# X-ray generation in Cosmic Sources

Dipankar Bhattacharya
IUCAA, Pune, India

## Production of X-ray radiation

Requires highly energetic particles

In the cosmic setting, X-rays are produced by three main processes:

1. From very hot gas (Temperature > 1 million K), thermal bremsstrahlung emission, atomic transitions

2. From relativistic electrons streaming through magnetic fields, synchrotron emission

3. Compton Scattering of low-energy radiation field by energetic electrons

# Classical radiation theory

Electromagnetic fields of moving charges

$$\vec{E}(\vec{r},t) = \frac{q}{4\pi\epsilon_0}\left[\frac{(\hat{n}-\vec{\beta})(1-\beta^2)}{\kappa^3 R^2}\right] + \frac{q}{4\pi\epsilon_0 c}\left[\frac{\hat{n}}{\kappa^3 R} \times \left\{(\hat{n}-\vec{\beta}) \times \dot{\vec{\beta}}\right\}\right]$$

$$\vec{H}(\vec{r},t) = \sqrt{\frac{\epsilon_0}{\mu_0}}\left[\hat{n} \times \vec{E}(\vec{r},t)\right]$$

where

$$\kappa = 1 - \frac{1}{c}\hat{n}(t') \cdot \vec{u}(t')$$

$$\vec{R} = \vec{r} - \vec{r}_0(t')$$

$$\hat{n} = \vec{R}/R$$

$$c(t-t') = R(t')$$

# An accelerated electric charge emits e.m. radiation

Uniformly moving charge:

Coulomb Field : ~ $1/r^2$ from the *current* location of the charge

Accelerated charge:

J.J. Thomson

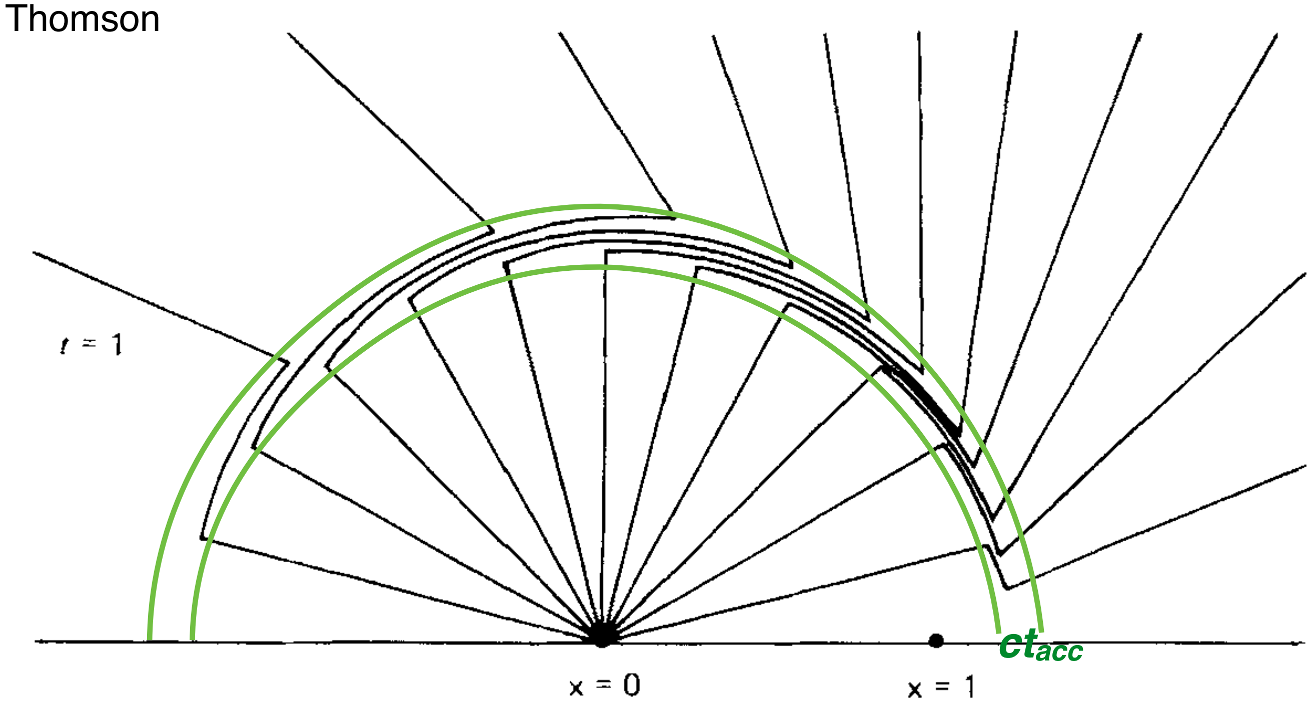



***Figure 3.2 Graphical demonstration of the 1/R acceleration field. Charged particle moving at uniform velocity in positive x direction is stopped at x = 0 and t = 0.***

*from Rybicki & Lightman 1979*

Field line density at the ring: ~ $1/(2\pi r \,.\, ct_{acc})$

Propagating transverse electric field (radiation):

$$E_\theta = \frac{q\,|\boldsymbol{a}|\sin\theta}{4\pi\,\varepsilon_0 c^2 r}$$

Associated transverse magnetic field:

$$|\boldsymbol{H}| = E_\theta/(\mu_0/\varepsilon_0)^{1/2}$$

$$\text{Emitted Power} = -\left(\frac{dE}{dt}\right) = \int |\boldsymbol{E}\times\boldsymbol{H}|r^2 d\Omega \; = \frac{q^2|\boldsymbol{a}|^2}{6\pi\,\varepsilon_0 c^3}$$

(Larmor Formula)

$\boldsymbol{a} =$ proper acceleration in the instantaneous rest frame of the charged particle

Moving Observer: $\mathrm{d}E/\mathrm{d}t = \mathrm{d}E'/\mathrm{d}t'$ (Lorentz invariant)

proper acceleration

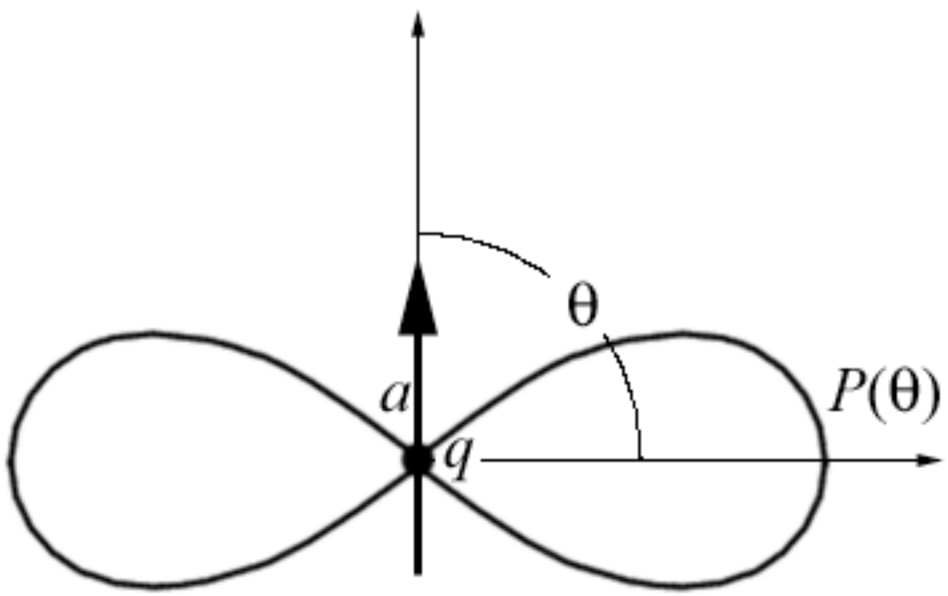
$$\boldsymbol{a}_{\mathbf{0}}^2 = \gamma^4(|a_\perp|^2 + \gamma^2|a_{||}|^2)$$

$\gamma$ = Lorentz factor

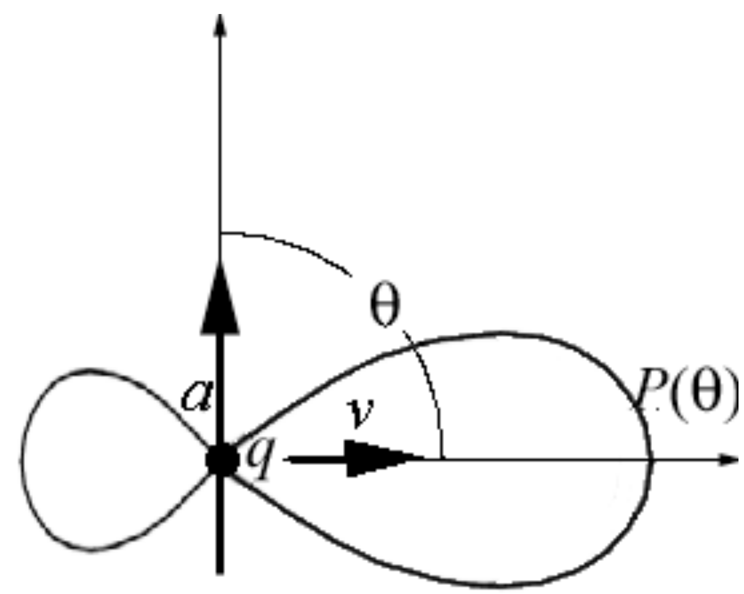
$$= \frac{1}{1 - \frac{v^2}{c^2}}$$

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_S = \frac{q^2\gamma^4}{6\pi\varepsilon_0 c^3}(|a_\perp|^2 + \gamma^2|a_{||}|^2)$$

# Radiation Pattern




Stationary
dipole




Moving
dipole

Motion introduces aberration and relativistic beaming

# Polarization

$$\vec{E} \propto \hat{n} \times [(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}]$$

At a single particle level, over short times, radiation is always polarized.

For slowly moving particle (or $\vec{\beta}$ nearly || to $\hat{n}$ ) polarization is || to the projected instantaneous acceleration.

Net observed polarization involves average over the particle's trajectory, and over the distribution of emitting particles.

# Spectrum:

*Fourier Transform of the time-varying electric field*

$$\dot{\boldsymbol{v}}(t) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \dot{\boldsymbol{v}}(\omega) \exp(-\mathrm{i}\omega t)\, \mathrm{d}\omega \,,$$

$$\dot{\boldsymbol{v}}(\omega) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{\infty} \dot{\boldsymbol{v}}(t) \exp(\mathrm{i}\omega t)\, \mathrm{d}t \,.$$

$$\int_{-\infty}^{\infty} |\dot{\boldsymbol{v}}(\omega)|^2 \mathrm{d}\omega = \int_{-\infty}^{\infty} |\dot{\boldsymbol{v}}(t)|^2\, \mathrm{d}t$$

$$= 2 \int_{0}^{\infty} |\dot{\boldsymbol{v}}(\omega)|^2\, \mathrm{d}\omega$$

$$\int_0^\infty I(\omega) d\omega = \int_0^\infty \frac{q^2}{6\pi\varepsilon_0 c^3} 2|\dot{\boldsymbol{v}}(\omega)|^2 d\omega$$

$$I(\omega) = \frac{q^2}{3\pi\varepsilon_0 c^3} |\dot{\boldsymbol{v}}(\omega)|^2$$

Specific Intensity $I_\nu$

$I_\nu/\nu^3$ **:** Lorentz Invariant

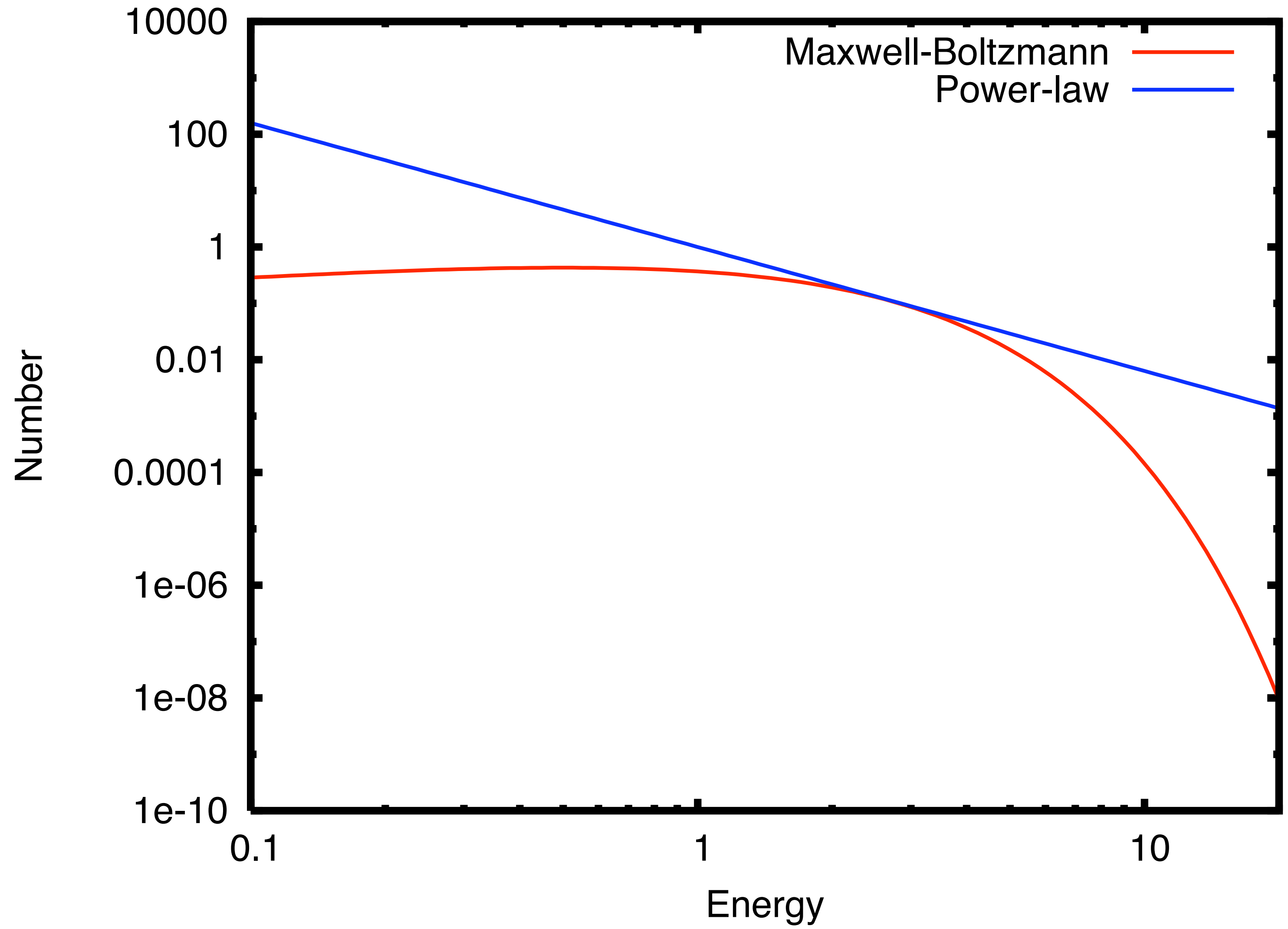
# Spectra

Radiation received from a source is the sum of emission from a large population of particles.

Energy distribution of the particles shape the spectra

Thermal distribution
*Maxwell-Boltzmann*

Non-thermal distribution
*Non-Maxwellian, e.g. power-law*



# *Radiation is modified during propagation through matter*

## Radiative transfer

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

$j_\nu$ = emission coefficient $\quad \epsilon_\nu = \int j_\nu \, d\Omega$

$\alpha_\nu$ = absorption coefficient

$$S_\nu \equiv j_\nu / \alpha_\nu \;; \;\; d\tau_\nu = \alpha_\nu ds$$

$$I_\nu = I_\nu^0 e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu})$$

$S_\nu$ for a thermal source is the Planck function $B_\nu$

$$B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$

# Quantum Mechanical View

All e.m. radiation arises from transition between levels with difference in electric or magnetic moment

$$\nu = \frac{\Delta E}{h}$$

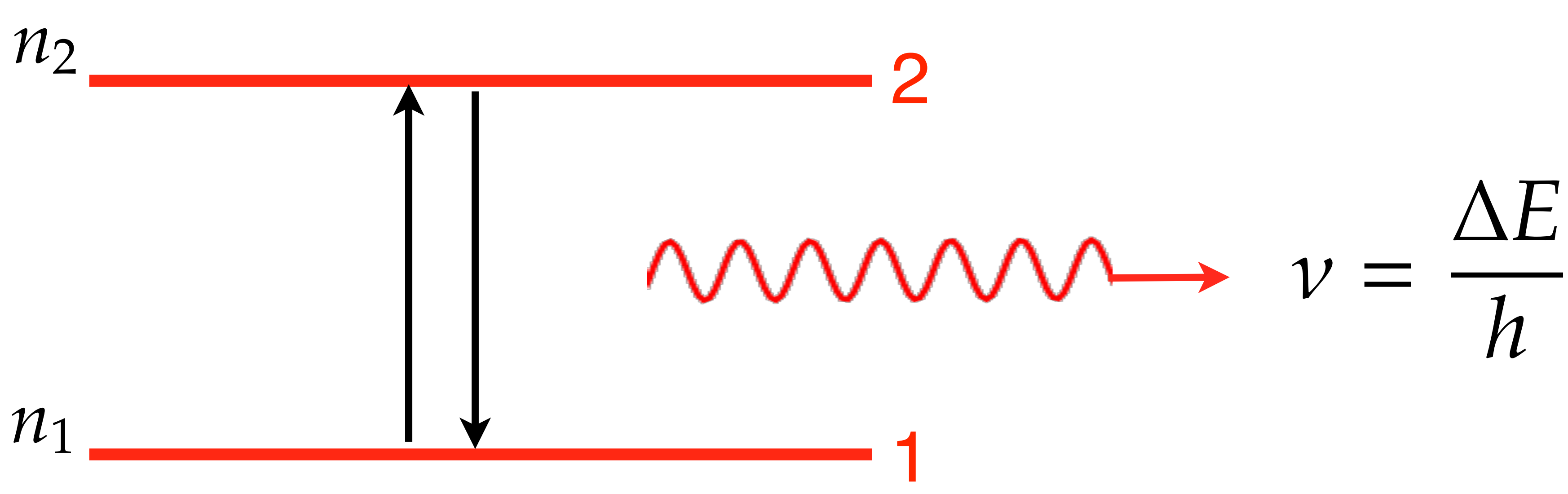
- Levels could be discrete or in continuum
- Between each pair of levels emission and absorption
- Transitions dipole / higher multipole

*Transition probability* $\propto \; |\langle f \,|\, \exp(i\vec{k}.\vec{r})\; \vec{l}.\Sigma\vec{\nabla}_j \,|\, i \rangle|^2$

[ dipole approximation $\exp(i\vec{k}.\vec{r}) \; = \; 1$ ]

All emission processes have their inverse (absorption, stimulated emission)

$$g_2 B_{21} = g_1 B_{12} \quad ; \quad A_{21} = 2h\nu^3 B_{21}/c^2$$




$$j_\nu = \frac{h\nu}{4\pi} n_2 A_{21}$$

$$\alpha_\nu = \frac{h\nu}{4\pi}(n_1 B_{12} - n_2 B_{21})$$

$\alpha_\nu < 0$ if $\frac{n_2}{n_1} > \frac{g_2}{g_1}$ : population inversion and maser emission

Blackbody constitutes the maximum emission by a thermal source at a given temperature

$$I_\nu = B_\nu(T) + e^{-\tau_\nu}(I_\nu^0 - B_\nu(T))$$

In Rayleigh-Jeans' regime $B_\nu(T) = 2\nu^2 kT/c^2$

Let background temperature $T_{\rm bg} = c^2 I_\nu^0 / 2\nu^2 k$

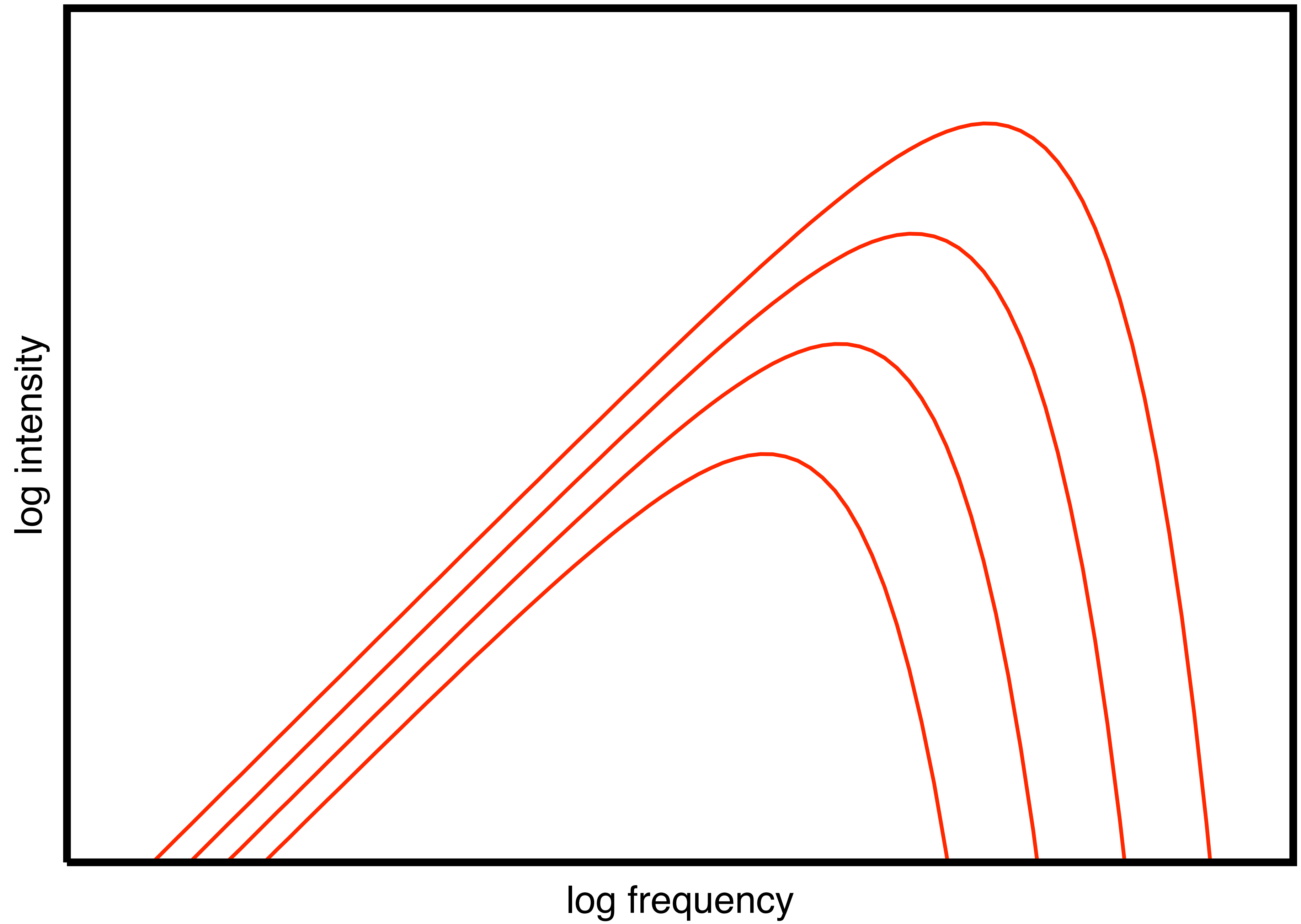
And "Brightness Temperature" $T_b = c^2 I_\nu / 2\nu^2 k$

Then $T_b = T + e^{-\tau_\nu}(T_{\rm bg} - T)$ : lies between $T_{\rm bg}$ and $T$

$T < T_{\rm bg}$ : "absorption"; $T > T_{\rm bg}$ : "emission"

Spectral lines: $\tau_\nu$ high over a narrow frequency range

# Blackbody function




At large optical depth a thermal source will emit blackbody intensity. Emission will be received from a photosphere

Optical depth is frequency-dependent. A source could be optically thick at some frequencies, optically thin at others.

# Radiation from accreting Compact Objects

## Sources of Radiation

- Accretion disk, corona, winds, jets, surrounding material

## Main radiation components

- Optically thick emission from disk: *Blackbody, multi-temperature*
- Spectral lines from disk photosphere: *e.g. Relativistic Fe line*
- Optically thin emission from corona, outflow, jets: *Bremsstrahlung, Synchrotron, Compton*
- Reflection from the disk: *Compton, Fluorescence*

Each has a distinct spectral signature

Matter accreting onto a compact star can have a high fraction $\eta = GM/(Rc^2)$ of its rest energy extracted.
$\eta \sim 10\%$ for NS/BH, 0.03% for WD. (compare: ~0.7% for H burn)

If converted directly to thermal energy then expect (*e.g. shock*)

$$kT \sim \eta m_{\rm p} c^2 \sim 100\,{\rm MeV}\left(\frac{\eta}{0.1}\right)$$

In practice energy release is more gradual, at lower temperatures

Maximum Radiative Luminosity (Eddington Limit)

$$L_{\rm Edd} = \frac{4\pi G \mu m_{\rm p} c}{\sigma_{\rm T}} M = 1.26 \times 10^{38}\ {\rm erg/s}\left(\frac{M}{M_\odot}\right)\mu$$

(inward gravitational force balanced by outward radiative force)

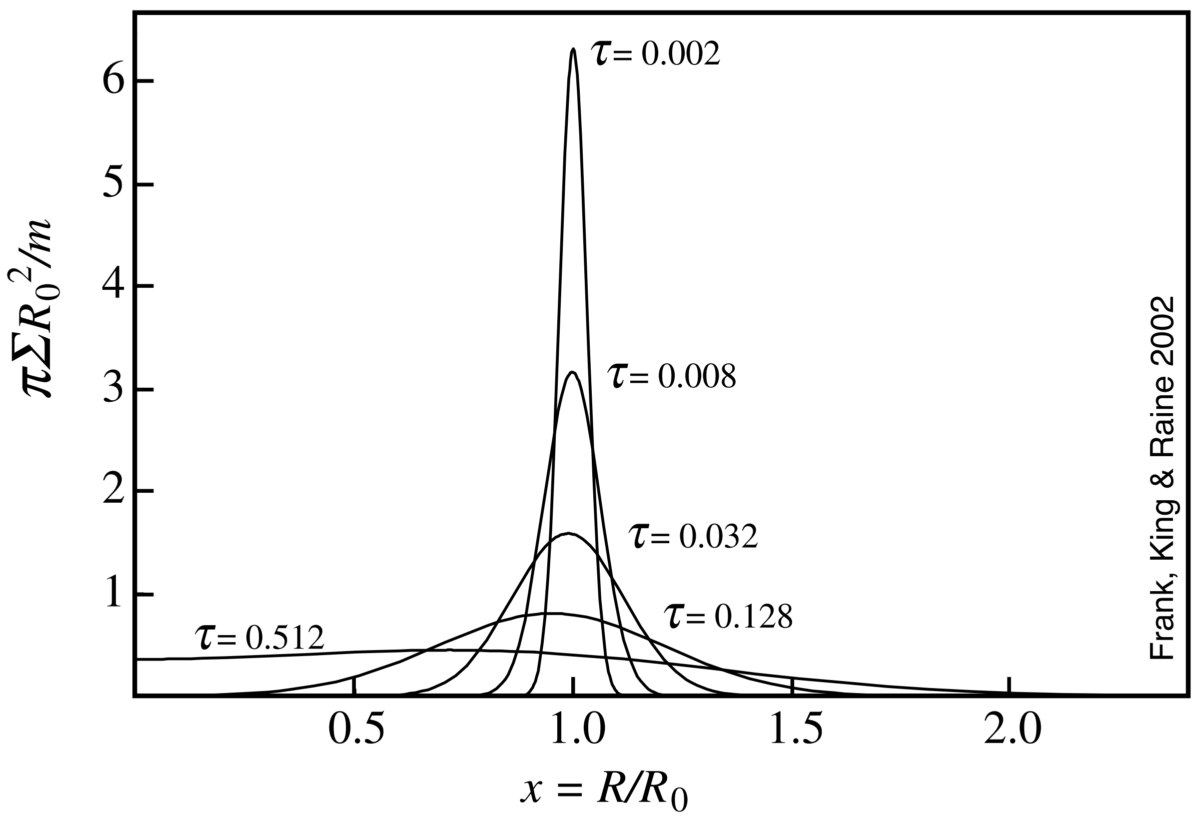
Hence Eddington accretion rate

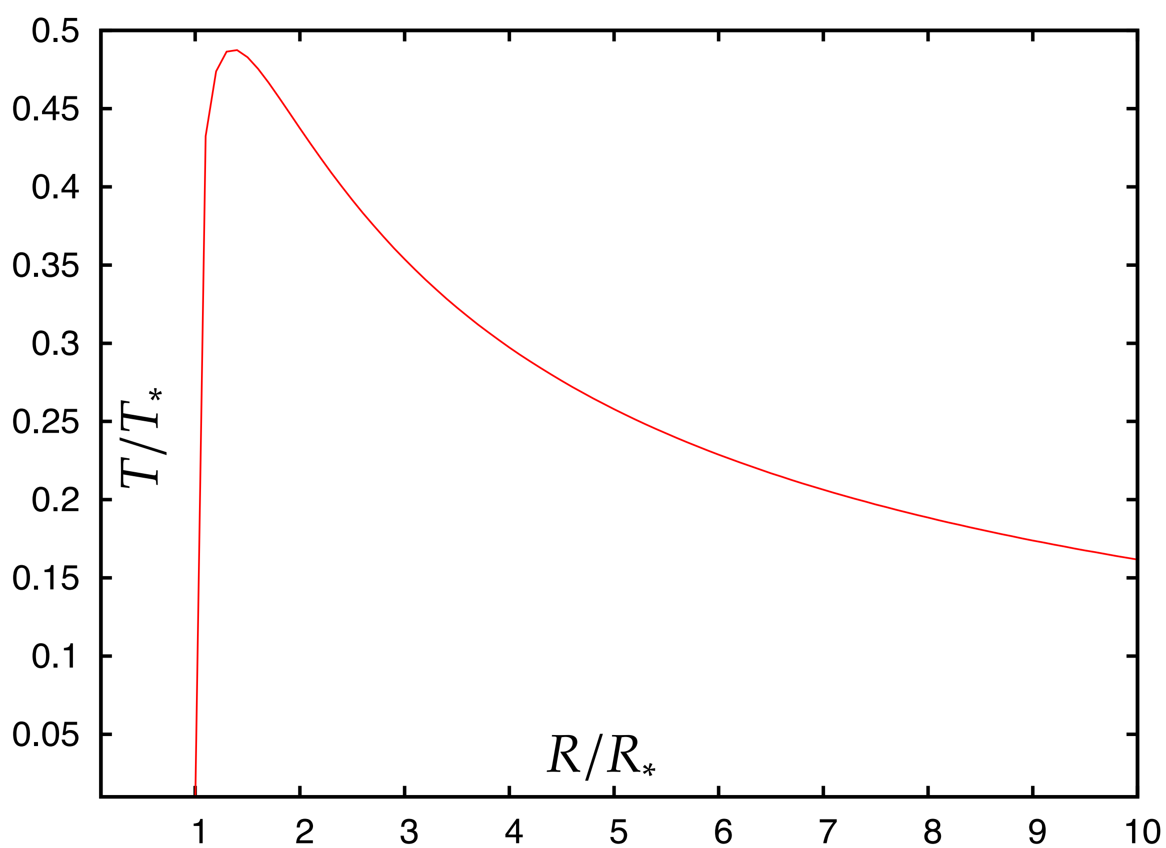
$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = 1.4 \times 10^{18}\ {\rm g/s}\left(\frac{M}{M_\odot}\right)\left(\frac{0.1}{\eta}\right)\mu$$

$\dot{M} > \dot{M}_{\rm Edd}$ may lead to heavy mass loss / common envelope evolution

# Accretion Disk

Disk forms due to angular momentum + viscosity




Keplerian thin accretion disk:

$$\Omega = \sqrt{GM/R^3} \qquad v_\phi = \sqrt{GM/R}$$

$$2\pi R\Sigma(R)v_r(R) = \dot{M}$$ accretion rate

$$\tau(R) = R(2\pi R)\nu\Sigma(R d\Omega/dR)$$ viscous torque

$$\dot{M}\frac{d(R^2\Omega)}{dR} = -\frac{d}{dR}\left[\nu\Sigma 2\pi R^3\frac{d\Omega}{dR}\right]$$

integrating,

$$\nu\Sigma = \frac{\dot{M}}{3\pi}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]$$

viscous dissipation rate per unit area:

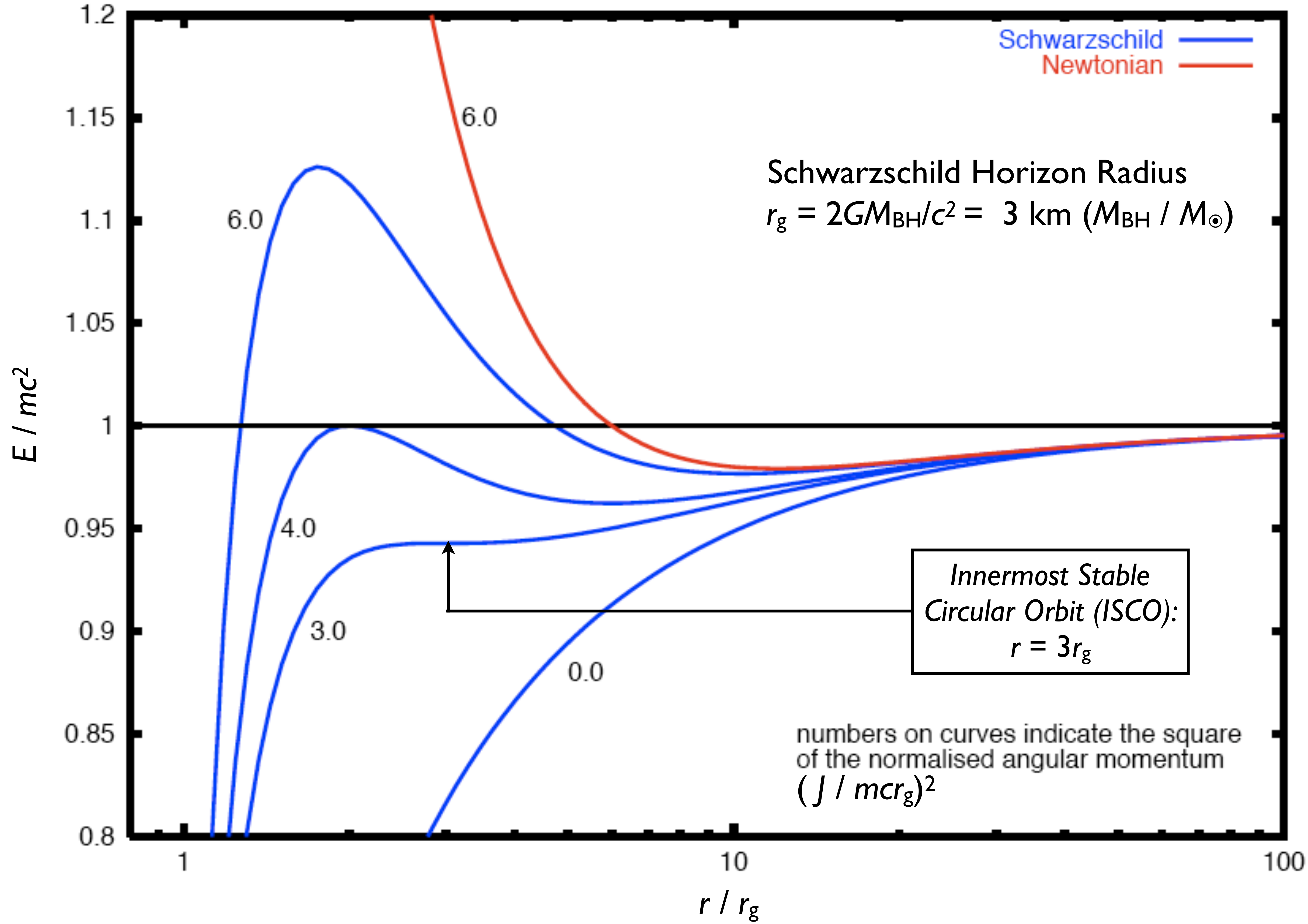
$$D(R) = \nu\Sigma\left(R\frac{d\Omega}{dR}\right)^2 = \frac{3GM\dot{M}}{4\pi R^3}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]$$

balancing this with local blackbody emission:

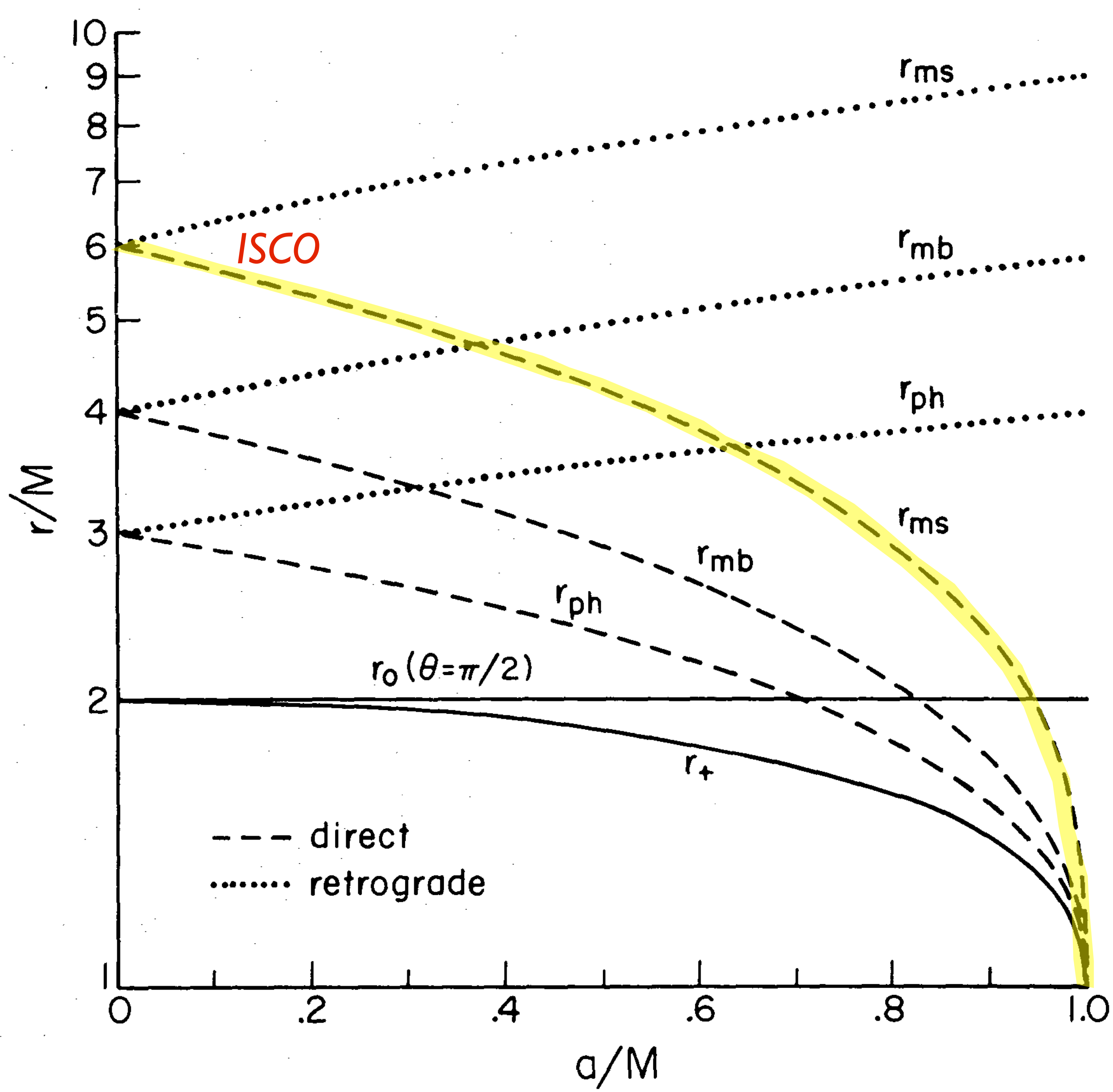
$$T(R) = \left\{\frac{3GM\dot{M}}{8\pi R^3\sigma}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]\right\}^{1/4}$$

$$T_* = \left(\frac{3GM\dot{M}}{8\pi R^3\sigma}\right)^{1/4} = 1.12\ \text{keV}(M/M_\odot)^{1/4}R_6^{-3/4}\dot{M}_{17}^{1/4}$$

# Keplerian motion near a Black Hole



# Critical radii in Kerr Geometry




*Bardeen, Press & Teukolsky 1972*

# Thermal emission from Accretion Disk

Standard Keplerian Disk can extend down to ISCO: $9(M_{BH}/M_\odot)$ km for non-rotating Black Hole, even closer for rotating BH.

Temperature of the disk is a function of radius. For standard optically thick, geometrically thin, keplerian accretion disk

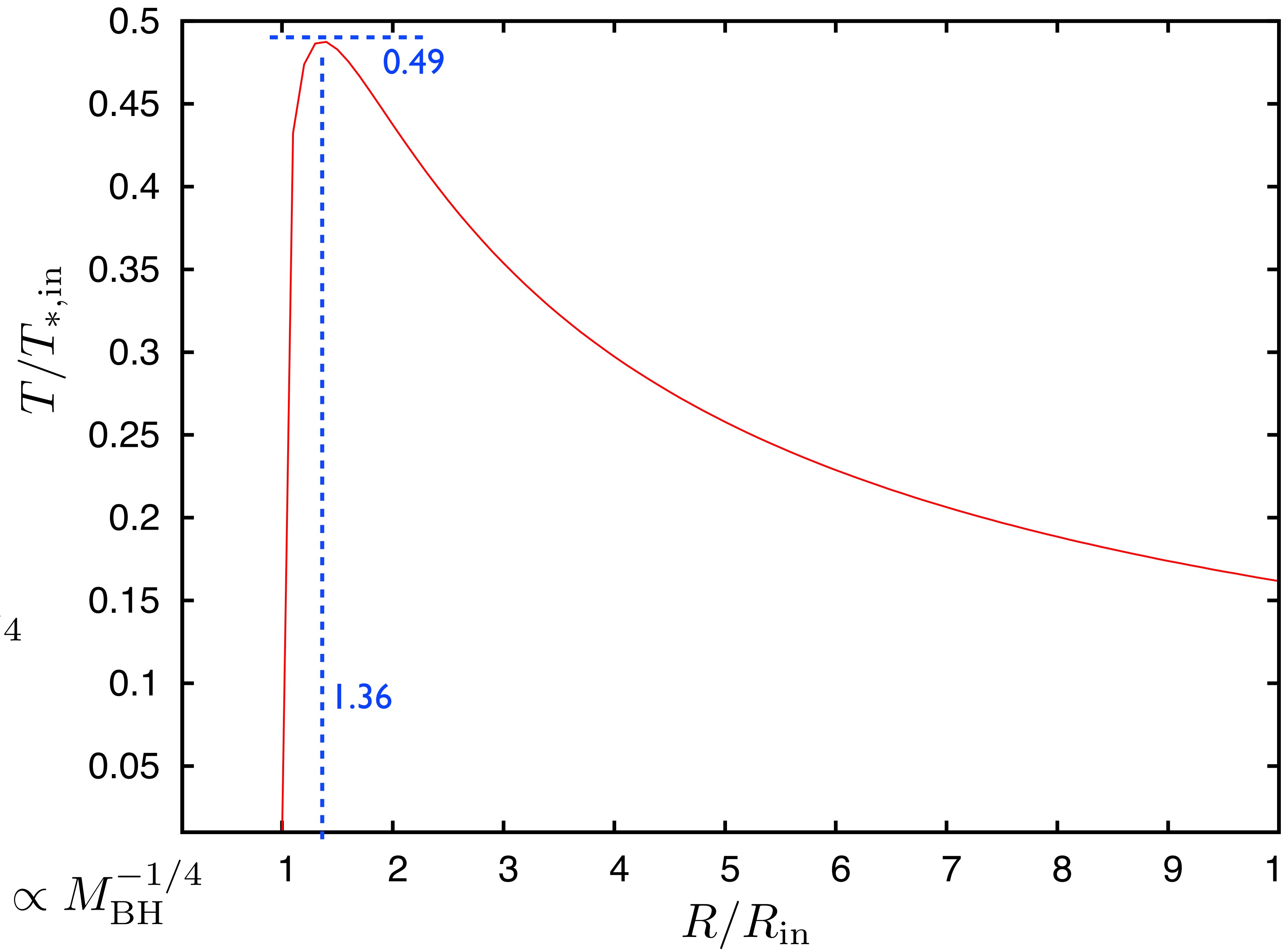
$$T(R) = T_* \left[1 - \left(\frac{R_{in}}{R}\right)^{1/2}\right]^{1/4}$$

where

$$T_* = \left(\frac{3GM\dot{M}}{8\pi R^3 \sigma}\right)^{1/4}$$

$$kT_* = 1.12\,\mathrm{keV}\left(\frac{\dot{M}}{10^{17}\,\mathrm{g/s}}\right)^{1/4} \times \left(\frac{M_{BH}}{M_\odot}\right)^{1/4}\left(\frac{R}{10\,\mathrm{km}}\right)^{-3/4}$$

*Typically soft emission*




"Multicolour Blackbody", $T_{max} \propto M_{BH}^{-1/4}$

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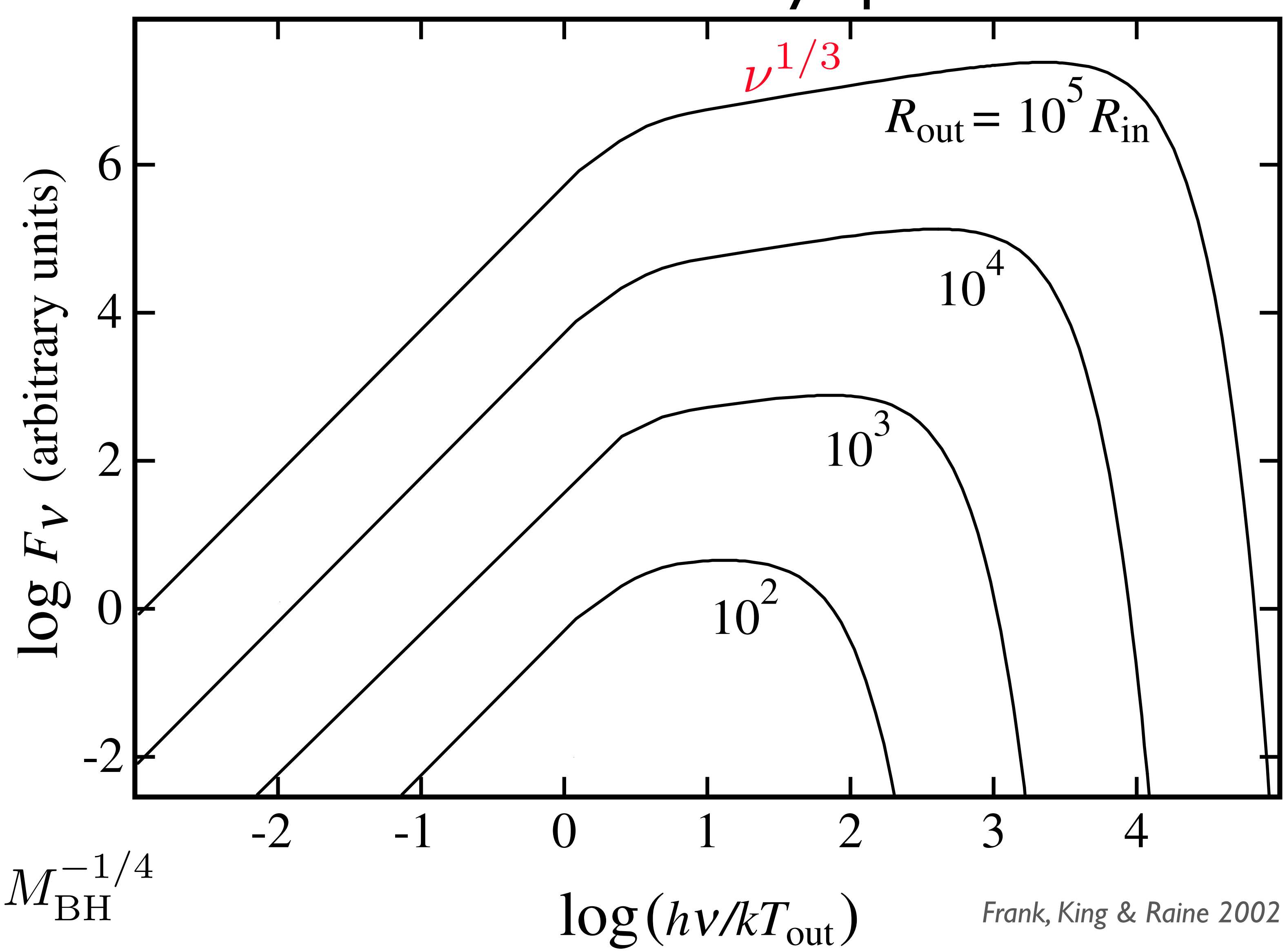
Disk Blackbody spectrum

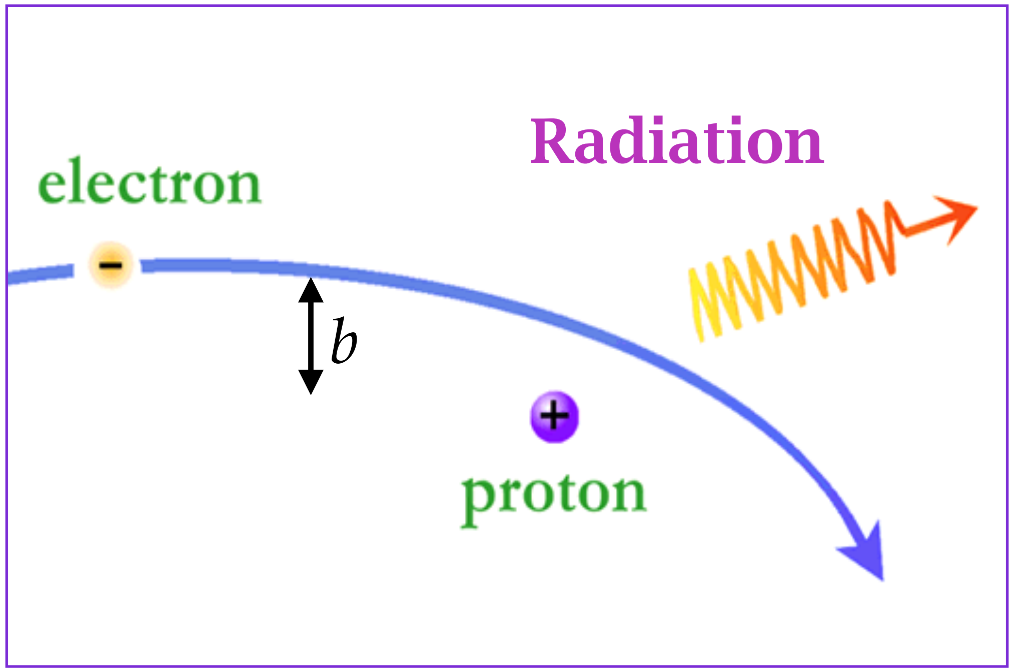


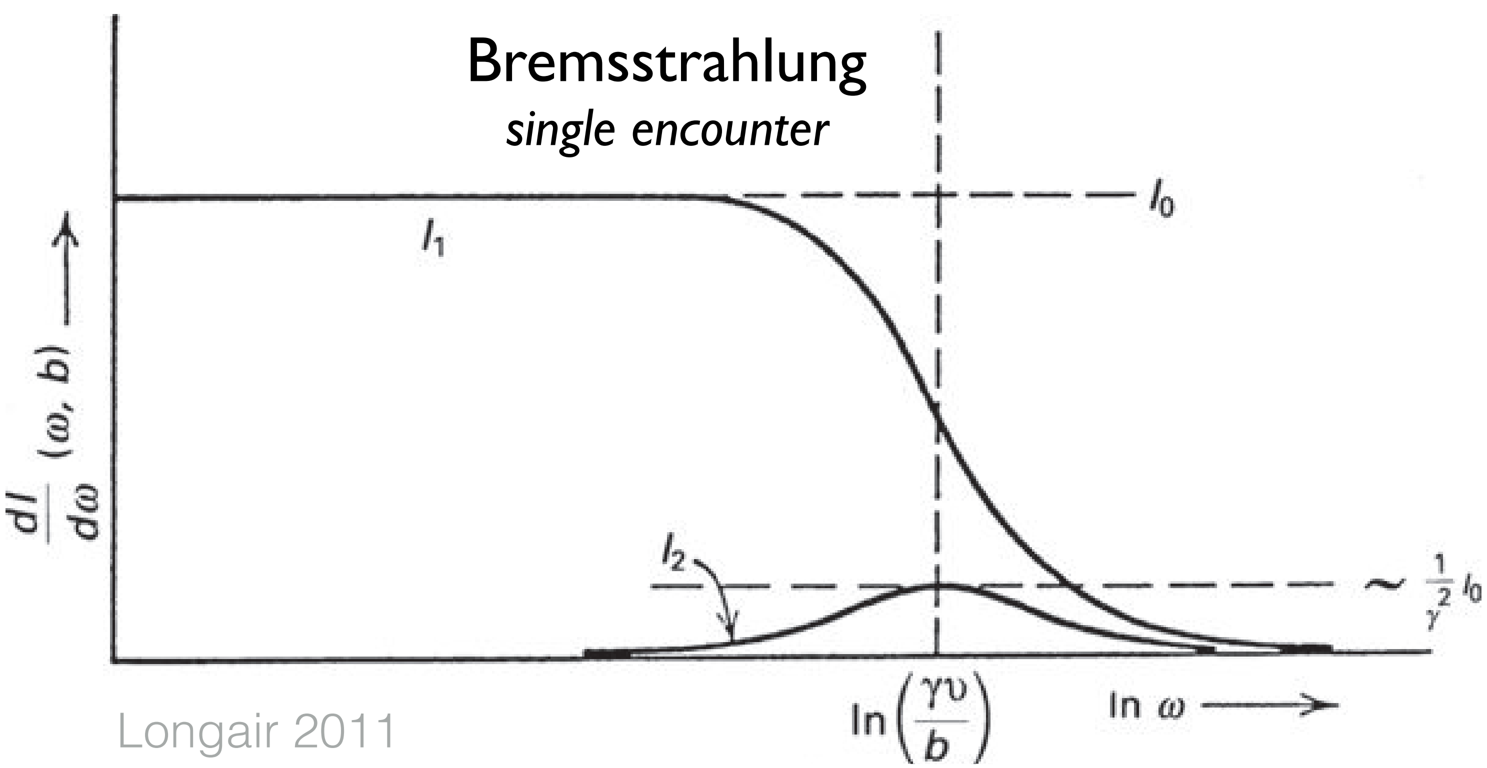

*Frank, King & Raine 2002*

"Multicolour Blackbody", $T_{max} \propto M_{BH}^{-1/4}$

# Continuum Emission Processes

# Bremsstrahlung (*free-free emission*)




Longair 2011

## Spectrum

*Electric field received by the observer is time dependent*

*Fourier transform of the electric field yields the spectrum*

$$I(\omega) = \frac{Z^2 e^6}{24\pi^4 \varepsilon_0^3 c^3 m_e^2 v^2} \frac{\omega^2}{\gamma^2 v^2} \left[ \frac{1}{\gamma^2} K_0^2\left(\frac{\omega b}{\gamma v}\right) + K_1^2\left(\frac{\omega b}{\gamma v}\right) \right]$$

*Net observed spectrum is the sum of spectra from all emitting particles*

$$I(\omega') = \int_{b'_{\min}}^{b'_{\max}} 2\pi b' \gamma N v K \, db'$$

All encounters of a single electron with velocity v

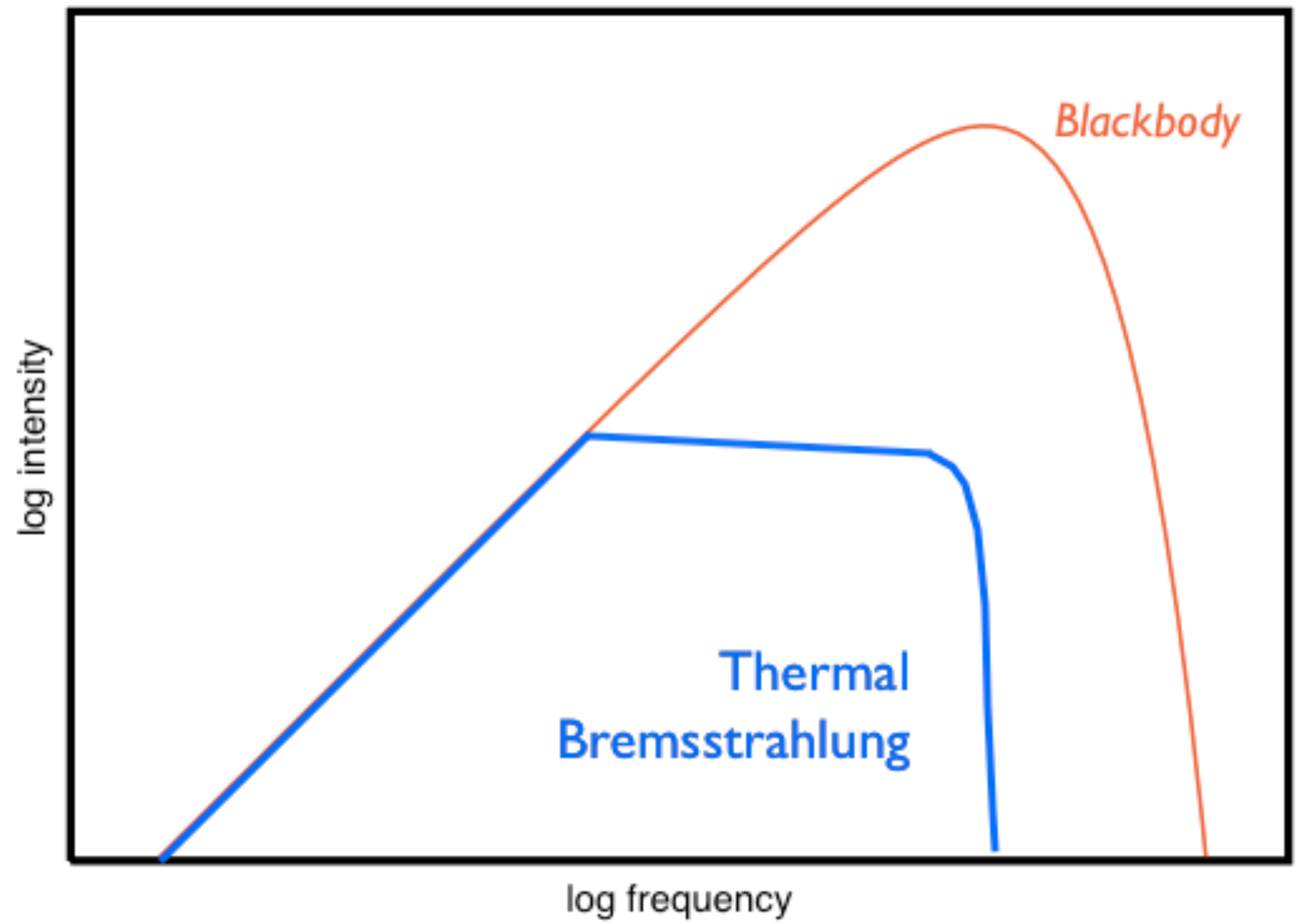
$$= \frac{Z^2 e^6 \gamma N}{12\pi^3 \varepsilon_0^3 c^3 m_e^2} \frac{1}{v} \ln\left(\frac{b'_{\max}}{b'_{\min}}\right)$$

Integrate this over the velocity distribution

# Thermal Bremsstrahlung

## Velocity distribution (Maxwellian)

$$N_e(v)\,dv = 4\pi N_e \left(\frac{m_e}{2\pi kT}\right)^{3/2} v^2 \exp\left(-\frac{m_e v^2}{2kT}\right) dv$$




## Emission per unit volume

$$I(\omega) \approx \frac{Z^2 e^6 N N_e}{12\sqrt{3\pi^3}\varepsilon_0^3 c^3 m_e^2}\left(\frac{m_e}{kT}\right)^{1/2} g(\omega, T)$$

$$g(\omega, T) = e^{-\hbar\omega/kT}\bar{g}_{ff}$$

## Emission coefficient :

$$\epsilon_\nu^{ff} = 6.8\times10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT}\bar{g}_{ff} \text{ erg s}^{-1}\text{ Hz}^{-1}\text{ cm}^{-3}$$

Bolometric: $\epsilon^{ff} = 1.4\times10^{-27} Z^2 n_e n_i T^{1/2}\bar{g}_{ff}$ erg s$^{-1}$ cm$^{-3}$

all $n$ values in cm$^{-3}$

## Free-free absorption coefficient:

$$\alpha_\nu^{ff} = 3.7\times10^{8} Z^2 n_e n_i T^{-1/2}\nu^{-3}\left(1-e^{-h\nu/kT}\right)\bar{g}_{ff} \text{ cm}^{-1}$$

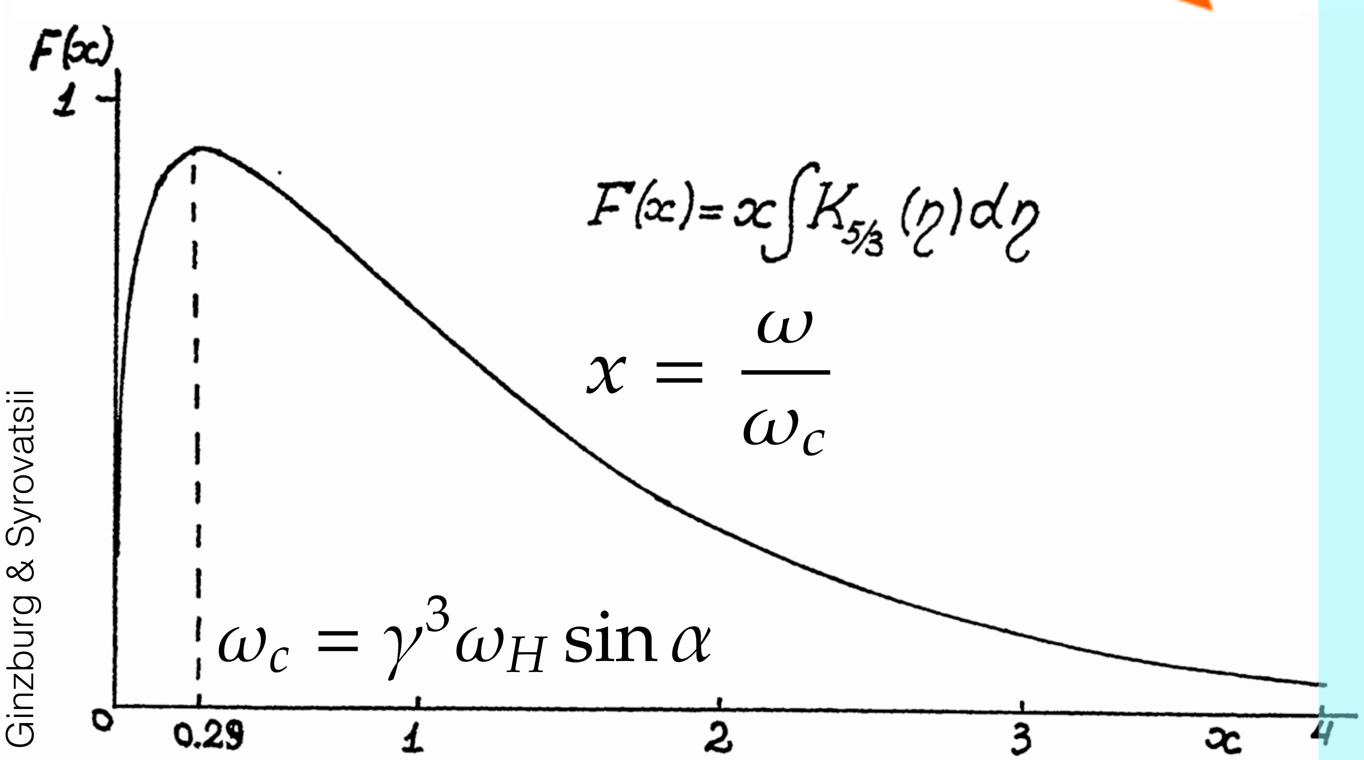
$$\approx 4.5\times10^{-25} Z^2 n_e n_i (kT)_{keV}^{-3/2}\nu_{MHz}^{-2}\bar{g}_{ff} \text{ cm}^{-1}$$

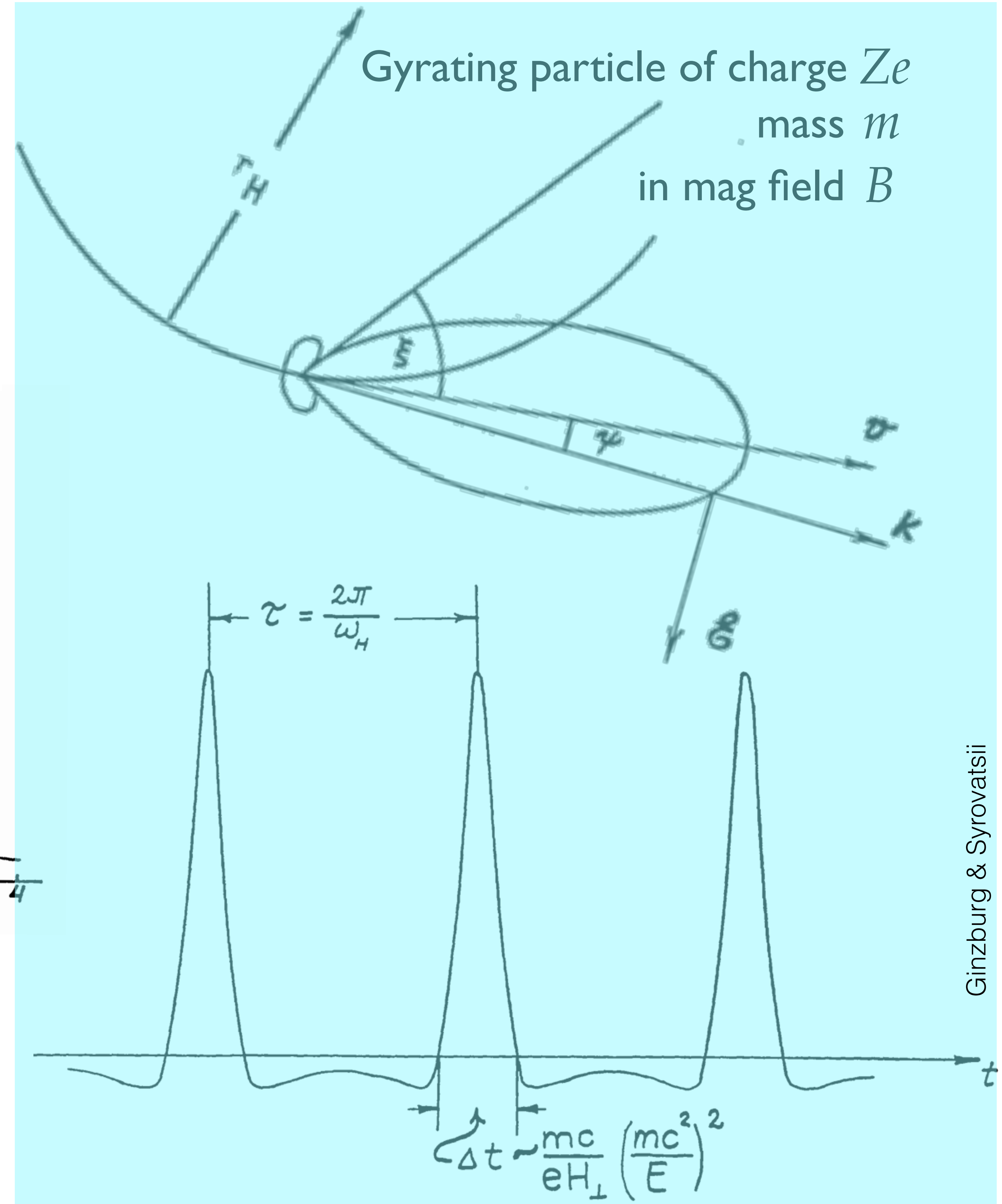
## Compare Thomson:

$$\alpha_T = n_e\sigma_T = 6.65\times10^{-25} n_e \text{ cm}^{-1}$$

# Relativistic electron in a magnetic field

## Synchrotron Radiation


$$\nu_{\rm peak} = 0.29\frac{\omega_c}{2\pi} \approx 0.81\gamma^2\left(\frac{B}{1\,\rm G}\right)\frac{Zm_e}{m}\ \text{MHz}$$

$$\text{Power} = \frac{4}{3}\sigma_T c\beta^2\gamma^2 U_B\left(\frac{Z^2 m_e}{m}\right)^2$$

$$= 2.0\times10^{-14}\gamma^2\left(\frac{B}{1\,\rm G}\right)^2\left(\frac{Z^2 m_e}{m}\right)^2\ \text{erg / s per particle}$$

# Curvature Radiation

*Relativistic Charged Particles moving* ***along*** *curved field lines*

- Shares most properties of Synchrotron Radiation (replace Larmor radius by the radius of curvature of field lines)

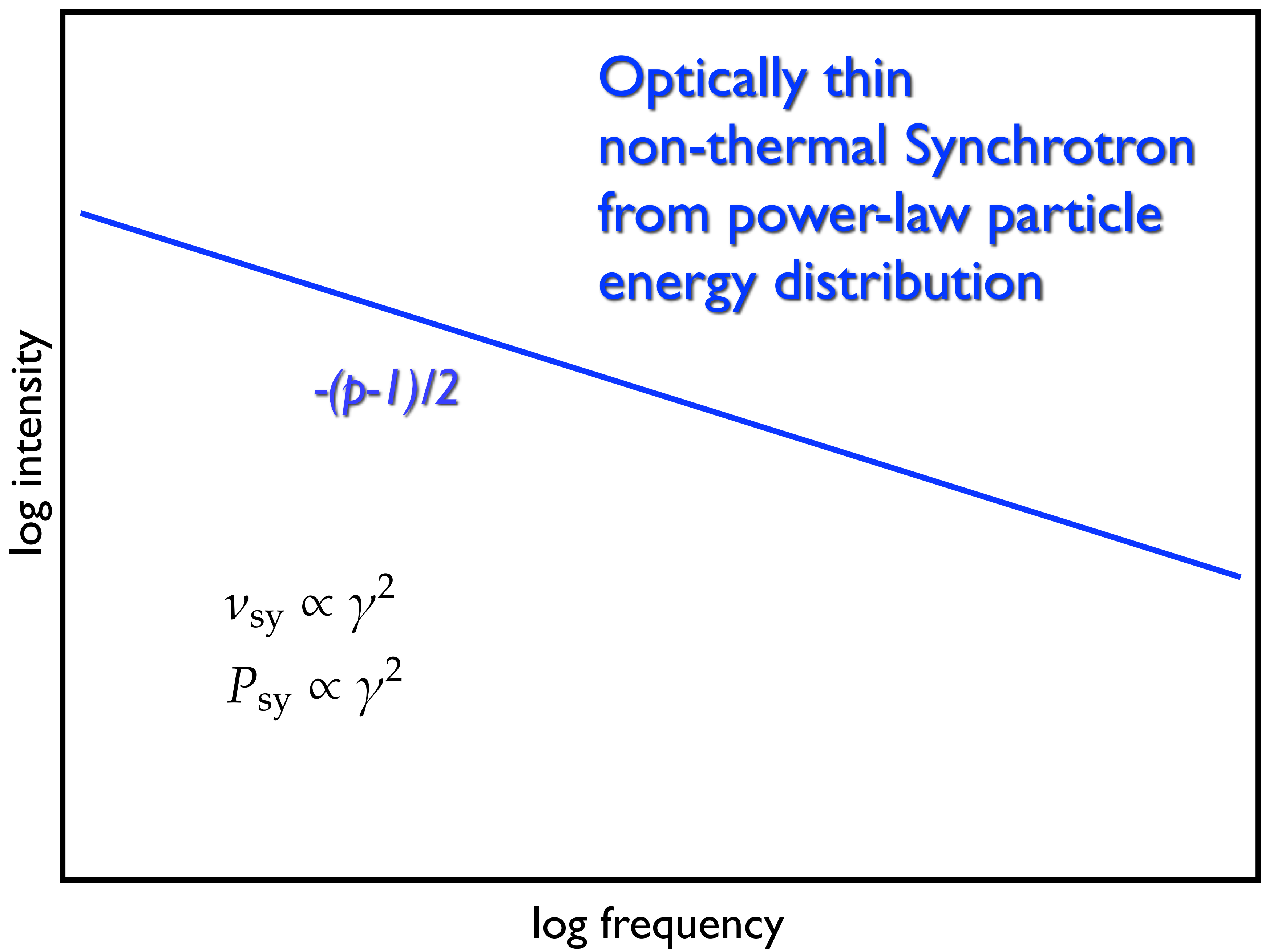
- Polarization || to the projected field lines (Synchrotron: polarization perp. to projected B)

**Important in pulsar magnetospheres, magnetars**

# Non-thermal Emission

Acceleration processes generating relativistic particles often produce a non-thermal, power-law distribution of particle energies: $N(\gamma) \propto \gamma^{-p}$

This produces a power-law synchrotron radiation spectrum:

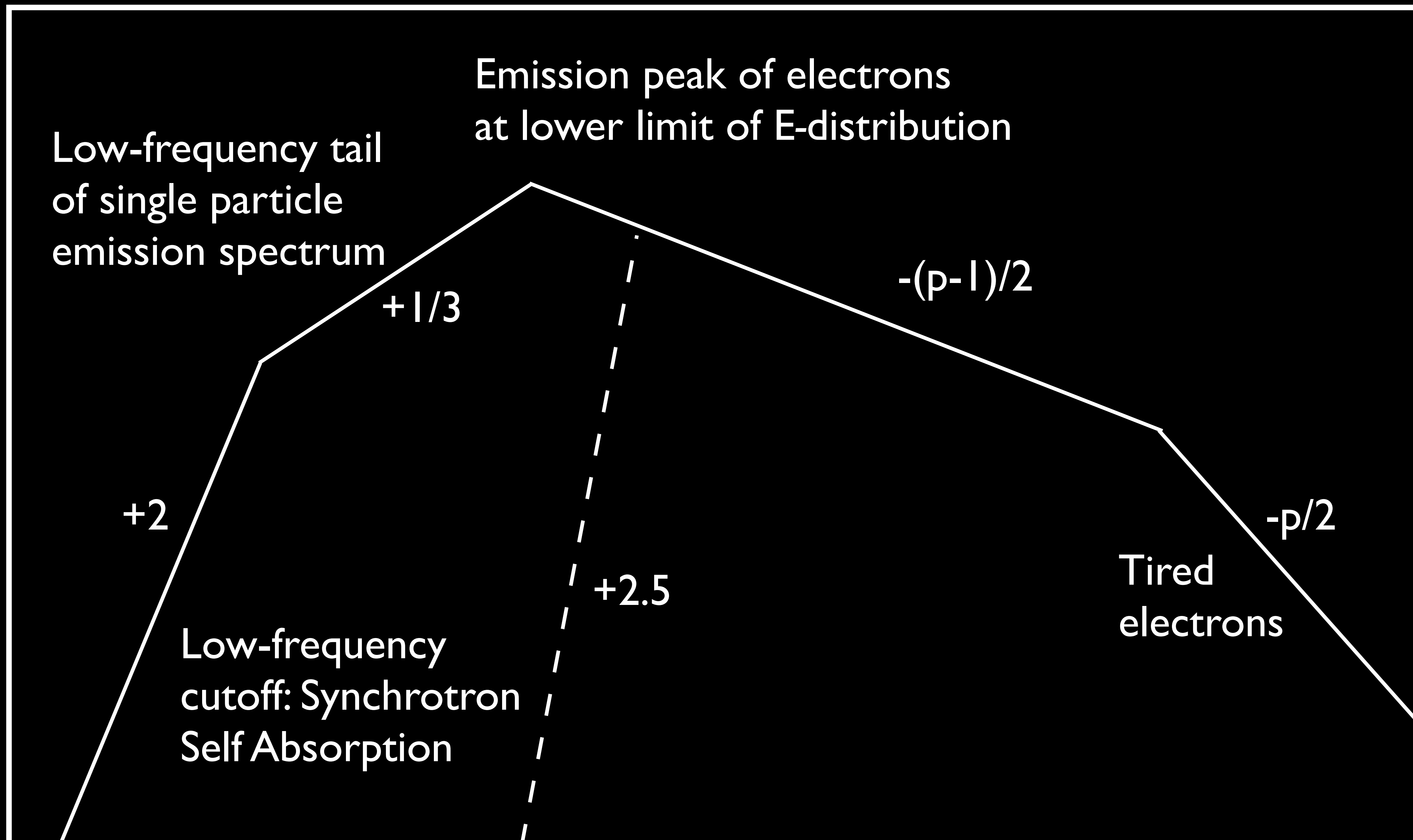



$j_\nu \propto \nu^{-(p-1)/2}$

$\alpha_\nu \propto \nu^{-(p+4)/2}$

$S_\nu \propto \nu^{5/2}$

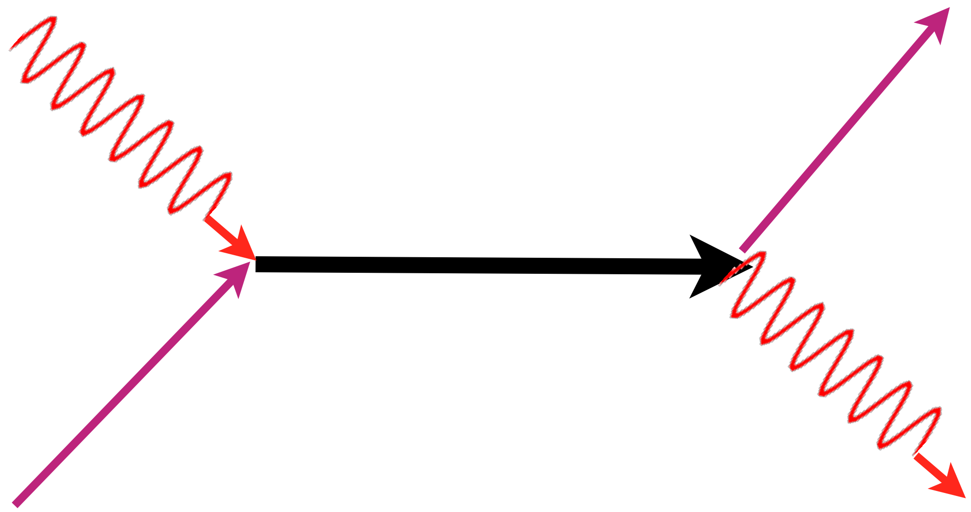
# Spectral regimes in Synchrotron Emission




Jitter radiation can steepen the low-frequency cutoff:

- Low energy particles have longer duration of E-field pulse per orbit
- More affected by pitch angle scattering before pulse completion

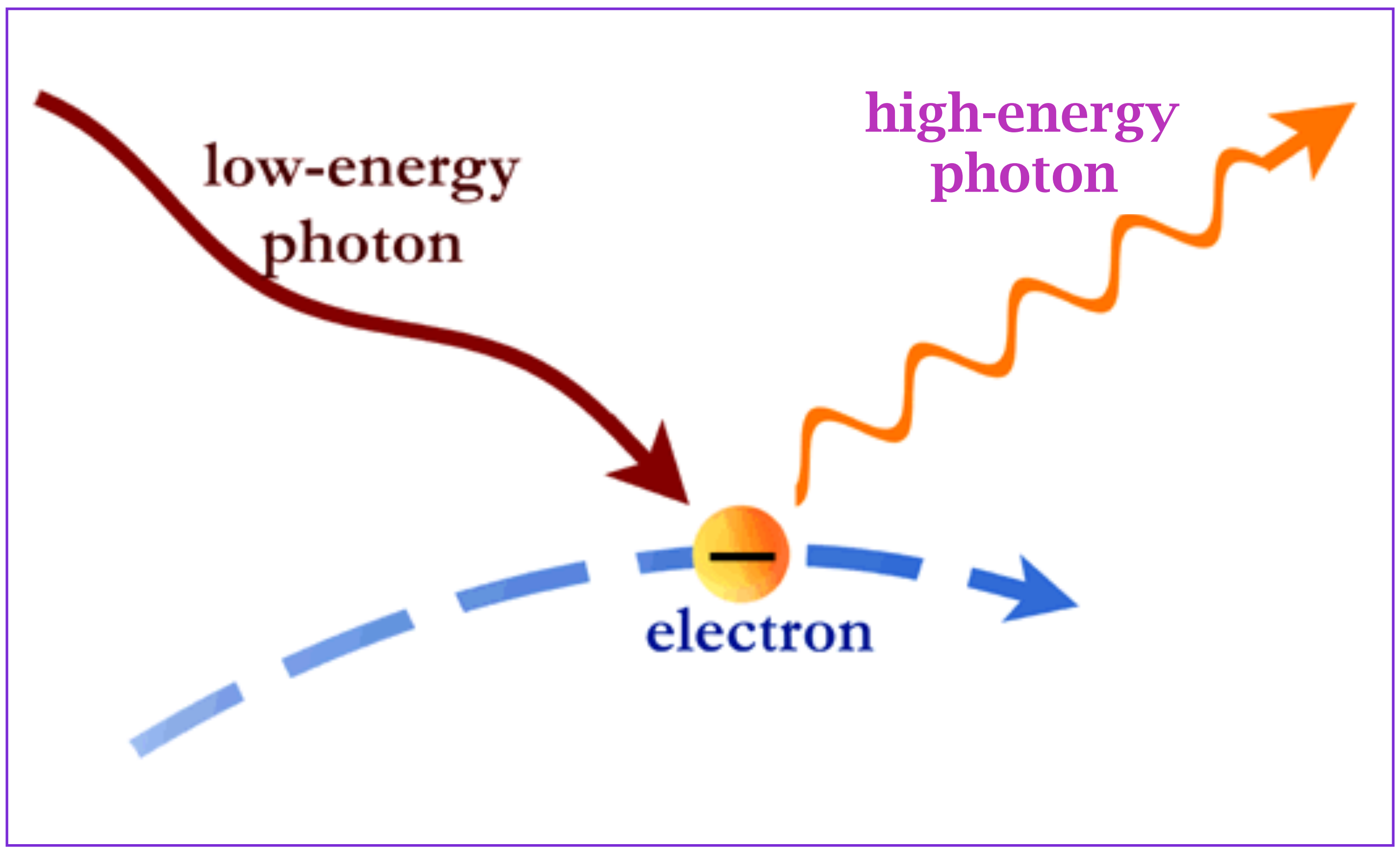
*(Medvedev 2000)*



# Scattering processes

*Non-resonant / resonant*

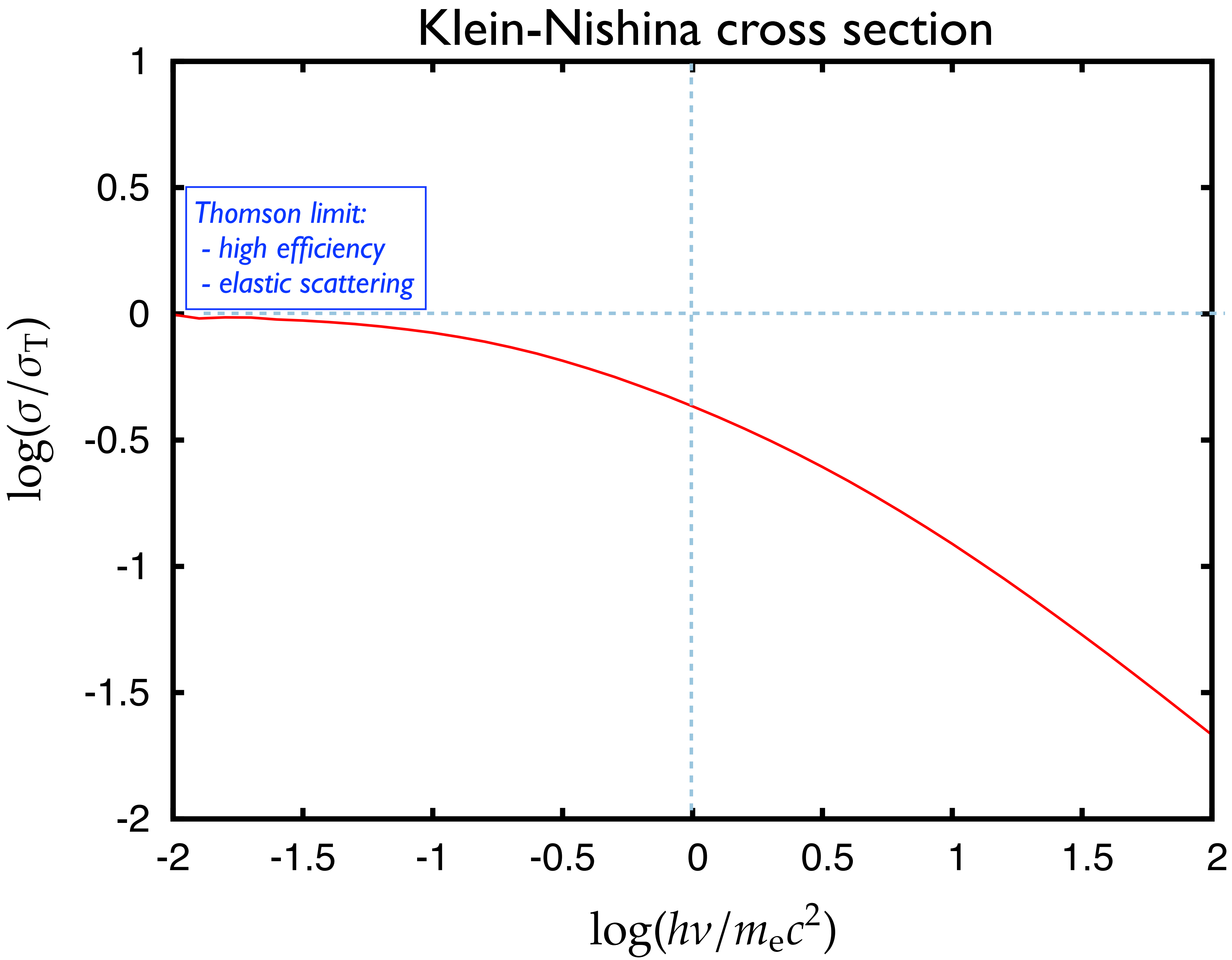
Inverse Compton Scattering




Related processes: Compton Scattering
Thomson Scattering

# Compton Scattering

Thomson cross section $\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65 \times 10^{-25}\,\mathrm{cm}^2$



# Inverse Compton Process

Synchrotron power: $\frac{4}{3}\sigma_T c\beta^2\gamma^2 U_B$

Compton power: $\frac{4}{3}\sigma_T c\beta^2\gamma^2 U_{\rm ph}$

per electron

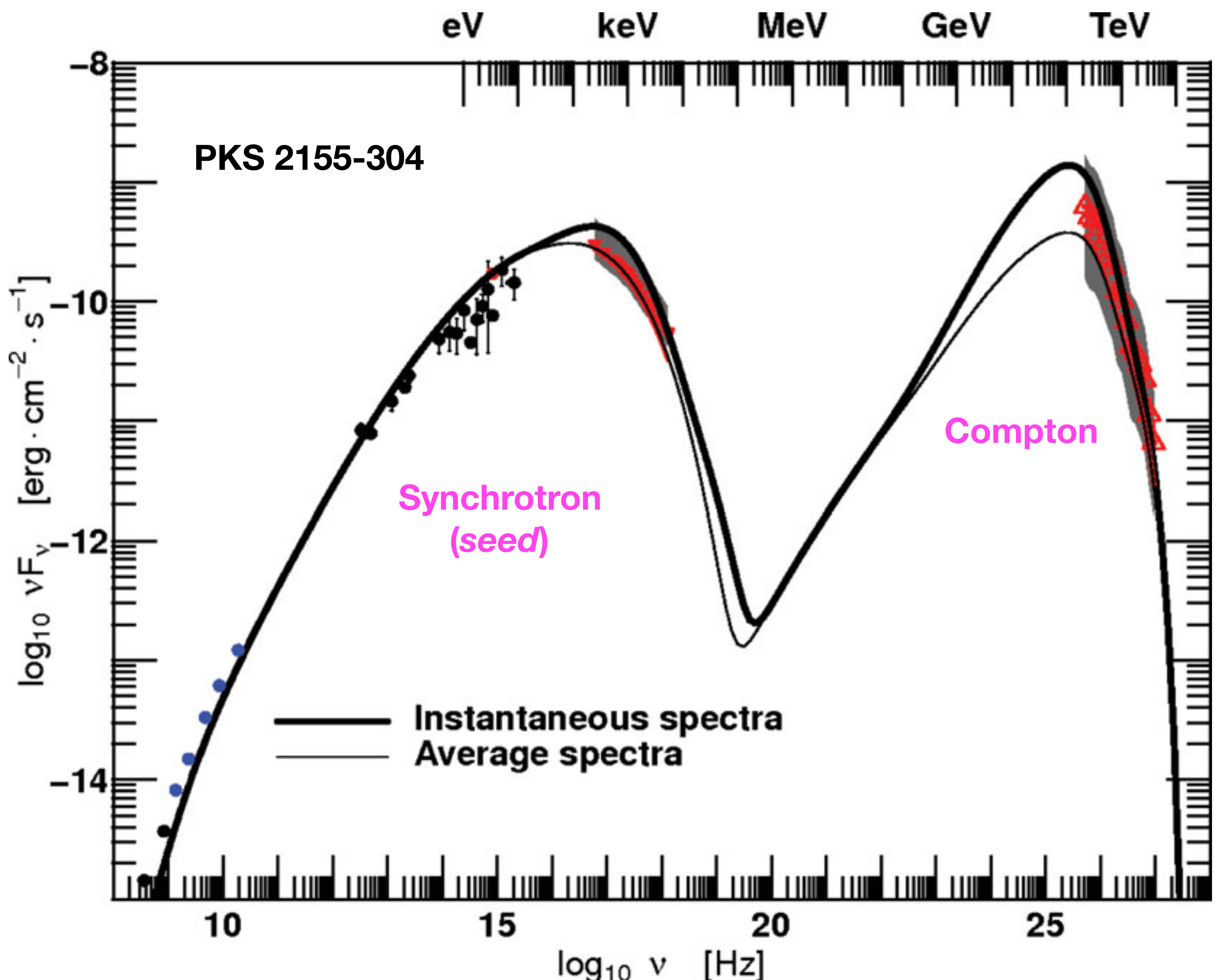
Scattered photon energy

$$\nu_{\rm i} : \nu' : \nu_{\rm f} = 1 : \gamma : \gamma^2$$

Like Synchrotron, here too $\nu_{\rm sc} \propto \gamma^2$ and $P_{\rm sc} \propto \gamma^2$

So ***non-thermal*** IC by electron energy distribution $N(\gamma) \propto \gamma^{-p}$ leads to a optically thin radiation spectrum $I_\nu \propto \nu^{-(p-1)/2}$

Synchrotron photons produced in an emission volume may be compton upscattered by the same electrons: *Synchrotron Self Compton*




Helene et al 2012

# Thermal Comptonization

- Thermal distribution of electron energies
- Repeated scatterings
- Energy transfer both ways: electron $\rightleftharpoons$ photon

*In general, numerical radiative transfer required to describe spectra adequately*

## The Compton y parameter : *a measure of importance of comptonization*

$y$ = (av. no. of scatterings) x (mean fractional energy change per scattering)

Electron scattering optical depth $\tau_{\mathrm{es}} \sim \sigma_{\mathrm{T}} R$

$\Rightarrow$ Av. number of scatterings = Max$(\tau_{\mathrm{es}}.\tau_{\mathrm{es}}^2)$

$\left(\frac{\Delta\epsilon}{\epsilon}\right)$ = Max $(\alpha, \alpha^2)$

per scattering

$[\alpha = 4kT/m_{\mathrm{e}}c^2]$

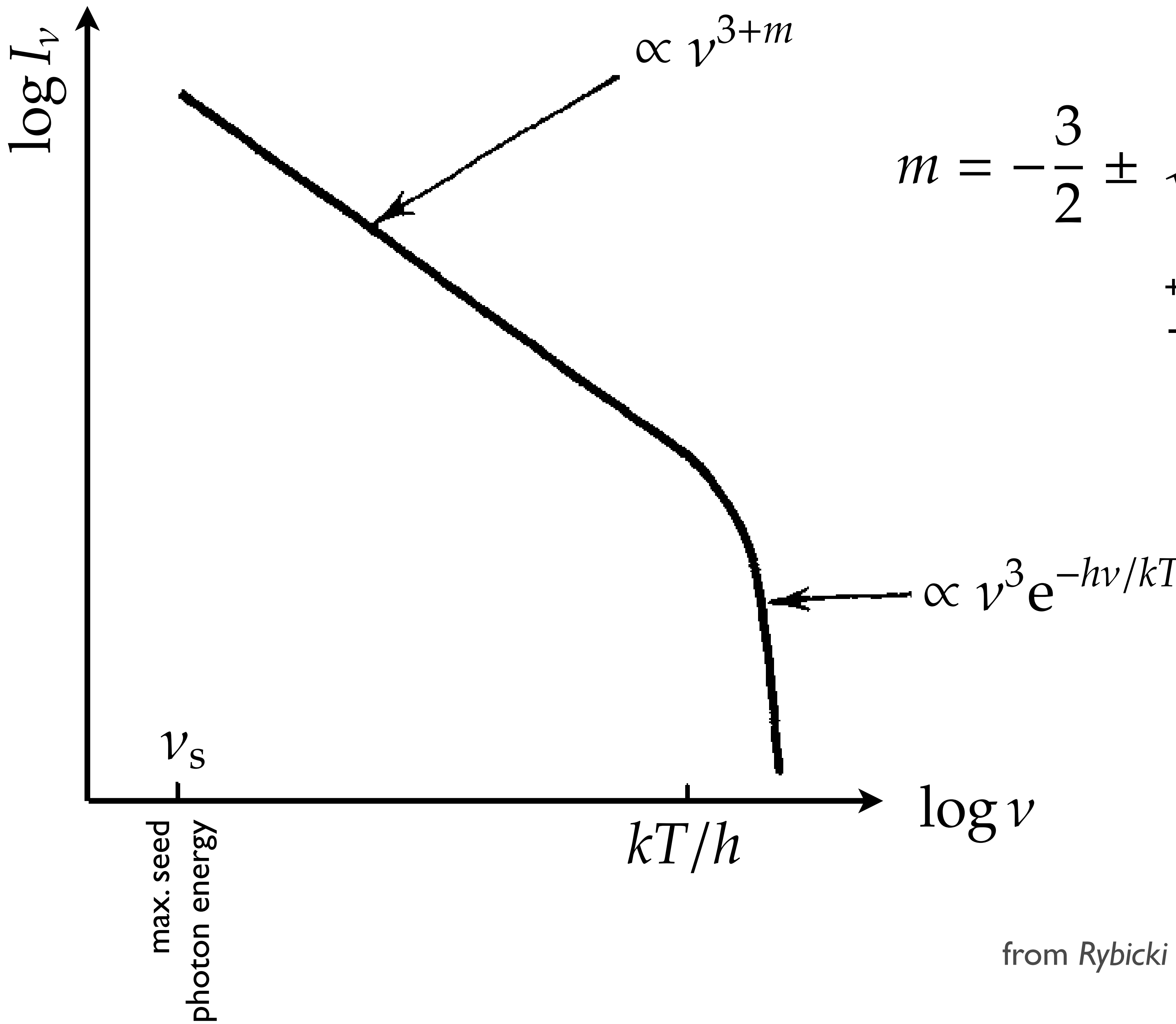
For $\alpha \gg 1$ and soft photon input $(\epsilon_{\mathrm{i}} \ll m_{\mathrm{e}}c^2/\alpha)$, emergent intensity $I(\epsilon) \propto \epsilon^{-k}$ if $\tau_{\mathrm{es}}$ is small. Here $k = -\ln(\tau_{\mathrm{es}})/\ln(\alpha^2)$

For $\alpha \ll 1$ (non-relativistic electrons), photons random walk in energy space.

Can be described by a Boltzmann Equation $\Rightarrow$ *Kompaneets Equation*

Result can be diverse, but some limiting cases have interesting properties

# Non-relativistic thermal Comptonization: *Unsaturated*

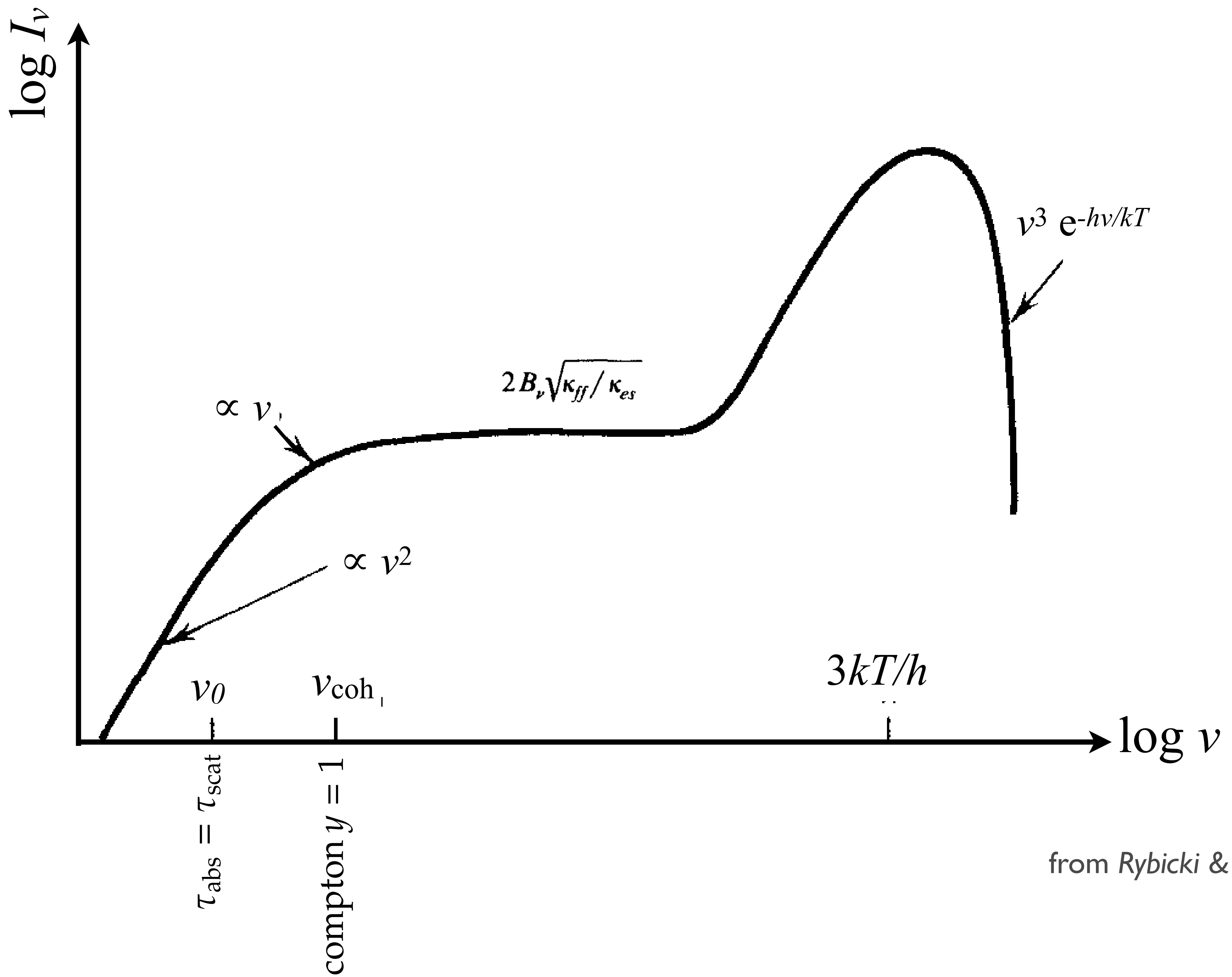



$$m = -\frac{3}{2} \pm \sqrt{\frac{9}{4} + \frac{4}{y}}$$

+ve for y >> 1
-ve for y << 1

from *Rybicki & Lightman 1979*

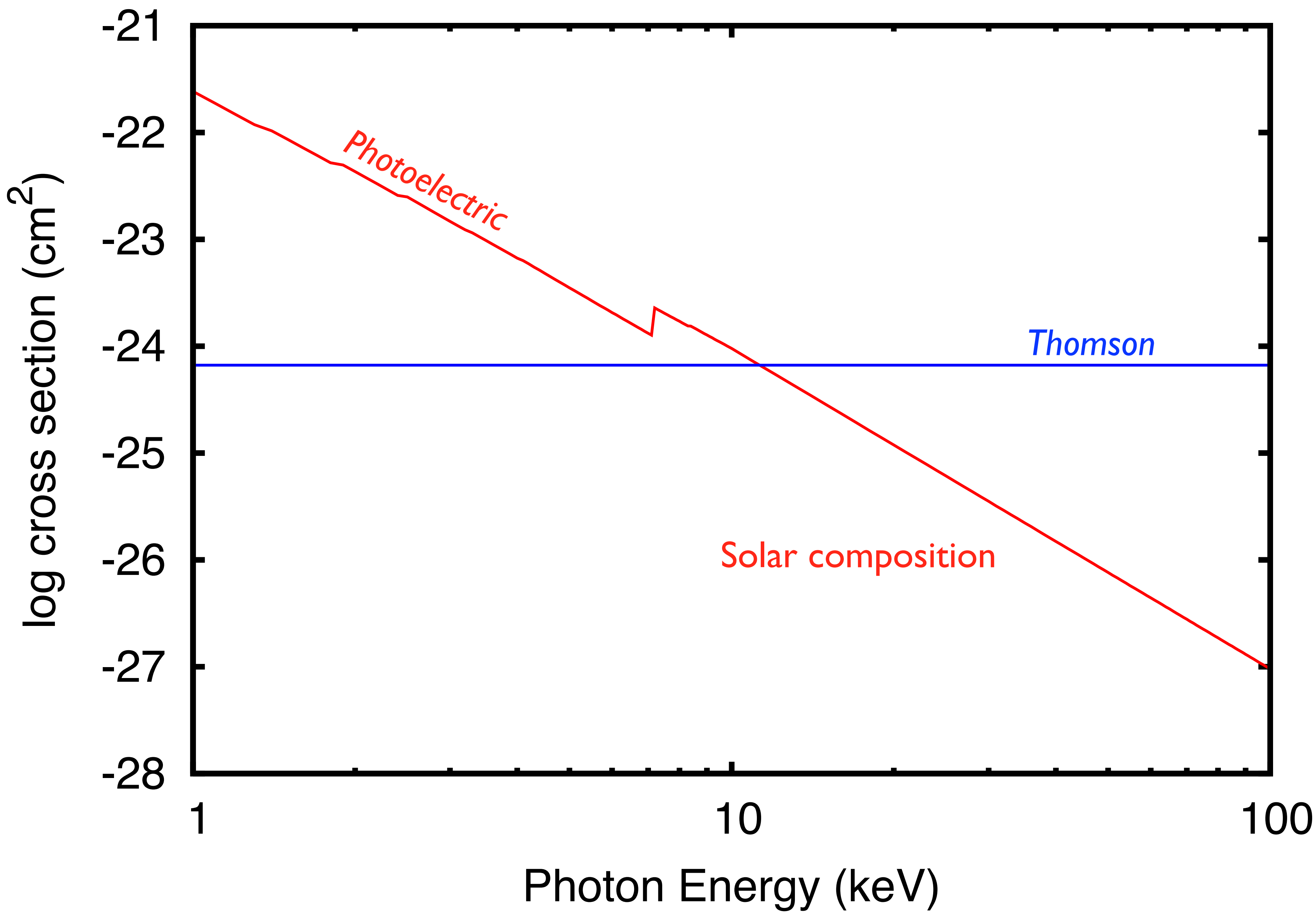
# Non-relativistic thermal Comptonization: *Saturated*




from *Rybicki & Lightman 1979*

# Compton Reflection (backscatter) from the accretion disk

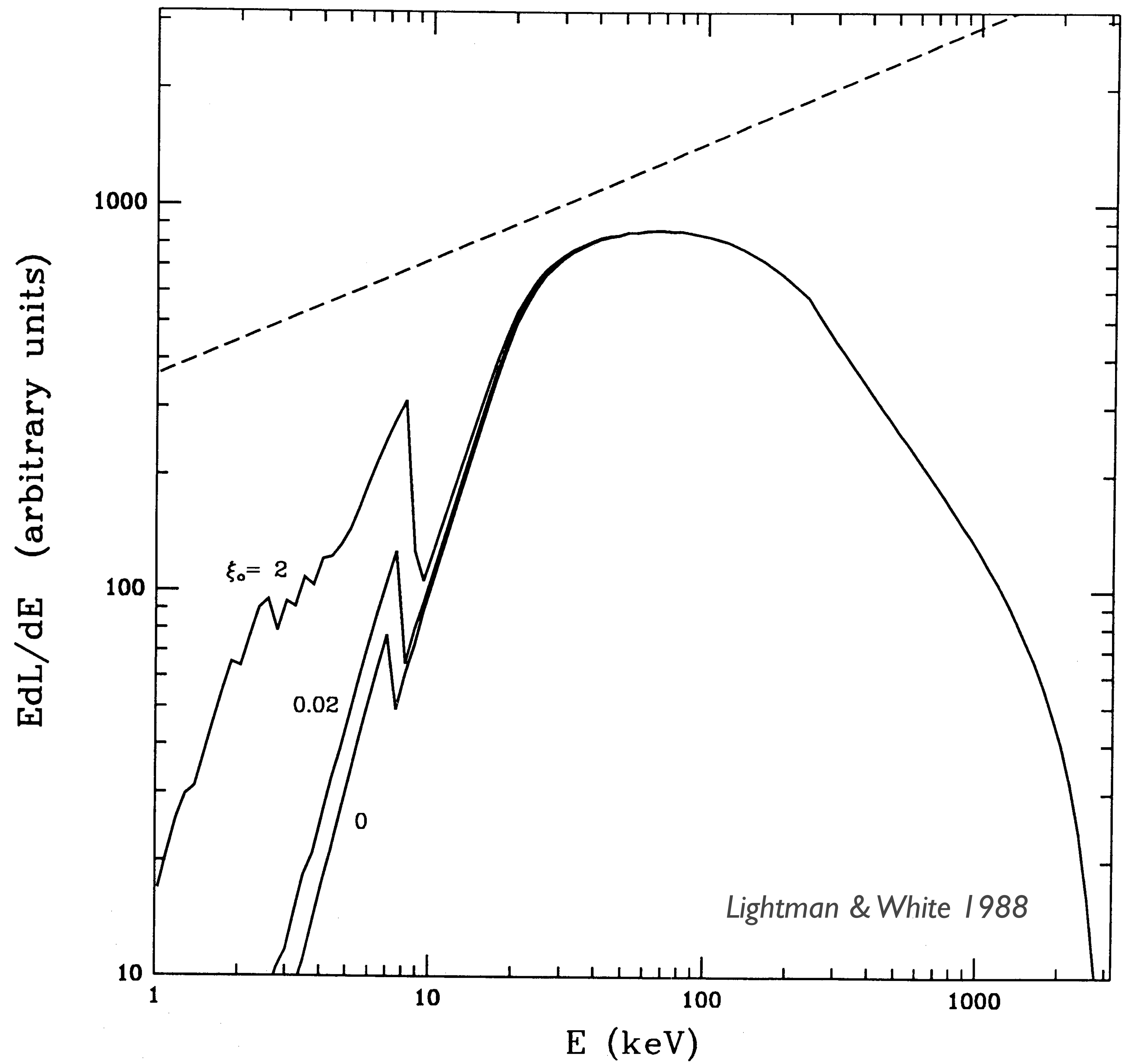
- Ineffective below 10 keV due to photoelectric absorption




- Drops above ~50 keV due to photon energy loss and KN cutoff

*Results in a broad reflection hump in hard X-rays*

# Compton Reflection (backscatter) from the accretion disk



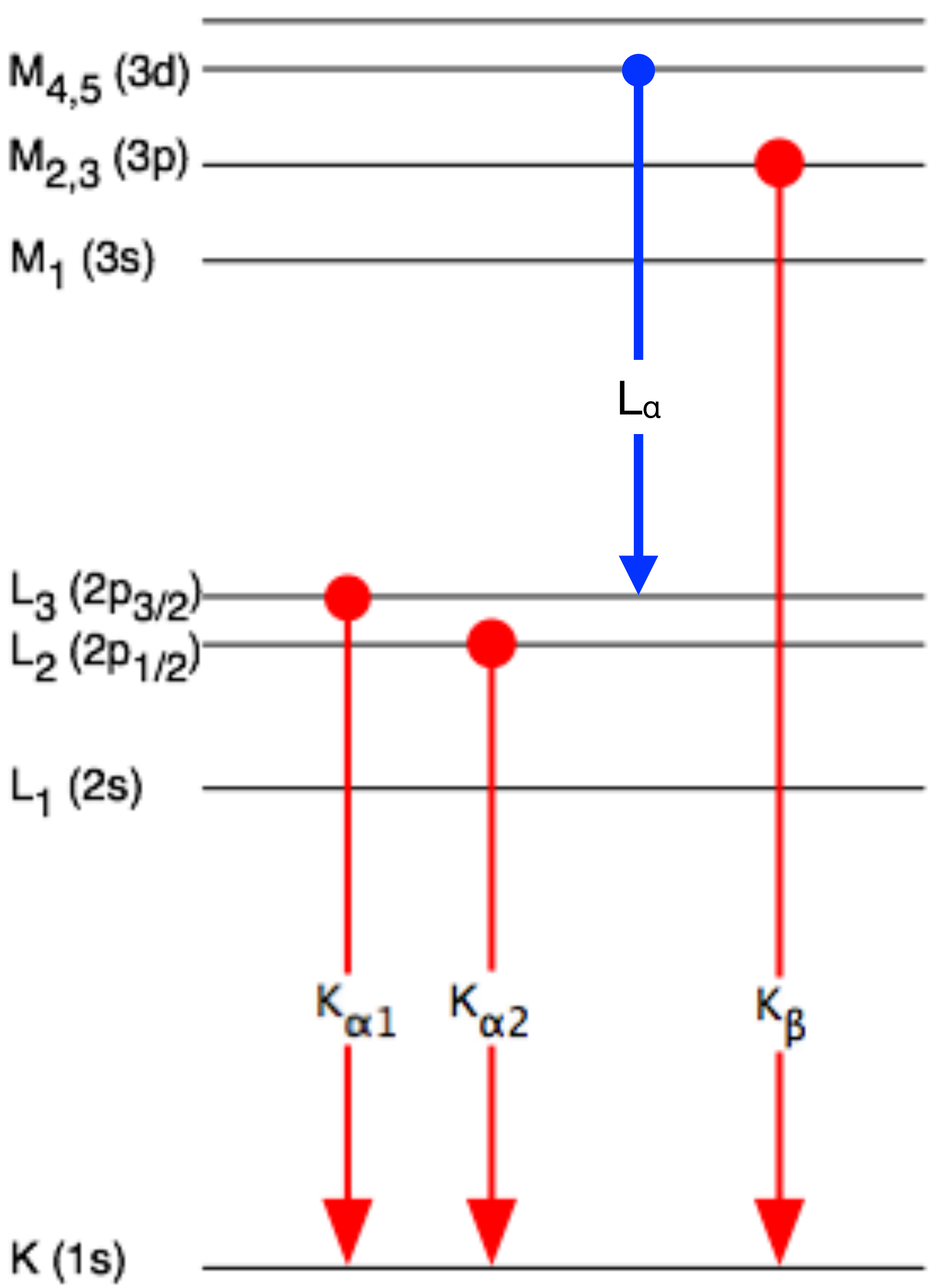

*Results in a broad reflection hump in hard X-rays*

# Line emission

# X-ray Spectral lines

Characteristic X-ray lines are generated by inner shell transitions

Can be used to identify elements



# X-ray Spectral lines

Gas at high temperature may be highly ionised

Abundance of different ionisation states determined by statistical equilibrium

- Photoionisation
- Collisional ionisation (*impact, charge exchange*)
- Autoionisation

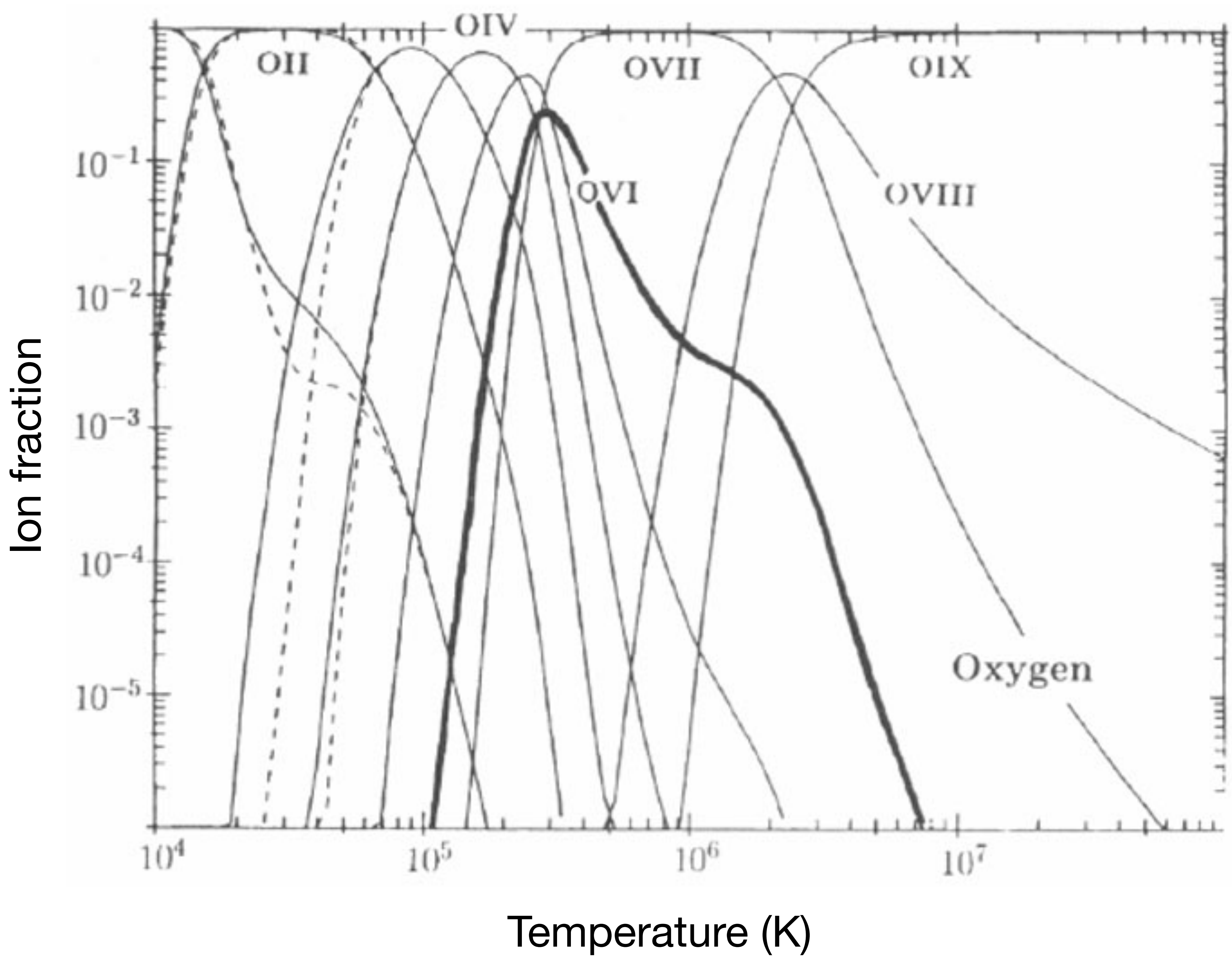
- Radiative recombination
- Charge exchange
- Dielectronic recombination

Detailed balance ⇒ Saha ionisation equilibrium

In general no detailed balance.
Statistical equilibrium: net upward = net downward
Rate equations to be solved to determine population

In rapidly evolving systems (e.g. young SNRs) ionisation equilibrium may not be reached ⇒ *NEI*

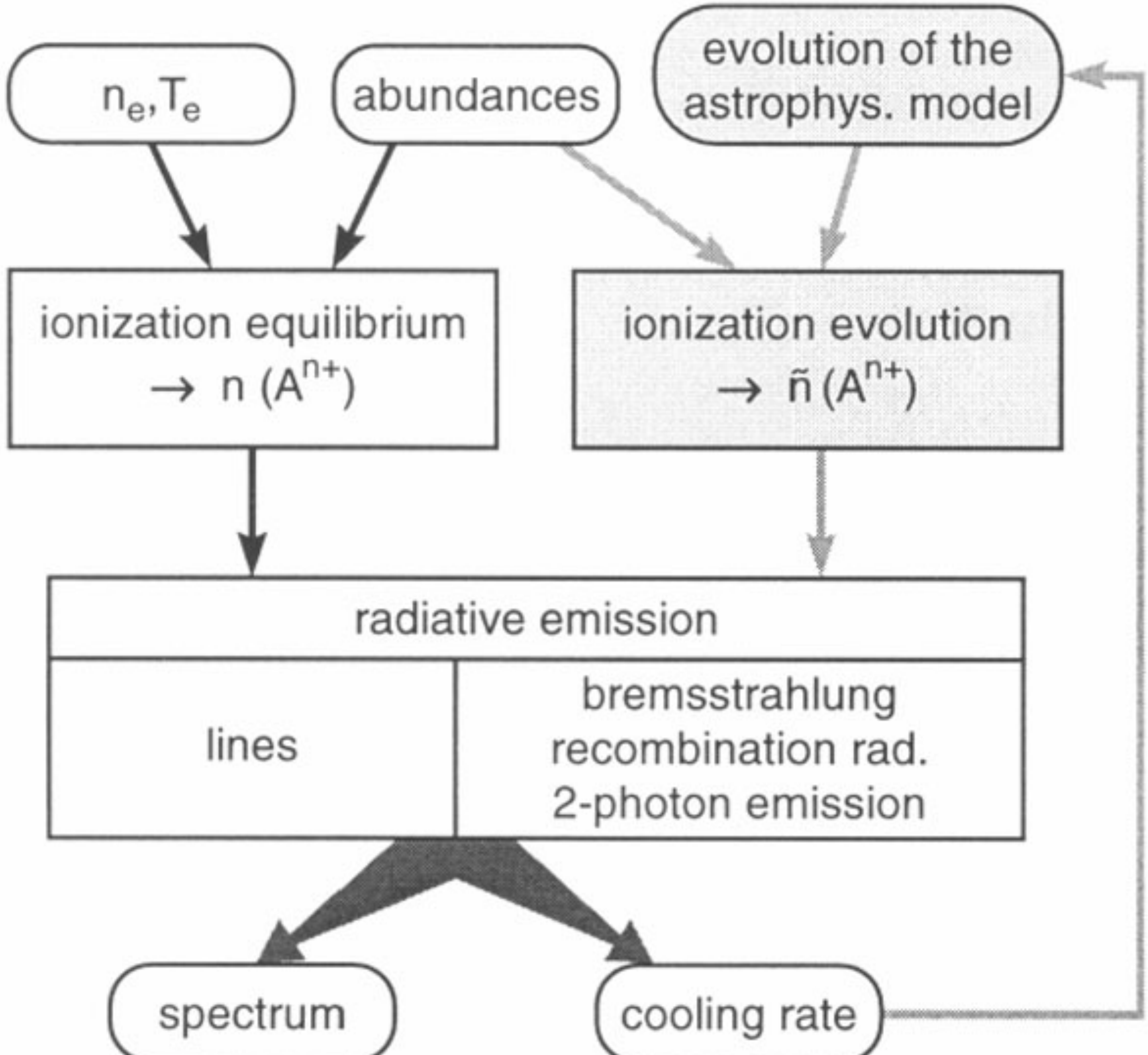
# Thermal Equilibrium Ionisation



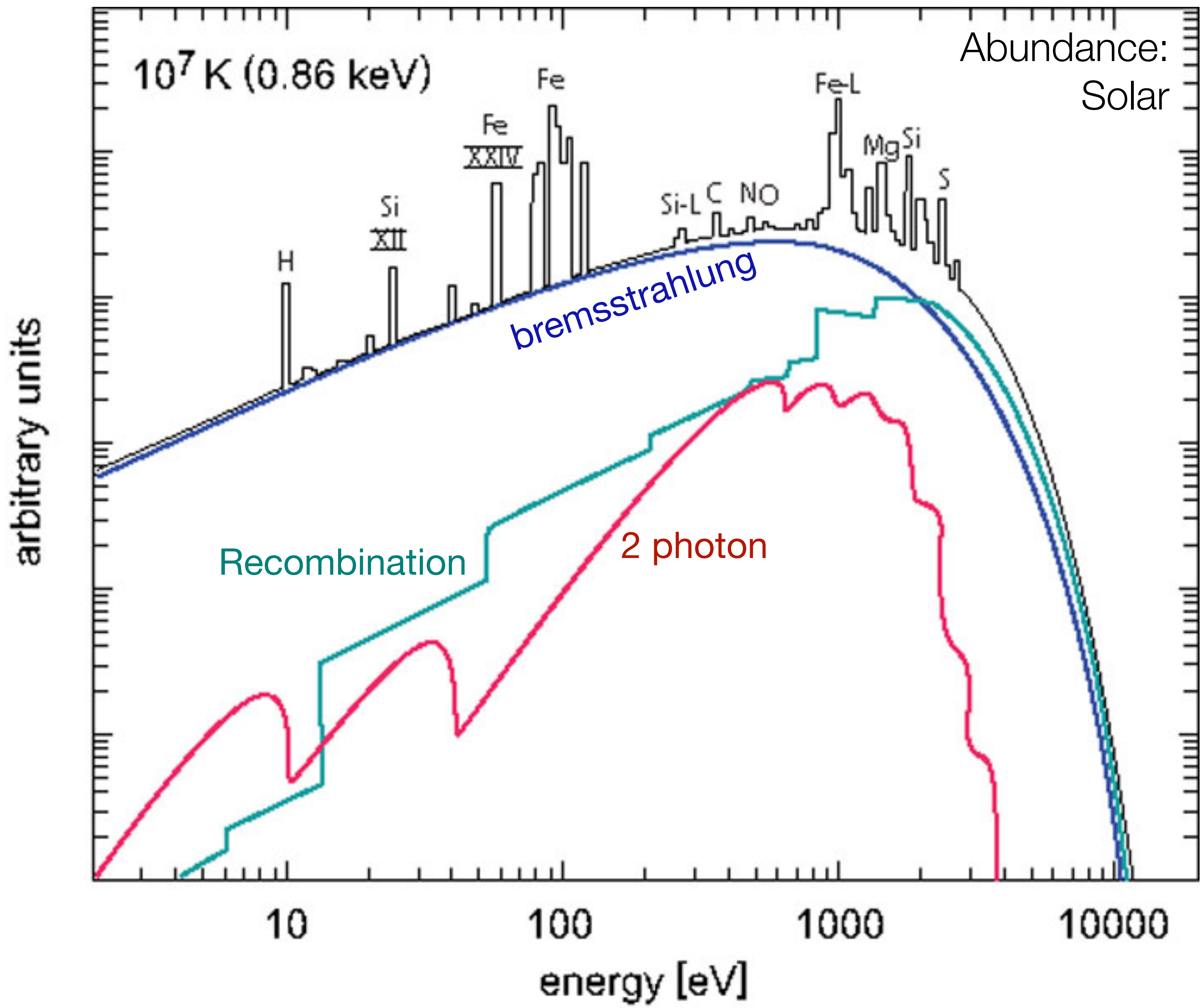

Böhringer 1998

# Computation of radiation from tenuous hot plasma

Transition rates from AtomDB




Böhringer 1998

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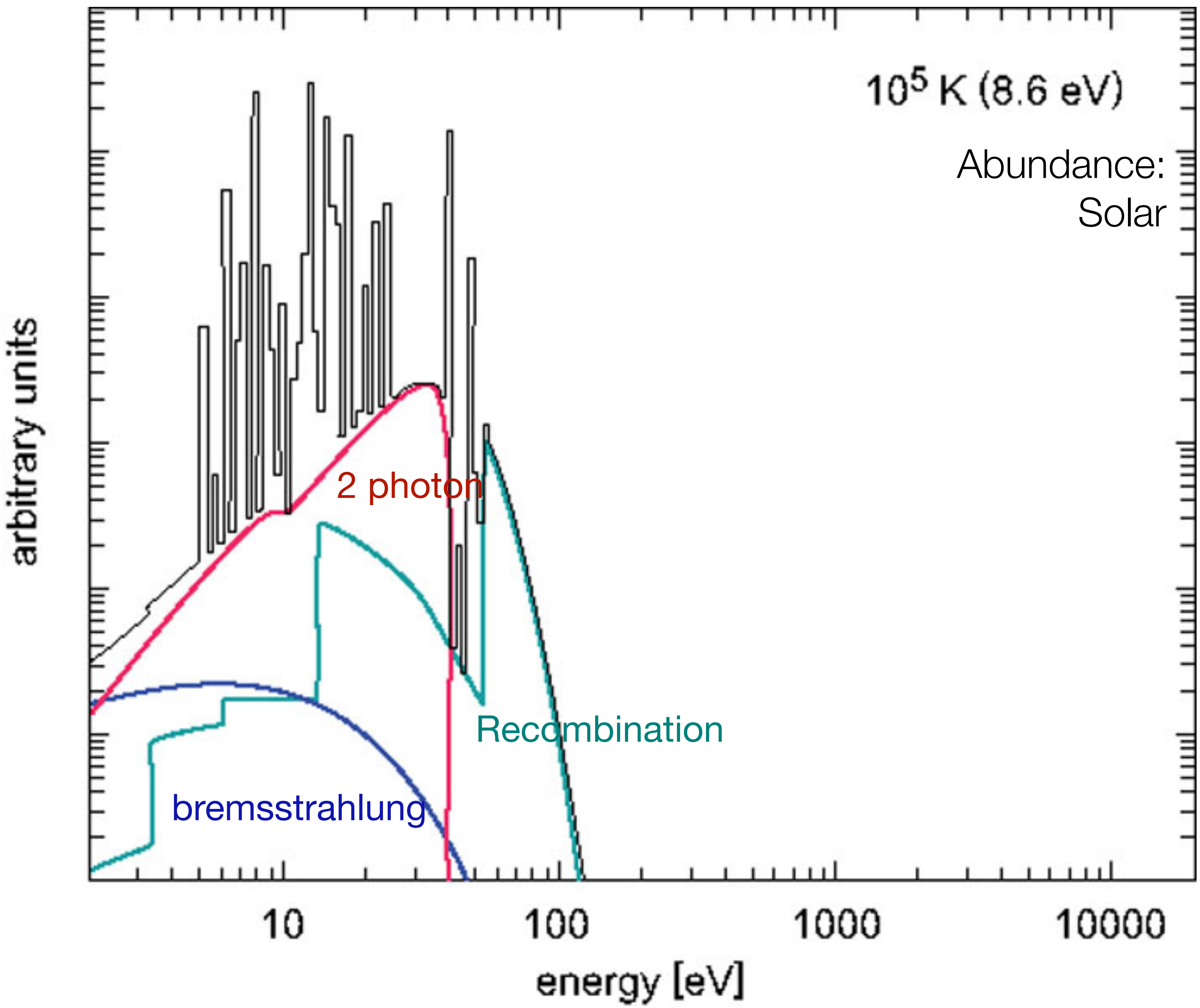


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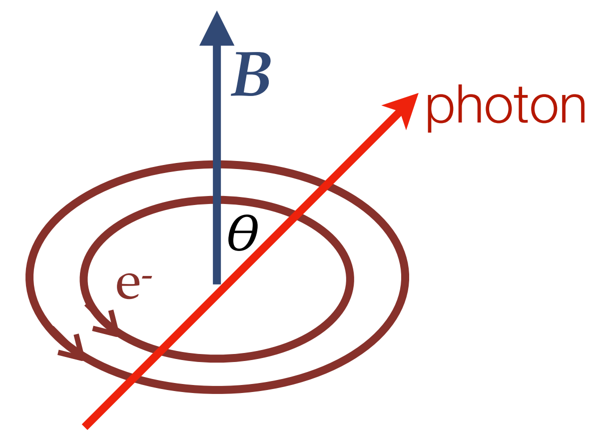
# Electron in a magnetic field

$$\frac{p_{\perp n}}{m_{\rm e}c} = \sqrt{2n(B/B_{\rm crit})} \;\; ; \;\; n = 0, 1, 2, \ldots$$

$$B_{\rm crit} = \frac{m_{\rm e}^2 c^3}{e\hbar} \sim 4.4 \times 10^{13}\ {\rm G}$$




$$E_n = \sqrt{m_{\rm e}^2 c^4 + c^2(p_{\parallel}^2 + p_{\perp n}^2)}$$

For $p_{\parallel} = 0$ and $B << B_{\rm crit}$

$$E_n - m_{\rm e}c^2 = n\hbar\omega_{ce}$$

$$\hbar\omega_{ce} \sim 12\, B_{12}\ {\rm keV}$$

Cyclotron Resonance:

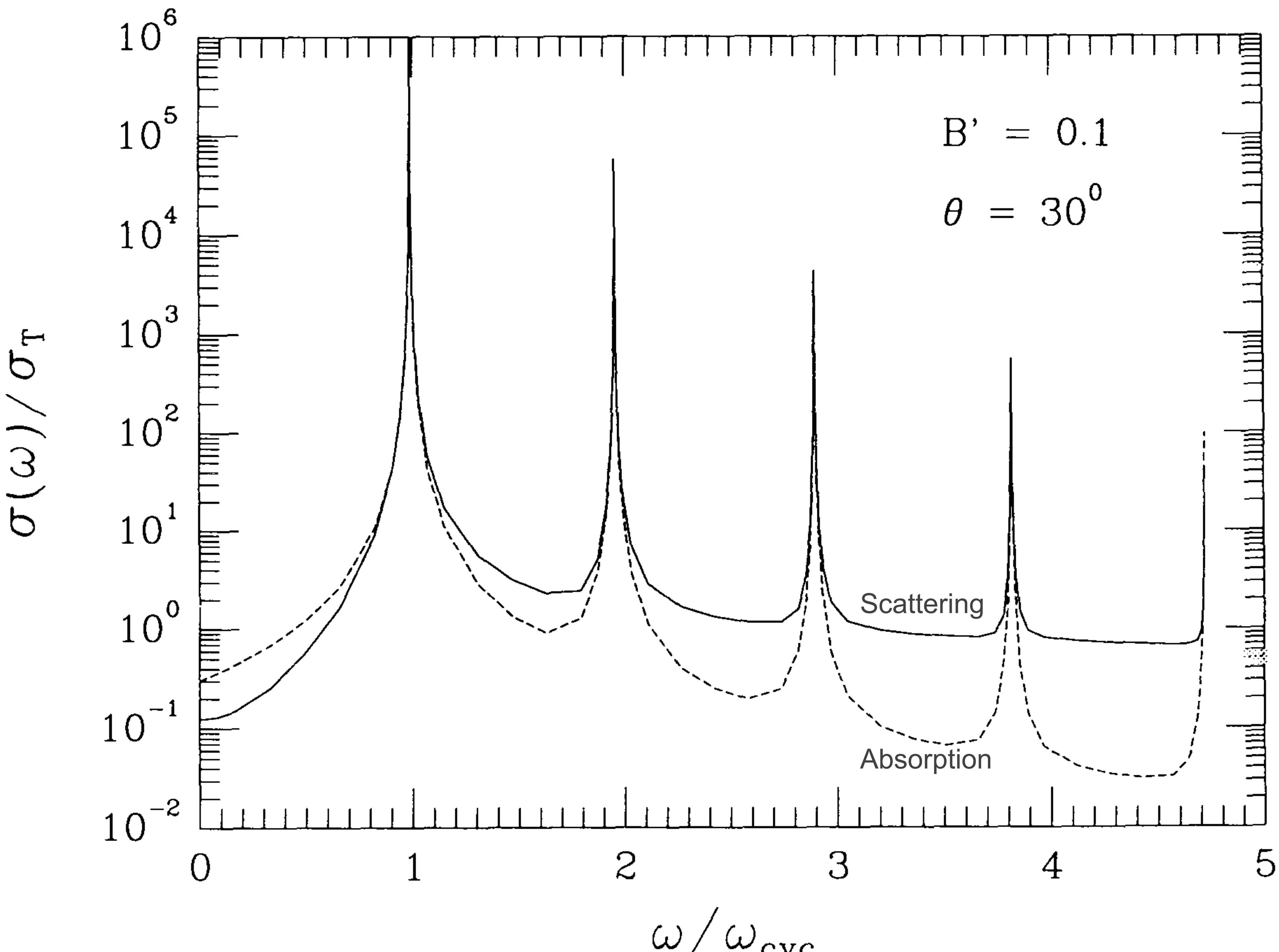
$$\frac{\hbar\omega_n^{\rm res}}{m_{\rm e}c^2} = \frac{\sqrt{1 + 2n(B/B_{\rm crit})\sin^2\theta} - 1}{\sin^2\theta}$$

for $p_{\parallel} = 0$

*Resonant processes*

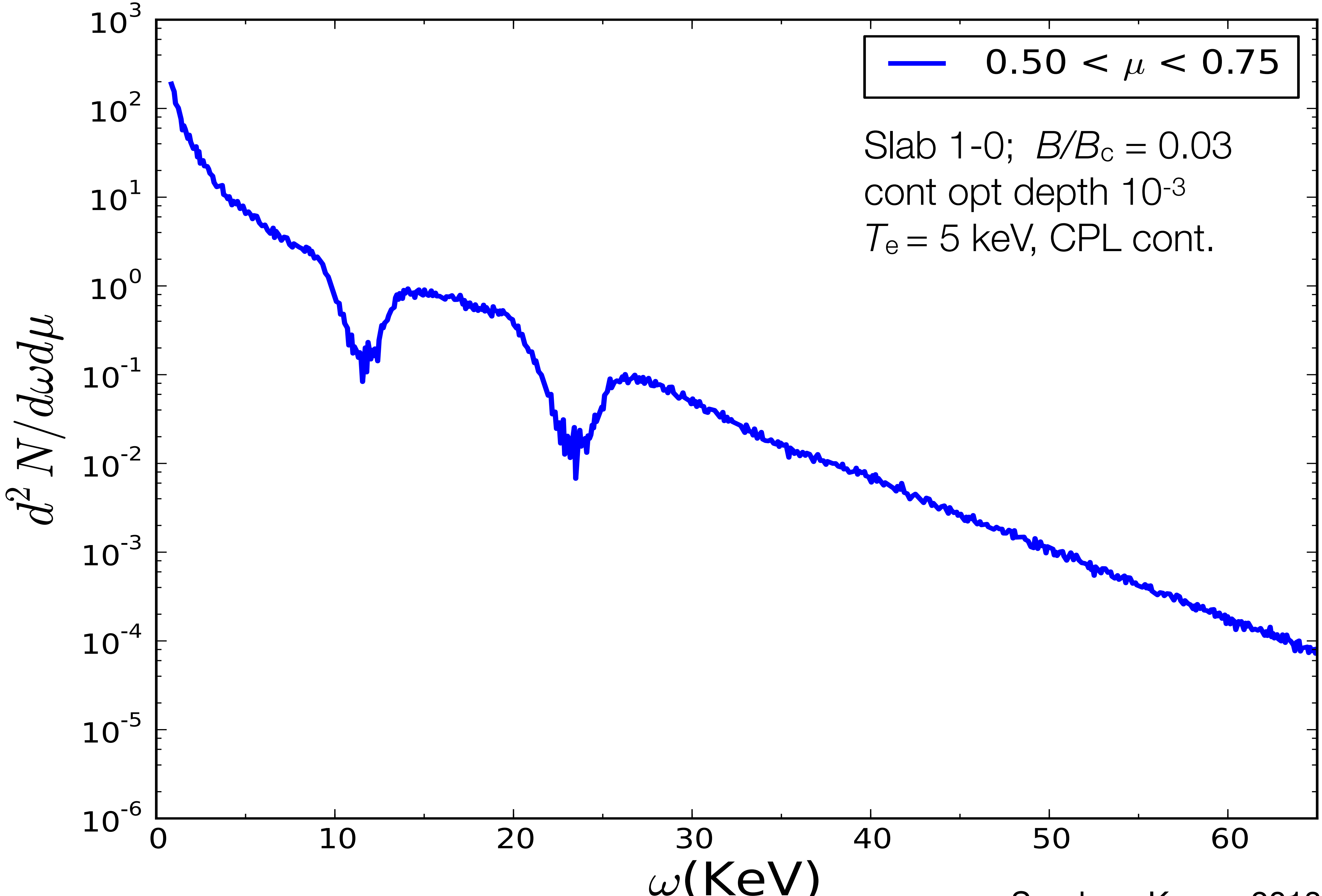
Absorption, Emission
Magneto-Compton scattering

# Resonant cross sections




Harding & Daugherty 1991

# Cyclotron resonance spectrum computed by Monte-Carlo method




Sandeep Kumar 2013

# Nuclear / particle processes

*Change in binding energy ➛ photon emission*

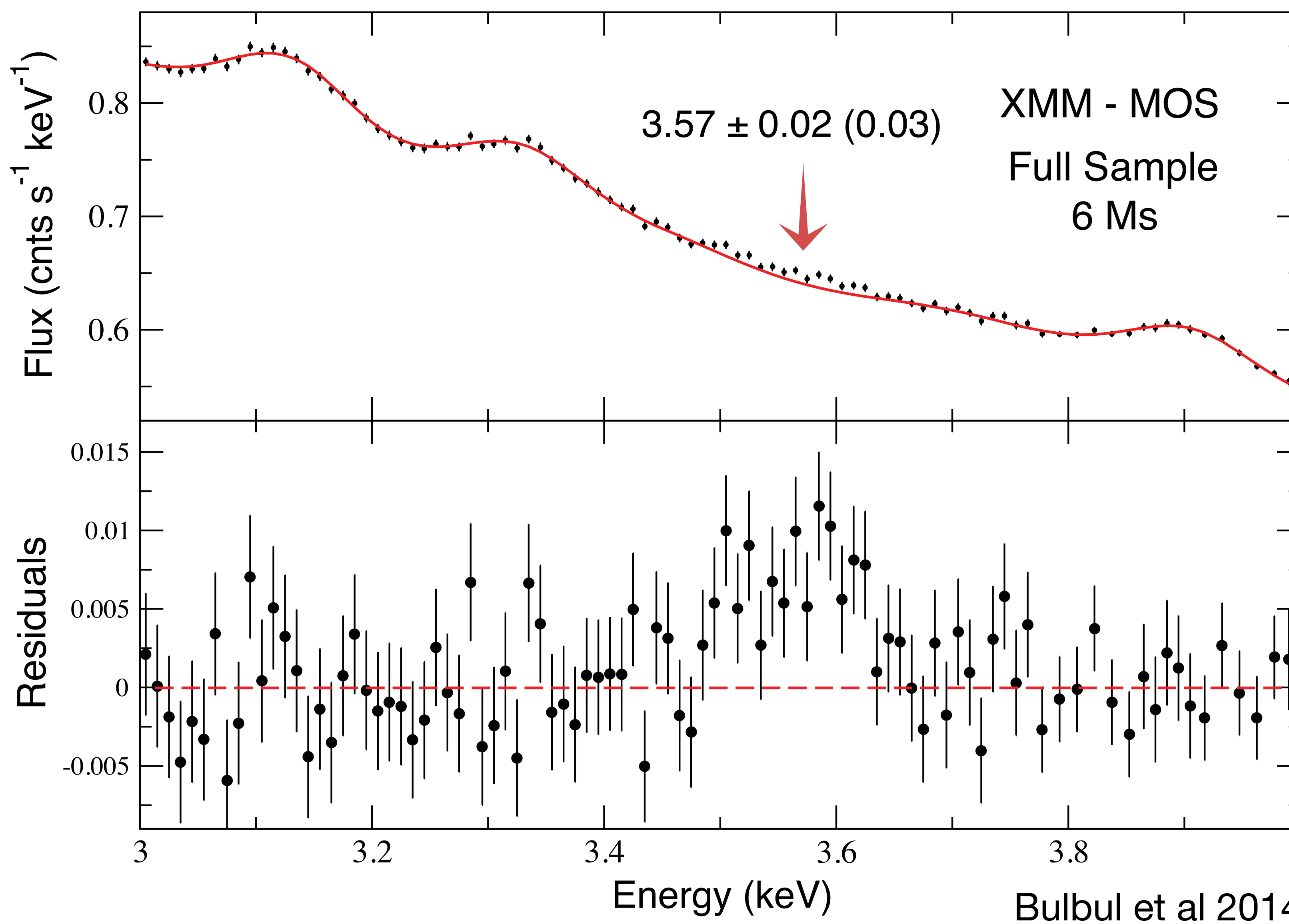
- Radioactivity (e.g. $Al^{26}$ 1.8 MeV)

- Decay of heavy mesons (e.g. $\Pi^0 \rightarrow 2\gamma$)
  generated in nuclear scattering ( $p + p \rightarrow \Pi^0$)

- Fusion

- Pair Annihilation

- **Dark matter decay**




Bulbul et al 2014