Violent Universe Explored by Japanese X-ray Satellites

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Asia Academic Seminar
CPS 8th International School of Planetary Science
September 30, 2011 at Awaji

Lecture Plan

September 30, 9:00-10:15

I. Basic processes in High energy astronomy

- **I-1: Why X-ray astronomy?**
- **I-2: Emission mechanisms**
- **I-3: Energy sources**

II. High energy phenomena

- **II-1: Stellar X-ray emission**

September 30, 10:45-12:00

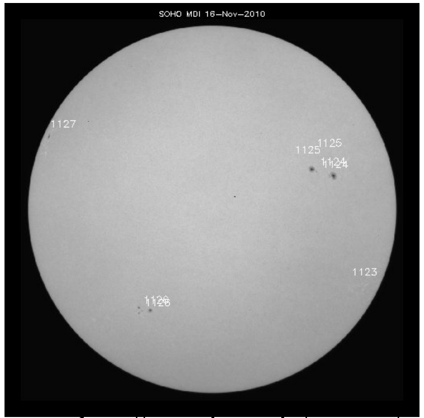
- **II-2: Supernova remnants (SNR)**
- **II-3: Neutron stars and blackholes**
- **II-4: Active Galactic Nuclei**
- **II-5: Cluster of galaxies and Cosmology**

I-1. Why X-ray astronomy?

1. Sun

http://swc.nict.go.jp/sunspot/

Optical Image



http://swc.nict.go.jp/sunspot/

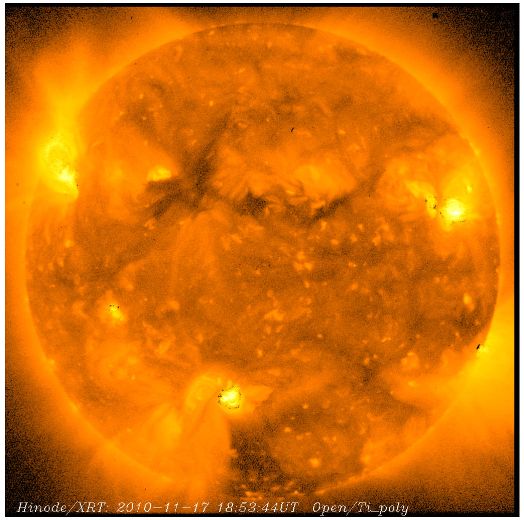
Photosphere : Black body radiation

T = 6430°K → λ_{peak} ～4500 A

Wien's law $\lambda T = 2800$ micron K

Density ～10^{14} atom/cc (10^{-6} g/cc)

X-ray Image by



http://hinode.nao.ac.jp/latest/

Corona : Thin thermal emission + lines

T = 10^6 ° K → λ_{peak} ～30 A (if BB)

Density ～10^{6-8} atom/cc

http://hinode.nao.ac.jp/latest/

I-1. Why X-ray astronomy?

2. Cluster of Galaxies

Optical image : Component galaxies

Emission from stars

Visible mass ~ **M**

X-ray image : Hot plasma

T ~ $10^{7\text{-}8}$°K

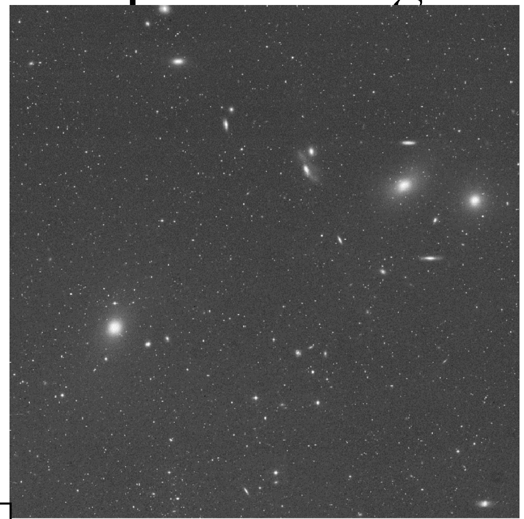
Plasma mass ~ **1-5 M**

Mass to bind hot gas in clusters

Dark matter

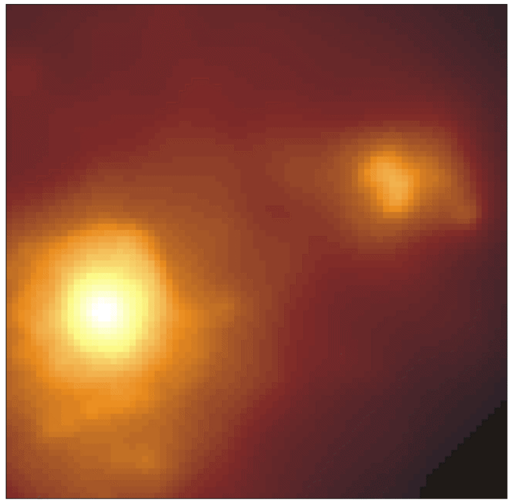
Mass ~ **5-20 M**

Optical Image



Virgo Cluster

X-ray Image by ASCA



Radiation and related physical processes

Radio λ= 0.1 - 100 mm

Molecular emission

Vibration, rotation

FM Radio frequency
80.7 MHz
$\lambda=3\text{x}10^{10}\text{cm}/8.07\text{x}10^{7}$
$= 4 \text{ x}10^{2}$ cm

Infrared λ= 1-100 micron

Dust emission

Low temp. stars

Black body radiation
37°C => 310 °K
~ 9 micron

Optical λ=4000-7000Å

Main sequence stars

T= 6430°K→ λ_{peak}~4500 A

Absorption & emission lines from excited atoms

H Ly-α	**1215Å**
Ly limit	**912Å**
H Ba-α (H-α)	**6562Å**

Radiation and related physical processes

Ultra-violet λ= 100-4000Å

Early type stars(<7000°K)

Emission lines

Binding energy
(Outer most electron)
H (13.6 eV), He (24.6 eV),
Li (5.4eV), Be(9.3eV)

X-rays λ= 1-100 Å

Plasma temp. 10^{5-8} K

Emission lines

(transition between levels)

Binding energy
(Inner most electron)
C(280eV), O(550eV)
Ar(3.1keV), Fe(7.1keV)

Gamma rays λ< 1Å

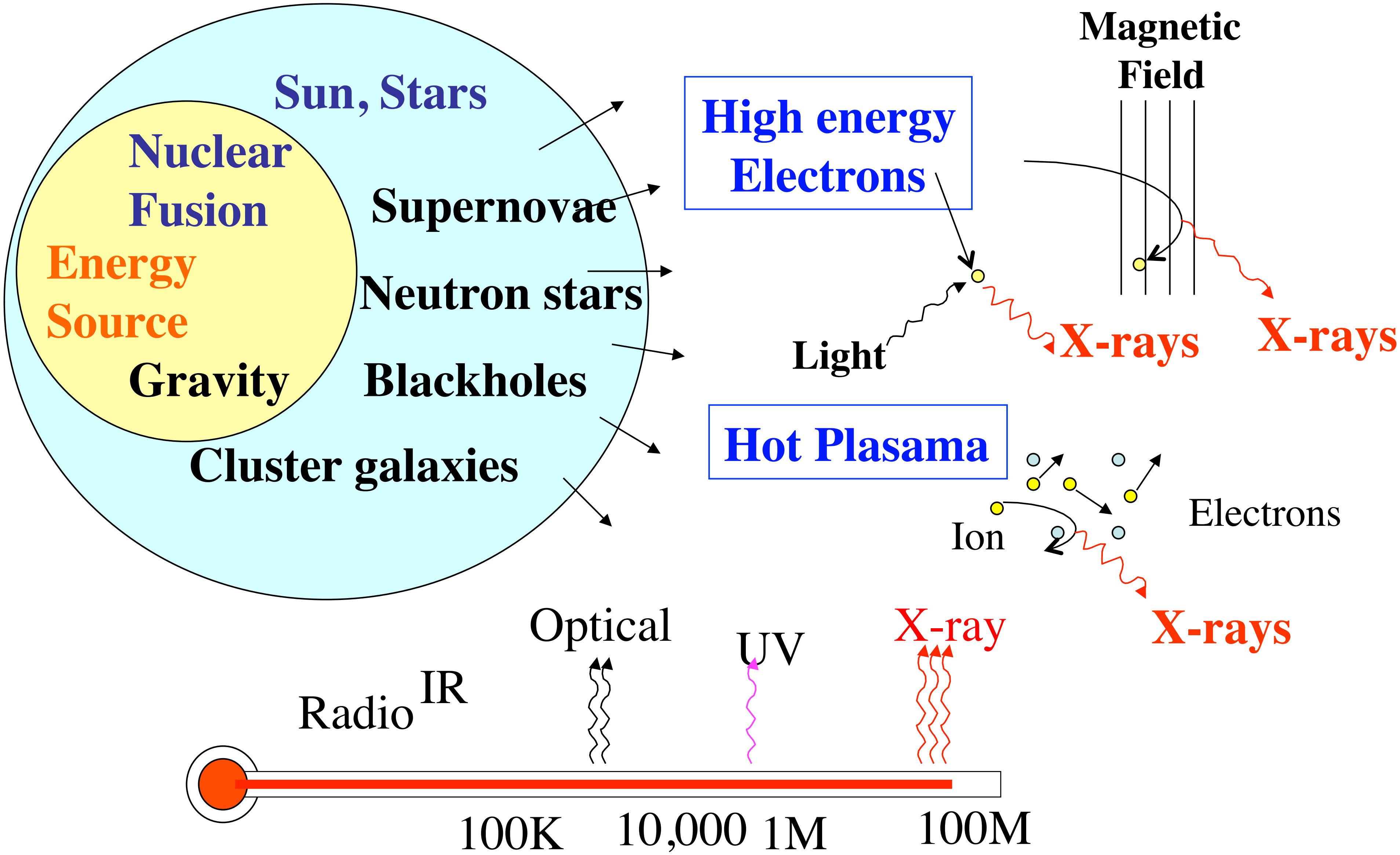
Nuclear transition

High energy particles

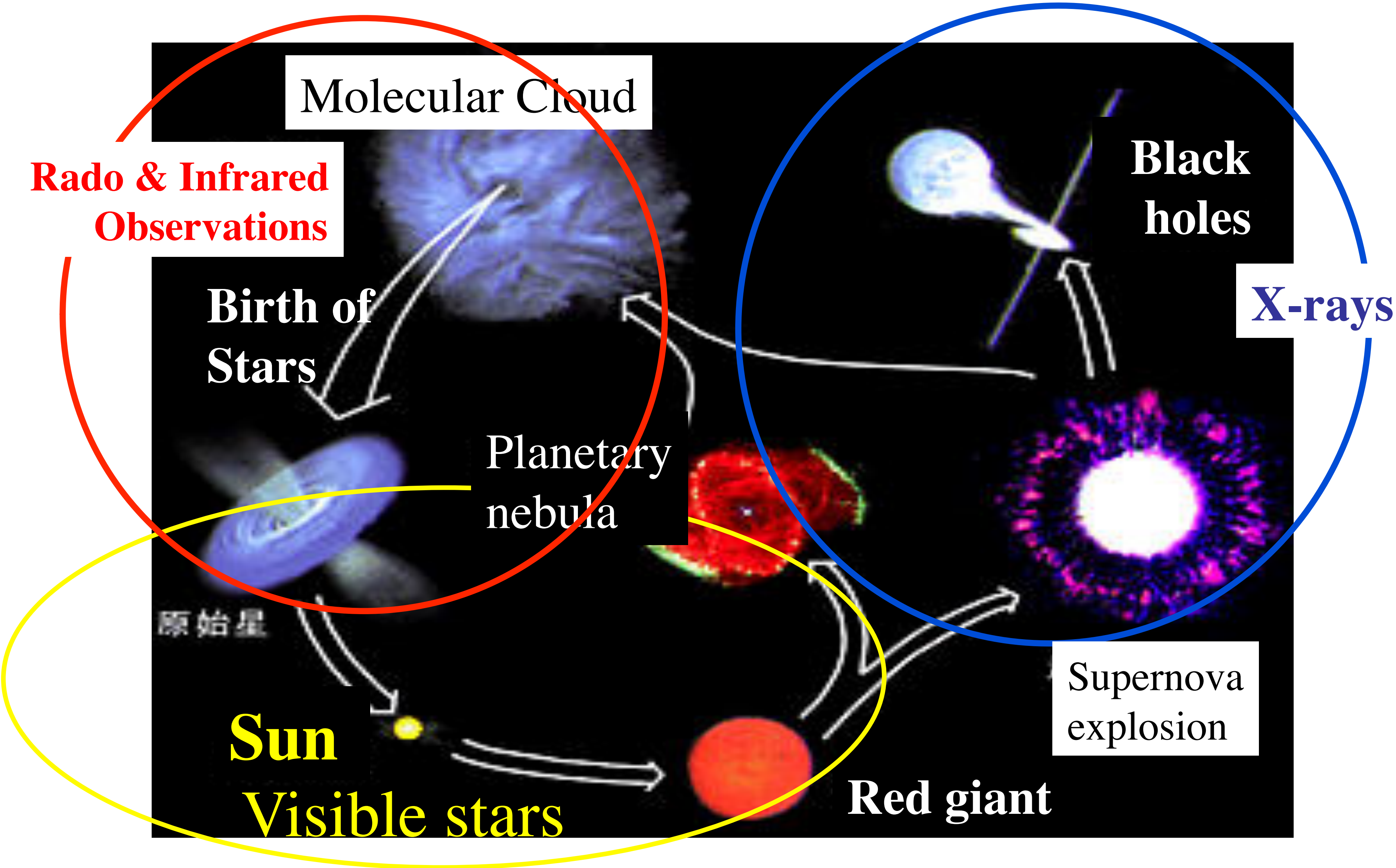
Synchrotron rad.

Compton rad.

Radiation mechanisms of X-rays

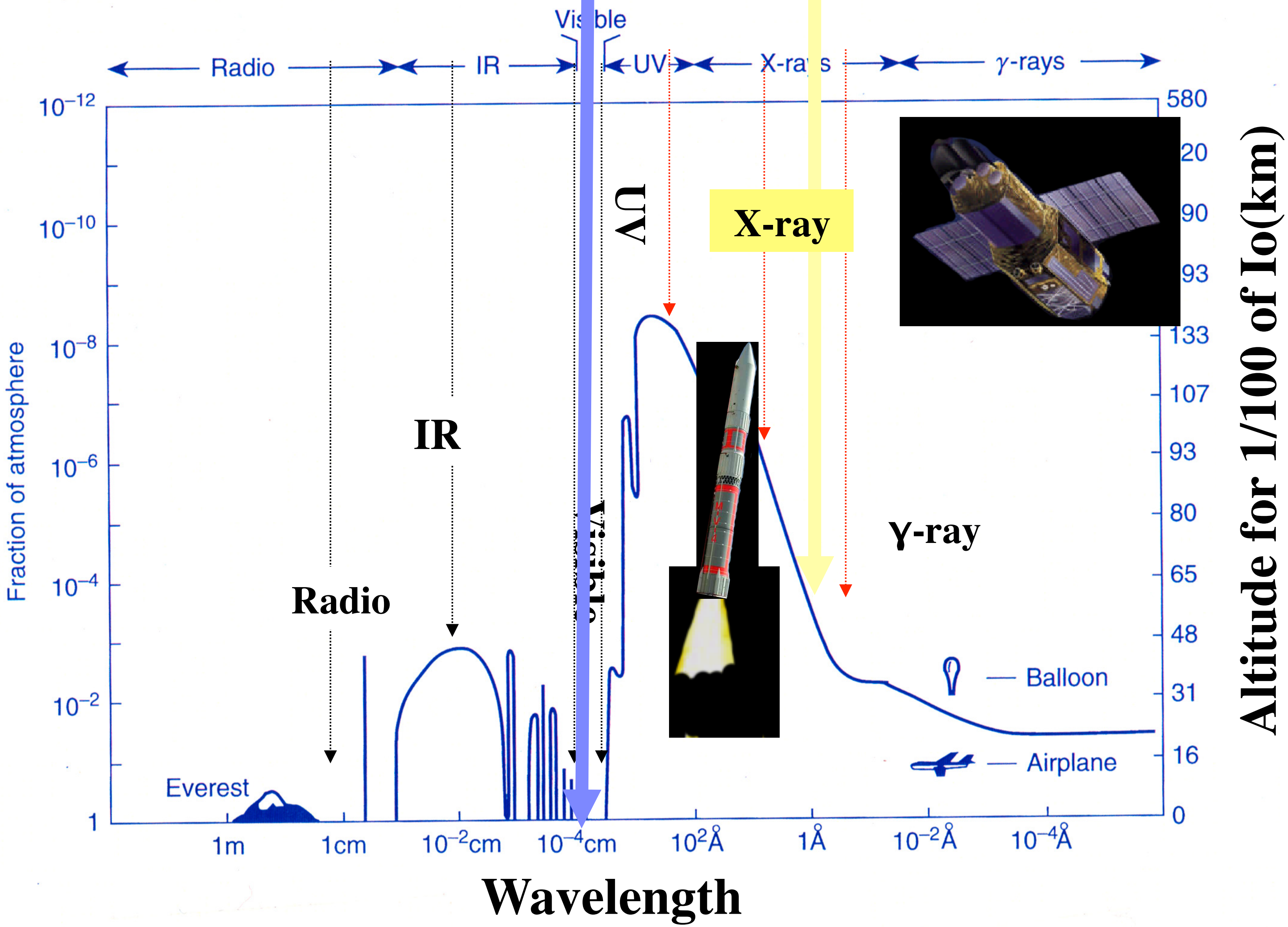


Life cycle of stars



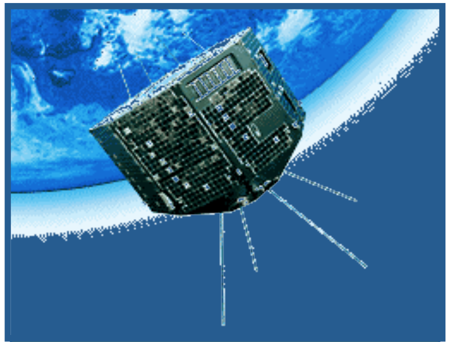
Narrow window at Visible light

X-rays are observable from out side atmosphere

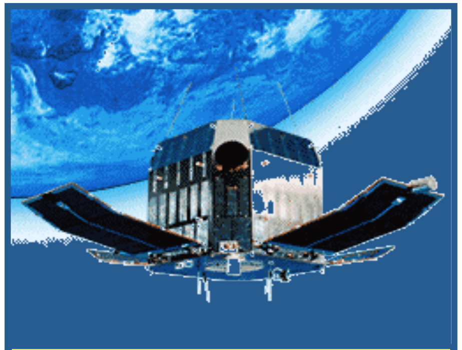


X-ray Telescope

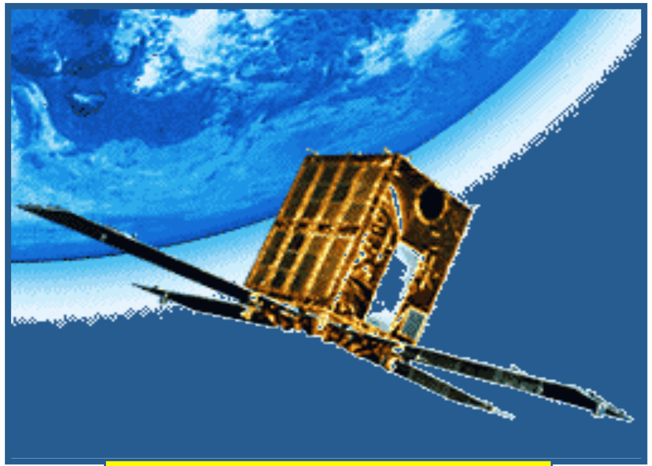
Japanese X-ray Satellites



Hakucho (1979)
90kg



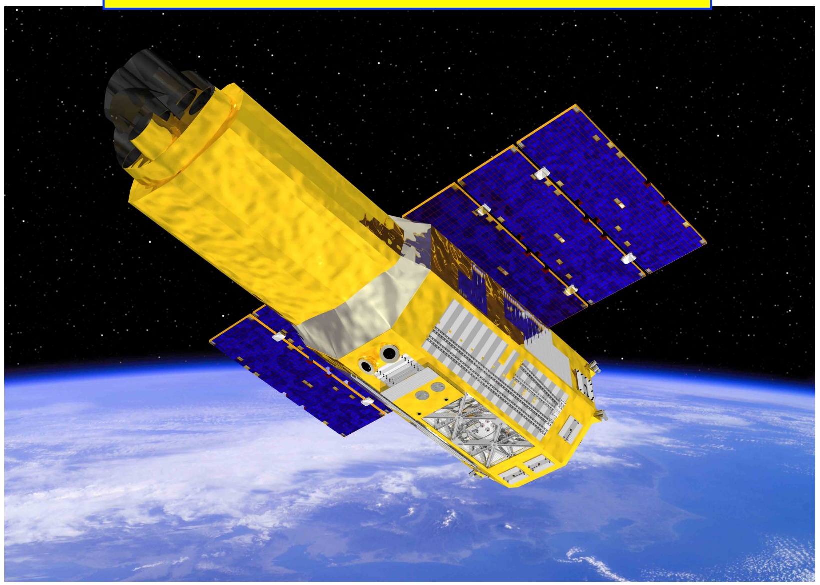
Tenma (1983)
200kg



Ginga (1987)
420kg

ASCA (1993) 420kg

Suzaku (2005) 1700kg



JAXA

II-2: Emission mechanisms

1. Black body radiation

Thermometry of steel furnaces based on the radiation

$E(\nu)\, d\nu = 2\, Z(\nu) kT\, d\nu$ Z(ν): lattice points in phase space

(1) Long wave side : Rayleigh-Jeans distribution

$$Z(\nu)\, d\nu = \frac{4\pi L^3}{C^3} \nu^2\, d\nu$$

$$U(\nu)\, d\nu = \frac{E(\nu)\, d\nu}{L^3} = \frac{8\pi kT}{C^3} \nu^2\, d\nu$$

When ν --> small, it well represents observed spectra
but when ν is large, U will become infinity.

II-2: Emission mechanisms

1. Black body radiation

(2) Short Wave side : Wien distribution

$$Z(\nu)\, d\nu = \frac{4\pi L^3}{C^3}\, \nu^2 \exp(-h\nu/kT)\, d\nu$$

$$U(\nu)\, d\nu = \frac{2 Z(\nu)\, h\nu\, d\nu}{L^3} = \frac{8\pi h}{c^3}\, \nu^3 \exp(-h\nu/kT)\, d\nu$$

When $h\nu/kT \gg 1$, it well represents observed spectra
but does not match with the data when $h\nu/kT \ll 1$

II-2: Emission mechanisms

1. Black body radiation

(3) Interpolation : Planck distribution

$$U(\nu) = \frac{8\pi h}{c^3} \frac{1}{\exp(h\nu/kT) - 1} \nu^3 d\nu$$ **Planck distribution**

When $h\nu/kT \ll 1$, $\exp(-h\nu/kT) = 1 + h\nu/kT$

$$U(\nu)\, d\nu = \frac{8\pi kT}{c^3} \nu^2 d\nu$$ **Rayleigh-Jeans**

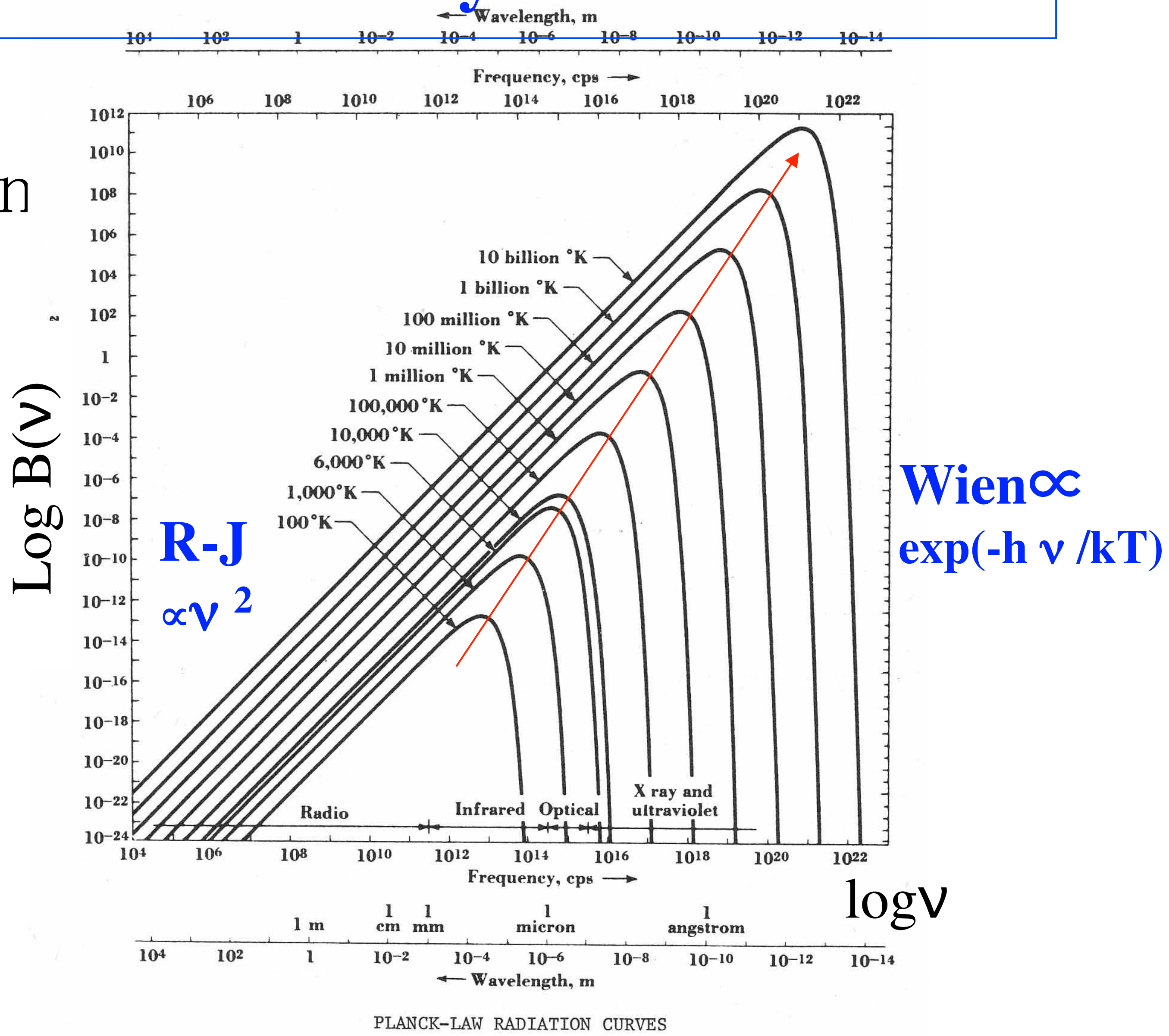
When $h\nu/kT \gg 1$, $\exp(h\nu/kT) \gg 1$

$$U(\nu)\, d\nu = \frac{8\pi kT}{c^3} \nu^3 \exp(-h\nu/kT)\, d\nu$$ **Wein**

II-2: Emission mechanisms

1. Black body radiation

Planck distribution



John D. Kraus, 1986: Radio Astronomy, Cygnus-Quasar Books ,81

II-2: Emission mechanisms

1. Black body radiation

Peak frequency : derivative of Planck's eq. = 0

$$U(\nu) = \frac{8\pi h}{c^3} \frac{1}{\exp(h\nu/kT) - 1} \nu^3 d\nu$$

Planck distribution

$$f(x) = \frac{x^3}{e^x - 1}$$

when $x = h\nu/kT$

$$\frac{\partial f}{\partial x} = \frac{3x^2(e^x - 1) - x^3 e^x}{(e^x - 1)^2} = 0$$

$3(1 - e^x) = x$ left term $= 0(x=0), =1.8(x=1), =2.4(x=2), =3(x=\infty)$

$x = 2.812$ $h\nu max = 2.82\ kT$

$\lambda maxT = 2900(\mu m \cdot K)$ **Wien's law**

II-2: Emission mechanisms

1. Black body radiation

Total brightness : Integration of Planck's eq.

$$B(\nu) = \frac{U(\nu)\, c}{4\pi}$$

$$\int B(\nu) d\nu = \frac{2\pi h}{c^2} \int \frac{1}{\exp(h\nu/kT) - 1} \nu^3 d\nu$$

When $x = h\nu/kT$

$$B = \frac{2h}{c^2} \left(\frac{kT}{h}\right)^4 \int \frac{x^3}{e^x - 1} dx \rightarrow = \frac{\pi^4}{15}$$

$$= \frac{2\pi^5 k^4}{15 c^2 h^3} T^4 = \sigma T^4$$

$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} deg^{-4} s^{-1} : Stefan-Boltzmann constant

II-2: Emission mechanisms

1. Black body radiation

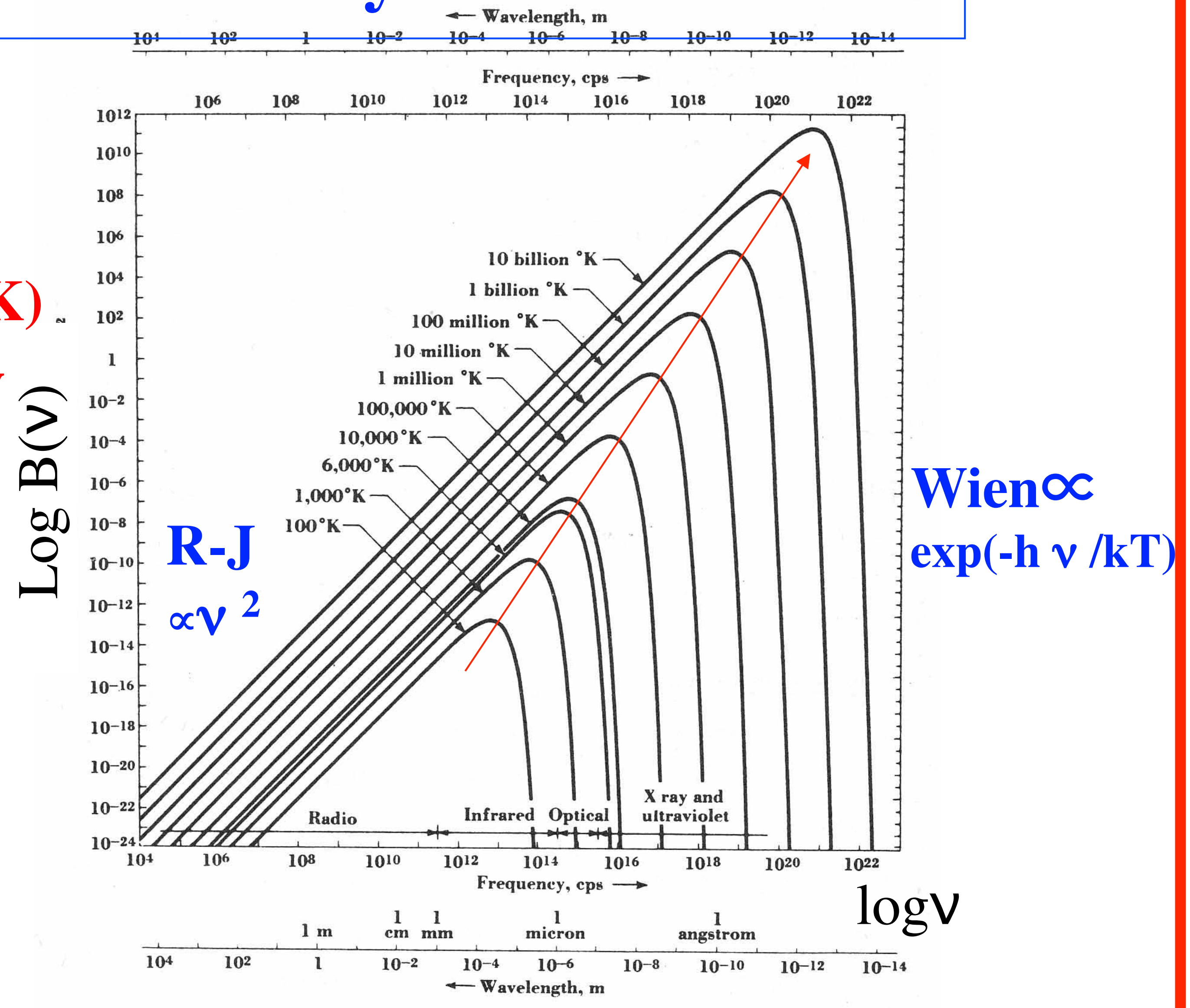
Planck distribution

λ maxT=2900(μm・K)

Wien's law

$B = \sigma \ T^4$

John D. Kraus, 1986: Radio Astronomy, Cygnus-Quasar Books ,81

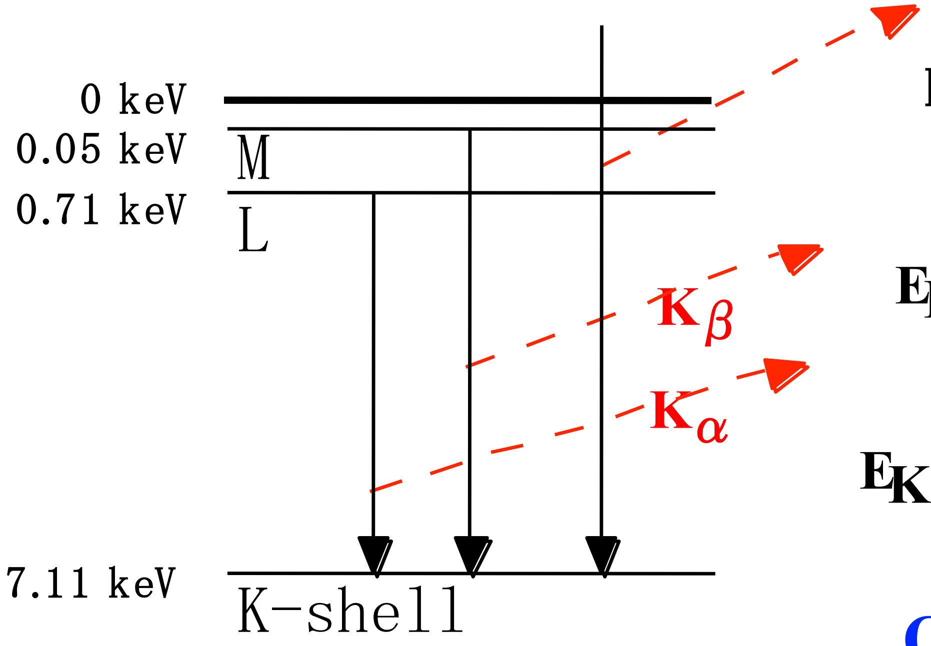


PLANCK-LAW RADIATION CURVES

II-2: Emission mechanisms

2. Line emission and absorption

Emission from Fe atoms



$E_{RC} = E_C - E_K$
> 7.11 keV(< 1.743 Å)

$E_{K\beta} = E_M - E_K$
$= 7.06$ keV(1.757 Å)

K X-rays

$E_{K\alpha} = E_L - E_K$
$= 6.40$ keV(1.937Å)

Characteristic X-rays

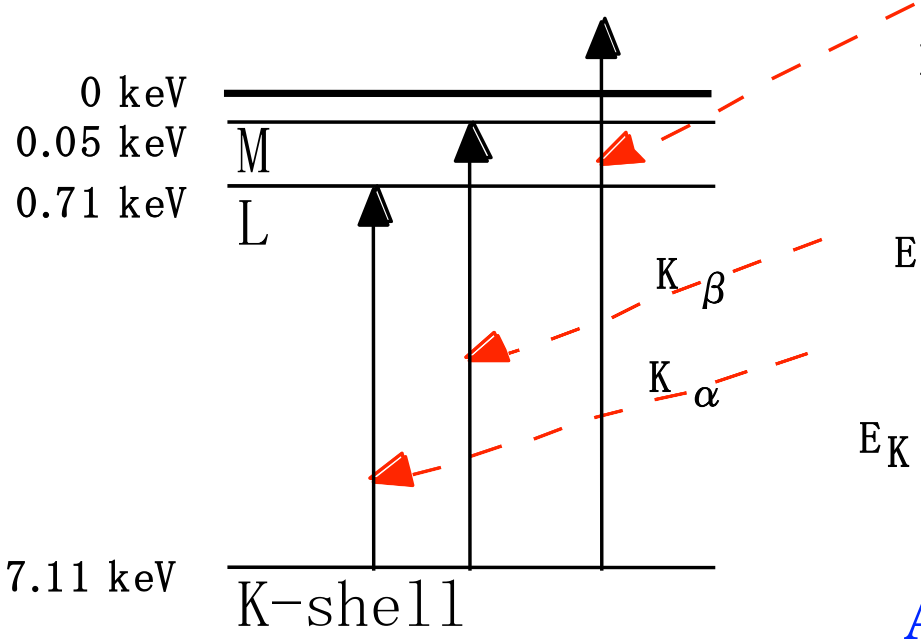
⬇

Analysis of elements

II-2: Emission mechanisms

2. Line emission and absorption

Absorption by Fe atom



Absorption edge

$E_{RC} = E_C - E_K$
> 7.11 keV (<1.743 Å)

$E_{K\beta} = E_M - E_K$
$= 7.06$ keV (1.757 Å)

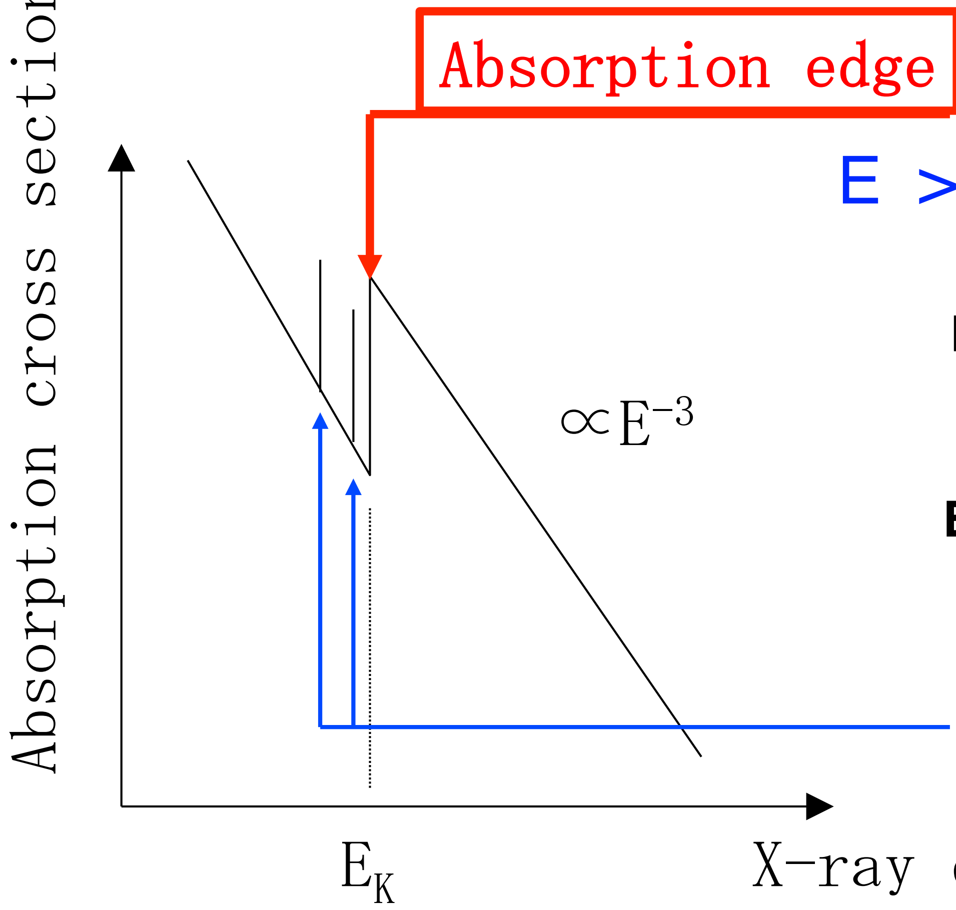
$E_{K\alpha} = E_L - E_K$
$= 6.40$ keV (1.937Å)

Absorption lines
If outer electrons are ionized

II-2: Emission mechanisms

2. Line emission and absorption

Absorption by Fe atom

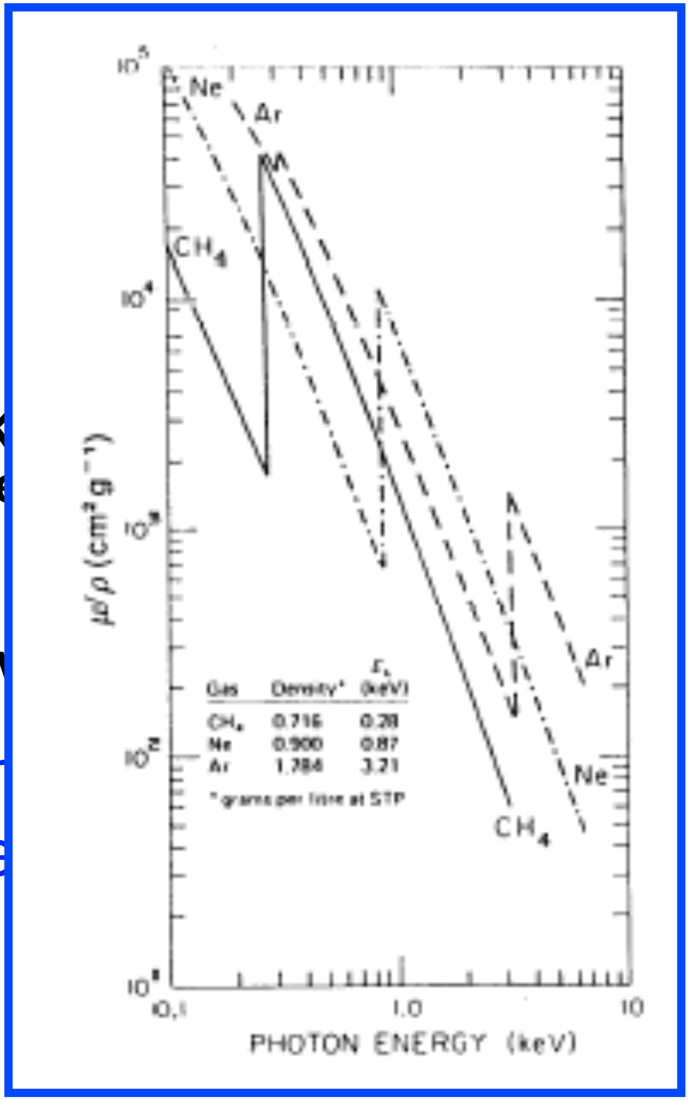


$E > E_K = 7.11$

$E_{K\beta} = E_M - E_K$
$= 7.06$ ke

$E_{K\alpha} = E_L - E_K$
$= 6.40$ keV

Absorptio
If outer ele



II-2: Emission mechanisms

Emission from hot plasmas

Ionization state

Electron collision/Photo ionization   Free electrons

Recombination ←→ Equilibrium

Lines from ionized ions

Binding energy increases after the removal of outer electrons

Fe XVII(16 electrons are removed) Fe Kα X-ray ～6.4 keV

Fe XVIII -XXV ～6.7 keV

Fe XXVI ～6.9 keV

Line energy ---> Ionization state

Line ratio of an element --->

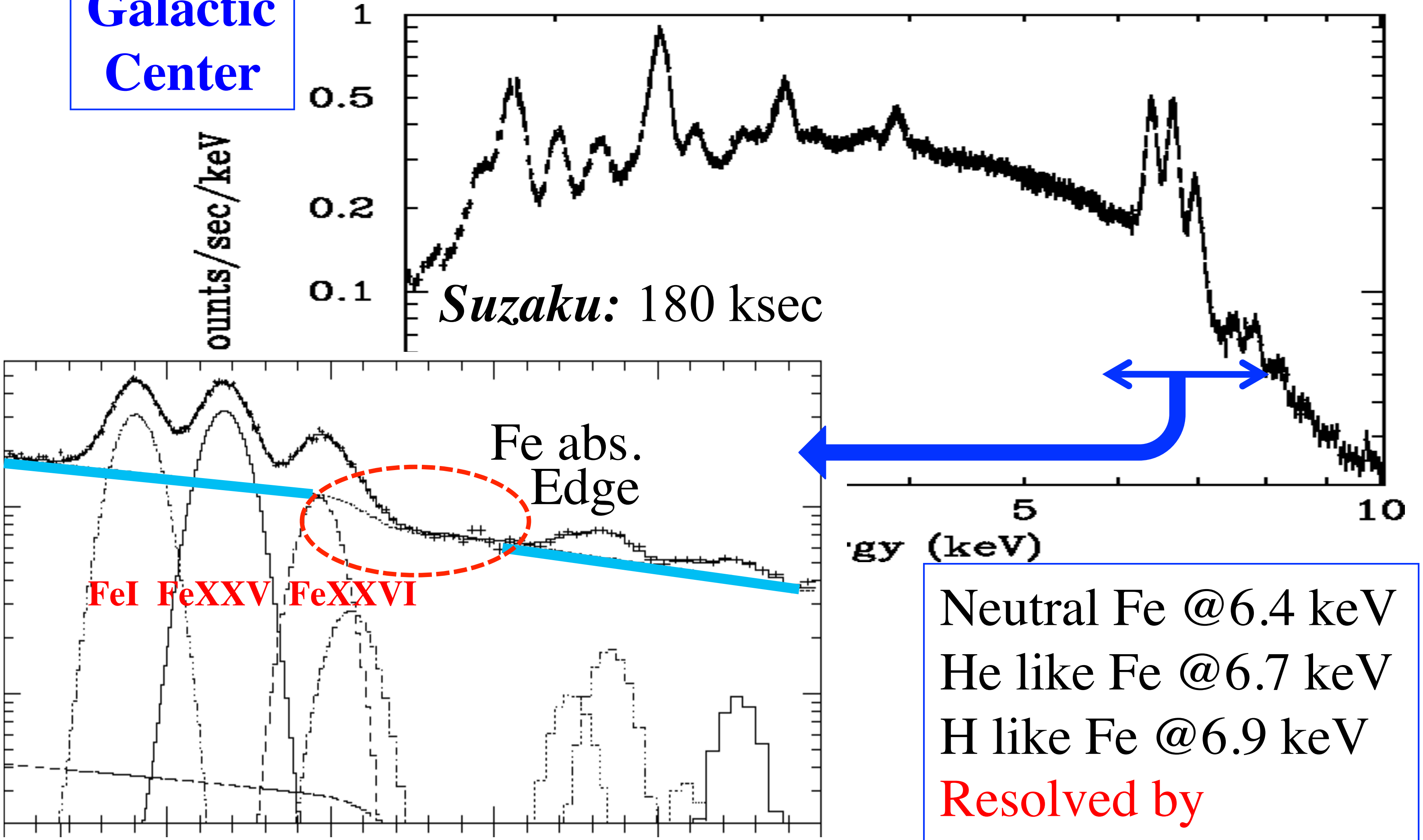
Tion, Te (Balance of ionization/recomb.)

Line ratio ----> Atomic abundance

II-2: Emission mechanisms

Emission from hot plasmas

Galactic Center

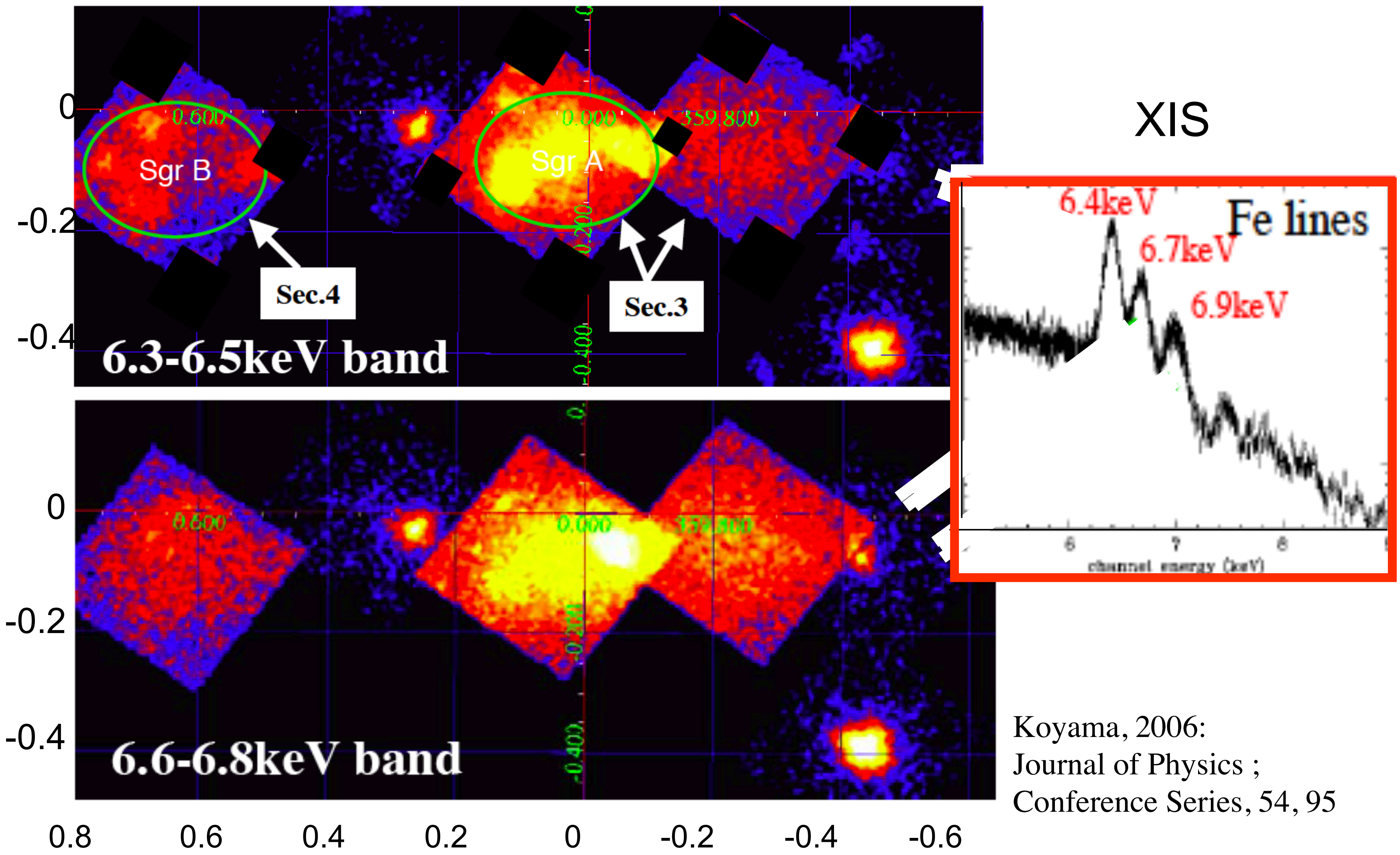


Neutral Fe @6.4 keV
He like Fe @6.7 keV
H like Fe @6.9 keV
Resolved by
ΔE~140 eV of CCD

Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 221
Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 245

II-2: Emission mechanisms

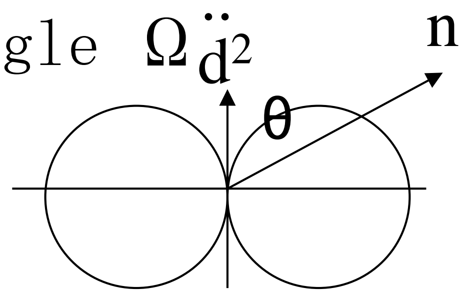
Emission from hot plasmas



Koyama, 2006:
Journal of Physics ;
Conference Series, 54, 95

3. Bremsstrahlung

Dipole **d** Radiation into the unit solid angle Ω



$$\frac{dP}{d\Omega} = \frac{\ddot{\mathbf{d}}^2}{4\pi c^3}\sin^2\theta$$

$$\frac{dW}{dt} = \frac{e^2}{16\pi^2\varepsilon_0 c}\int d\Omega\,(\mathbf{n}(t)\times(\mathbf{n}(t)\times\dot{\boldsymbol{\beta}}(t)))^2$$

If θ is the angle between $\dot{\beta}$(t) and **n,**

$$= \frac{e^2}{16\pi^2\varepsilon_0 c}\int d\Omega\,\sin^2\theta\,(\dot{\boldsymbol{\beta}}(t))^2 -$$

→Max. at perpendicular direction

$$= \frac{e^2}{16\pi^2\varepsilon_0 c}(\dot{\mathbf{v}}(t))^2\int d\Omega\,\sin^2\theta\,(\dot{\boldsymbol{\beta}}(t))^2$$

$\boldsymbol{\beta} = \boldsymbol{v}/c$

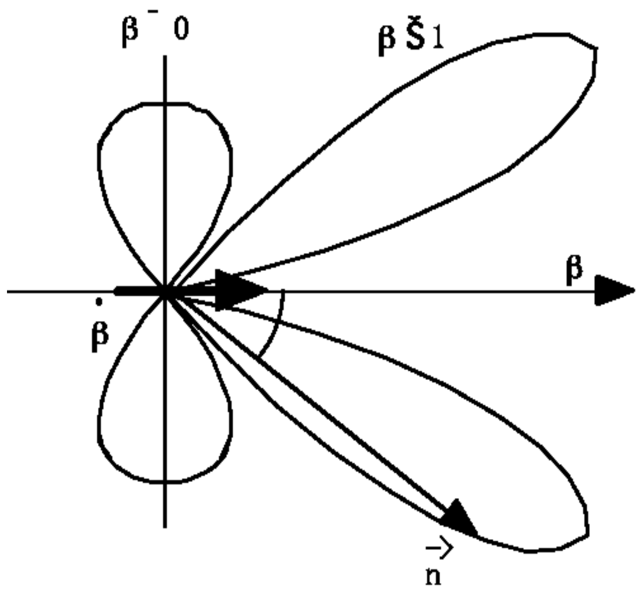
II-2: Emission mechanisms

3. Bremsstrahlung

When $d\Omega = \sin\theta \, d\theta \, d\psi$

$$\frac{dW}{dt} = \frac{e^2}{6 \pi \varepsilon_0 c^3} (\dot{\mathbf{v}}(t))^2$$

$$\frac{dW}{dt} = \frac{e^2 \dot{v}^2 (t)}{16 \pi^2 \varepsilon_0 c} \int d\Omega \frac{\sin\theta}{(1 - v(t) \cos\theta / c)^5}$$



When $\beta = v/c \rightarrow 1$

Isotropic in the rest frame

→ Lorentz transformation → **Beaming**

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

II-2: Emission mechanisms

3. Bremsstrahlung

Lorentz transformation

$$x' = \gamma (x - vt)$$
$$y' = y$$
$$z' = z$$
$$t' = \gamma (t - vx/c^2)$$

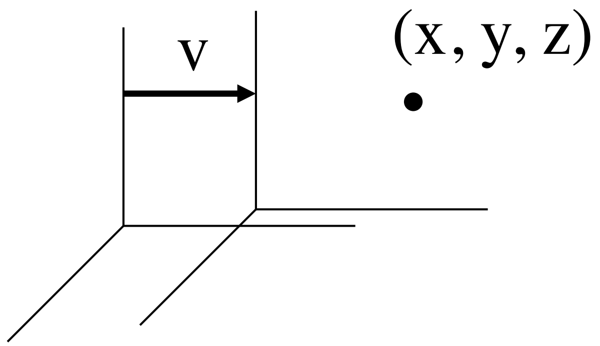
$$x = \gamma (x' + vt)$$
$$y = y'$$
$$z = z'$$
$$t = \gamma (t' + vx'/c^2)$$

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

$$u_x = dx/dt = \frac{\gamma (dx' + vdt')}{\gamma (dt' + vdx/c^2)} = \frac{u_x' + v}{1 + vu_x'/c^2}$$

$$u_y = \frac{u_y'}{\gamma(1 + vu_x'/c^2)}$$

$$u_z = \frac{u_z'}{\gamma(1 + vu_x'/c^2)}$$



II-2: Emission mechanisms

3. Bremsstrahlung

Measured in the moving system

Velocity u', direction θ',

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

Parallel component to v is affected by the motion v

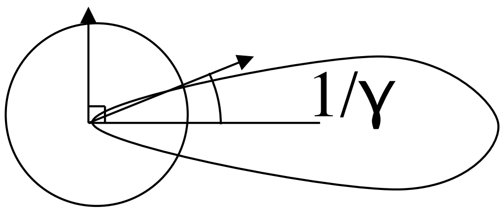
$$u_{\parallel} = \frac{u_{\parallel}' + v}{1 + v u_{\parallel}' / c^2} \qquad u_{\perp} = \frac{u_{\perp}'}{\gamma(1 + v u_{\parallel}' / c^2)}$$

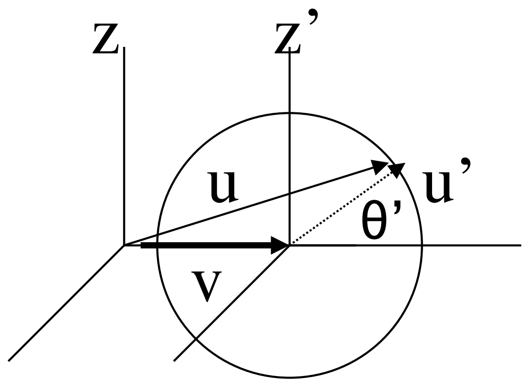
In the moving system, light direction is θ' is changed to θ

$$\sin\theta = \frac{u_{\perp}}{c} = \frac{c \sin\theta'}{c\,\gamma(1 + v\cos\theta' / c)}$$

Here, $u'=c$, $u_{\parallel} = c\cos\theta$, $u_{\perp} = c\sin\theta$

If $\theta = \pi/2$, $\sin\theta = 1/\gamma$

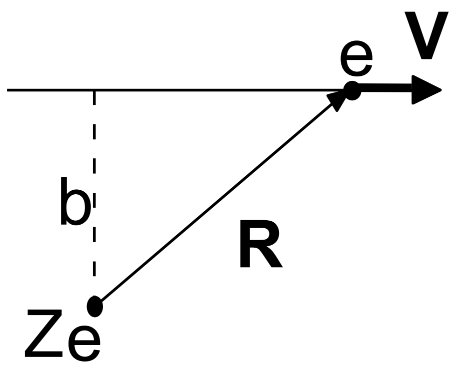




II-2: Emission mechanisms

3. Bremsstrahlung

Thermal bremsstralung



Impact parameter b

$$\frac{dW}{d\omega} = \frac{2e^2}{3\pi c^3} \left| \Delta \mathbf{V} \right|^2 \qquad \omega\tau << 1 \qquad \tau = b / v$$

$$\Delta \mathbf{V} = \frac{Ze^2}{m} \int \frac{b\,dt}{(b^2 + v^2t^2)^{3/2}} = \frac{2Ze^2}{mbV}$$

$$\frac{dW(b)}{d\omega} = \frac{8Z^2e^6}{3\pi c^3m^2v^2b^2} \qquad b << v/\omega$$

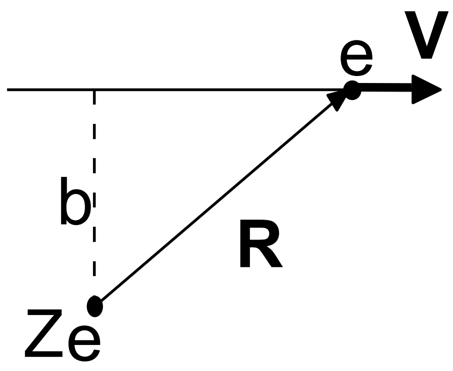
II-2: Emission mechanisms

3. Bremsstrahlung

Thermal bremsstralung

Ion density n_i electron density n_e

Integrate b from b_{min} to ∞



$$\frac{dW}{d\omega\, dV dt} = n_e\, n_i\, 2\pi v \int_{b_{min}}^{\infty} \frac{dW(b)}{d\omega}\, b\, db$$

$$= \frac{16 e^6}{3 c^3 m^2 v}\, n_e\, n_i\, Z^2 \ln\left(\frac{b_{max}}{b_{min}}\right)$$

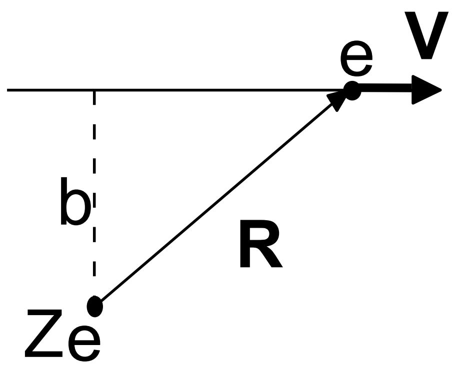
$$= \frac{16 \pi e^6}{3\sqrt{3}\, c^3 m^2 v}\, n_e\, n_i\, Z^2\, g_{ff}(v, \omega) \qquad \text{(eq 5.11)}$$

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 158

II-2: Emission mechanisms

3. Bremsstrahlung

Thermal bremsstralung



Thermal distribution of electrons

$dP \propto \exp(-E/kT)\, d^3v = \exp(-mv^2/2kT)\, d^3v$

$$\frac{dW}{dV\,dt\,d\omega} = \frac{\displaystyle\int_{v_{min}}^{\infty} \frac{dW(v,\omega)}{d\omega\, dV\, dt} v^2 \exp(-mv^2/2kT)\, dv}{\displaystyle\int_{0}^{\infty} v^2 \exp(-mv^2/2kT)\, dv}$$

$d\omega = 2\pi\, d\nu$

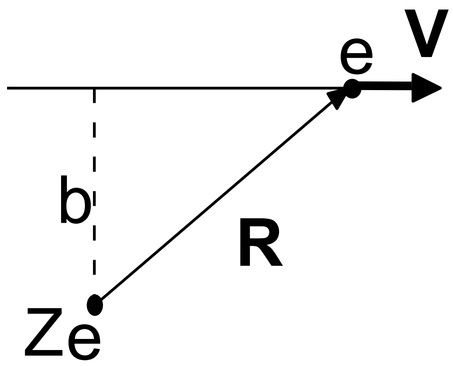
$$\frac{dW}{dV\,dt\,d\nu} = \left(\frac{2\pi}{3km}\right)^{1/2} \frac{2^5 \pi e^6}{3mc^3} T^{1/2} Z^2 n_e n_i e^{-h\nu/kT} g \qquad \text{(eq. 5.14a)}$$

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 160

II-2: Emission mechanisms

3. Bremsstrahlung

Thermal bremsstralung



Thermal distribution of electrons

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$d\omega = 2\pi\, d\nu$

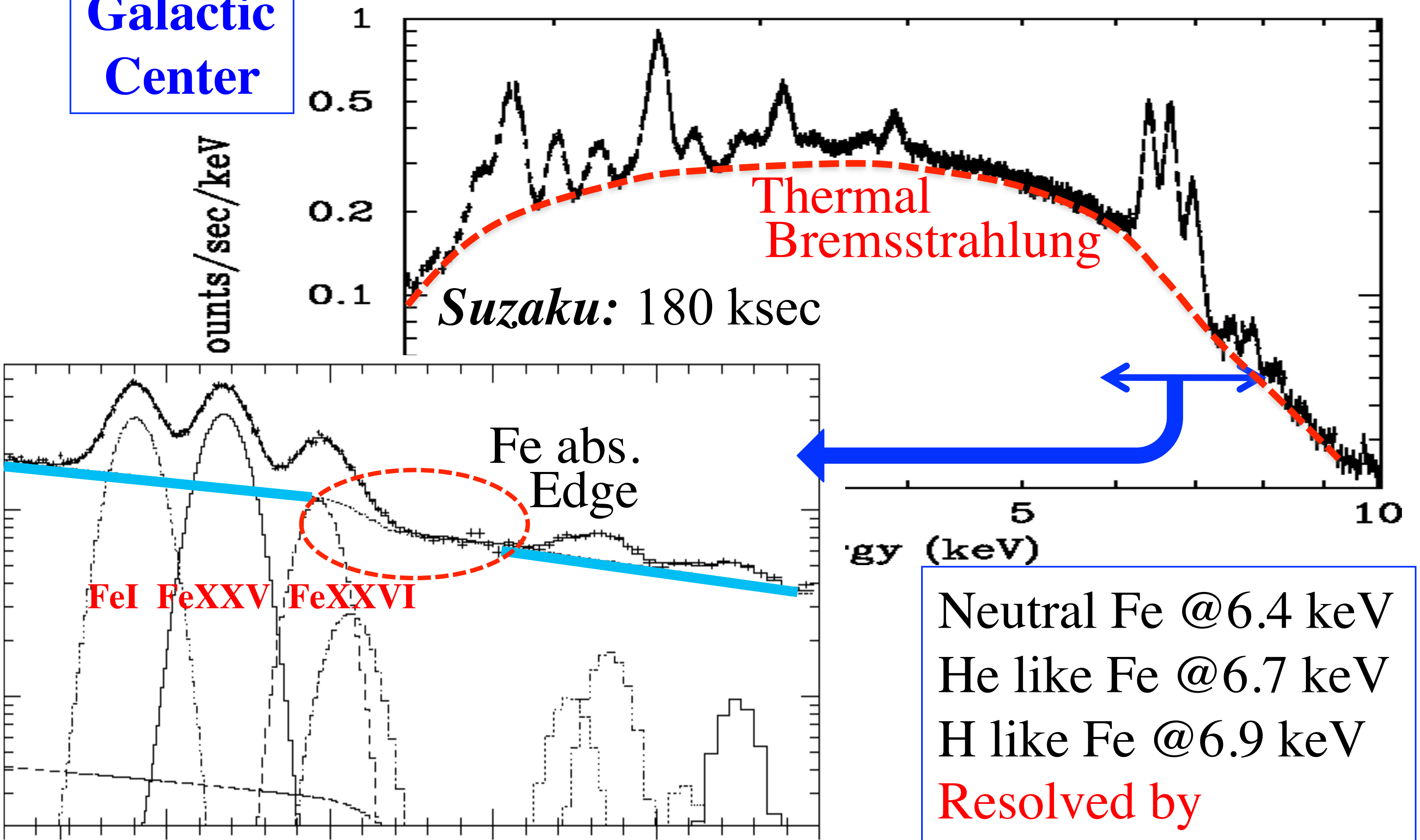
$$\frac{dW}{dV\,dt\,d\nu} = \left(\frac{2\pi}{3km}\right)^{1/2} \frac{2^5 \pi e^6}{3mc^3} T^{1/2} Z^2 n_e n_i e^{-h\nu/kT} g \quad \text{(eq. 5.14a)}$$

$$\frac{dW}{dV\,dt} = \left(\frac{2\pi kT}{3m}\right)^{1/2} \frac{2^5 \pi e^6}{3hmc^3} Z^2 n_e n_i g \quad \text{(eq. 5.15a)}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 160-161

Emission from hot plasmas

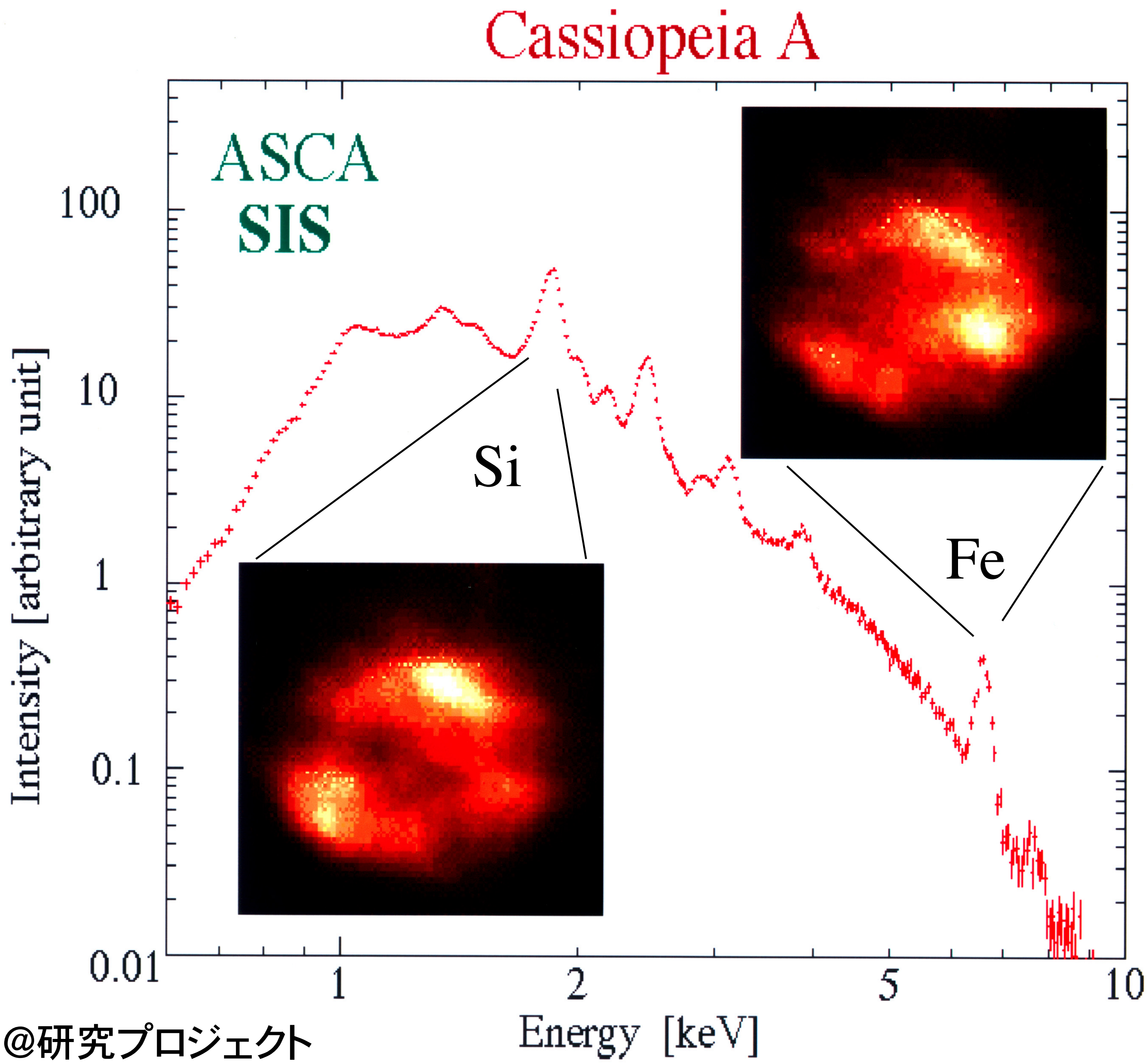
Galactic Center



Neutral Fe @6.4 keV
He like Fe @6.7 keV
H like Fe @6.9 keV
Resolved by
ΔE~140 eV of CCD

Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 221
Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 245

Thermal radiation from SNR

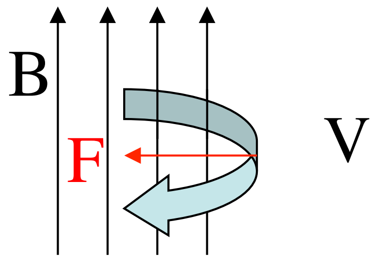


名古屋大学Ux研@研究プロジェクト
http://www.u.phys.nagoya-u.ac.jp/r_e/r_e3_4.html

4. Synchrotron radiation

$$\frac{q}{c}\,\mathbf{v}\times\mathbf{B} = mr\omega^2 \qquad = \frac{d}{dt}(\gamma m\mathbf{v})$$

$$\omega = \frac{qB}{mc}$$ **Cyclotron frequency** $$= \frac{qB}{\gamma mc}$$



$$<P> = \frac{2\,q^2 v_\perp{}^2 \omega^2}{3\,c^3}$$

$$\gamma = (1 - v^2/c^2)^{-1/2}$$

$$P = \frac{4}{3}\,\sigma_{Th}\,c\,\beta^2\gamma^2 U_B \qquad \text{(eq. 6. 7b)}$$

dp/dt=

$U_B = B^2/8\pi$: Energy density of B

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 169

II-2: Emission mechanisms

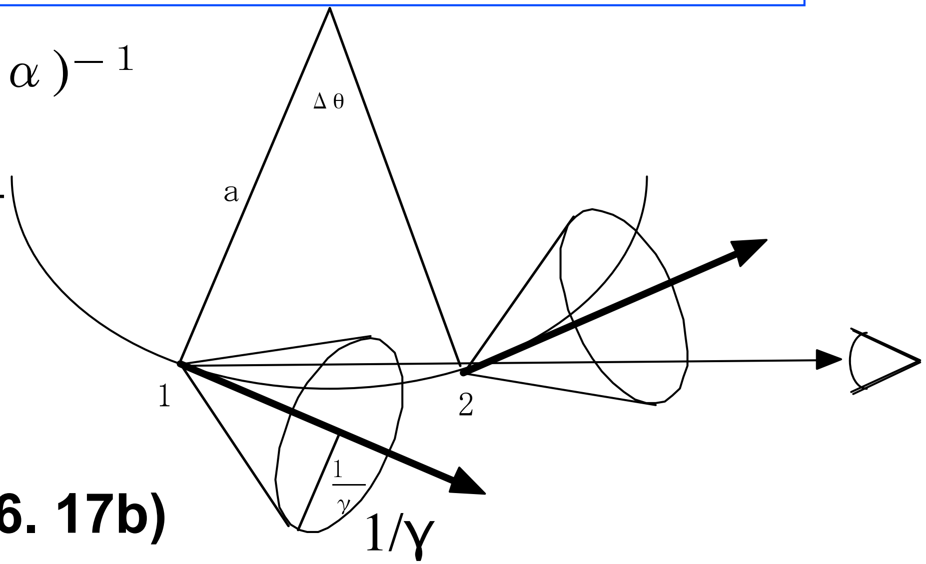
4. Synchrotron radiation

Typical frequency $\Delta t = (\gamma^{3} \omega_B \sin\alpha)^{-1}$

$$\omega_C = \frac{3}{2} \gamma^{3} \omega_B \sin\alpha = \frac{3\gamma^2 qB \sin\alpha}{2mc}$$

$$P = \frac{2 q^4 B^2 \gamma^2 \beta^2 \sin^2\alpha}{3 m^2 c^3}$$

(eq. 6. 17b)



If energy spectrum of electrons is power law,
$N(\gamma)\, d\gamma = C_2\, \gamma^{-P}\, d\gamma$

$P_{tot}(\omega) \propto \omega^{-(p-1)/2} \int F(x)\, x^{(p-3)/2}\, dx$ (eq. 6. 22a)

$$s = \frac{p-1}{2}$$

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 173-174

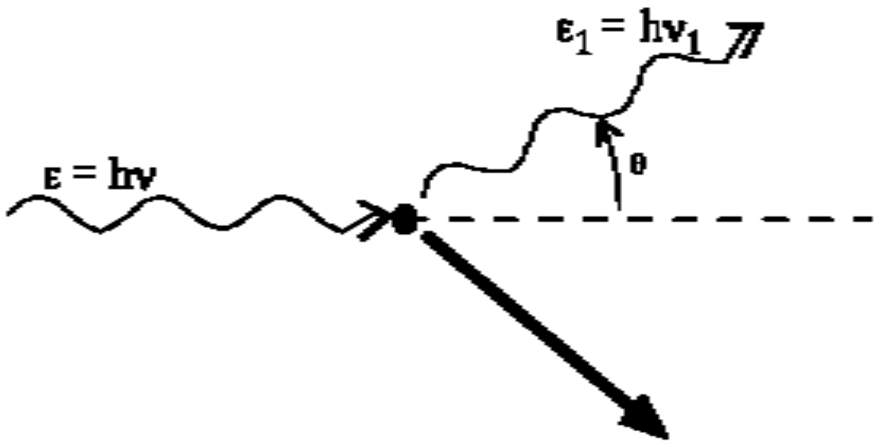
5. Compton scattering

$$\frac{d\sigma_T}{d\Omega} = \frac{1}{2} r_o^2 (1+\cos^2\theta)$$

$$\sigma_T = \frac{8\pi}{3} r_o^2$$

In relativistic cases,

$$\frac{\varepsilon}{\varepsilon_1} = 1 + \frac{\varepsilon}{mc^2}(1-\cos\theta)$$



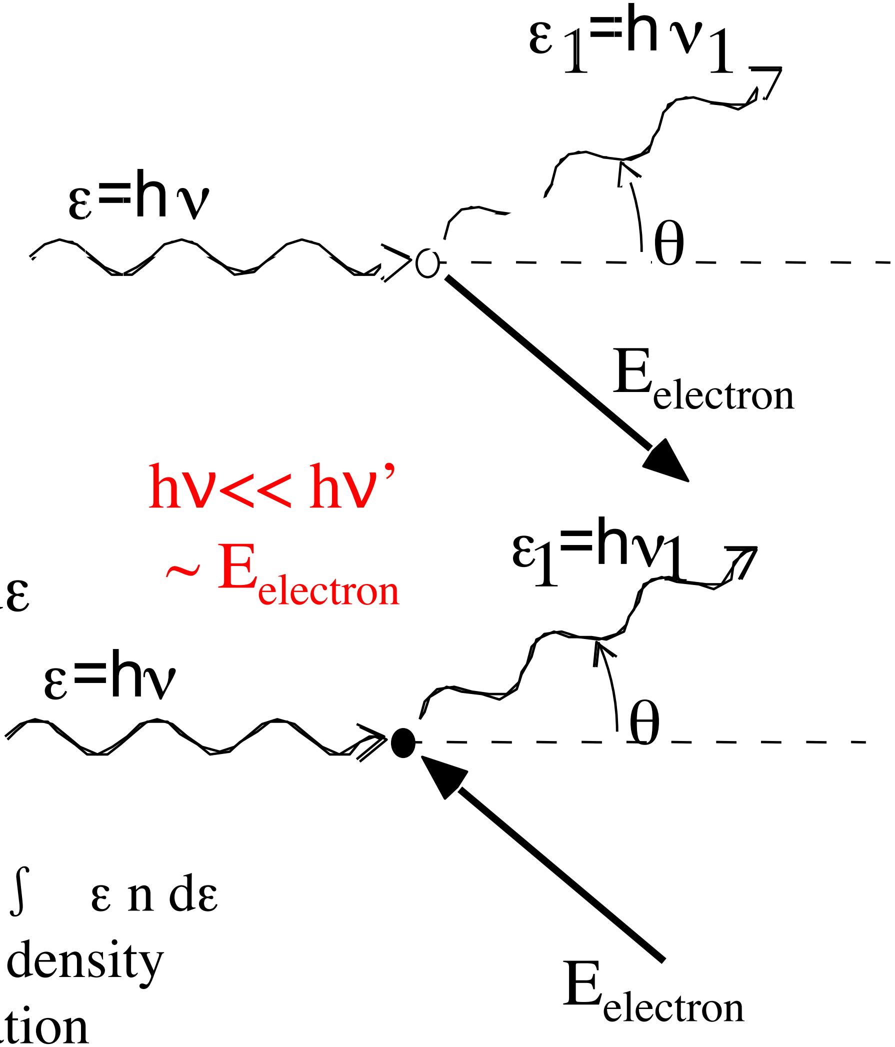
$$\frac{d\sigma}{d\Omega} = \frac{r_o^2 \varepsilon_1^2}{2\varepsilon^2}\left(\frac{\varepsilon}{\varepsilon_1} + \frac{\varepsilon_1}{\varepsilon} - \sin^2\theta\right) \quad \text{eq(7.4)}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 197

5. Compton scattering

Inverse

If E_{el} is large (>> $m_e c2$), observer frame has to be referred to the incident photon



$$\varepsilon' = \varepsilon \gamma (1-\beta \cos\theta)$$

$$\frac{\delta E_1}{dt} = c\sigma_T \gamma^2 \int (1-\beta\cos\theta)^2 \varepsilon n \, d\varepsilon$$

$$P = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{PH}$$

$U_{PH} = \int \varepsilon n \, d\varepsilon$
Energy density of radiation

Radiation Processes

Line emissions

Thermal Bremsstrahlung ------> Blackbody radiation

$$\frac{dW}{dV\,dt} = \left(\frac{2\pi kT}{3m}\right)^{1/2} \frac{2^5 \pi e^6}{3hmc^3} Z^2 n_e n_i g \qquad \text{(eq. 5.15a)}$$

Synchrotron

$$P = \frac{4}{3} \sigma_{Th} c \beta^2 \gamma^2 U_B \qquad \text{(eq. 6. 7b)}$$

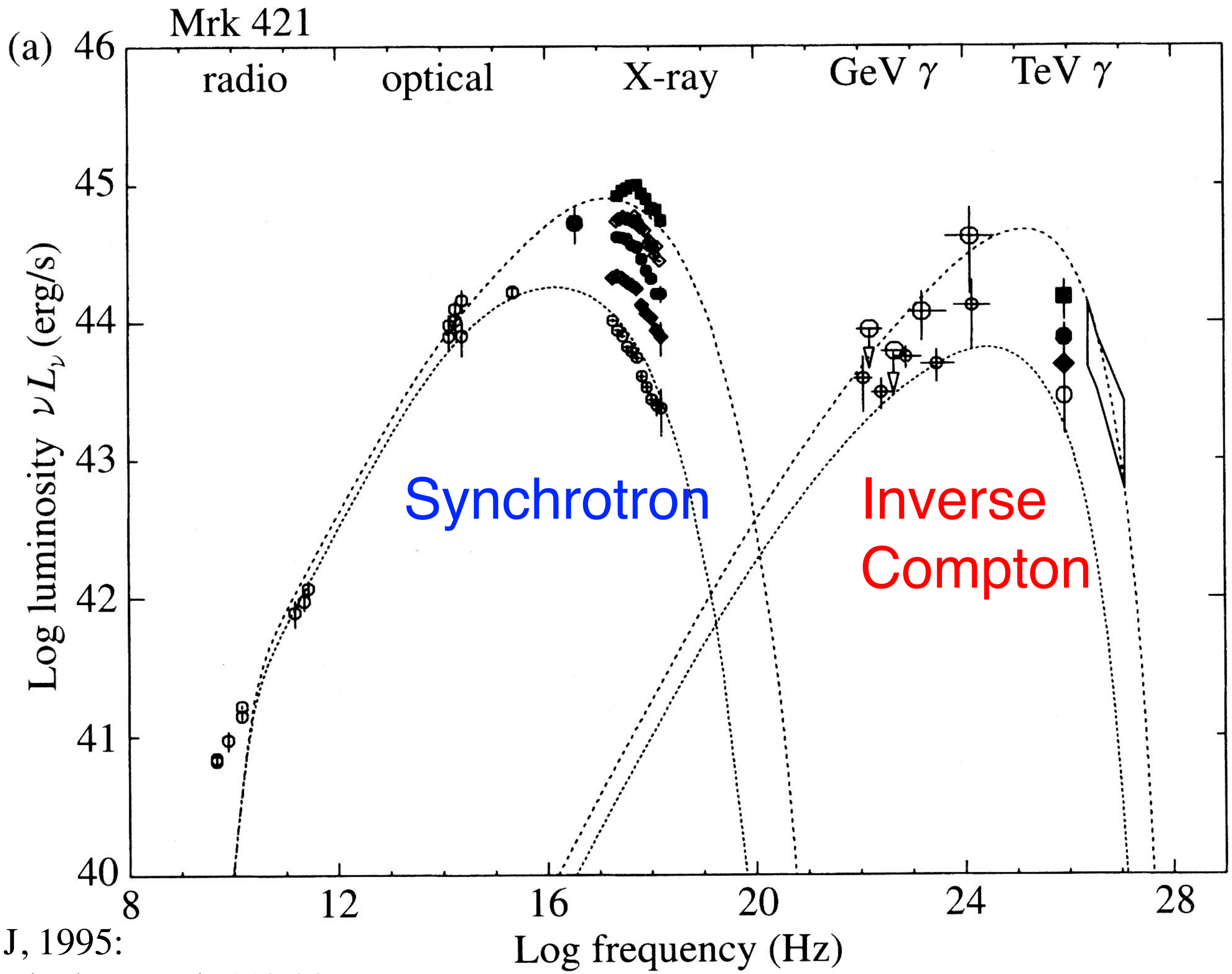
Inverse Compton

$$P = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{PH}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 161

II-2: Emission mechanisms of high energy photons

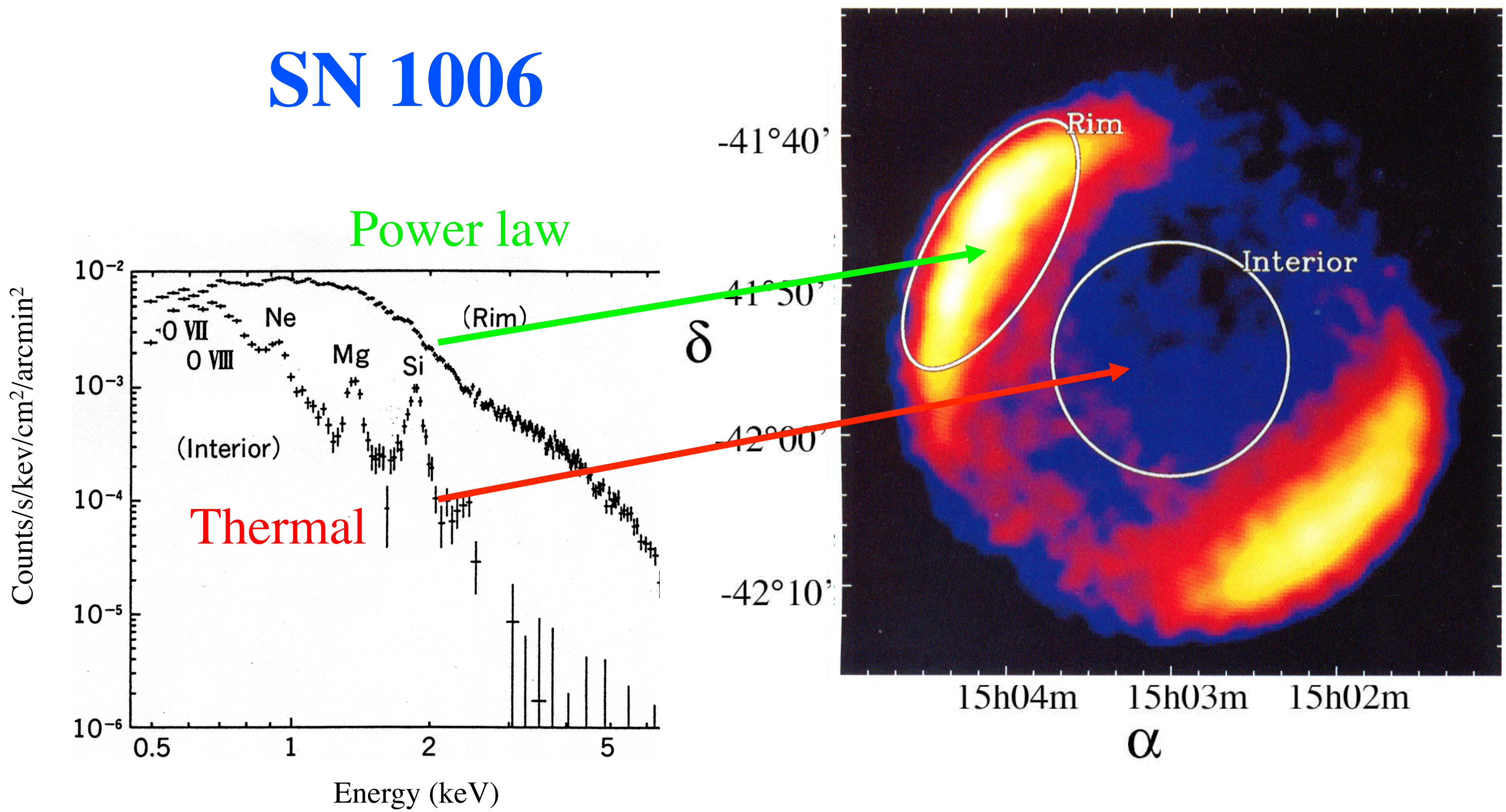
Synchrotron-self-Compton Model for a Blazer



Macomb, D, J, 1995:
The AstroPhysical Journal, 449,99

II-2: Emission mechanisms of high energy photons

Non-thermal component of SNR



I-3: Energy sources of high energy phenomena

Energy release of X-ray sources

Sun	L_{opt}~10^{33} erg/s L_X~10^{27} erg/s	Nuclear fusion
SN	E ~ 10^{51} erg	Gravitational Energy
AGN	L~$10^{41\text{-}47}$ erg/sec	Gravitational Energy
Cluster	E~10^{60} erg	Dynamical+G Energy
γ burst	E~10^{52} erg/sec	Hypernovae?

1. Nuclear energy

SUN

Energy release of the Sun

--> Black body radiation
kT=6430°K、 r = 600,000 km、 σ= 5.67x10^{-5}

$L = 4\pi r^2 \sigma T^4 =$ **4.4 x 10^{33} erg/s**

t = 3600 s/h x 24 h/d x 365 d/y x 46 x 10^{8} y
= 1.45 x 10^{17} sec

(3.15 x 10^{7} sec/y)

E = L x t = 6 x 10^{50} erg

1. Nuclear energy

SUN

Nuclear reactions

P-P chain (I) $p + p \rightarrow {}^{2}H + e^{+} + \underline{\nu_e\ 0.16MeV}$

$^{2}H + p \rightarrow {}^{3}He + \gamma$ [6.7MeV/3H]

for $kT > 8\ 10^{6}K$

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ [**26.1MeV/4H**]

(II) $kT > 2\ 10^{7}K$になると

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be + e^{+}\ \underline{\nu_e\ 7\ MeV}$ **Solar neutrino**

$^{8}Be \rightarrow 2\,{}^{4}He$

CNO cycle

He burning

C O burning---> Fe

2. Gravitational energy

Sun — 3.8×10^{48} erg

↓ Supernova

Neutron stars — $R = 10^6$ cm

$E = 2 \times 10^{53}$ erg → Neutrino

Blackholes — $R = 3 \times 10^5$ cm

1 M_{Solar} — $E = 7 \times 10^{53}$ erg

Neutrino → 1% → Mechanical E of Expanding shell

Neutrino → 99% → Escape

KAMIOKANDE

Escape velocity
$v_{es}^2 = 2GM/R$

At **Rg**, $v_{es} = c$
Then $Rg = 2GM/c^2$
$= 3\ (M/M_{solar})$ km

$E = GM^2/R$
$\sim Mc^2$

II. High energy phenomena
II-1 : Stellar X-ray emission

1. Stellar X-ray emission

(1) Evolution and X-ray emission from proto-stars

Contraction of molecular cloud

Release of angular Momentum

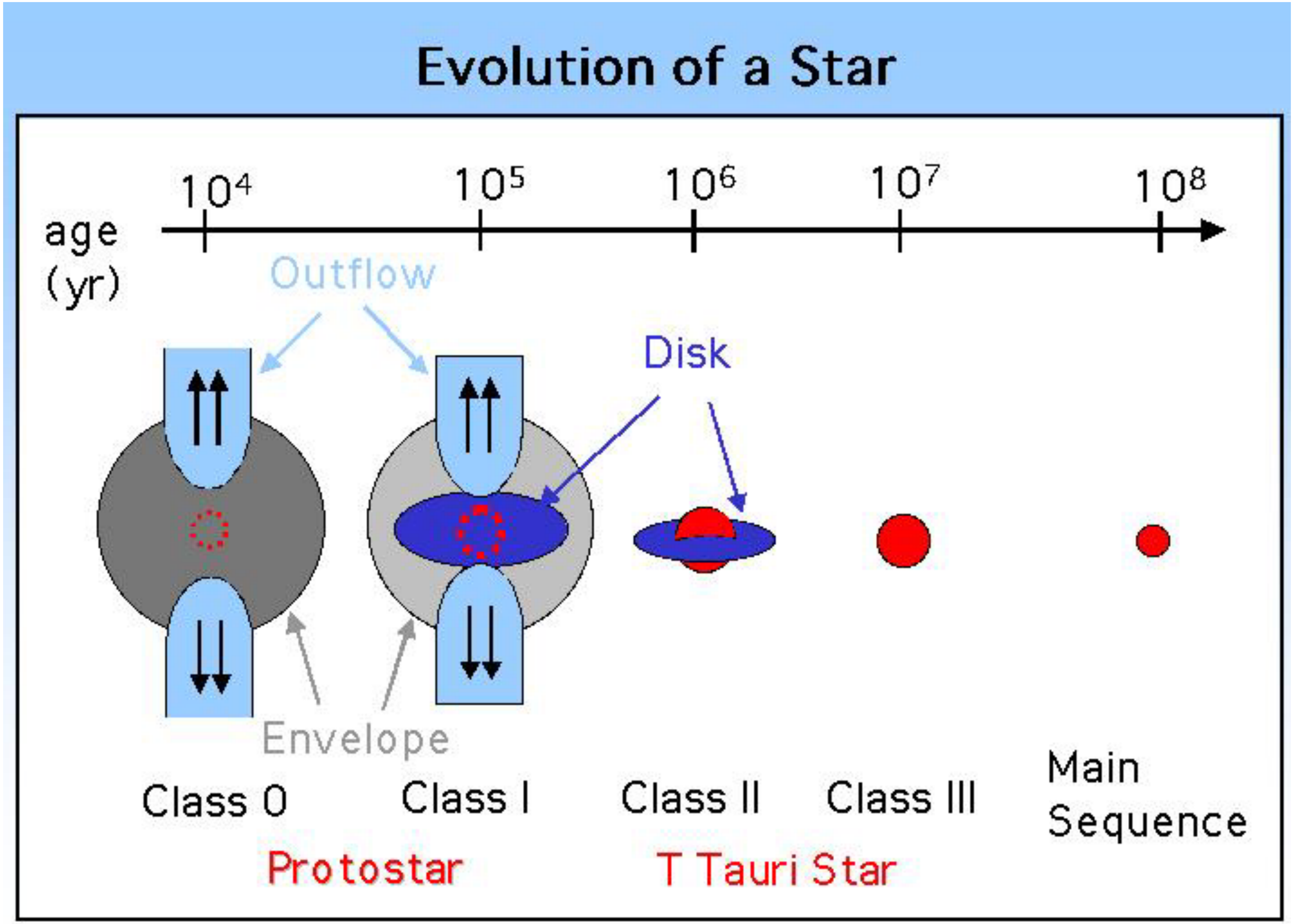
Class 0	Accretion disk
I	Bipolar flow
	X-rays emission discovered by ASCA
II	Central star
III	Central star (Nuclear reaction)

Gravitational E --> Heating

--> Rotation --> B -->**Hot plasmas**

High energy electrons

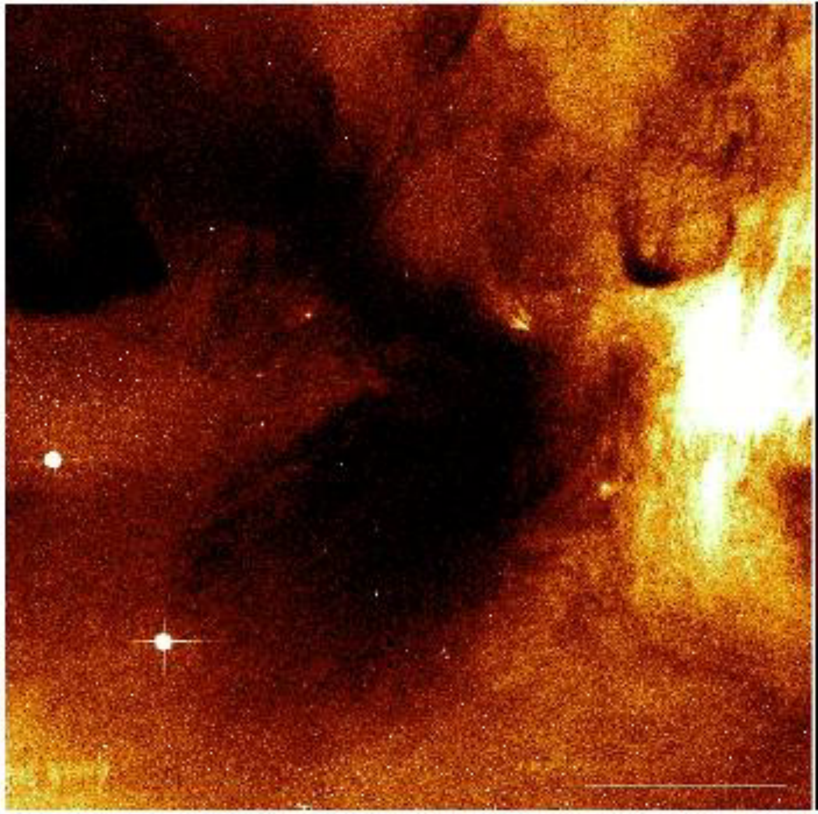
Hard X-rays


Evolution of a Star
age (yr)
10^4
10^5
10^6
10^7
10^8
Outflow
Disk
Envelope
Class 0
Class I
Class II
Class III
Main Sequence
Protostar
T Tauri Star

Star forming region

ρ Oph Molecular Cloud

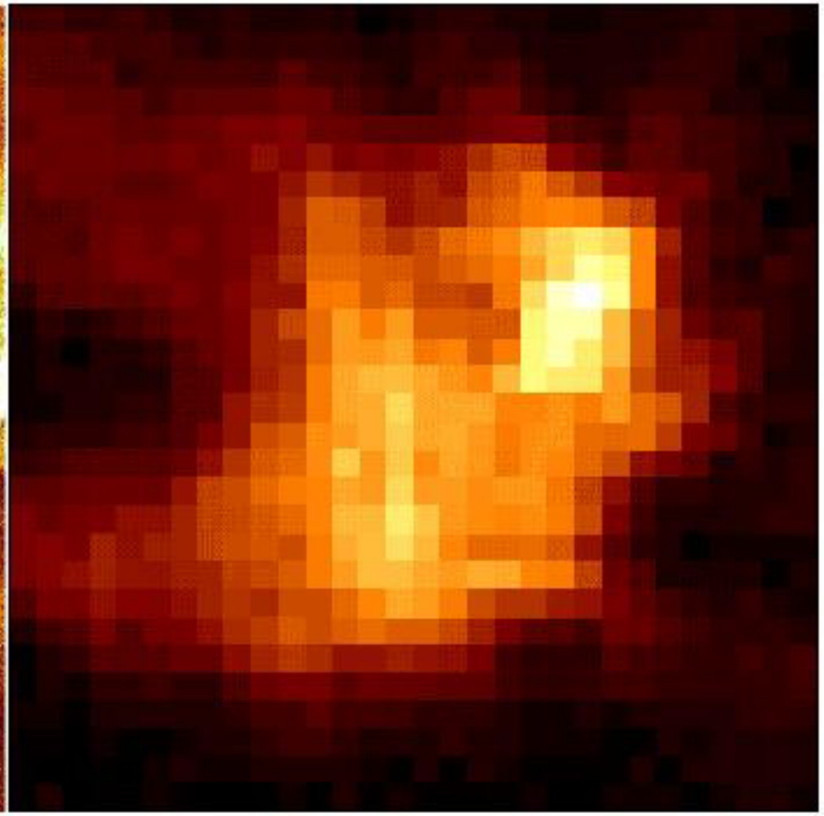
Optical (Digitized sky survey)



2 light years

Optical image (Extinction)

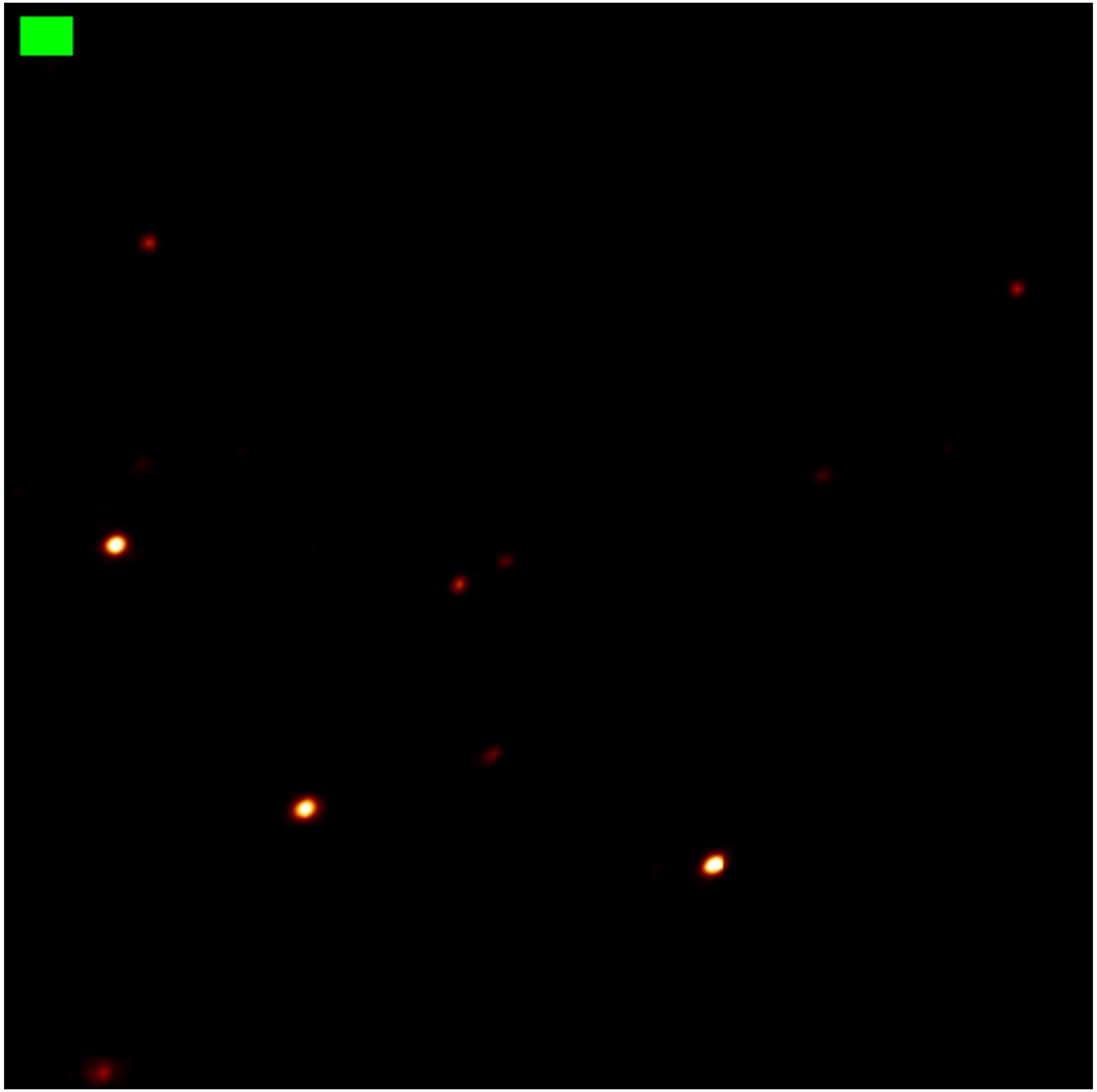
Radio (^{13}CO) (NANTEN telescope)



2 light years

Radio image (Molecular cloud

X-ray blinking of proto stars in SFR



(2) Solar X-rays

Main sequence stars

Core Temp. and Density --> Ignition of **Nuclear reaction**

Photo-sphere: T ~ 6000°K Blackbody

Corona: T ~ $10^{6\text{-}7}$ K --> several keV --> X-rays

Nuclear energy --> Convection/Rotation --> **B**

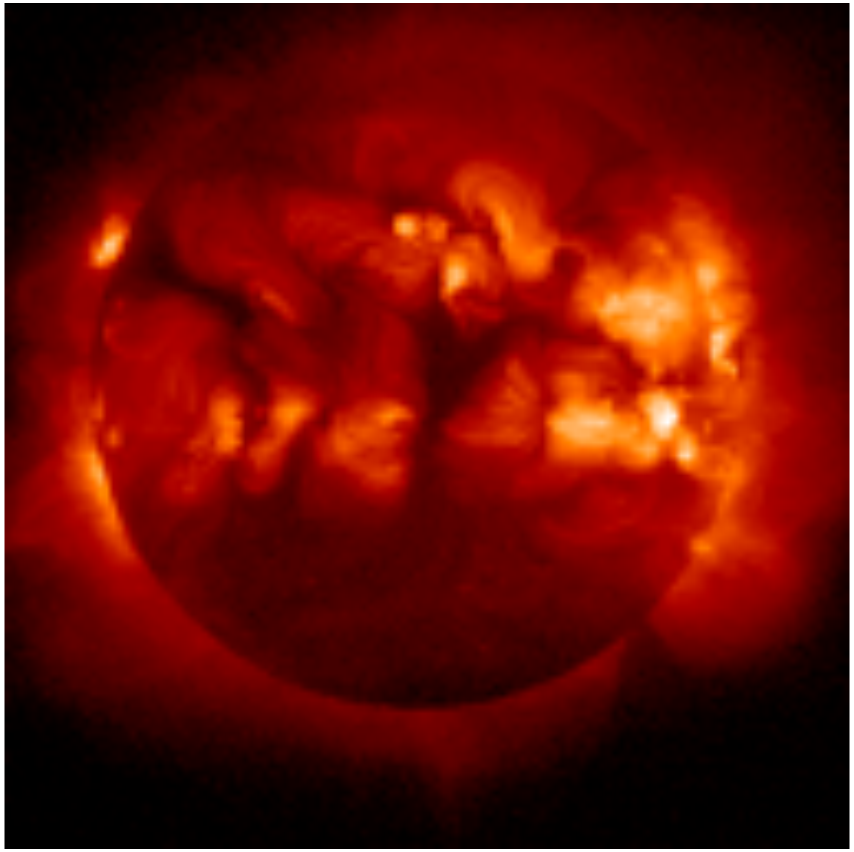
Solar magnetic field --> Extends into the atmosphere

Reconnection --> **E** -->Acceleration of $\mathbf{e^-}$

--> Thermalization --> **Soft X-rays**

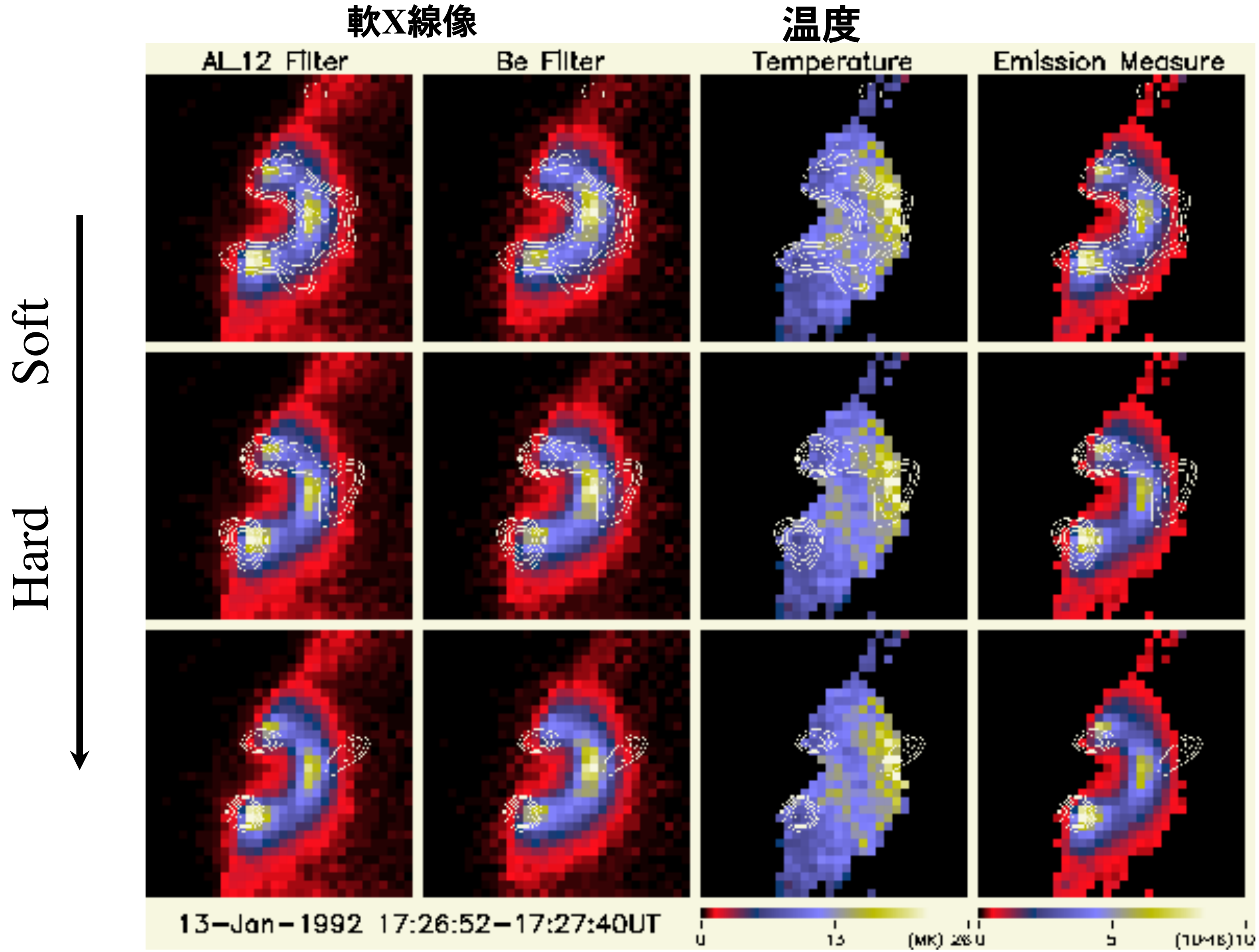
--> **Hard X-rays**

Soft X-ray Movie of the Sun by Yohkoh



http://www.isas.jaxa.jp/home/solar/yohkoh/

Solar Flare observed by Yohkoh



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- ようこう
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