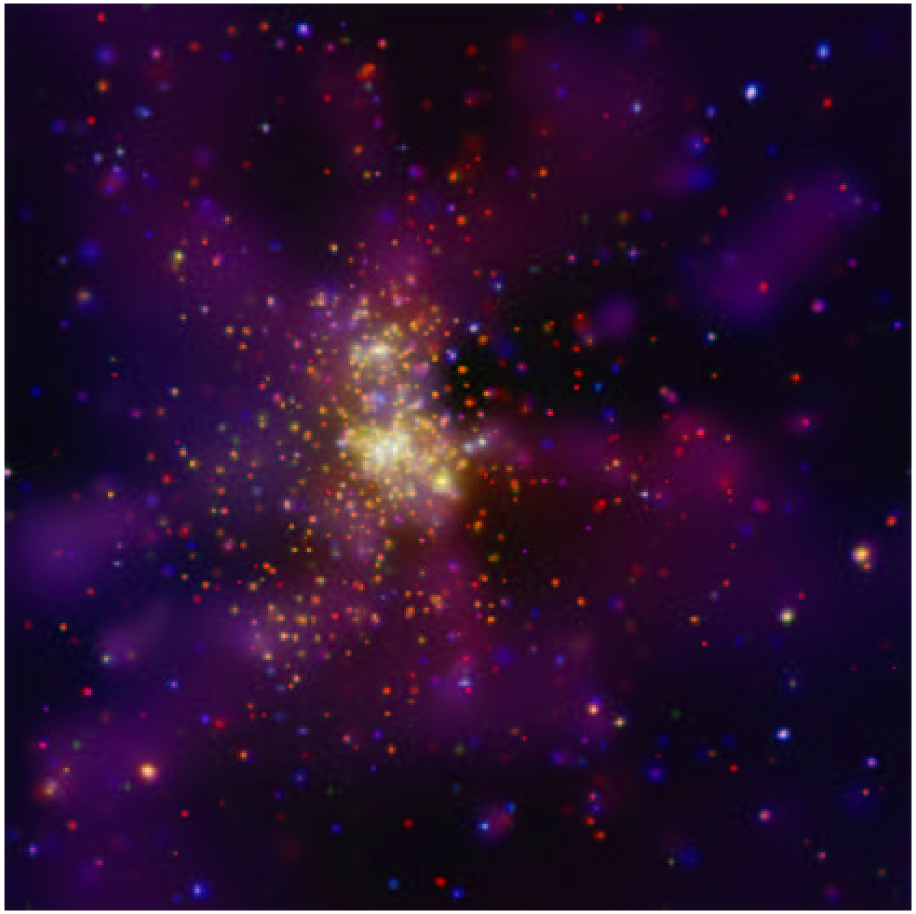
The X-Ray Universe

Potsdam University



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Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d=2×10^4ly

Reminder: X-ray Detectors

Weak source against a strong background.

Source detection is done on a photon-by-photon basis.

Non-imaging (e.g. Proportional counters) and imaging (e.g. CCD) detectors

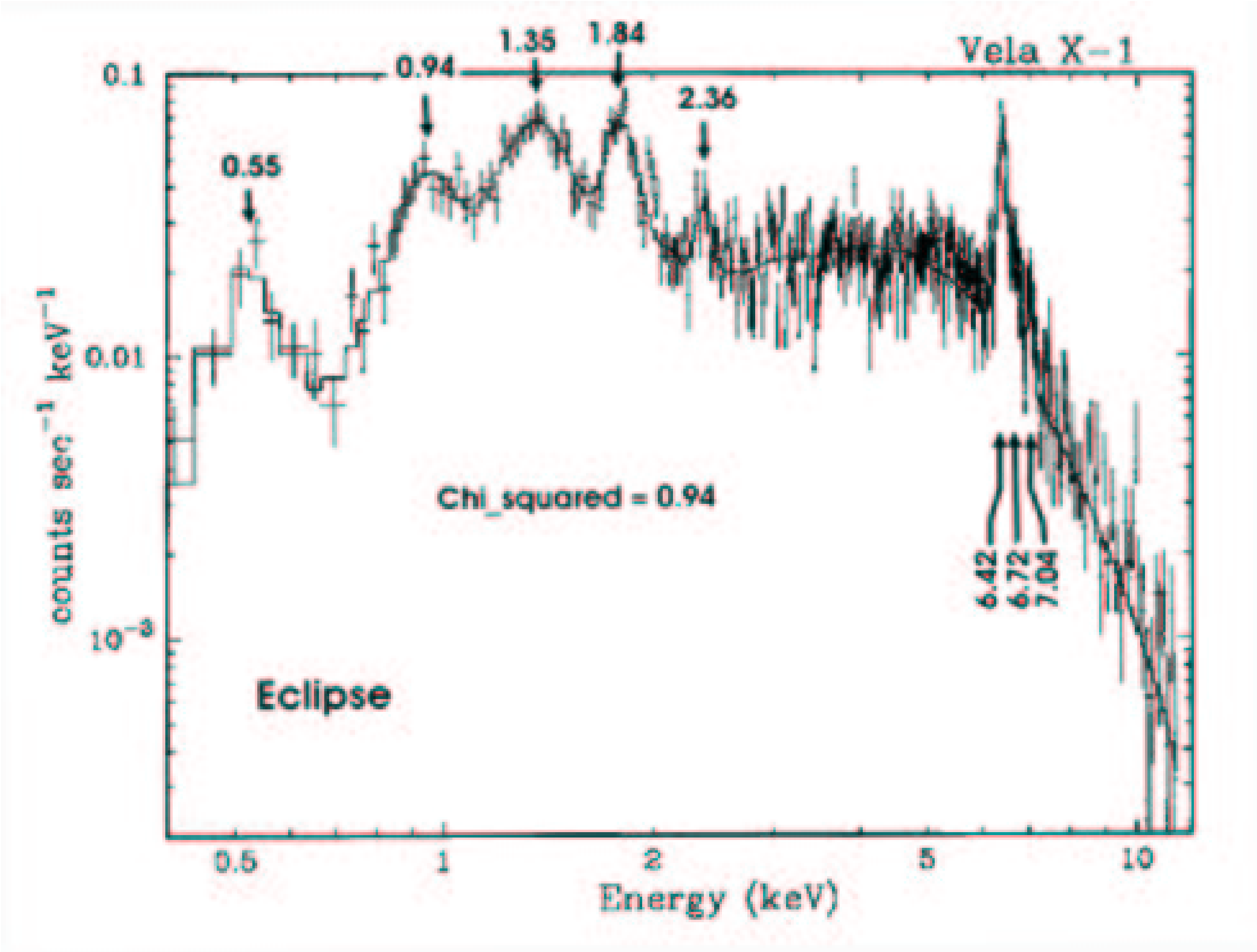
CCD: front illuminated (MOS) and back illuminated (PN)

- **Ionization detectors:** X-ray hits detector and ionizes an atom:
- **Mesured charge** is proportional to the deposited energy

- **Microcalorimeters:** Exited electorns go back to the original energy
- **Measured heat** is proportional to the deposited energy

High-resolution spectroscopy: grazing gratings (e.g. RGS XMM-Newton)

IV. Radiation Processes



http://heasarc.gsfc.nasa.gov/docs/objects/binaries/v

IV. 1. Principle Interactions

- Electron + nucleus: continuum Bremsstrahlung radiation
- Electron + ion: line recombination radiation
- Electron + magnetic filed: cyclotron and synchrotron

The emerged spectrum can be modified by:

* Interaction with ions: photoelectric absorption
* Interaction with electrons: comptonisation
* Interaction with energetic photons: photon-photon pair production

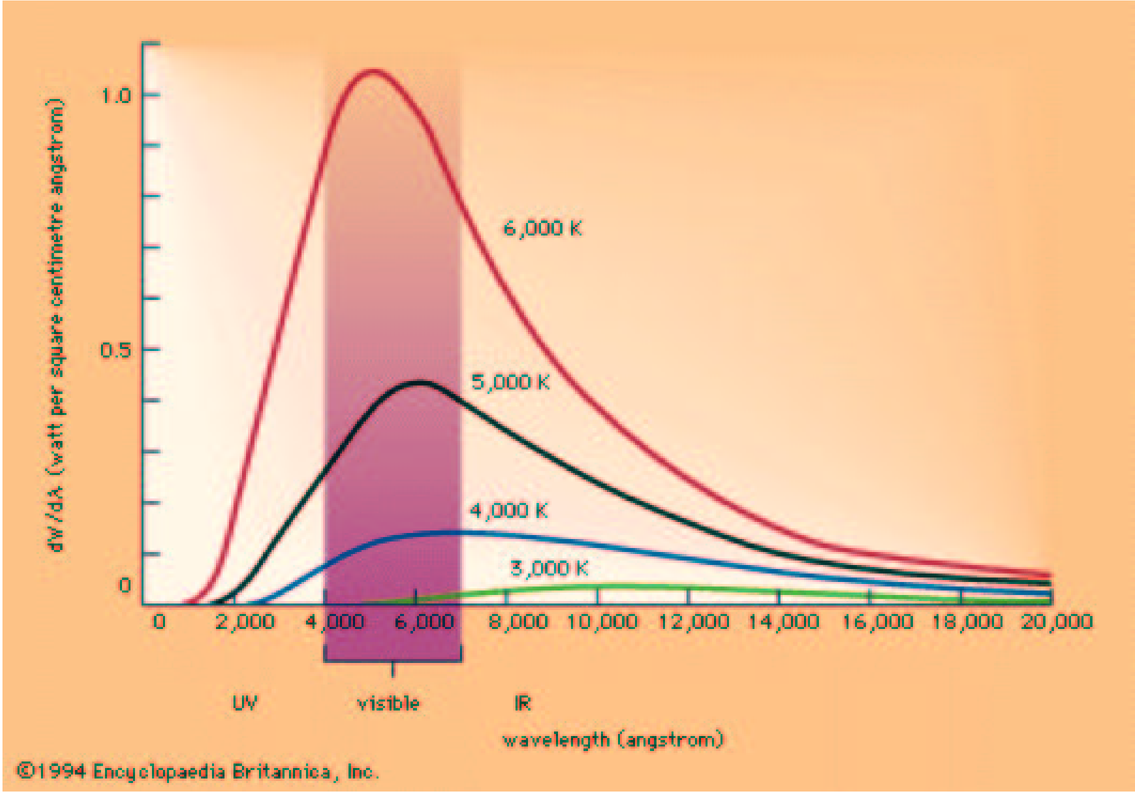
If particle-particle collisions are importnat
then the energy distribution of electrons is **thermal: T**

If particle-particle collisions are **not** importnat
then the energy distribution of electrons is **non-thermal**
acceleration process, photoionized plasmas

IV. 2. Some simplifications

- Atoms only: Molecules and dust are usually not observed
- No nucler transitions: These are γ-rays
- No 3-body transitions: Astrophisically non-important
- No metal-metal collisions: X-ray plasmas are tenious,
  - even He-He collisions are not important
- No neutral gas: X-ray emitting plasma always ionized,
  - i.e. $n_e = n_i$

IV. 3. Thermodynamic equilibrium. Black Body



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$$I_\nu(T)d\nu = \frac{2h\nu^3}{c^2}(\exp\frac{h\nu}{kT} - 1)^{-1}d\nu$$

Wien’s displacement law:

$$\lambda_{max}[\text{Å}] \approx \frac{29}{T[\text{MK}]}$$

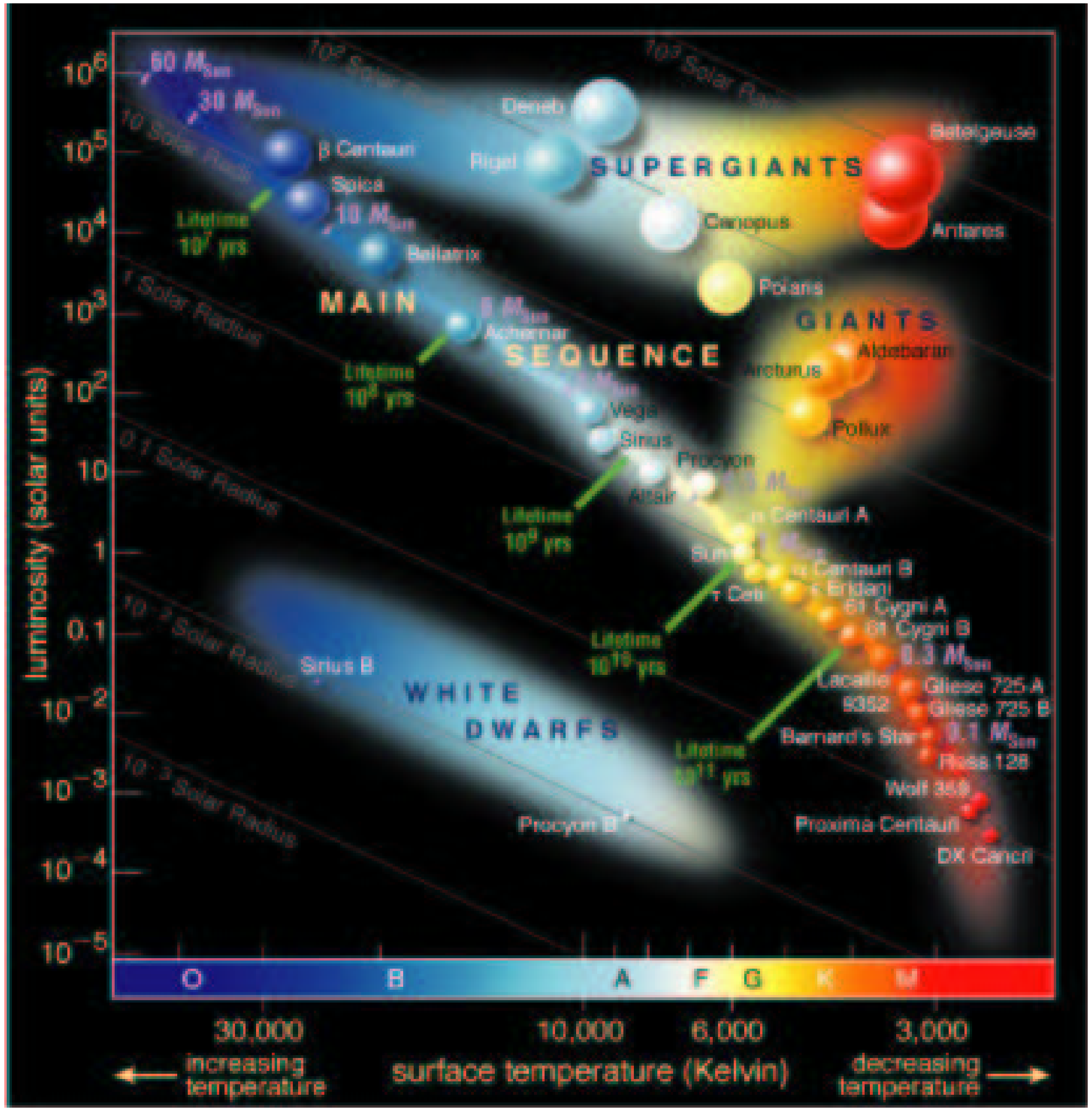
X-rays λ=1..100Å : T=30MK .. 30kK

Thermodynamic equilibrium: stellar interior

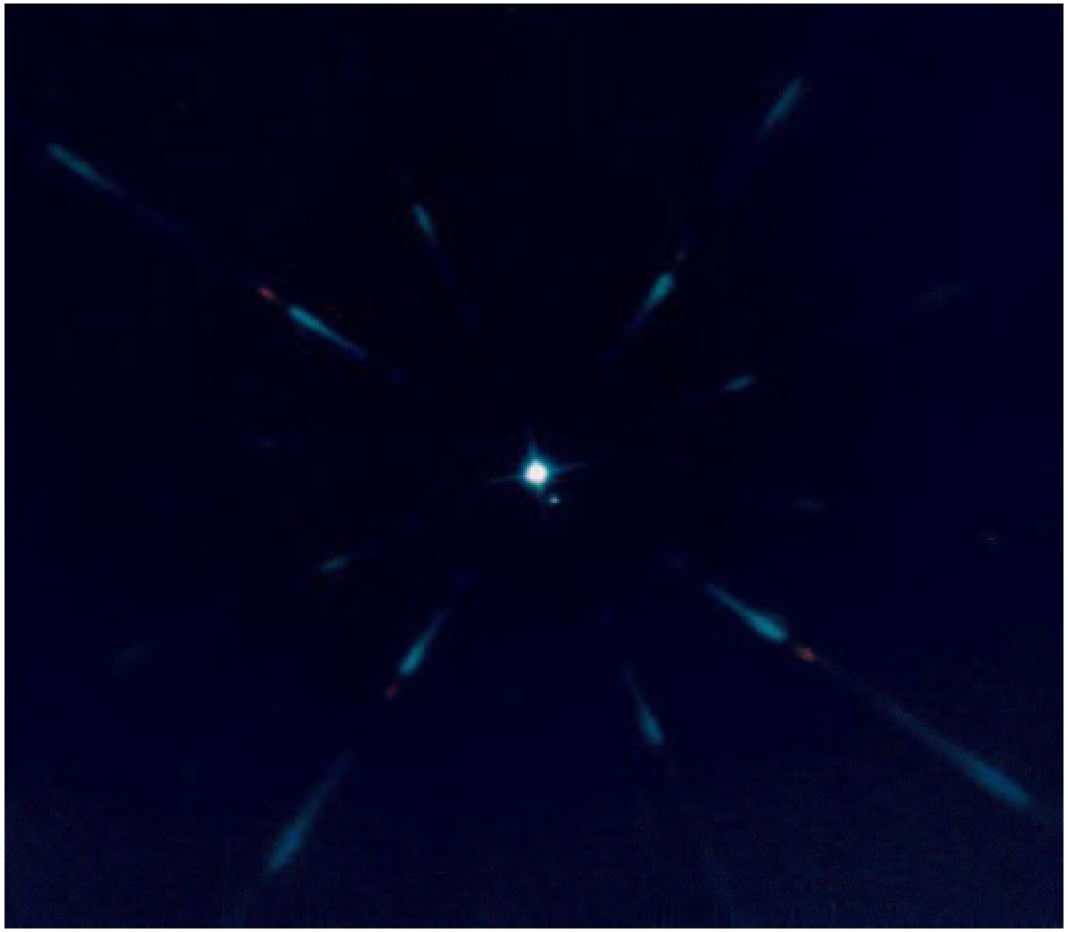
But stellar photospheres are not that hot: 1kK … 200kK

May be only hottest white dwarfs, neutron stars

IV. 4. Reminder Hertzsprung-Russell-Diagramm

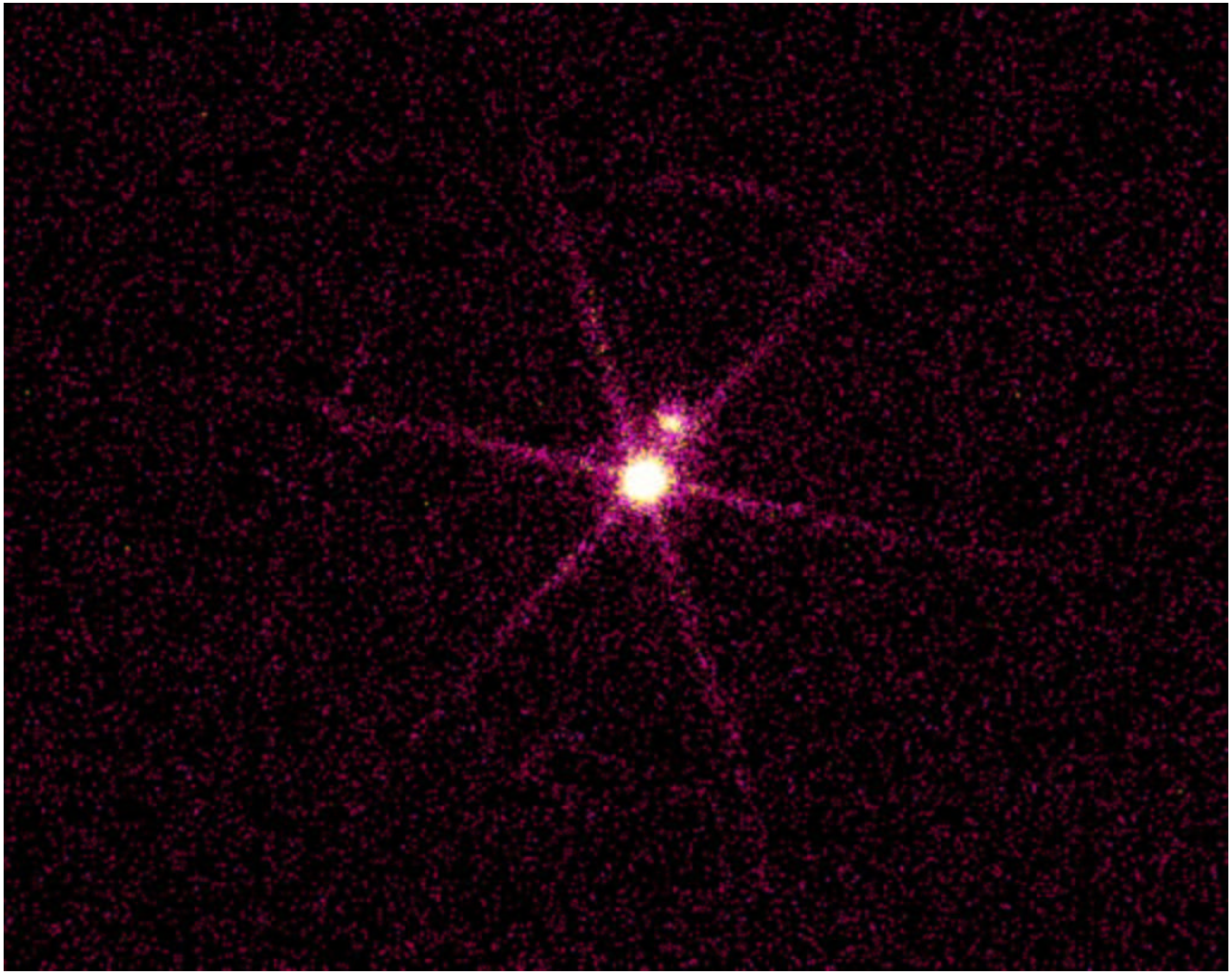


Sirius in optical



Credit: McDonald Observatory

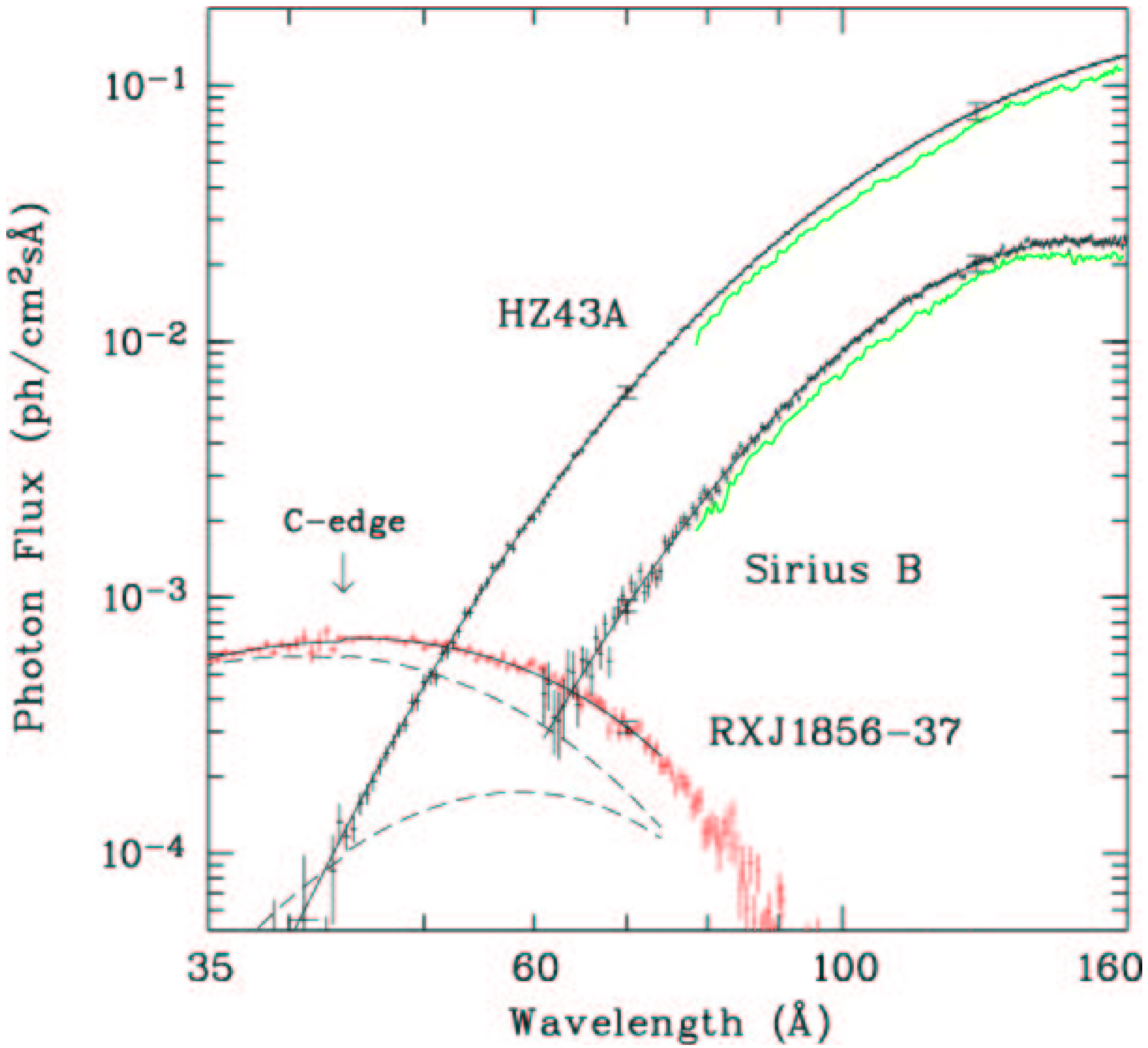
IV. 5. Chandra’s Sirius B



http://chandra.harvard.edu/photo/2000/0065

Sirius B, WD T=25 000 K, X-rays: the Wien part of the Plank curve

IV. 6. Black body: neutron stars and white dwarfs



http://chandra.harvard.edu/photo/2000/0065

Sirius B

WD T=25 000 K

the Wien part of the Plank curve

Neutron Star RXJ1856-37

T=374361 K,

λ_{max} = 77Å

Hot spot T=719479K,

λ_{max} = 40Å

Blackbody spectrum is modified by

1) instrumental responce 2) interstellar abosrption

IV. 7. Thermal plasma

Thermodynamic equilibrium occurs if $N_{\ddot{e}} > 10^{14} T_e^{0.5} \Delta E_{ij}^3 \, \mathrm{cm}^{-3}$

For T=10 MK and H-like Iron, $N_{\ddot{e}} > 10^{27} \, \mathrm{cm}^{-3}$

For T=0.1 MK and H-like Oxigen, $N_{\ddot{e}} > 10^{24} \, \mathrm{cm}^{-3}$

These are very high densities occuring hardly anywhere outside stars

Astrophiscally important plasmas

- Coronal/Nebular $N_e < 10^{16} \, \mathrm{cm}^{-3}$
- Collisional-Radiative $N_e < 10^{24} \, \mathrm{cm}^{-3}$

$KT_e \approx I_p$

- * Ionization and exitations are by collisions
- * In coronal plasmas decay is mainly radiative
- * IN CR plasma, a level may be collisionally de-excited
- * Produced X-rays leave without interacting with the plasma,
- * plasma is optically thin for X-rays!

IV. 8. Equilibrium in thermal plasma

Thermal plasma can be in equilibrium or out of it.

- Ionization equilibrium (CIE plasma)

  the equiation of stationarity are dominated by collisional terms

  $I_{rate}(Ion)+R_{rate}(Ion)=I_{rate}(Ion-)+R_{rate}(Ion+)$

  Plasma codes that calculate spectra:

  e.g. Astrophysical Plasma Emission Code - APEC

  Large variety of astrophysical sources: stars

- Non-equilibrium ionization (NIE plasma)

  ionization rate is higher than recombination

  recombination rate is higher than ionization

  others, i.e. some additional energy source

  NEI - codes

  occurs e.g. in supernova remnants

IV. 9. APEC

Collisional-Radiative plasma code

Atomic data: Astrophysical Plasma Emission Database (APED)

spectral models for hot CIE plasmas

- collisional and radiative rates
- recombination cross sections
- dielectronic recombination rates
- stationary plasma

comapring observed and model spectra

physical parametes of the plsama: T, ρ, chemical composition

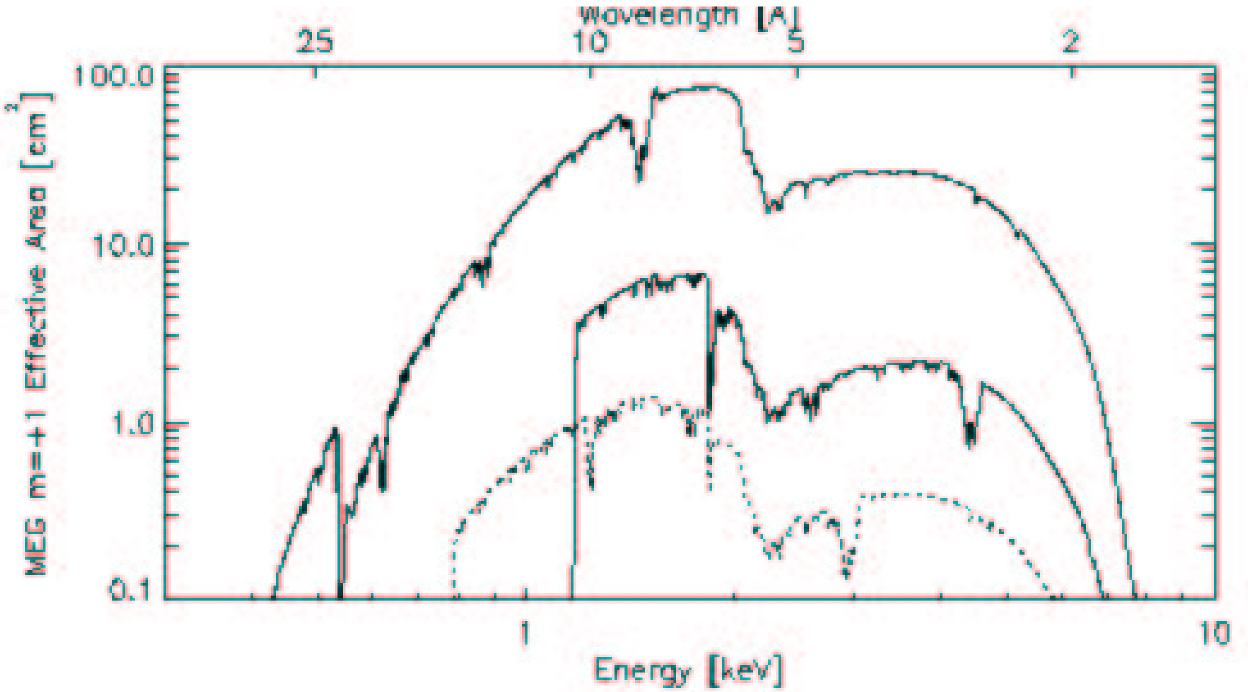
The spectral emission per unit volume

$$\frac{dP_B}{dV} = 2.7 \times 10^{-15} \sqrt{T} N_e N_Z \; f_{nn'} g_{nn'} \; [\mathrm{erg\ cm^{-3} s^{-1}}]$$

model spectrum should be folded with instrumental responce

before comapring to the data

IV. 9. Instrumental responce. Chandra MEG

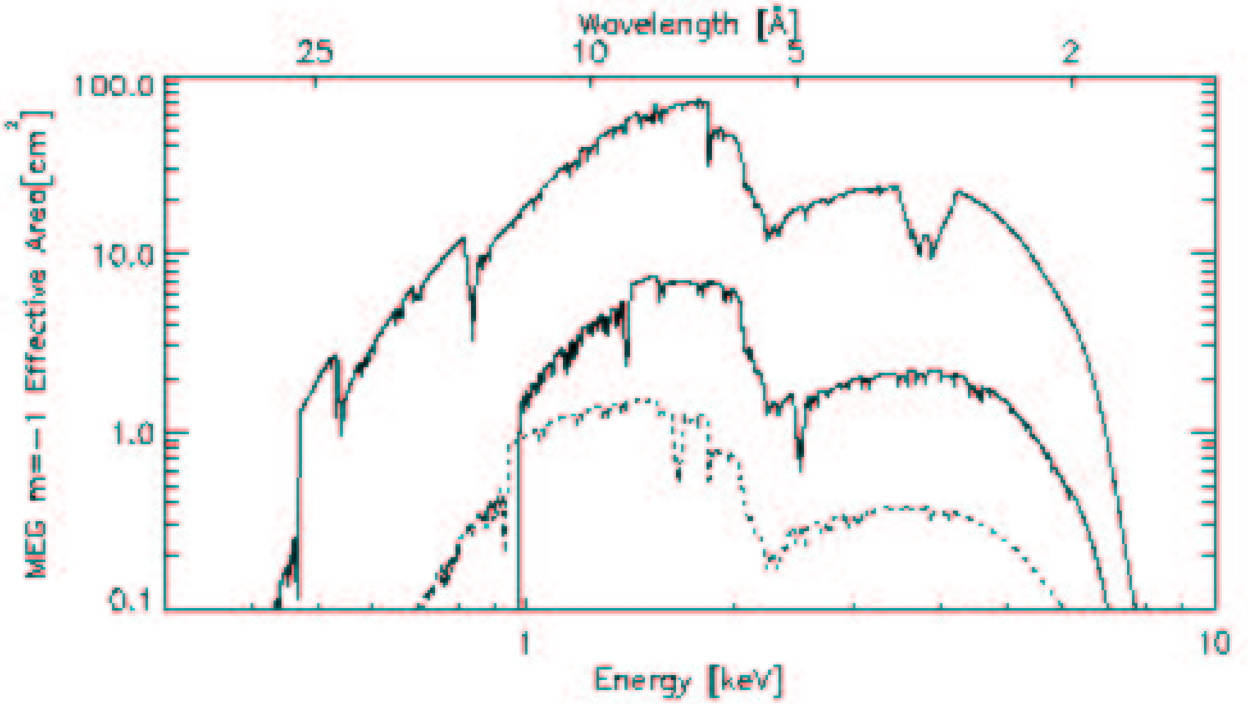


Example of instrument

effective area

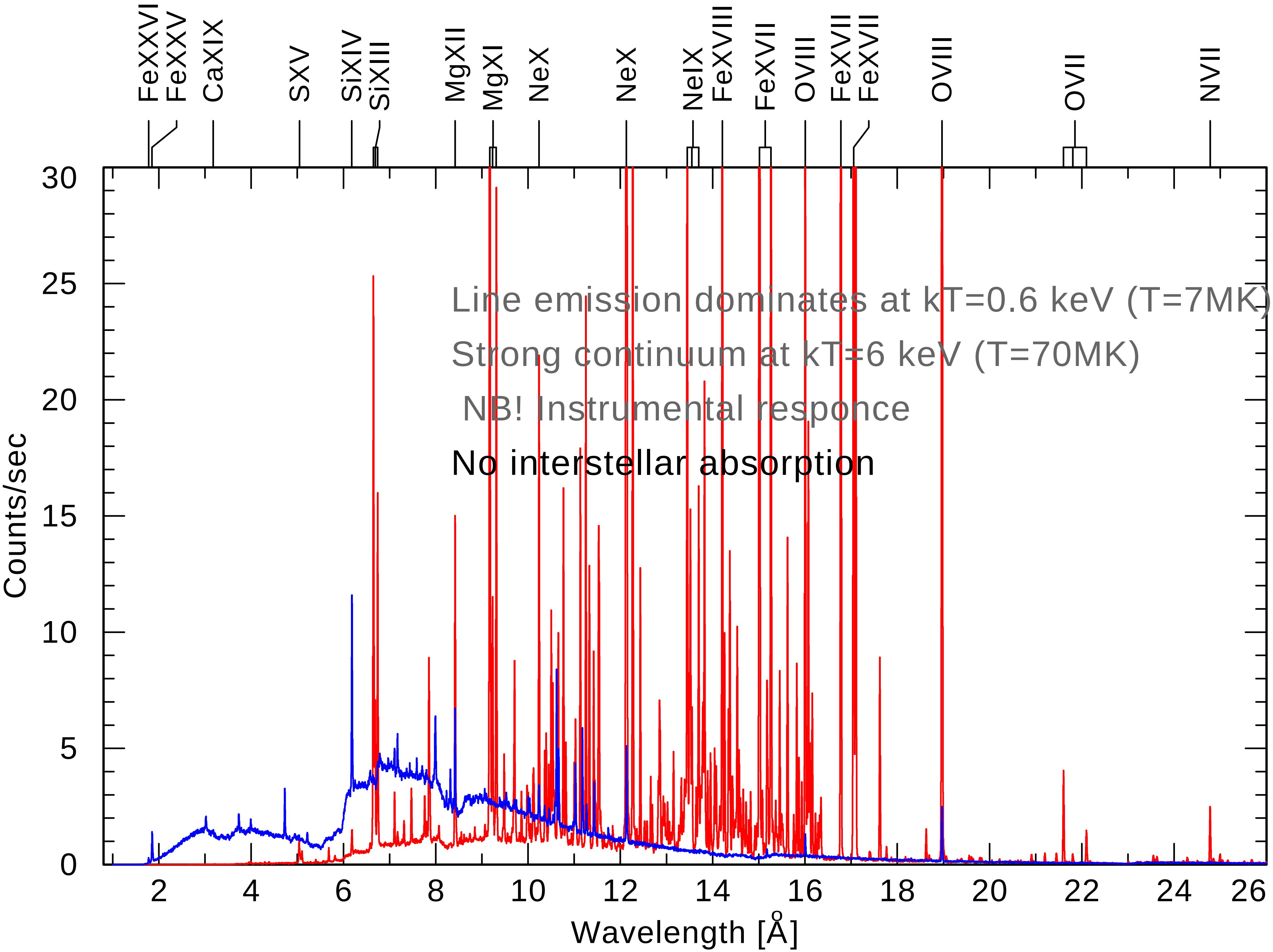
Chandra medium energy grating

+1, +2, +3 orders



-1, -2, -3 orders

IV. 10. APEC simulated spectrum for Chandra MEG+1



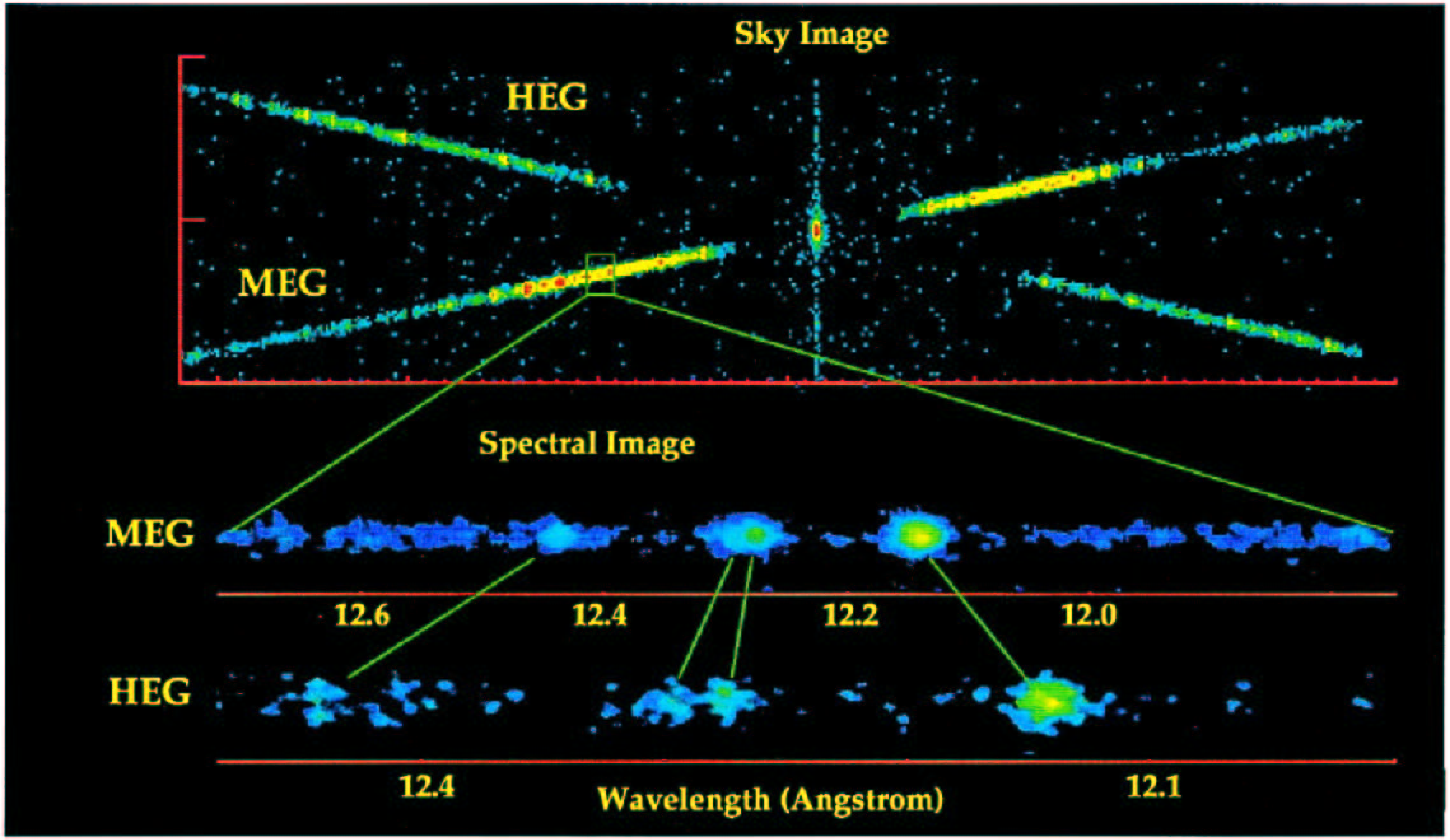
Line emission dominates at kT=0.6 keV (T=7MK)

Strong continuum at kT=6 keV (T=70MK)

NB! Instrumental responce

No interstellar absorption

IV. 11. Chandra observation of Capella G8III+G1III



ApJ 539, L41

Spectrum shown as an image in sky coordinates

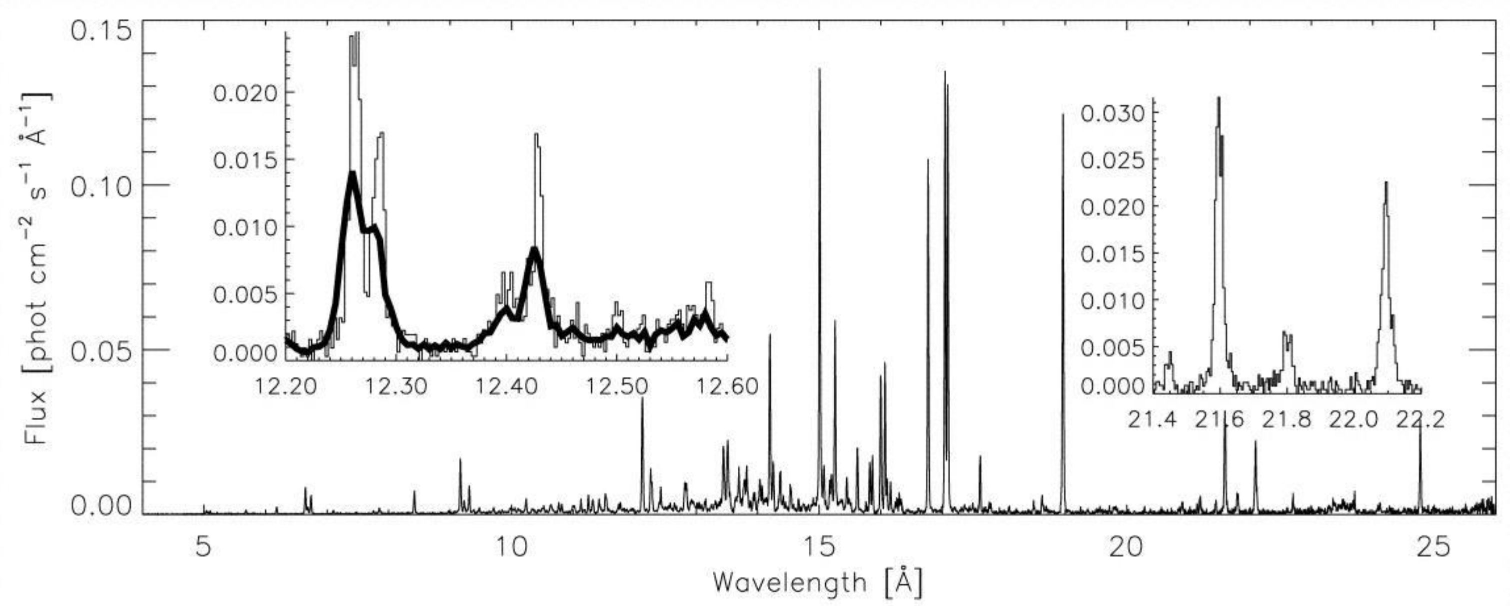
The zeroth-order image is in the center

(the vertical streak is caused by the CCD

The sky image has been blurred for visual presentation

A small portion of each spectrum is shown at the bottom

IV. 12. Spectrum of Capella G8III+G1III



ApJ 539, L41

Temperature T=2MK..15MK

Density $N_e = 10^{10}$ cm^{-3} (more later)

Solar abundancies

IV. 13. Which process can produce thermal plasma?

Collisional equilibrium, unique temperature T_X

Gas is heated to at least 0.5-1 MK by some process

E.g. strong shocks

The Rankine--Hugoniot condition:

shock waves normal to the oncoming flow

$$kT_X = \frac{3}{16}\mu m_H U^2$$

U is velocity jump in the shock, for hydrogen plasma μ=0.5,

$$U[1000\mathrm{km/s}] = 0.3\,\sqrt{T_X[\mathrm{MK}]}$$

To get 1 MK plasma a shock jump 300 km/s or 1 Million km/hr is needed

or "coronal heating"

Solar corona has T > 1 MK

Acustic waves? Nanoflare heating?

IV. 14. Thermal Bremssshtrahlung

http://www.desy.de

Bremssshtrahlung calculations

Find spectrum from single encounter of electron and ion with given impact parameter

Integrate over all possible impact paraemters

Integrate over distribution of electron velocities (in this case Maxwellian)

Important when temperatures are very high:10...100 MK

The dominant emission from cluster of galaxies

The total bremsstrahlung emission:

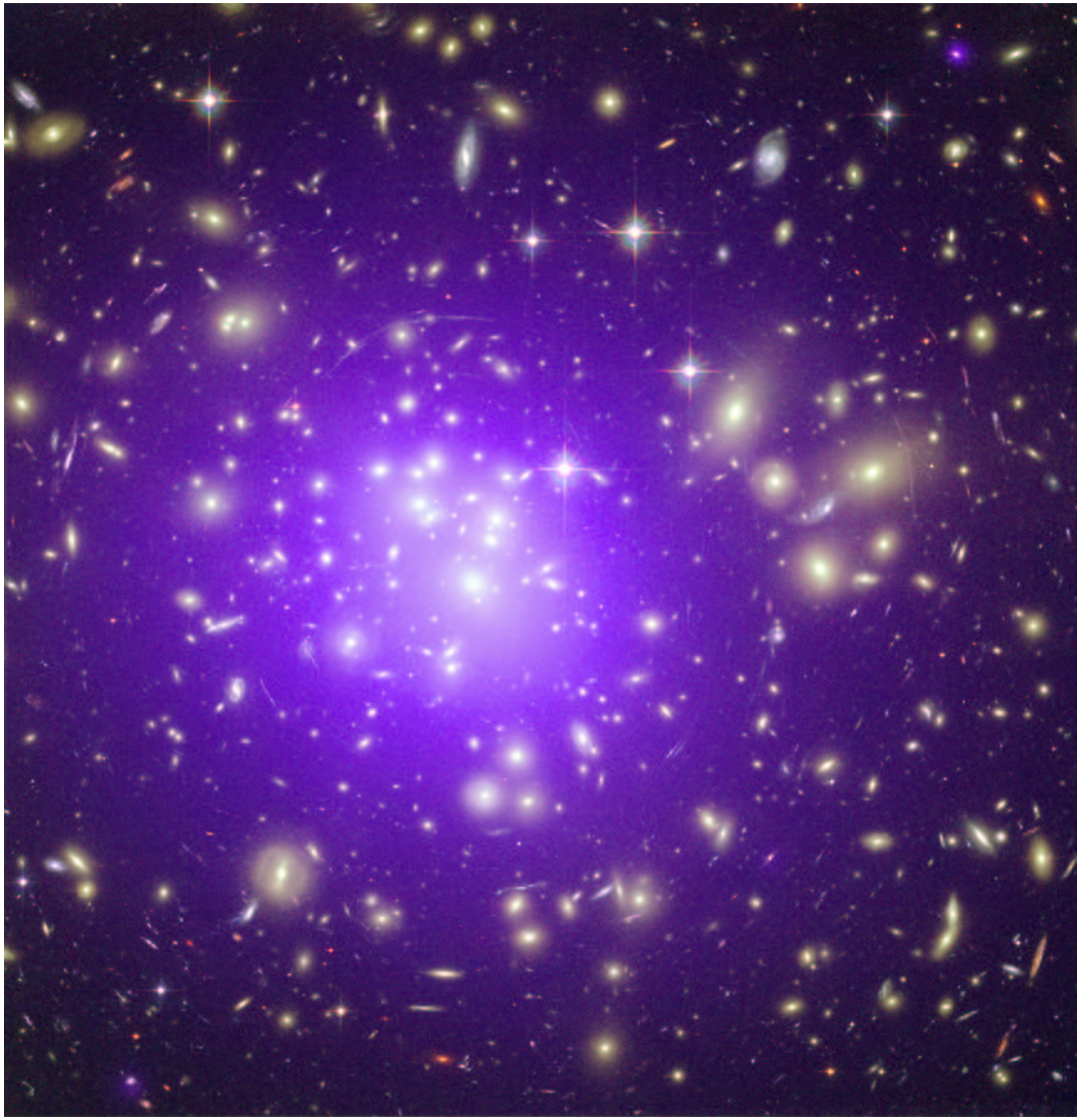
$$\frac{dP_B}{dV} = 2.4 \times 10^{-27} \sqrt{T} N_e^2 \quad [\text{erg cm}^{-3} \text{s}^{-1}]$$

Note that electron distribution can be non-thermal,

$J(E)=J_0 E^{-s}$ [erg $cm^{-2} s^{-1} erg^{-1}$] →

spectral shape depends on the elesctron spectrum

IV. 15. Example galaxy cluster Abell 1689



http://chandra.harvard.edu/photo/2008/a1689/

Composit Chandra+HST

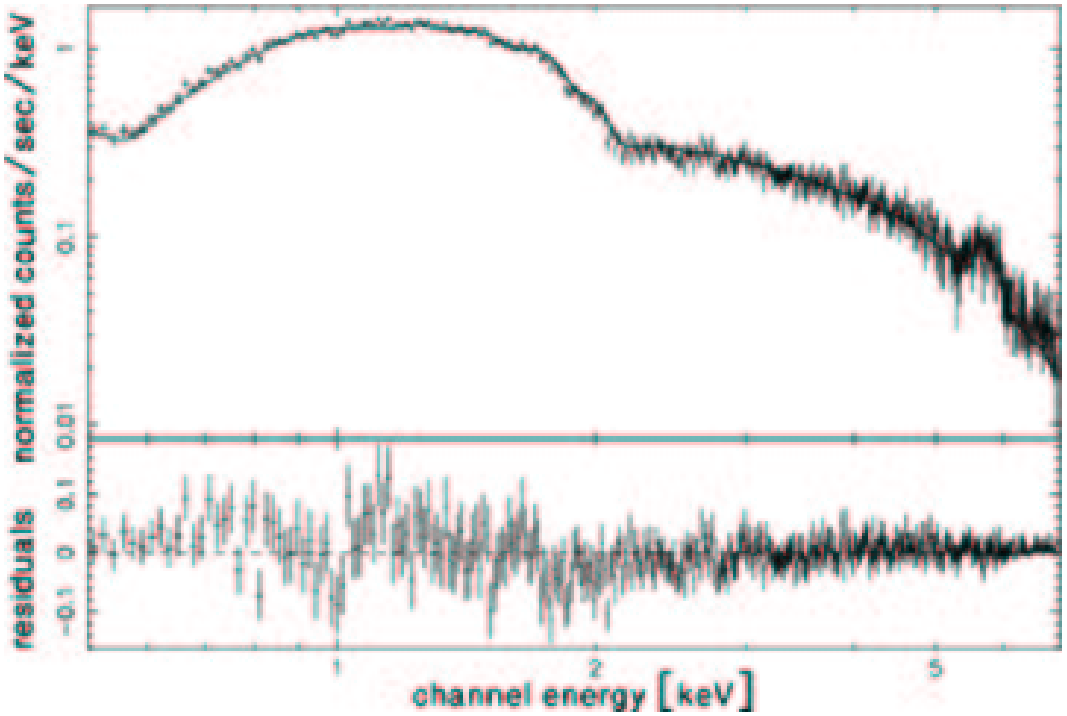
Massive galaxy cluster:

more than 100s galaxies

one of the most massive clusters known

2.3 billion light years away

T=100MK



IV. 16. Photoionization

Physics of gaseous nebulae.

* For each ion:

Ionization rate ~ photon flux

Recombination rate ~ electron density

* For the gas as a whole

Heating ~ photon flux

Cooling ~ electron density

* Plasma state depend on **ionisation parameter**

ionisation parameter is ratio of photon flux to gas density

at distance r from the source of ionizing radiation

$$\xi = \frac{L_X}{nr^2}$$

IV. 17. Consequences of Photoionization

- Temperature is lower for same ionization than coronal,
- $T_{\mathrm{X}} \approx 0.1 \frac{E_{\mathrm{th}}}{k}$
- Temperature is not a free parameter
- Temperature depends on spectrum of ionizing radiation
- Microphysical processes, such as dielectronic recombination, differ
- Observed spectrum differs

There are a number of photoionization codes

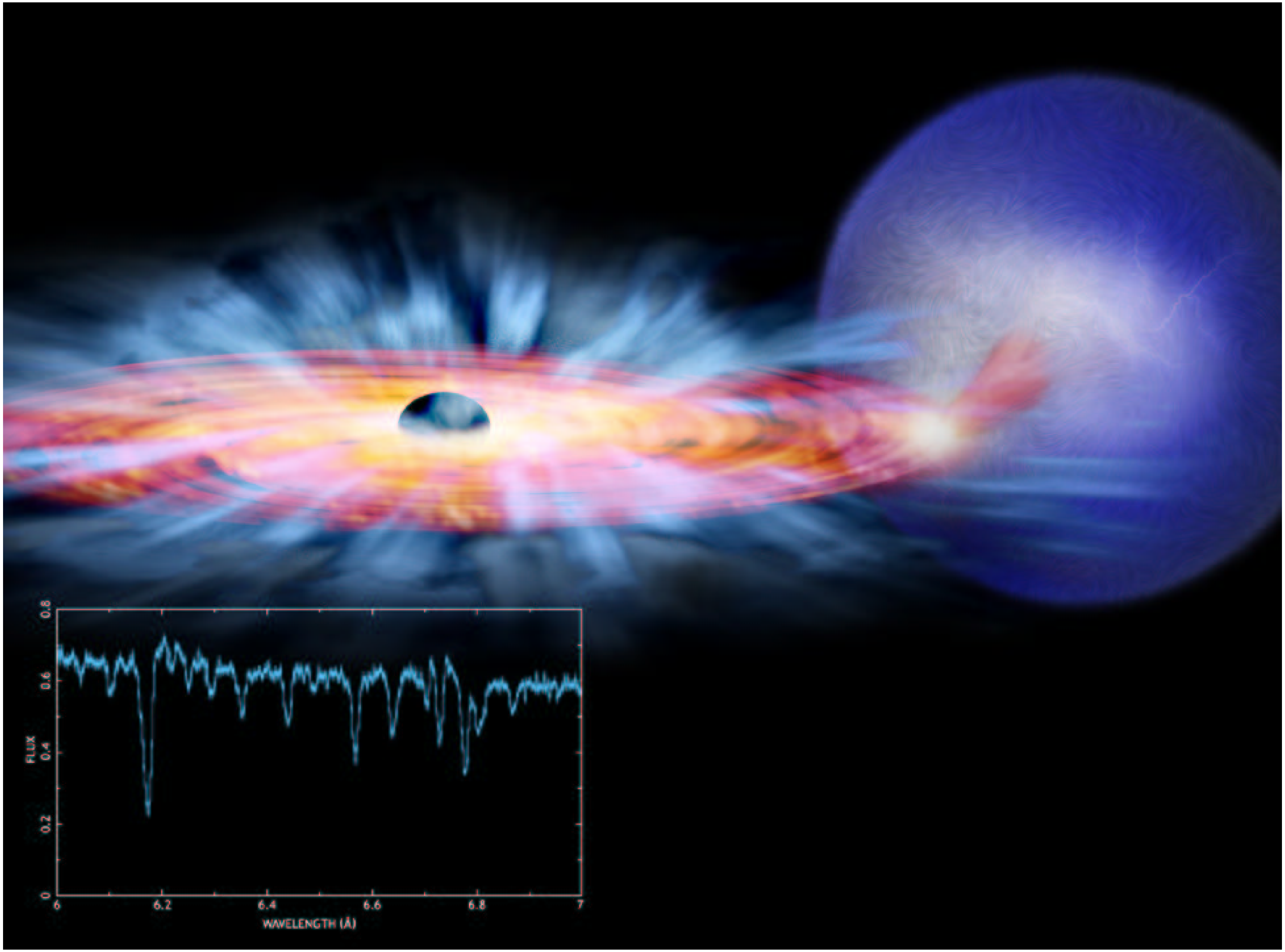
In X-ray domain **XSTAR**

model spectra can be compared with observed

Astrohysically: X-ray binaries

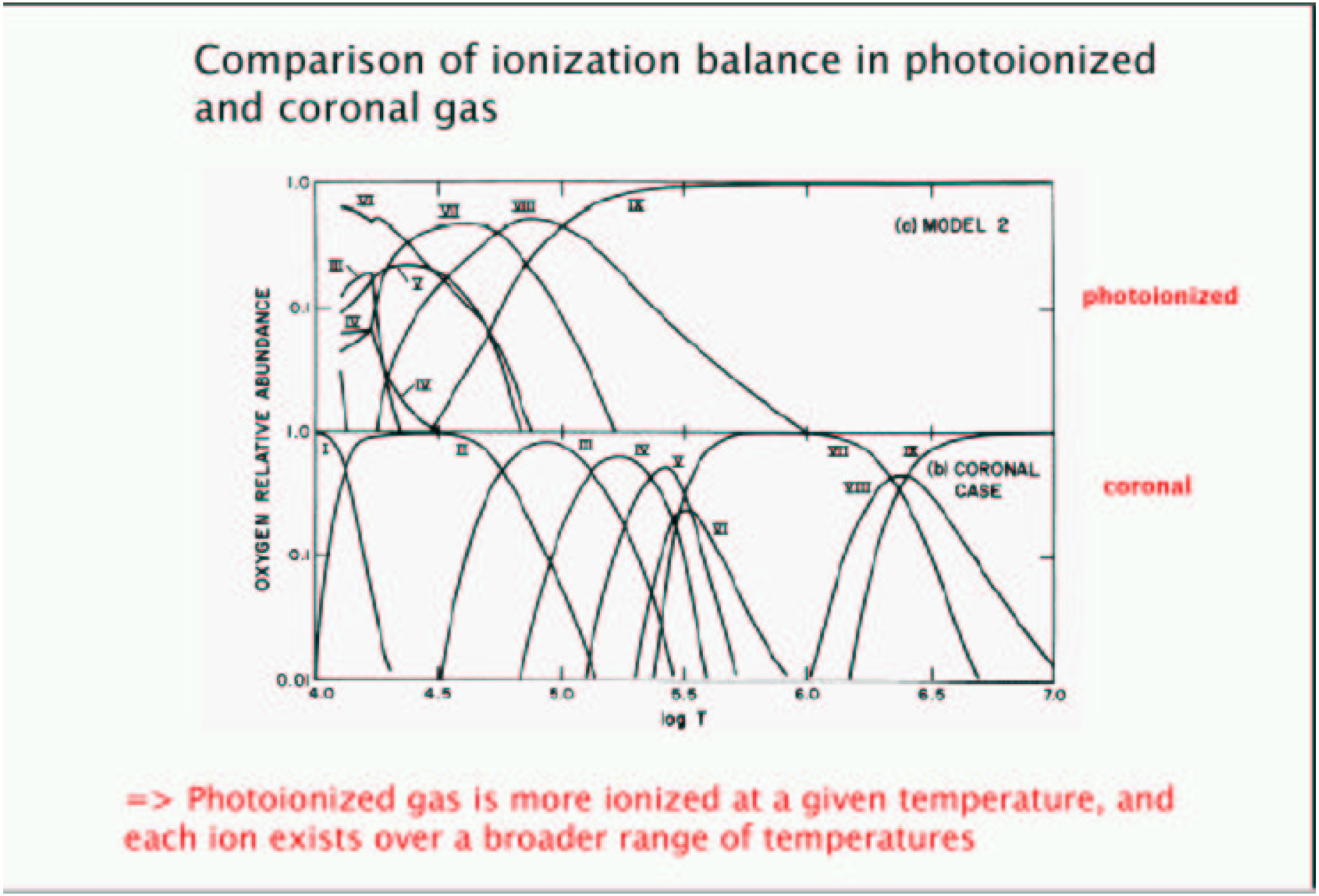
X-rays from accretion on compact object illuminate stellar gas

IV. 18. Example GRO J1655-40: black hole and normal star



http://chandra.harvard.edu/photo/2006/j1655/

IV. 19. Comaprison of photoionized and collisional plasma



Comparison of ionization balance in photoionized and coronal gas

=> Photoionized gas is more ionized at a given temperature, and each ion exists over a broader range of temperatures

http://heasarc.gsfc.nasa.gov/docs/xrayschool-2007

IV. 20. Observed Spectrum: Emission

- In coronal gas, need kTe~ΔE to collisionally excite lines.
- In a photoionized gas there are fewer lines which satisfy this condition
- Recombination continua (RRCs):

  recombination by cold electrons directly to the ground state.

  The width of these features is directly proportional to temperature
- it is more likely that diverse ions such as N VII, O VIII, Si XIV

  can coexist and emit efficiently than it would be in a coronal gas
- Inner shell ionization and fluorescence is also important

  in gases where the ionization state is low enough to allow ions with

  filled shells to exist.

IV. 21. Ionisation

- Collisional ionization: $\mathbf{e^- + I \rightarrow I^+ + 2e^-}$
- Photoionization: $\gamma + I \rightarrow I^+ + e^-$
- Inner shell ionization: $e^-, \gamma + I \rightarrow I^{*+} + 2e^- \rightarrow I^+ e^-, \gamma$

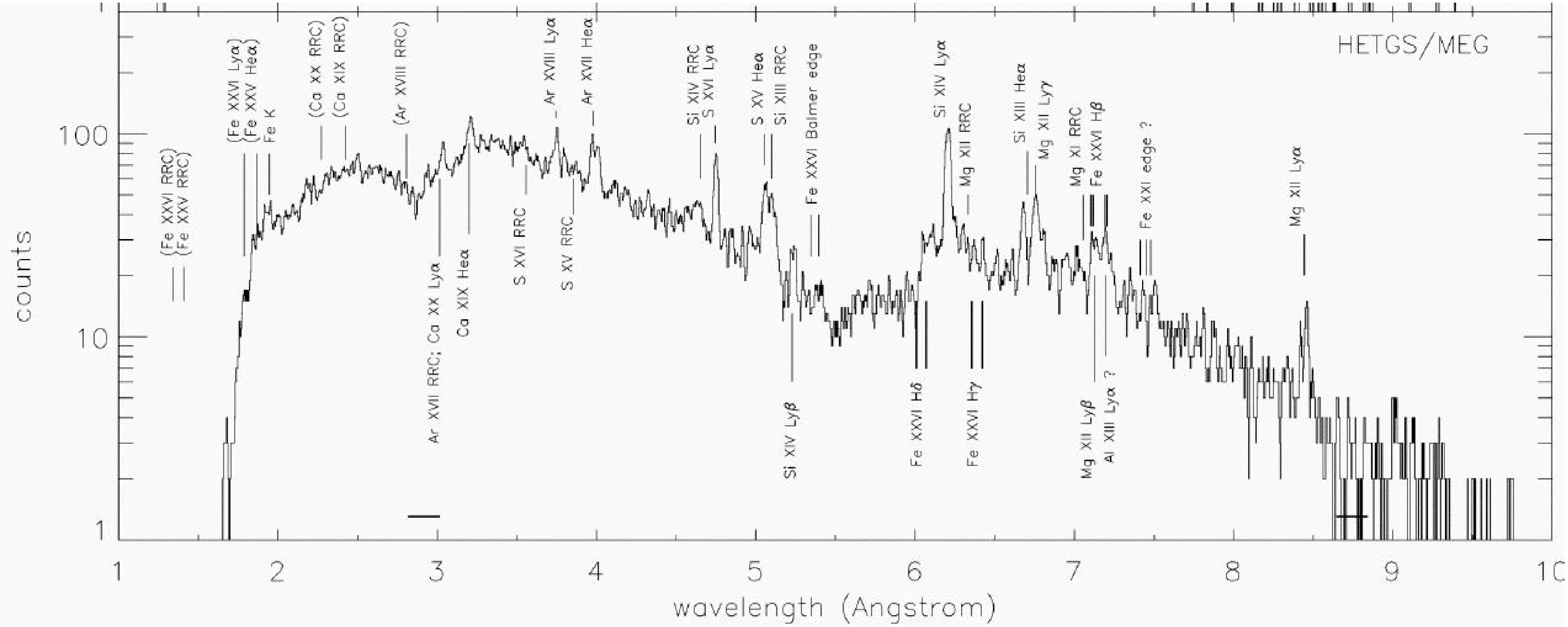
Inner shell ionization:K-shell electron (ie 1s electron) is removed.

Remining ion is very unstable. It will either emit a photon (radiatively stabilize) or an electron, called an Auger electron.

Whether a photon or an electron is emitted depends upon chance and the ion involved. As Z increases, the probability of a photon being emitted increases; for iron, it is ~30%. For oxygen, it is ~ 1%.

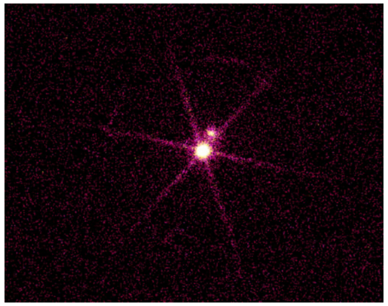
Innershell ionization of Fe I - Fe XVI tends to emit a 6.4 keV photon, commonly called the cold or neutral iron line.

IV. 22.Extended Emission from Cygnus X-3 Detected with Chandra

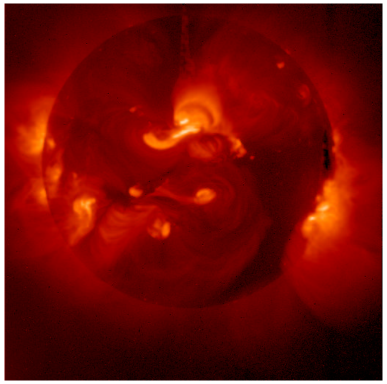


ApJ 2003, 588,L97

IV. 23. Summary of Part I

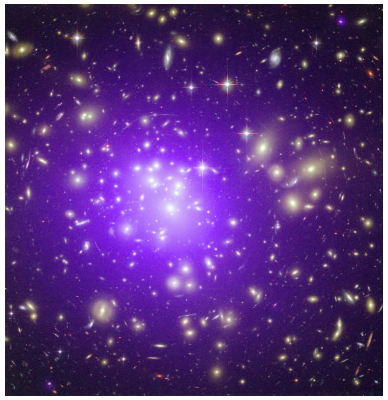


Blackbody: Neutron stars, WD

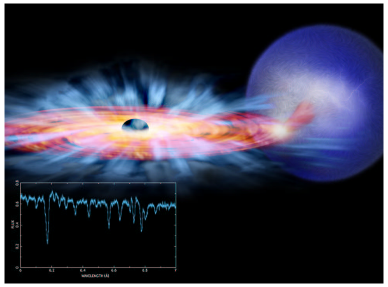


CIE plasma: stellar coronae

NEI: supernova remnants



Bremsstrahlung: galaxy clusters



Photoionized plasma: X-ray binaries