Today:

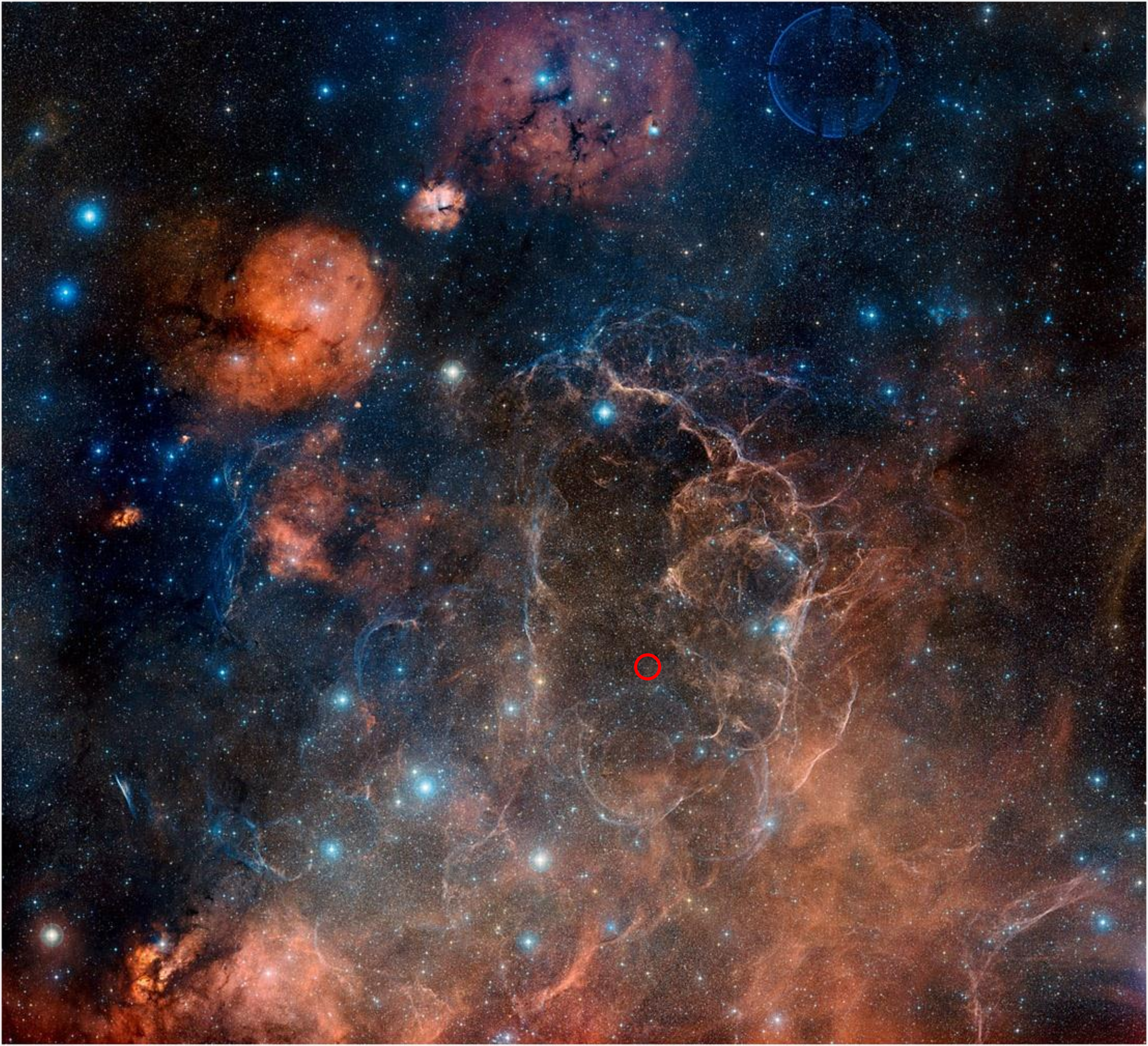
Recap on 1st lecture:

- Basic properties of the ISM
  - HII regions, dark nebulae, reflection nebulae
  - Cold, warm and hot phases of the ISM (properties etc.)

Look in detail at HII regions:

- Ionization/recombination, emission/absorption
- Thermal balance (heating/cooling)
- Sizes

Vela Supernova Remnant



Data from the Digitized Sky Survey
Image processing by Davide De Martin

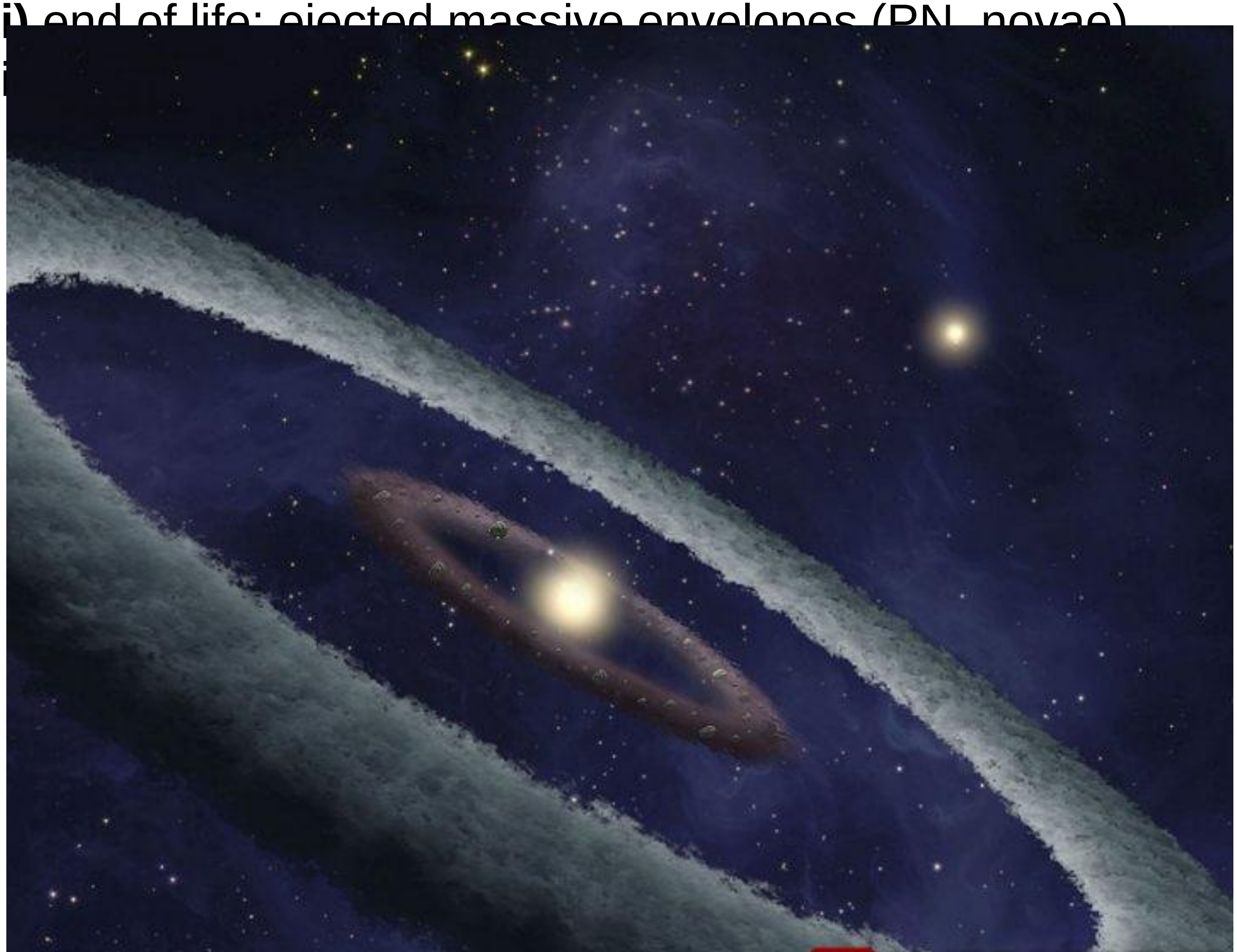
ISM:

built from remains of stars

(i) during life: stellar winds (slow and steady during lifetime)

(ii) end of life: ejected massive envelopes (PN, novae)

(ii



Can we classify the ISM?

- Diffuse emission nebulae: When in the vicinity of OB-type stellar associations (i.e. near young stars), they become ionized are called HII regions:
  - The gas emits photons due to recombination.
  - Generally found near the plane of the Galaxy, at heights of ≥ 50 pc.
  - Masses ~ 100–10 000 $M_{\odot}$; Sizes ~ few pc; Temps ~ 10 000 K; Densities ~ 10^3 hydrogen ions/cm^3

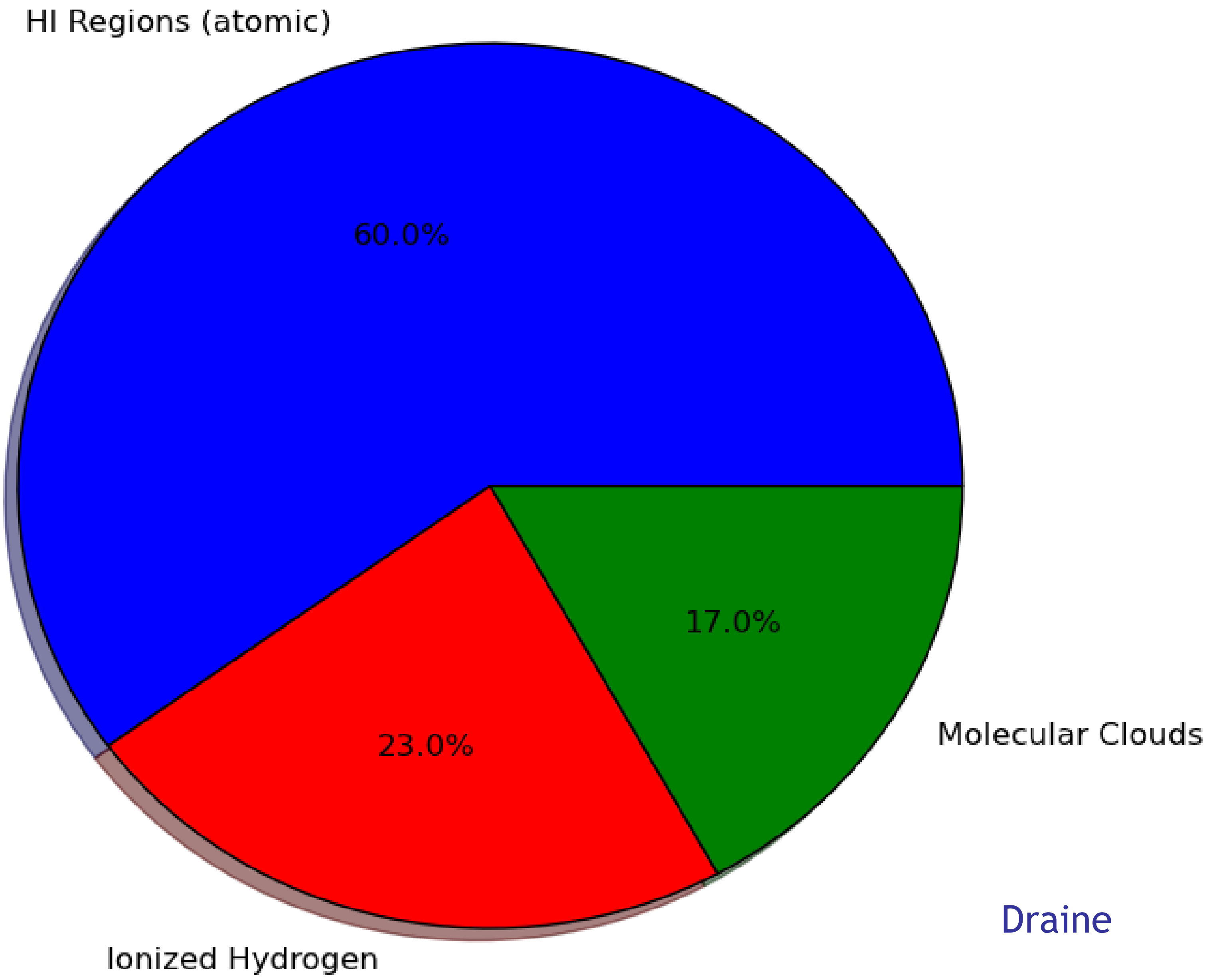
  (compare with air density of 10^{19} /cm^3, or stellar atmosphere ~ 10^{15} /cm^3)

- Dark clouds are denser and colder

$>10^4$ /cm^3 and T ~ 10–100K - are potential sites of star-formation.
They block most optical radiation.
H_2 molecules form within them on the surface of dust grains.
Variety of sizes: pc-sized up to Giant Molecular Clouds

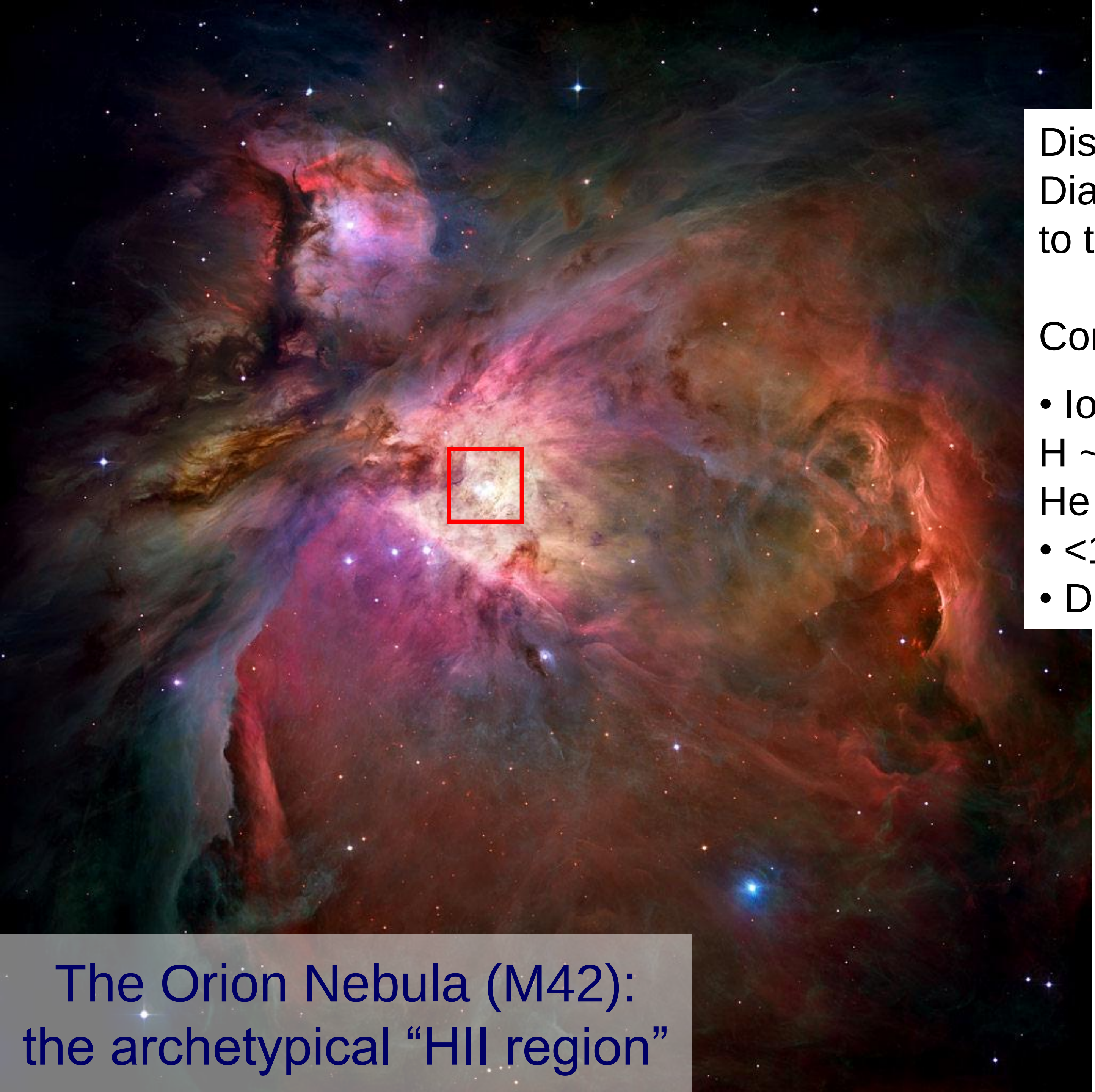
- Reflection nebulae near bright stars appear bluish due to the efficient scattering, by dust particles, of blue-wavelength light (say 400 nm) – same process as that which makes the sky blue

Distribution of Cold Gas in the ISM



Draine

The Orion Nebula (M42): the archetypical “HII region”

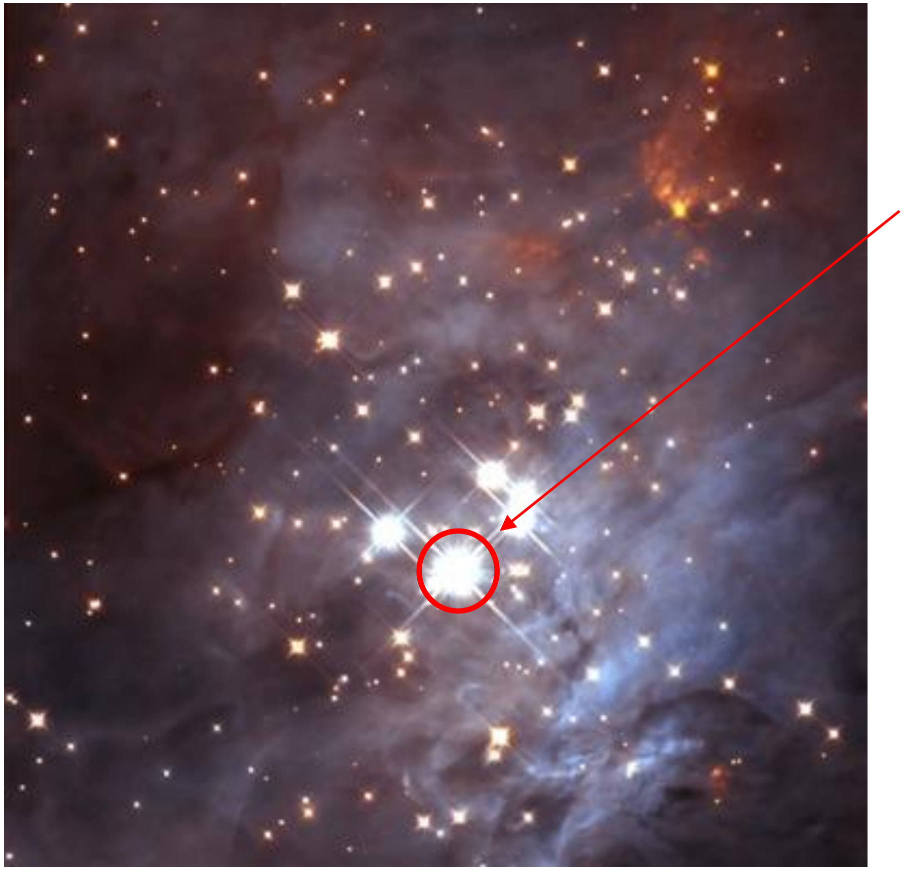


Distance = 450 pc
Diameter ~ 1° (similar to the full moon)

Composition:

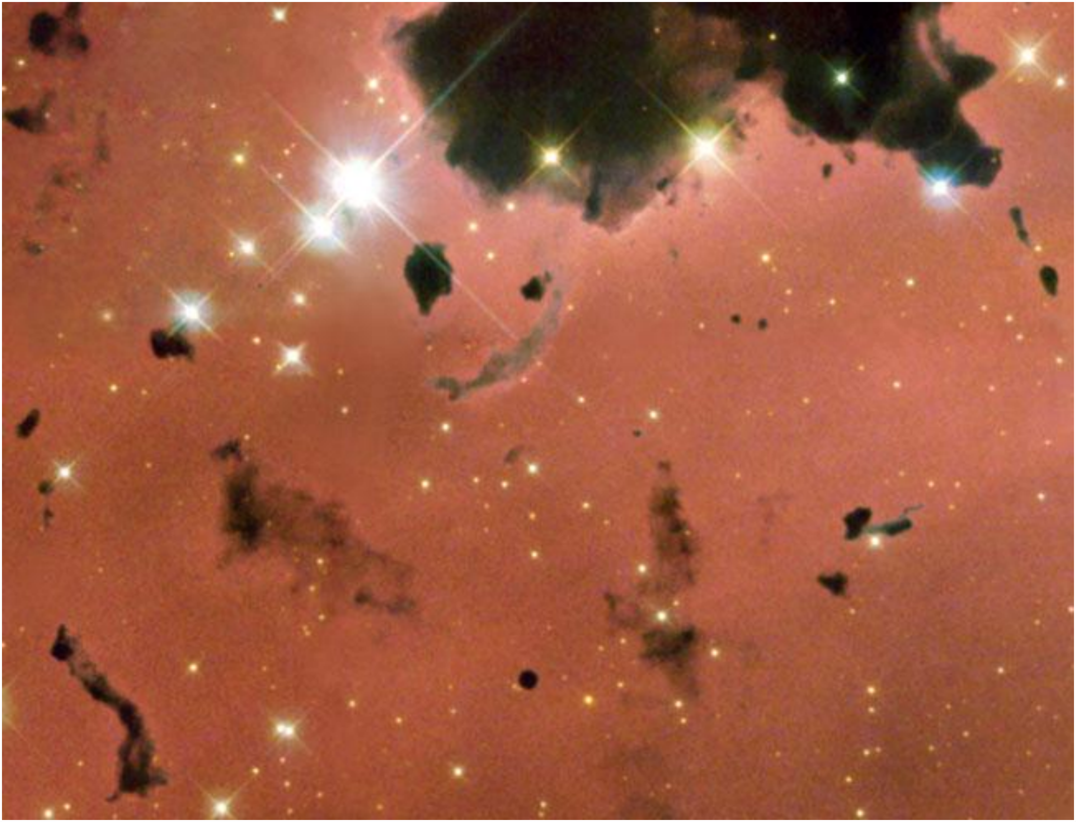
- Ionized gas:
H ~ 90% (by number)
He ~ 10% (by number)
- <1% Heavier elements
- Dust

The Trapezium Cluster



dominant star: θ^1 *Ori-C*
spectral type O6V: T ~ 20 000 K

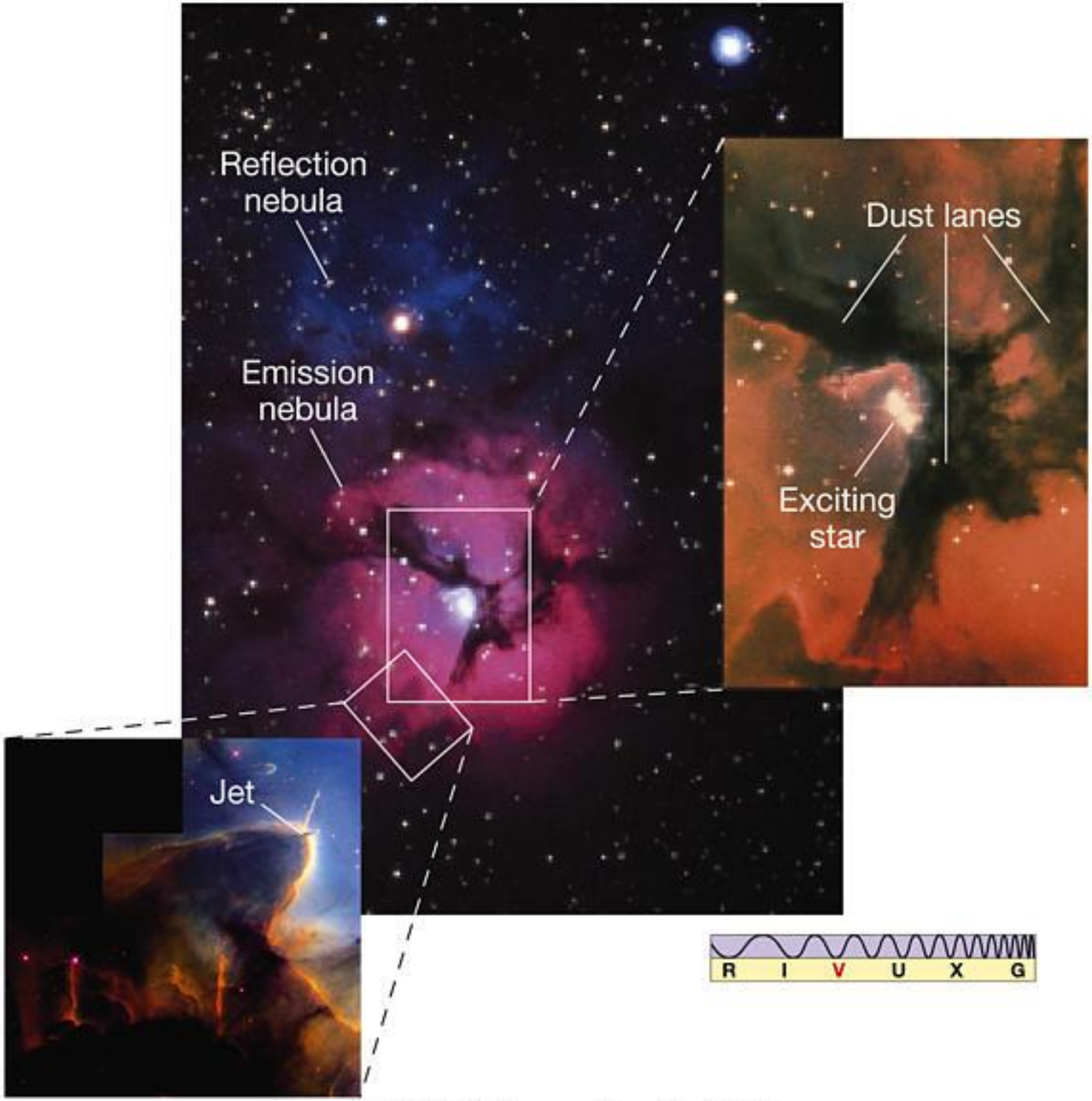
emits a great number of energetic photons that ionize the gas



Bok globules

- relatively much denser that general diffuse ISM clouds:
  densities ~10^4 - 10^9 particles per cm^3
- made up of atoms, molecules and dust particles
- have low temperatures of 10-100 K.


NGC 6723
Reflection Nebula NGC 6726/6727
Gamma CrA
Variable Nebula NGC 6729
Epsilon CrA
Dark Nebula Bernes 157
Double Star BRS 014
Reflection Nebula IC 4812


Reflection nebula
Emission nebula
Dust lanes
Exciting star
Jet
R I V U X G

ISM: average properties

- Mean density of ISM (in our Galaxy) ~ 10^6 particles/m^3 (1 particle/cm^3) <u>but</u> is HIGHLY CLUMPED: filling factor ~3%.

- The GAS is mainly:
    - Hydrogen (90%)
    - Helium (10%)
    - metals (C,N,O, ... Fe) <1% by number

- Dust grains : gas atoms ratio = approx 1 : 10^{12}
- Dust grains have a power-law size distribution
  radii ~ $5\times10^{-9} – 2\times10^{-7}$ m (smaller grains are more abundant)

A global model:

the 3+1 phases of the ISM

- Cold, neutral medium (CNM)

  $n \sim 1\text{–}10^3$ /cm^3, $T < 100$ K, volume fraction: ~1–5%

- Hot, ionized medium (HIM)

  $n \sim 10^{-4}\text{–}10^{-2}$ /cm^3, $T \sim 10^6\text{–}10^7$ K, volume fraction: ~30–70%

- Warm interface media
  - Warm ionized medium (WIM)

    $n \sim 0.01$ /cm^3, $T \sim 1000$ K, volume fraction: ~20–50%
    hydrogen ionization fraction (X_H) ~ 70%
  - Warm neutral medium (WNM)

    $n \sim 0.1\text{–}10$ /cm^3, $T \sim 1000\text{–}5000$ K, volume fraction: ~10–20%
    hydrogen ionization fraction (X_H) ~ 10%

⊕ Dark neutral (molecular) clouds

$n \sim 10^3$□10^6 /cm^3, $T \sim 10$□50 K, volume fraction: <1%

A global view

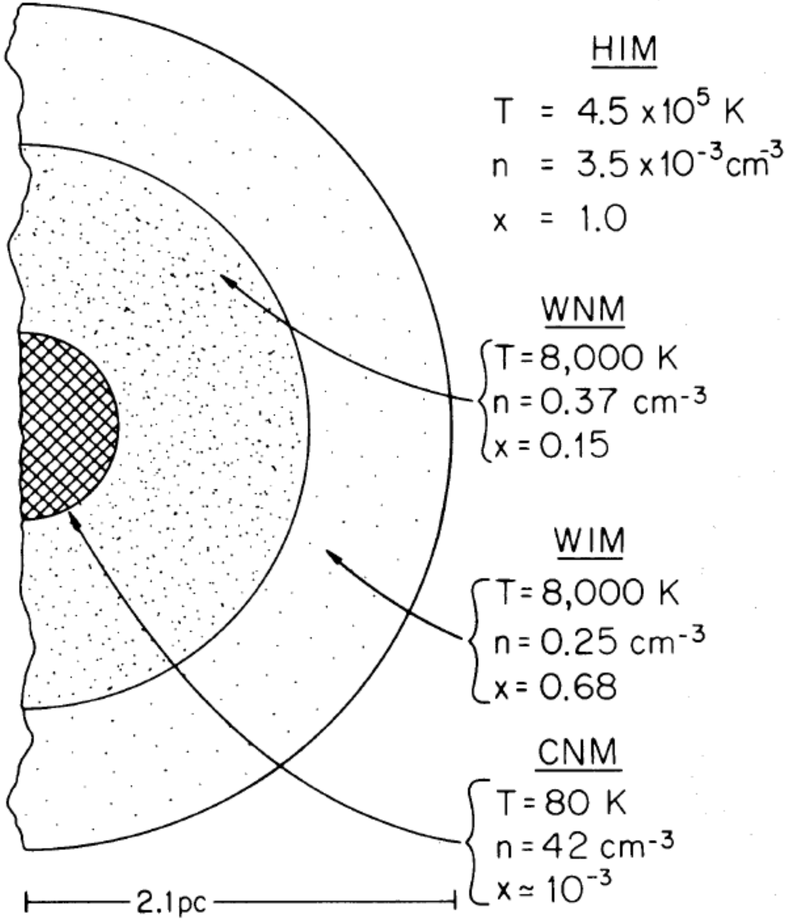


FIG. 1

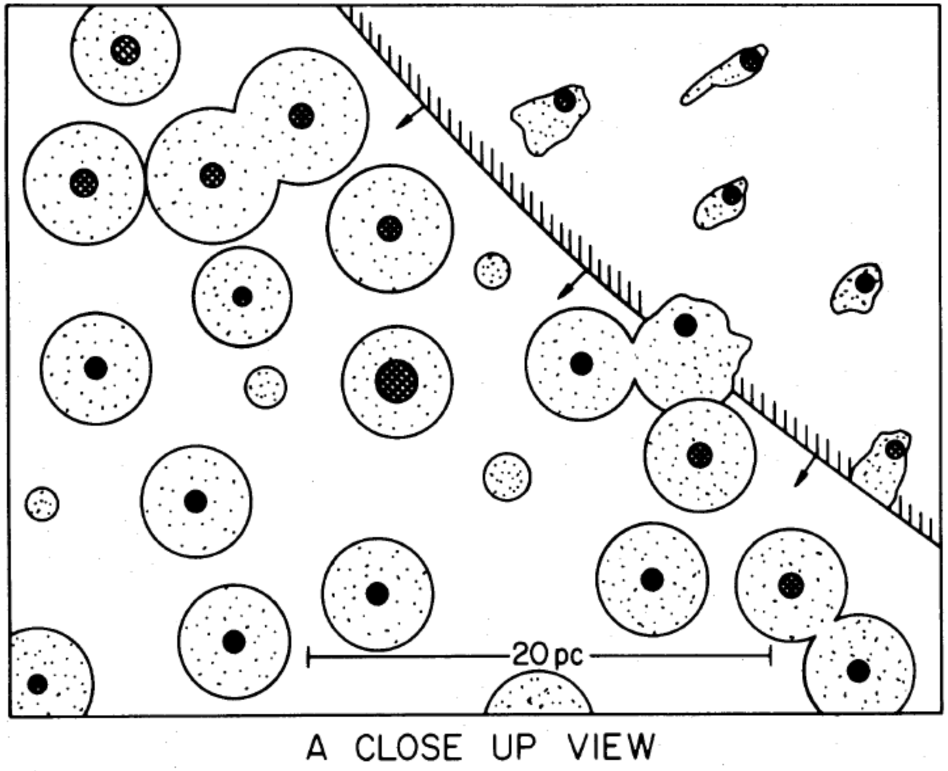
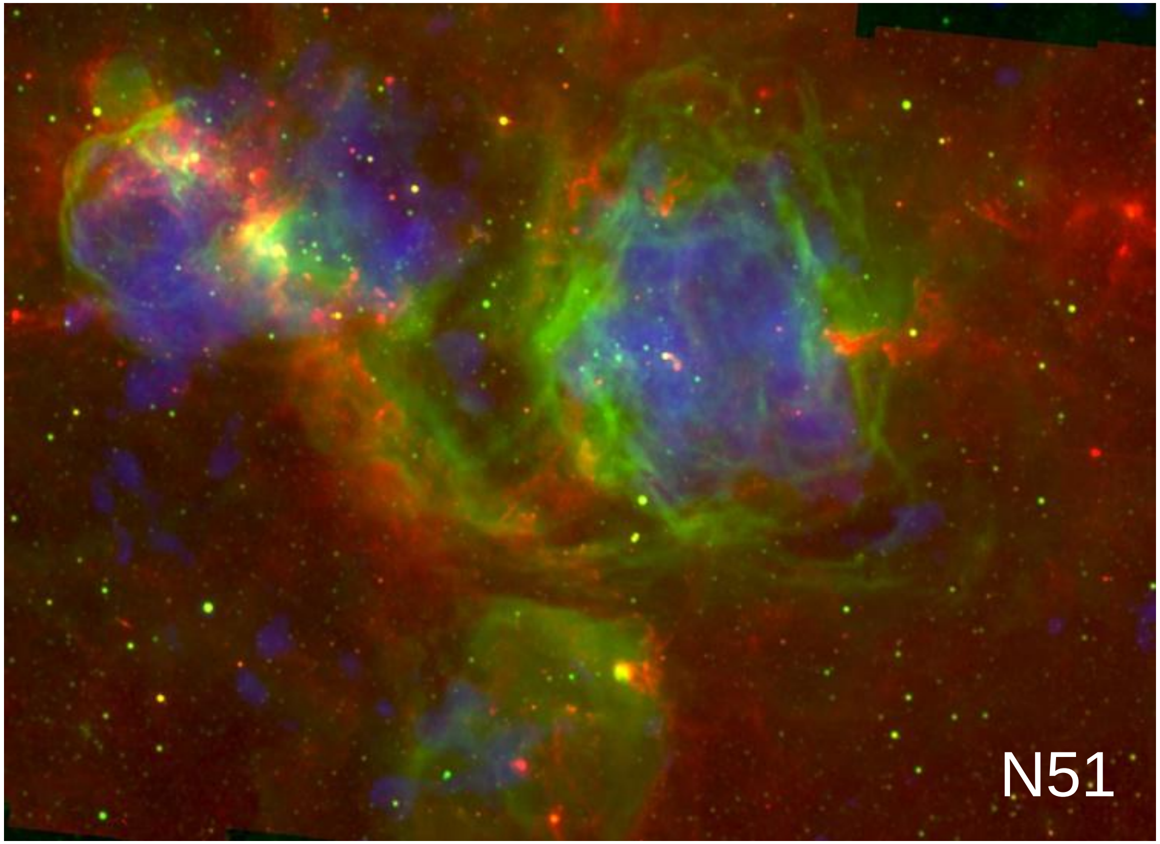


FIG. 2

Hot, ionized medium (HIM)

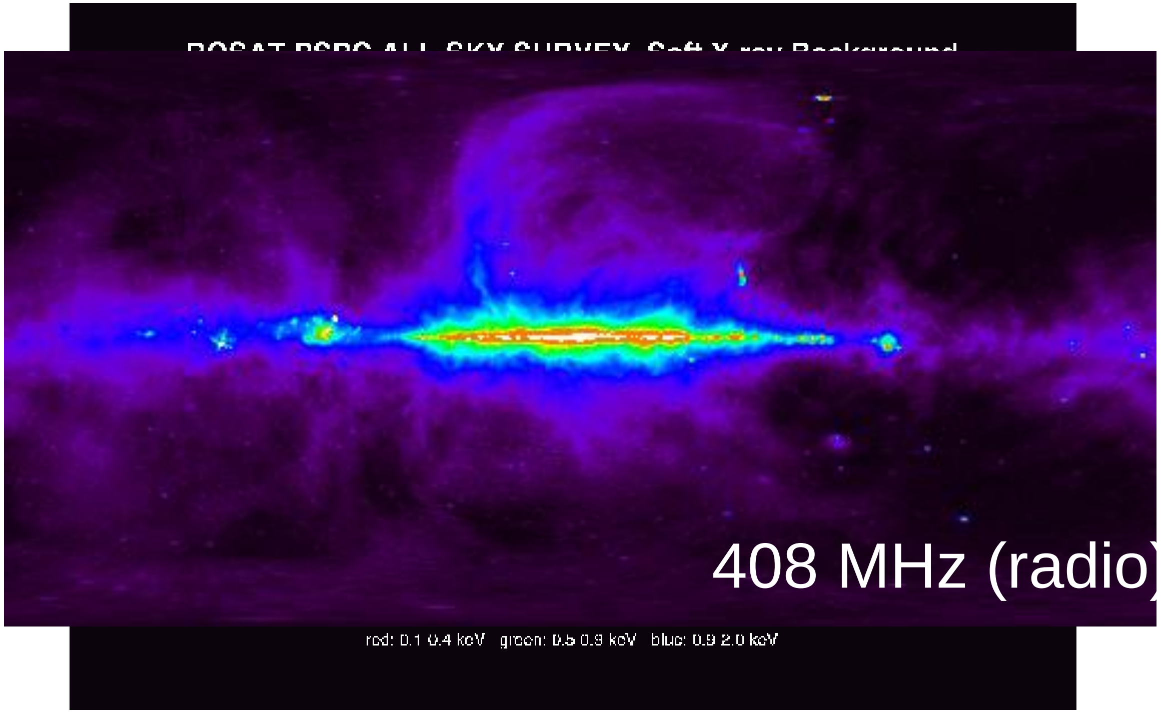
Arises through the heating and energy input from overlapping Supernova explosions and their remnants: directly seen in X-rays.



Optical = red and green
X-ray = blue

Hot, ionized medium (HIM)

Arises through the heating and energy input from overlapping Supernovae explosions and their remnants: directly seen in X-rays.



- Supernovae occur in the Galactic plane: causes hot gas to rise to high distances above/below the plane of the Galaxy
- Gives rise to a halo of hot gas around the galaxy.
- This gas then cools and falls back to the galactic plane, and is replenished by further SN: the Galactic Fountain model.

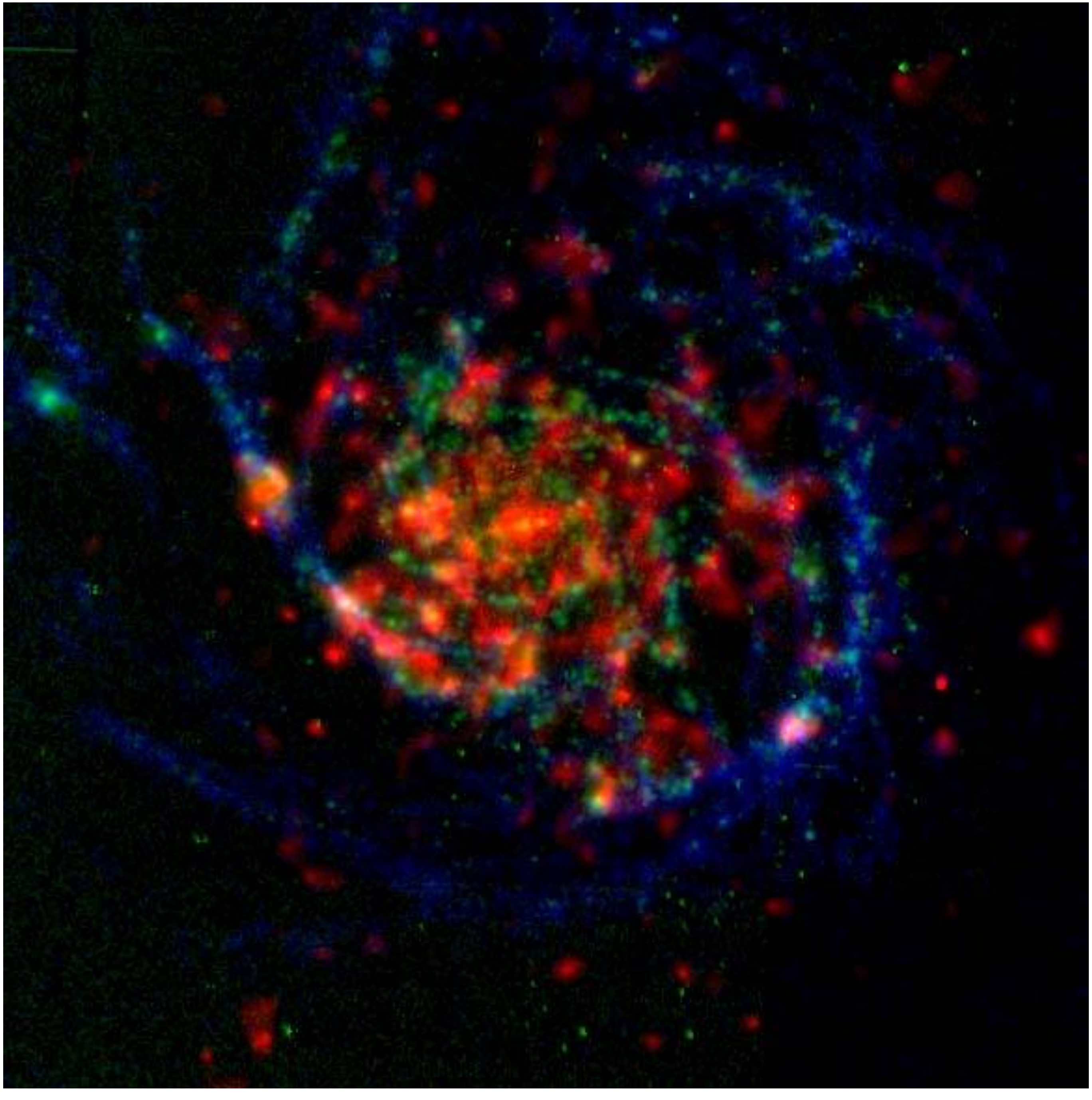
Cold, neutral medium (CNM)

- dominated by diffuse clouds with $n \sim 10^1$–10^3 /cm^3, $T \sim 30$–100 K, individual cloud radii = few pc

- cold enough that simple molecules can form, e.g. H_2 and CO.

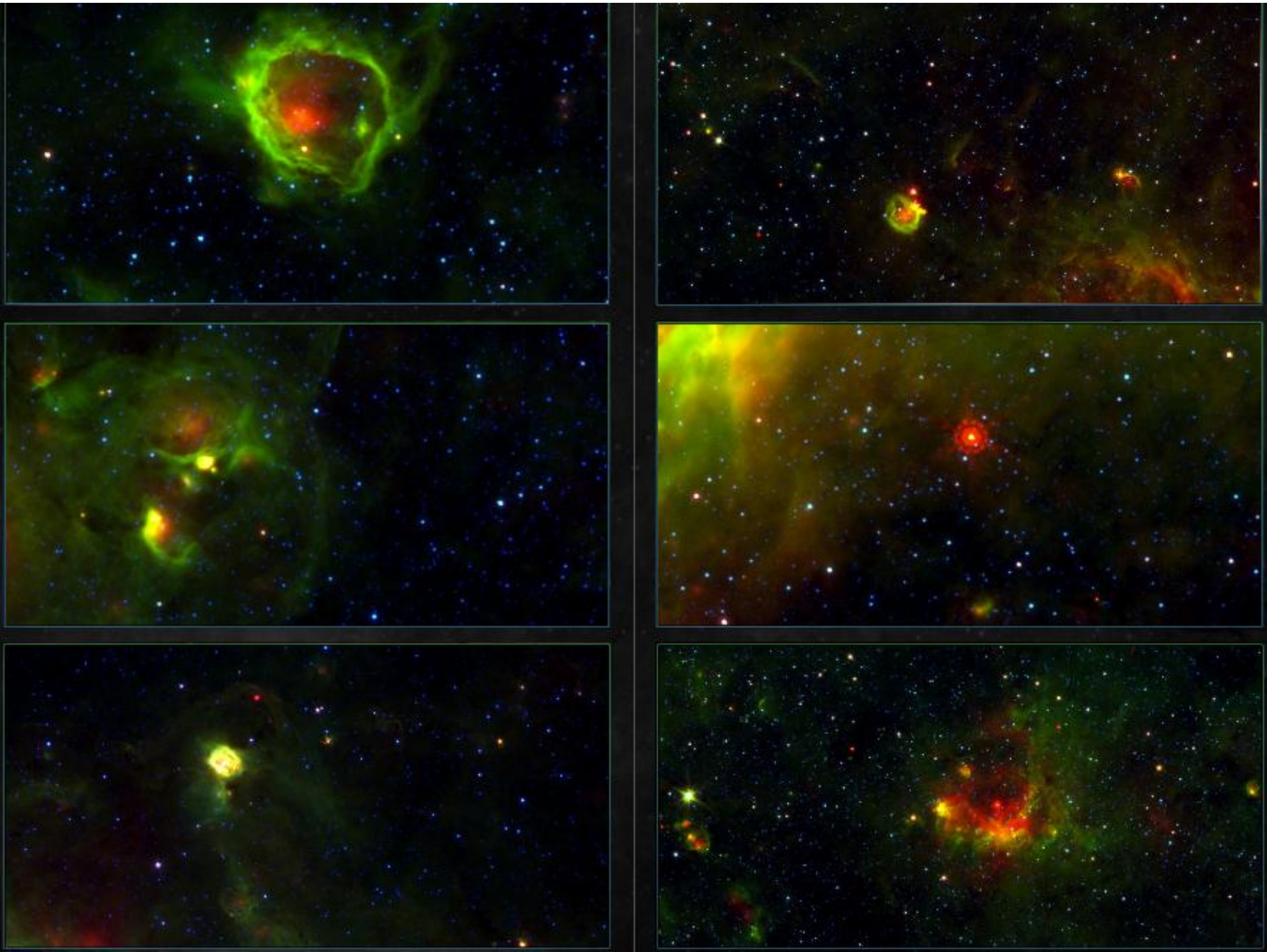
- however, most INTERSTELLAR MOLECULES are mainly found in the denser DARK CLOUDS (Barnard Objects and Bok Globules) with $n \sim 10^6$–10^7 /cm^3 and $T \sim 10$ K.

- Still denser regions are the GIANT MOLECULAR CLOUDS with $n \sim 10^{10}$ /cm^3 and $T \sim 50$ K. These are associated with sites of new STAR FORMATION.



THE MILKY WAY PROJECT

www.milkywayproject.org

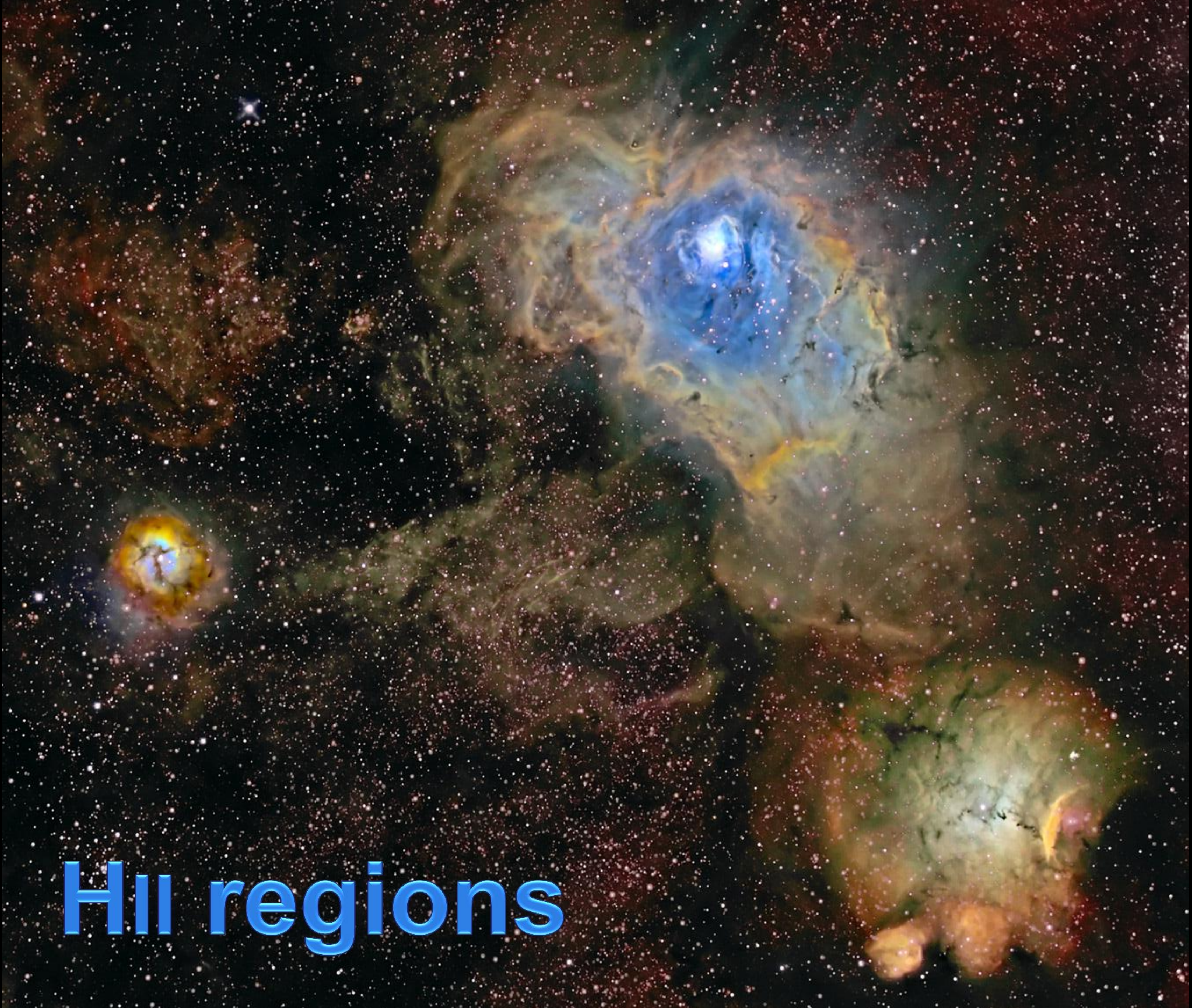


Today:

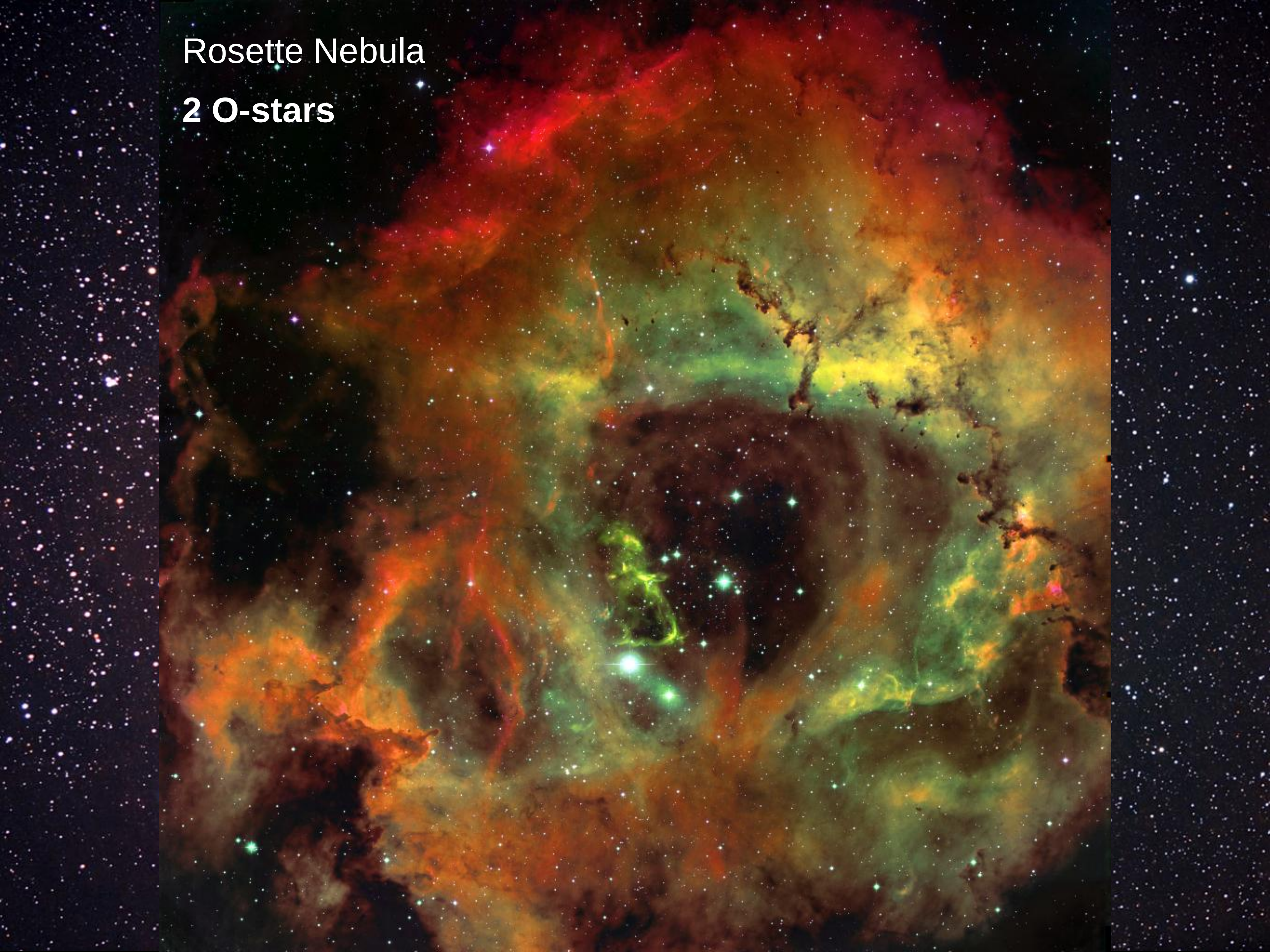
HII regions:

- Ionization/recombination, emission/absorption
- Thermal balance (heating/cooling)
- Sizes

- The addition of metals
    - Forbidden lines
    - Metal line cooling
    - Density/temperature diagnostics

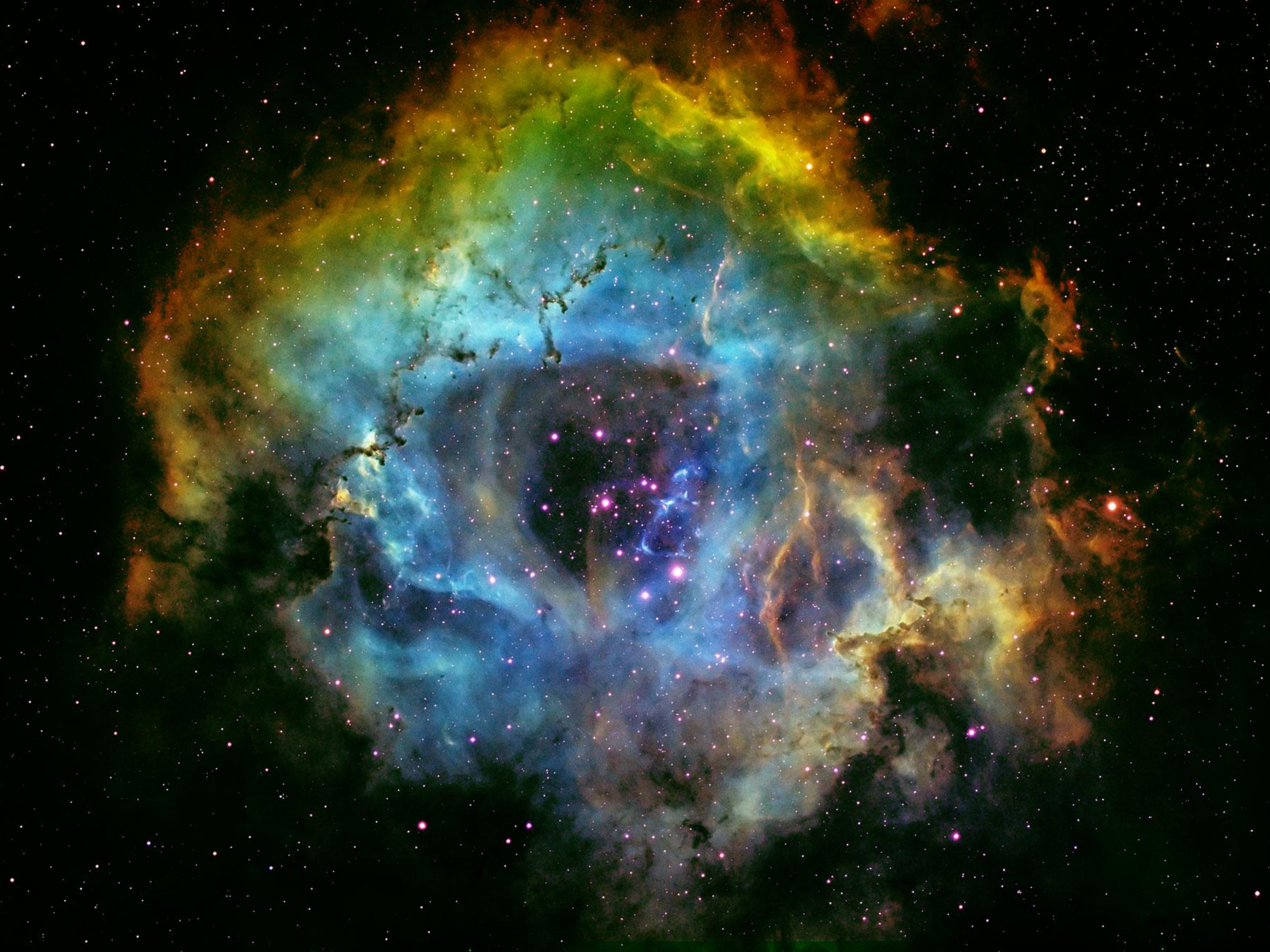


HII regions



Rosette Nebula

2 O-stars

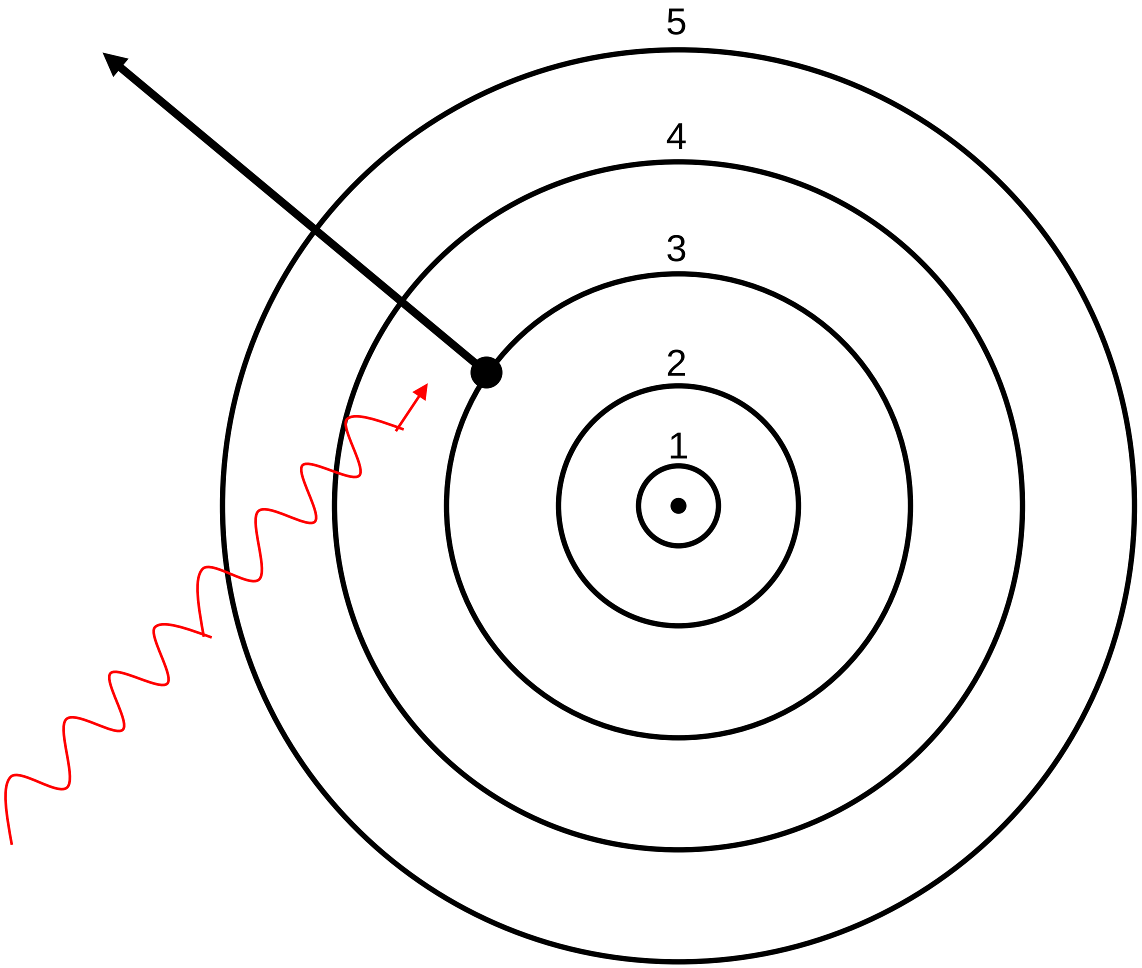


Photoionisation

Photoionisation: the removal of electrons from gas atoms by photons.

$$\mathrm{H} + (\text{ionizing photon}) \rightarrow \mathrm{p} + e^{-} \qquad \text{(Eqn. 1)}$$

Photoionisation



13.6 eV =

λ < 912 Å

Photoionisation: the removal of electrons from gas atoms by photons.

$$\text{H} + (\text{ionizing photon}) \rightarrow \text{p} + \text{e}^- \qquad \text{(Eqn. 1)}$$

For Hydrogen (most abundant atom) photons need to have an energy of *at least* **13.6 eV** (corresponding to $\lambda <$ **912 Å**)

13.6 eV therefore = the "Ionisation Potential" of Hydrogen ($\boldsymbol{I}_{\mathbf{H}}$)
= called **one Rydberg**

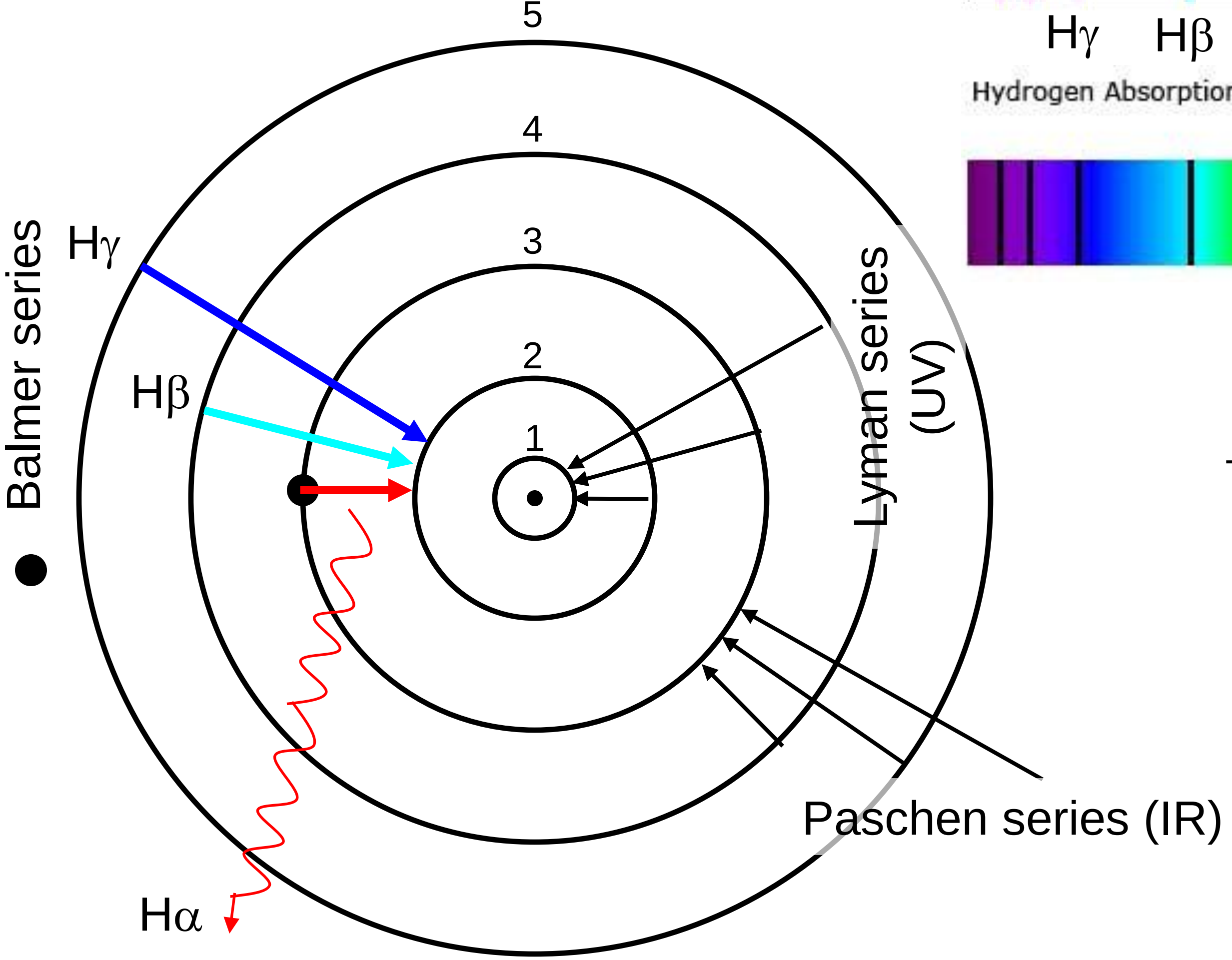
Only stars with $T > 20\,000$ K (*spectral types O and B*) emit 'ionising' photons

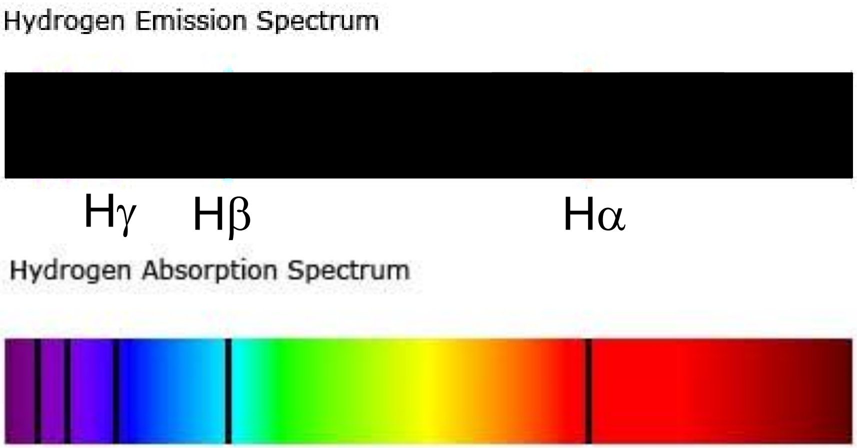
Recombination

Attraction between protons and electrons leads to the recapture of the electron.

$$p + e^{-} \rightarrow H + \text{(ionizing photon)}$$

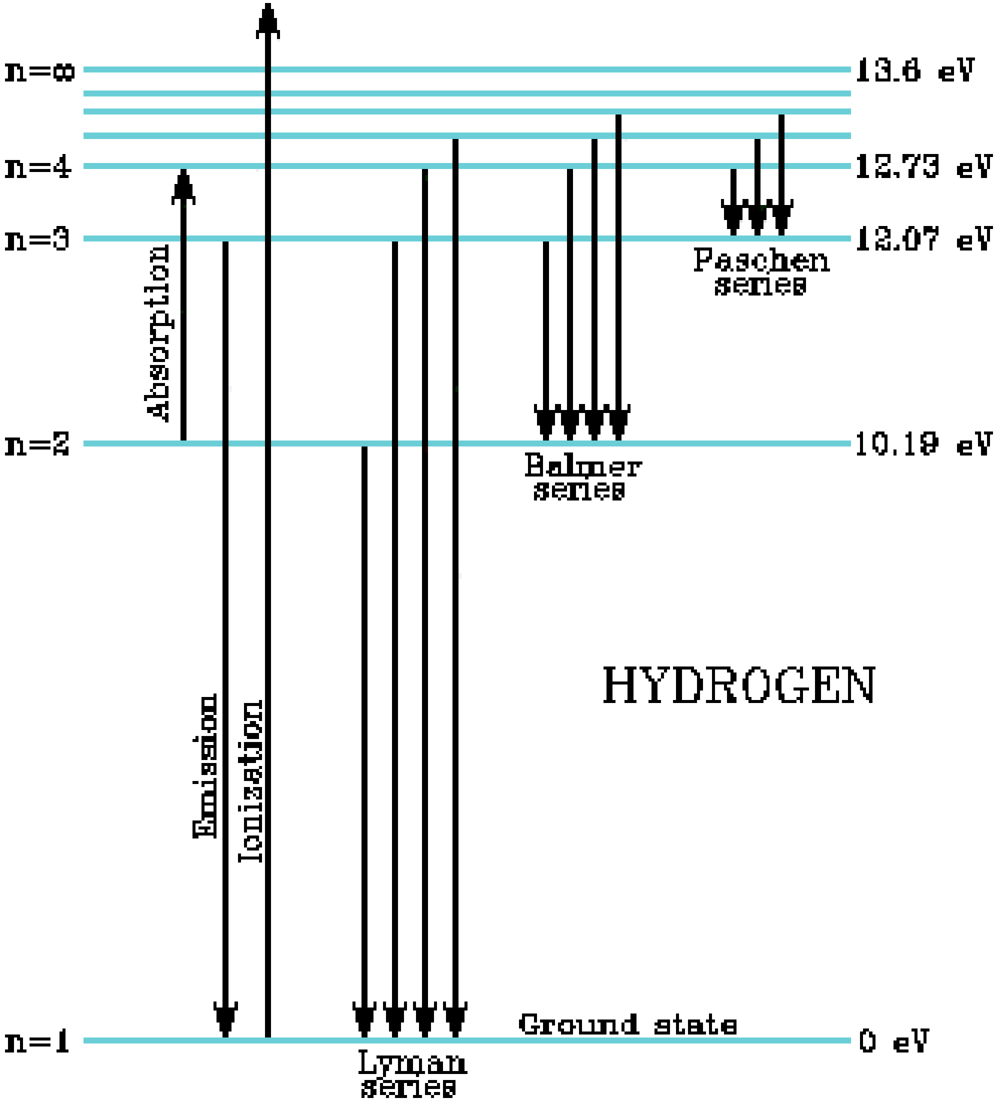
Recombination cascade in H-atom

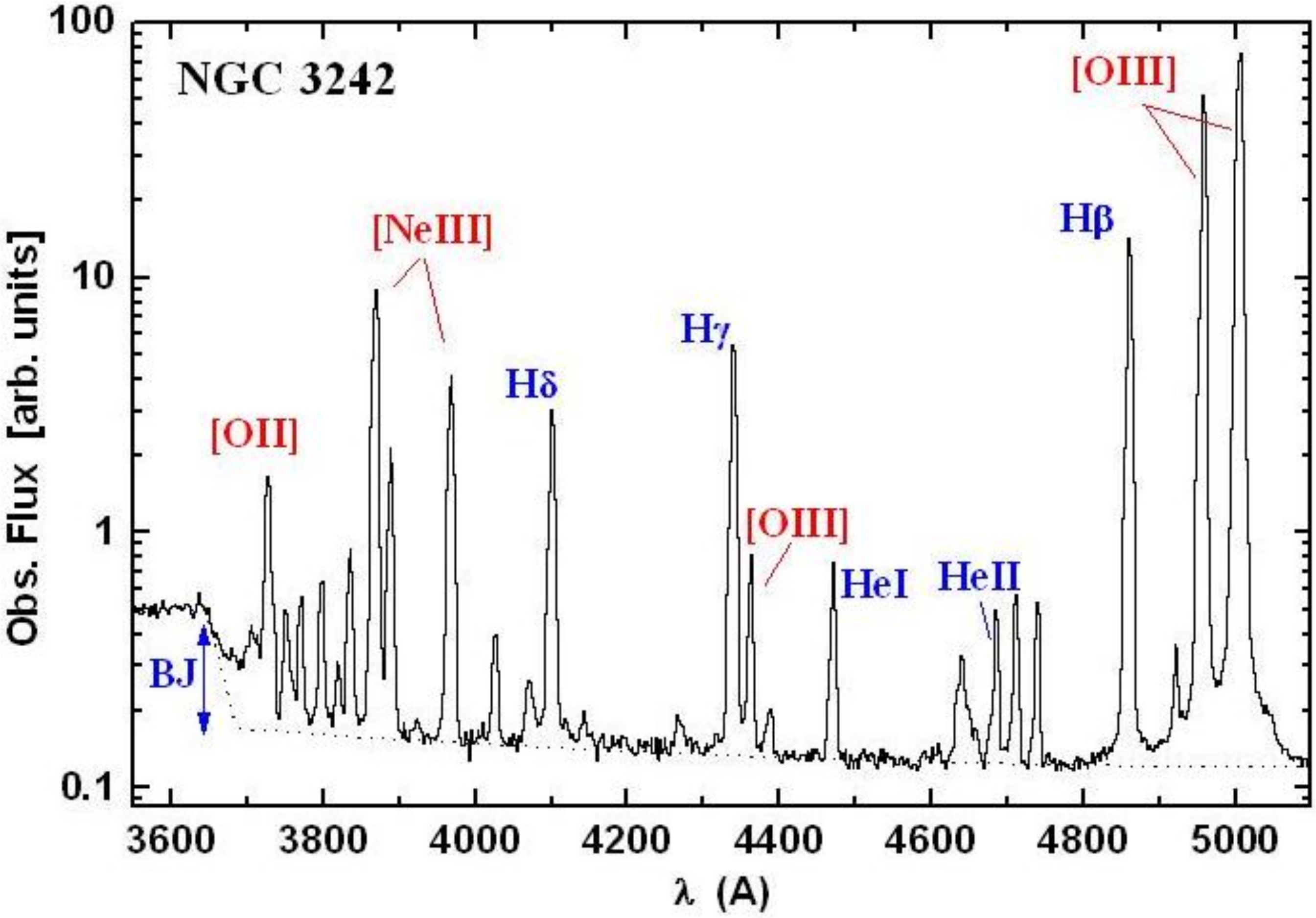




$$\frac{1}{\lambda} = R\left(\frac{1}{N^2} - \frac{1}{n^2}\right)$$

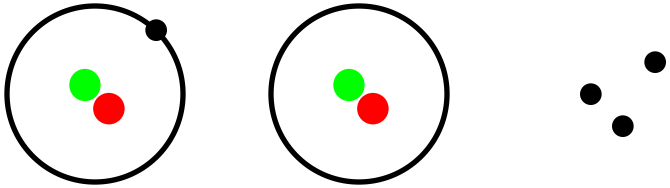
N = no. of inner orbit
n = No. of outer orbit
R = Rydberg const.


n=∞
13.6 eV
n=4
12.73 eV
n=3
12.07 eV
Paschen series
Absorption
n=2
10.19 eV
Balmer series
HYDROGEN
Emission
Ionization
Ground state
n=1
0 eV
Lyman series



Planetary Nebula: NGC 3242
(ESO 1.5-m in Chile)

Blue = recombination lines of H and He
Red = forbidden lines of ‘metals’



To a good approx. the nebula contains only neutral H, protons (p), and electrons (e^{-})

The energy of the free electrons can be “anything” above 13.6 eV

The *total* energy available for photoionization depends on the *total* number of photons.

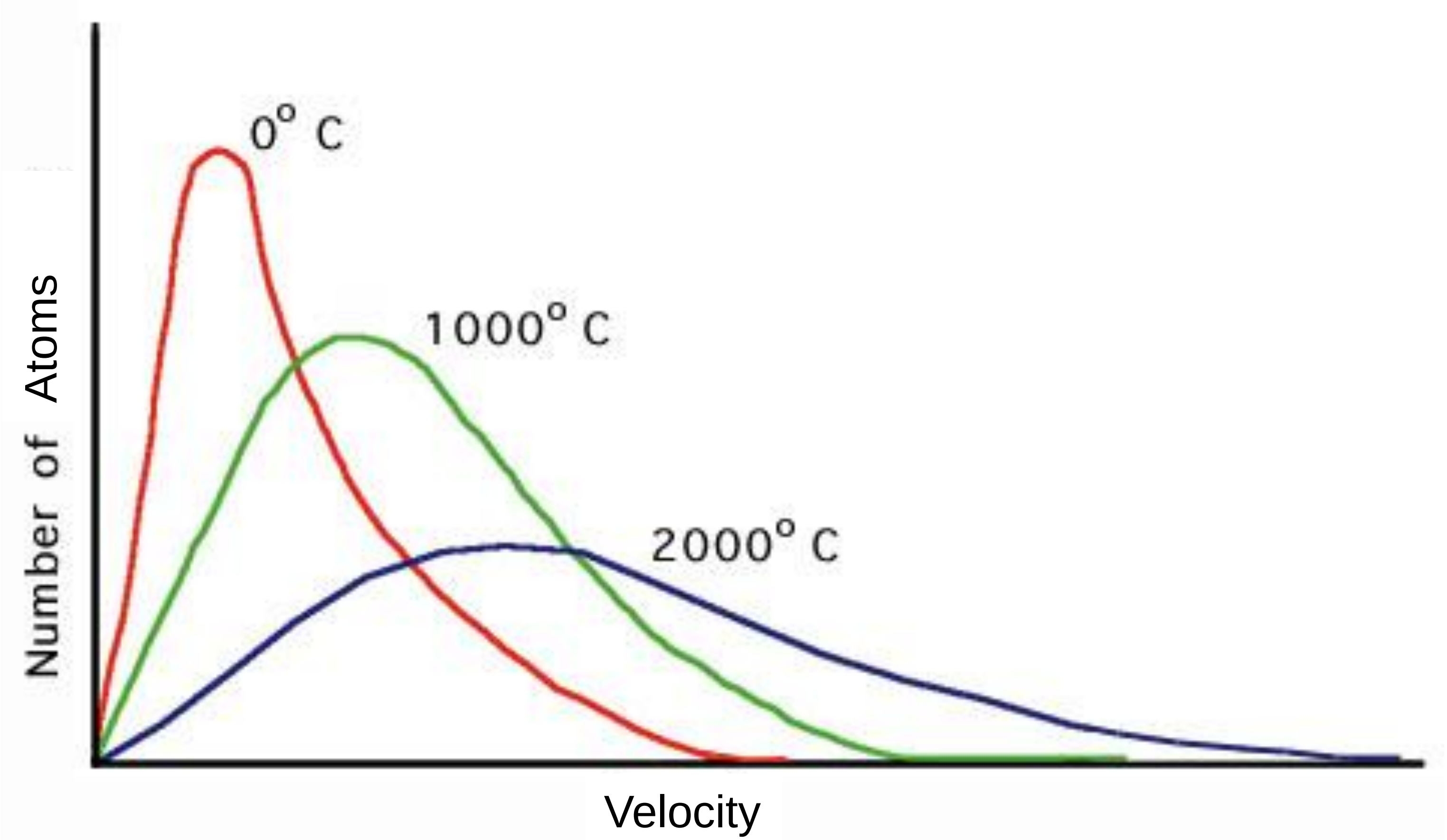
This is a function of the effective temperature (T_{eff}) of the ionizing star

The energy is spread out (**shared**) between all the particles (by collisions) and acquires a single ‘kinetic temperature’ for *all 3 types* of particle.

We say the *plasma* becomes ‘thermalized’.

The distribution of velocities within the gas can now be described by a ‘Maxwellian distribution’

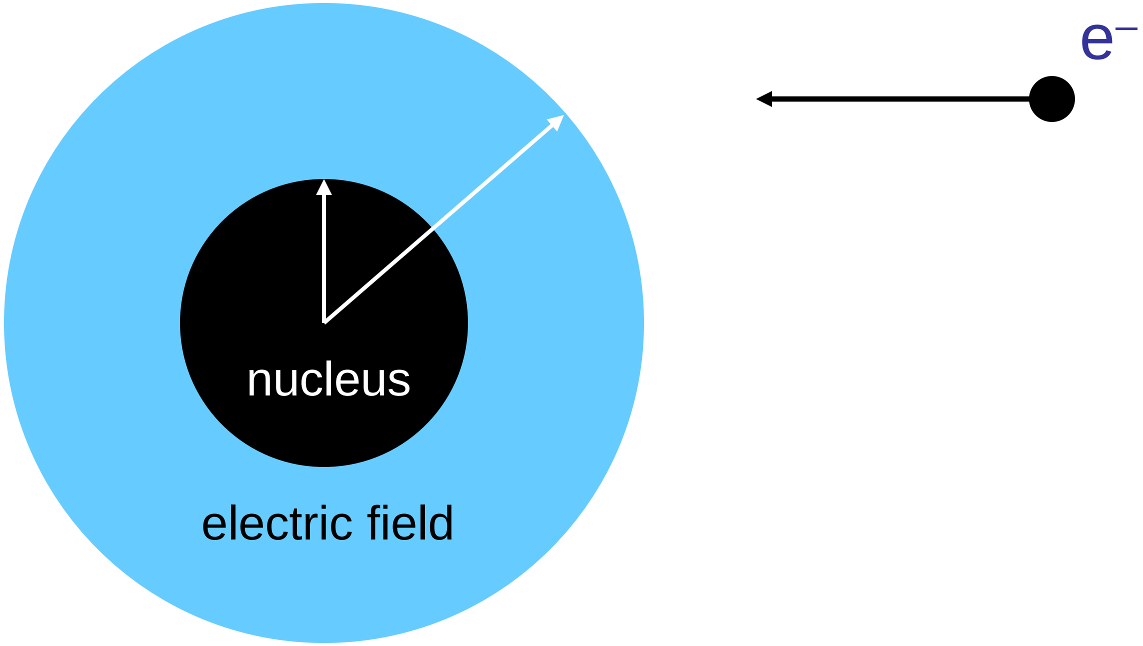
The Maxwellian Distribution



Photoionisation rate [number of events/m^3/sec]:

$$N_{PI} = a \; n_{HI} \; J \qquad [\mathrm{m}^{-3}\ \mathrm{s}^{-1}]$$

a = photoionsation cross section (= 6.8×10^{-22} m^2)
n_{HI} = number density of neutral H (HI)
J = rate of incident ionising photons (with E >13.6 eV) (m^{-2} s^{-1})



cross section = likelihood (probability) of interaction between particles

Photoionisation rate [number of events/m³/sec]:

$$N_{PI} = a \; n_{HI} \; J \qquad [\mathrm{m^{-3}\,s^{-1}}]$$

$\boldsymbol{a}$ **=** photoionsation cross section (= 6.8×10^{-22} m²)
$\boldsymbol{n_{HI}}$ **=** number density of neutral H (HI)
$\boldsymbol{J}$ = rate of incident ionising photons (with E >13.6 eV) ($\mathrm{m^{-2}\,s^{-1}}$)

Recombination rate [number of events/m³/sec]:

$$N_R = n_e \; n_p \; \alpha_n = n_e^2 \, \alpha_R \qquad [\mathrm{m^{-3}\,s^{-1}}]$$

$\boldsymbol{n_e}$, $\boldsymbol{n_p}$ = number density of electrons & protons (in equilibrium $n_e = n_p$)
$\boldsymbol{\alpha_R}$ = recombination coefficient = $2\times10^{-16}\, T_e^{-3/4}\ \mathrm{m^3\,s^{-1}}$]

Ionisation balance

Equilibrium occurs when there is a balance between the forward and backward rates

i.e. Photoionization rate, N_{PI} = Recombination rate, N_R

$$\mathrm{H} + (\text{ionising photon}) \leftrightarrow p + e^{-}$$

The degree of ionisation can be described as:

$$n_e = n_p = X\, n$$

X = fraction of *ionised* H atoms
n = number density of H nuclei (proton+neutral atom densities)

$$n_{\mathrm{HI}} = n - X\, n$$

n_{HI} = number density of neutral H (HI)

Now we can use these equations in the previous relations…

- $N_{PI} = a\ n_{HI}\ J$
- $N_R = n_e^2\ \alpha_R(T_e)$
- $n_e = n_p = X\,n$
- $n_{HI} = n - X\,n$

In equilibrium, $N_{PI} = N_R$, so:

$$a\,(n - X\,n)\,J \;=\; (X\,n)^2\,\alpha_R$$

We can now calculate X (the ionisation fraction) for a specific value of J and n at some distance from a star, r

$$J = S_\star\,/\,(4\,\pi r^2) \qquad\qquad [\mathrm{m}^{-2}\ \mathrm{s}^{-1}]$$

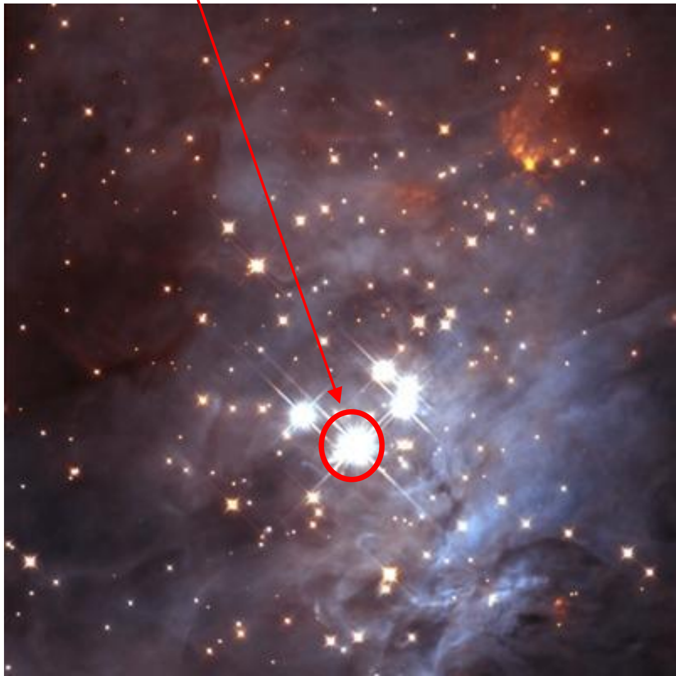
$\boldsymbol{S_\star}$ = no. of ionising photons emitted by the star per sec

For a typical O-star (e.g. the O6V star in the Trapezium)
$S_{\star} = 10^{49}\ \mathrm{s^{-1}}$

Typical nebula, $n = 10^{8}\ \mathrm{m^{-3}}$; $T_e = 10^{4}$ K

At $r = 1$ pc, $J = 8.4\times10^{14}\ \mathrm{m^{2}\,s^{-1}}$

giving $X = 0.9999999$
i.e. the HII region is almost fully ionised!



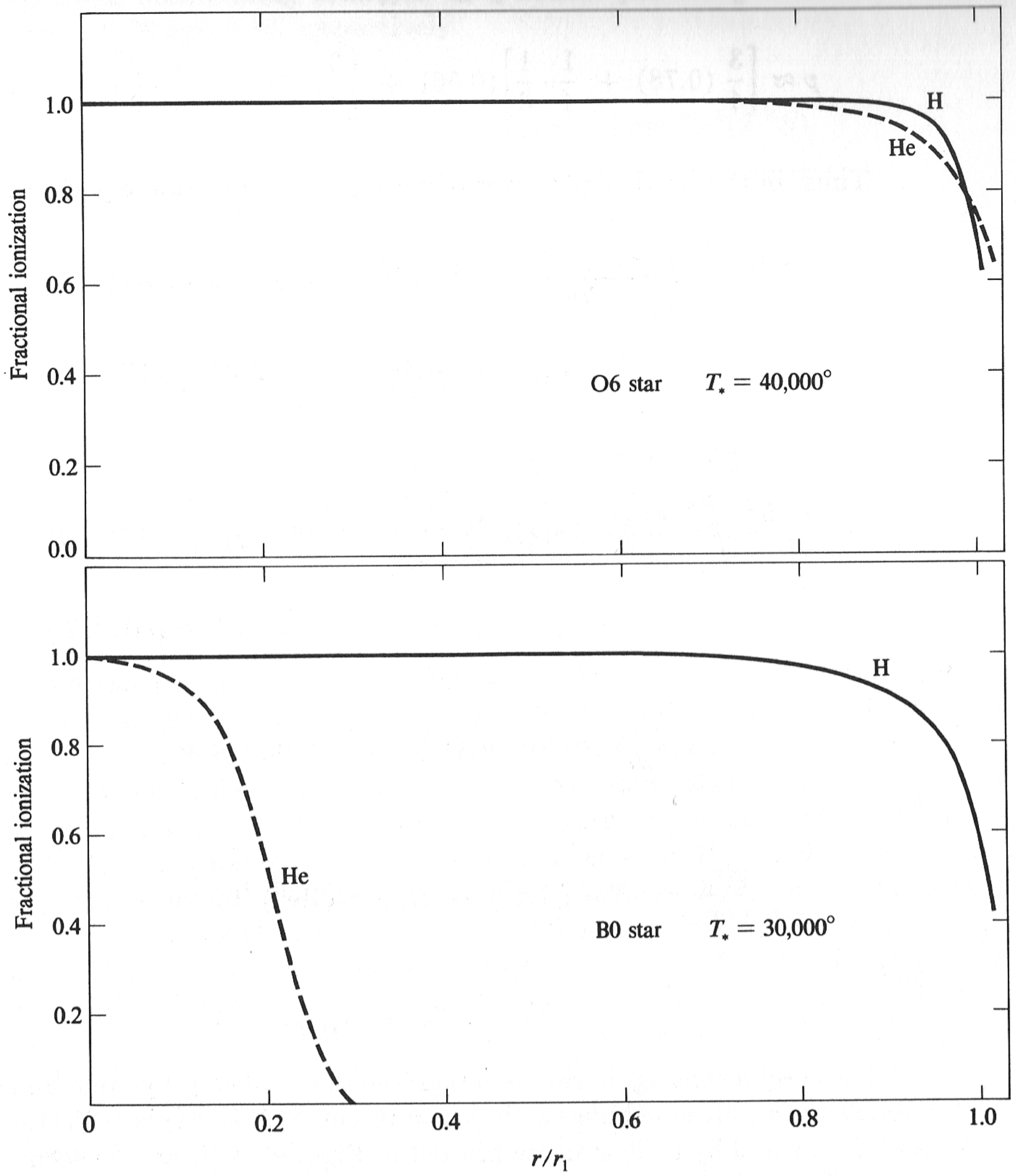
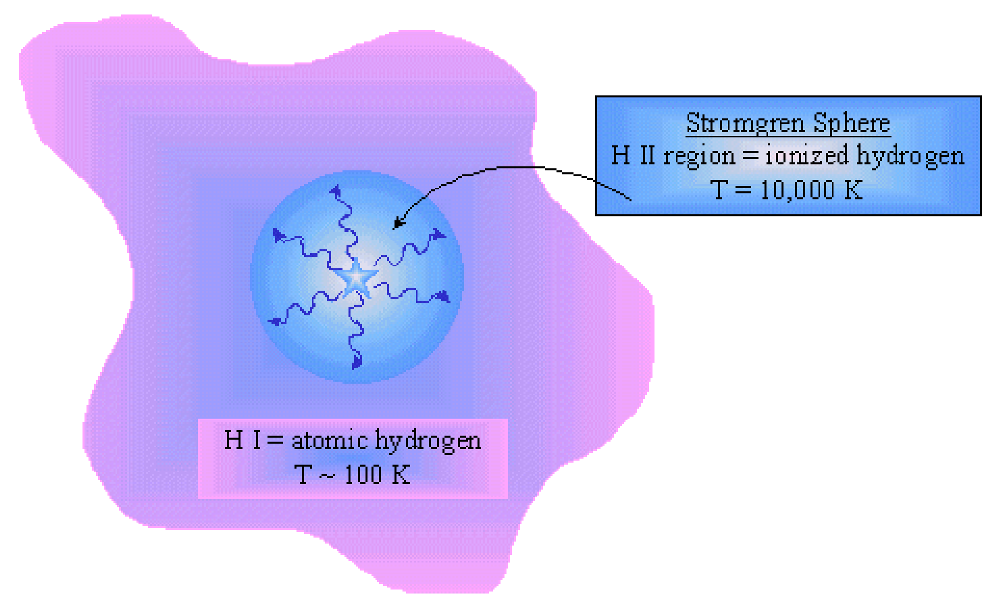


FIGURE 2.4
Ionization structure of two homogeneous H + He model H II regions.


M43

1. no. of ionising photons
    - Hotter star
    - More hot stars
2. amount of gas (gas density)


Strongren Sphere
H II region = ionized hydrogen
T = 10,000 K

H I = atomic hydrogen
T ~ 100 K


IC 1274

Thermal balance in ionized nebulae

Photoionization adds kinetic energy (KE) into the H cloud since it creates hot, fast photoelectrons.

T can increase indefinitely though… Energy must be lost somehow

Energy can be lost through photons: H recombination means KE of e^- → photon which can escape

On average, heat lost per recombination = $3/2\ k\ T_e$
so Cooling rate is:

$$L = (3/2\ k\ T_e)\ N_R \qquad [\mathrm{J\ m^{-3}\ s^{-1}}]$$

Energy input, or the Heating rate

$$G = N_{PI}\, Q \qquad [\mathrm{J\ m^{-3}\ s^{-1}}]$$

Q = the heating energy injected into the gas per photoionization (in Joules)

in equilibrium, $\boldsymbol{G = L}$ (and $N_R = N_{PI}$) ➔ $T_e = (2/3)Q/k.$

However, Q per ionization is: (3/2) $kT_{\star}$ ➔ $T_\mathrm{e} = T_{\star}$

For OB-type ionizing stars $\boldsymbol{T_{\star}}$ = 30 000 – 60 000 K

These temperatures are much higher than observations

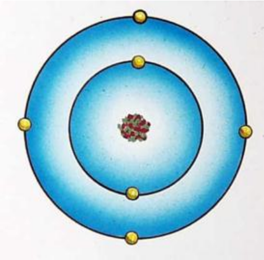
Typical nebula gas temperature has T_e ~ 10 000 K.

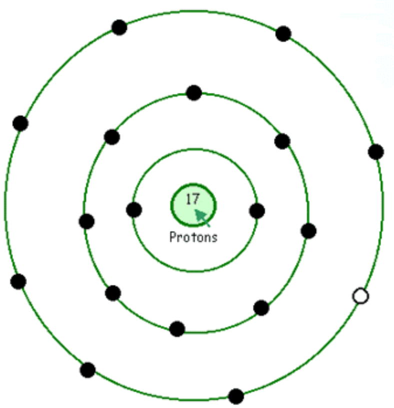
➔ *There must be other ways to cool the gas*

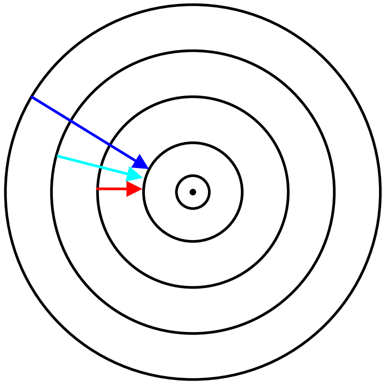
What if we relax our assumption of a pure H nebula?

Metals

- Real nebulae contain more than just H
- Metals (heavy elements, C, N, O, Ne, S, Ar, Cl, etc.) are found in proportion to Hydrogen of ~10^{-4} – 10^{-8}



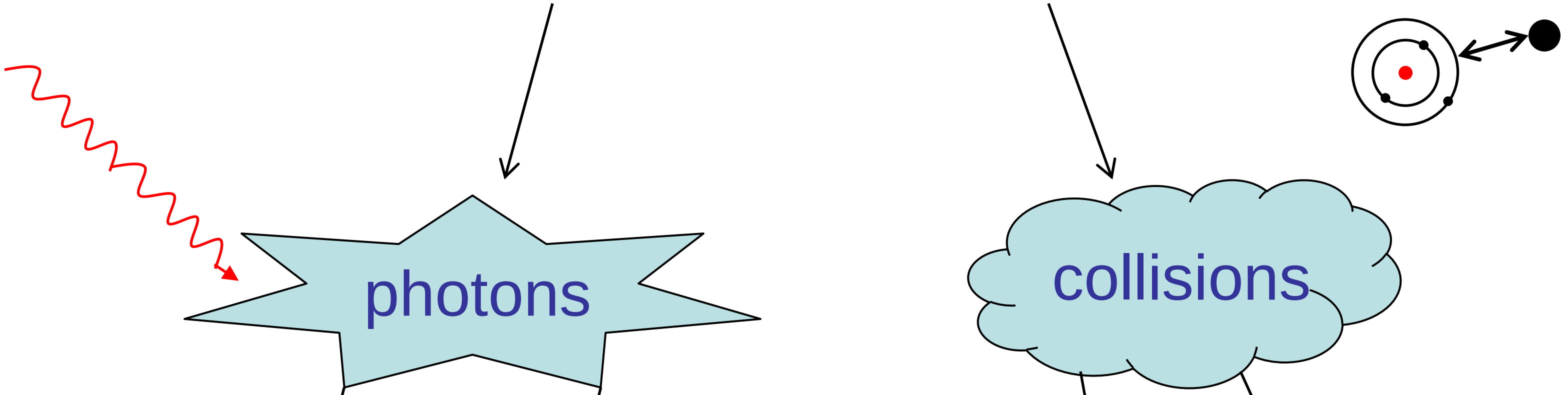




H recombination = ALLOWED transitions

high probability of occurring (~10^9 per sec)

excitation/de-excitation of bound electrons



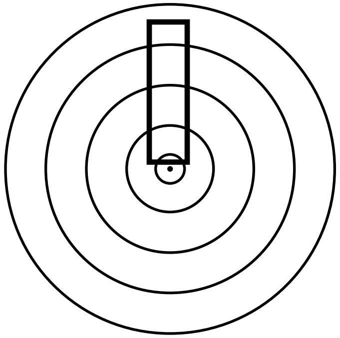
photons

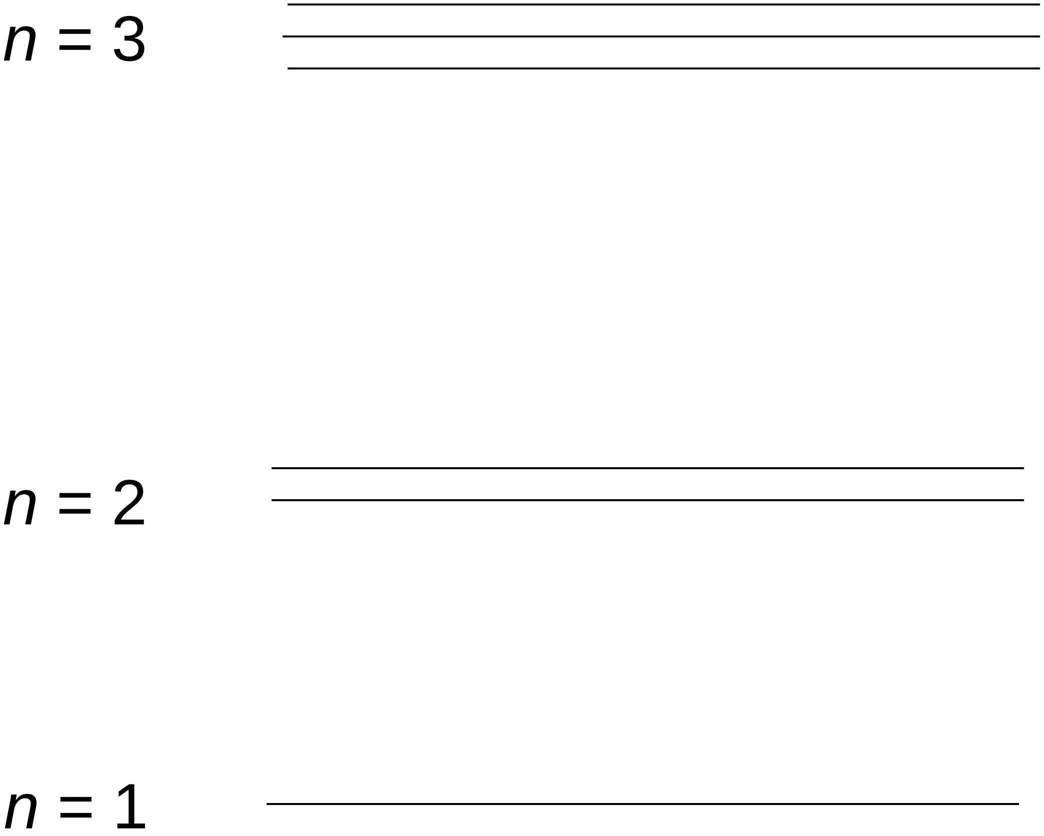
collisions

absorption/emission

non-radiative
excitation/de-excitation

energy levels (→ transitions) in metals are not as simple as H!



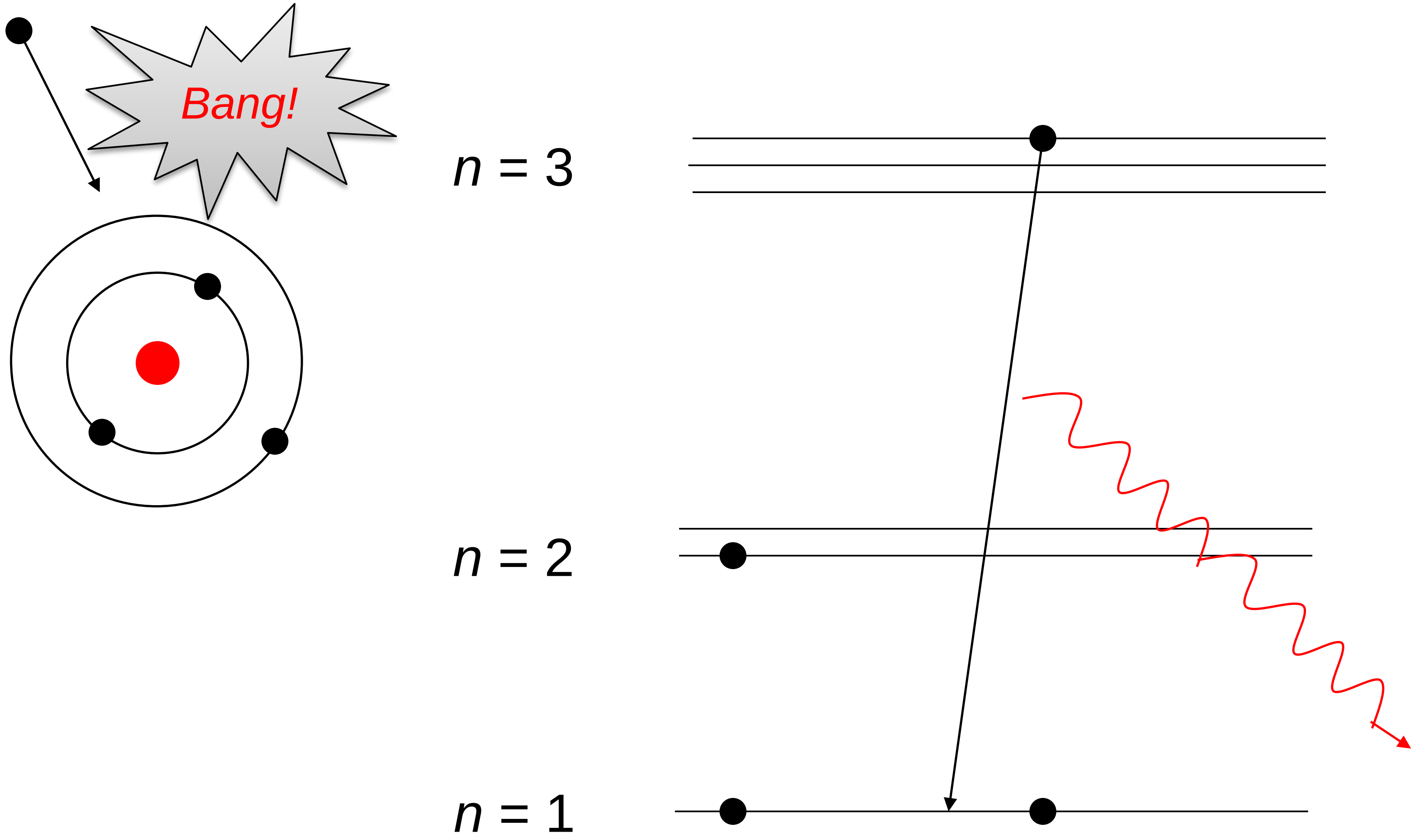


n = 3

n = 2

n = 1

Collisionally excited lines (CELs)



Forbidden lines

Forbidden line: arises when an electron is excited by a collision into a ‘metastable state’.

When densities are higher (e.g. our atmos. – greater than about 10^8 per cm^3), electron would almost immediately be knocked out of metastable state by collision and not be given time to emit a photon (collisional de-excitation = no photon).

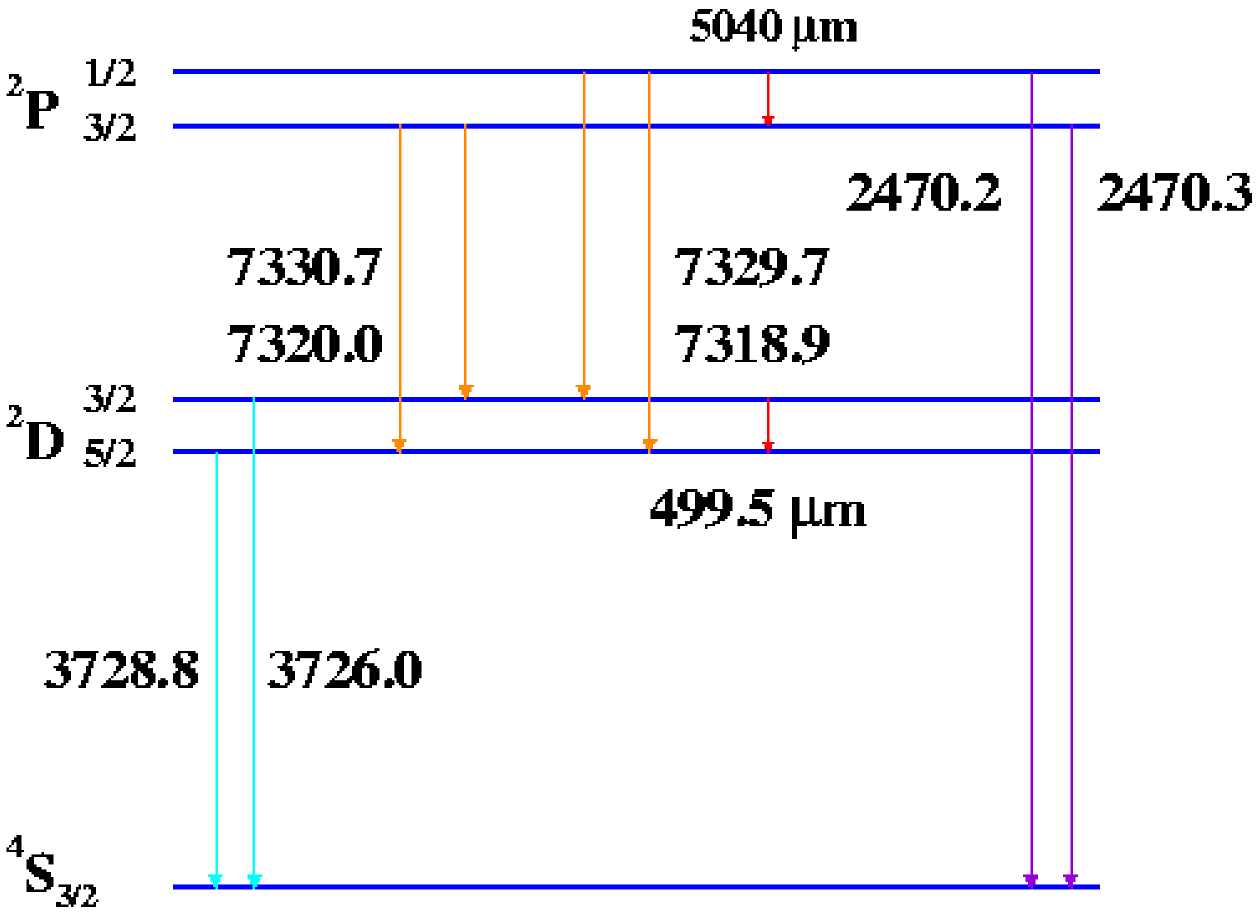
But in a low density nebula, the time between collisions ~ 10 – 10,000 seconds
(v. long time)
➔ allowed time to radiate spontaneously

In a nebular environment, practically every ion goes to the ground state by forbidden radiation

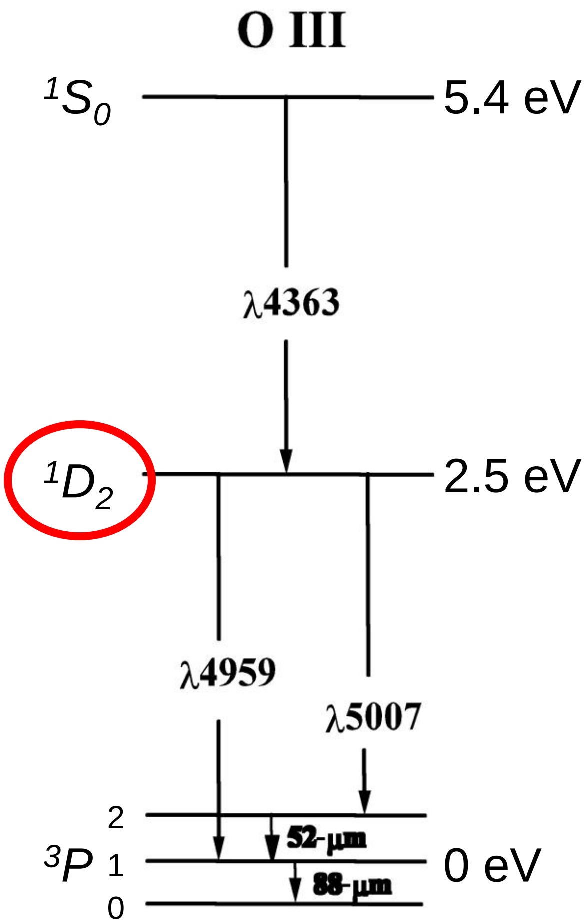
The term ‘Forbidden’ refers to quantum mechanical rules - a little misleading!

More intuative name: <u>Collisionally excited lines</u> (CELs) - line emission following collision with electron

O$^+$

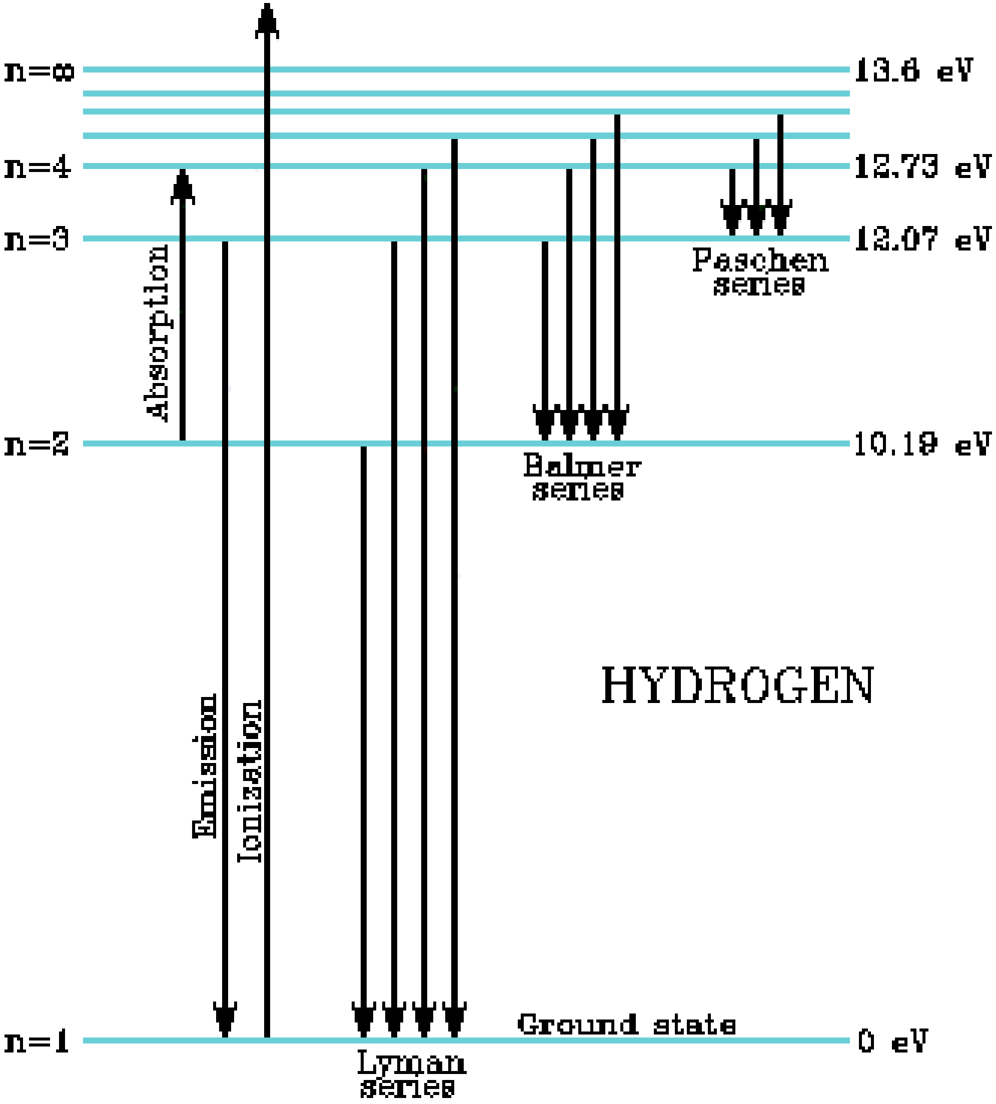


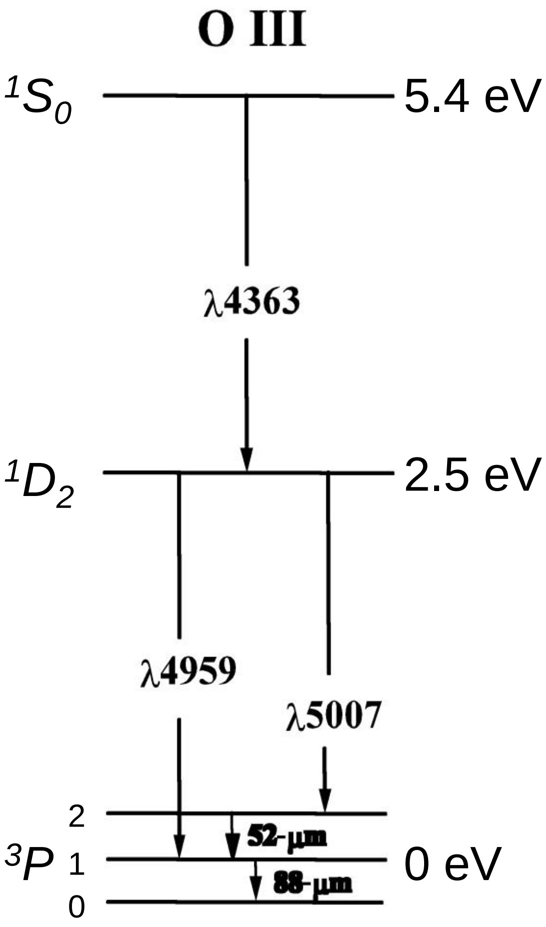
CELs (forbidden lines) are written with [ ]   e.g. [OII] 3726Å

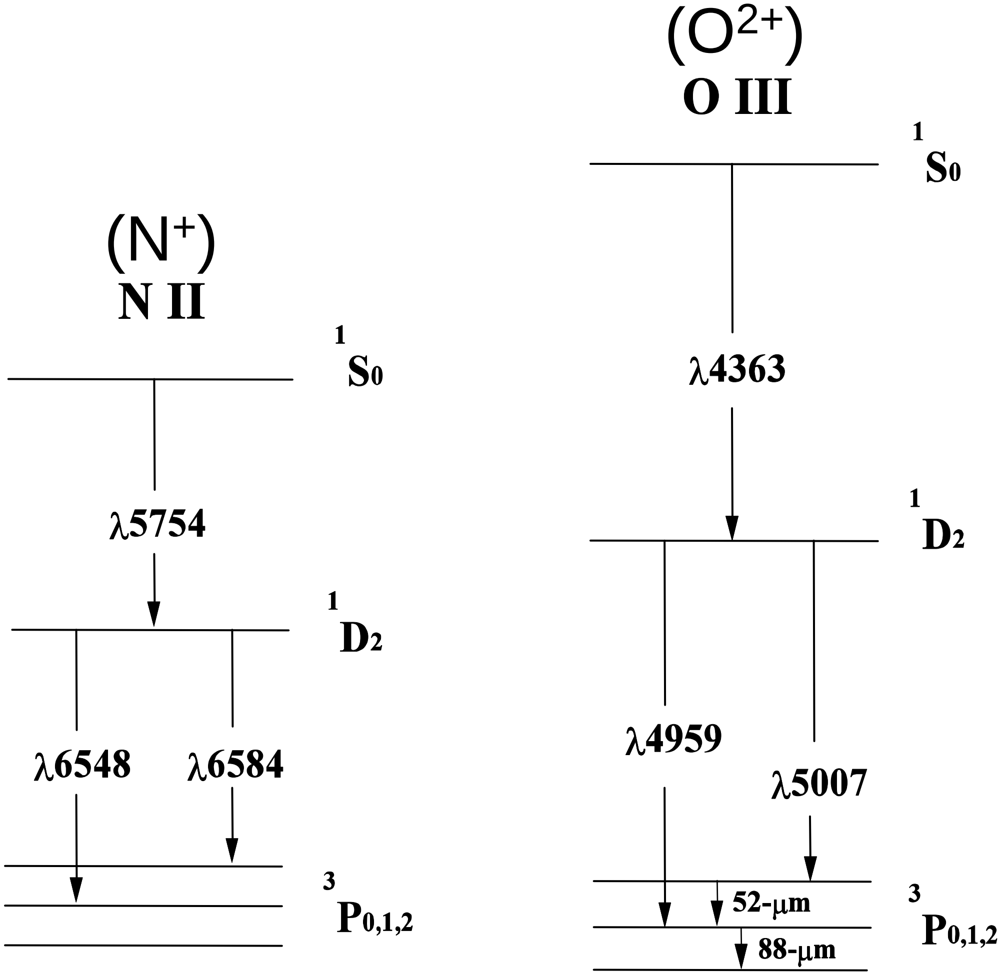


critical density for collisional de-excitation
$= 7 \times 10^5$ cm^{-3}

10^5 cm^{-3} = density where collisional de-excitation of many of the bright lines begins to matter


n=∞
13.6 eV
n=4
12.73 eV
n=3
12.07 eV
Paschen series
Absorption
n=2
10.19 eV
Balmer series
HYDROGEN
Emission
Ionization
n=1
Ground state
0 eV
Lyman series


O III
$^1S_0$
5.4 eV
λ4363
$^1D_2$
2.5 eV
λ4959
λ5007
2
^3P
1
0
52-µm
88-µm
0 eV


(N^+)
N II
$^1S_0$
λ5754
$^1D_2$
λ6548
λ6584
$^3P_{0,1,2}$
(O^{2+})
O III
$^1S_0$
λ4363
$^1D_2$
λ4959
λ5007
52-μm
88-μm
$^3P_{0,1,2}$

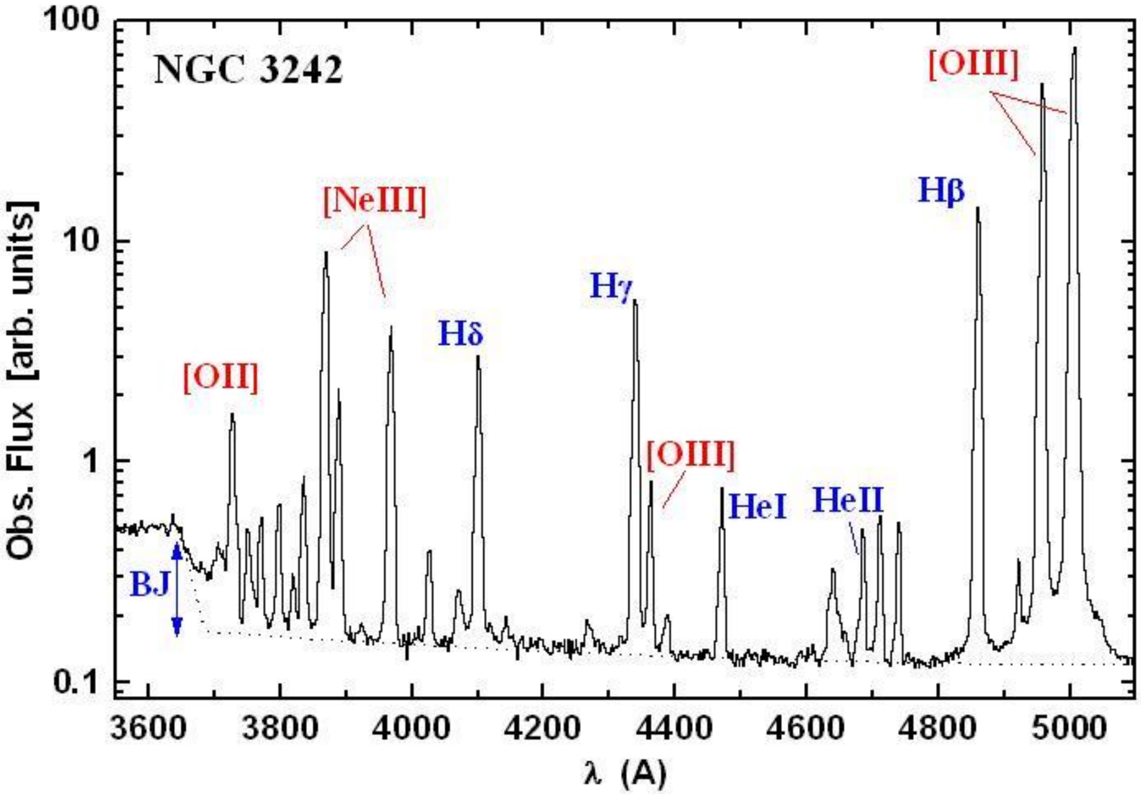
Forbidden line cooling

transition rates very low: ~10^{-3} – 100 per sec
(compared to H recombination rates: 10^9 per sec)

Therefore photons are v. likely to escape nebula before being absorbed
➔ can ignore absorption

They can remove a lot of heat from the nebula, thus solving our problem

Common forbidden lines:
Optical: [OIII] 4959,5007 Å, [NII] 6548,6584 Å, [SII] 6717,6731 Å
Infrared: [OIII] 52,88 μm, [NIII] 57 μm



Consequence of forbidden-line cooling:

the higher the metallicity (i.e. heavy-element content) of a nebula, the faster it cools to thermal equilibrium

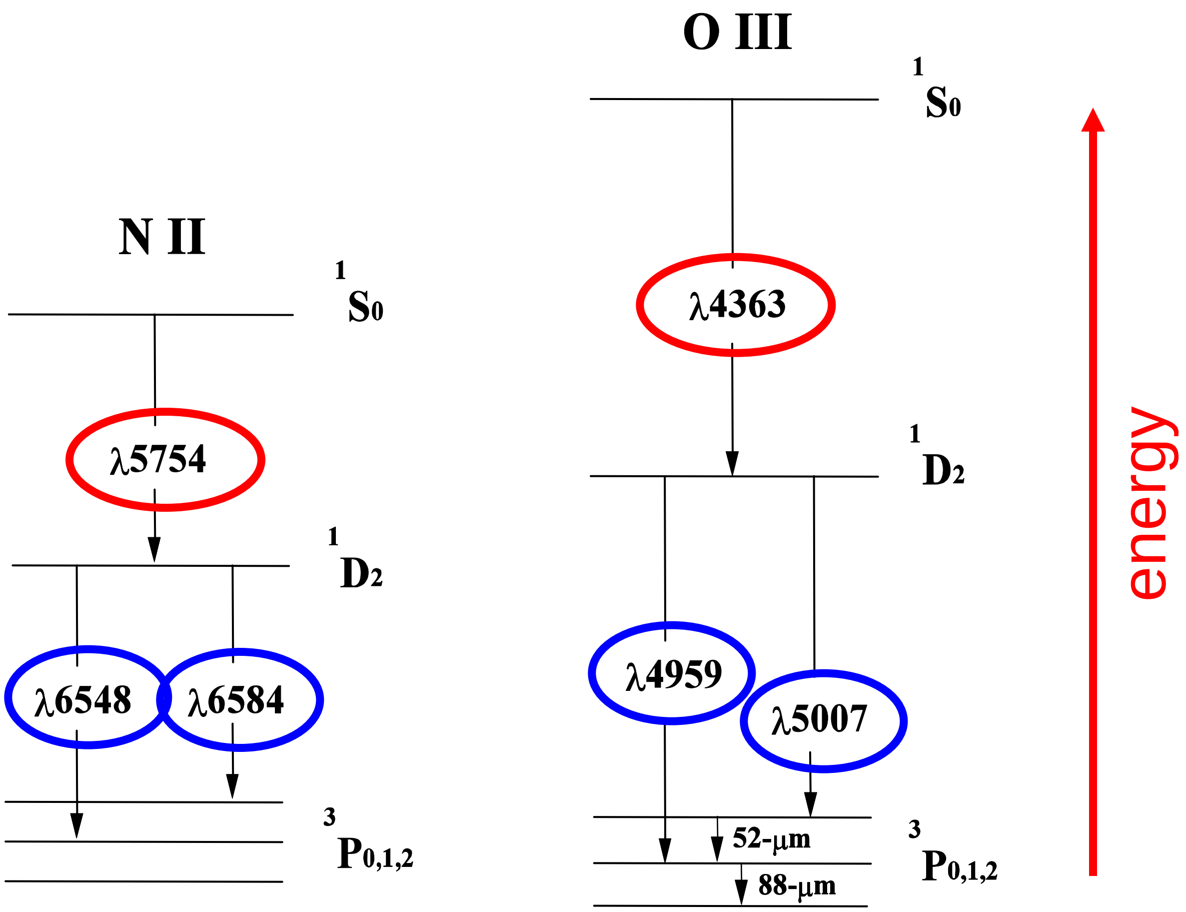
and the stronger the forbidden lines are

The Jodcast

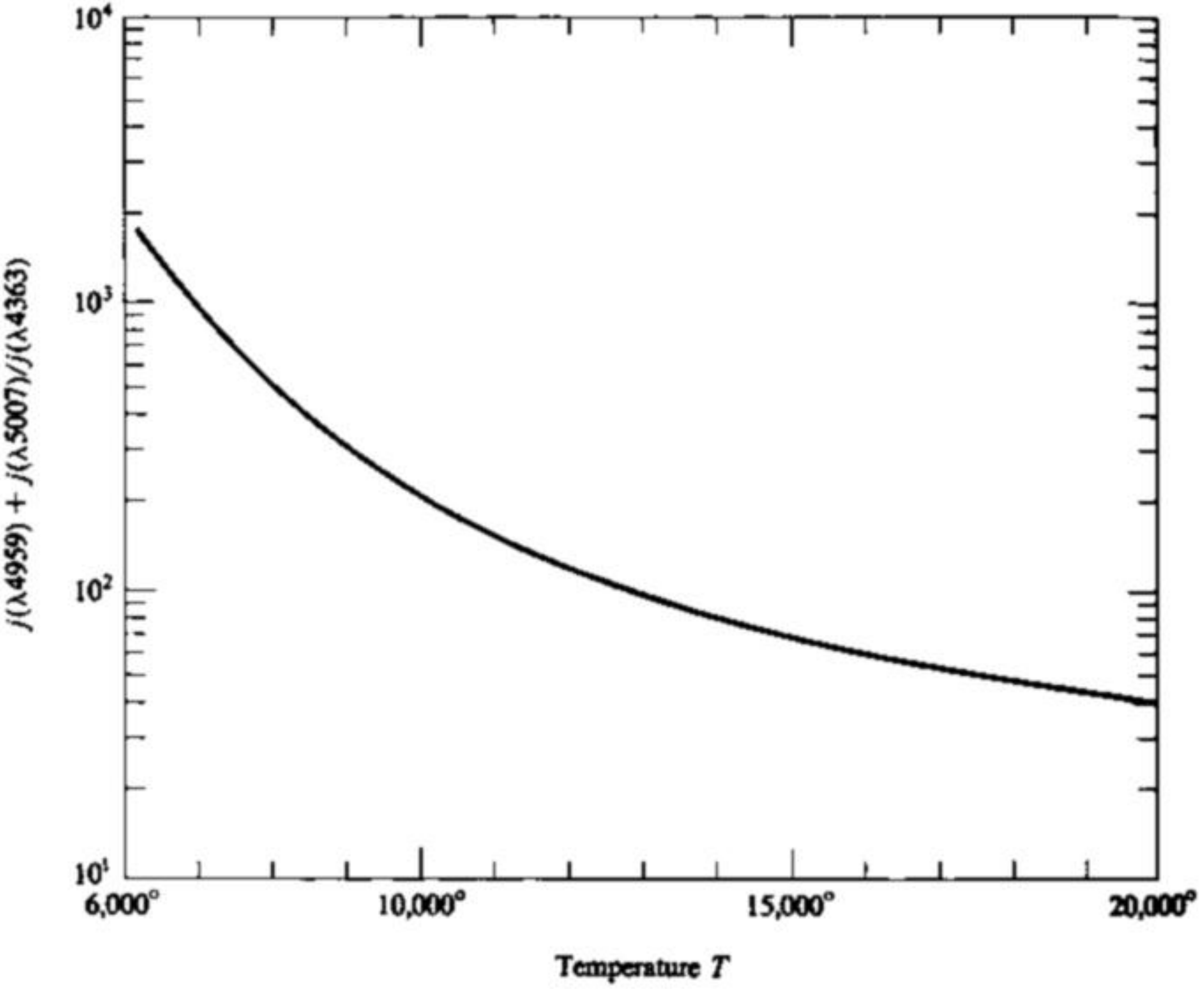
www.jodcast.net

Topical podcast with two monthly episodes,
featuring interviews, news items, night sky,
“Ask an astronomer”, humour
(and occasionally videos)

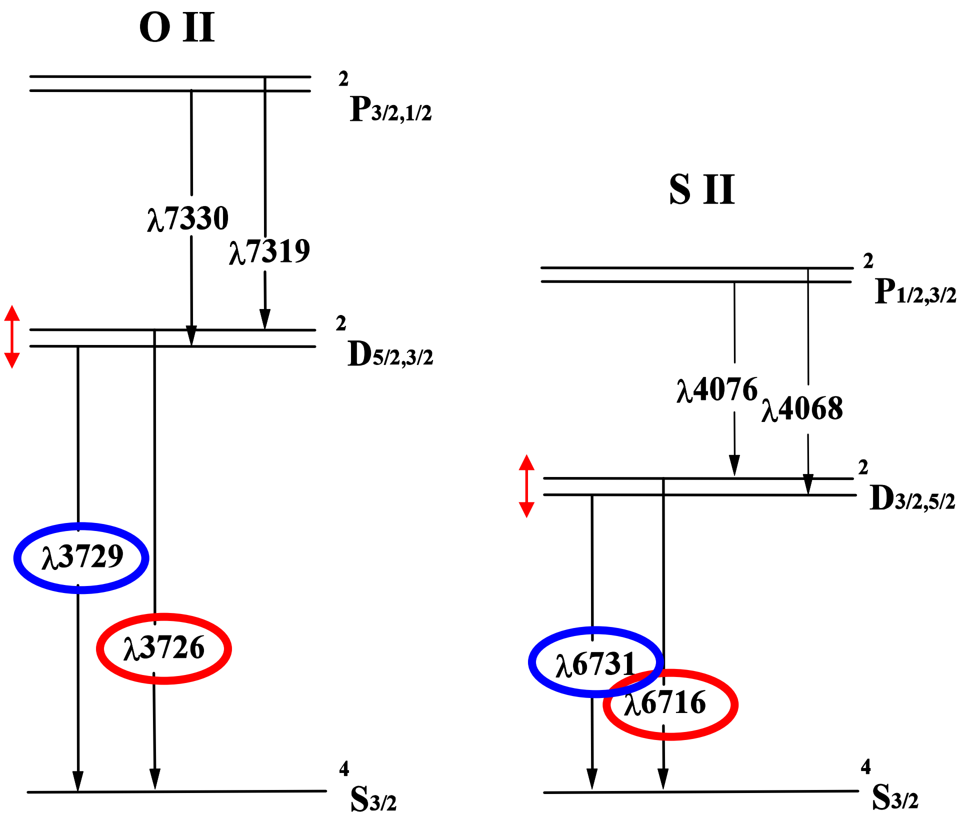
Temperatures



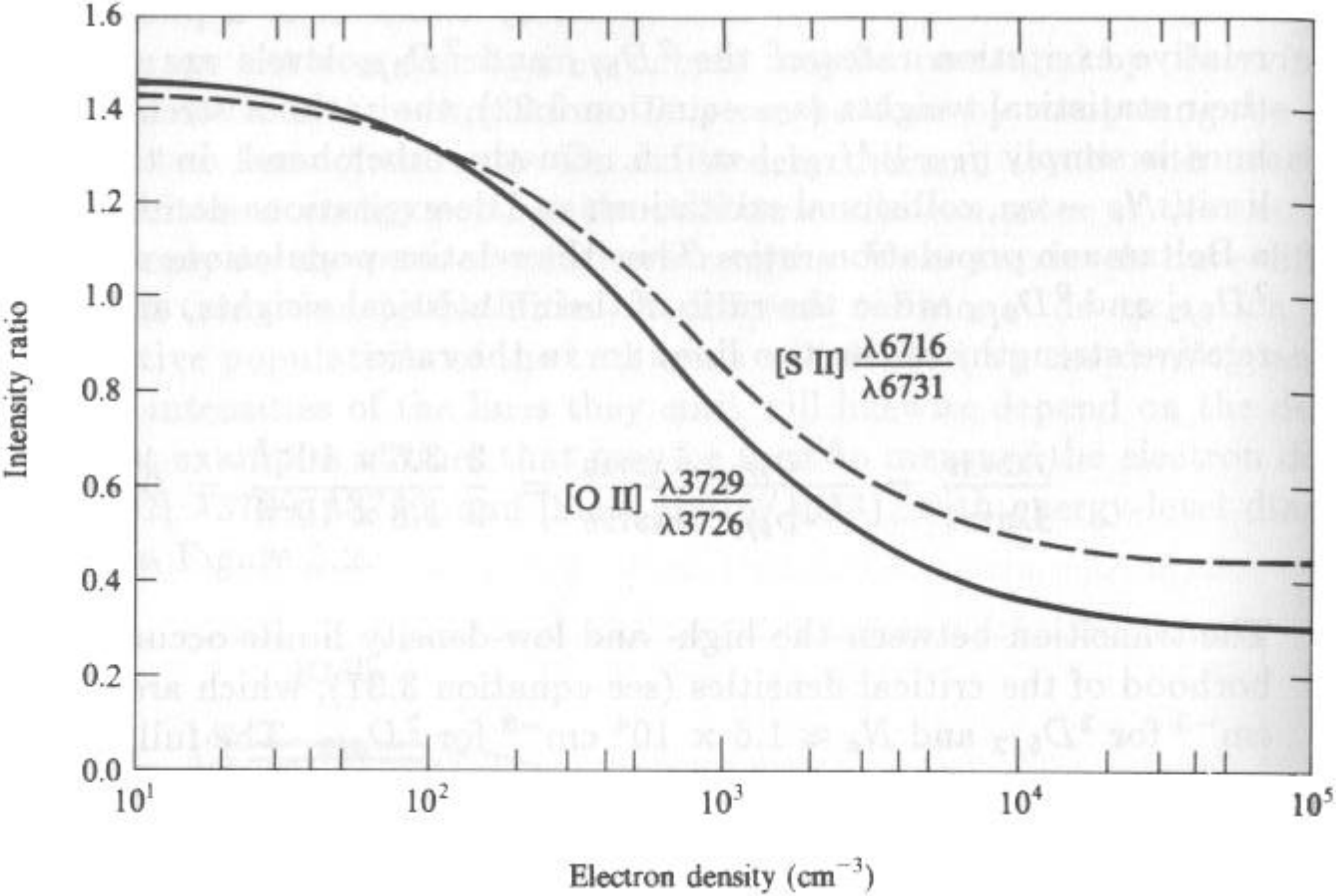
Observation ➔ T_e of ~7000–10000 K for HII regions
~9000–15000 K for PNe


10^4
10^3
10^2
10^1
$j(\lambda 4959) + j(\lambda 5007)/j(\lambda 4363)$
6,000°
10,000°
15,000°
20,000°
Temperature T

Densities



Observations ➔ $n_e \sim 100\ \mathrm{cm}^{-3}$ for HII regions
$\sim$ a few $1000\ \mathrm{cm}^{-3}$ for PNe


Intensity ratio
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^1
10^2
10^3
10^4
10^5
Electron density (cm^{-3})
[S II] $\frac{\lambda 6716}{\lambda 6731}$
[O II] $\frac{\lambda 3729}{\lambda 3726}$

Abundances

Now we know T_e and n_e

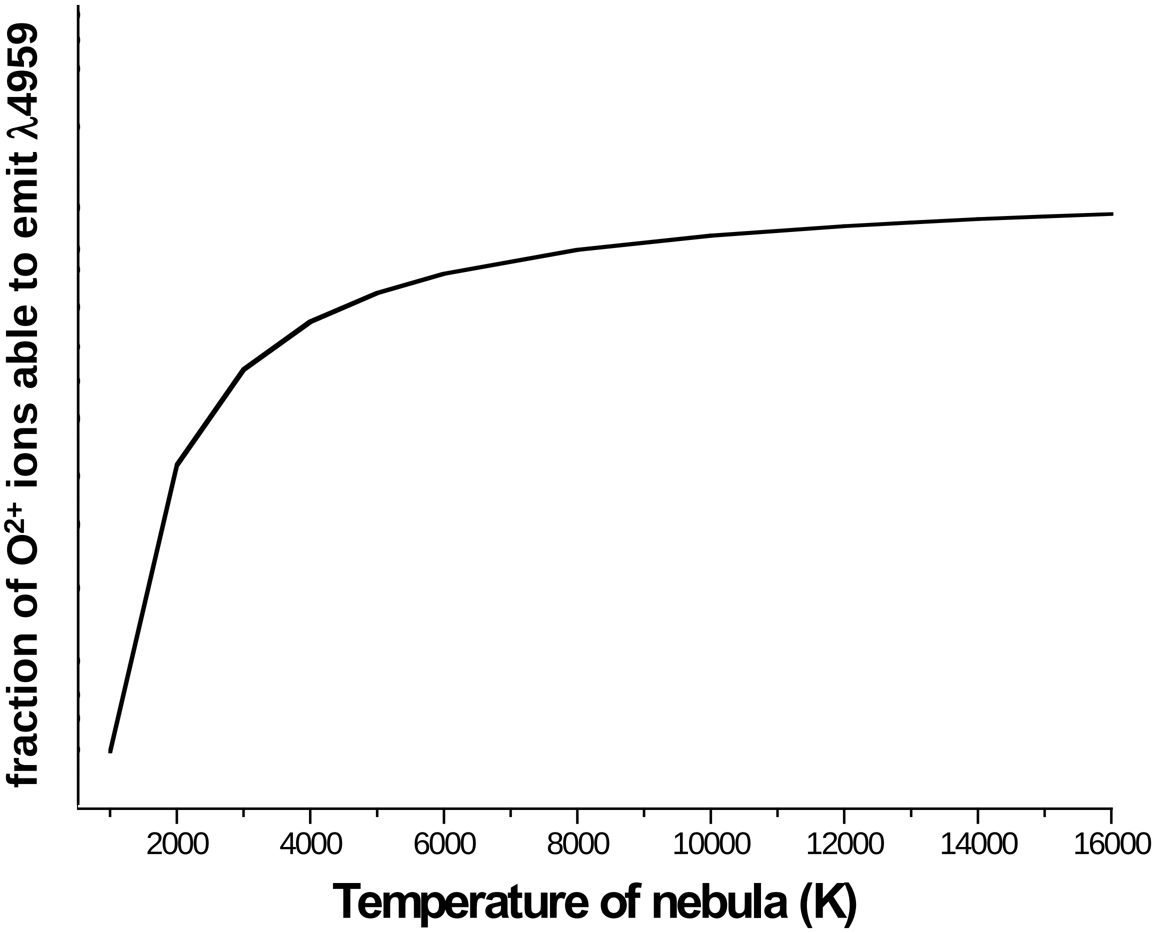
we can calculate the abundance of all the different ions emitting the forbidden lines

For example in the case of oxygen ions (but also for ions of C, N, Ne, S, Ar, Cl etc):

$$\frac{N(O^{2+})}{N(H^{+})} \sim \frac{n_e}{f(T_e)} \frac{I(\lambda 4959)}{I(H\beta)}$$

n_e = electron density
$f(T_e)$ = fraction of O^{2+} ions able to emit at 4959 Å (strong dependence on nebular temp)
$I(\lambda 4959)/I(H\beta)$ = flux of the [OIII] 4959 Å line relative to $H\beta$

➔ Gives the number of O^{++} ions *relative to* the number of H^+ (the most abundant ion in a nebula).



Measure forbidden lines from all ionic stages of an element (e.g. O, O^+, O^{2+})

add up all the abundances to find the total abundance relative to hydrogen.

Problem:

We need to know abundance of all ions of particular element to really know its abundance - not always possible

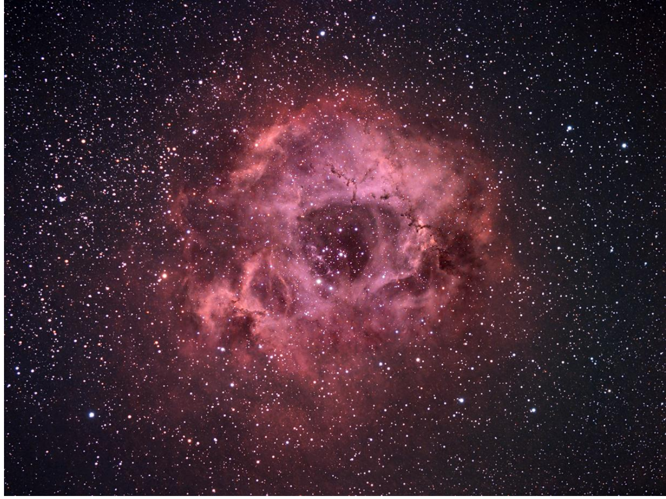
some lines are weak
➔ need to use big telescope

For more distant objects (e.g. galaxies), this becomes even more of a problem!

some lines are unobservable
➔ ionization corrections (theoretical)

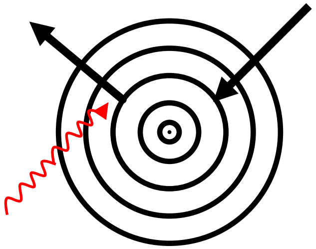
End of last lecture

Last lecture(s):

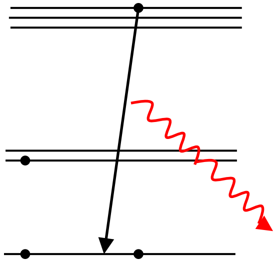


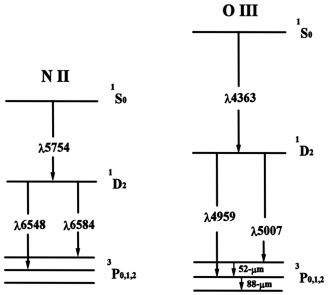
Recap on essentials from last lecture

Looked in detail at: HII regions



- Photoionization and recombination
- Heating and cooling processes
  - H heating problem → Metals → Forbidden lines
  - Temp and density diagnostics, abundances



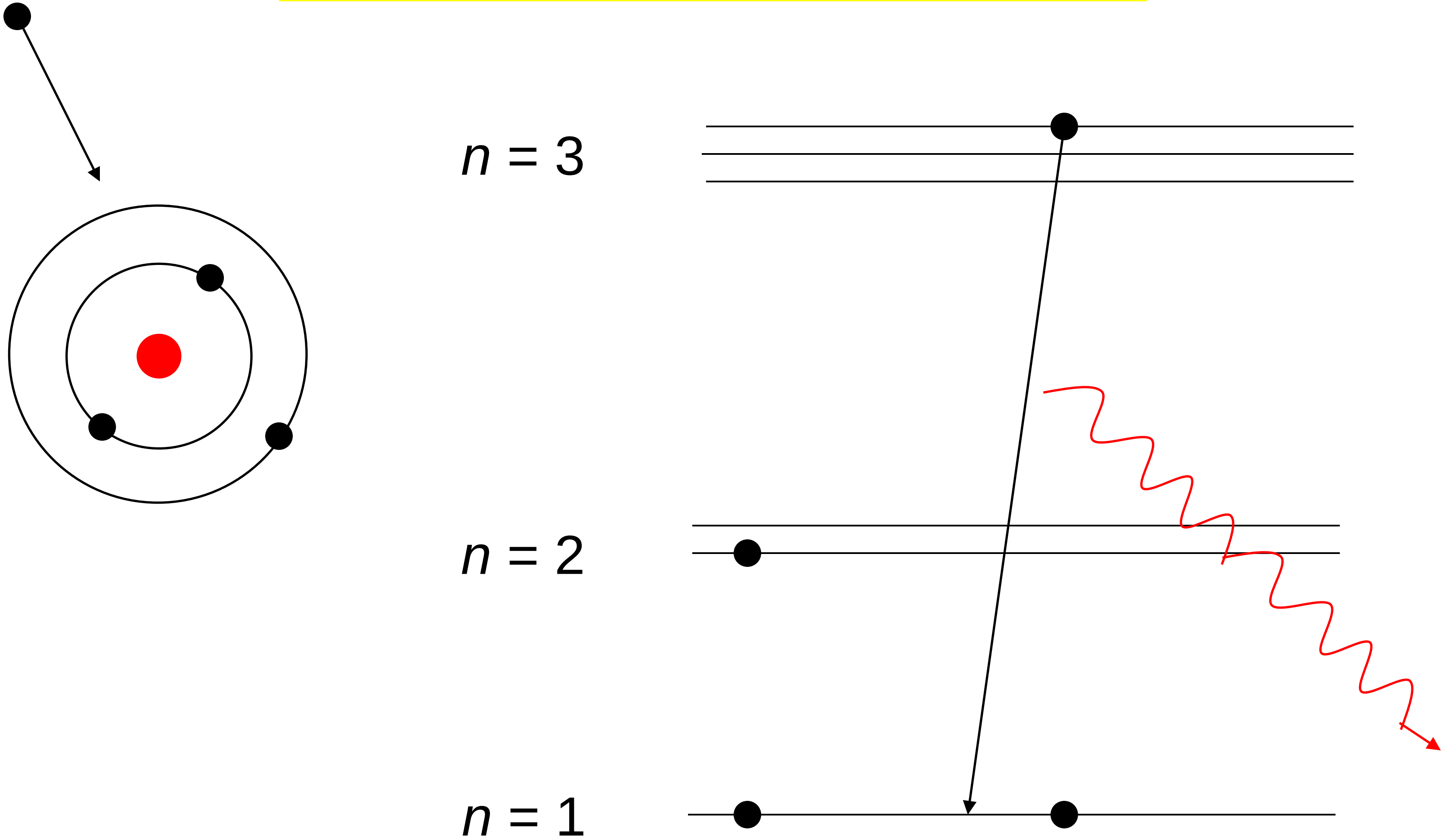


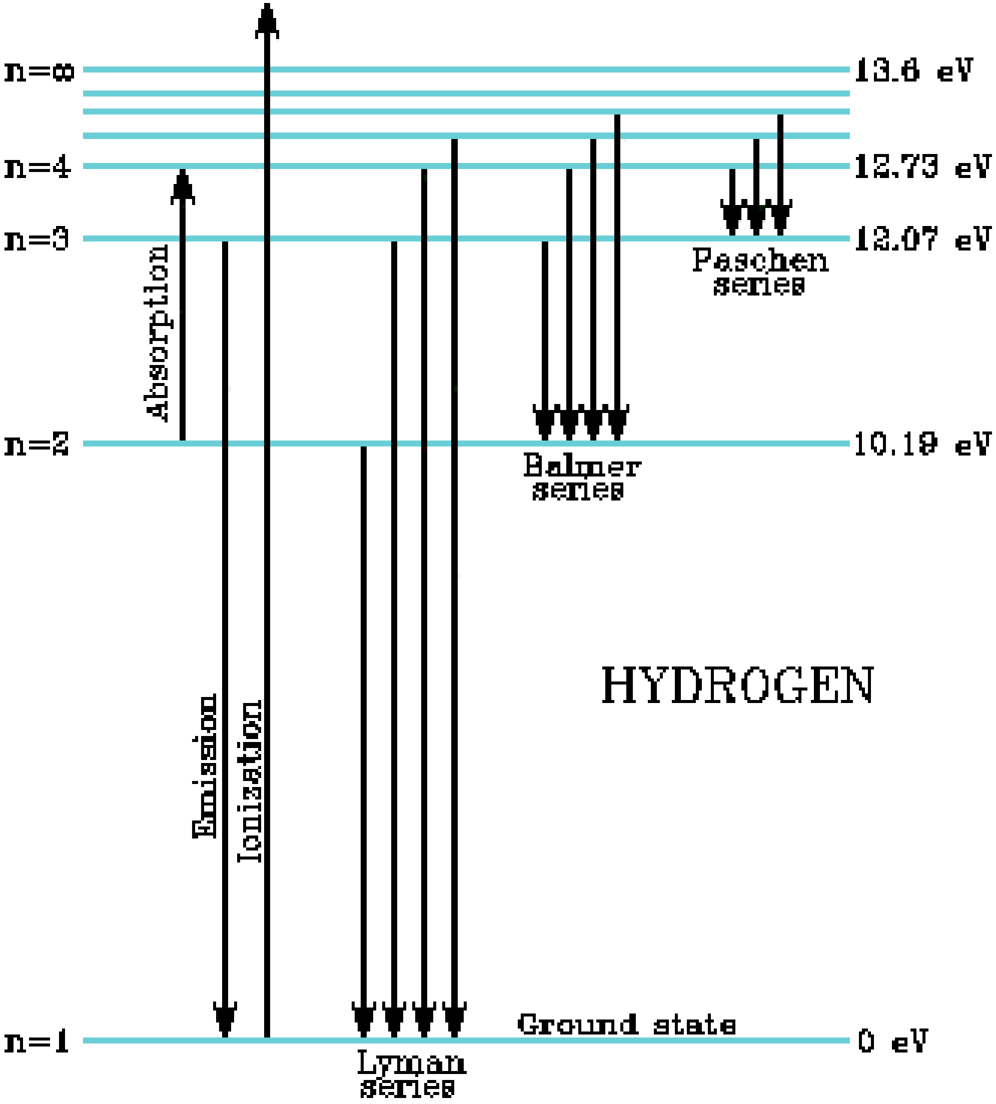
Today:

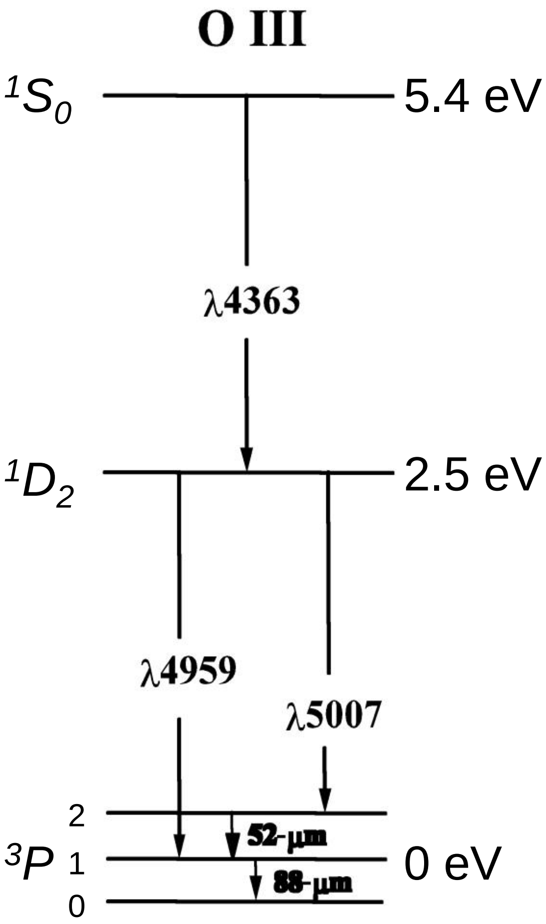
HII regions: Practical methods & examples

Cooler phases of ISM - non-ionised material

Forbidden line = Collisionally excited lines (CELs)




n=∞
13.6 eV
n=4
12.73 eV
n=3
12.07 eV
Paschen series
Absorption
n=2
10.19 eV
Balmer series
HYDROGEN
Emission
Ionization
n=1
Ground state
0 eV
Lyman series


O III
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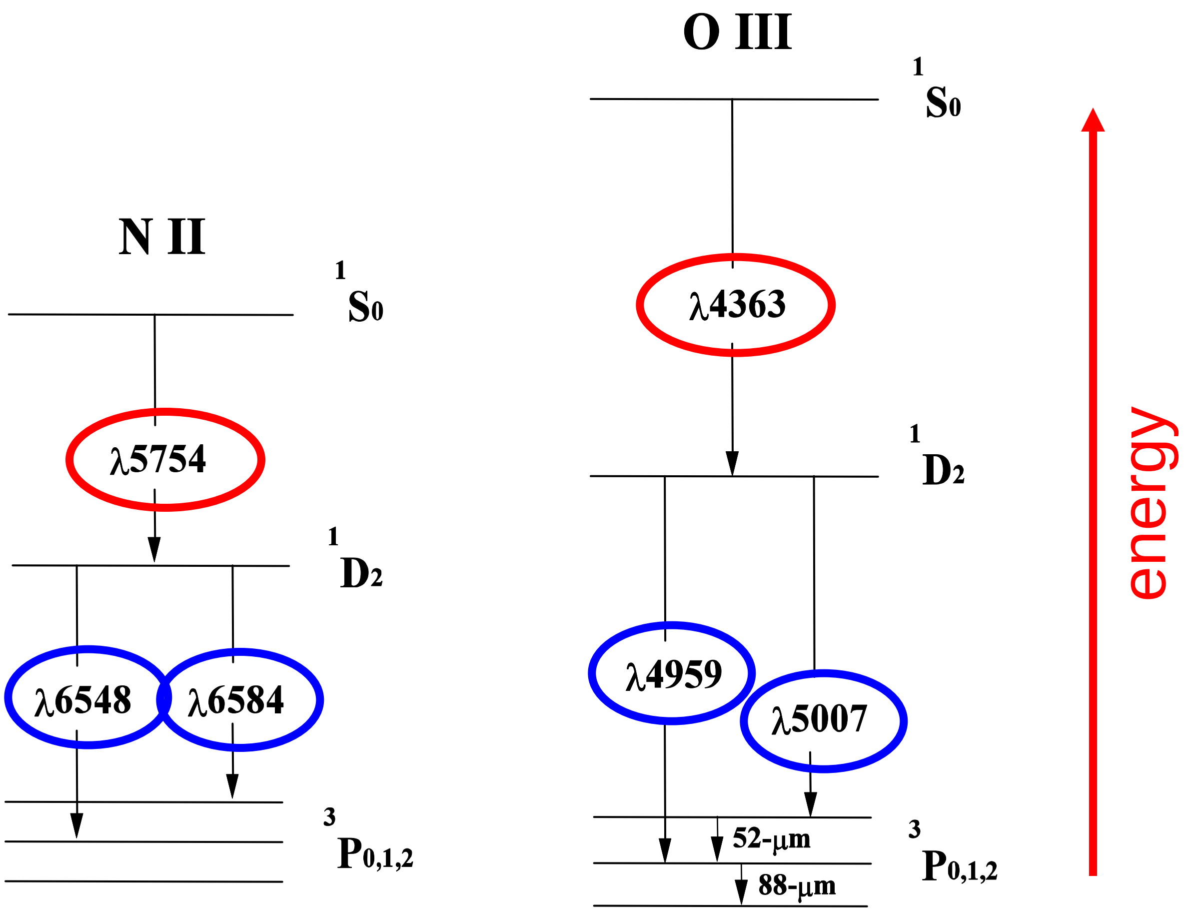
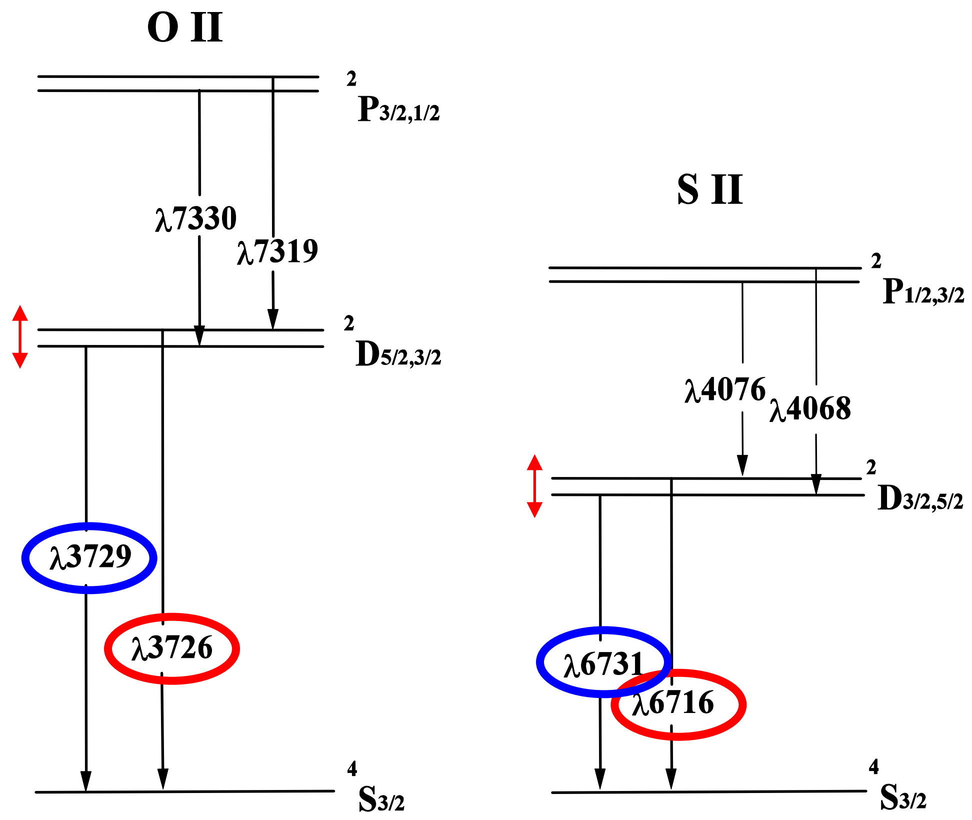
1
0
52-μm
88-μm
0 eV

Temperatures



Observation ➔ T_e of ~7000–10000 K for HII regions
~9000–15000 K for PNe

Densities



Observations ➔ n_e ~ 100 cm^{-3} for HII regions
~ a few 1000 cm^{-3} for PNe

Now we know T_e and n_e

we can calculate the abundance of all the different ions emitting the forbidden lines

add up all the abundances to find the total abundance relative to Hydrogen.

Problem:

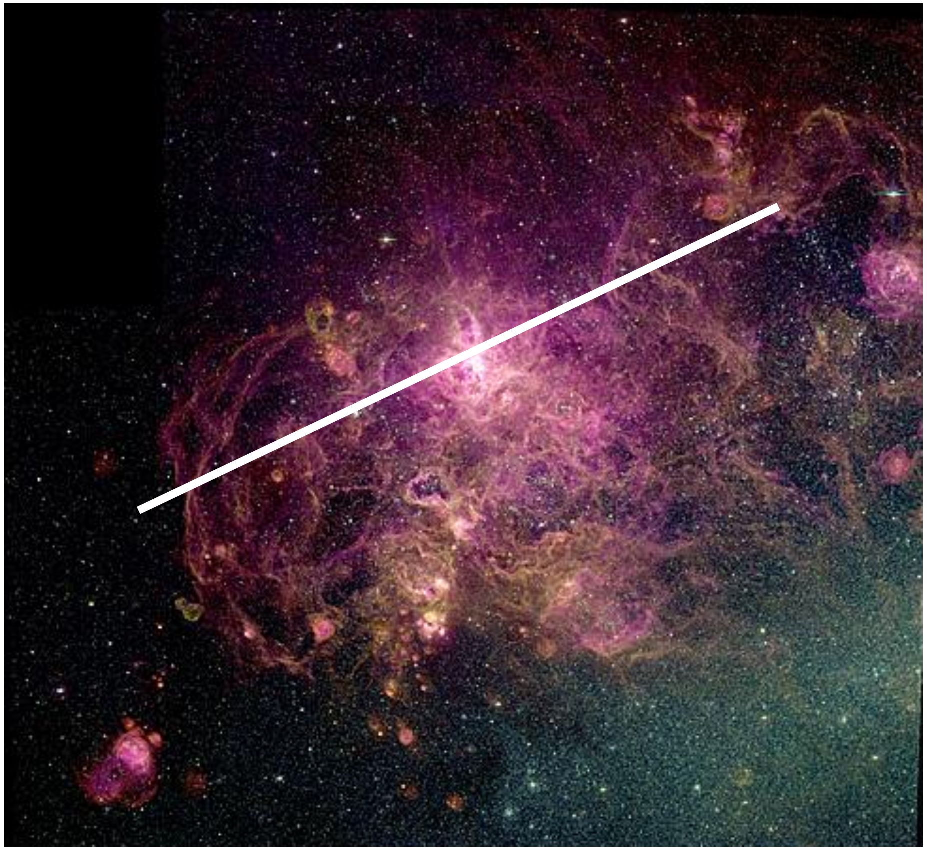
We need to know abundance of all ions of particular element to really know its abundance - not always possible

some lines are weak
➔ need to use big telescope

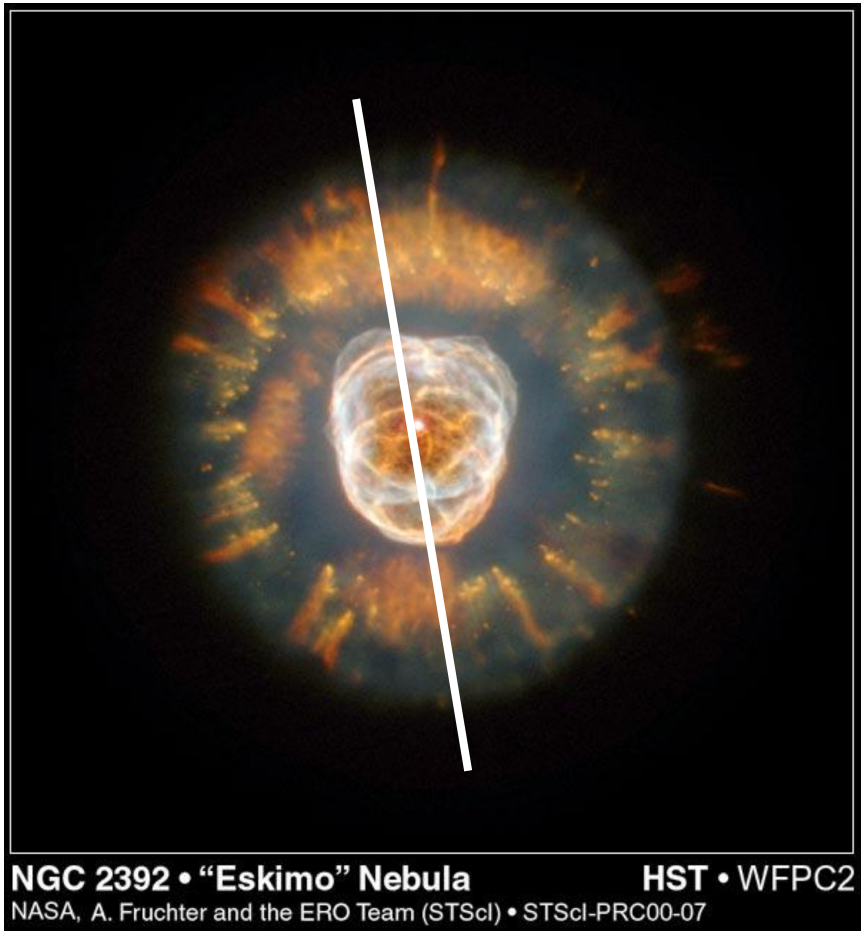
For more distant objects (e.g. galaxies), this becomes even more of a problem!

some lines are unobservable
➔ ionization corrections (theoretical)

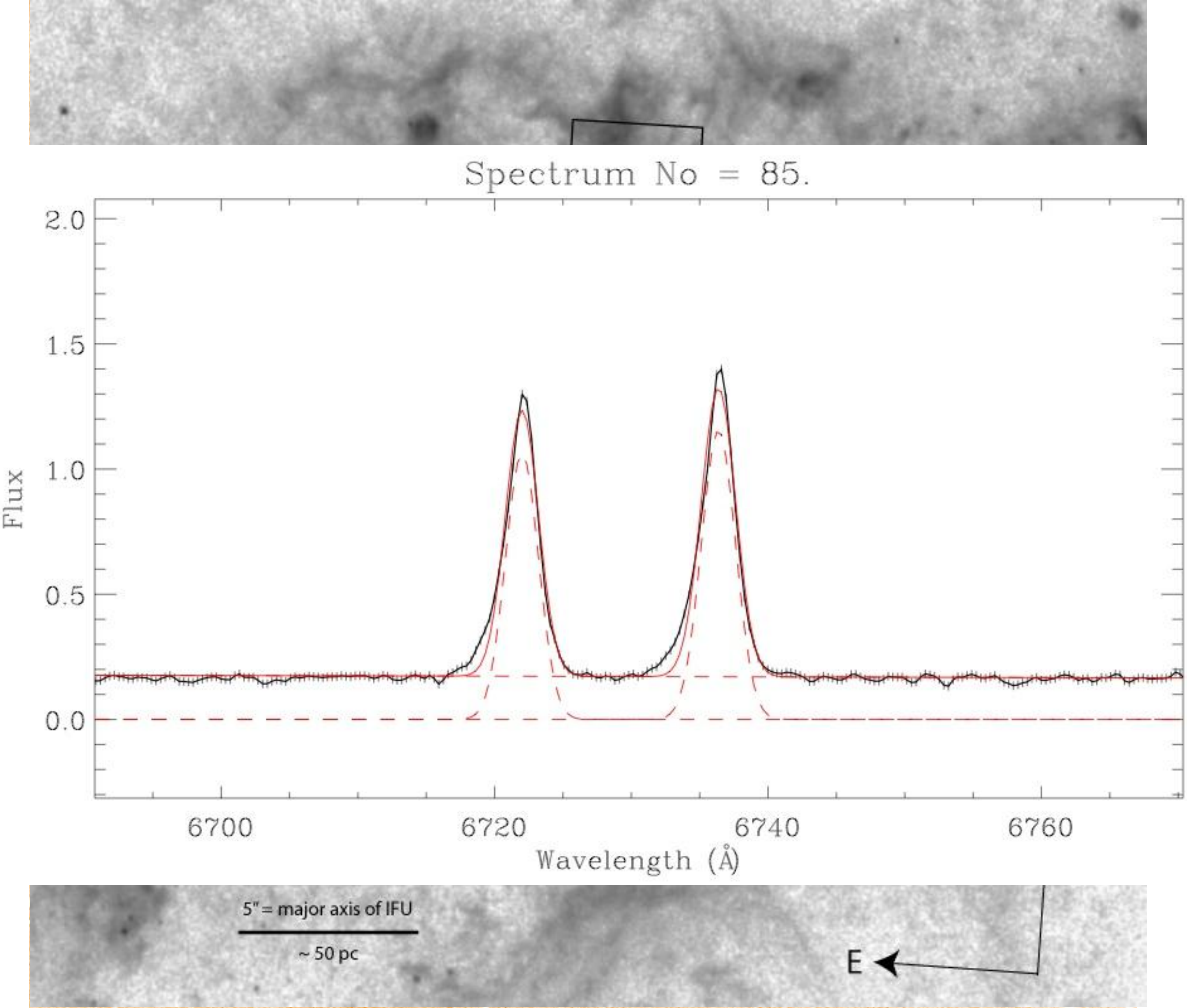
Practical methods and examples

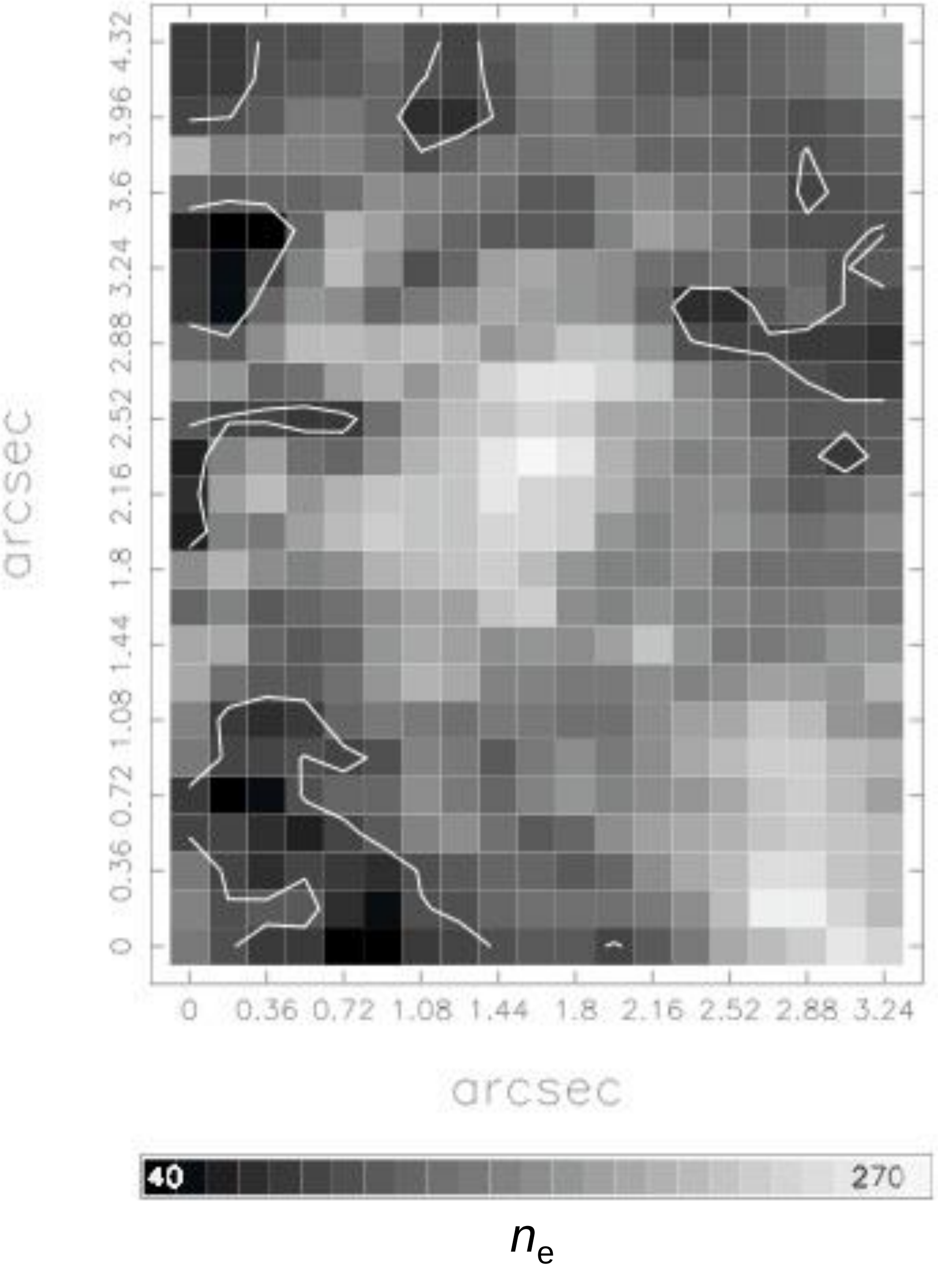


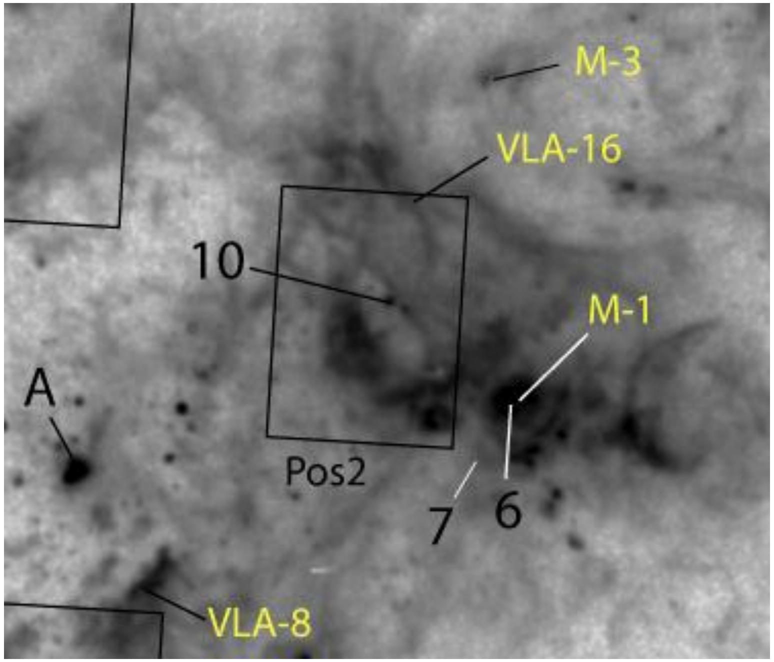
30 Dor (HST ACS)

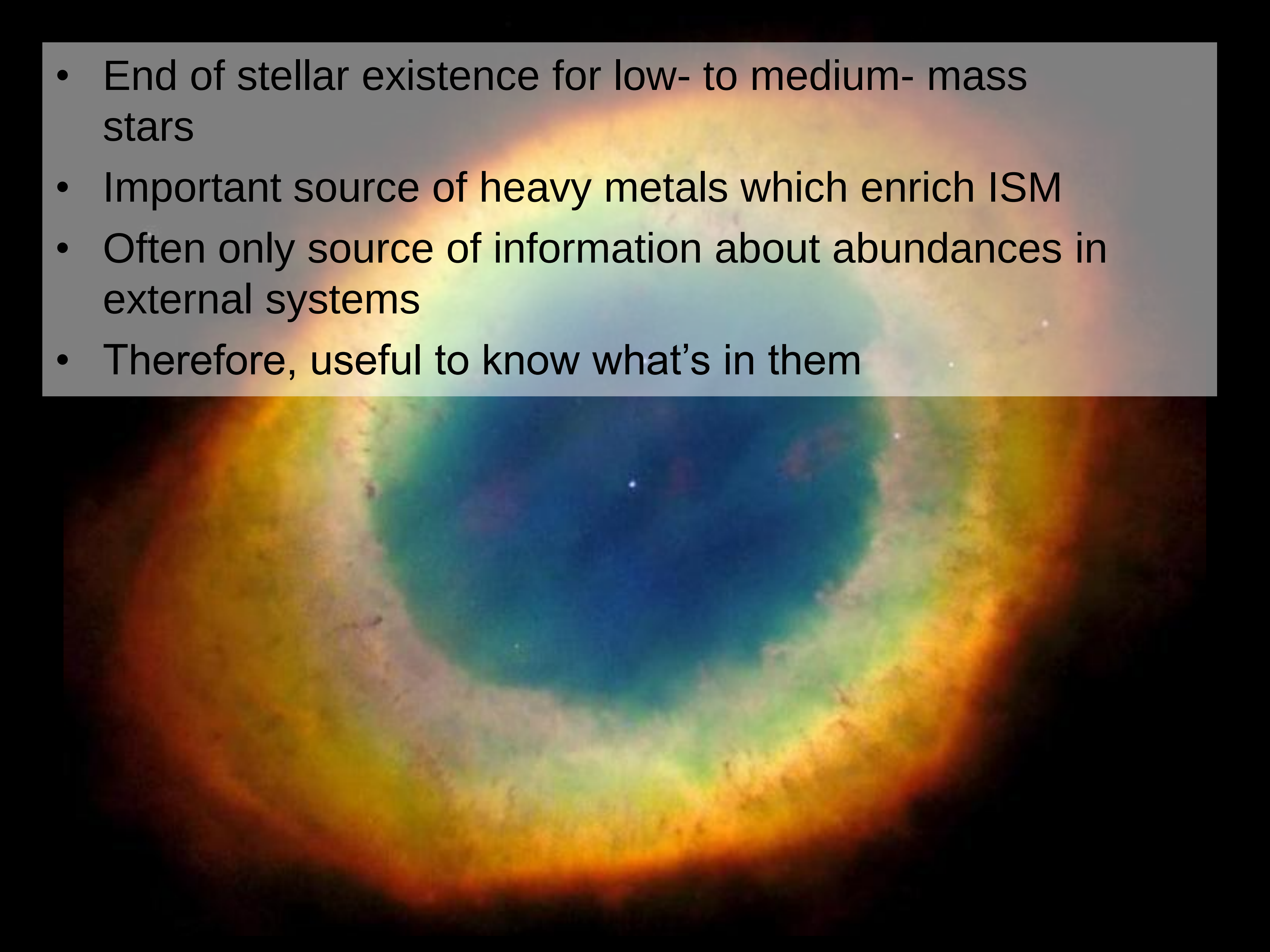


- Observe with spectrograph
- Measure line strengths ("fluxes") of forbidden lines and representative H recomb. line (e.g. Hα)
- Use ratios to calculate temp and density
- Calculate abundances relative to H


Spectrum No = 85.
Flux
2.0
1.5
1.0
0.5
0.0
6700
6720
6740
6760
Wavelength (Å)
5" = major axis of IFU
~ 50 pc
E


arcsec
0
0.36
0.72
1.08
1.44
1.8
2.16
2.52
2.88
3.24
3.6
3.96
4.32
arcsec
0
0.36
0.72
1.08
1.44
1.8
2.16
2.52
2.88
3.24
40
270
n_e

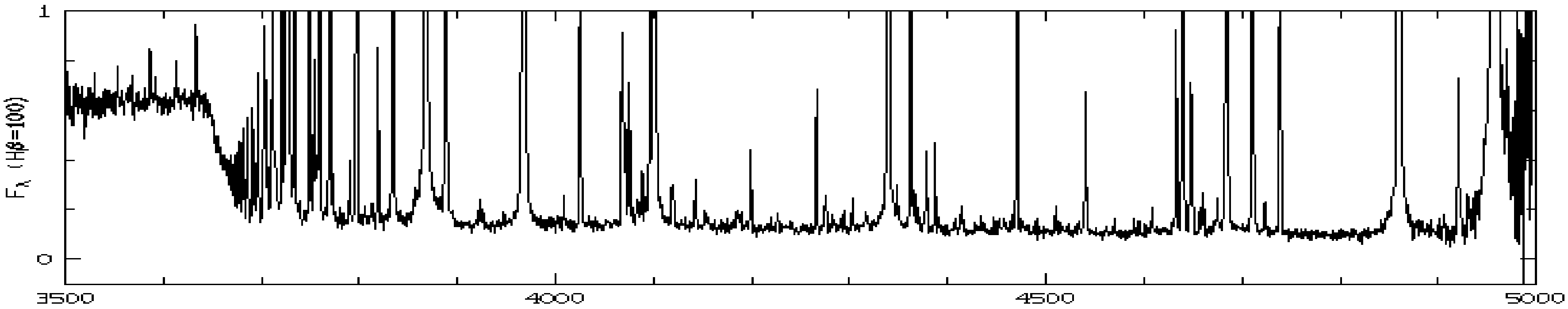

M-3
VLA-16
10
M-1
A
Pos2
7
6
VLA-8



- End of stellar existence for low- to medium- mass stars
- Important source of heavy metals which enrich ISM
- Often only source of information about abundances in external systems
- Therefore, useful to know what’s in them

So how do we find out what’s in them?

- Spectroscopic analysis
- Historically relied on brightest emission lines **– collisionally excited lines**
- These are easily observable, but very very sensitive to physical conditions
- Small error in assumed temperature = big error in derived abundance



Optical Recombination Lines

- ORLs of hydrogen and helium are strong, but those of heavy elements are much weaker
- Much less sensitive to physical conditions, so should be more reliable to derive abundances from
- Should be…

…but is it?

- Unfortunate problem – in PNe they **always** give higher abundances relative to hydrogen than CELs
- Factors range from 3 – 30 and beyond

Possible solutions?

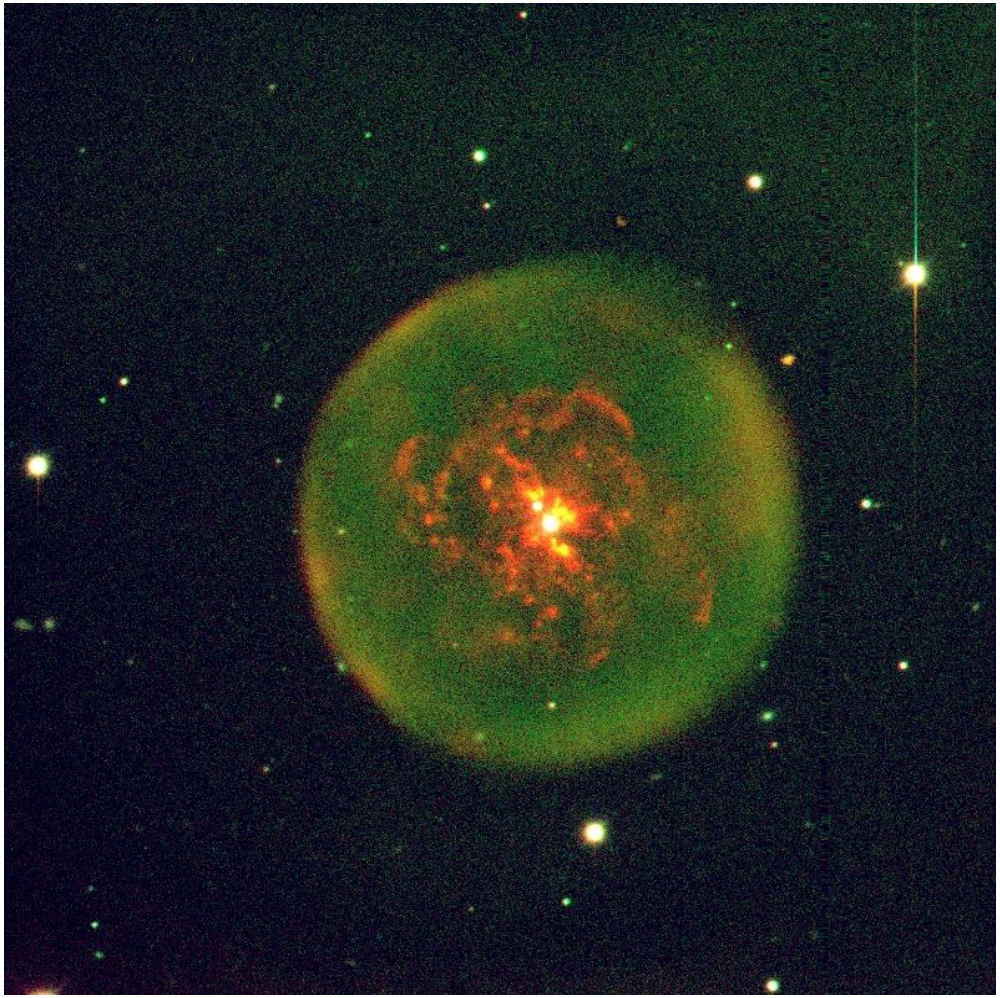
- Possibility 1: Temperature fluctuations in homogeneous gas
  - Hotter regions preferentially emit CELs, cooler regions preferentially emit ORLs. Assuming uniform temperature results in underestimated CEL abundances.

Easily ruled out with high-res spectroscopy

- Possibility 2: density fluctuations in chemically homogeneous gas
  - Very dense regions (n_e~10^6 cm^{-3}) would quench emission of [O III] 4959,5007 lines
  - [O III]4363 has higher critical density and is not quenched. Therefore [O III] ratio underestimated, T_e overestimated, CEL abundances underestimated.

Measuring density of hydrogen gas (through method we haven't seen) rules this out

- Possibility 3: Chemical inhomogeneities
  1. Strongly metal-rich zone near central stars could give rise to observed spectra – ruled out by spatially-resolved analysis
  2. Small metal-rich knots (too small to be directly resolved), cooled strongly by high metal content

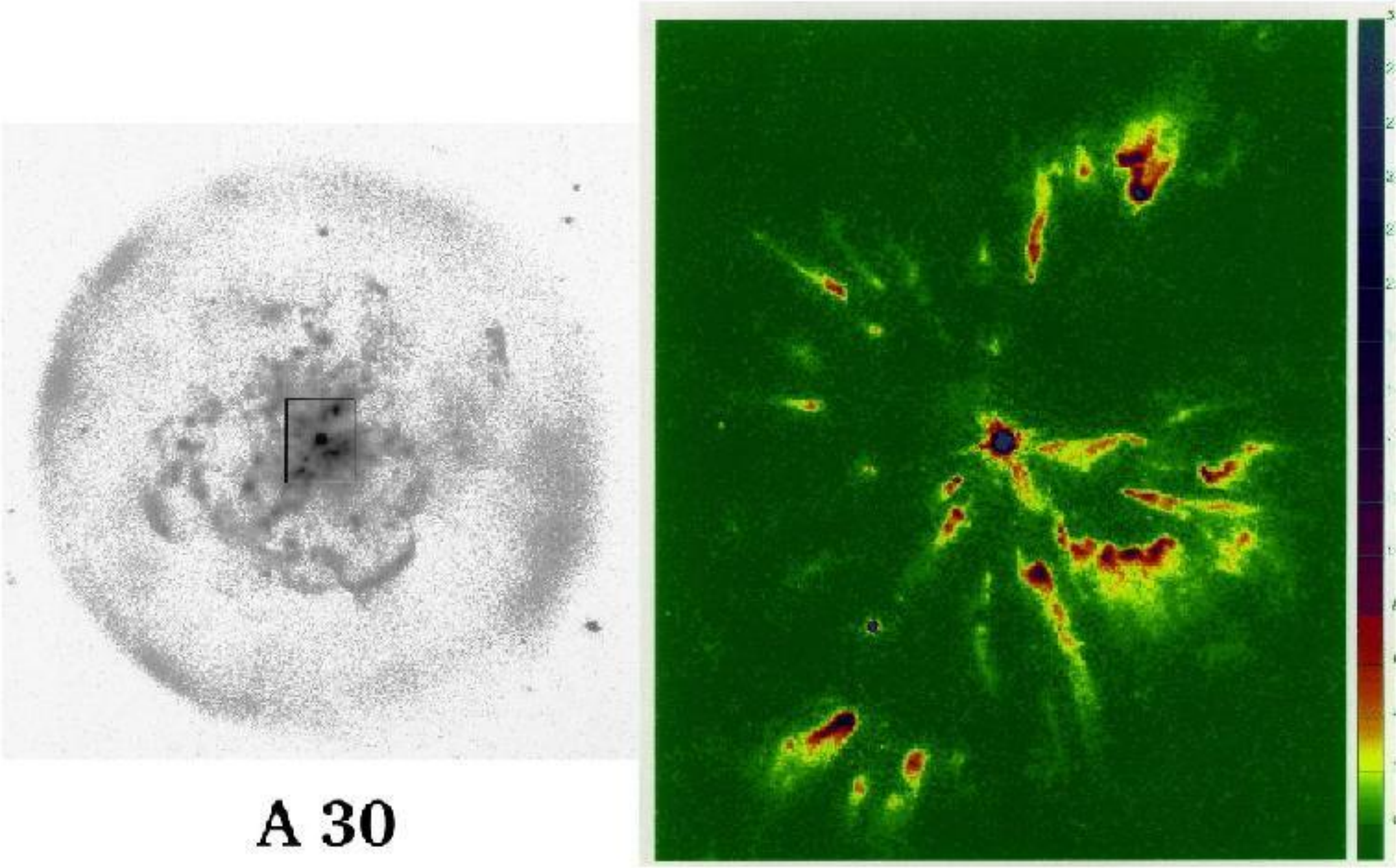


PN: Abell 30

Knots: Abell 30

- Results of empirical analysis:
  T([O III]) ~16000 K
  T(He I) ~5000–10000 K
  T(O II) <2000 K

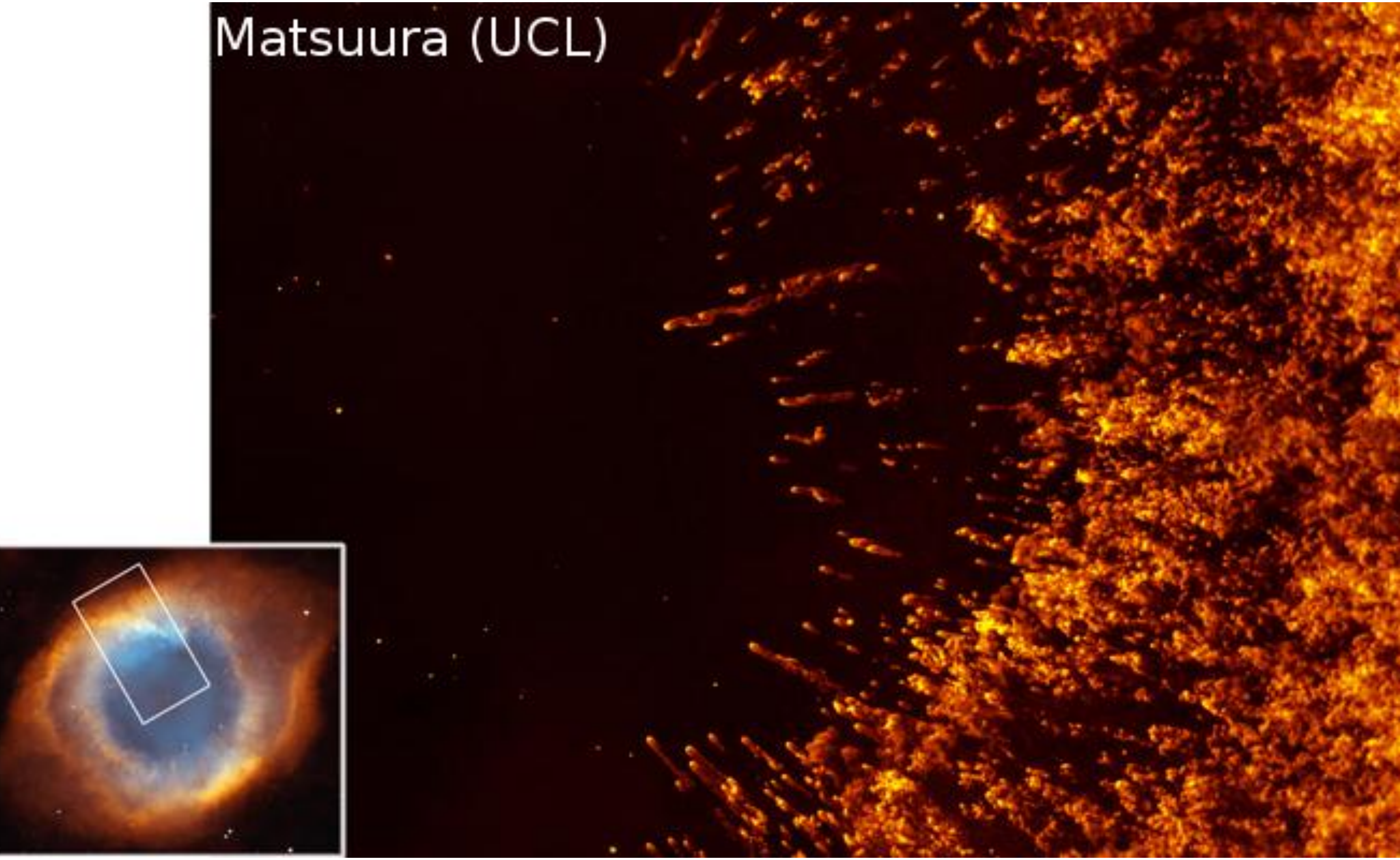
- Abundances: ORL abundances exceed CEL abundances by factors of 300-700!!



HST imaging

Conclusions

- Cold H-deficient knots are confirmed as existing in planetary nebulae
- Simple temperature fluctuations are ruled out from spatially resolved spectroscopy
- Evidence strongly suggests existence of cold metal-rich knots in most planetary nebulae.


Matsuura (UCL)

Open questions

- No direct observations in vast majority of cases. Where did the knots come from? Why are they there?
- What is their distribution?
- What is overall chemical content of PNe?