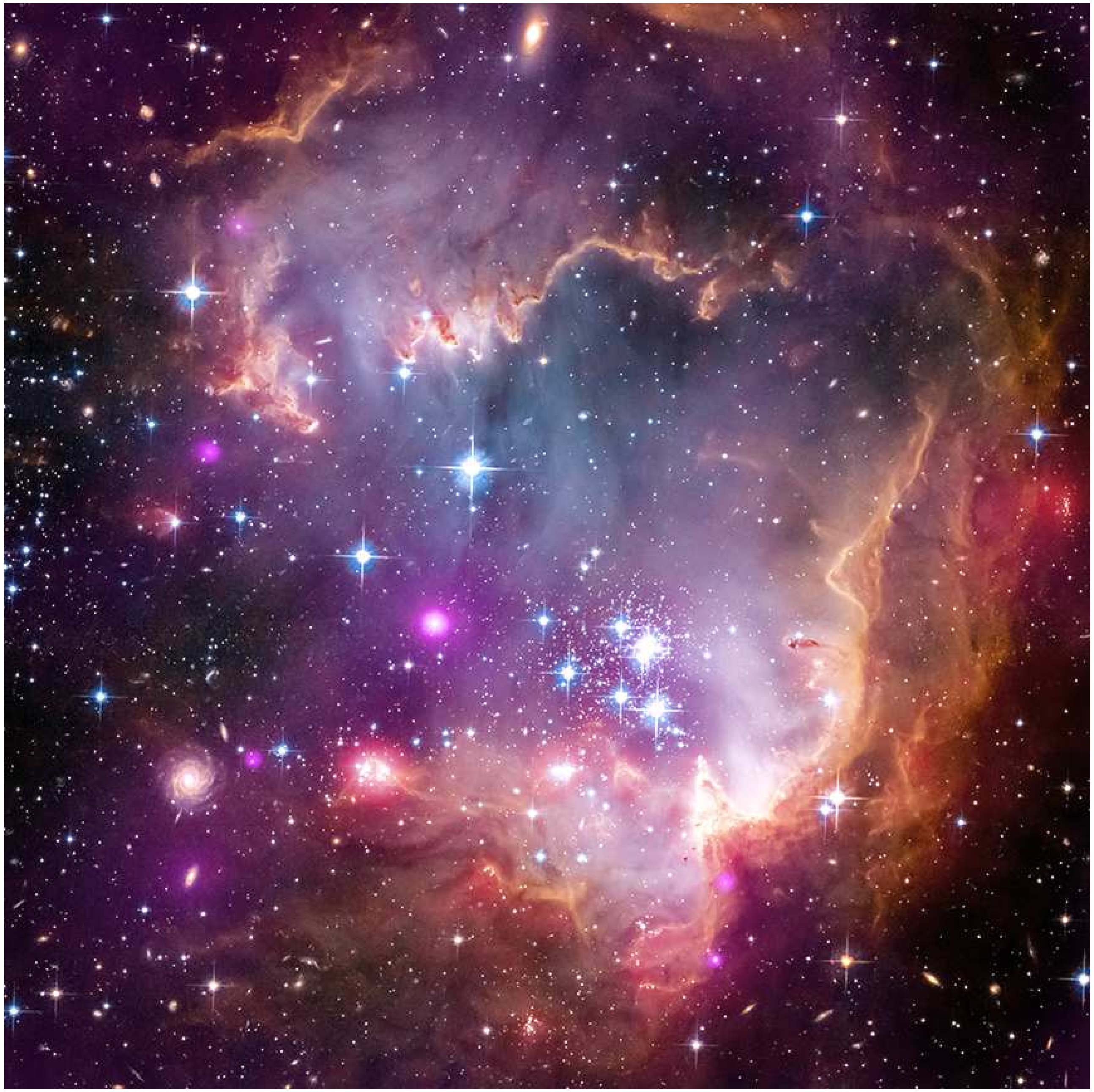
The X-Ray Universe



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astro.physik.uni-potsdam.de/~lida/x-ray.html

Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc

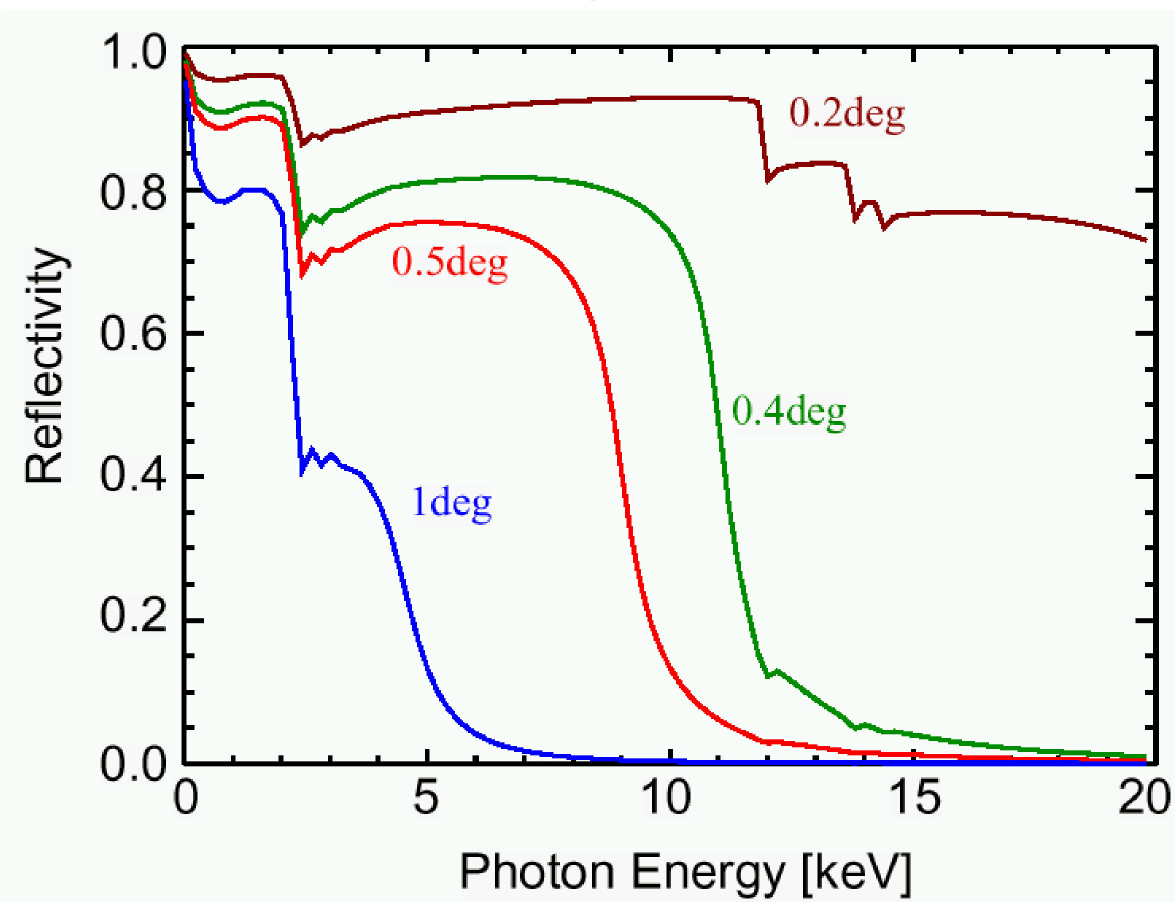
Reflection of X-rays

Critical angle $\alpha_c \approx 0.5' \frac{\lambda}{1Å} \sqrt{\frac{\rho}{1\,g\,cm^{-3}}}$

Optical λ=6000Å $\Rightarrow \alpha_c \approx 50^\circ \sqrt{\frac{\rho}{1\,g\,cm^{-3}}}$

X-ray λ=6Å $\Rightarrow \alpha_c \approx 3' \sqrt{\frac{\rho}{1\,g\,cm^{-3}}}$

Grazing!



To increase α_c need high ρ

XMM-Newton: gold

Chandra: iridium

see Ais-Nielsen & McMorrow, 2004, Elements of modern X-rays physics

Bragg's Effect:

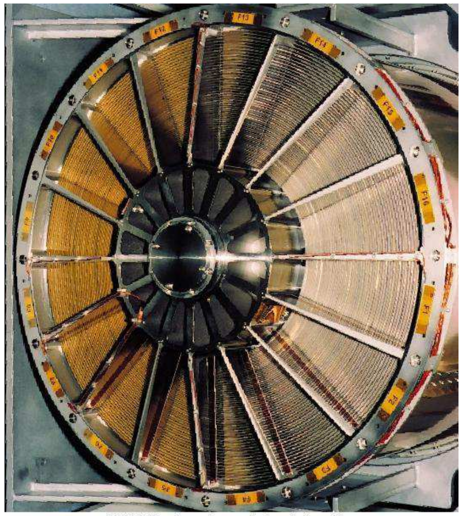
X-ray diffraction (XRD)

direct evidence for the periodic atomic structure of crystals

Nobel Prize in physics in 1915

X-ray telescopes: Summary

Collimators (RXTE)


XMM-Newton mirrors during integration
Image courtesy of Dornier Satellitensysteme GmbH European Space Agency

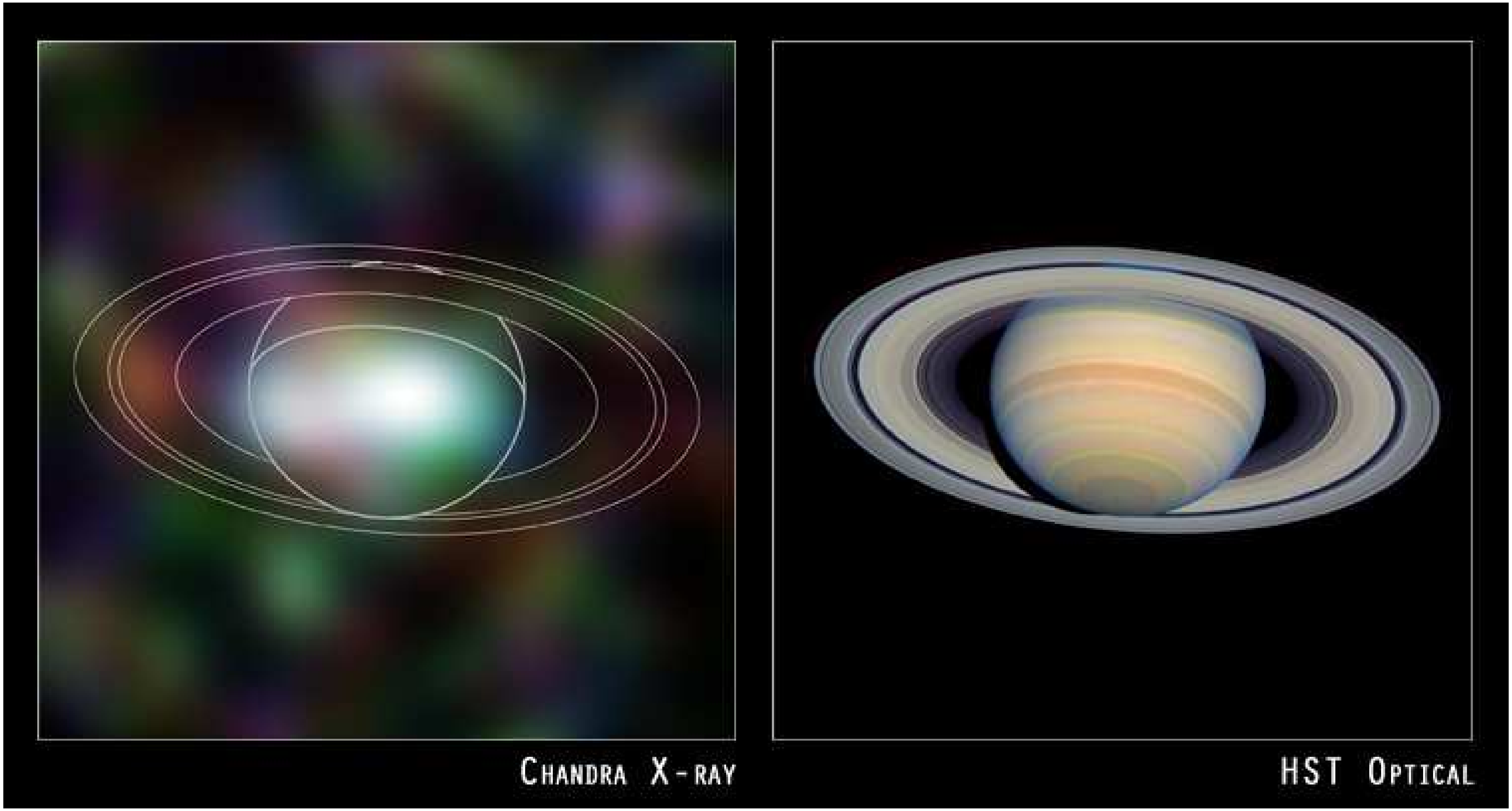
Wolter I mirrors

XMM-Newton, Chandra, SWIFT, SUZAKU

New Technology: Multylayer, Silicon Pore Optics

FUTURE MISSIONS: eROSITA, ASTRO-H, ATHENA, ...

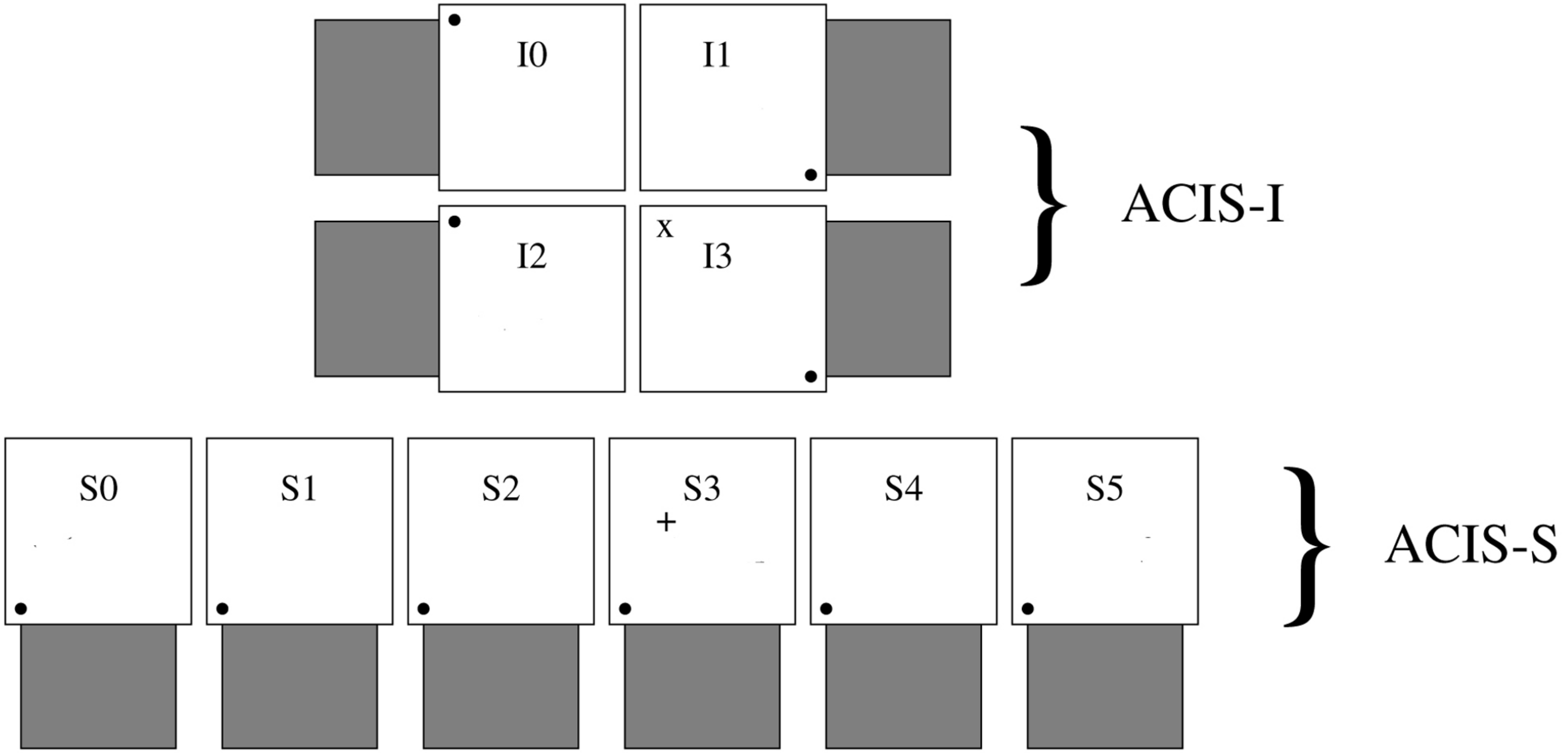
III. X-ray Detectors

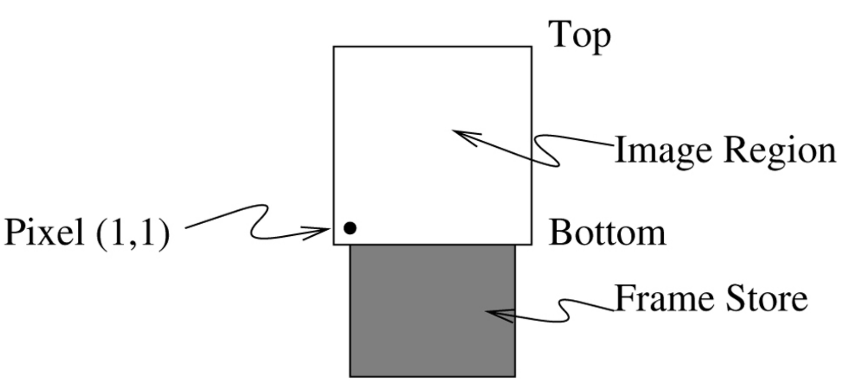


http://chandra.harvard.edu/resources/

Chandra ACIS: Advanced CCD Imaging Spectrometer

ACIS FLIGHT FOCAL PLANE





10 chips, 8 FI, 2 BI

Each CCD 1024 x 1024 pixels

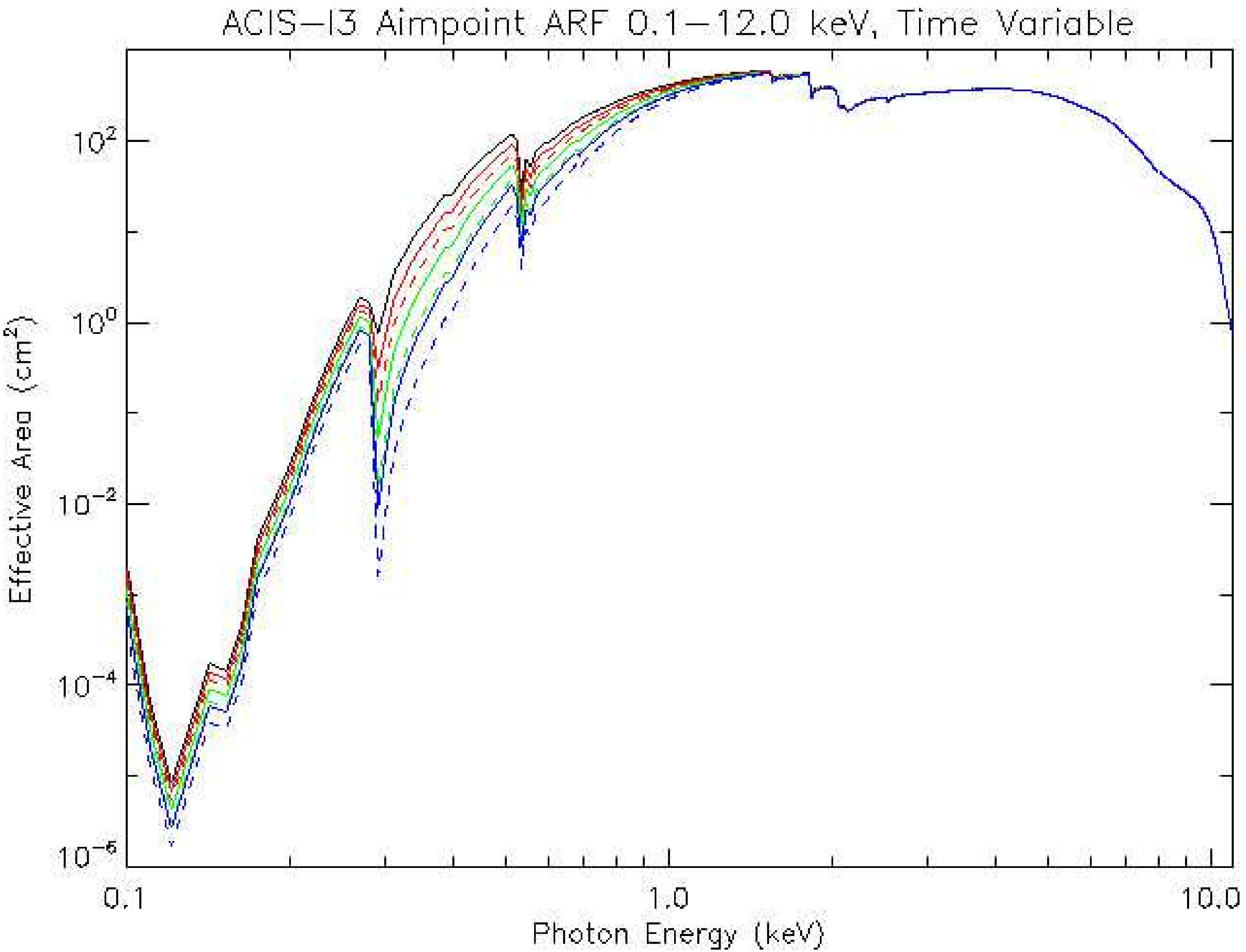
Pixel size 24 micron (0.5 arcsec)

Array size 17 x 17 arcmin

Nominal frame time 3.2s

http://asc.harvard.edu/proposer/POG/

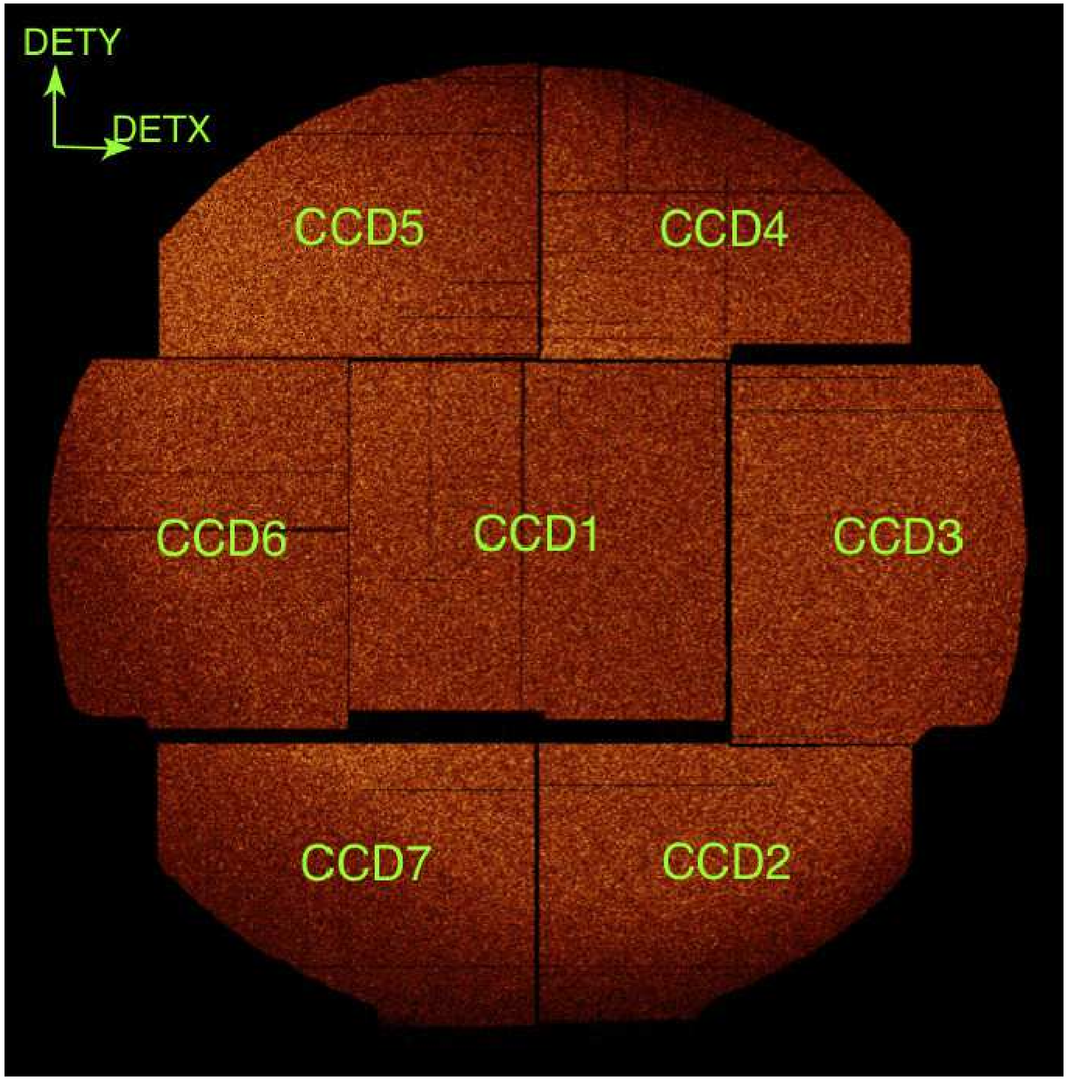
Chandra ACIS-I Effective Area ARF

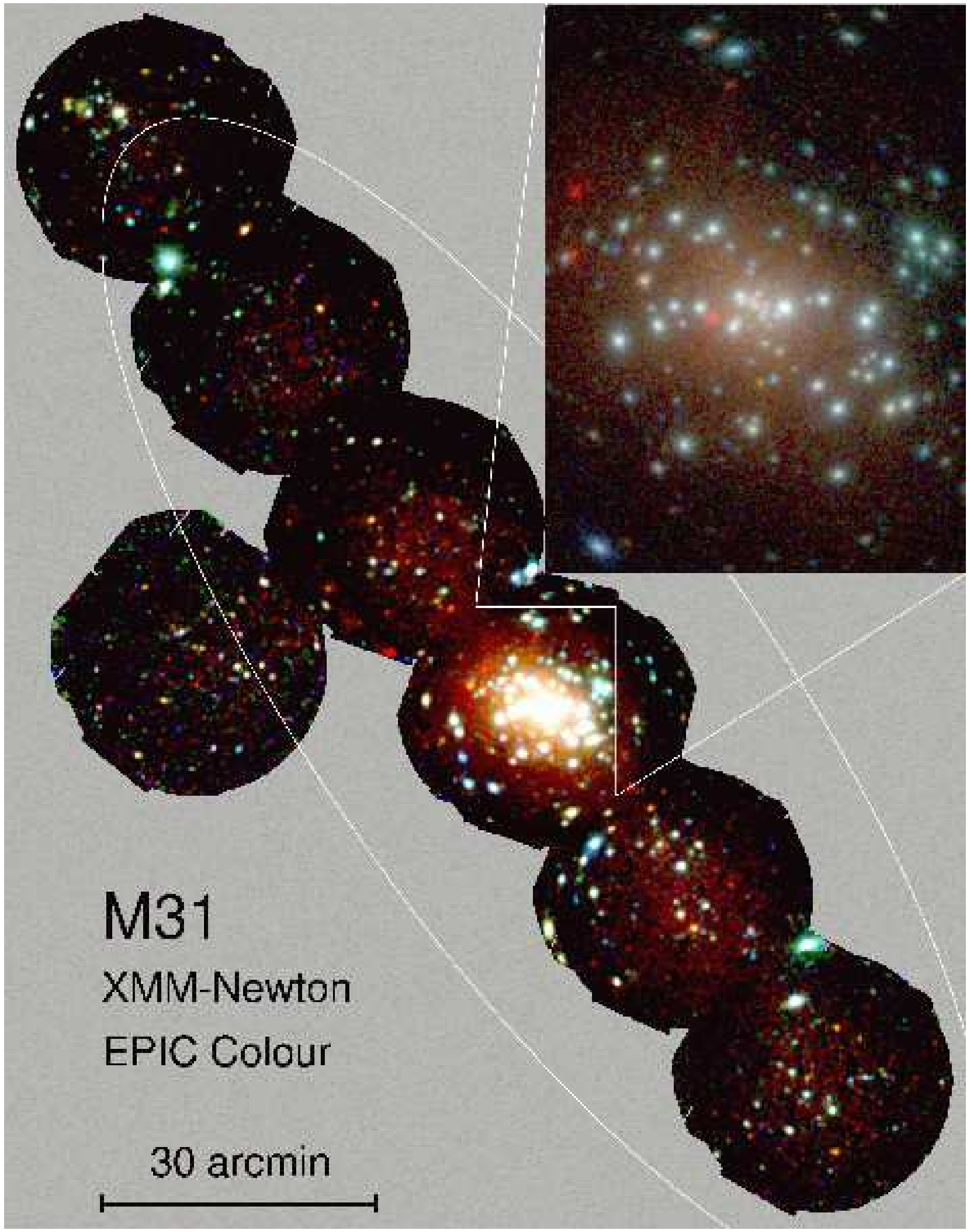


XMM-Newton has 5 cameras

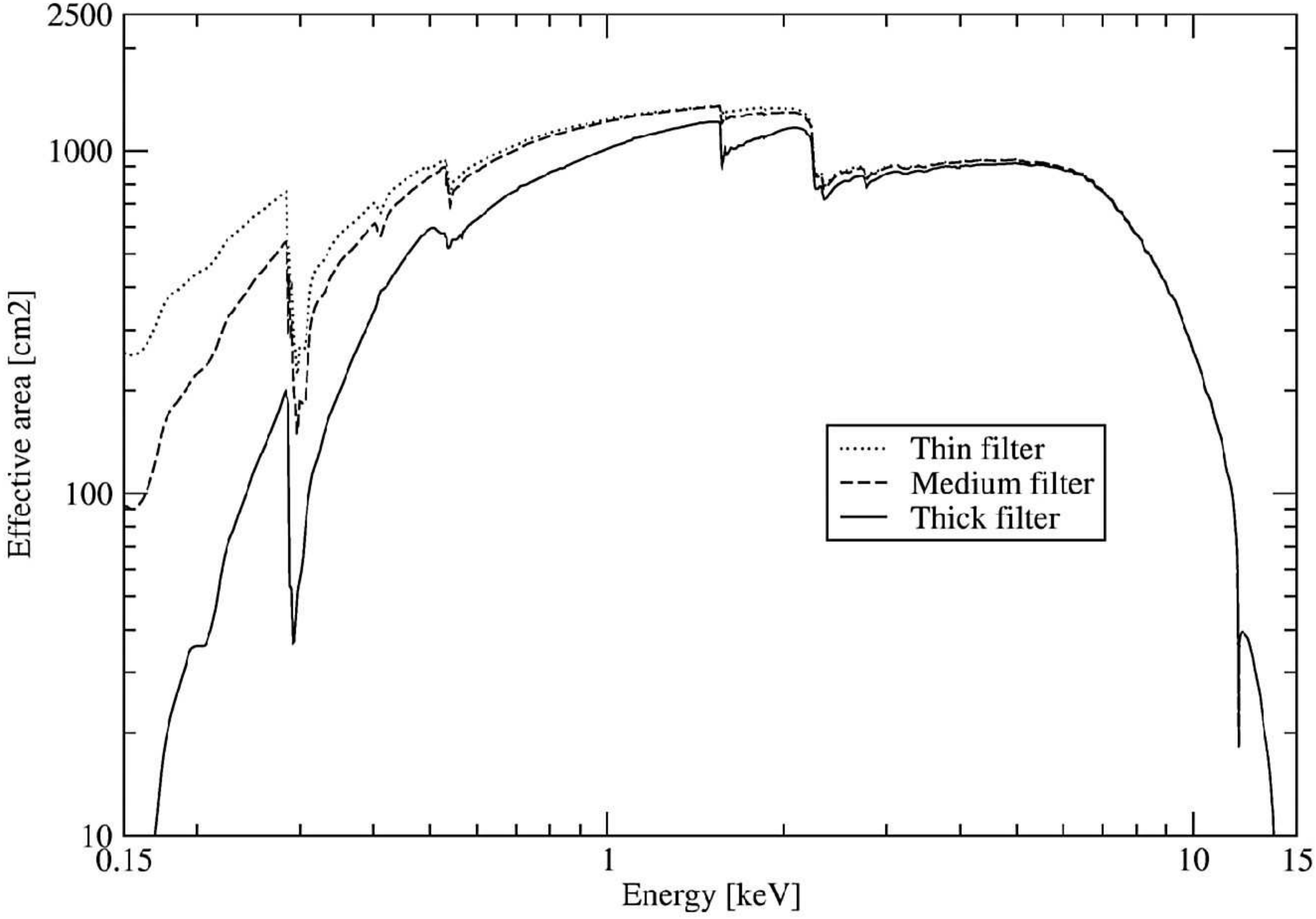
- MOS1,2 and PN = EPIC

RGS1 and RGS2





XMM-Newton PN Effective Area ARF



CCD X-ray spectroscopy

- Photoelectric interaction of a single X-ray photon with a Si atom produces free electrons:

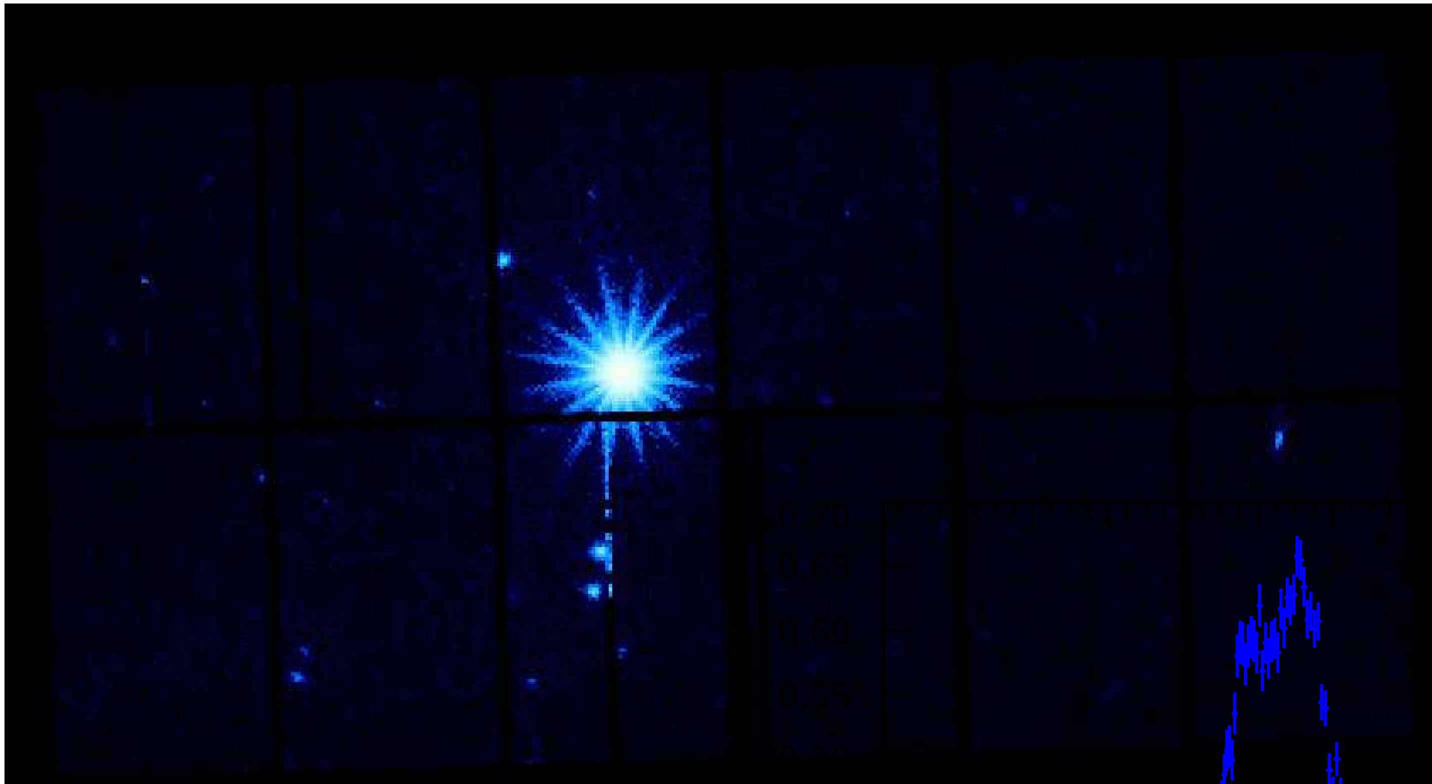
  $N_e = E_X / W$, where W=3.7eV

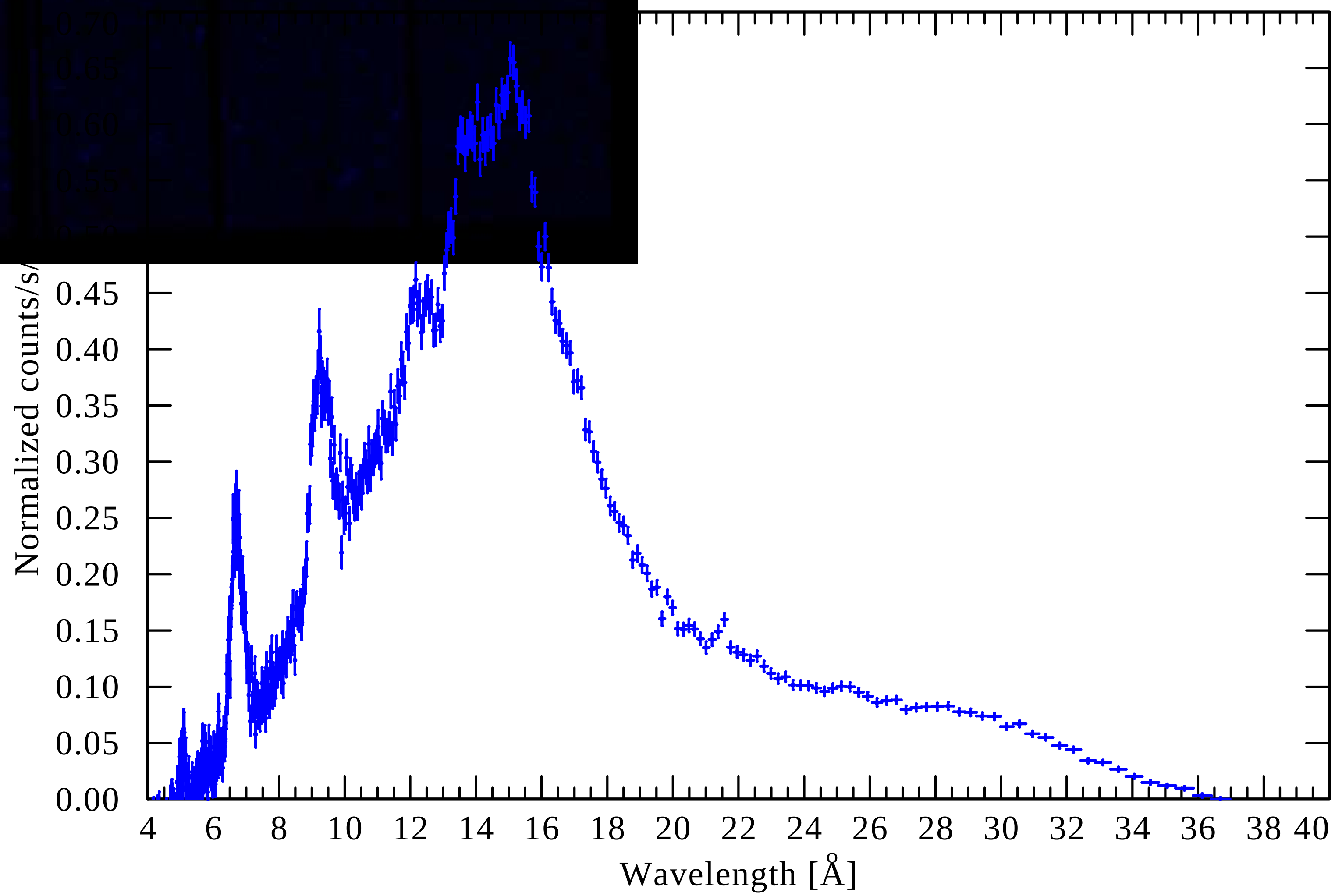
- Spectral resolution depends on CCD readout noise and physics of secondary ionization:

  At 1 keV ACIS-I: 50eV; MOS: 70eV, PN 80eV

- CCD characteristics that maximize spectral resolution:
  - * Good charge collection and transfer efficiencies
  - * Low readout and dark-current noise (low ccd temperature)
  - * High readout rate (requires tradeoff vs. noise)

XMM-Newton PN image of O type star ζ Puppis

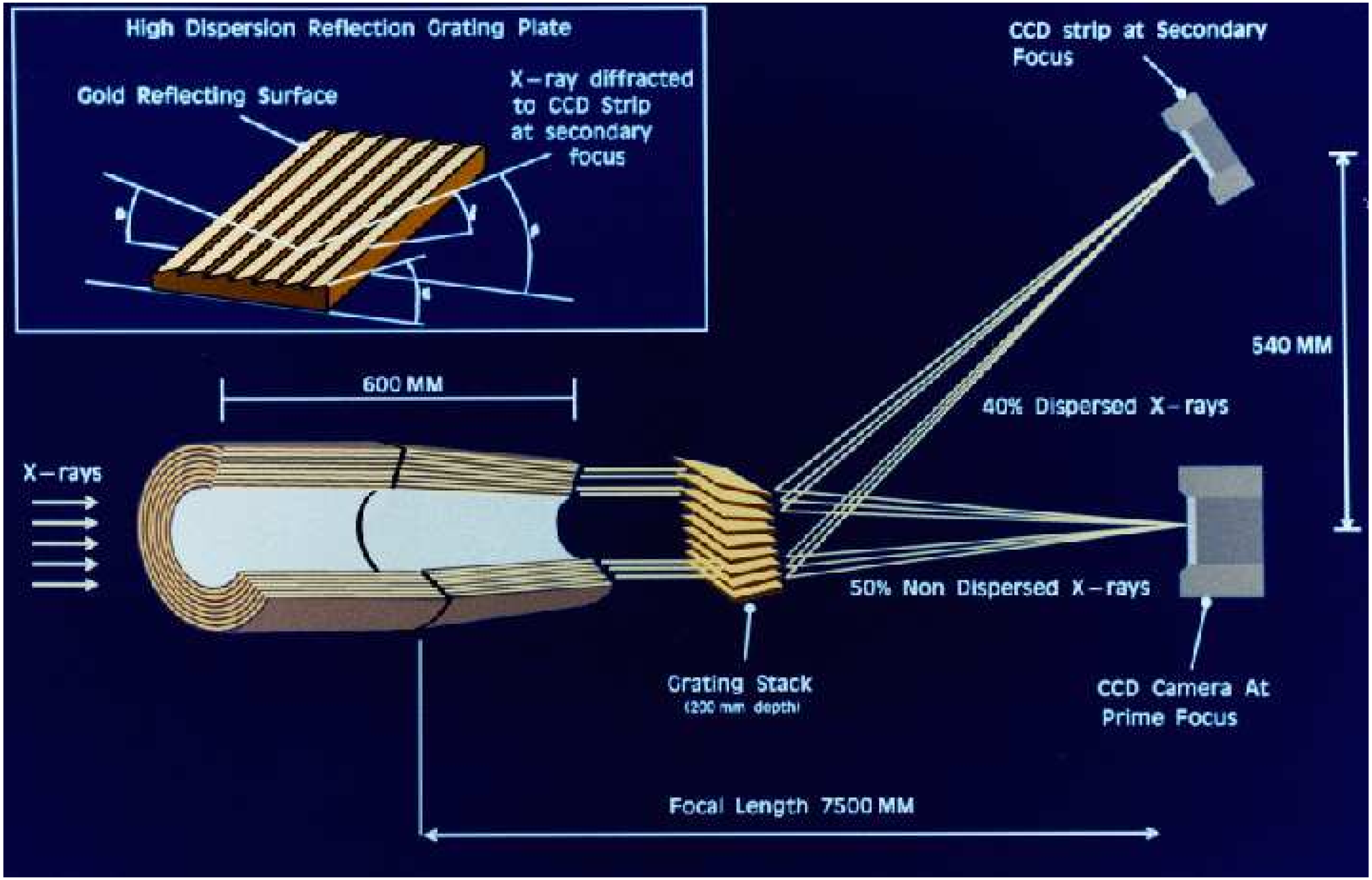




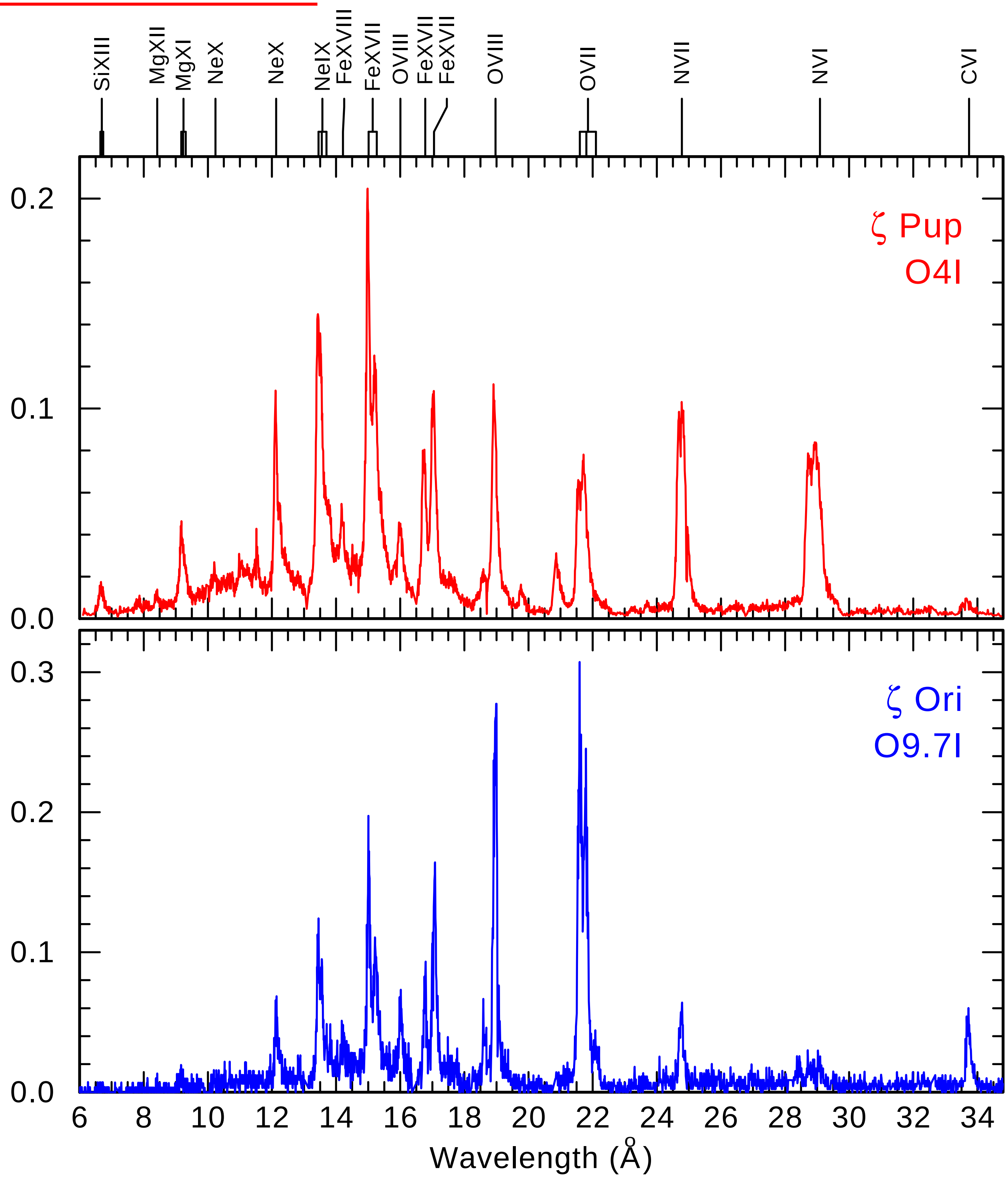
Very few lines resolved

No line structure

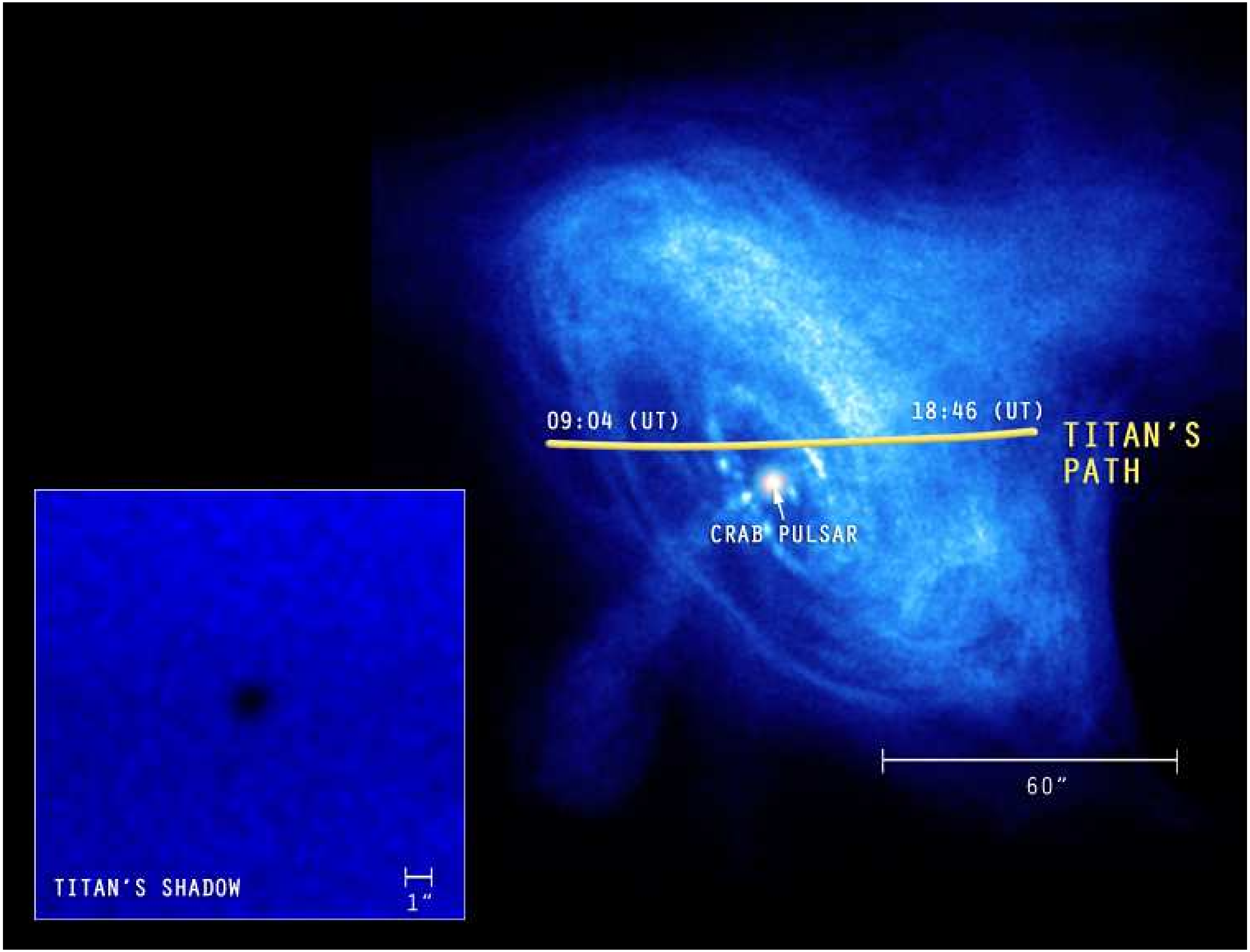
XMM and Chandra telescopes have grating spectrometers



Science spectra of O stars



High quality images and spectra



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

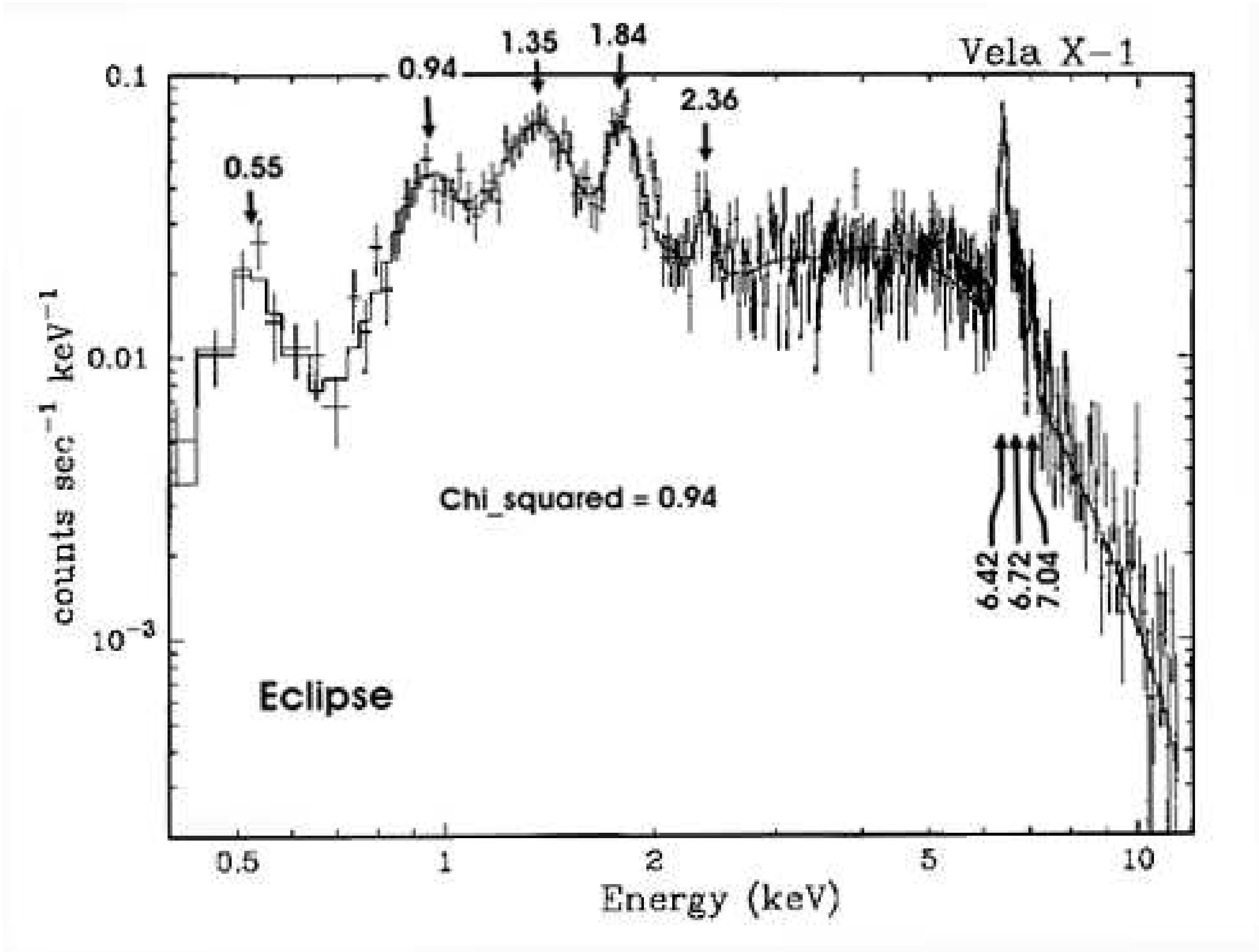
CCD: front illuminated (MOS) and back illuminated (PN)

- **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

Principle Interactions

- Electron + ion: 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, photoionization
* 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**
stellar coronae, galaxy cluster halos

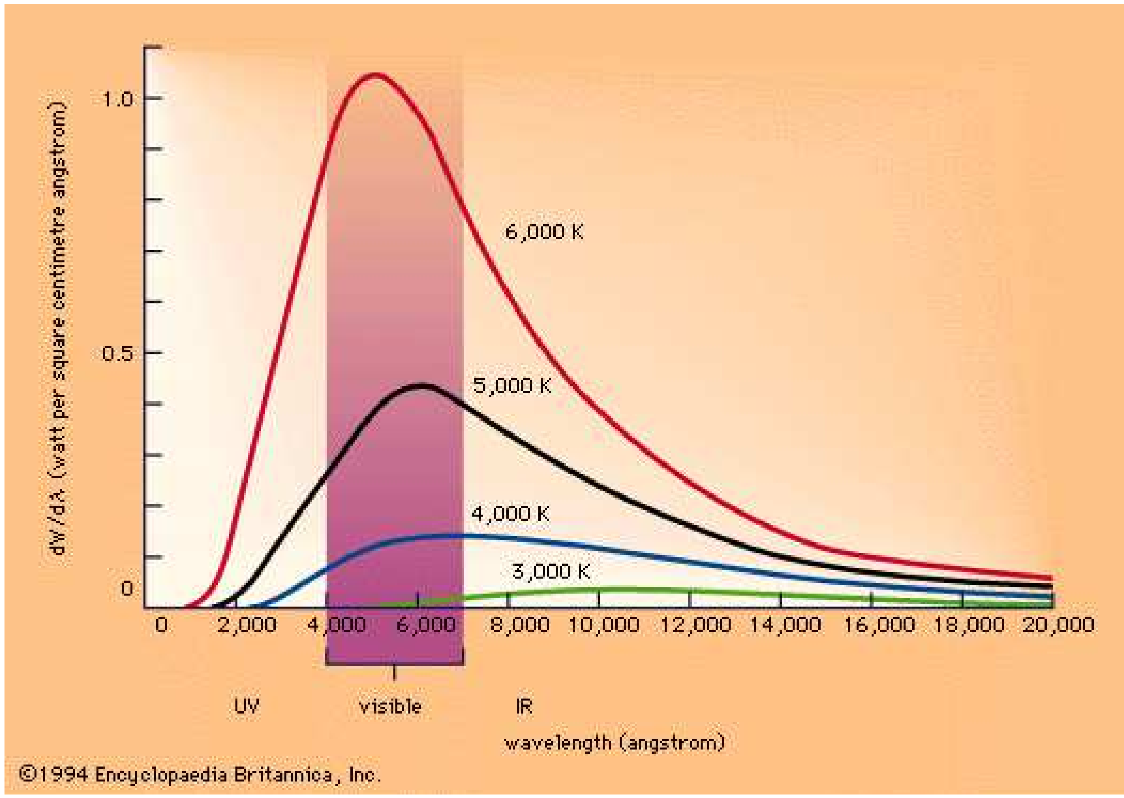
If particle-particle collisions are **not** importnat
then the energy distribution of electrons is **non-thermal**
acceleration process, photoionized plasmas

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
- Generally, no neutral gas:

X-ray emitting plasma is always ionized $n_e = n_i$

Thermodynamic equilibrium. Black Body



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

Wien's displacement law:

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

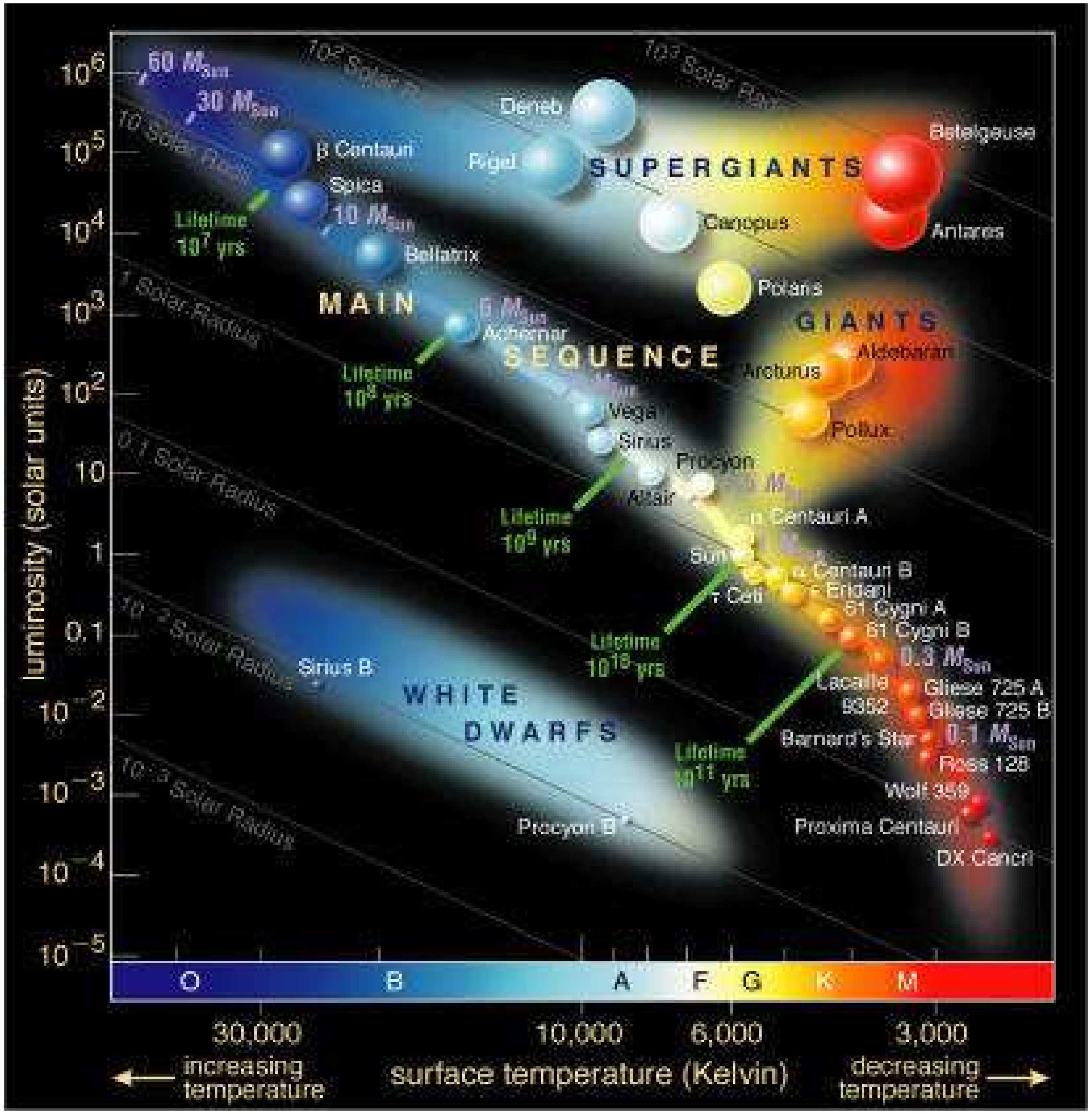
X-rays λ=1..50Å : T=30MK .. 1MK

Thermodynamic equilibrium: stellar interior

But normal stellar photospheres are not that hot: 1kK ... 200kK

Hottest white dwarfs, neutron stars

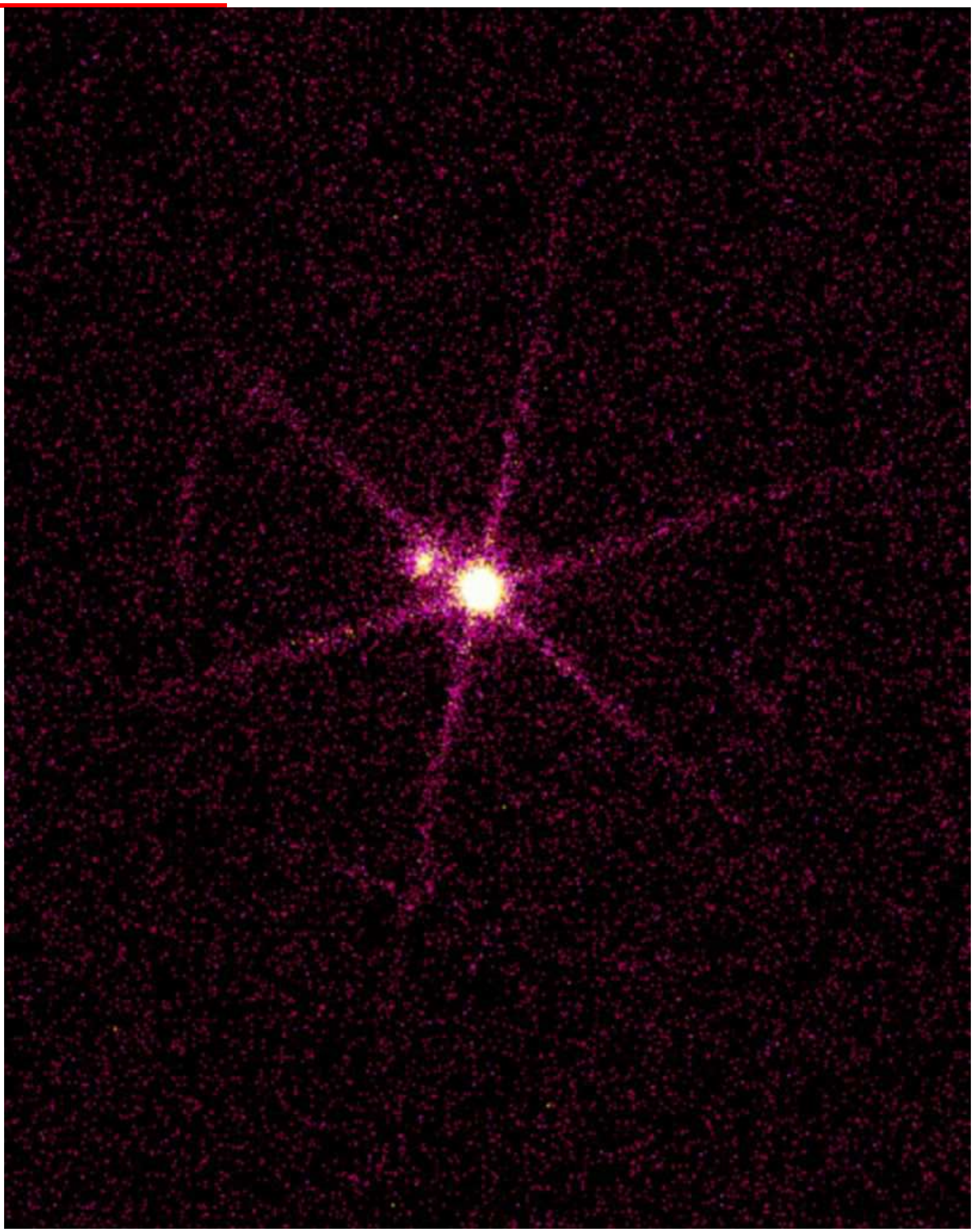
Reminder Hertzsprung-Russell-Diagramm



Sirius in optical

Credit: McDonald Observatory

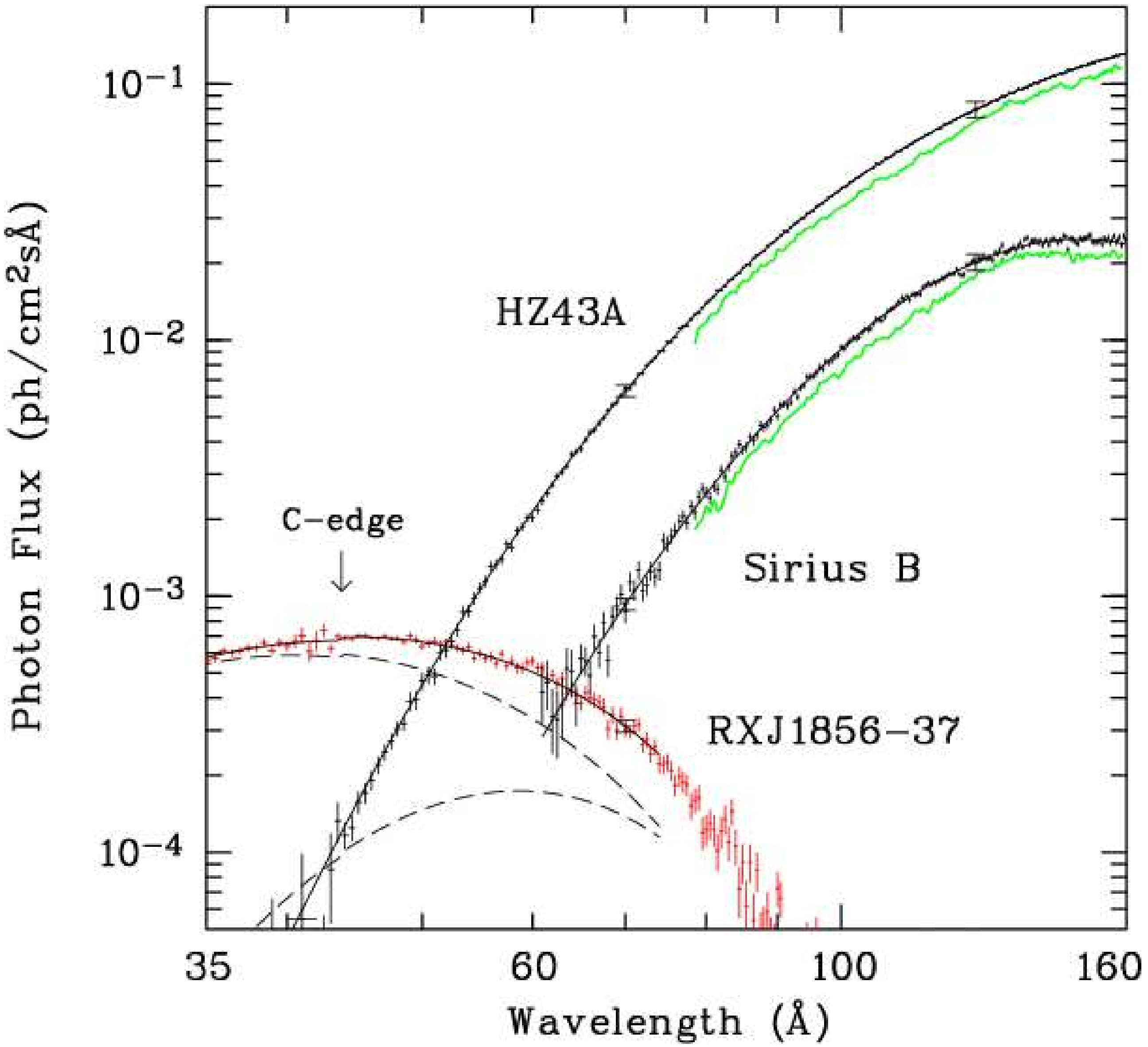
IV. 5. Chandra's Sirius B



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

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

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

Thermal plasma

Thermodynamic equilibrium occurs if $N_e > 10^{14} T_e^{0.5} \Delta E_{ij}^3$ cm^{-3}

For T=10 MK and H-like Iron, $N_e > 10^{27}$ cm^{-3}

For T=0.1 MK and H-like Oxigen, $N_e > 10^{24}$ cm^{-3}

These are very high densities occuring hardly anywhere outside stars

Astrophiscally important plasmas

- Coronal/Nebular $N_e < 10^{16}$ cm^{-3}

$kT_e \approx I_p$

* Ionization and excitations are by collisions
* is balanced by radiative and dielectronic recombinaiton
* The state of ionization is determined by the temperature
* Excited ions return to the ground state t(recomb) < time(collision)
* Cooling is radiative
* Produced X-rays leave without interacting with the plasma,

Ionisation

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

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

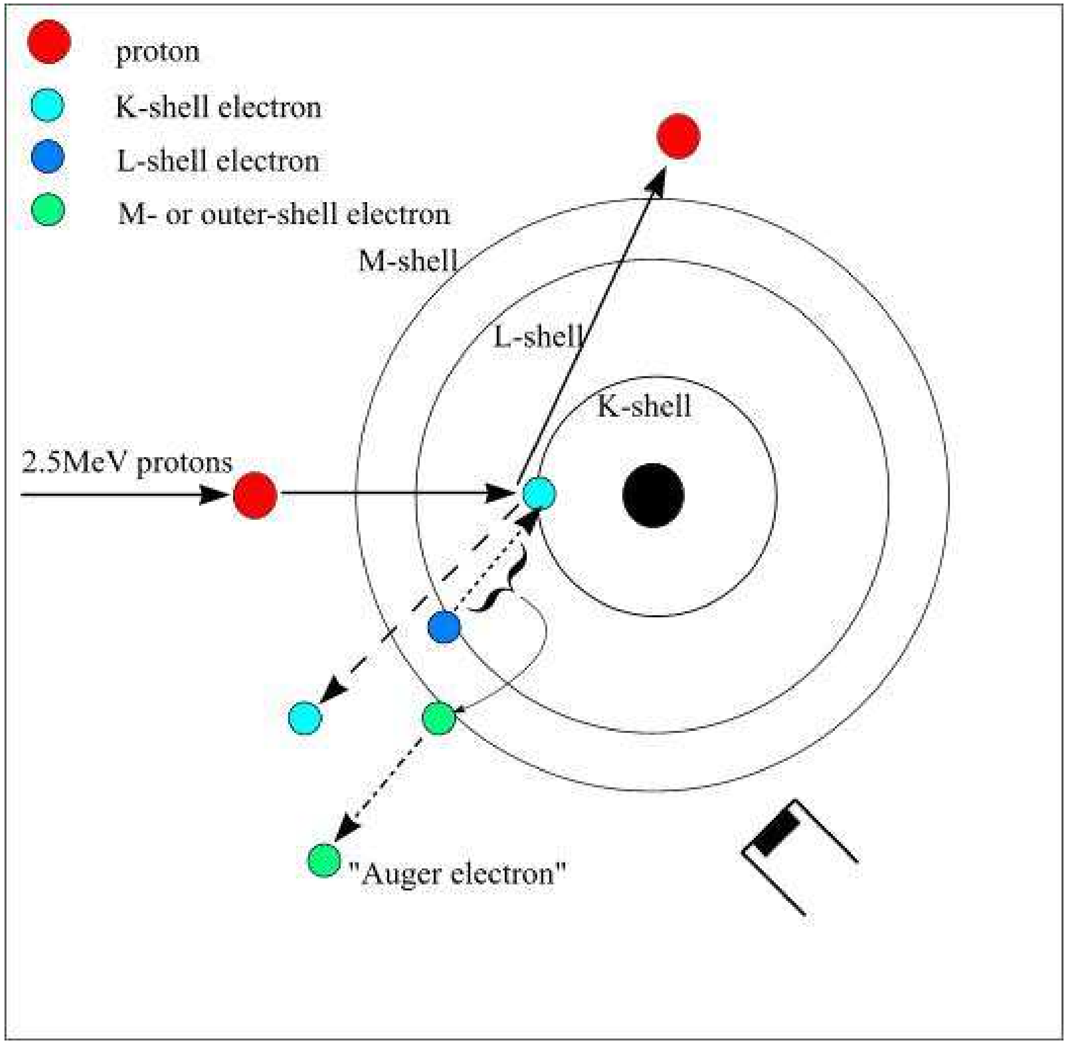
Remining ion is very unstable. It will either emit a photon (radiatively stabilize) or an electron, called an Auger electron.

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%.

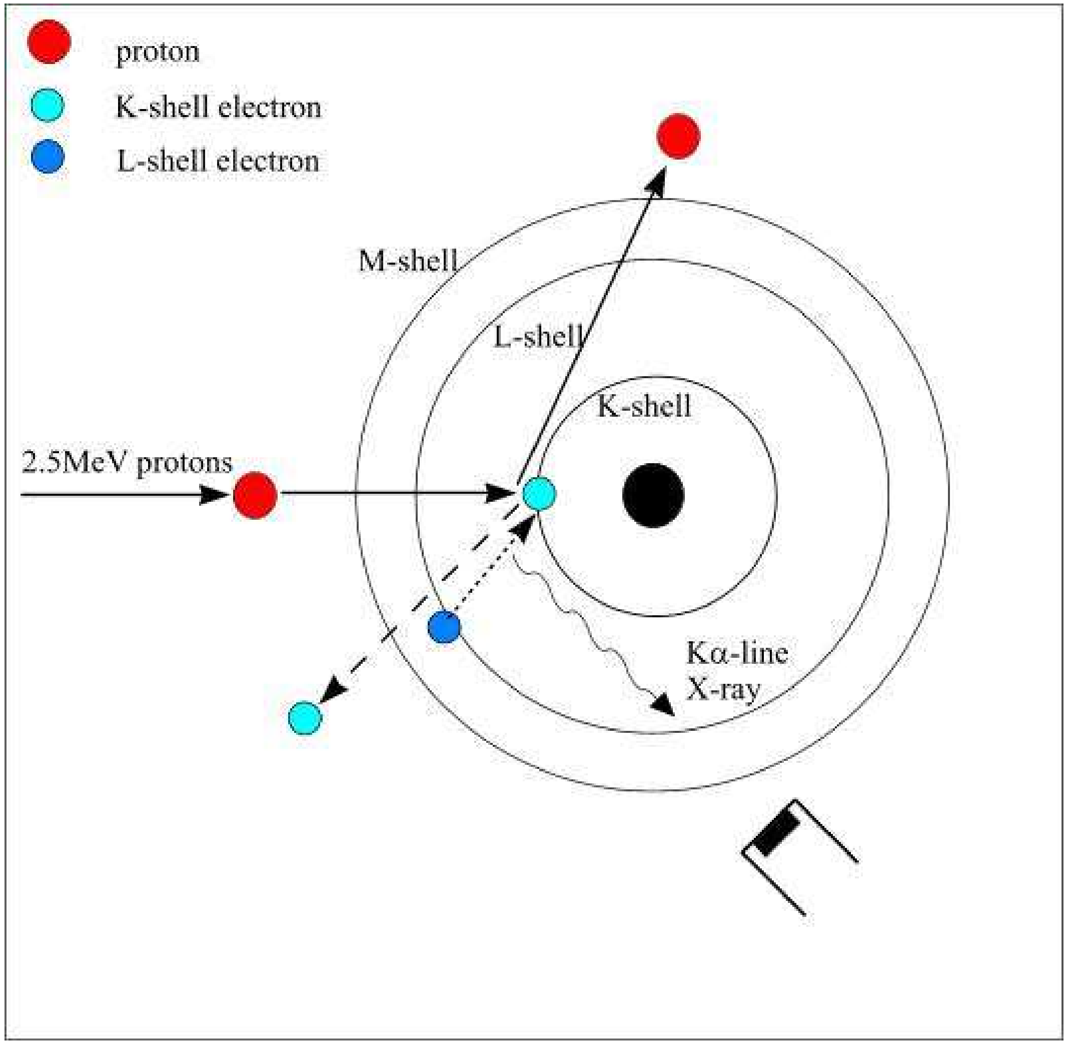
Innershell ionization of Fe I - Fe XVI tends to emit a 6.4 keV photon, commonly called the cold or neutral iron line.

Inner Shell Processes

Auger ionization - inverse process



Inner Shell Processes



X-ray fluorescence An electron can be removed from inner K-shell (how many electornes are there?)

The vacancy is filled by a L-shell electron Kα-line. If the vacancy is filled by M-shell electron Kβ-line.

Iron is abundnat element with relatively large cross-section for K-shell ionization: Kα line at 6.4 keV is commonly observed from astrophysical objects

See Grotrian diagrmans in Kallman+ 04, ApJSS 155, 675

Equilibrium in thermal plasma

Thermal plasma can be in equilibrium or out of it.

- Ionization equilibrium (CIE plasma)

  Ionization of ion z of element Z is balanced by recombination

  $C_{\mathrm{Z,z-1}}$ ionization rate, $\alpha_{\mathrm{Z,z}}$ recombination rate

$$n_{\mathrm{Z,z-1}} C_{\mathrm{Z,z-1}} = n_{\mathrm{Z,z}} (\alpha^{\mathrm{rad}}_{\mathrm{Z,z}} + \alpha^{\mathrm{di}}_{\mathrm{Z,z}})$$

  Plasma codes: e.g. Astrophysical Plasma Emission Code - APEC

  Large variety of astrophysical sources: stars

- Non-equilibrium ionization (NIE plasma)

  - ionization rate is higher than recombination

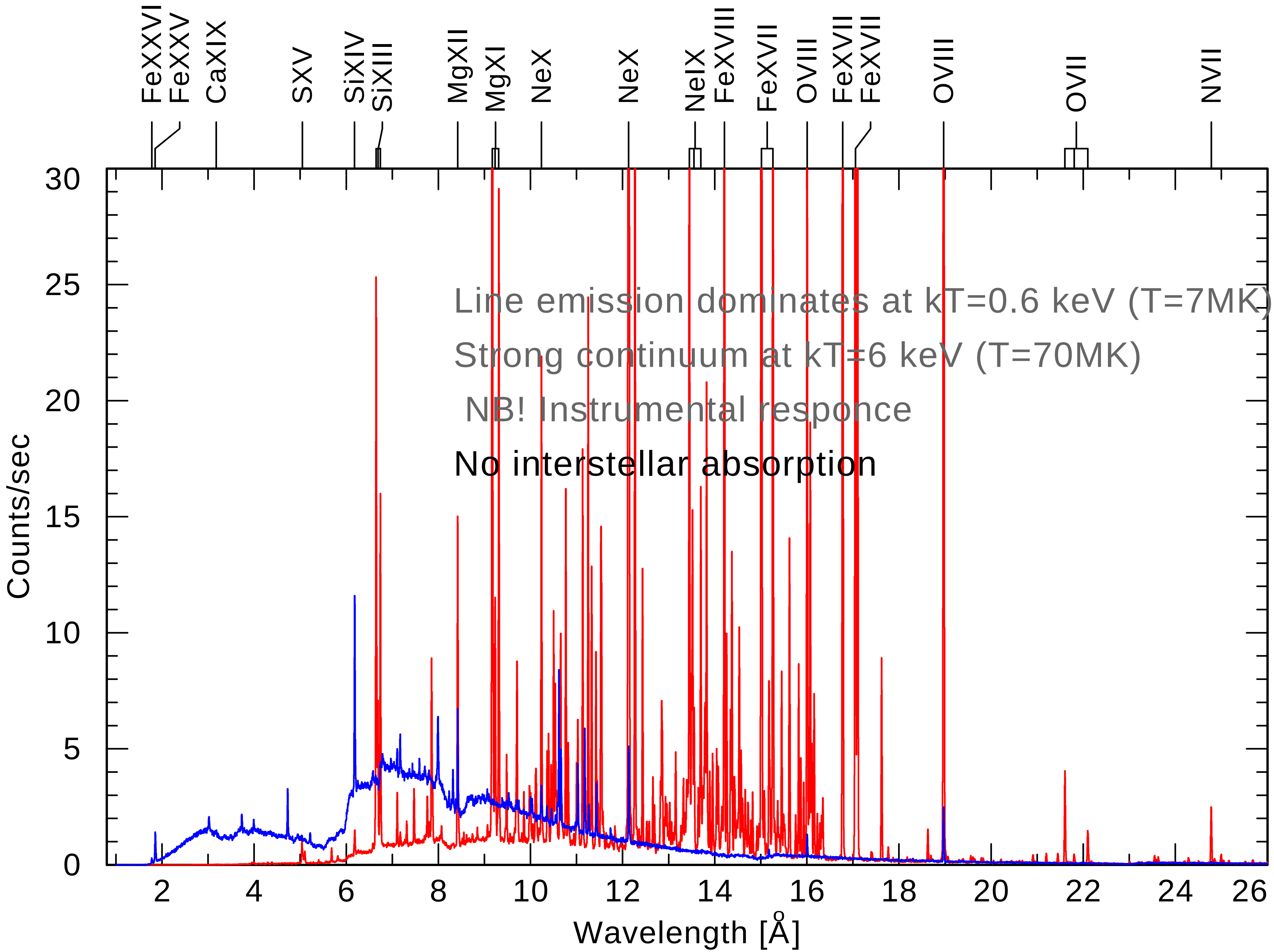
  - or recombination rate is higher than ionization

  dynamic time scale is shorter than required to establish IE

  NEI - codes

  occurs e.g. in supernova remnants

APEC simulated spectra for two different T(Chandra MEG+1)



Which processes 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,

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

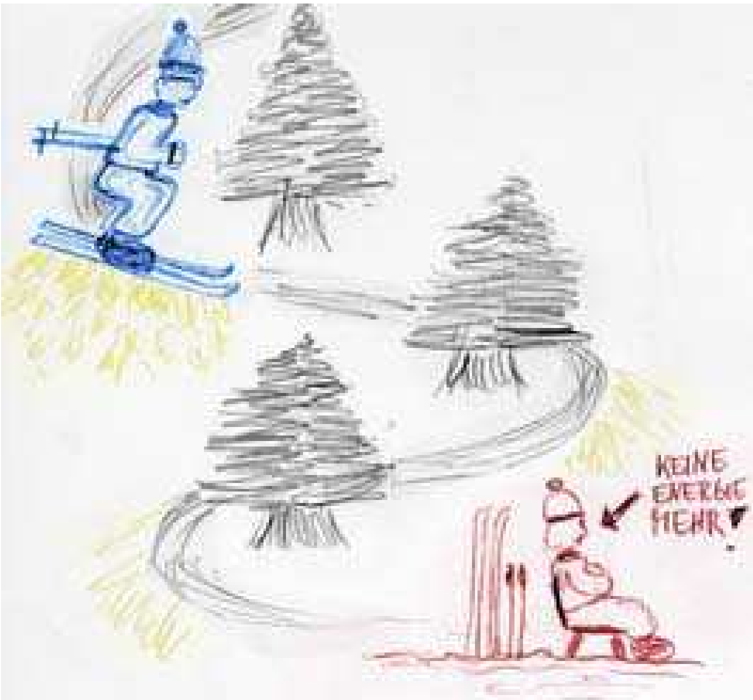
To get 1 MK plasma a shock jump 300 km/s or 1 Million km/hr is needed

or "coronal heating"

Solar corona has T > 1 MK

Acustic waves? Nanoflare heating?

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:

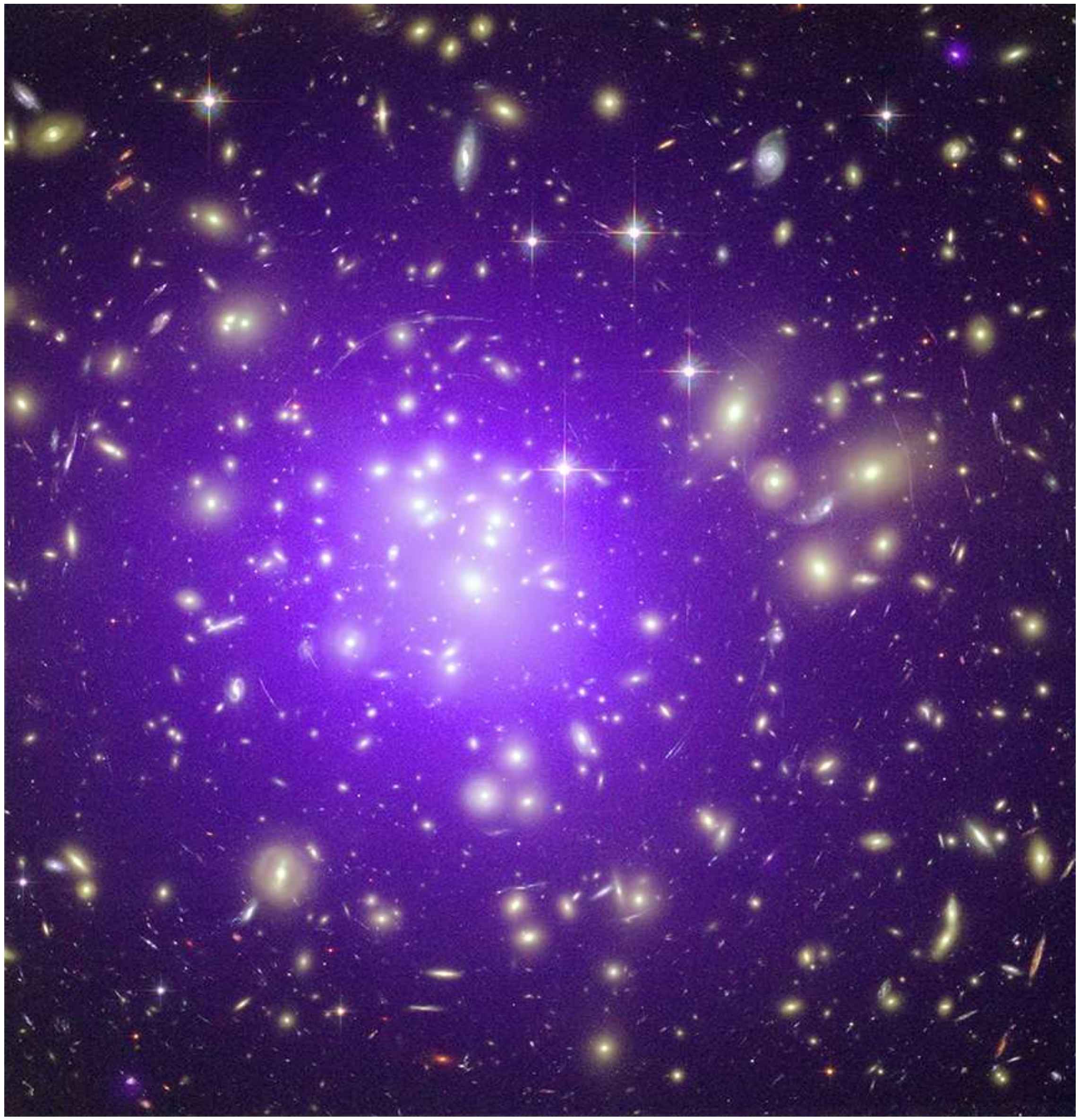
$$\frac{dP_{\mathrm{B}}}{dV} = 2.4 \times 10^{-27} \sqrt{T} N_{\mathrm{e}}^2 \quad [\mathrm{erg\ cm^{-3}\, s^{-1}}]$$

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

Example galaxy cluster Abell 1689



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

Composit Chandra+HST

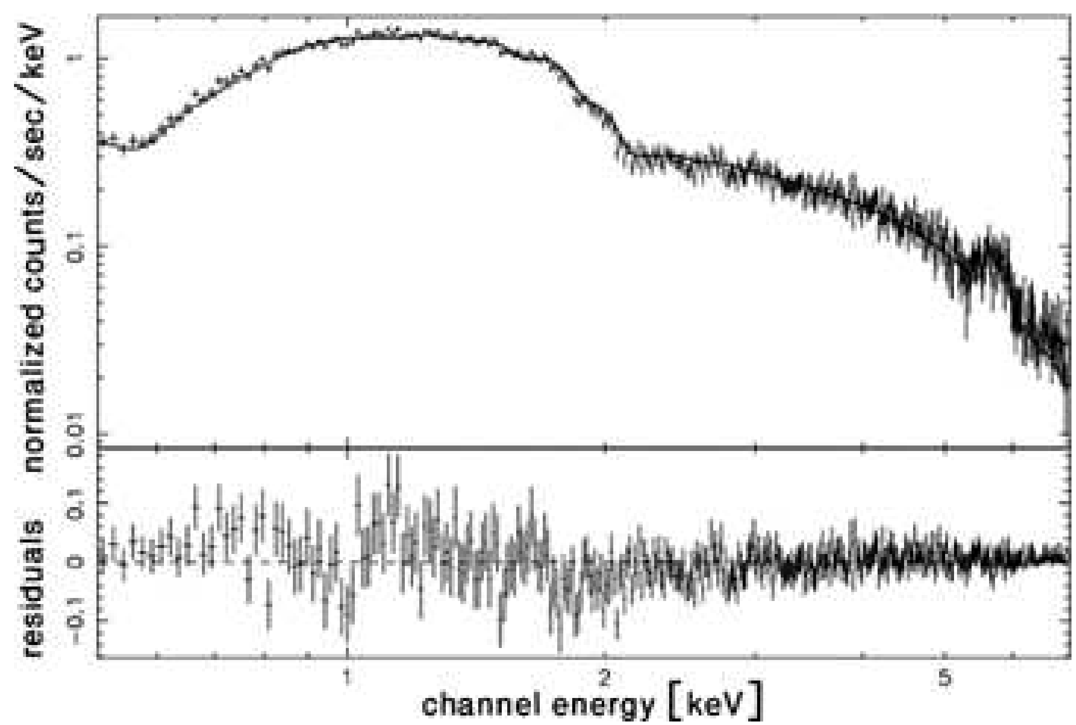
Massive galaxy cluster:

more than 100s galaxies

one of the most massive clusters known

2.3 billion light years away

T=100MK



Photoionization

Different from collisionally ionized plasma

* For each ion:

Ionization rate is not by collisions but by X-ray photons

Recombination rate ~ electron density

* For the gas as a whole

Heating ~ photon flux, cooling ~ electron density

Temperature is lower for same ionization fraction, $T_X \approx 0.1 \frac{E_{th}}{k}$

* 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

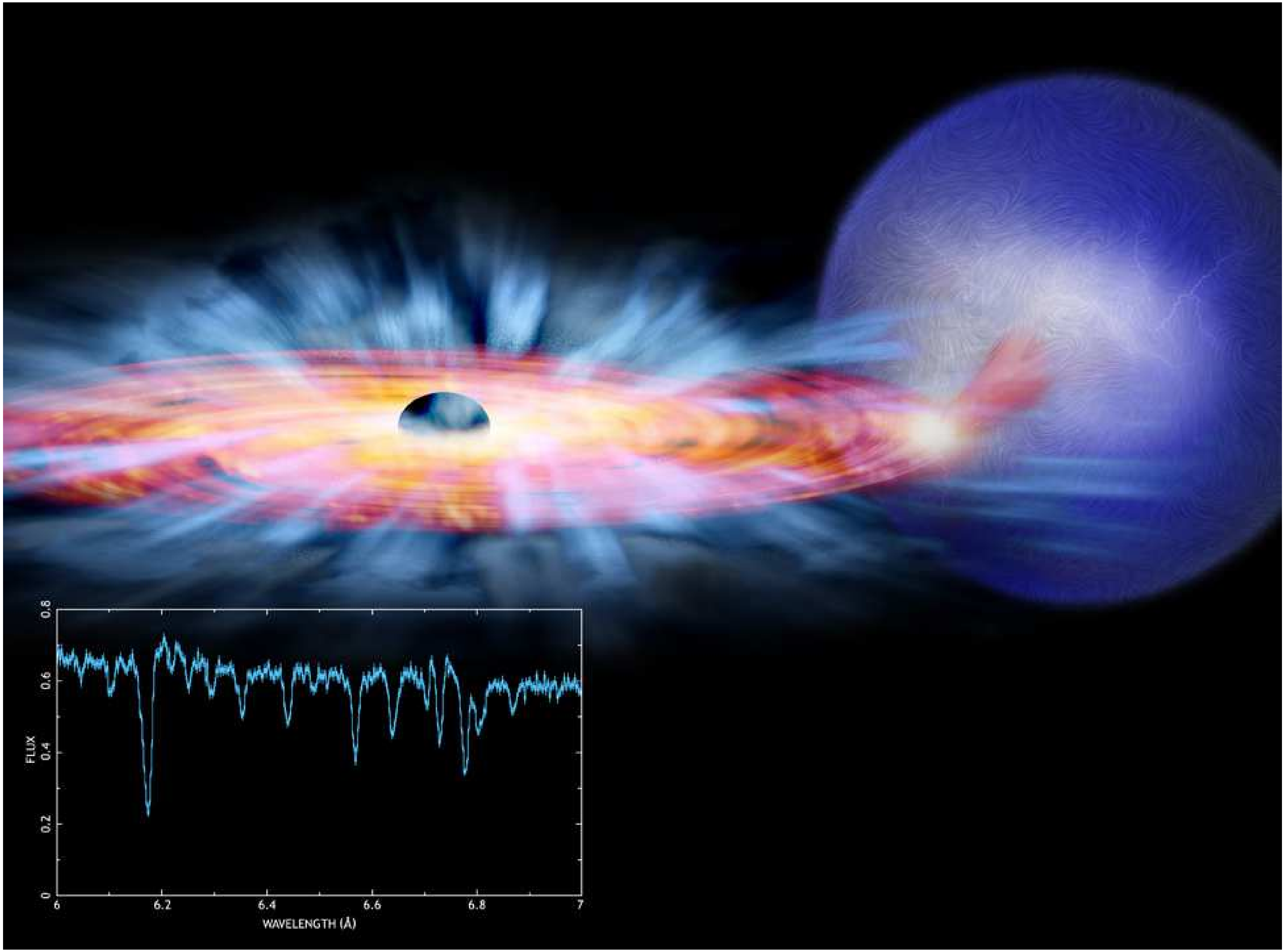
$$\xi = \frac{L_X}{nr^2}$$

photoionization codes in X-ray domain e.g **XSTAR**

model spectra can be compared with observed

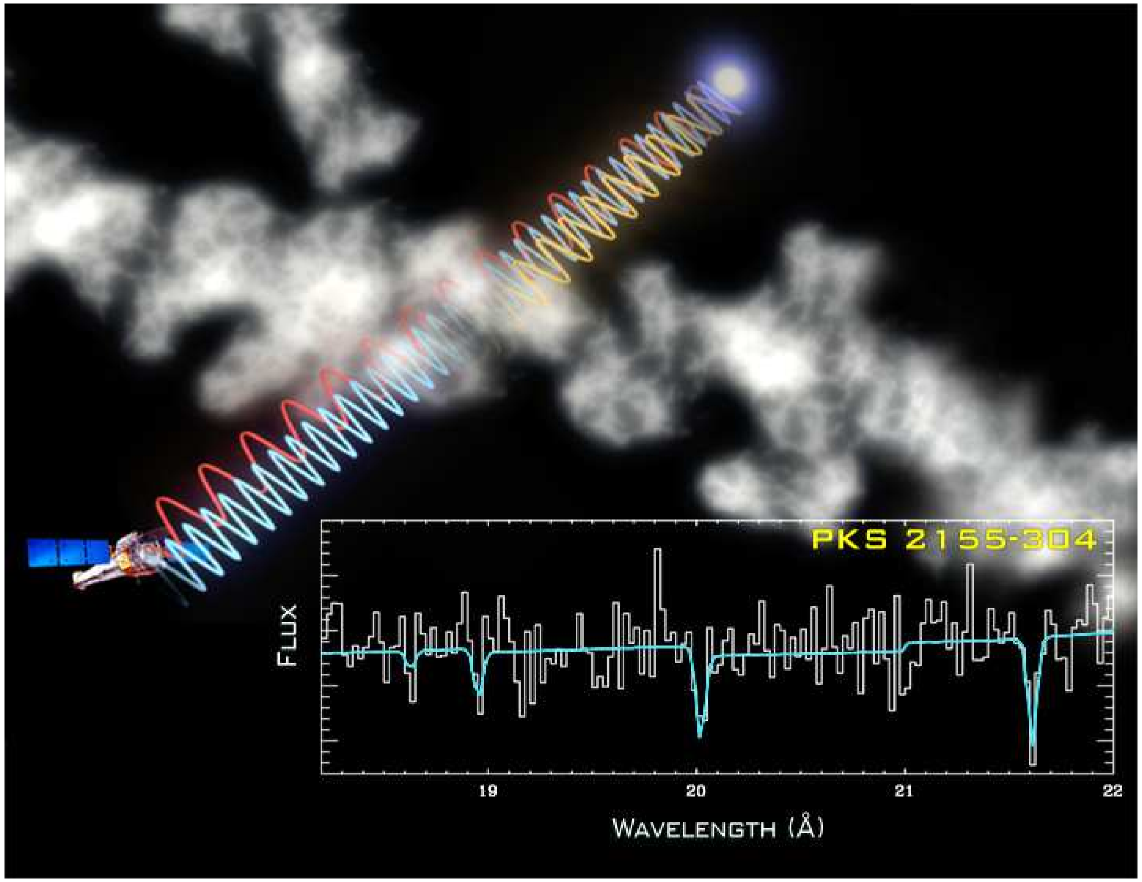
Binaries: X-rays from accretion on compact object illuminate gas

Example GRO J1655-40: black hole and normal star



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

Warm-Hot Intergalactic Medium and a Missing Barion problem

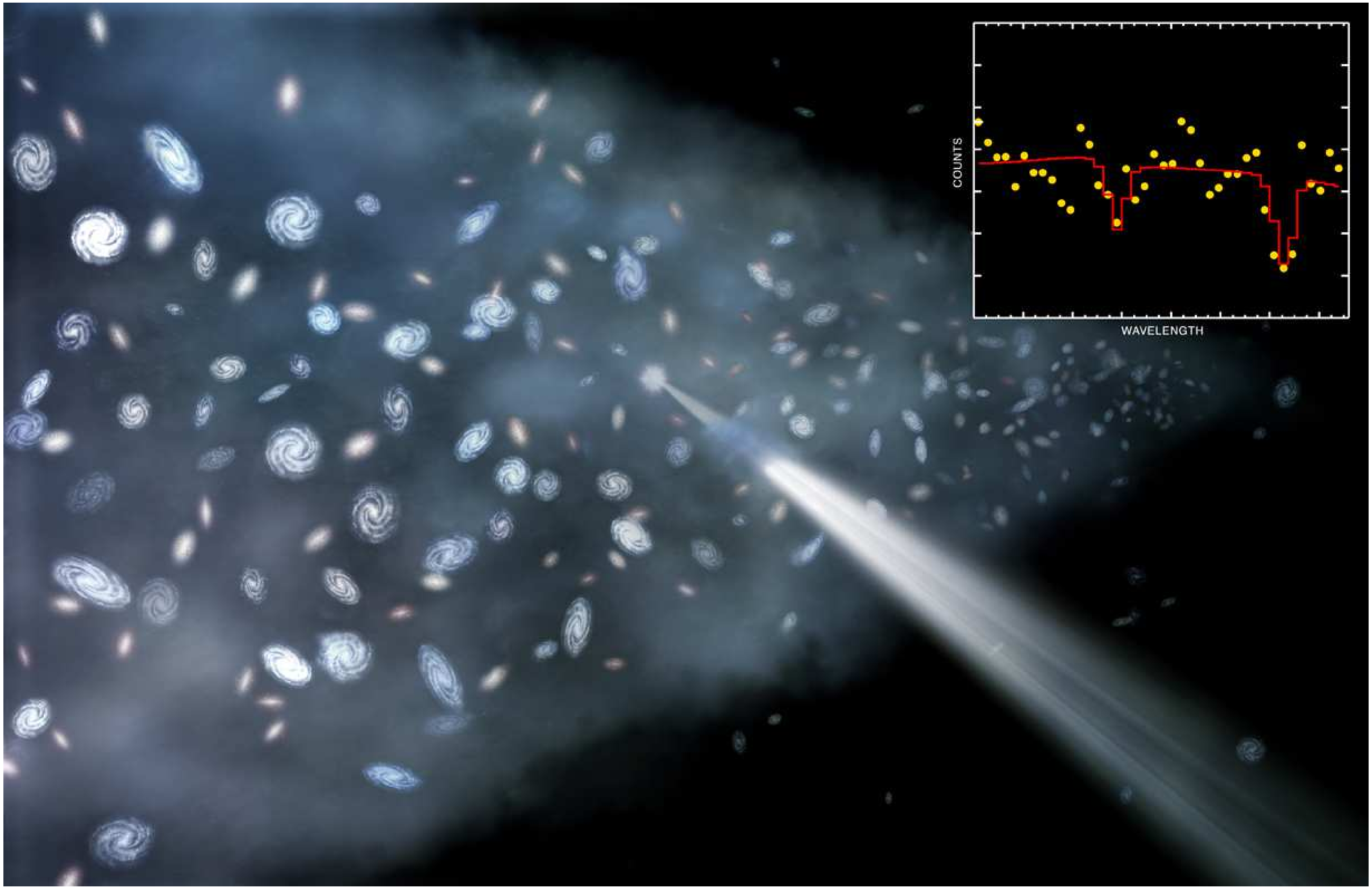


NASA/CXC/A.Hobart; Spectrum: NASA/MIT/T.Fang et al.

The total amount of the luminous baryons in the nearby universe probed by the stellar light, narrow Lyα absorption, as well as the X-ray emission from the hot intracluster and intragroup medium, accounts for at most 50% of the total baryonic matter in the low-redshift universe (e.g., Fukugita et al. 1998).

Large-scale, cosmological hydrodynamic simulations predict that most of the missing baryons are distributed as filamentary structures between galaxies, in the form of a warmhot interintergalactic medium WHIM with $T=10^5$-10^7 K

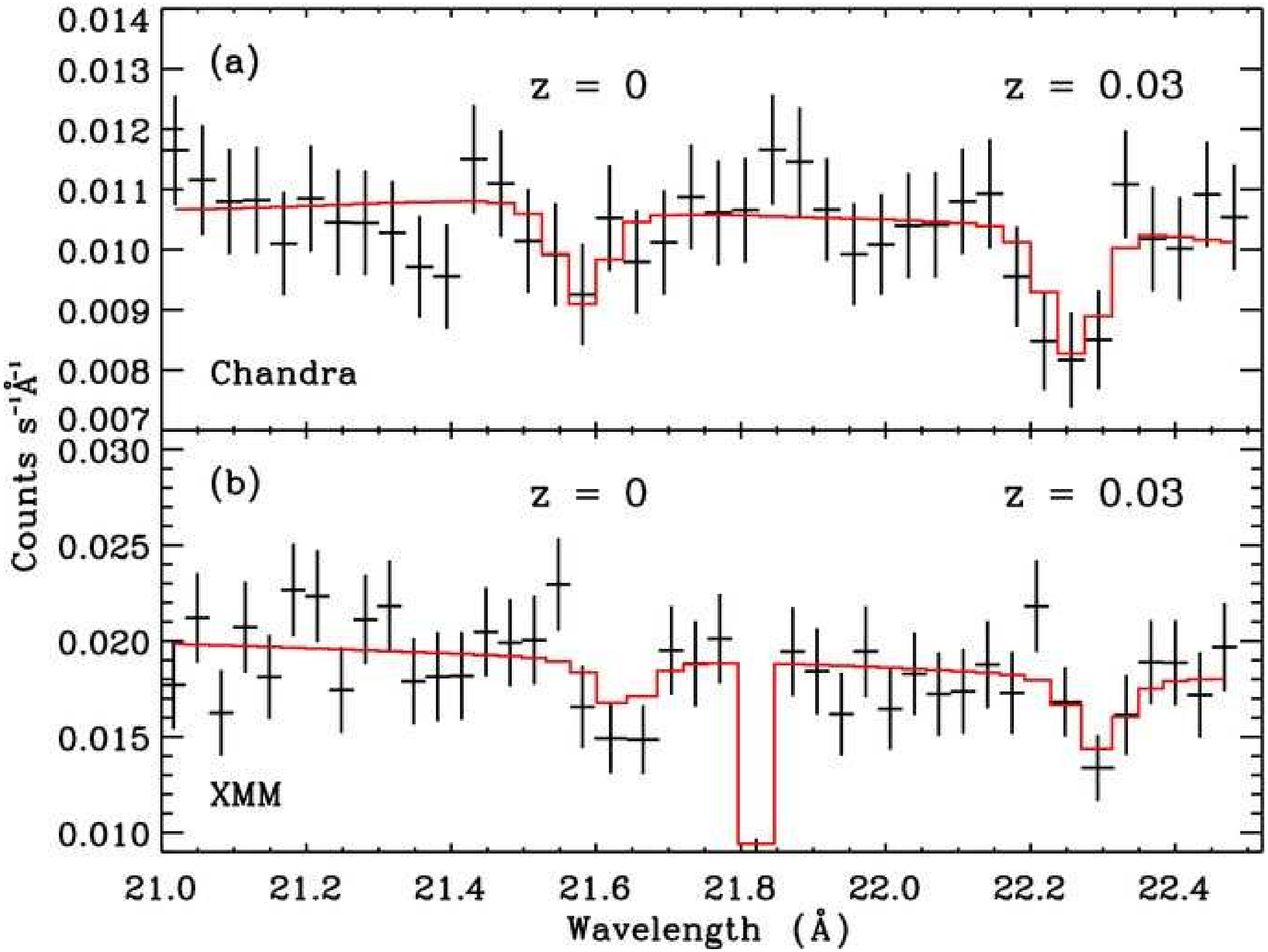
Warm-Hot Intergalactic Medium and a Missing Barion problem



NASA/CXC/M.Weiss;NASA/CXC/Univ. of California Irvine/T. Fang et al.

Presence of absorption lines is confirmed by both Chandra and XMM-Newton observatories.

WHIM photoionizaed or collisional?

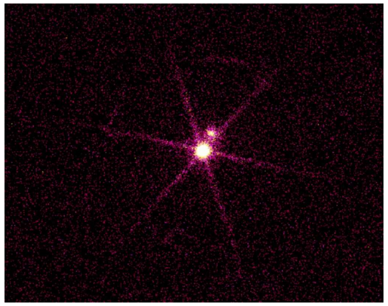


The Astrophysical Journal 714 (2010) 1715

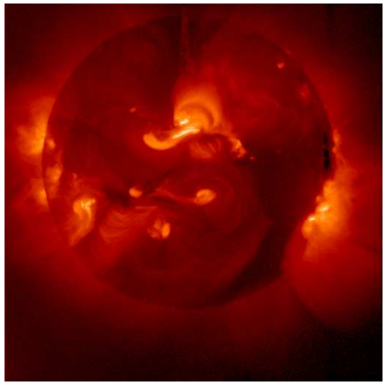
OVII Kα absorption lines at the positions corresponding to the local (z=0) absorber and the Sculptor Wall (z=0.03)

To understand the properties of the absorber (i.e. oxigen abundance), we shall know how OVII is formed: photoionization or collisions.

Summary of Thermal Plasma

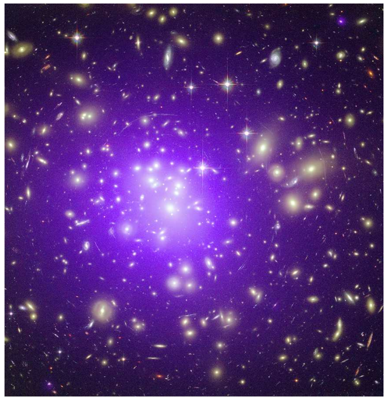


Blackbody: Neutron stars, WD

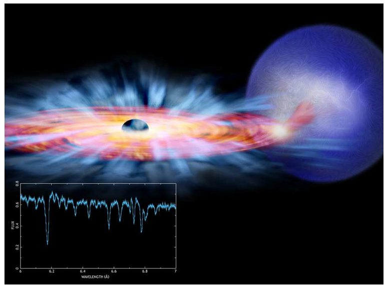


CIE plasma: stellar coronae

NEI: supernova remnants



Bremsstrahlung: galaxy clusters



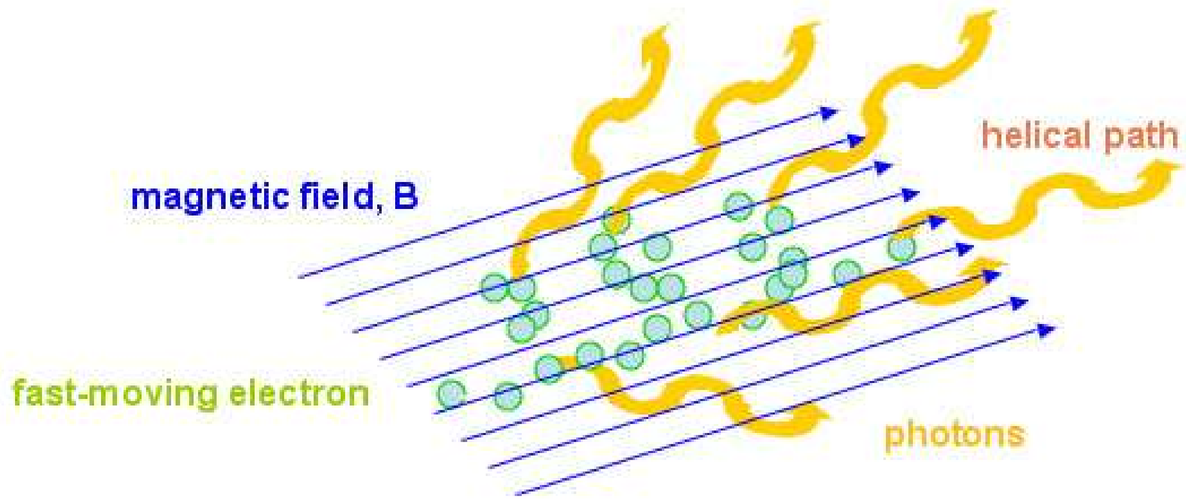
Photoionized plasma: X-ray binaries

Non-thermal radiation

Synchrotron emission

Synchrotron emission is non-thermal radiation generated by electrons spiralling around magnetic field lines at close to the speed of light.

The electrons are always changing direction: i.e accelerating and emitting photons with frequencies determined by the speed of the electron at that instant. **Magnetobremsstrahlung.**



http://astronomy.swin.edu.au/cosmos/

The radiation emitted is confined to a narrow cone pointing in the direction of the motion of the particle: beaming.

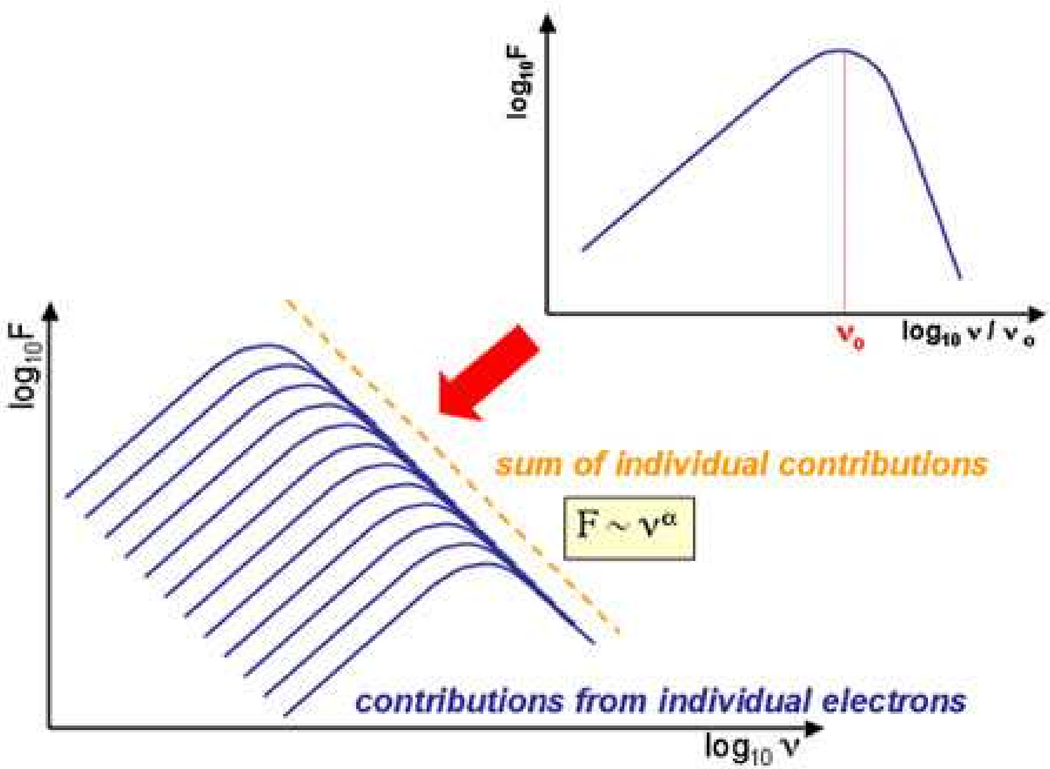
Radiation is polarised in the plane perpendicular to the magnetic field: the degree and orientation of the polarisation providing information about the magnetic field.

Spectrum of synchrotron emission

The spectrum of synchrotron emission: Σ the spectra of individual electrons.

As the electron spirals around the magnetic field,
it emits radiation over a range of frequencies peaking at ν_0 the critical frequency.

* The longer the electron travels around the magnetic field,
* the more energy it loses,
* the narrower the spiral it makes,
* and the longer the wavelength of the critical frequency.



$$\nu_0 = 4.3 \times 10^6 B \gamma^2 \sin\alpha \quad \text{[Hz]}$$

Σ spectra of e →

→ $P = 2.3 \times 10^{-22} B \sin\alpha F(\nu/\nu_0)$ [erg/s/Hz]

F(u) an integral over modified Bessel function

Power low spectrum $F \propto \nu^a$

Radio Galaxy: a=-0.7

Pulsar: a=-2...-3

AGN: a=-1...+1

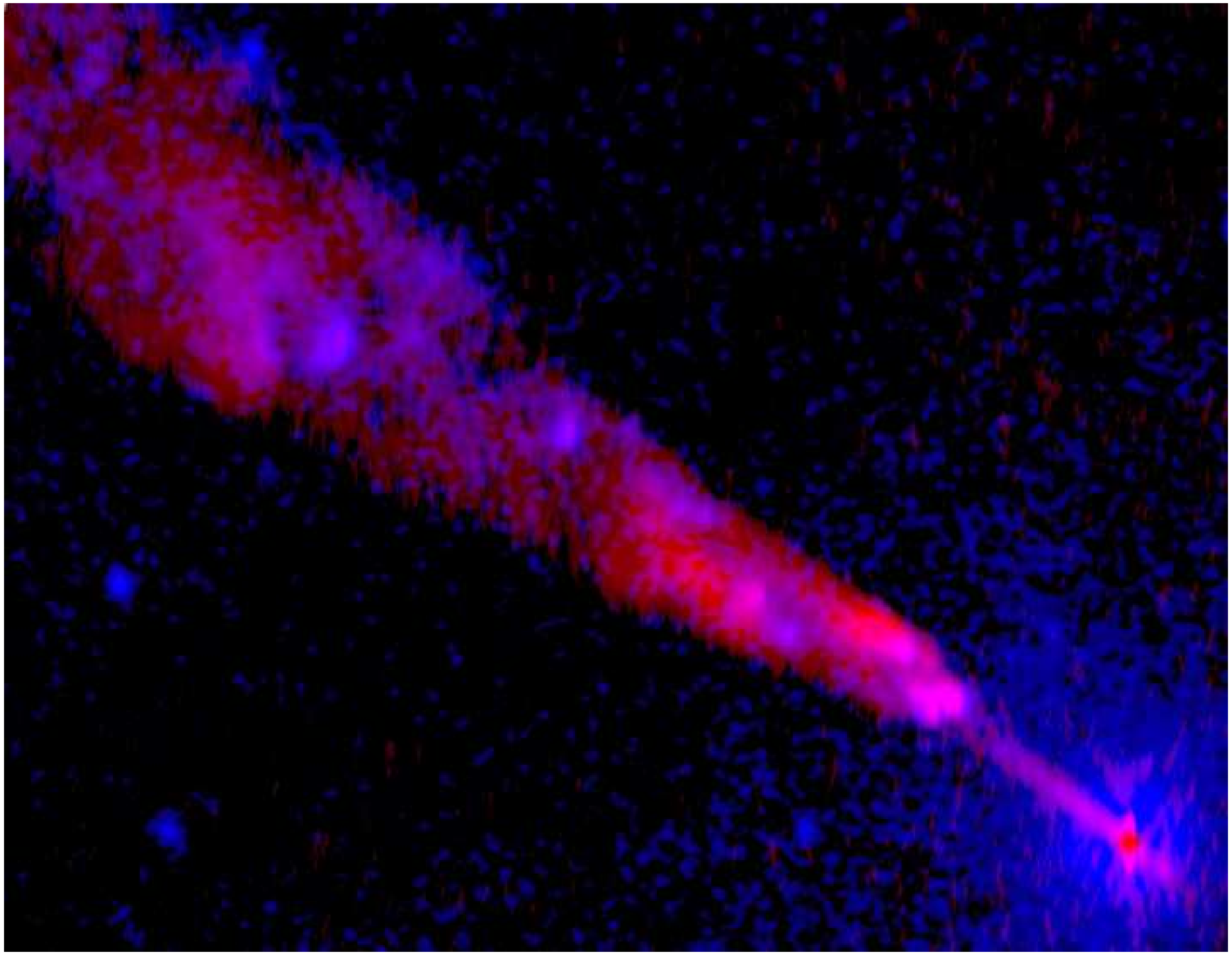
theoretical maximum a=+2.5

http://astronomy.swin.edu.au/cosmos/

Example: Jets from active galaxies

Magnetized jet in Centaurus A (NGC5128): an active elliptical galaxy. Chandra X-ray (blue) VLA radio (red)

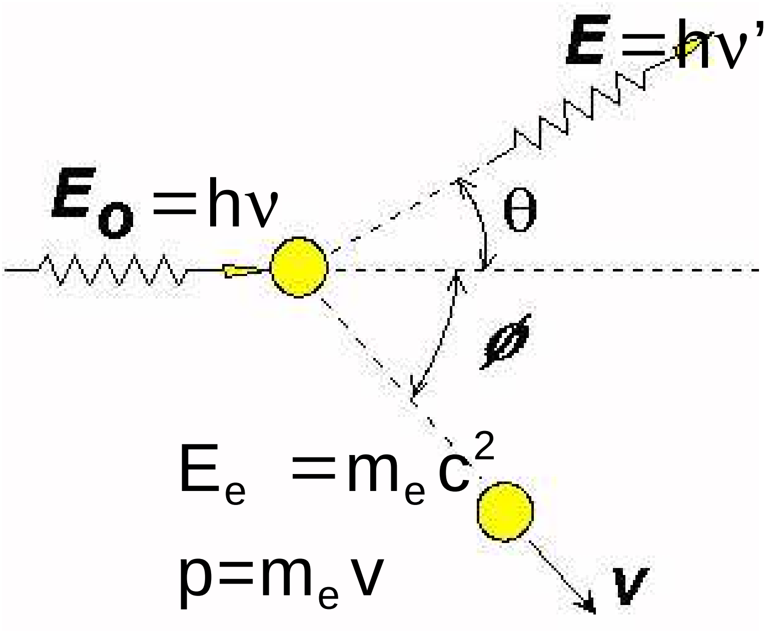
>0.5c - speed of electrons, 11 million light years



http://chandra.harvard.edu/photo/2003

Compton Effect

Compton scattering (Compton effect) is the decrease in energy of an X-ray photon, when it interacts with matter.



E(photon) ~ eV

comparable to the binding energy of e in atom →

photoeffect i.e. ejection of an electron

E(photon)~ keV

comparable to the binding energy of e →

i.e. electron may be considered free

energy and momentum is conserved

Compton effect

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

E(photon)~ MeV

comparable to the binding energy of p →

Pair production (positron and e)

Compton effect (cont.)

1923 Arthur Compton → 1927 Nobel Prize in Physics.

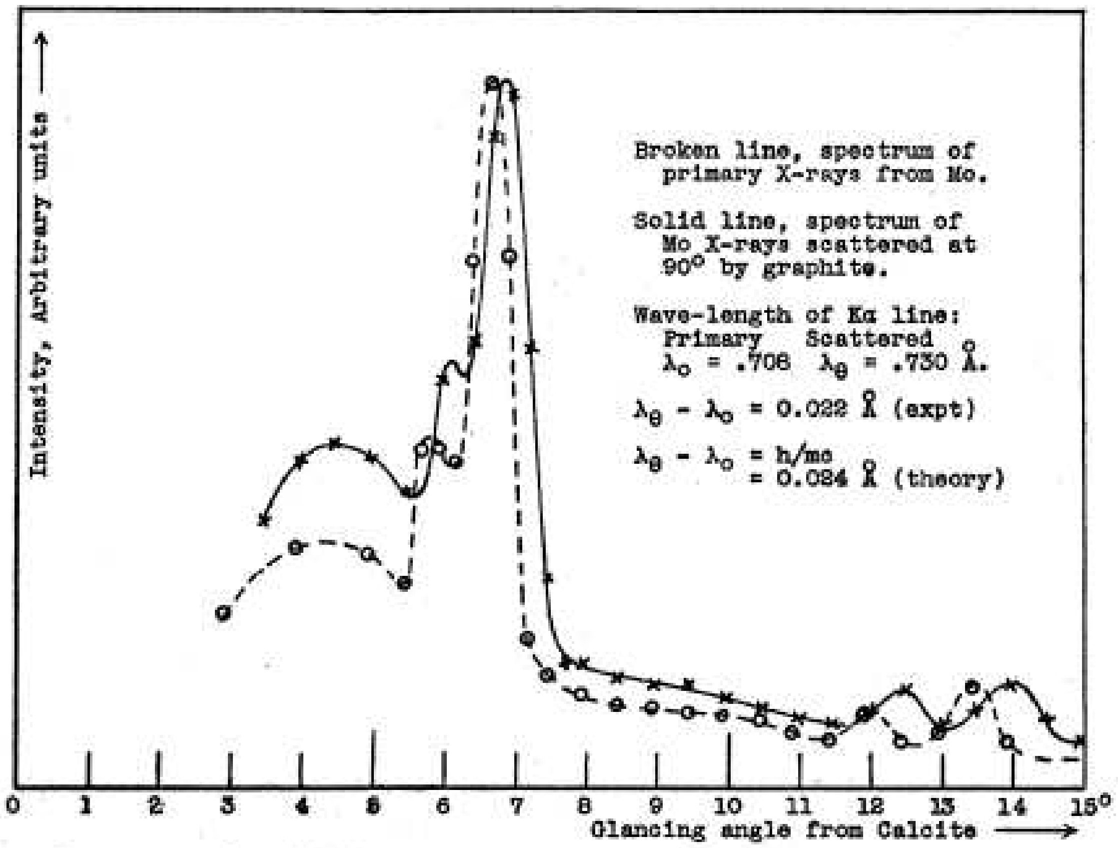


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

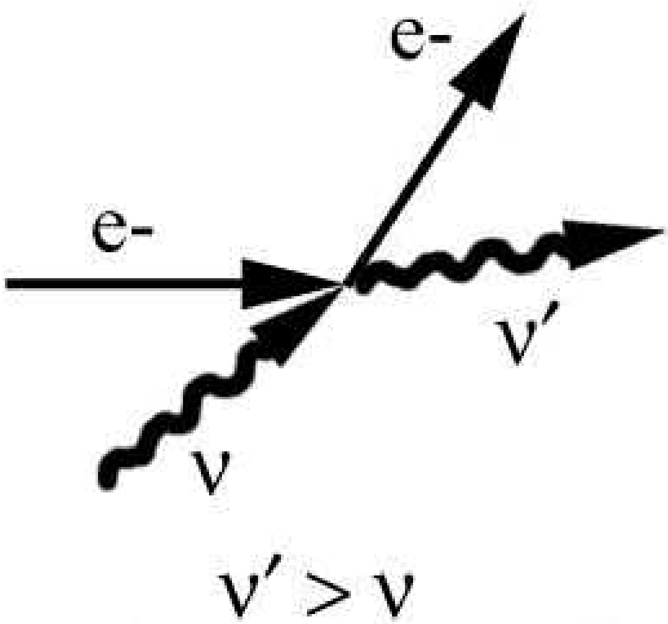
Prove: light cannot be explained purely as a wave phenomenon.

Classical cross-section of electron: Thomson

The Klein-Nishina formula incorporates radiation pressure, corrects for relativistic quantum mechanics, and takes into account the interaction of the spin and magnetic moment of the electron with electromagnetic radiation.

Inverse Compton scattering

Electron cannot be considered at rest (astrophysically more important)



High energy e- initially
e- loses energy

http://venables.asu.edu/quant/proj/compton.html

The energy is transferred from the e to the ph

Lets hν << γmc^2, γ is Lorentz factor

i. the cross-section is independent of the ph energy and is approximately Thomson cross-section σ_T

ii. The mean frequency of the ph after the collision is found to increase by a factor γ^2

iii. high frequency radio photons in collisions with relativistic e ($\gamma = 10^3 - 10^4$) are **boosted** to X-rays.

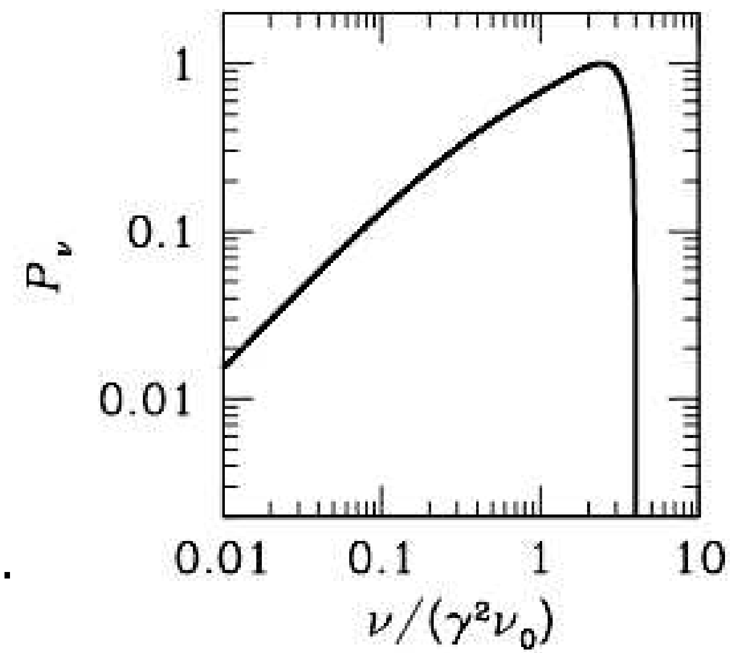
$h\nu' = h\nu + \gamma mc^2$, maximum E=$\gamma mc^2$

Isotropic distribution of ph: emitted power

$P_{IC} = 4/3\sigma_T\gamma^2\beta^2 U_{rad}$ [erg/s]

The inverse-Compton spectrum of electrons with energy γ irradiated by photons of frequency ν_0.

Maximum: $\nu/\nu_0 = 4\gamma^2$



Comptonisation

If the spectrum of a source is primarily determined by Compton processes it is termed Comptonised. The hotter the gas, the more chance of Comptonisation.

- hot gas near binary X-ray sources
- hot plasma near center of active galactic nuclei
- hot plasma in clusters of galaxies
- primordial gas cooling after the Big Bang

From thermodynamic considerations

(using a thermal distribution of electrons T_e $\frac{3}{2}kT_\mathrm{e} = \frac{1}{2}m_\mathrm{e}v^2$)

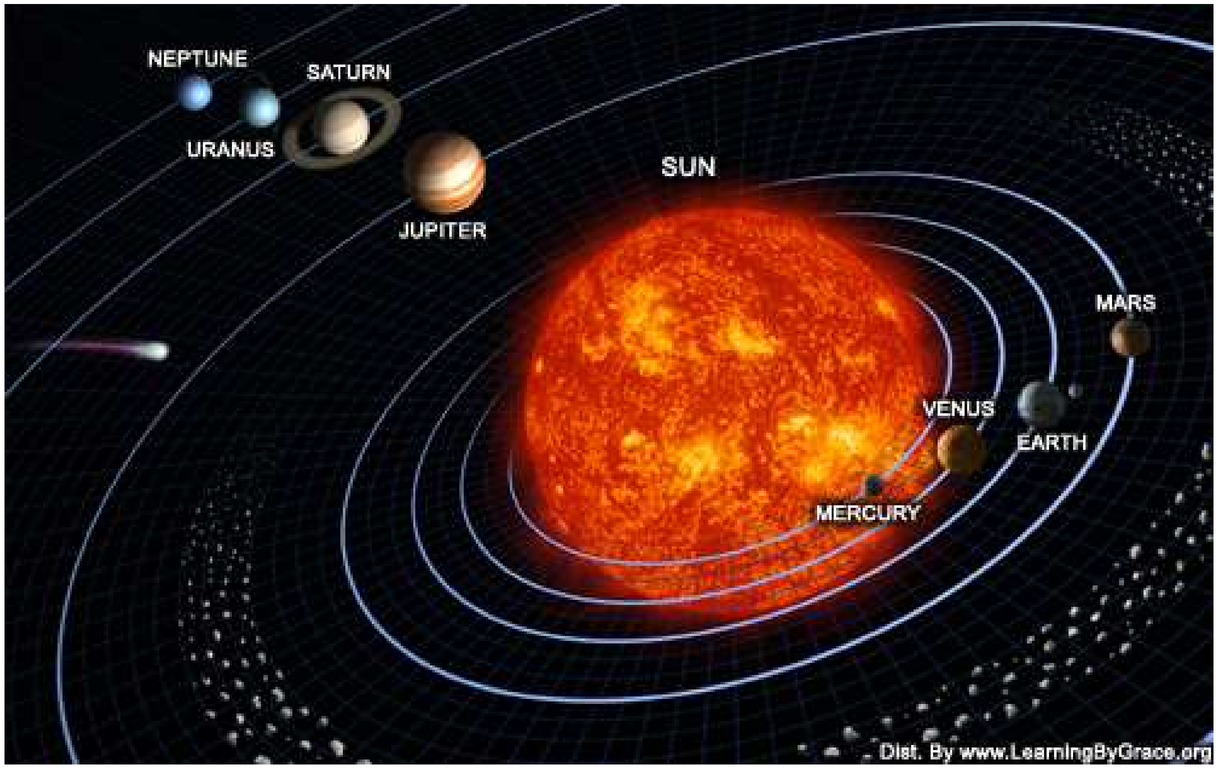
$$\Delta E = \frac{E}{m_\mathrm{e}c^2}(4kT_\mathrm{e} - h\nu)$$

- $E = 4kT_e$, there is no energy exchange
- $E > 4kT_e$, electrons gain energy
- $E < 4kT_e$, electrons loose energy

Charge exchange

Important in environment where ions and neutrals can interact

Such as planetary systems, i.e. solar



http://www.thejubileeacademy.org/marketing/media/solar_system1.jpg

High ions are produced in corona and are carried by solar wind

Neutrals can be found in Comets, planetary atmospheres

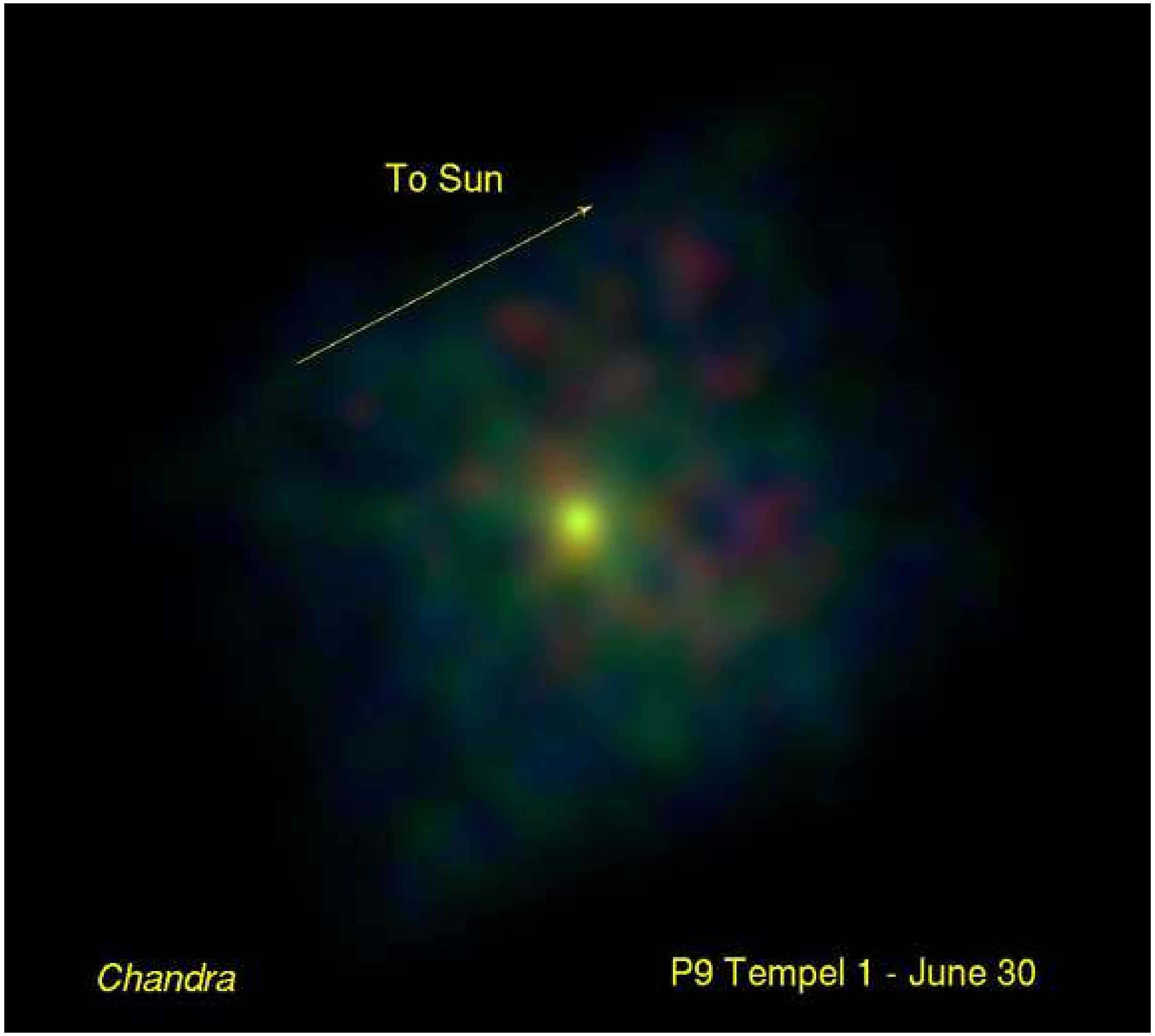
During interaction electron is transferred

$$A^{q+} + N \rightarrow A^{(q-1)+,*} + N^{-} \rightarrow A^{(q-1)+} + N^{-} + h\nu_{\mathrm{X}}$$

A^{q+} is high ion (i.e. O, C, Fe), N is neutral(i.e. H, H_2O, O)

De-exitation cascade in $A^{(q-1)+,*}$ leads to emission of X-ray photon

if ion is singly ionized, it may become neural. If it was bound to a magnetic field line, it becomes un-bound



http://www.thejubileeacademy.org/marketing/media/solar_system1.jpg

X-rays from Comet Tempel 1

X-rays are primarily due to the interaction between highly charged oxygen ions in the solar wind and neutral gases from the comet.

$$A^{q+} + N \rightarrow A^{(q-1)+,*} + N^{-} \rightarrow A^{(q-1)+} + N^{-} + h\nu_{\mathrm{X}}$$

A^{q+} is high ion (i.e. O, C, Fe), N is neutral(i.e. H, H_2O, O)

De-exitation cascade in $A^{(q-1)+,*}$ leads to emission of X-ray photon

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Summary of Radiative Processes

- Blackbody: Neutron stars, WD
- CIE plasma: stellar coronae
- NEI: supernova remnants
- Bremsstrahlung: galaxy clusters
- Photoionized plasma: X-ray binaries
- Synchrotron: AGN jets
- Componisation: AGN, BH, galaxy clusters
- Charge Exchange: planetary systems