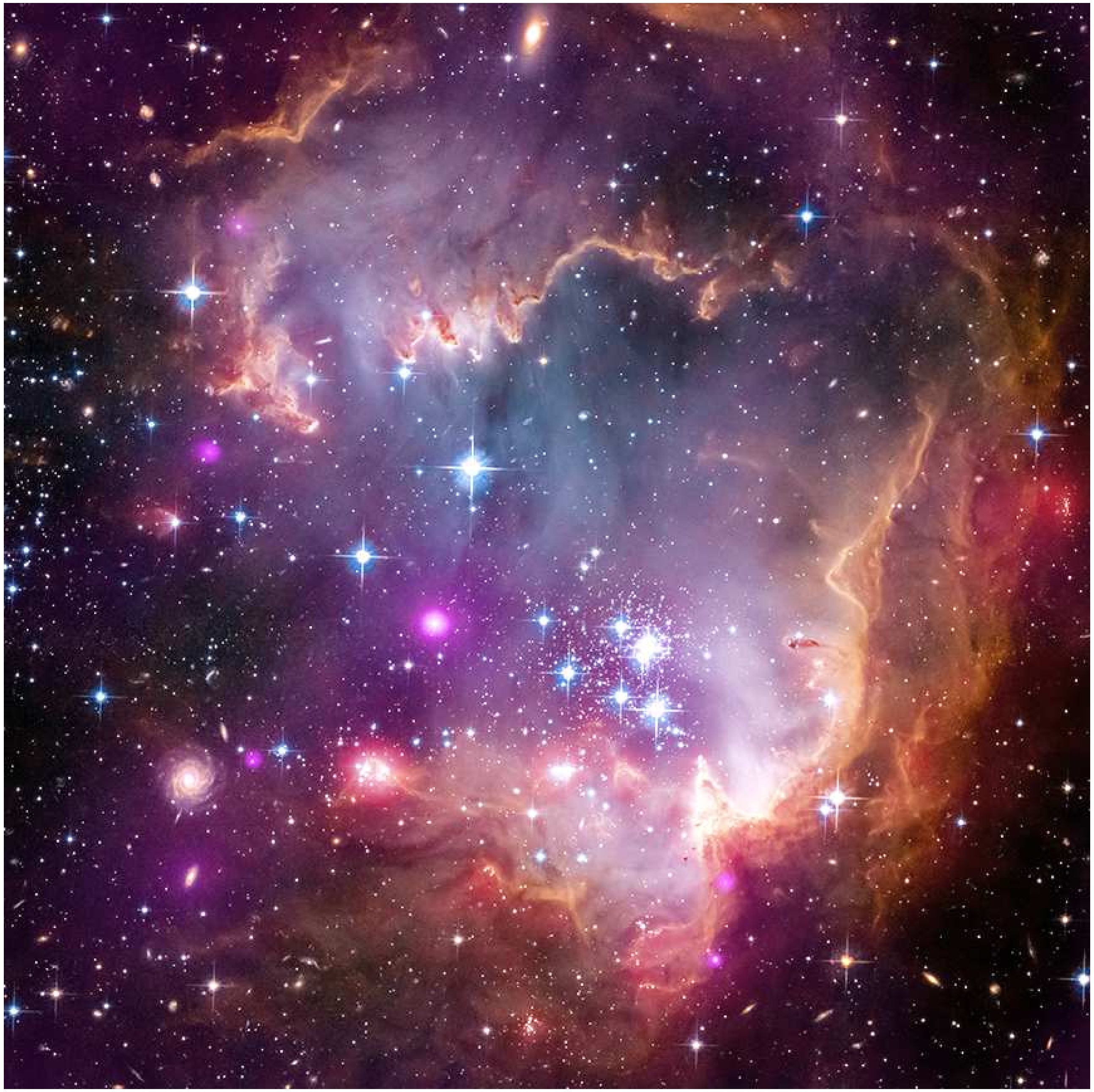
The X-Ray Universe



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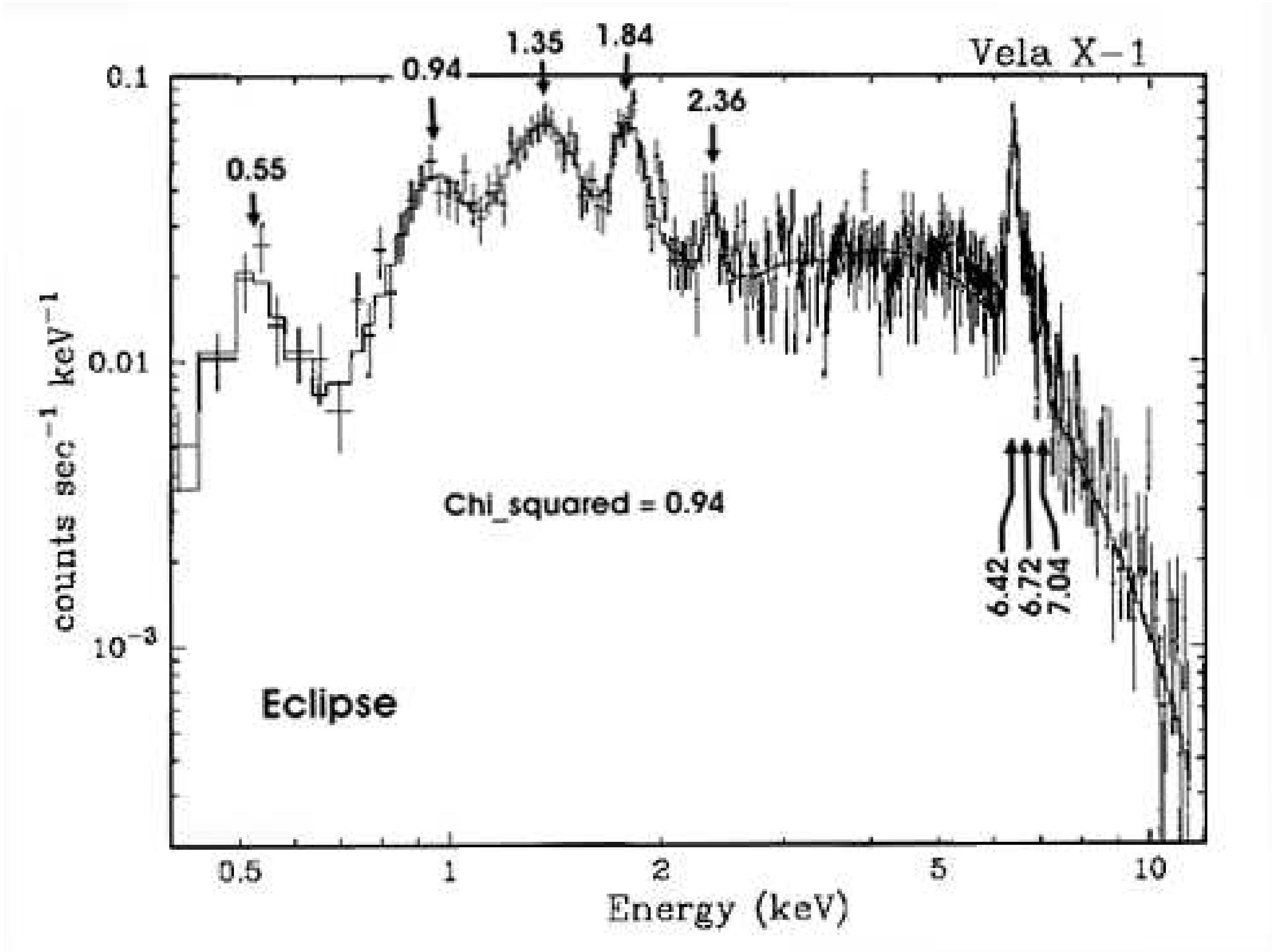
~lida/vorlesungXRAYSo17.html

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

IV. Radiation Processes



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

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: $e^- + I \rightarrow I^+ + 2e^-$
- 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.

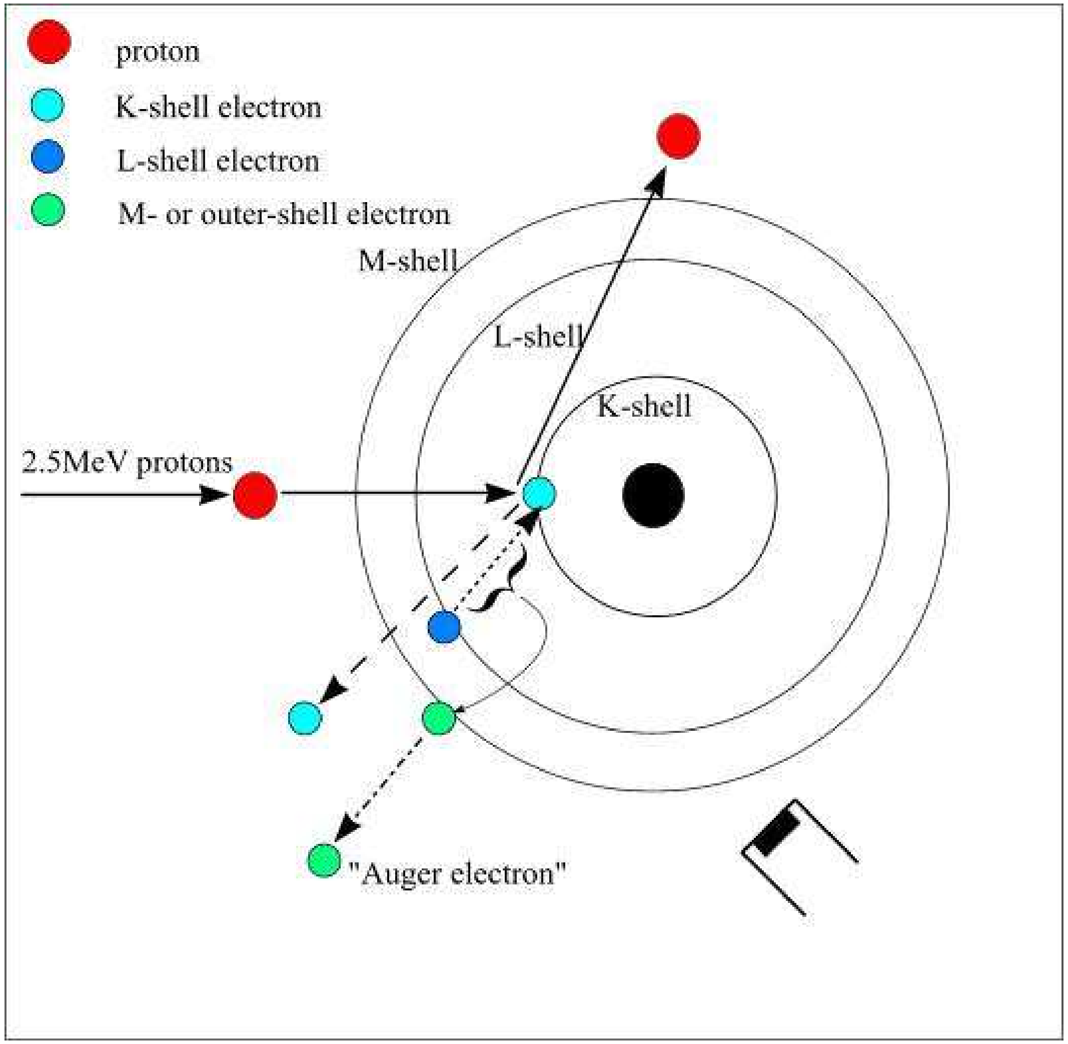
Remining ion is very unstable. It will either emit a photon (radiatively stabilize) or an electron, called an Auger electron.

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%.

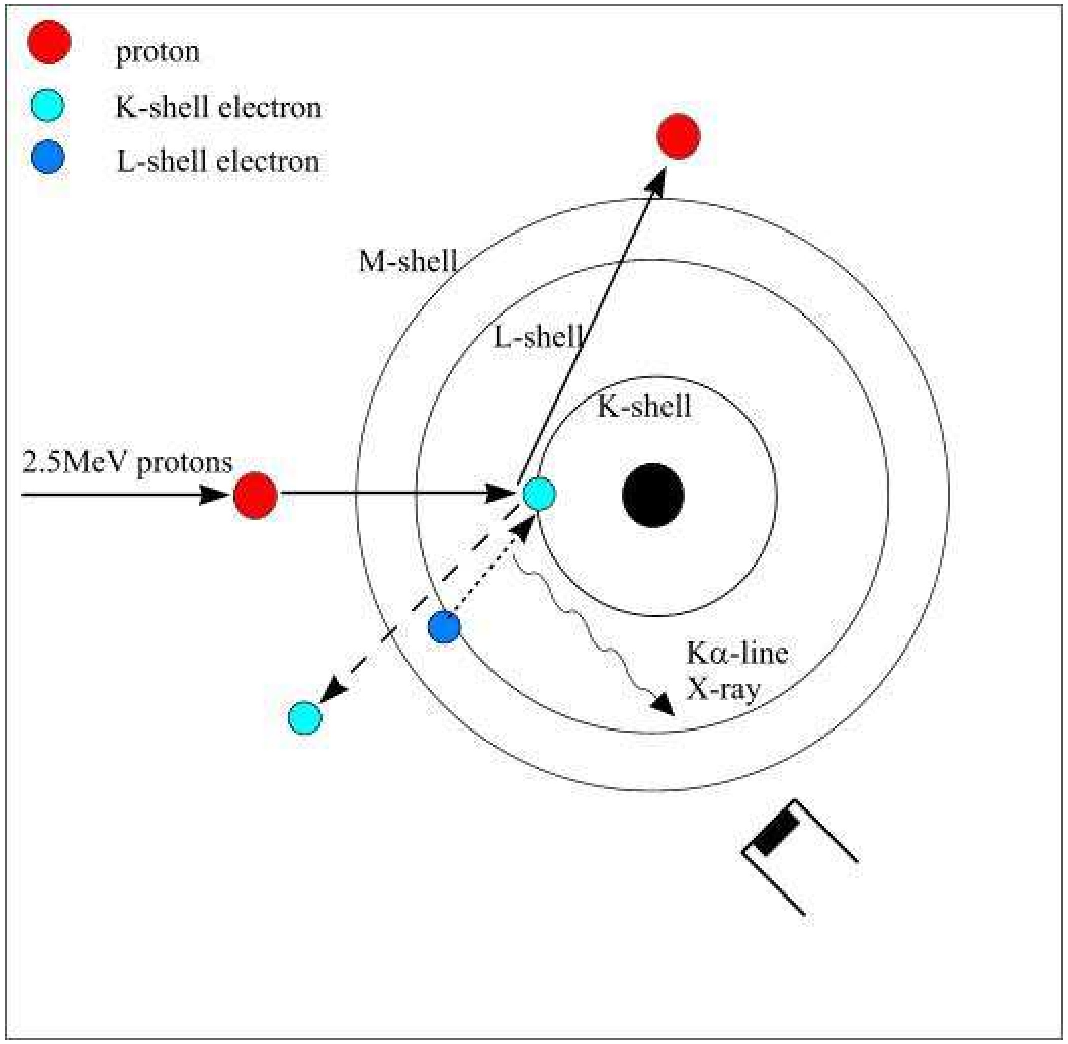
Innershell ionization of Fe I - Fe XVI tends to emit a 6.4 keV photon, commonly called the cold or neutral iron line.

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

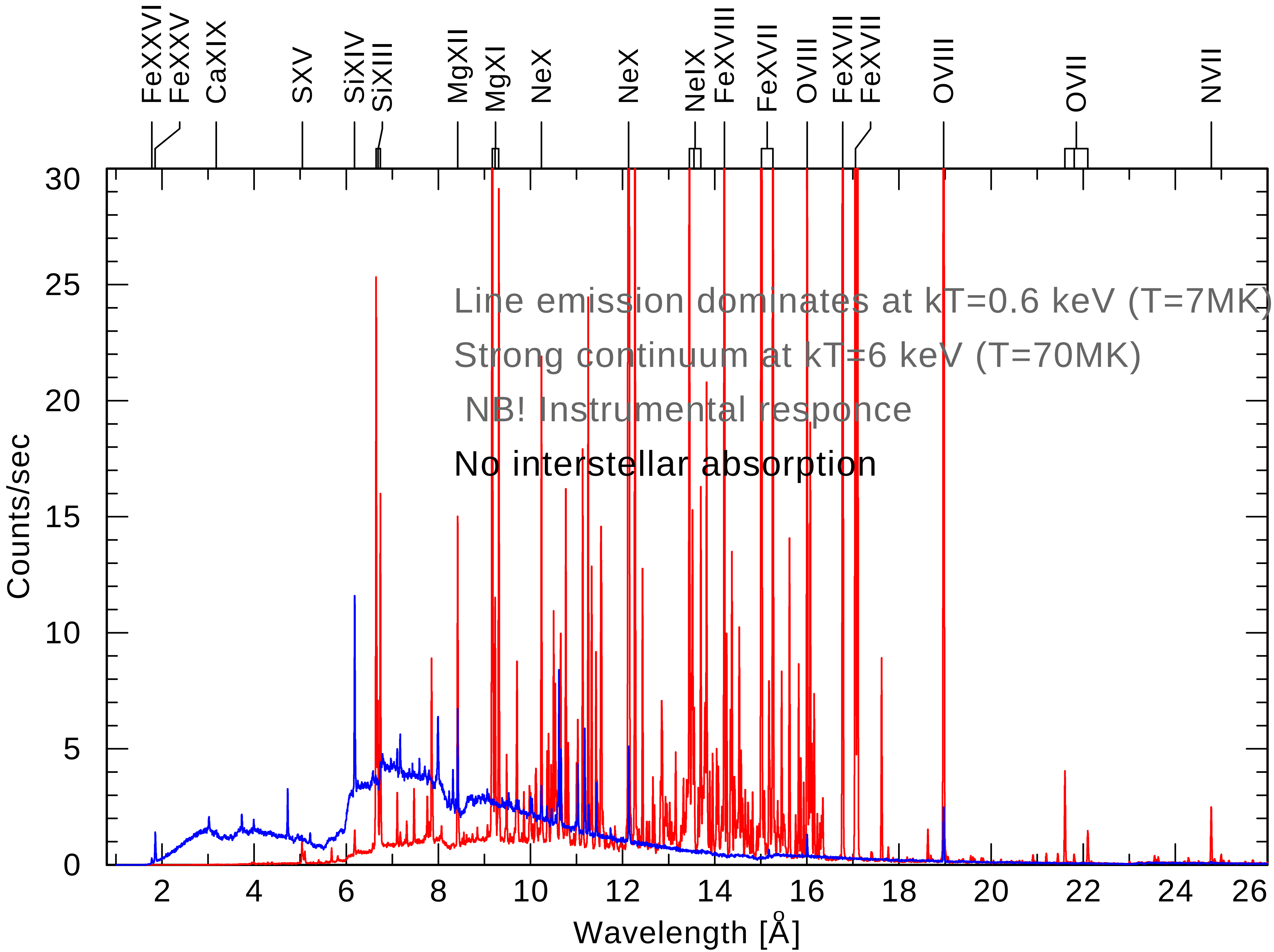
  - or recombination rate is higher than ionization

  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,

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

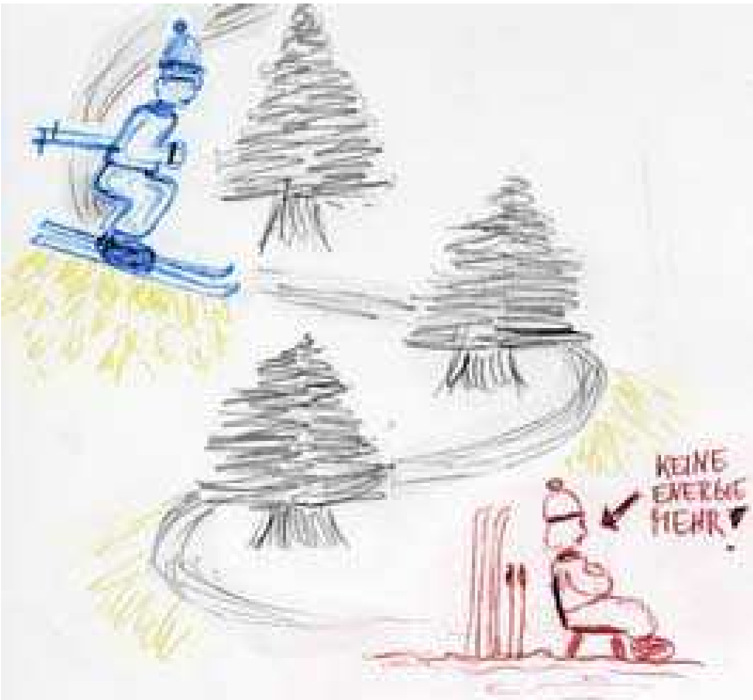
To get 1 MK plasma a shock jump 300 km/s or 1 Million km/hr is needed

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:

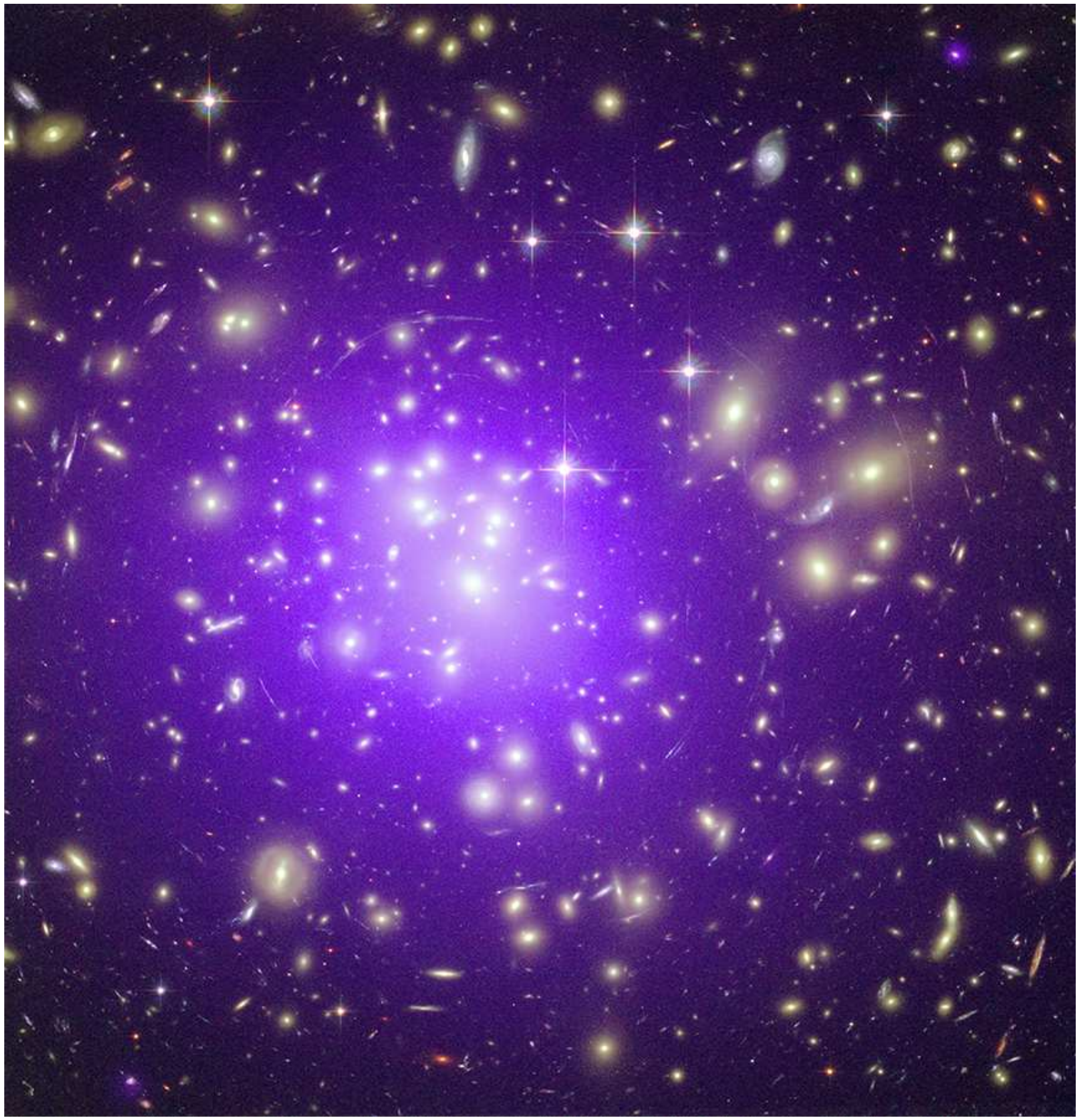
$$\frac{dP_B}{dV} = 2.4 \times 10^{-27} \sqrt{T} N_e^2 \quad \text{[erg cm}^{-3}\text{s}^{-1}\text{]}$$

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

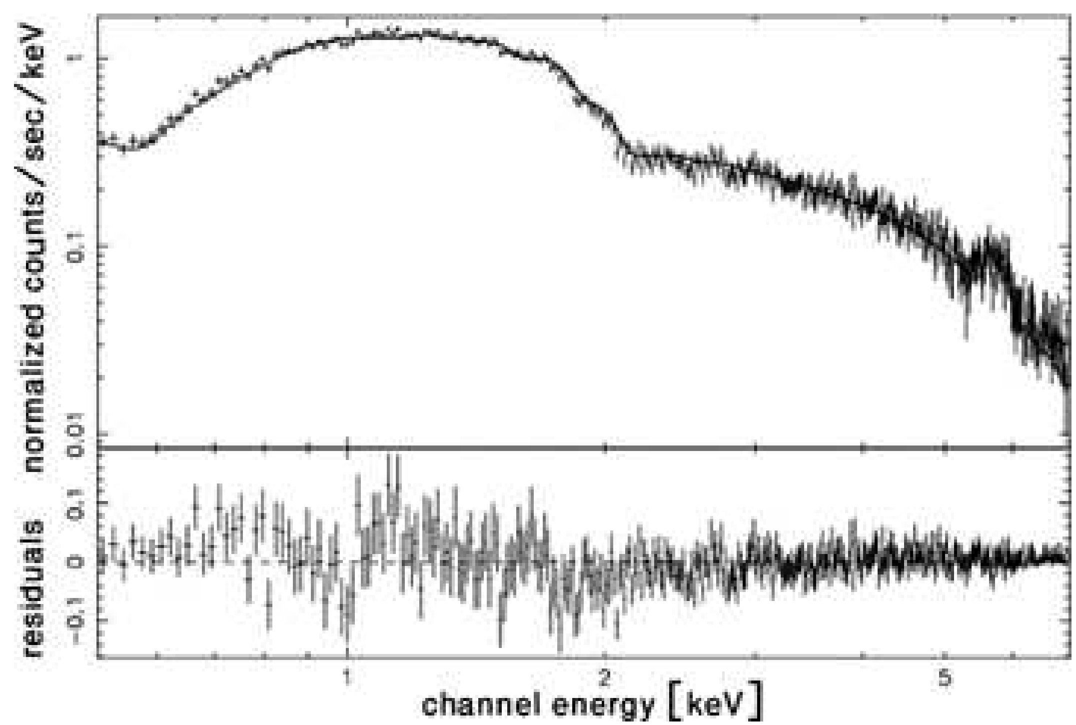
Massive galaxy cluster:

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

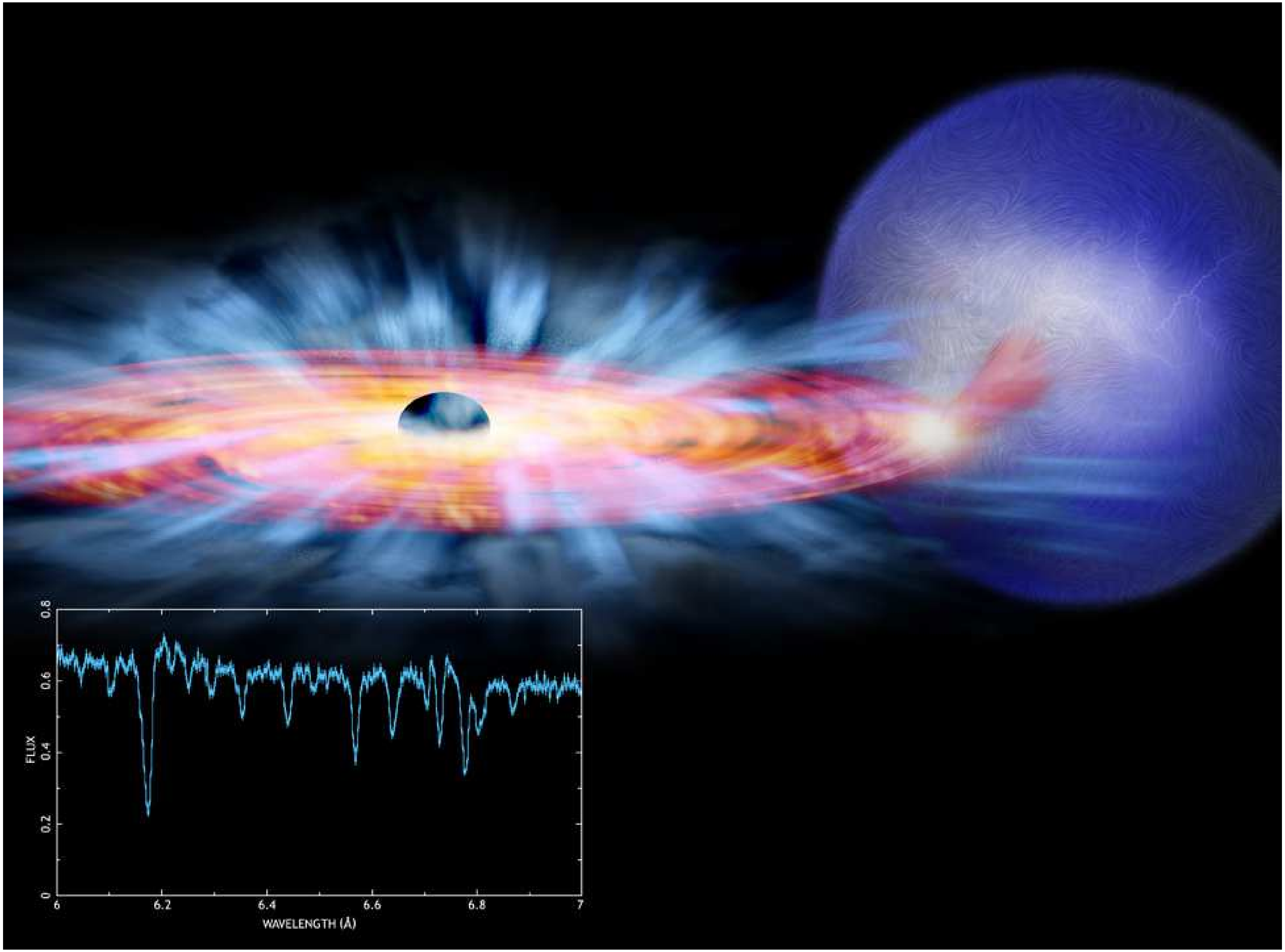
$$\xi = \frac{L_X}{nr^2}$$

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

model spectra can be compared with observed

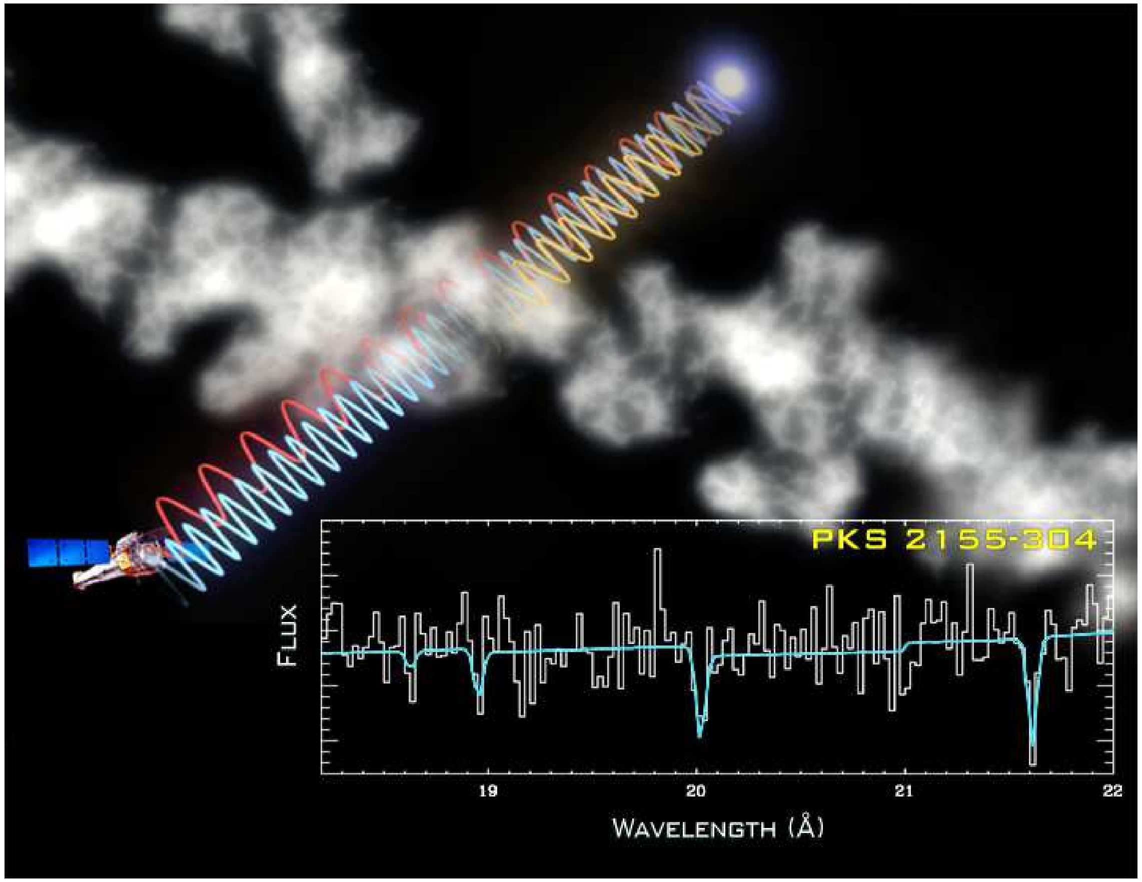
Binaries: X-rays from accretion on compact object illuminate gas

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

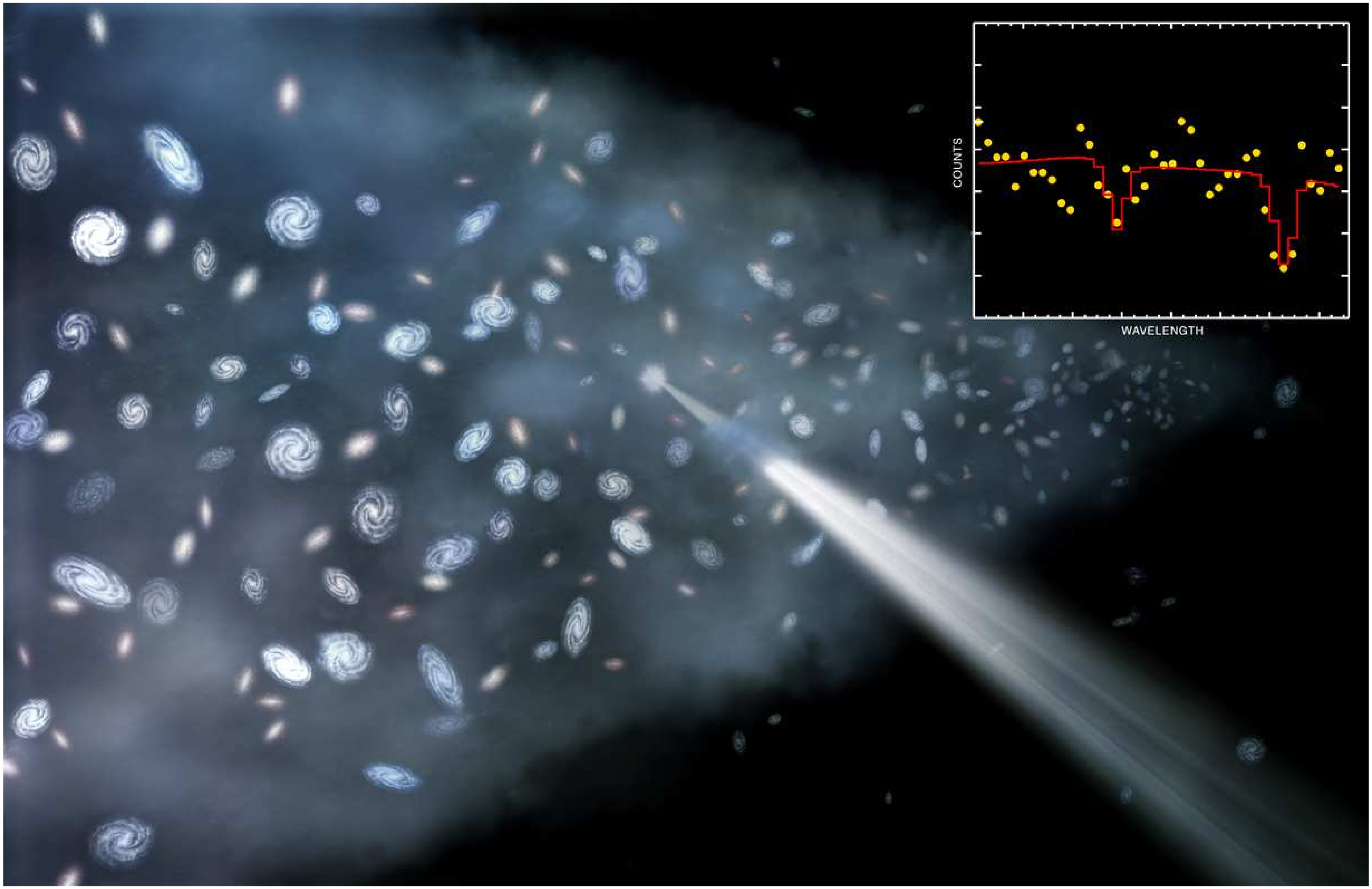


NASA/CXC/A.Hobart; Spectrum: NASA/MIT/T.Fang et al.

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

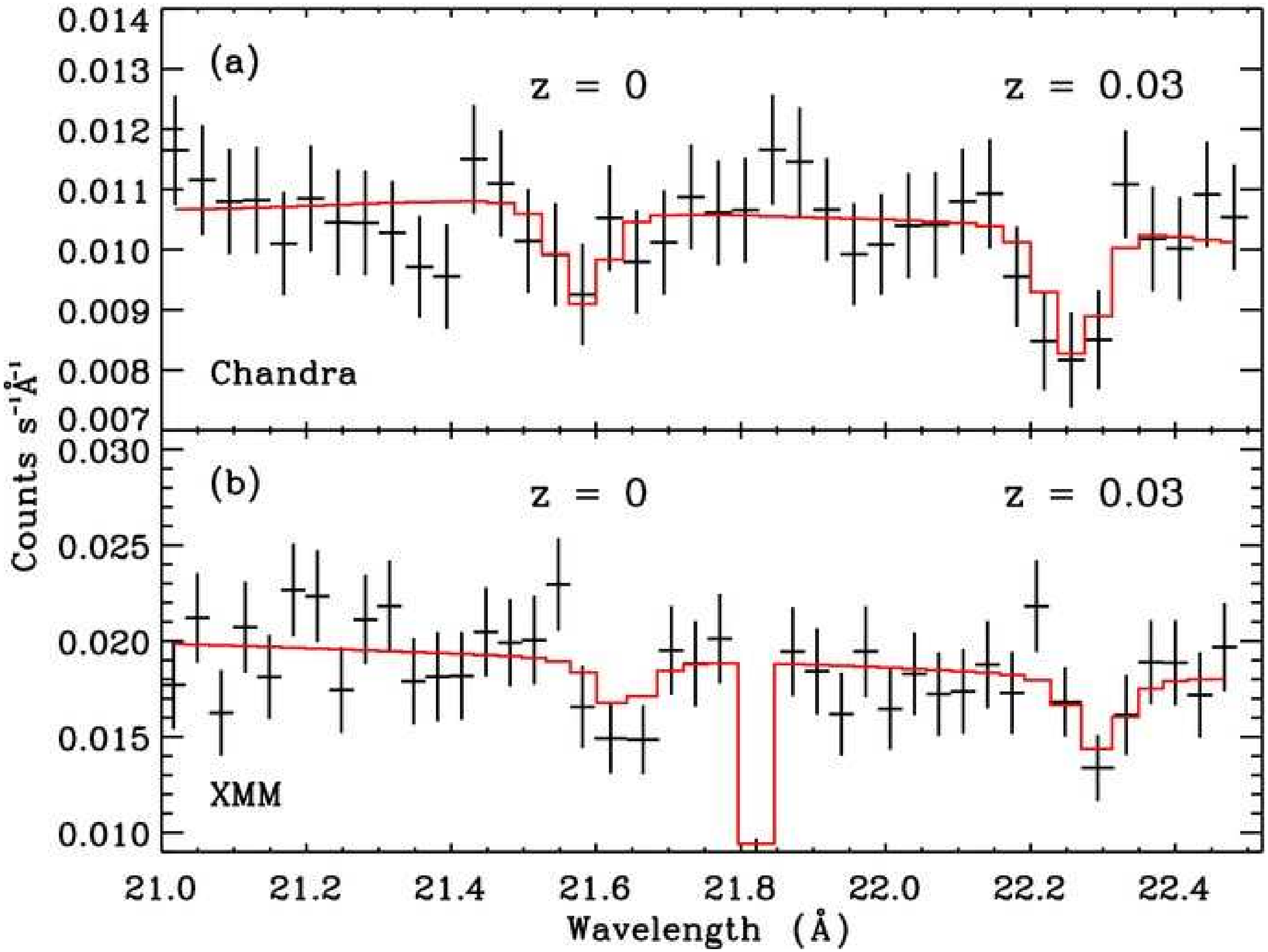
Warm-Hot Intergalactic Medium and a Missing Barion problem



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?

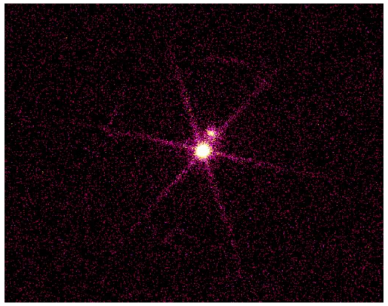


The Astrophysical Journal 714 (2010) 1715

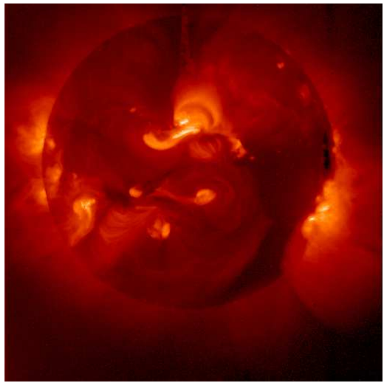
OVII Kα absorption lines at the positions corresponding to the local (z=0) absorber and the Sculptor Wall (z=0.03)

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

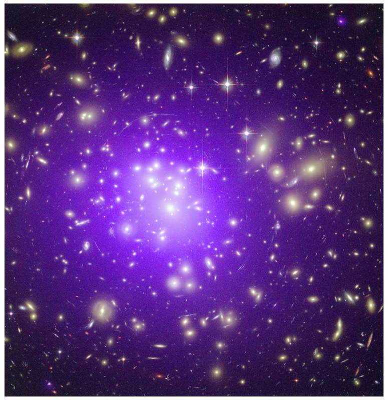


Blackbody: Neutron stars, WD

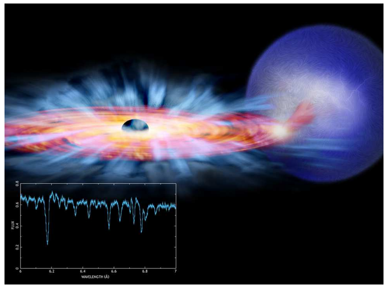


CIE plasma: stellar coronae

NEI: supernova remnants



Bremsstrahlung: galaxy clusters



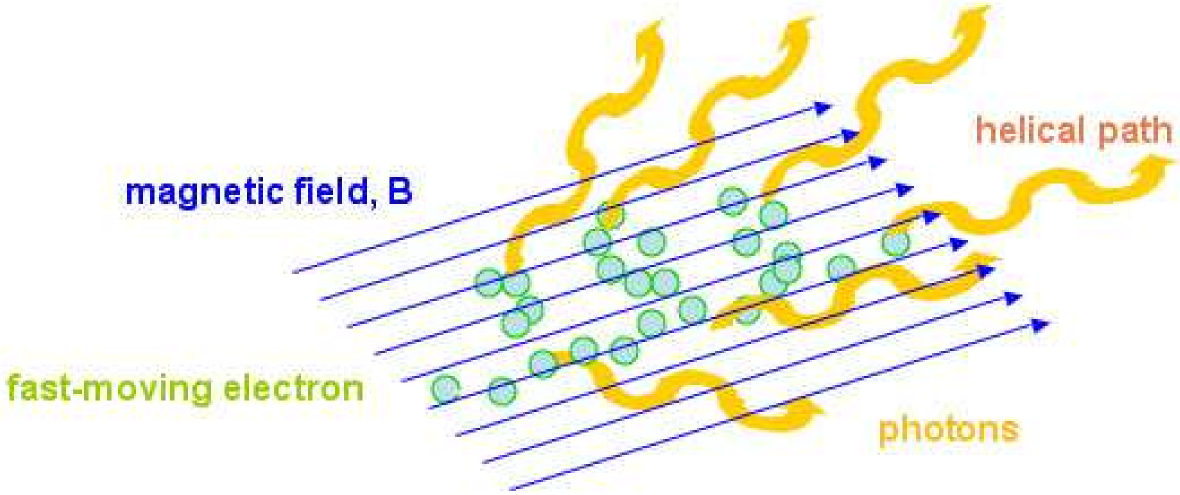
Photoionized plasma: X-ray binaries

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/

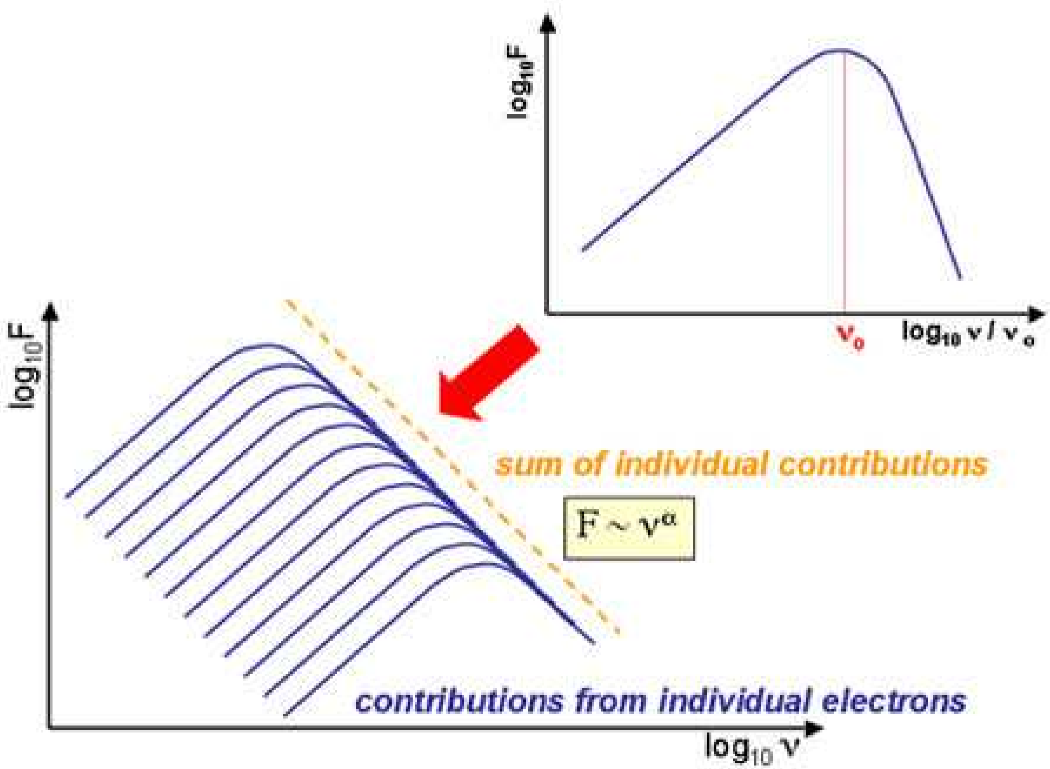
The radiation emitted is confined to a narrow cone pointing in the direction of the motion of the particle: beaming.
Radiation is polarised in the plane perpendicular to the magnetic field: the degree and orientation of the polarisation providing information about the magnetic field.

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.



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

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

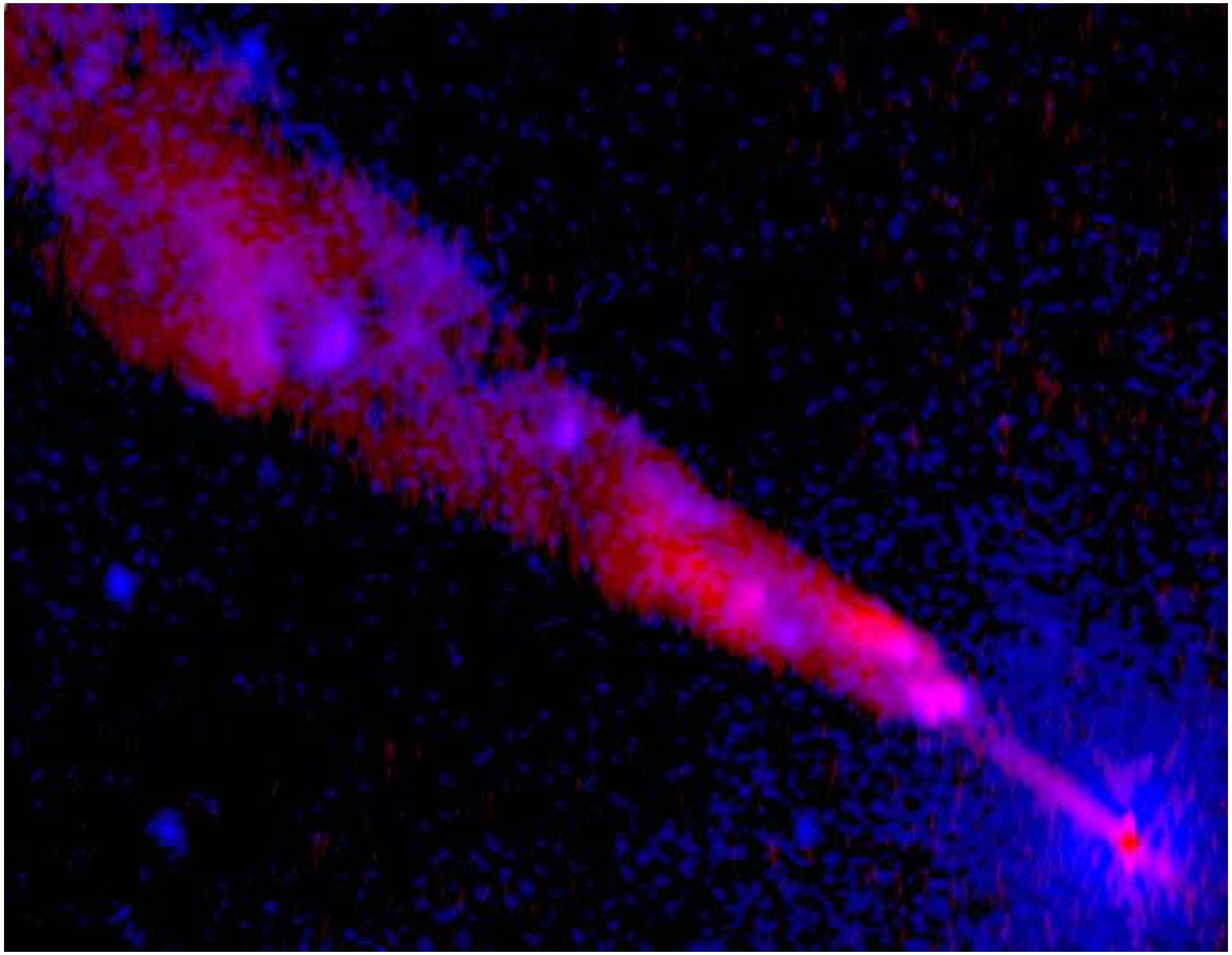
theoretical maximum a=+2.5

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)

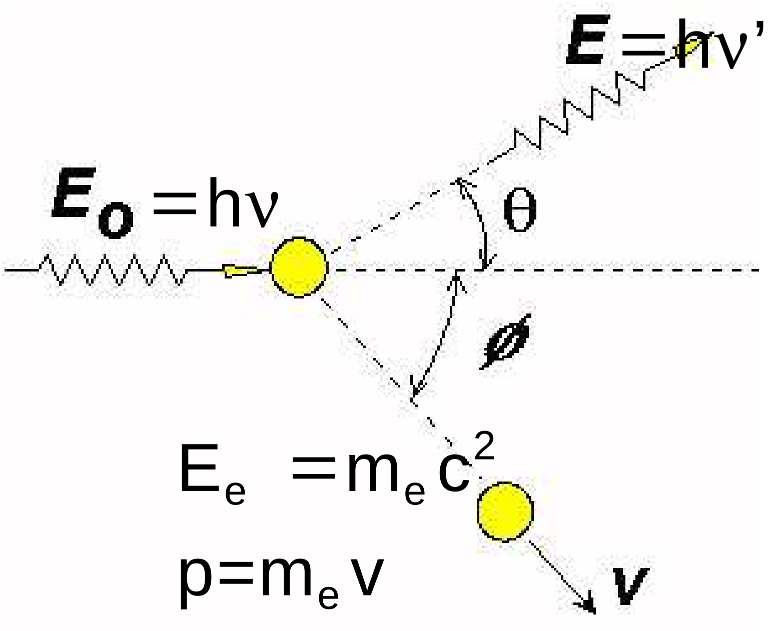
>0.5c - speed of electrons, 11 million light years



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.



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

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

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.

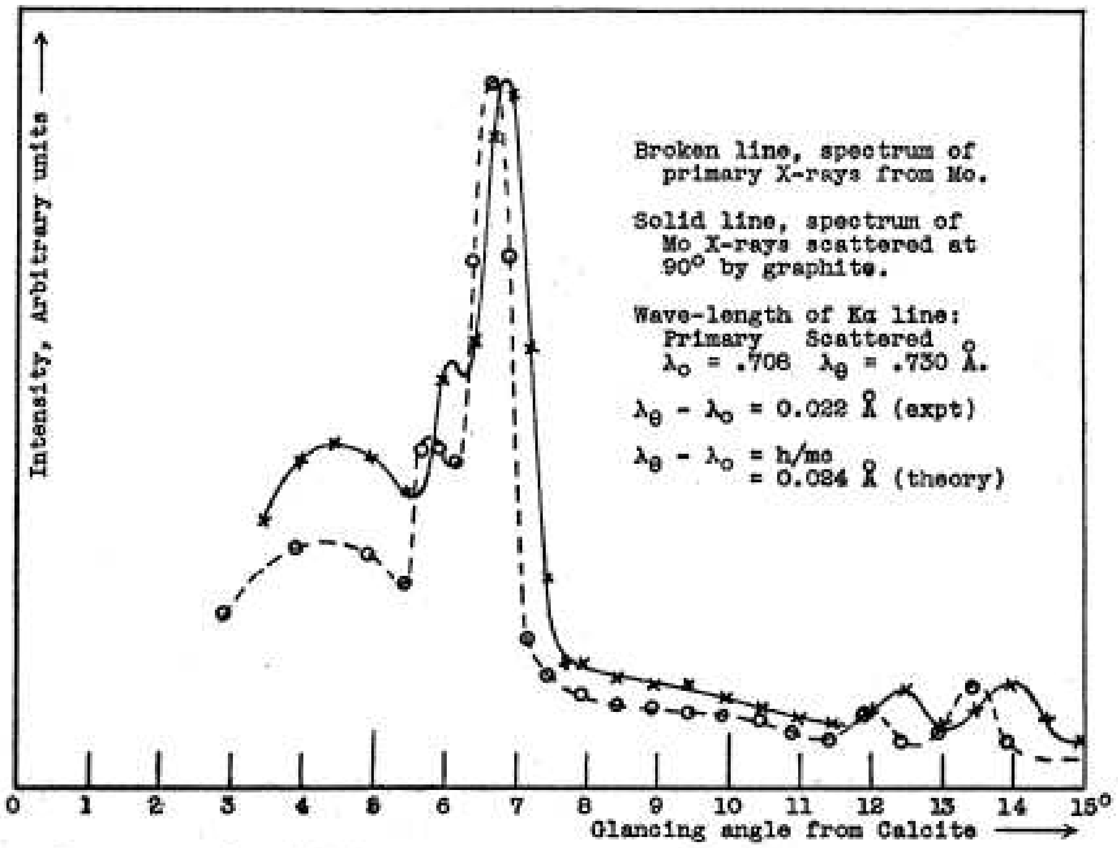


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

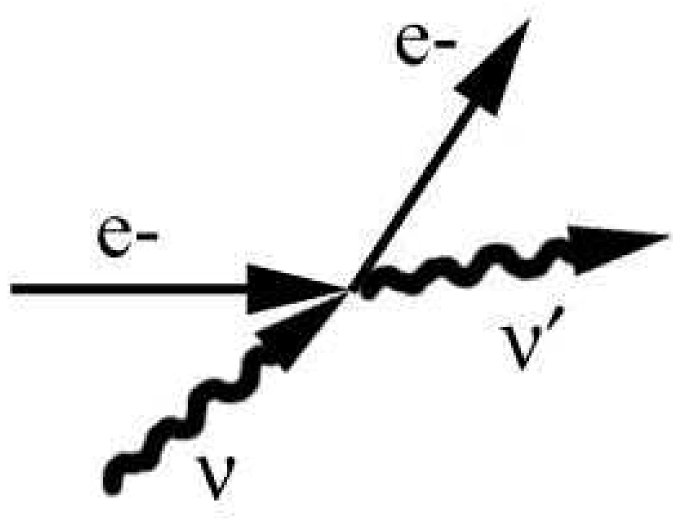
Prove: light cannot be explained purely as a wave phenomenon.

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.

Electron cannot be considered at rest
(astrophysically more important)

Inverse Compton scattering



$\nu' > \nu$
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 $h\nu << \gamma mc^2$, 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.

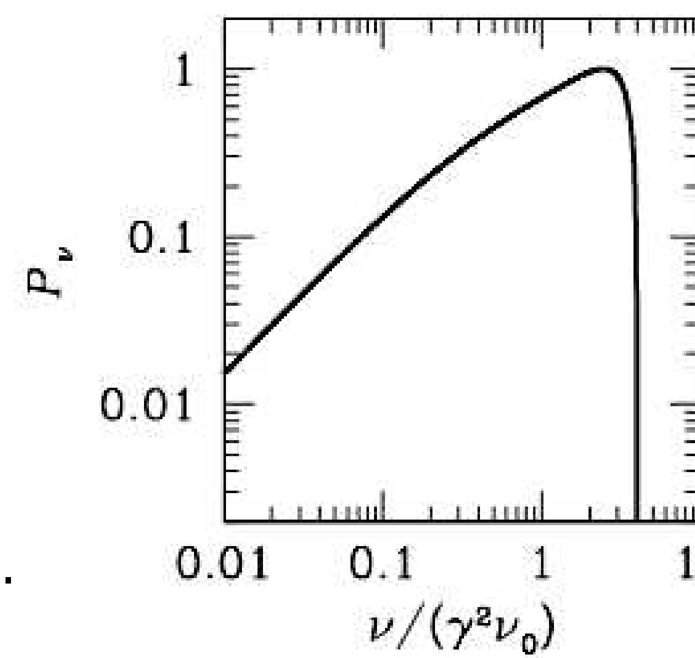
$h\nu' = h\nu + \gamma mc^2$, maximum E=$\gamma mc^2$

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 $\frac{3}{2}kT_e = \frac{1}{2}m_e v^2$)

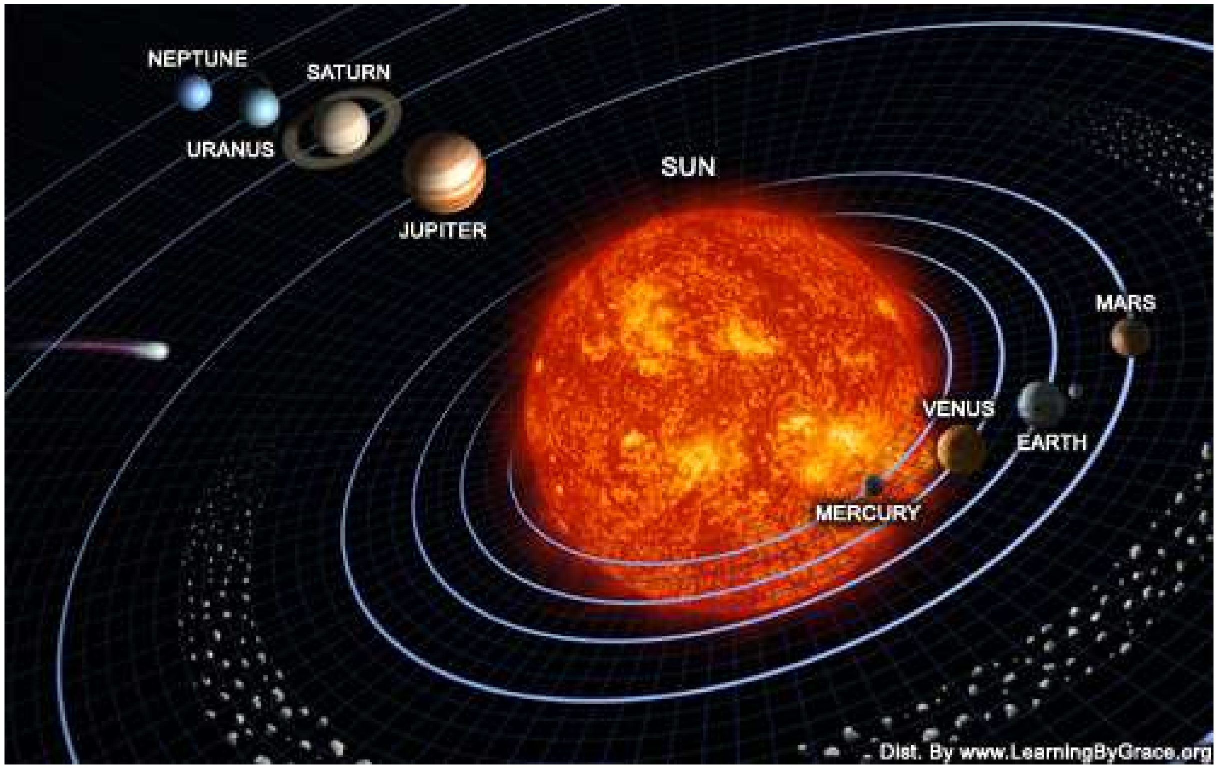
$$\Delta E = \frac{E}{m_e c^2}(4kT_e - h\nu)$$

- $E = 4kT_e$, 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

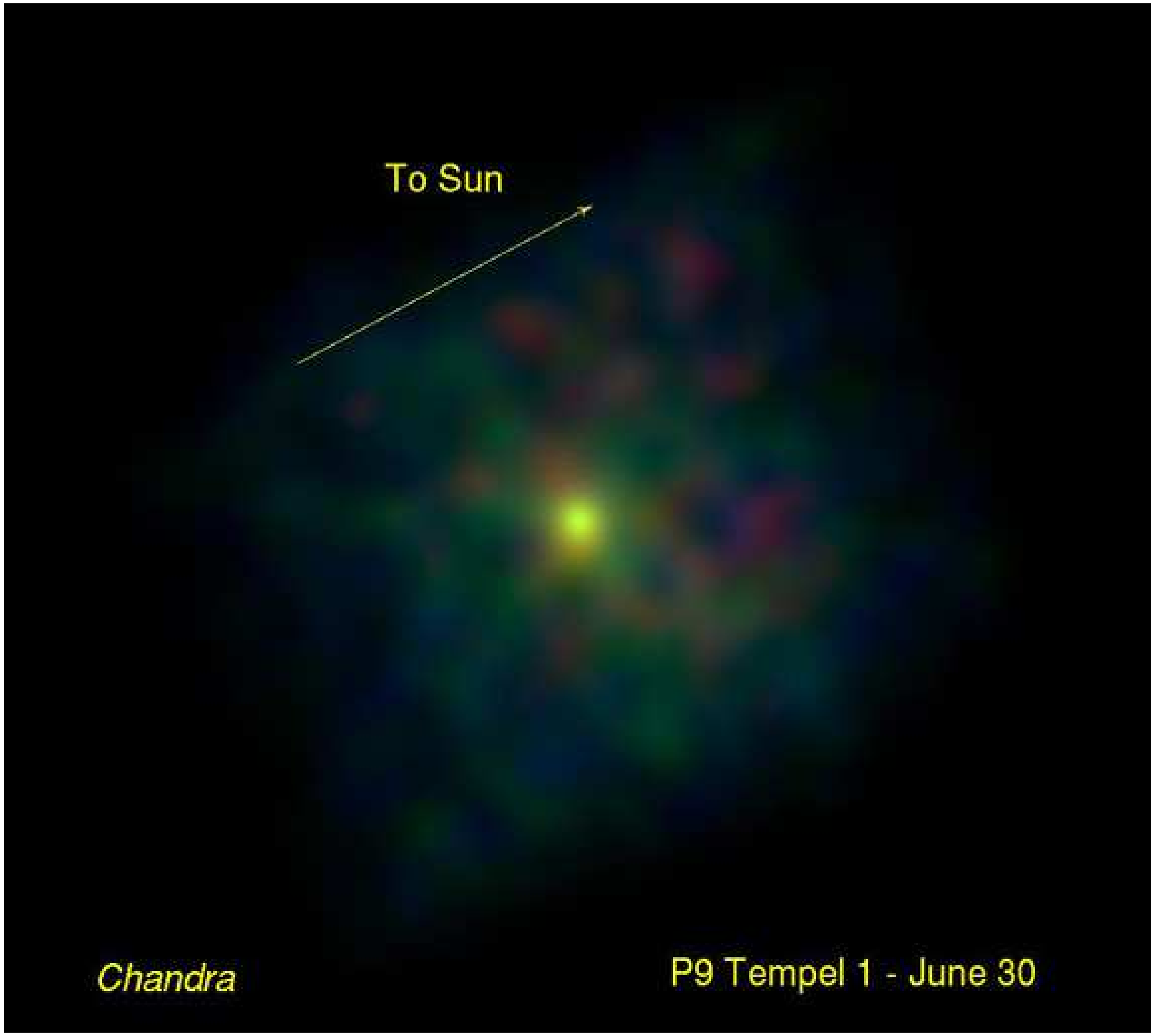
During interaction electron is transferred

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

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.

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

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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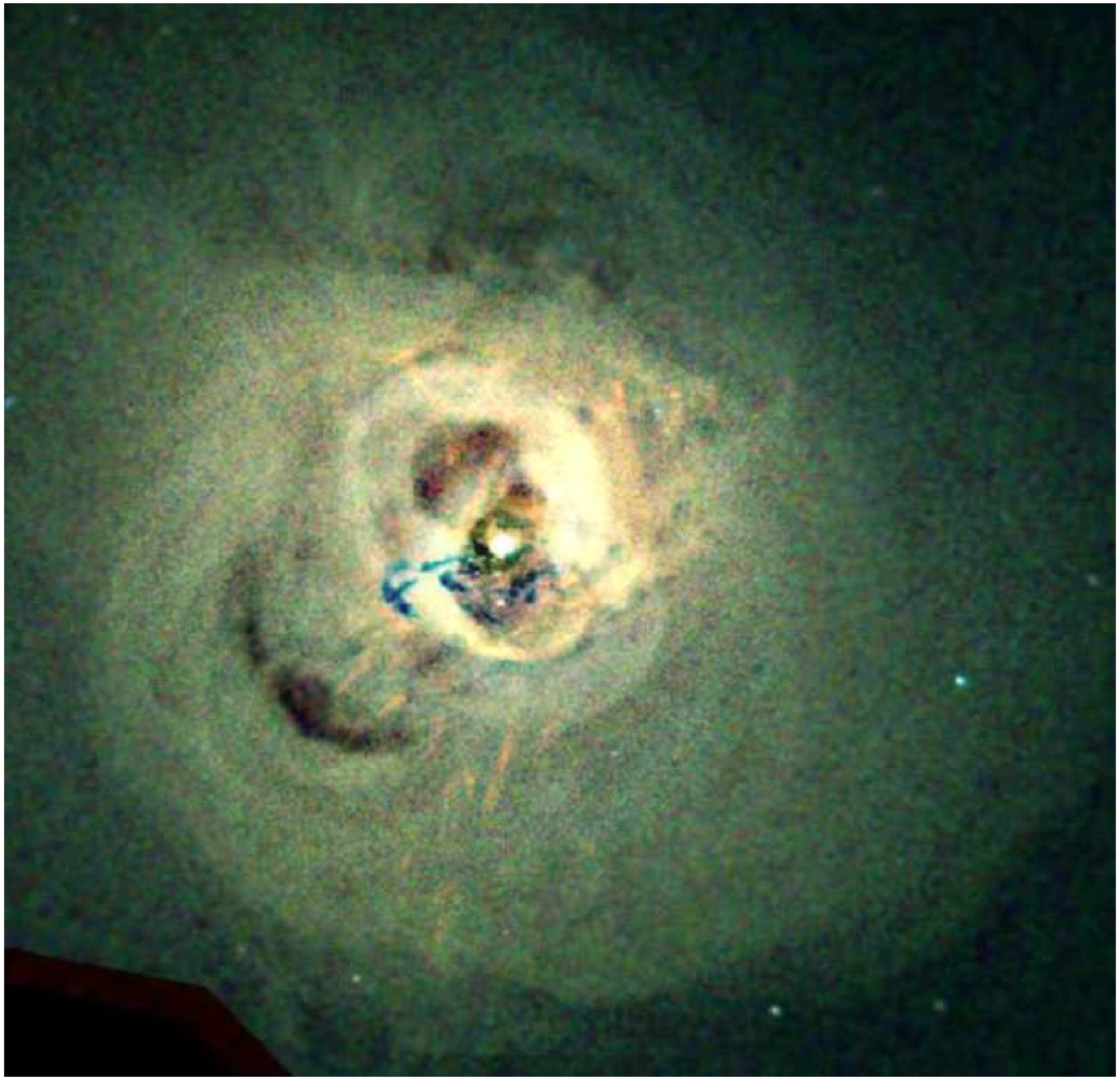
Summary of Radiative Processes

- 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

Clusters of galaxies



http://chandra.harvard.edu/

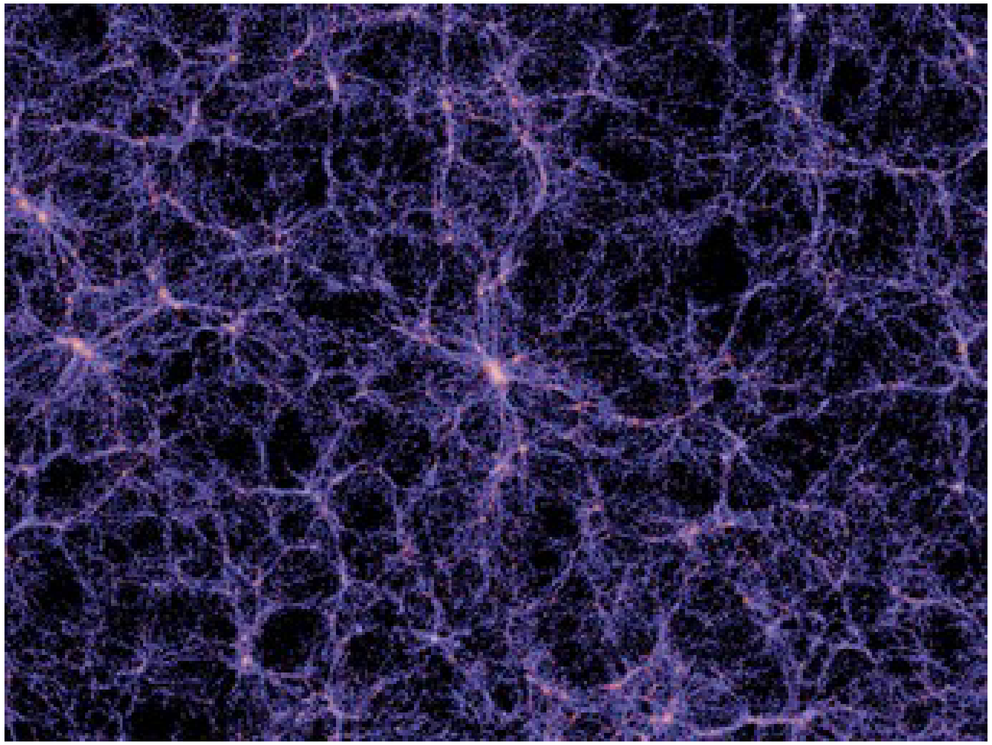
Galaxy clusters

HST Coma cluster z=0.023

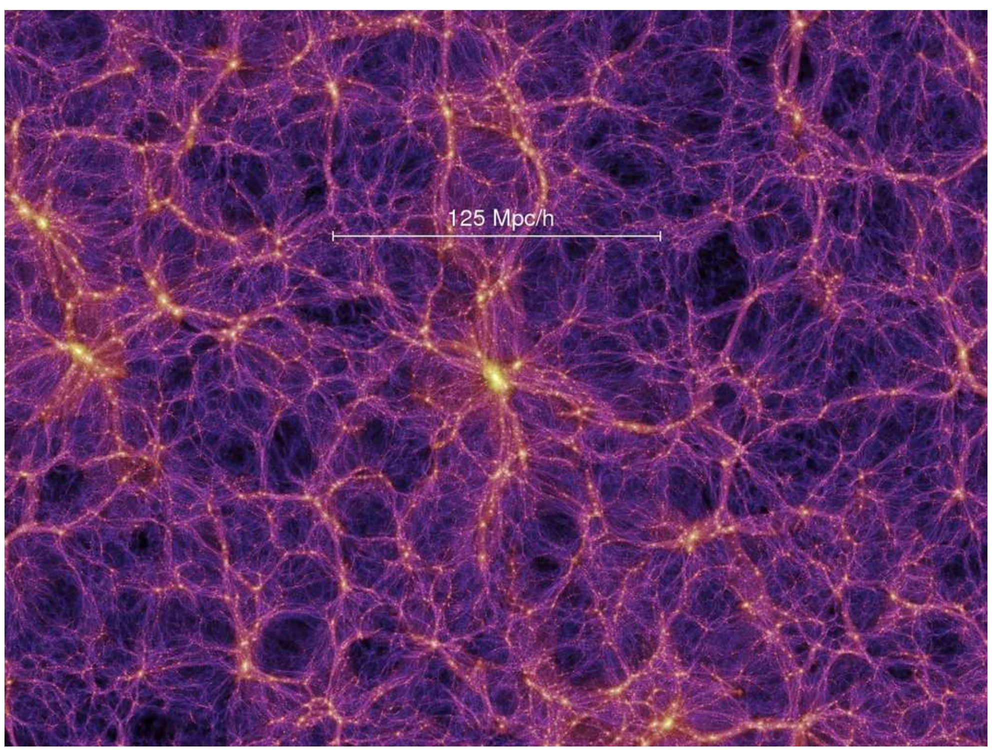
- Total masses of 10^{14} to 10^{15} solar masses.
- Largest gravitationaly bound objects in the Universe
- Diameter from 2 to 10 Mpc
- They contain 50 to 1000 galaxies, Intra Cluster Matter (ICM) and dark matter
- The MW belongs to the Local Group: over 35 galaxies. The MW is the most massive and second largest in the Local Group,

Structure in the Universe

cluster of galaxies: DM distribution



luminous matter distribution distribution



Millennium Simulation, Nature 2005, 435, 629

- Clusters of galaxies are formed from the extreme high end (high σ peaks) of the initial fluctuation spectrum. They exist at the intersections of the Cosmic Web.
- The way that structure evolves depends on the geometry and contents of the Universe (total density, dark matter density, dark energy density).
- Because clusters are formed from the high sigma peaks their numbers and evolution in time depend sensitively on cosmological parameters.

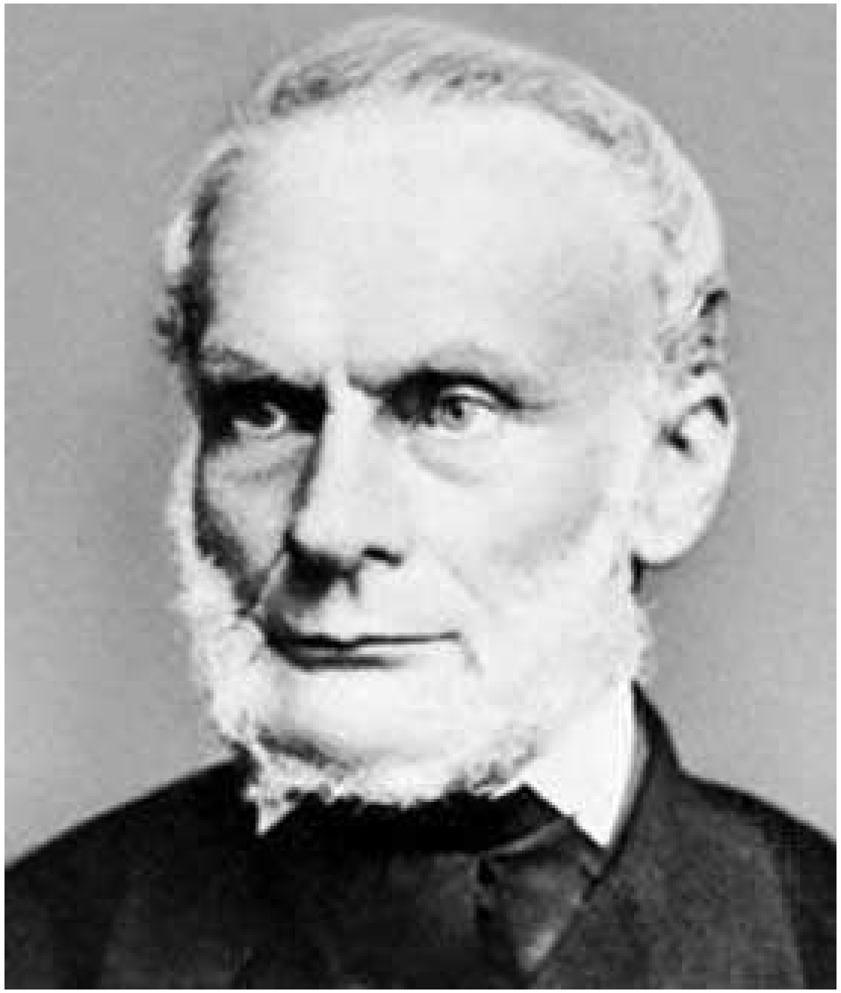
Structure in the Universe

- Fluctuations in density are created early in the Universe. When the Universe has cooled enough for atoms to form from electron-proton plasma they leave their imprint on the microwave background. COBE, WMAP, PLANK
- Fluctuations continue growing as overdense regions collapse under their own gravitational attraction.
- Baryons fall into the gravitational potential wells produced by the dark matter. Potential energy is converted to kinetic then thermalized.
- Clusters contain gas, stars, and compact objects organized in galaxies. Galaxies are about 2% of cluster mass.
- Clusters are isolated and have enough time to relax

Virial Theorem (very briefly)

Rudolf Julius Emanuel Clausius (1822 - 1888)

- 1865 mathematical formulation of concept of entropy, and its name. unit 'Clausius' (symbol: Cl)
- 1870 Virial theorem Virial is plural for vis (Latin: force)



source Wikipedia

The Nature of the Theorem

* Applications: dynamical, thermodynamical, and (some) relativistic systems, systems with velocity dependent forces, viscous systems, systems exhibiting macroscopic motions such as rotation, systems with magnetic fields.
* Classical mechanics: a systems is described by the force equations using the Lagrange and Hamilton formalism or Boltzmann transport equation.
* Those equations are non-linear, second-order, vector differential equations which, exhibit closed form solutions only in special cases.
* The virial theorem deals in scalar quantities and is applied on a **global scale** → reduction in complexity from a vector description to a scalar one which enables us to solve the resulting equations. But! loss of information. Deals with averages

A simple example

- A light particle m on circular orbit R around a heavy particle M.

- On a circular orbit centrifugal force = gravitational force:
$$\frac{mv^2}{R} = \frac{GmM}{R^2}$$

- The potential energy is $E_{\mathrm{P}} = E_{\mathrm{g}} = -\frac{GMm}{R}$

- Kinetic energy: $E_{\mathrm{K}} = \frac{mv^2}{2} = \frac{GmM}{2R}$

- Thus, $E_{\mathrm{K}} = -\frac{E_{\mathrm{P}}}{2}$ **, this is the statement of virial theorem**

Virial theorem

- In a finite collection of interacting point particles in equilibrium, where
  - 1. The time averages of the total kinetic energy and the total potential energy are well-defined.
  - 2. The positions and velocities of the particles are bounded for all time.
- Then **$\langle E_K \rangle = -\langle E_P \rangle / 2$, where $\langle E_K \rangle$ is the time average of the total kinetic energy, and $\langle E_P \rangle$ is the time average of the total potential energy.**

(after John Baez)

Zwicki: Dark matter in Coma Cluster

- $2E_K + E_P = 0$ → **from temperature of a gravitationaly bound object → its mass**
- Velocity dispersion of the galaxies Zwicki 1937

$$\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2} = 3\overline{v_{pj}^2} \rightarrow T = \frac{1}{2}\sum_i m_i \vec{v}_i^2 = \frac{3}{2} M \overline{v_{pj}^2}$$

$$E_P = \frac{GM^2}{R} \rightarrow \quad M = \frac{3}{G}\overline{v_{pj}^2} R$$, where R is mean separation

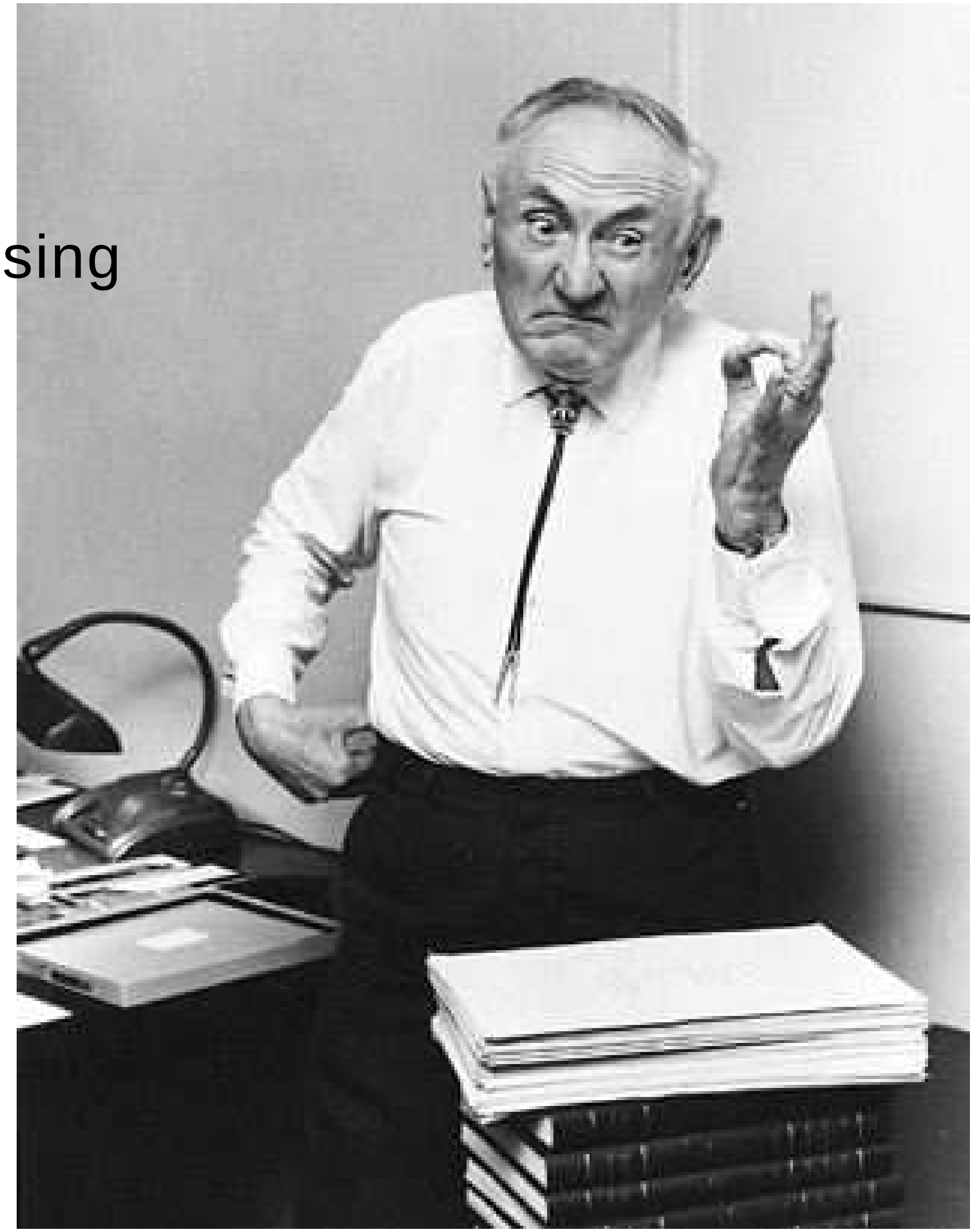
- Zwicky: calculate the total mass of the Coma Cluster from his measured galactic velocities
- Measured the total light output of all the cluster's galaxies.
- The light output per unit mass for the cluster smaller by a factor > 400 compared to normal star systems.
- Zwicki "Coma Cluster must contain a large amount of matter not accounted for by the light of the stars." He called it **"dark matter."**

Dark matter

Supernovae

Cosmic rays

Gravitational lensing



Fritz Zwicky (1898-1974)

Gas temperature

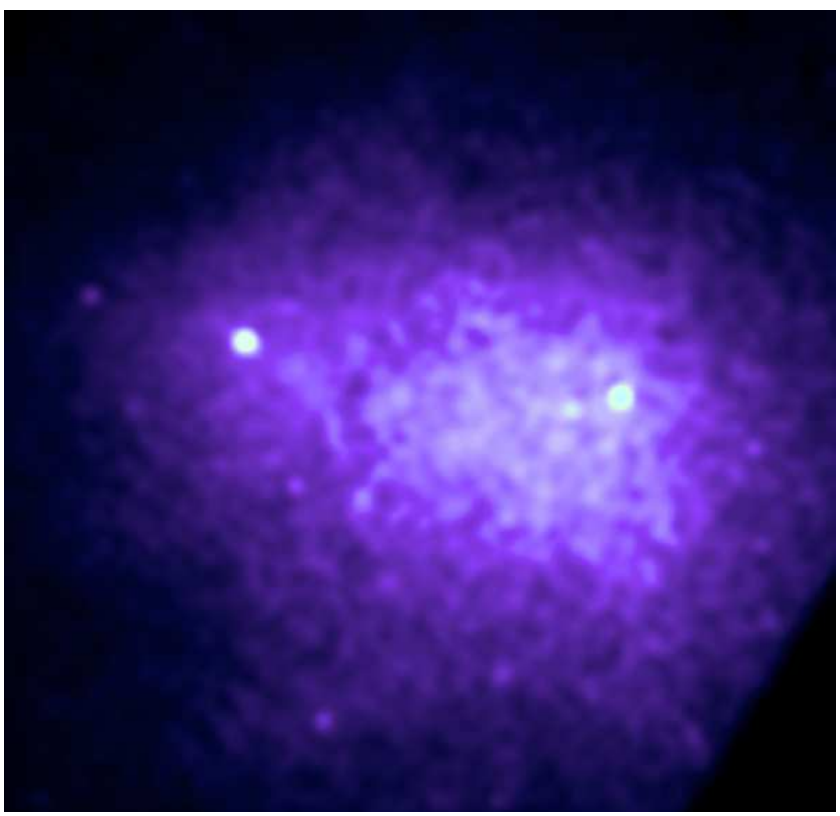
- Itracluster medium is filled with gas. What is it temperature?

- $2E_K + E_G = 0$, E_K is the internal energy of ideal gas
- $E_K = C_V \langle T \rangle M$, $C_V = 3R/2\mu$ (monoatomic), $R = 8.310^7$ erg/K mol, $\mu = 0.5$ g/mol → $\langle T \rangle = \frac{GM}{R}\frac{\mu}{3\mathcal{R}}$ → $\langle M \rangle = const \langle T \rangle R$

- The expected temperature 10^7 K. **Galaxy clusters shall be X-ray sources**

Coma cluster HST: 9 arcmin wide

Coma cluster CXO: 17 arcmin wide



NASA/CXC/SAO/A.Vikhlinin et al.

42 X-rays from Clusters of Galaxies

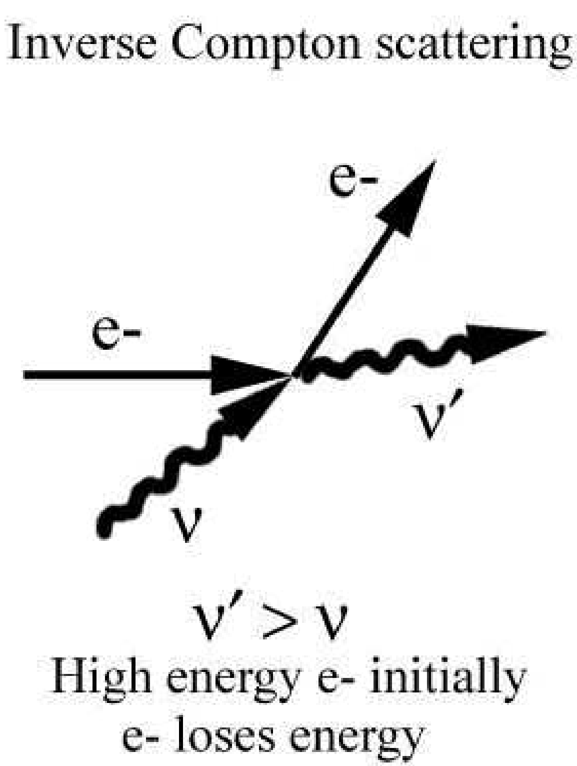
- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped barions: ICM and galaxies.
- The baryons in the ICM thermalize to > 10^6 K making clusters strong X-ray sources.
- Most of the baryons are in the hot ICM plasma - only 10-20% are in the galaxies.
- Lets rememeber what is bremsstrahlung

43 Sunyaev-Zeldovich effect

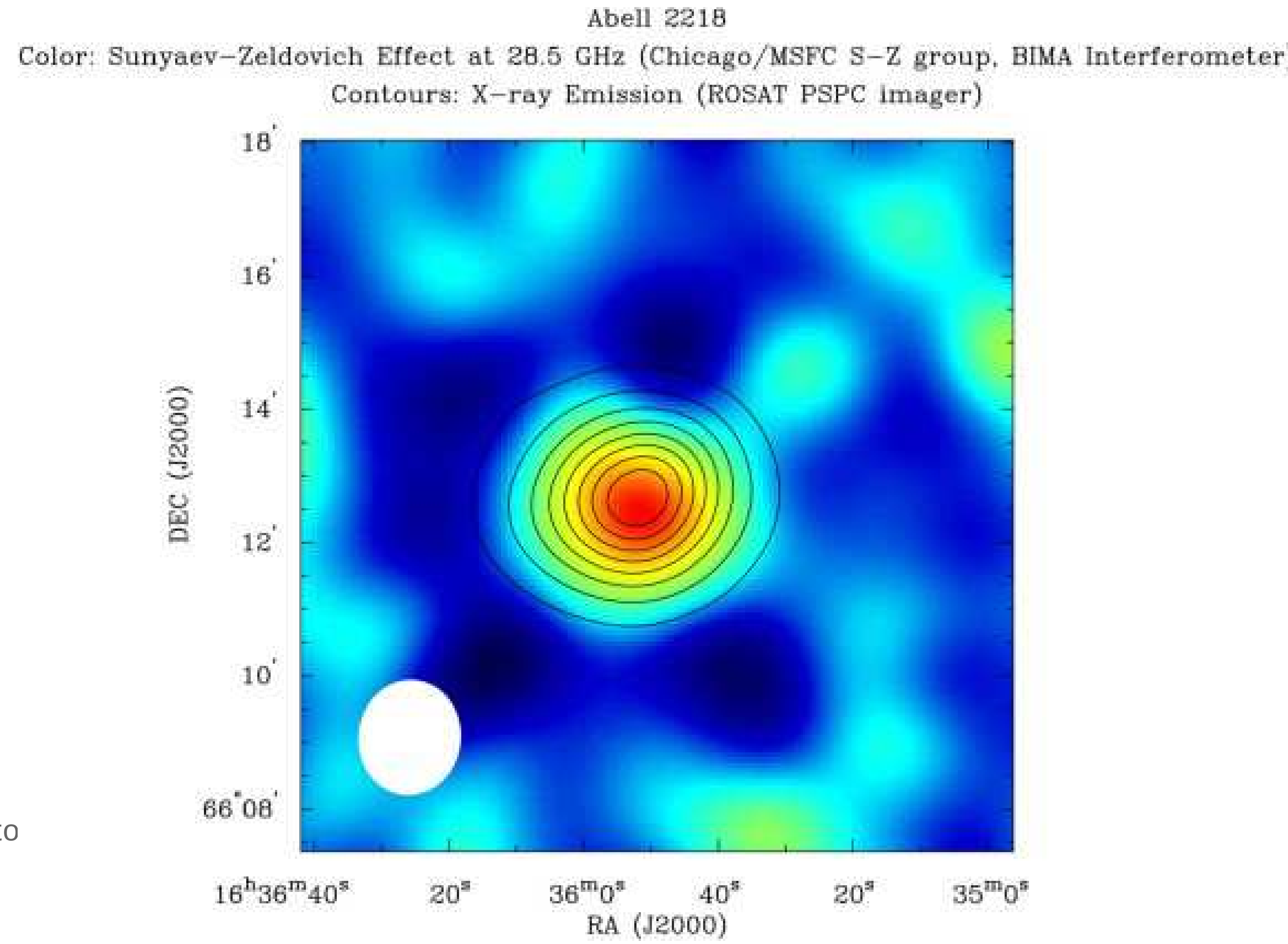
- Interaction between Cosmic Microwave Background Radiation (CMB) and hot gas in the galaxy clusters.
- CMB photons passing through the hot ICM have a ~1 per cent chance of inverse Compton scattering off the energetic electrons, causing a small (~1 mK) distortion of the CMB spectrum: the Sunyaev-Zeldovich effect.
- The ICM emits X-rays primarily through thermal bremsstrahlung. The SZE is a function of the integrated pressure, $\Delta T \propto \int n_e T_e dl$, the integration is along the line of sight.
- The X-ray emission: $S_X \propto \int n_e^2 \Lambda dl$, Λ is the cooling function.
- The different dependences on density, along with a model of the cluster gas, enable a direct distance determination to the galaxy cluster.

Reminder: Inverse Compton effect

Occurs when electron cannot be considered at rest



http://venables.asu.edu/quant/proj/compto



The energy is transferred from the e to the ph

SZE and galaxy clusters

- $M_{\text{cl}} \sim \times 10^{14}\, M_{\odot}$, $R_{\text{cl}} \sim$ Mpc
- Gas in hydrostatic equilibrium within a cluster's gravitational potential well must have electron temperature T_e:
  - $kT_{\text{e}} \approx \frac{GMm_{\text{p}}}{2R} \approx 7\frac{m}{r}$ keV, where $m=M/M_{cl}$, $r=R/R_{cl}$
- Scattering optical depth $\tau=n_e \sigma_T R_{cl}$ (approx 0.01)
- $\delta\nu/\nu \approx kT_{\text{e}}/m_{\text{e}}c^2 \approx 0.01$
- The change in the intensity 10^{-4}. A signal which is about ten times larger than the cosmological signal in the microwave background radiation detected by COBE. (Planck is 1000 times more sensitve)
- The primordial and SZE effects can be distinguished. SZE are localized: they are seen towards clusters of galaxies. Primordial structures in the CMB are non-localized: they are not associated with structures at other wavebands: distributed at random over the sky.