to 30 keV
- Features in residuals
  - Broad iron Fe Kα emission line
  - Fe K absorption edge
  - Hard X-ray bump
  - Narrow absorption line at 6.7 keV (stellar wind)
- Pile-up in XIS reduces S/N dramatically (#toomanyphotons)





Tomsick et al., ApJ 2014, 780, 80

Cyg X-1 reflection component

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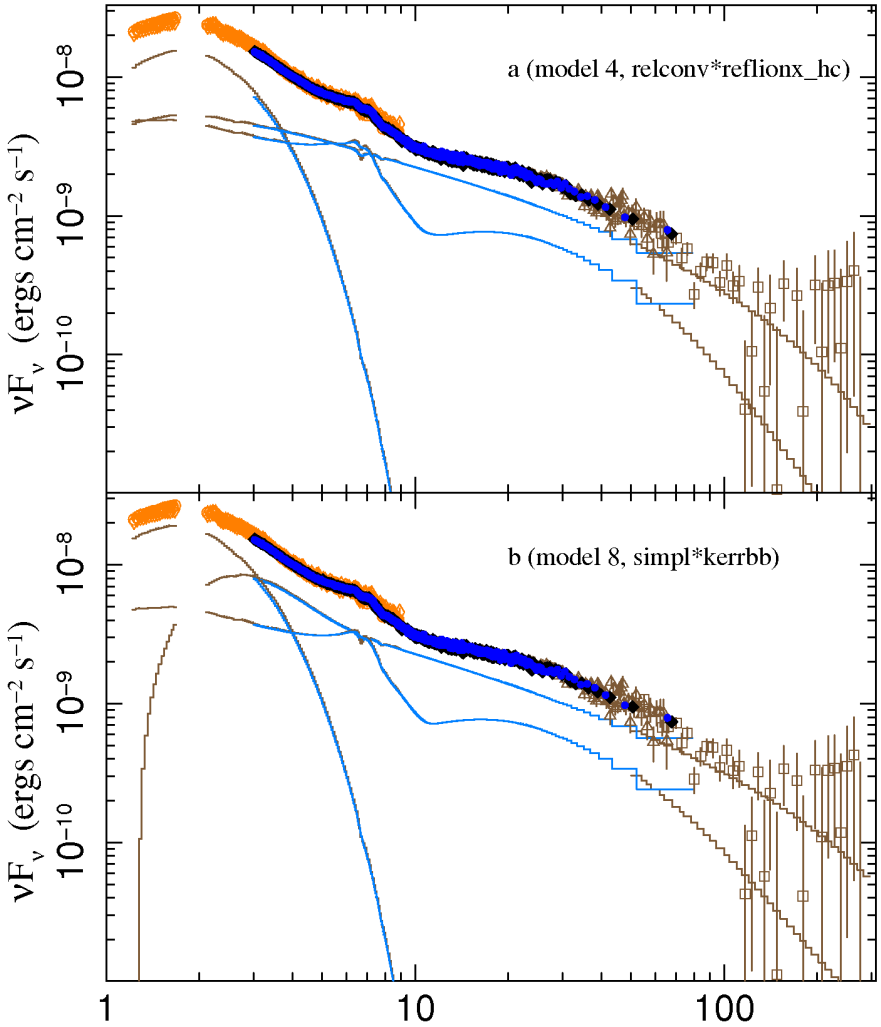
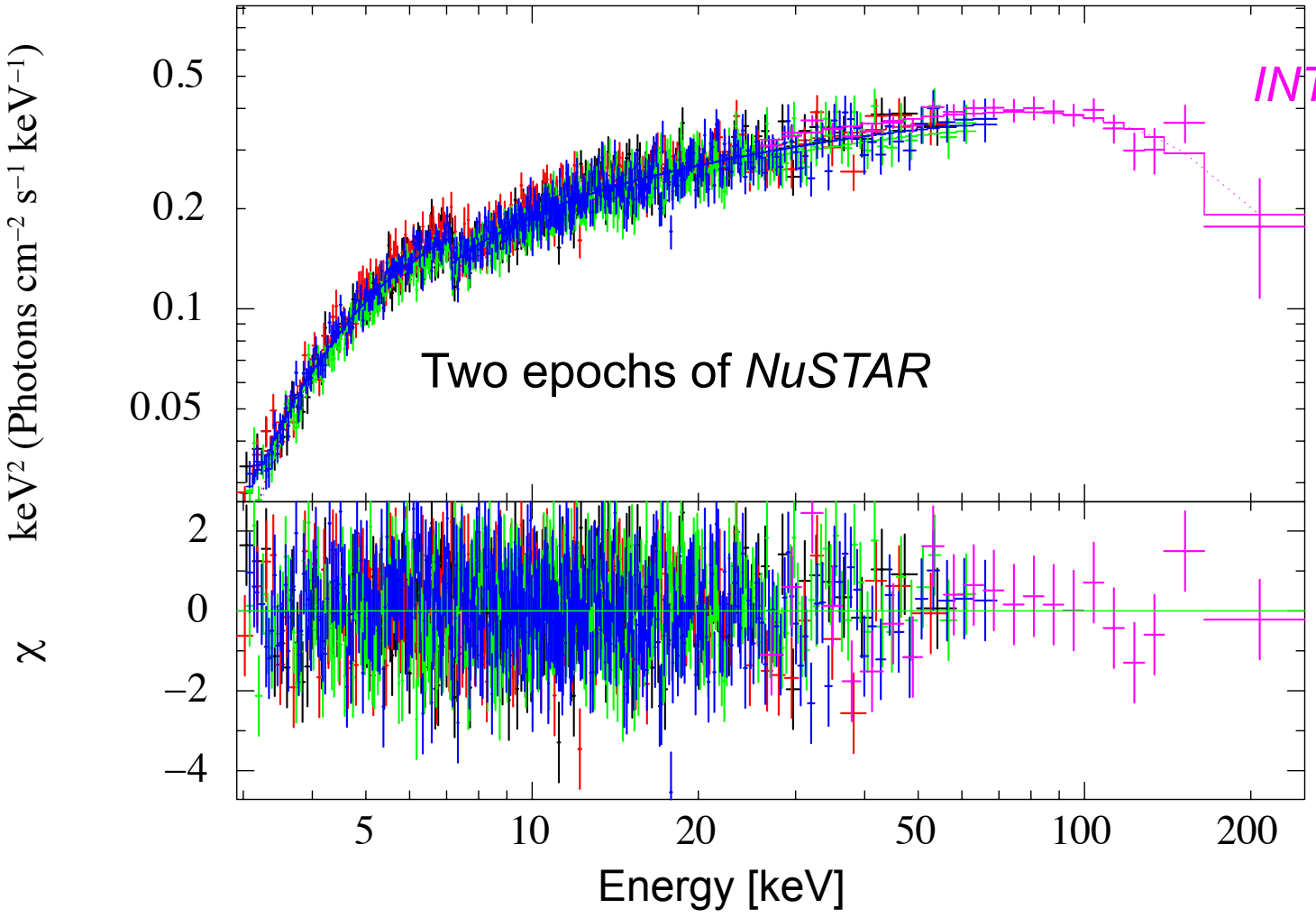
  - *NuSTAR*: Source rate is 25-1000x background for all energy bins up to 30 keV
- Features in residuals
  - Broad iron Fe Kα emission line
  - Fe K absorption edge
  - Hard X-ray bump
  - Narrow absorption line at 6.7 keV (stellar wind)
- BH spin: $a_* > 0.83$ (based on fitting with several models)
- i > 40° different from binary inclination (27.1±0.8° from Orosz et al. 2011)



Tomsick et al., ApJ 2014, 780, 80

1E 1740.7-2942



Clear cutoff with plasma temperature ~40keV measured

Natalucci et al., 2014, ApJ 780, 63

Galactic Binaries

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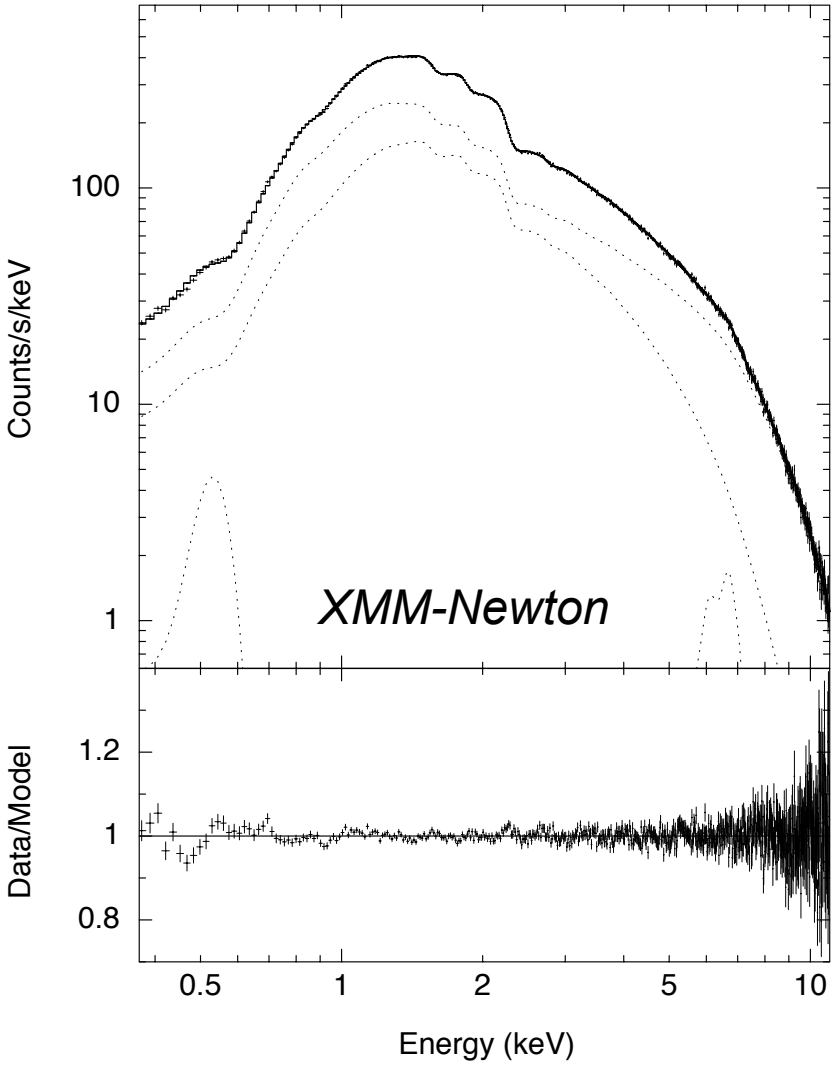
GX 339-4

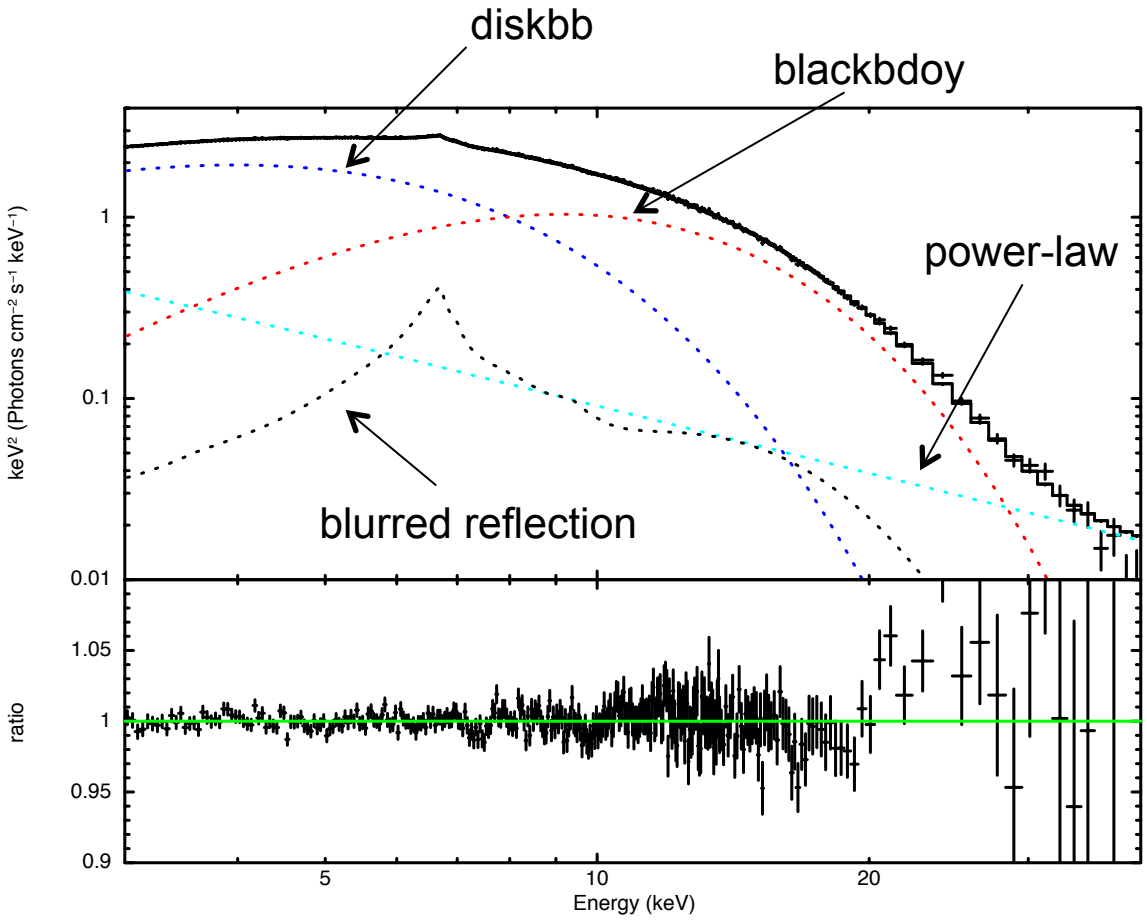
Serpens X-1



- LMXB with neutron star, proven by the observation of Type-1 X-ray bursts
- Bright spectrum, with blackbody and comptonized component
- Indications for broadened iron line in *XMM-Newton* data, but pile-up an issue of debate

Bhattacharyya & Strohmayer, 2007

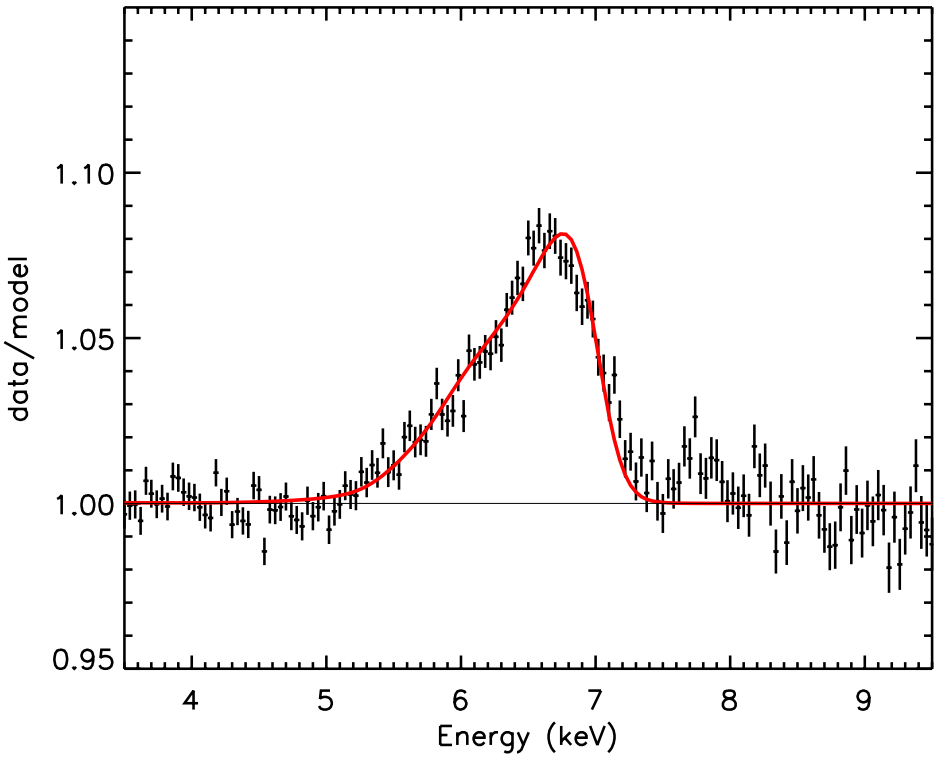
Ser X-1: reflection spectrum



- 40ks *NuSTAR* observation
- *NuSTAR* does not pile-up
- broad-band spectrum, described with disk-blackbody, blackbody, hard power-law and **relativistically blurred reflection**

Miller et al. 2013, ApJL, 779, L2

Ser X-1: Broad iron line



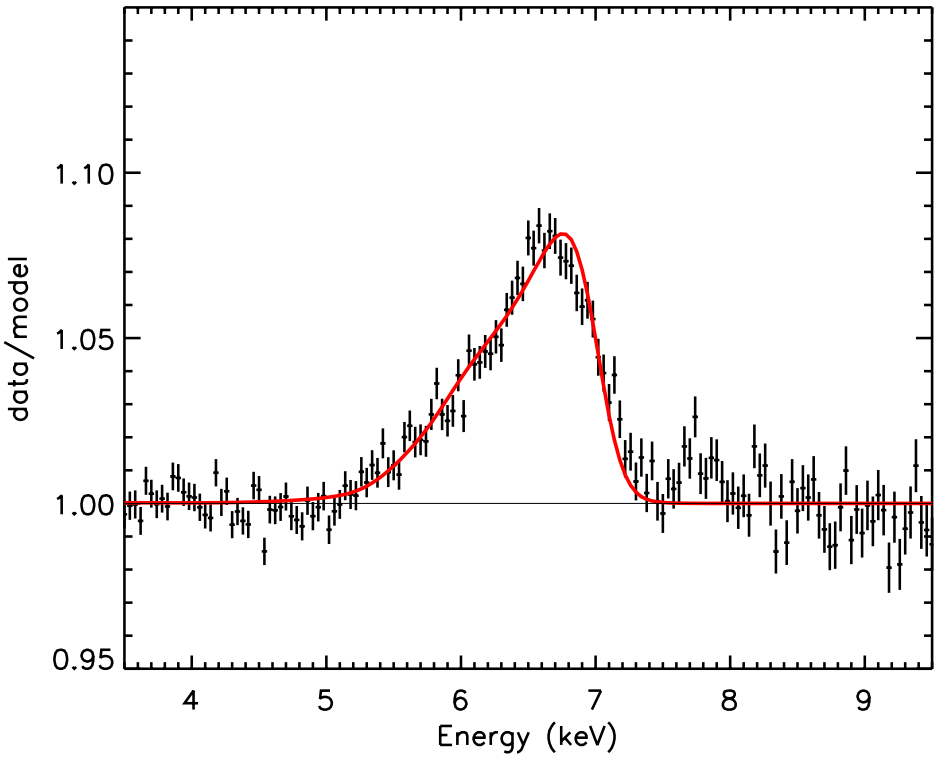
- ratio residuals in the iron line region of a continuum fit without reflection

- 'kerrdisk' in red
- Clear **broadened, asymmetric shape** of the iron line
- Energy consistent with Fe XXVI

- relativistic line profile preferred over broad Gaussian with 5.3σ

Miller et al. 2013, ApJL, 779, L2

Ser X-1: Broad iron line



best fit indicates

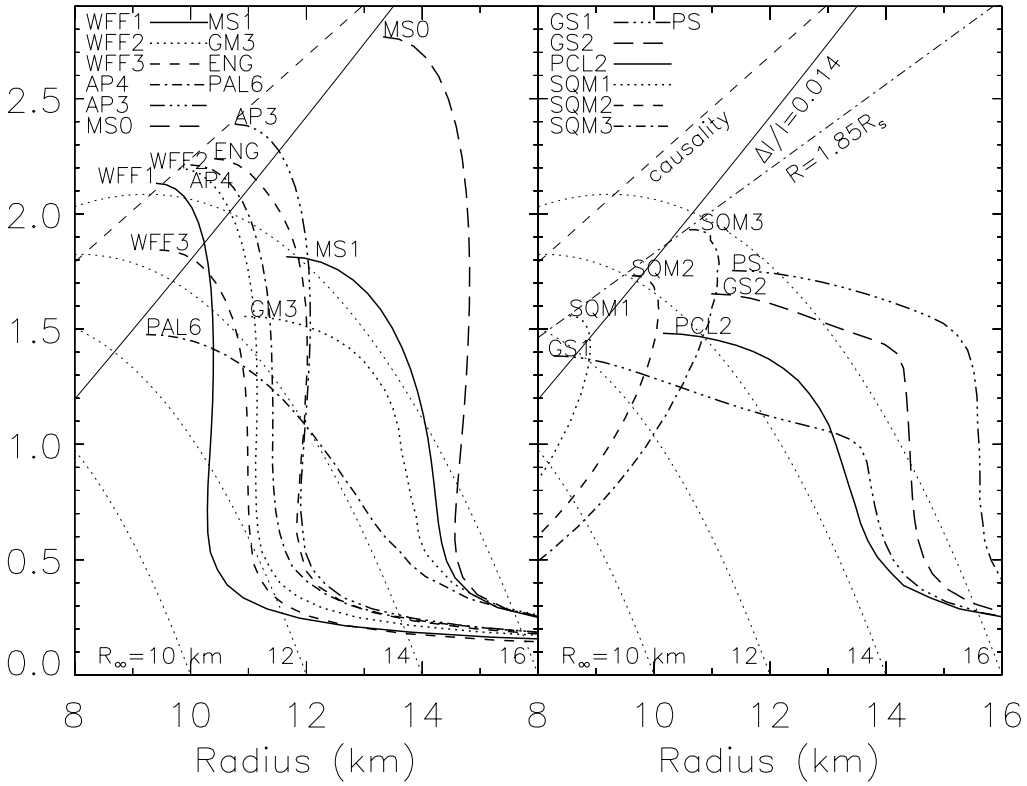
- spin 0= a* < 0.14
- accretion disk extends very close to the ISCO, $r=1.3r_{ISCO}$
- During high flux state, even $r=1r_{ISCO}$

⇒ R_{NS}≤ 12.6km
(for $M_{NS}=1.4M_{\odot}$)

Miller et al. 2013, ApJL, 779, L2

Summary Ser X-1

- *NuSTAR* spectrum show clear broad iron line and reflection component in 40ks exposure
- **Very promising results for further LMXB observations**
- little steps in helping to constrain the EoS with relativistic broadening



Lattimer & Prakash, 2001

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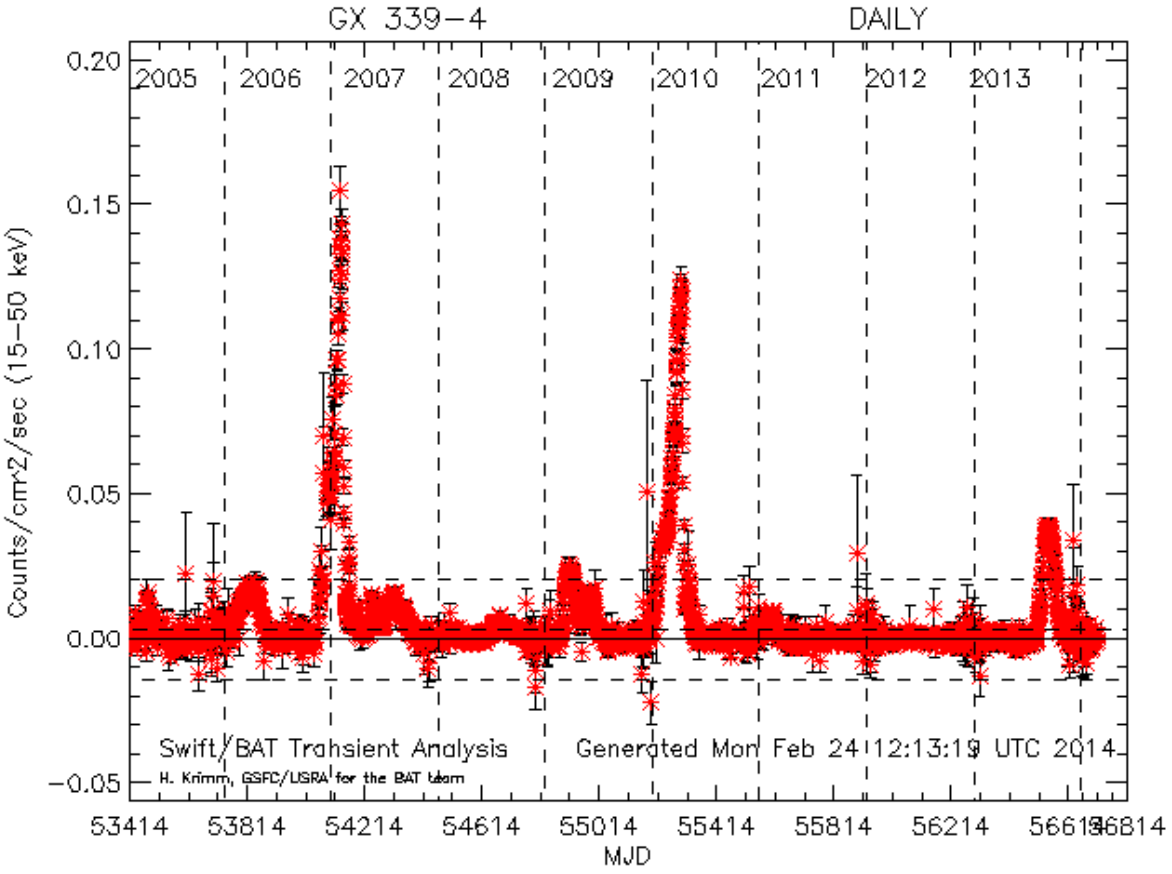
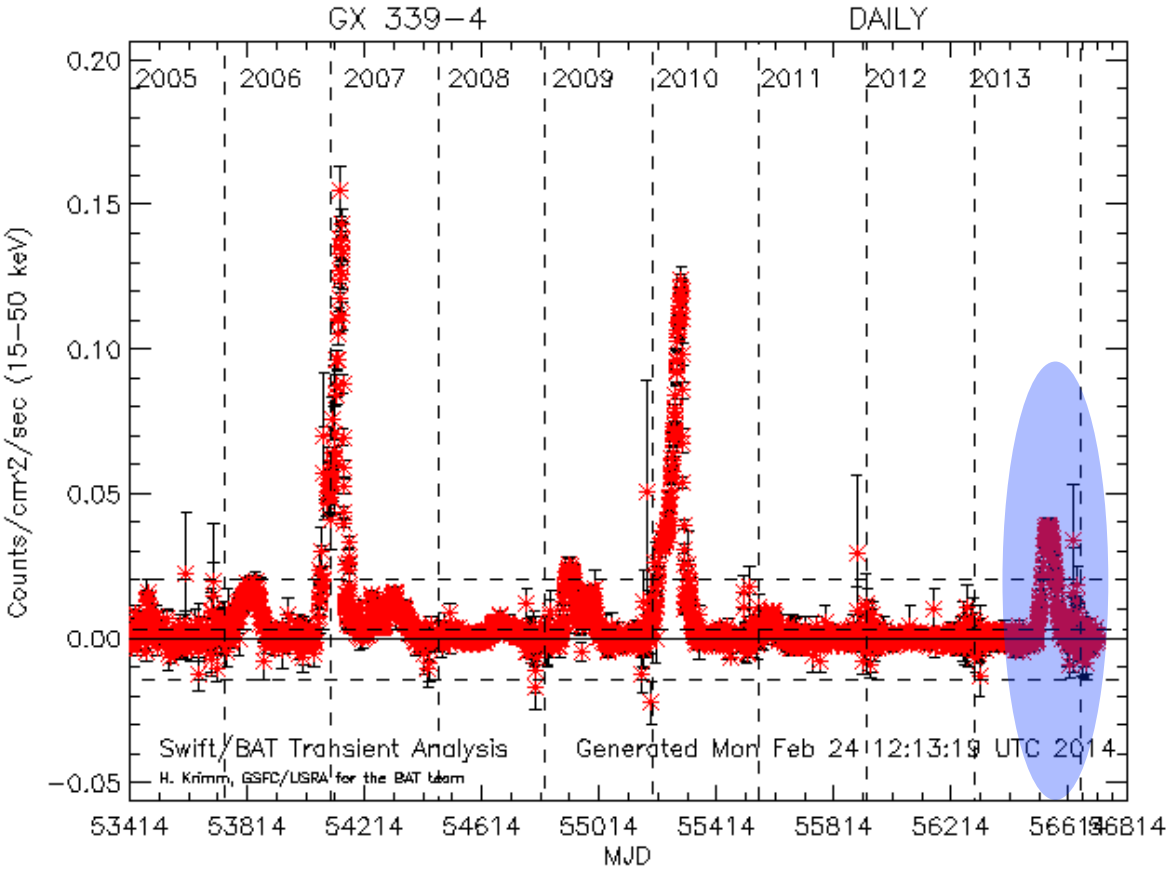
GX 339-4



- Transient LMXB with semi-regular outbursts
- Outburst typically evovles over two states:
1. Low-hard state: hard power-law emission dominates
2. High-soft state: strong disk-blackbody component dominant
- Truncated accretion disk in the hard state?

http://swift.gsfc.nasa.gov/results/transients/weak/GX339-4/

GX 339-4



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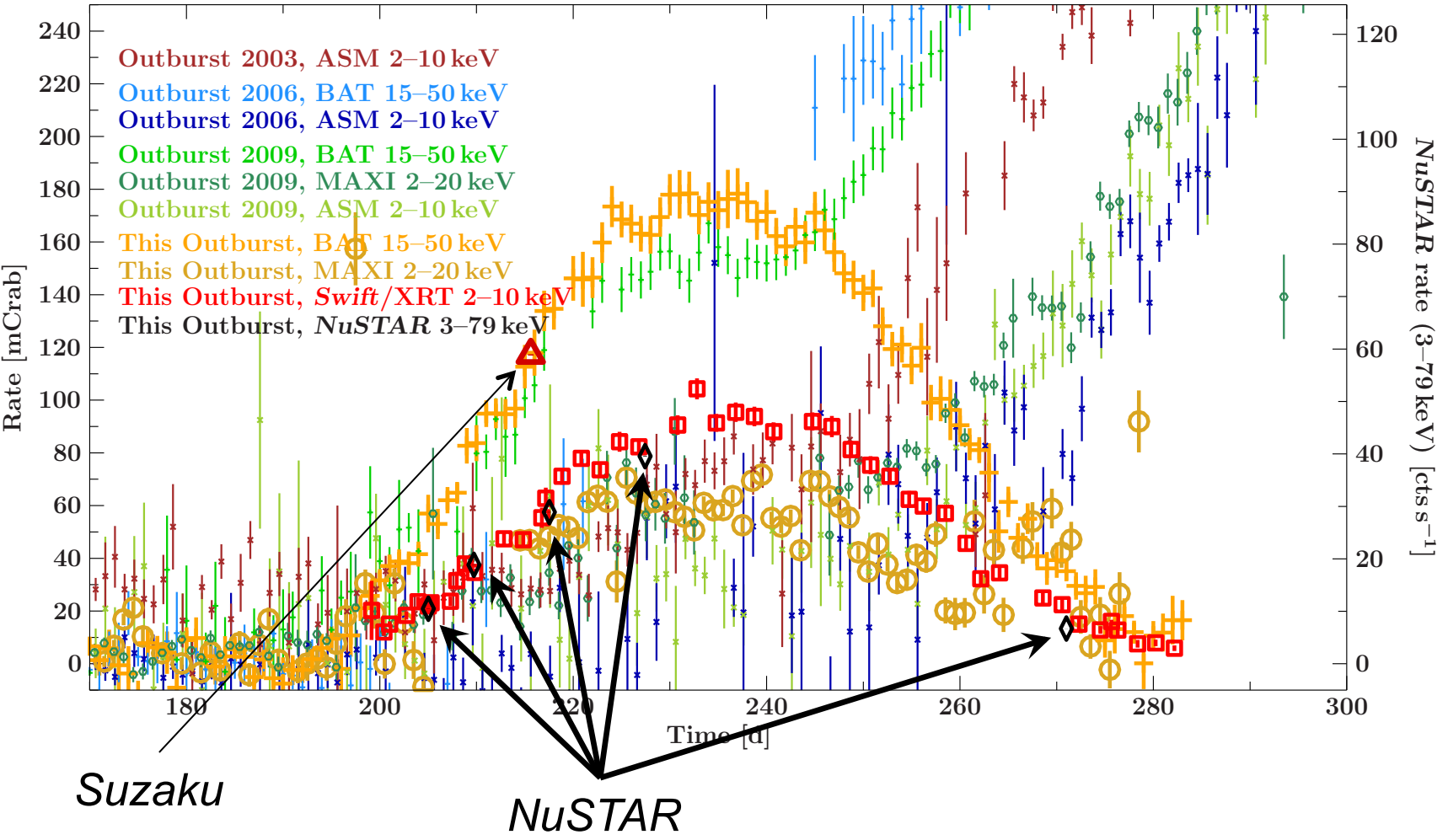
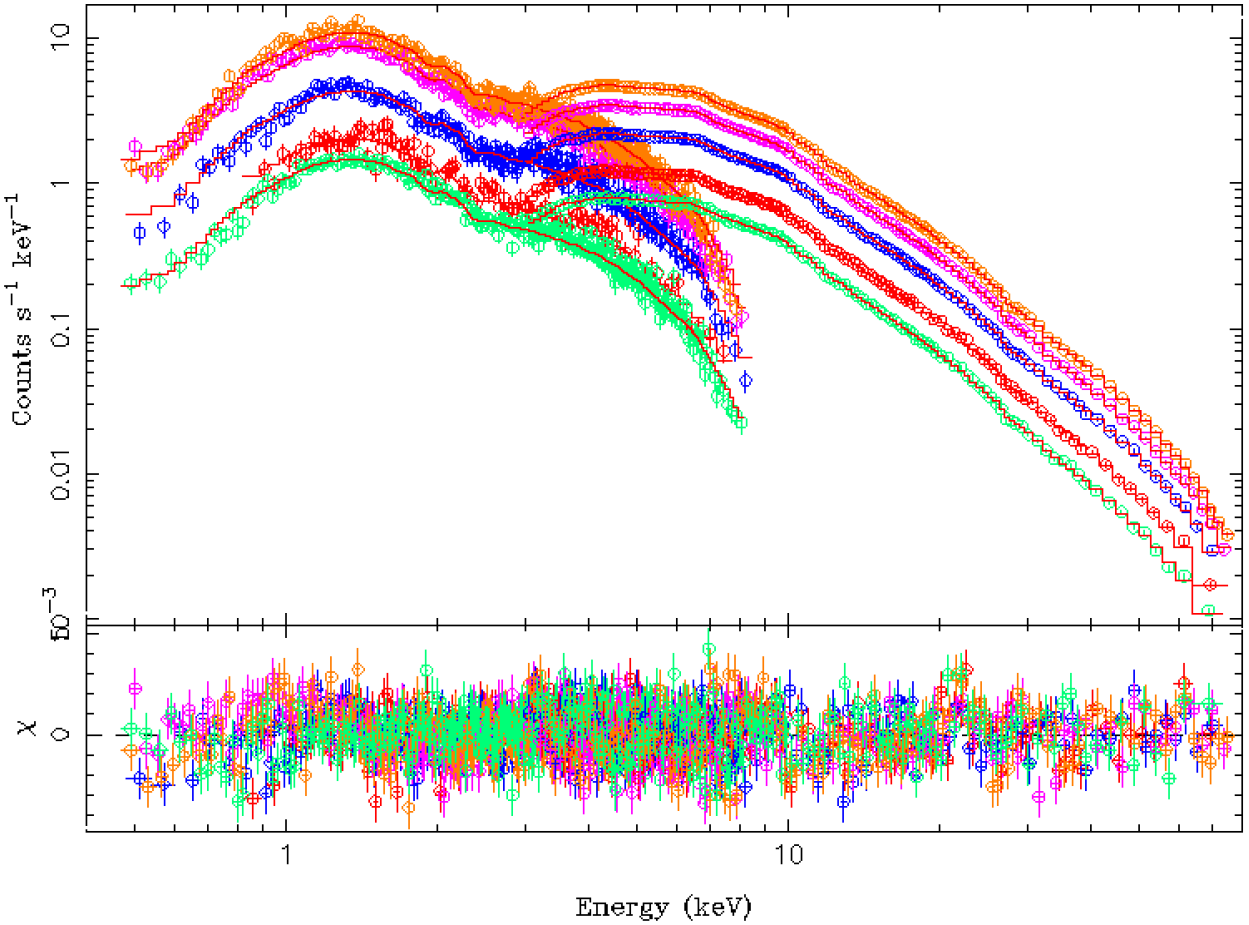
http://swift.gsfc.nasa.gov/results/transients/weak/GX339-4/

GX 339-4: Current outburst



GX 339-4: Available spectra



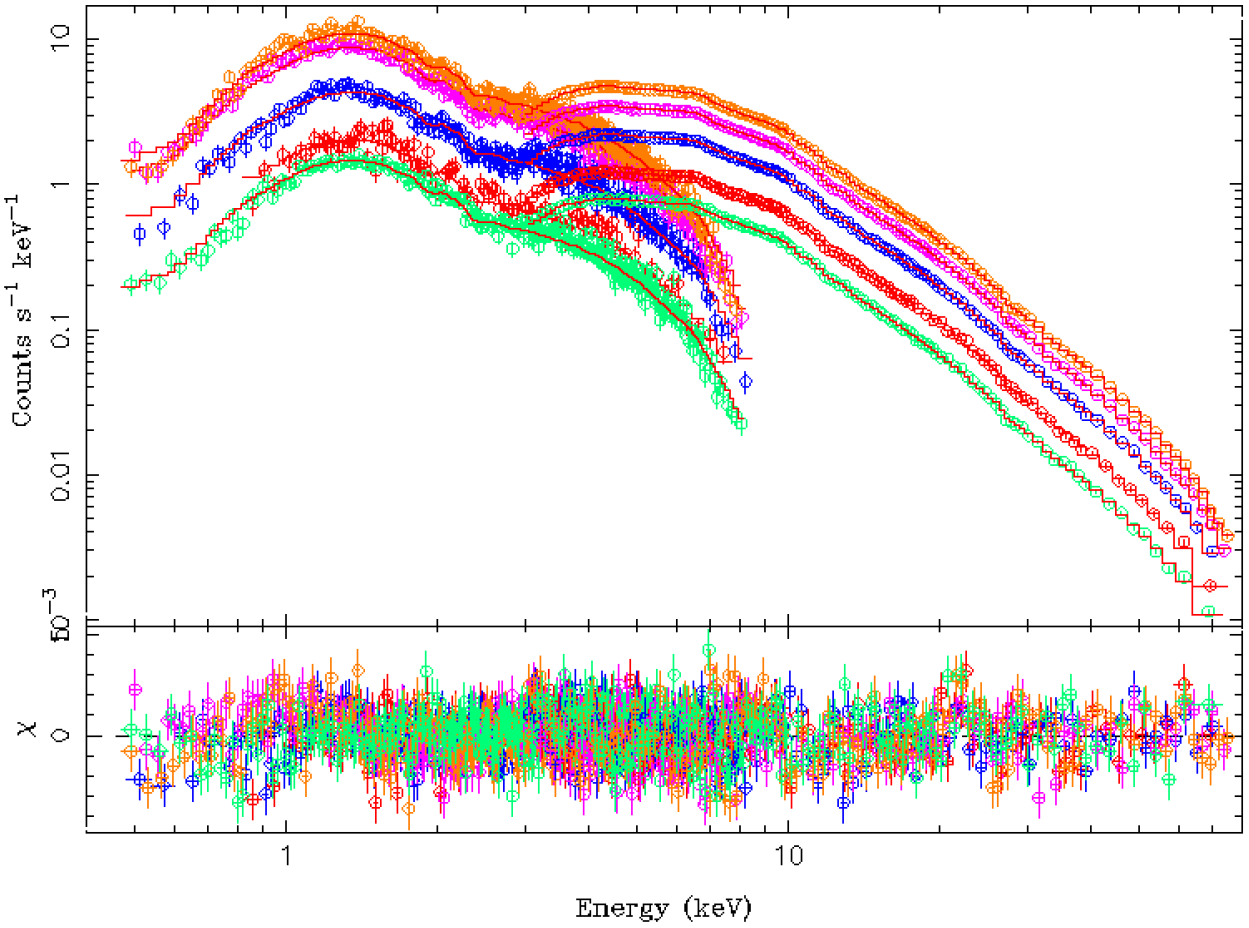
Observation times [ks]

	Swift	NuSTAR
Obs I	1.06	42.2
Obs II	1.86	47.38
Obs III	1.50	50.40
Obs IV	1.16	61.94
Obs V	9.61	98.21

NuSTAR 3-78 keV
Swift/XRT 0.8-9 keV

Fürst et al., 2014, in prep.

GX 339-4: Available spectra



Hard spectrum with Γ=1.56

Weak (but significant) reflection

Relativistic smearing necessary for the iron line shape.

Fürst et al., 2014, in prep.

Outlook

- *NuSTAR* is doing a splendid job for **bright** sources

→ study spectra evolution on time-scales of 100s

→ no pile-up woes

→ broad band coverage to nail down continuum (reflection fraction!)

→ good energy resolution to study shapes of lines (CRSF and broadened FeKα)

- Calibration is already very good; good agreement with *XMM-Newton*, *Suzaku*, *Chandra*, *Swift*, and *INTEGRAL*

- X-ray binaries will continue to be an important class, expect more interesting results in the next year!