3.1 Applications: neutron star spectroscopy

Part I: continuum spectroscopy

continuum shape is explicitly sensitive to
effective temperature
log g
chemical composition (though mainly through photoelectric edges)

broad 'features' (bumps, dents):
extremely important clues, but difficult to interpret uniquely (especially if they involve a ***B***-field)

one thing continuum spectroscopy does:
if you know the distance,
you can measure the stellar radius!

from the stellar atmosphere: $I_\nu(\mathbf{n})$

star is not (angularly) resolved, so we see the *flux*:

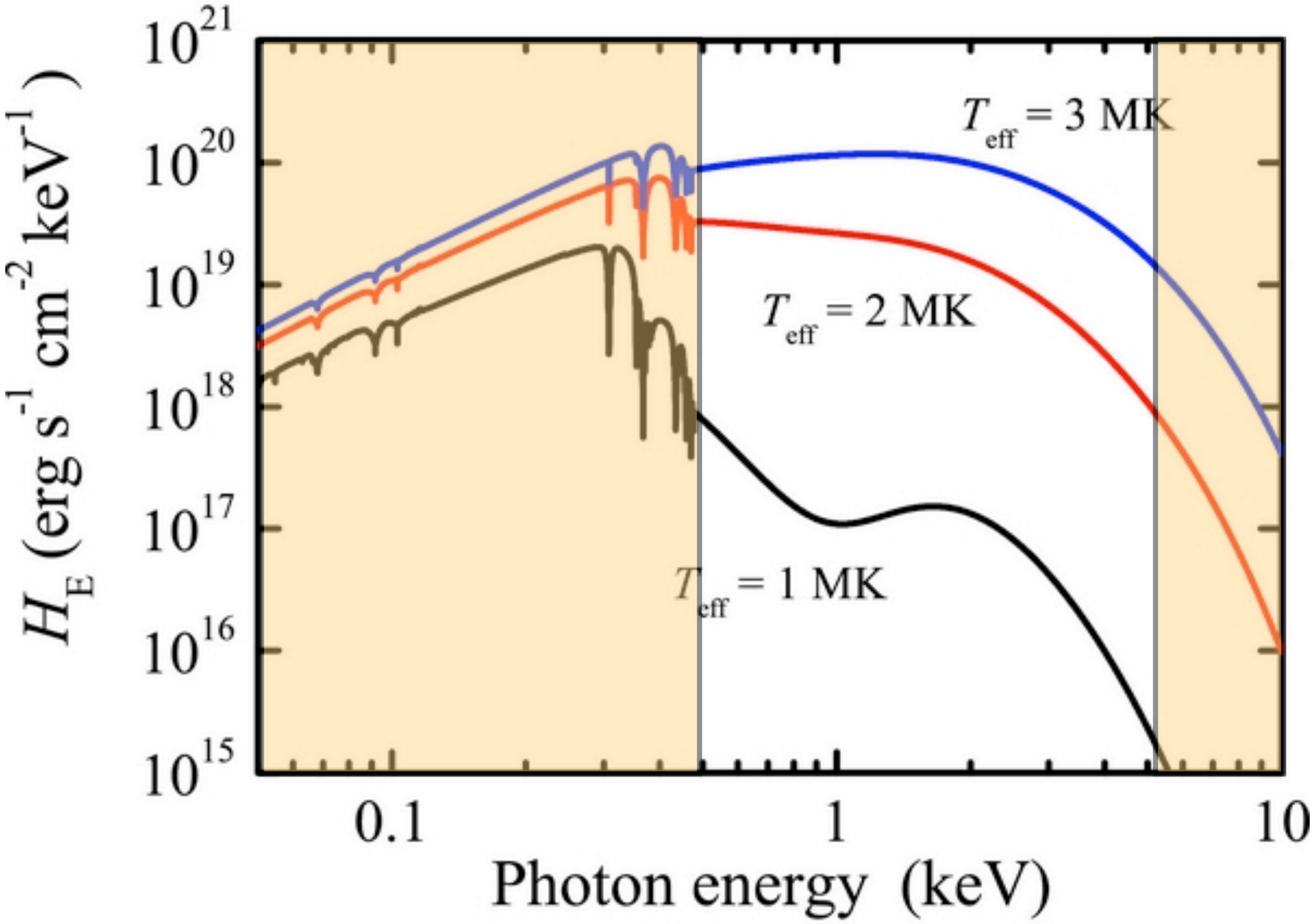
angle-weighted average of $I_\nu(\mathbf{n})$ over the stellar disk;

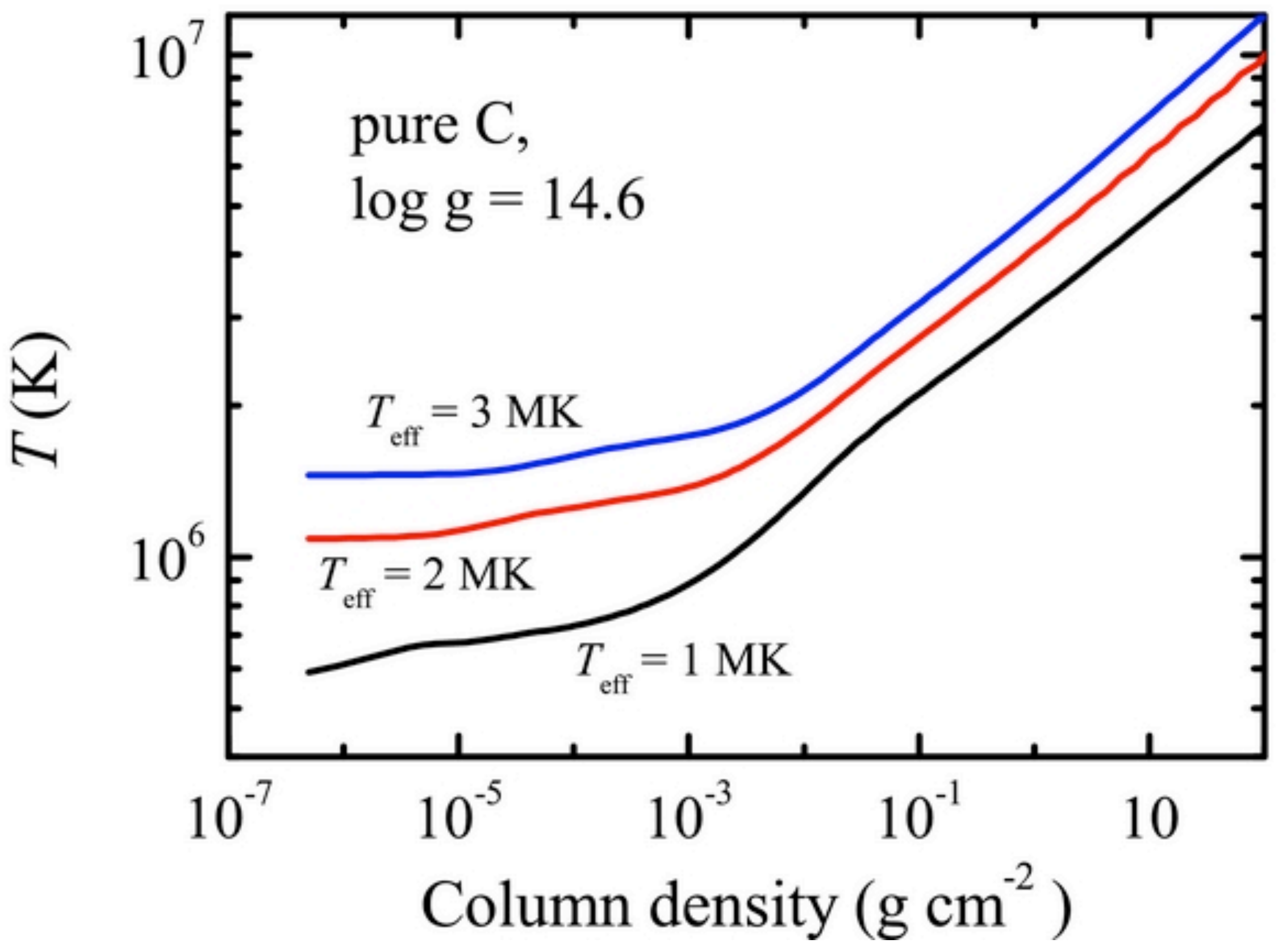
at the stellar surface:

$$F_\nu = 4\pi \frac{1}{2} \int_{-1}^{+1} I_\nu(\mu) \mu d\mu$$

We measure $f_\nu = (R/D)^2 F_\nu$, so with D and the correct F_ν (from a model atmosphere calculation), get R.

The problem is getting the right F_ν.





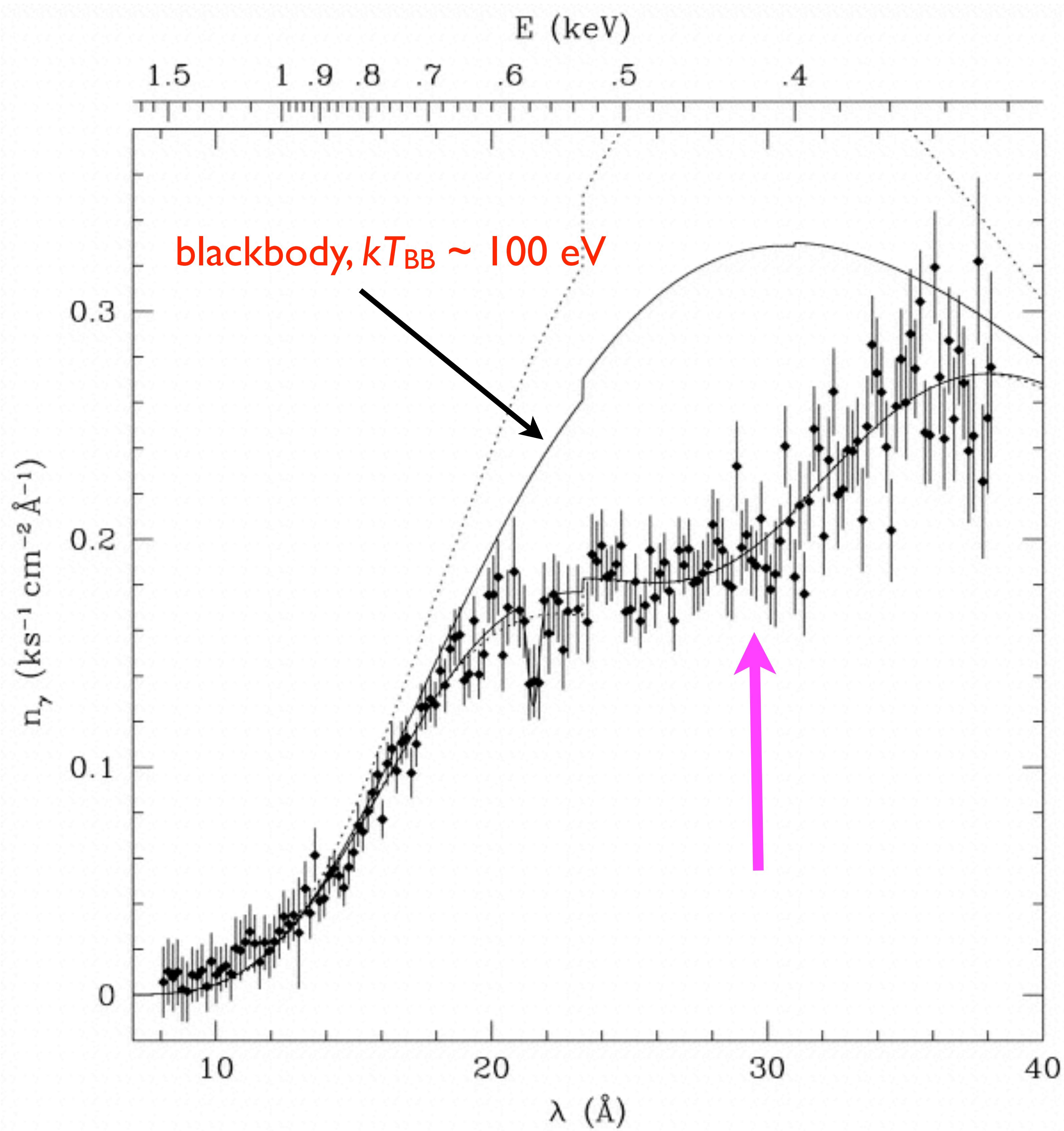
Pure C atmospheres

We see only the continuum in 0.5-few keV; depends on T_{eff}, and (to lesser extent) log *g*.

Often 'degenerate' with interstellar absorption!!

Suleimanov et al. 2014

broad features (bumps, dents): ? B-fields?



RX J1605.3+3249
van Kerkwijk et al. 2004

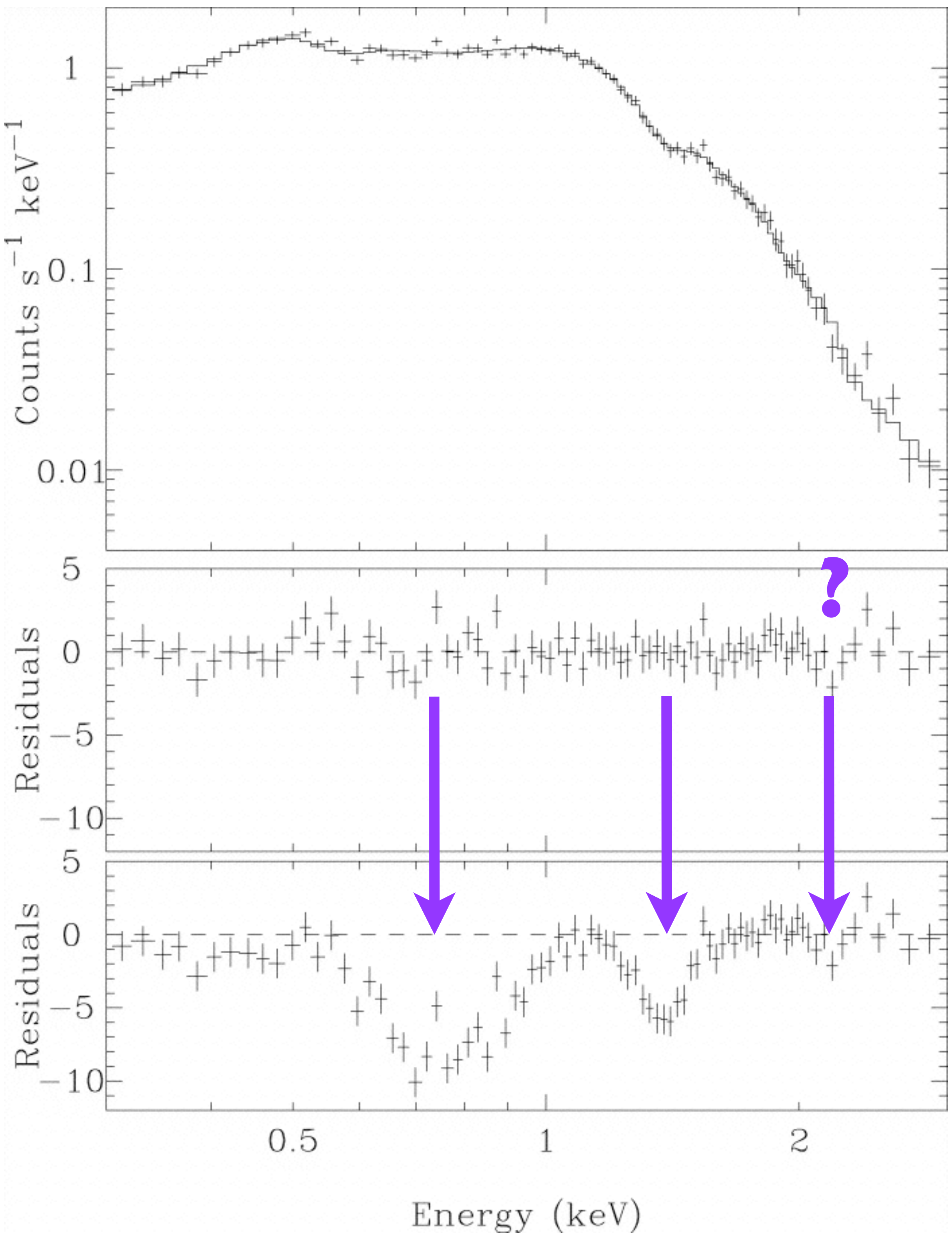
XMM-RGS, 110 ksec

if this is *resonant cyclotron absorption*, must be proton(*):
$E_c = qB/mc$,
and B ~ few 10^{13} G (from spindown)
(*but B inconsistent with spindown!*)

broad features (bumps, dents): ? B-fields?

(*) problem? transition probability for proton cyclotron transitions is small (m_e/m_p times smaller than corresponding electron resonance)

dents may not always be magnetic resonances



XMM/EPIC PN spectrum of 1E1207.4-5209 (in SNRG295.5+10.0) three (?) cyclotron harmonics

Sanwal et al. 2002 (*Chandra*); Mereghetti et al. 2002 (XMM)

cyclotron (electrons):
$B \sim 10^{11}$ G (*)

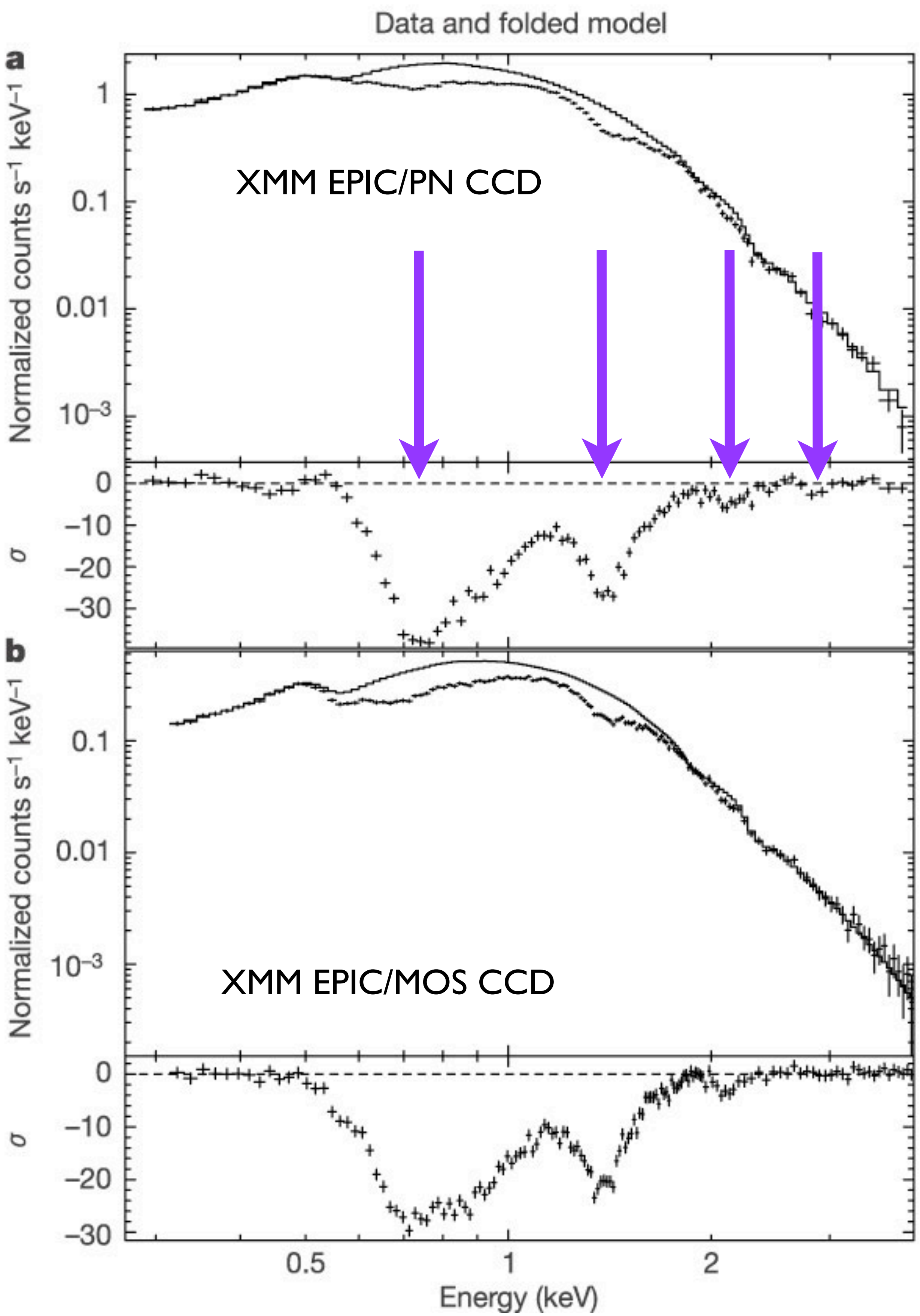
cyclotron (protons):
$B \sim 2 \times 10^{14}$ G

but
spindown: $B_{dipole} \sim 3 \times 10^{12}$ G(**)

(**) revised to $B < 3 \times 10^{11}$G, Gotthelf & Halpern 2007 - *consistent with* e^-

(*) *B* measurement coupled to the unknown redshift!

dents may not always be magnetic resonances



1E1207: deeper XMM data (Bignami et al. 2003)

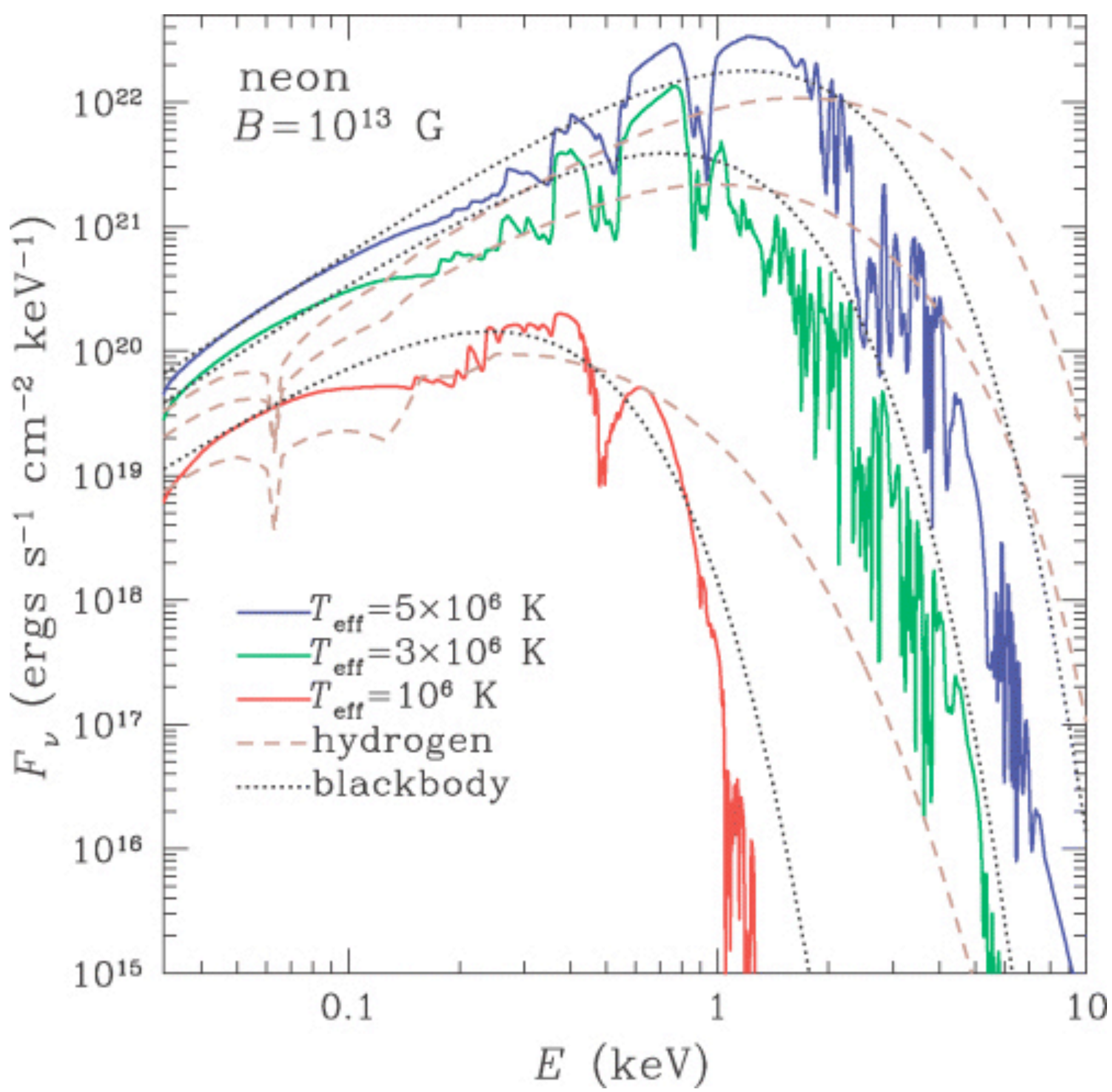
positive indication for *three* harmonics, maybe four

(my own crazy idea from condensed matter physics: it's the cyclotron energy for an electronic excitation with an effective mass of ~10-30m_e...)

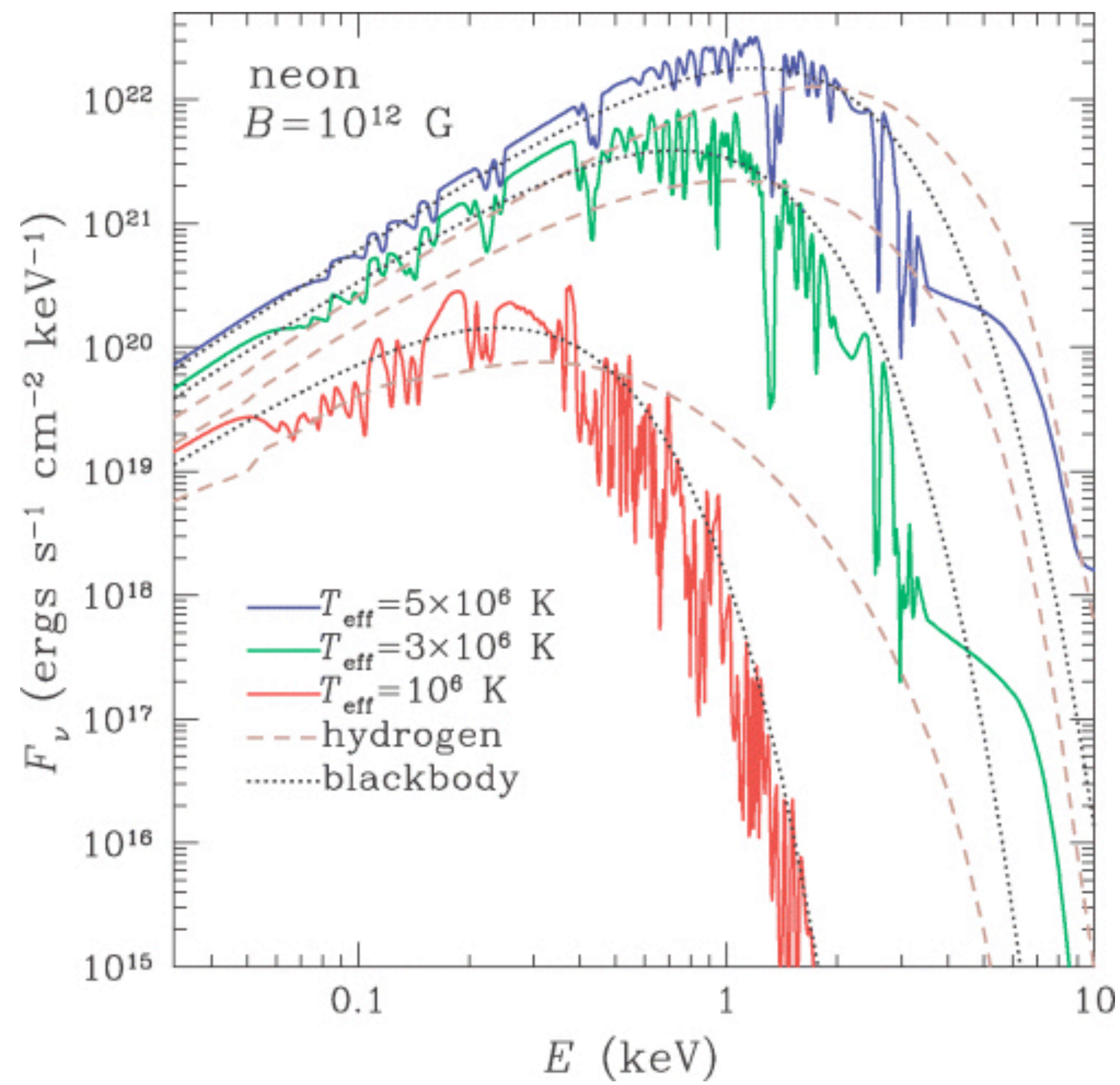
dents may not always be magnetic resonances

heavy elements in strong *B*-field also work!
and *B* more like ~10^{12} G!

10^{13} G neon



10^{12} G neon



Mori and Ho, 2007

dents may not be discrete cyclotron resonances

(*i.e.* due to transitions between Landau levels)

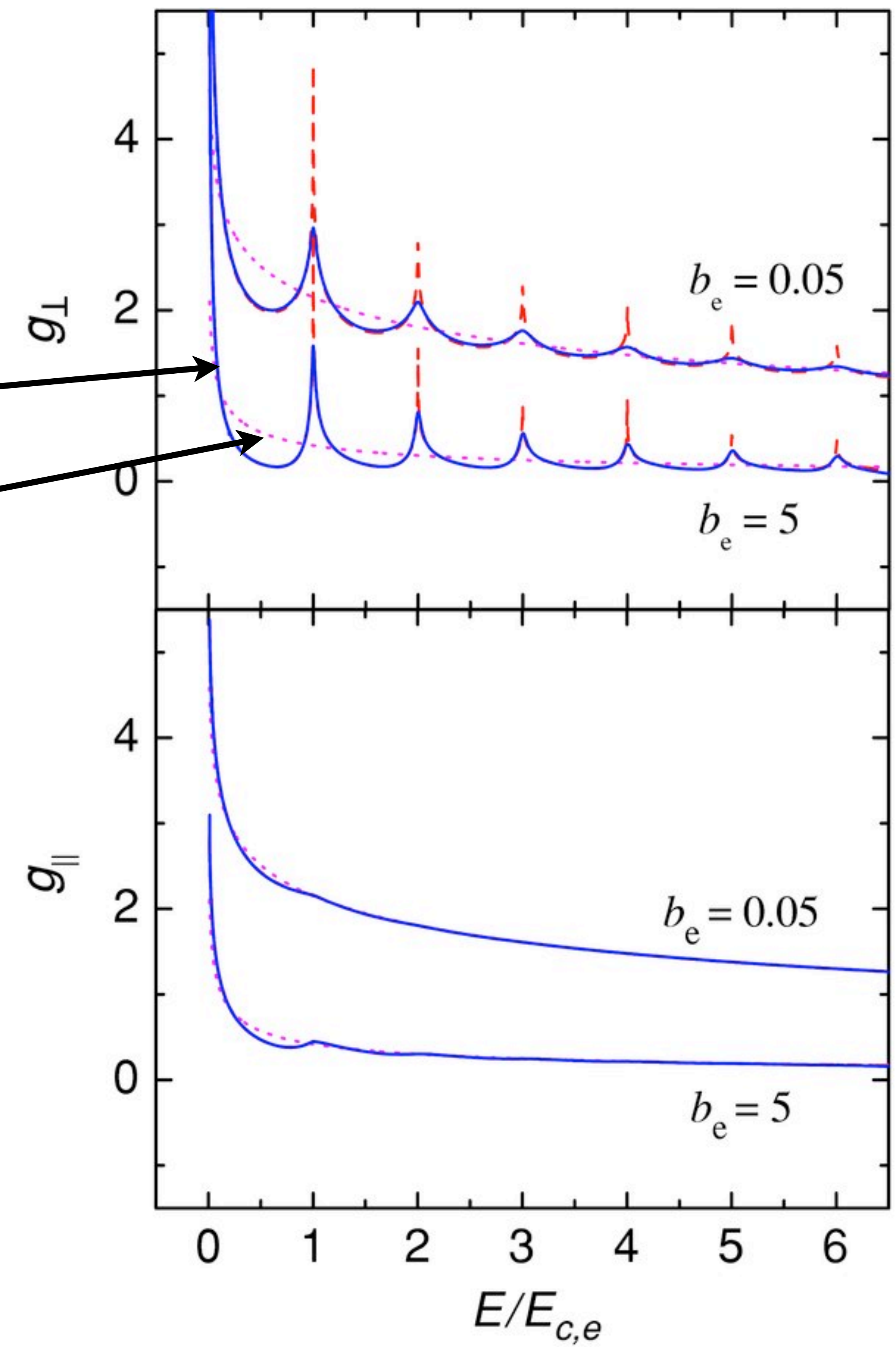
problem with cyclotron resonances: higher harmonics should be almost unobservably weak
(transition probability scales like $E/m_e c^2$)
(even allowing for rad transfer & saturation in n=1-2)

instead: resonances in ff continuum absorption cross section in presence of B field

Gaunt factors for ff absorption,
in presence of *B*-field
(Suleimanov, Pavlov, Werner 2010)

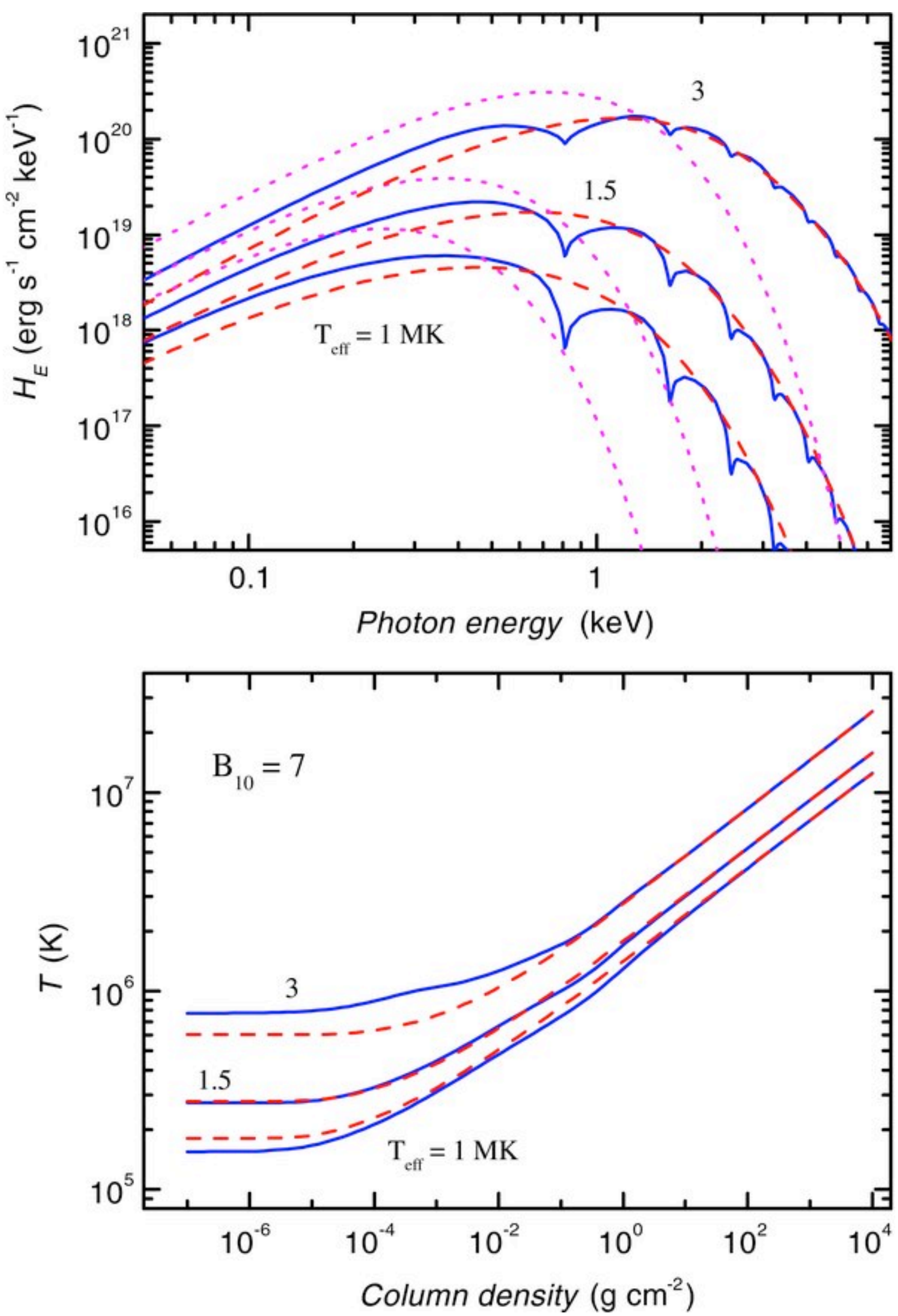
solid blue: with *B*

dotted: no *B*

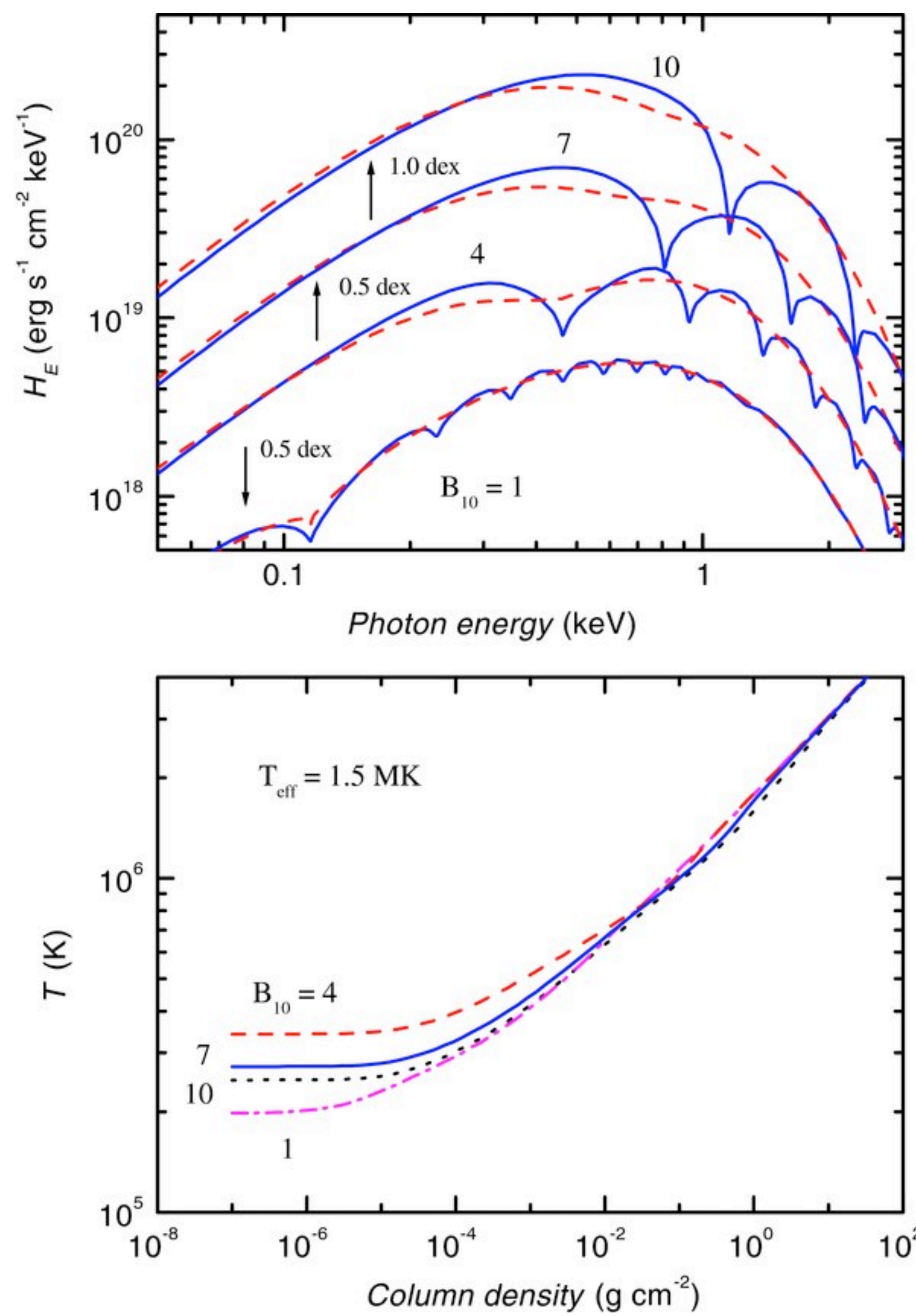


two cases shown: $b = E/kT = 0.05, 5$

model spectra

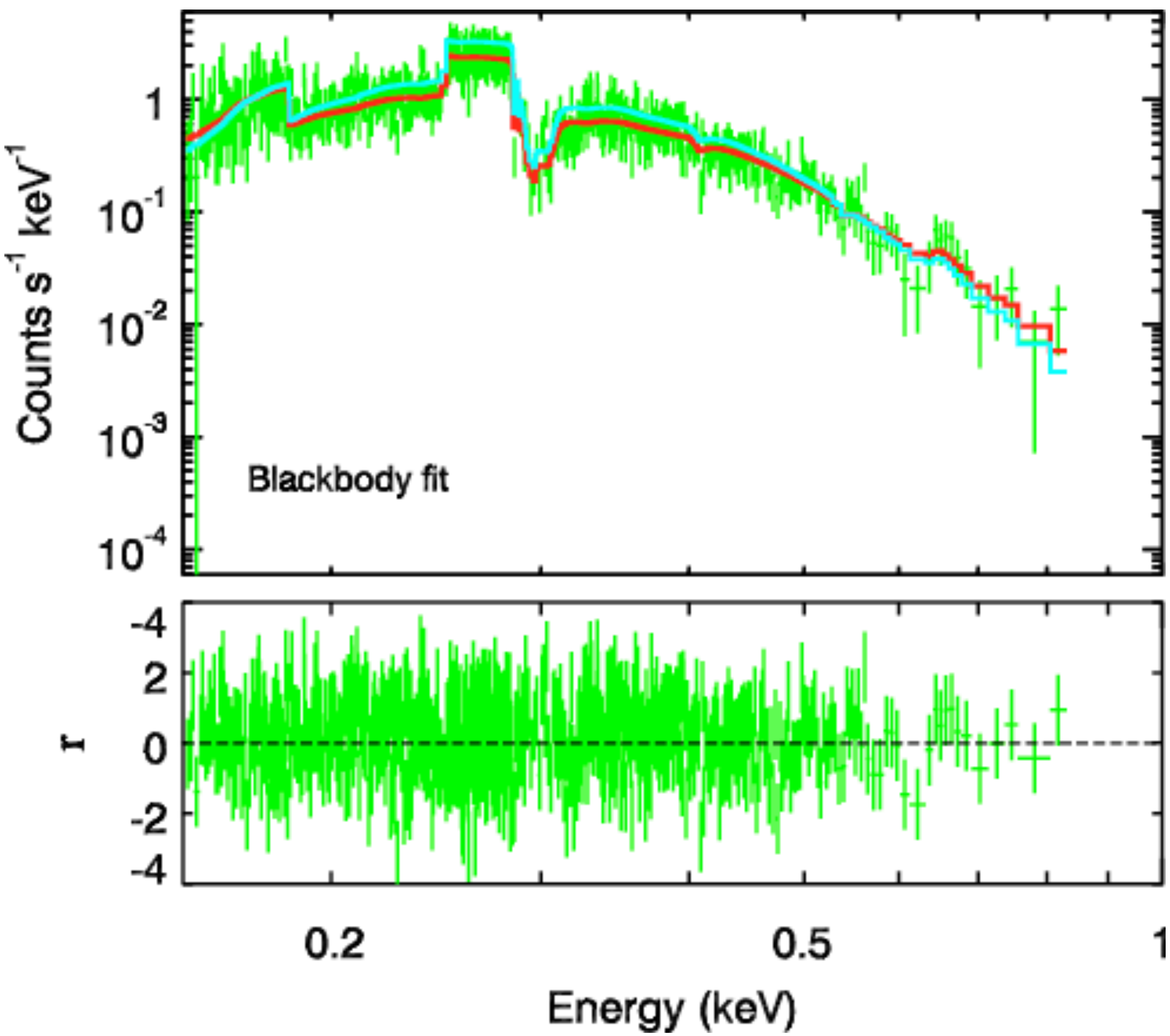


dependence on $T_{\rm eff}$



dependence on ***B***

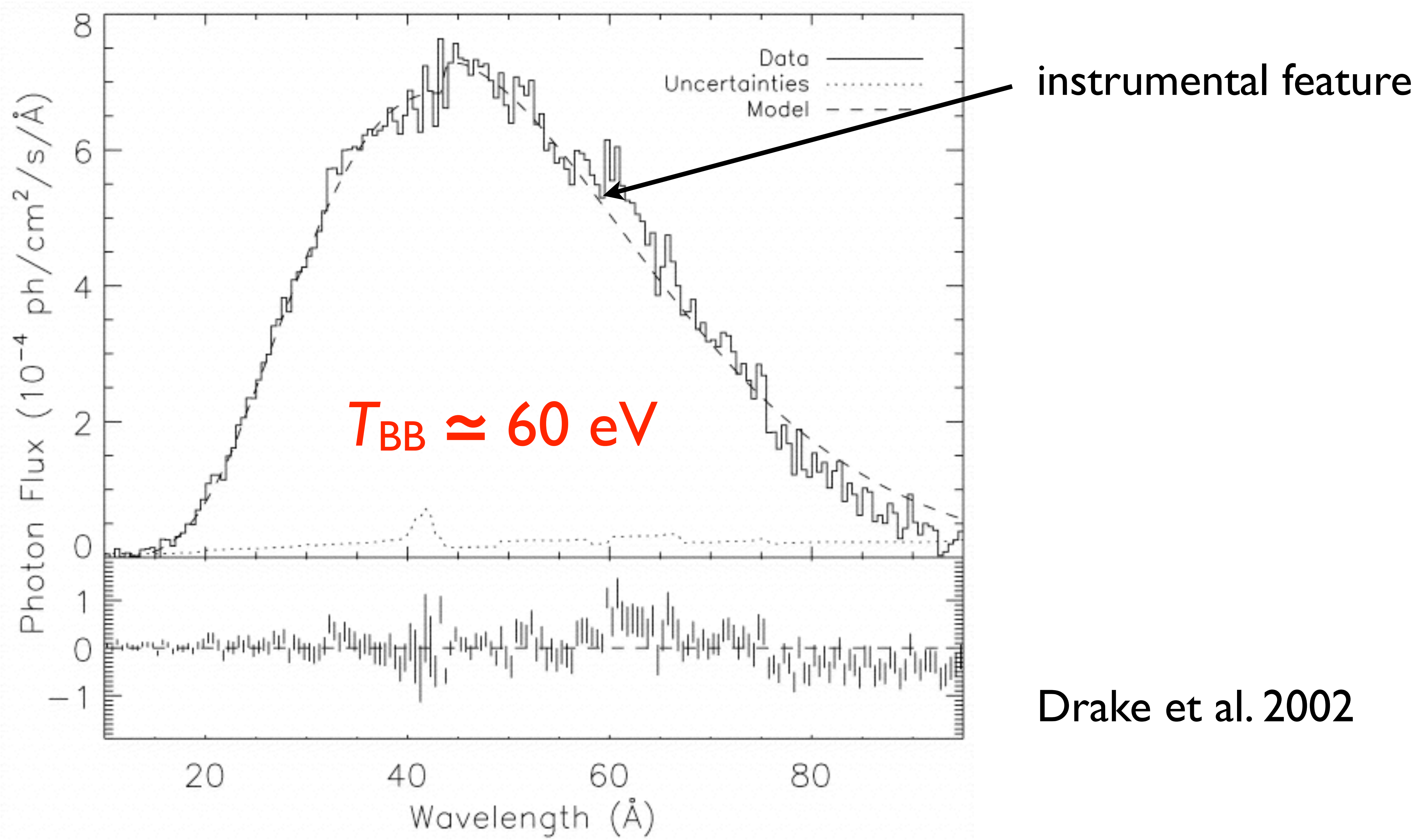
the biggest mystery of all:
the spectrum of RX J1856.5-3754: a perfect blackbody??



spectrum obtained with the LETGS on *Chandra*;
kT_{BB} = 57 +/- 3 eV
(Burwitz et al. 2001)

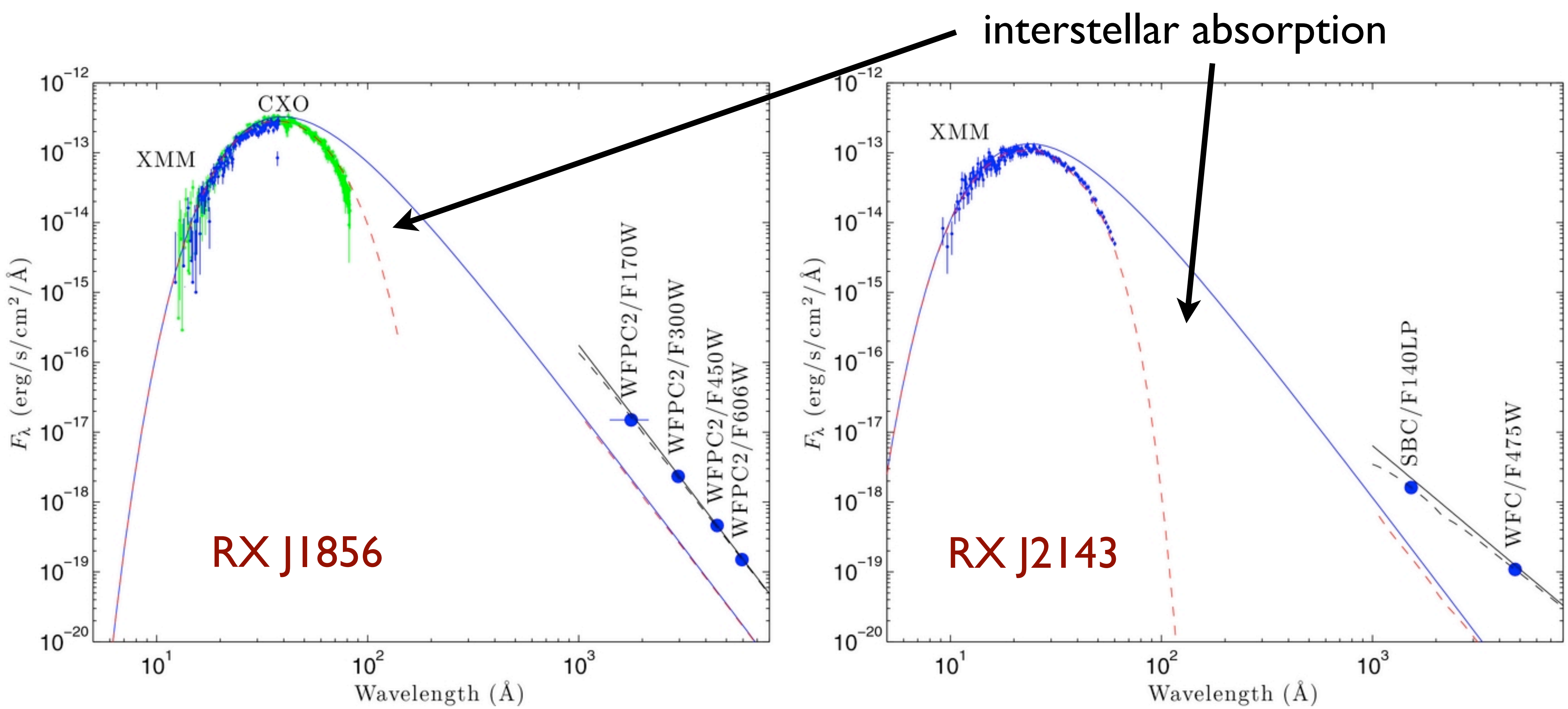
(based on work by Fred Walter using ROSAT PSPC data)

deep *Chandra*/LETGS spectrum: still blackbody...



Drake et al. 2002

unclear what the measured surface area(s) mean; almost certainly not $4\pi R_{star}^2$



optical and X-ray surface areas do not match
(e. g. Kaplan et al. 2011)

If magnetic fields are important,
emission spectra will be polarized!
we need:
an efficient astrophysical X-ray spectropolarimeter!

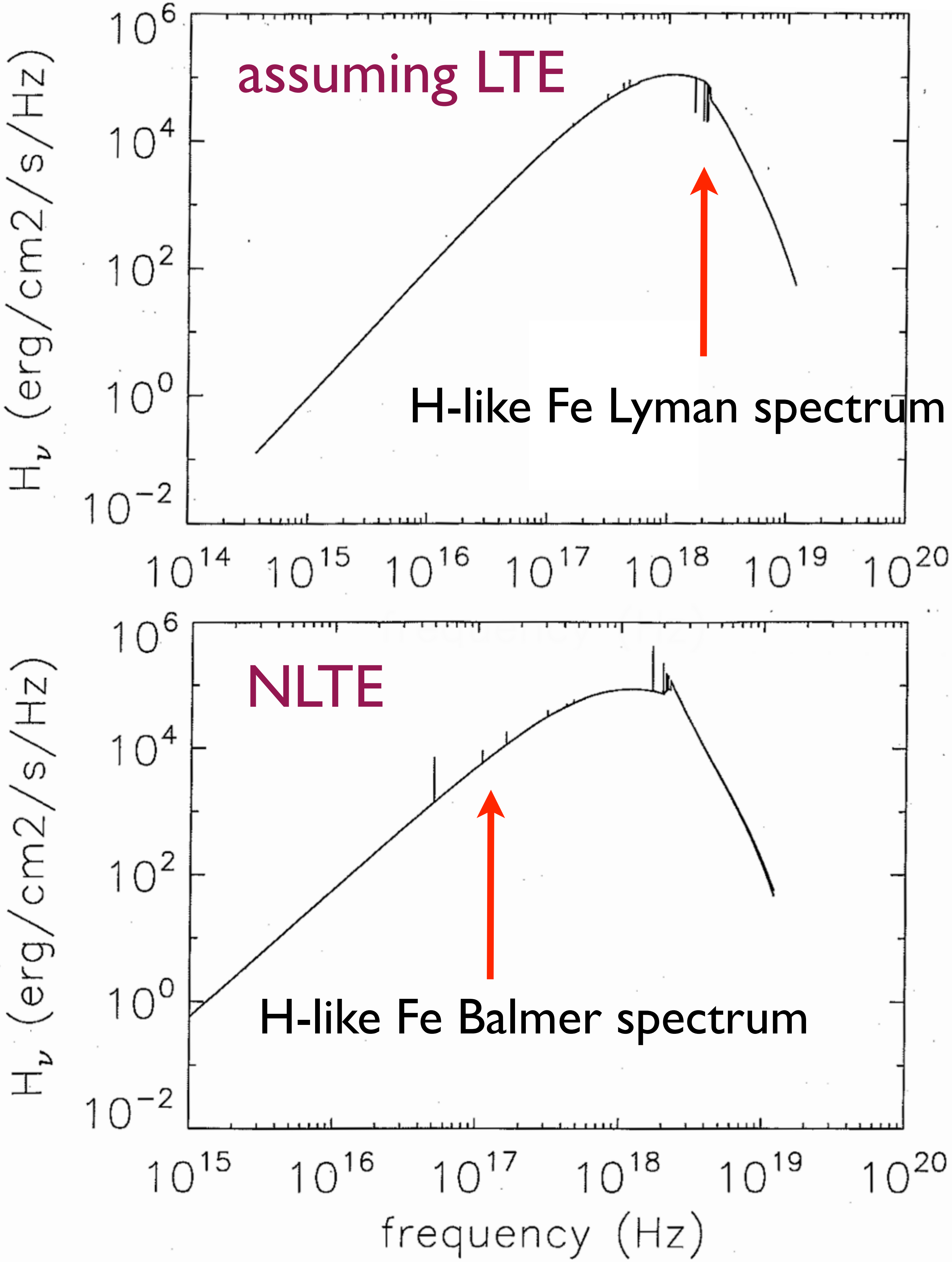
Part II: line spectroscopy

potentially much more sensitive to
stellar parameters-
but requires a lot more photons
(and high-resolution spectrometers)

neutron star model atmospheres calculations

I: NLTE, emission lines and edges!

II: Fe K spectroscopy



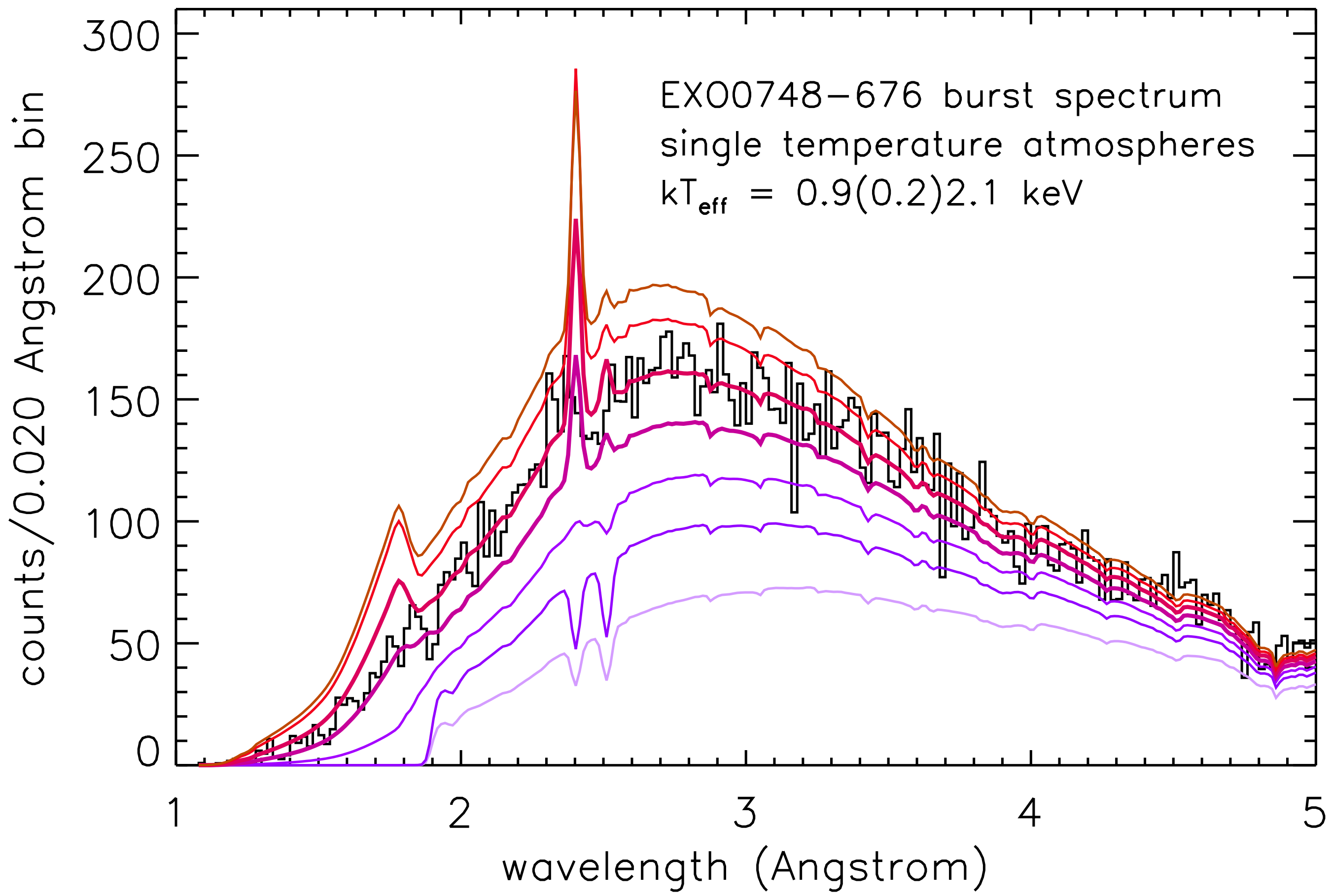
neutron star atmospheres

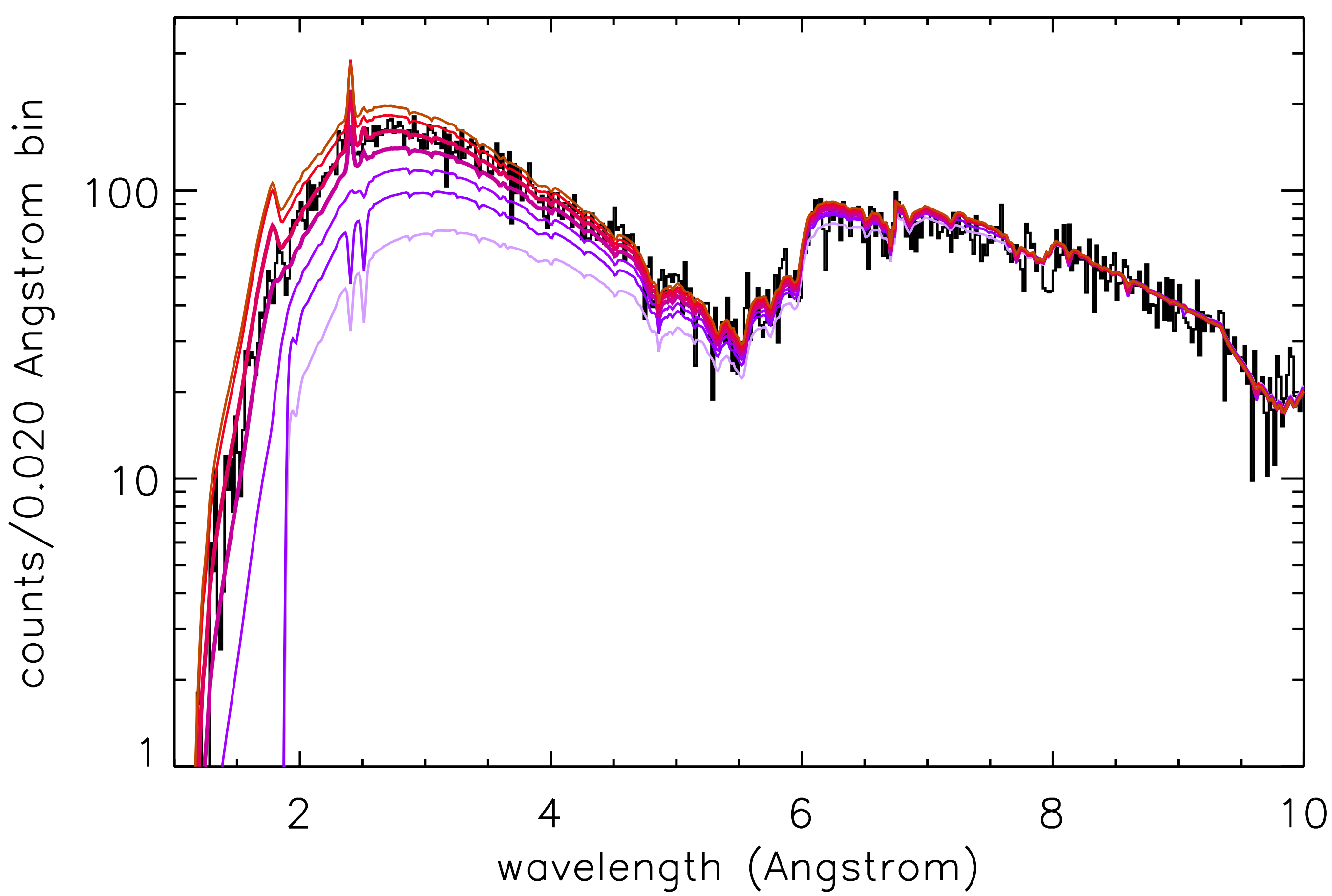
calculated with code TLUSTY (Hubeny, adapted for this problem by Lanz)

T_{eff} = 1.5 x 10^{7} K,
log g = 14.3
H + Fe; Fe/H = 10^{-4}

note the difference LTE/NLTE:
lines, edges appear in emission in NLTE

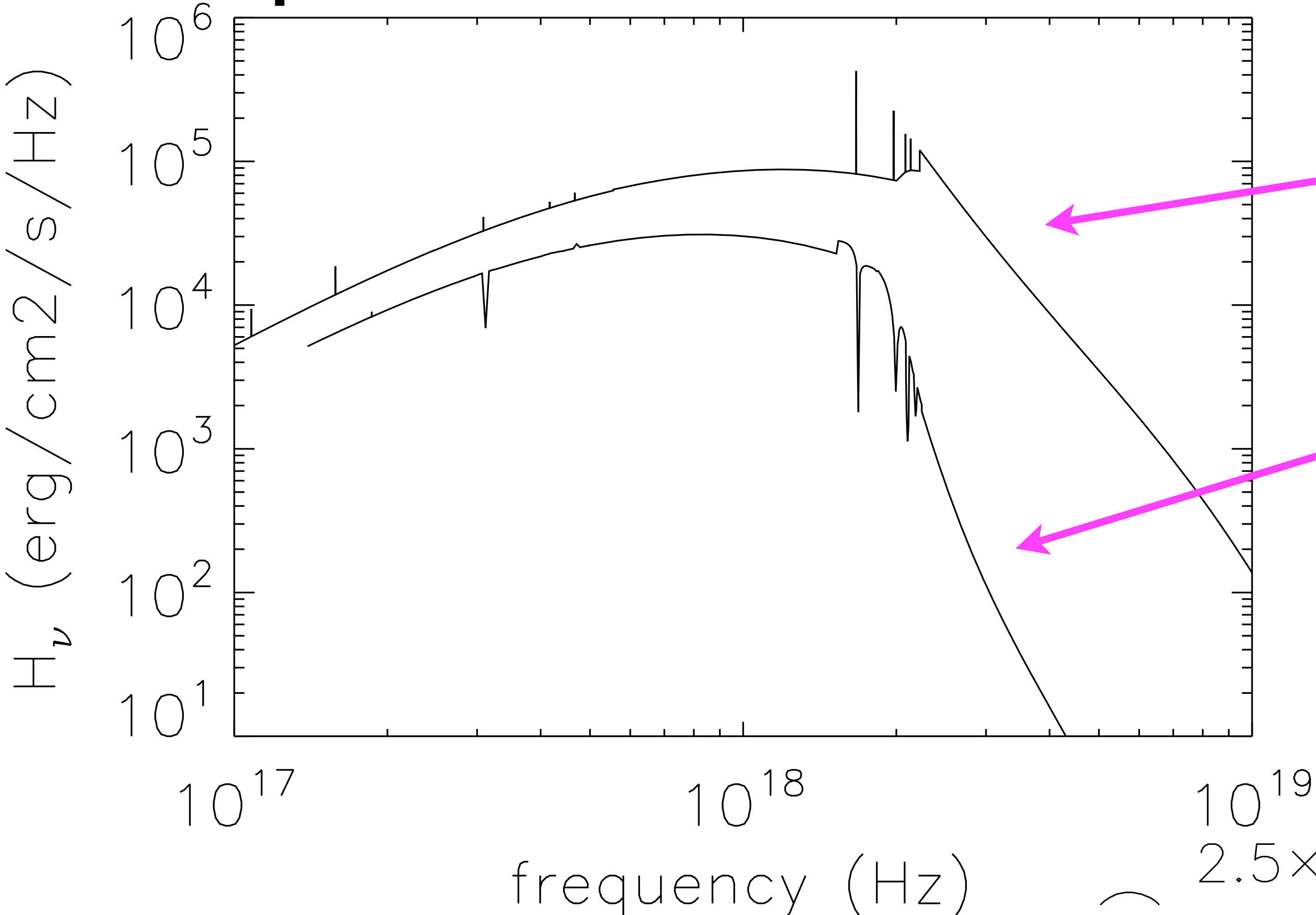
lines may go into emission as T_{eff} goes up





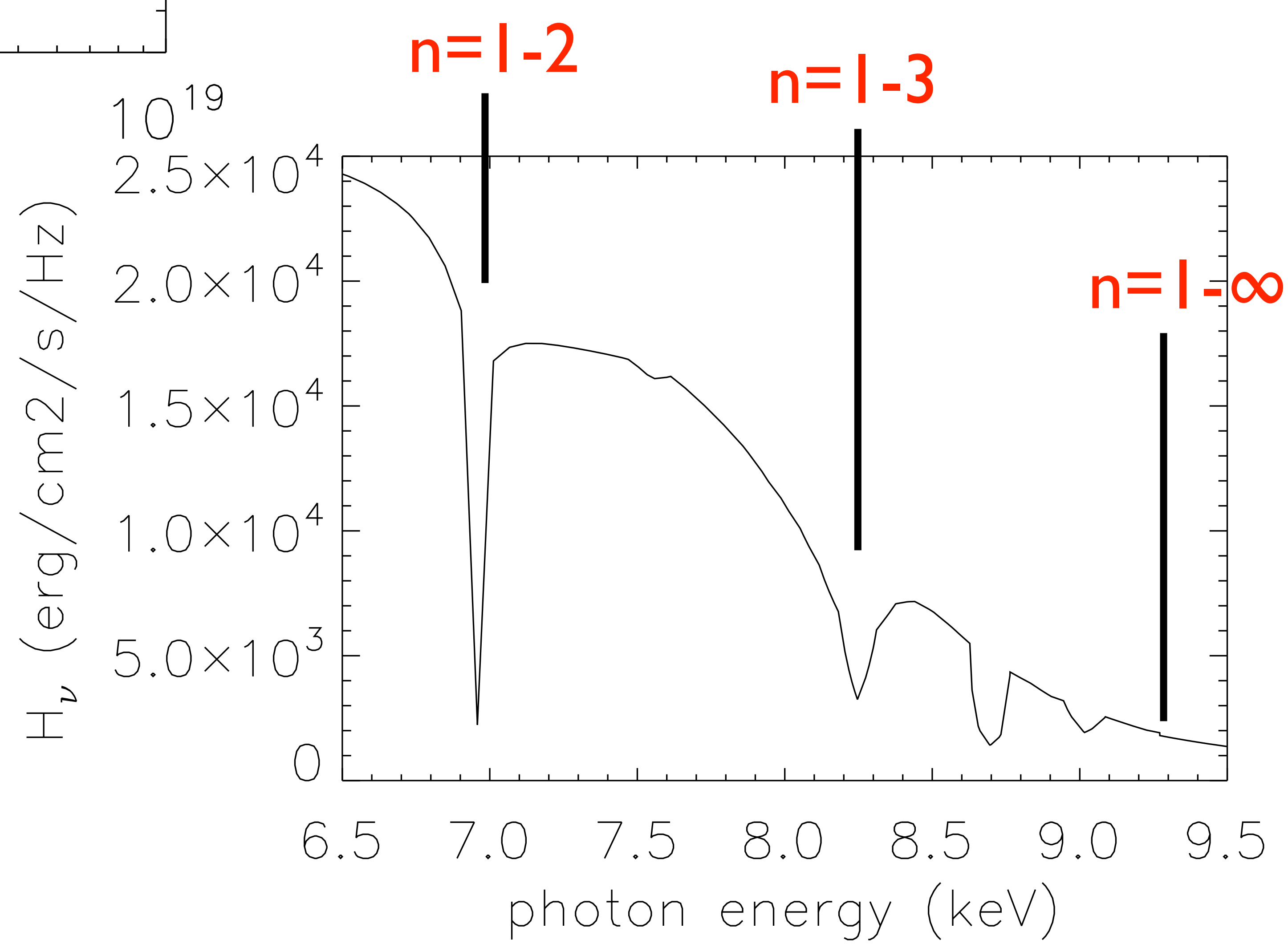
Chandra HETGS
EXO0748-676
burst spectrum

H-like Fe Lyman spectroscopy:
pressure ionization as a log g diagnostic



T_{eff} = 1.5 x10^7 K; log g = 14.3; Fe/H = 10^{-4}
no Stark broadening

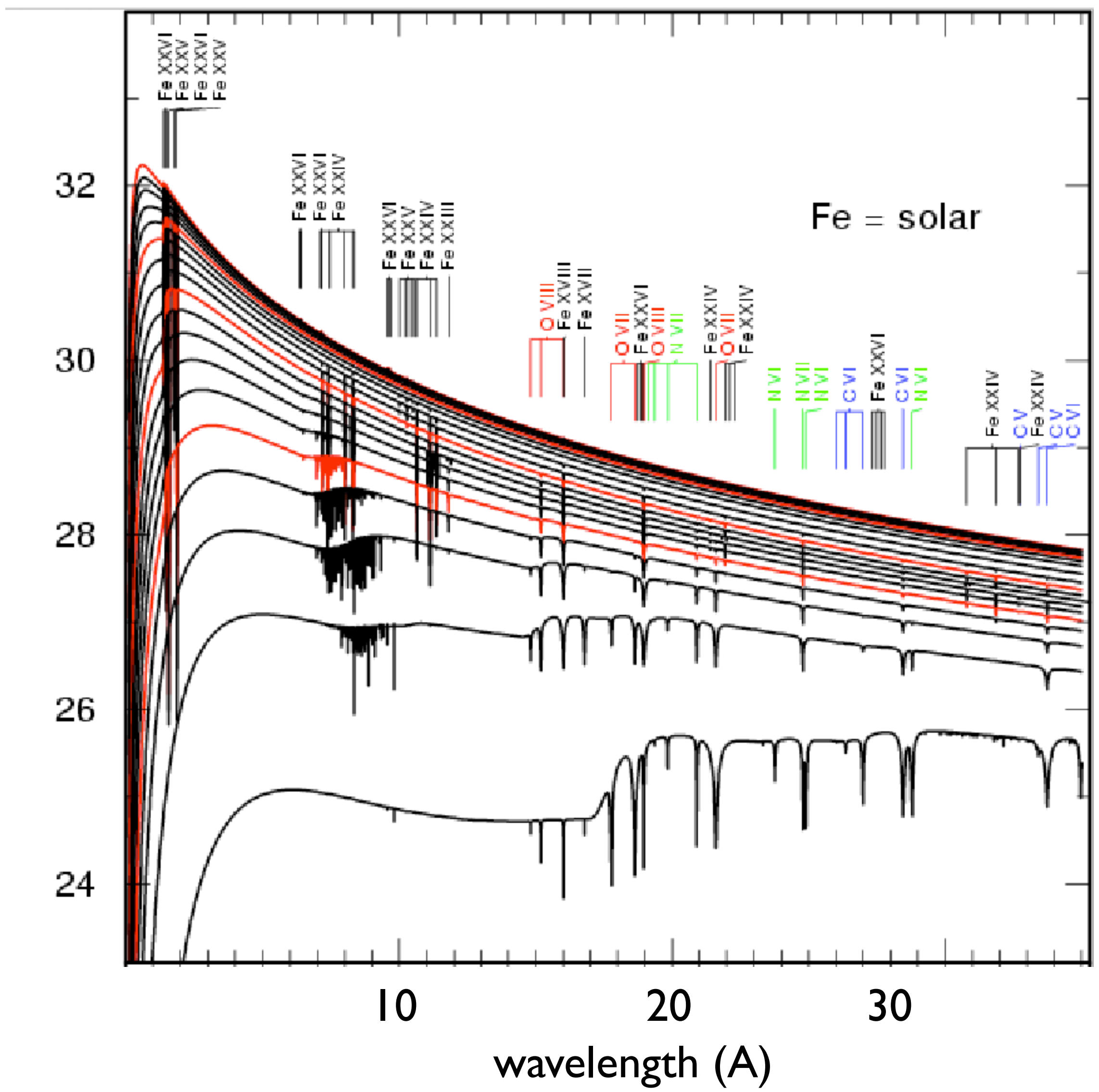
T_{eff} = 1.0 x10^7 K; log g = 14.3; Fe/H = 10^{-4}
with Stark broadening

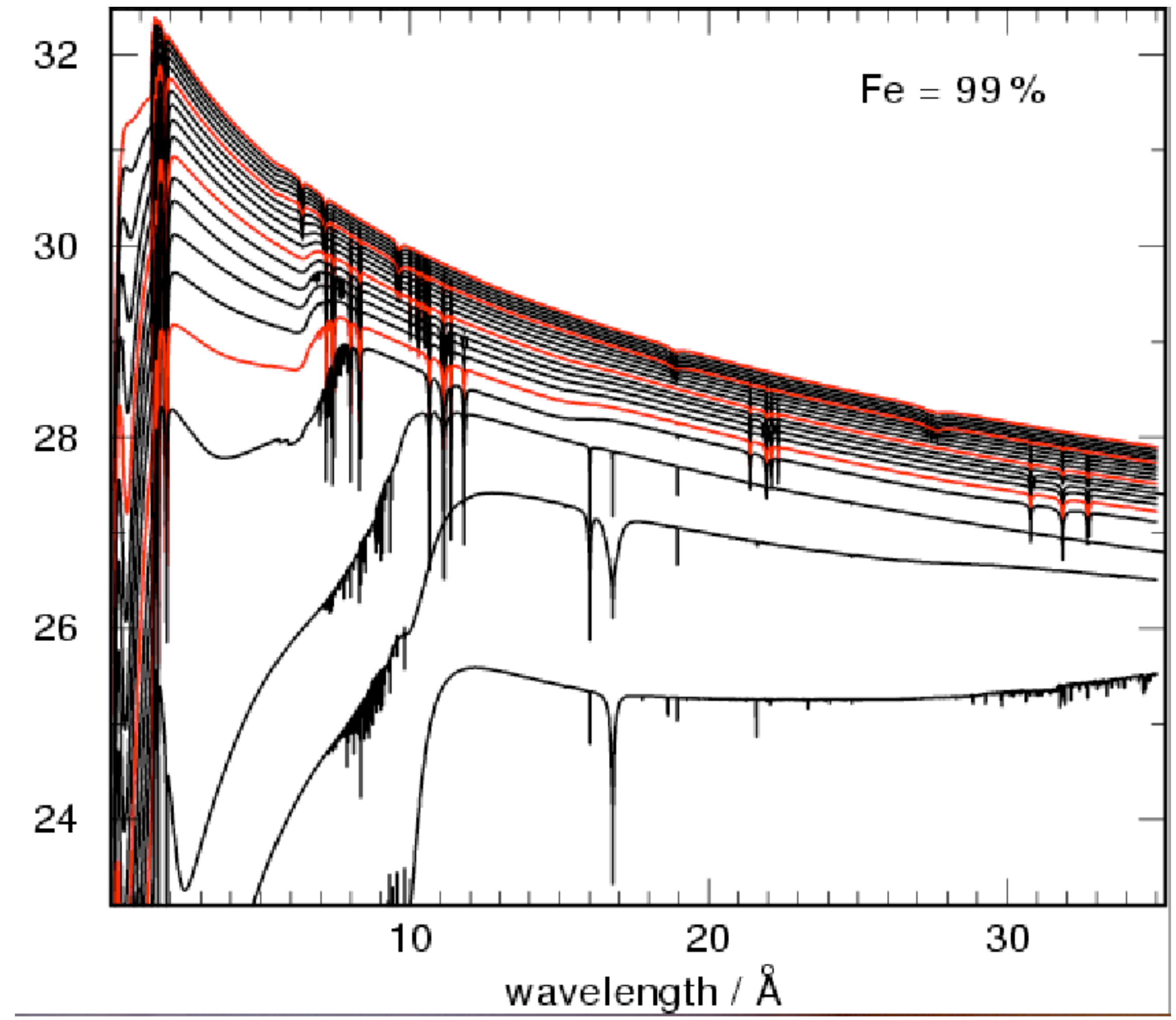


NLTE; extreme broadening;

more work:
radiative transfer in lines;
accurate atomic models;
broadening theory!

effect of varying Fe abundance





code built by Rauch, Suleimanov, Werner

is line spectroscopy feasible?

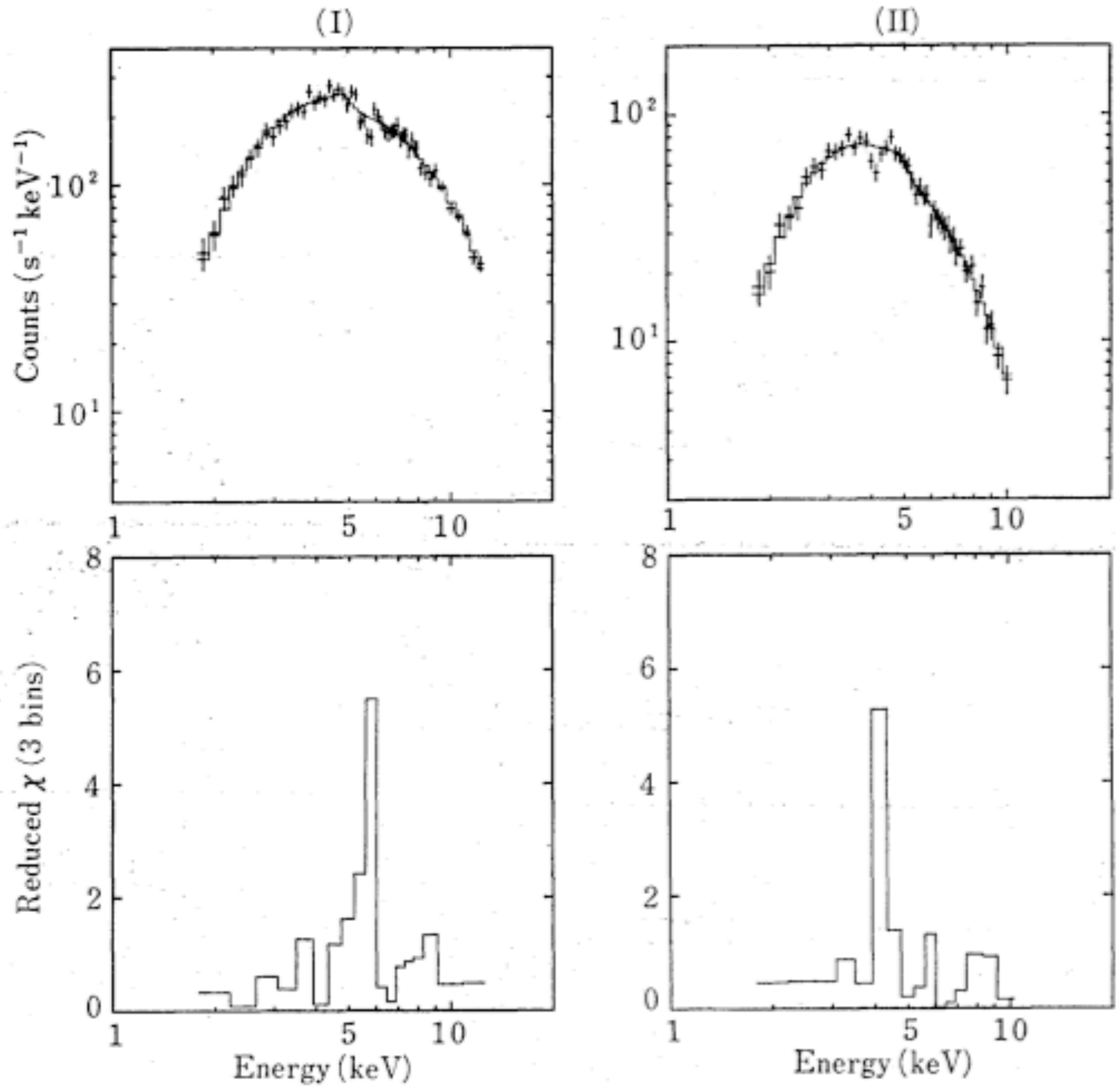
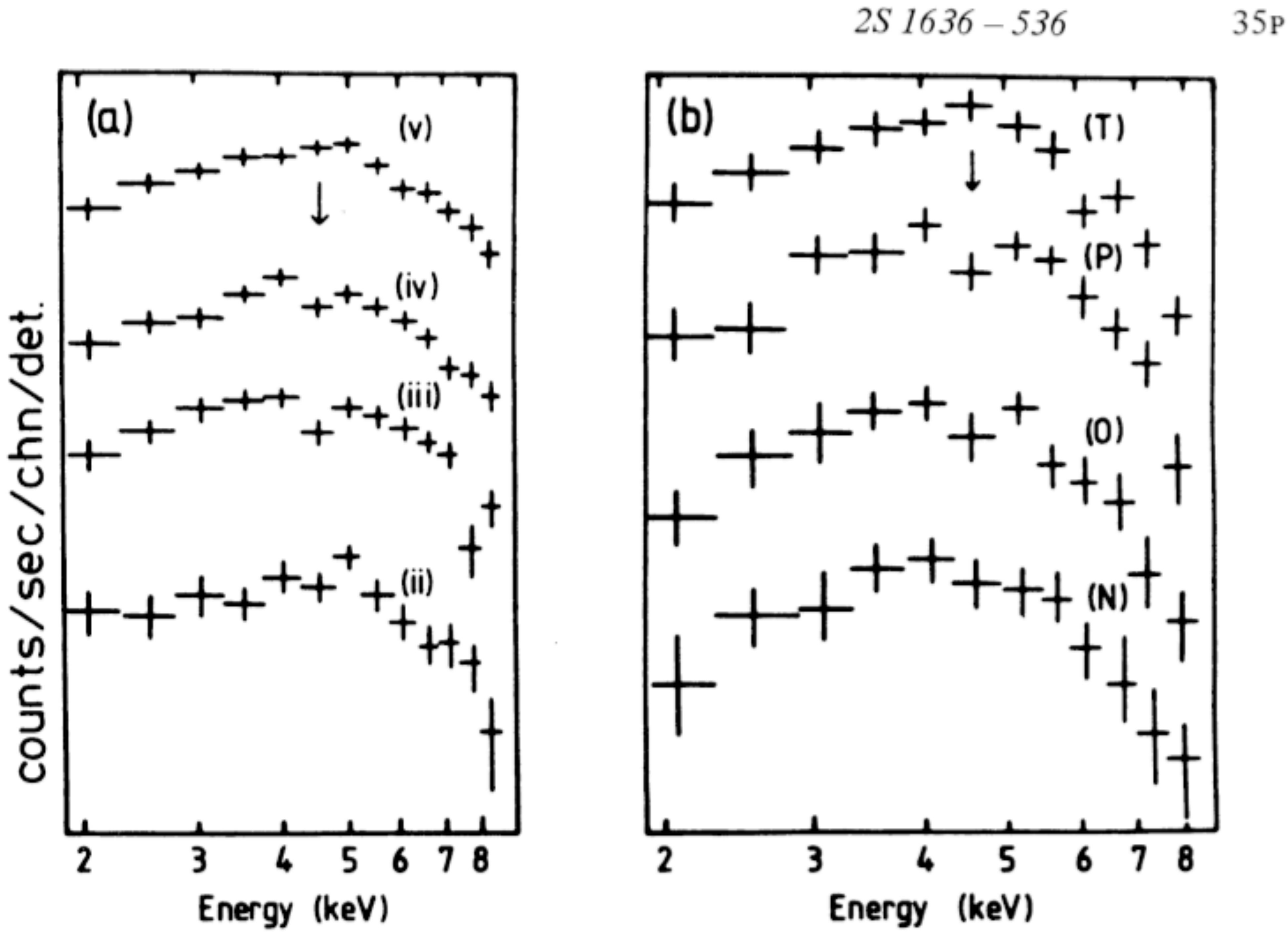


Fig. 2. Two energy spectra of burst D. Spectrum I (upper-left panel) is the average for the first 8 s from the burst onset, and Spectrum II (upper-right panel) is the average over the period 8–36 s from the onset. The best-fit blackbody models according to equation (1) are shown by the histograms, respectively. The distributions of mean χ^2-values of three consecutive energy bins are shown in the lower panels.

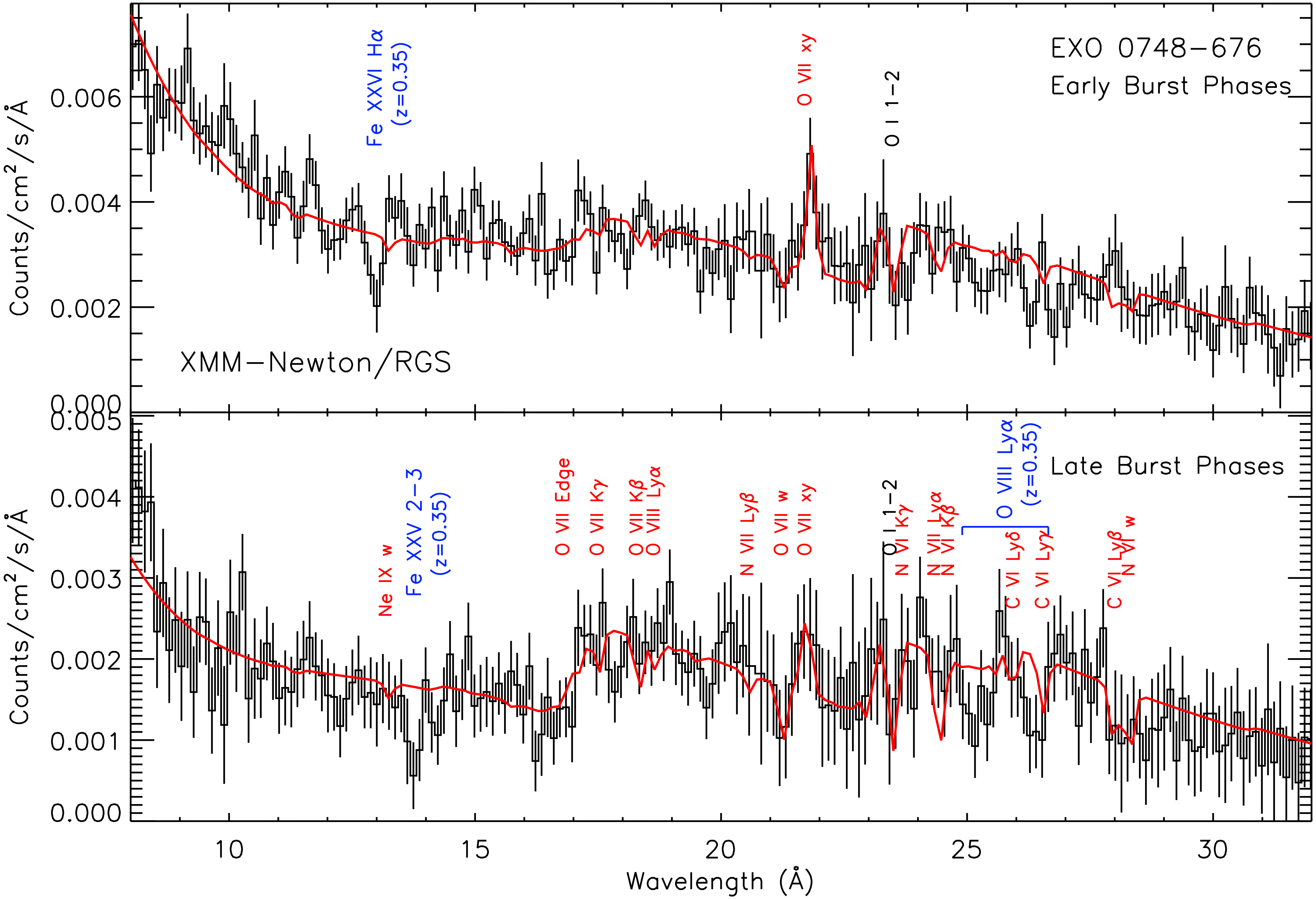
Waki et al. 1984/ Tenma burst in X1636-536 feature at 4.5-5 keV; EW 100-200 eV

but note:
counter gas (Xe) has absorption edge at 4.7 keV

same source, different detector



Turner&Breedon/ Exosat ME 1984
counters Argon-filled, no edge at 4.5 keV



burst spectrum of EXO0748-676:

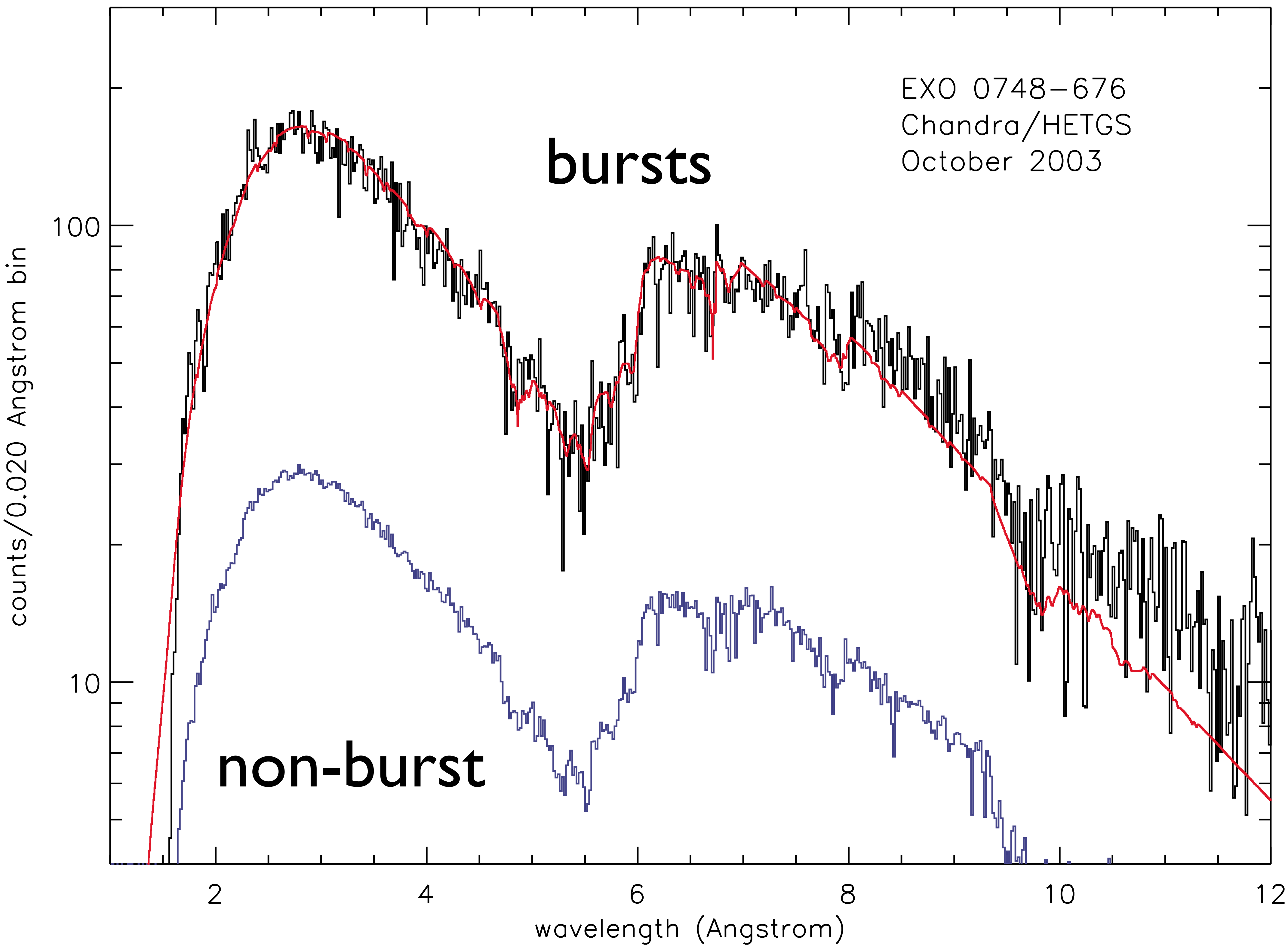
? redshifted H, He-like Fe Balmer lines ? if so, z = 0.35

Cottam, Paerels, Mendez (2002)/ XMM-RGS

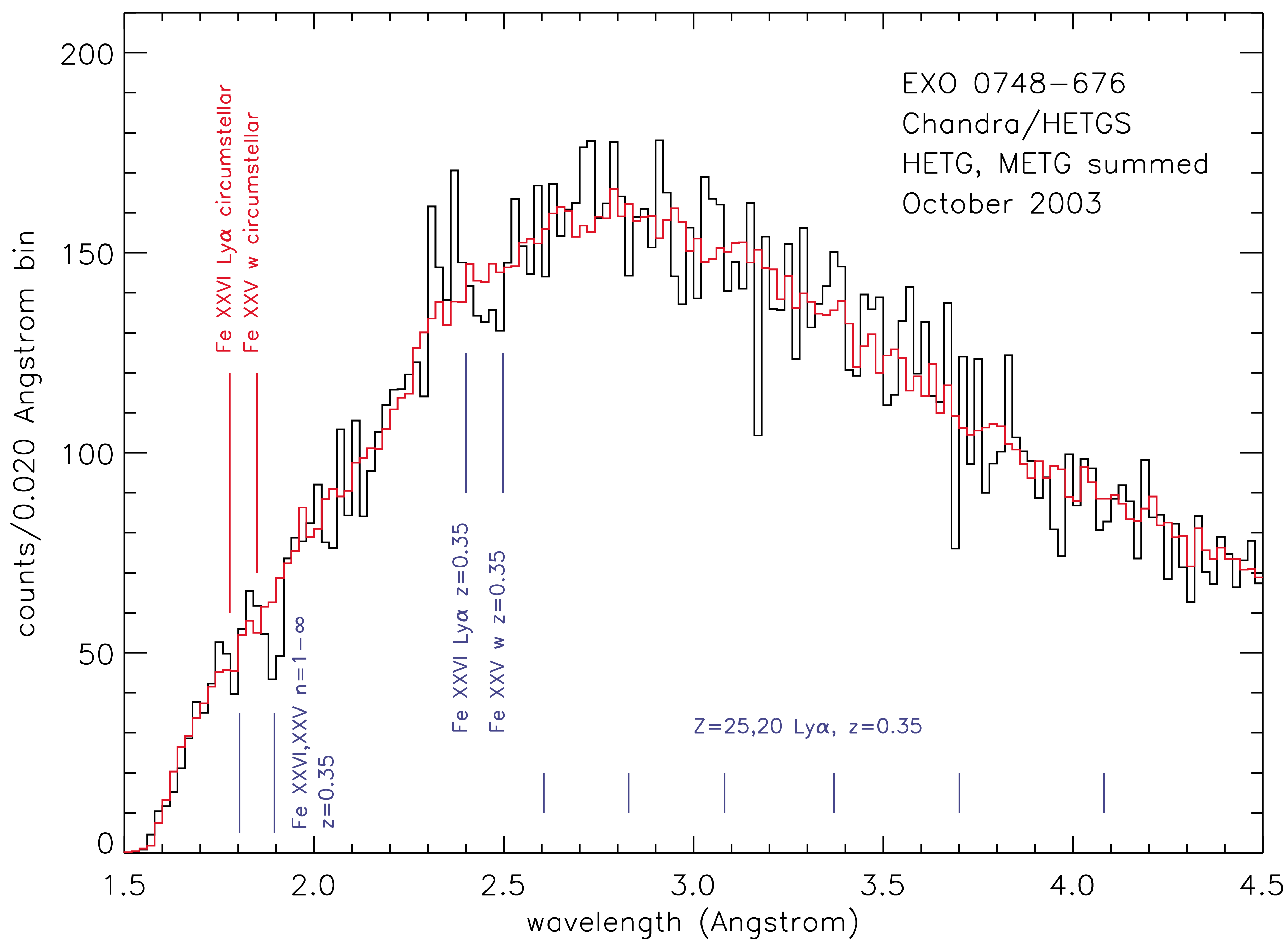
at the time: f_{spin} = 95 Hz !! but now f_{spin}= 550 Hz;

also: viewed edge-on...

also did a deep observation of the Fe Lyman band with *Chandra* HETGS: negative result

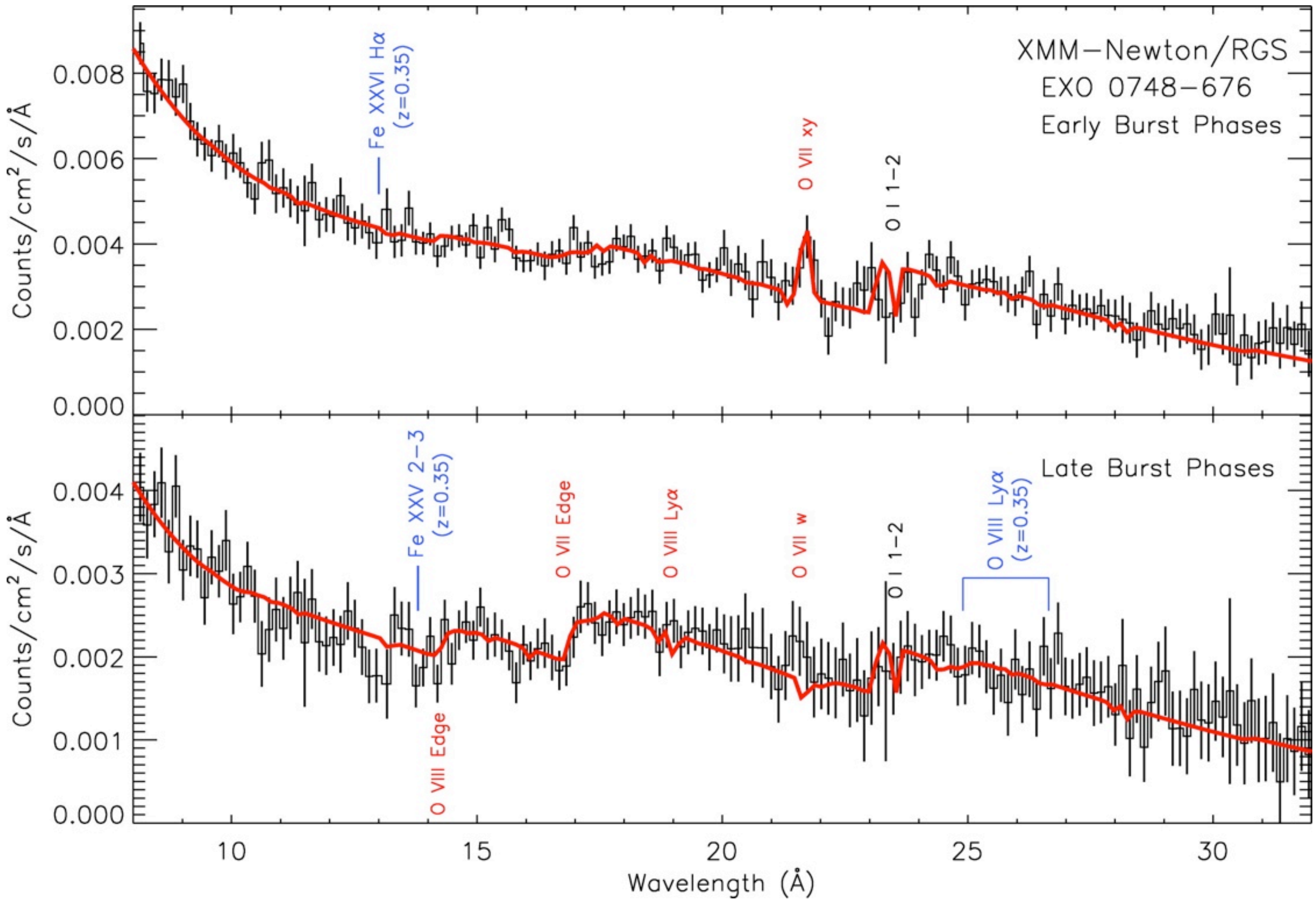


also did a deep observation of the Fe Lyman band with *Chandra* HETGS: negative result

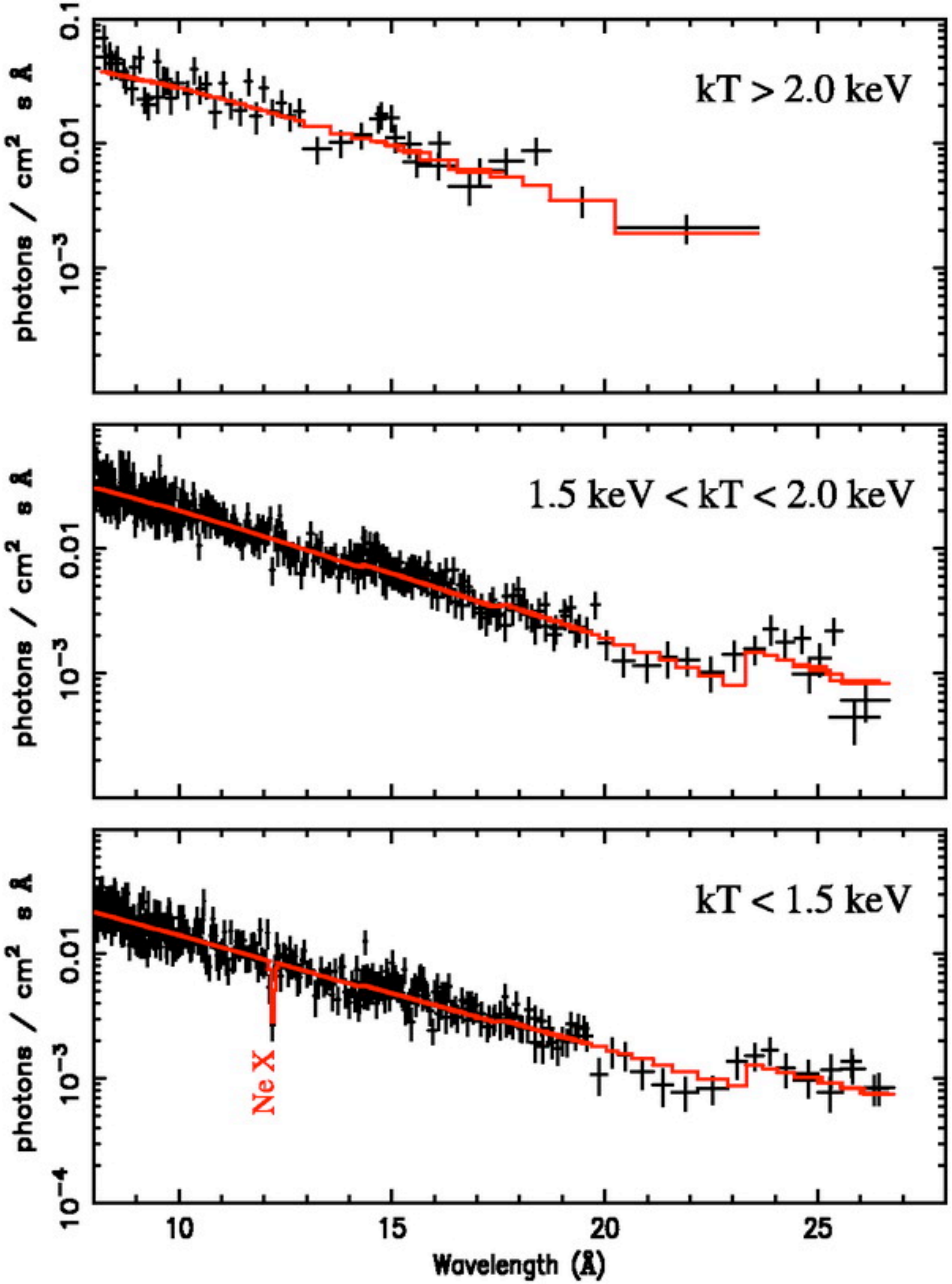


red: the non-burst spectrum scaled as template

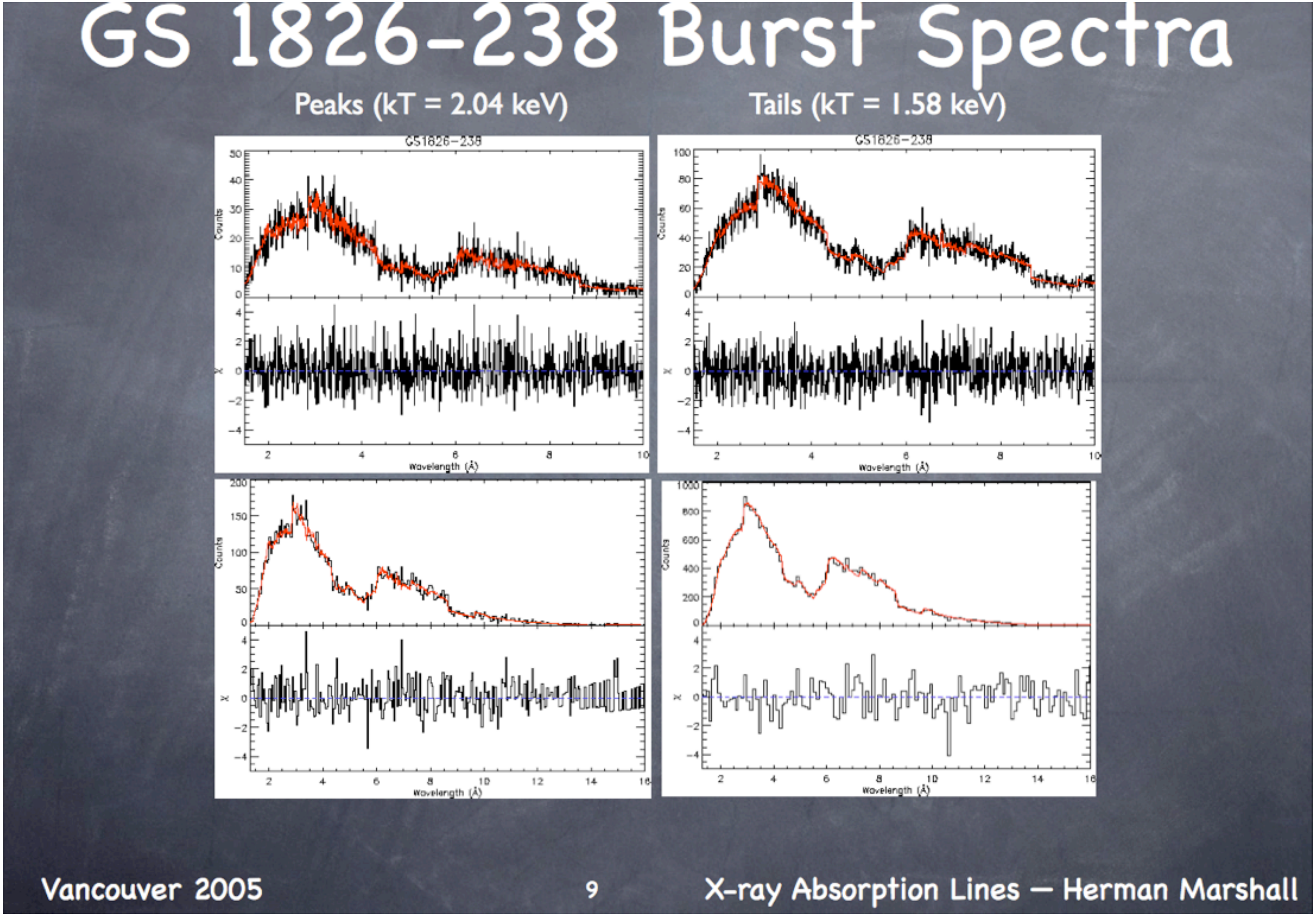
reobservation with XMM/RGS



Cottam et al., 2008



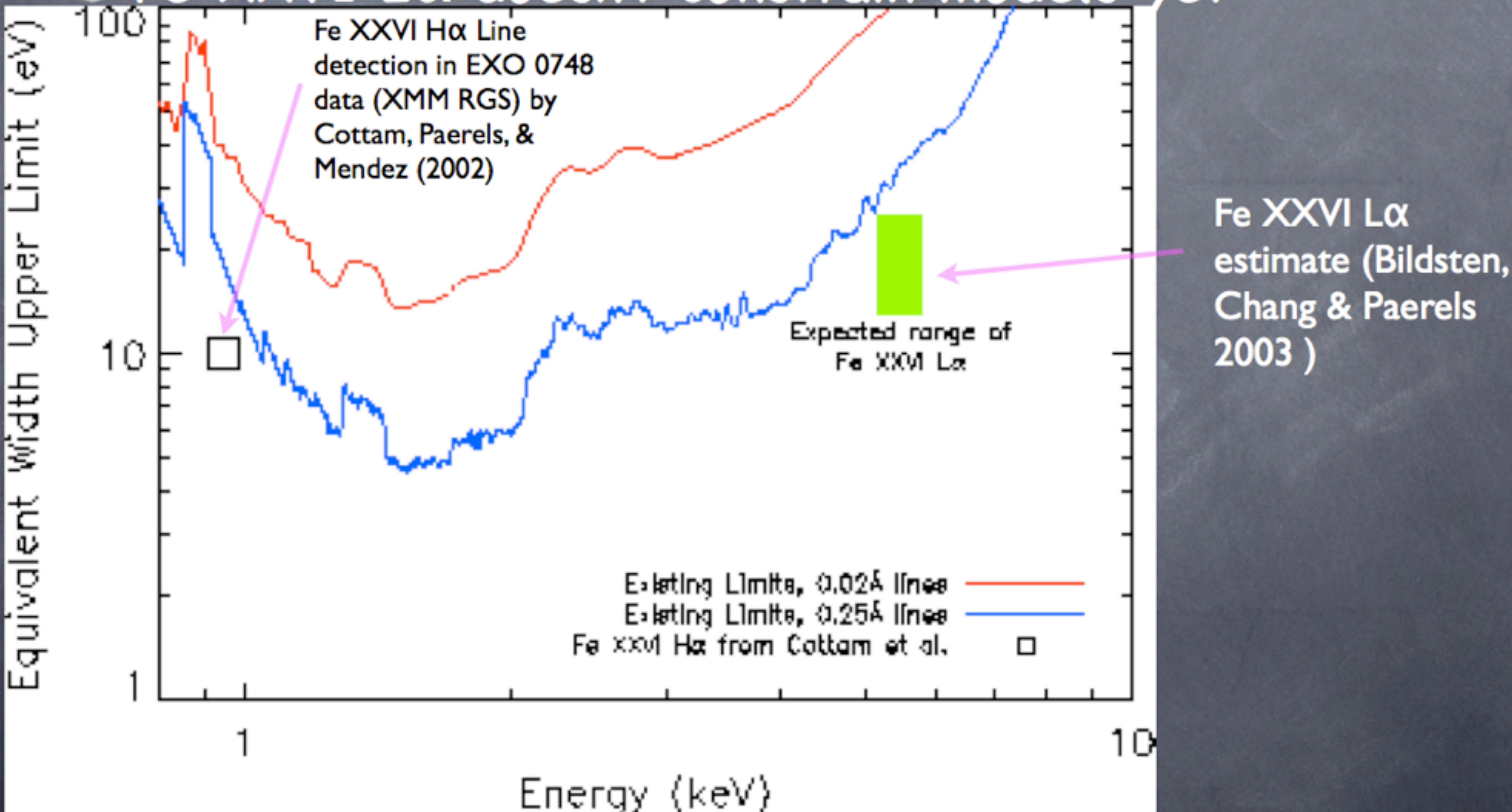
Kong et al. 2007
XMM/RGS
GS1826-24



GS1826-238 with *Chandra* HETGS (Marshall)

Burst Peak Results

- Fe XXV Hα limit is not as good as in EXO 0748 XMM data (Cottam et al. 2002)
- Fe XXVI Lα doesn't constrain models yet



brief break

3.2 Applications: Future Plans, and the SXS microcalorimeter spectrometer on Astro-H

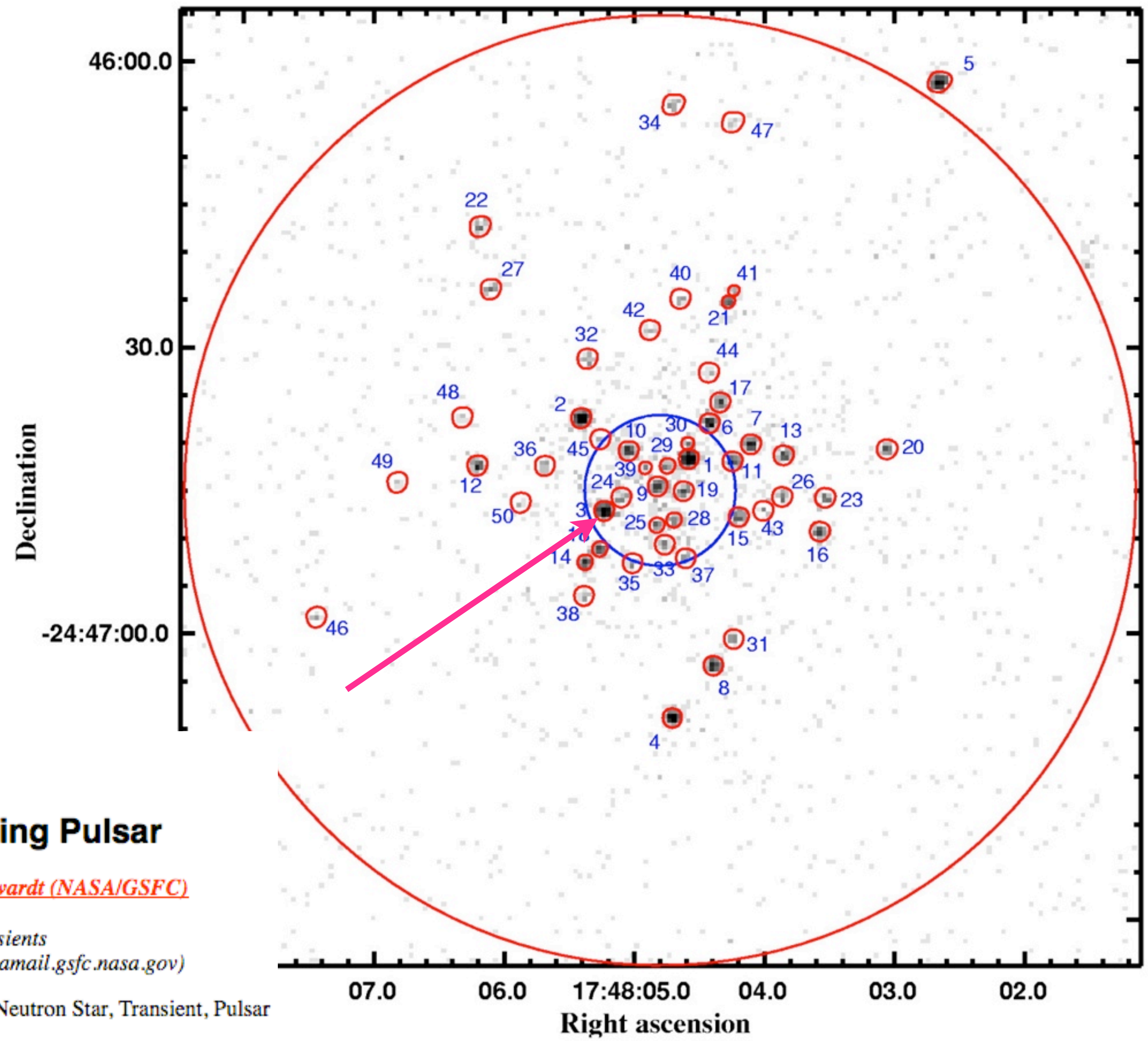
photospheric line spectroscopy:

focus on X-ray bursts:
non-magnetic; metals should be present in photosphere

target selection:
a slow-spin NS, or a
low-inclination binary, or
try to spin-phase resolve the bursts

slow-spin bursting neutron star

we know of *one*: source X-3 in the globular cluster Terzan 5;
but it is transient



Heinke et al. (2006)

[Previous | Next | ADS]

EXO 1745-248 is an 11 Hz Eclipsing Pulsar

ATel #2929; *T. E. Strohmayer (NASA/GSFC), C. B. Markwardt (NASA/GSFC)*
on 13 Oct 2010; 05:29 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Craig B. Markwardt (craigm@lheamail.gsfc.nasa.gov)

Subjects: X-ray, Request for Observations, Binary, Globular Cluster, Neutron Star, Transient, Pulsar

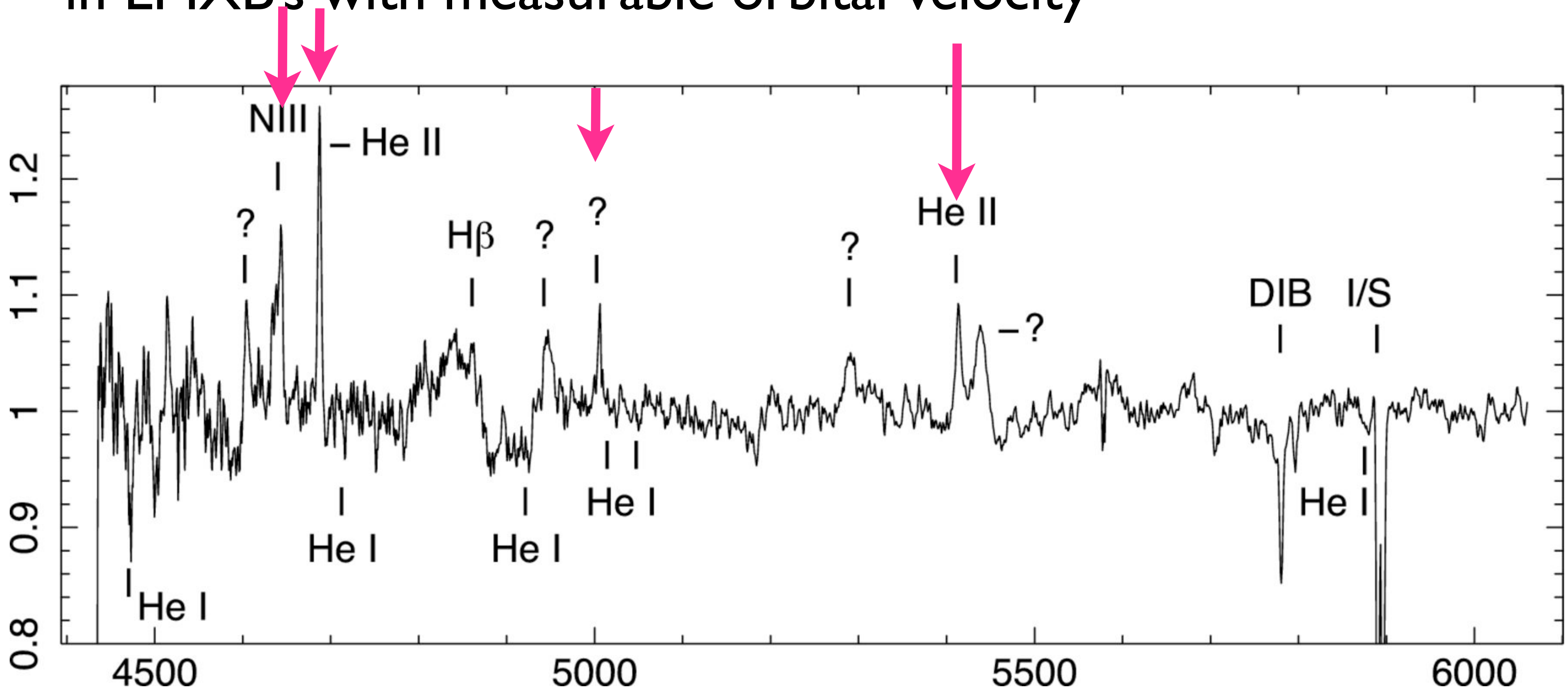
Referred to by ATel #: 2932, 2933, 2939, 2940, 2946, 2952, 2958, 2974, 3000, 3044, 3264, 3714, 3892

Tweet 0 Recommend 0

RXTE pointed observations of the ongoing outburst of EXO 1745-284 (ATEL #2919, #2920, #2922, #2924) began at approximately 2010-10-13 at 00:13 UTC, for an exposure of 3.2 ksec. The flux of the source is approximately 95 mCrab (2-10 keV). The observation reveals strong pulsations at a barycentric frequency of 11.0452(2) Hz.

a low-inclination binary

recent progress in optical spectroscopy finds narrow lines in LMXB's with measurable orbital velocity



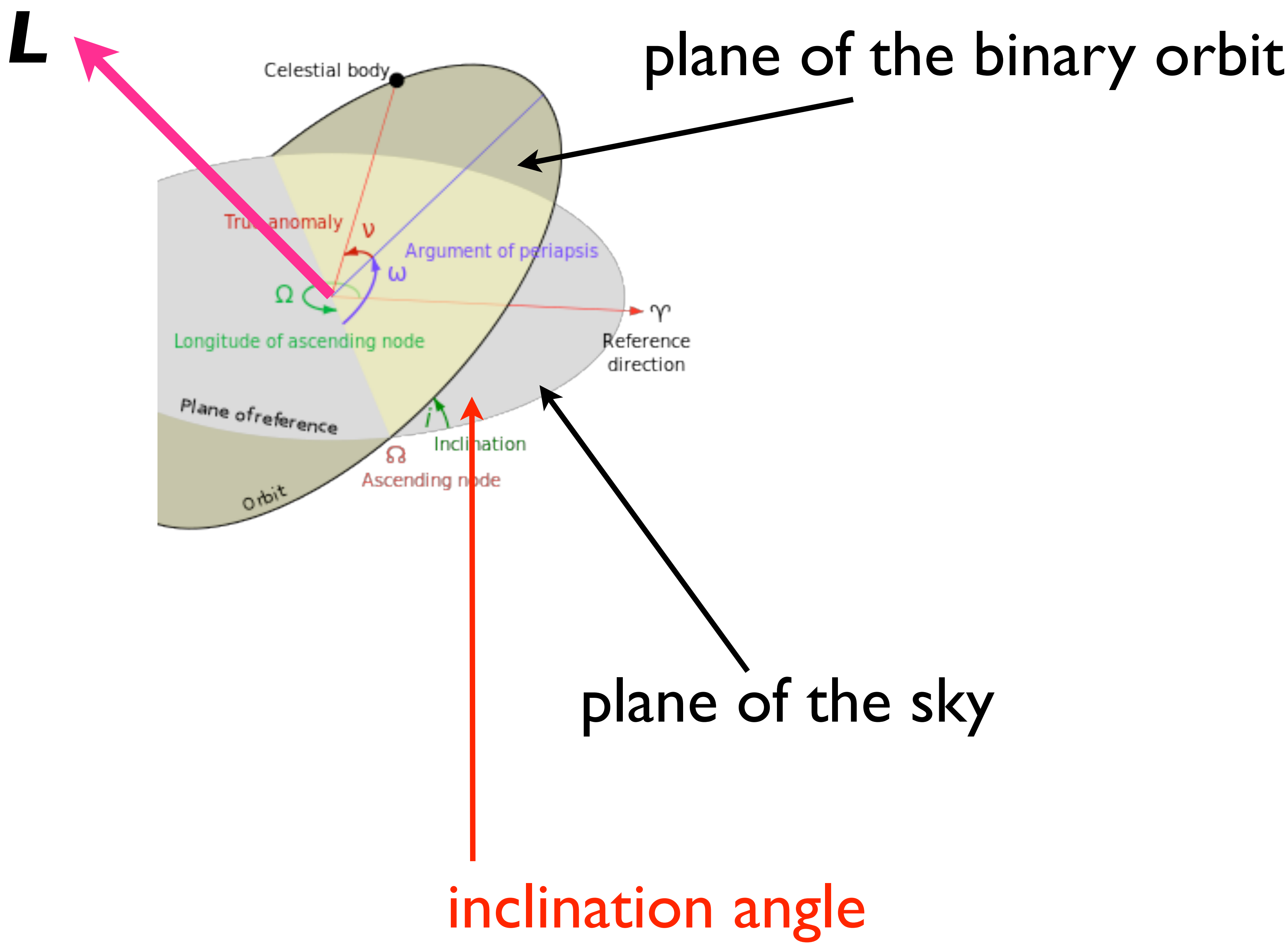
Example: Ser X-1:

narrow lines reveal binary period (2.2 hrs), and:

radial velocity amplitude very small, so: $i < 10^\circ$!!

(Cornelisse et al. 2013)

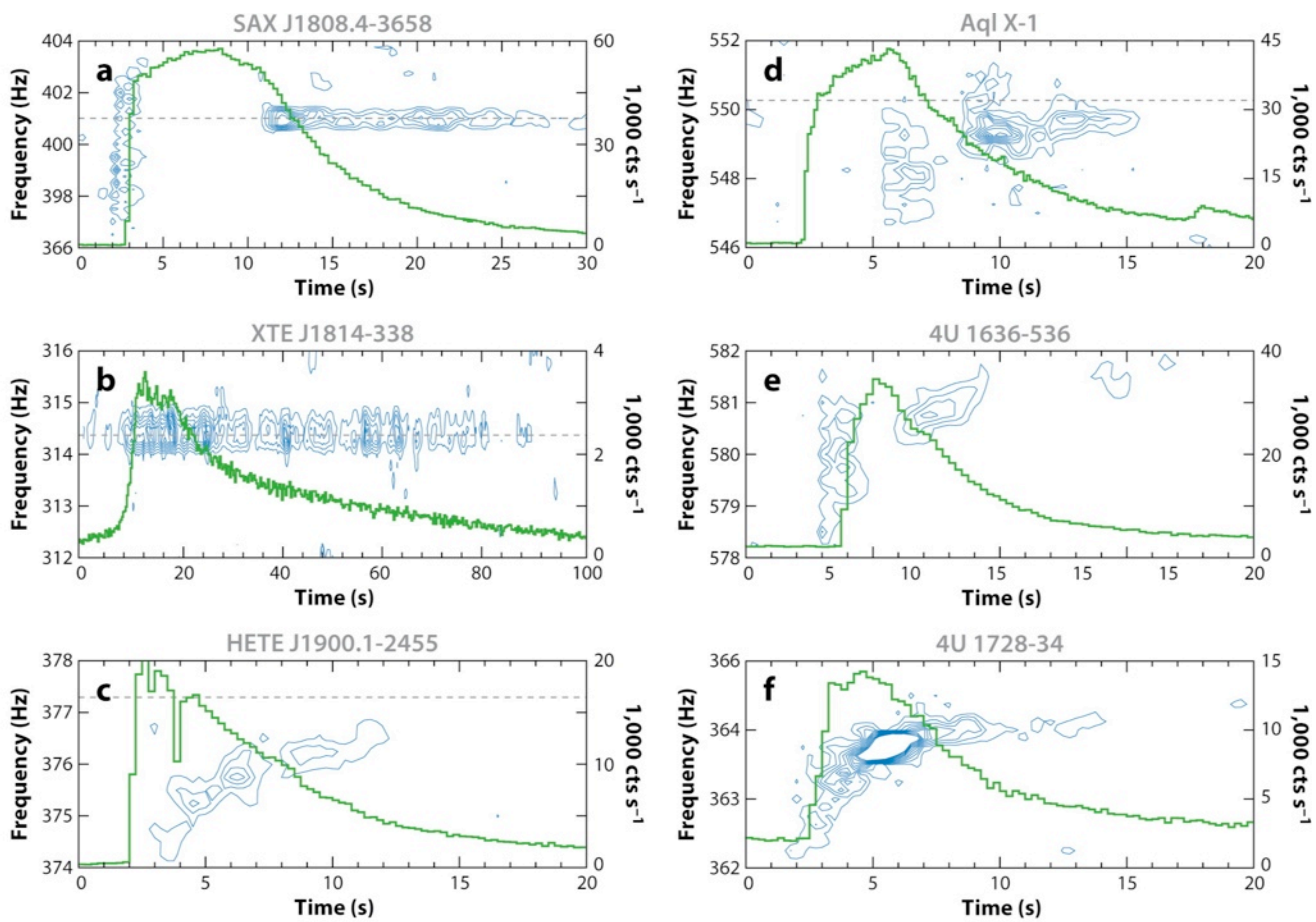
a low-inclination binary



low inclination means: neutron star seen nearly pole on

spin phase resolution:
either continuum or line: Doppler shifts

emission during early burst phases often spin-modulated



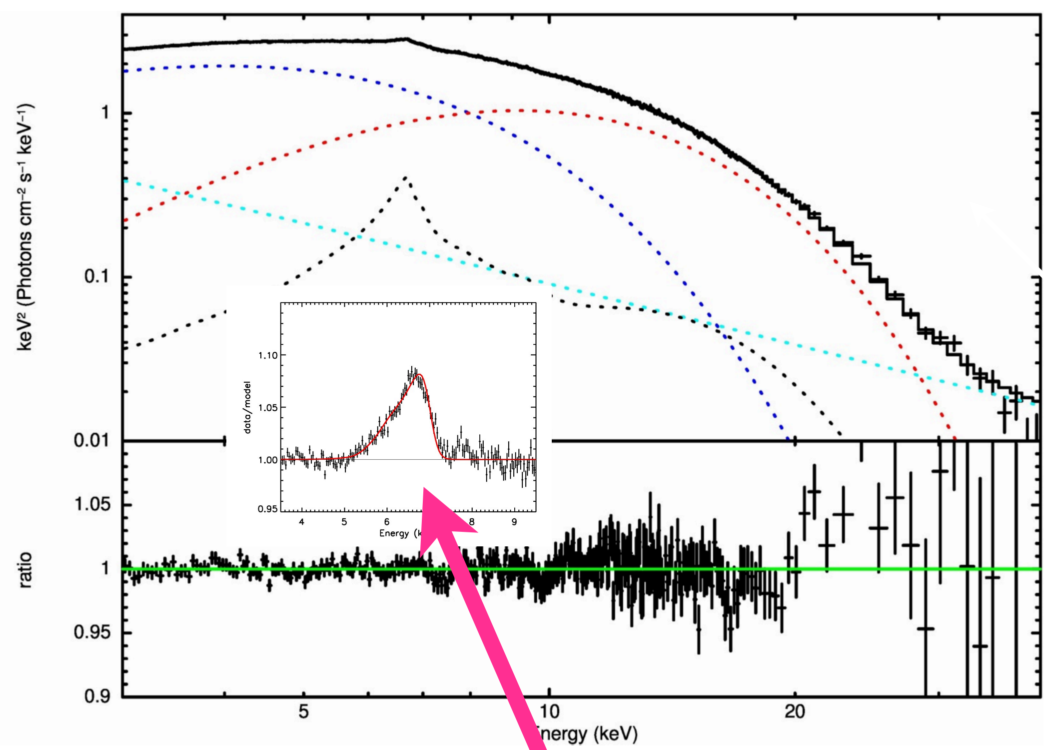
Watts AL. 2012.
Annu. Rev. Astron. Astrophys. 50:609–40

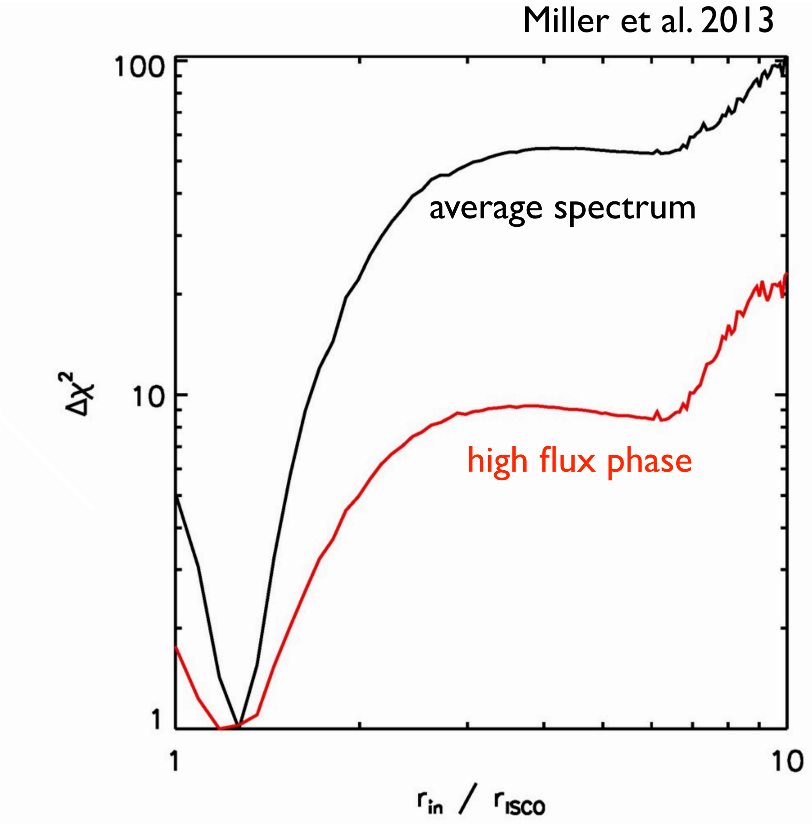
need ~100 microsecond time resolution

what about using spectroscopy of the accretion flow?

slide from presentation by Jon Miller (U Michigan)

NuSTAR: Serpens X-1



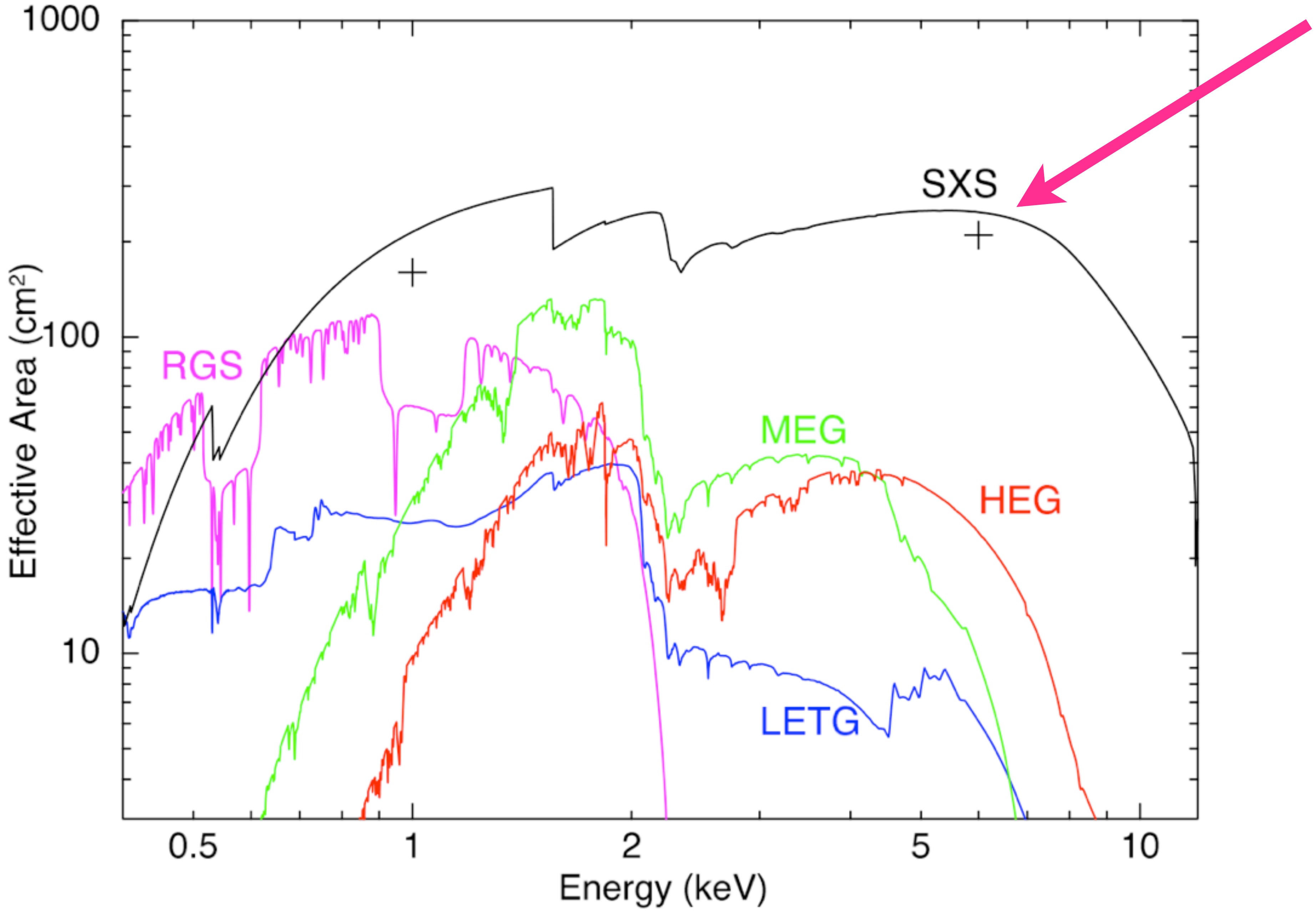


Excellent fit with reflection.
Disk illumination by blackbody.
Gaussian ruled out > 5σ
No pile-up.

$R \leq 7.8\ GM/c^2$
$z \geq 0.16$
$R \leq 6\ GM/c^2 = 12.6$ km
$z \geq 0.22$

relativistically broadened Fe K

for all of the above ideas:
need lots of photons, and possibly
high time resolution (sub-msec)



compare the collecting areas for the current grating spectrometers with that of the Astro-H microcalorimeter, especially above 2keV!

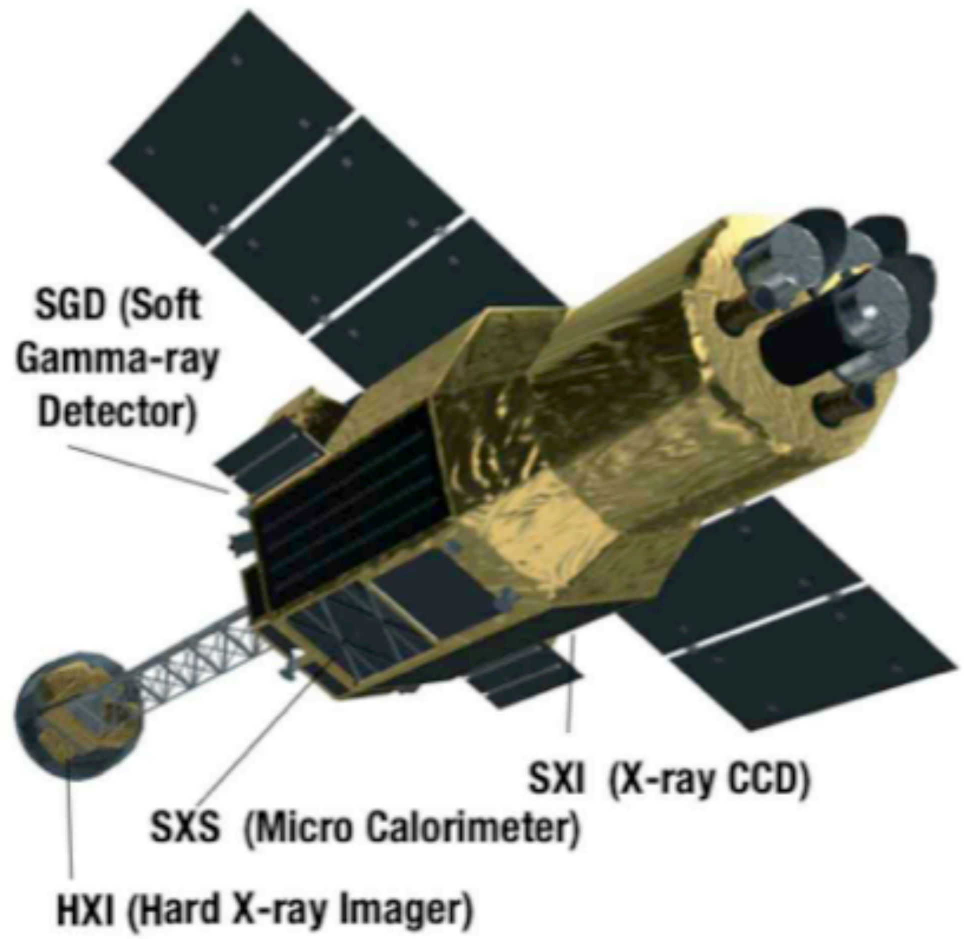
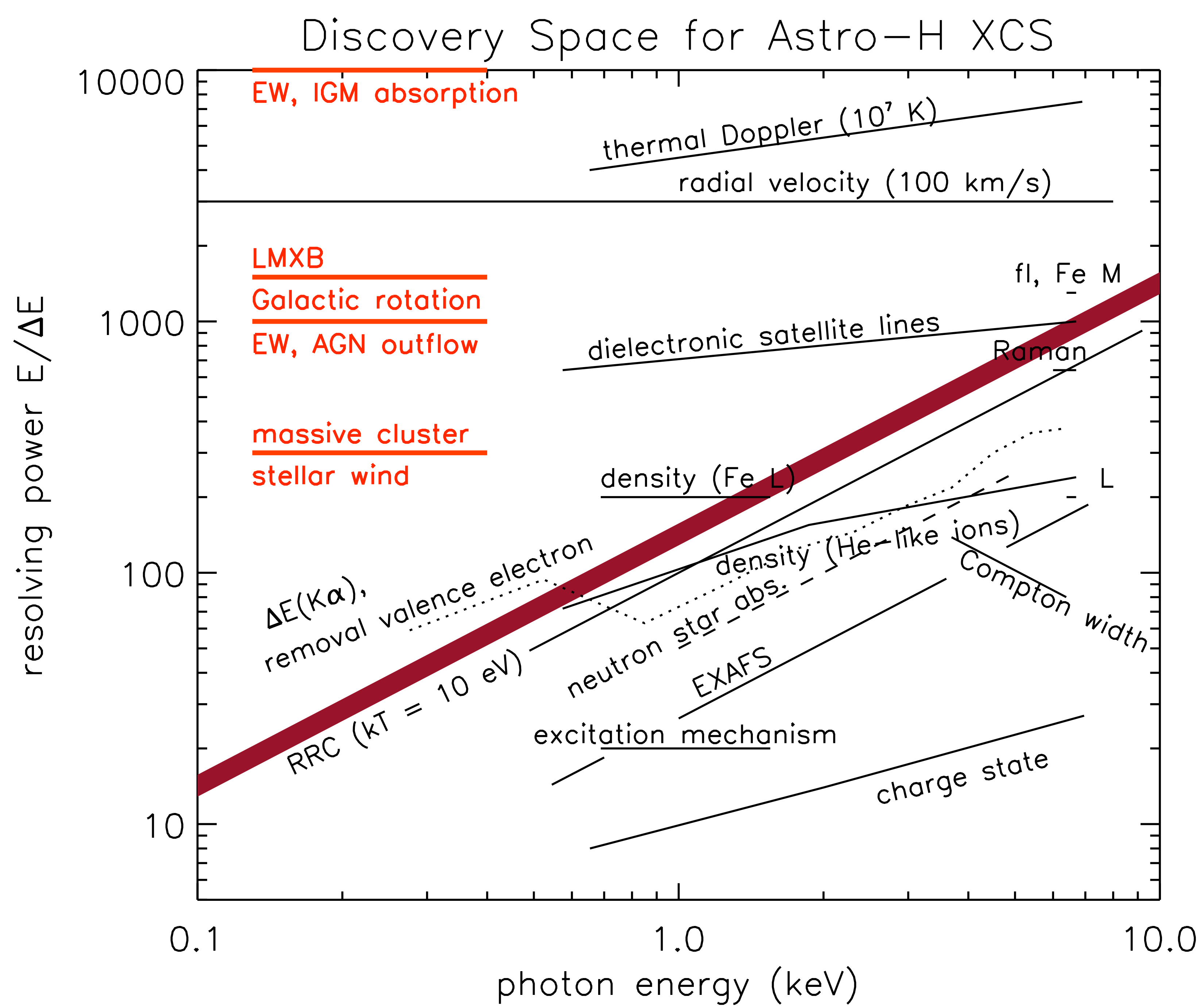


Figure 1. Schematic view of the ASTRO-H satellite. The total mass at launch will be ~ 2700 kg. ASTRO-H will be launched into a circular orbit with altitude of 500 – 600 km, and inclination of ~ 31 degrees.

Table 1. ASTRO-H Mission

Launch site	Tanegashima Space Center, Japan
Launch vehicle	JAXA H-IIA rocket
Orbit Altitude	~550 km
Orbit Type	Approximate circular orbit
Orbit Inclination	~ 31 degrees
Orbit Period	96 minutes
Total Length	14 m
Mass	~ 2.7 metric ton
Power	< 3500 W
Telemetry Rate	8 Mbps (X-band QPSK)
Recording Capacity	12 Gbits at EOL
Mission life	> 3 years

reference: Takahashi et al., http://arxiv.org/abs/1210.4378 also note: grating spectrometers rely on CCD readout (4 sec integration time!)



the resolving power of the µCalorimeter also favors E > 2 keV

Astro-H and the Soft X-ray Spectrometer (SXS)

detection principle:

photon energy > directly to heat

$$\Delta T = E_\gamma / c_\mathrm{V}$$

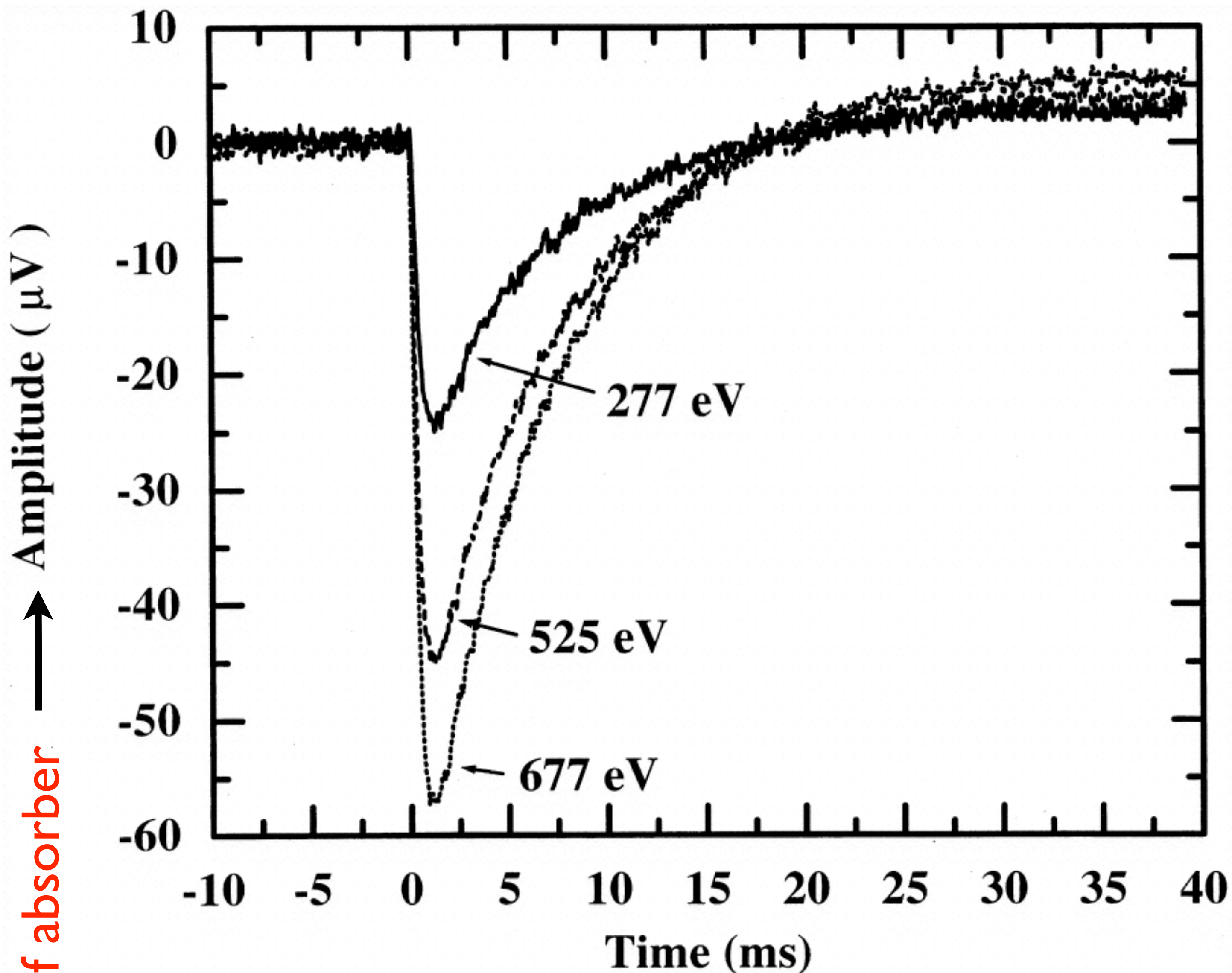
T-jump large if c_V small:

(1) small mass

(2) very low *T*!!

(heat capacity of solids collapses below Debye temperature)

single photon event: heat is deposited and leaks away to 'bath'



tracks temperature of absorber

noise level: spontaneous heat exchange with bath

from the X-ray Quantum Calorimeter experiment; McCammon et al. 2002

Stat Mech/ Canonical Ensemble: $$\Delta E^2 = kT^2 \frac{\partial < E >}{\partial T}$$

make this very small, at low *T*! (QM)

leads to nearly constant energy resolution, ΔE

practical implementation for Astro-H: 4-5 eV resolution
future large observatories: <1 eV

note: make imaging arrays
thermal relaxation timescale sets count rate limit,
now ~ 10 msec; but t-resolution ~5 μsec

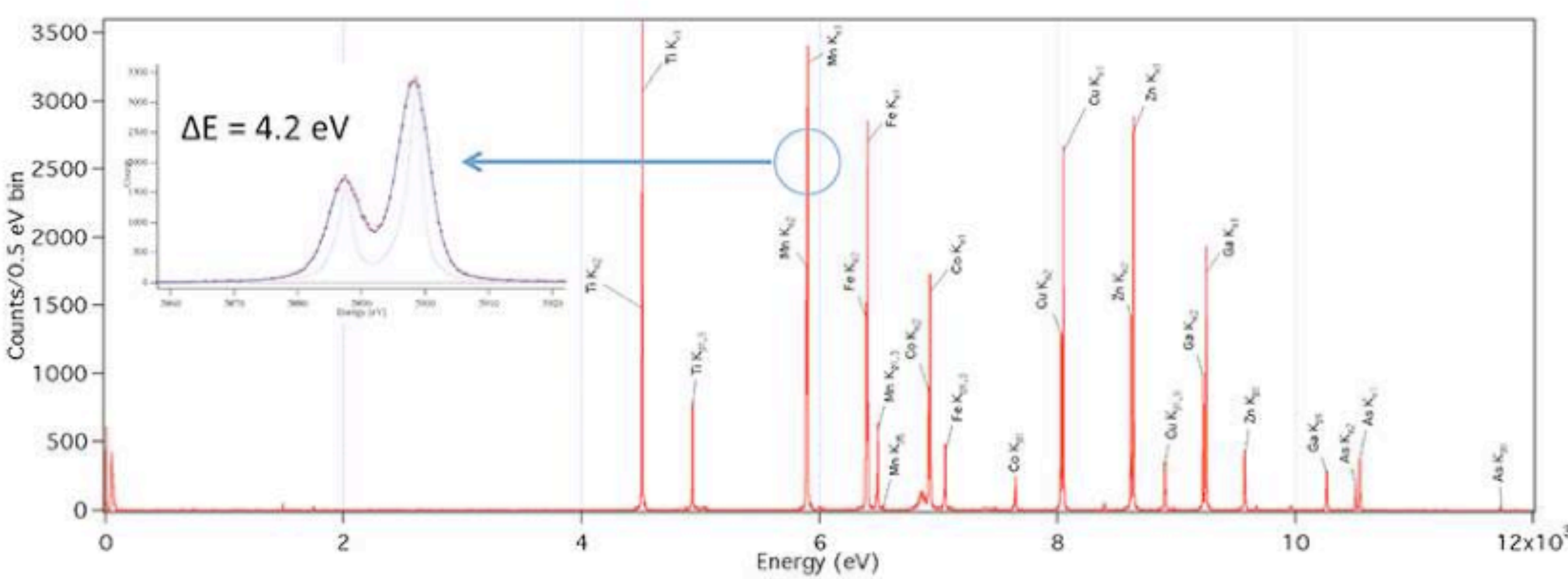


Figure 4. Laboratory X-ray spectrum obtained with the Astro-H Soft X-Ray Spectrometer engineering model detector assembly. The spectrum shows the enormous spectral dynamic range that can be obtained. The spectral resolution is 4.2 eV over the entire array, and is achieved over the full energy range where astrophysically abundant atomic transitions will be detected (less than about 8 keV), providing a resolving power of about about 1400 at 6 keV. The required resolution is 7 eV.

Takahashi et al. 2012

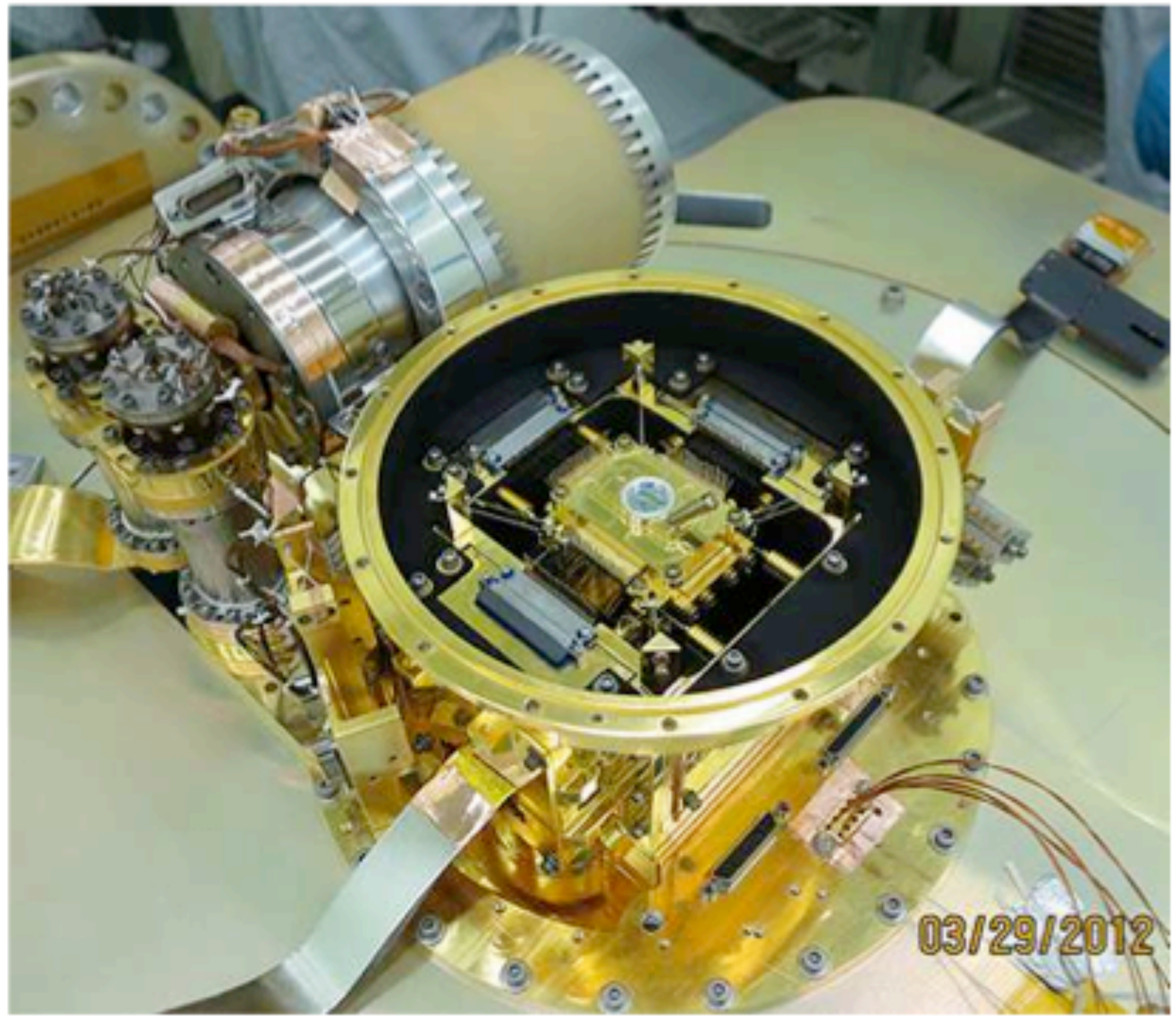


Figure 3. The SXS engineering model detector assembly. At the center of the assembly is the x-ray calorimeter housing. This is suspended from the outer structure using Kevlar, and electrical connections to the housing are made using tensioned wires to reduce the sensitivity to microphonics. At the center of the calorimeter housing is an aluminum/polyimide blocking filter and a ^{55}Fe calibration source used to illuminate a dedicated calibration pixel for monitoring the absolute gain. The overall assembly is about 12.7 cm in diameter.

Takahashi et al. 2012

Table 2. Key parameters of the ASTRO-H payload

Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ-ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm^2@30 keV	210 cm^2@6 keV 160 cm^2 @ 1 keV	360 cm^2@6 keV	>20 cm^2@100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.5 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	$<$ 7 eV (@6 keV)	$<$ 200 eV (@6 keV)	$<$ 4 keV (@60 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	$\sim 9 \times 9$ $arcmin^2$	$\sim 3 \times 3$ $arcmin^2$	$\sim 38 \times 38$ $arcmin^2$	0.6×0.6 deg^2 ($<$ 150 keV)
Time resolution	25.6 μs	5 μs	4 sec/0.1 sec	25.6 μs
Operating temperature	$-20^{\circ}C$	50 mK	$-120^{\circ}C$	$-20^{\circ}C$

this we may be able to do with the SXS on Astro-H

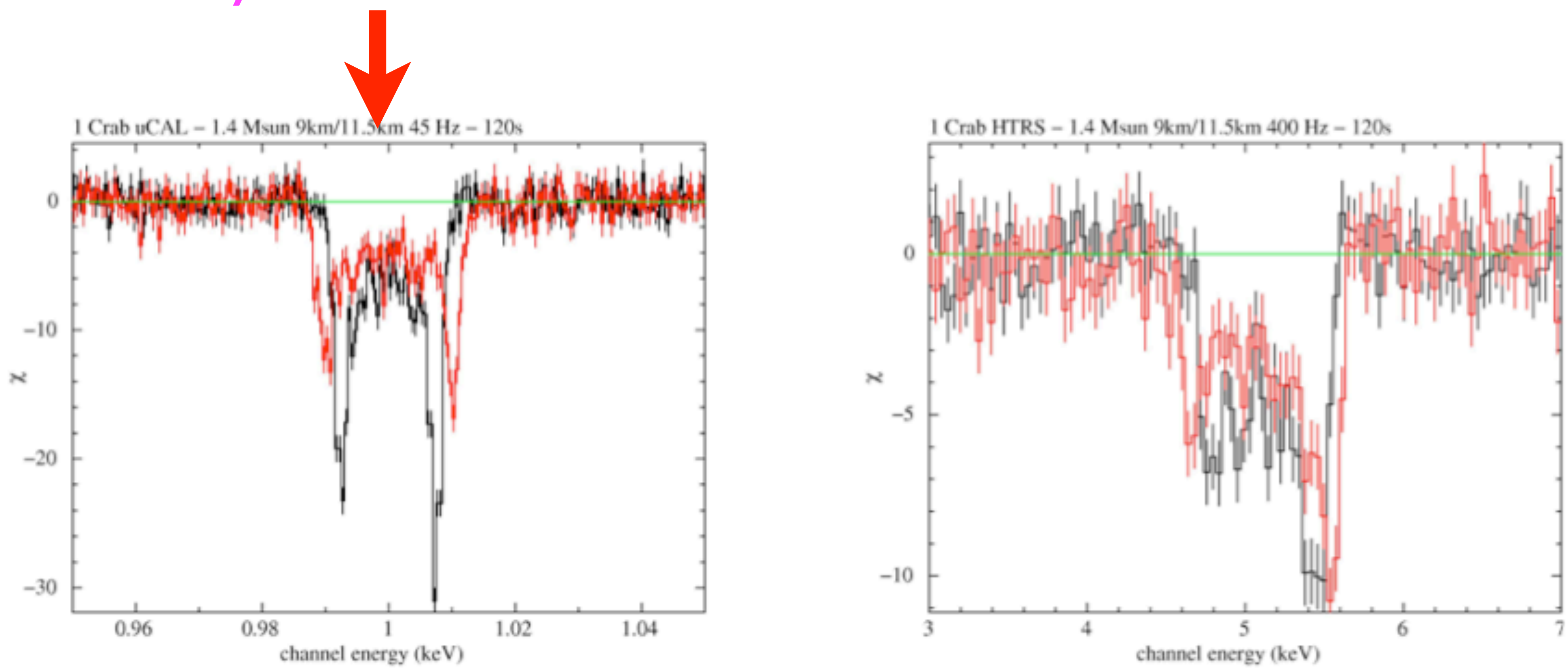
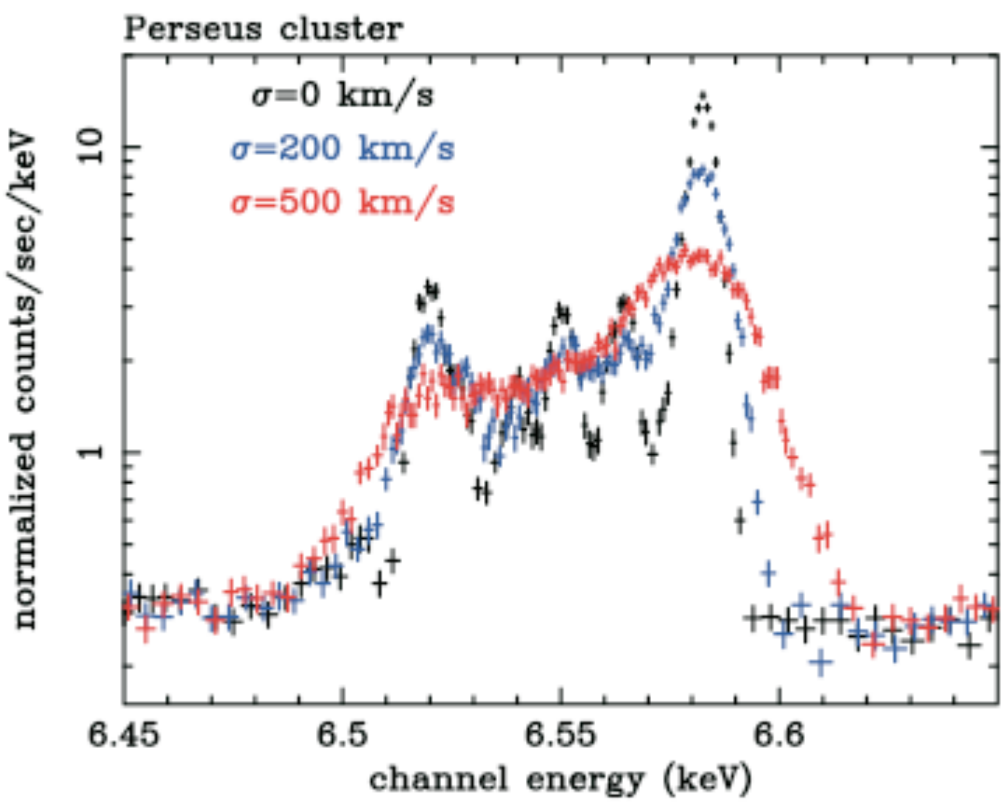


Figure 3: **High resolution X-ray spectroscopy of the photospheric emission of a hot neutron star is sensitive to the fundamental stellar parameters**, through the effects of pressure broadening, relativistic kinematics (rotation, Doppler shift, time dilation, beaming), and general relativity (light bending around the star, gravitational redshift, frame dragging) on atomic absorption lines (Özel and Psaltis 2003; Bhattacharyya, Miller, and Lamb 2006). The absorption line spectrum of a $1.4 M_\odot$ neutron star, spinning at 45 Hz, showing the effects of rotational Doppler-splitting, observed at 2 eV spectral resolution (*left panel*), in 120 sec of exposure of a moderately bright X-ray burst with the microcalorimeter spectrometer as envisioned for the *IXO* mission. Black and red histograms refer to a star with a radius of 9 and 11.5 km, respectively. Emission is concentrated in a hot equatorial belt, seen at 5 degree inclination. The absorption line is Fe XXVI Hα. **High time resolution spectroscopy can phase-resolve the Doppler broadening** of a rapidly spinning star (400 Hz) if the surface emission is azimuthally asymmetric. With $\sim$ 100 eV energy resolution, and sub-msec time resolution (such as for the fast timing instrument on *IXO*), the Doppler profiles *in the right hand panel* will be phase-resolved, allowing unambiguous determination of the line broadening mechanism, and an absolute radius measurement (Fe XXVI Lyα; same stellar parameters as before).

from a White Paper submitted to NRC/NAS Decadal Survey (Paerels et al. 2010)

two examples from other fields (simulated)



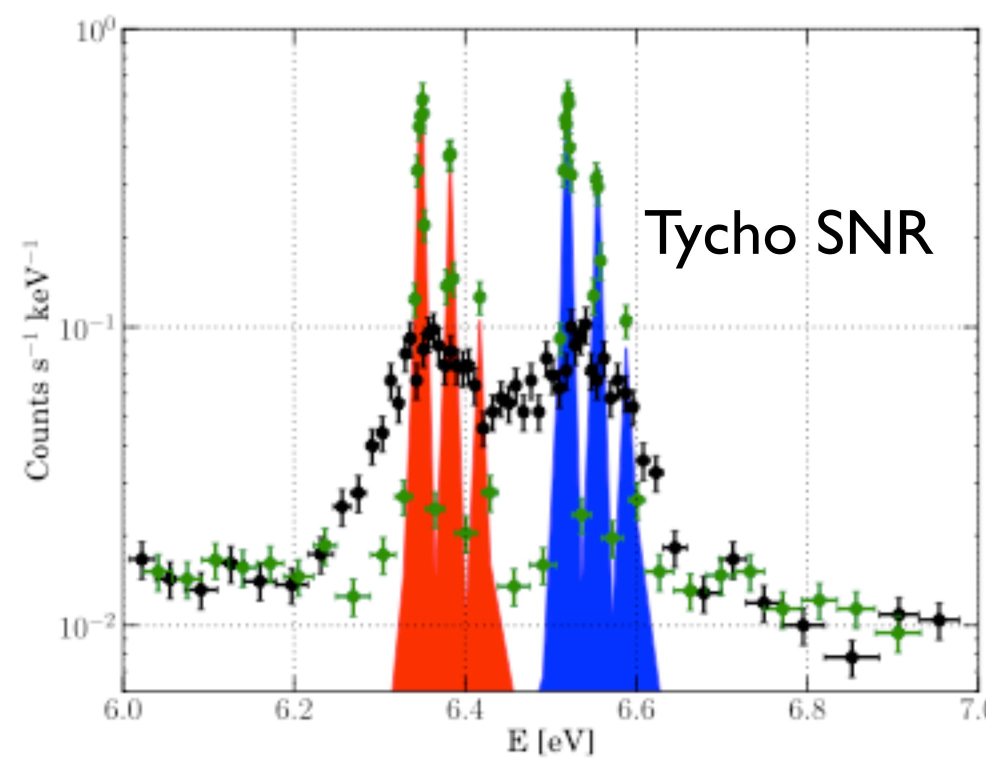
measuring the turbulent velocity field in the intracluster gas

(check on hydrostatic equilibrium, measure gravitational potential to measure total cluster mass- important cosmological data)

measure the thermal Doppler widths as a function of atomic mass behind supernova remnant shocks

(check on post-shock e/i equilibration; physics of collisionless shocks)

$$kT_i = \frac{1}{2} M_i v_{\rm shock}^2 \ ? \rightarrow kT_e?$$



some final thoughts about NS spectroscopy

we should try everything!
strive towards multiply redundant techniques
detailed line spectroscopy can do that:
- gives gravitational redshift (M/R)
- spin-broadening: Doppler (R if spin known)
- GR effects (M/R) modify line shape
- pressure broadening: log g (M/R^2)

multiple lines in same series break degeneracies
combine with continuum shape, spindown rate, etc.
find best targets! (exceptionally difficult problem)

And with Astro-H we may have the first chance to do this!