The Non-Equilibrium Ionization Model in *ISIS*

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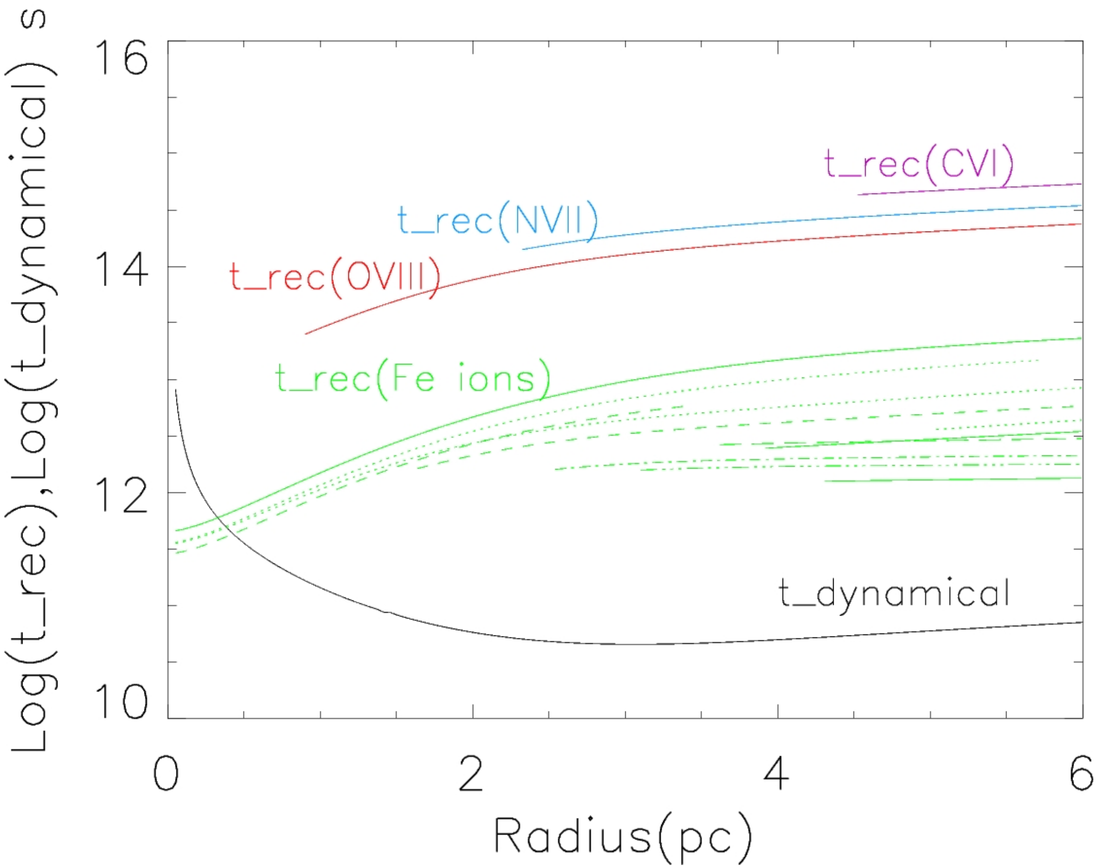
X-ray Spectroscopy Workshop July 11-13 2007

Outline

- Why do we care about Non-equilibrium Ionization (NEI)?
- What's our NEI code and its improvements in *ISIS*?

NEI Introduction



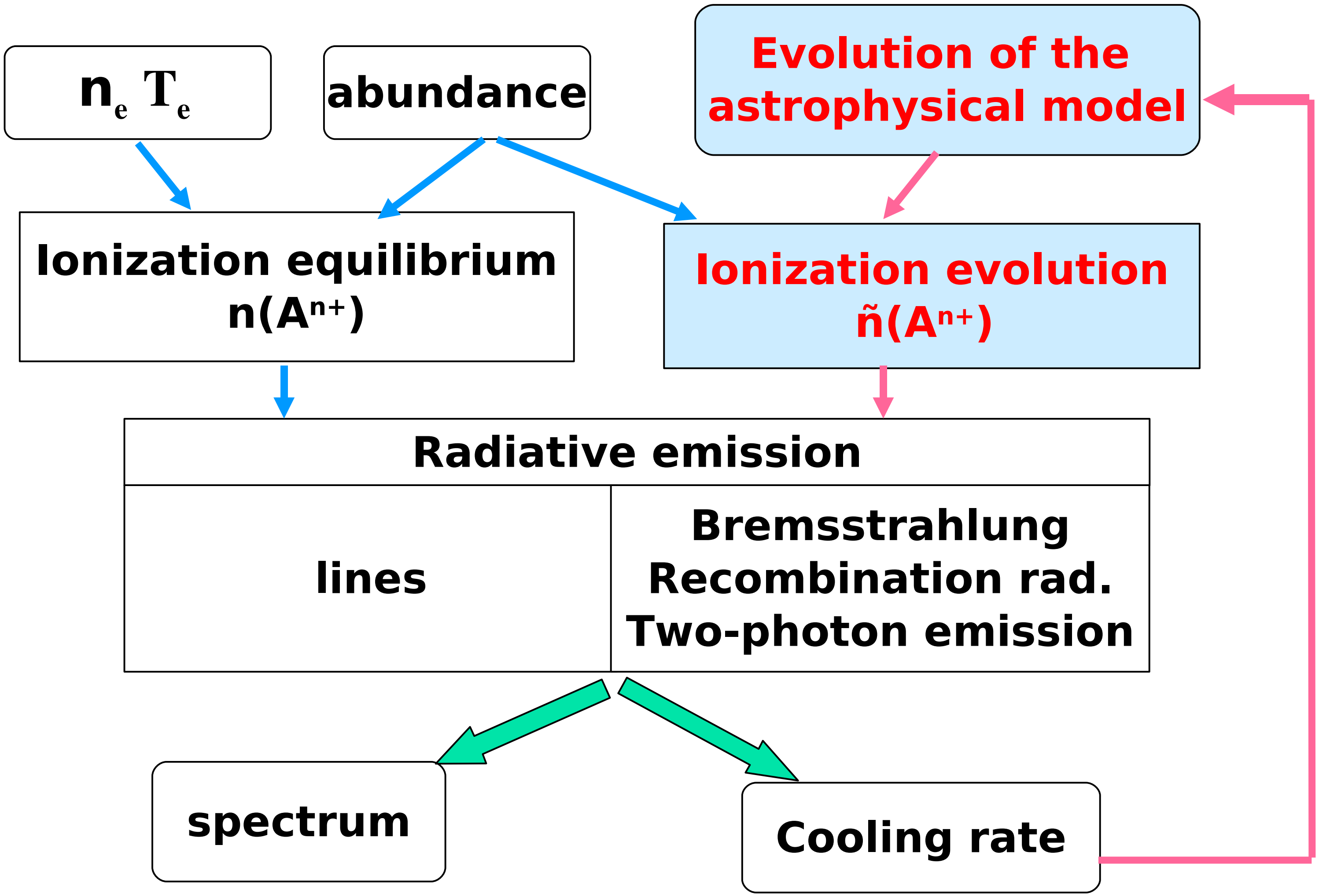
$$t_{dyn} < t_{intrinsic}$$

$$t_{dyn} \equiv T/(dT/dt)$$

The plasma could be under-ionized or over-ionized

Ji et al. 2006

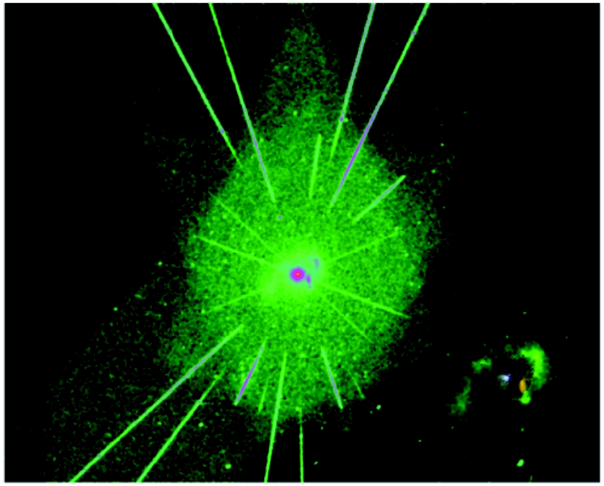
Basic structure of plasma emission models



Credit: Hans Böhringer 1997

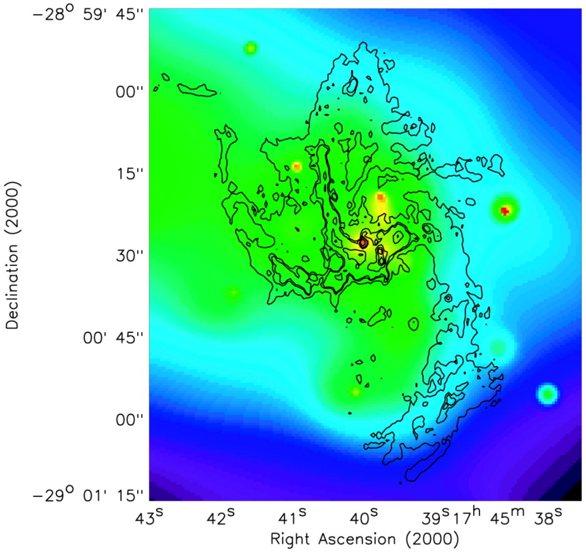
- colliding wind binaries
- accretion flow in AGN
- super starcluster winds
- galactic winds
- radiative shock flows in IGM

Eta Car



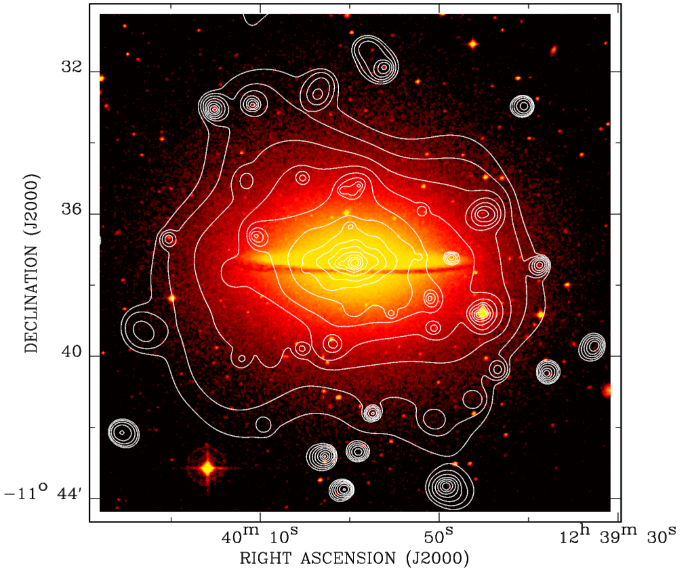
Poster by Corcoran et al

Sgr A*



Baganof et al 2003

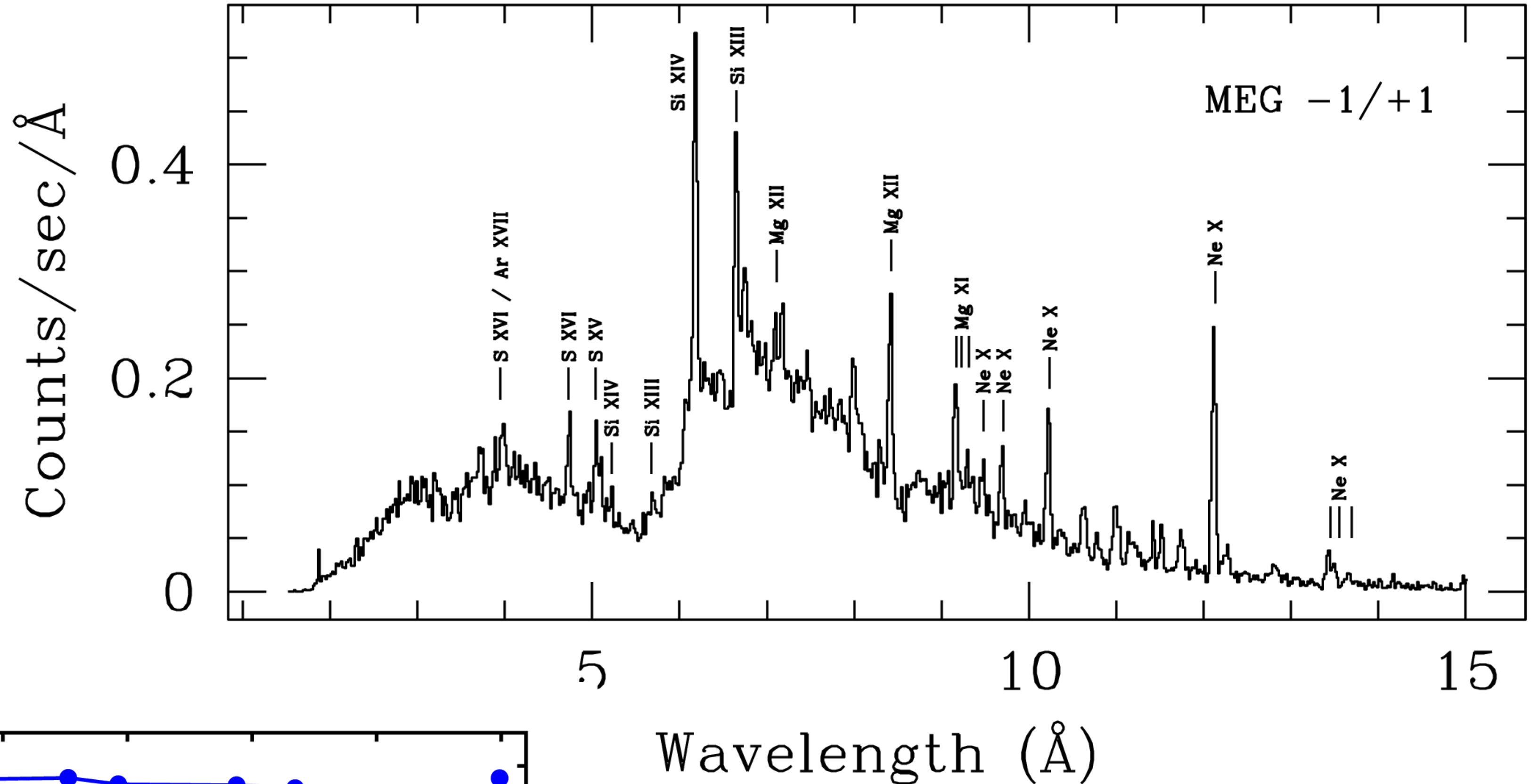
M104 Sombrero

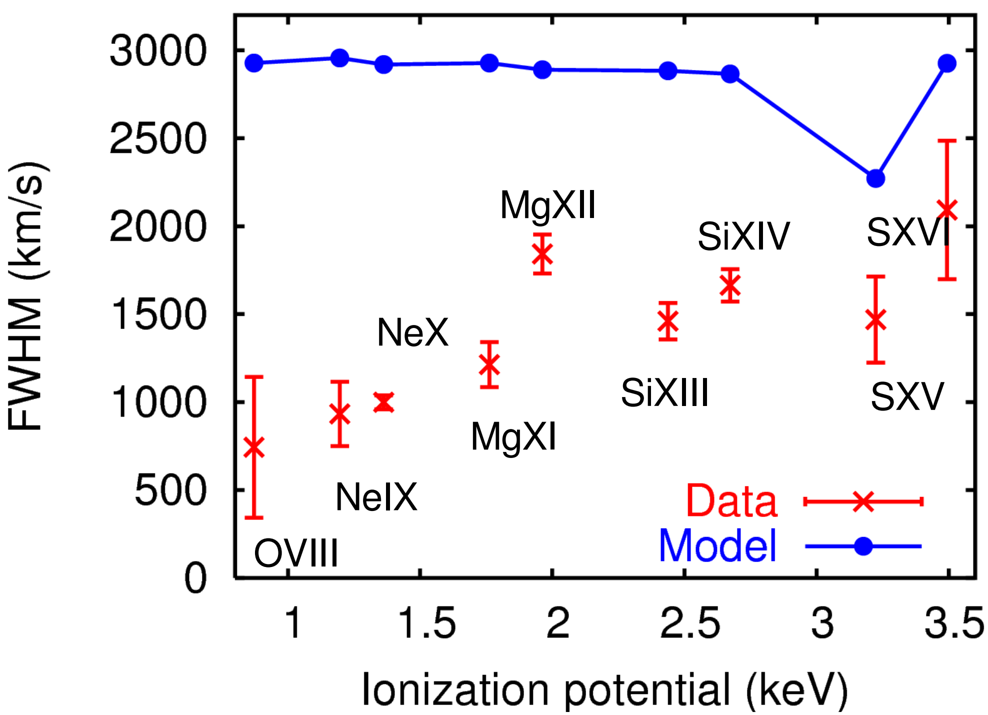


Li et al. 2007

WR 140

the archetype colliding-wind binary



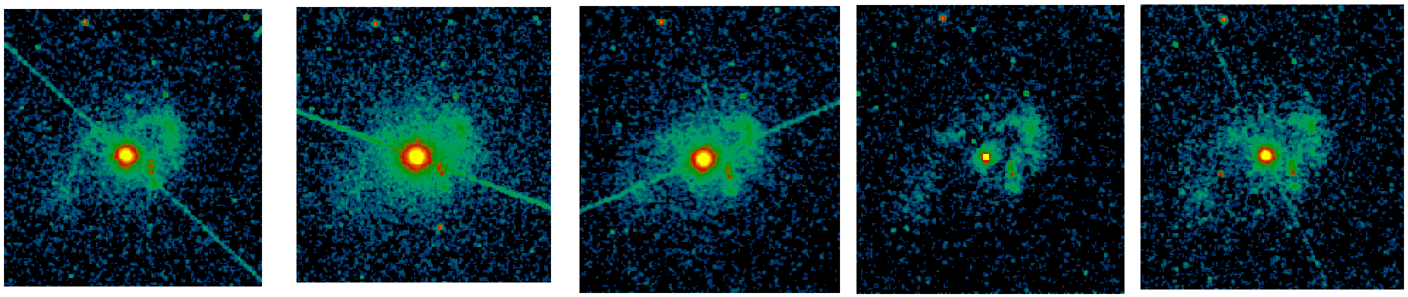


Model: hydrodynamical simulations + CIE

Pittard &Dougherty 2006

Eta Car

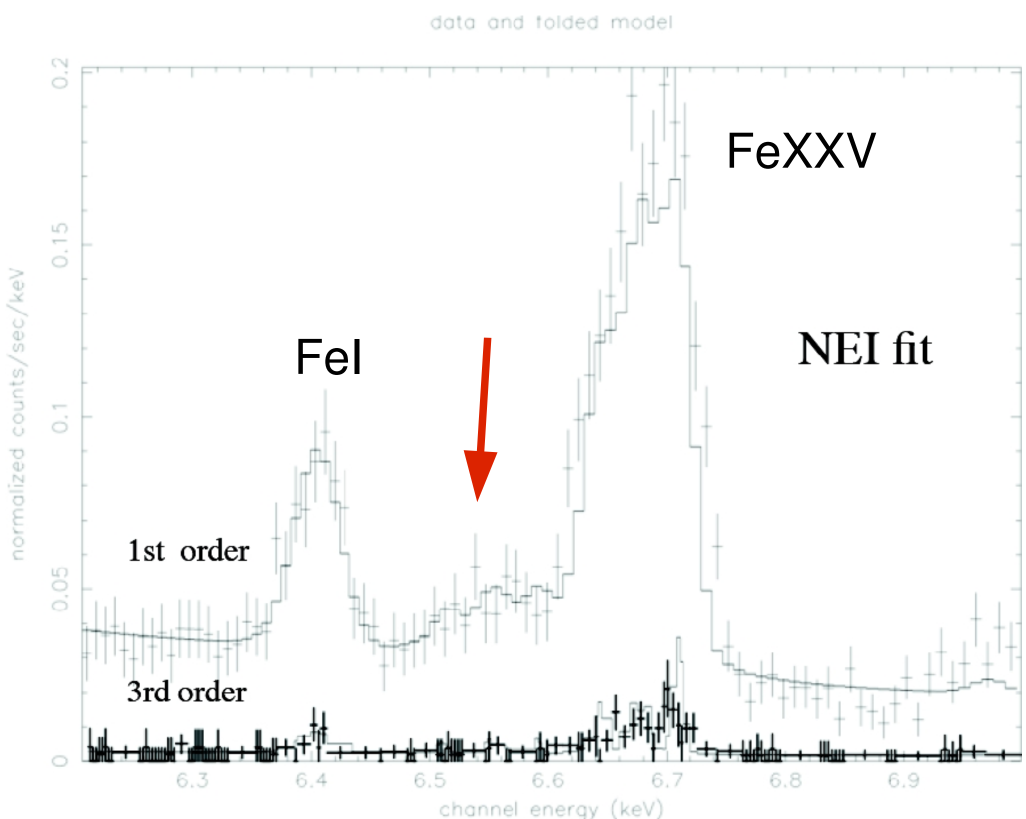
- the Galaxy's most massive & luminous star (5×10^6 L⊙ ; 100 M⊙)



Oct 16 2002 | May 3 2003 | Jun 16 2003 | Jul 20 2003 | Sep 26 2003

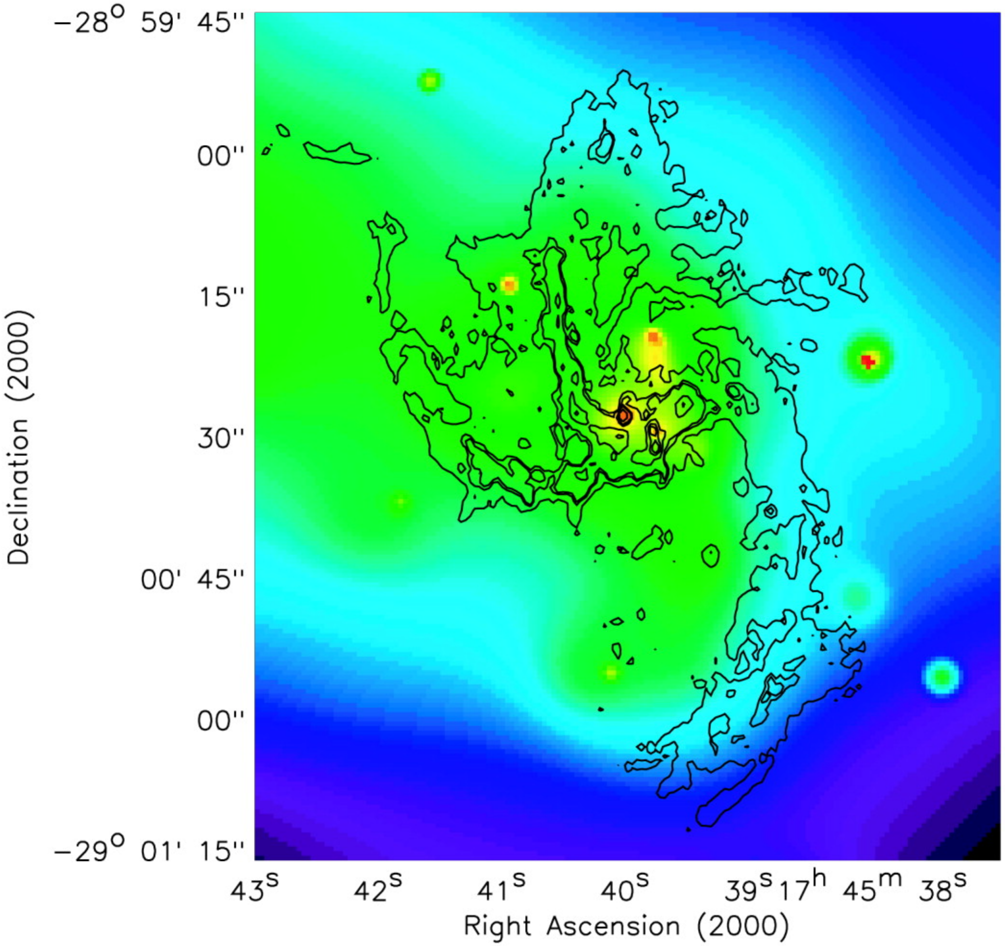
5 HETG 100ksec

- 0.1-0.5 red ; 0.5-1.0 green ; 1.0-10keV blue

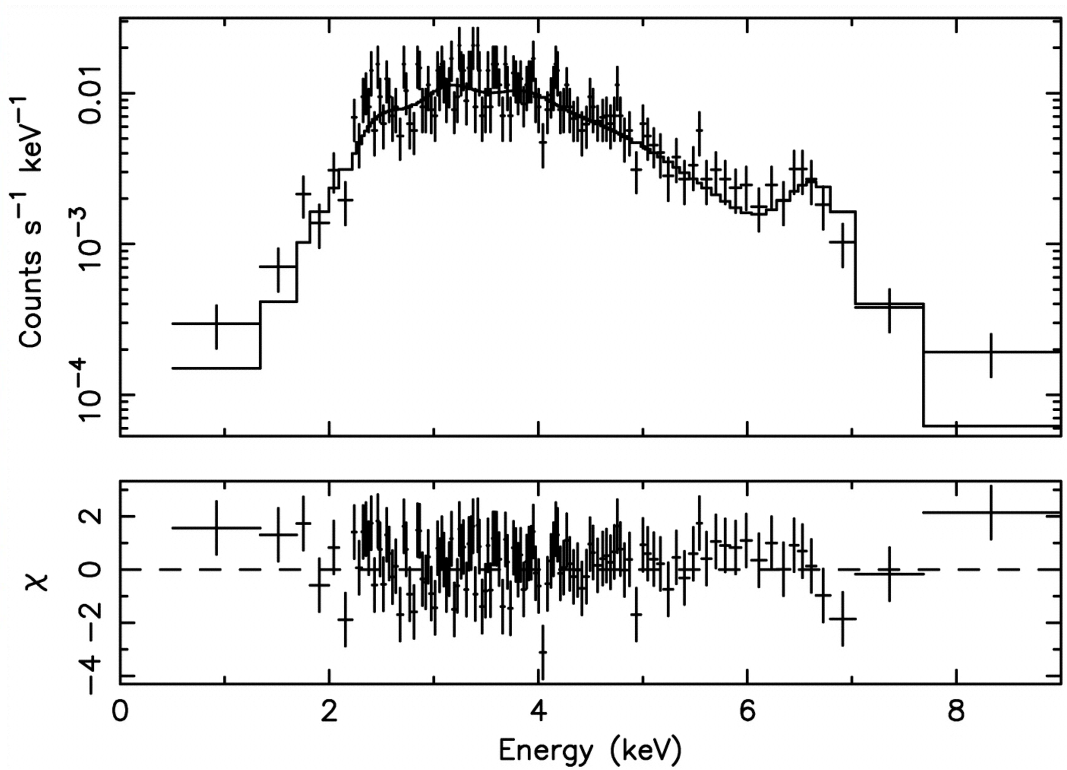


Poster by Corcoran et al.

Sgr A*



r < 10 arcsec (~0.4pc)



Chandra ACIS-I : 0.5 – 7keV 1.'3 X 1.'5

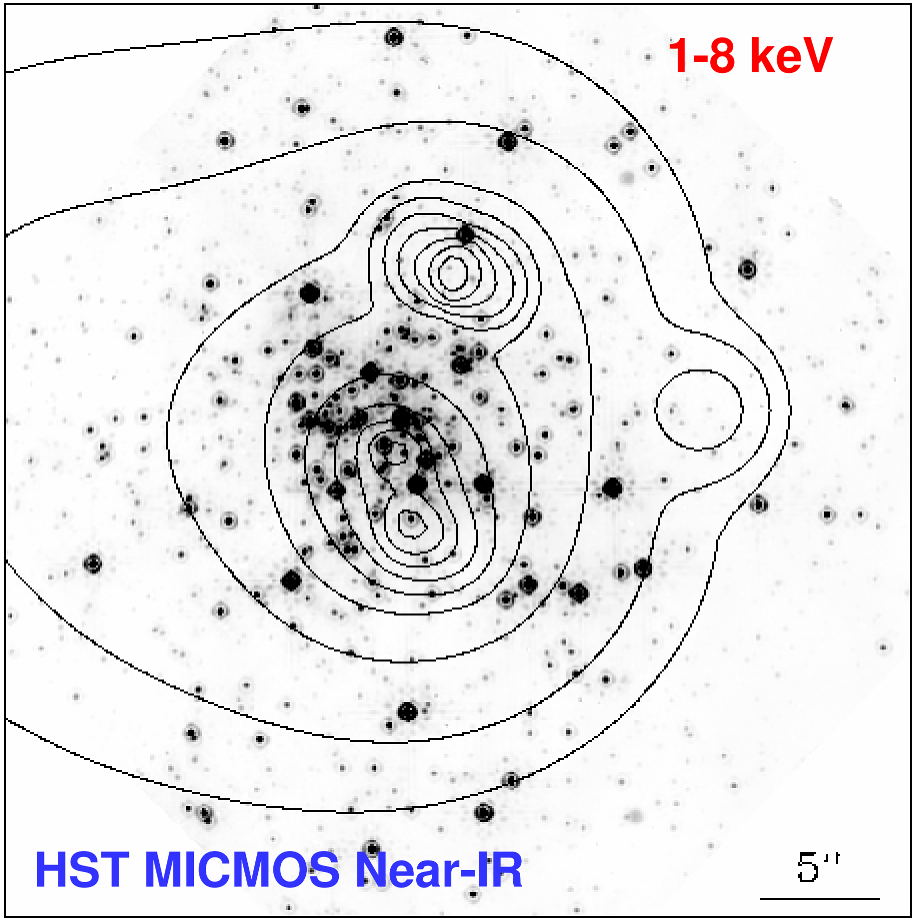
Contours : VLA 6 cm

$$6.5^{+0.1}_{-0.2} keV$$

0.5 -1.5keV red
1.5-3keV yellow
3-6 keV green
6-7keV blue

Baganoff et al. 2003
Xu et al. 2006

Arches cluster and its vicinity



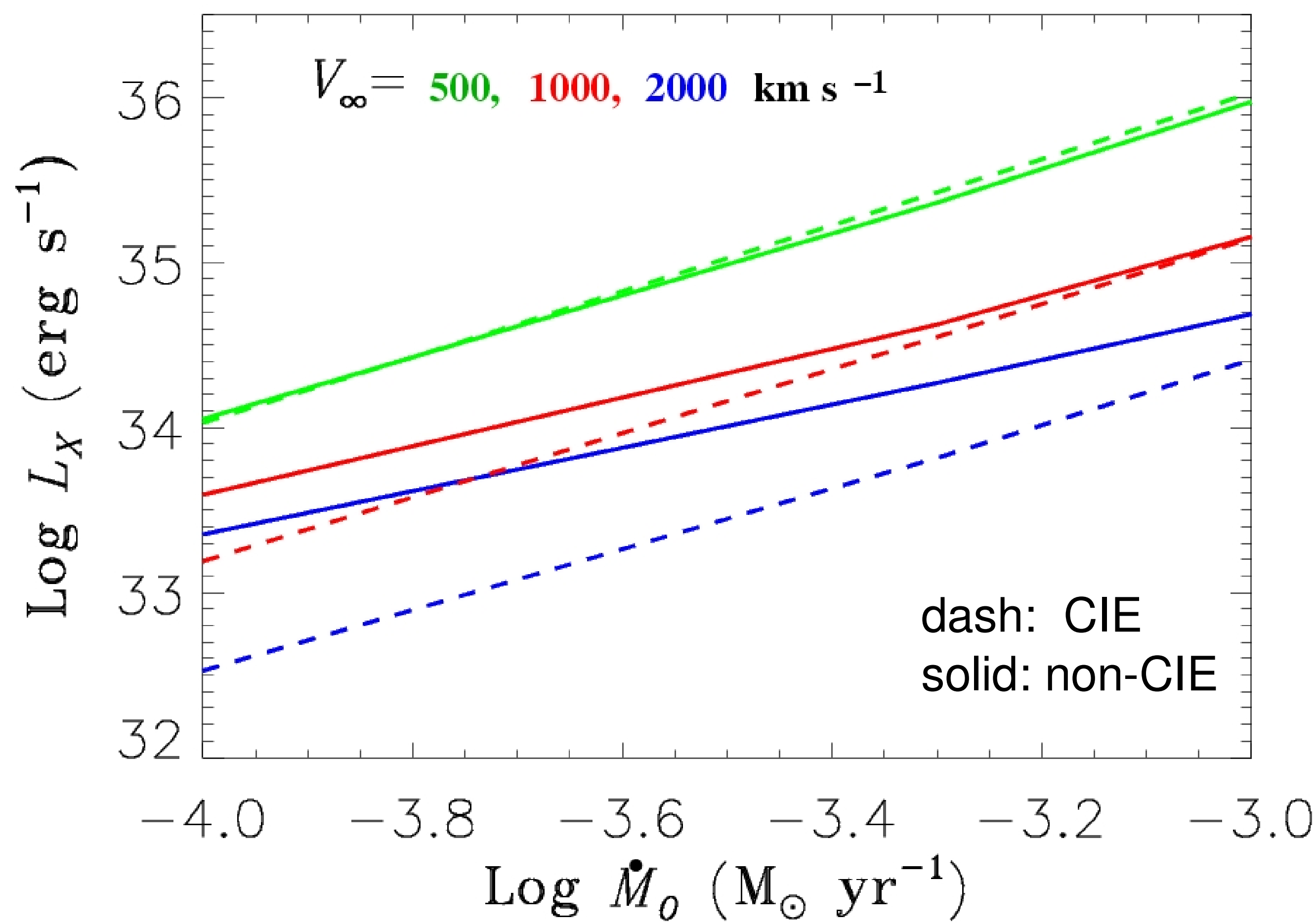
Figer et al. 2000, Wang et al. 2006

super stellar clusters (SSCs):

- lie in extra-galactic star-forming galaxies (e.g. M82) or in local regions (e.g. NGC3603, R136 in 30 Doradus, Arches cluster)

- mass and energy loss from massive stars energize ISM by their winds (stellar cluster wind)

- Because of both the shock-heating in the wind-wind collision and the fast adibatic cooling in the subsequent expansion, the wind gas is in highly NEI state.

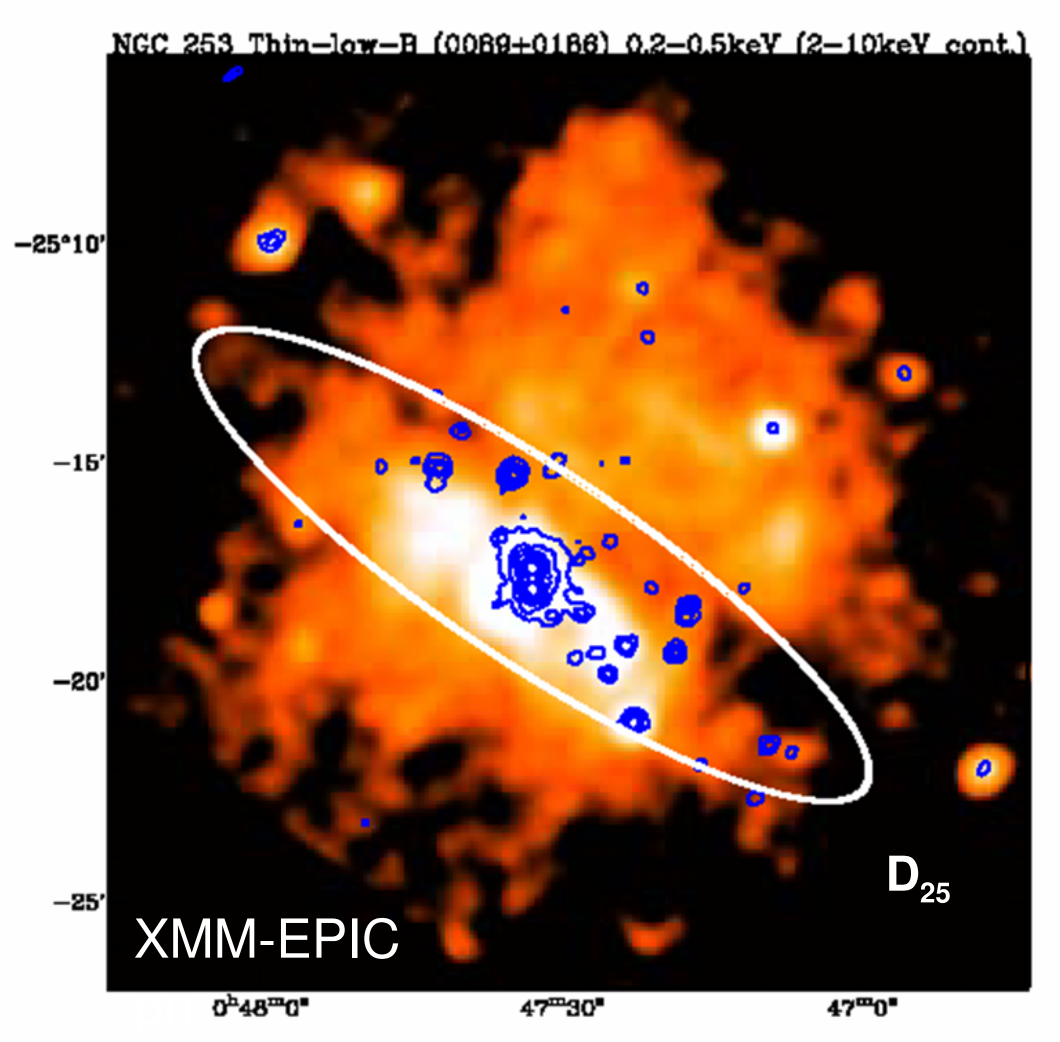


V_∞= 500, 1000, 2000 km s $^{-1}$
36
35
34
33
32
Log L_X (erg s^{-1})
dash: CIE
solid: non-CIE
−4.0
−3.8
−3.6
−3.4
−3.2
−3.0
Log $\dot{M}_0$ ($M_\odot$ yr^{-1})

Ji et al. 2006

NGC253

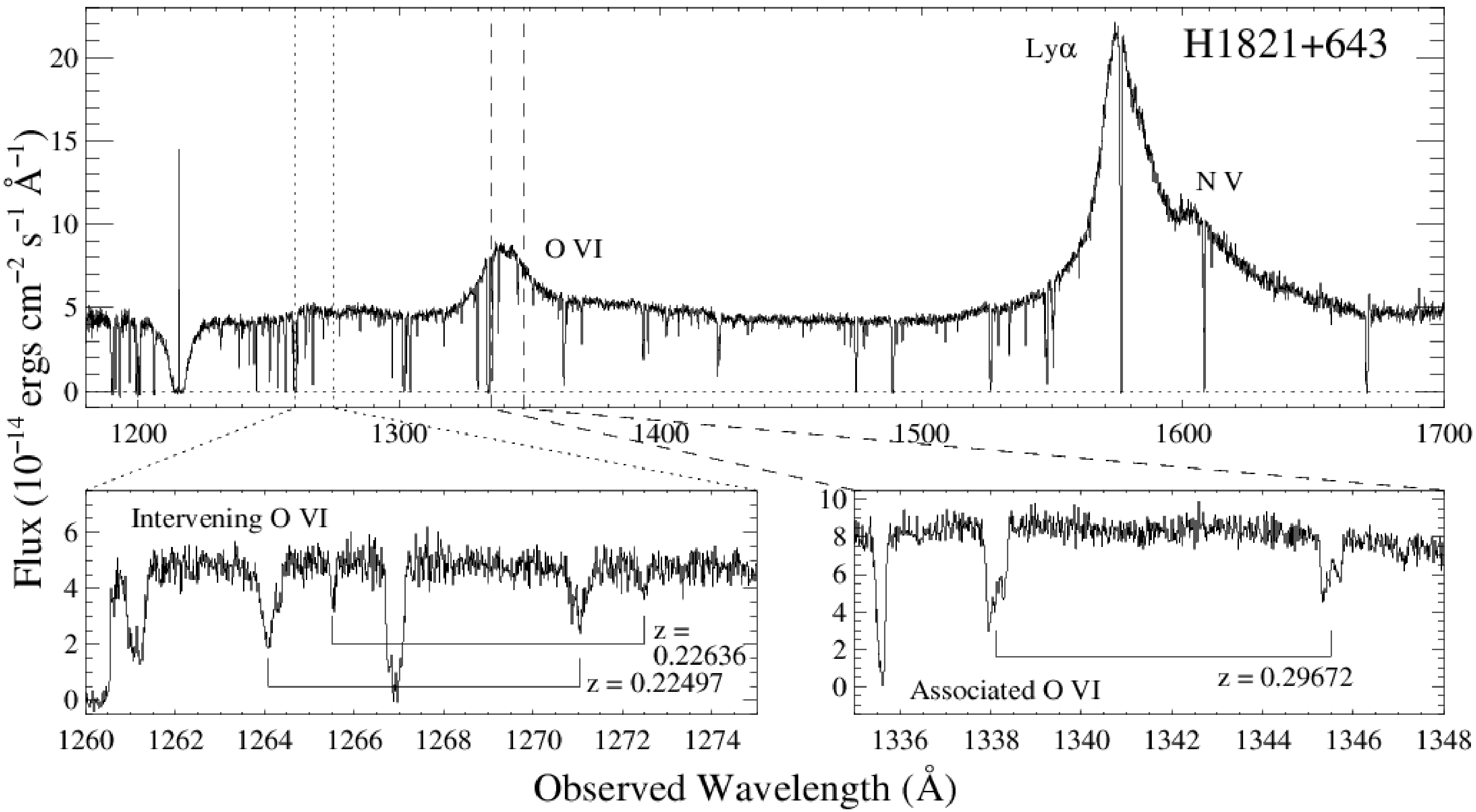
2-10 keV
0.2-0.5 keV



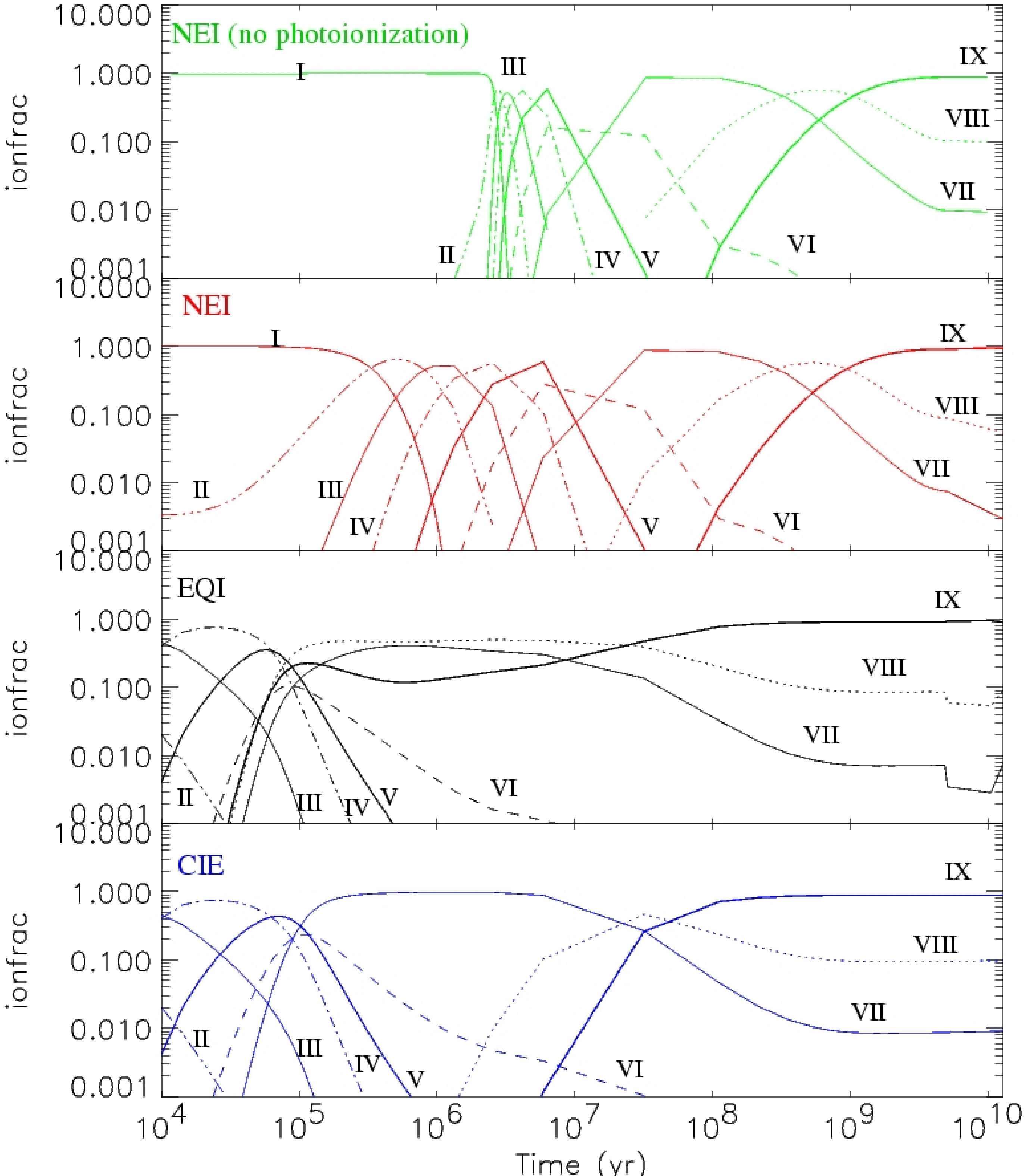
- abundance puzzle exists in the analysis of X-ray gas of starburst galaxies, such as in NGC253 (Strickland et al. 2002) based on one/two temperature CIE assumption.

Breitschwerdt 2002

- WHIM is too tenuous to be observed in emission
- Tracers for WHIM: various UV and X-ray absorption lines (e.g. CIV, OVI, OVII, NeVIII etc.) from *FUSE*, *Chandra*, *XMM-Newton*.
- Radiative shock flow could be suitable scenario



Tripp et al. 2005



$T_0 = 5 \times 10^6\, K$

$Te_0 = 1 \times 10^4\, K$

$n_0 = 1 \times 10^{-5}\, cm^{-3}$

Oxygen ionic fraction

NEI : without UV & X-ray background radiation (UVBR)

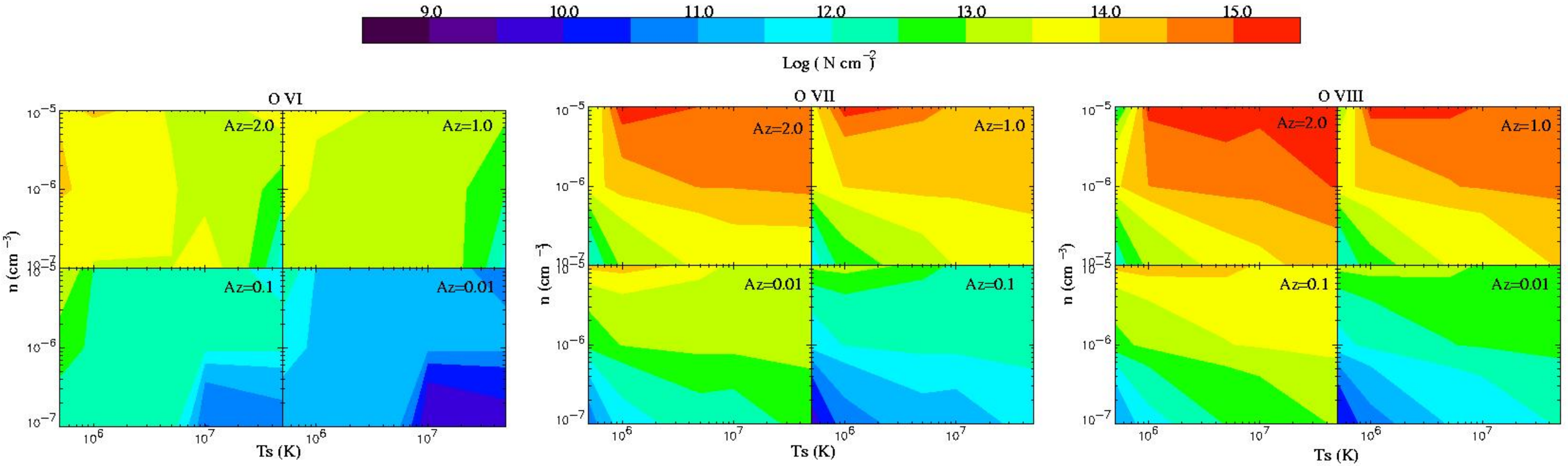
NEI: with UVBR

EQI: equilibrium ionization with UVBR

CIE: collisional equilibrium ionization with UVBR

Ji et al. 2007

Column density maps



Ts =[5e5, 7e5] K
n0 = [10^{-7}, 10^{-5}] cm $^{-3}$
Az = [0.01, 2.0] Z⊙

Ji et al. 2007

Characteristics of our spectral code (*Ji PhD thesis 2006*)

- based on the updated atomic data *(CHIANTI , APED)* the atomic data and the code are *separate*

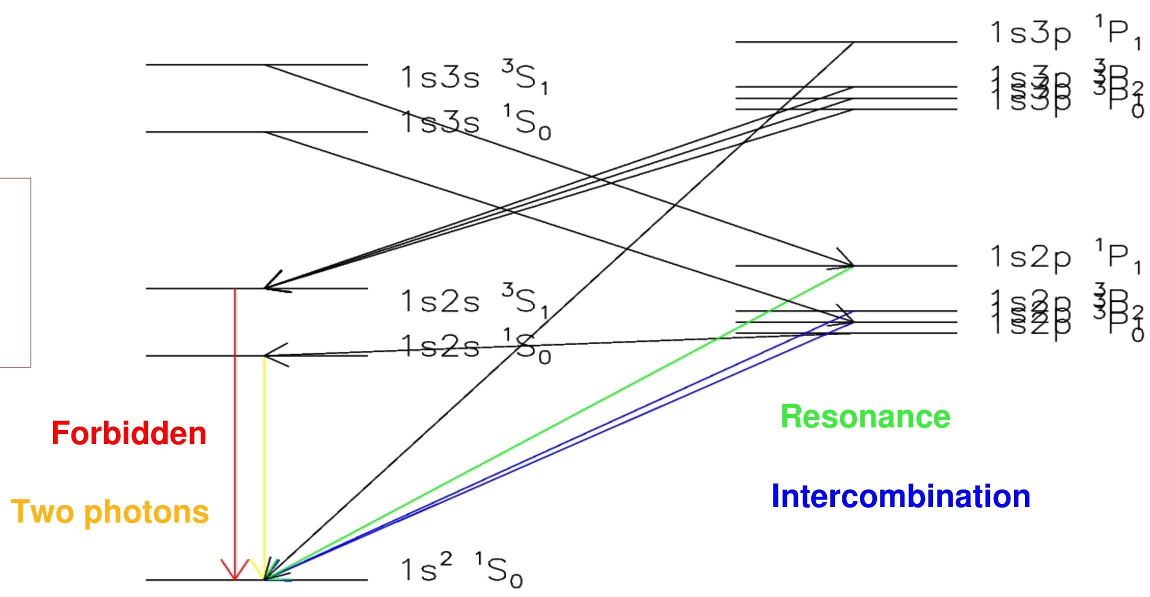
- fine structure energy levels have been regrouped and the collisional rate and A-rates have been re-calculated in order to save computational time. In addition, it is *flexible* to include fine structures for interested ions.

- including the atomic process of *cascading down following recombinations into highly excited levels*

- allowing electron temperature evolution due to *Coulomb interaction*

- dealing with dynamics and ionization *self-consistently*

For the collisional ionization plasma & the photoionization plasma exposed in the external radiation field



ISIS --- Interactive Spectral Interpretation System

(Houck 2002)

- All *XSPEC* models + mathematical scripts of *IDL*/*Matlab*
  (TCL in *XSPEC* is not mathematical
  e.g. models may be scripts, not just C/C++ or Fortran

- Very extensible: easy to add new features by wrapping external libraries (like LSODE) as importable modules (e.g. *XSTAR*)

- Fully programmable *APED* interface

- Distributed parallelism with PVM, and multicore parallelism with OpenMP

Noble et al. 2007 in preparation

New developments in *ISIS* *(on-going)*

1. Incorporate photoionization effects
   - --- Atomic data from *XSTAR*
   - --- Allowing atomic data to be queried and manipulated according to different physical scenarios.
   - --- Facilitating time-dependent NEI photoionization modelling e.g. NEI versions of *XSPEC* photemis/warmphot etc.

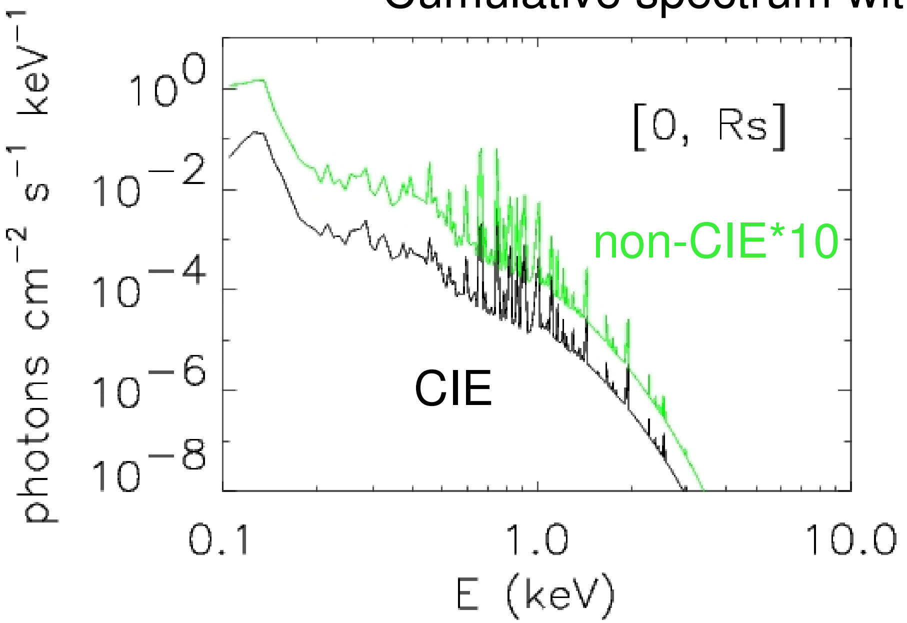
2. Develop template NEI models for simple dynamics
   - --- e.g. 1D steady-state adiabatic wind (Ji et al. 2006), single radiative shock flow in IGM (Ji et al. 2007), a slab of photoionization plasma with time-evolving ionization sources.
   - --- allowing self-consistent modelling of NEI plasmas
   - --- parallel computation (Noble et al. 2006)
   - --- friendly for custom users

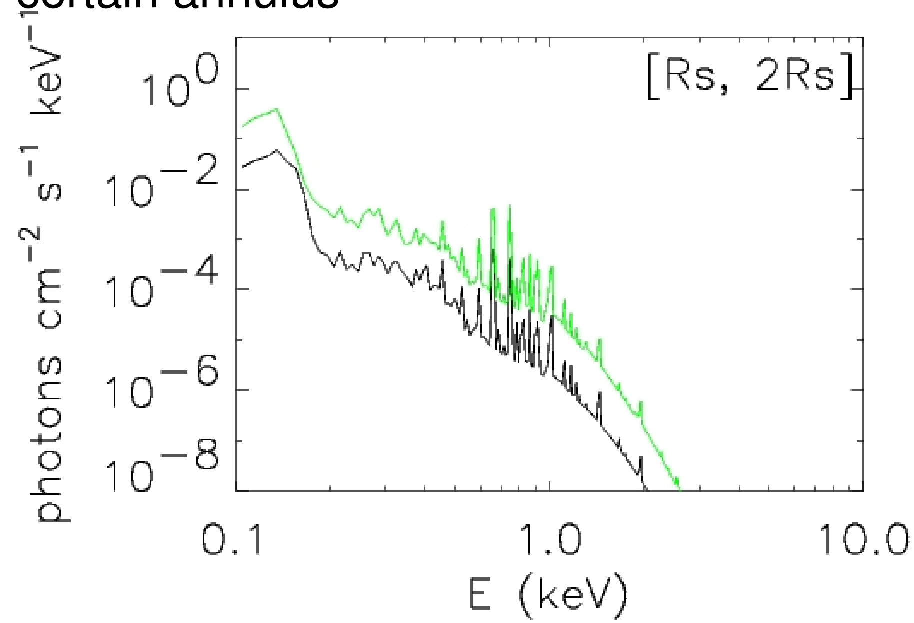
Thanks!

Comparisons for inner regions

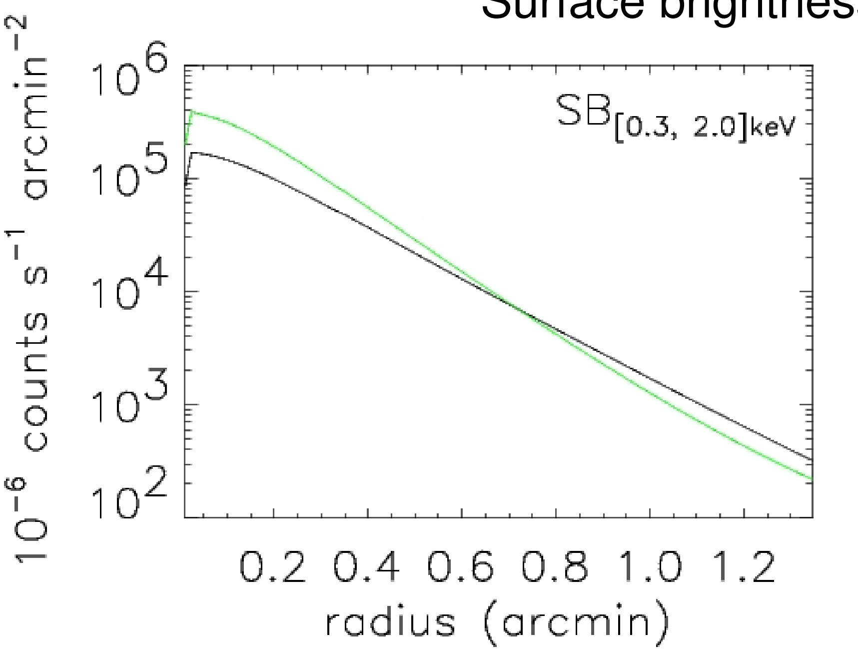
$V_{\infty}=500\,km\,s^{-1}$
$\dot{M}_0=10^{-4}M_{sun}\,yr^{-1}$

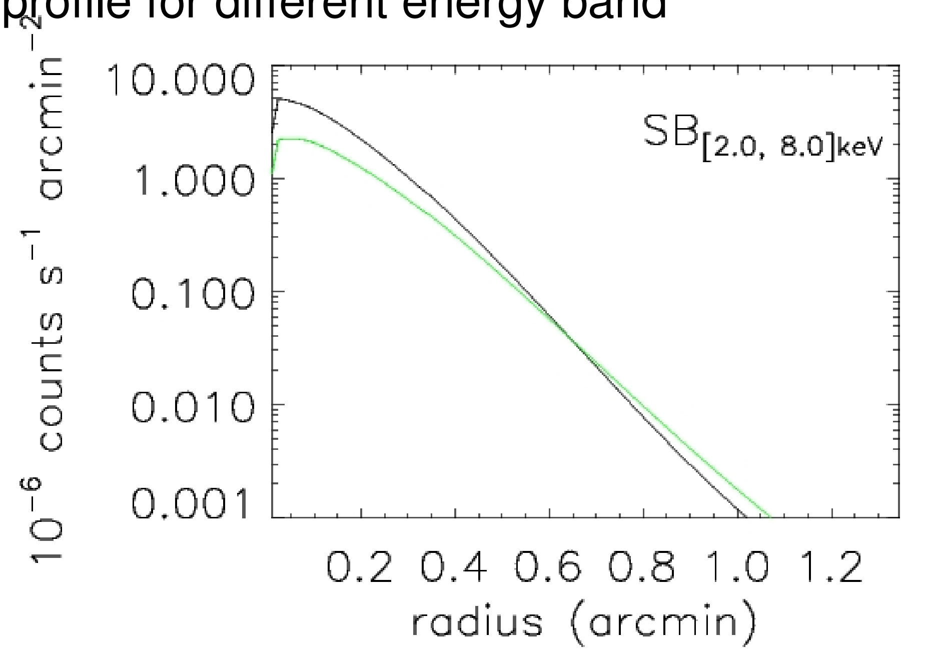
Cumulative spectrum within certain annulus





Surface brightness profile for different energy band





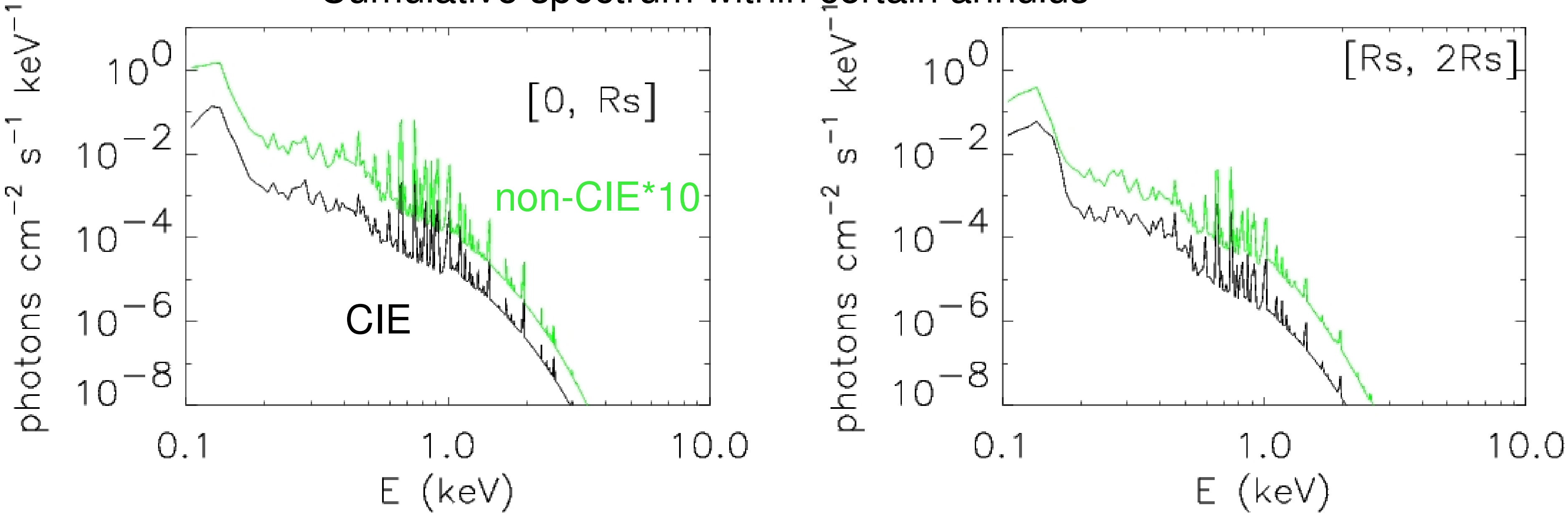
CIE could be a fair good approximation for stellar winds with small V_{∞} in the inner region

Comparisons for inner regions

$V_{\infty} = 500\, km\, s^{-1}$

$\dot{M}_0 = 10^{-4} M_{sun}\, yr^{-1}$

Cumulative spectrum within certain annulus



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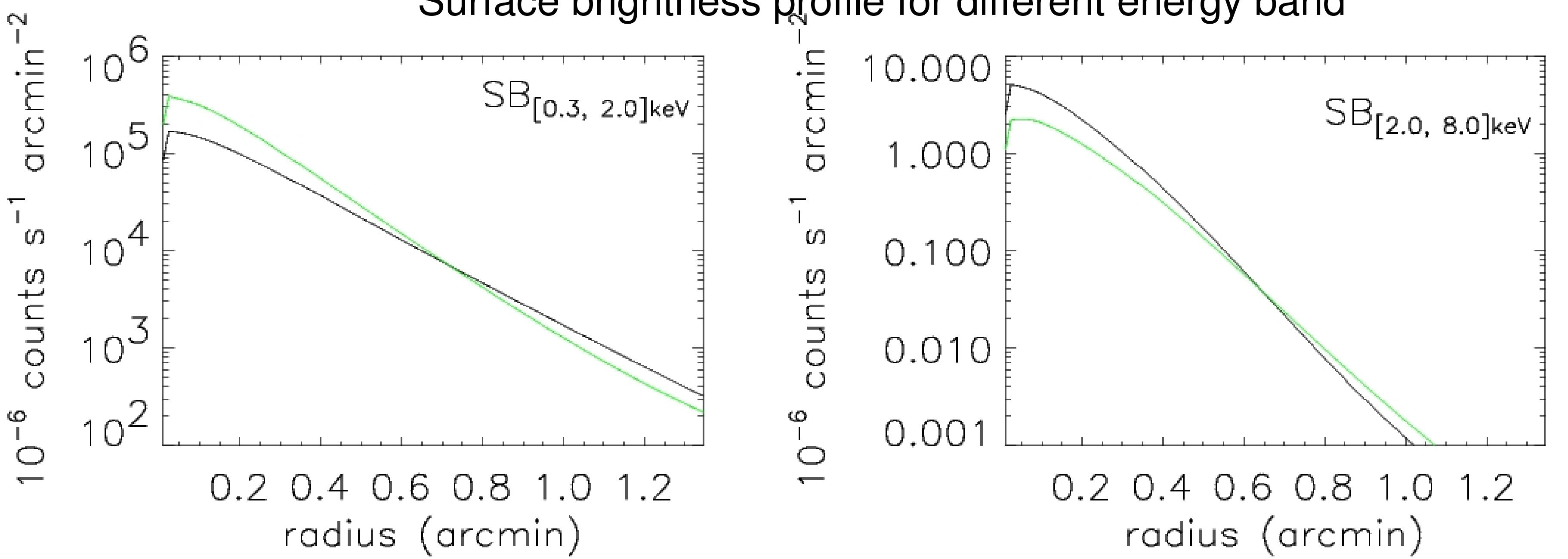
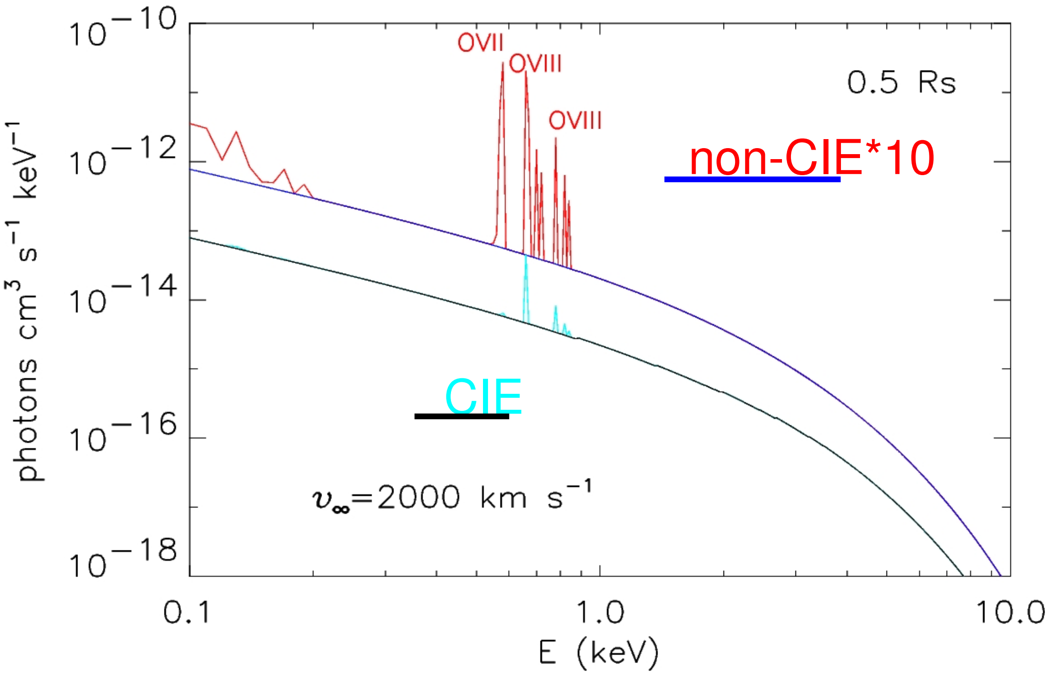
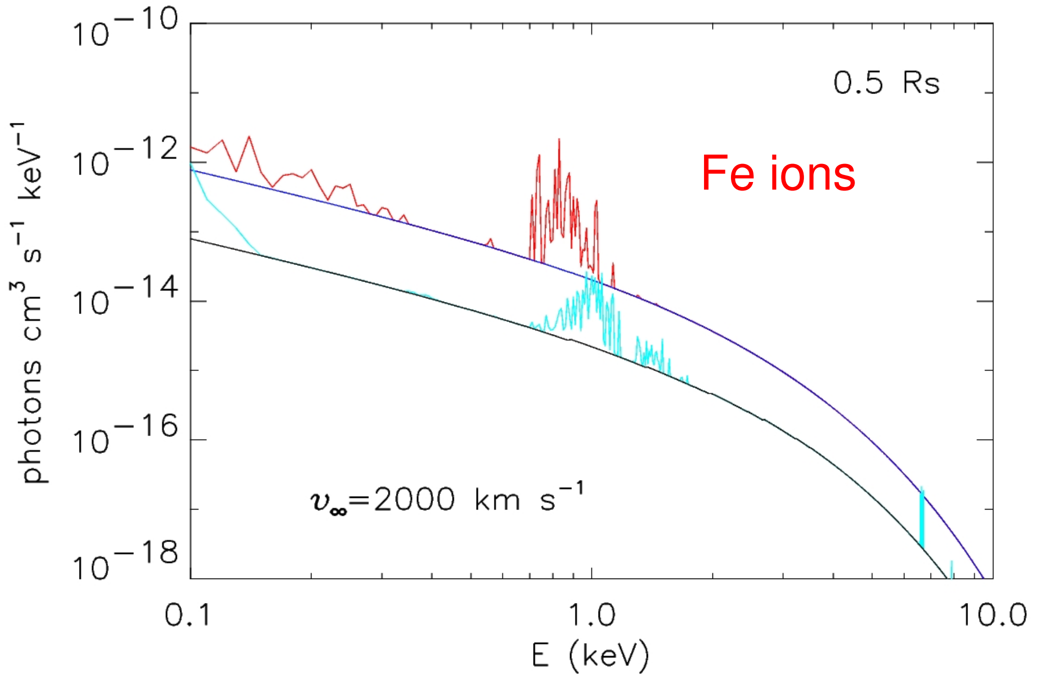


CIE could be a fair good approximation for stellar winds with small V_{∞} in the inner region

$$V_{\infty}=2000\,km\,s^{-1}$$
$$\dot{M}_0=10^{-4}\,M_{sun}\,yr^{-1}$$

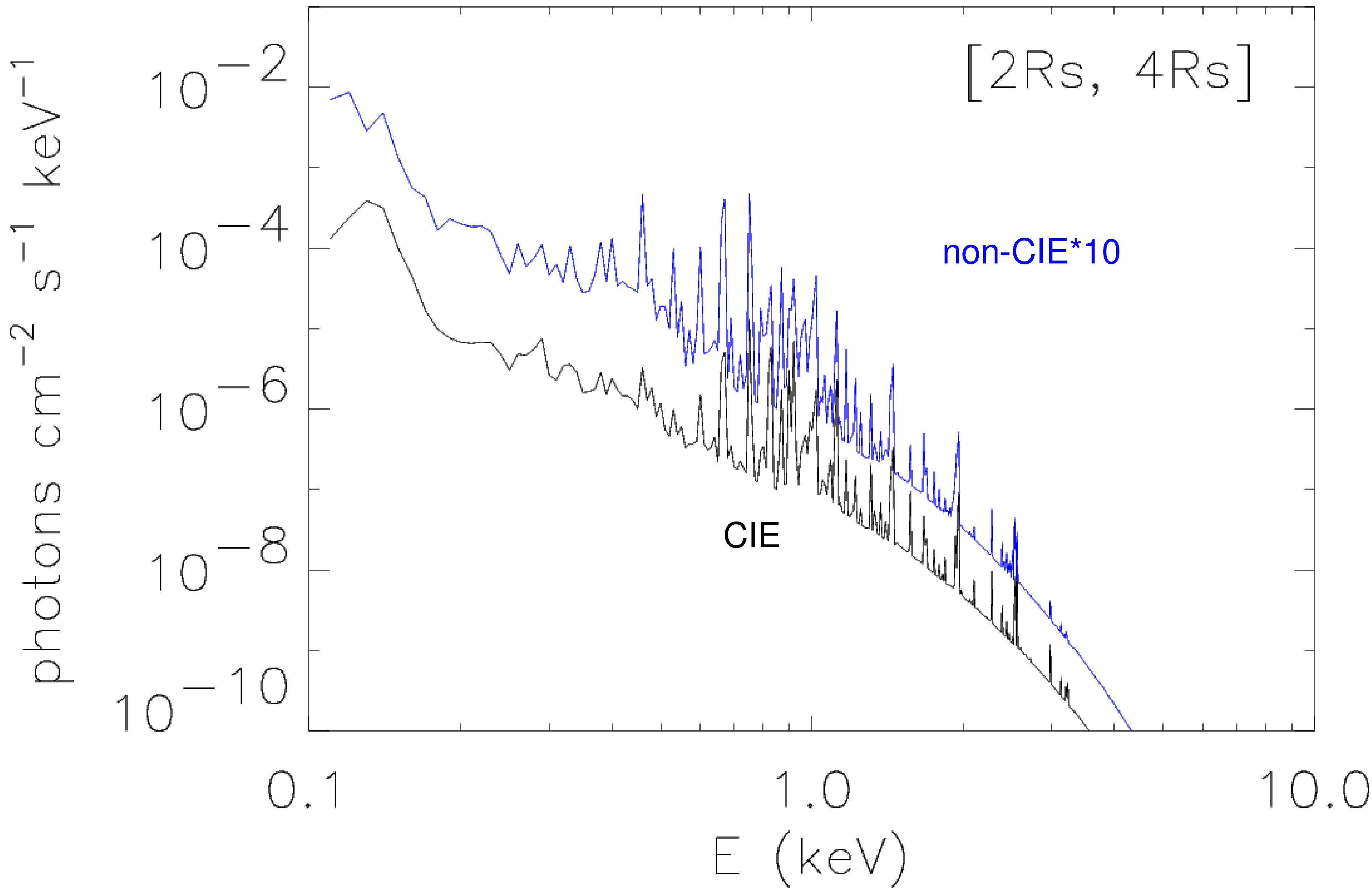




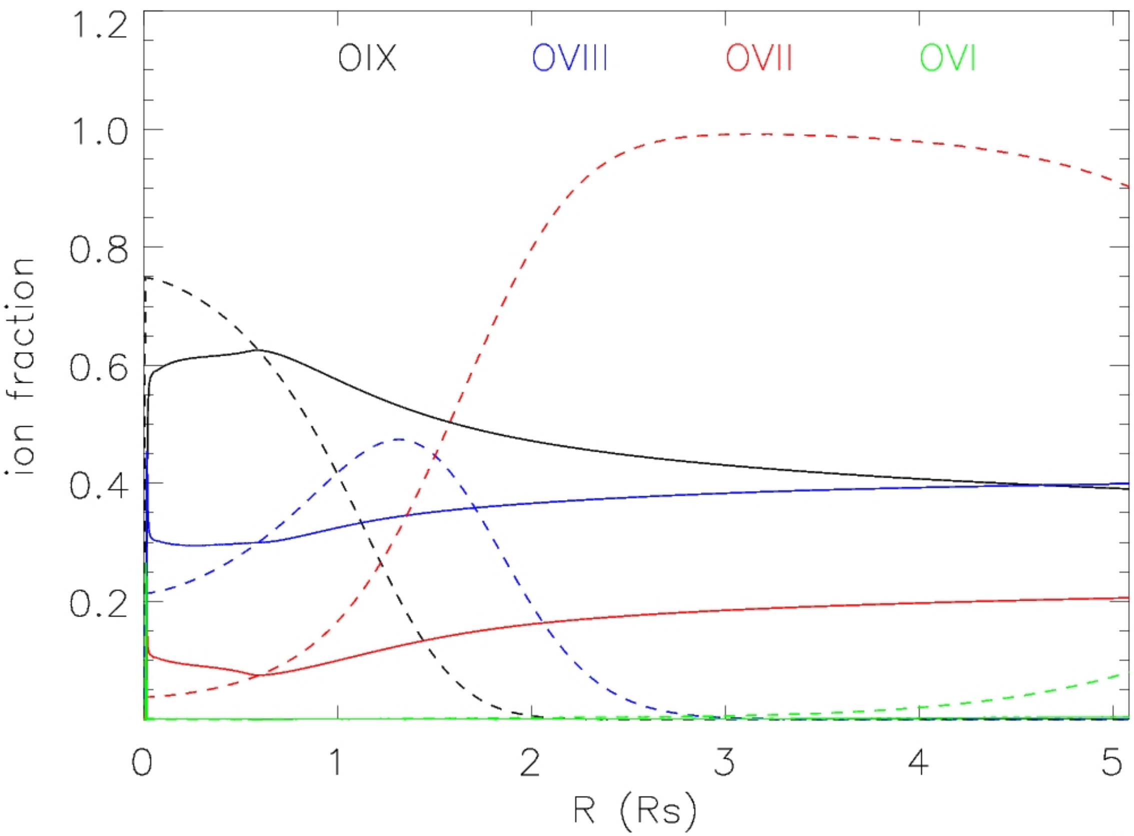
partially ionized ions from C,N,O and Fe account for the soft-excess in non-CIE case

Comparisons for outer regions

$V_\infty = 2000 km\, s^{-1}$
$\dot{M}_0 = 10^{-3} M_{sun} yr^{-1}$



CIE could be a fair good approximation for stellar winds with large V_∞ in the outer region



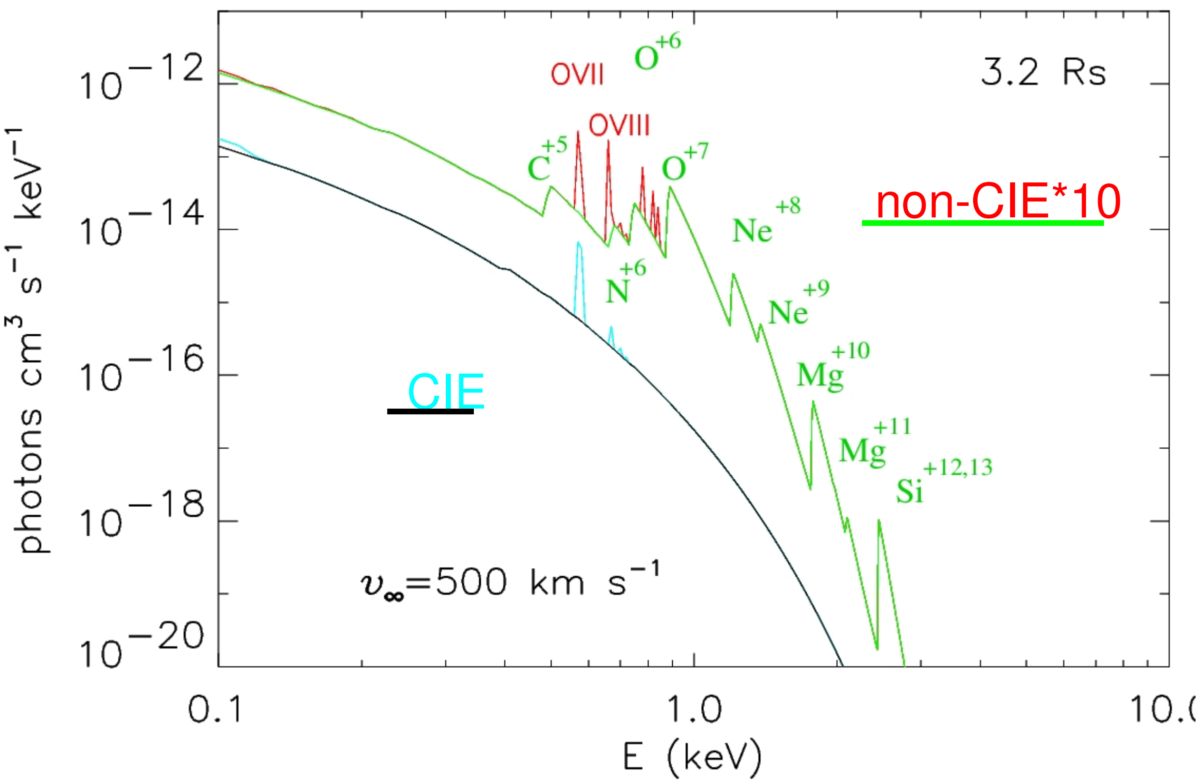
$V_\infty = 500 km\, s^{-1}$

$\dot{M}_0 = 10^{-3} M_{sun} yr^{-1}$

CIE: dash lines
non_CIE: solid lines

- *delayed recombination dominates in outer region*

- *recombination edges and cascade lines due to recombination into highly excited energy levels account for the difference*



An illustration

an adiabatic expanding stellar cluster wind

$\dot{M} \sim 3 \times 10^{-5} M_{sun} yr^{-1}$

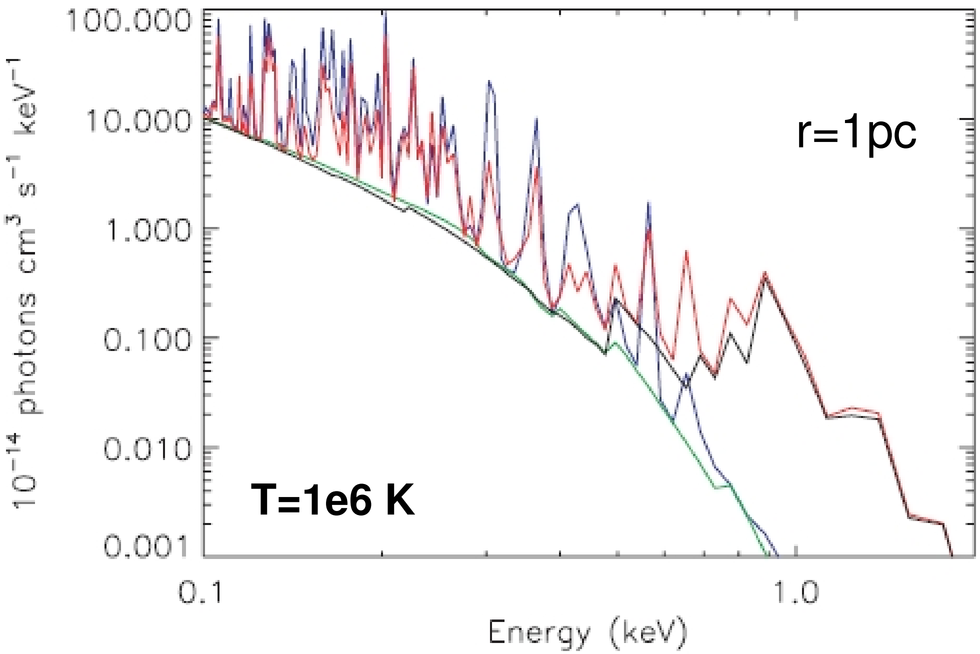
$v = 1000\, km\, s^{-1}$

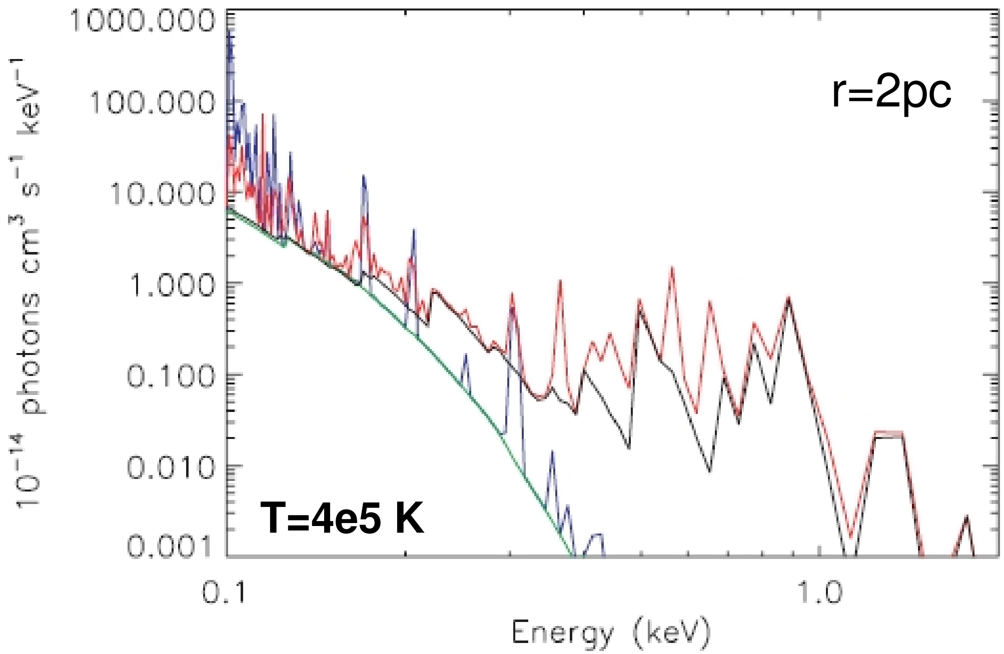
$T = T_0 (r/r_0)^{-4/3}$

$T_0 = 5 \times 10^6 K$

$r_0 = 0.3\, pc$

Comparison of Equilibrium/Non-CIE spectrum

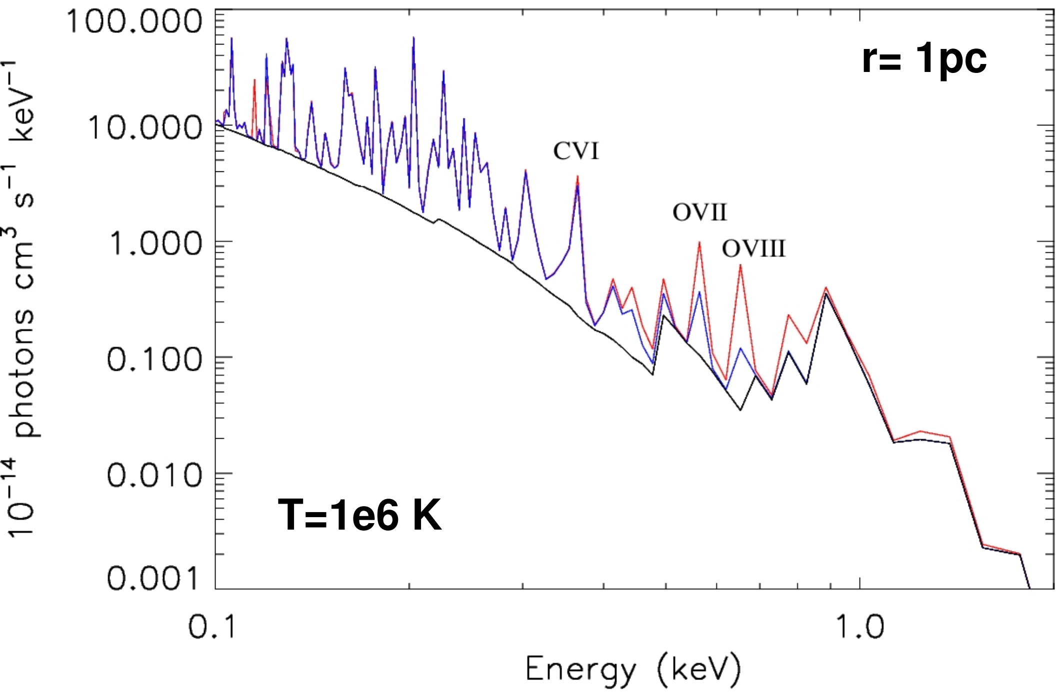


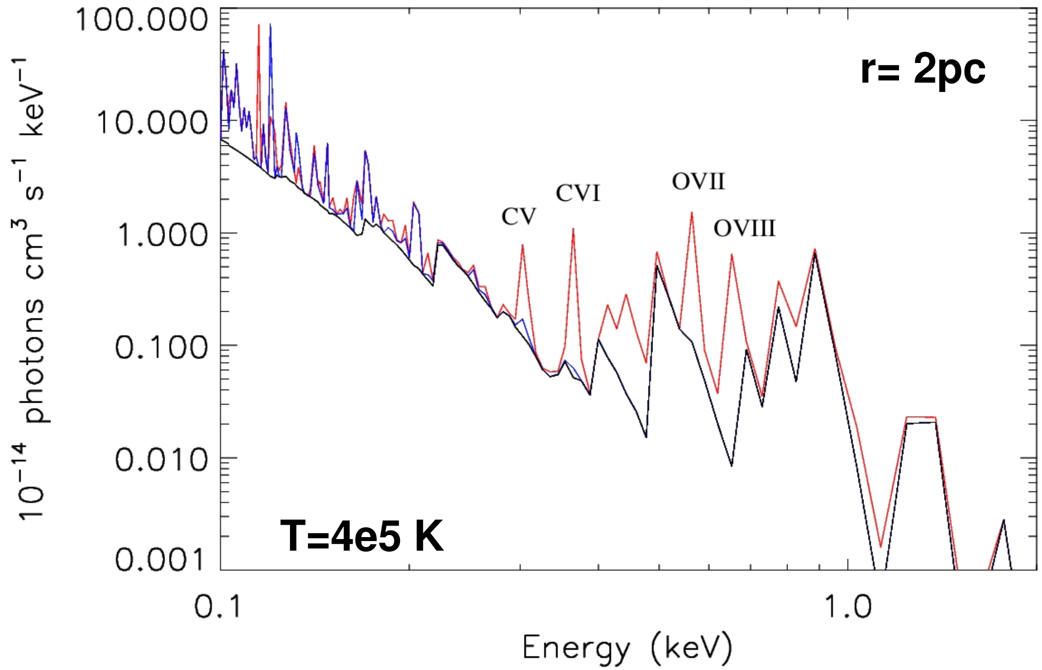


An illustration

Comparison of spectral code with/without including

recombinations into highly excited levels for non-CIE case





Level balance equations

$$n_i \sum_{j \neq i} \alpha_{ij} = \sum_{j \neq i} n_j \alpha_{ji} + n_{\mathrm{e}} \frac{N(Z^{+(z+1)})}{N(Z^{+z})} RR(Z^{+(z+1)})_i$$

$$= n_j (n_{\mathrm{e}} C_{ji} + A_{ji}) + n_{\mathrm{e}} \frac{N(Z^{+(z+1)})}{N(Z^{+z})} RR(Z^{+(z+1)})_i$$