EM processes in astrophysics and where to find them

Planck spectrum: hot and dense material, like stars

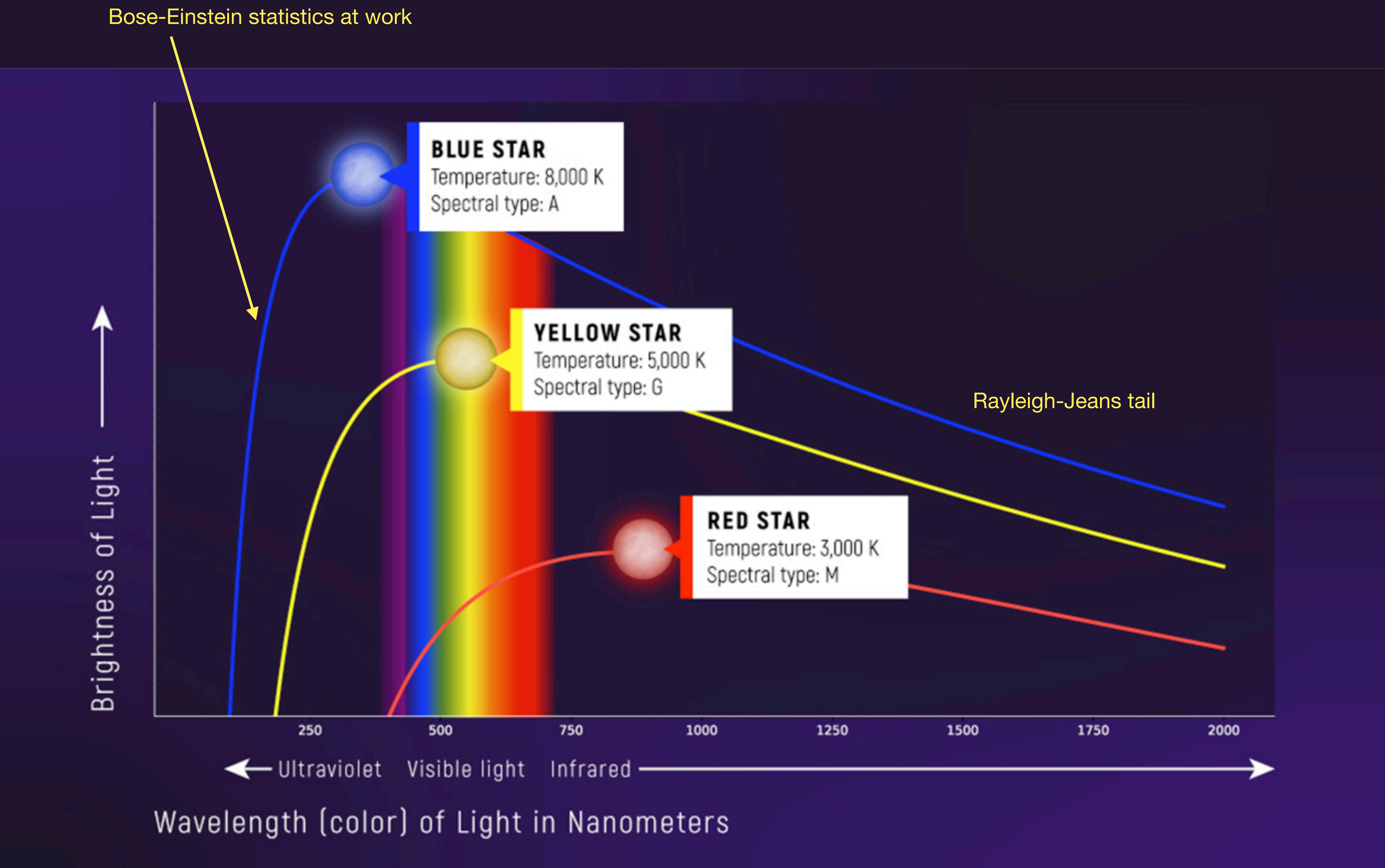
Emission spectrum: hot and diffuse material, like nebulae

Absorption spectrum: cool and diffuse intervening gas, like a stellar atmosphere

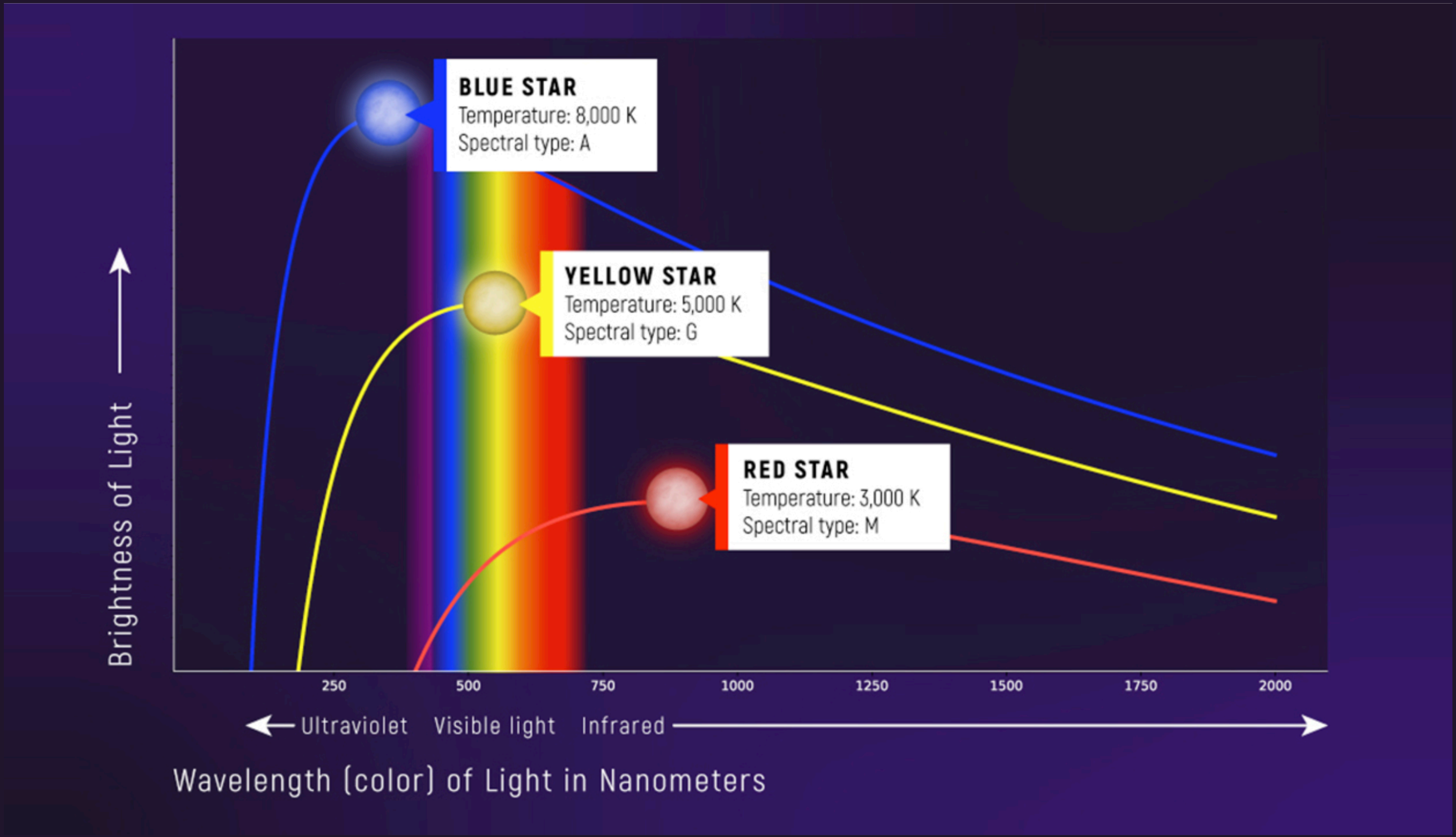
Bremsstrahlung: hot and diffuse gas, like intracluster medium

Synchrotron: relativistic gas with strong magnetic fields, like jets

(Inverse) Compton: gas near strong photon source, like an AGN disk



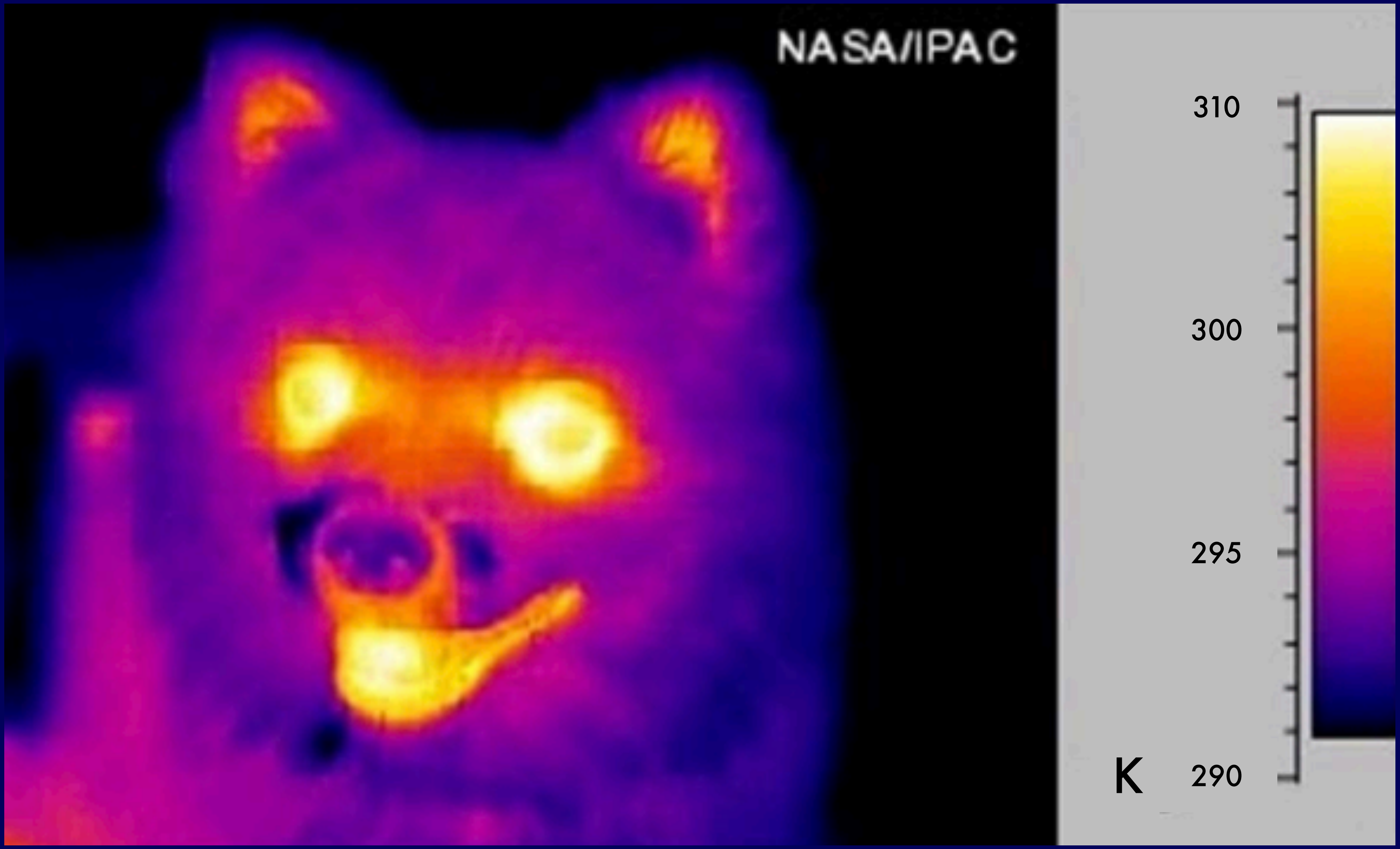
Bose-Einstein statistics at work
BLUE STAR
Temperature: 8,000 K
Spectral type: A
YELLOW STAR
Temperature: 5,000 K
Spectral type: G
RED STAR
Temperature: 3,000 K
Spectral type: M
Rayleigh-Jeans tail
Brightness of Light
250
500
750
1000
1250
1500
1750
2000
Ultraviolet
Visible light
Infrared
Wavelength (color) of Light in Nanometers



$$\lambda_{\text{peak}} = \frac{0.29\,\text{cm}}{T}$$

$$L = 4\pi \mathrm{R}^2 \sigma \mathrm{T}^4$$

Practice: At what wavelength does this pupper glow?



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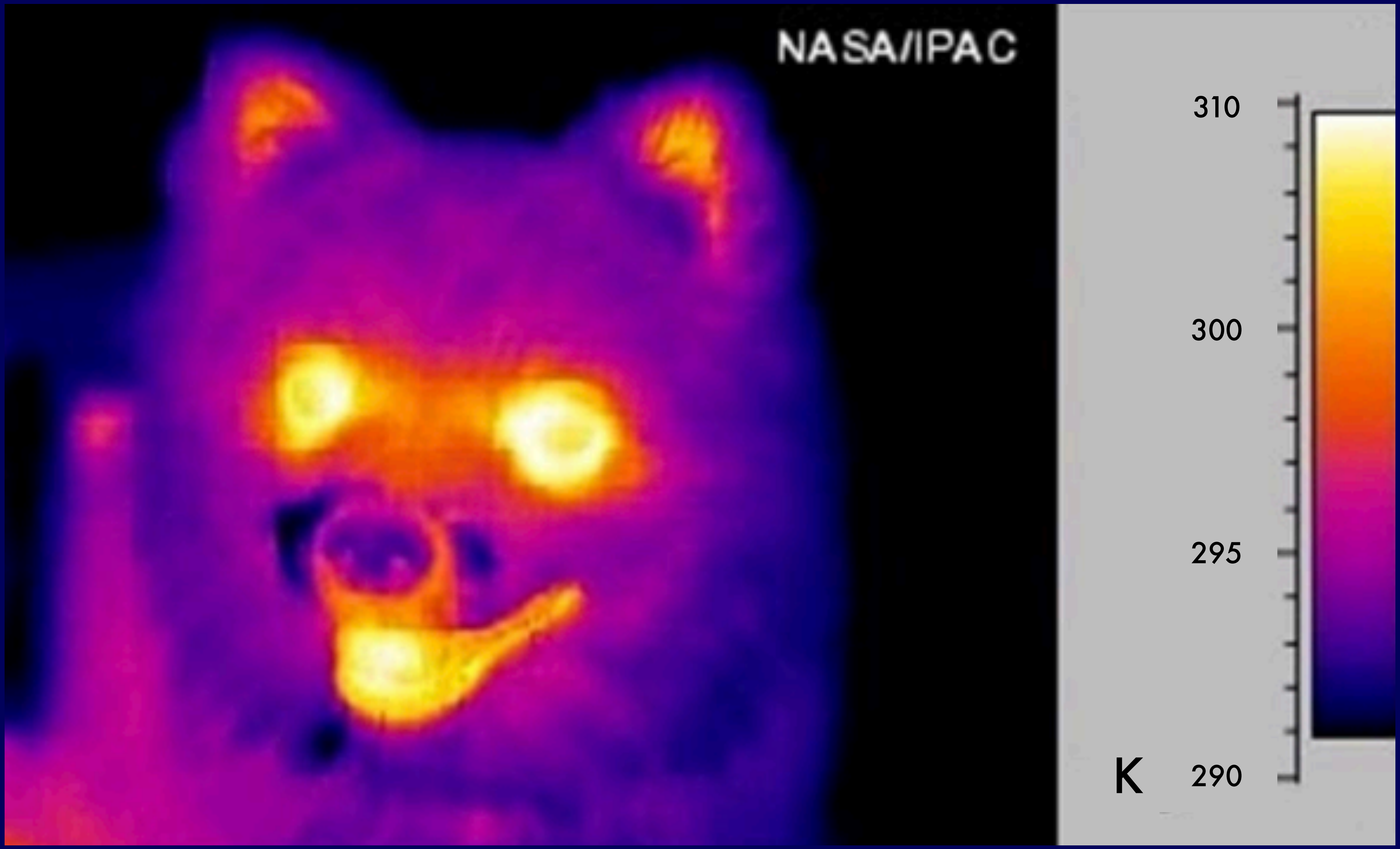
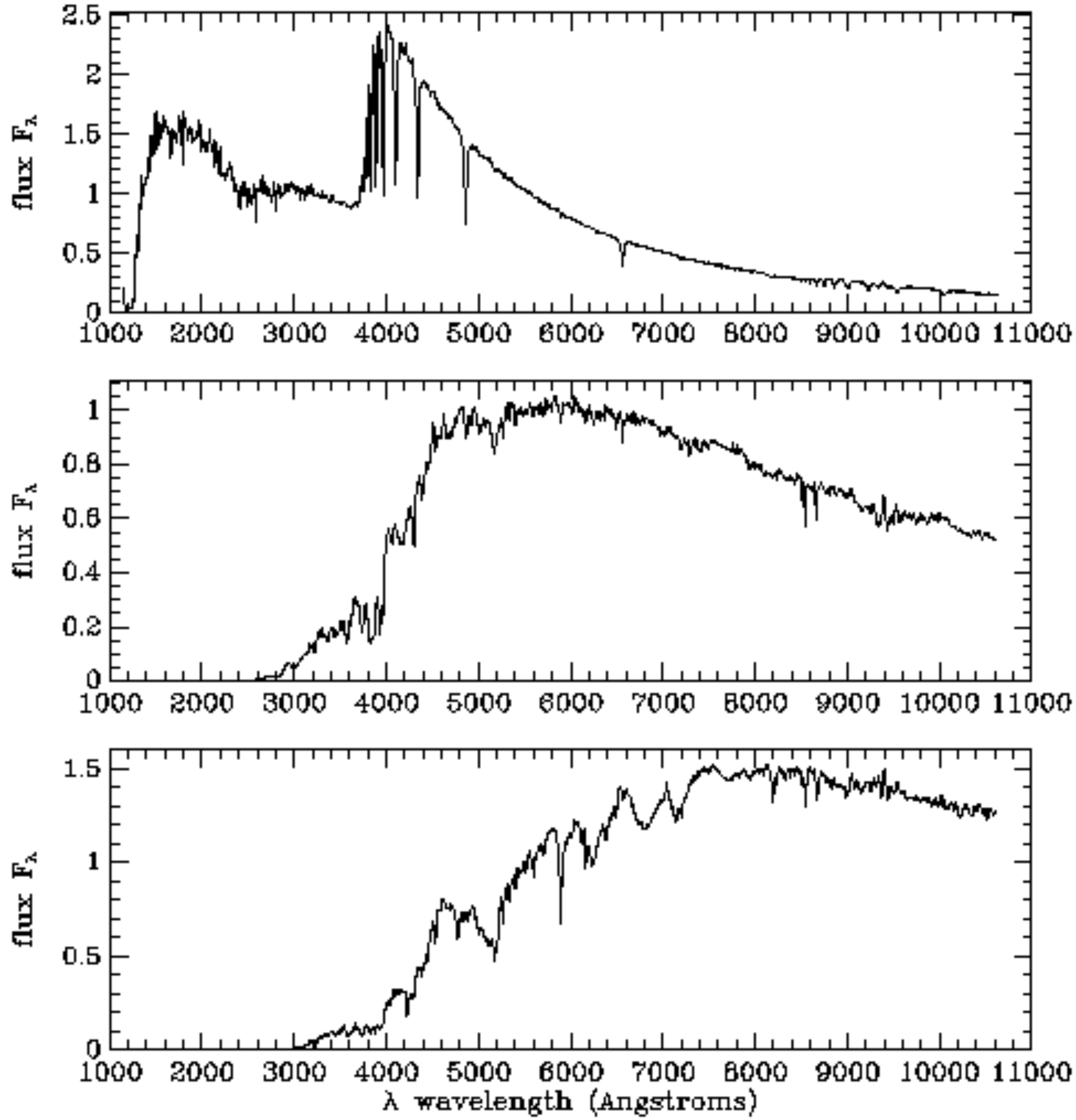


$$\lambda_{\rm peak} = \frac{0.29\,{\rm cm}}{T} \sim 9\mu{\rm m}$$

Blackbody radiation + stellar atmospheric absorption

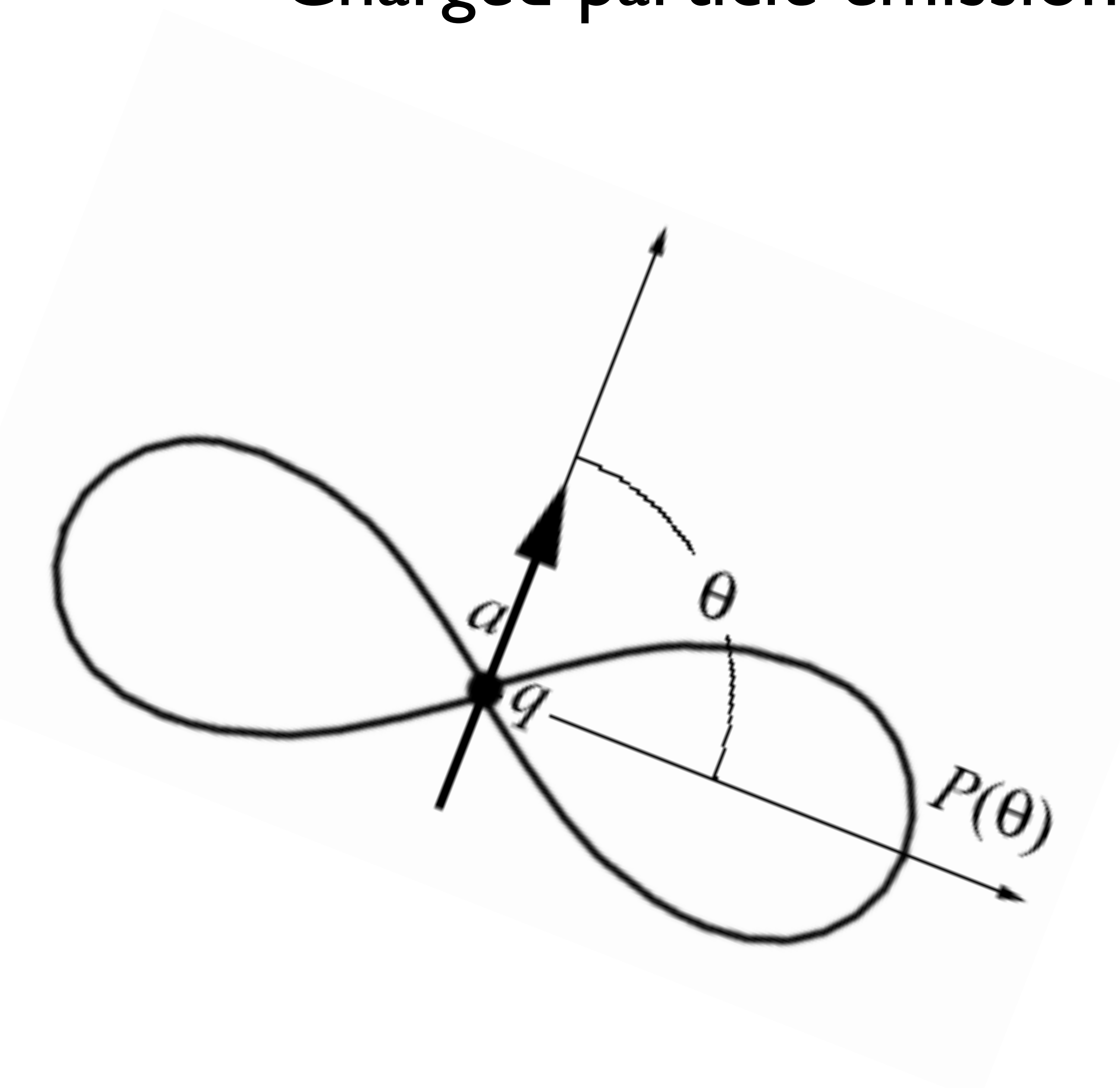


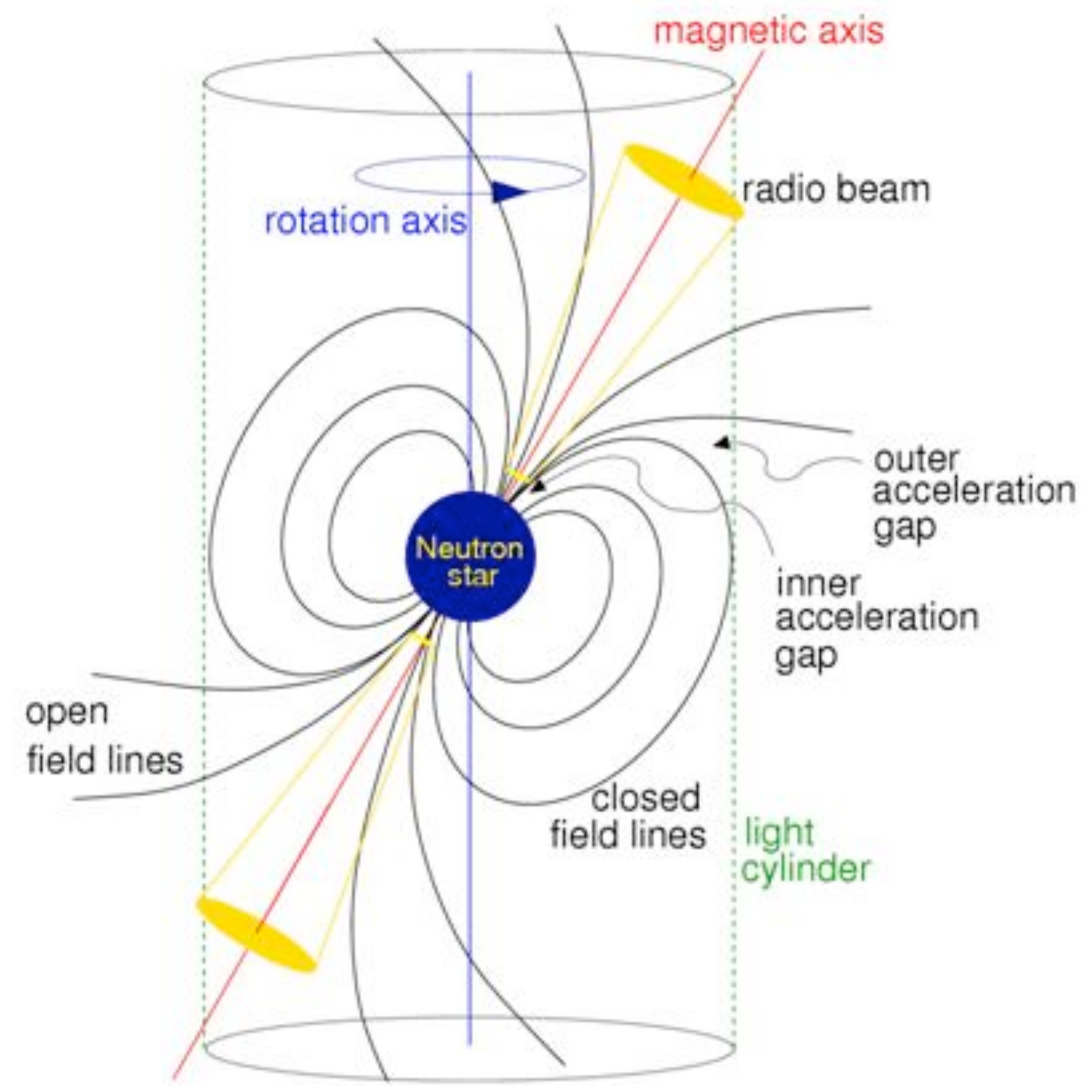
Larmor Formula

[redacted]

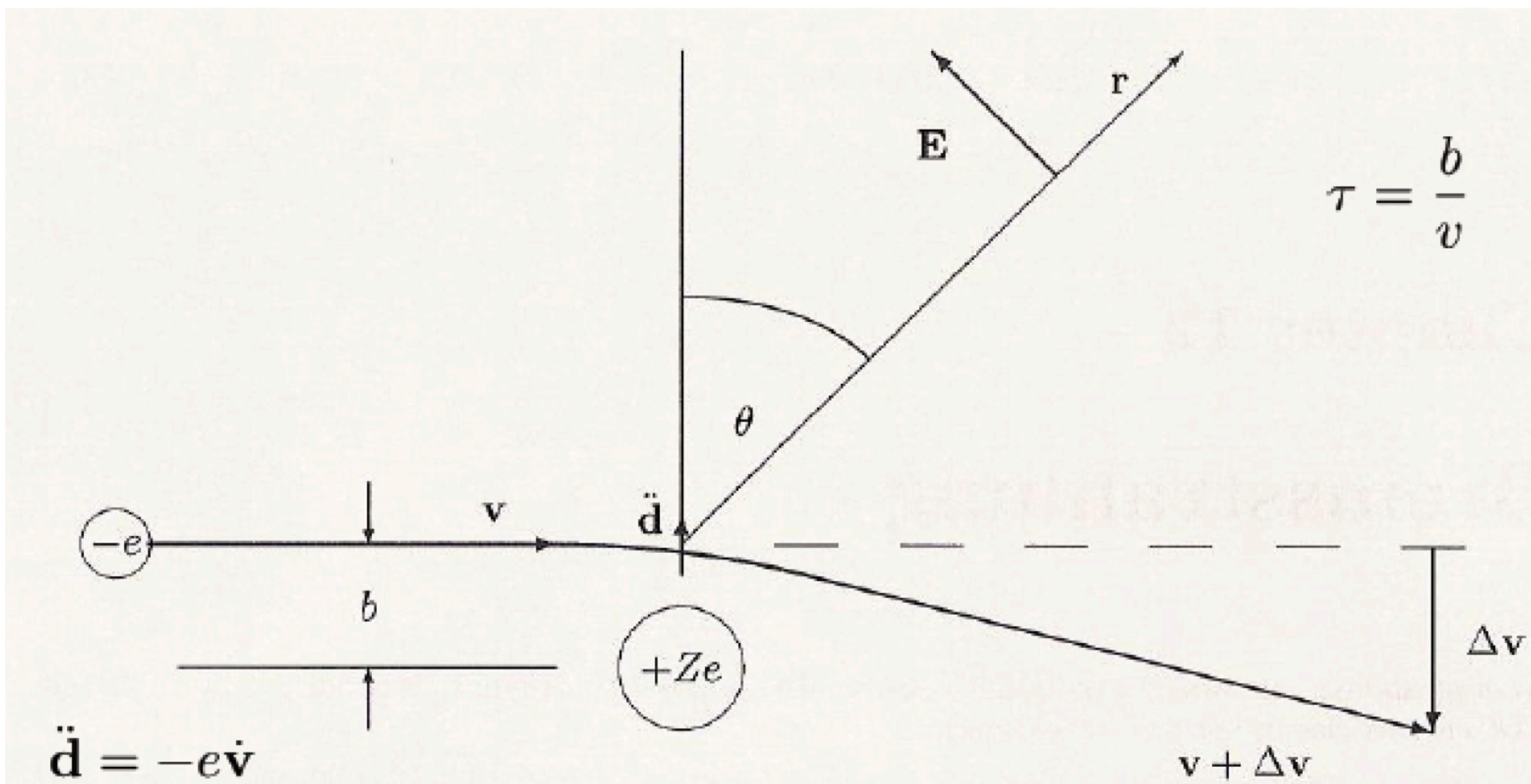
$$P = \frac{2}{3}\frac{q^2 a^2}{c^3} \text{ (cgs units)}$$

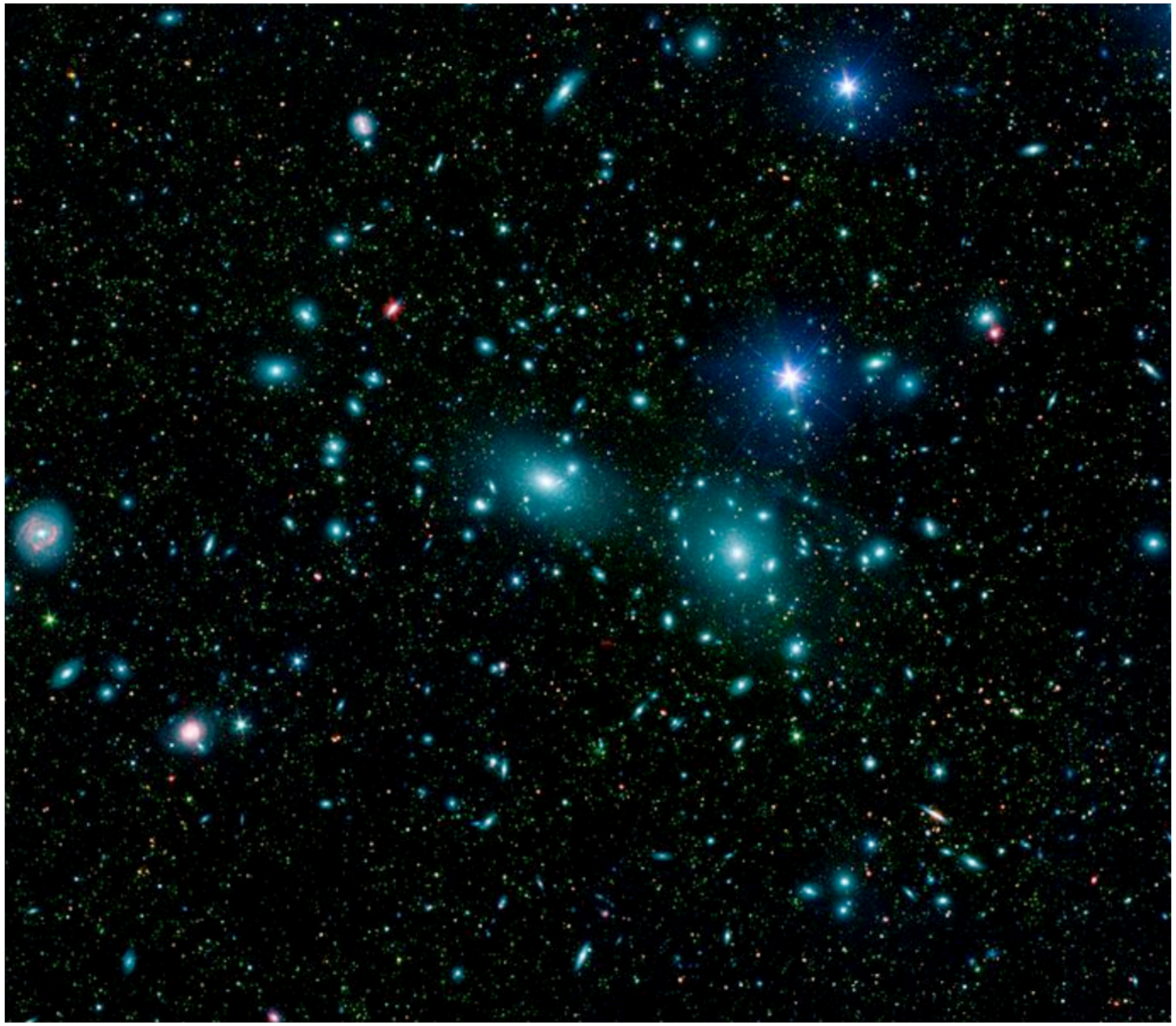
Charged particle emission pattern is a dipole



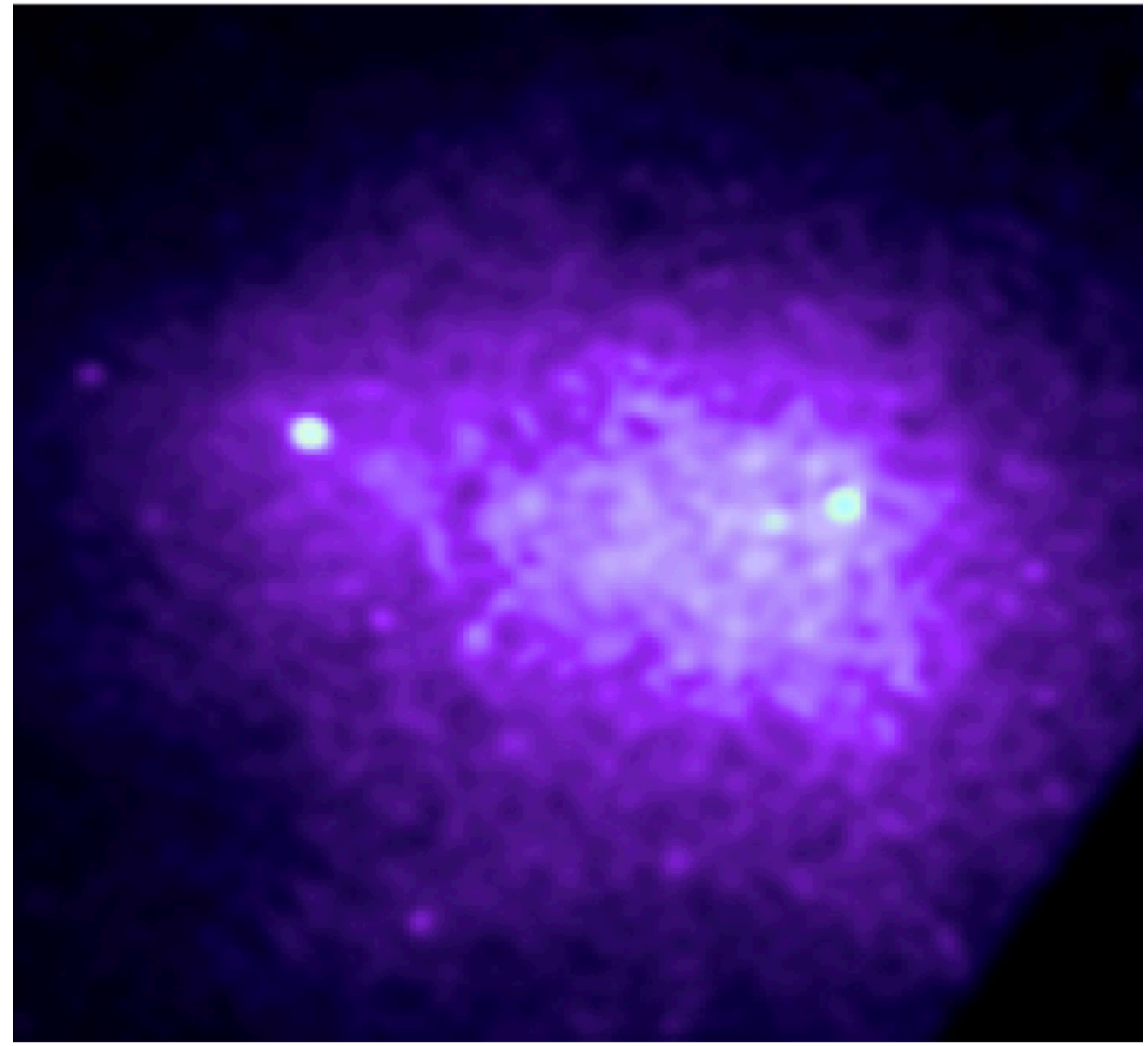


Bremsstrahlung radiation comes from the deceleration of a charged particle moving past a heavy ion





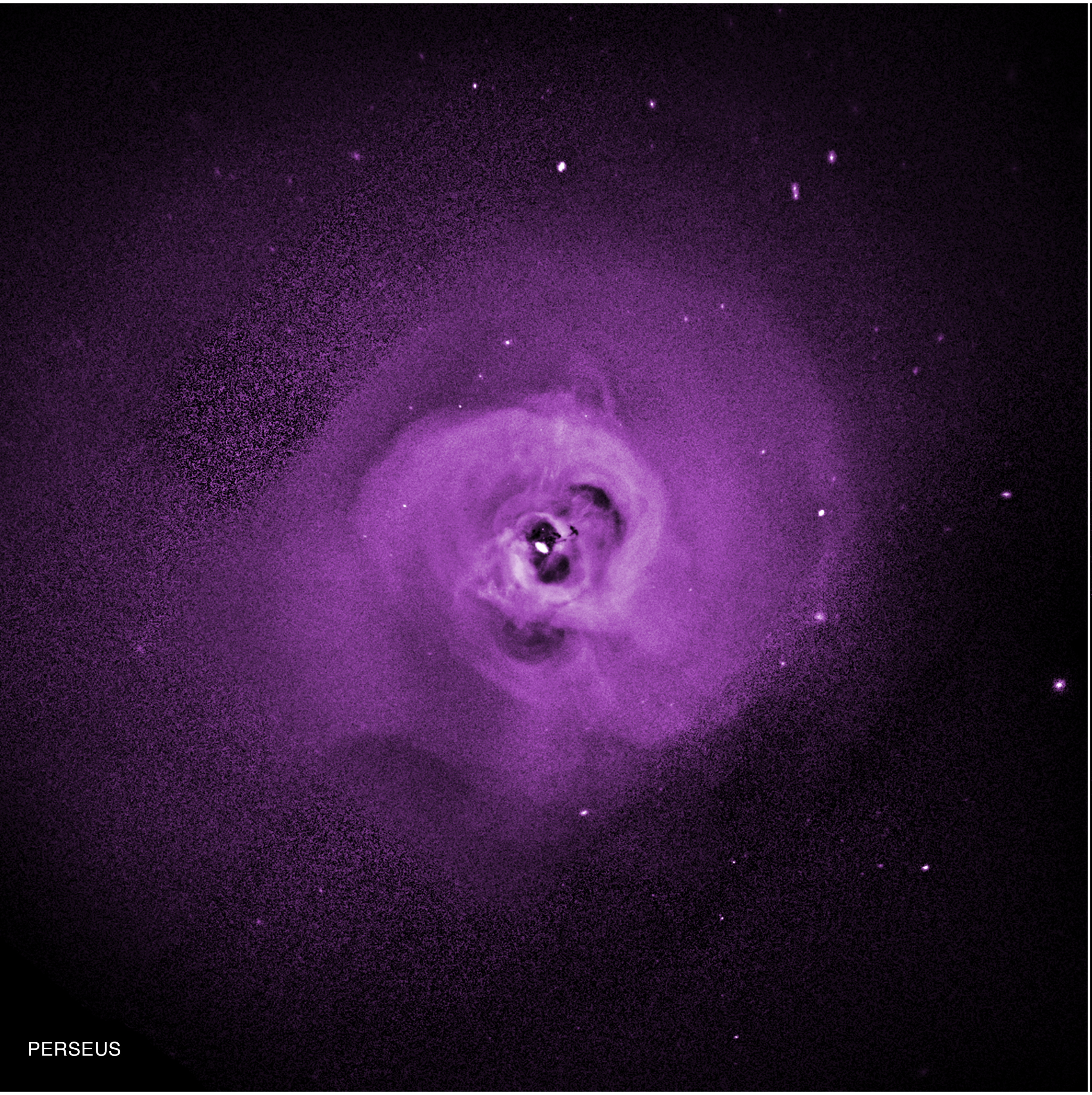
Coma cluster in optical

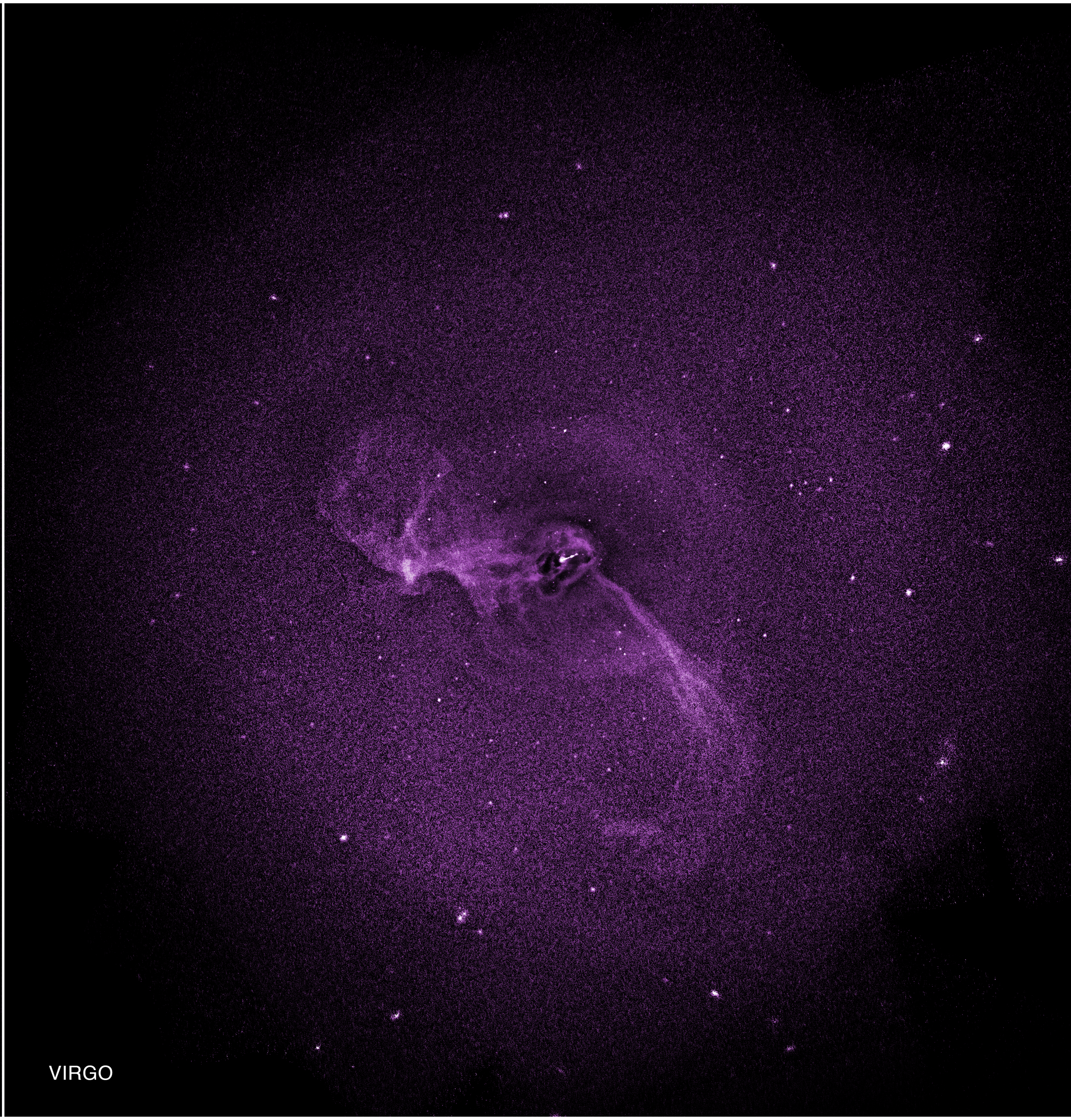


Coma cluster in Xray

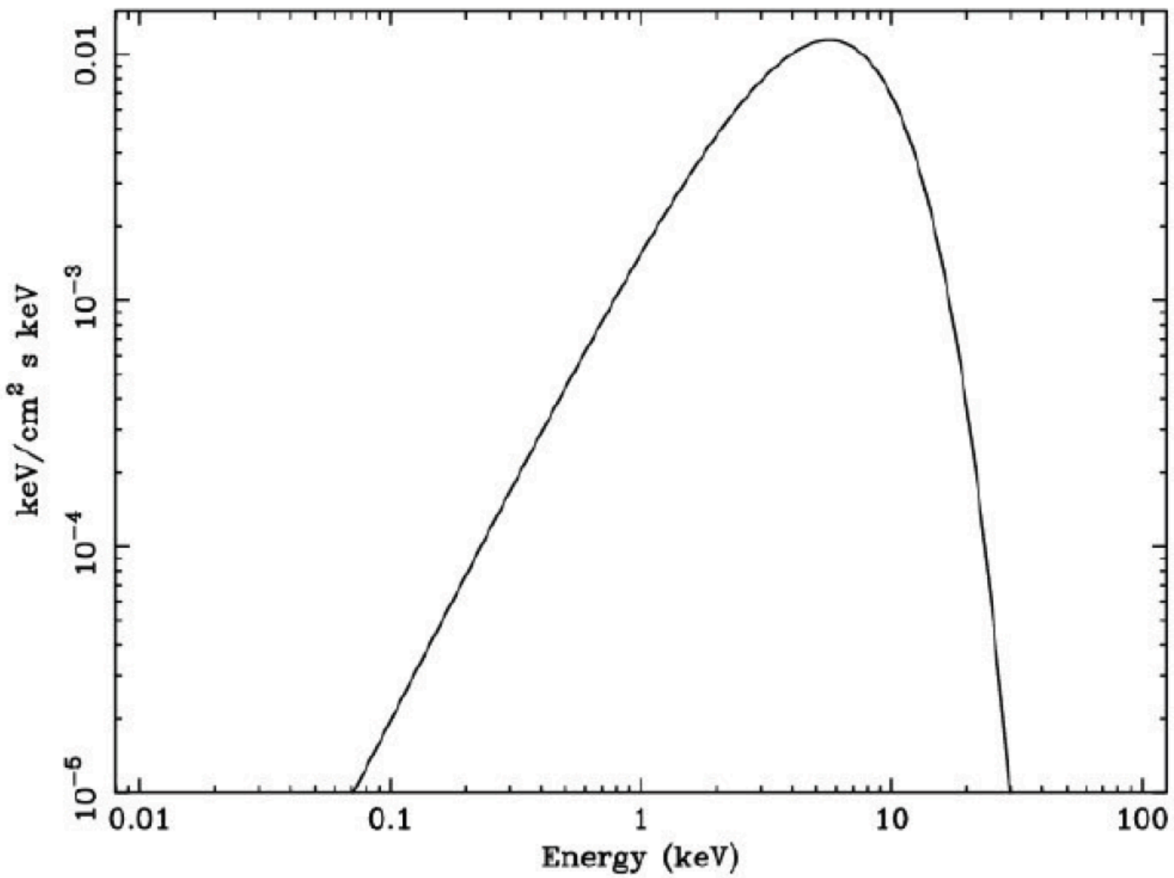
Most of the baryonic matter in the entire universe is emitting via bremsstrahlung right now!

Chandra images of hot halo gas in galaxy clusters reveal AGN heating, turbulence, structure!

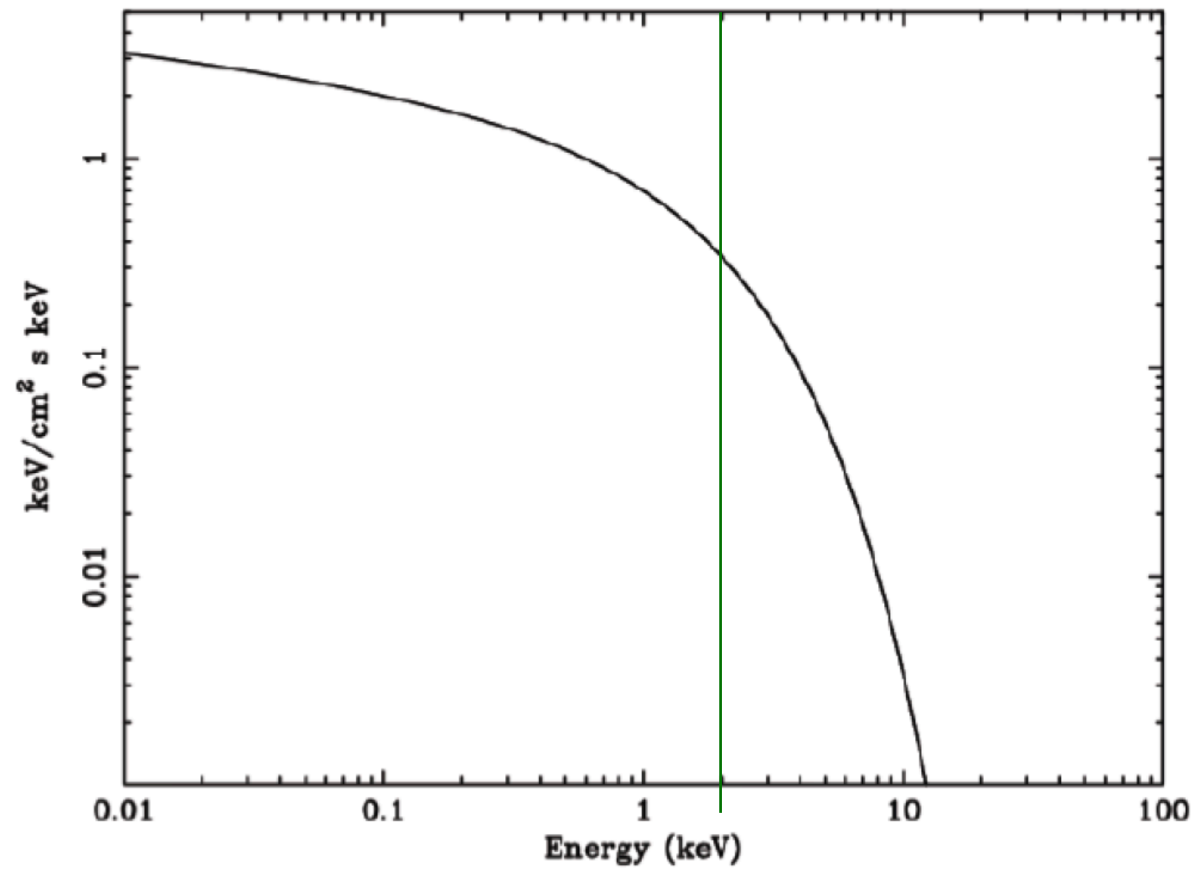




2 keV Blackbody spectrum



2 keV Bremsstrahlung spectrum



$$\mathrm{kT} = 2\,\mathrm{keV}$$

$$\mathrm{T} = ?$$

Hot gas: thermal Bremsstrahlung

In astrophysically interesting cases, electrons have a velocity distribution.

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

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Thermal Bremsstrahlung falls off exponentially at high energies

emitted power per unit volume per frequency

$$e_{ff} = g_{ff}\frac{2^5\pi e^6}{2m_e c^3}\left(\frac{2\pi}{3m_e k}\right)^{1/2} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT}$$

Two particles interacting

Hot gas: thermal Bremsstrahlung

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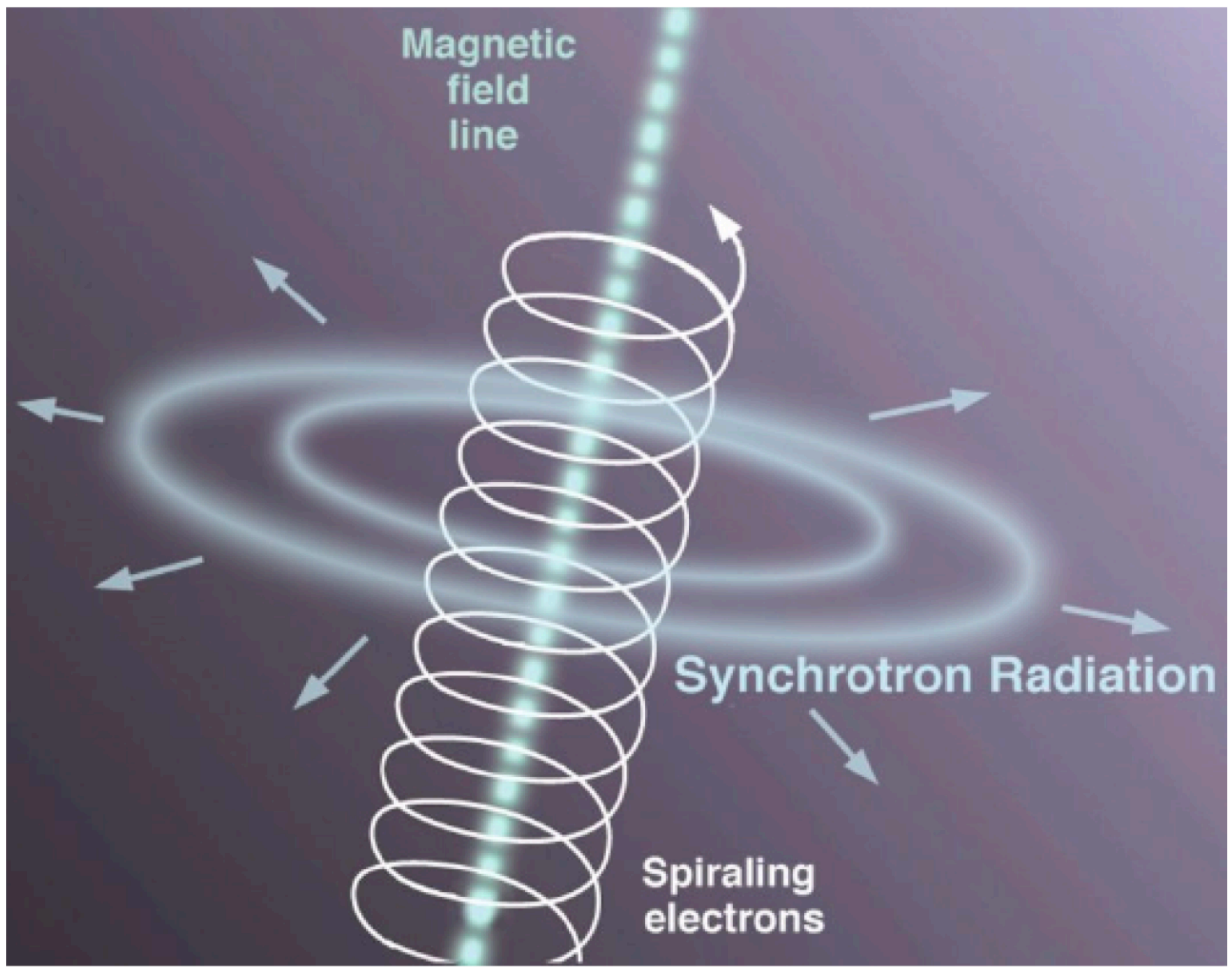
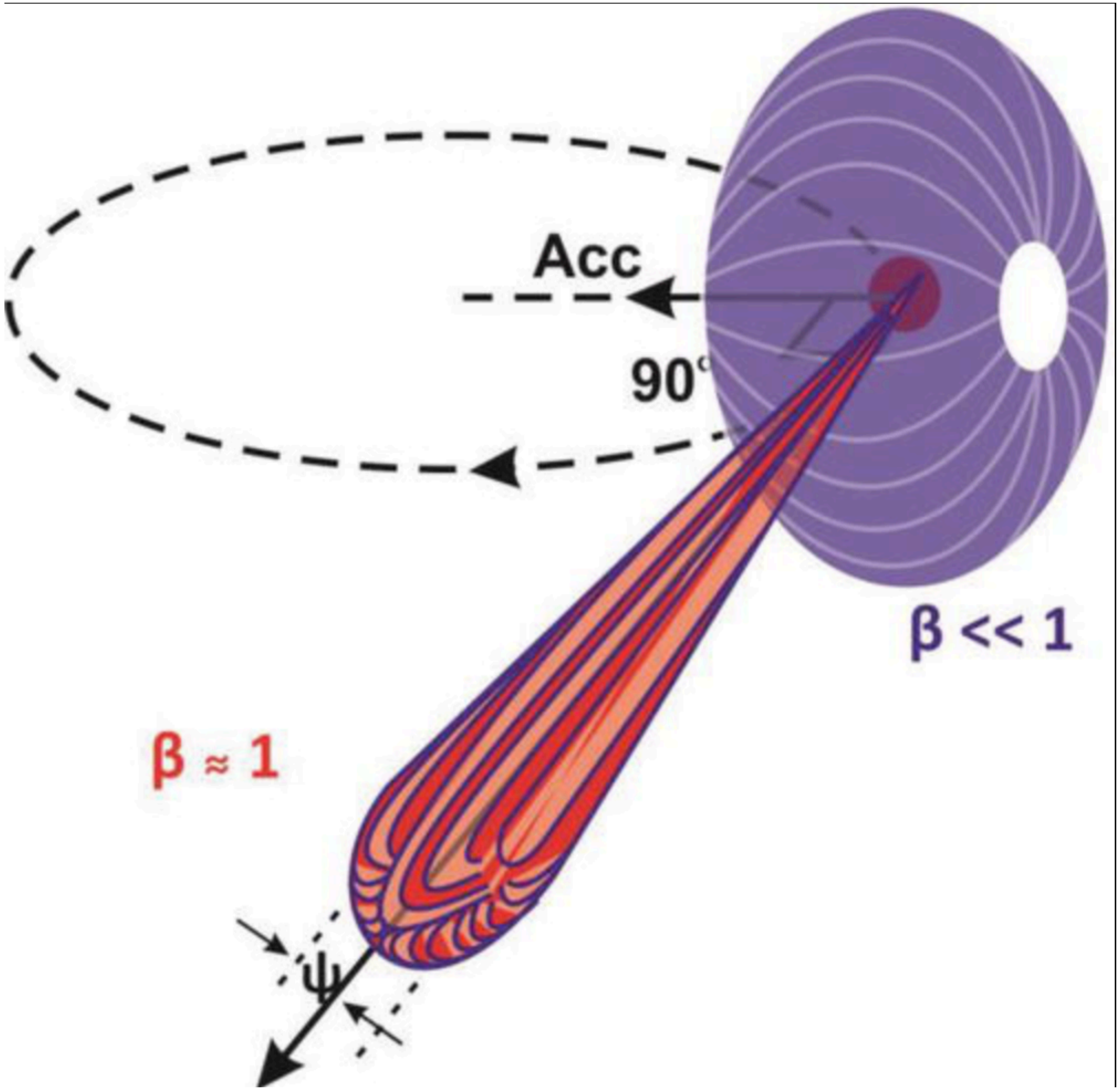
integrating in frequency :

$$e^{ff} = 1.4\times10^{-27} g_B Z^2 n_e n_i T^{-1/2} \text{ in erg s}^{-1}\text{ cm}^{-3}$$

Synchrotron Radiation




Acc
90°
β << 1
β ≈ 1
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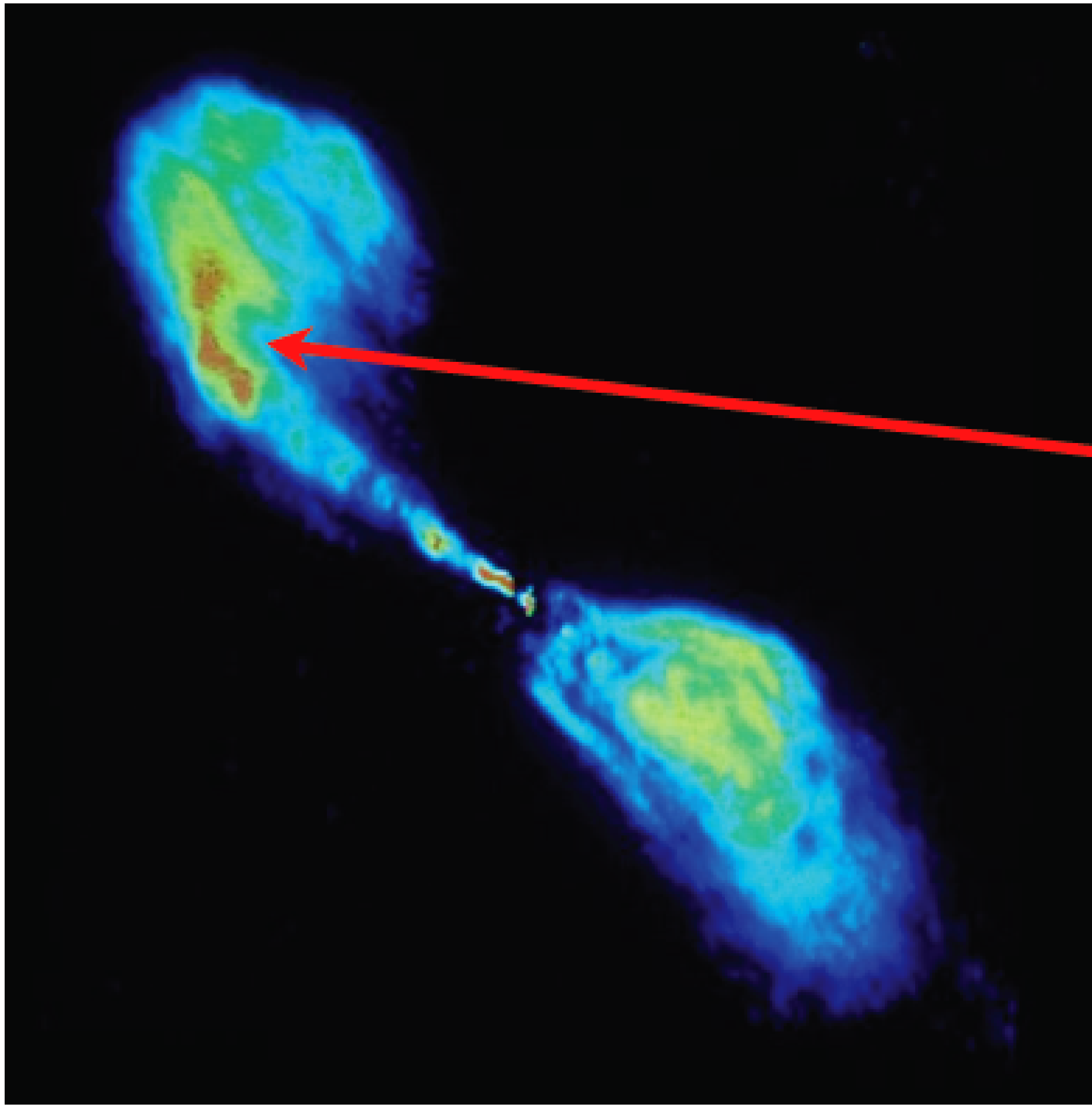
Centaurus A



Hot Spot

VLA Observations at 6cm

Synchrotron radiation from jets and black hole.

lobe magnetic field strength

10^{-9} tesla $= 10^{-5}$ G

30 000 light-years long

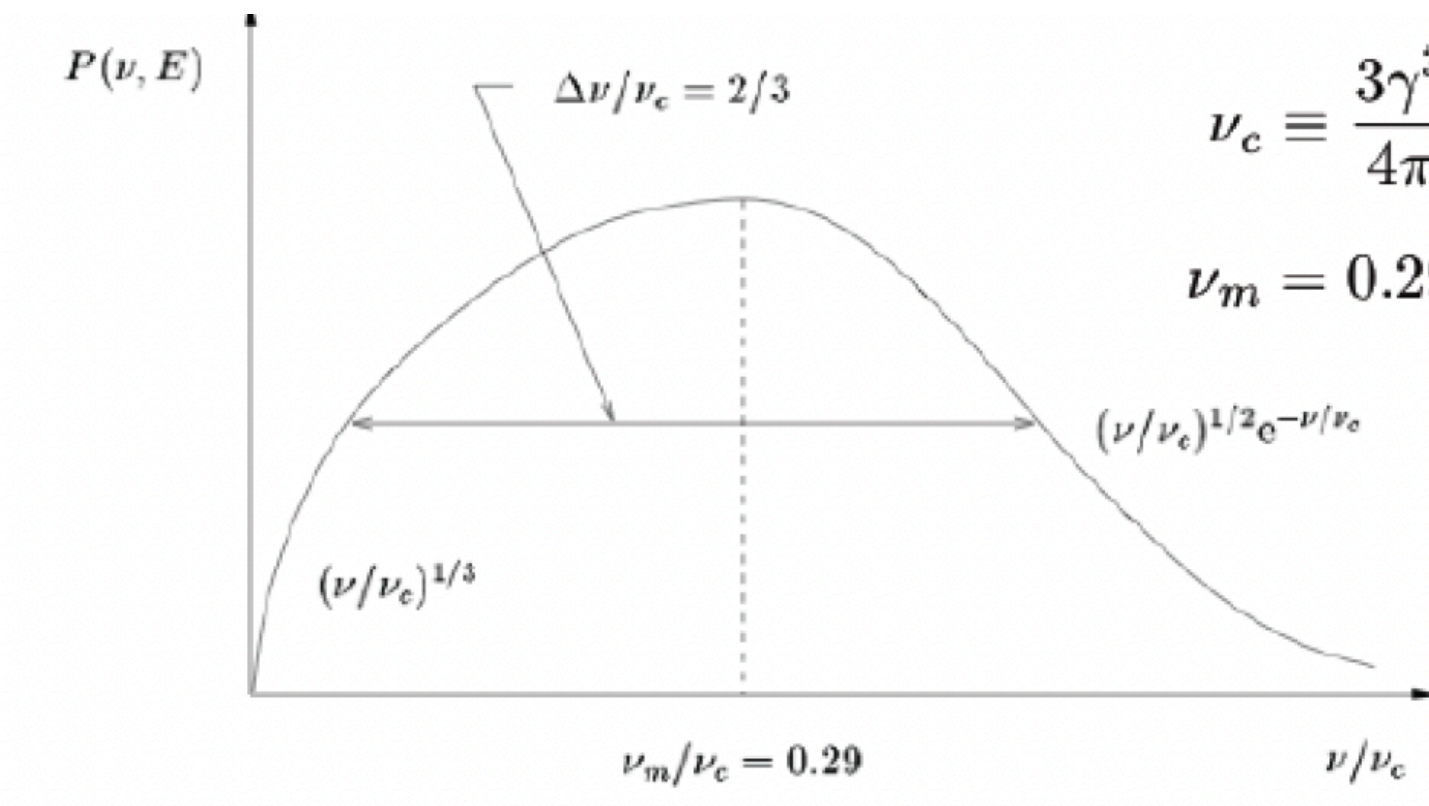
Crab Nebula -- Synchrotron from Pulsar

(Nearly totally gratuitous clip of pulsar sounds)

Synchrotron power for 1 electron:

$$P = \frac{-dE}{dt} = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 U_B$$

Synchrotron spectrum for 1 electron:

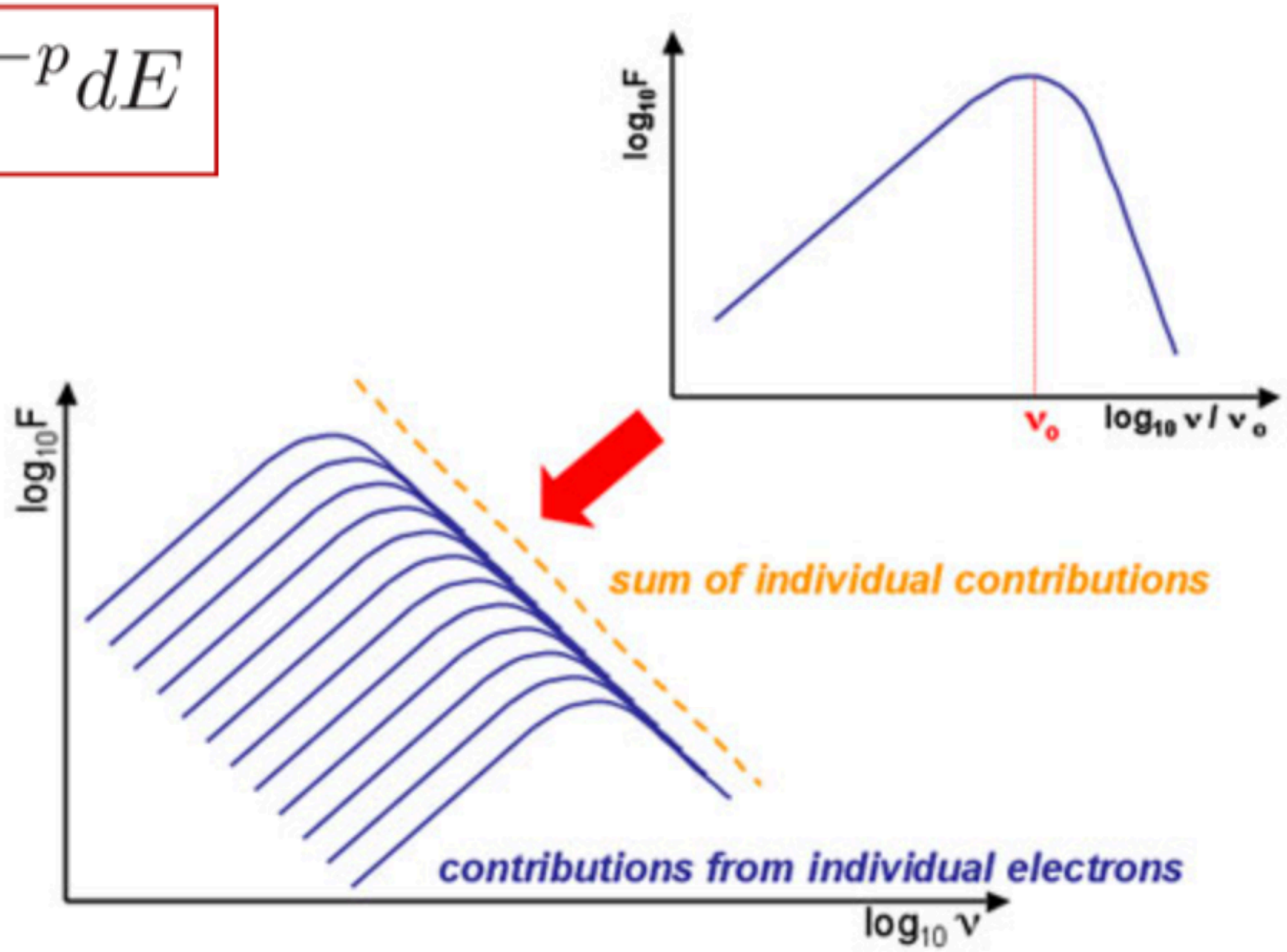


$$\nu_c \equiv \frac{3\gamma^3}{4\pi}\,\omega_B \,\sin\alpha = \frac{3}{2}\Delta\nu$$

$$\nu_m = 0.29\nu_c = 1.26 \times 10^6 B\gamma^2$$

Typically, synchrotron electron energies are distributed in a power-law distribution

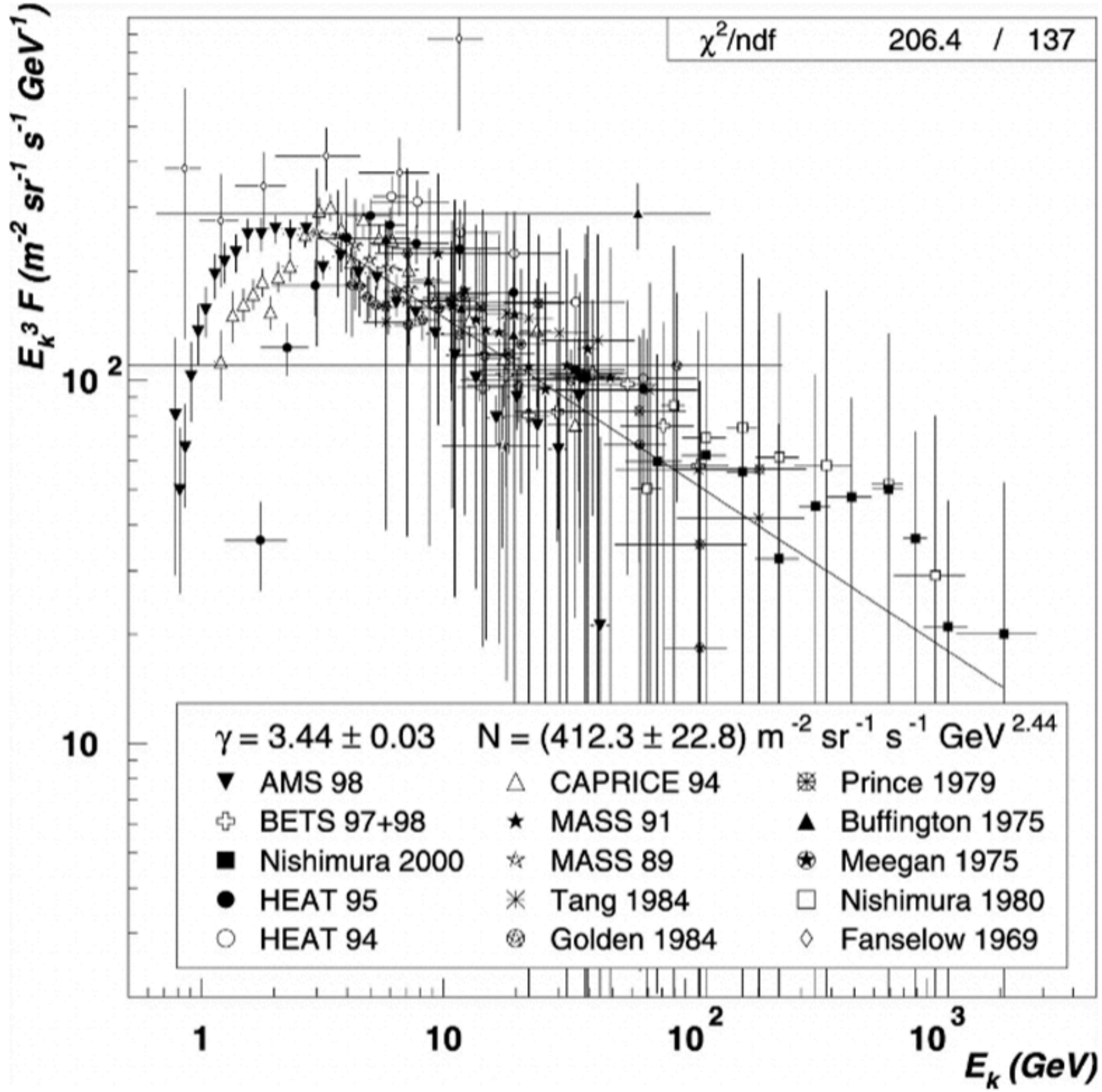
$$\boxed{N(E)d(E) = \kappa E^{-p} dE}$$



$$P_{tot} = \frac{\sqrt{3}q^3 CB\sin\alpha}{2\pi mc^2(p+1)}\Gamma\left(\frac{p}{4}+\frac{19}{12}\right)\Gamma\left(\frac{p}{4}-\frac{1}{12}\right)\left(\frac{mc\omega}{3qB\sin\alpha}\right)^{-(p-1)/2}$$

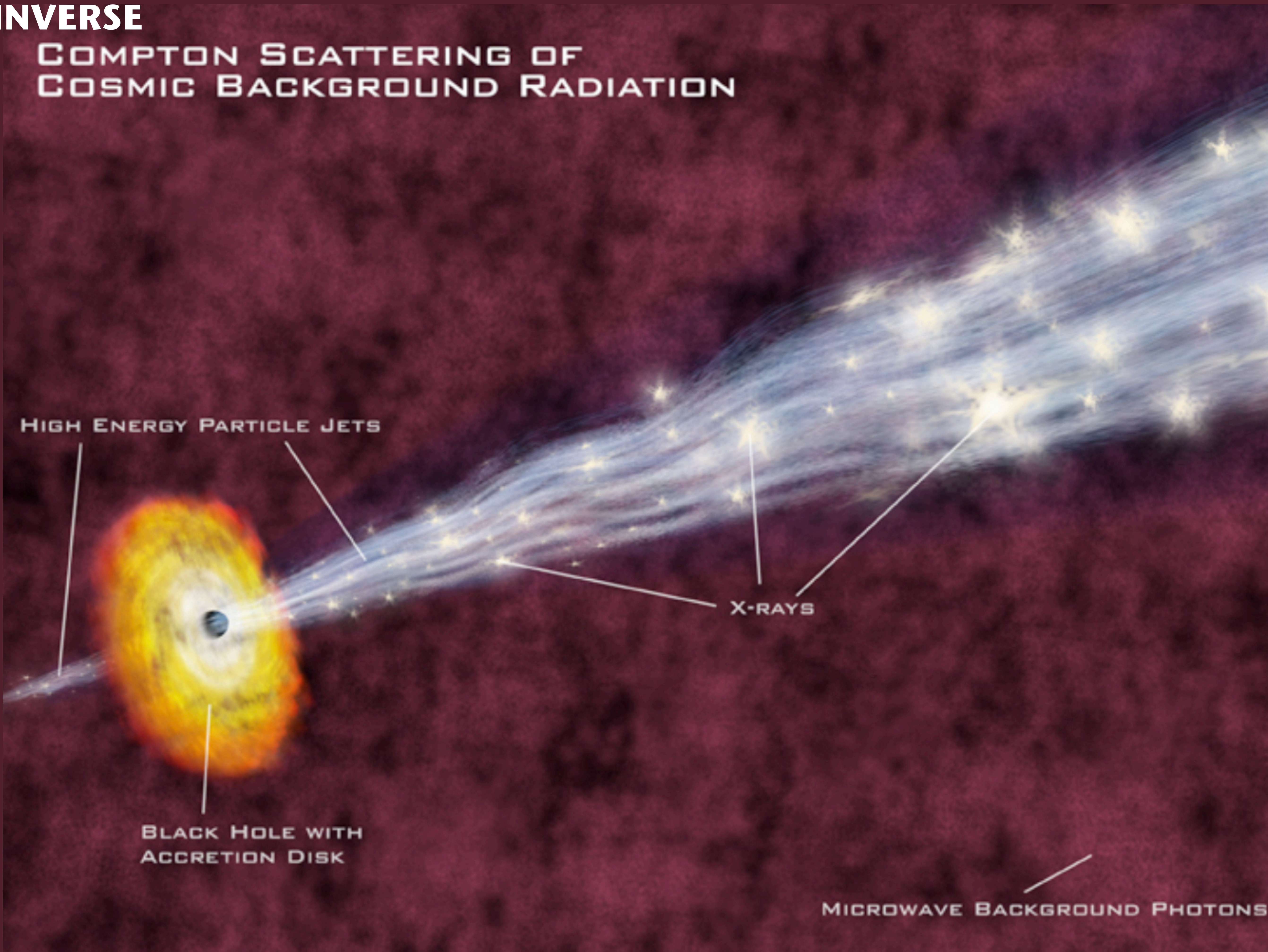
$$s = (p-1)/2$$

Recall the cosmic ray spectrum from yesterday — charged particles in a magnetic field



-The energy spectrum of cosmic-ray electrons in the local interstellar medium (Casadei, D., & Bindi, V. 2004, ApJ, 612,262). In the energy range above a few GeV, N(E) is a power law with slope p =2.4.

INVERSE



Compton Scattering of
Cosmic Background Radiation
High Energy Particle Jets
X-rays
Black Hole with
Accretion Disk
Microwave Background Photons

Compton effect shows up in:

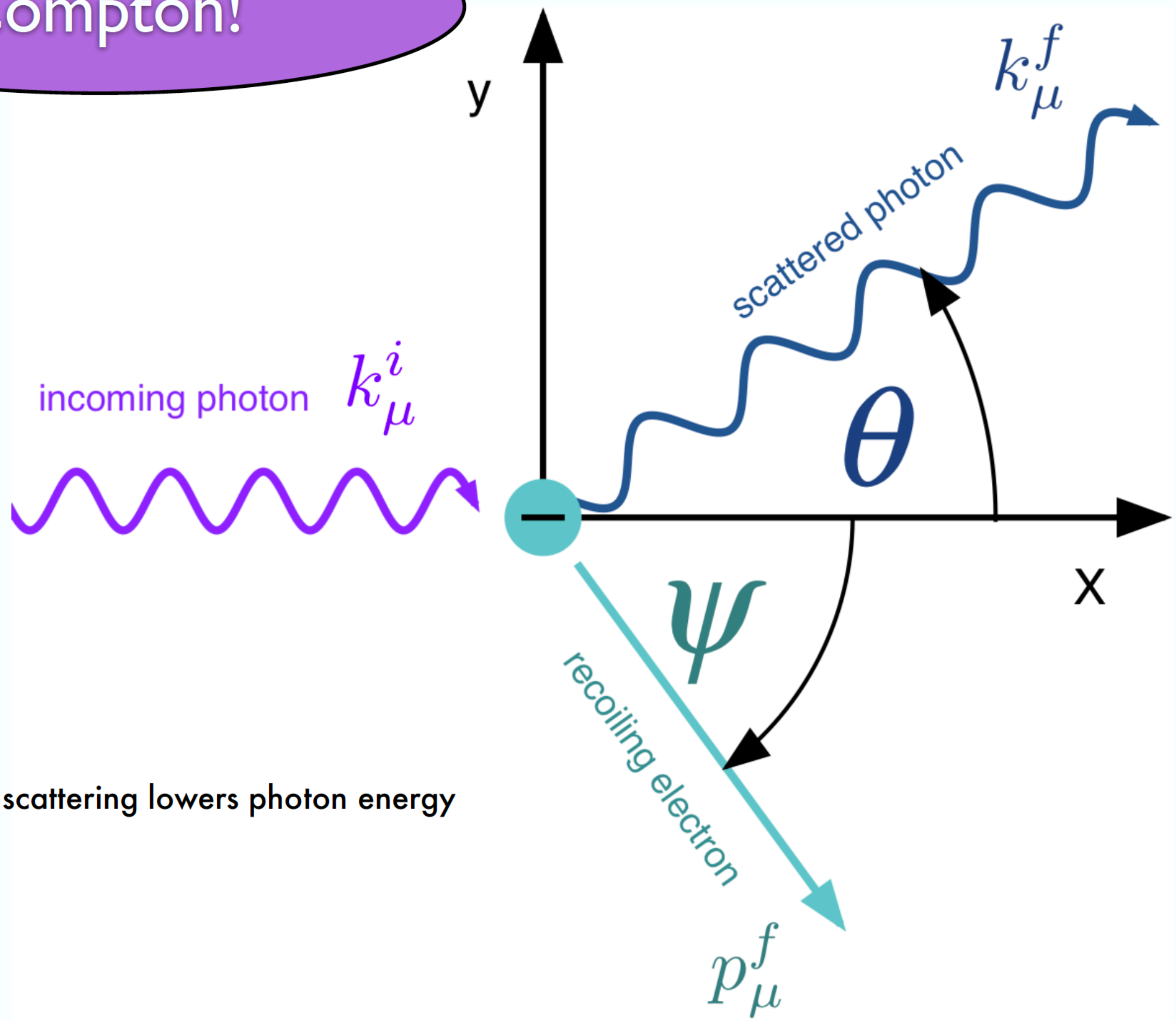
hot gas near binary Xray sources

hot plasma near active galactic nucleii

hot gas in galaxy clusters

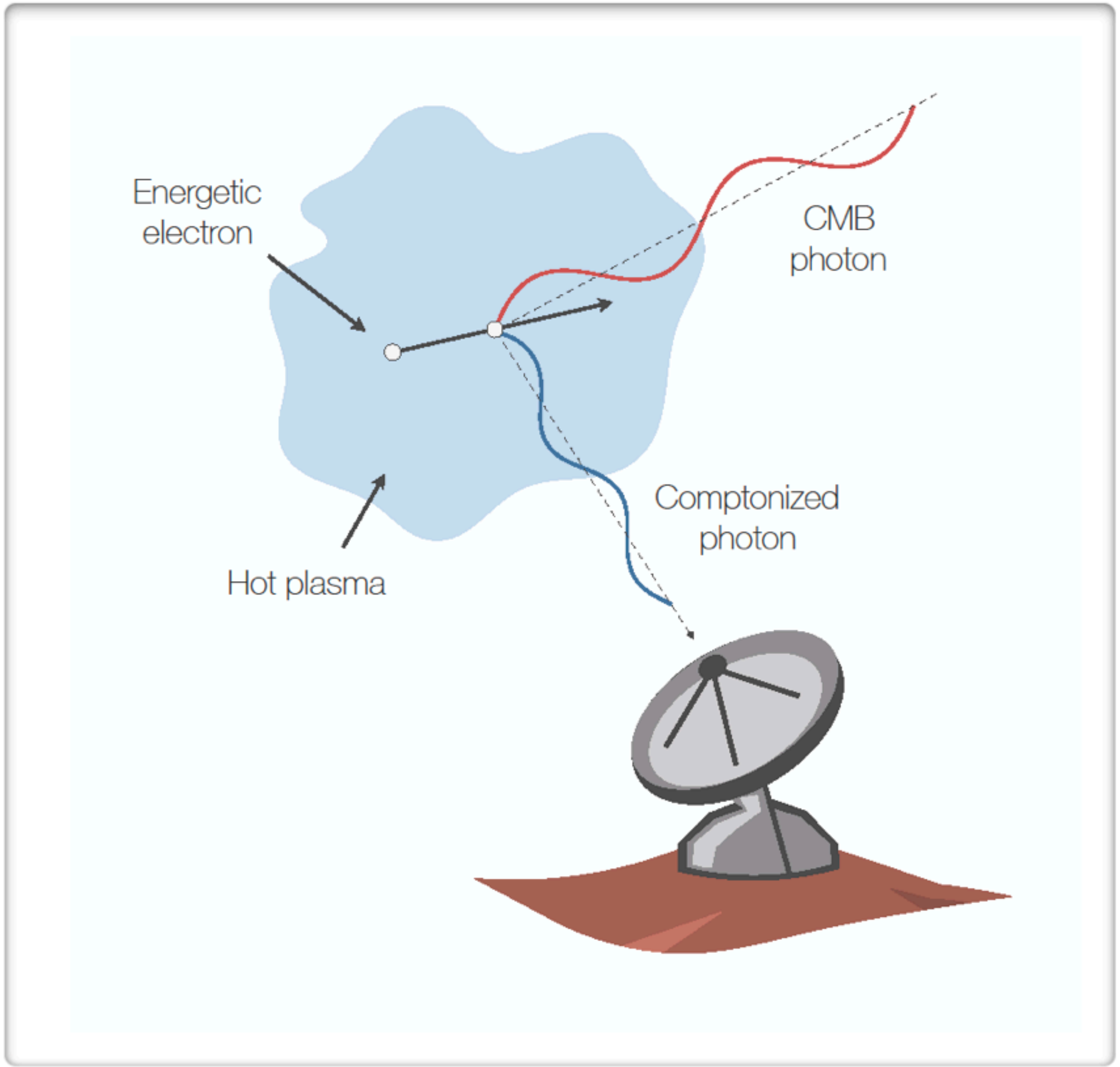
primordial gas cooling after the Big Bang

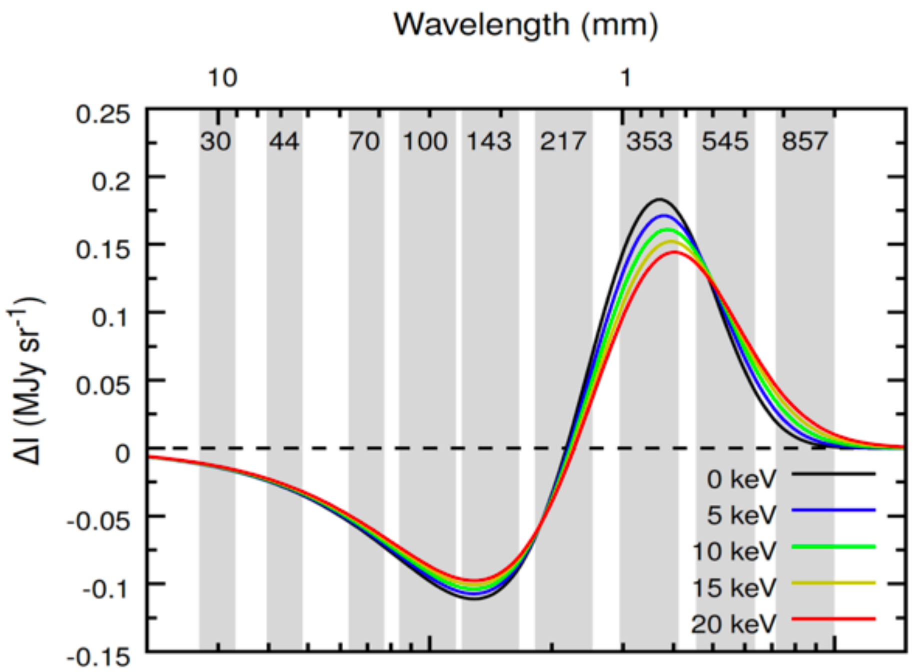
Compton!

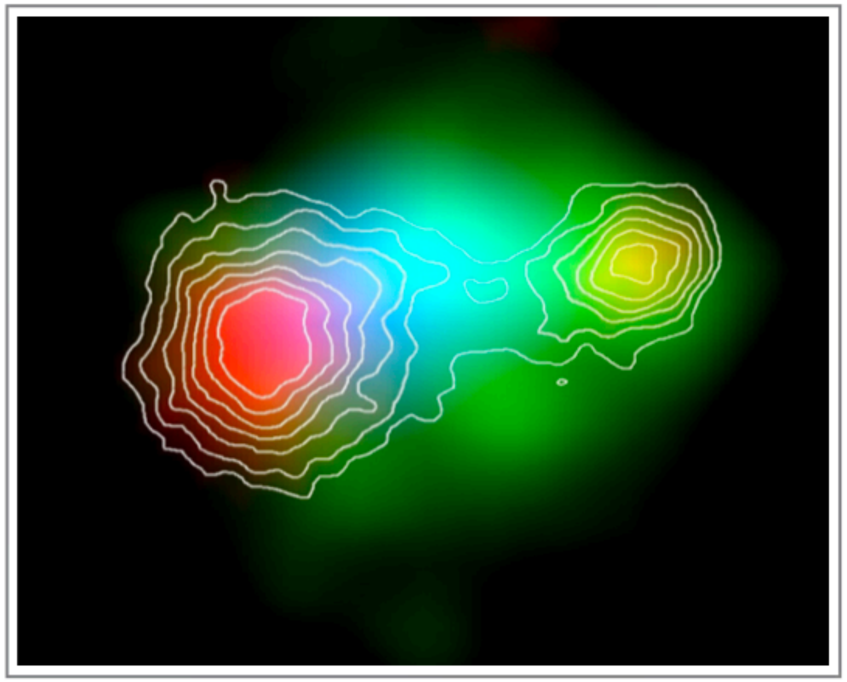


Compton scattering lowers photon energy

Inverse Compton scattering boosts the energy of the detected light

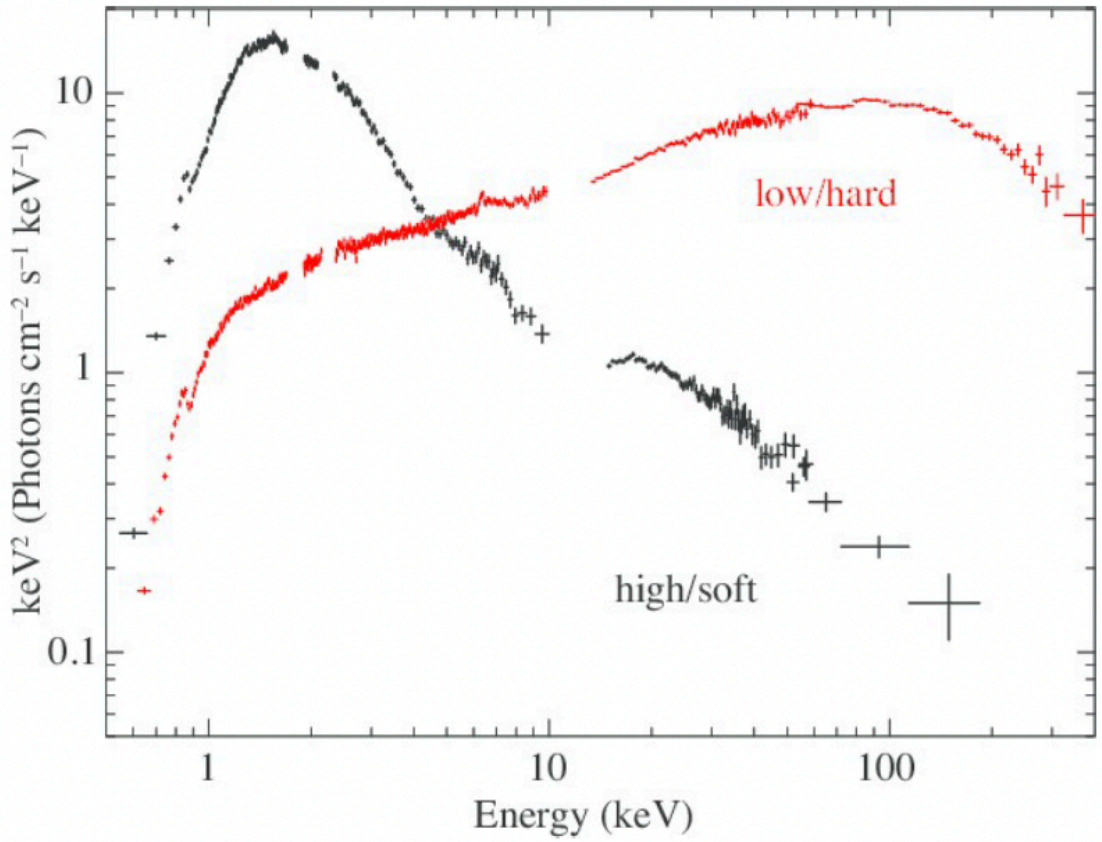


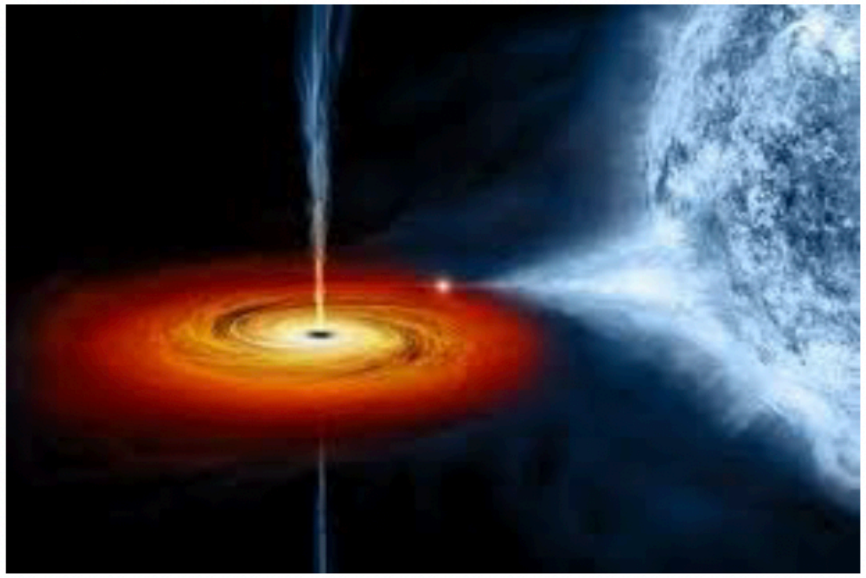




Photon scattering by electrons - Overview

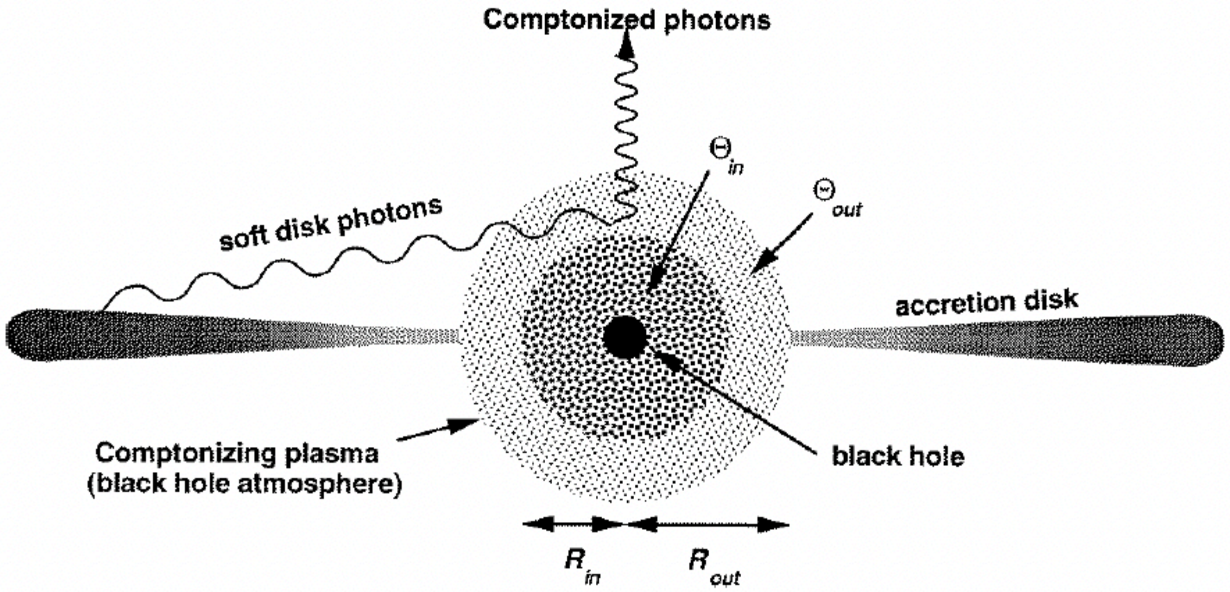
	Low energy photons $\hbar\omega \ll m_e c^2$	**High energy photons** $\hbar\omega \geq m_e c^2$
$v \ll c$	Thomson scattering Classical treatment frequency unchanged	Compton scattering Quantum treatment incorporating photon momentum frequency decreases
$v \sim c$	$\gamma\hbar\omega \ll m_e c^2$ Inverse Compton Photons gain energy from relativistic electrons Approximate with classical treatment in electron rest frame Frequency increases	$\gamma\hbar\omega \geq m_e c^2$ Inverse Compton Quantum treatment in electron rest frame Photons gain energy from relativistic electrons





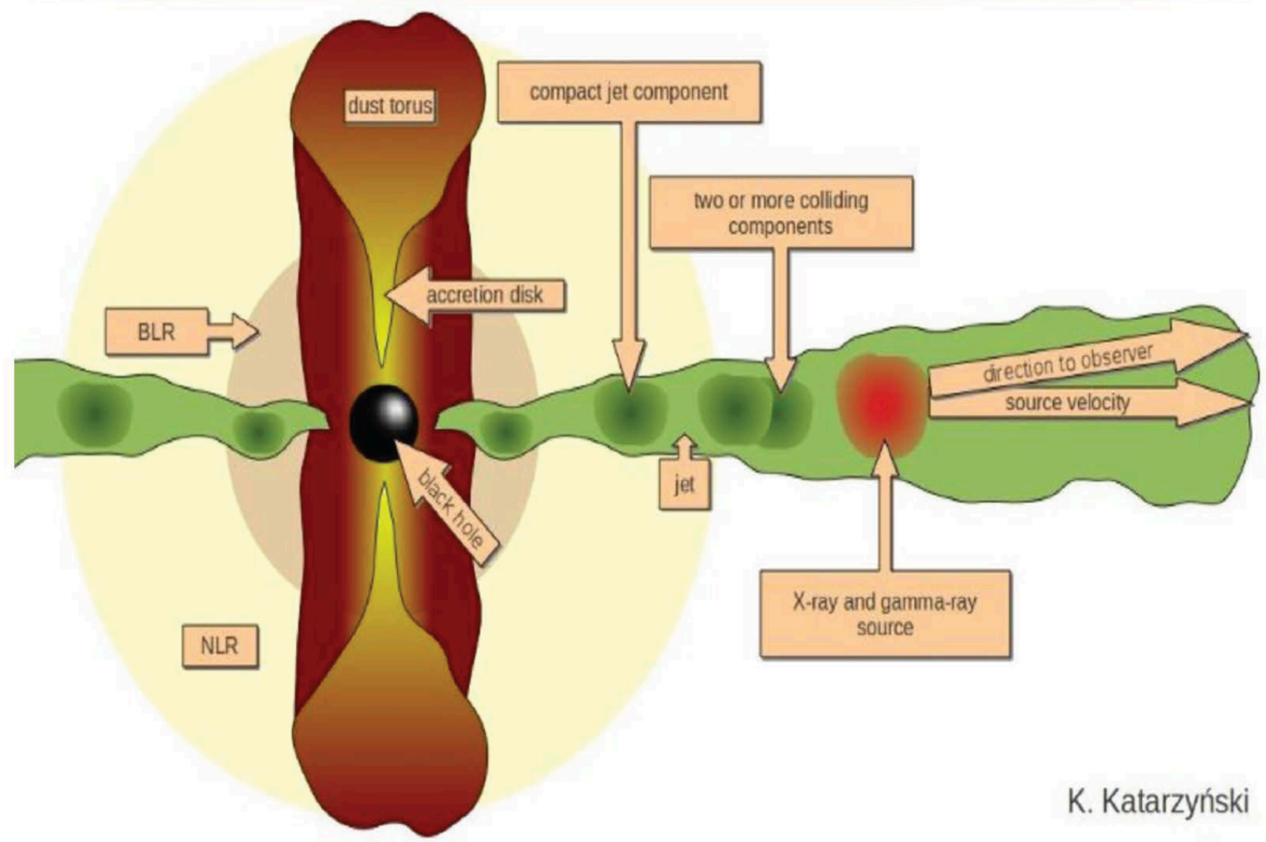
Cygnus X-1

15 solar mass Black Hole around a Blue Supergiant

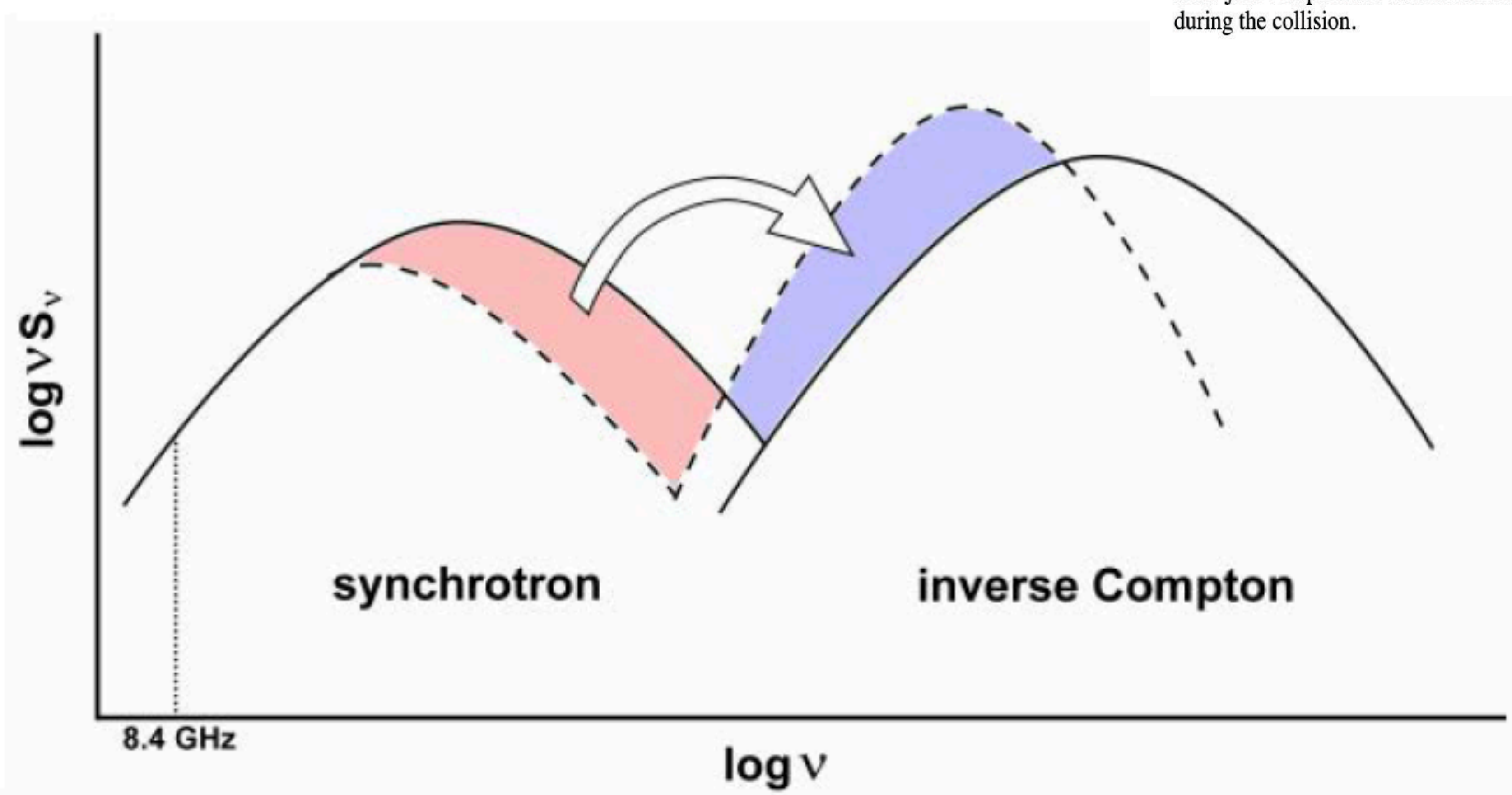


Inverse Compton!

There is an interplay between synchrotron and inverse Compton

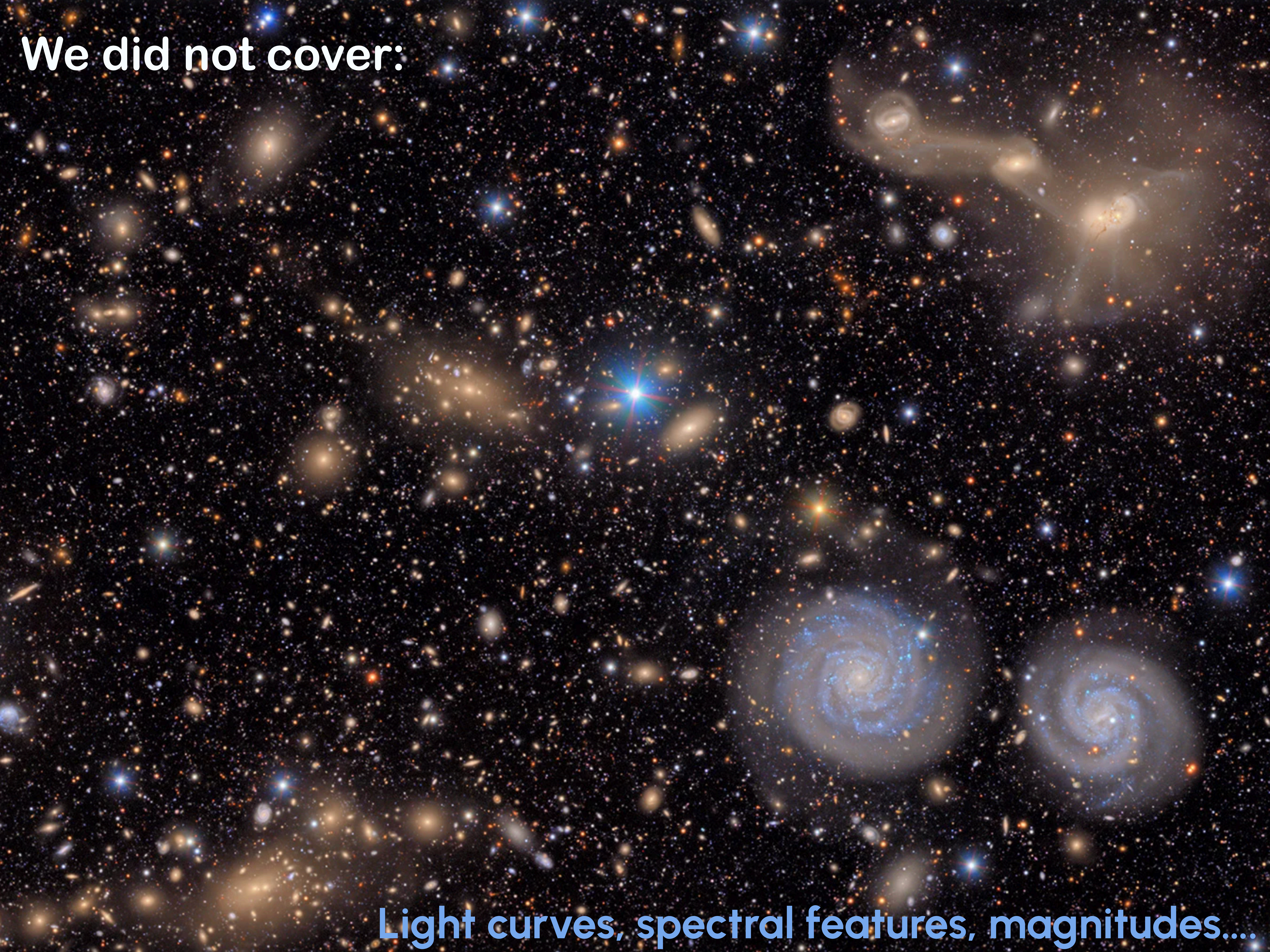


Cross section of Active Galactic Nucleus. Source of the high energy emission, a blob is created by collision of two or more jet's components. Particles inside the jet are accelerated efficiently a the front of the shock wave that is created during the collision.



$$P = \frac{-dE}{dt} = \frac{4}{3}\sigma_T c \beta^2 \gamma^2 \cancel{U_B}$$

U_γ


We did not cover:
Light curves, spectral features, magnitudes....