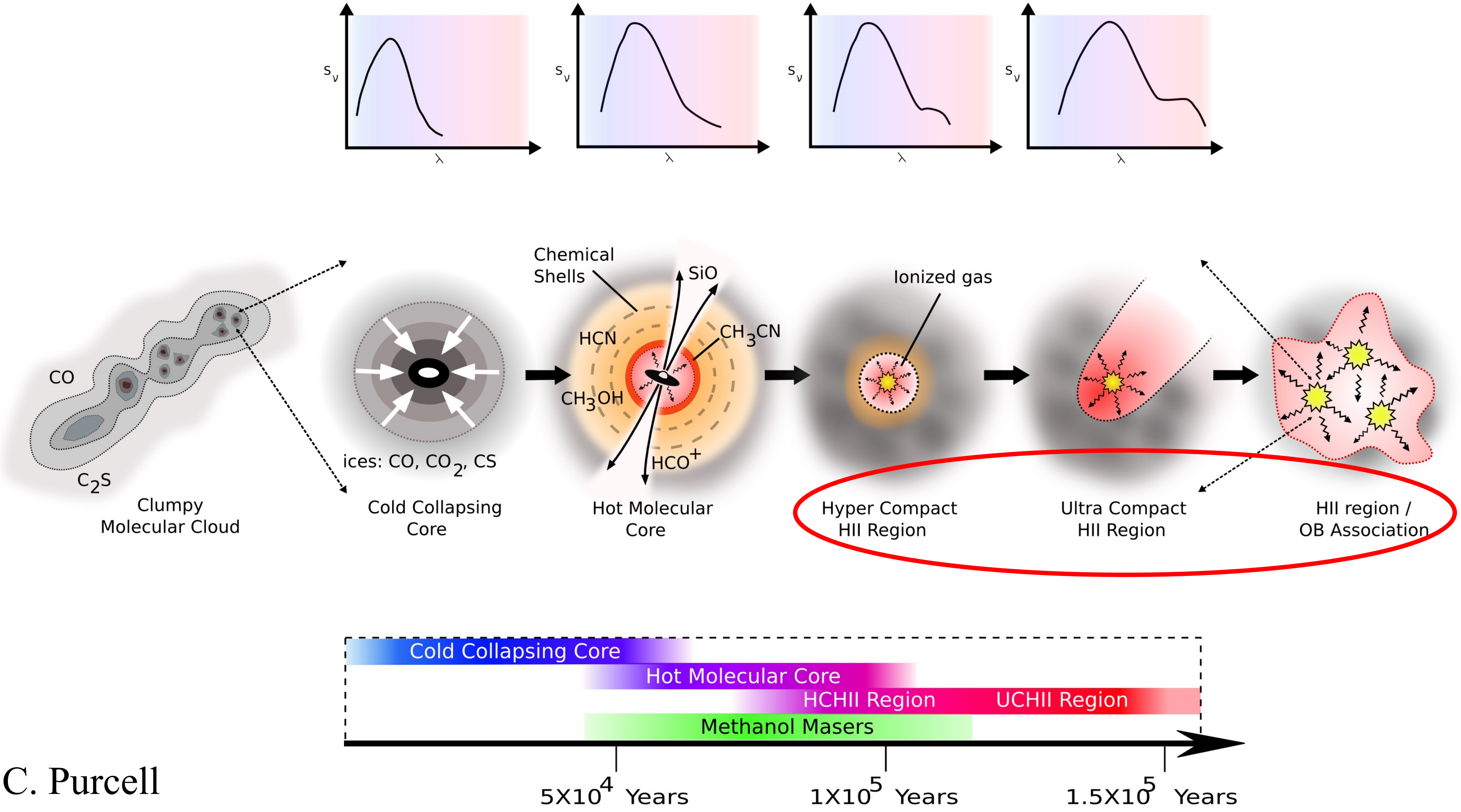
H II Regions

- Massive Star Formation
- H II Region Radio Properties
- H II Regions in Galaxies
- Other Galactic Radio Sources

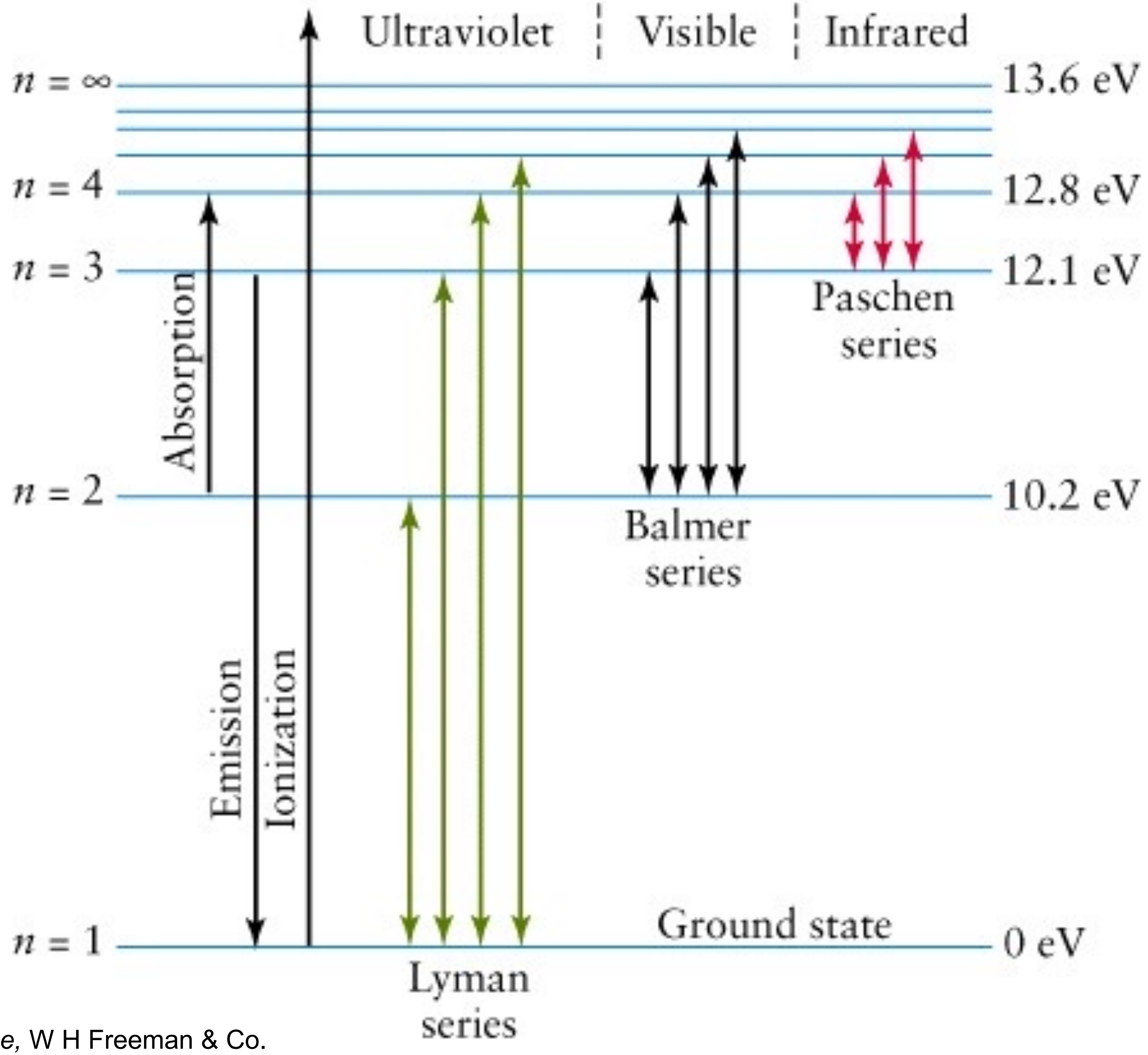
Massive Star Formation



C. Purcell

H II Region

- Region of ionized gas surrounding a massive young star
- Surrounding gas is left over from the star formation process – molecular cloud
- Only massive stars are hot enough to ionize hydrogen



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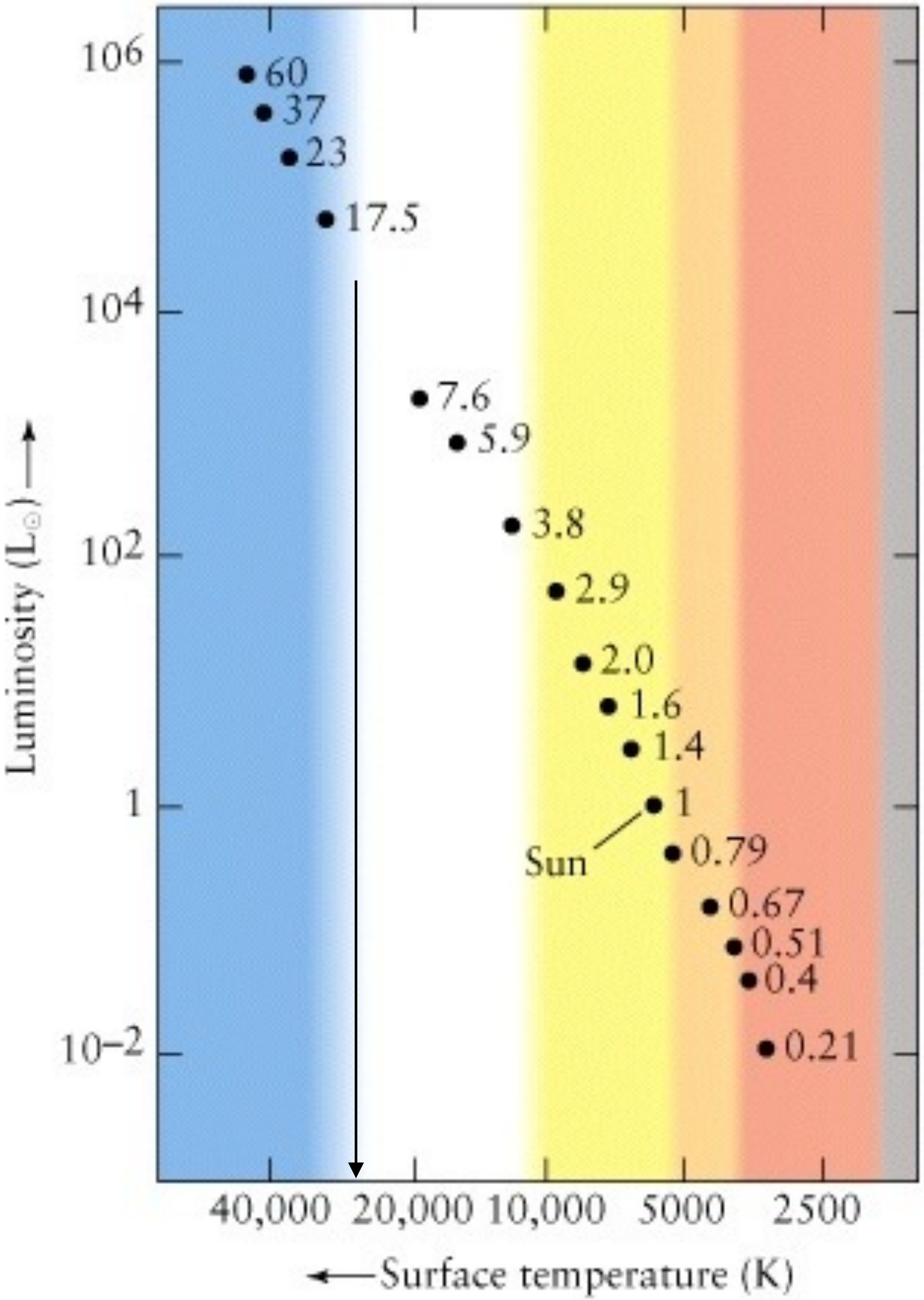
Stellar masses along the main sequence



$T_{eff} > 30\,000$ K

$M > 10\ M_\odot$

From Universe textbook

Physical Conditions

- Number density of the gas is typically 10^{10} m^{-3}
- (Note that astronomers still use cgs rather than SI units so this would be 10^4 cm^{-3})
- The excess energy of photons with E>13.6 eV goes in to heating the gas
- Typical T~ 10 000 K

Ionization Equilibrium

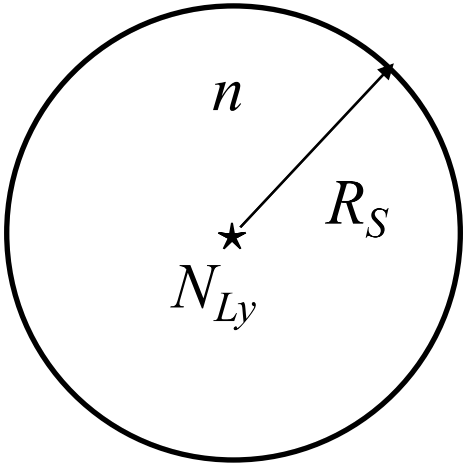
- There is a balance between photo-ionization and recombination

$$\mathrm{H} + h\nu \longleftrightarrow p + e$$

- This balance determines the initial size of the H II region

Strömgren Radius

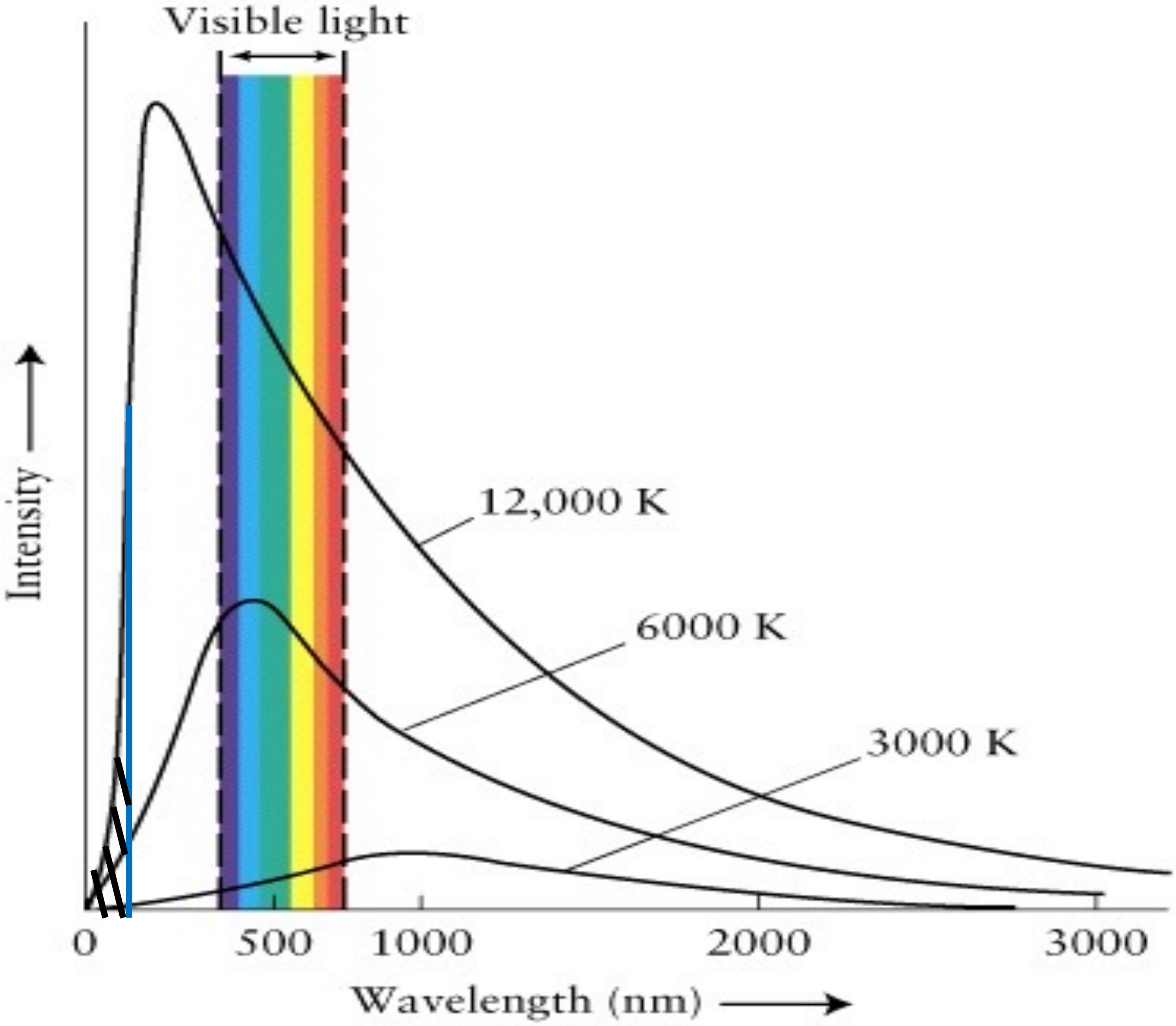
- If we consider a region with a constant number density, *n* (m^{-3}), around the central star it will ionize a sphere with radius, R_S, called the Strömgren radius



- The number of ionizing photons (Lyman continuum) emitted by the star per second is N_{Ly}

$$N_{Ly} = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

where L_ν is the luminosity as a function of frequency (WHz^{-1} or Js^{-1}Hz^{-1})

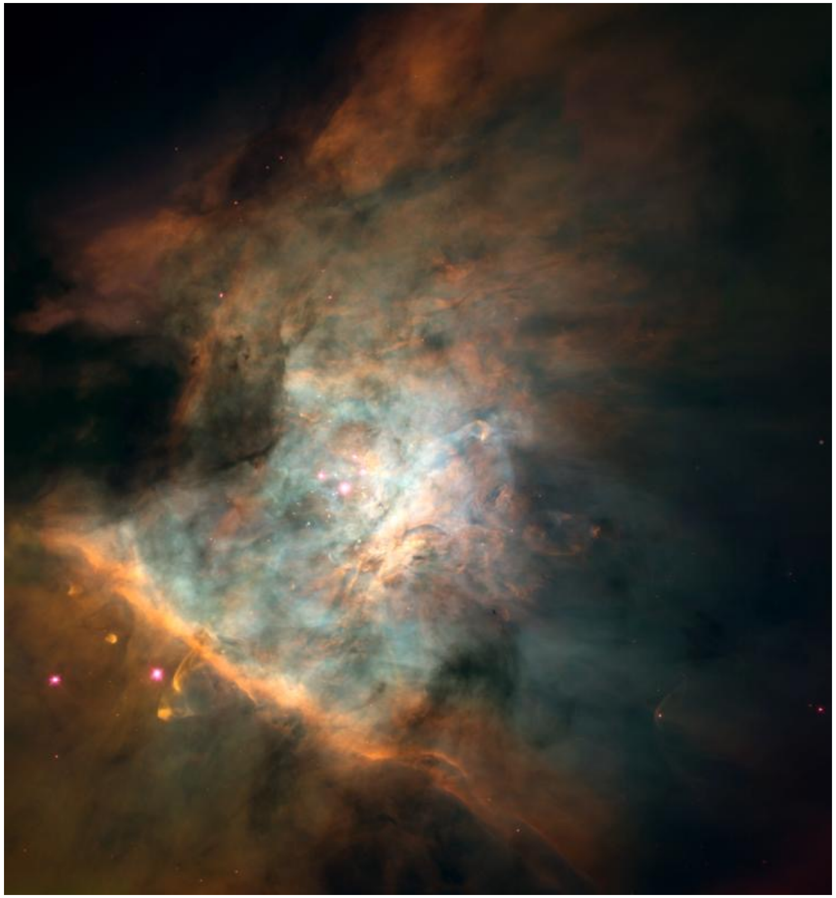

Visible light
Intensity
12,000 K
6000 K
3000 K
0
500
1000
2000
3000
Wavelength (nm)

- The number of recombinations of a proton and electron per unit volume is given by $n_p n_e \alpha_H$ (m^{-3}s^{-1})
- Ionization equilibrium gives

$$N_{Ly} = \int n_p n_e \, \alpha_H dV$$

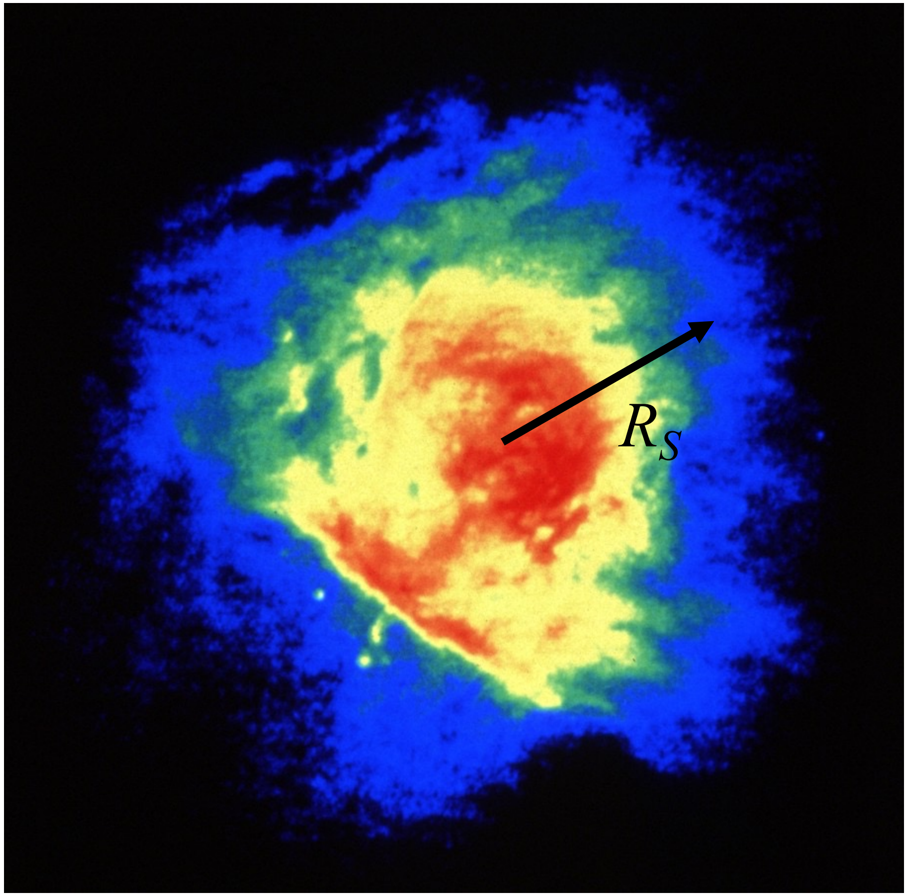
- For fully ionized material then $n_p \sim n_e$ so

$$N_{Ly} = \frac{4}{3}\pi \alpha_H n_e^2 R_s^3$$



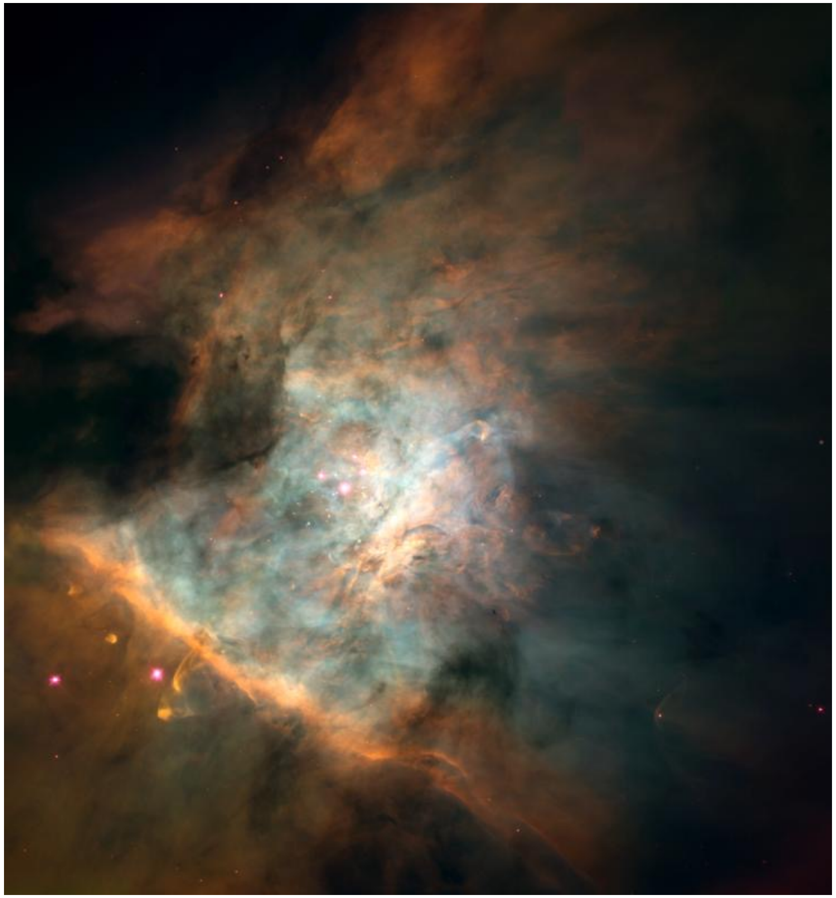
HST (Optical)

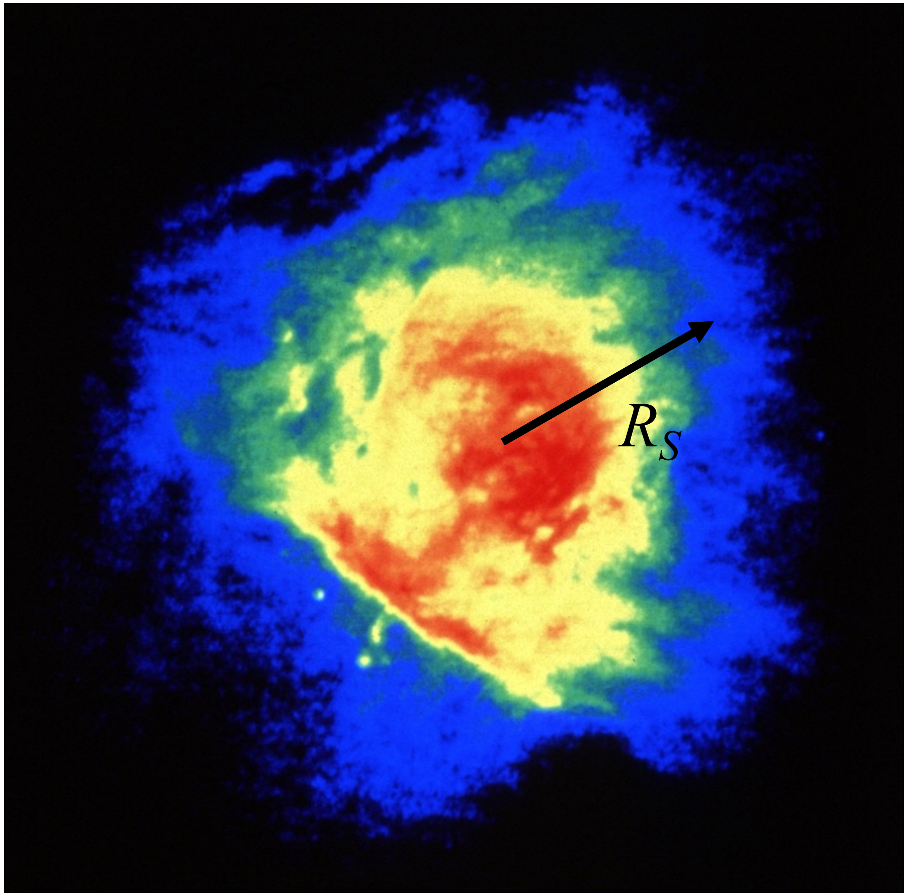
Credit: NASA and C.R. O'Dell
(Vanderbilt University):



VLA Radio

Image courtesy
of NRAO/AUI

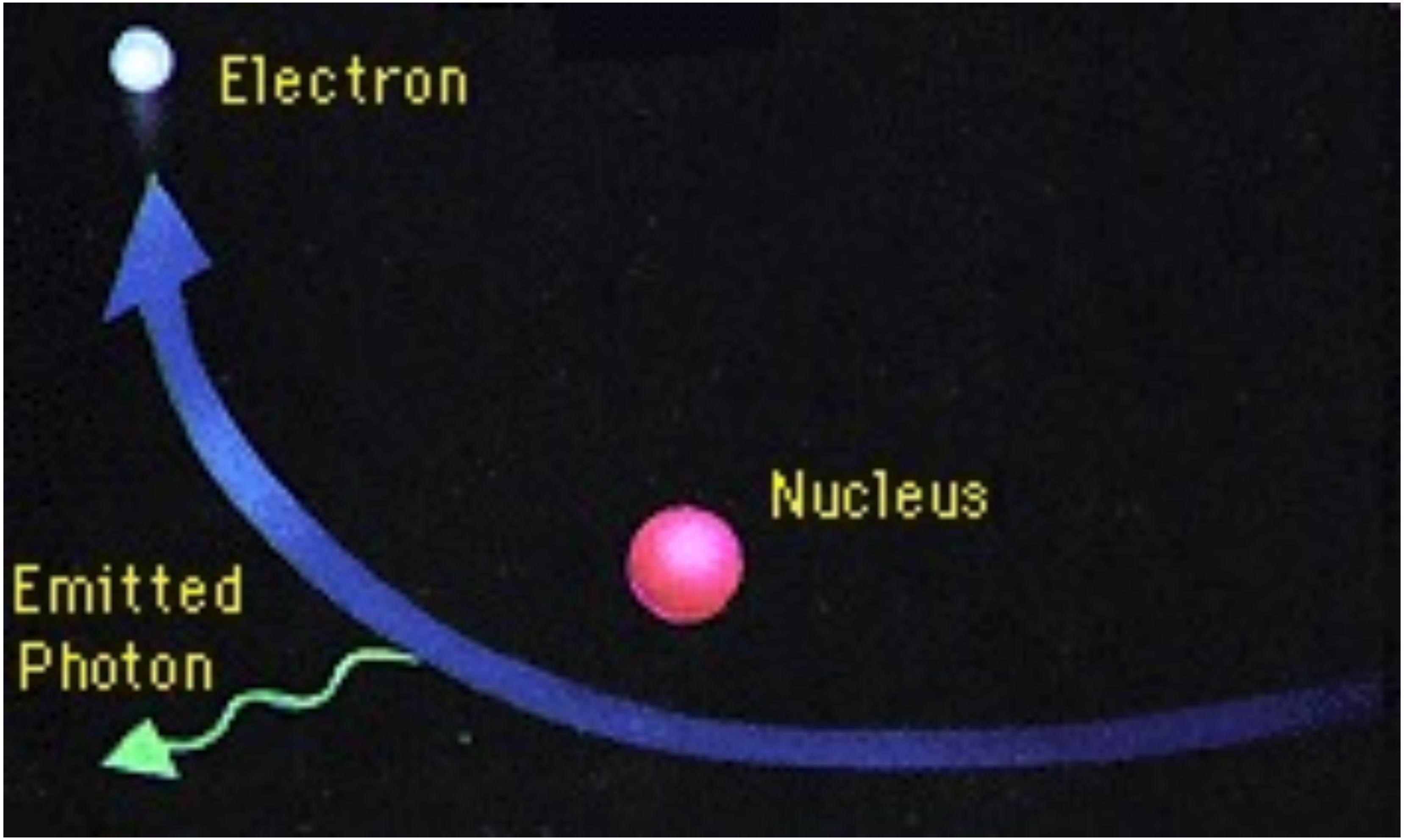




Discussion: What are the main differences the optical and radio image and why?

Radio Emission

- H II regions emit strong radio continuum radiation via the thermal free-free or Bremsstrahlung mechanism



Bremsstrahlung mechansim. NASA Goddard Space Flight Center.

Free-Free Opacity

$$\kappa_\nu \propto \frac{n_i n_e}{\nu^{2.1} T^{1.35}}$$

- Two-body process, hence $\propto n_i n_e$
- Need to take account of Maxwellian distribution of electron velocities, hence *T* dependance

- Frequency dependance of optical depth

$$\tau_\nu \propto \nu^{-2.1}$$

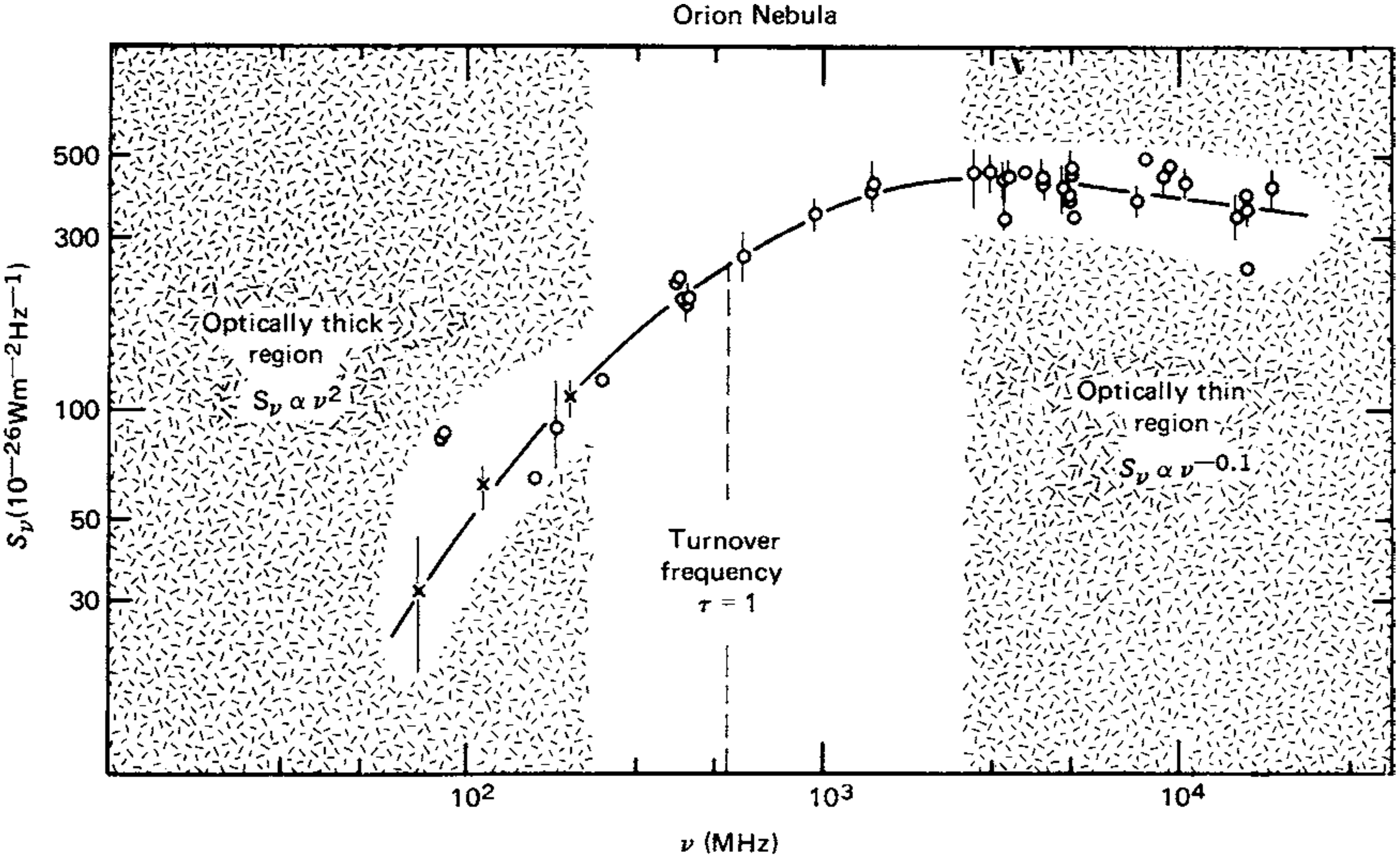
- So optically thick (τ_ν>>1) at low frequencies where

$$I_\nu = B_\nu = \frac{2kT\nu^2}{c^2} \propto \nu^2$$

- And optically thin (τ_ν<<1) at high frequencies where

$$I_\nu = B_\nu \tau_\nu \propto \nu^2 \nu^{-2.1} \propto \nu^{-0.1}$$

- Gives the typical radio spectral energy distribution (SED) for an H II region



From Radio Recombination Lines by Gordon & Sorochenko

Spectral Index

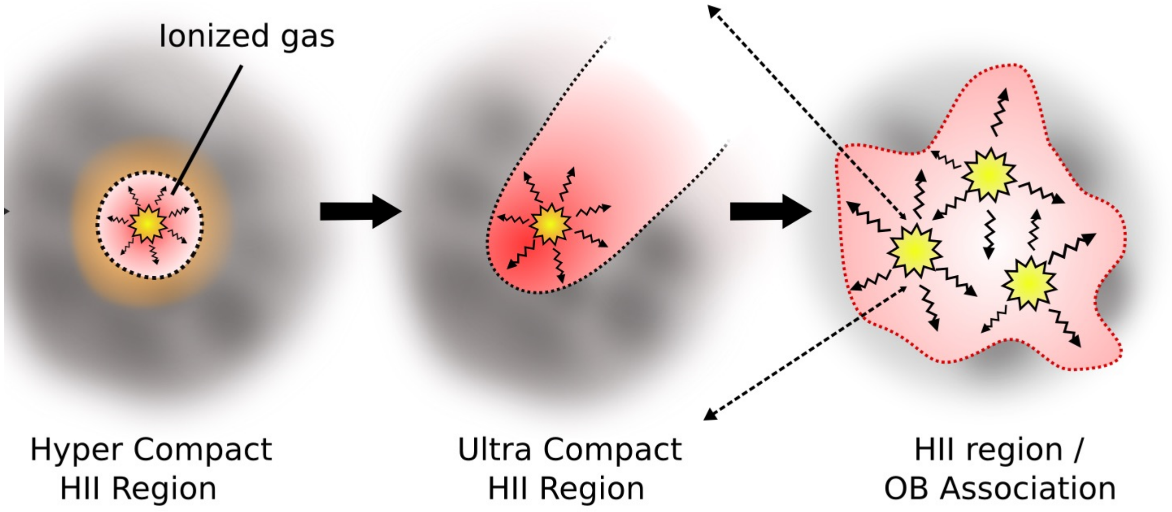
- The slope of the radio continuum spectrum can give information on the optical depth

$$S_\nu \propto \nu^\alpha$$

- So for constant density H II regions
  - α = -0.1 when optically thin
  - α = +2 when optically thick
- (Caution – extragalactic astronomers tend to use the opposite definition $S_\nu \propto \nu^{-\alpha}$)

Evolution of H II Regions

- H II regions expand as they have a higher pressure than their surrounding molecular cloud



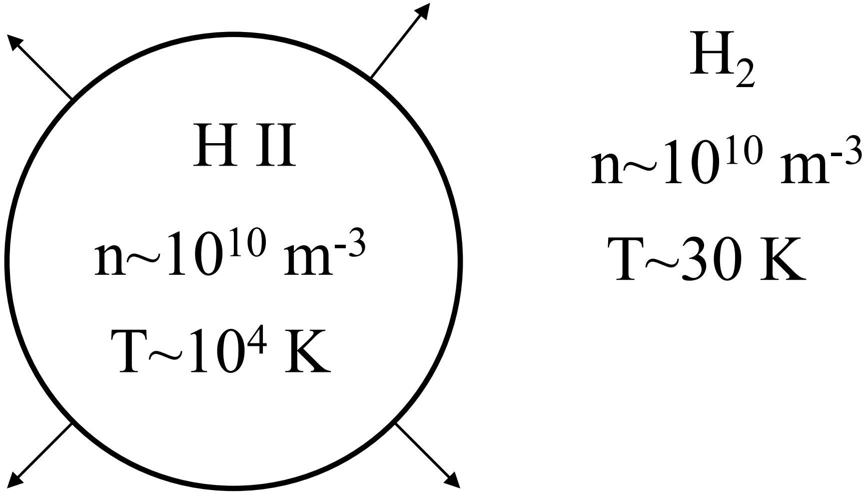
Thermal Pressure

$$PV = n_{mol}RT$$

$$P = \frac{n_{mol}RT}{V}$$

$$P \propto nT$$

where n is number density



H II

$n \sim 10^{10}\ \mathrm{m^{-3}}$

$T \sim 10^{4}$ K

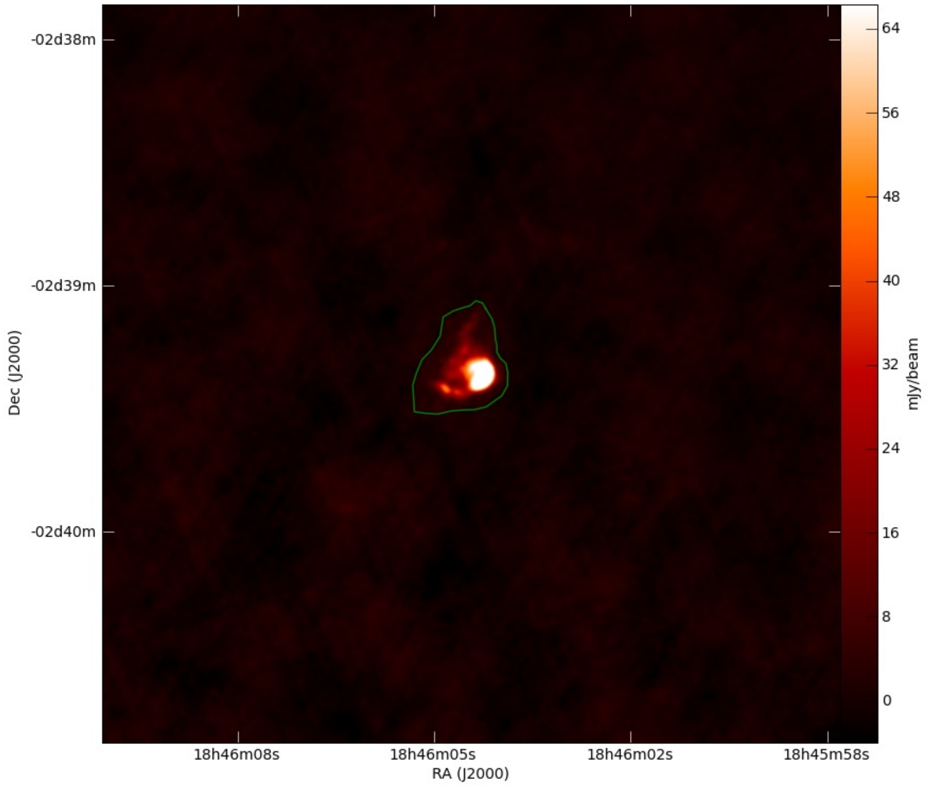
H_2

$n \sim 10^{10}\ \mathrm{m^{-3}}$

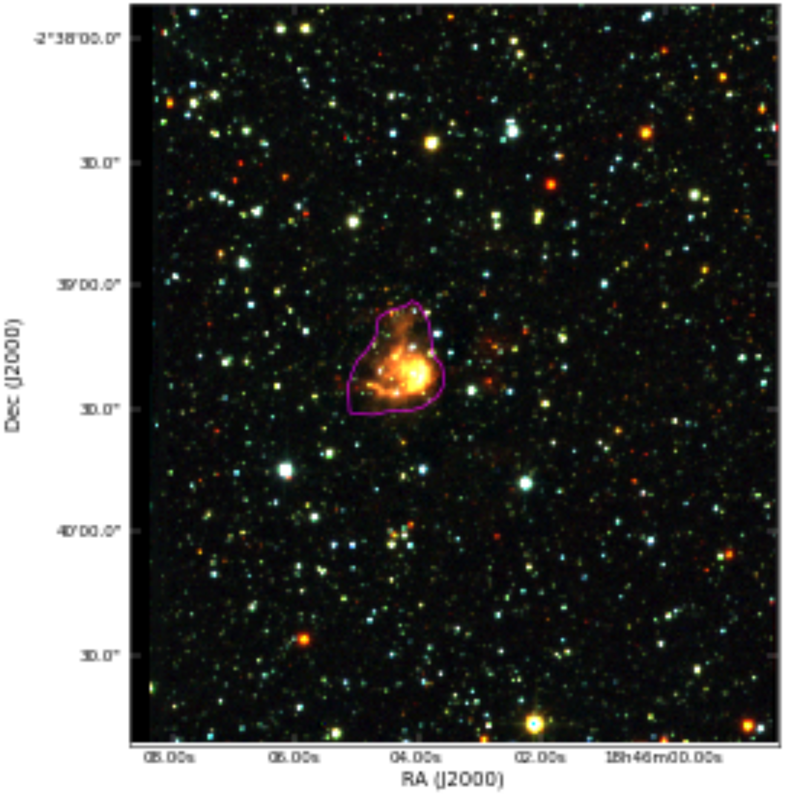
$T \sim 30$ K

So pressure inside H II region is ~ 1000 times higher than the surrounding molecular cloud

Ultra-Compact H II Regions



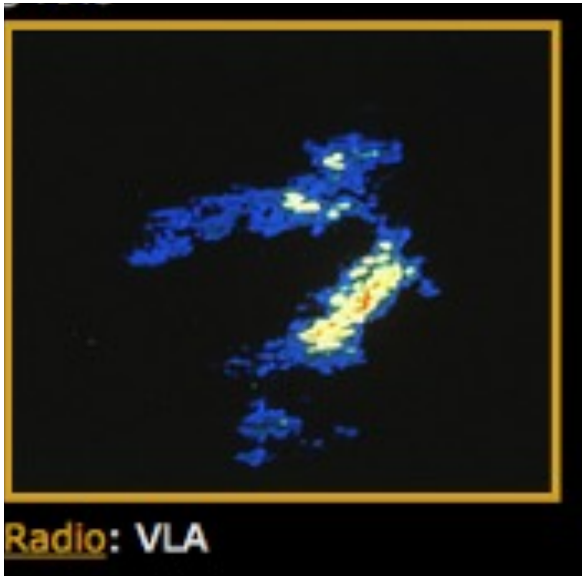
Radio image



Near-infrared image

Invisible in optical – radio unaffected by dust extinction

Evolved H II Region



Radio: VLA

Near-Infrared: 2MASS

Visible: Color © AAO

OB Star Associations

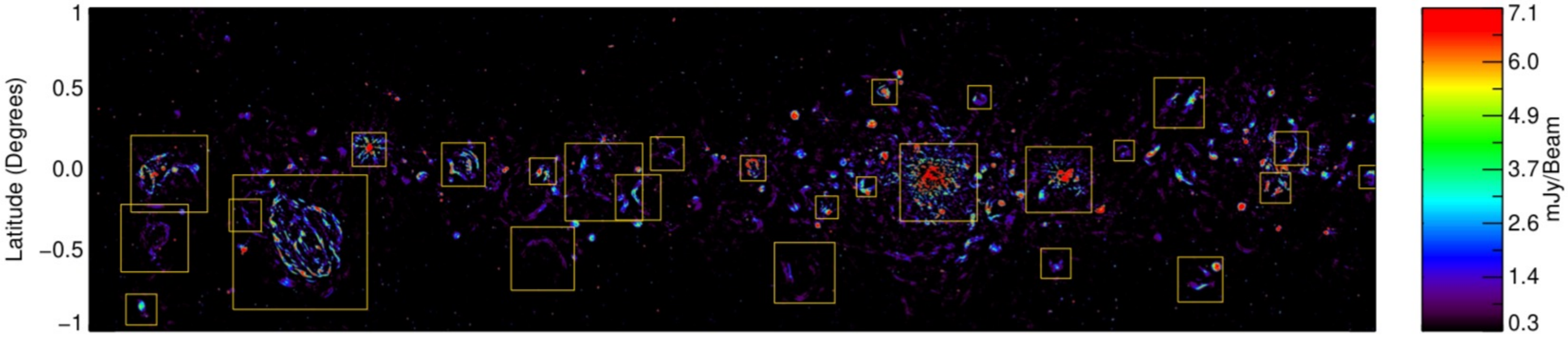
Optical image **Credit:**ESO/G. Beccari

Discussion

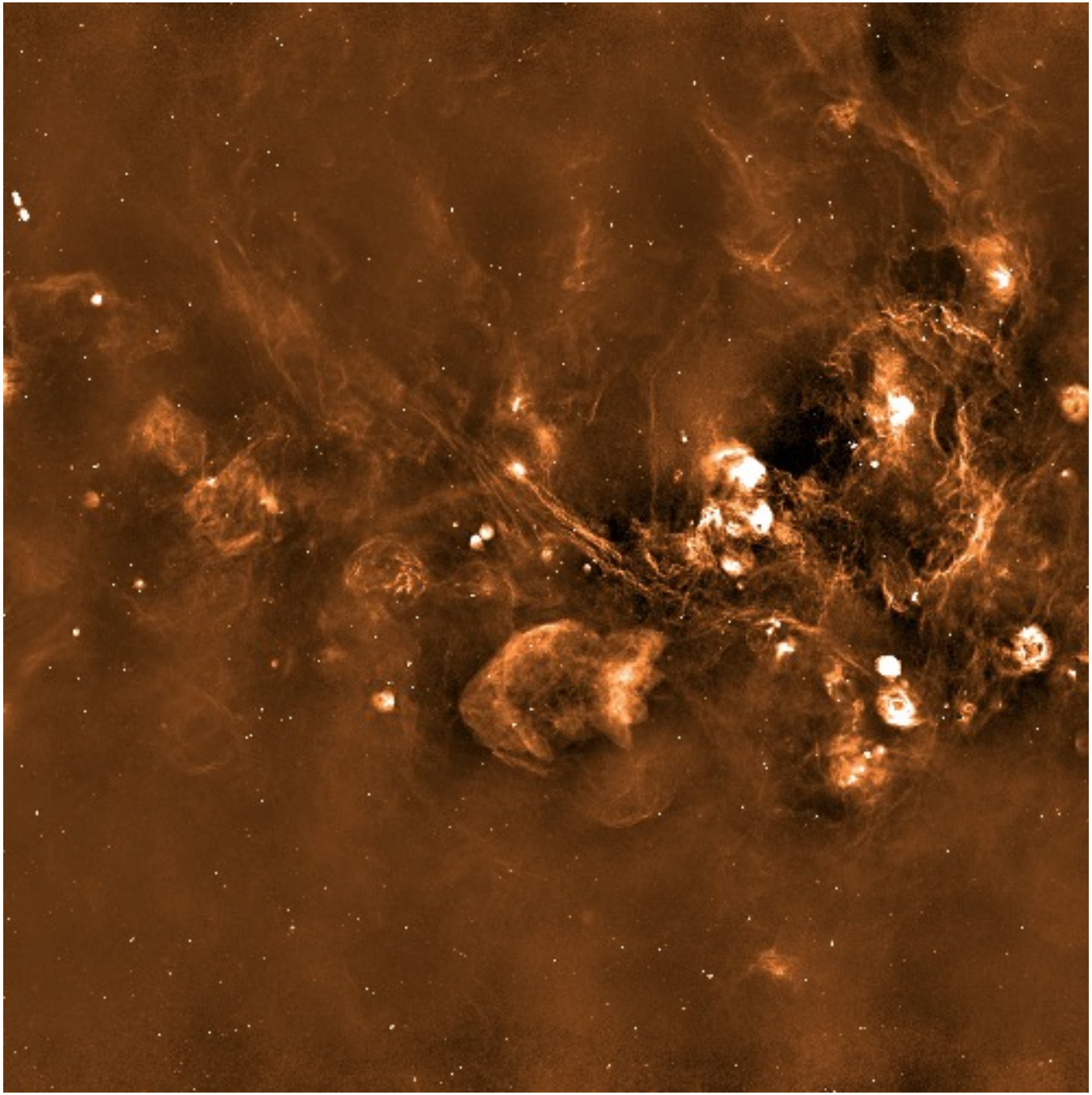
If the star forming cloud was bound by gravity initially why do the resulting star clusters disperse over time?

The Galactic Plane

- The plane of our Galaxy is full of radio sources
- Mainly H II regions, supernova remnants and planetary nebula

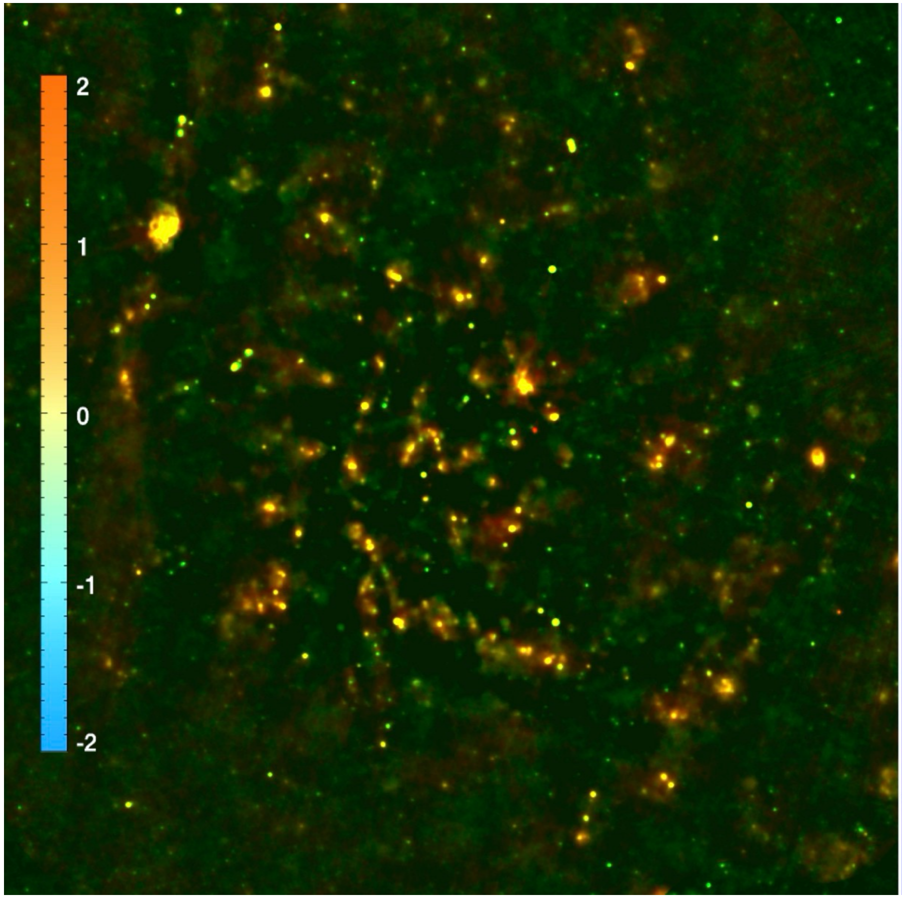


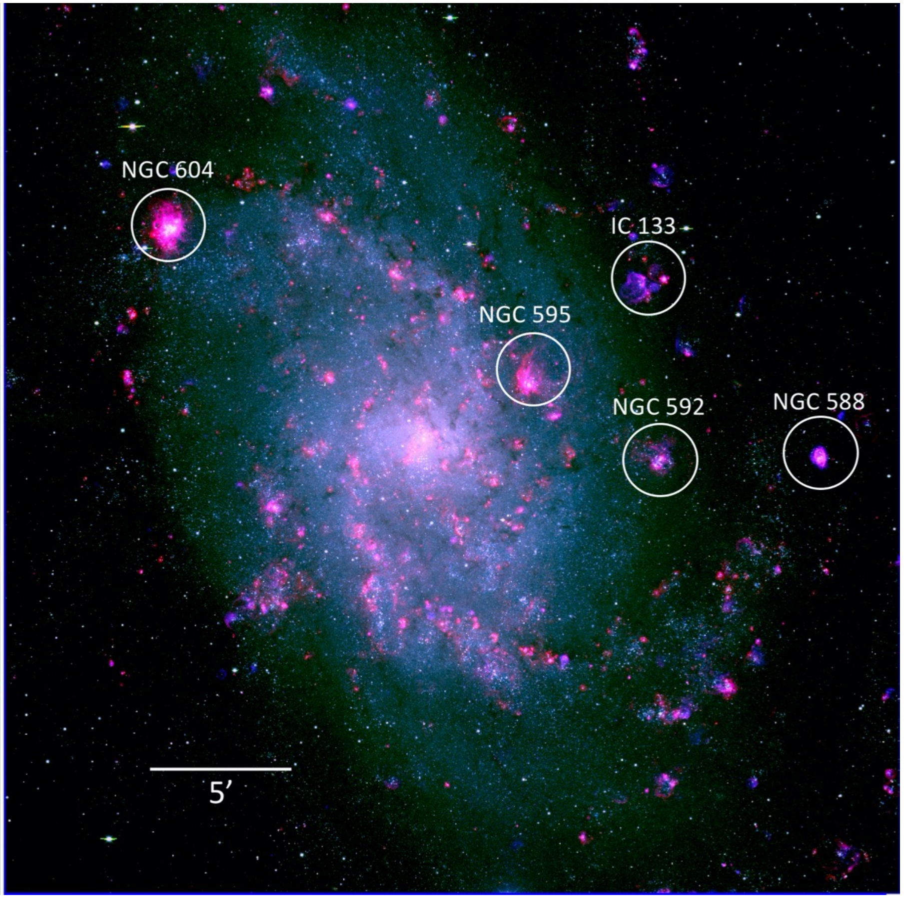
GLOSTAR 5 GHz VLA survey of the plane



MeerKAT 1.4 GHz survey of the plane

H II Regions in Nearby Galaxies



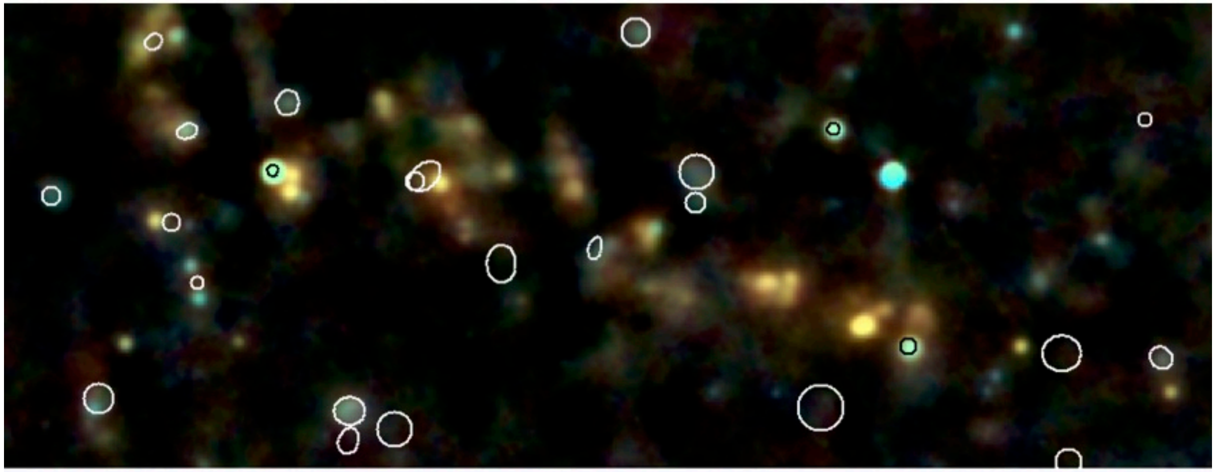


Radio image
Colour – spectral index

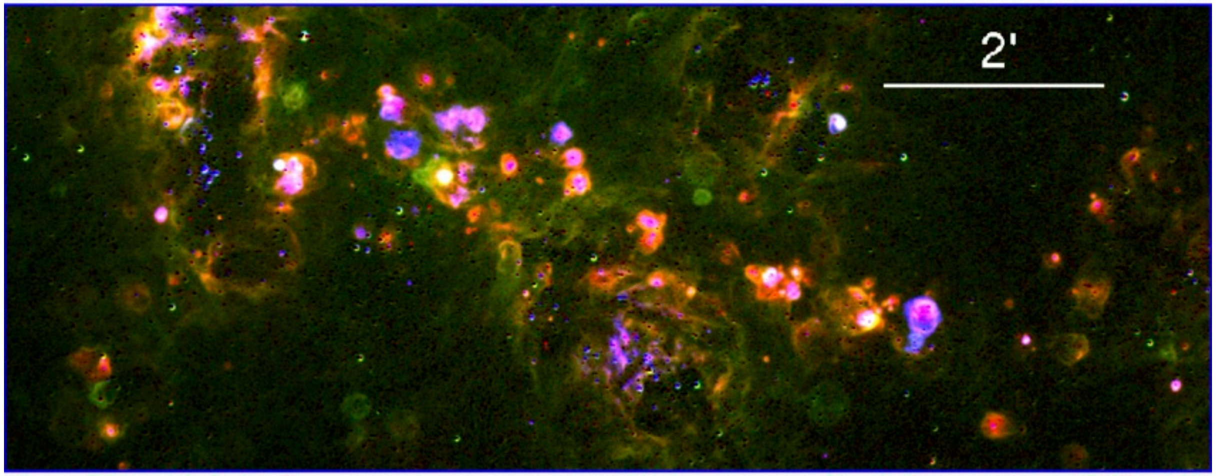
M33 White et al. (2019)

Optical image
Purple - Hα – H II Regions

Close-up on Spiral Arm



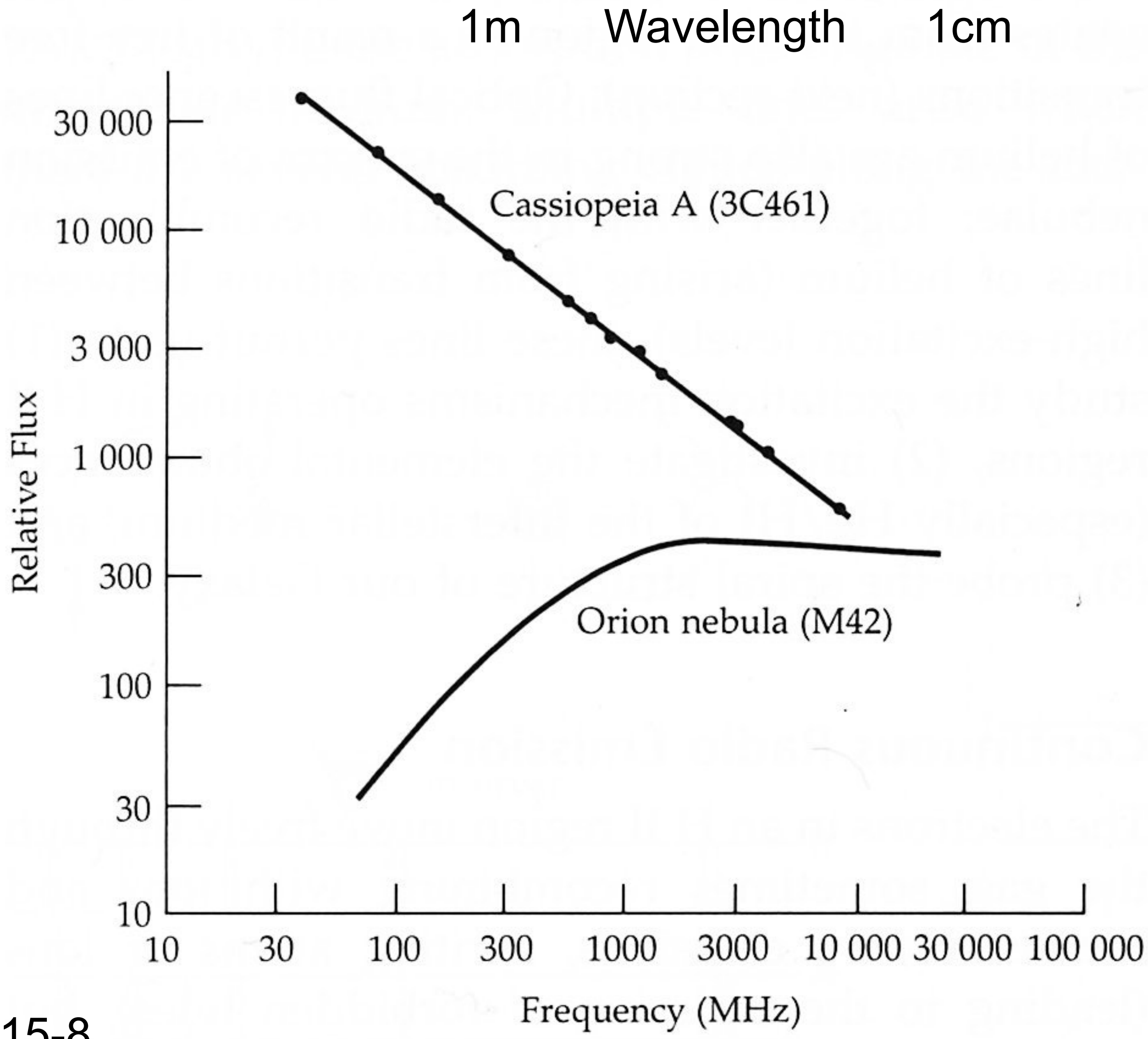
Radio image
Colour – spectral index



Optical image
Yellow – H II Regions
Blue - Supernova Remnants

M33 White et al. (2019)

- Note the different slopes of the radio spectra for thermal sources like the H II region M42 and non-thermal sources like the SNR Cas A



Zeilik Fig 15-8

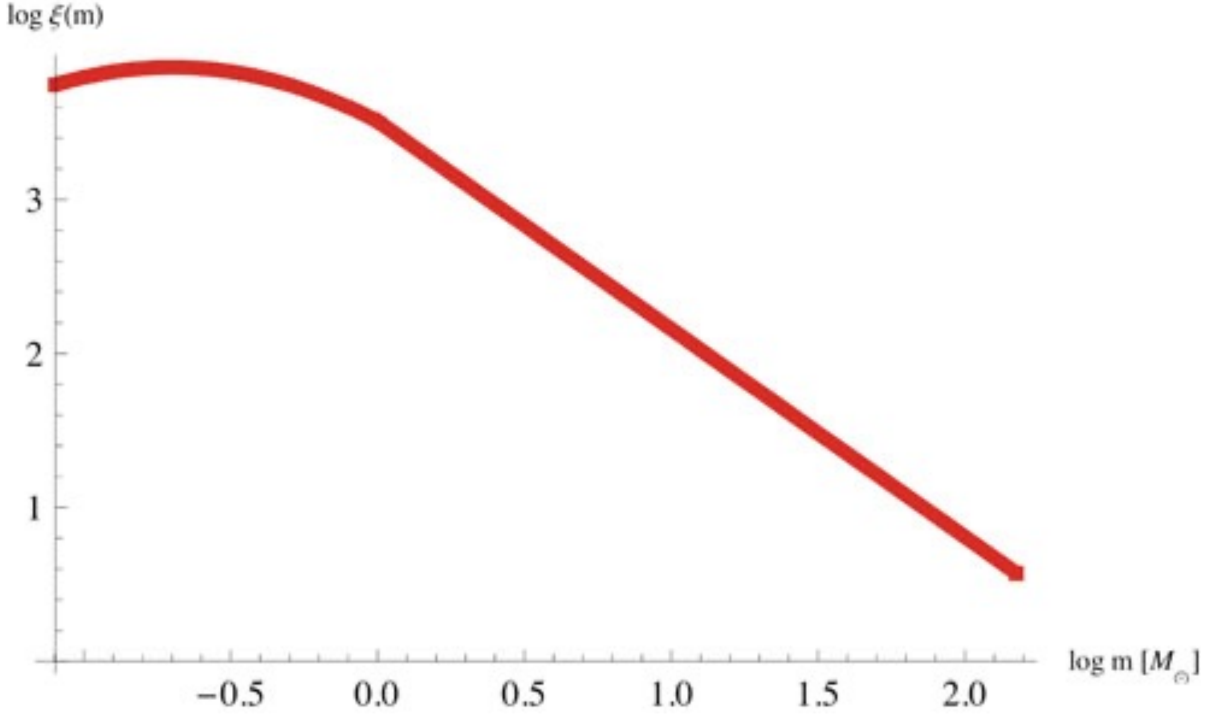
Star Formation Studies

- Although massive stars are rare they can be used to trace star formation over cosmic time
- Tracers of massive stars such as H II regions and supernova remnants are easily studied at radio wavelengths

Initial Mass Function (IMF)

- Thought that the IMF is relatively constant across time and location

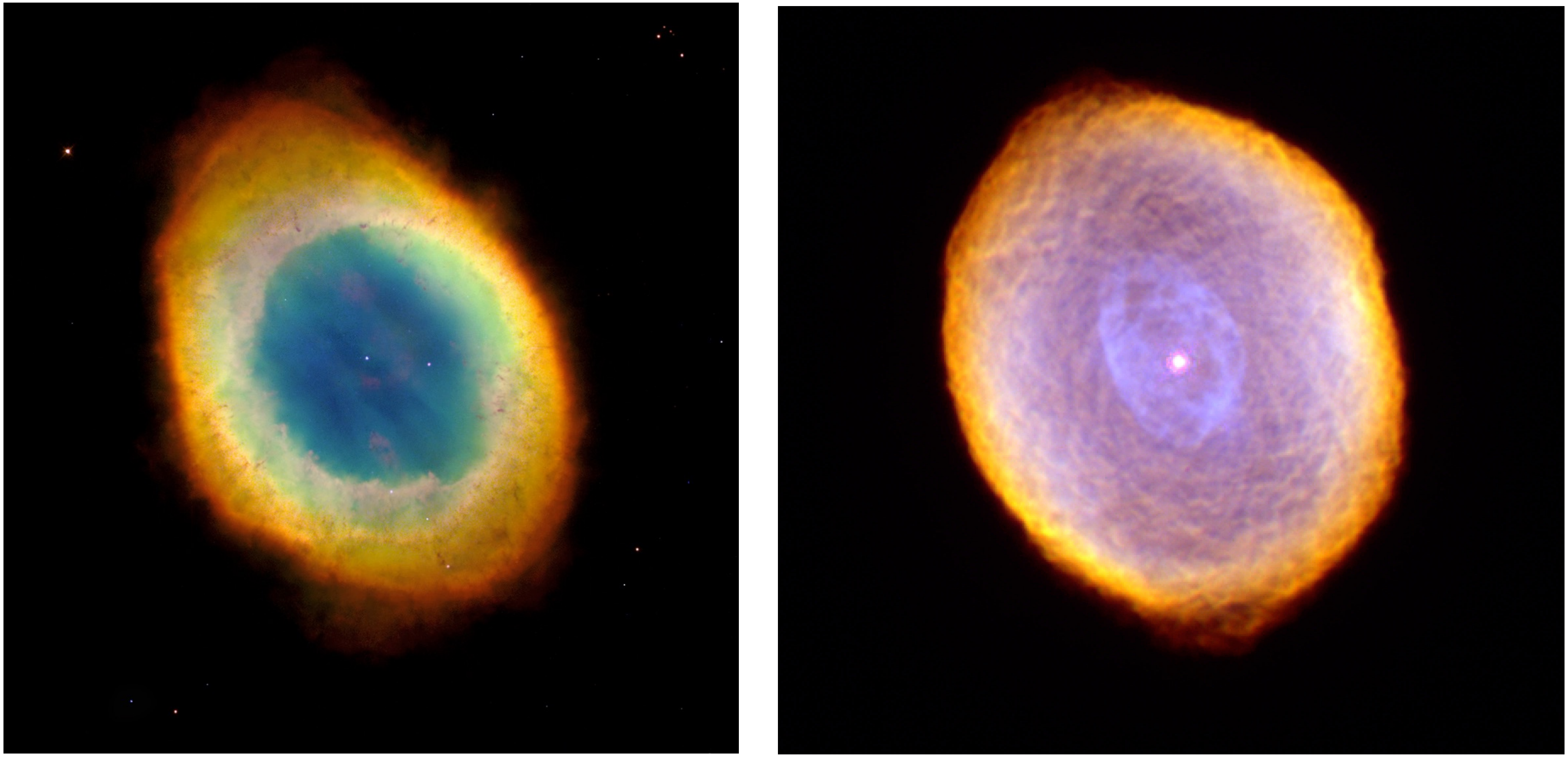
Number of stars per logarithmic mass bin



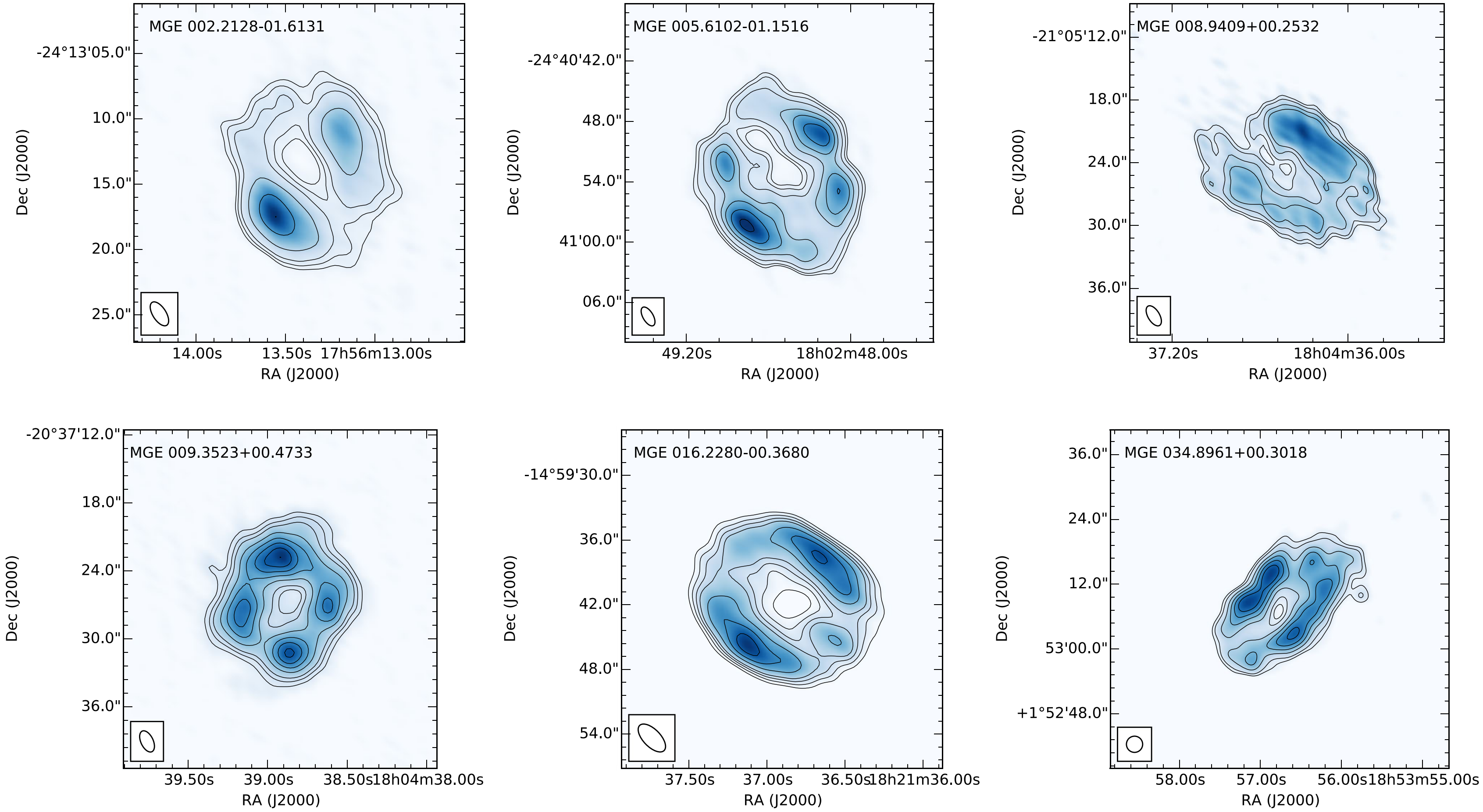
Planetary Nebula

- Some stages of evolved stars also have photo-ionized nebula
- E.g. the ionized ejected envelopes of intermediate mass stars form planetary nebulae (nothing to do with planets)
- Very similar radio properties to H II regions

- Optical images of planetary nebulae



- Radio images of planetary nebulae



Ingallinera et al. (2016)

Summary

- Spiral galaxies like the Milky Way contain many extended radio sources
- H II regions trace the birth of massive stars
- Supernova remnants mainly trace the death of massive stars
- Planetary nebulae trace the death of intermediate mass stars