Inverse Compton Scattering
Summary of Radiation Properties

<table>
<thead>
<tr>
<th></th>
<th>Thermal</th>
<th>Blackbody</th>
<th>Bremsstrahlung</th>
<th>Synchrotron</th>
<th>Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optically thick</strong></td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td><strong>Maxwellian</strong></td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td><strong>distribution</strong></td>
<td><strong>of velocities</strong></td>
<td><strong>Maxwellian</strong></td>
<td><strong>distribution</strong></td>
<td><strong>of velocities</strong></td>
<td><strong>Maxwellian</strong></td>
</tr>
<tr>
<td><strong>speeds</strong></td>
<td><strong>Relativistic</strong></td>
<td><strong>speeds</strong></td>
<td><strong>Relativistic</strong></td>
<td><strong>speeds</strong></td>
<td><strong>Relativistic</strong></td>
</tr>
<tr>
<td><strong>Main</strong></td>
<td>Matter in thermal</td>
<td>Matter AND</td>
<td>Accelerating</td>
<td>Accelerating</td>
<td>Relativistic</td>
</tr>
<tr>
<td><strong>Properties</strong></td>
<td>equilibrium</td>
<td>radiation in</td>
<td>particles in</td>
<td>particles in</td>
<td>electron/photon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>thermal equilibrium</td>
<td>electric field</td>
<td>magnetic field</td>
<td>collisions</td>
</tr>
</tbody>
</table>

Blackbody → **thermal** radiation
Bremsstrahlung → **thermal** and **non-thermal** radiation
Synchrotron → **non-thermal** radiation
# Summary of Radiation Properties

<table>
<thead>
<tr>
<th></th>
<th>Thermal</th>
<th>Blackbody</th>
<th>Bremsstrahlung</th>
<th>Synchrotron</th>
<th>Compton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optically thick</strong></td>
<td>–</td>
<td>YES</td>
<td>NO</td>
<td>–</td>
<td>?</td>
</tr>
<tr>
<td><strong>Maxwellian distribution of velocities</strong></td>
<td>YES</td>
<td>YES</td>
<td>–</td>
<td>NO</td>
<td>?</td>
</tr>
<tr>
<td><strong>Relativistic speeds</strong></td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Main Properties</strong></td>
<td>Matter in thermal equilibrium</td>
<td>Matter AND radiation in thermal equilibrium</td>
<td>Accelerating particles in electric field</td>
<td>Accelerating particles in magnetic field</td>
<td>Relativistic electron/photon collisions</td>
</tr>
</tbody>
</table>

- **Blackbody** → **thermal** radiation
- **Bremsstrahlung** → **thermal** and **non-thermal** radiation
- **Synchrotron** → **non-thermal** radiation
Compton scattering

\[ v' < v \]
Electron is initially at rest
e- gains energy

Inverse Compton scattering

\[ v' > v \]
High energy e- initially
e- loses energy

Direct
Inverse
Sunyaev Zel'dovich Effect
Black hole engine

Low-energy gamma rays

Faster shell

Slower shell

Colliding shells emit low-energy gamma rays (internal shock wave)

Jet collides with ambient medium (external shock wave)

Prompt emission

Afterglow

High-energy gamma rays

X-rays

Visible light

Radio
Inverse Compton

(Recall Section 3, Eq. 3.14 and 3.15)

Step 1: Photon and e- in lab frame → e- rest frame

Step 2: Photon and e- interact in e- rest-frame

Step 3: Back to the lab frame

Remember: the notation ' means you are in the Rest Frame K' (electron at rest)
the subscript 1 means you are considering quantities after the scattering
Inverse Compton

(Recall Section 3, Eq. 3.14 and 3.15)

Step 1: Photon and e- in lab frame → e- rest frame
Step 2: Photon and e- interact in e- rest-frame
Step 3: Back to the lab

\( \theta \) is the angle between velocity and line of sight
\( \psi \) is the angle between velocity and photon direction
Inverse Compton

**Step 1:** lab frame $\rightarrow$ e- rest frame

$x' = x\gamma(1 - \beta \cos \psi)$

$x$ is the energy of the photon in K
$x'$ is the energy of the photon in K'

$x = \frac{h\nu}{m_e c^2}$

BEFORE THE SCATTERING
Inverse Compton

**Step 1:** lab frame $\rightarrow$ e- rest frame

$$x' = x\gamma(1 - \beta \cos \psi)$$

**Step 2:** Photon and e- interact in e- rest-frame

$$\cos \psi = \frac{\beta + \cos \psi'}{1 + \beta \cos \psi'}$$

$$x' = \frac{x}{\gamma(1 + \beta \cos \psi')}$$

$$\cos \theta' = \cos(\pi - \psi') = -\cos \psi'$$

$$x' = x\delta$$
**Inverse Compton**

**Step 1:** Photon and e- in lab frame:

\[ x' = x\gamma(1 - \beta \cos \psi) \]

\[ \cos \psi = \frac{\beta + \cos \psi'}{1 + \beta \cos \psi'} \]

**Step 2:** Photon and e- interact in e- rest-frame

We are now in K' and we assume that the photon energy is \(<<\) electron energy. Therefore Thomson scattering:

\[ x'_1 = x' \]

\[ x' = \frac{x}{\gamma(1 + \beta \cos \psi')} \]

\[ \cos \theta' = \cos(\pi - \psi') = -\cos \psi' \]

\[ x' = x\delta \]
Because Thomson is an elastic process

\[
x_1 = x_1' \gamma (1 + \beta \cos \psi_1')
\]

\[
\cos \psi_1' = \frac{\cos \psi_1 - \beta}{1 - \beta \cos \psi_1}
\]

\[
x_1 = x \frac{1 - \beta \cos \psi}{1 - \beta \cos \psi_1}
\]
Due to relativistic electron

Due to relativistic electron

Here we still need $h\nu' \ll mc^2$

Due to Thomson scattering

Due to relativistic electron
Because Thomson is an elastic process

For an isotropic distribution of incident photons and for gamma >> 1 the average photon energy after one scattering is:

\[ \langle x_1 \rangle = \frac{4}{3} \gamma^2 x \]
Single Photon Spectrum

Typical Inverse Compton frequency: \( x_1 \approx \gamma^2 x \)

Cutoff frequency: \( 4 \gamma^2 x \)

Emissivity:

\[
\epsilon_{IC}(x_1) = \frac{\sigma_T n I_0 (1 + \beta)}{4 \gamma^2 \beta^2 x_0} F_{IC}(x_1)
\]

\[
F_{IC}(x_1) = \frac{x_1}{x_0} \left[ \frac{x_1}{x_0} - \frac{1}{(1 + \beta)^2 \gamma^2} \right]; \quad \frac{1}{(1 + \beta)^2 \gamma^2} < \frac{x_1}{x_0} < 1 \quad \text{Downscattering}
\]

\[
F_{IC}(x_1) = \frac{x_1}{x_0} \left[ 1 - \frac{x_1}{x_0} \frac{1}{(1 + \beta)^2 \gamma^2} \right]; \quad 1 < \frac{x_1}{x_0} < (1 + \beta)^2 \gamma^2 \quad \text{Upscattering}
\]
Inverse Compton Power

\[ U_{\text{rad}} = \frac{1}{c} \int I \, d\Omega. \]

\[ \frac{dn}{d\Omega} = \frac{c}{4\pi} \frac{U_{\text{rad}}}{\hbar \nu} \]

Number of particles per solid angle passing in a unit time through a unit area

\[ \frac{dN}{dt} = \sigma_T \int (1 - \beta \cos \psi) \frac{dn}{d\Omega} \, d\Omega. \]

\[ P_c(\gamma) = \left( \frac{\# \text{ of collisions}}{\text{sec}} \right) \text{(average phot. energy after scatt.)} \]

Does this remind you of any other radiative process?
Inverse Compton Power

\[ U_{\text{rad}} = \frac{1}{c} \int I \, d\Omega. \]

\[ \frac{dn}{d\Omega} = \frac{c}{4\pi} \frac{U_{\text{rad}}}{\hbar \nu} \quad \text{Number of particles per solid angle passing in a unit time through a unit area} \]

\[ \frac{dN}{dt} = \sigma_T \int (1 - \beta \cos \psi) \, \frac{dn}{d\Omega} \, d\Omega. \]

\[ P_c(\gamma) = \left( \frac{\# \text{ of collisions}}{\text{sec}} \right) \quad \text{(average photon energy after scatt.)} \]

Synchrotron and Compton powers are identical with \( U_r \) replacing \( U_B \).
Compton Reflection Hump and Iron Line

Diagram showing a black hole with a hot corona and an accretion disk. Arrows indicate the direction of the power law and reflected light. An inset image shows a companion star, accretion stream, and accretion disc.
Compton Reflection Hump

\[ \frac{dE_\gamma}{dt} = \sigma_T c \gamma^2 \int (1 - \beta \cos \psi)^2 \epsilon n(\epsilon) d\epsilon \]
Iron Line is a powerful diagnostic for black hole spin, but also neutron star magnetic fields and accretion disc physics.