EMISSION MECHANISMS

LESSON 1

CHIARA FERRARI

REFERENCE TEXT:

"ASTROPHYSICAL PROCESSES" BY H. BRADT
CAMBRIDGE UNIVERSITY PRESS (2008)

OUTLINE OF THIS LESSON

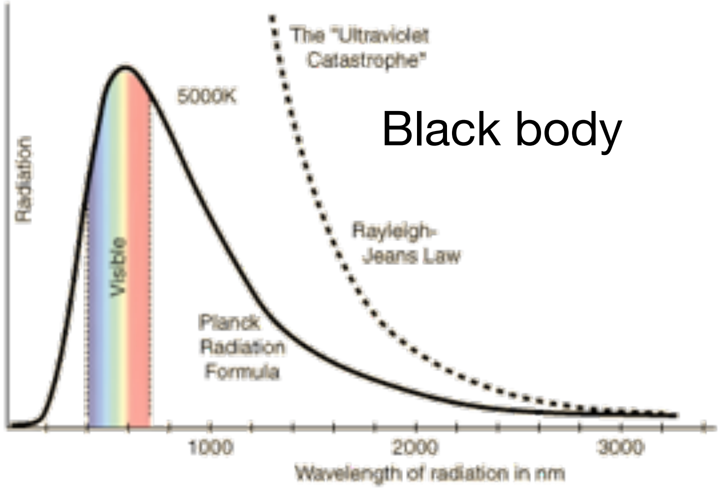
- Overview of this part of the "Cosmology" course
  1. Emission mechanisms
  2. Astrophysical examples

- Thermal bremsstrahlung radiation (with a general introduction)
  1. Measurable quantities in astrophysics
  2. Thermal bremsstrahlung from a hot plasma of ionized atoms

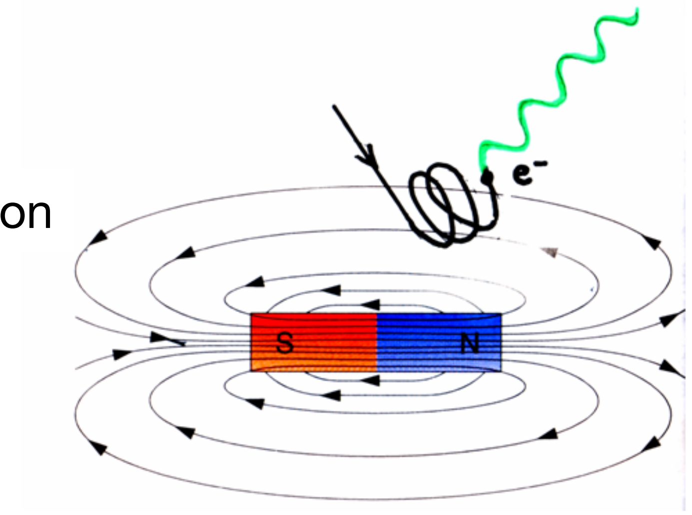
EMISSION MECHANISMS

- Thermal bremsstrahlung radiation
- Blackbody radiation
- Synchrotron radiation
- Compton scattering

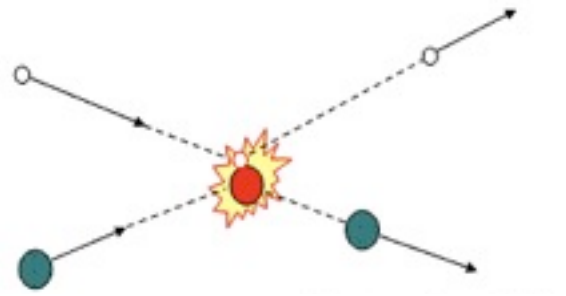
Bremsstrahlung



Black body

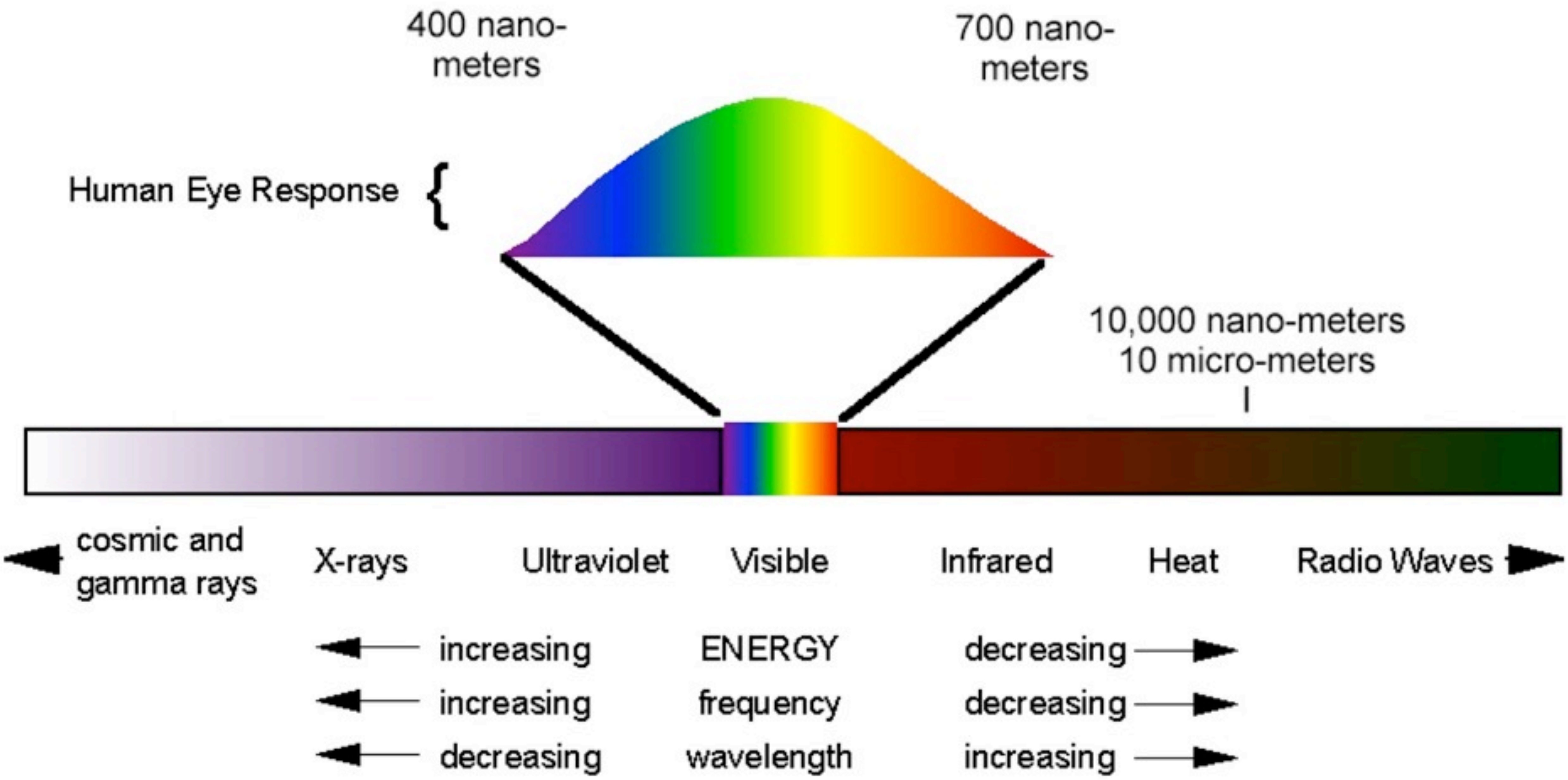


Synchrotron



Compton scattering

Emission Mechanisms



ASTROPHYSICAL EXAMPLES

Multi-wavelength emission

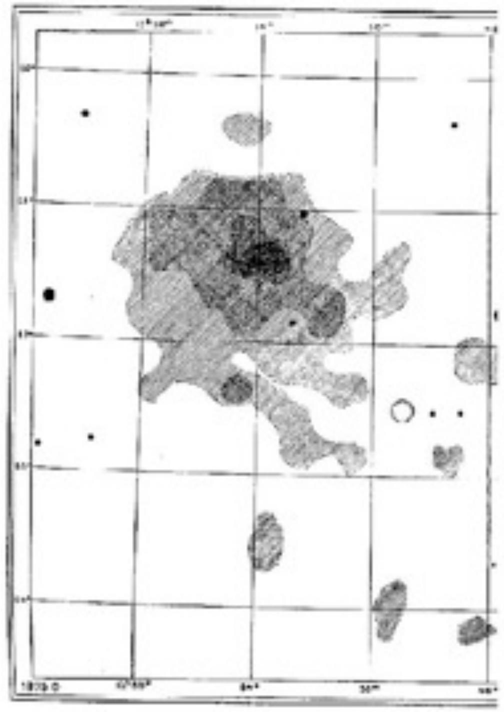
- from galaxies ...

- ... and from galaxy clusters

DISCOVERY OF GALAXIES & GALAXY CLUSTERS

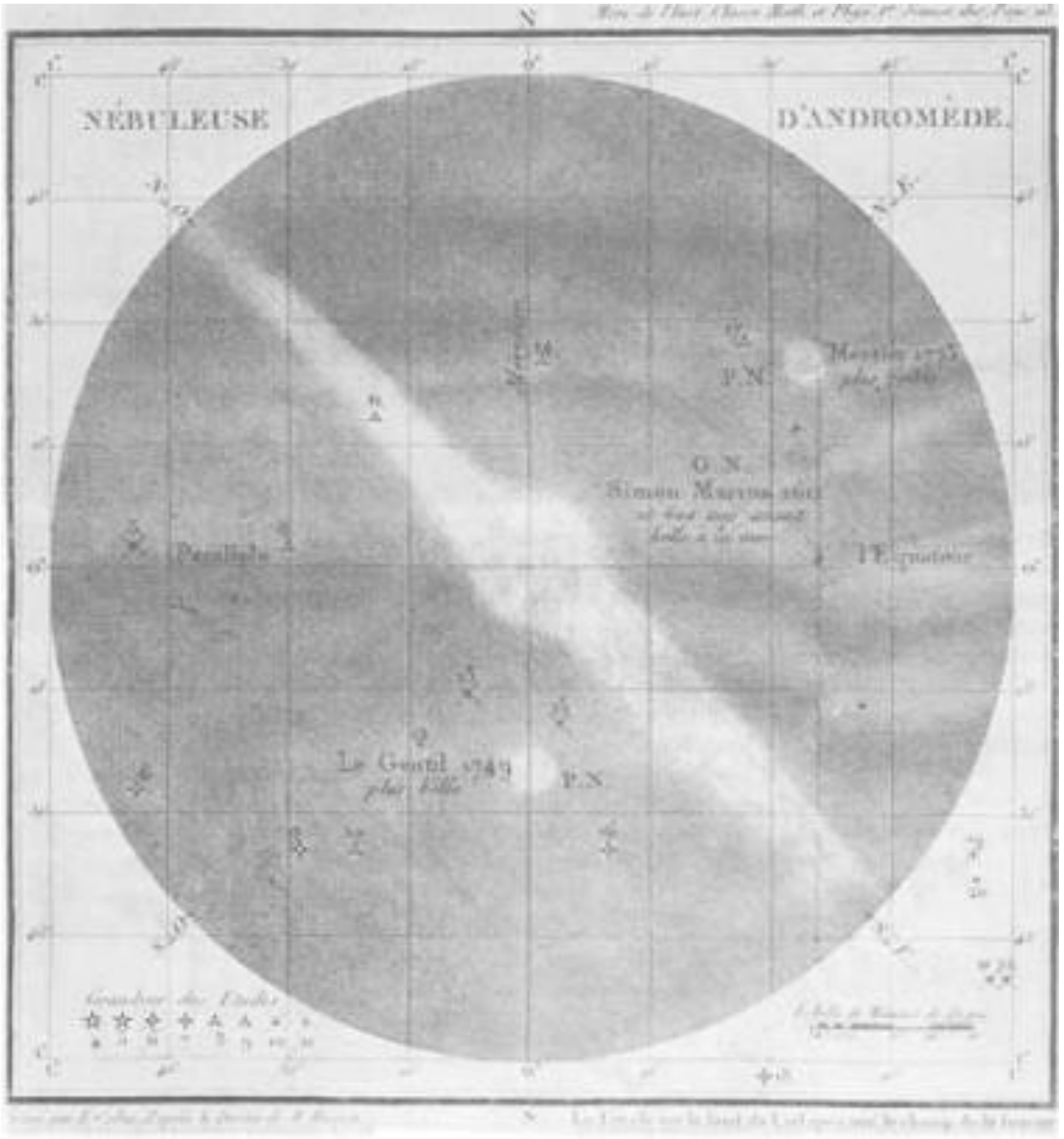
XVIII century: Messier and Herschel note the existence of "*nebulae*" and concentrations of them in the sky

1901: Wolf produce the first map of visible light distribution in a cluster of nebulae (Coma)



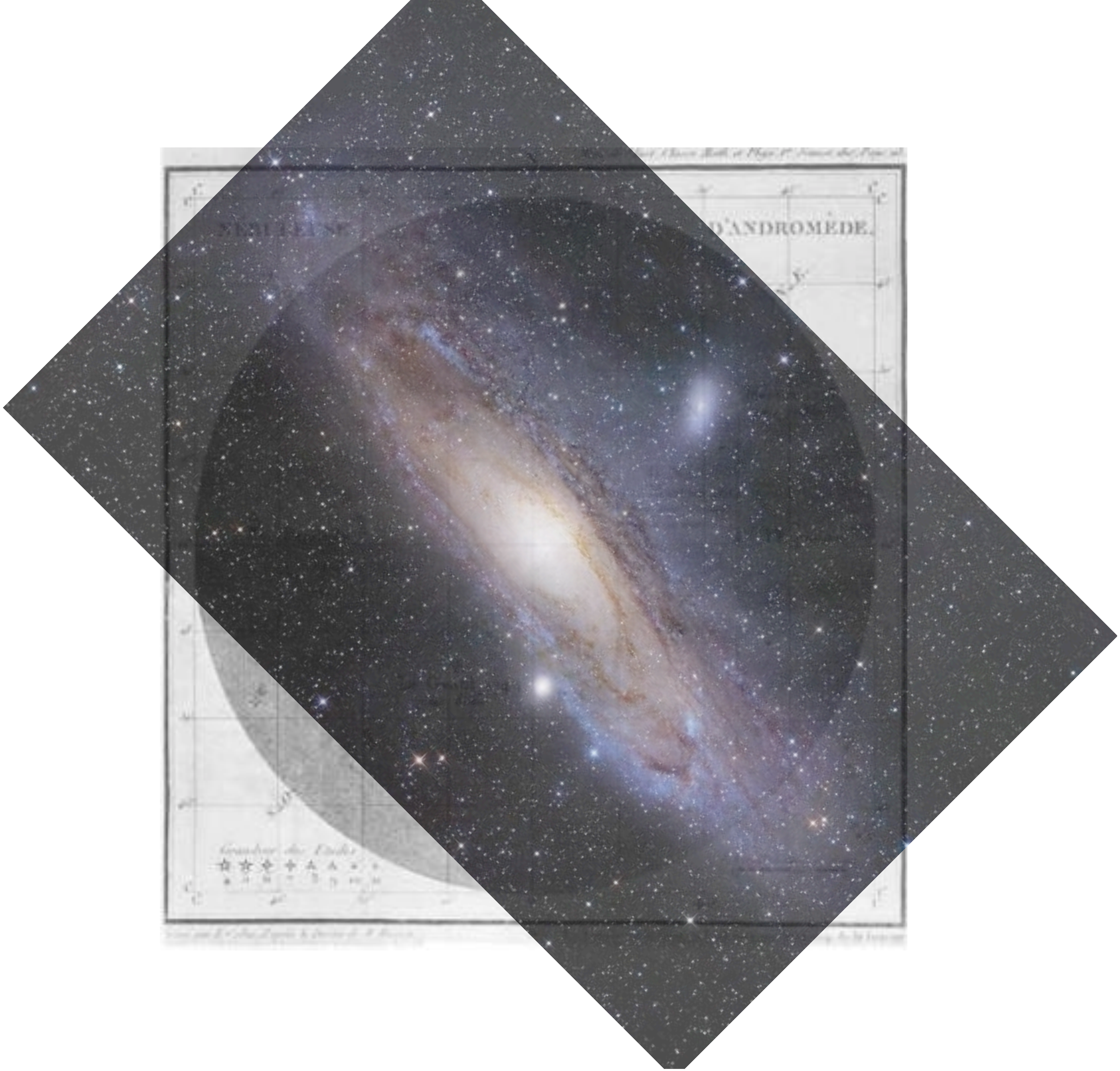
1920: "Great debate" by Curtis & Shapley

THE ANDROMEDA GALAXY



... as seen by Messier ...

... and by the Hubble Space Telescope


D'ANDROMEDE.
Grandeur des Etoiles

1923: OUR GALAXY IS NOT UNIQUE!

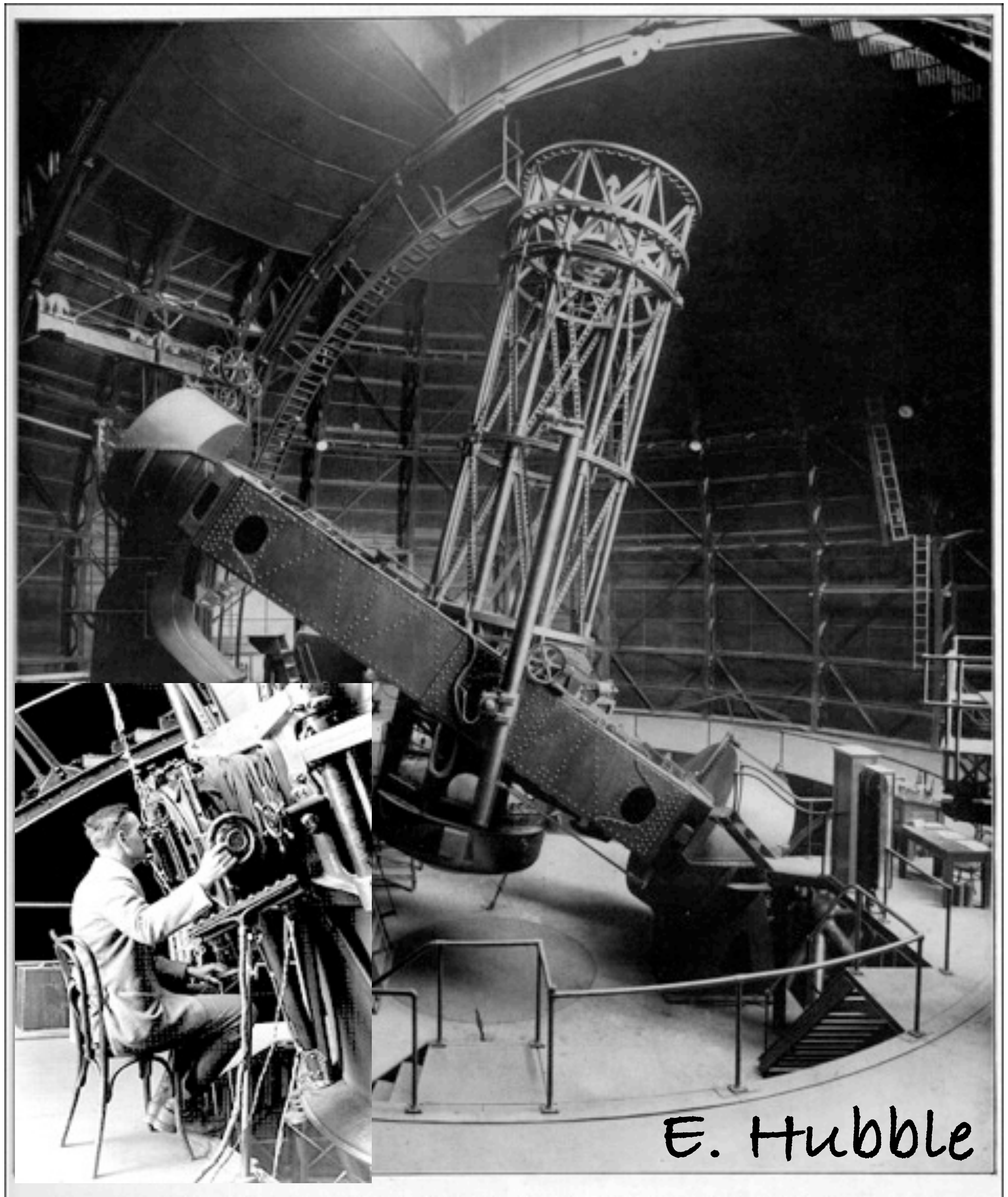


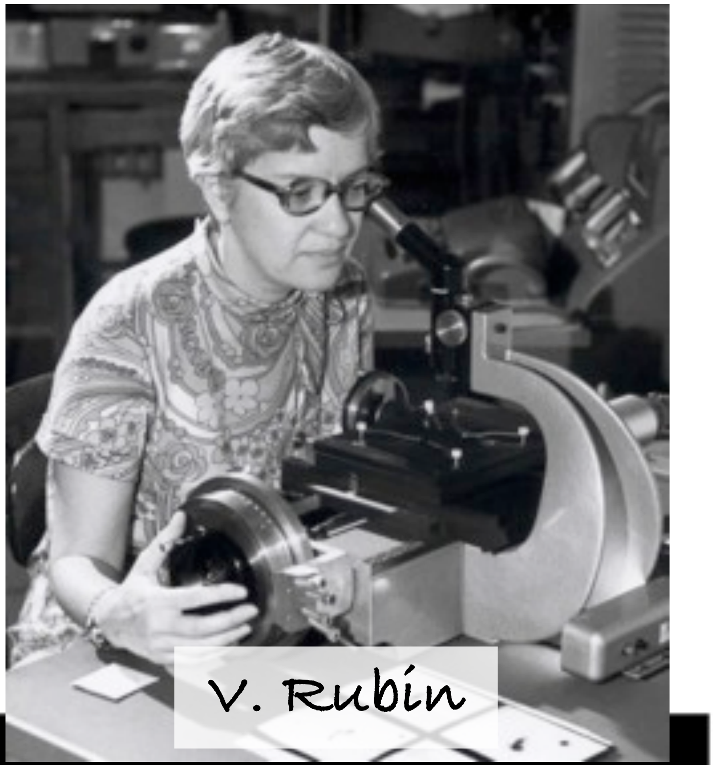
PLANCHE 31. — LE TÉLESCOPE HOOKER DE 2 m, 56 DE L'OBSERVATOIRE DU MONT WILSON.
PLATE 31. — THE 101-INCH HOOKER REFLECTOR, MOUNT WILSON OBSERVATORY.

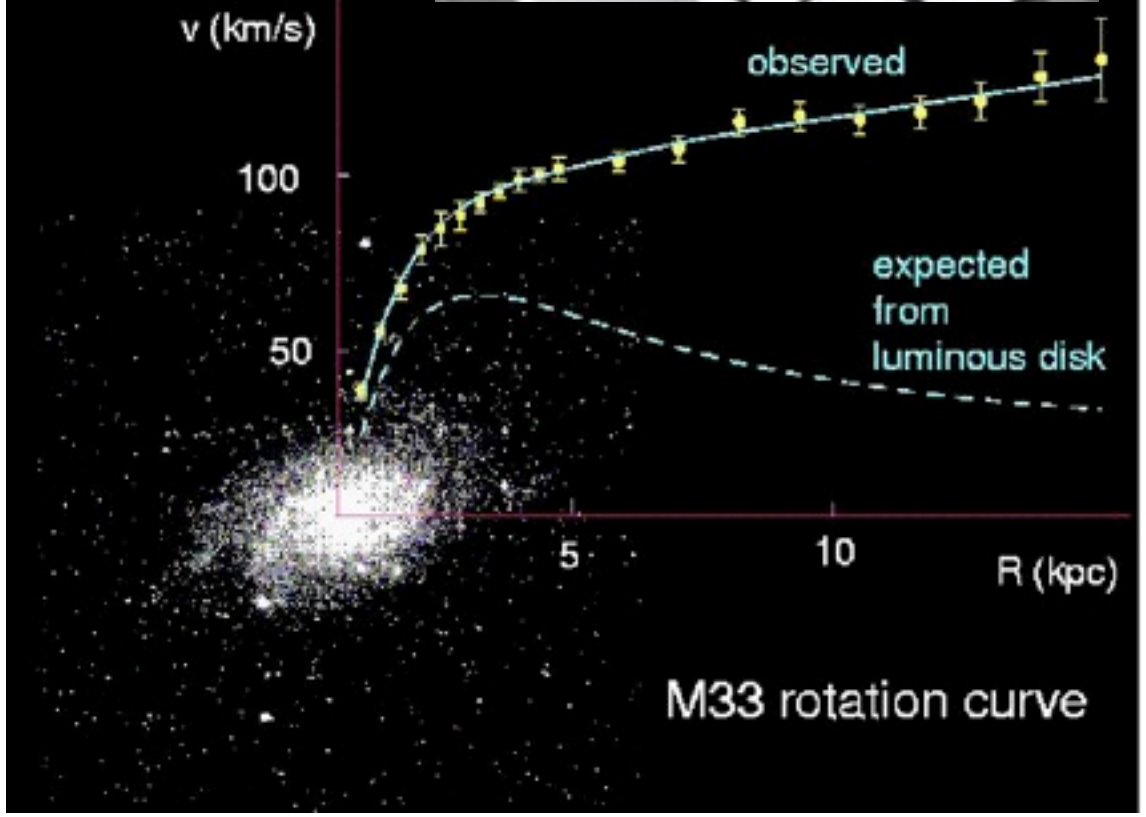
plaque 335 du 6 Octobre 1923 de E Hubble au télescope Hooker
de 100" du Mont Wilson. il trouve des "nova" dans M31 mais une
(coin haut à droite) est particulière; c'est une céphéide,
il remplace le N par VAR (Variable)
on va pouvoir ainsi mesurer la distance de M31
document Mont-Wilson

THE MASS OF GALAXIES & GALAXY CLUSTERS

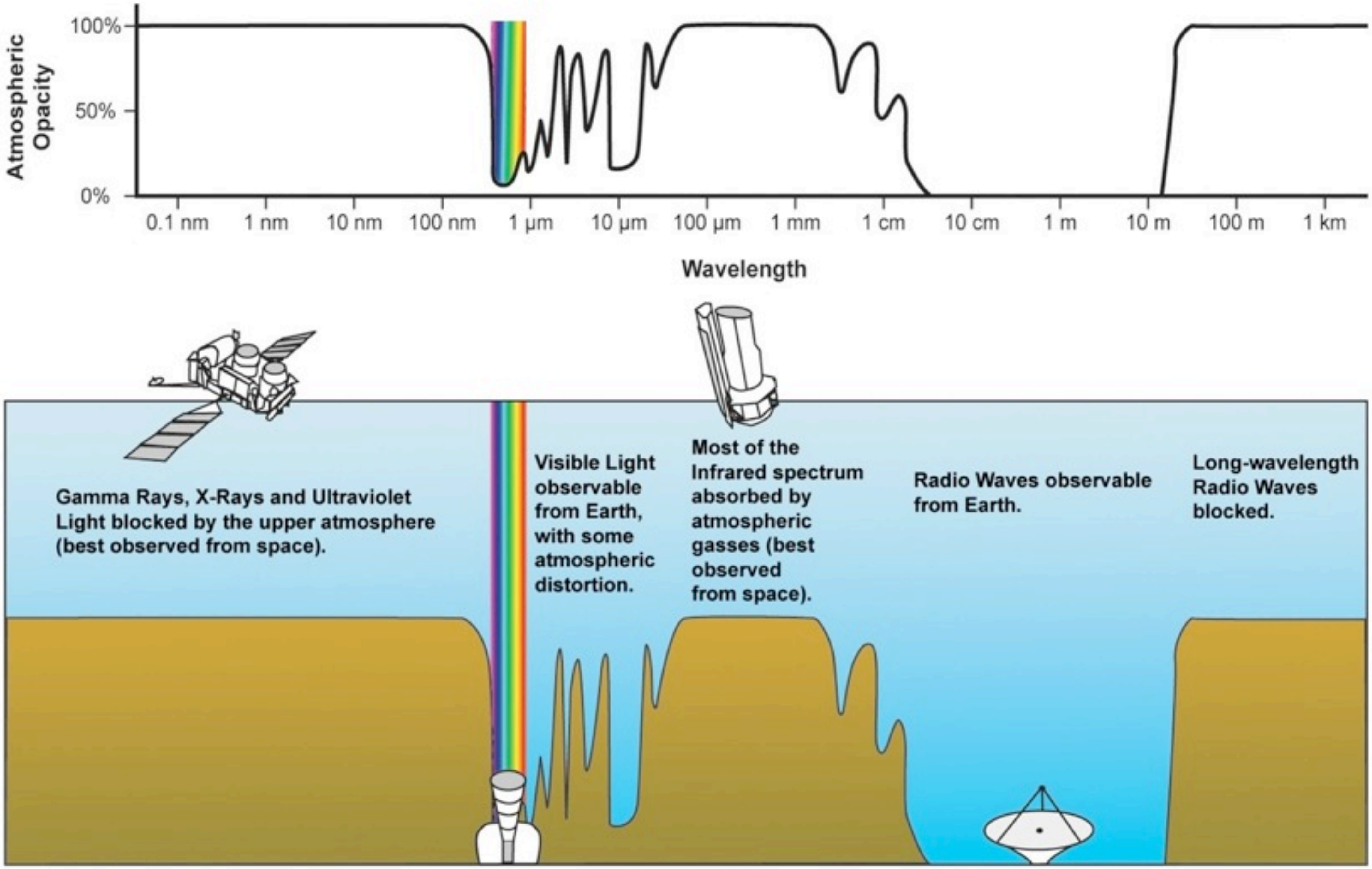
<u>30’s & 70’s:</u> unobserved form of matter in clusters and galaxies...

The Dark Matter problem catch the attention of astronomers





NOT ONLY VISIBLE LIGHT:
NOT ONLY STARS AND GALAXIES...



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

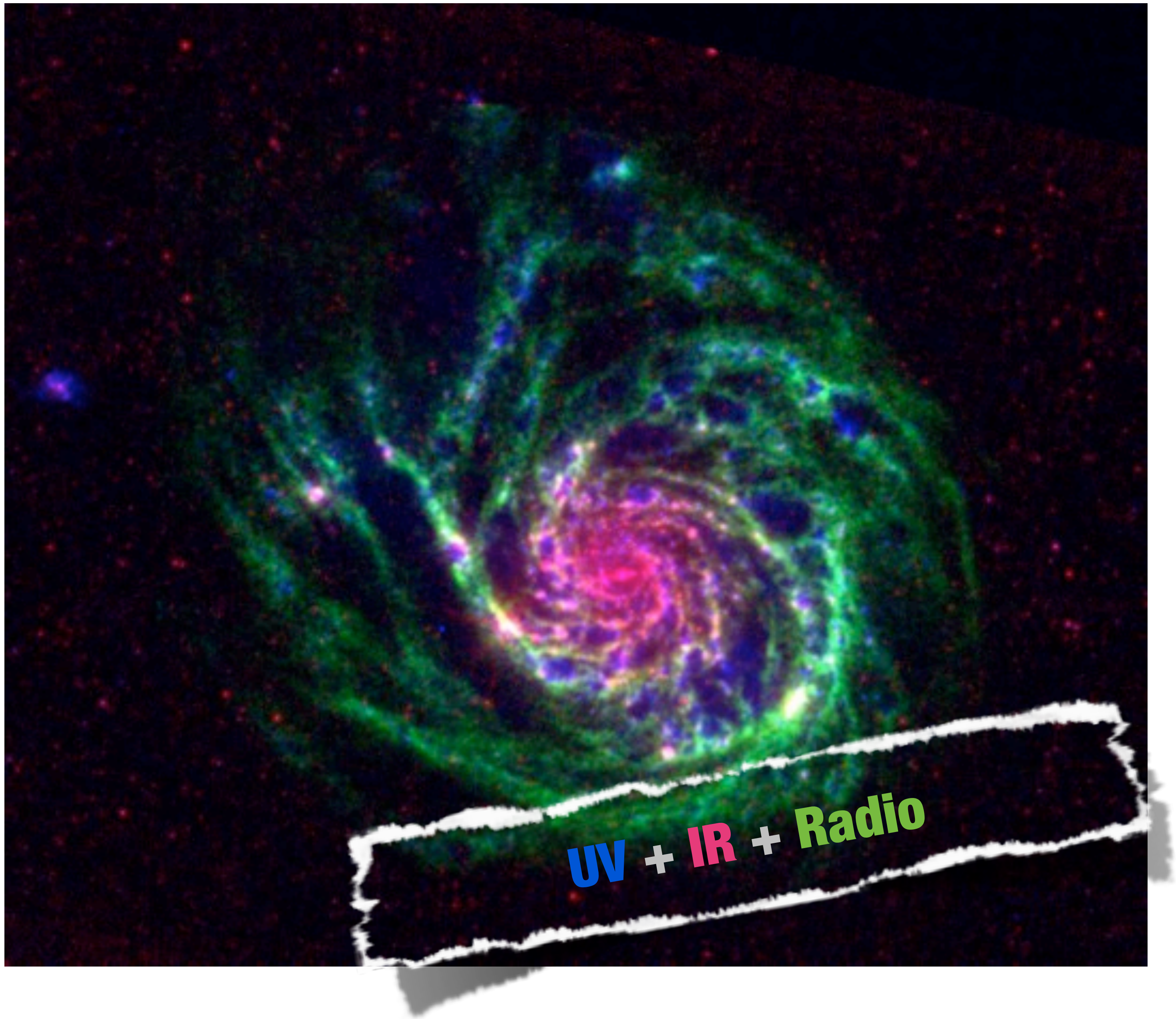
Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

ASTROPHYSICAL EXAMPLES

Multi-wavelength emission

- from galaxies ...
- ... and from galaxy clusters



ASTROPHYSICAL EXAMPLES

Multi-wavelength emission

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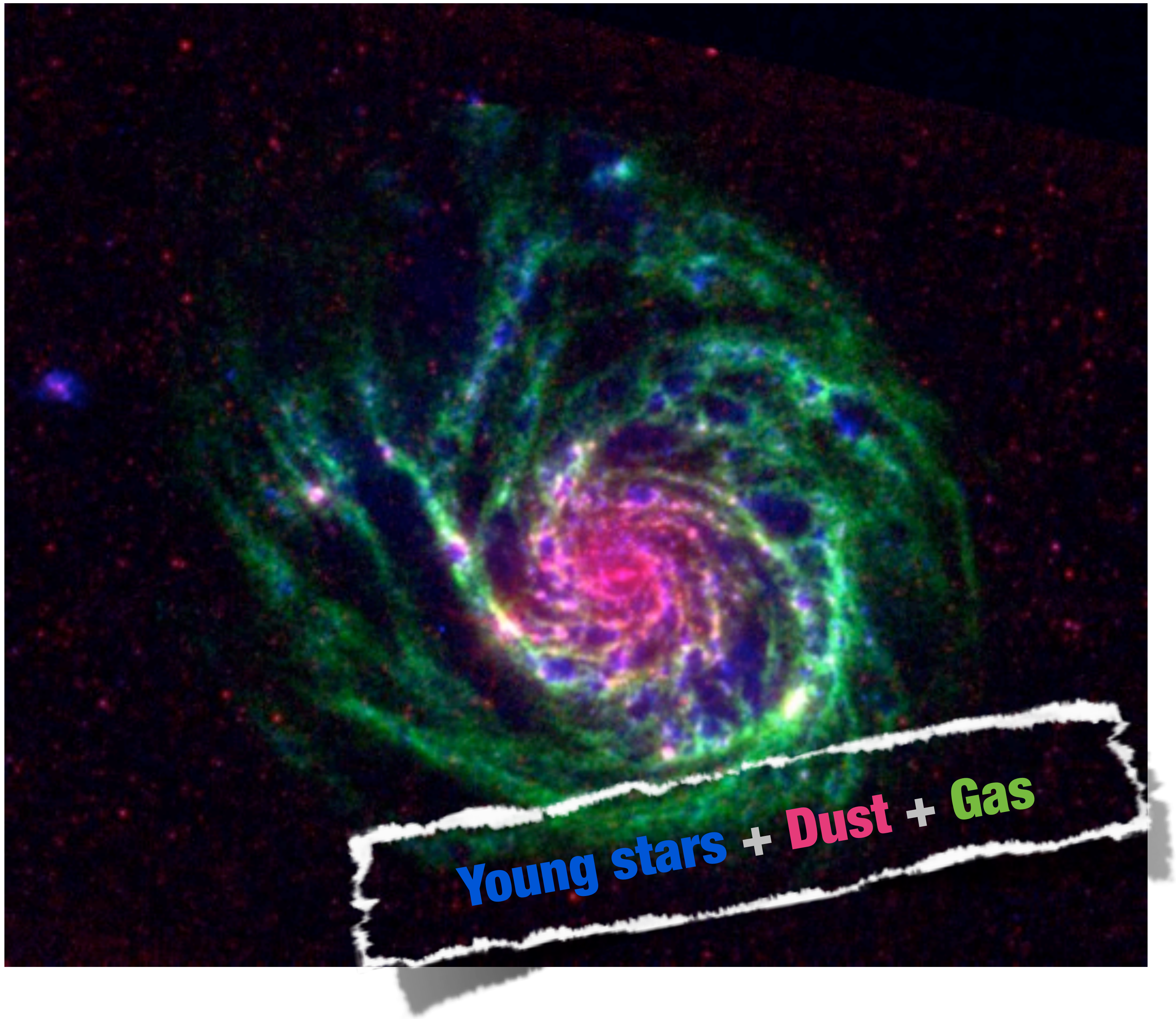

Young stars + Dust + Gas

- ... and from galaxy clusters

ASTROPHYSICAL EXAMPLES

Multi-wavelength emission

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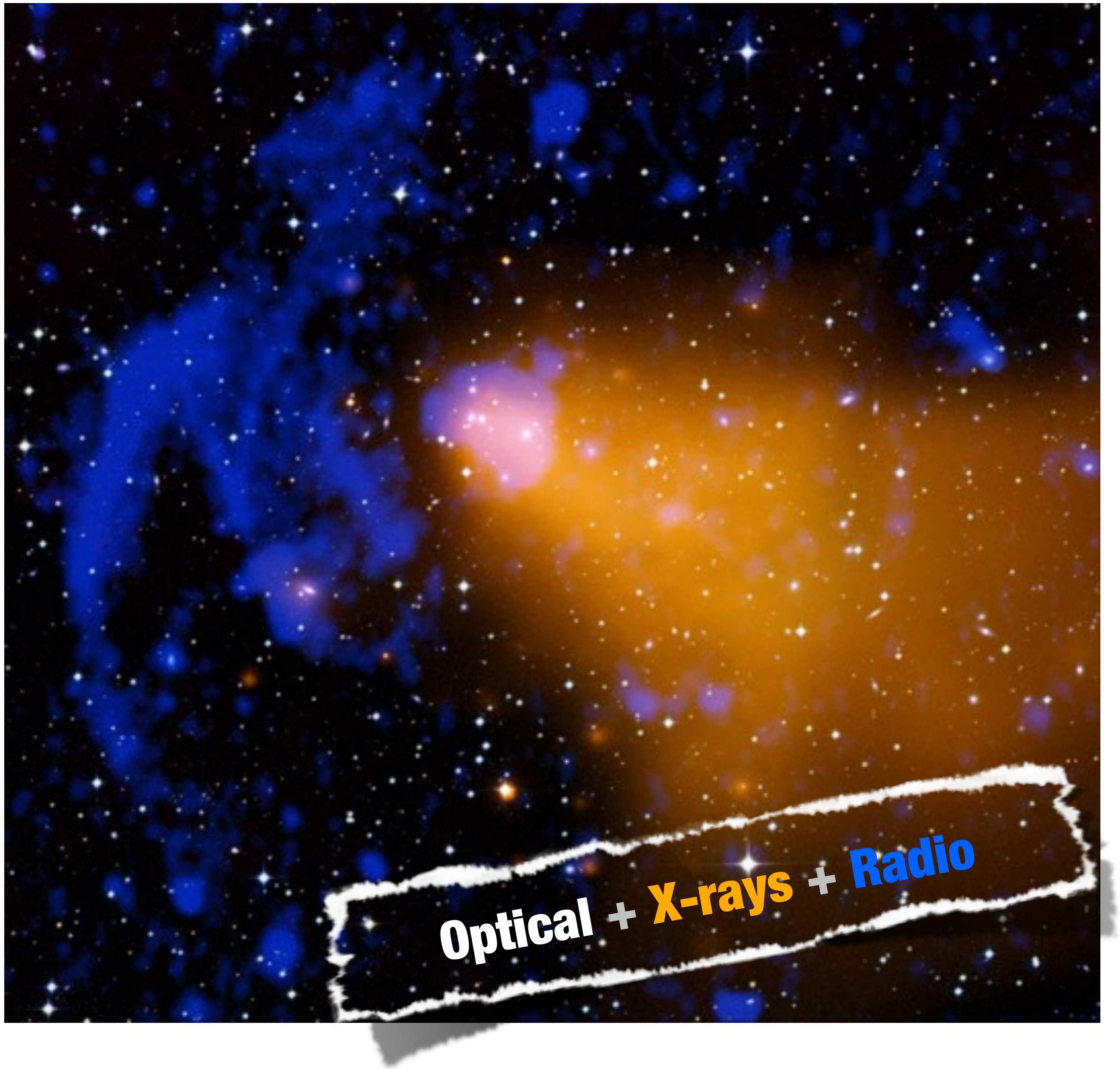

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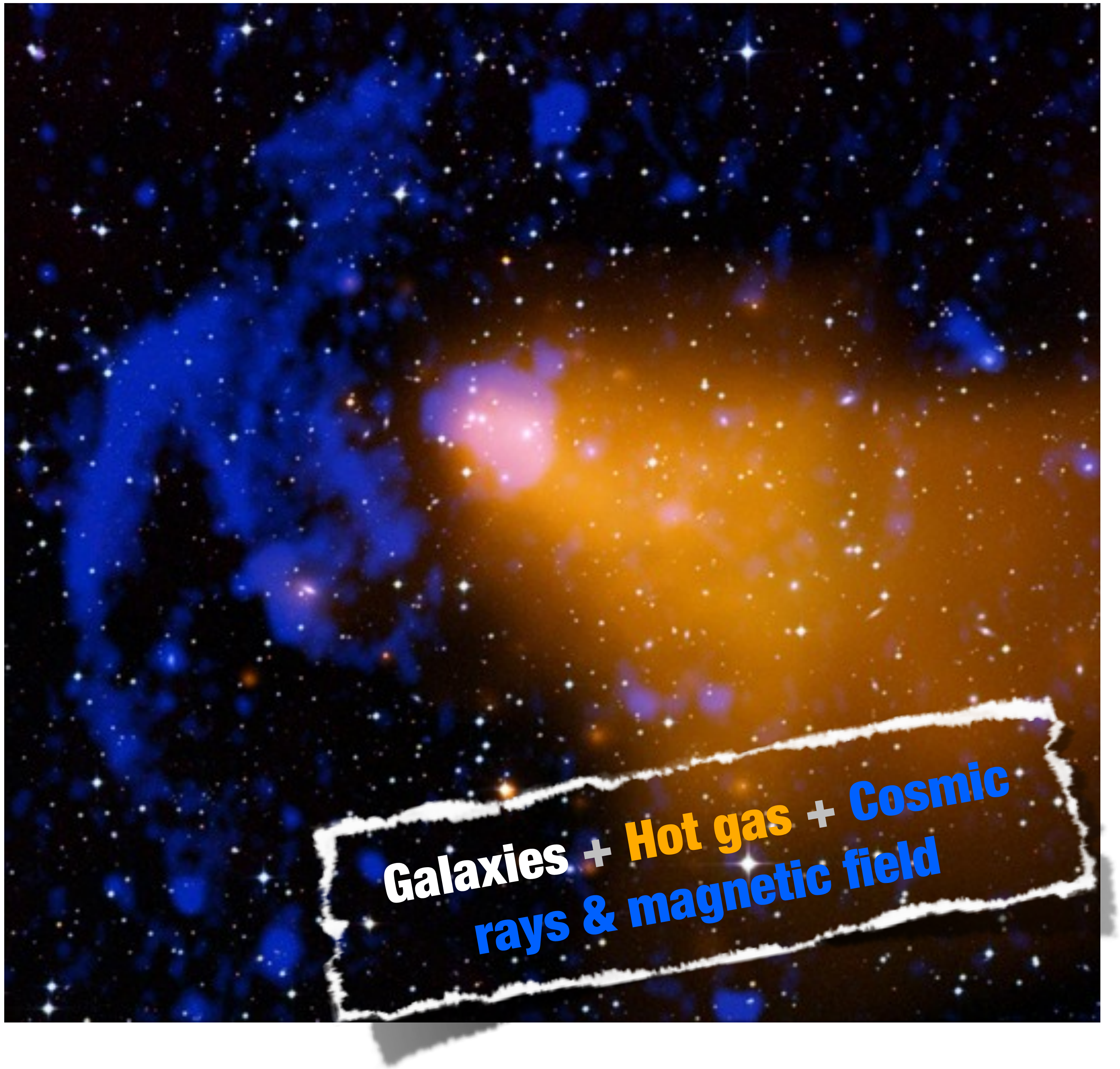
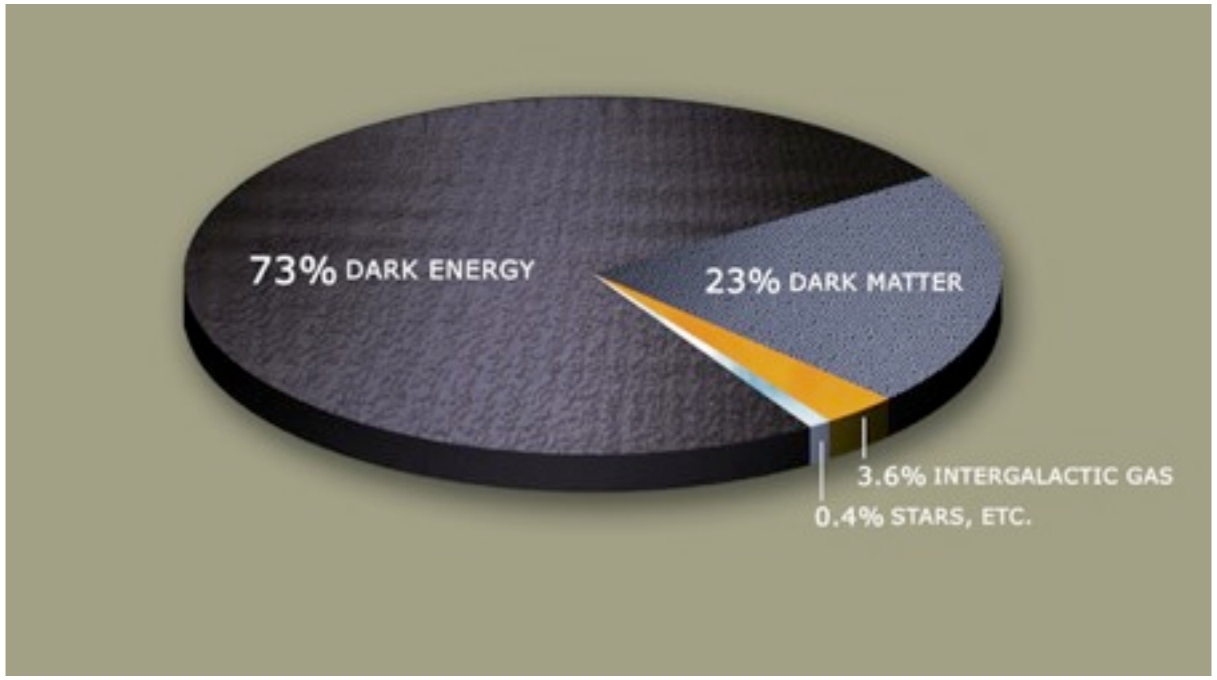
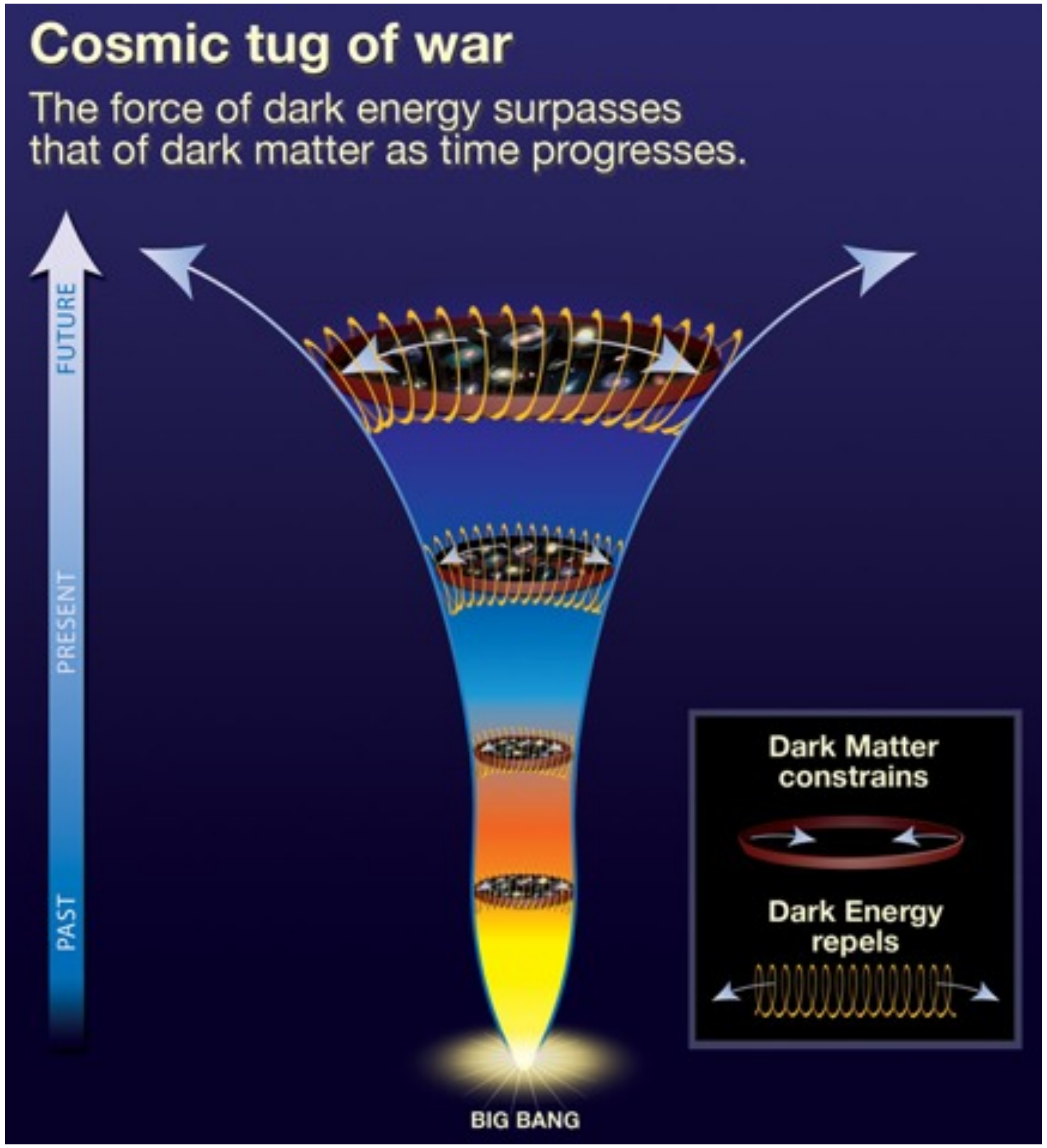


Galaxies + Hot gas + Cosmic rays & magnetic field

DARK MATTER: STILL AN OPEN ISSUE...

...AND NOT EVEN THE BIGGEST ONE!





2011: Nobel in Physics goes to

Perlmutter (U.S.), Schimdt (AUS) & Riess (U.S.)

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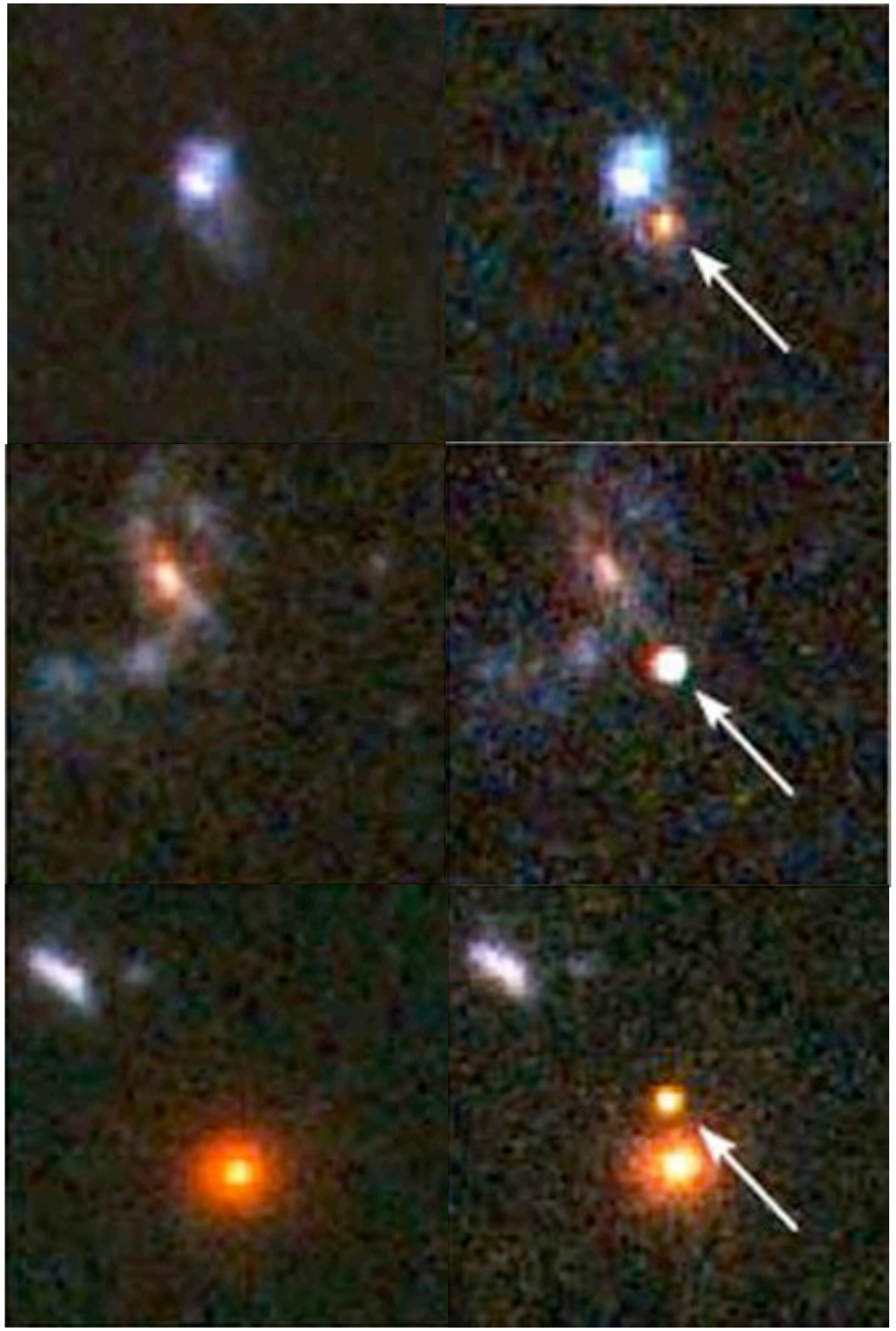


OUTLINE OF THIS LESSON

- Overview of this part of the “Cosmology” course
  i. Emission mechanisms
  ii. Astrophysical examples

- **Thermal bremsstrahlung radiation** (with a general introduction)
  i. Measurable quantities in astrophysics
  ii. Thermal bremsstrahlung from a hot plasma of ionized atoms

GENERAL INTRODUCTION
MEASURABLE QUANTITIES IN ASTROPHYSICS

- Luminosity :

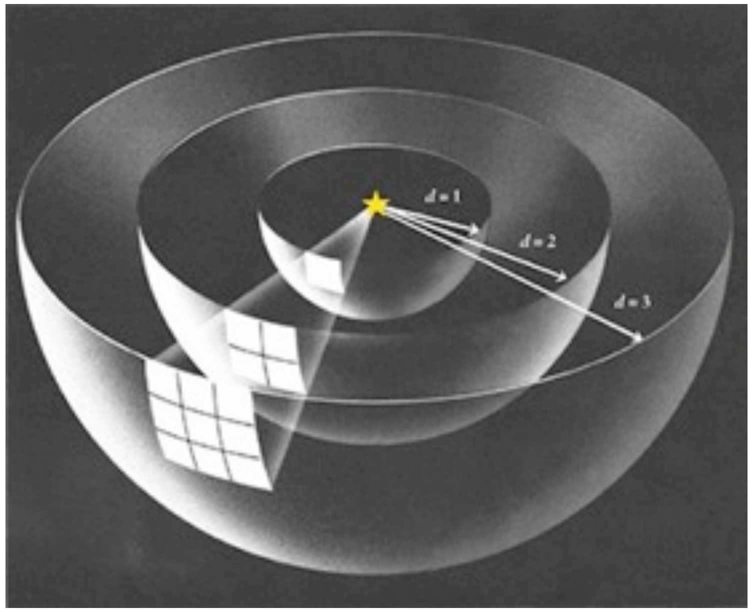
$$L = \int_{\mathrm{SV}} j \ \mathrm{d}V = \int_0^\infty L(\nu)\mathrm{d}\nu$$

L = total or absolute luminosity (W)

$L(\nu)$ = monochromatic luminosity (W Hz^{-1})

SV = source volume

j = total power radiated per unit volume (W/m^3)



- Spectral flux density:

$$S(\nu) = L(\nu)/(4\pi R^2) = \int\int I(\nu, T)\mathrm{d}\Omega$$

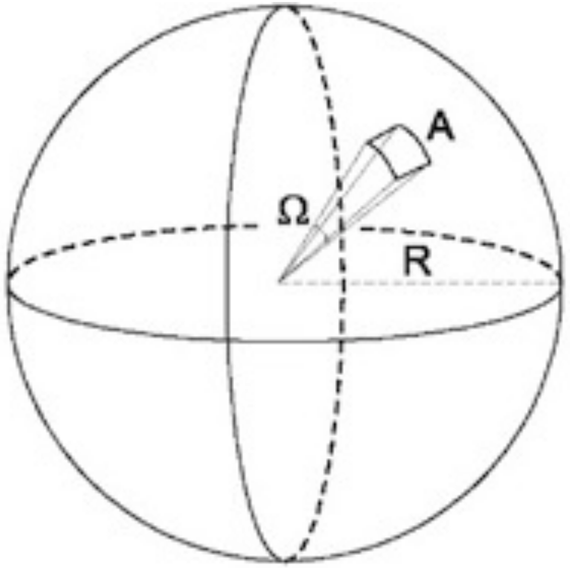
$S(\nu)$ = spectral flux density (W m^{-2} Hz^{-1})

$L(\nu)$ = monochromatic luminosity (W Hz^{-1})

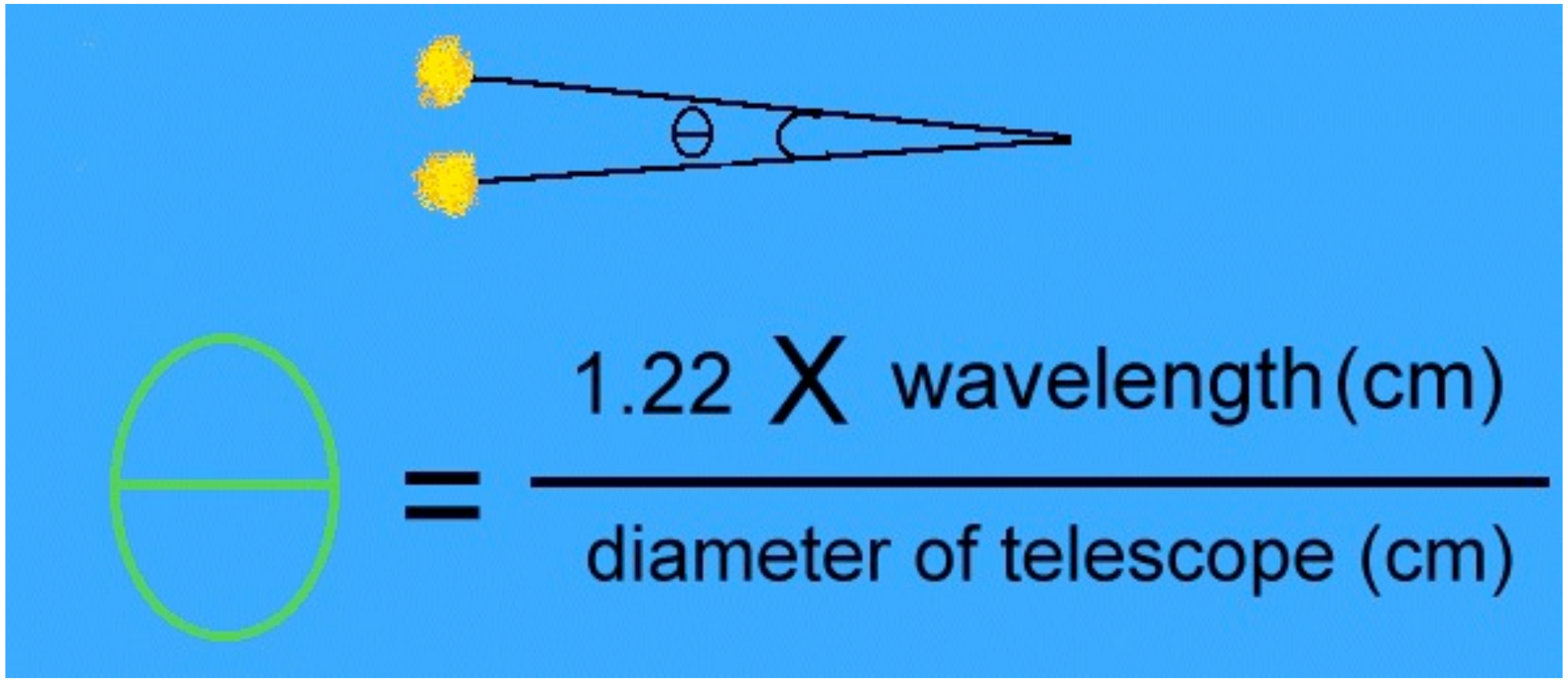
R = source distance

$I(\nu, T)$ = specific intensity (W m^{-2} Hz^{-1} sr^{-1})

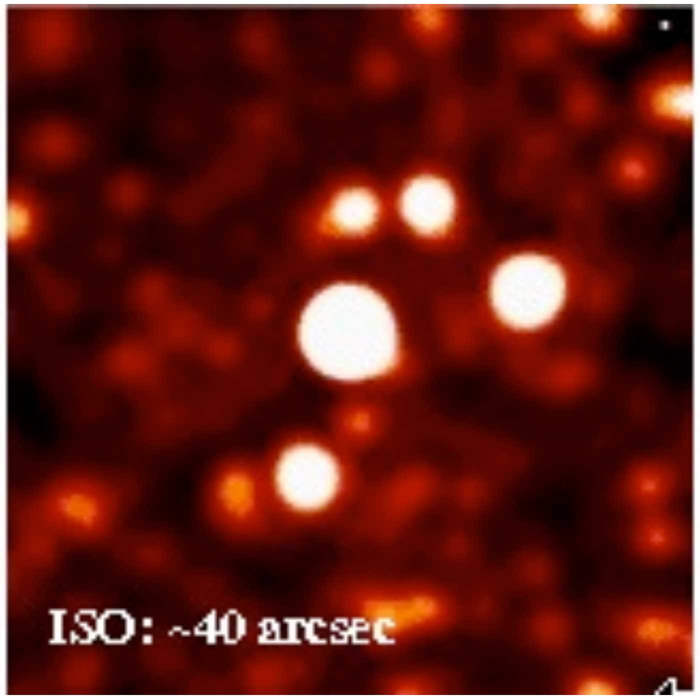
$\mathrm{d}\Omega$ = increment solid angle

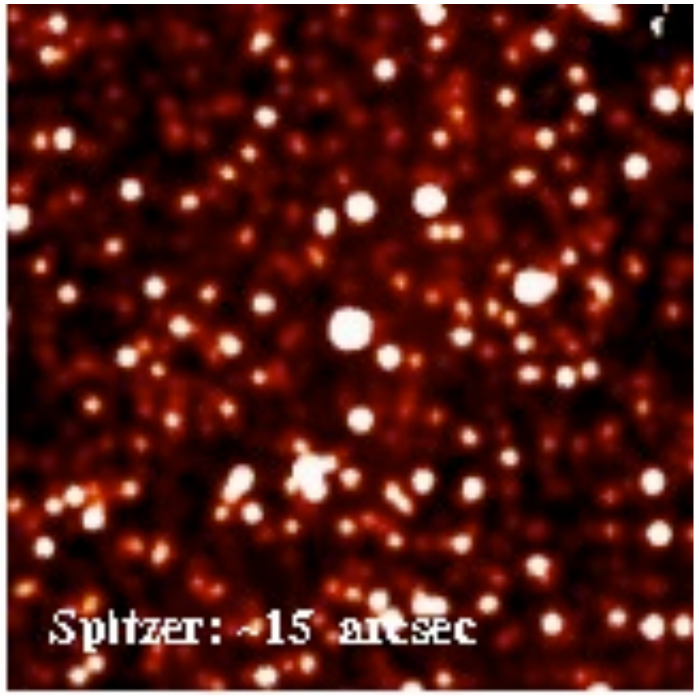


ANGULAR RESOLUTION



$$\Theta = \frac{1.22 \times \text{wavelength (cm)}}{\text{diameter of telescope (cm)}}$$

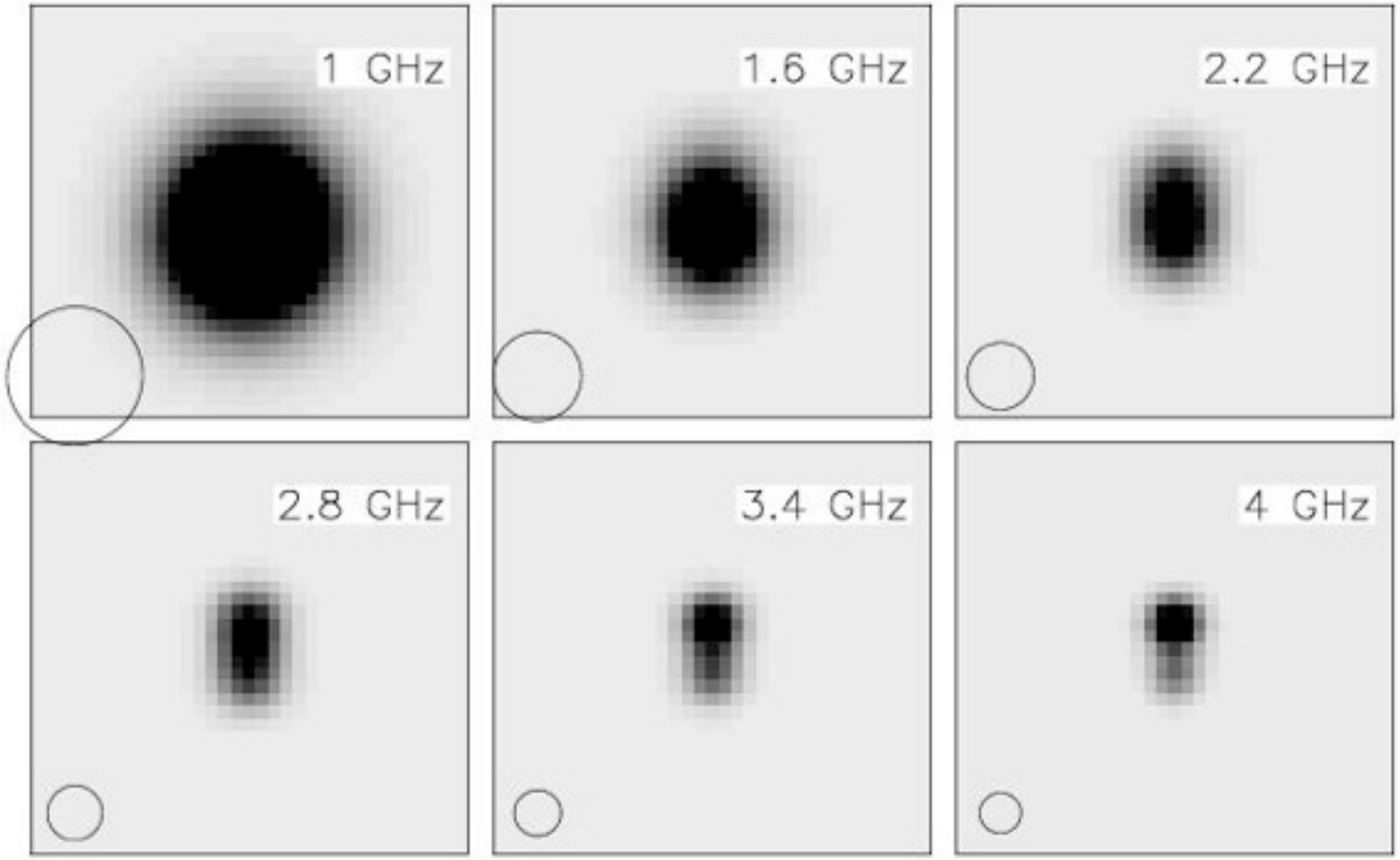


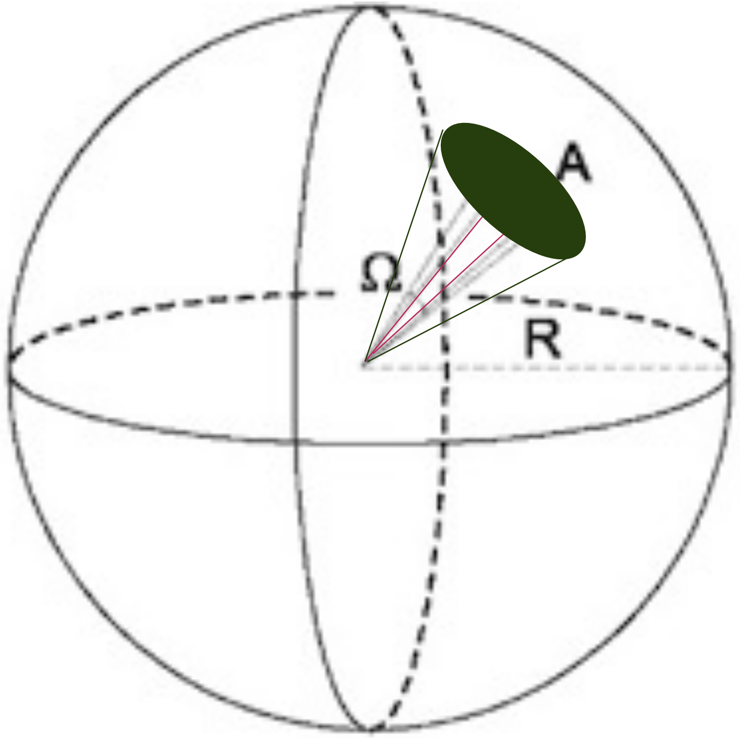


Very Large Array (U.S.)

$$Res \propto D^{-1}$$

RESOLVED & UNRESOLVED SOURCES





$$S(\nu) = L(\nu)/(4\pi R^2) = \int\int I(\nu, T)\mathrm{d}\Omega$$

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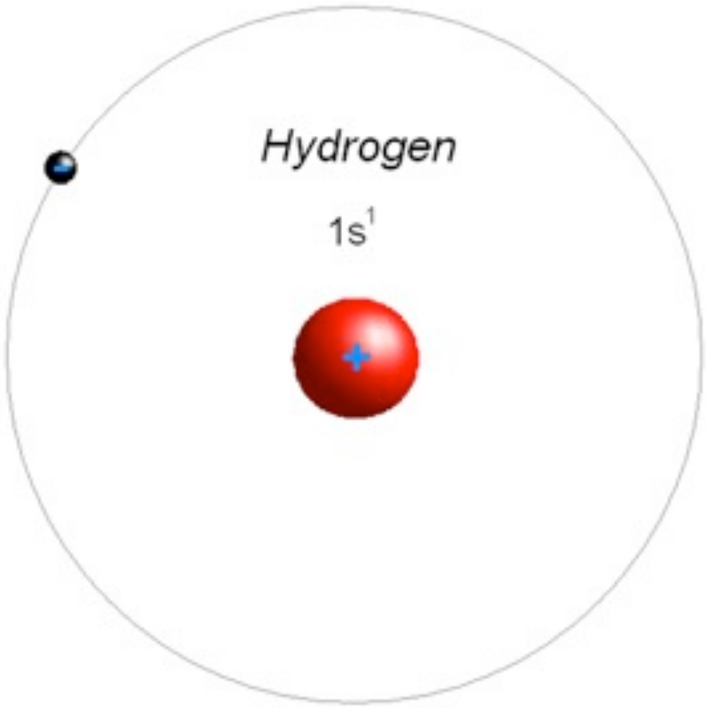
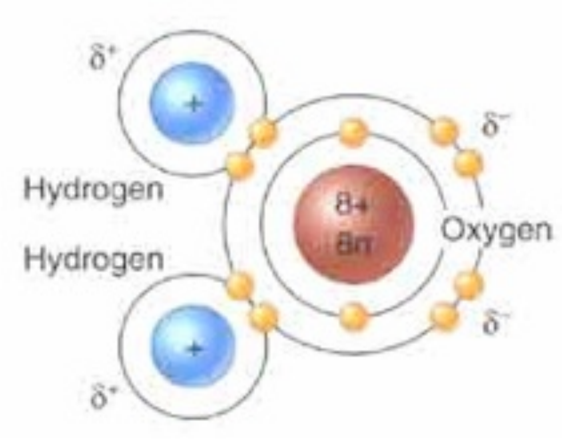
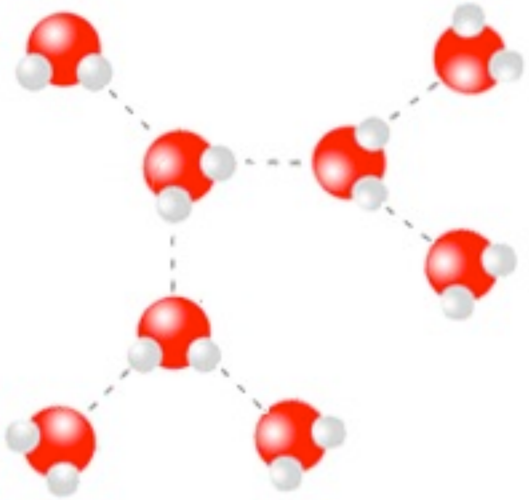
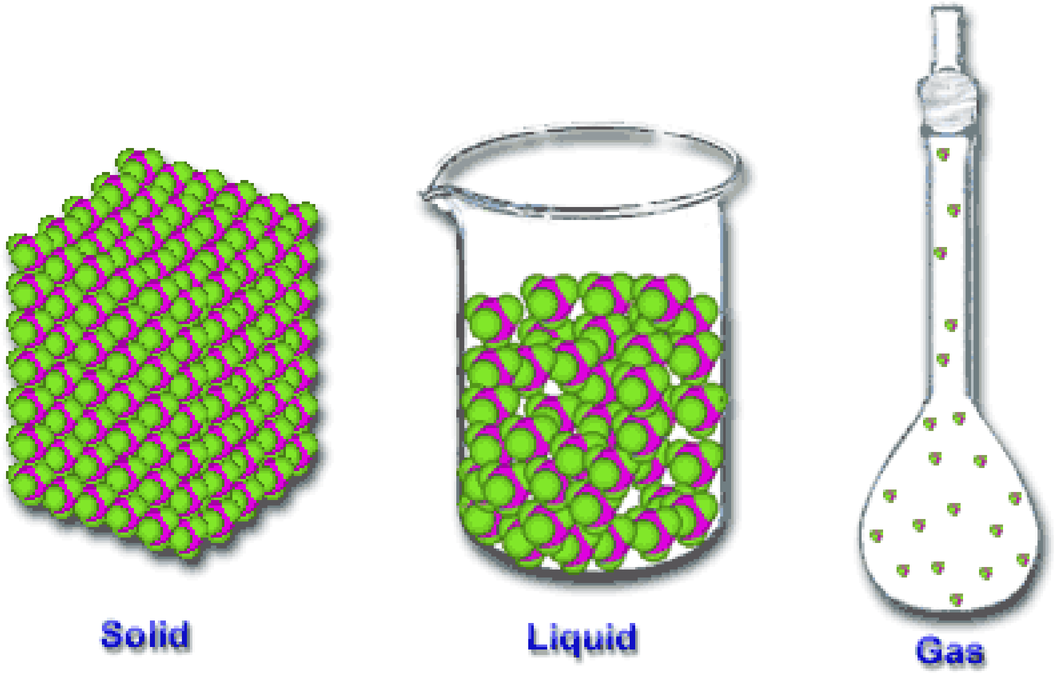
STATES OF MATTER





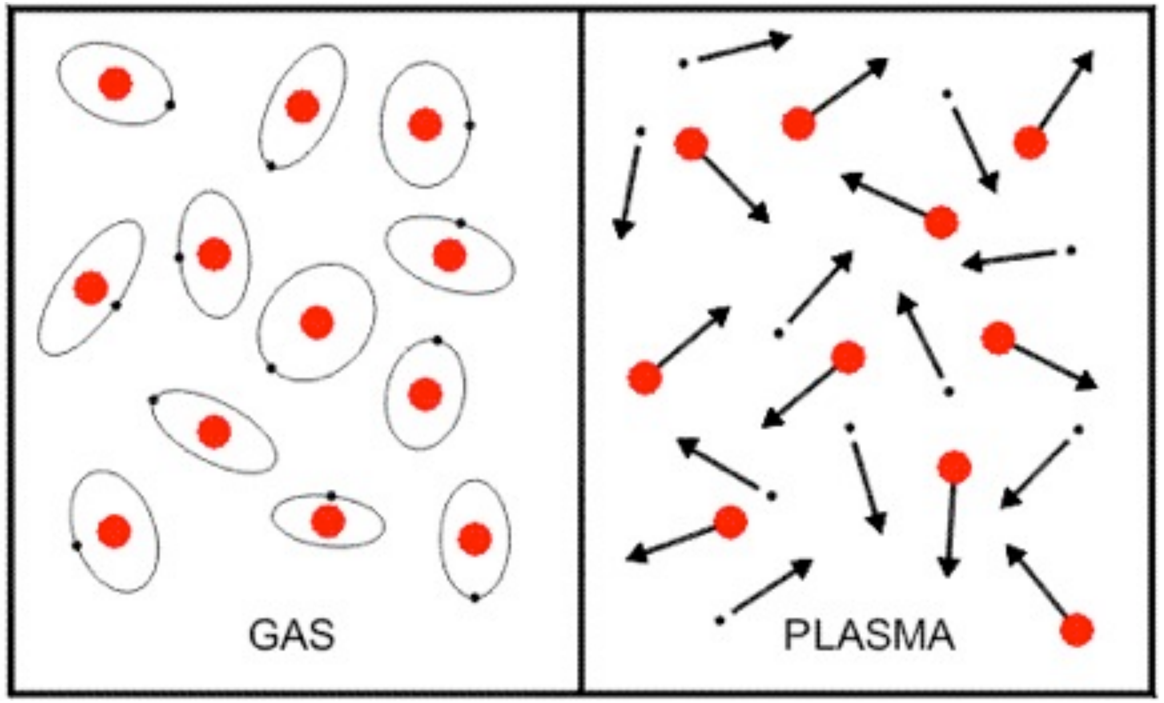




THERMAL BREMSSTRAHLUNG

INTRODUCTION: HOT PLASMA

- Gas of charged ions and electrons
- Quasi-neutral over a large volume
- Fourth state of matter
- Ionization if gas:
  - very hot → collisions between atoms sufficiently strong to remove electrons
  - very rarefied → electrons hardly encounter an ion with which to recombine
  - subjected to an external source of energy → strong electric fields or radiation



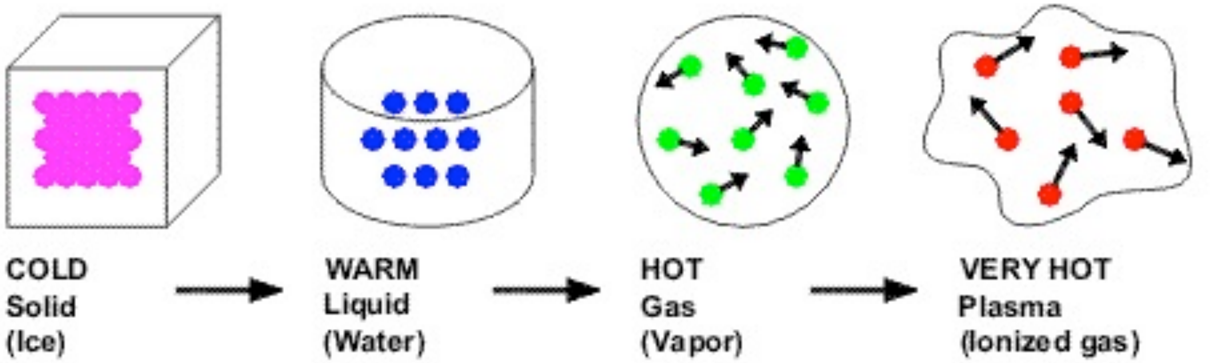
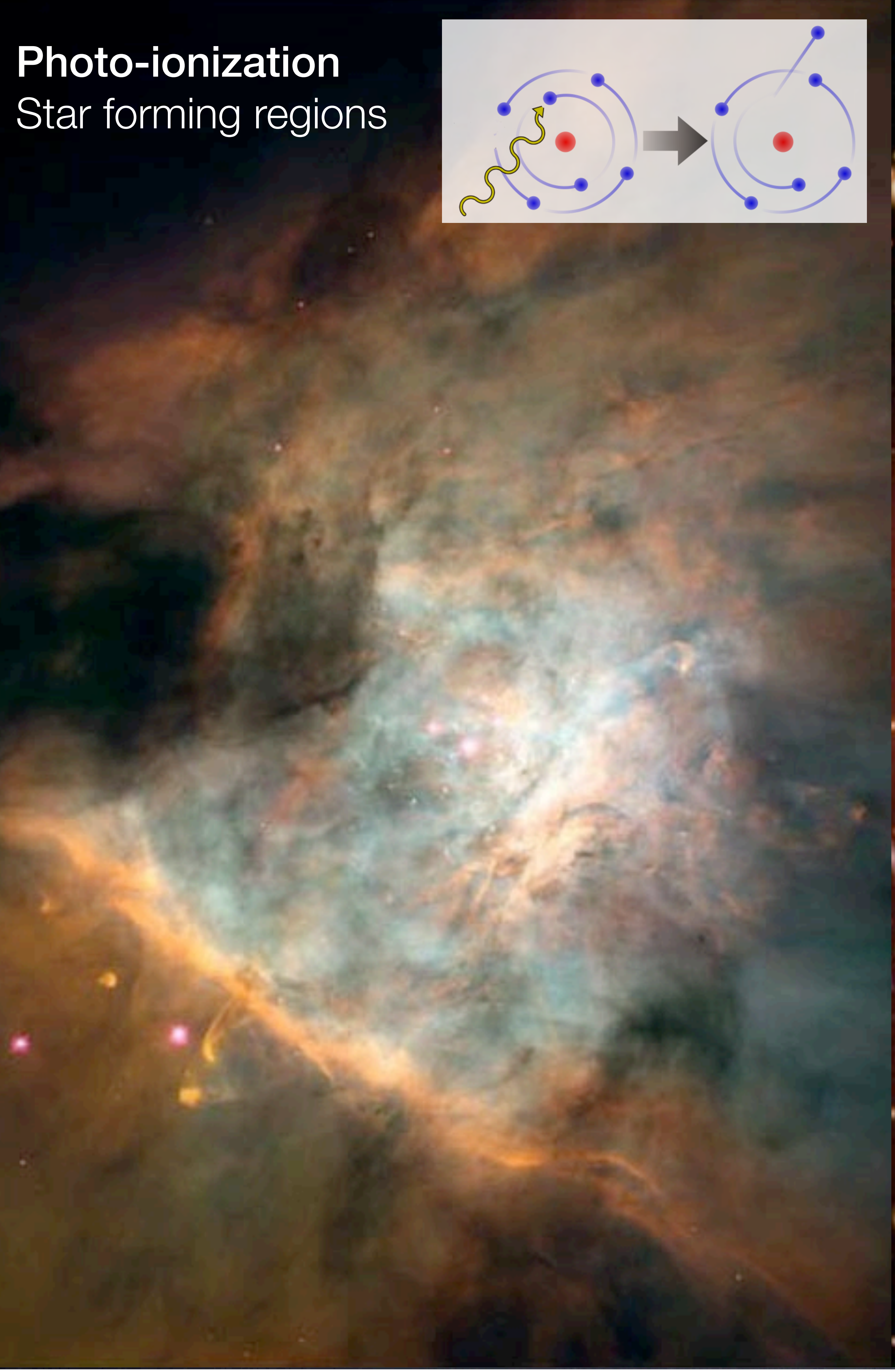


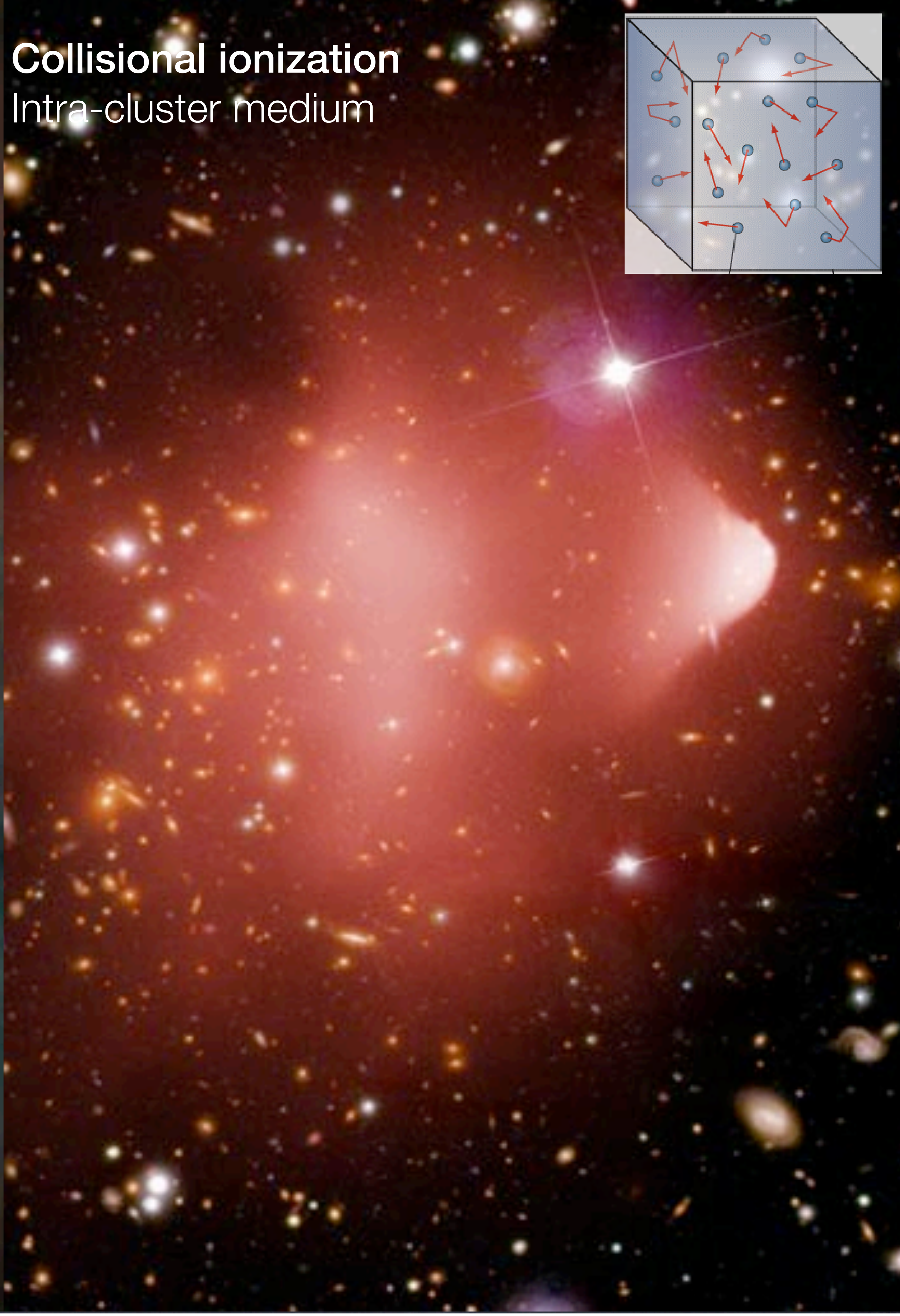
Photo-ionization

Star forming regions



Collisional ionization

Intra-cluster medium



Thermal Bremsstrahlung

How We will Derive the Final Equations

Thermal Bremsstrahlung - Part I

Collision of an Electron with an Ion

↓

Thermal Bremsstrahlung - Part II

Collision of Thermal Electrons with an Ion

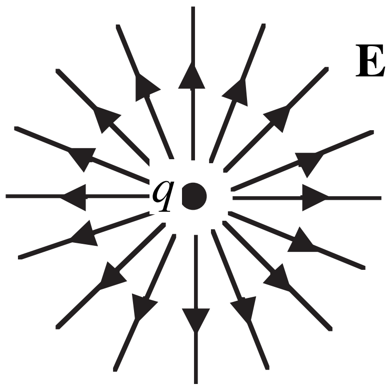
↓

Thermal Bremsstrahlung - Part III

Collision of thermal Electrons with ions

PART I: AN ELECTRON & AN ION

RADIATION BASICS



Instantaneous pattern of electric field of a charge *q* moving in a straight line at speed *v* << *c*

Poynting Vector & Radiation Pattern

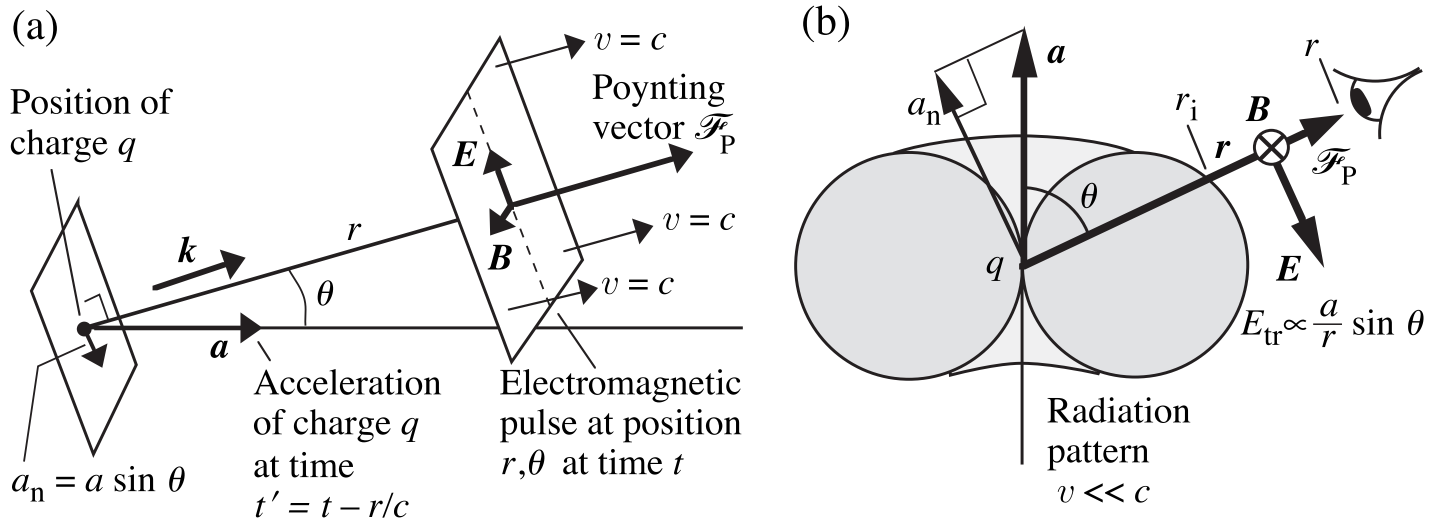


Fig. 5.2: Astrophysics Processes (CUP), © H Bradt 2008

Acceleration of the non-relativistic charge → distorted field lines→ distortions propagate outward at speed *c* → propagating electromagnetic wave

$$\mathbf{E}(\mathbf{r},t) = E_{tr}\hat{\mathbf{n}} = \frac{qa(t')sin\theta}{4\pi\epsilon_0 c^2 r}\hat{\mathbf{n}}$$

$\mathbf{E}(\mathbf{r}, t)$ = Transverse electric vector; V/m; $v << c$

$$\epsilon_0 E^2/2 = \text{energy density of electric field}$$

$$B^2/2\mu_0 = \text{energy density of magnetic field}$$

$$B = E/c$$

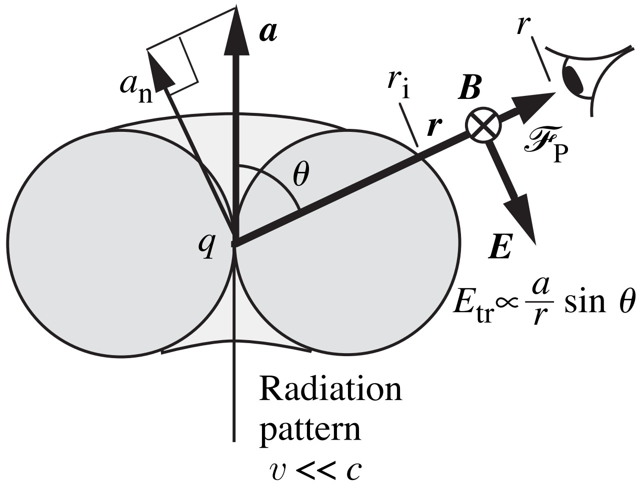
$$c^2 = 1/\mu_0\epsilon_0$$

$\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1} = permeability of free space

$\epsilon_0 = 8.854 \times 10^{-12}$ s^4 A^2 m^{-3} kg^{-1} = permittivity of the vacuum

Part I: an Electron & an Ion

Radiation Basics



$$\mathcal{F}_P = \frac{\mathbf{E}\times\mathbf{B}}{\mu_0}$$

$\mathcal{F}_P$ = Poynting vector; W/m^2
= direction & magnitude of the e.m. wave energy flow

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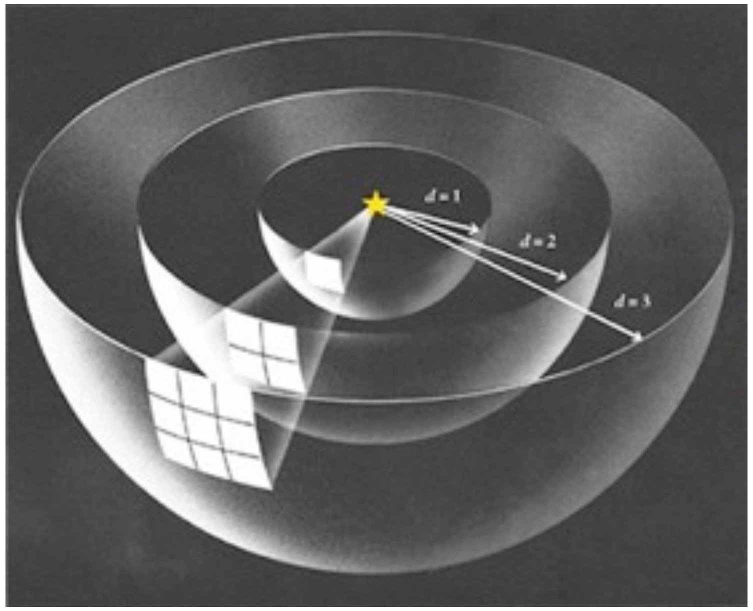

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PART I: AN ELECTRON & AN ION

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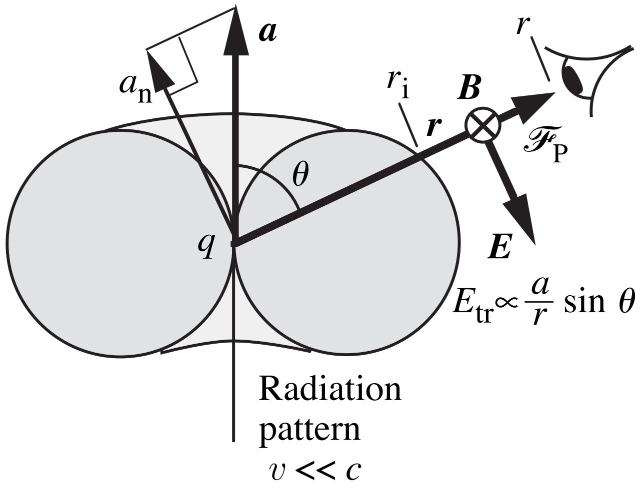
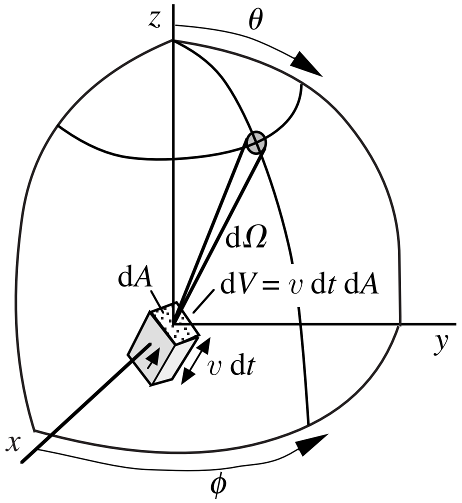


$$\mathcal{F}_P(r,\theta,t) = \frac{q^2 sin^2\theta a^2(t')}{(4\pi)^2\epsilon_0 c^3 r^2}$$

$\mathcal{F}_P(r,\theta,t)$ = magnitude of Poynting vector in vacuum $v << c$; W/m^2

[for an observer at distance r and angle θ from acceleration direction]



PART I: AN ELECTRON & AN ION

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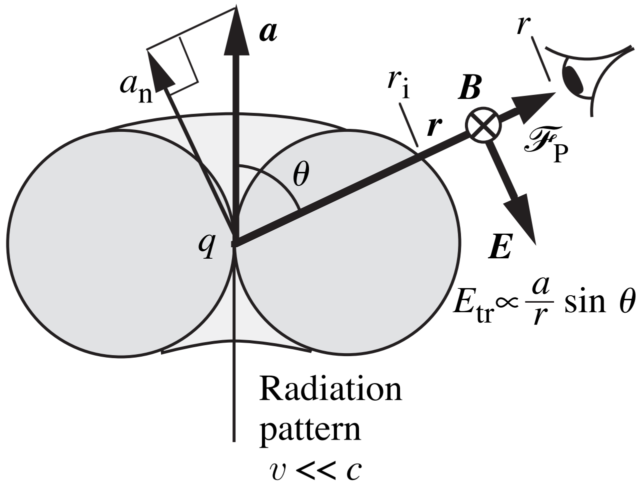

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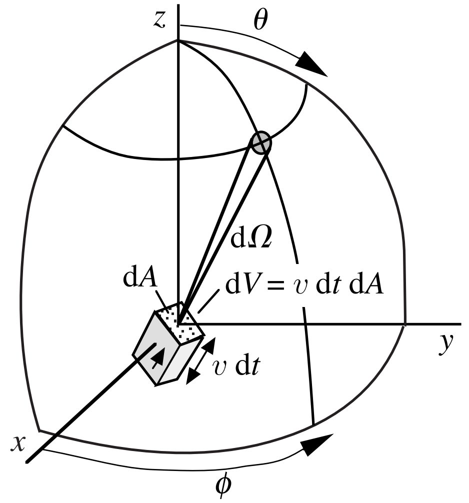


$$\mathcal{P}(t) = \int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} \mathcal{F}_P(r,\theta,t)\ r^2\ sin\theta\ d\phi\ d\theta$$

$$\rightarrow \mathcal{P}(t) = \frac{1}{6\pi\epsilon_0}\frac{q^2 a(t)^2}{c^3}$$

Larmor's formula

- Power (W) radiated by an electron as it accelerates
- It is valid if the radiating electron is not relativistic (v << c)

PART I: AN ELECTRON & AN ION

ENERGY RADIATED PER COLLISION

Impact parameter b

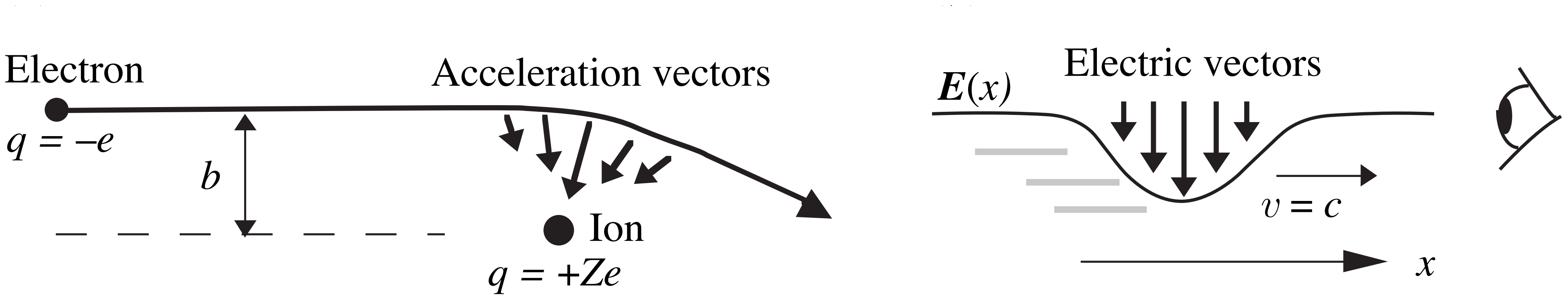


Fig. 5.3: Astrophysics Processes (CUP), © H Bradt 2008

$$\mathbf{a} = \frac{\mathbf{F}}{m} = -\frac{1}{4\pi\epsilon_0}\frac{Ze^2}{r^2 m}\hat{\mathbf{r}} \quad (\mathrm{m/s^2})$$

$\mathbf{a}$ = acceleration experienced by an electron of charge $-e$ and mass m at a distance r from an ion of charge Ze

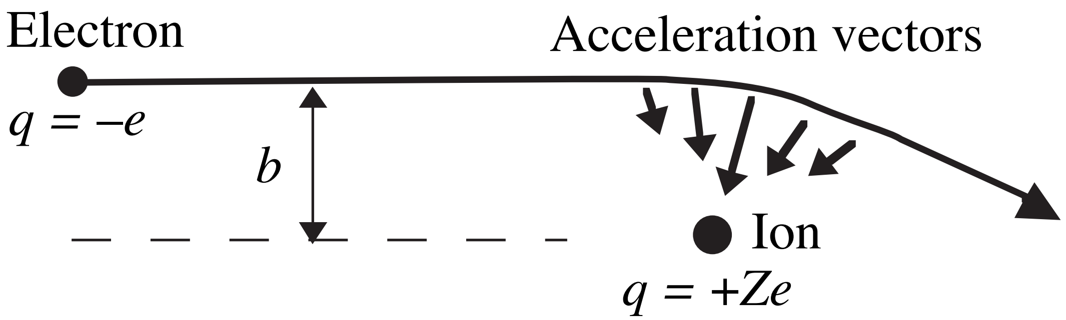
$$a_{\max} \approx \frac{1}{4\pi\epsilon_0}\frac{Ze^2}{b^2 m} \quad \text{(maximum acceleration of the electron)}$$

$$\tau_b \approx b/v \quad \text{(collision time)}$$

PART I: AN ELECTRON & AN ION

ENERGY RADIATED PER COLLISION

$$a_{\max} \approx \frac{1}{4\pi\epsilon_0}\frac{Ze^2}{b^2 m}$$



$$\tau_b \approx b/v$$

$$\mathcal{P}(t) = \frac{1}{6\pi\epsilon_0}\frac{q^2 a(t)^2}{c^3}$$

$$Q(b,v) = \int_{-\infty}^{+\infty} \mathcal{P}(t)\mathrm{d}t = \frac{1}{6\pi\epsilon_0}\frac{e^2}{c^3}\int_{-\infty}^{+\infty} a(t)^2 \mathrm{d}t$$

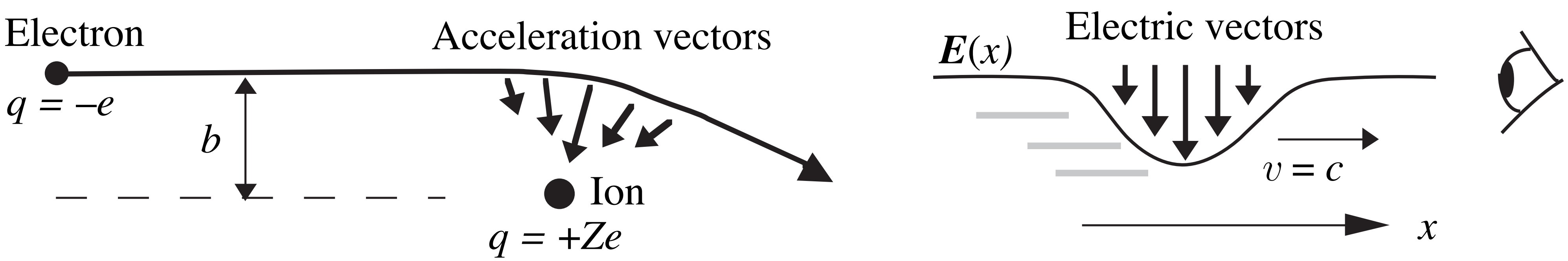
(total energy emitted by the electron during the transit)

$$\rightarrow Q(b,v) \approx \frac{1}{6\pi\epsilon_0}\frac{e^2}{c^3} a_{max}^2 \tau_b$$

$$\rightarrow Q(b,v) \approx \frac{1}{(4\pi\epsilon_0)^3}\frac{2}{3}\frac{Z^2 e^6}{c^3 m^2 b^3 v} \quad \text{(J/collision)}$$

PART I: AN ELECTRON & AN ION

FREQUENCY OF EMITTED RADIATION



- Emitted electric vectors in the same direction as the projected acceleration
- Acceleration increases & decreases once → Electric vectors go to a maximum and decreases only once → Single pulse of electric vectors

$$\rightarrow \omega = 2\pi\nu \approx 1/\tau_b = v/b$$

$$\rightarrow \nu = \omega/2\pi \approx v/2\pi b$$

$$\rightarrow b \approx v/2\pi\nu$$

$$\rightarrow \mathrm{d}b \approx -v \ \mathrm{d}\nu/2\pi\nu^2$$

PART II: MANY ELECTRONS & AN ION

SINGLE-SPEED ELECTRONS

$$Q(b,v) \approx \frac{1}{(4\pi\epsilon_0)^3}\frac{2}{3}\frac{Z^2e^6}{c^3m^2b^3v} \quad \text{(J/collision)}$$

n_e = electron density

$$b \approx v/2\pi\nu$$

$$\mathrm{d}b \approx -v\ \mathrm{d}\nu/2\pi\nu^2$$

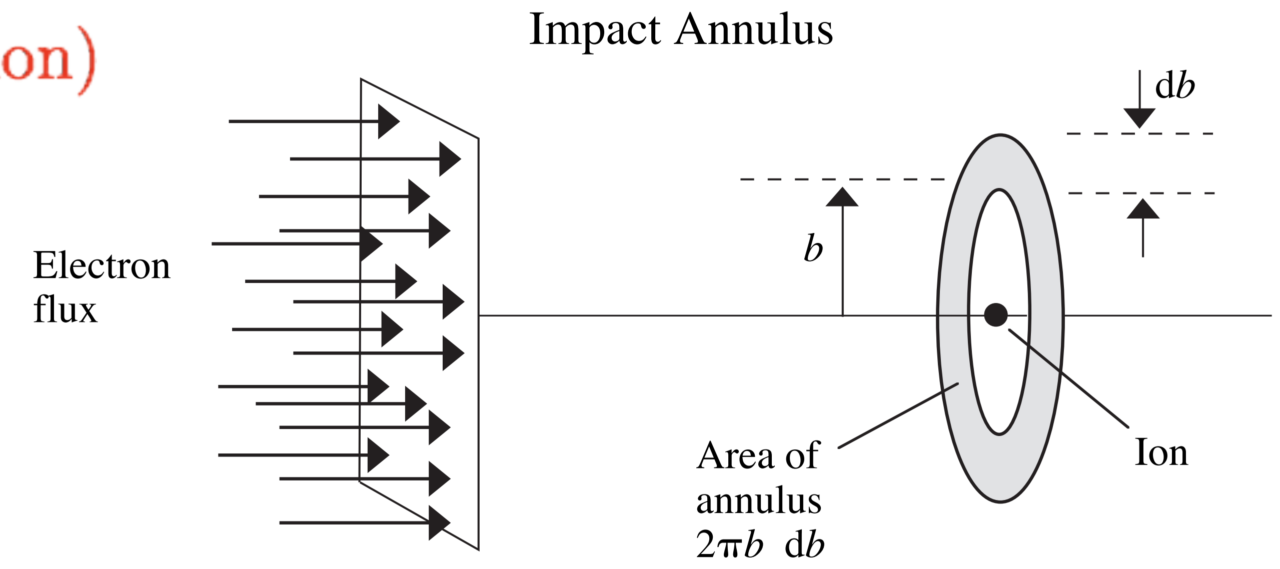


Fig. 5.4: Astrophysics Processes (CUP), © H Bradt 2008

$$\mathcal{P}_b(b,v) = Q(b,v)\ n_e\ v\ 2\pi b\ \mathrm{d}b \quad \text{(W/ion in d}b\text{ at }b\text{)}$$

$\mathcal{P}_b(b,v)$ = power coming from an ion and a flux of electrons of density n_e

$$\int_{b_1}^{b_2}\mathcal{P}_b(b,v)\ \mathrm{d}b = -\int_{\nu_1}^{\nu_2}\mathcal{P}_\nu(\nu,v)\ \mathrm{d}\nu$$

$$\rightarrow \mathcal{P}_\nu(\nu,v) = -\mathcal{P}_b(b,v)\frac{\mathrm{d}b}{\mathrm{d}\nu}$$

$$\rightarrow \mathcal{P}_\nu(\nu,v)\ \mathrm{d}\nu \approx \frac{1}{(4\pi\epsilon_0)^3}\frac{8\pi^2}{3}n_e\frac{Z^2e^6}{c^3m^2v}\mathrm{d}\nu$$

$\mathcal{P}_\nu(\nu,v)$ = power per unit-frequency interval (W/ion in dν at ν)

PART II: MANY ELECTRONS & AN ION

SINGLE-SPEED ELECTRONS

$$\mathcal{P}_\nu(\nu, v)\,\mathrm{d}\nu \approx \frac{1}{(4\pi\epsilon_0)^3}\frac{8\pi^2}{3}n_e\frac{Z^2e^6}{c^3m^2v}\mathrm{d}\nu$$

$\mathcal{P}_\nu(\nu, v)$ = power per unit-frequency interval (W/ion in $\mathrm{d}\nu$ at ν)

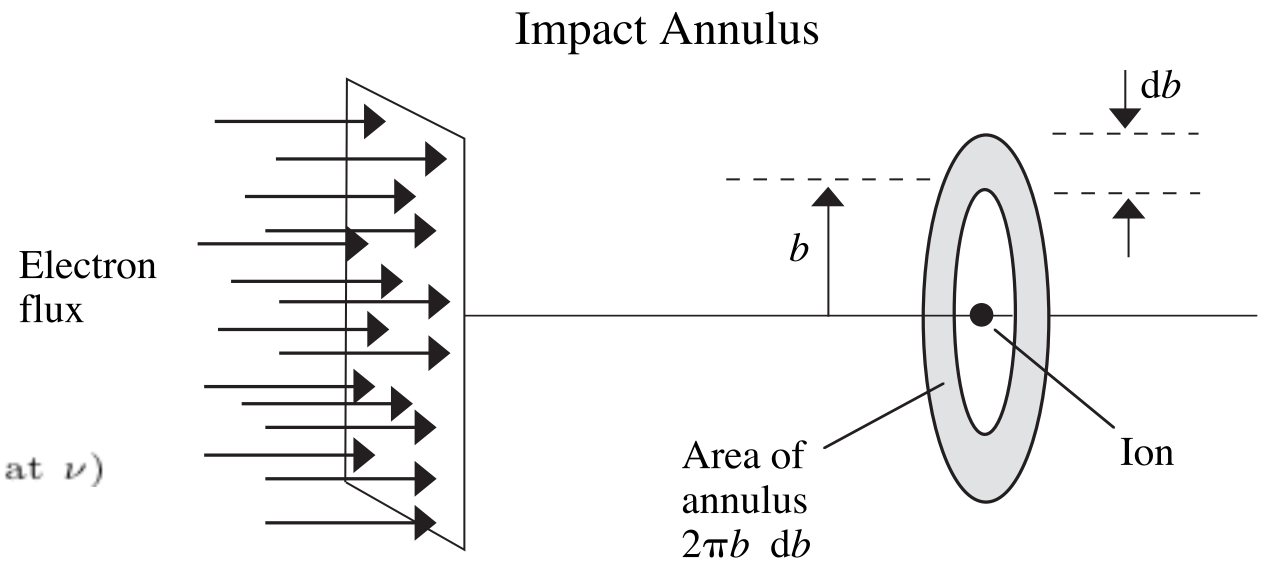


Fig. 5.4: Astrophysics Processes (CUP), © H Bradt 2008

- Derived equation independent of frequency/impact parameter: more collisions for large *b* values (bigger annulus), but each emits a lower energy photon compared to smaller *b*
- Cutoff frequency: the maximum photon energy is limited by electron velocity ($h\nu_{max} < mv^2/2$)
- The derived classical result is correct (with the addition of a Gaunt factor, see below) as long as electrons are non-relativistic ($kT << m_ec^2$ - $T << 6 \times 10^9$ K)

PART II: MANY ELECTRONS & AN ION

MANY-SPEED ELECTRONS

$$P(\mathbf{v}) = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{\left(-\frac{mv^2}{2kT}\right)} \quad \text{(Maxwell-Boltzmann distribution)}$$

$P(\mathbf{v})$ = probability of finding a particle with vector velocity $\mathbf{v}$ per unit 3-D velocity space

$$P(v)\mathrm{d}v = P(\mathbf{v})\ 4\pi v^2\ \mathrm{d}v$$

$P(v)$ = probability of an electron's having speed v in $\mathrm{d}v$

$4\pi v^2\ \mathrm{d}v$ = volume of a shell in velocity space at speed v

$$\langle \mathcal{P}_\nu(\nu)\rangle_{ion} = \int_{v_{min}}^{\infty} \mathcal{P}_\nu(\nu, v) P(\mathbf{v})\ 4\pi v^2 \mathrm{d}v \quad (\mathrm{W\ ion^{-1}\ Hz^{-1}})$$

= Power emitted at ν from an ion in a sea of electrons with a Maxwellian-Boltzmann distribution of speed

$$v_{min} = (2h\nu/m)^{1/2}$$

= Minumum velocity an electron can have for emitting an $h\nu$ energy photon

PART III: MANY ELECTRONS & MANY IONS

VOLUME EMISSIVITY

Radiation from a plasma that contains n_i ions per unit volume & n_e electrons per unit volume. They have a Maxwell-Boltzmann distribution of speeds

$$j_\nu(\nu)\mathrm{d}\nu = n_i \left\langle \mathcal{P}_\nu(\nu) \right\rangle_{ion} \mathrm{d}\nu$$

$j_\nu(\nu)$ = Power emitted per unit volume per hertz (W m^{-3} Hz^{-1})

$$\left\langle \mathcal{P}_\nu(\nu) \right\rangle_{ion} = \int_{v_{min}}^{\infty} \mathcal{P}_\nu(\nu, v) P(\mathbf{v})\ 4\pi v^2 \mathrm{d}v$$

$$\mathcal{P}_\nu(\nu, v)\ \mathrm{d}\nu \approx \frac{1}{(4\pi\epsilon_0)^3} \frac{8\pi^2}{3} n_e \frac{Z^2 e^6}{c^3 m^2 v} \mathrm{d}\nu$$

$$P(\mathbf{v}) = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{\left(-\frac{mv^2}{2kT}\right)}$$

$$v_{min} = (2h\nu/m)^{1/2}$$

$$j_\nu(\nu)\mathrm{d}\nu = \frac{1}{(4\pi\epsilon_0)^3} \frac{32}{3} \left(\frac{1}{8} \frac{\pi^3}{k\ \ m^3}\right) \frac{Z^2 e^6}{c^3} n_e n_i e^{-h\nu/kT}\ T^{-1/2}\ \mathrm{d}\nu$$

PART III: MANY ELECTRONS & MANY IONS

VOLUME EMISSIVITY

Radiation from a plasma that contains n_i ions per unit volume & n_e electrons per unit volume. They have a Maxwell-Boltzmann distribution of speeds

$$j_\nu(\nu)\mathrm{d}\nu = \frac{1}{(4\pi\epsilon_0)^3}\frac{32}{3}\left(\frac{1}{8}\frac{\pi^3}{k\ \ m^3}\right)^{1/2}\frac{Z^2e^6}{c^3}n_e n_i e^{-h\nu/kT}\ T^{-1/2}\ \mathrm{d}\nu$$

Correct result (without our approximations)

$$\boxed{j_\nu(\nu)\mathrm{d}\nu = \mathbf{g}(\nu,\mathbf{T},\mathbf{Z})\frac{1}{(4\pi\epsilon_0)^3}\frac{32}{3}\left(\frac{\mathbf{2}}{\mathbf{3}}\frac{\pi^3}{k\ \ m^3}\right)^{1/2}\frac{Z^2e^6}{c^3}n_e n_i e^{-h\nu/kT}\ T^{-1/2}\ \mathrm{d}\nu}$$

$$g(\nu,T,Z)\approx 1$$

$$j_\nu(\nu)\mathrm{d}\nu = C_1\ g(\nu,T,Z)\ Z^2\ n_e n_i\ e^{-h\nu/kT}\ T^{-1/2}\ \mathrm{d}\nu$$

PART III: MANY ELECTRONS & MANY IONS

EXPONENTIAL SPECTRUM

$$g(\nu, T, Z) \approx 1$$

$$j_\nu(\nu)\mathrm{d}\nu = C_1\ g(\nu, T, Z)\ Z^2\ n_e n_i\ e^{-h\nu/kT}\ T^{-1/2}\ \mathrm{d}\nu$$

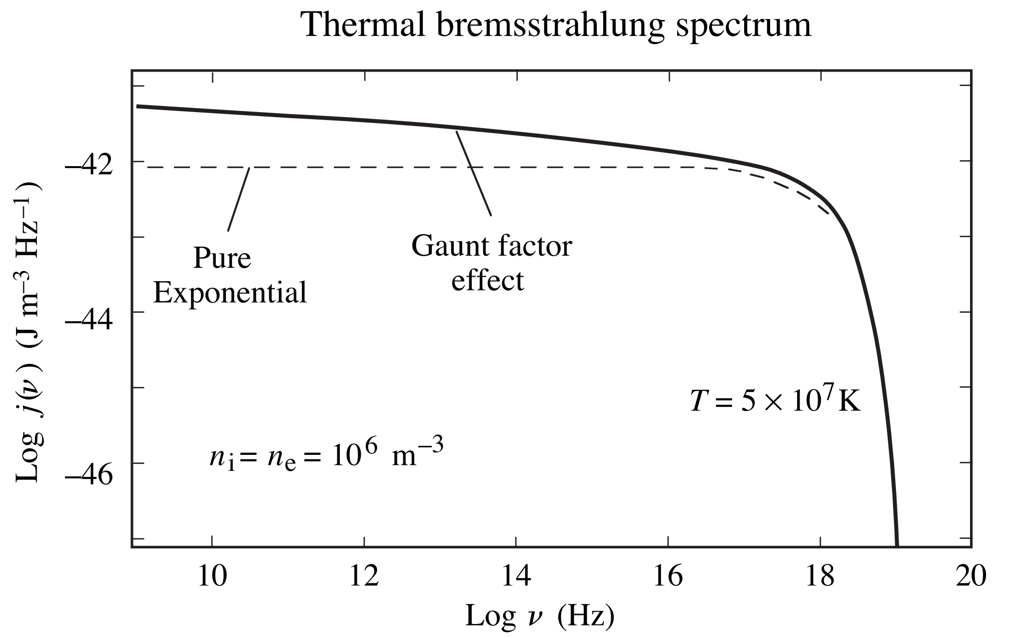


Fig. 5.5: Astrophysics Processes (CUP), © H Bradt 2008

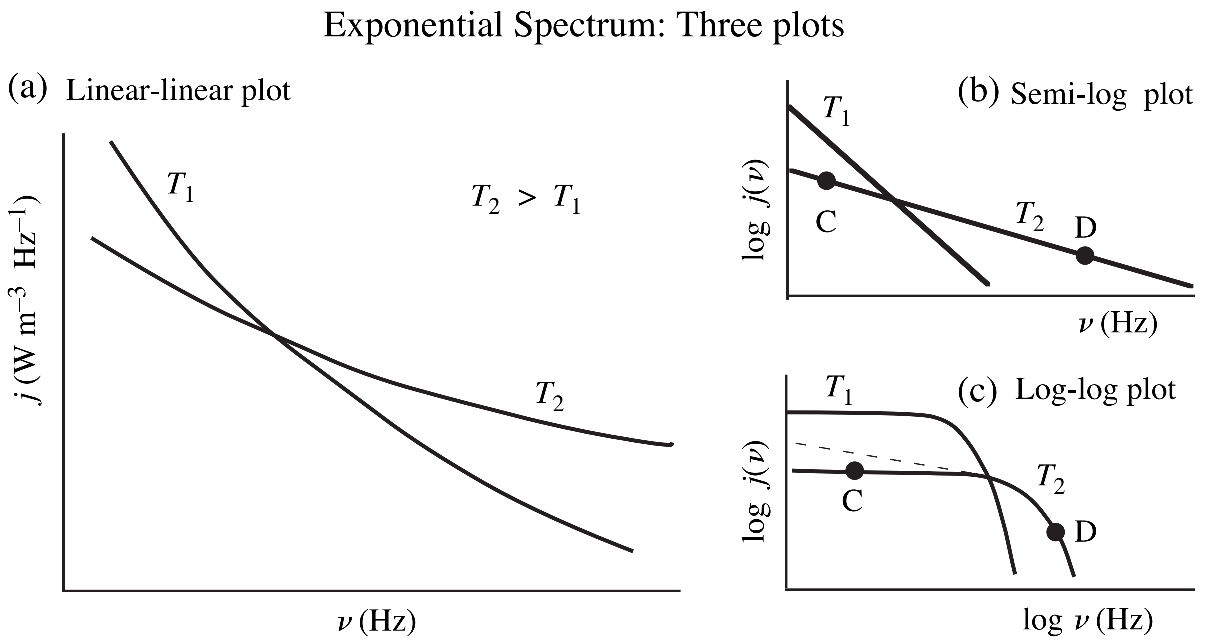


Fig. 5.6: Astrophysics Processes (CUP), © H Bradt 2008

PART III: MANY ELECTRONS & MANY IONS

INTEGRATED VOLUME EMISSIVITY

$$g(\nu, T, Z) \approx 1$$

$$j_\nu(\nu)\mathrm{d}\nu = C_1 \; g(\nu, T, Z) \; Z^2 \; n_e n_i \; e^{-h\nu/kT} \; T^{-1/2} \; \mathrm{d}\nu$$

It can be shown that most of the power from a bremmstrahlung emitting plasma arises in the frequency band near the cutoff (@ *h* ν ~ *k T*)

Integrated volume emissivity

$$\boxed{j(T) = \int_0^\infty j_\nu(\nu)\mathrm{d}\nu = C_2 \; \bar{g}(T, Z) \; Z^2 \; n_e n_i \; T^{1/2} \quad (\mathrm{W/m^3})}$$

with

$$C_2 = 1.44 \times 10^{-40} \; \mathrm{W \; m^3} \; K^{-1/2}$$

THERMAL BREMSSTRAHLUNG

FINAL EQUATIONS

Volume emissivity of hydrogen plasma:

$$j_\nu(\nu,T) \propto g(\nu,T) n_e^2 T^{-1/2} e^{-h\nu/kT} \quad \mathrm{W\ m^{-3}\ Hz^{-1}}$$

$$I(\nu,T) = \int_0^\Lambda \frac{j_\nu(r,\nu,T)}{4\pi} \mathrm{d}r = \frac{j_{\nu,\mathrm{av}}(\nu,T)}{4\pi}\Lambda$$

Photon Emission by Plasma

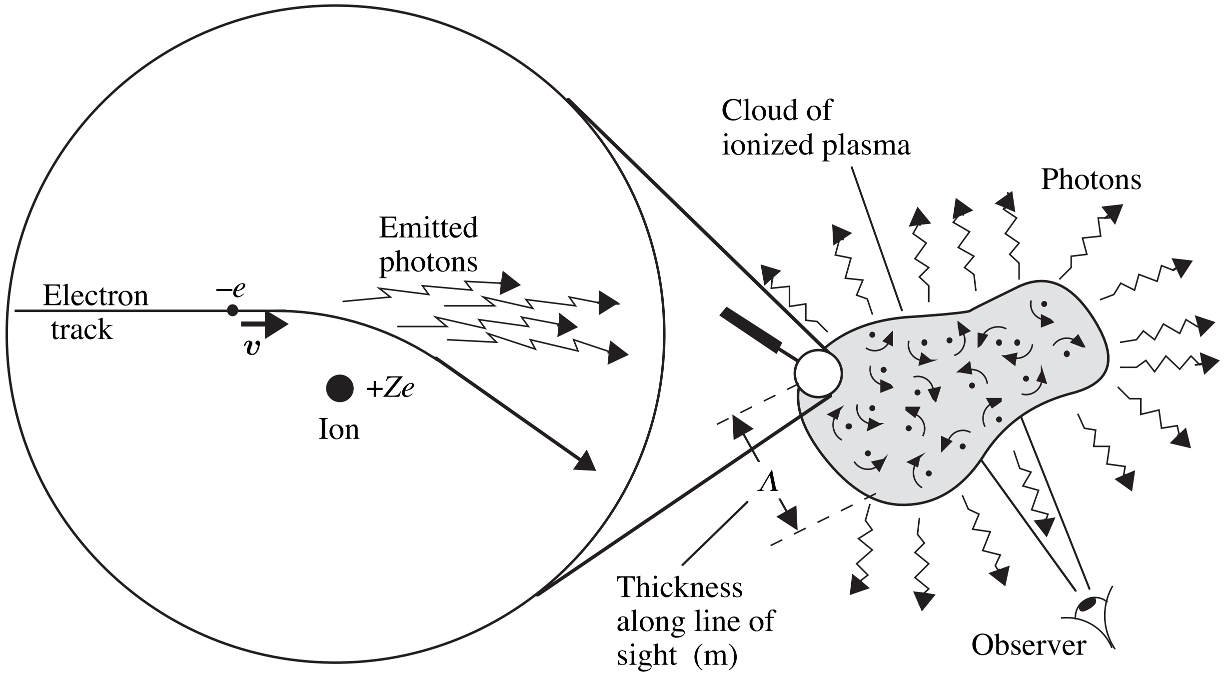


Fig. 5.1: Astrophysics Processes (CUP), © H Bradt 2008

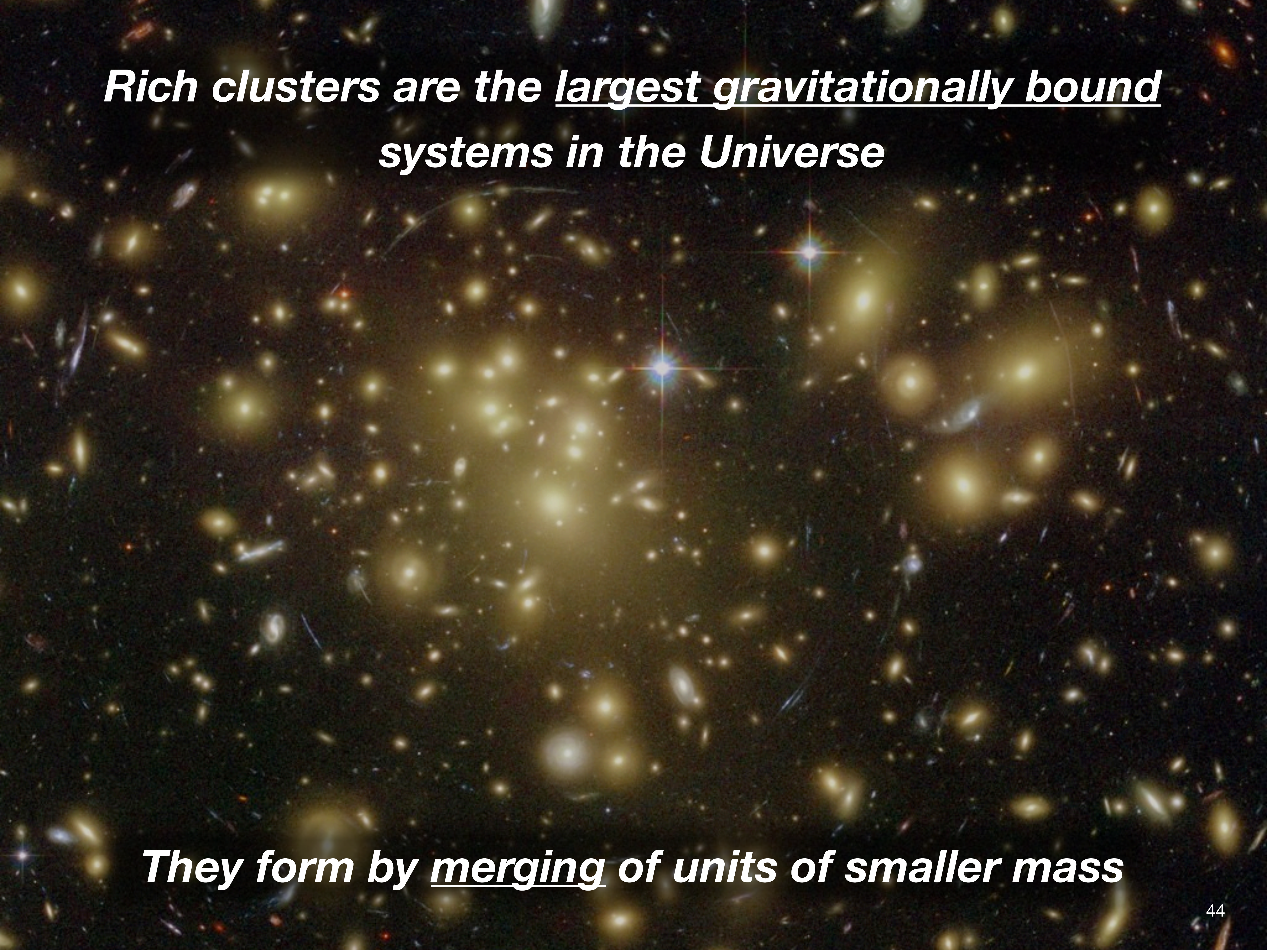
Specific intensity of hydrogen plasma:

$$I(\nu,T) \propto g(\nu,T) n_e^2 T^{-1/2} e^{-h\nu/kT} \Lambda \quad \mathrm{W\ m^{-2}\ Hz^{-1} sr^{-1}}$$

DISCOVERY OF GALAXY CLUSTERS

Most galaxies are not isolated in the Universe. They are bound together by their mutual gravity in structures containing from a few galaxies, to hundreds or even thousands galaxies

«...remarkable collection of many hundreds of nebulae which are to be seen in what I have called the nebulous stratum of Coma Berenices» - W. Herschel (1785)



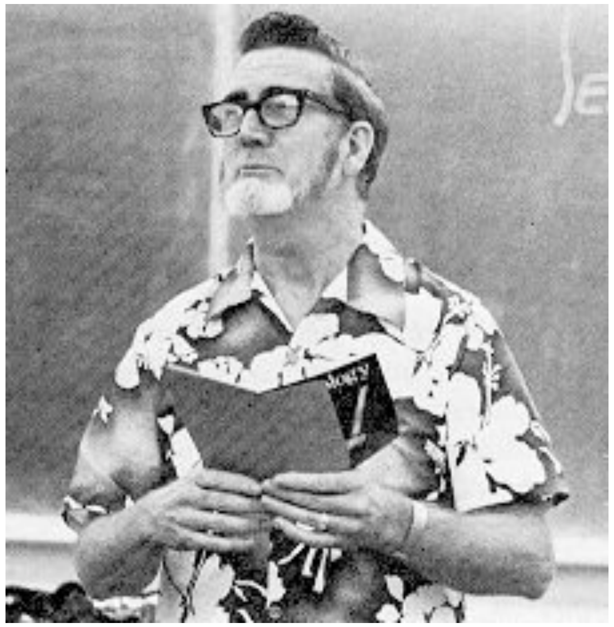
Rich clusters are the largest gravitationally bound systems in the Universe

They form by merging of units of smaller mass

A VERY SHORT HISTORICAL OVERVIEW OF OPTICAL OBSERVATIONS

→ Discovery of concentration of nebulae (1785)

W. Herschel

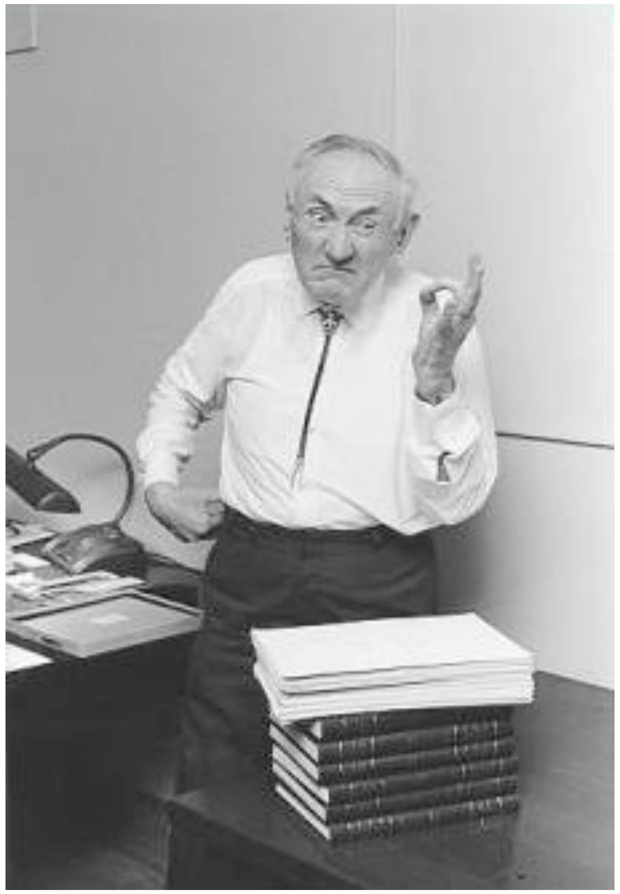


→ First statistical significative sample of clusters (1958; 1989)

G.O. Abell

→ Most of the observed nebulae are other galaxies (1925)

E. Hubble



→ Discovery of an unobservable matter in clusters (1933)

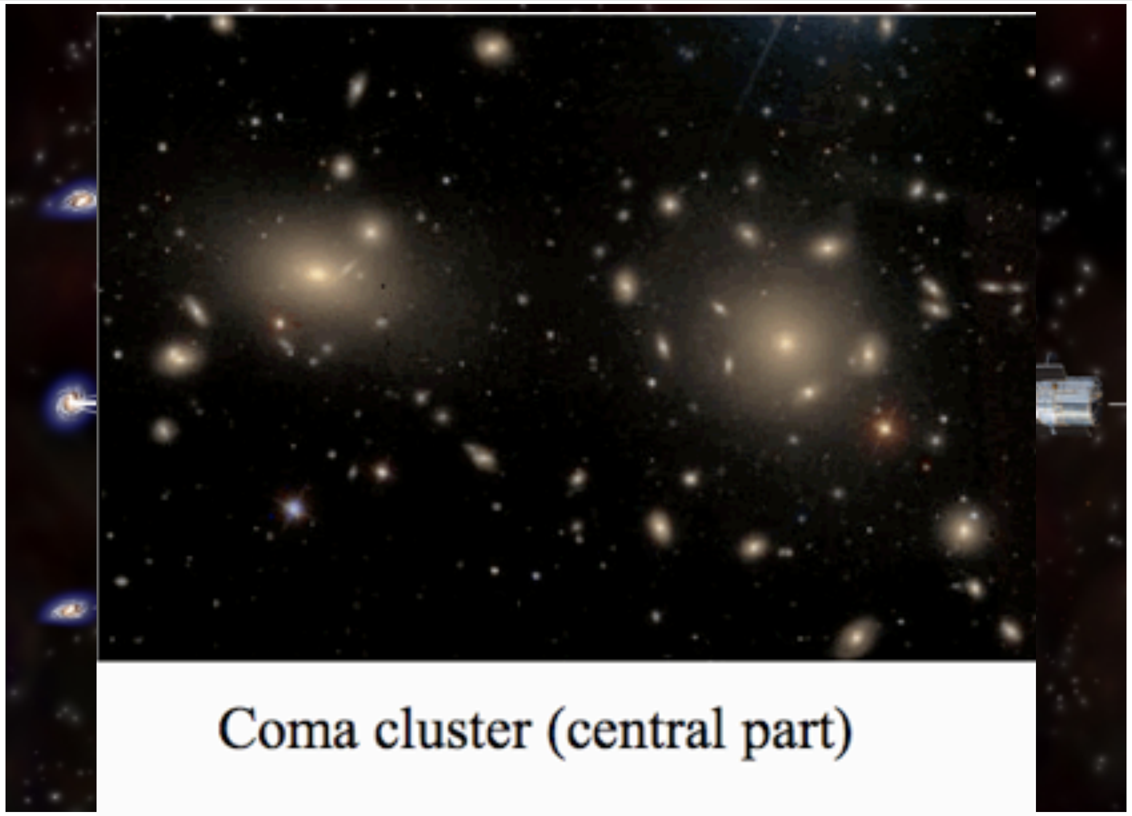
F. Zwicky

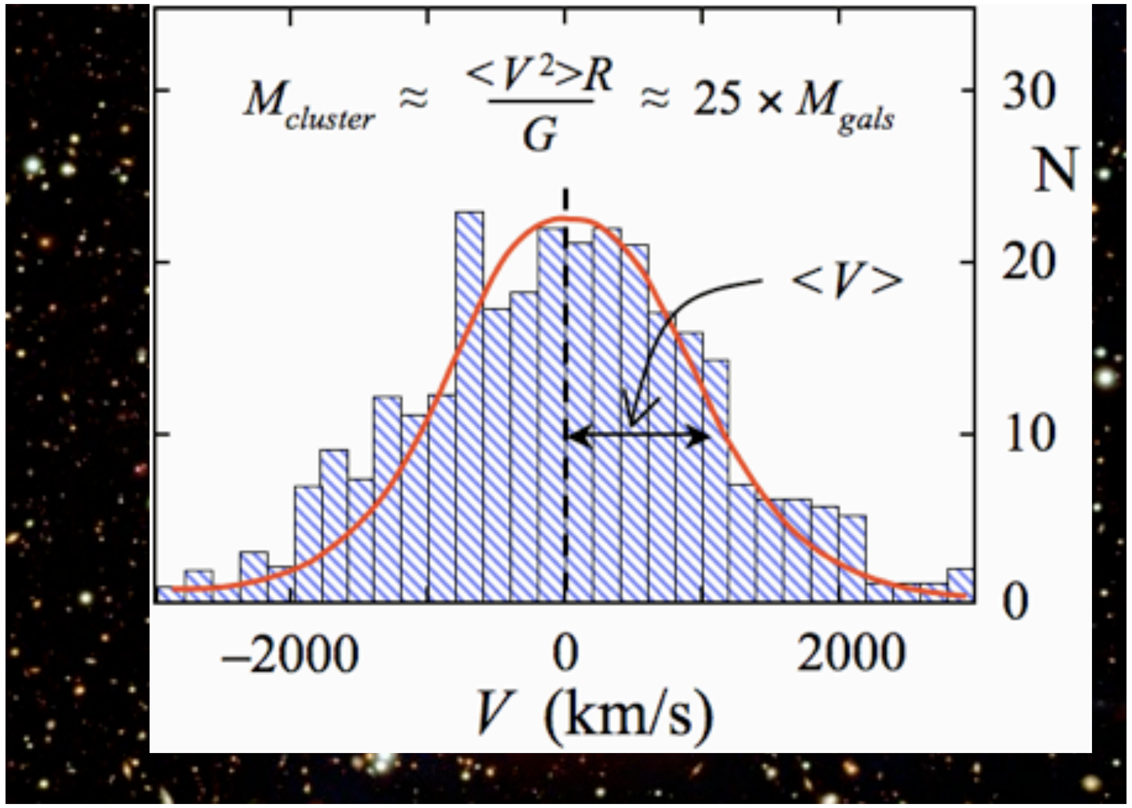
DOMINANT MASS COMPONENT OF CLUSTERS: DARK MATTER

Equilibrium is maintained by the balance between the potential energy associated with the mass of the system and the kinetic energy of its individual components:

virial equilibrium

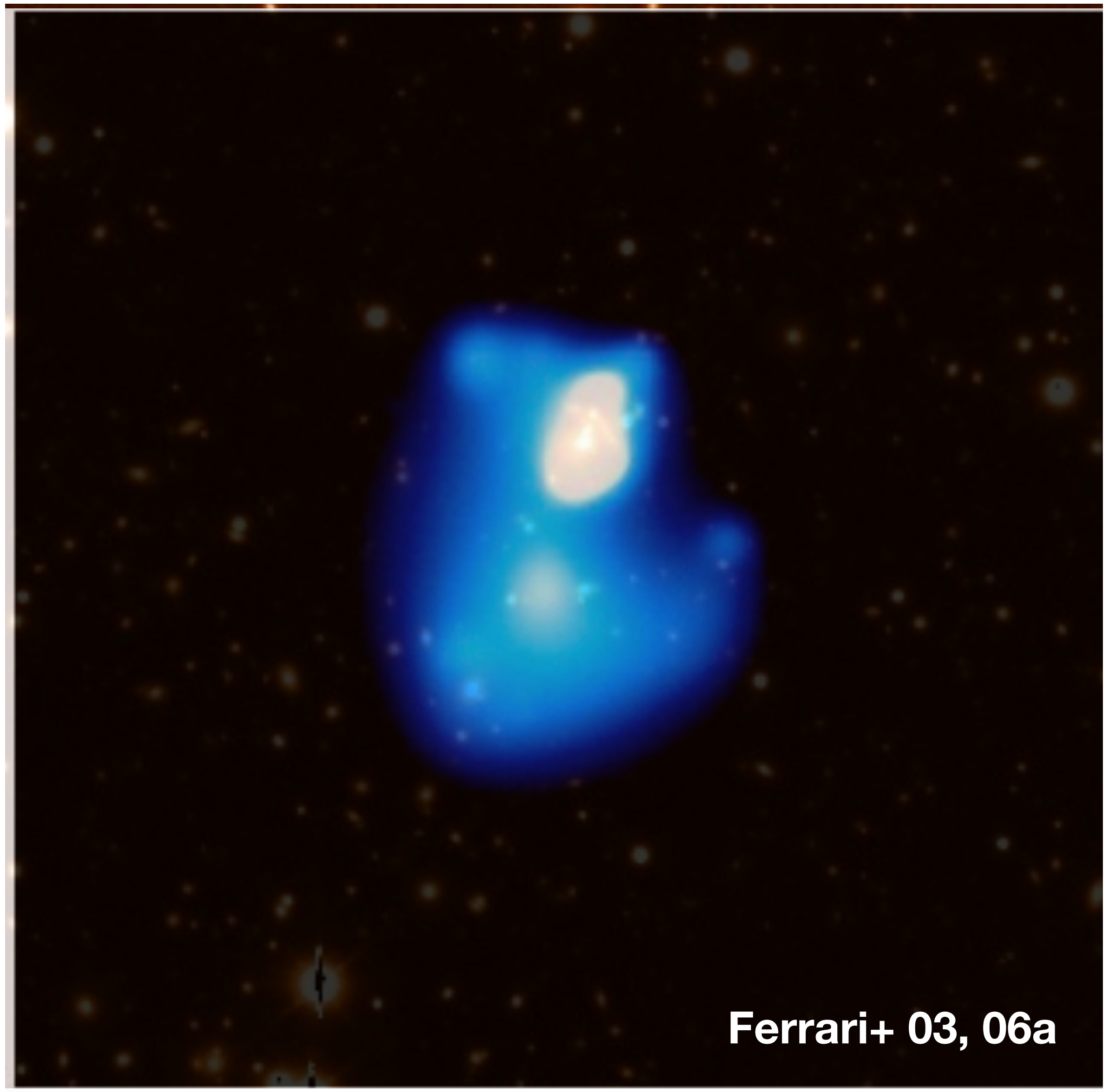
$$2\,E_k + E_p = Vir = 0$$


Coma cluster (central part)

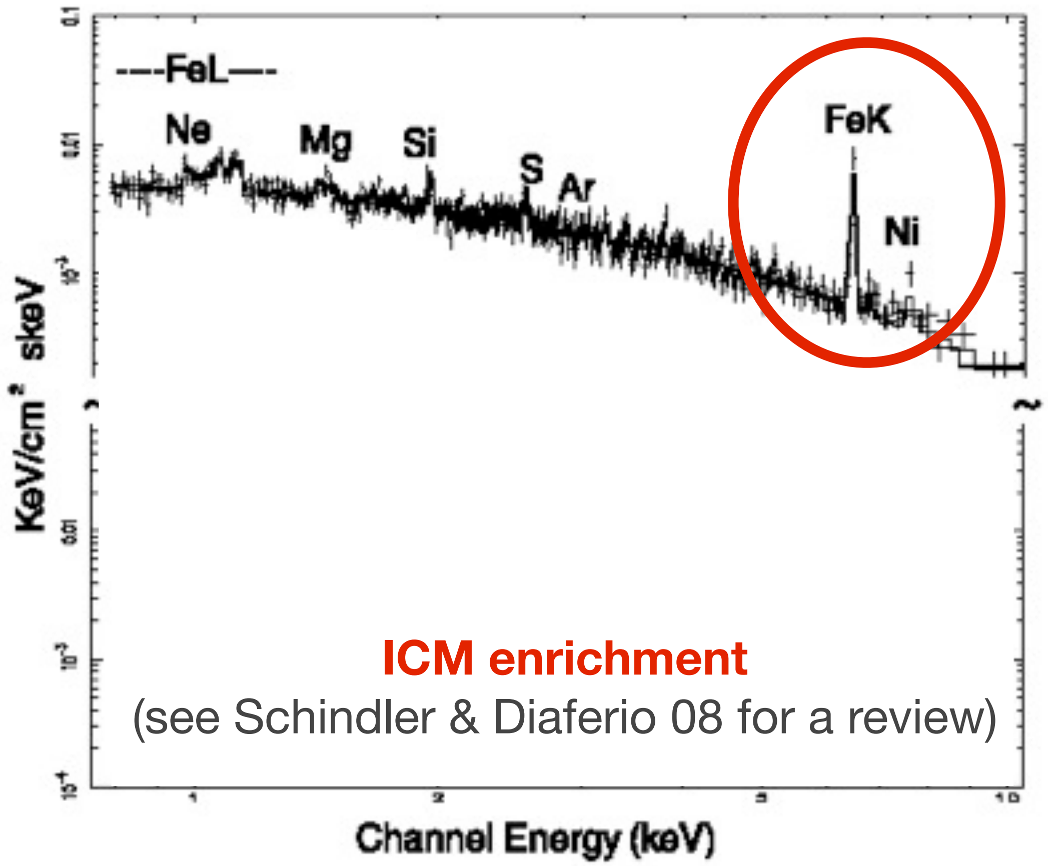


The dominant baryonic component of clusters: hot (10^7-10^8 K) intracluster medium (ICM)

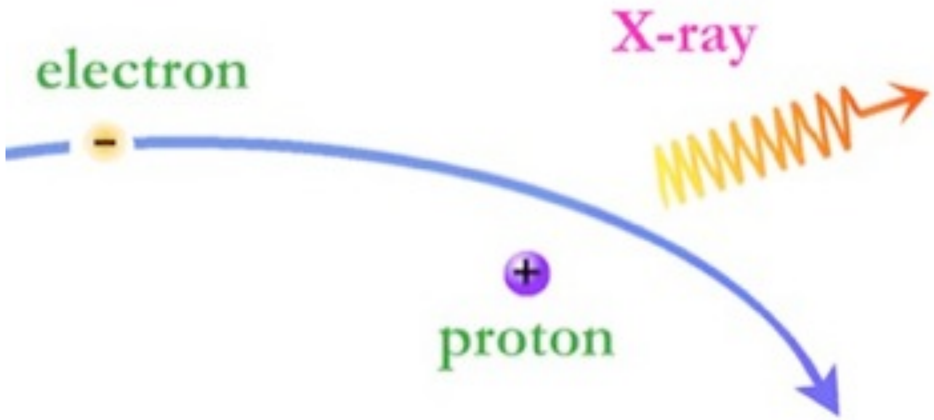
$$\epsilon_{\nu,T} \propto T^{-1/2} e^{-h\nu/kT} n_e n_Z \text{ erg cm}^{-3}\text{s}^{-1}\text{Hz}^{-1}$$

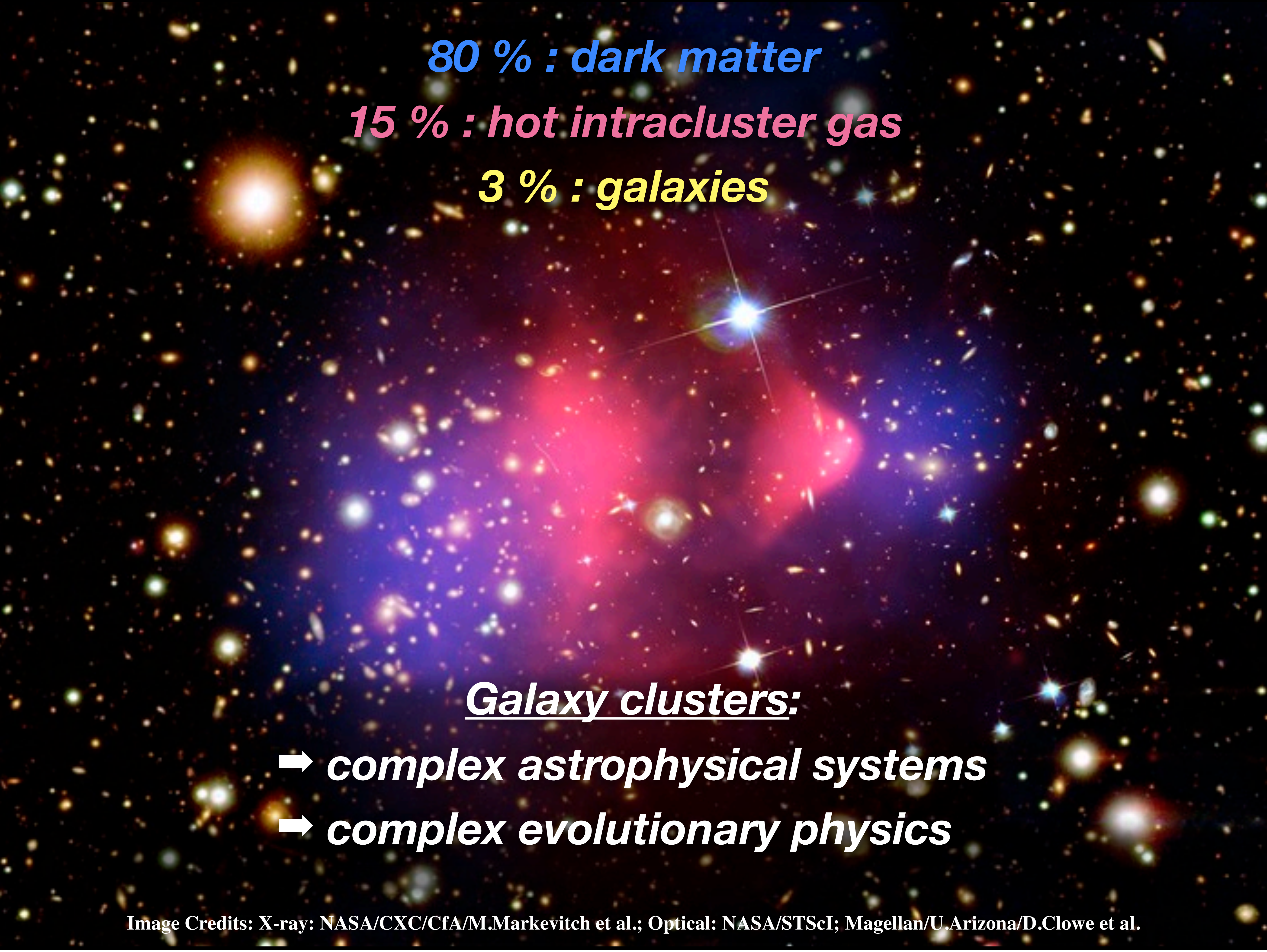


Ferrari+ 03, 06a



ICM enrichment
(see Schindler & Diaferio 08 for a review)





80 % : dark matter

15 % : hot intracluster gas

3 % : galaxies

Galaxy clusters:

➡ complex astrophysical systems

➡ complex evolutionary physics

Image Credits: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

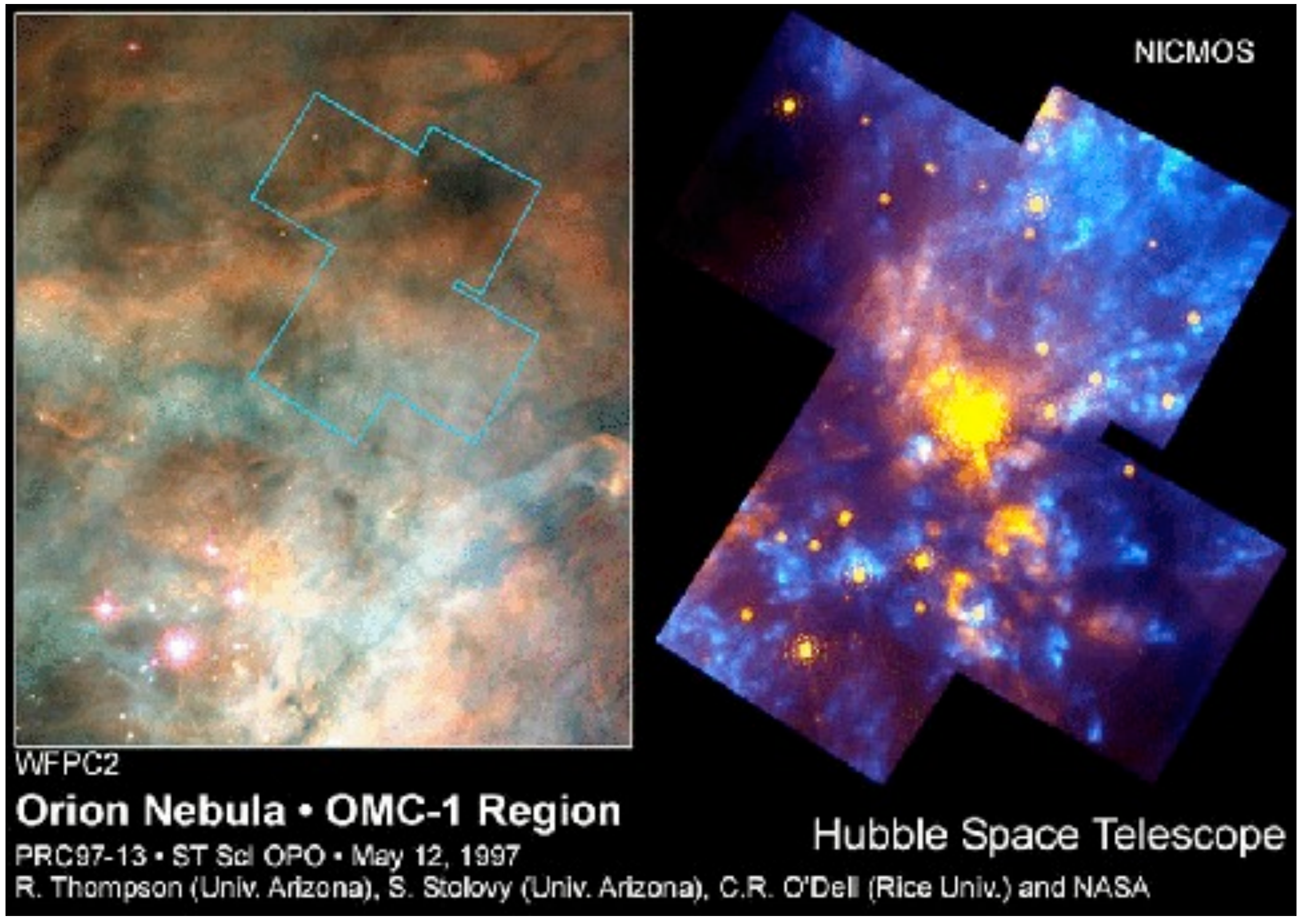
Schindler & collaborators
Innsbruck University

EXERCICE

The Orion nebula, an HII region, is radiating by thermal bremmstrahlung. Consider it to be spherical (radius = 8 light years), optically thin, and at a temperature T = 8000 K. Let Z = 1 , g = 1, $n_e = n_i = 6 \times 10^{-8}$ m^{-3}.

(a) Find the luminosity (W) of the entire nebula in terms of solar luminosities.

(b) In what wavelength band or bands will the power from the Orion nebula be radiated ?



Orion Nebula • OMC-1 Region

Hubble Space Telescope

PRC97-13 • ST ScI OPO • May 12, 1997

R. Thompson (Univ. Arizona), S. Stolovy (Univ. Arizona), C.R. O'Dell (Rice Univ.) and NASA

IMAGE CREDITS FOR THIS LECTURE

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- NASA/CXC/SAO/A. Vikhlinin; ROSAT; DSS; NSF/NRAO/VLA/IUCAA/J.Bagchi
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