Stellar X-ray astronomy: The last three decades

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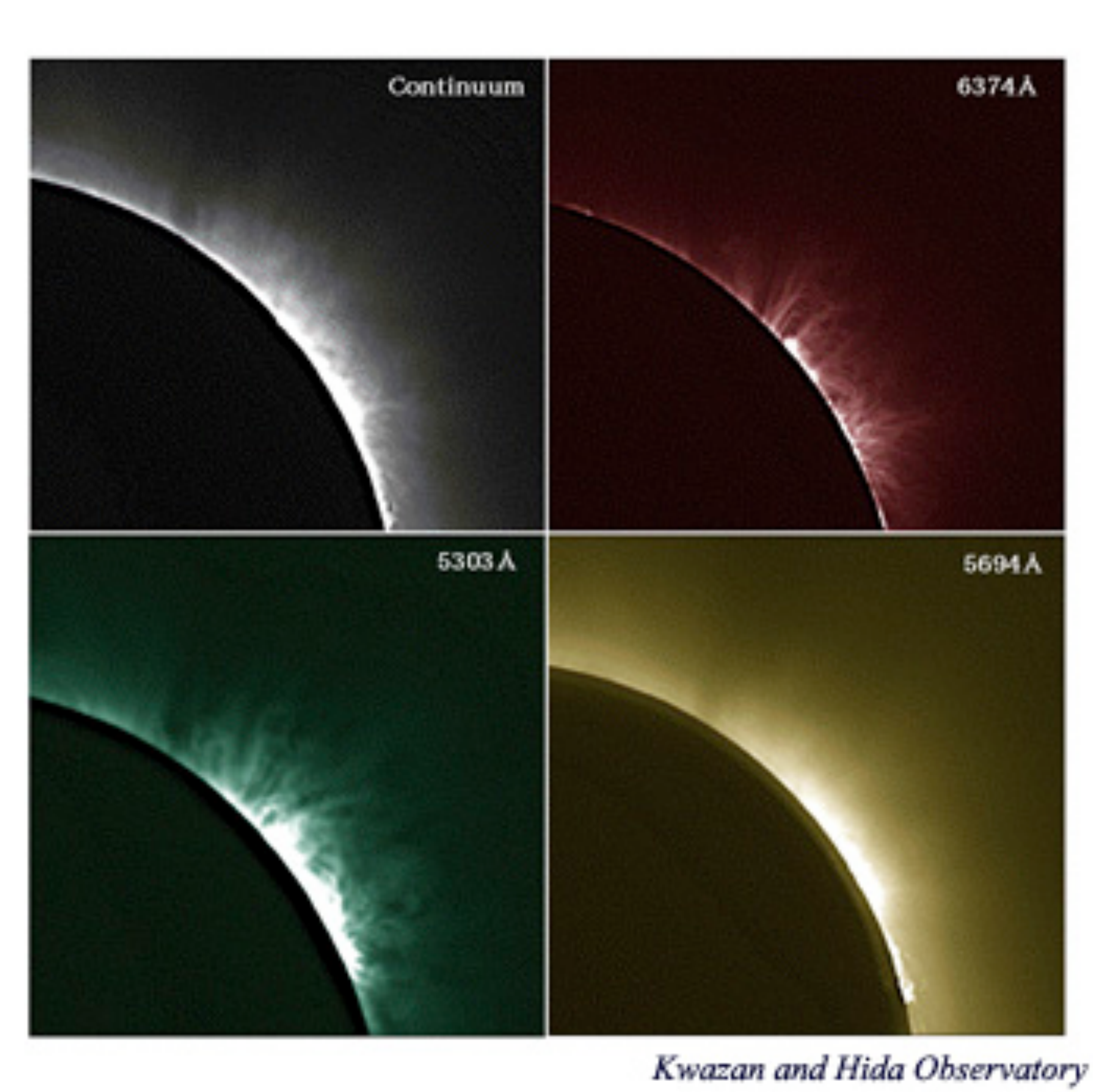
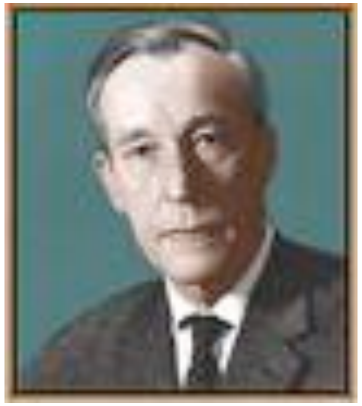
X-ray school Palermo
May 18 2009

Outline:

- The solar corona
- Einstein and ROSAT: X-ray emission throughout the HR-diagram
- XMM-Newton and Chandra: Plasma diagnostics of stellar coronae


Continuum
6374 Å
5303 Å
5694 Å
Kwazan and Hida Observatory

B. Edlen, MNRAS, 1945, 105, 323



THE IDENTIFICATION OF THE CORONAL LINES

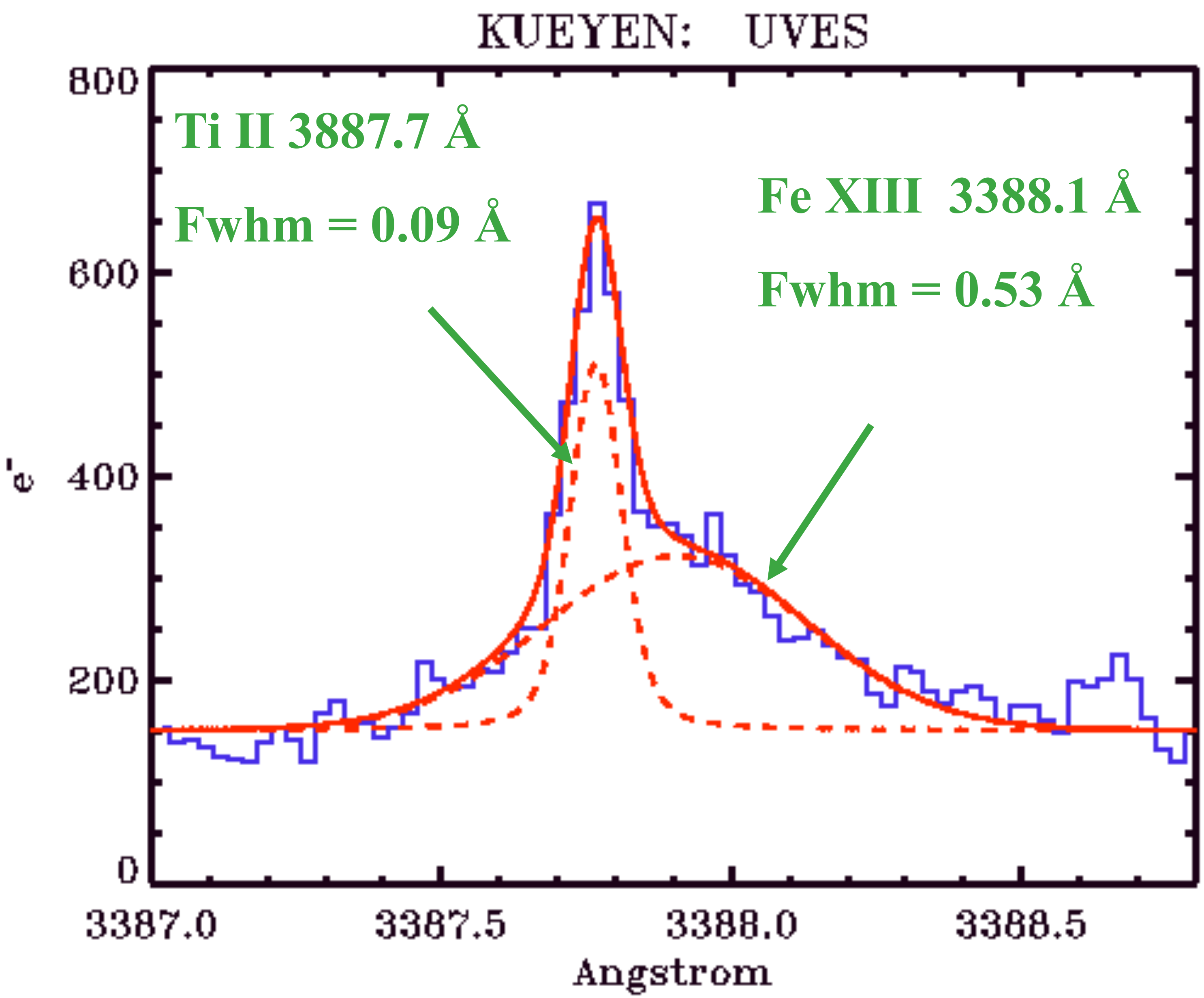
(*George Darwin Lecture, delivered by Professor Bengt Edlén on* 1945 *October* 12)

The coronal emission lines are superimposed on the continuous radiation of the inner parts of the solar corona, the region of their appearance extending from the top of the chromosphere to a height generally not exceeding 10 minutes of arc (half a million kilometers) from the Sun's limb. The lines are responsible for only a small fraction of the total intensity of the corona.

the infra-red part of the spectrum. At present, as a net result of all observations, the wave-lengths of some twenty coronal emission lines have been established. Six of these lines are much stronger than the rest. These conspicuous lines are: λ 3388, λ 5303, λ 6374, λ 7892, λ 10747 and λ 10798. None of the coronal lines has been observed in a laboratory light-source and there is no real coincidence with any of the Fraunhofer lines nor with any line in the chromospheric spectrum. The coronal lines were in fact a unique feature of the solar corona until in 1932

the spectrum of the recurrent nova RS Ophiuchi. Recently the coronal lines have

CN Leo: M6.5: Schmitt et al. (2001)

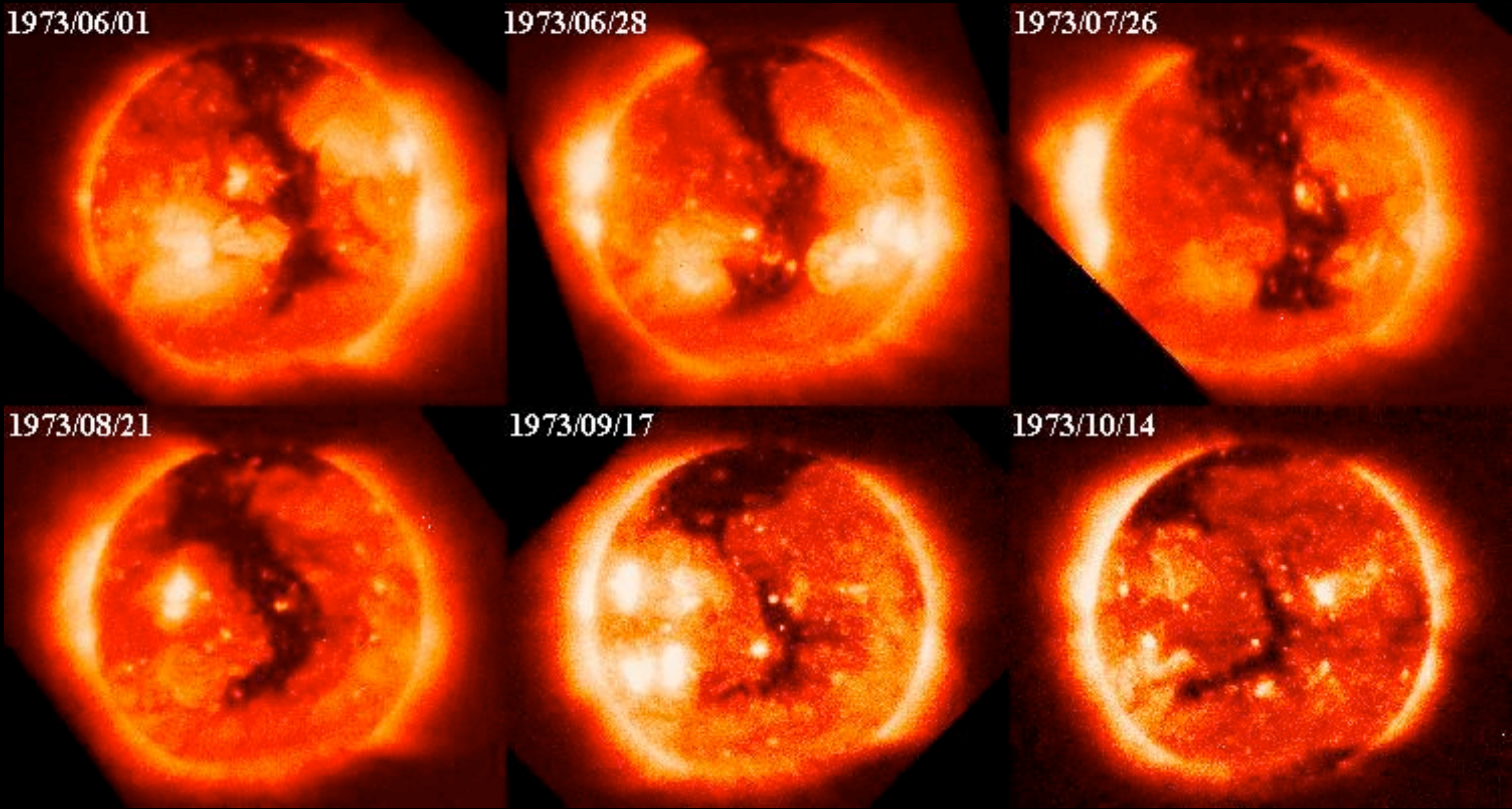


H. Friedman

R. Giacconi

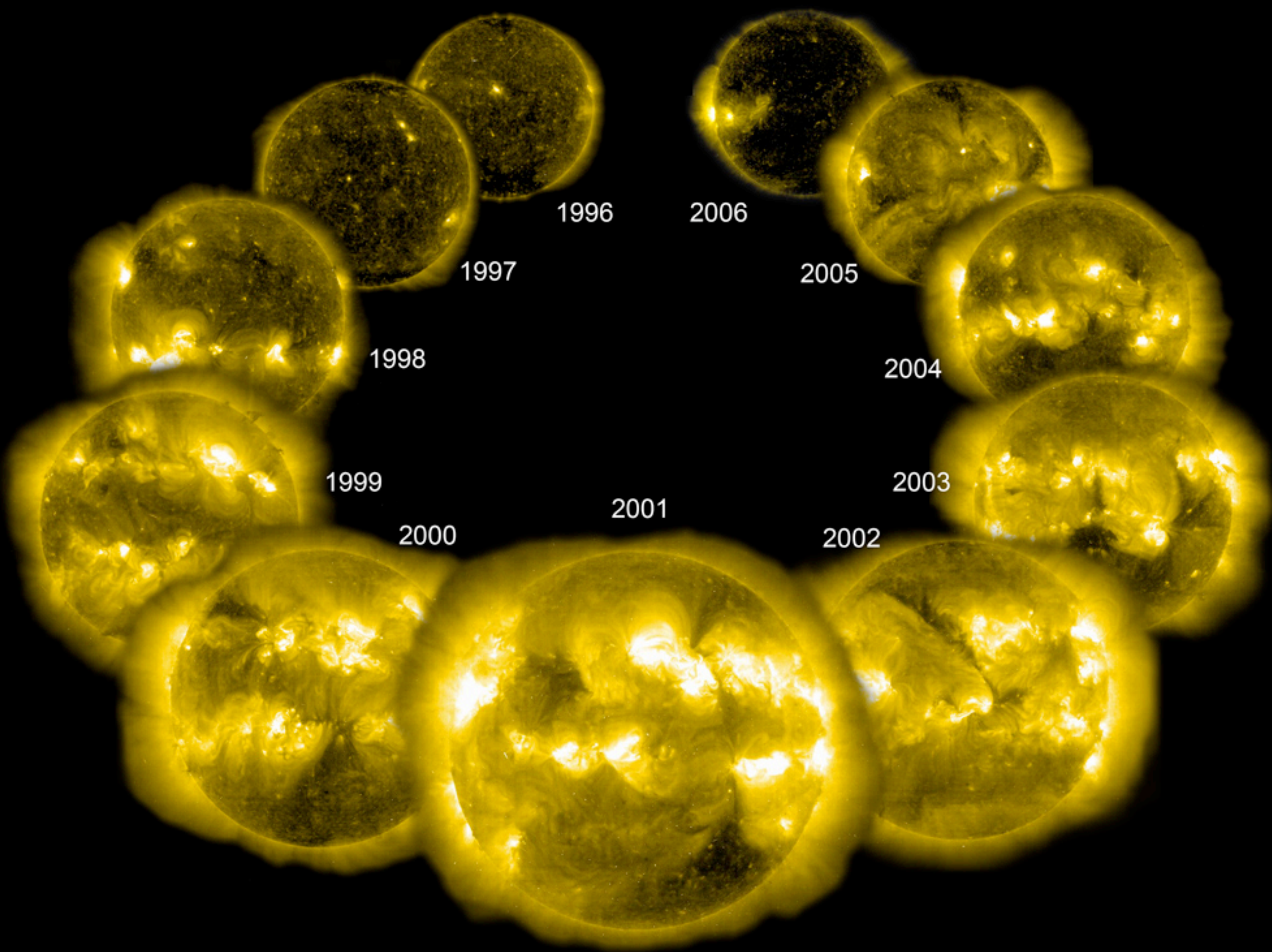
Skylab 1973

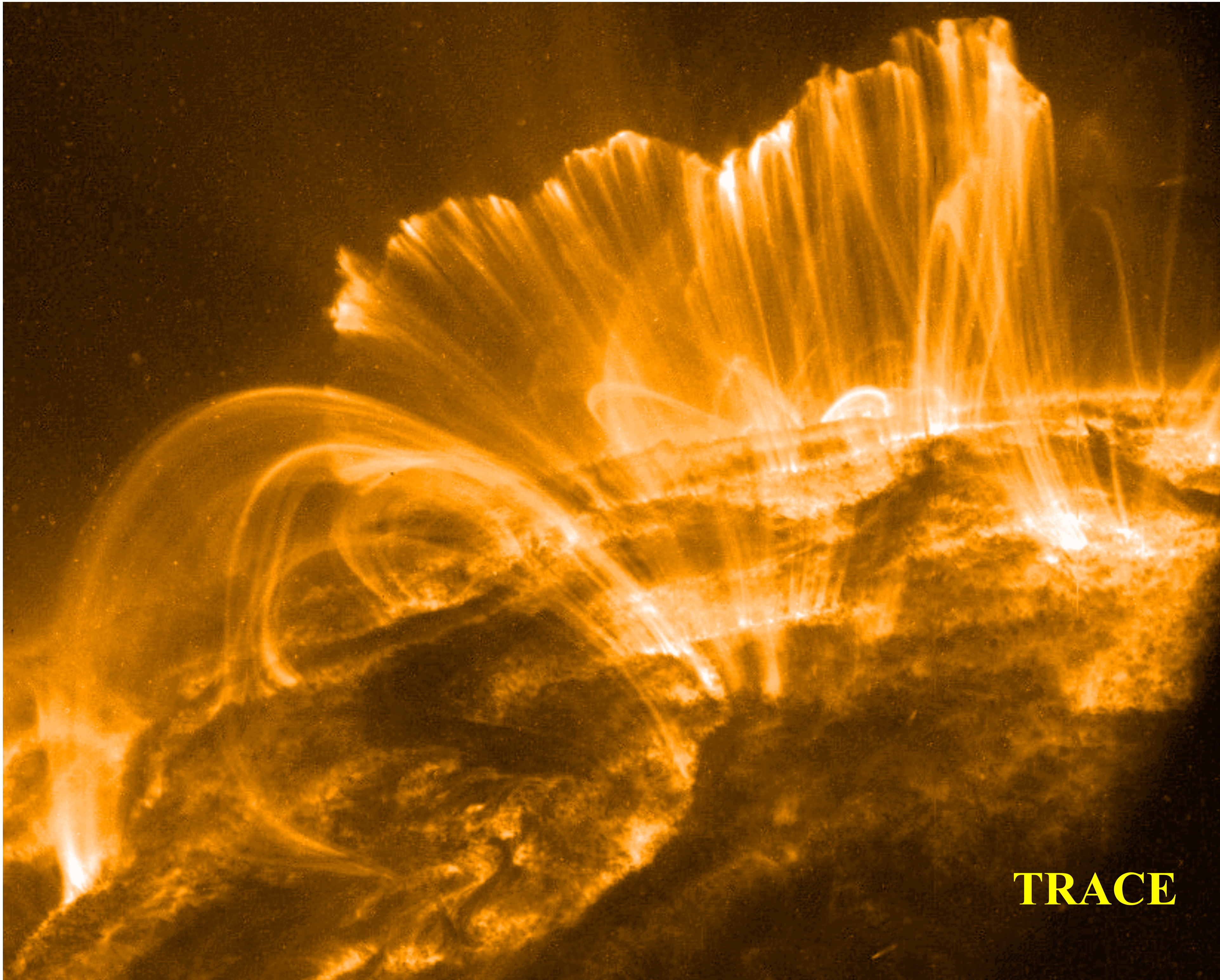
The X-ray Sun



Skylab

The SOHO Sun




TRACE

Solar corona: Why care ?

Existence	Heating problem	⬅
Structure	Magnetic field	⬅
Energy loss	Thermal emission	⬅
Variability (flares, active region evolution, cycles)	Instability of field configuration	⬅

➡ Is the Sun a prototype for other stars/other astrophysical systems ?

Detectability of stellar coronae:

- X-rays
- radio
- optical

The Sun as an X-ray source

$L_x = 2 \times 10^{27}$ erg/sec

Placed at a distance of 10 pc:

$f_x = 1.8 \times 10^{-13}$ erg/sec/cm^2

Sensitivity limit of ROSAT all sky-survey:

$f_{x,lim} \sim 2 \times 10^{-13}$ erg/sec/cm^2

CCD X-ray spectrum of the Sun (it is actually Altair)

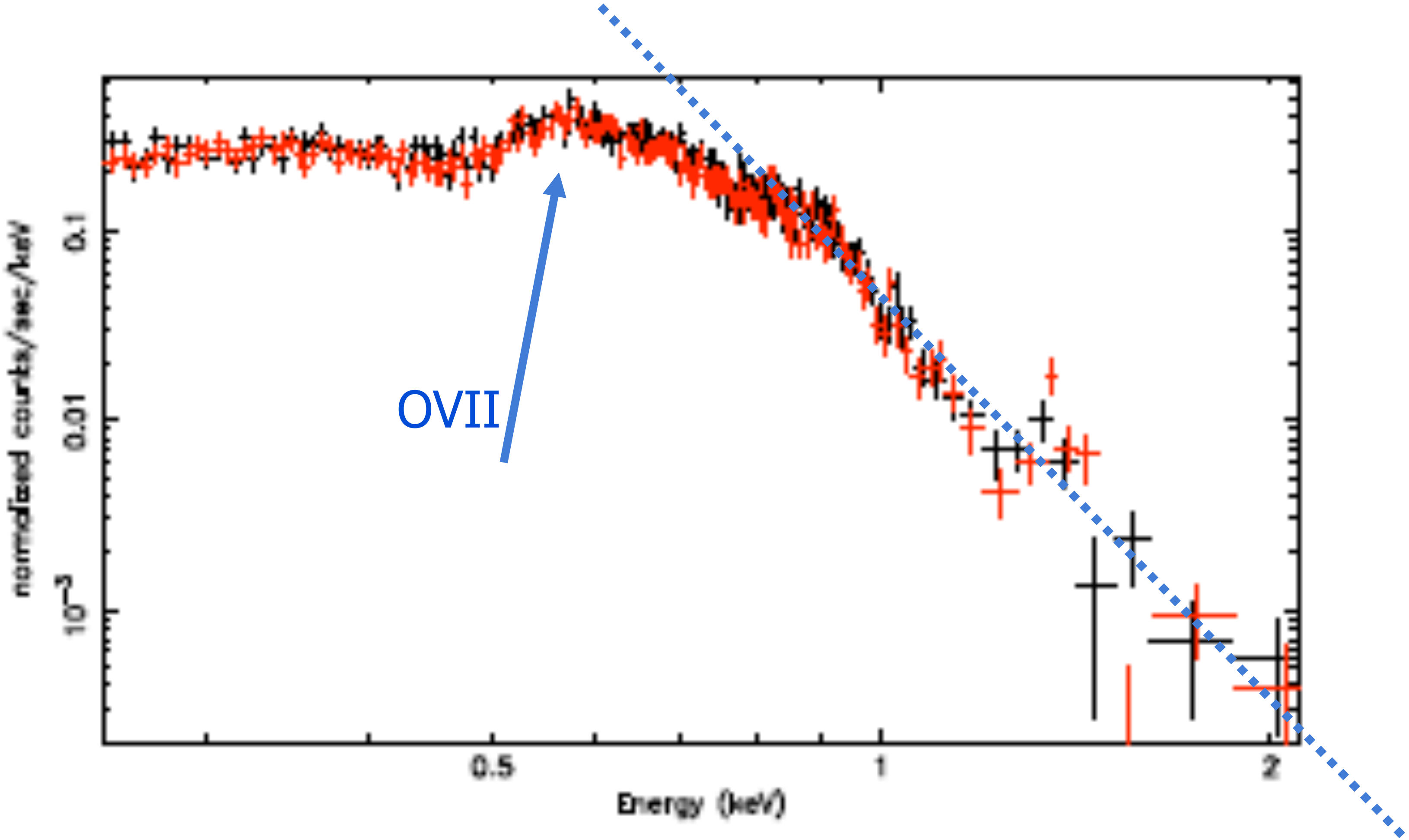


Fig. 3. EPIC PN spectra of the two observations. The spectra are very similar and are dominated by rather cool X-ray emitting plasma

Robrade et al. (2009)

Capella !

THE ASTROPHYSICAL JOURNAL, 196:L47–L49, 1975 March 1

EVIDENCE FOR X-RAY EMISSION FROM CAPELLA

R. C. CATURA, L. W. ACTON, AND H. M. JOHNSON
Lockheed Palo Alto Research Laboratory
Received 1974 November 7; revised 1974 December 5

ABSTRACT

X-ray emission in the range from 0.2 to 1.6 keV has been detected from an area of the sky which contains the binary star system Capella. The X-ray source is at most a few arc minutes in extent and shows no spectral turnover at low energy, consistent with a nearby source. We suggest Capella as the source of this emission and that this object belongs to a new class of galactic X-ray sources with a luminosity of 10^{31}–10^{34} ergs s^{-1}. Emission from this class of objects is variable, predominantly below 2 keV, and originates from nearby stellar objects.

Subject headings: spectra, X-ray — stars, individual — X-ray sources

Vega !

THE ASTROPHYSICAL JOURNAL, **229**:661–668, 1979 April 15

DETECTION OF SOFT X-RAYS FROM α LYRAE AND η BOOTIS WITH AN IMAGING X-RAY TELESCOPE

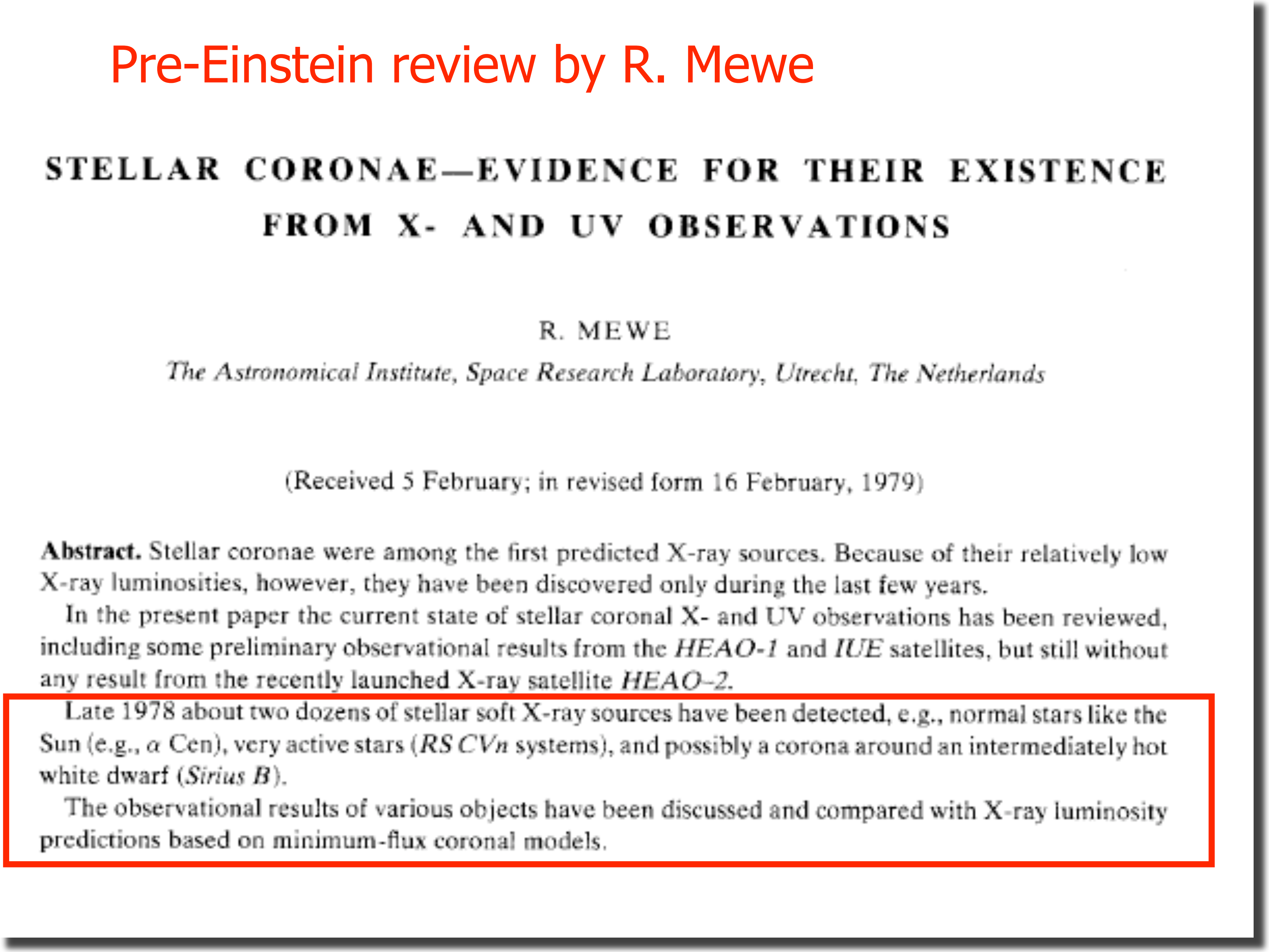
K. TOPKA, D. FABRICANT, F. R. HARNDEN, JR., P. GORENSTEIN, AND R. ROSNER
Harvard-Smithsonian Center for Astrophysics
Received 1978 October 2; accepted 1978 October 24

ABSTRACT

Two nearby stars have been detected in the soft X-ray band with an imaging X-ray telescope flown aboard two sounding rockets. The exposure times were 4.8 and 4.5 s for the images of the A0 V star α Lyrae (Vega) and the G0 IV star η Bootis, respectively. Laboratory measurements rule out the possibility that the observed signals were due to UV contamination. These X-ray observations imply luminosities of $L_X(0.2\text{–}0.8 \text{ keV}) \approx 3 \times 10^{28}$ ergs s^{-1} for Vega and $L_X(0.15\text{–}1.5 \text{ keV}) \approx 1 \times 10^{29}$ ergs s^{-1} for η Boo. A coronal interpretation of the X-rays from Vega is in serious conflict with simple convective models for early-type main-sequence stars. Magnetic field activity may be responsible for heating the corona, as has been suggested for the Sun. In the case of η Boo, a coronal interpretation is also favored; however, if the unseen companion of η Boo is degenerate, the X-ray emission may instead originate in a stellar wind accreting upon a white dwarf or neutron star.

Subject headings: stars: coronae — stars: individual — X-rays: sources

Pre-Einstein review by R. Mewe



STELLAR CORONAE—EVIDENCE FOR THEIR EXISTENCE FROM X- AND UV OBSERVATIONS

R. MEWE

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(Received 5 February; in revised form 16 February, 1979)

Abstract. Stellar coronae were among the first predicted X-ray sources. Because of their relatively low X-ray luminosities, however, they have been discovered only during the last few years.

In the present paper the current state of stellar coronal X- and UV observations has been reviewed, including some preliminary observational results from the *HEAO-1* and *IUE* satellites, but still without any result from the recently launched X-ray satellite *HEAO-2*.

Late 1978 about two dozens of stellar soft X-ray sources have been detected, e.g., normal stars like the Sun (e.g., α Cen), very active stars (*RS CVn* systems), and possibly a corona around an intermediately hot white dwarf (*Sirius B*).

The observational results of various objects have been discussed and compared with X-ray luminosity predictions based on minimum-flux coronal models.

Einstein Observatory

1978 - 1981

Launch: Nov 13 1978

G.S. Vaiana

R. Rosner

THE ASTROPHYSICAL JOURNAL 244:163–182, 1981 April 1

RESULTS FROM AN EXTENSIVE *EINSTEIN* STELLAR SURVEY

G. S. VAIANA,[1] J. P. CASSINELLI,[2,4] G. FABBIANO, R. GIACCONI, L. GOLUB, P. GORENSTEIN, B. M. HAISCH,[3,4] F. R. HARNDEN, JR., H. M. JOHNSON,[4,6] J. L. LINSKY,[3,4,5] C. W. MAXSON, R. MEWE,[4,7] R. ROSNER, F. SEWARD, K. TOPKA, AND C. ZWAAN[4,7]
Harvard-Smithsonian Center for Astrophysics
Received 1980 April 2; accepted 1980 September 22

ABSTRACT

We report the preliminary results of the *Einstein* Observatory stellar X-ray survey. To date, 143 soft X-ray sources have been identified with stellar counterparts, leaving no doubt that stars in general constitute a pervasive class of low-luminosity galactic X-ray sources. We have detected stars along the entire main sequence, of all luminosity classes, pre–main sequence stars as well as very evolved stars. Early type OB stars have X-ray luminosities in the range $\sim 10^{31}$ to $\sim 10^{34}$ ergs s^{-1}; late type stars show a somewhat lower range of X-ray emission levels, from $\sim 10^{26}$ to $\sim 10^{31}$ ergs s^{-1}. Late type main-sequence stars show little dependence of X-ray emission levels upon stellar effective temperature; similarly, the observations suggest weak, if any, dependence of X-ray luminosity upon effective gravity. Instead, the data show a broad range of emission levels (~three orders of magnitude) throughout the main sequence later than F0. Comparison of the data with published theories of acoustically heated coronae shows that these models are inadequate to explain our results. The data are consistent with magnetically dominated coronae, as in the solar case.

Subject headings: stars: coronae — X-rays: sources

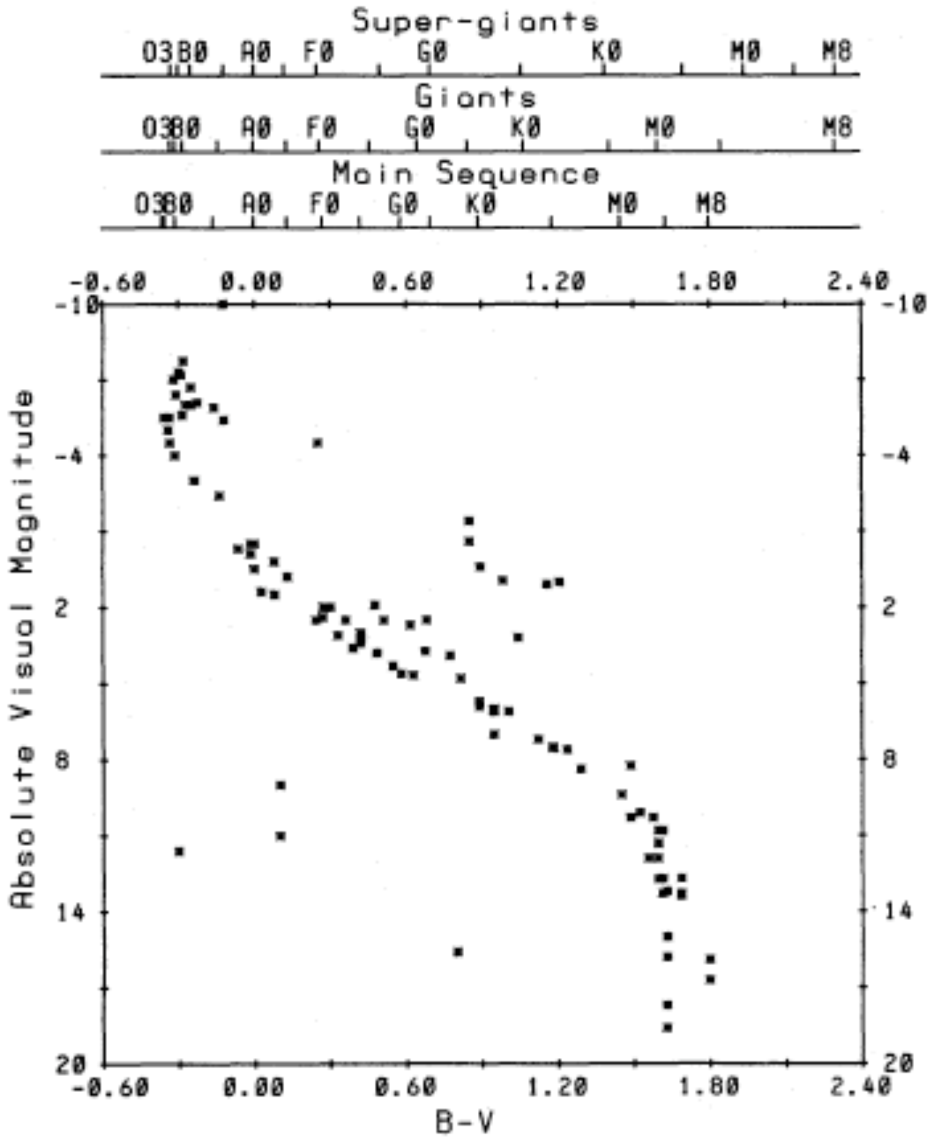
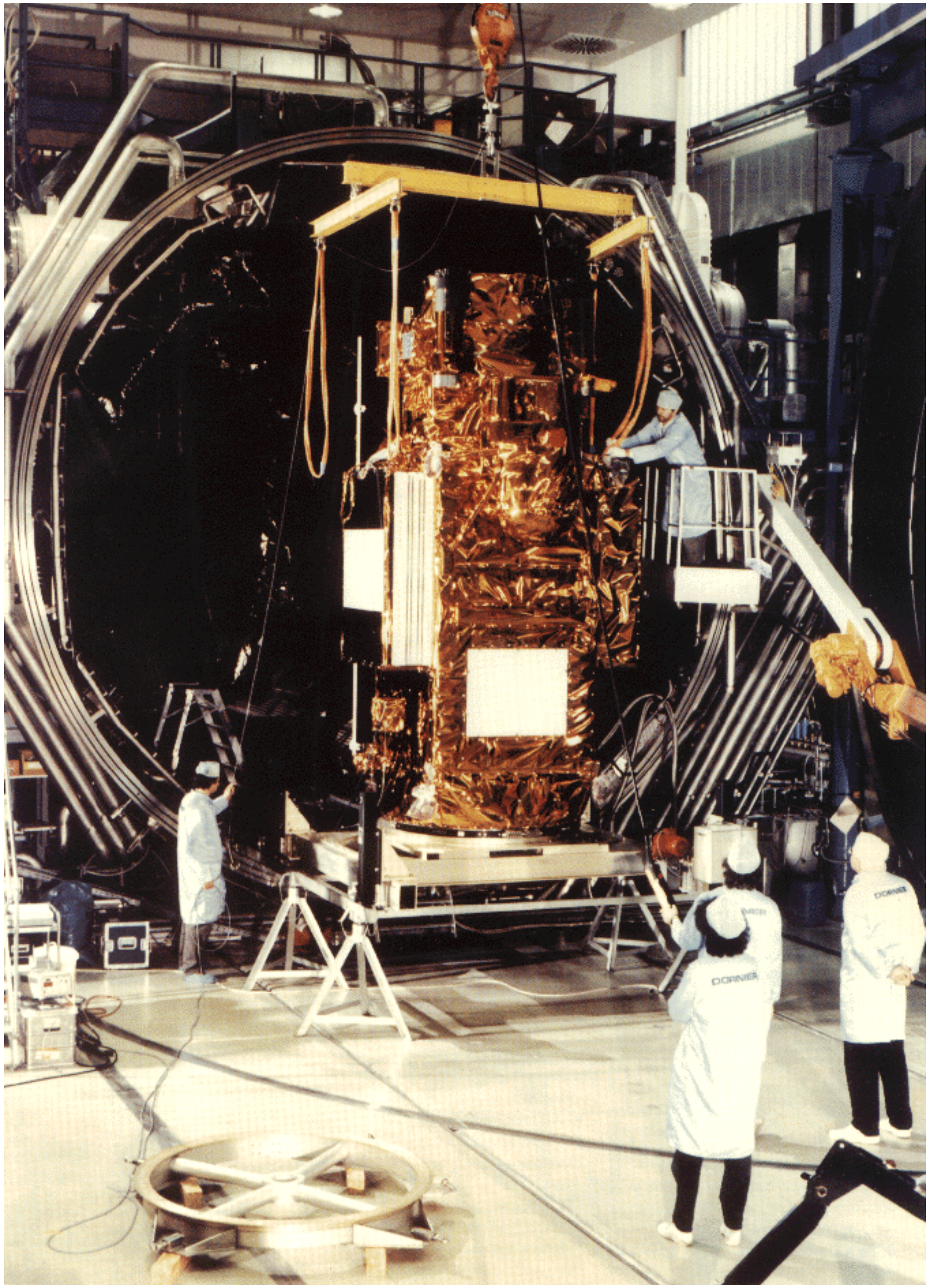


FIG. 1.—An H-R diagram for stars detected as soft X-ray sources by *Einstein*. The figure only includes that subset of Survey stars for which absolute visual magnitude could be determined either from the luminosity class or from parallax data; these stars are referred to as the "optically well-classified" sample.

Vaiana et al. (1981)

R. Harnden (and the Crab Pulsar)

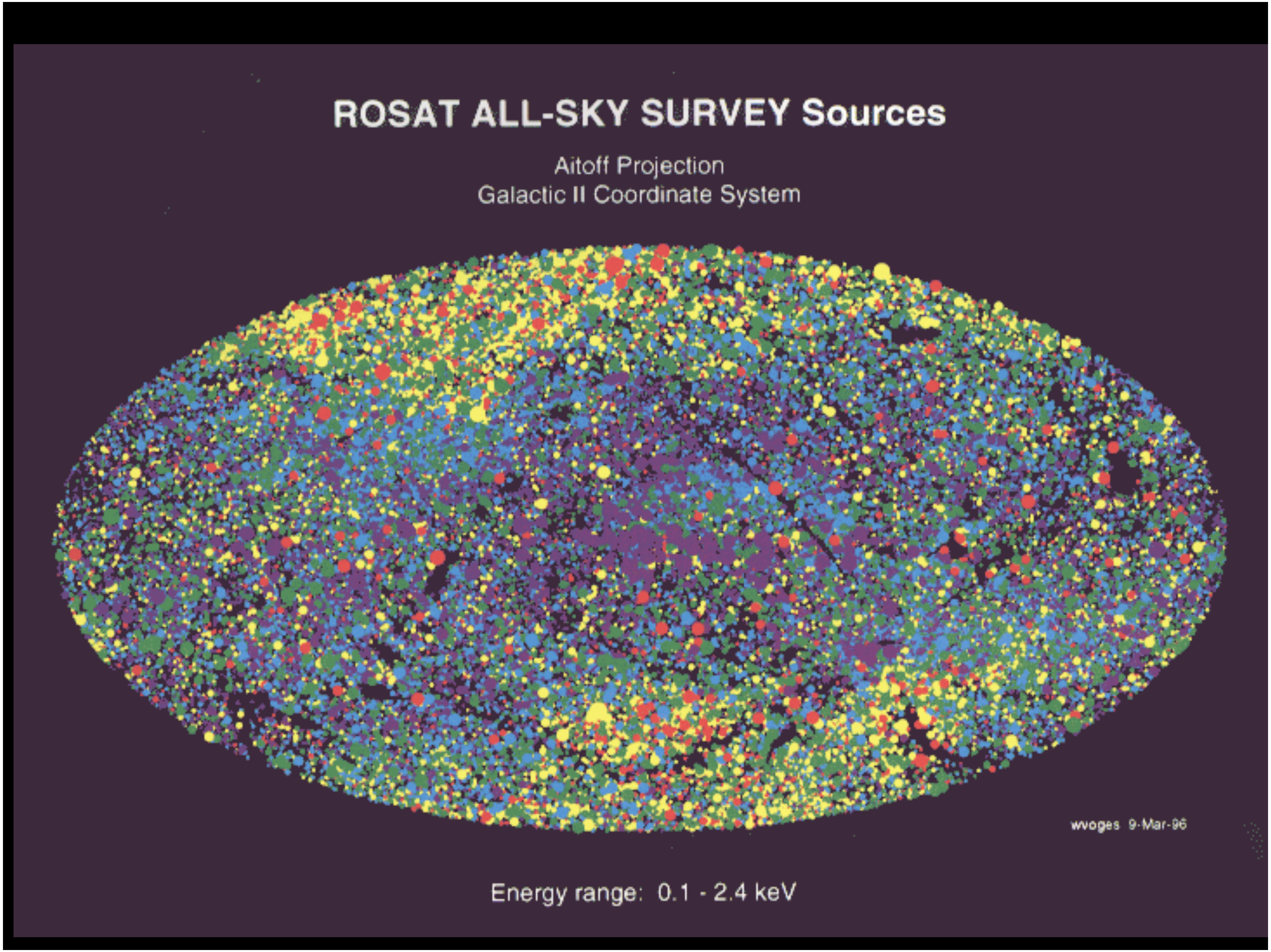
Note the ultramodern computer equipment !



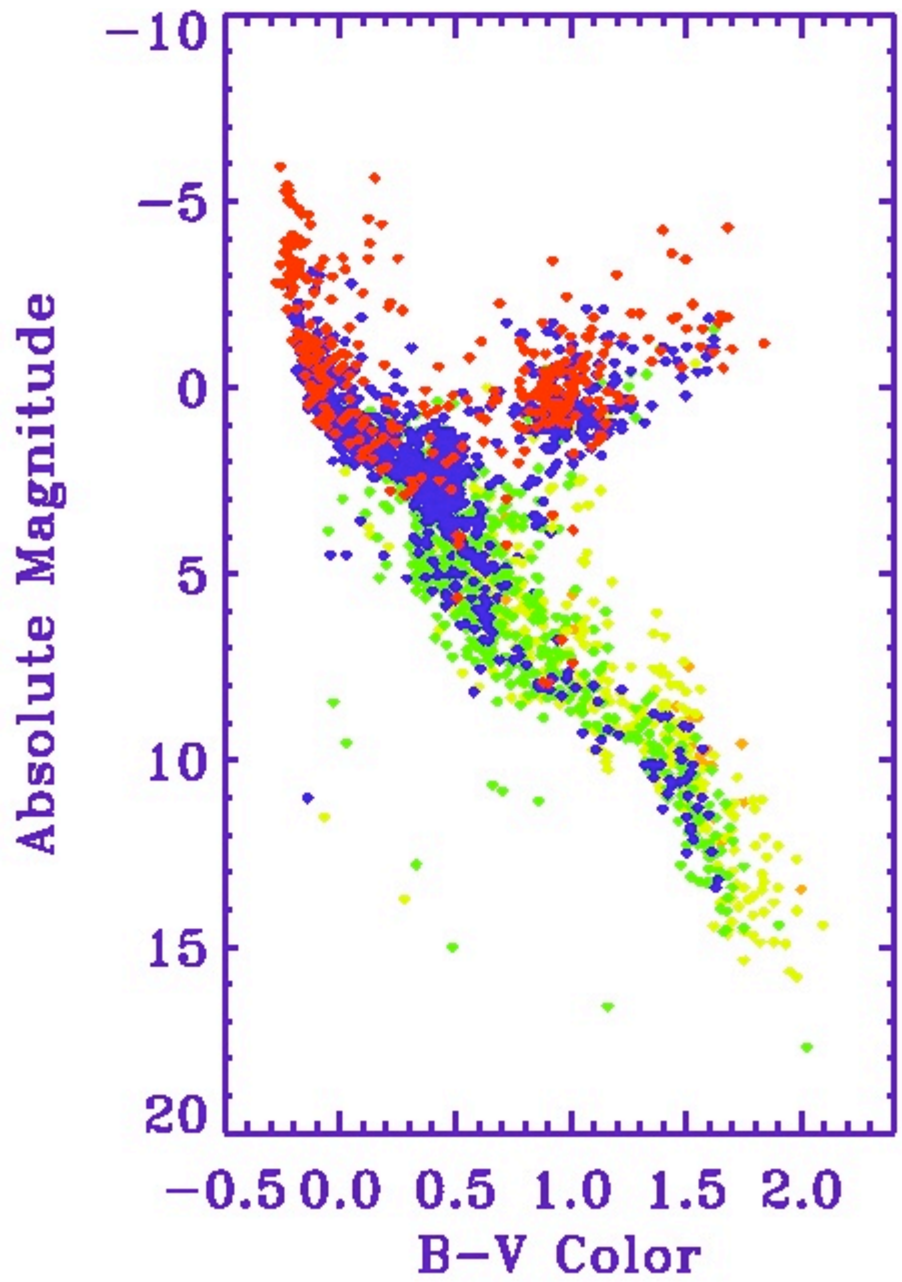
ROSAT Satellite

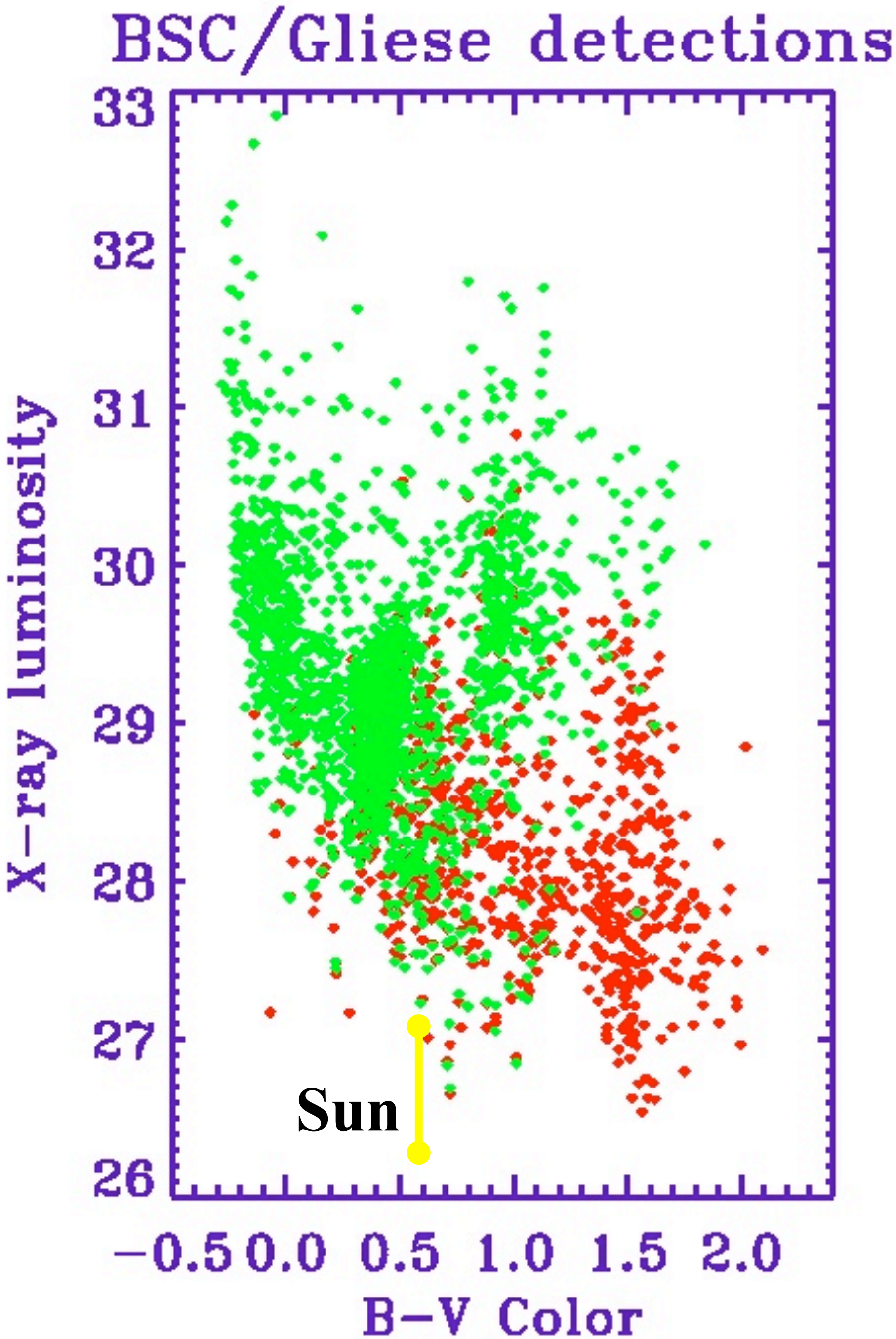
1990 - 1998

Launch: Jun 1 1990


ROSAT ALL-SKY SURVEY Sources
Aitoff Projection
Galactic II Coordinate System
wvoges 9-Mar-96
Energy range: 0.1 - 2.4 keV

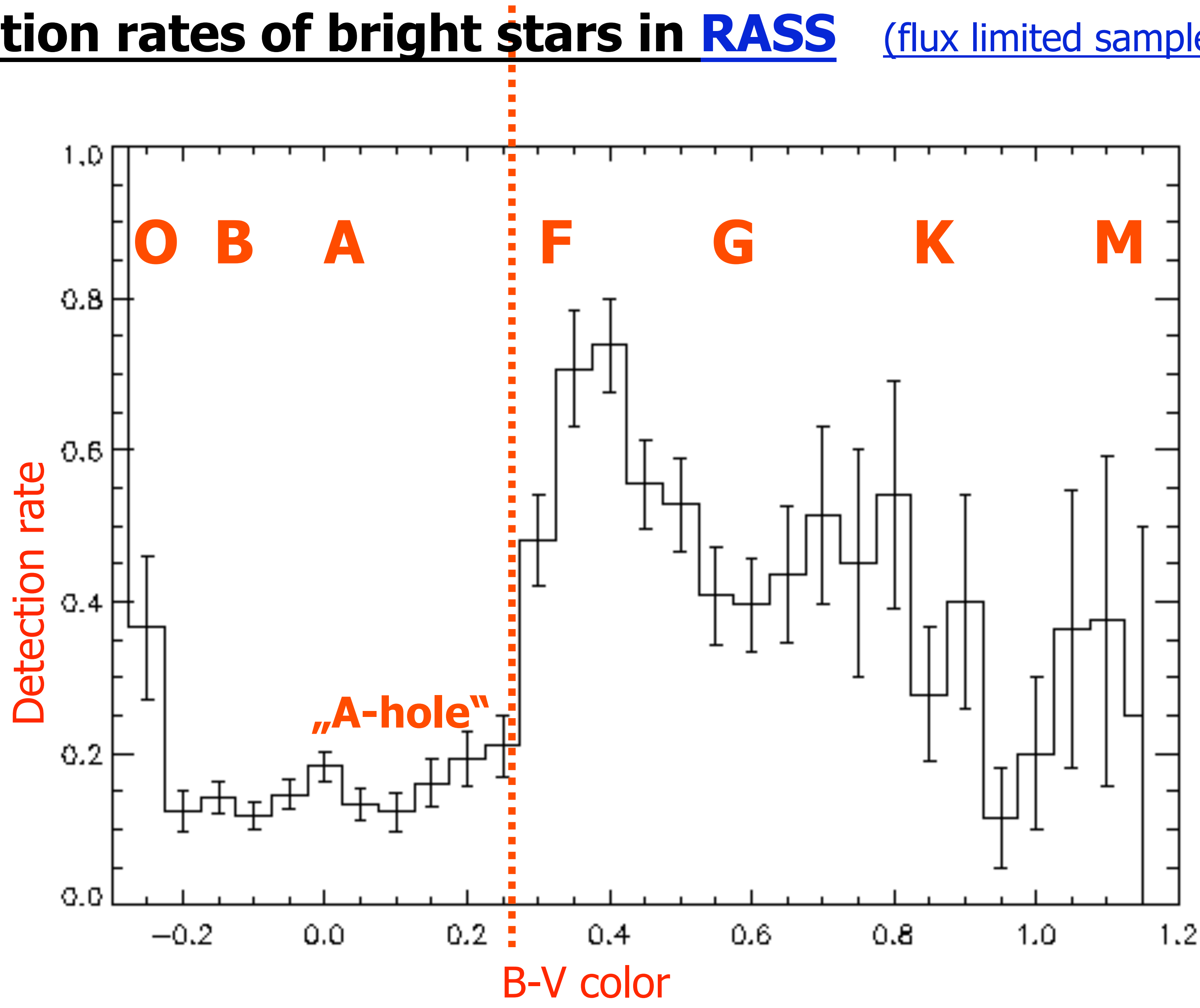
Hertzsprung-Russell-Diagram of X-ray detected stars





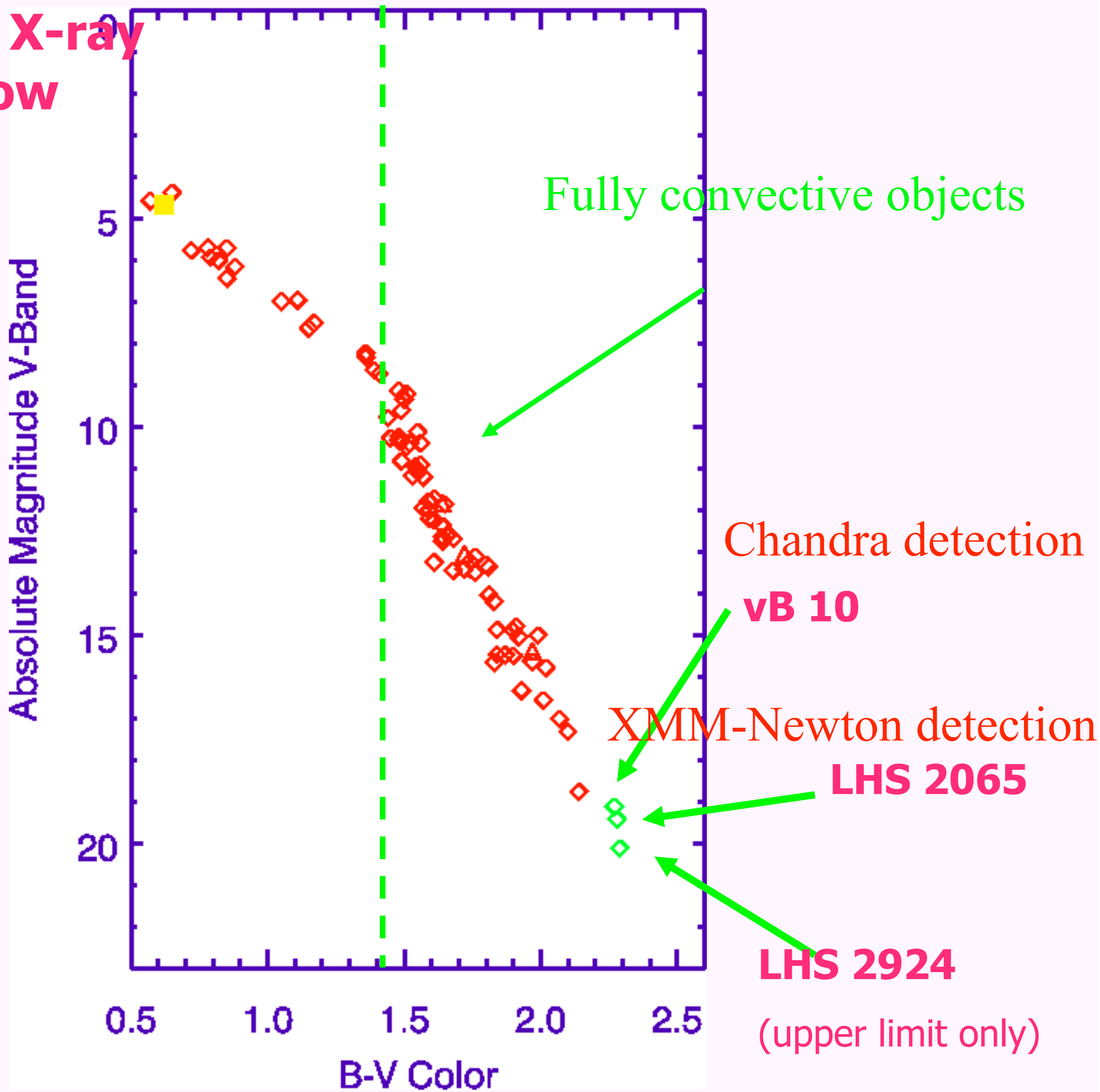
BSC/Gliese detections
X-ray luminosity
33
32
31
30
29
28
27
26
Sun
−0.5
0.0
0.5
1.0
1.5
2.0
B−V Color

Detection rates of bright stars in RASS (flux limited sample)

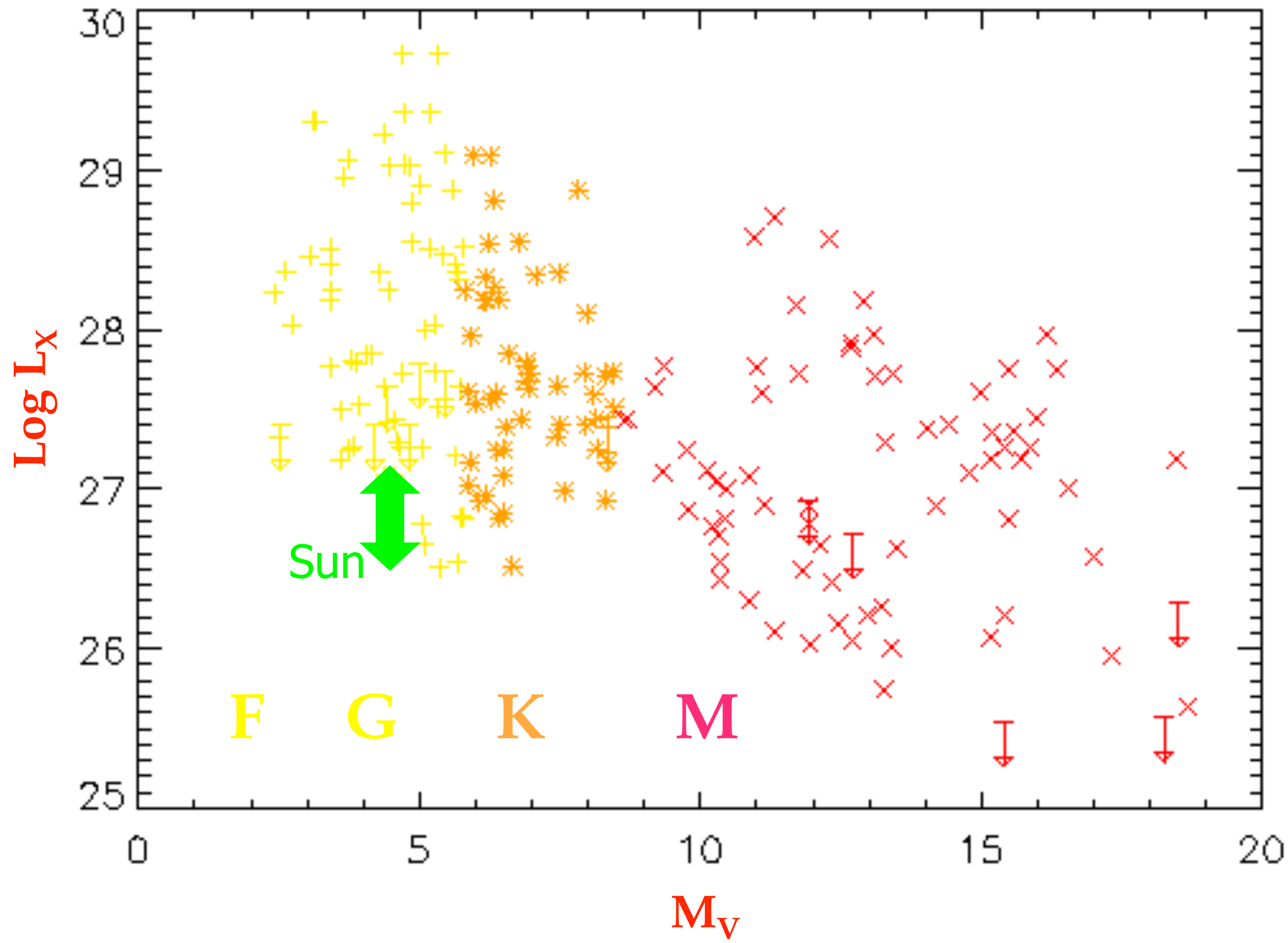


Onset of convection

HR-diagram of X-ray detections of low mass stars

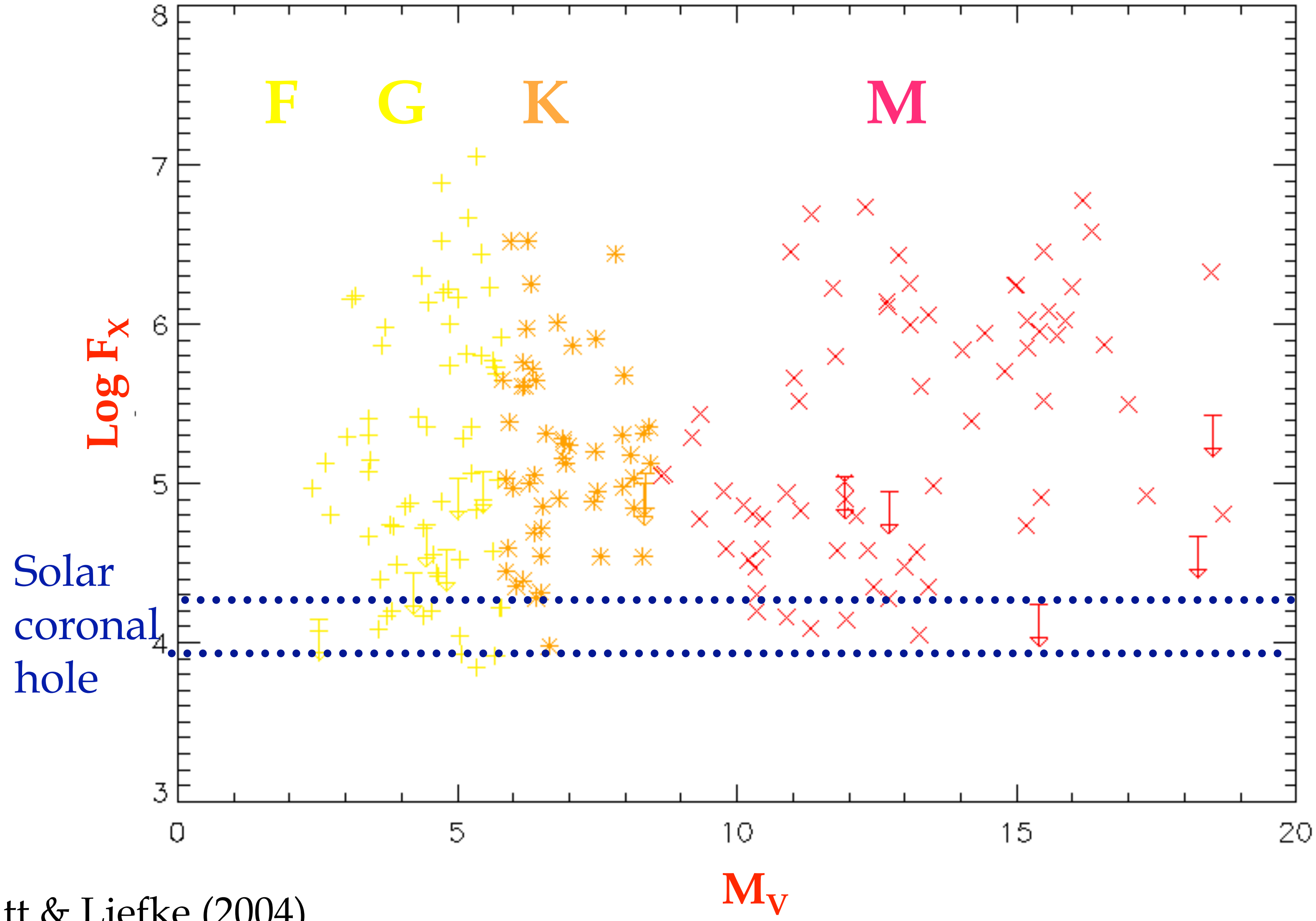


Volume-limited sample of F,G,K,M dwarfs: L_X vs. M_V



Schmitt & Liefke (2004)

Volume-limited sample of F,G,K,M dwarfs: F_X vs. M_V



Schmitt & Liefke (2004)

→

Coronal formation (= hot plasma) is a universal process for cool stars

But …

What determines the X-ray luminosity of a given star ?

What do stellar coronae look like ?

RELATIONS AMONG STELLAR X-RAY EMISSION OBSERVED FROM *EINSTEIN*, STELLAR ROTATION AND BOLOMETRIC LUMINOSITY

R. Pallavicini,[1] L. Golub, R. Rosner, and G. S. Vaiana[2]
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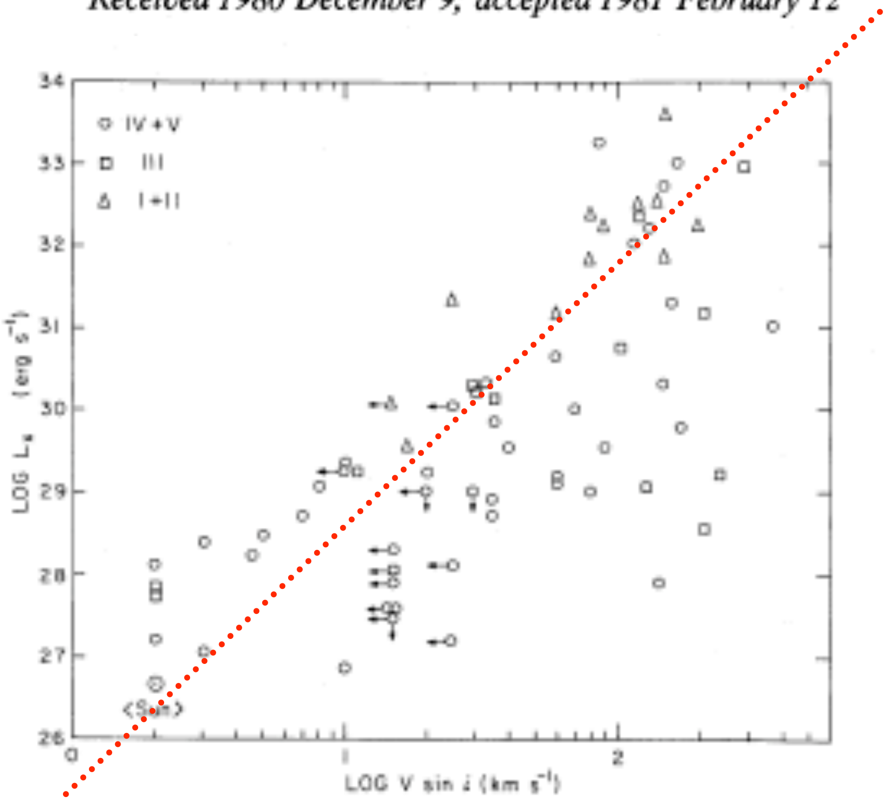
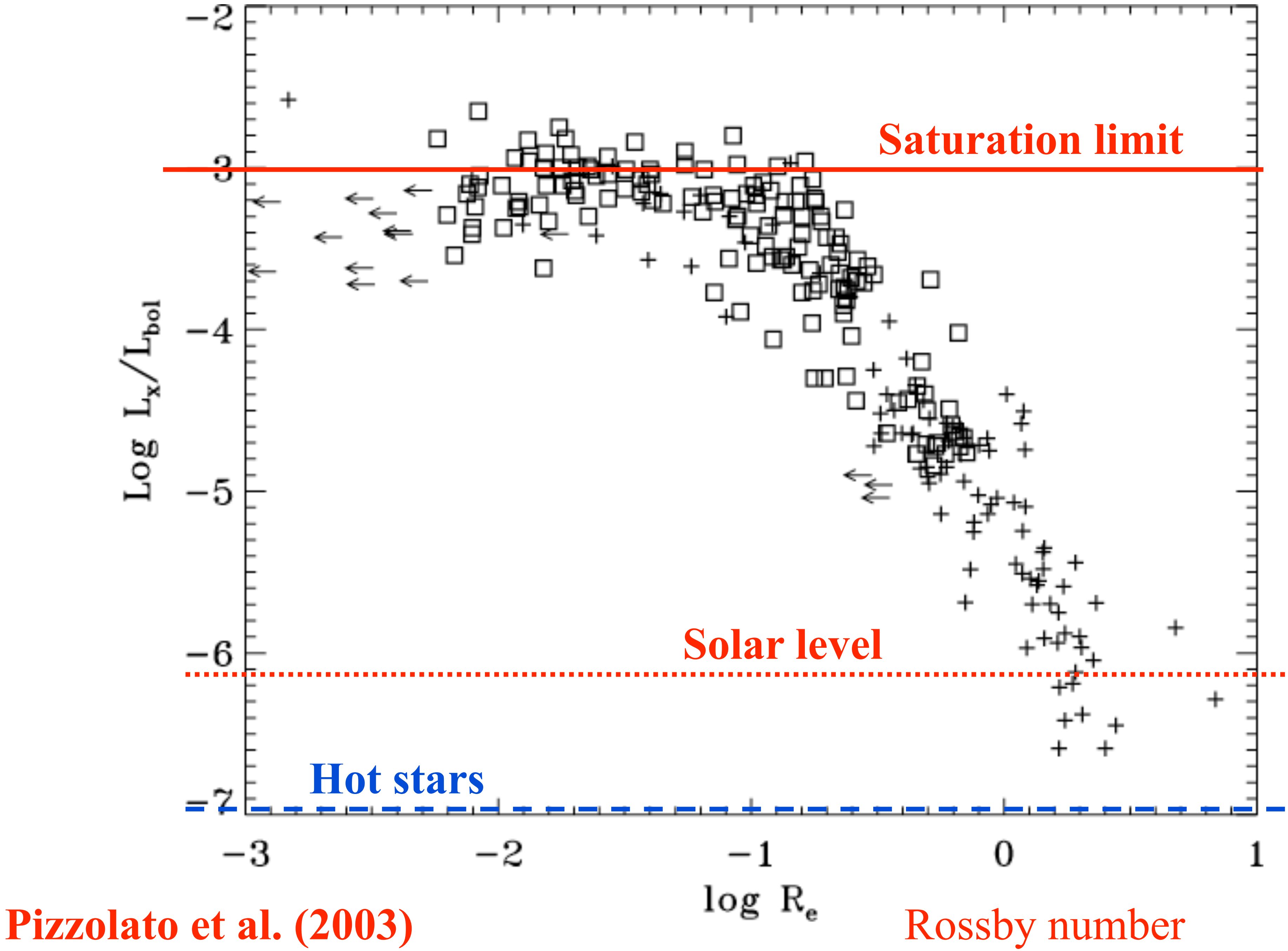
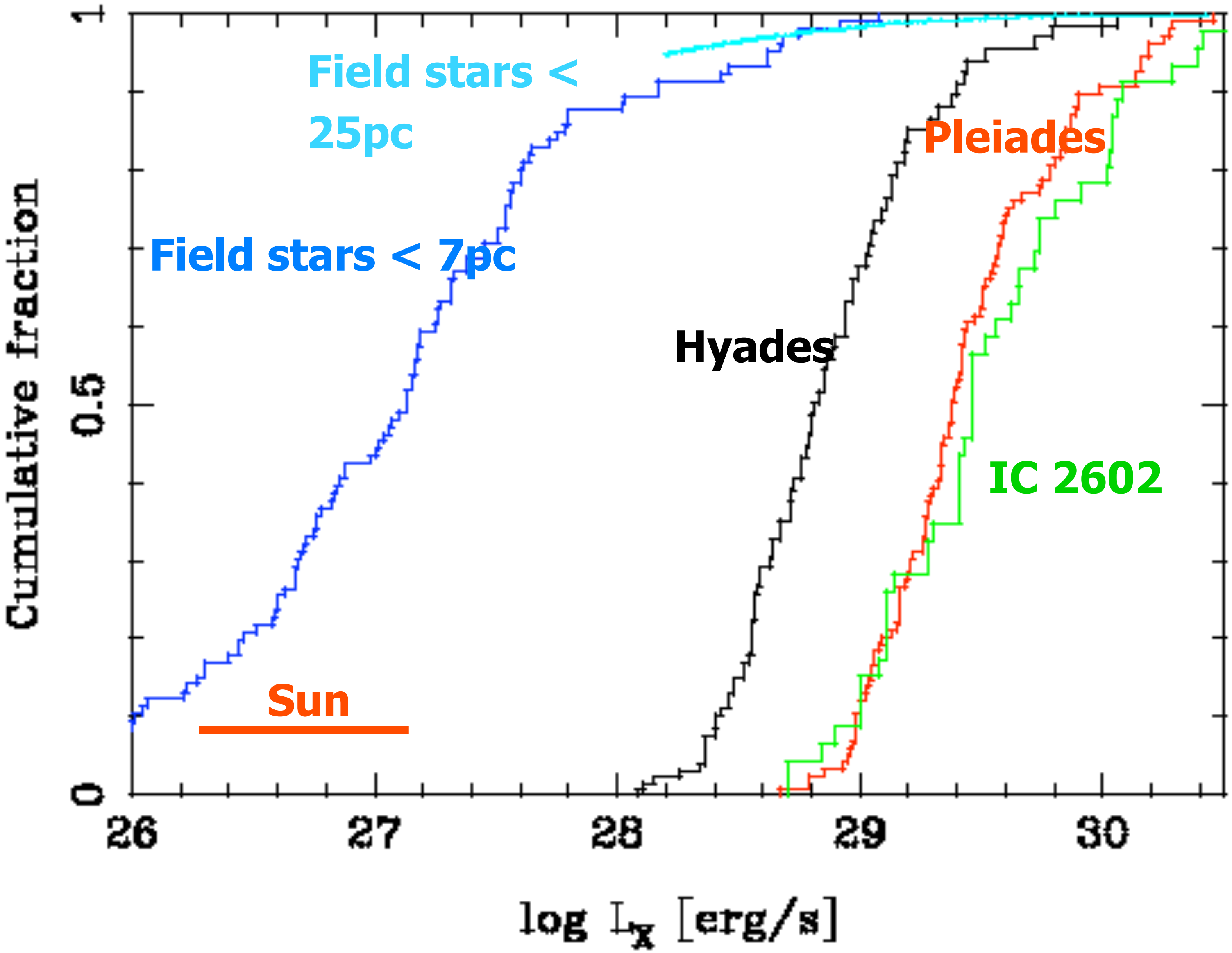
T. Ayres[3]
Laboratory for Atmospheric and Space Physics
and
J. L. Linsky[3, 4]
Joint Institute for Laboratory Astrophysics
Received 1980 December 9; accepted 1981 February 12

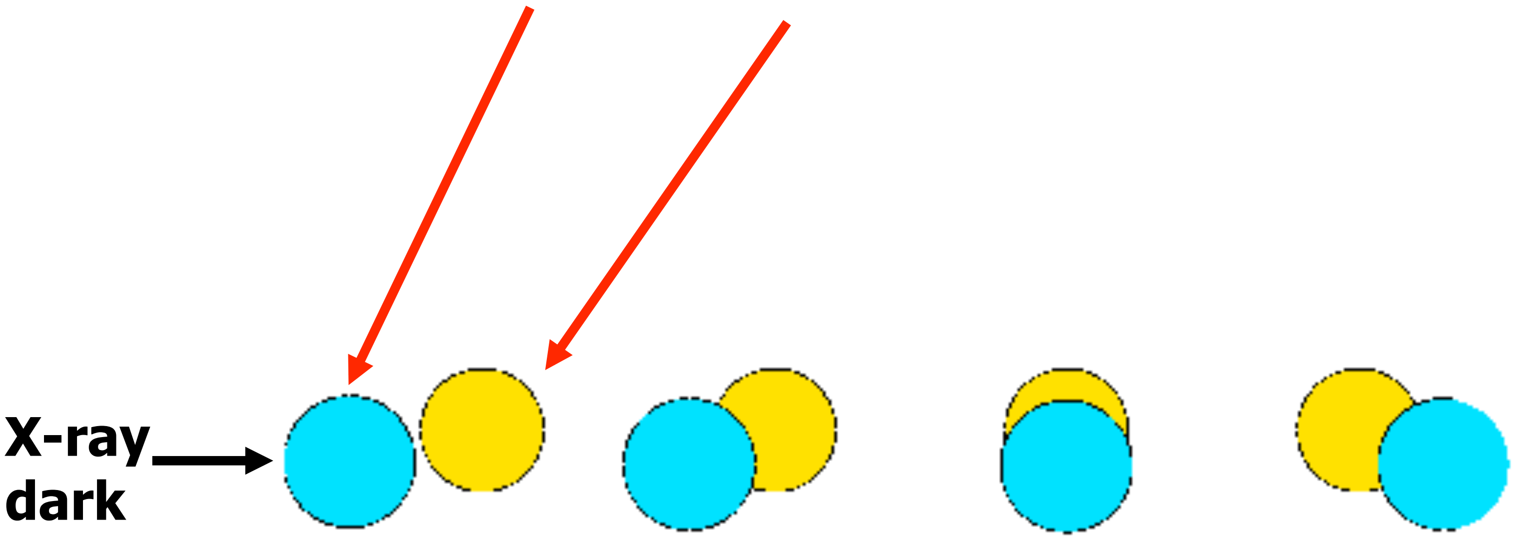



Saturation limit
Solar level
Hot stars
Log L_x/L_{bol}
log R_e
−2
−3
−4
−5
−6
−7
−1
0
1
Pizzolato et al. (2003)
Rossby number

X-ray luminosities of solar-like stars



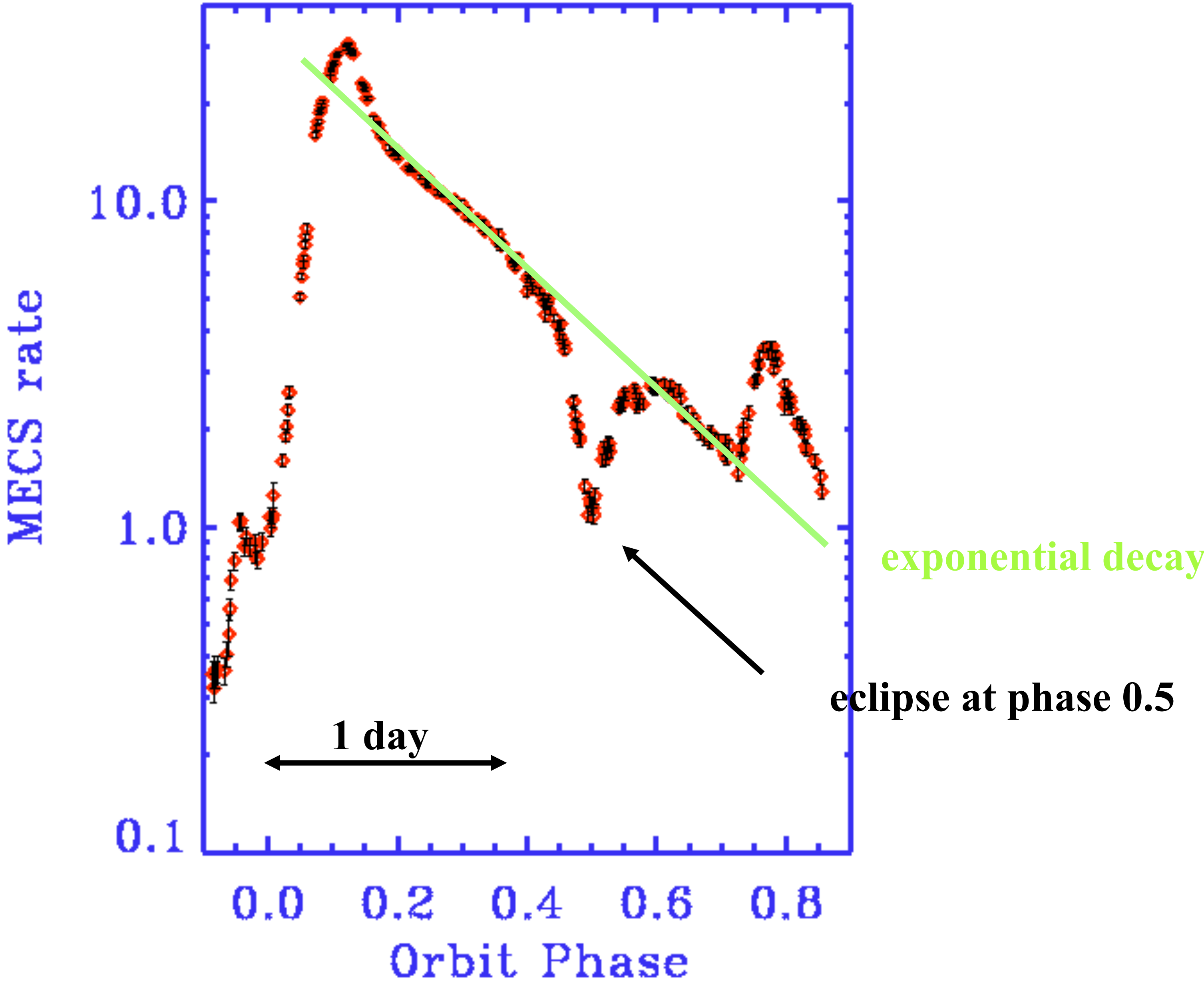
Algol: B8V+K2III Eclipse Geometry

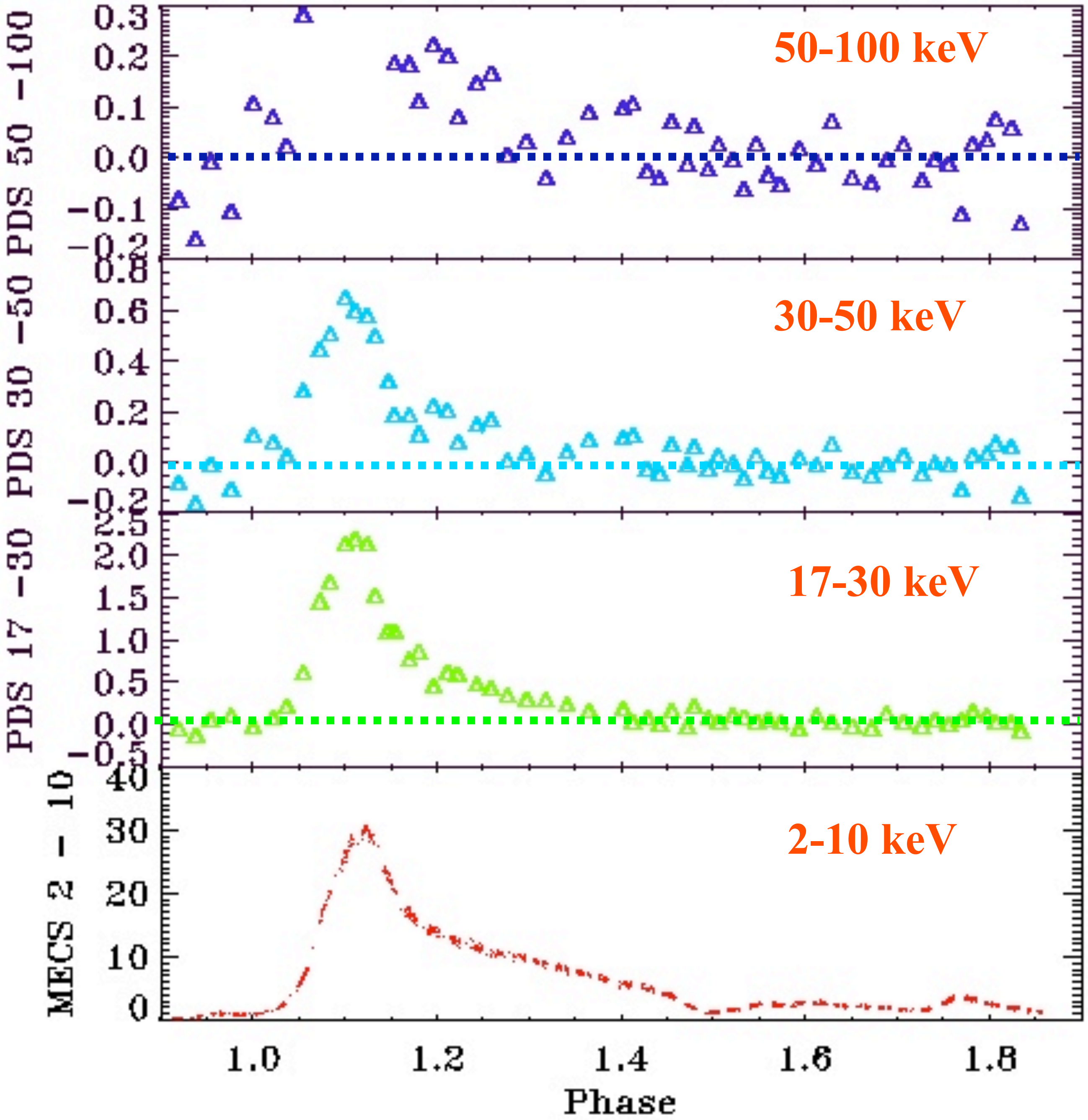


Phase: 0.42 0.45 0.5 0.55

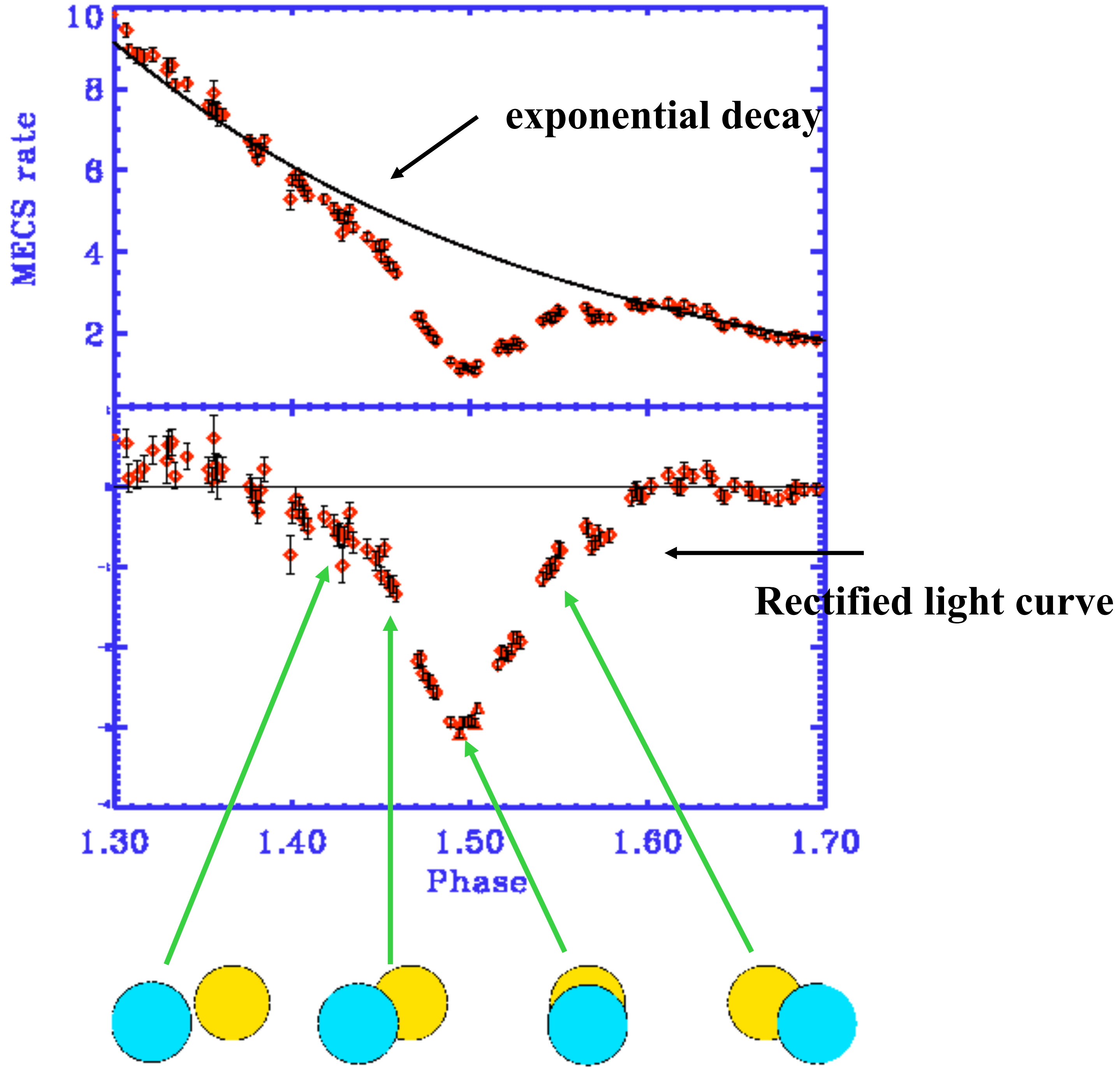
Giant X-ray flare on Algol observed with BeppoSAX

(Schmitt & Favata 1999)

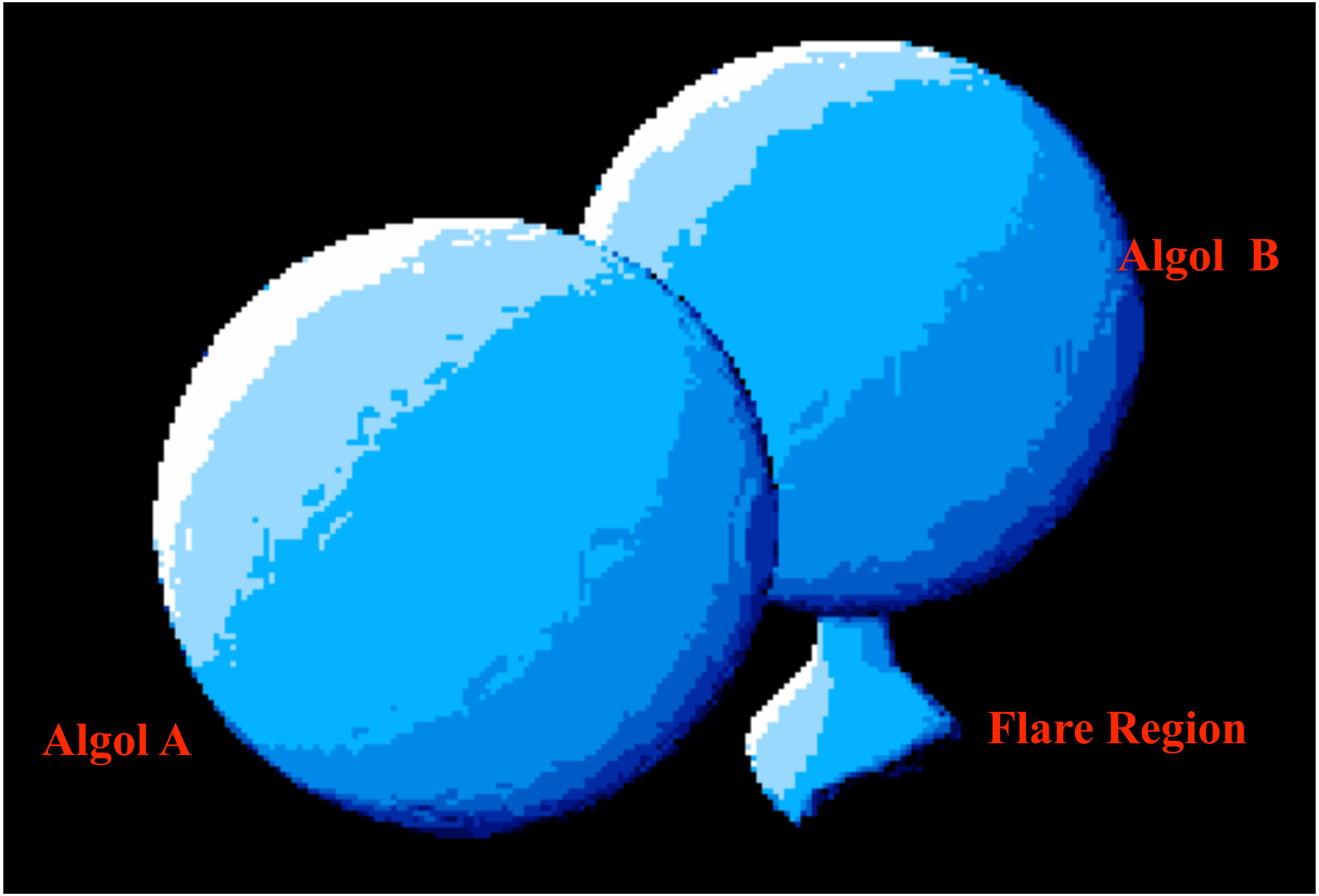




50-100 keV
30-50 keV
17-30 keV
2-10 keV
PDS 50 -100
PDS 30 -50
PDS 17 -30
MECS 2 - 10
Phase



exponential decay
Rectified light curve
MECS rate
Phase
10
8
6
4
2
1.30
1.40
1.50
1.60
1.70



Phase: φ = 1.45

Algol Flare Energetics

Observables

- $T_{max} = 10^8$ K
- $EM = 10^{55}$ cm^{-3}
- $E_{tot} > 10^{37}$ erg
- $V_{max} < 10^{33}$ cm^3

→ $P_{gas} = 2\ n\ k\ T$

→ $n = (EM/V)^{1/2}$

Assumptions

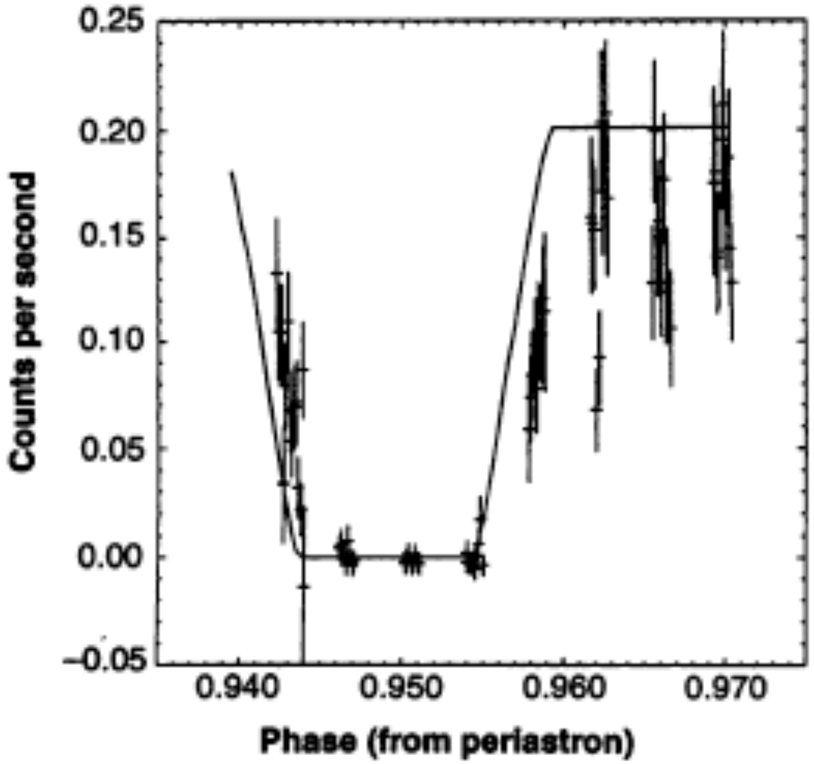
- Magnetic Field Annihilation
- Magnetic confinement of heated plasma
- Photospheric magnetic field

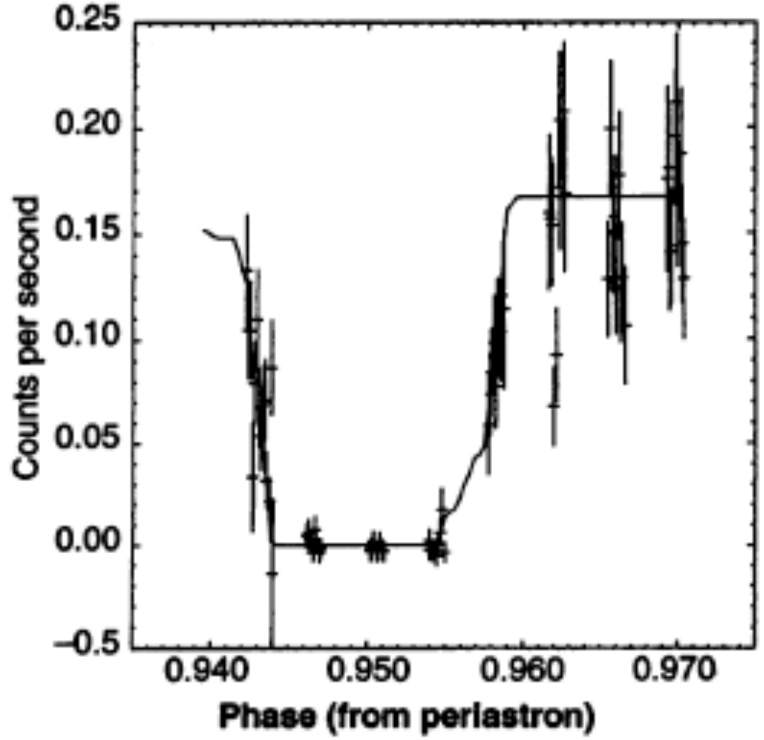
→ $B_{annih} > 500$ G

→ $B_{conf} > 260$ G

→ $B_{phot} \sim 1500$ G

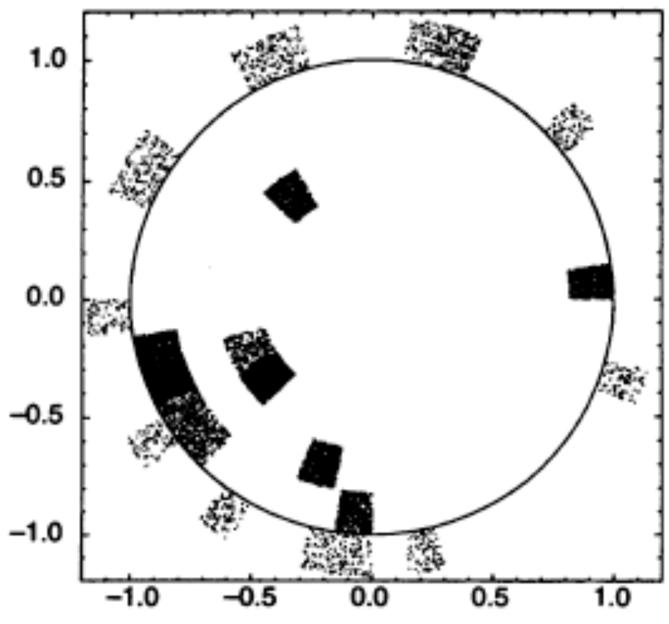
$B_{cor} > 560$ G





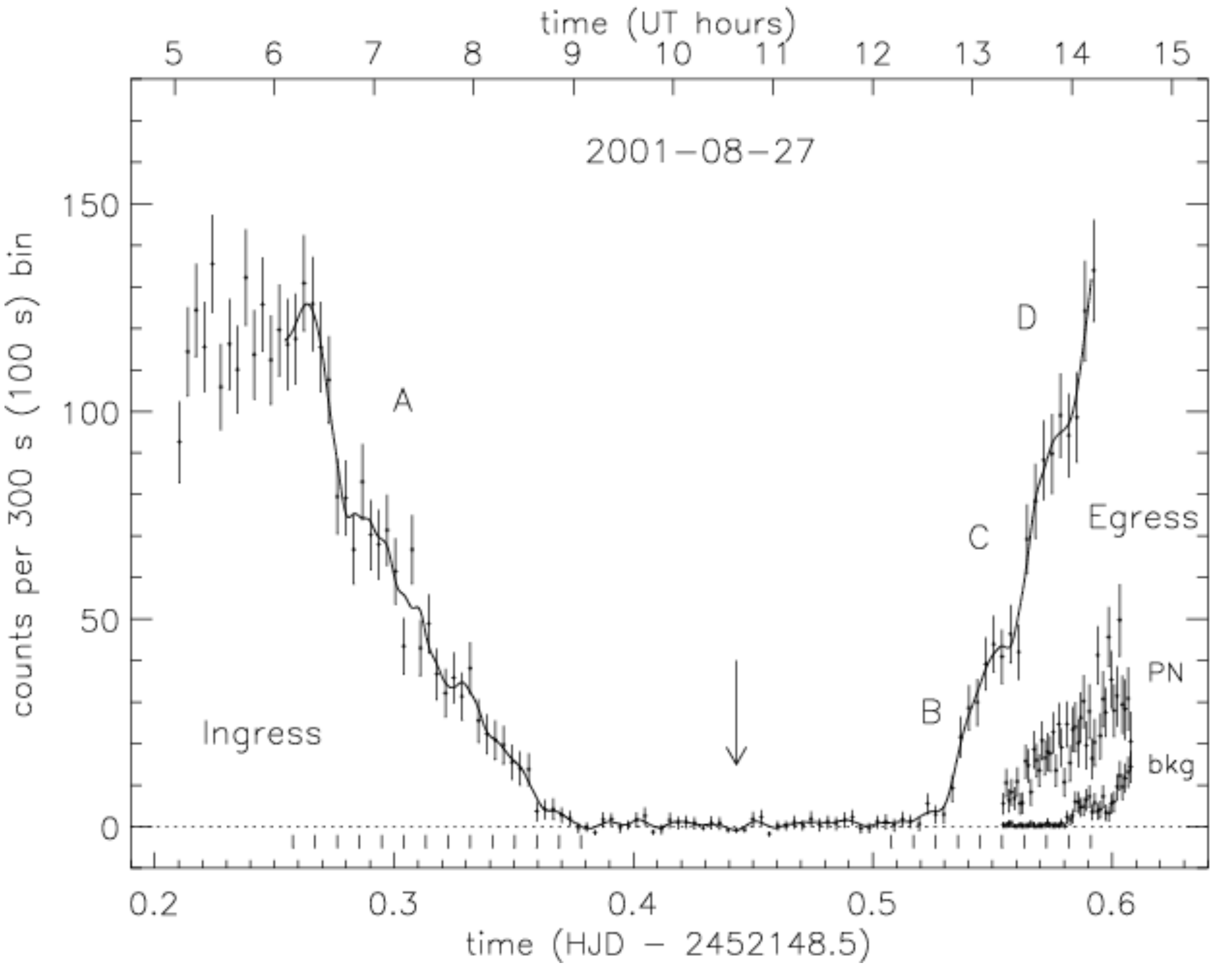
Schmitt & Kürster

(1993)



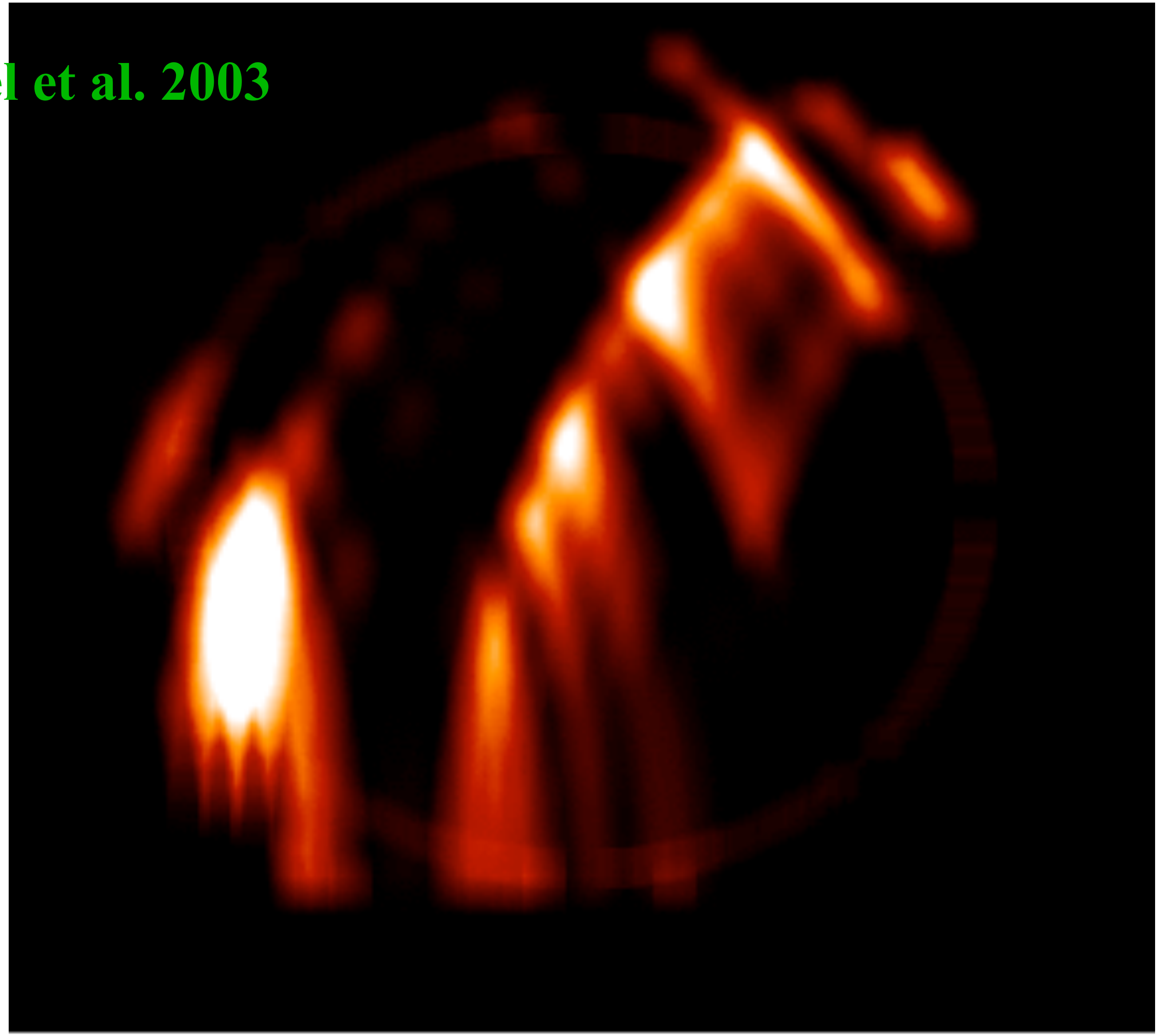
α CrB: Reconstruction of intensity structures from eclipse

Güdel et al. 2003



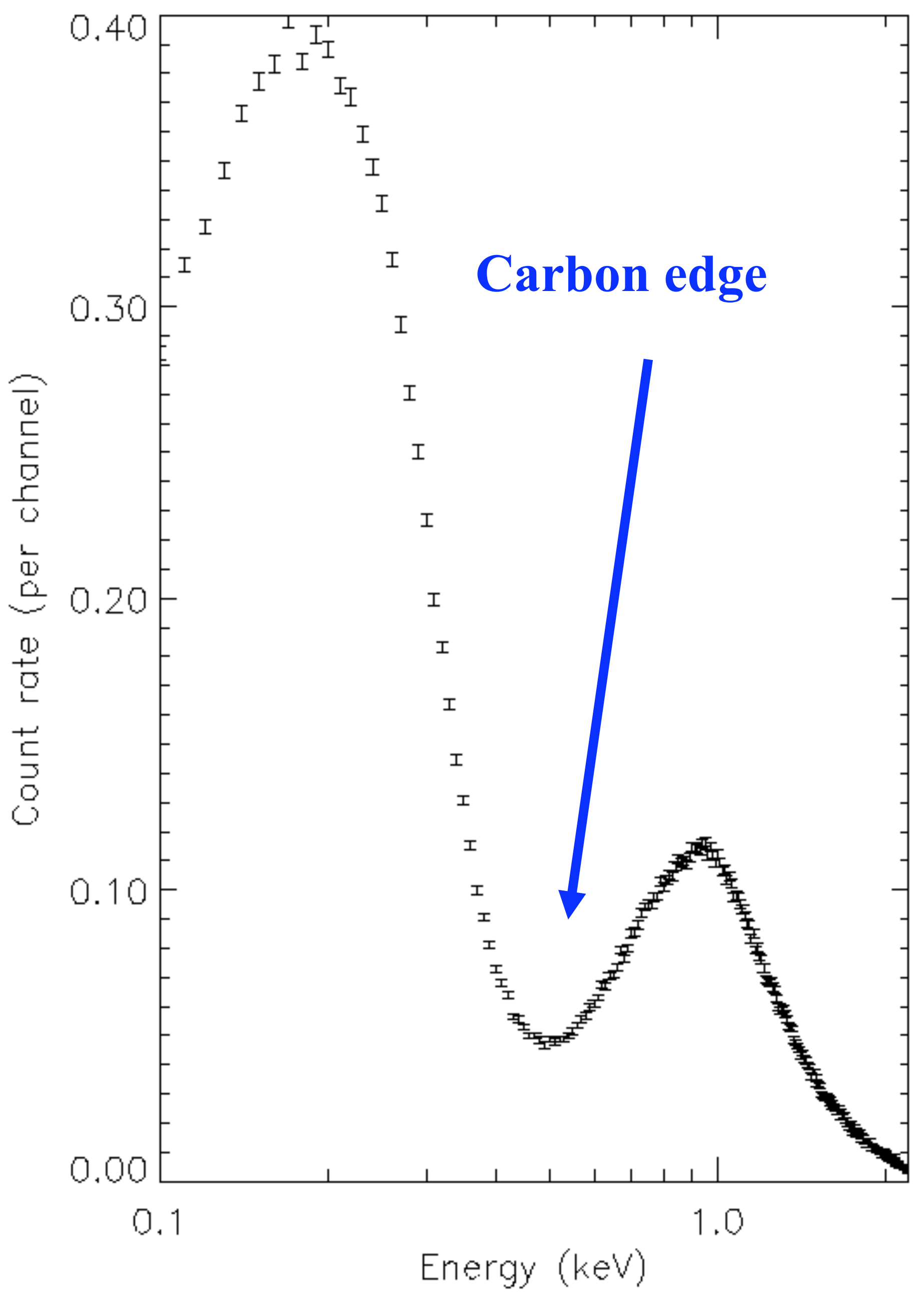
α CrB: Reconstruction of intensity structures from eclipse

Güdel et al. 2003



Spectral resolution:

PSPC :	$E/\Delta E$	$\approx$ 2.3	@1 keV	X
CCD:	$E/\Delta E$	$\approx$ 8.3	@1 keV	X
LETGS:	$E/\Delta E$	$\approx$ 400	@1 keV	X
UVES:	$E/\Delta E$	$\approx$ 45000	@3.64eV	O

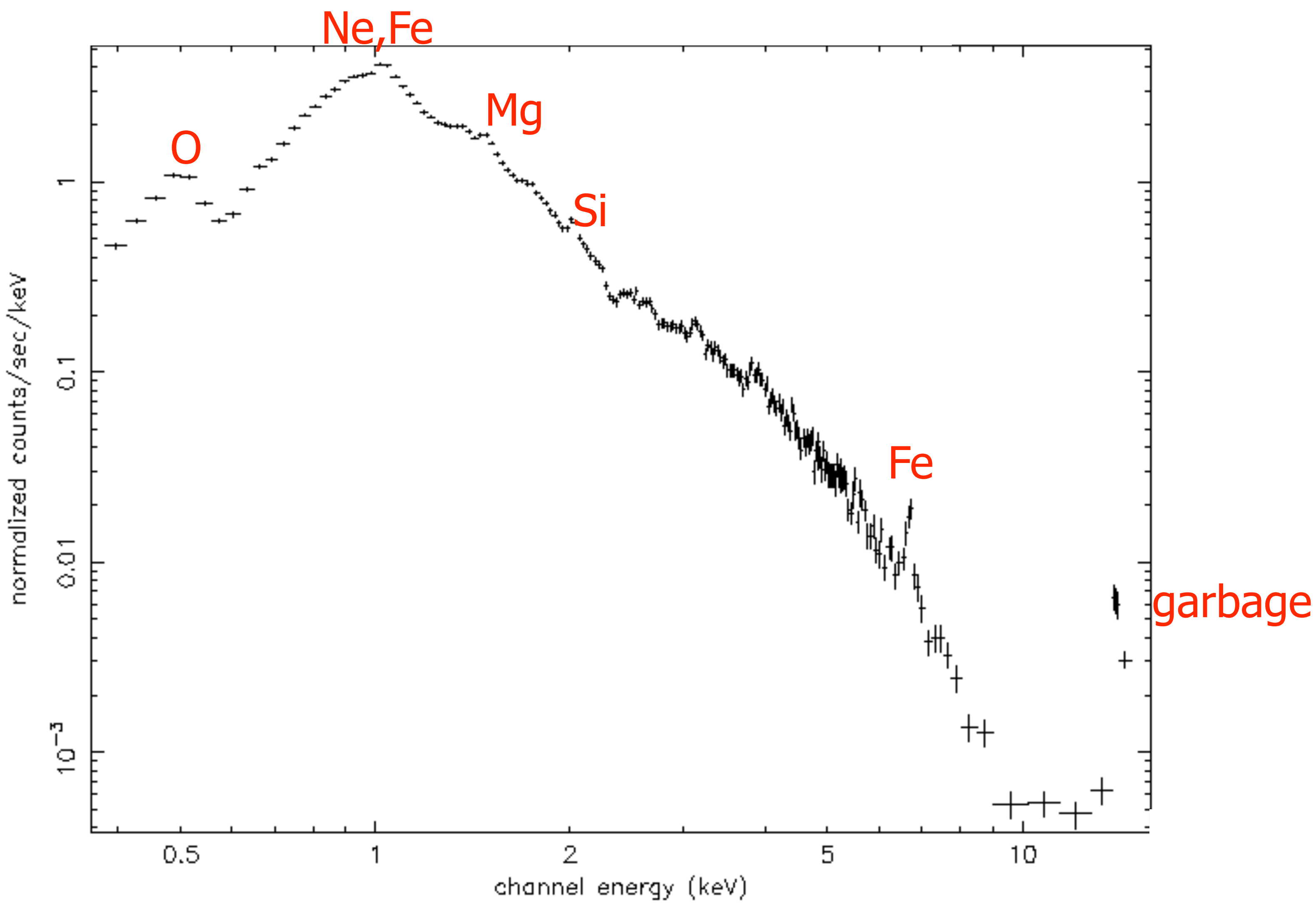


ROSAT PSPC spectrum of Algol

(Proportional counter)

1990

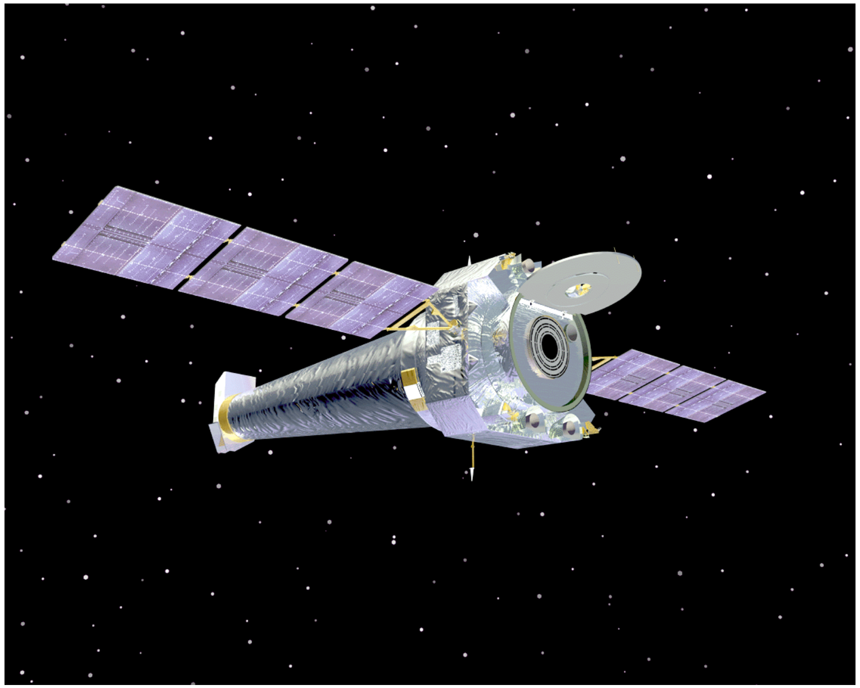
ASCA (CCD) : Algol 1996

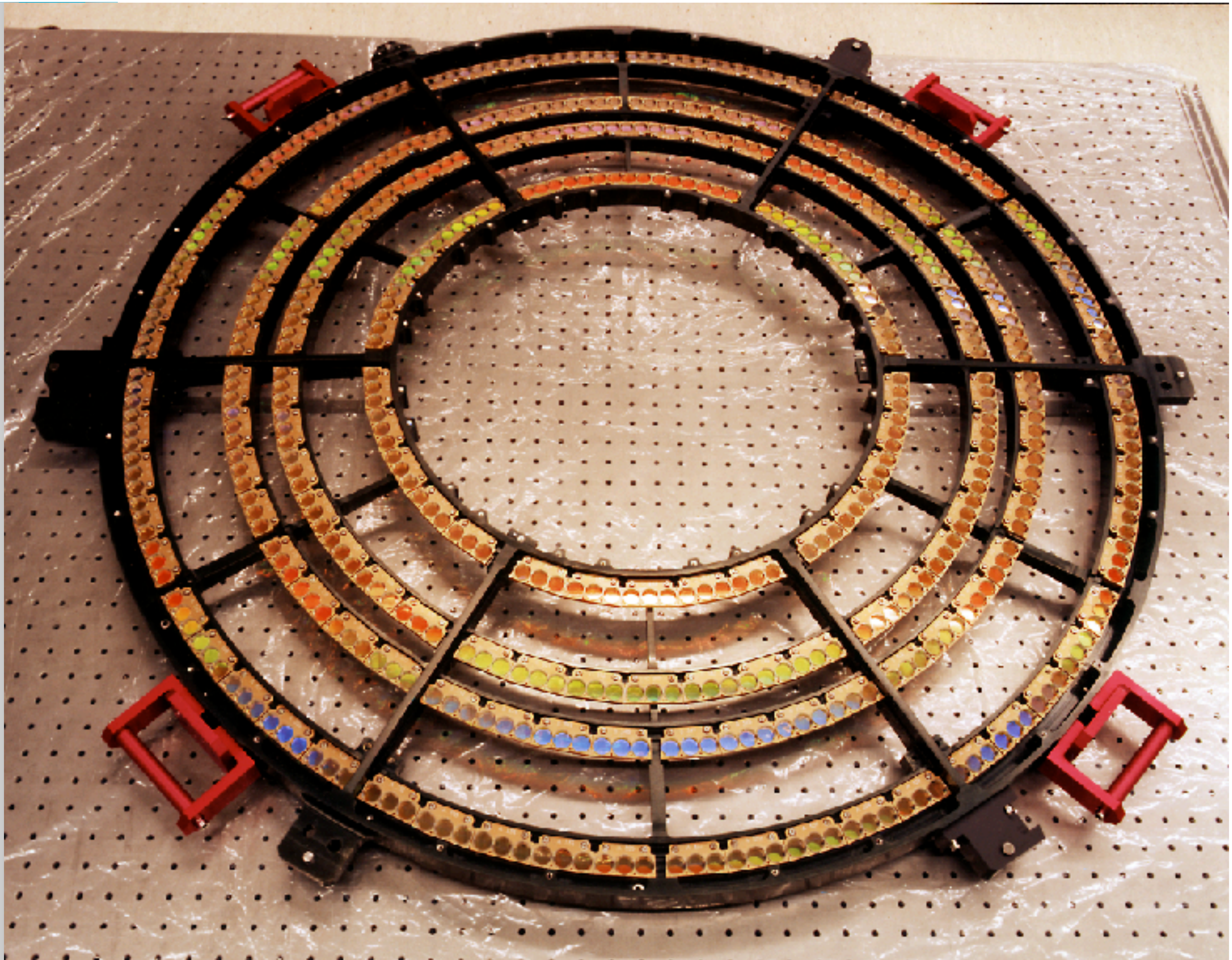


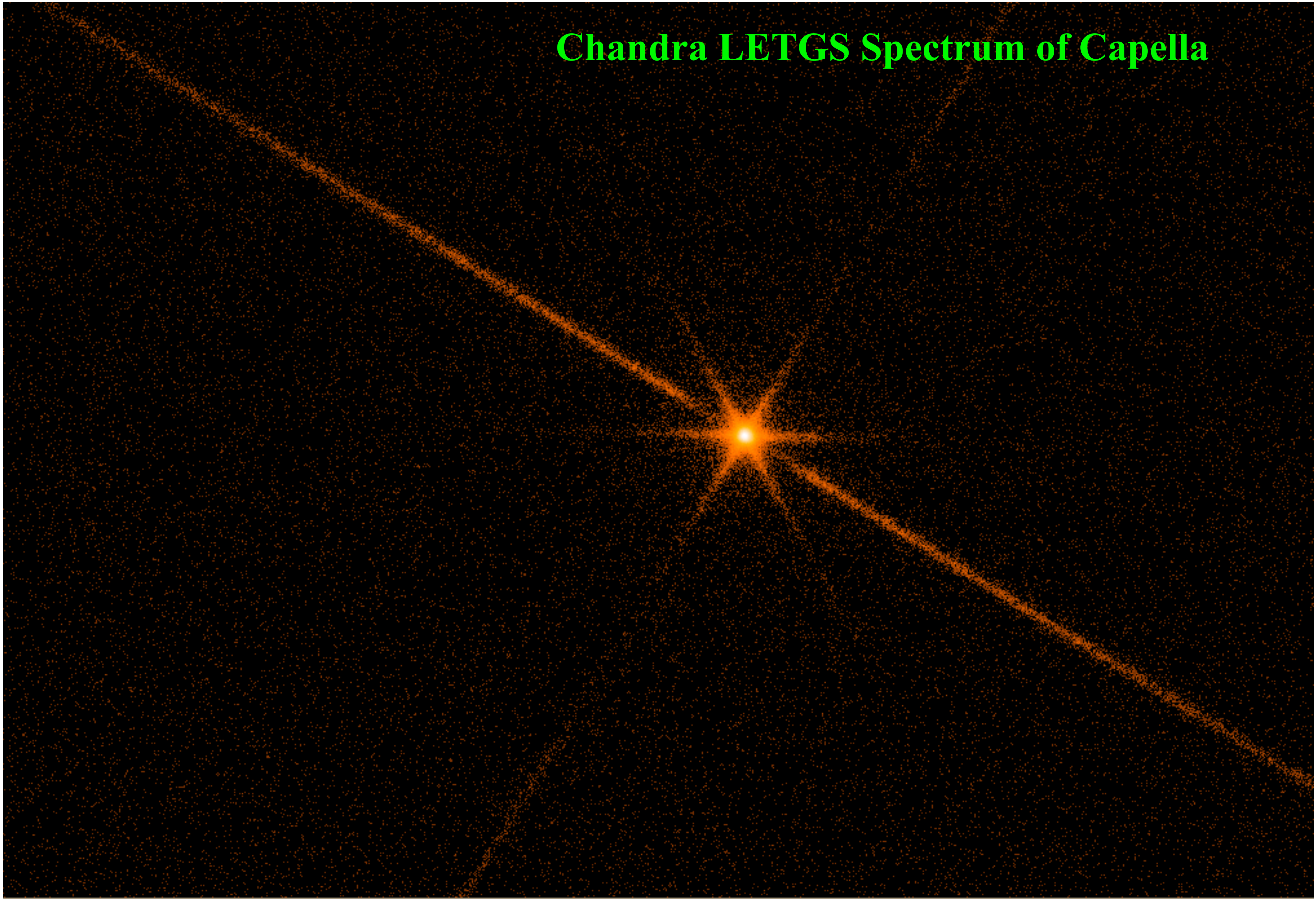
XMM-Newton and Chandra

- ***XMM-Newton*** **(ESA)**
  - Launch: December 1999
  - Orbit: 48 hours
- Reflection Grating Spectrometer (RGS)

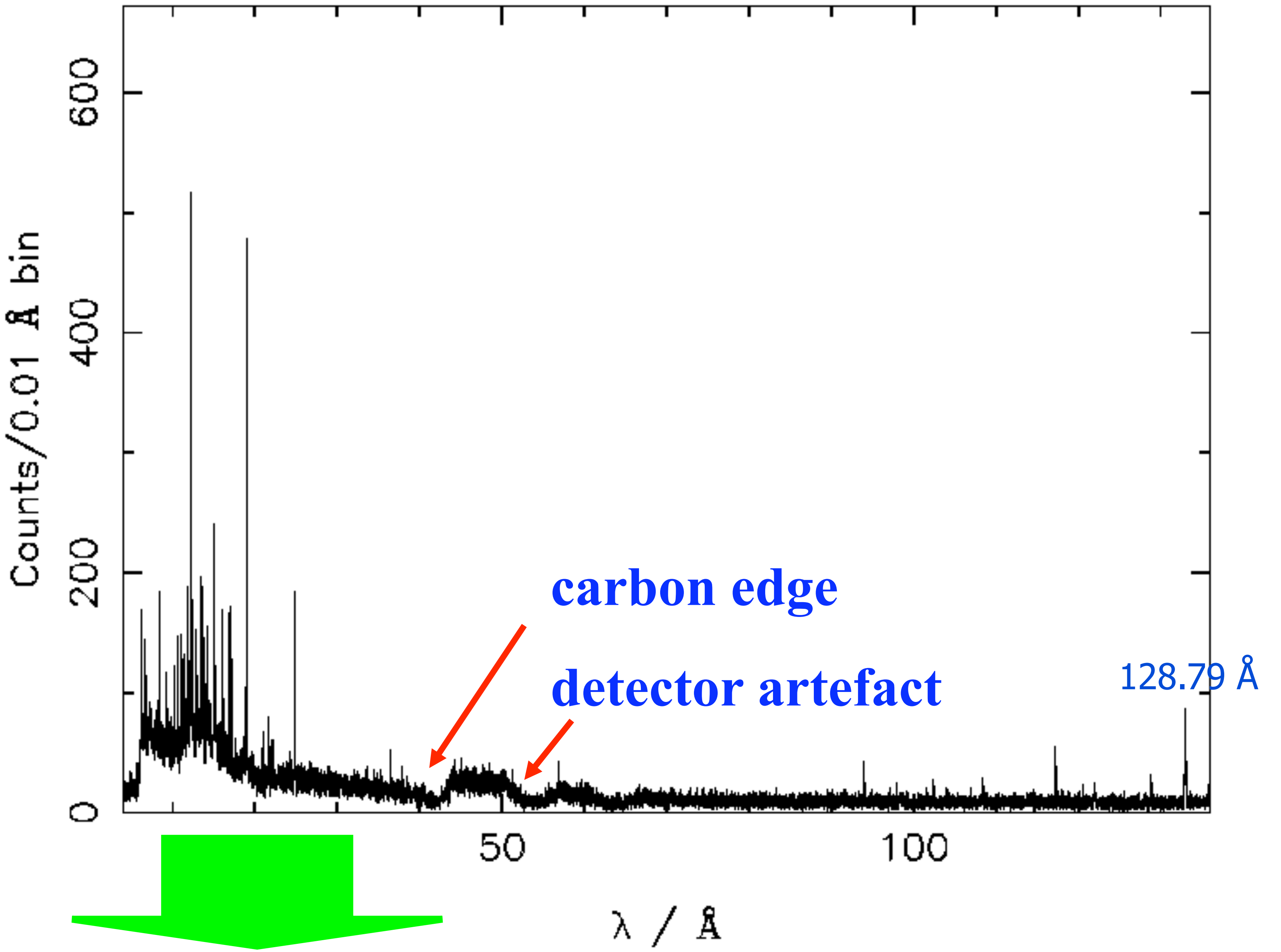
- ***Chandra*** **(NASA)**
  - Launch: July 1999
  - Orbit: 64 hours
- Transmission gratings
  - LETGS
  - HETGS





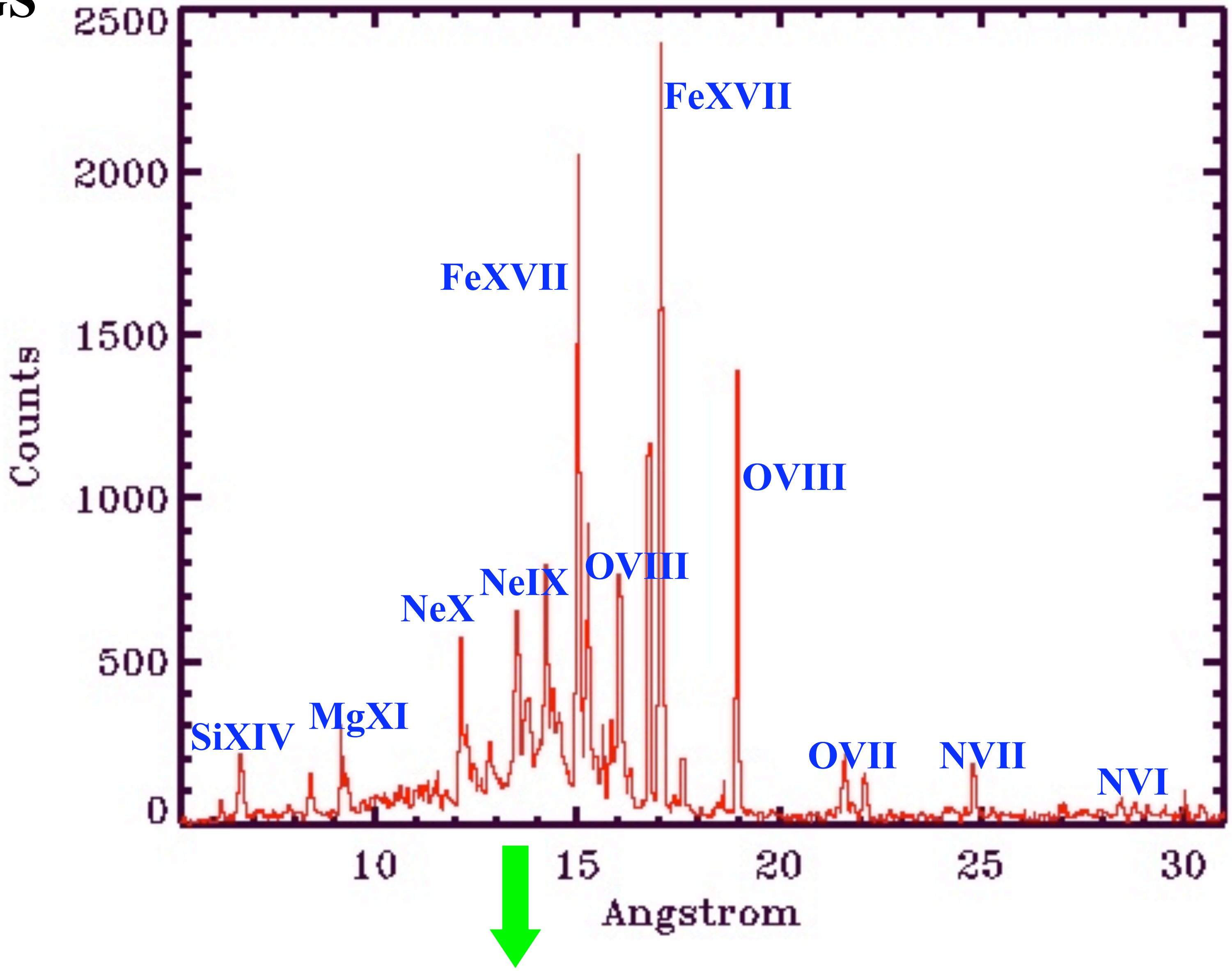

Chandra LETGS Spectrum of Capella

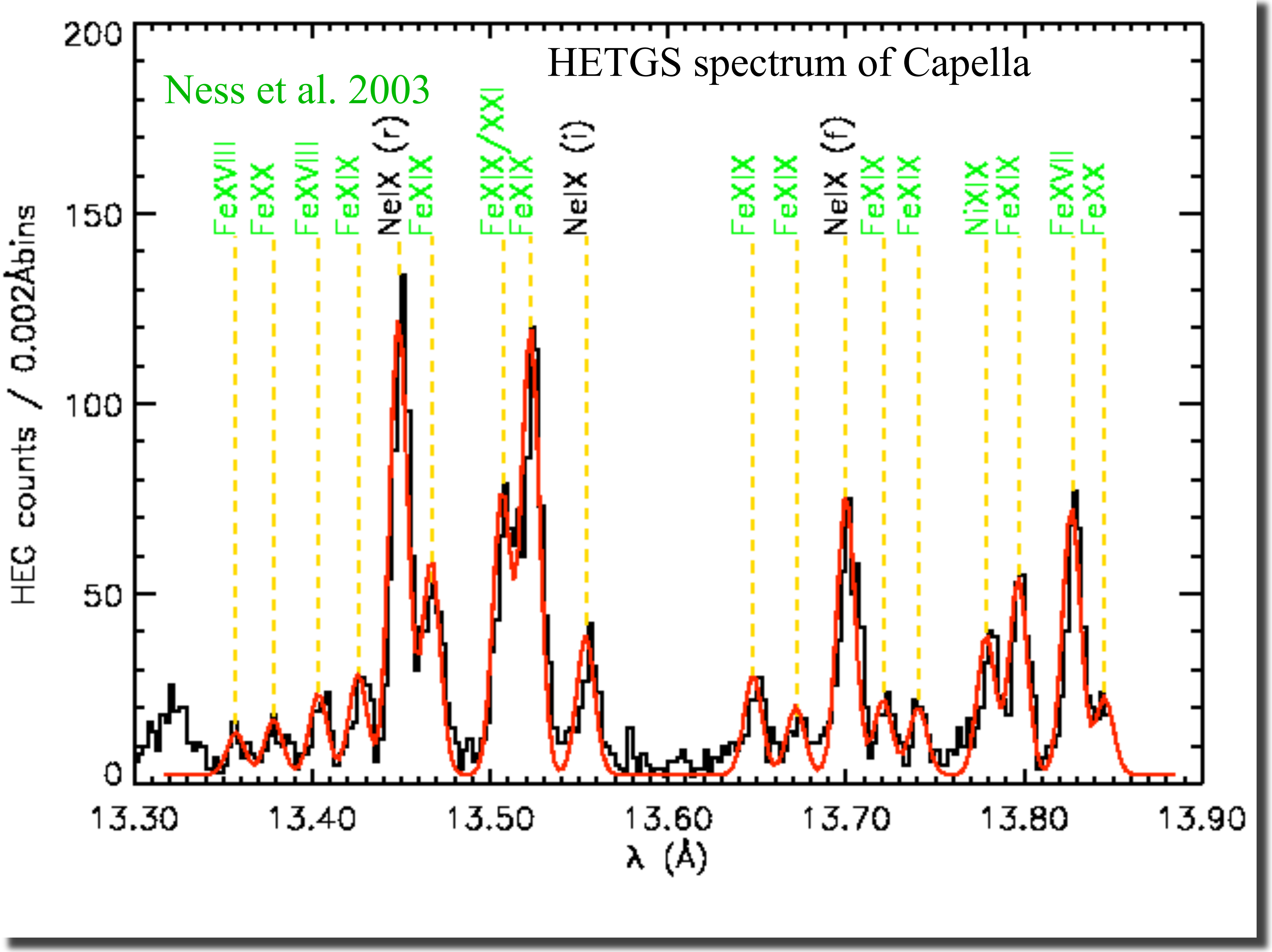
LETGS raw spectrum (of Algol 80 ksec)   2000



Capella

Chandra LETGS



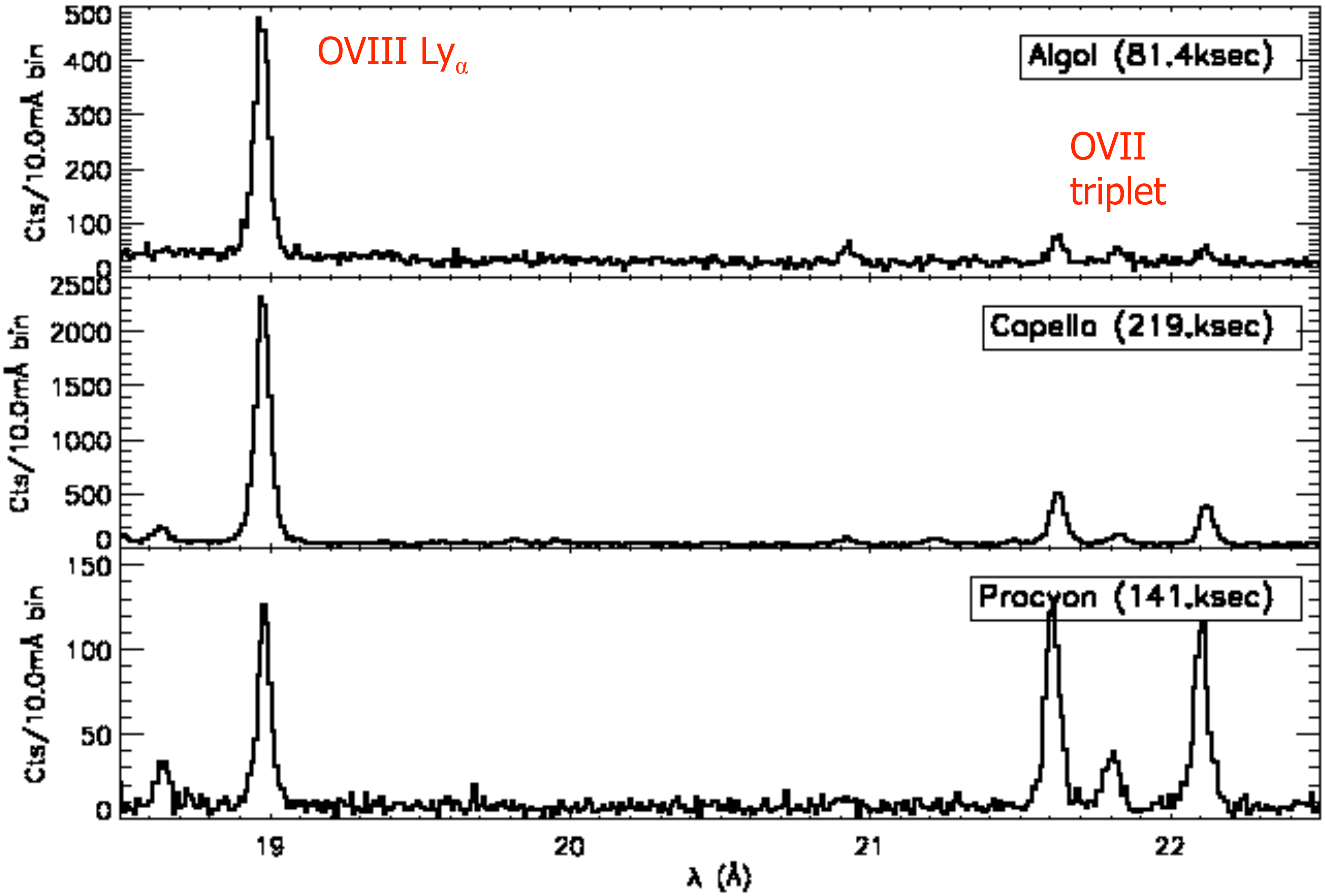


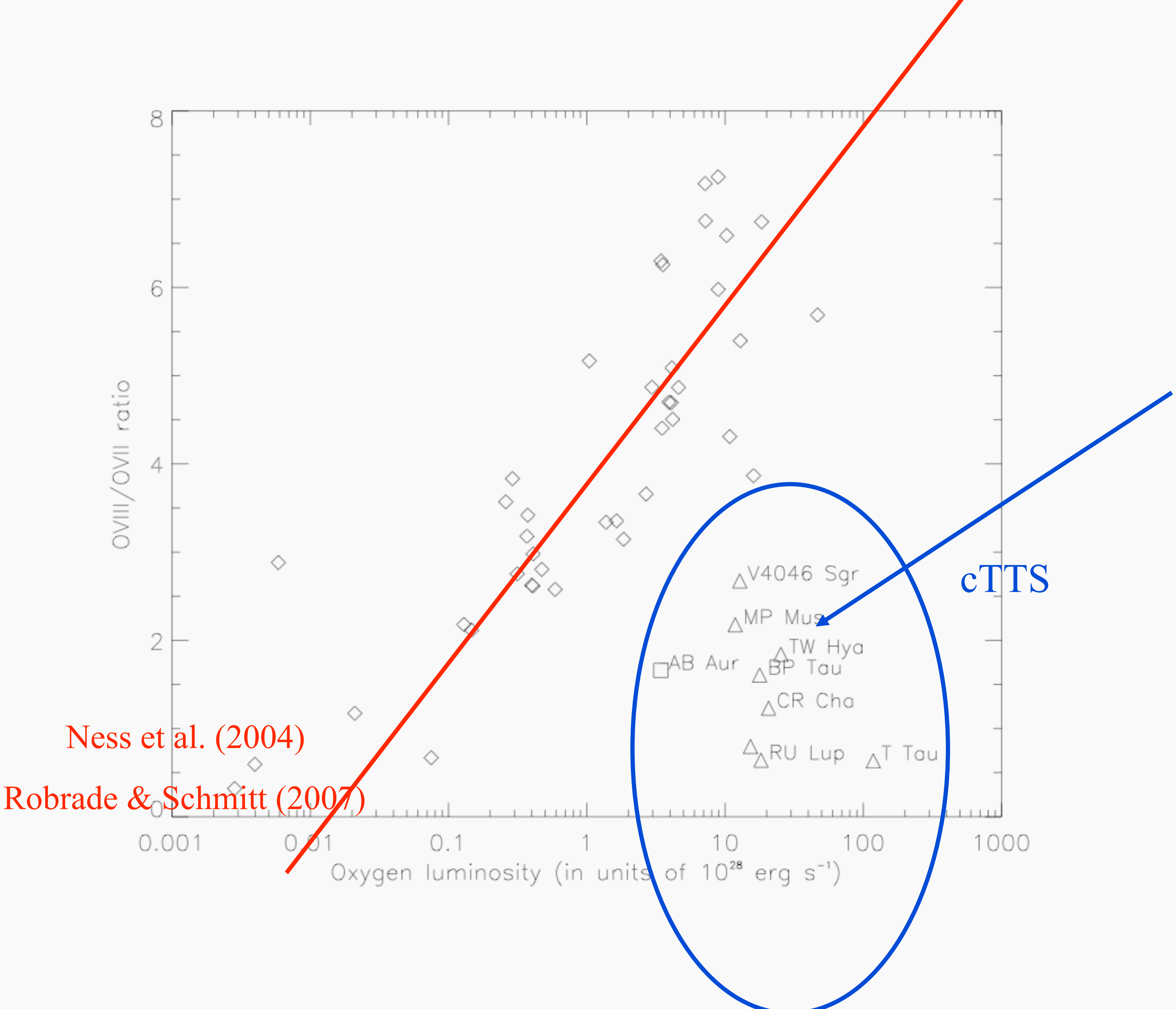
HETGS spectrum of Capella
Ness et al. 2003
FeXVIII
FeXX
FeXVIII
FeXIX
NeIX (r)
FeXIX
FeXIX/XXI
FeXIX
NeIX (i)
FeXIX
FeXIX
NeIX (f)
FeXIX
FeXIX
NiXIX
FeXIX
FeXVII
FeXX
HEG counts / 0.002Åbins
200
150
100
50
0
13.30
13.40
13.50
13.60
13.70
13.80
13.90
λ (Å)

Diagnostic capabilities:

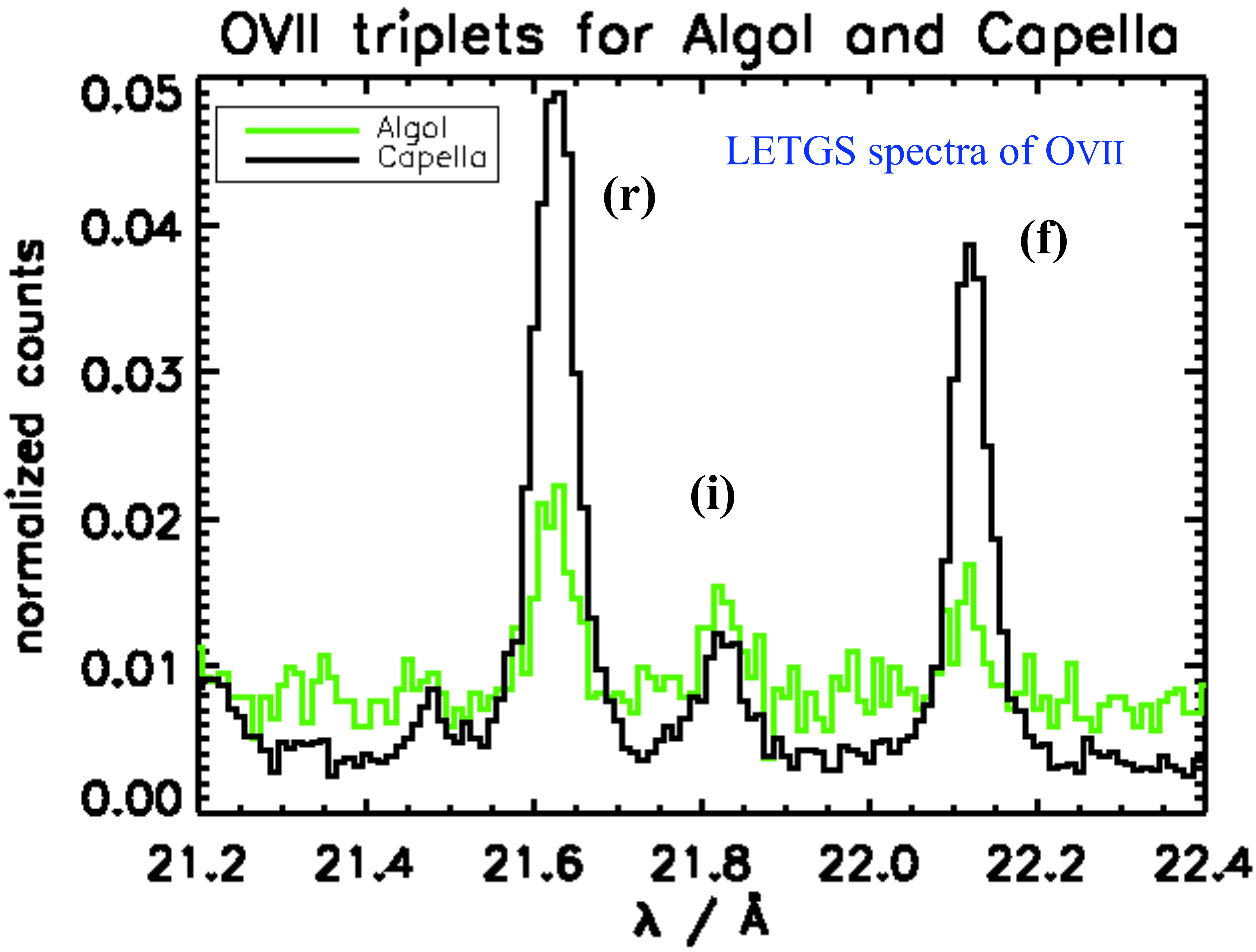
- Plasma temperature
- Plasma density
- Elemental composition
- Optical depth effects
- Doppler effects

Chandra LETGS:

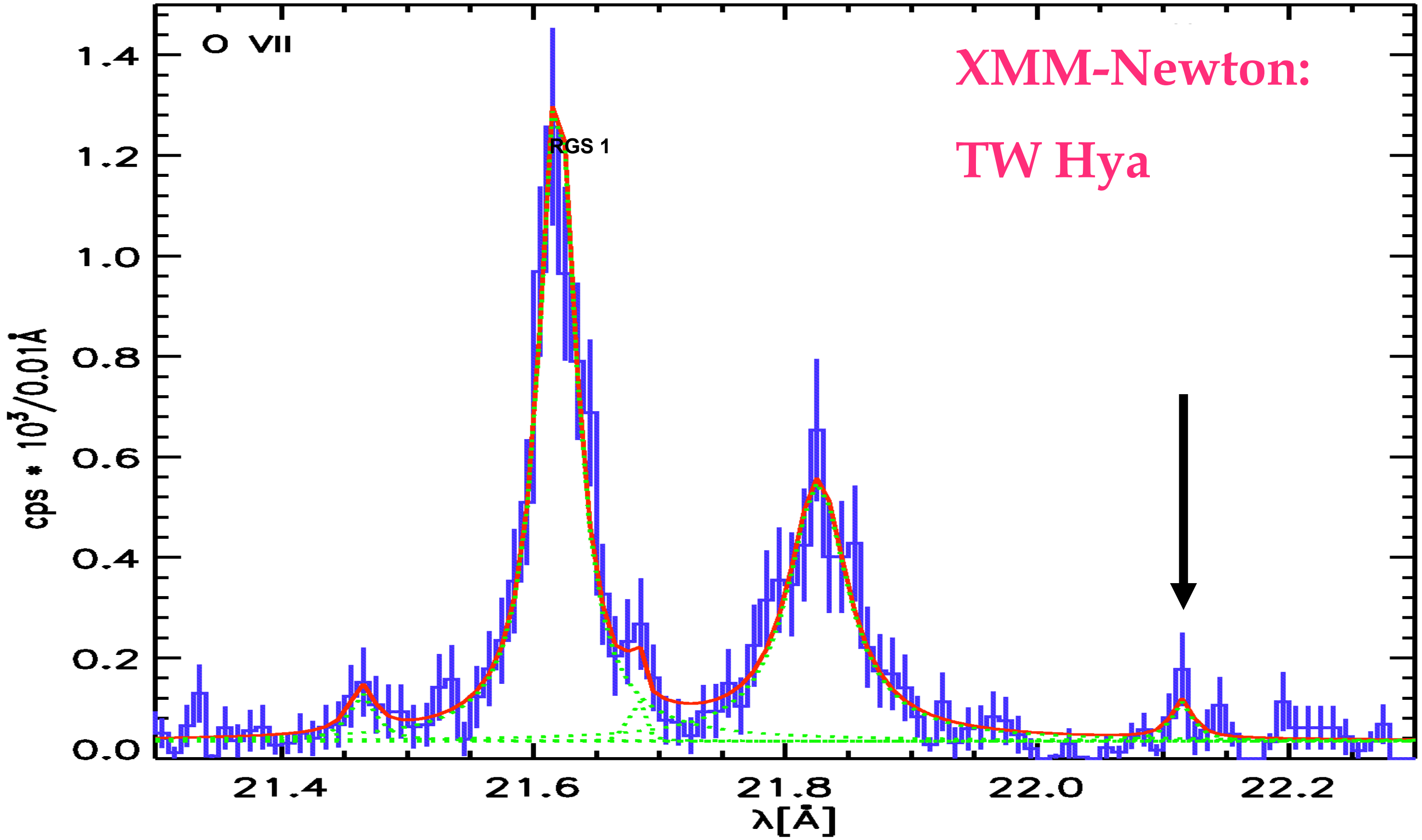




OVIII/OVII ratio
Oxygen luminosity (in units of 10^{28} erg s^{-1})
0.001
0.01
0.1
1
10
100
1000
0
2
4
6
8
V4046 Sgr
MP Mus
TW Hya
AB Aur
BP Tau
CR Cha
RU Lup
T Tau
cTTS
Ness et al. (2004)
Robrade & Schmitt (2007)


OVII triplets for Algol and Capella
Algol
Capella
LETGS spectra of OVII
(r)
(i)
(f)
normalized counts
0.00
0.01
0.02
0.03
0.04
0.05
21.2
21.4
21.6
21.8
22.0
22.2
22.4
λ / Å

X-ray spectrum of TW Hya (CTTS): OVII triplet



forbidden line almost absent !

Stelzer & Schmitt (2004) TW Hya

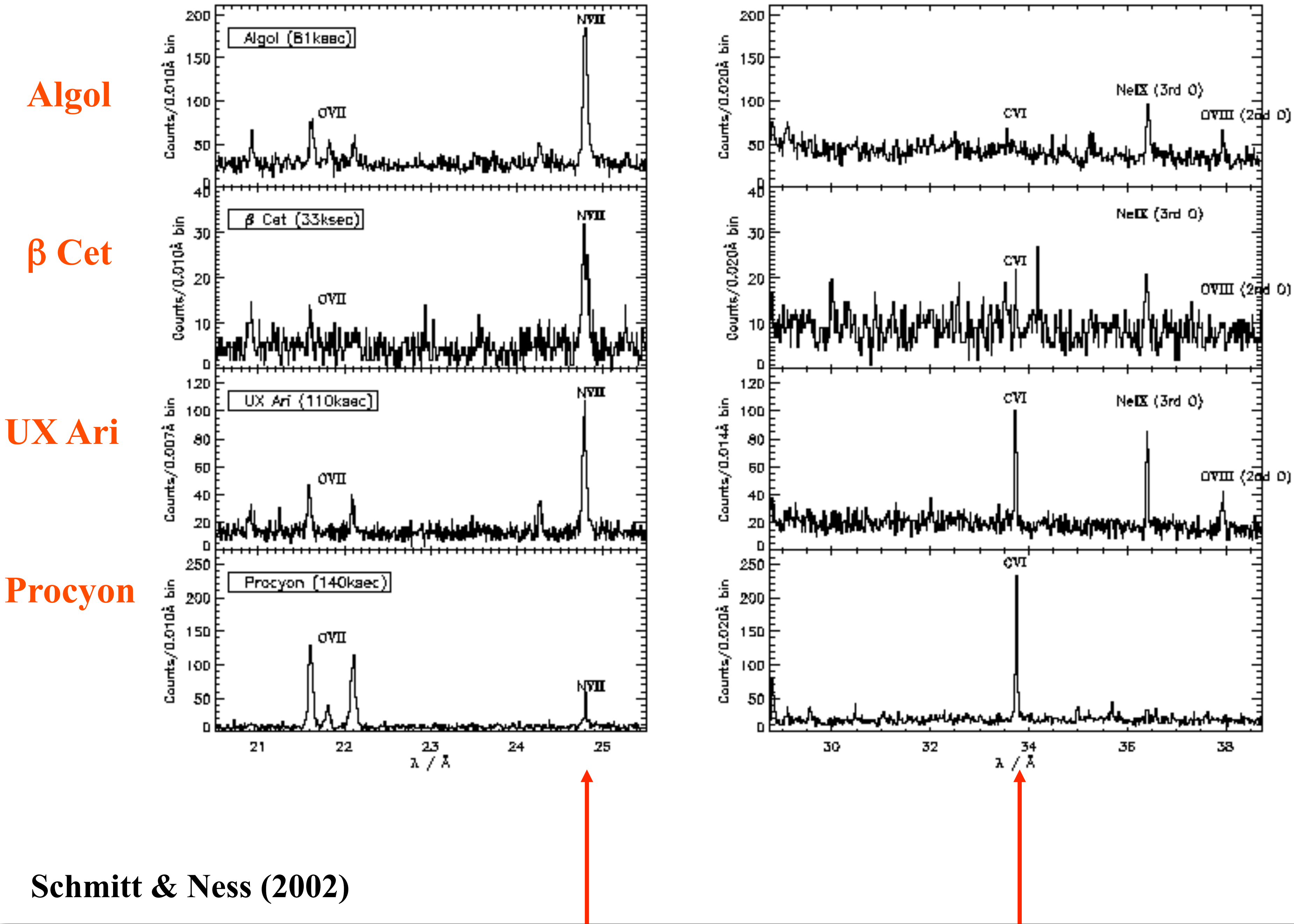
Schmitt et al. (2005) BP Tau

$n_e \geq 10^{13}\ cm^{-3}$

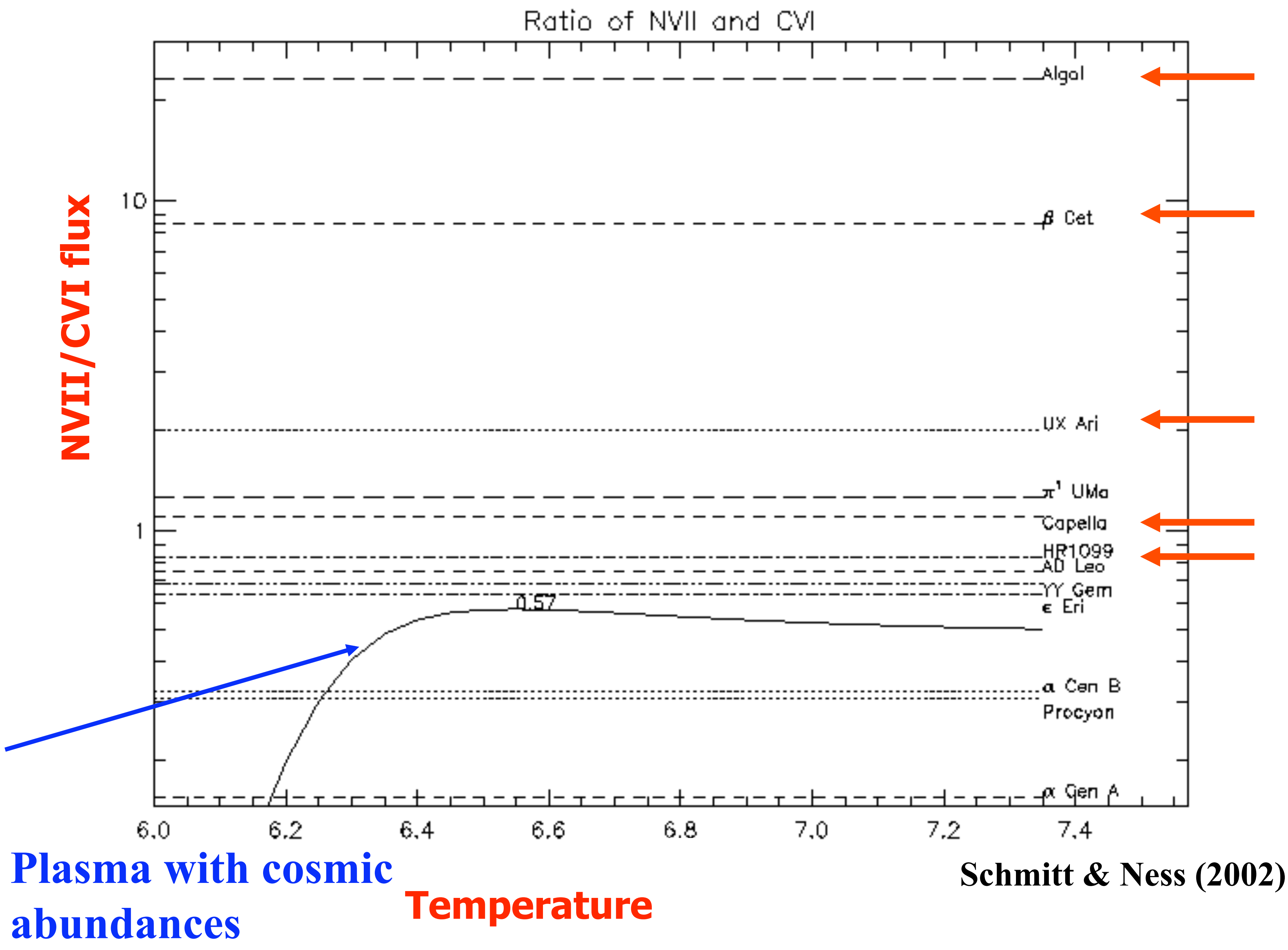
$T \approx 2.8\ 10^6\ K$

$L_X \approx 10^{30}\ \ erg/\sec$

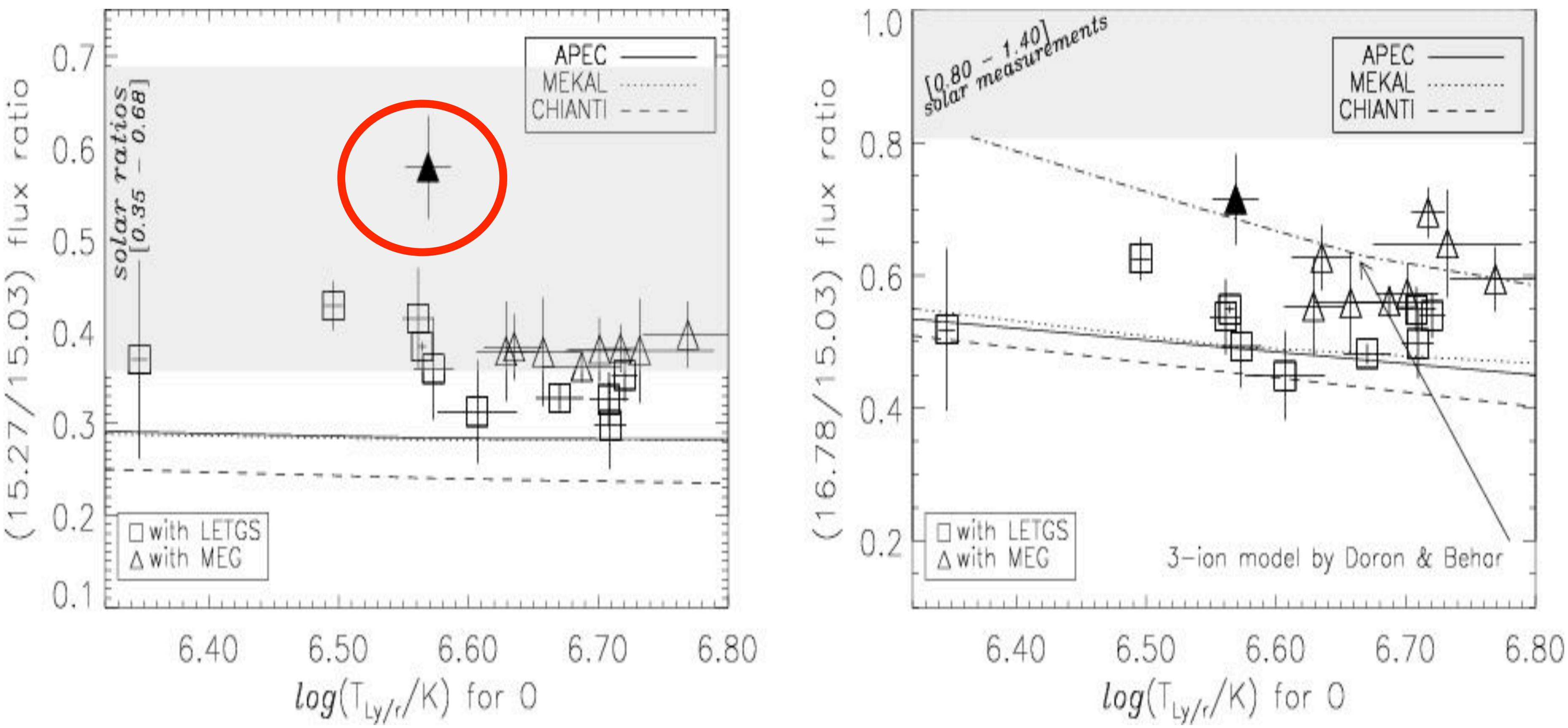
metal-depleted accretion shock !



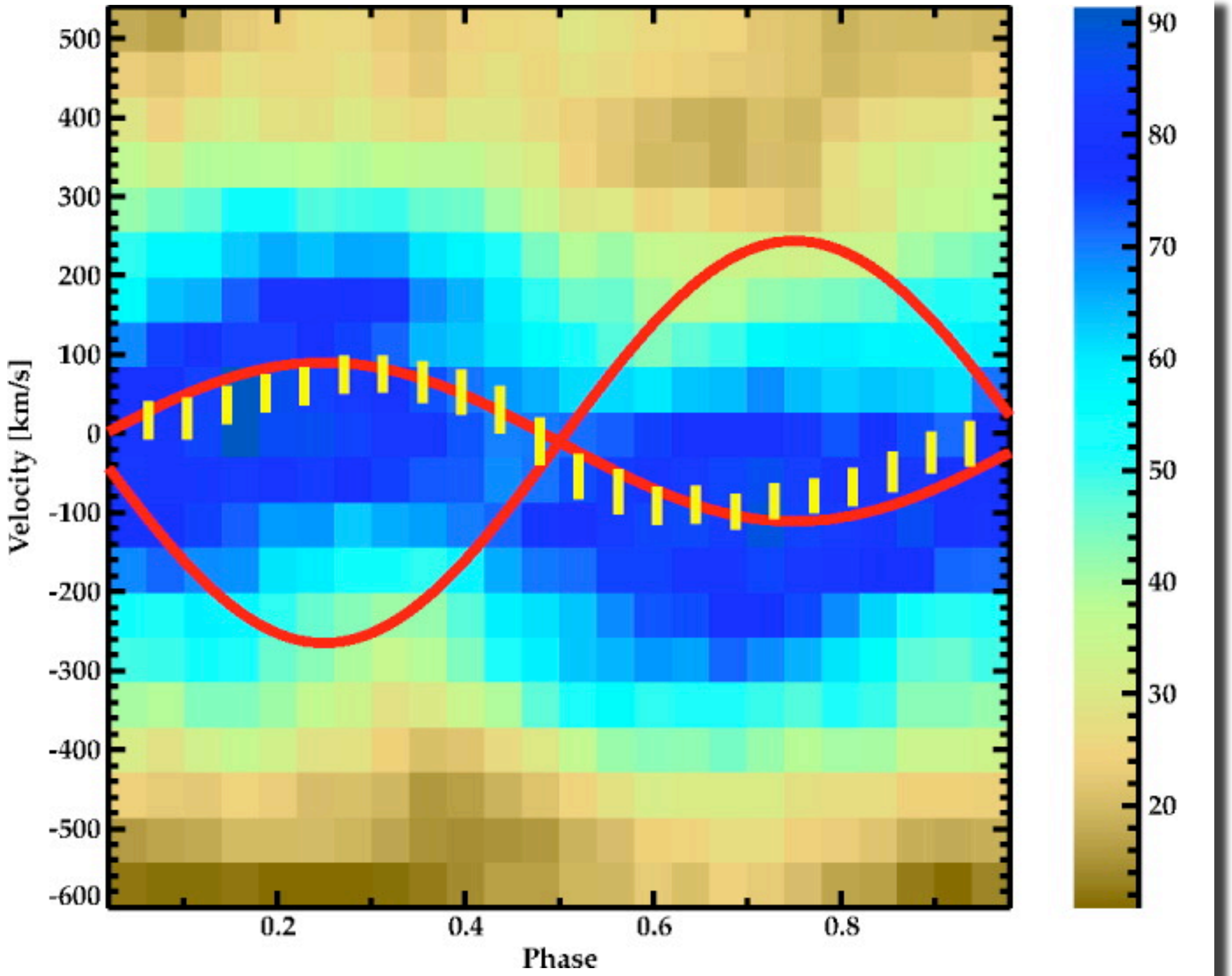
Schmitt & Ness (2002)



Schmitt & Ness (2002)



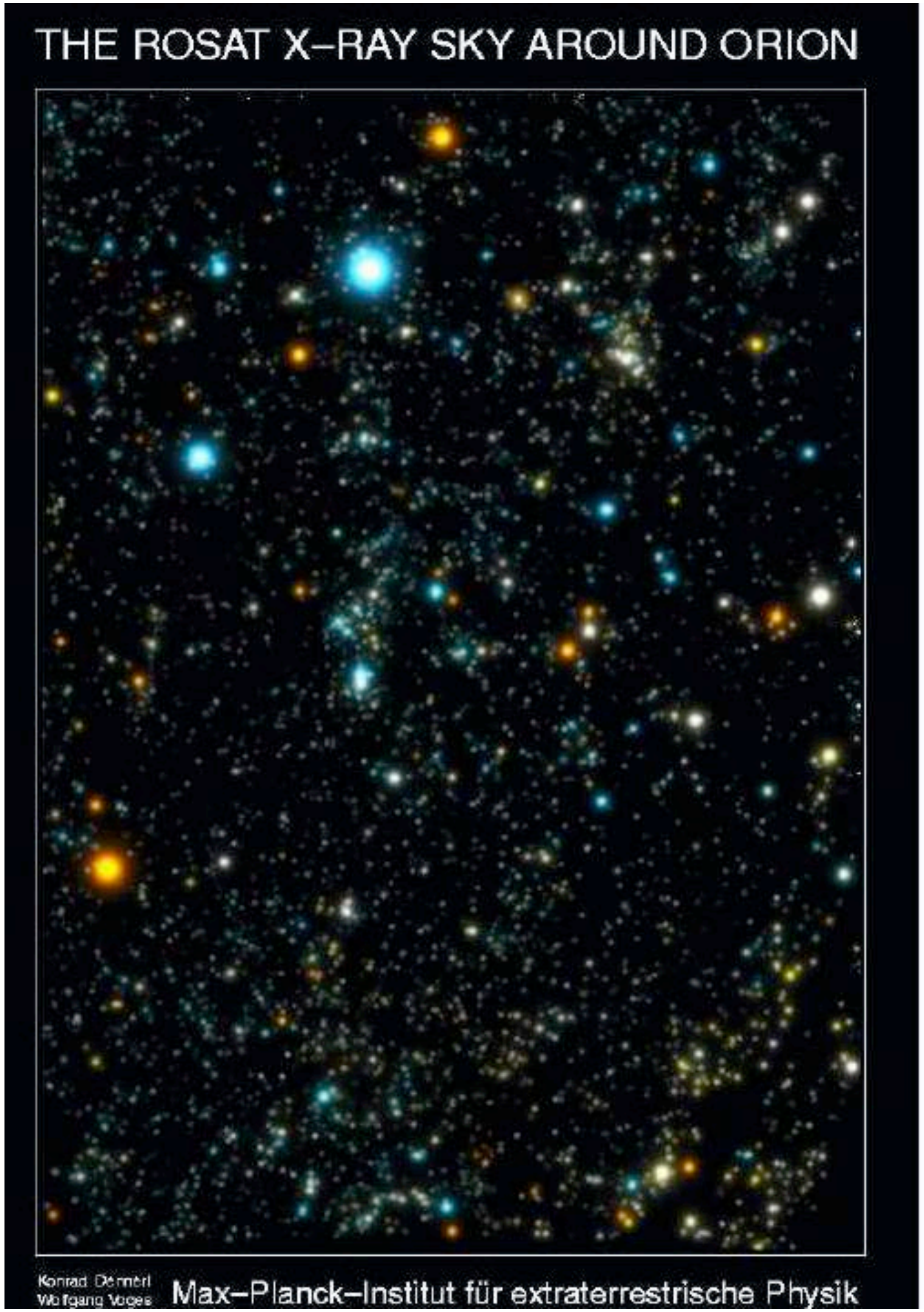
Ness et al. (2003)



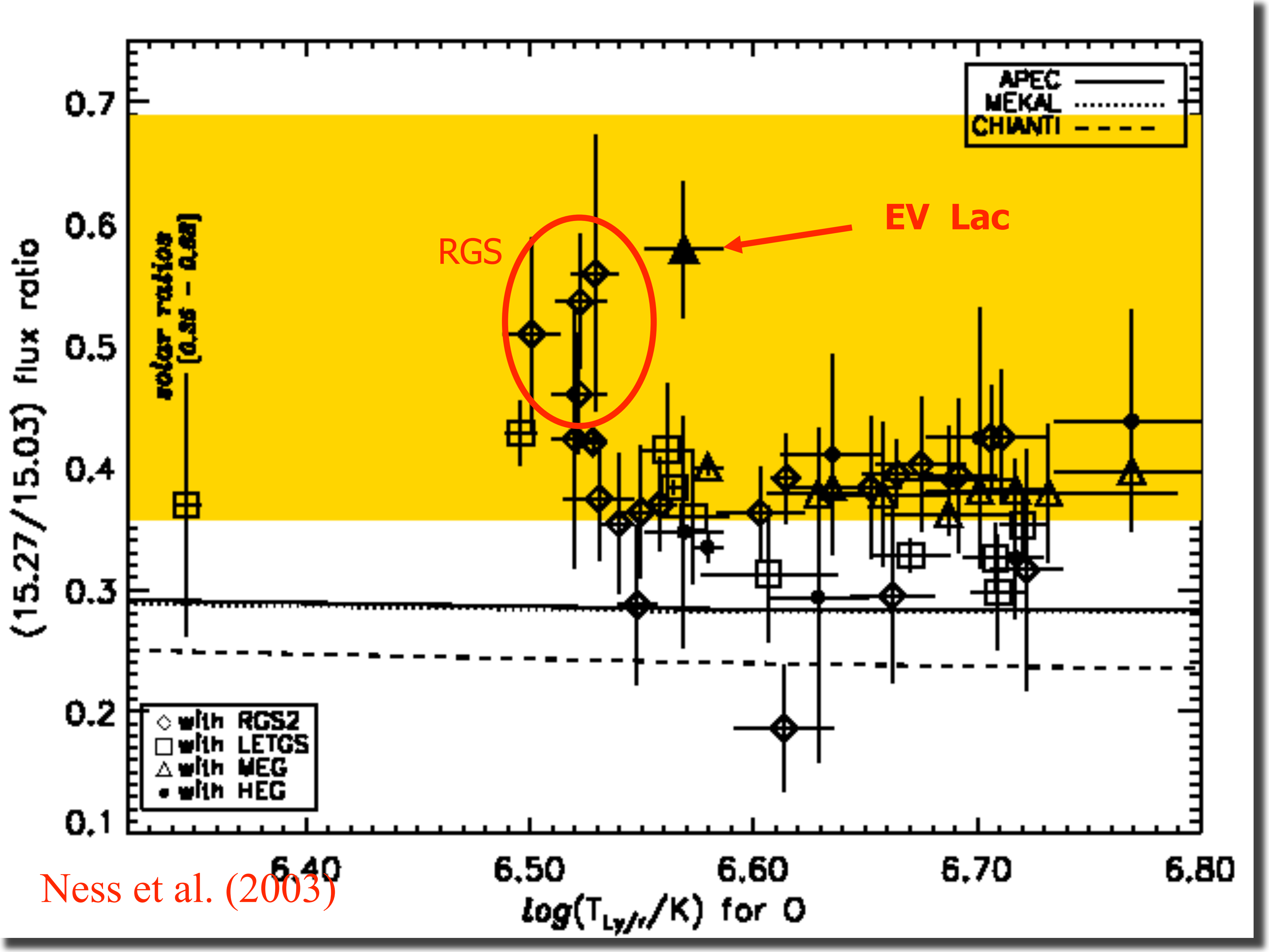
VW Cep: Huenemoerder et al. (2006)

Conclusions:

- Magnetic activity is ubiquitous among late-type stars
- The Sun shows (atypically ?) weak activity phenomena
- X-ray spectra are thermal
- High-resolution spectra otained Chandra and XMM-Newton have opened a new world
- Plasma diagnostics of stellar coronae


THE ROSAT X–RAY SKY AROUND ORION
Konrad Dennerl
Wolfgang Voges
Max–Planck–Institut für extraterrestrische Physik


THE OPTICAL SKY AROUND ORION
Konrad Dennerl
Wolfgang Voges
Max–Planck–Institut für extraterrestrische Physik



Ness et al. (2003)