Time ~~Evolution~~Observation of De-excitation Line Shapes in Solar Flare

Wei, Chen and W. Q. Gan
Purple Mountain Observatory, China

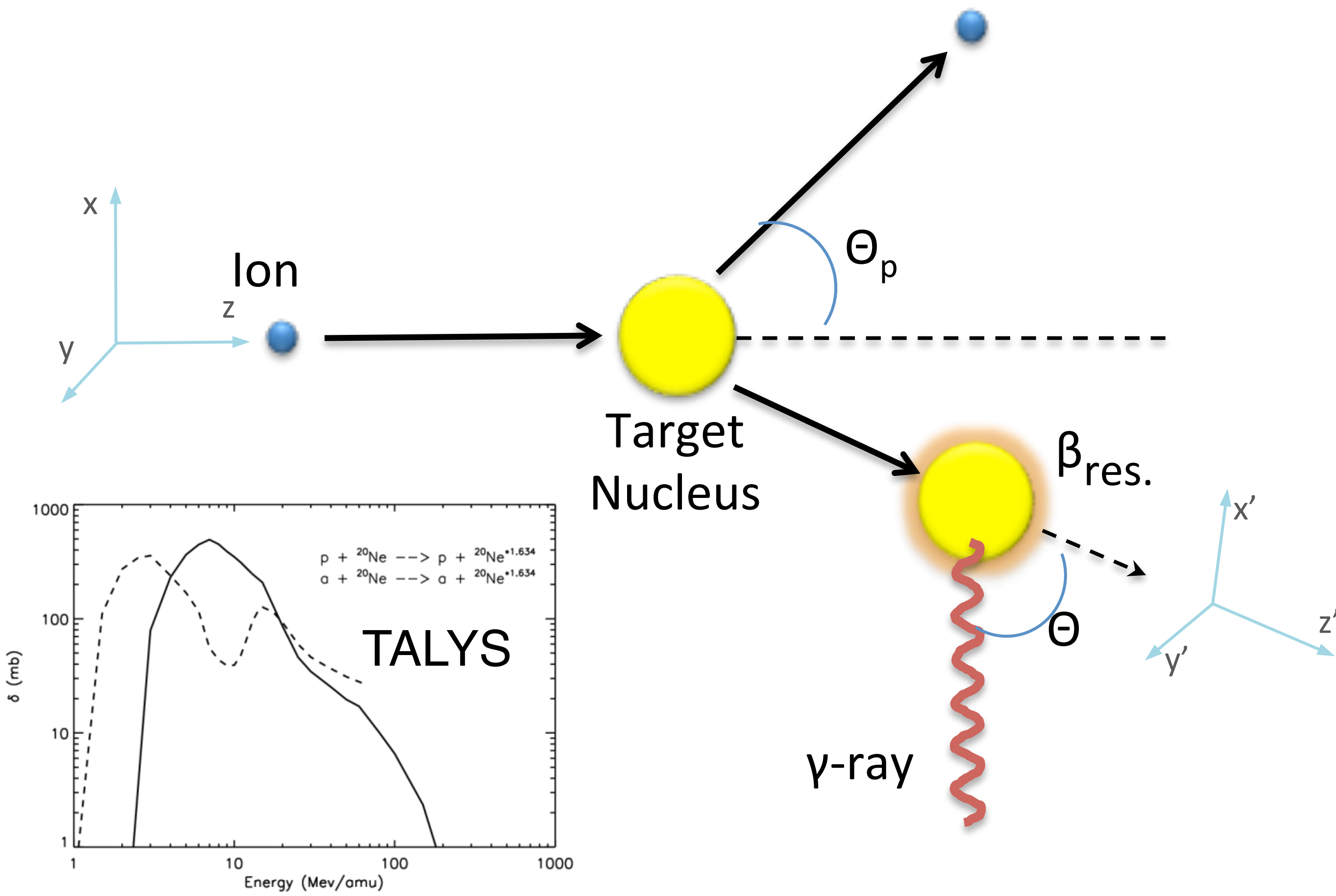
中国科学院紫金山天文台
PURPLE MOUNTAIN OBSERVATORY, CAS

15th RHESSI Workshop, 2016.7.26-30, Graz

Introduction

- Solar de-excitation lines, produced from nuclear reactions of accelerated ions interacting with solar atmospheric media, are the most direct diagnosis of the accelerated ions.
- How to derive the ion's information?
    - Estimate the fluency ratio of the 4-7 MeV band to the neutron capture lines (Murphy & Ramaty, 1984; Murphy et al. 2007).
    - Spectrscopic fit the whole gamma-ray spectrum (Chen & Gan, 2012).
- The lines shapes, include energy shifts and width of lines, reveal the angular distribution of the interacting ions (Ramaty & Crannell 1976). Smith (2003) report the first measurements of de-excitation lines shapes by the RHESSI.

Spectral line shapes calculation



Scheme of gamma emission from inelastic collision

1. Recoil nucleus emit isotropically in the CM frame;
2. Isotropic gamma-ray emissions in the excited nucleus rest frame

$$\upsilon_{tx} = \frac{\upsilon_{tcm} * \cos(\theta_{cm}) + \upsilon_{cm}}{1 + \upsilon_{tcm} * \cos(\theta_{cm}) * \upsilon_{cm}}$$

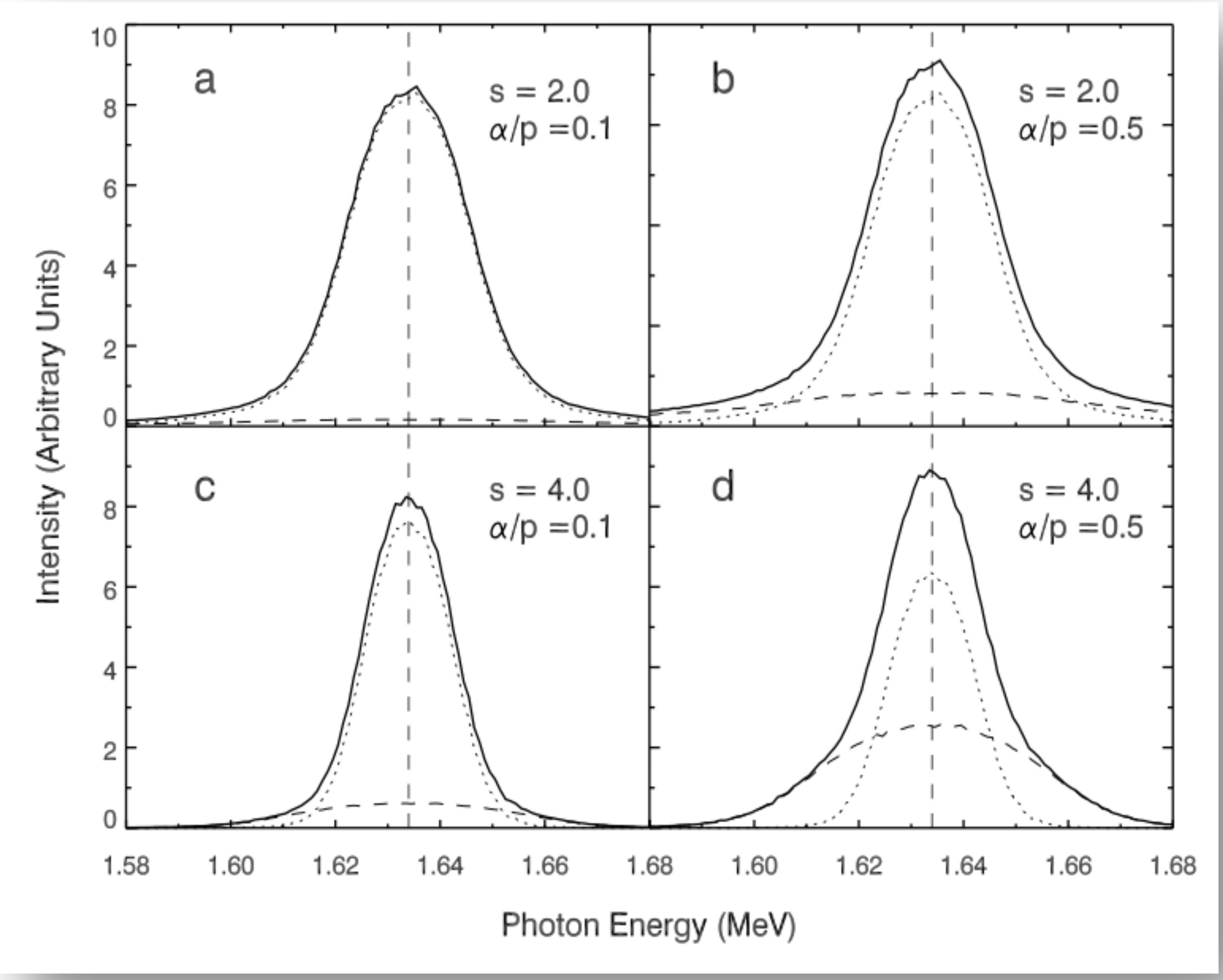
$$\upsilon_{ty} = \frac{\upsilon_{tcm} * \sin(\theta_{cm})}{\gamma(1 + \upsilon_{tcm} * \cos(\theta_{cm}) * \upsilon_{cm})}$$

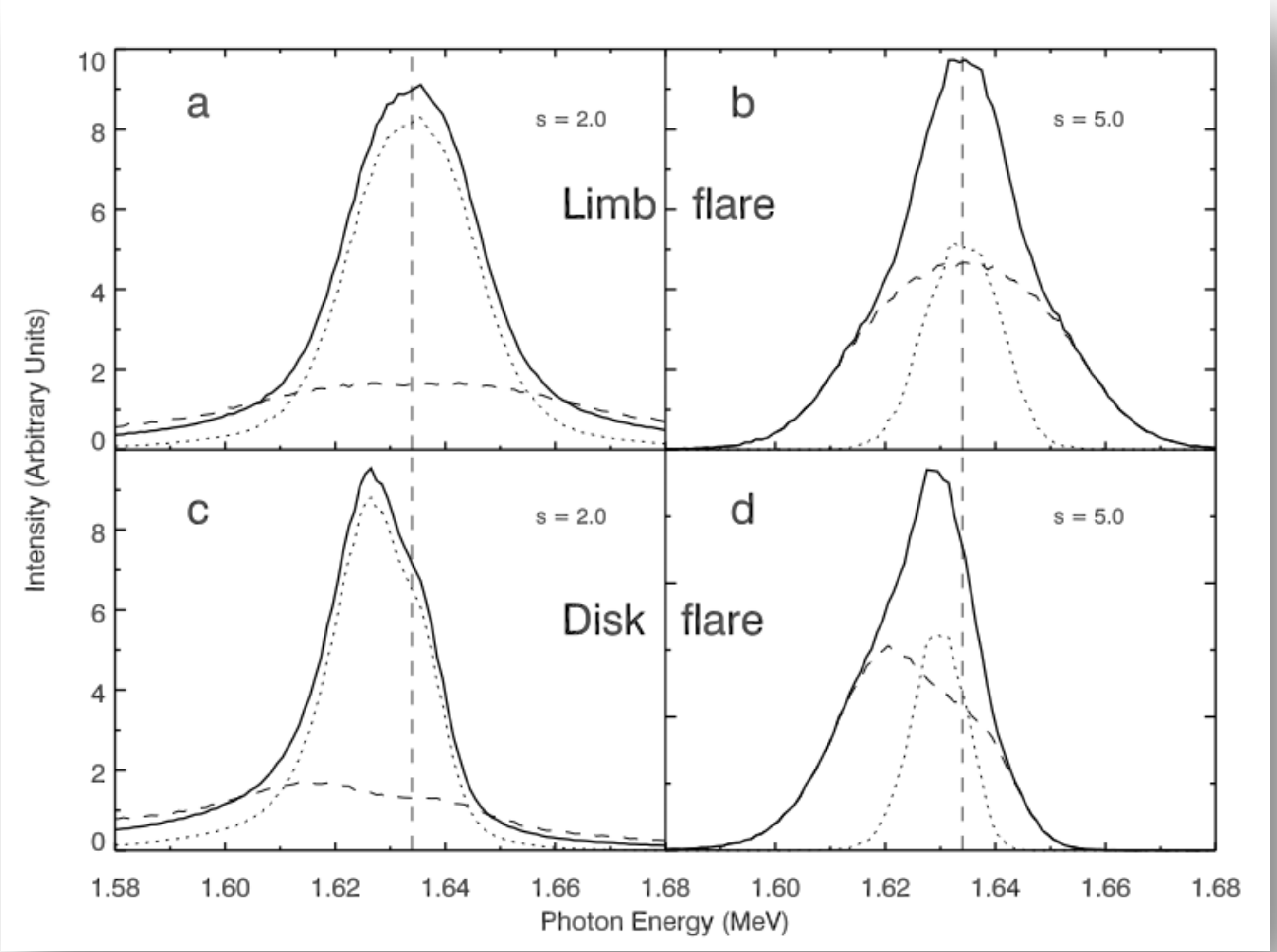
$$E_\gamma = E_0/\gamma(1 - \beta_{res} cos\theta)$$
$$= E_0(1 + \beta_{res}\cos\theta) \qquad \gamma \ll 1$$

$$v_{res} = \sqrt{v_{tx}^2 + v_{ty}^2}$$

$$\theta = \tan^{-1}\left(\frac{\upsilon_{tx}}{\upsilon_{ty}}\right)$$

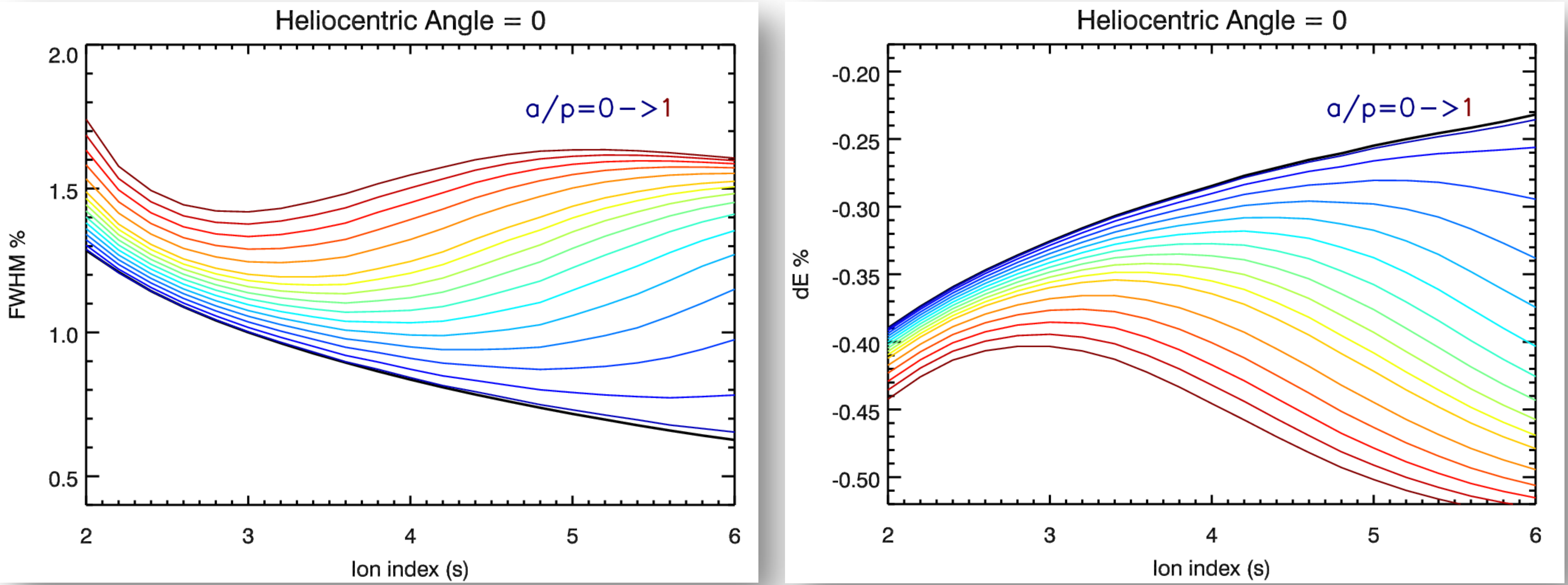
- Shapes of ^{20}Ne line





Calculated shapes of r-ray lines from the de-excitation of 20Ne relative to: (left)the isotropic incident ions for the various spectrum, (right)and the different flare location with downward-isotropic ions.

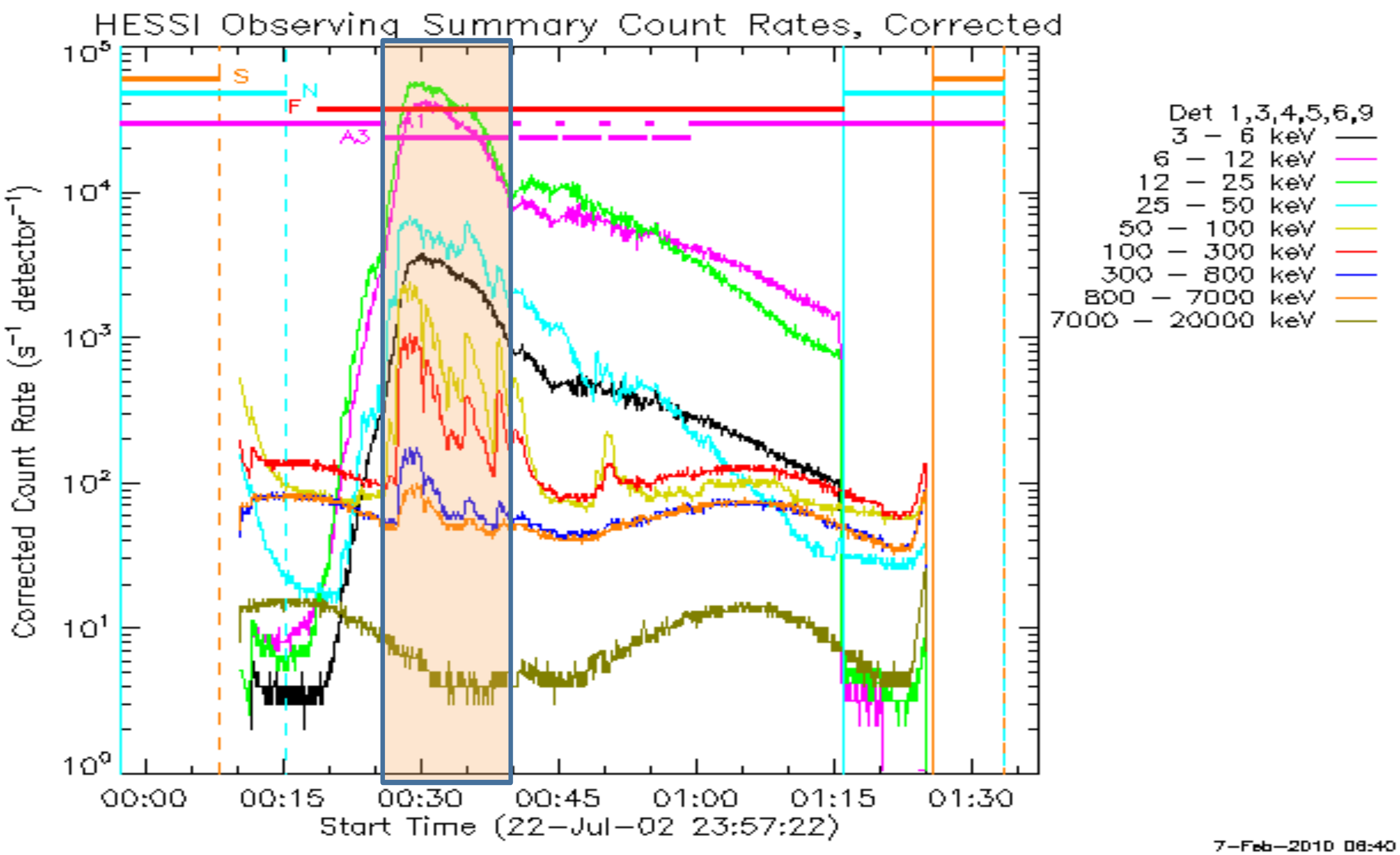
- Property of ^{20}Ne line shapes (FWHM, Redshift)



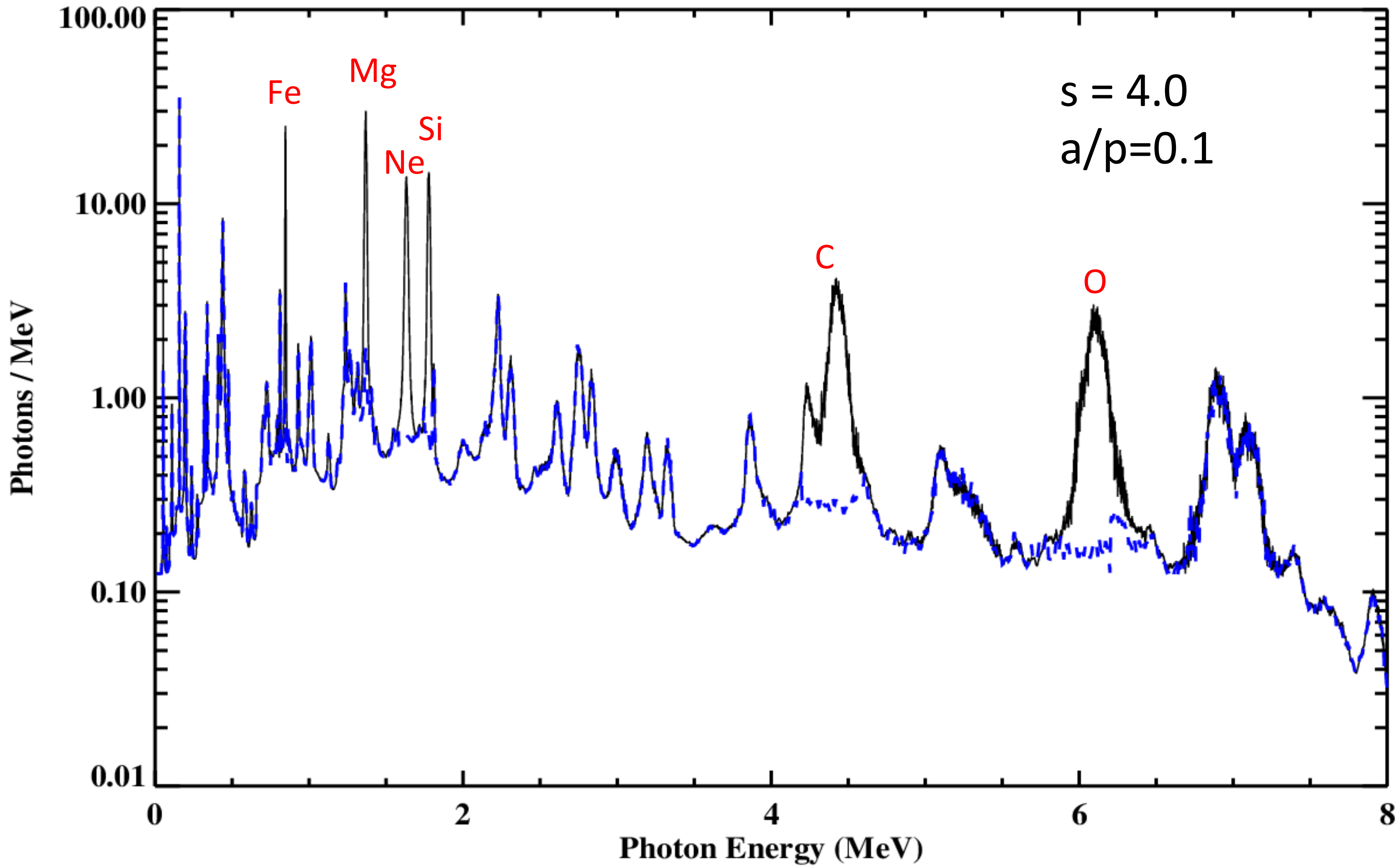
Property of 1.634 MeV line shapes varied with the spectral index (s) and *a*/p for downward-isotropic ions at flare sites near the center of the Sun. Left: line width (FWHM); Right: center energy shift.

Analysis of observation data

- 2002 Jul 23 X4.8 event, 00:27:20-00:39:56
- S13 E72 ,heliocenter angle ≈ 73°



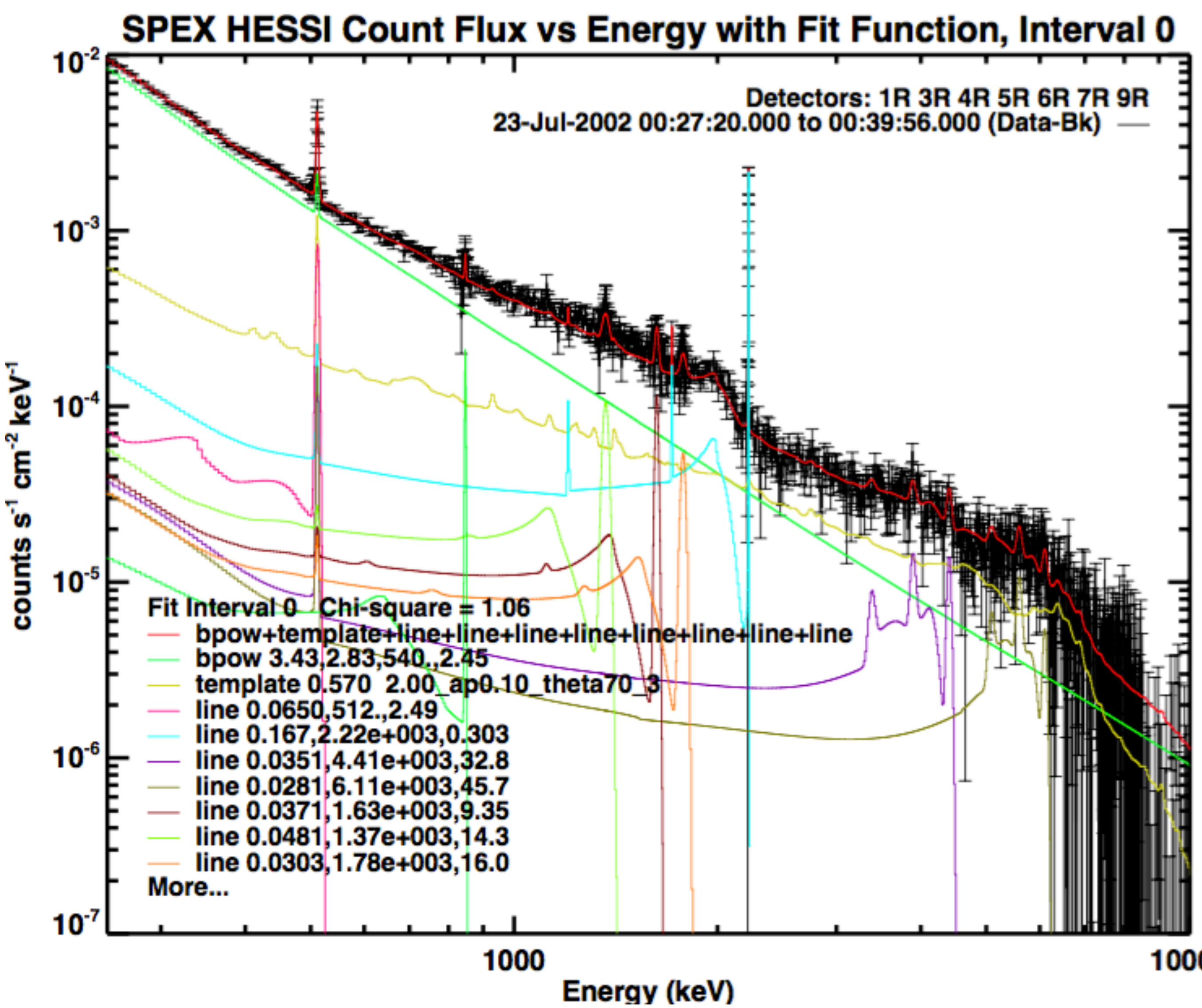
De-excitation lines spectrum template



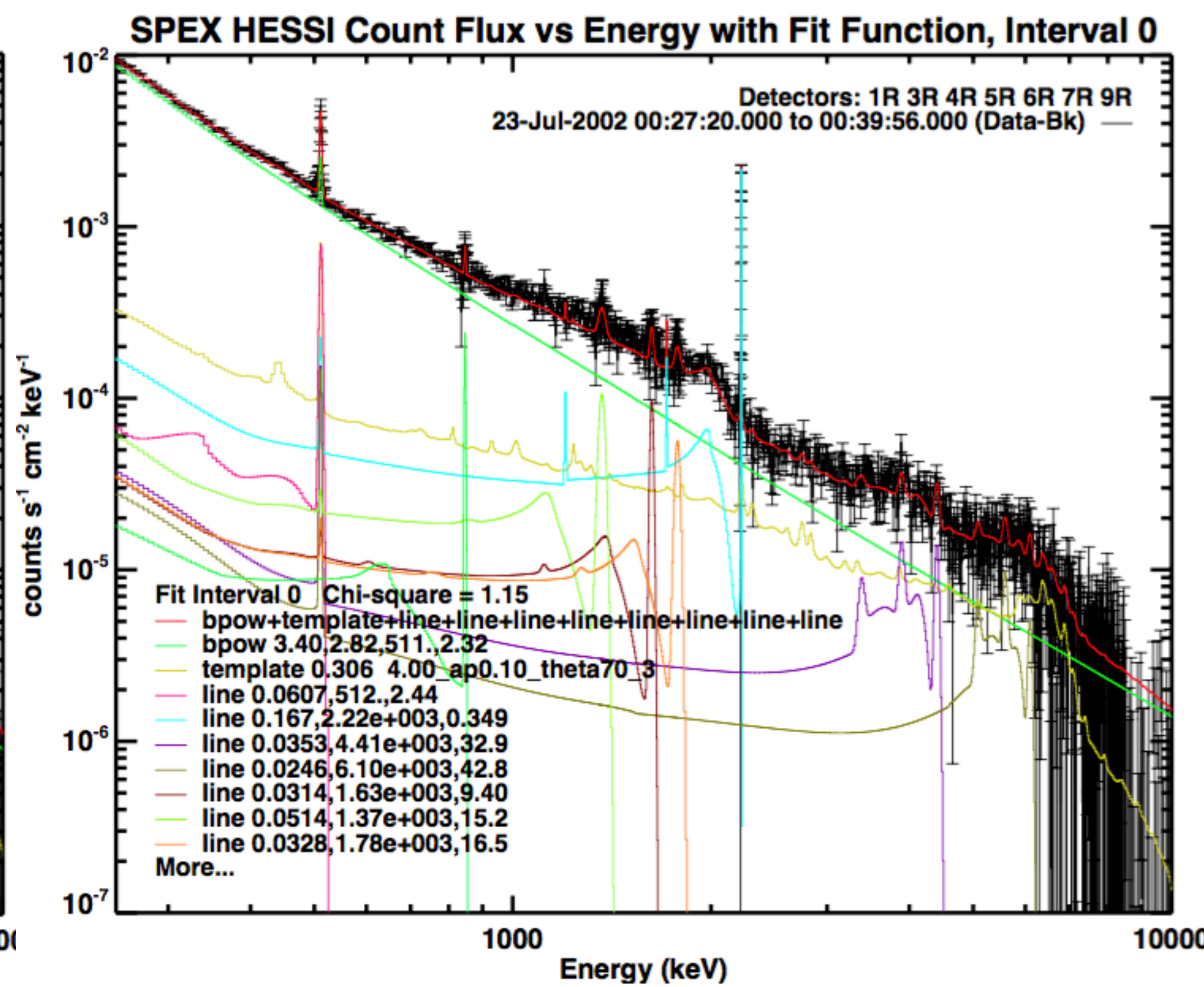
Solar de-excitation lines spectrum for ions index of 4.0 and alpha-to-proton ratio of 0.1. Blue curve represent the whole spectrum exclude the lines of Fe 0.847 MeV, Mg 1.369 MeV, Ne 1.634 MeV, Si 1.779 MeV, C 4.438 MeV and O 6.129 MeV. (Chen & Gan, 2011)

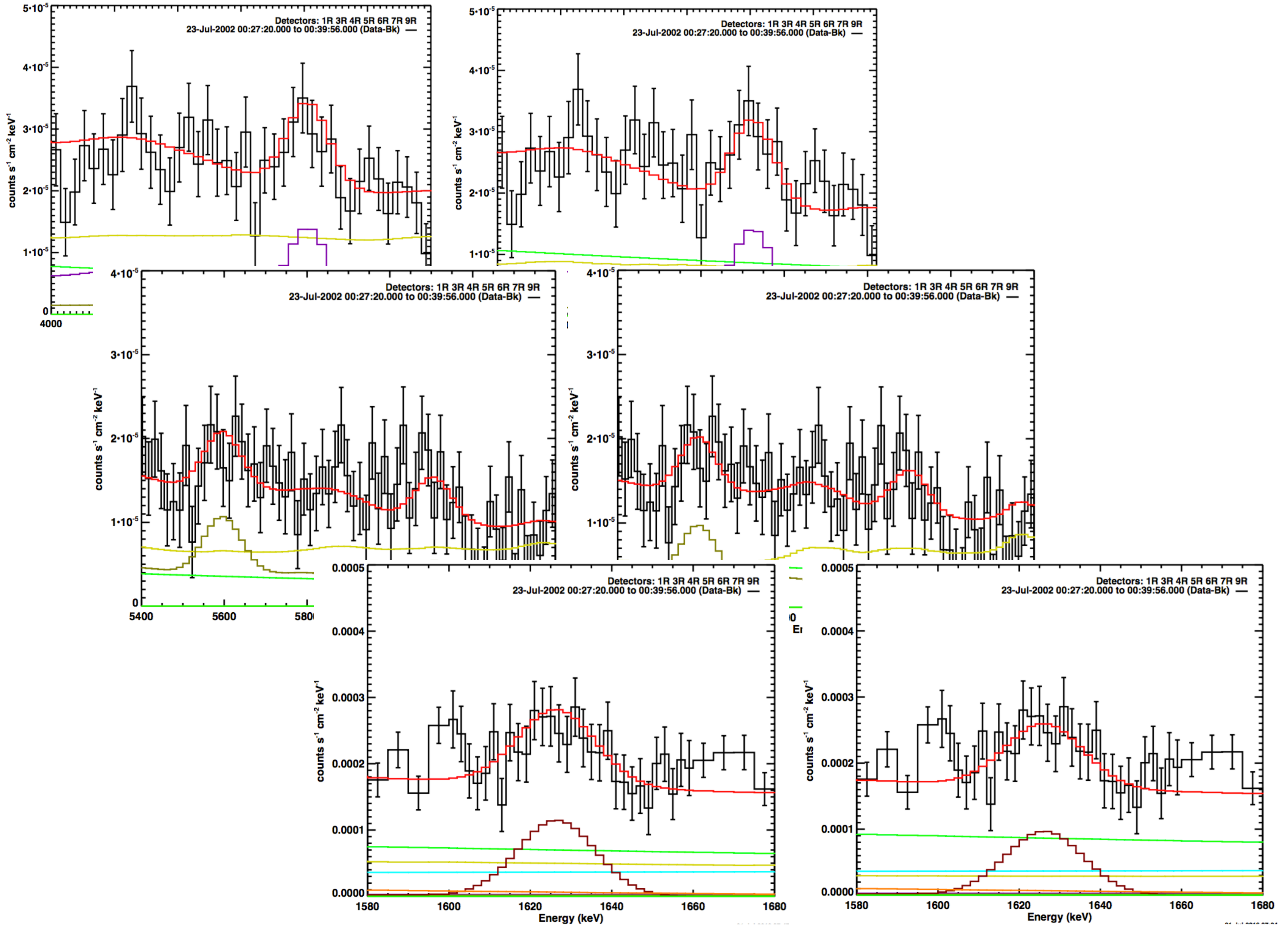
Fitting results for different templates of de-excitation lines spectrum

s=2.0 *a*/p=0.1 Downward-Isotropic
at Heliocentric Angle of 70°



s=4.0




Detectors: 1R 3R 4R 5R 6R 7R 9R
23-Jul-2002 00:27:20.000 to 00:39:56.000 (Data-Bk)
counts s^{-1} cm^{-2} keV^{-1}
5·10^{-5}
4·10^{-5}
3·10^{-5}
2·10^{-5}
1·10^{-5}
0
4000
5400
5600
5800
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
1580
1600
1620
1640
1660
1680
Energy (keV)

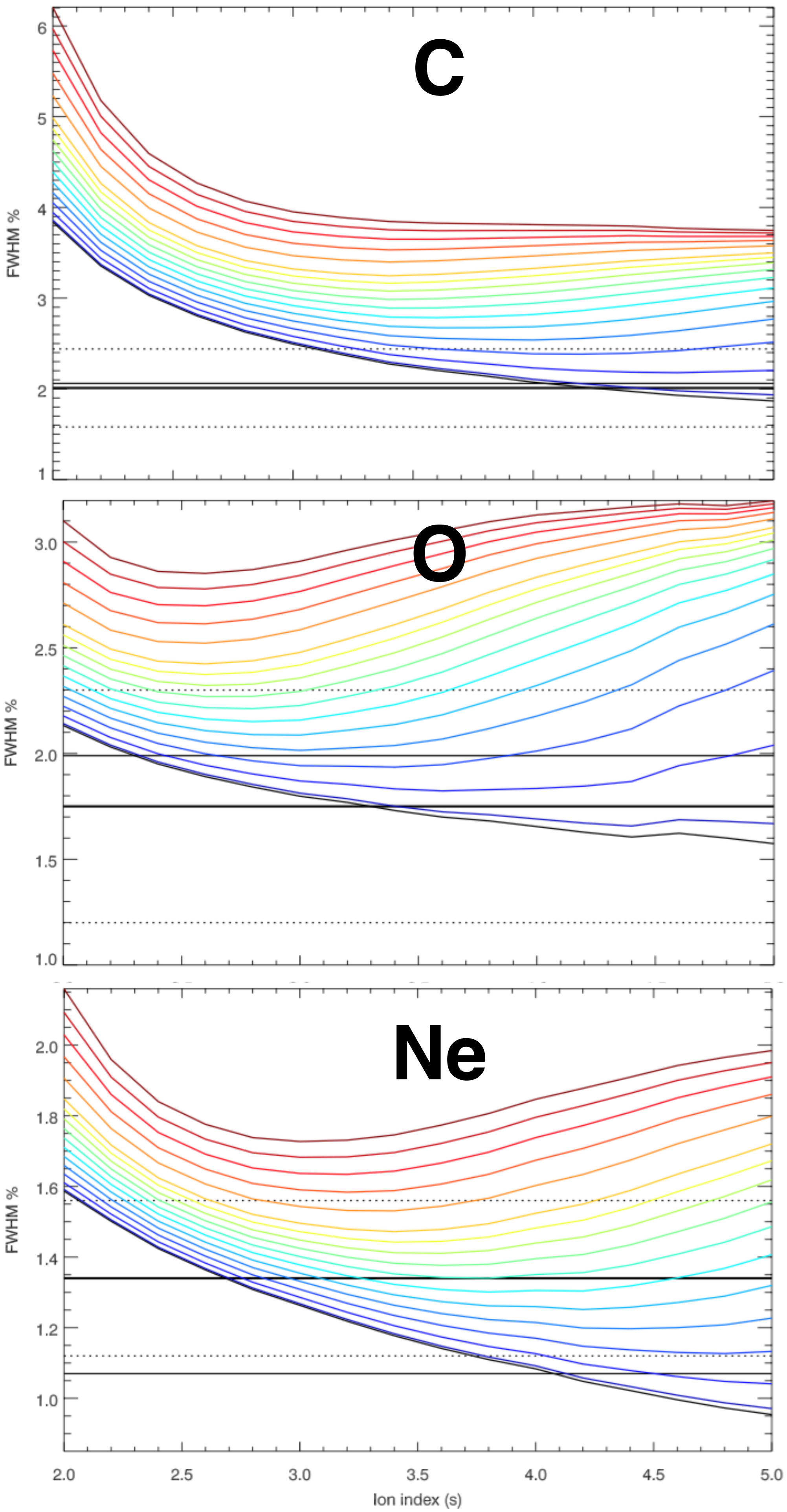
- Best-fit gaussian parameters for lines

Isotope	Rest energy (keV)	Fit energy (keV)	% Redshift	FWHM (keV)	% FWHM
C	4438	4405 ± 9	0.74 ± 0.20	89 ± 19	2.01 ± 0.43
O	6129	6105 ± 17	0.39 ± 0.28	107 ± 34	1.75 ± 0.55
Ne	1634	1628.6 ± 1.5	0.33 ± 0.10	21.9 ± 3.6	1.34 ± 0.22
Mg	1369	1366.3 ± 2.7	0.20 ± 0.20	33.6 ± 6.5	2.45 ± 0.47
Si	1779	1779.2 ± 2.9	-0.01 ± 0.16	37.6 ± 6.7	2.11 ± 0.38
Fe	847	846.8 ± 0.7	0.04 ± 0.08	3.0 ± 3.3	0.36 ± 0.40

BEST-FIT GAUSSIAN PARAMETERS FOR PROMPT NUCLEAR LINES

ISOTOPE	REST ENERGY (keV)	FIT ENERGY (keV)	% REDSHIFT	FWHM (keV)	% FWHM	FLUENCE (photons cm^{-2})
^{56}Fe	847	$846.09^{+0.70}_{-0.60}$	$0.11^{+0.08}_{-0.07}$	$1.2^{+2.9}_{-1.1}$	$0.14^{+0.34}_{-0.13}$	$7.5^{+3.4}_{-2.3}$
^{24}Mg	1369	$1363.6^{+2.3}_{-2.0}$	$0.40^{+0.17}_{-0.14}$	$21.0^{+8.0}_{-5.4}$	$1.54^{+0.59}_{-0.39}$	$28.3^{+7.2}_{-6.6}$
^{20}Ne	1634	$1628.8^{+1.7}_{-1.7}$	$0.32^{+0.10}_{-0.10}$	$17.6^{+4.3}_{-3.6}$	$1.07^{+0.26}_{-0.22}$	$21.4^{+3.8}_{-4.5}$
^{28}Si	1779	$1776.8^{+1.9}_{-2.1}$	$0.12^{+0.11}_{-0.12}$	$16.7^{+4.5}_{-5.4}$	$0.94^{+0.25}_{-0.30}$	$17.1^{+4.0}_{-4.5}$
^{12}C	4438	4403^{+10}_{-10}	$0.79^{+0.23}_{-0.22}$	92^{+42}_{-29}	$2.06^{+0.95}_{-0.65}$	$28.6^{+13.1}_{-8.6}$
^{16}O	6129	6094^{+15}_{-18}	$0.58^{+0.24}_{-0.29}$	122^{+68}_{-51}	$1.99^{+1.11}_{-0.83}$	$34.2^{+12.8}_{-15.5}$

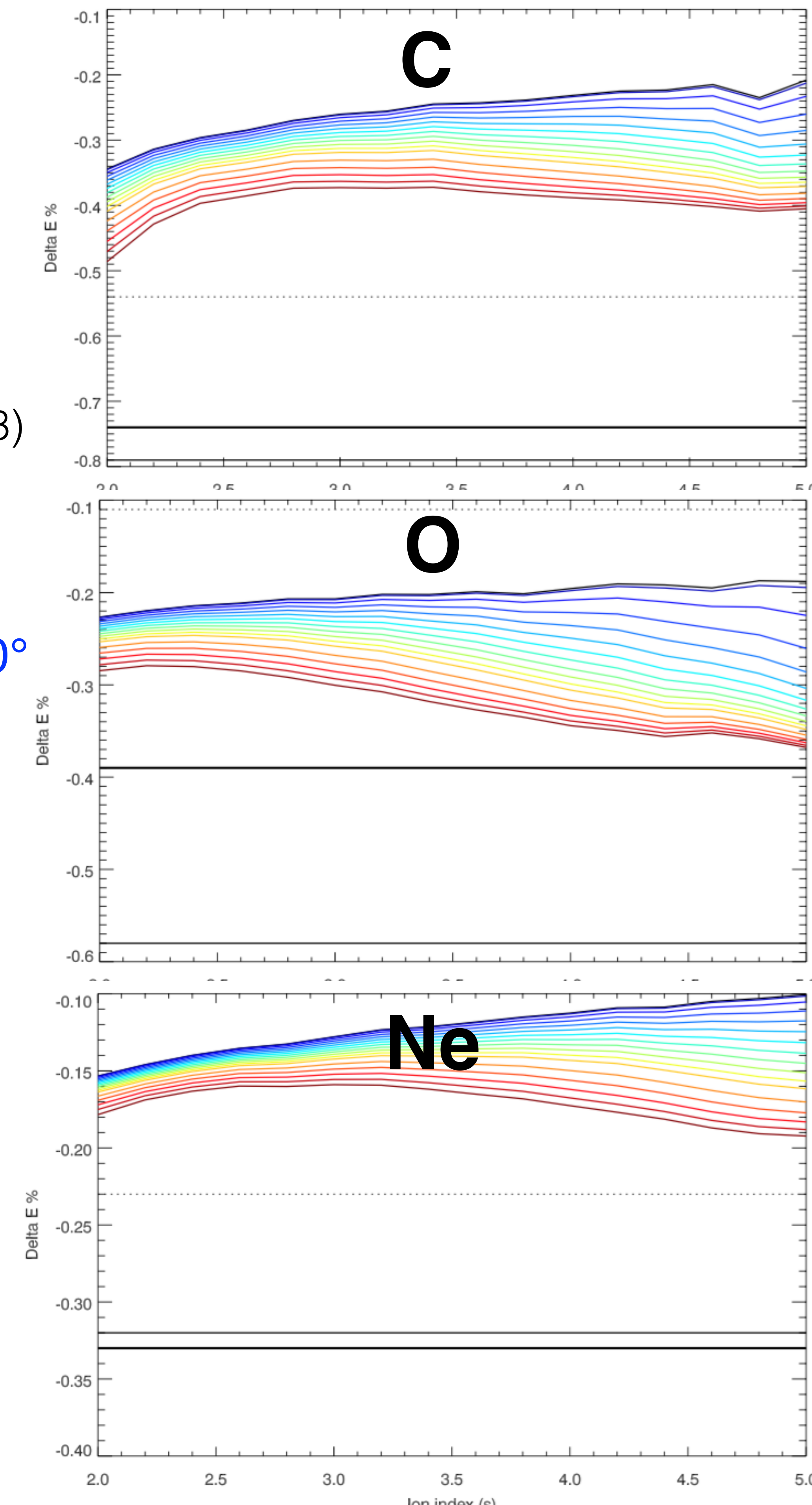
Smith, 2003

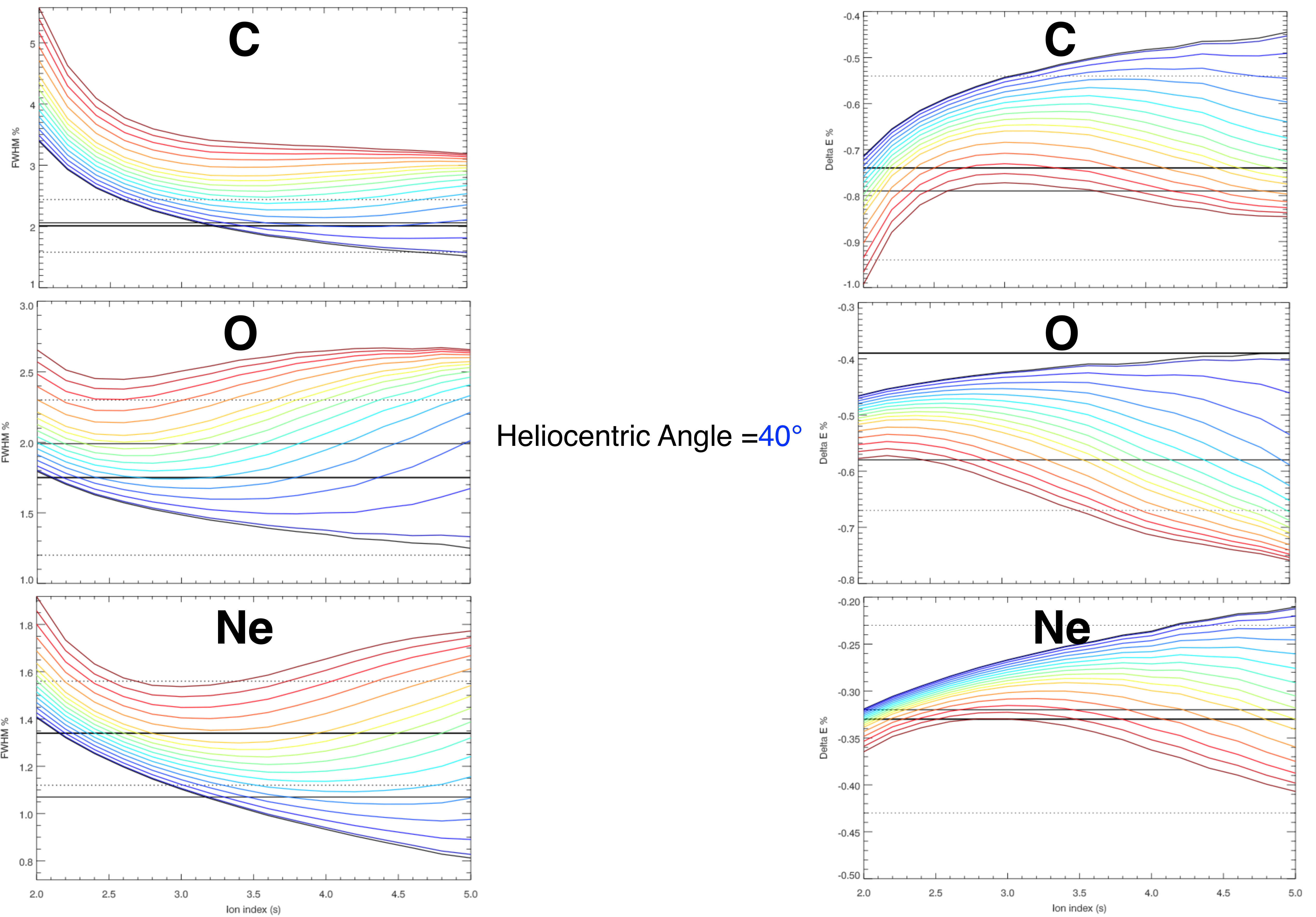


The comparison of line shapes property between measurements and calculations.

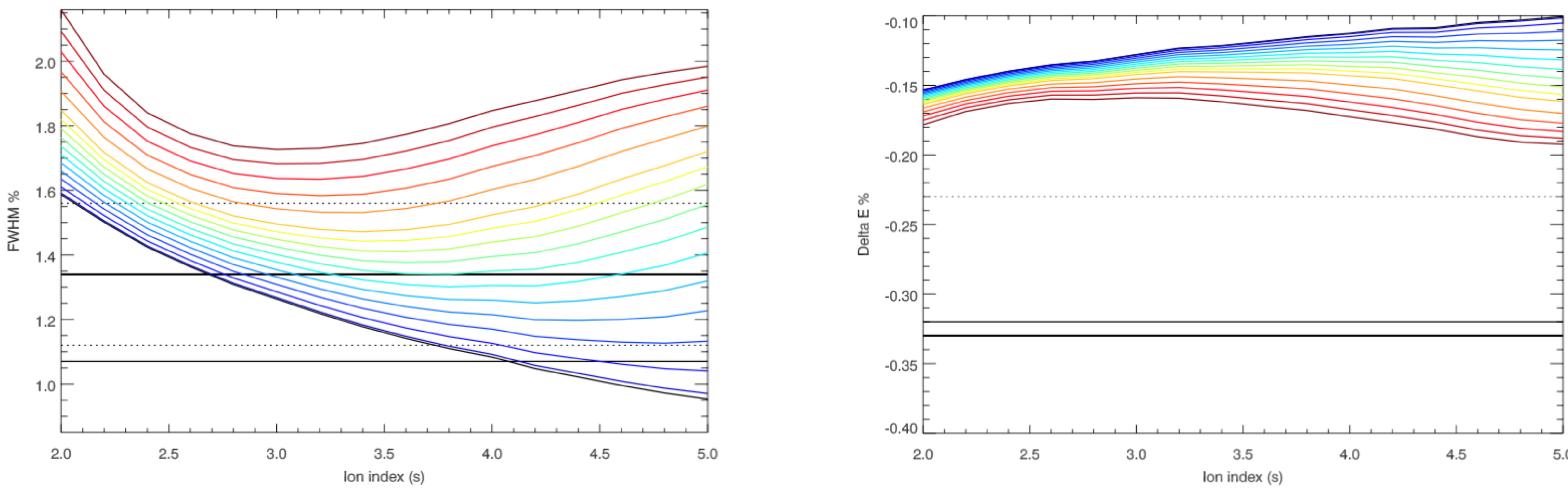
Thick horizontal line: measure from us;
Thin horizontal line: measure from Smith (2003)

Heliocentric Angle =70°

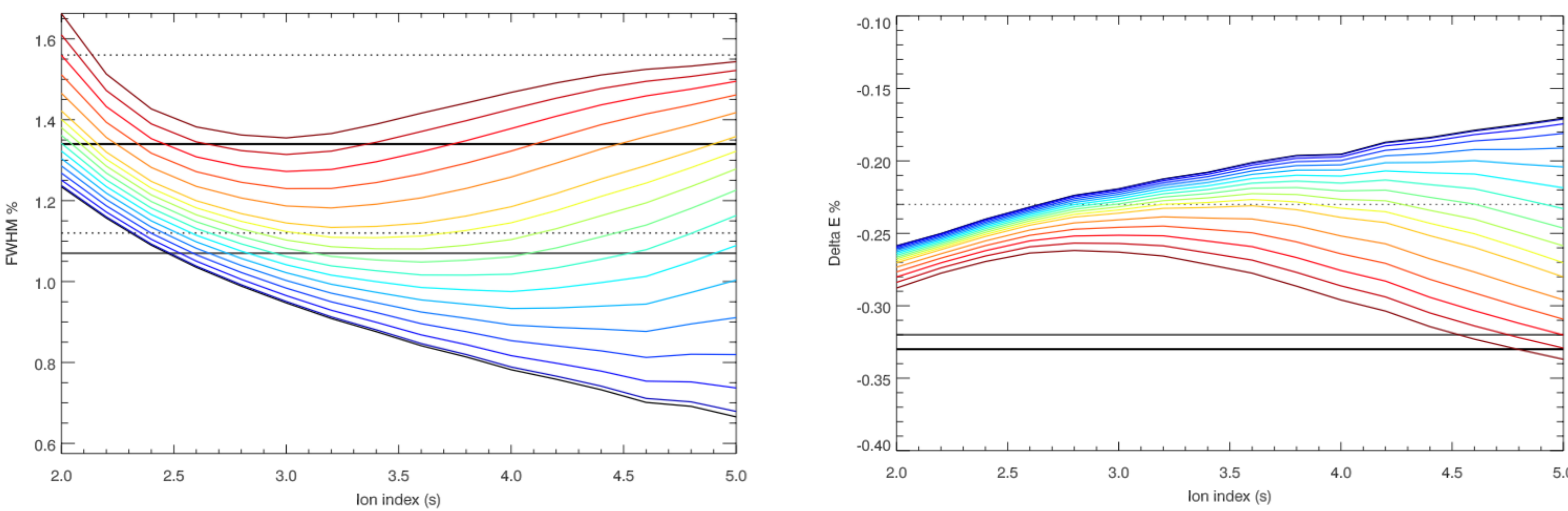



C
FWHM %
C
Delta E %
O
FWHM %
O
Delta E %
Heliocentric Angle =40°
Ne
FWHM %
Ne
Delta E %
Ion index (s)
Ion index (s)

Downward isotropic injection



Beam injection



Discussion

- De-excitation line shape analysis method is a new window for studying ion's property.
  - NOT rely much on the fitting model of whole spectrum
  - WITH abundant lines observations
  - POOR count rate and sensitivity in observation
  - EXISTENCE of multiple solutions of one fitting parameter. e.g. Combine α-α line（$^{7}Be^{0.429}$ -> g.s.， $^{7}Li^{0.478}$ ->g.s.）

- The observation redshifts of C, O and Ne lines are larger than theoretical calculation for a model of interacting ions with downward-isotropic in a radial magnetic field. Beam injection of accelerated ions or tilt of the magnetic field to the solar surface?

- The results of ions property by analyzing different lines shape are not completely consistent. The property of accelerated ions is varied as flare evolution.

Thanks for your attention!