CBK PAN

eHeroes

SEVENTH FRAMEWORK PROGRAMME

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SOLAR FLARE SULFUR ABUNDANCE

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Offer from solar soft X-ray spectroscopy

- **Spectra** are formed in optically thin multimilion K plasmas; every formed photon escapes the source region (coronal part of active region or flare)
- **Continuum** is pronounced again, fomed in **f-f**, **f-b**, and two-photon processes
  - **f-f** arises a consequence of bremsstahlung on protons
  - **f-b** depends somewhat on plasma composition; important are more abundant elements
  - Two-photon emission is weak ~100 x less important
- **Lines** seen in emission arise as a consequence of presence of heavier elements in trace quantities
  - Line intensities are proportional to abundance of contributing element
  - Noble element argon resonance spectra are strong, (no lines of Ar are significant in other spectral ranges for the Sun)

Solar coronal abundances

Emission line flux from a volume V is

$$F_{line} = \frac{const.}{4\pi(A.U.)^2} \frac{N_E}{N_H} \int G(T_e) N_e{}^2 dV$$

where

$$G(T_e) = \frac{N_{ion}}{N_E} \frac{e^{-W/kT_e}}{T_e{}^{1/2}}$$

So we can get the **absolute element abundance** N_E/N_H knowing excitation and ionization parameters for the line (these depend on T_e).

Soft X-rays are formed in T > 1 MK, so derived composition relates to coronal structures not the photosphere

Important properties of X-ray spectrometers for abundance studies

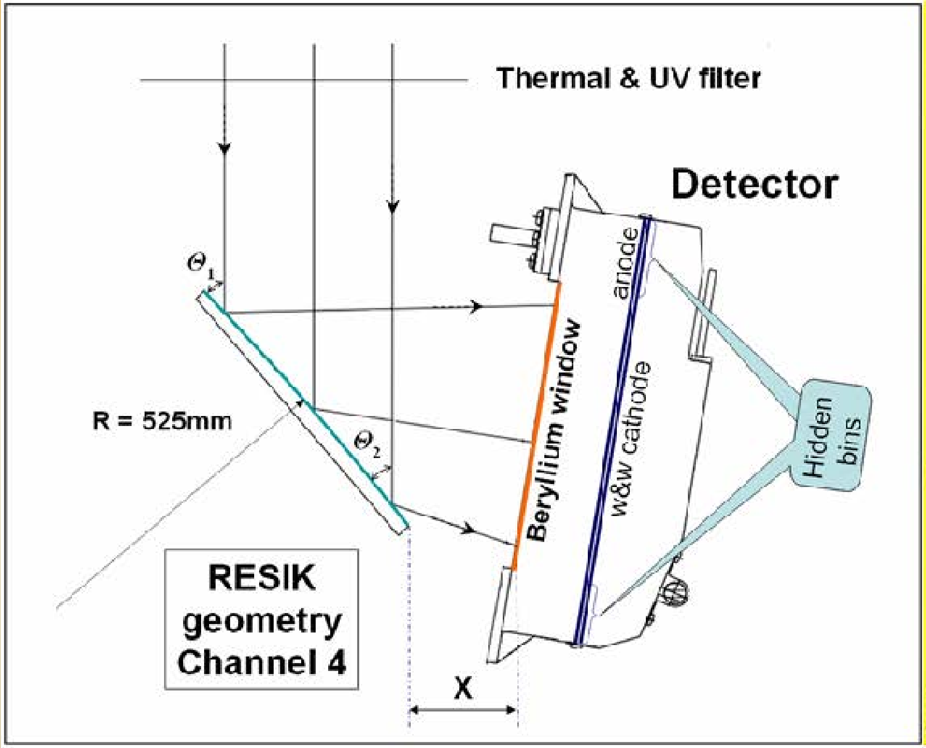
- **Good spectral resolution**, allowing to distinguish individual unblended lines of particular element
- **Good sensitivity** allowing to see lines of rare odd-Z atomic number elements like Cl and K
- **Reliable continuum** level **can** be measured – this allows for **absolute** abundance determinations (relative to hydrogen)
  - this was very hard to accomplish requirement as the observed „continuum" is usually strongly contaminated by fluorescence.
  - Early Bragg spectroscopy: *Intercosmos*, *P78*, *Hinotori*, XRP on *SMM*, BCS on *Yohkoh* – *always contaminated*

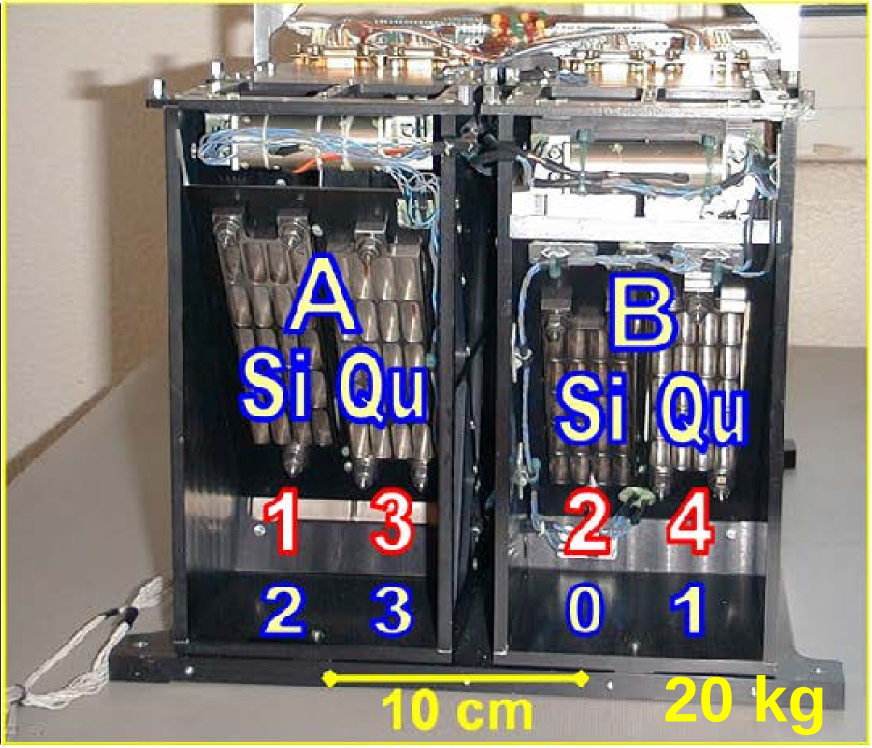
Improved was RESIK, Bragg law:

$$k\lambda = 2d \sin\Theta$$

Рентгеновский Спектрометр с Изогнутыми Кристаллами

Measures spectra in the range: ~ **3.3 Å ÷ 6.1 Å, instantly in all λ**

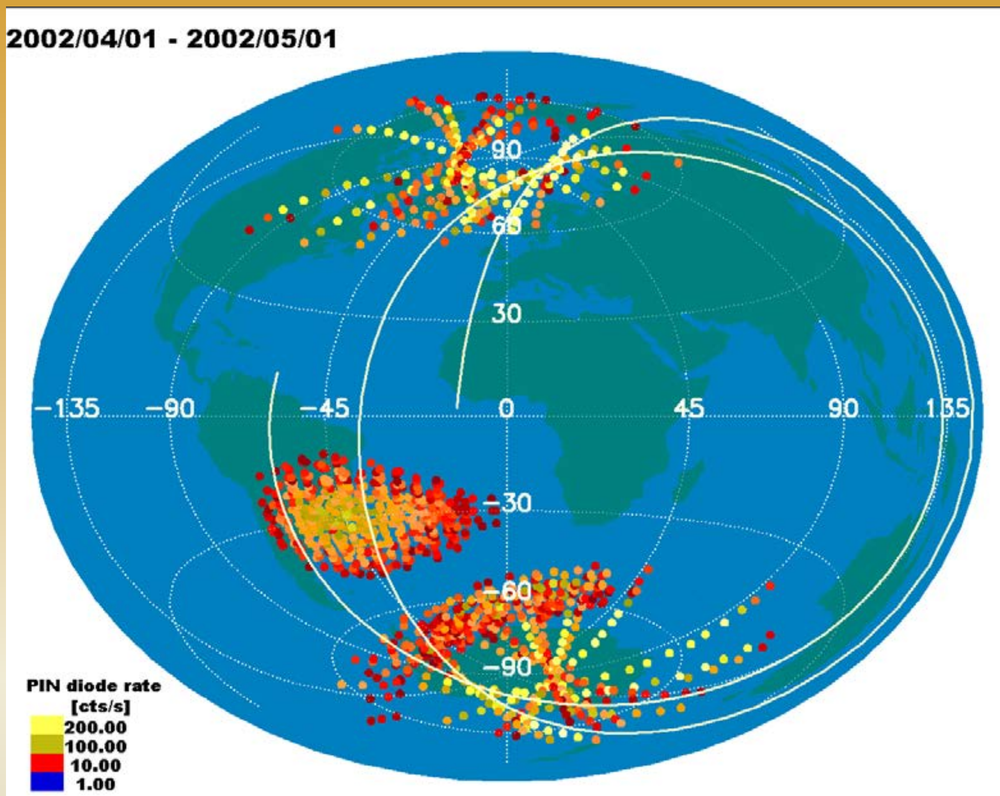




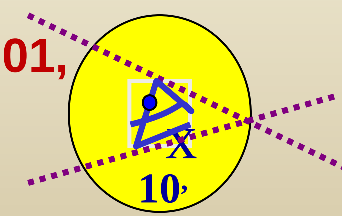
UCL MSSL · CLRC · NRL · POLISH ACADEMY OF SCIENCES SPACE RESEARCH CENTRE · IZMIRAN

Key people: **Len Culhane, George Doschek V.D. Kuznetsov, Jim Lang, R.D. Bentley**

RESIK operated aboard CORONAS-F Russian satellite



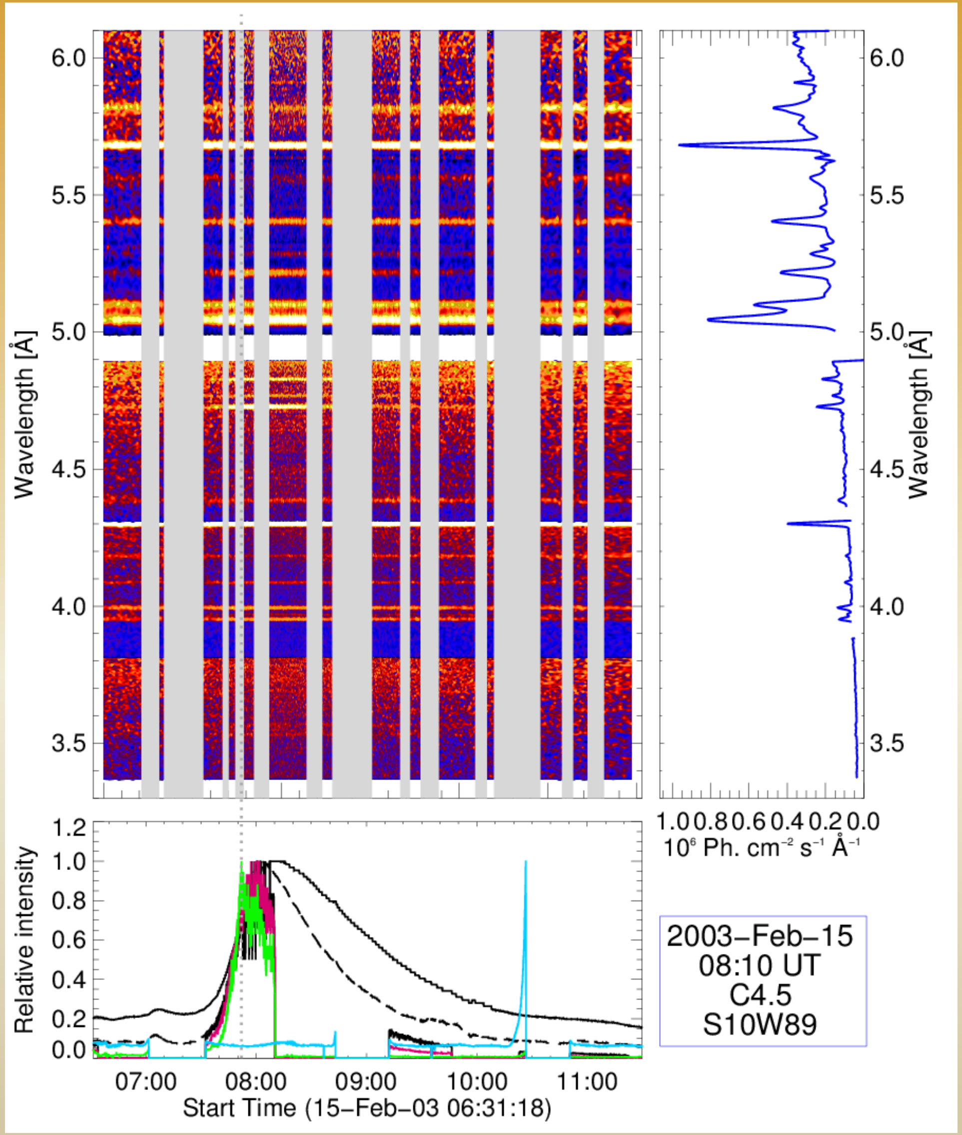
Launched 31 July 2001, polar orbit, 95min, ~550 km semi-Sun-synchronous



- **15 Dec. 2002 – 15 March 2003** optimum settings were used
- **~60 000 spectra available**
  - 10% processed to Level2 science grade using results of RAL ground calibrations

Example flare timeline

http://www.cbk.pan.wroc.pl/experiments/resik/RESIK_Level2/index.html

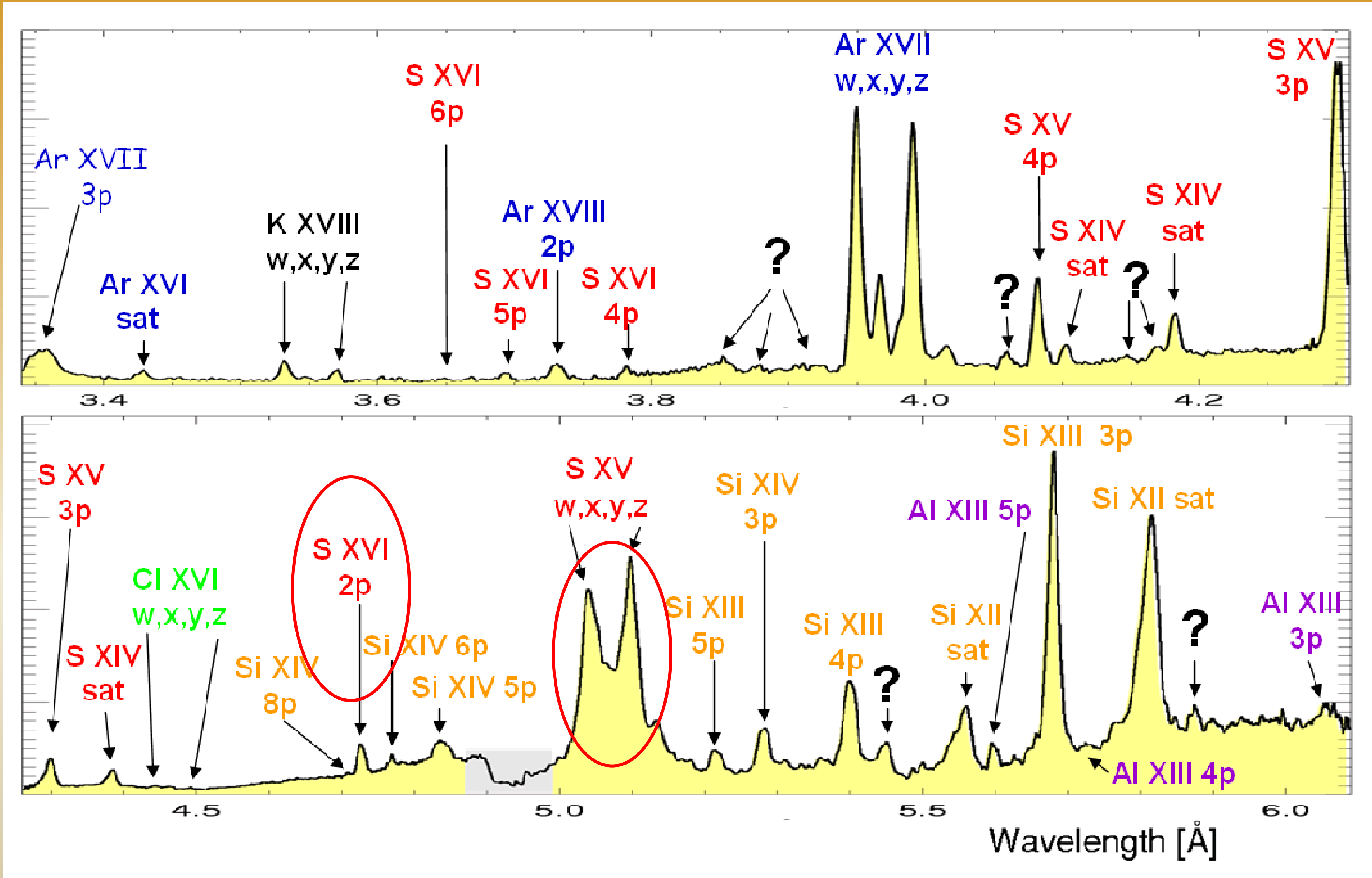


- 30 Flares processed to Level2
  - -from B to X class events
  - ~4000 individual spectra are available,
  - **GOES data collected for each DGI**

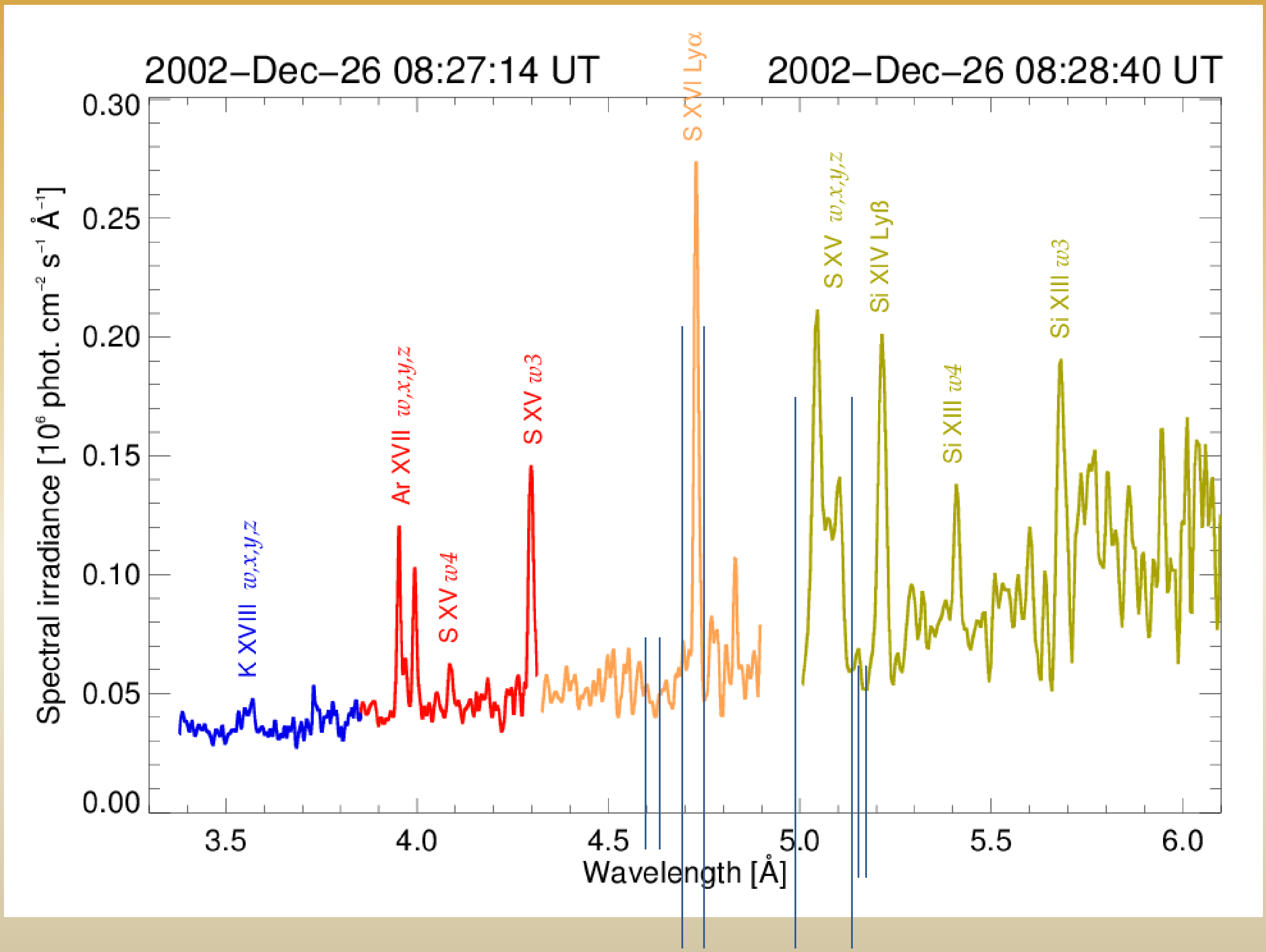
    → average T & EM
  - DGI 2 s ÷ 300 s
- ~300 non-flaring AR spectra
  - DGI 312 s

Absolute accuracy 10-20% !!!

RESIK Spectra, T-range 3-30 MK



The method of S abundance determinations



Select spectral bands containing Sulfur lines

Select bands for continuum, next to the lines

Subtract continuum from the line bands-making allowance for different band-widths

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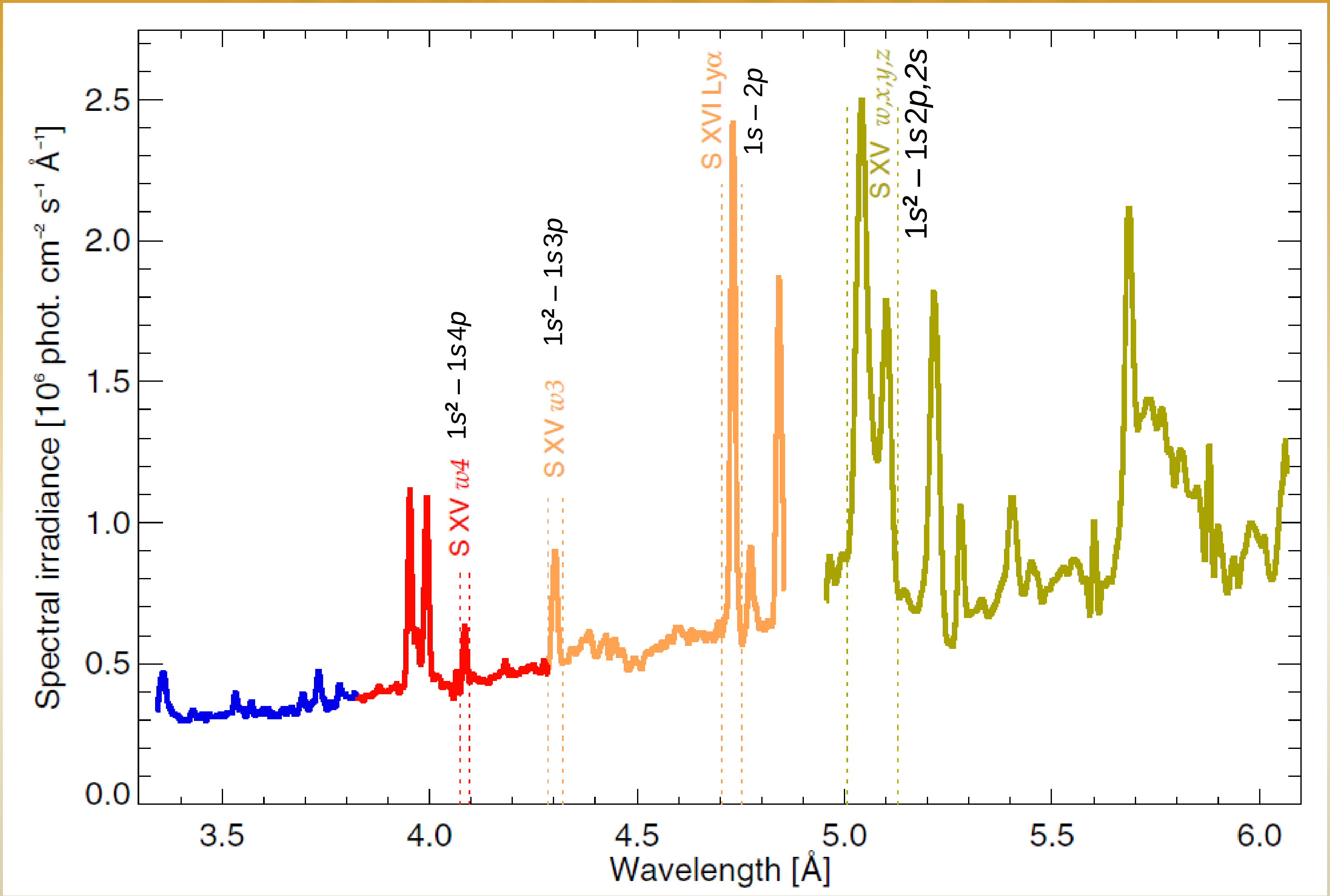
Actual line selection



J. SYLWESTER[1], B. SYLWESTER[1], K. J. H. PHILLIPS[2], AND V. D. KUZNETSOV[3]

The method of S abundance determinations II

$$\underset{\text{KNOWN}}{F_{line}} = \frac{const.}{4\pi(A.U.)^2} \underset{A_S}{\frac{N_E}{N_H}} G(T_e) \underset{\text{EM}}{\int N_e^2 dV}$$

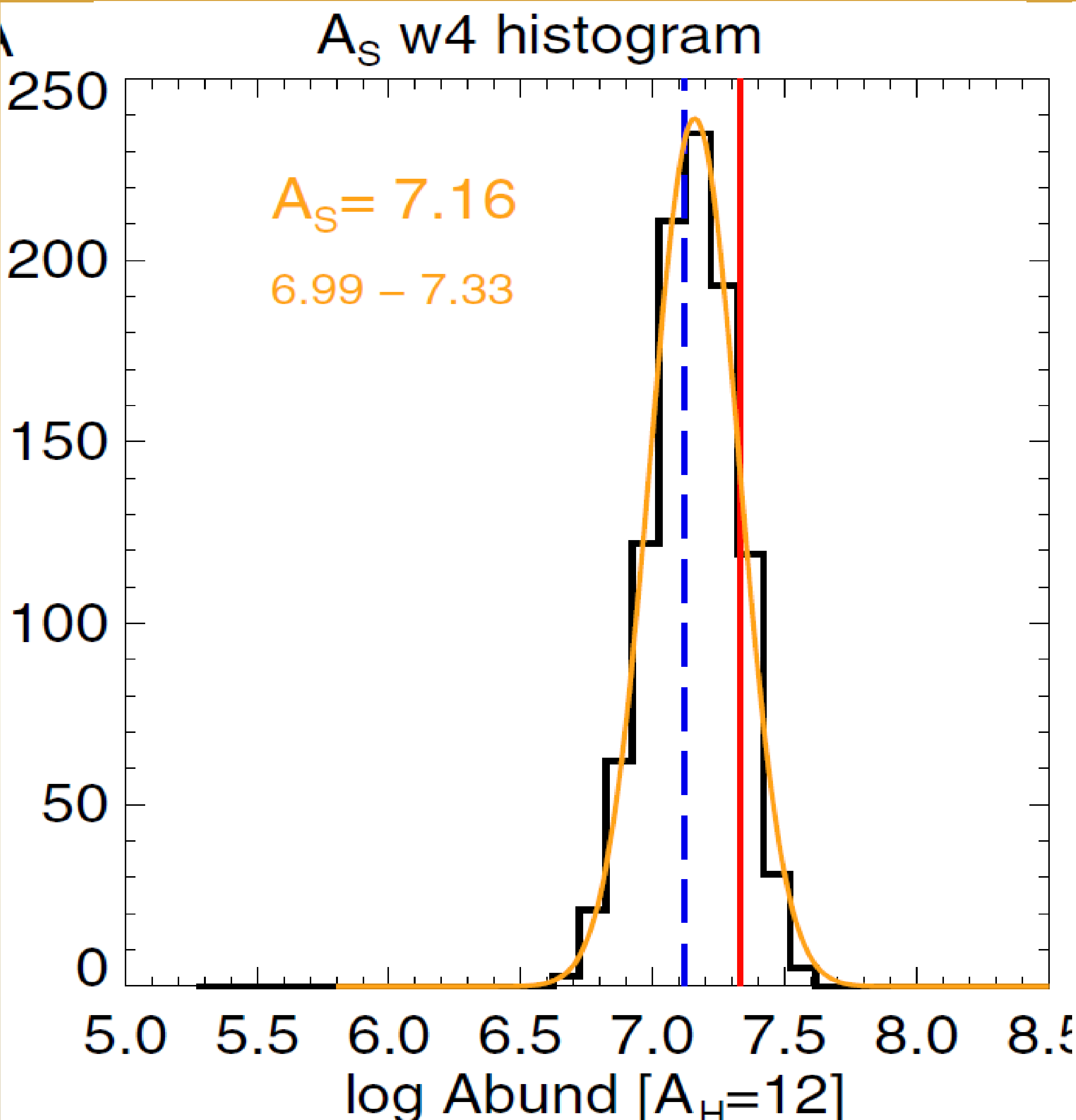
G(T$_e$*)* for appropriate spectral band containing dominating line of interest is calculated using CHIANTI v7.0 spectral package, (all lines „in band" are included)
http://www.chiantidatabase.org/

We take ***T***$_e$ & ***EM*** values from standard ***GOES*** measurements interpretation

- The line fluxes depend on *T* and **EM**
  - Directly proportional to EM
  - Calculable *G(T*$_e$*)* shape defines the dependence on T_e

The results for Sulfur *w4* line,

He-like ion



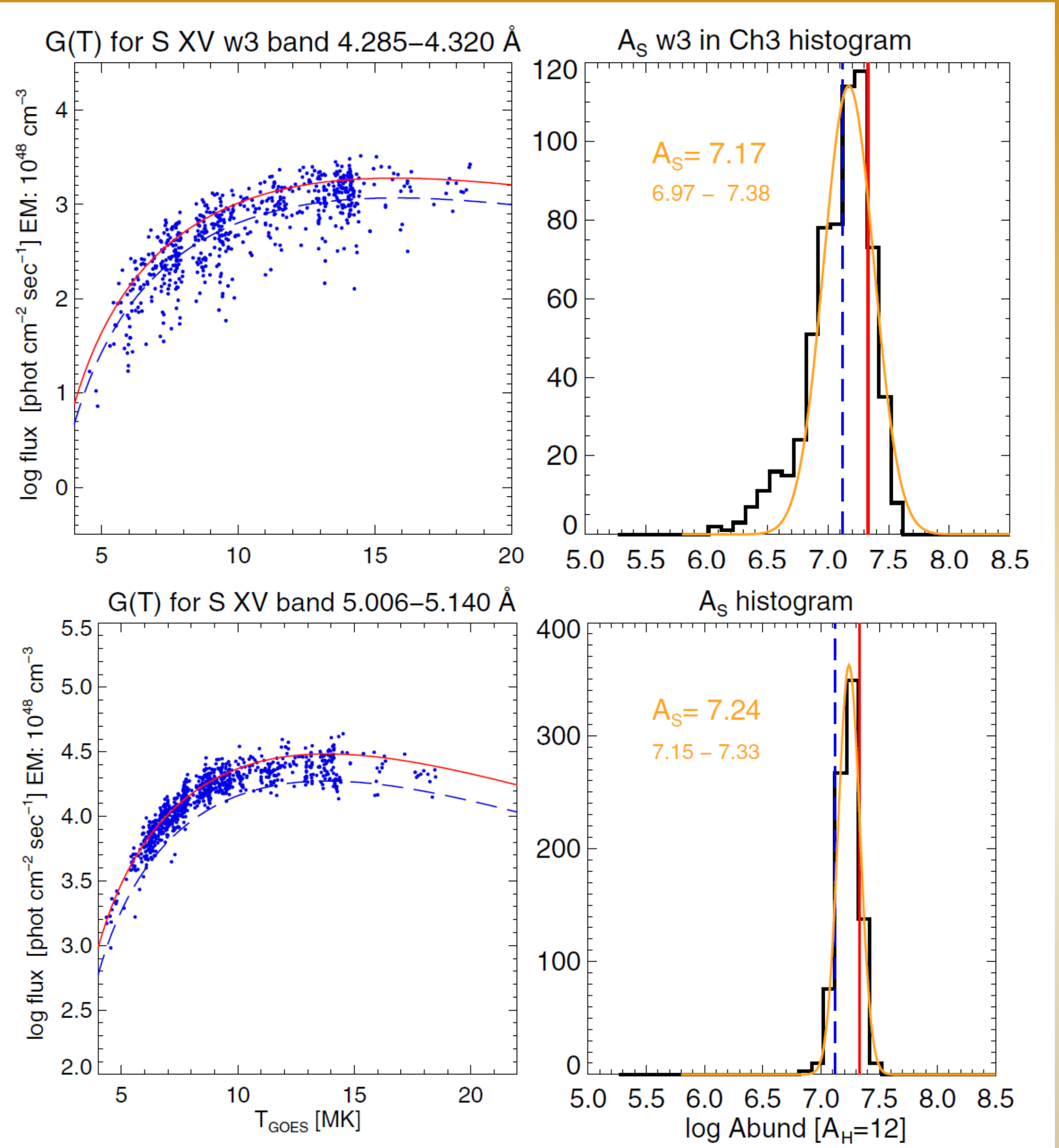
Distribution of abundance determinations with best-fit Gaussian curve. From the peak and width of the Gaussian, the S abundance is determined to be

***A*(S) = 7.16 ± 0.14**

The vertical blue dashed and red lines correspond to the photospheric and coronal abundance, respectively.

The results for Sulfur *w3* and w2 bands,

He-like ion



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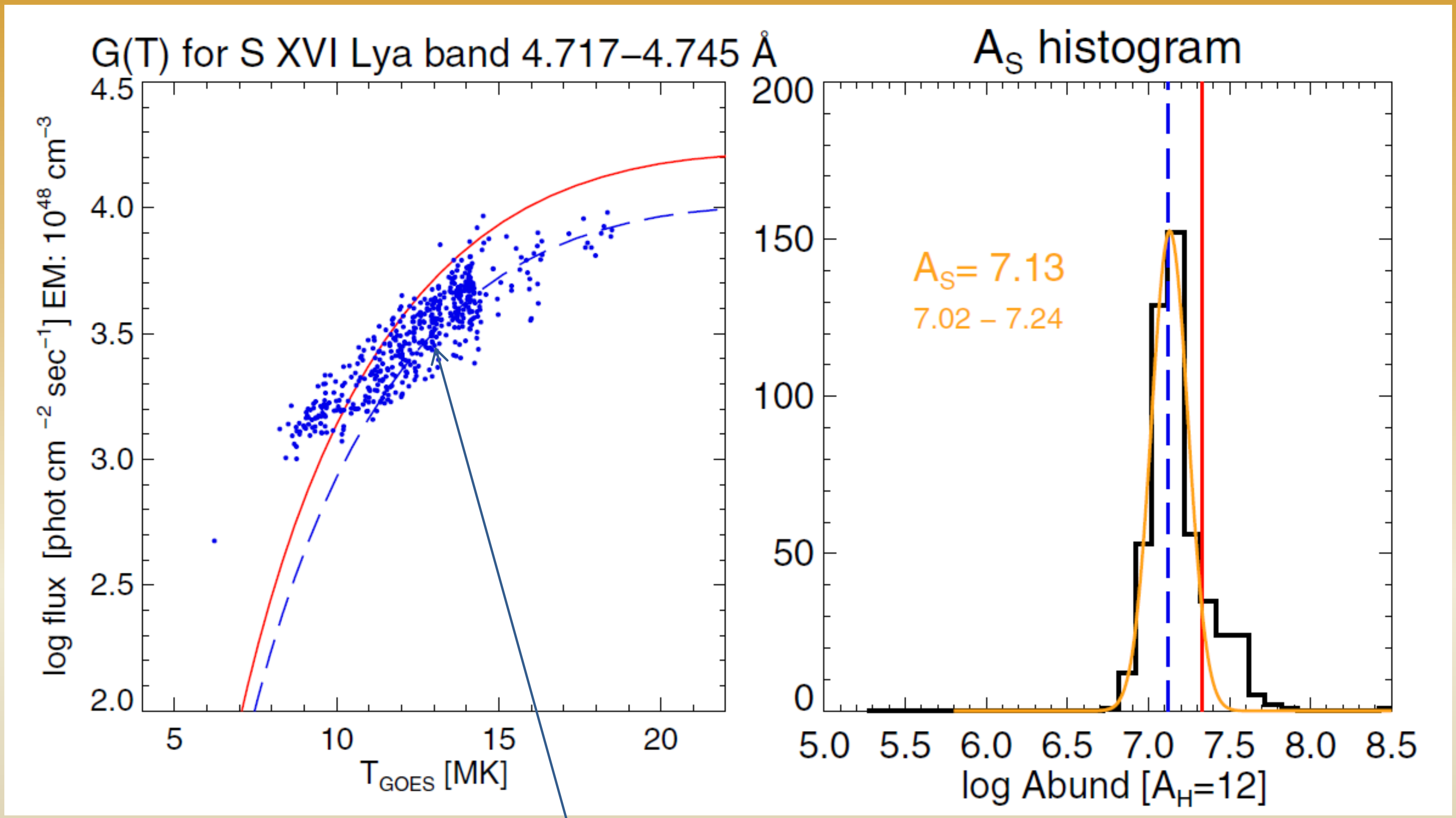
and S XVI Lyman α, H-like ion

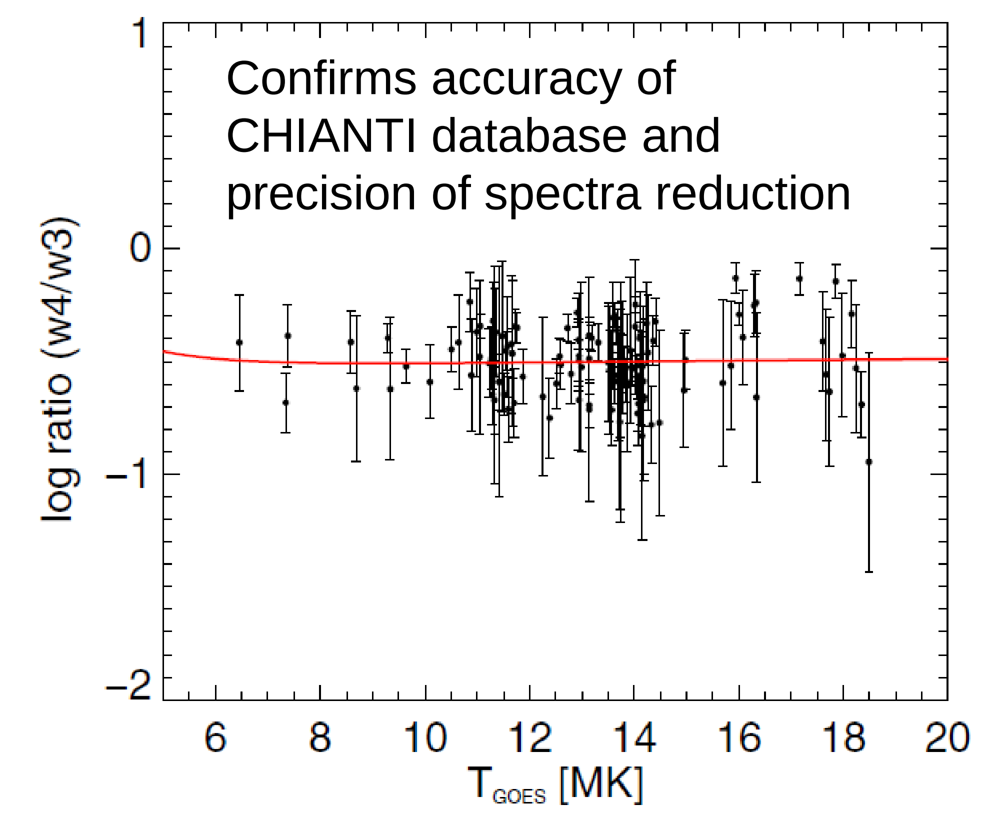


Shape of observed dependence is different from theoretically predicted: non-isothermal (DEM) and/or non-euilibrium

The Astrophysical Journal, 751:103 (7pp), 2012 June 1 doi:10.1088/0004-637X/751/2/103

Summary

This analysis of highly ioniz
flare spectra has led to sever
abundance which can be co
previous values. We conside
viz. **A(S) = 7.16 ± 0.17**, to be
in RESIK's channel 2 which
channels 3 and 4 where the
solar continuum practically
fluorescence can be measure
line flux ratio and comparin
theory (this is independent
equilibrium calculations), w
w3 line only ever appears in
edge possible anomalous re
effects can be neglected. This then enables another estimate of the sulfur abundance, **A(S) = 7.17 ± 0.20**, similar as expected to that from the w4 line.



Conclusions

- New aprroach is proposed for determination of elemental abundances from X-ray line spectra
- This approach has been successfully used for estimates of K, Cl and Ar coronal abundances as well.
- The method has been used to interpret *RHESSI* measurements of Fe line group intensities (Phillips & Dennis, ApJ, **748**:52, 2012, ***A*(Fe) = 7.91 ± 0.10**
- It forms a basis for a new experimental project: **ChemiX** Bragg spectrometer for Russian Interhelioprobe, sister mission for Solar Orbiter 10 x better spectral resolution, accuracy will exceed photosperic determinations; ChemiX is under design at SRC PAS

RESIK average abundances compared with other determinations

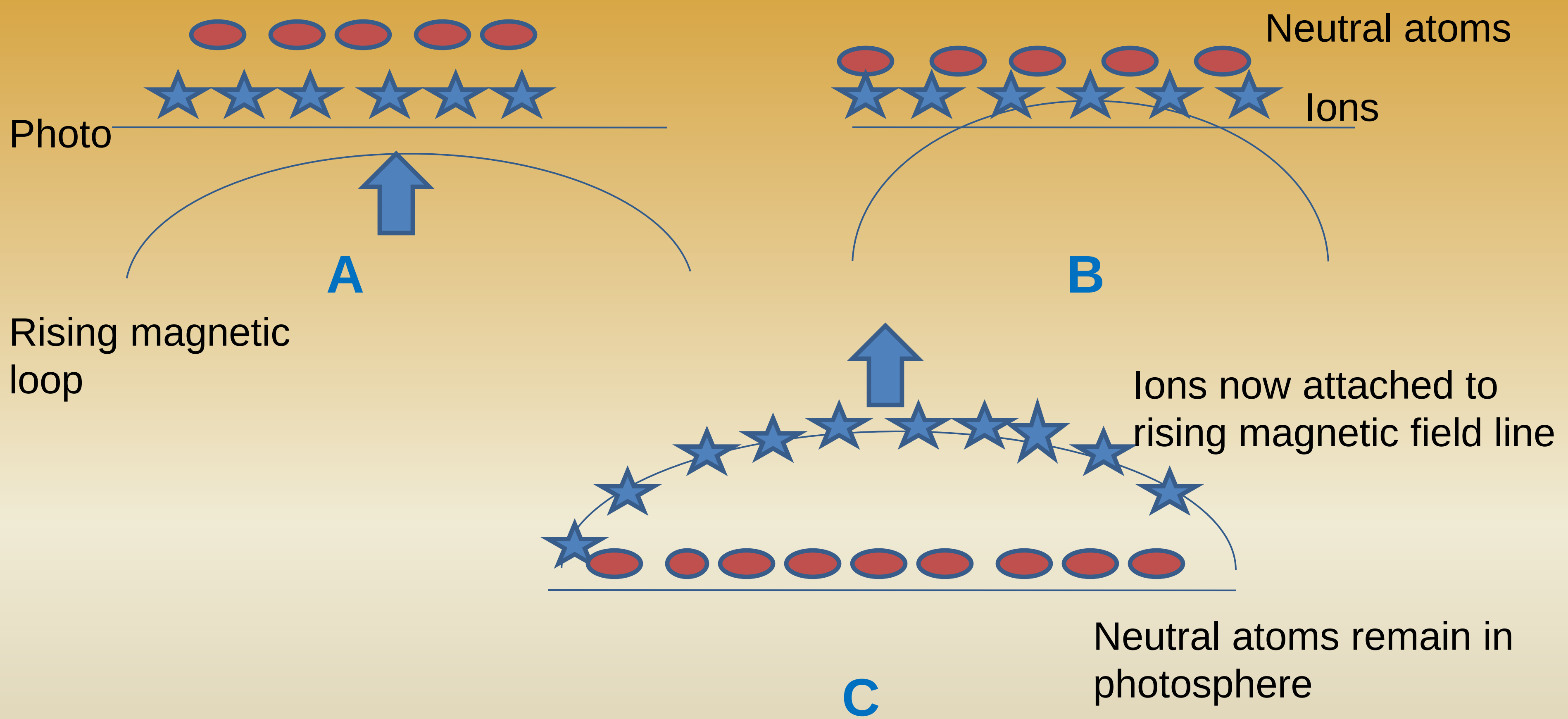
Element & FIP eV	$A_{phot.}$	$A_{coronal}$	A_{RESIK}	References
K 4.34	5.03 ± 0.09	5.67	**5.86 ± 0.20**	ApJ, 710, 2010
Ar 15.76	6.40 ± 0.13*	6.58	**6.45 ± 0.07**	ApJ, 720, 2010
Cl 12.97	5.50 ± 0.30	5.50	**5.75 ± 0.26**	ApJ, 738, 2011
S 10.36	7.12 ± 0.03	7.27	**7.16 ± 0.17**	ApJ, 751, 2012
Si 8.15	7.51 ± 0.09	8.10	**7.91 ± 0.15**	Sol. Phys., submitted

$A_{phot.}$ from Asplund et al. Annu. Rev. Astron. Astrophys. 2009. 47:481–522,
$A_{coronal}$ from CHIANTI, extended coronal, mostly Feldman, U., Mandelbaum, P., Seely, J.L., Doschek, G.A., Gursky H., 1992, ApJSS, 81, 387

* from proxies

Thank you!

A possible FIP mechanism: Rising magnetic loop



Ions enrich the corona

DIAGRAM FOR A LOW-FIP ELEMENT, courtesy KJHP