Phases/Components of the Interstellar Medium ("the stuff between the stars")

Phase	Temperature	Density	Filling Factor	Radiative Process	Wavelength
Cold Molecular gas *(where star formation happens!)*	10K	10^4 cm^{-3}	Low	molecular emission lines (vibration/rotation modes)	radio, mm
Cool Atomic gas	100K – 1000K	10^3 cm^{-3}	Low	e^- spin flip	21cm radio
Warm Ionized gas	10,000K	10^2 cm^{-3}	Moderate	Recombination emission lines, plus some free-free continuum emission	optical, radio
Hot Ionized gas	10^5 K – 10^6 K	1 cm^{-3}	High	free-free continuum emission	X-rays
Dust grains	10K – 30K		Patchy	hydrocarbon emission lines, blackbody	mid-IR, far-IR

Neutral Hydrogen (HI)

Cool gas (100K – 1000K): atoms are in ground state. No optical emission lines.

Radiates via spin-flip of the electron. Flip happens spontaneously, with 10 million year timescale.

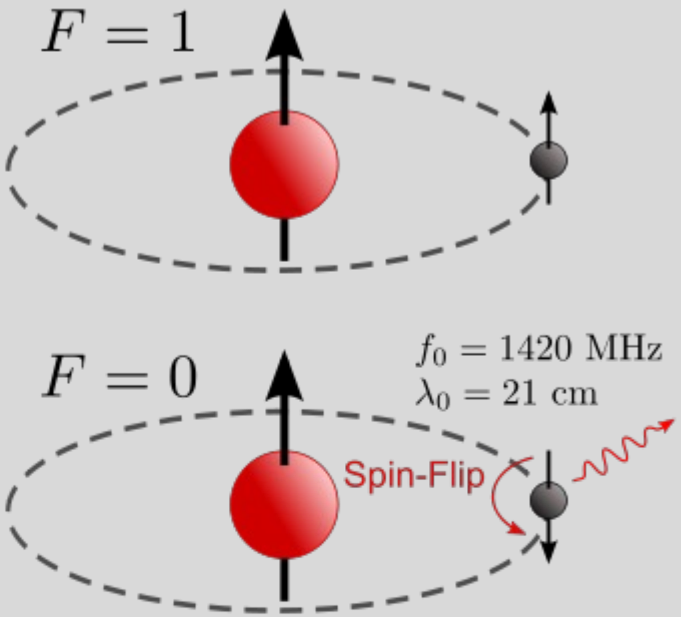
One flip produces one photon, with $\lambda = 21$ cm. Radio emission!

If the gas is optically thin (i.e., no absorption, we see all the photons), then:

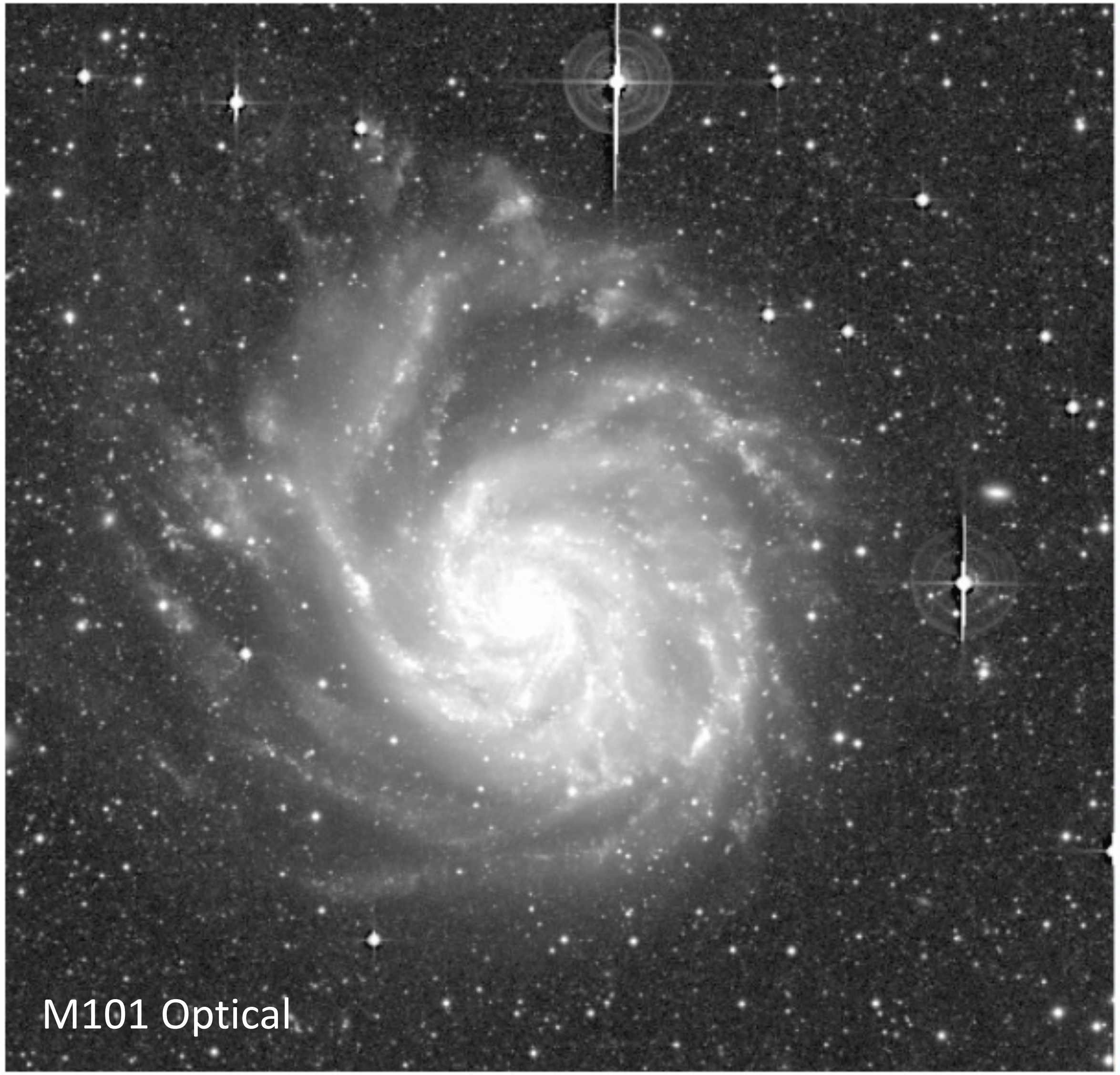
- 21cm surface brightness ➜ surface density of atomic gas
- 21cm luminosity ➜ total mass of atomic gas

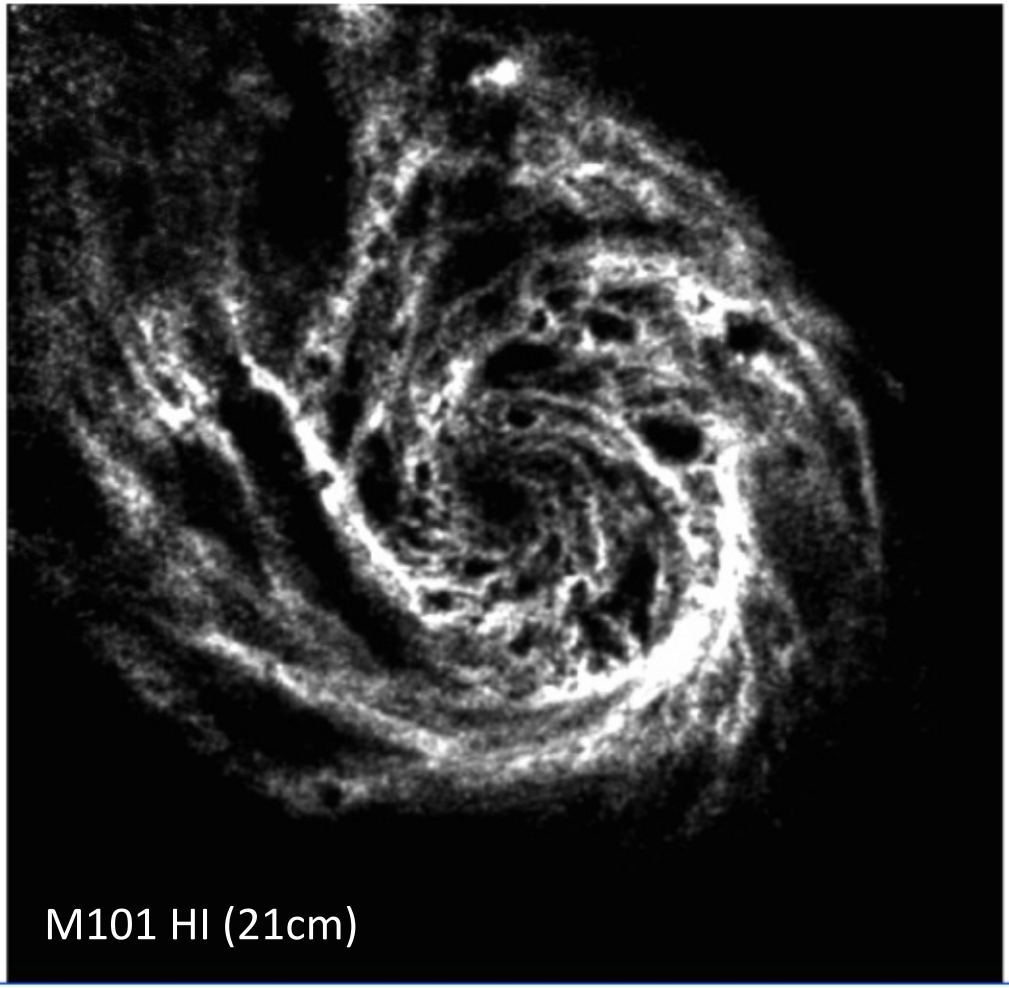
Also, since it is an emission line:

- wavelength ➜ gas velocity
- line width ➜ gas turbulent velocity



Neutral Hydrogen (HI)

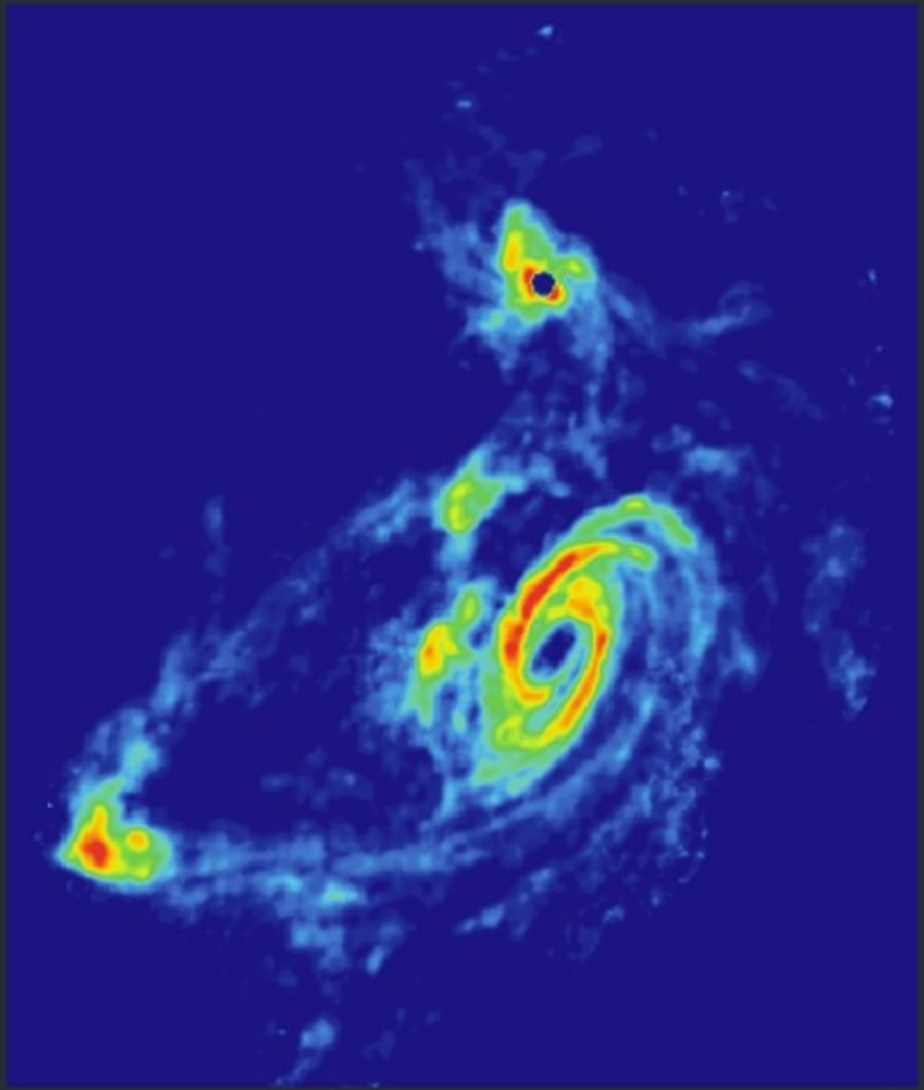




TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution



Molecular Gas

Molecular gas radiates through vibration and rotation modes.

Need a changing dipole moment to produce radio waves. For example, the CO_2 molecule ➞

The most common molecule is H_2, but that has no dipole moment, so does not radiate (much).

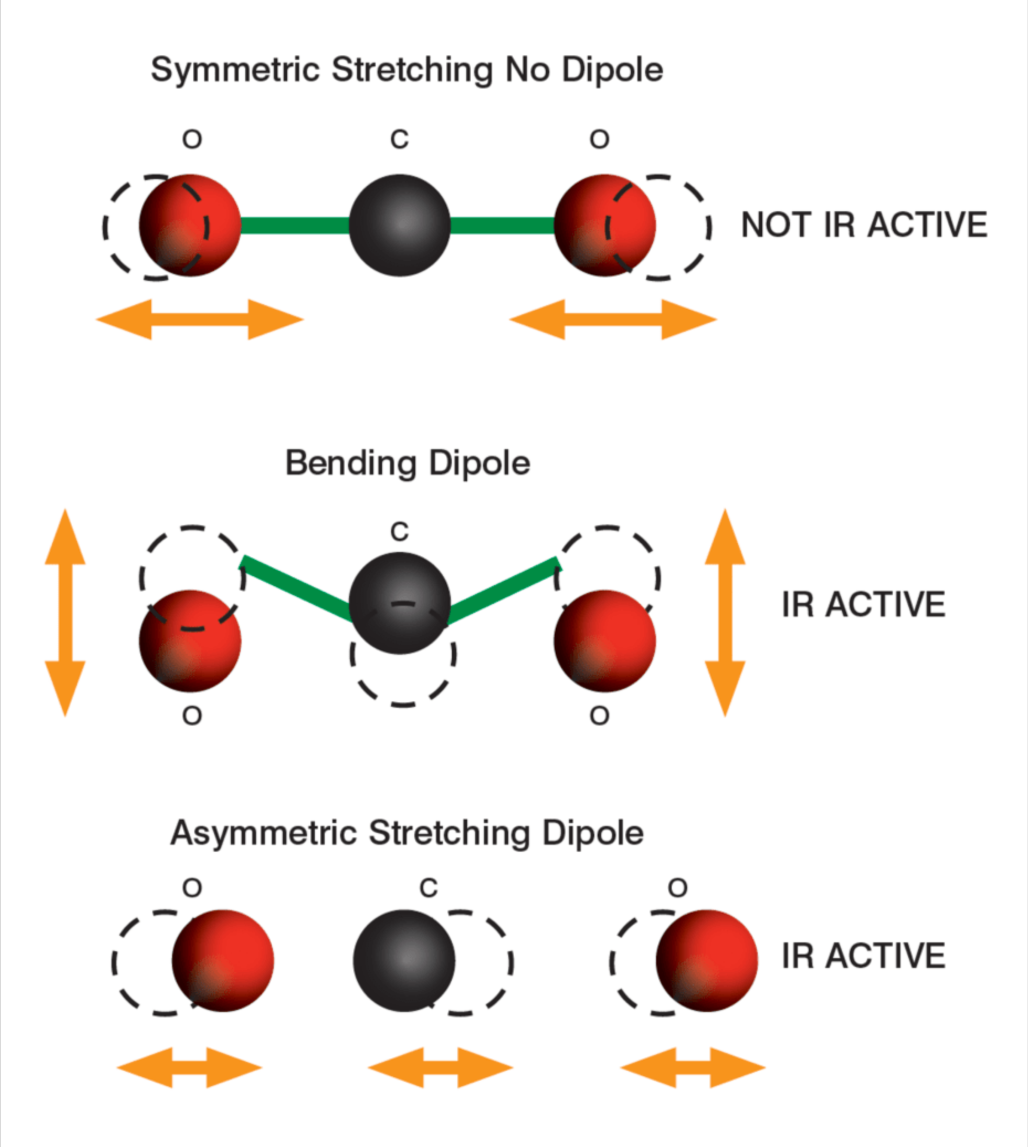
CO is common, and bright, so we use that as a tracer. If there is molecular CO, there must be tons of molecular H_2 as well.

$M(H_2) = X_{CO}\, L_{CO}$ where

L_{CO} = Luminosity of CO emission
X_{CO} = Conversion factor (but is it the same everywhere?)

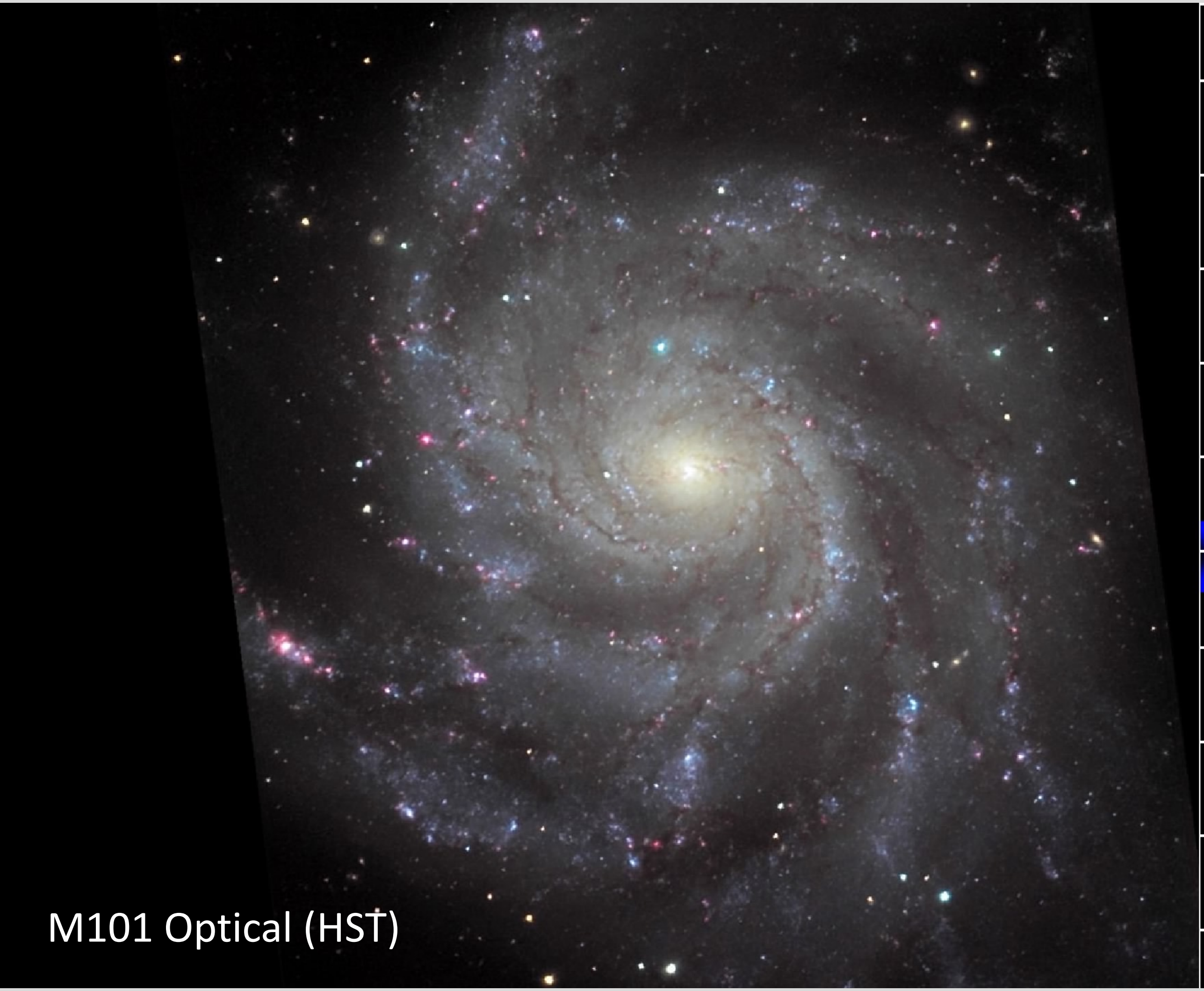
Other molecules trace even higher density gas, eg ^{13}CO, HCN, CO_2

Vibration modes in the CO_2 molecule

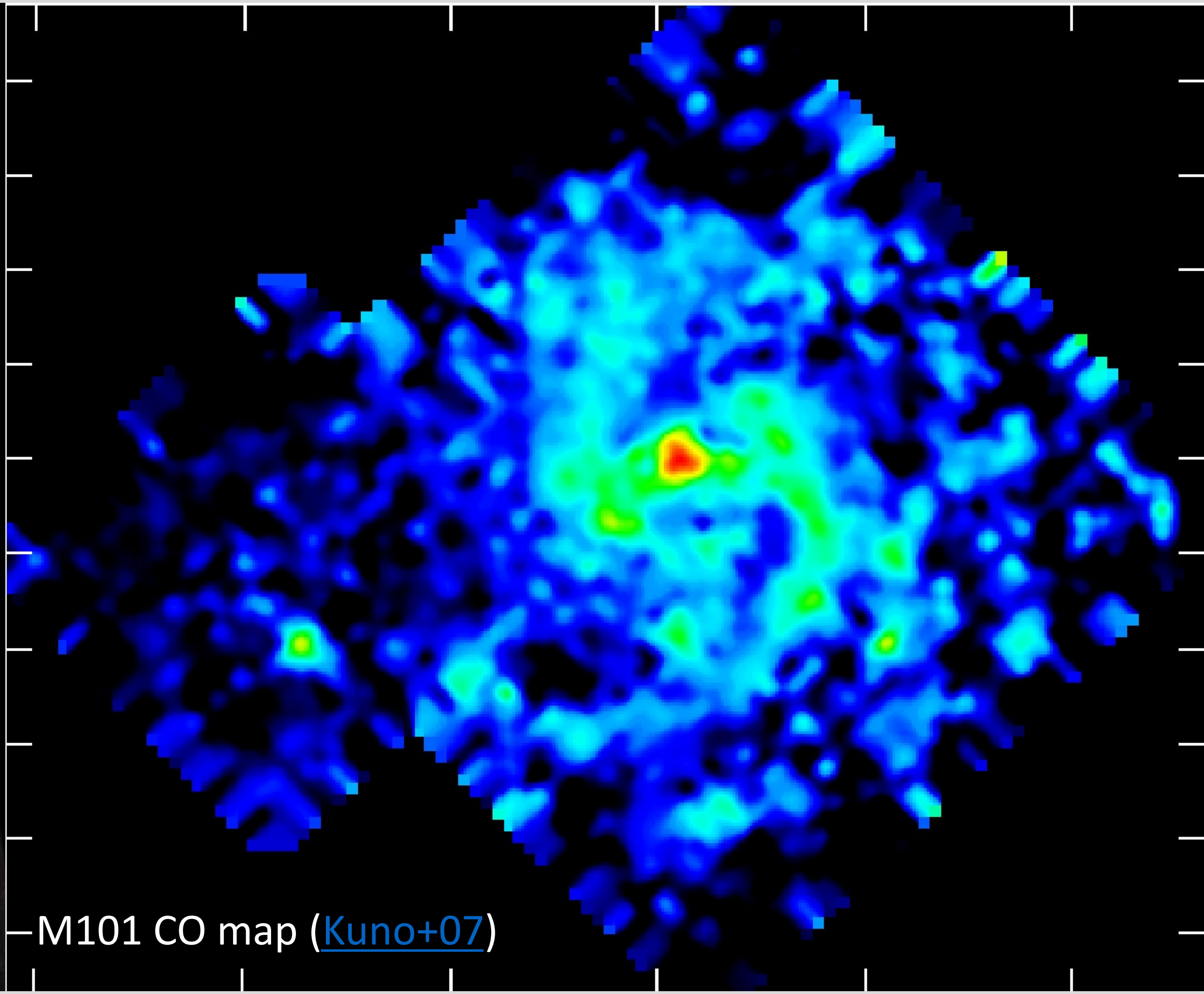


Molecular Gas

Much more centrally concentrated the the HI (neutral hydrogen) gas. Strongly associated with star formation.



M101 Optical (HST)

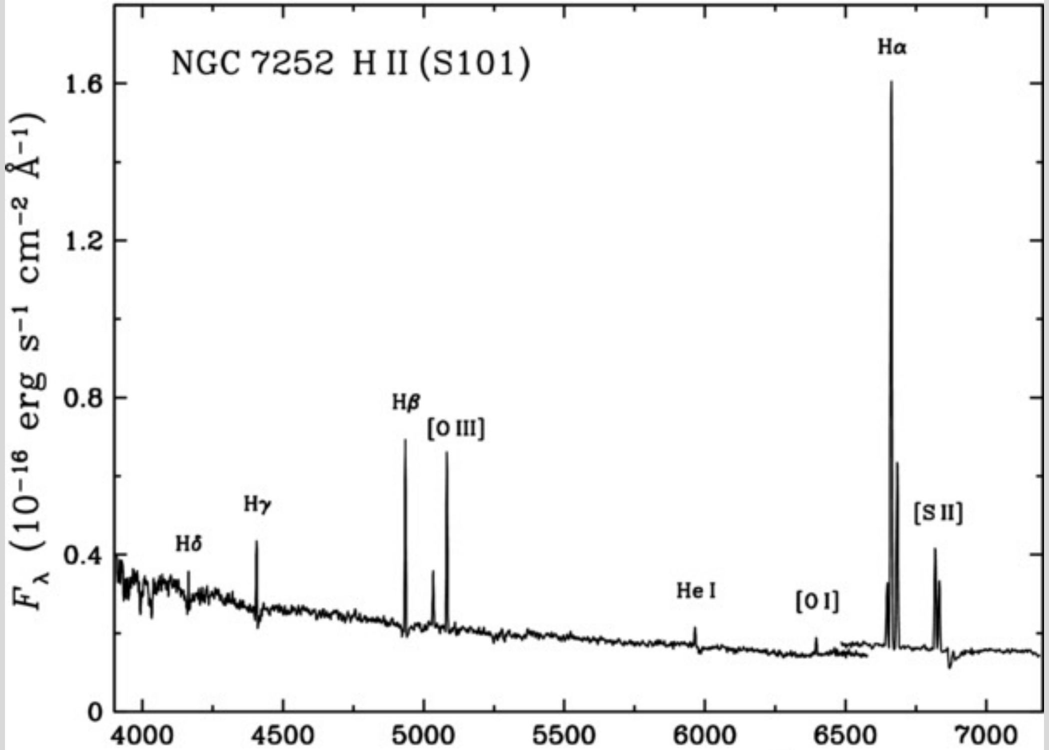


M101 CO map (Kuno+07)

Ionized Gas

Gas heated by photoionization (from young stars or AGN) or collisional ionization in shocks (turbulence, stellar/AGN winds).

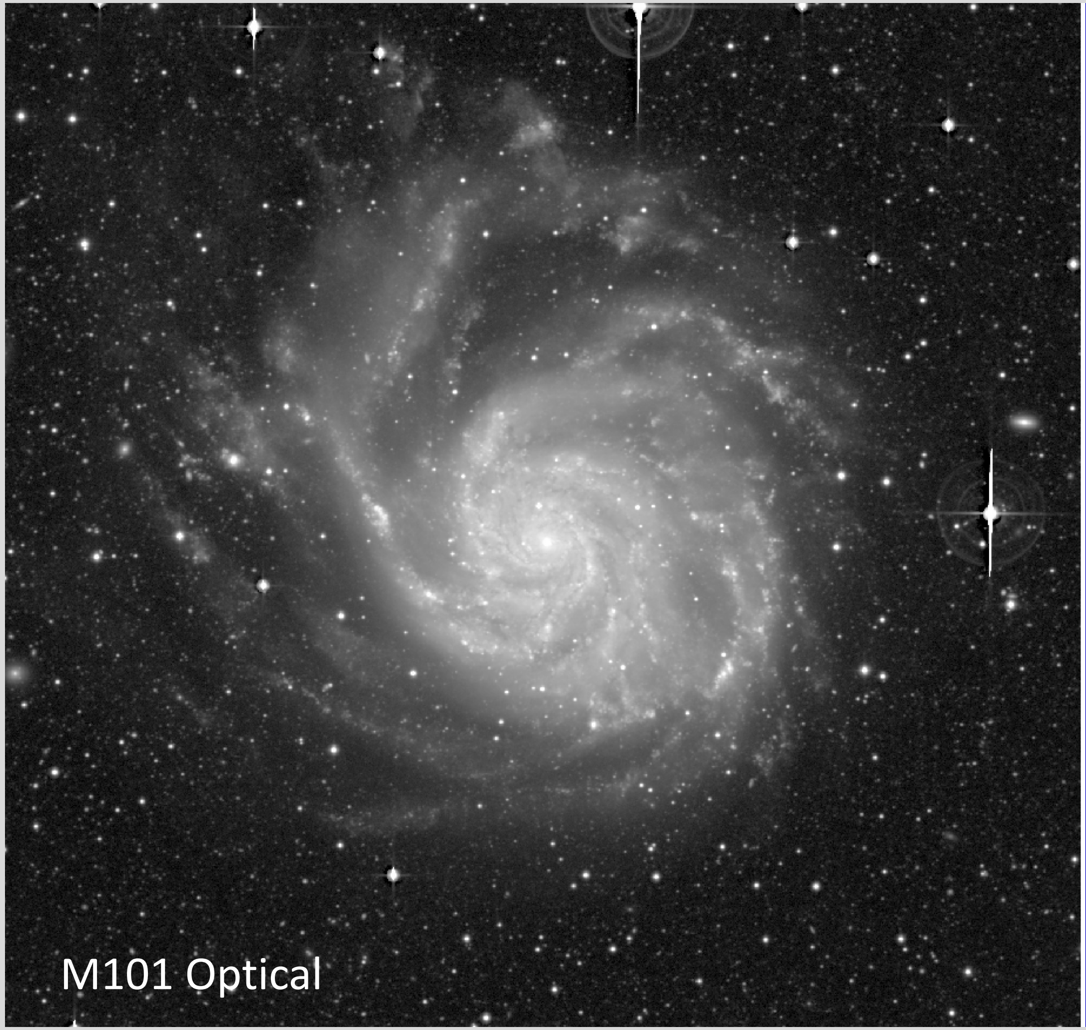
Radiates through recombination and subsequent downward cascades through atomic energy levels. Predominantly emission line radiation.

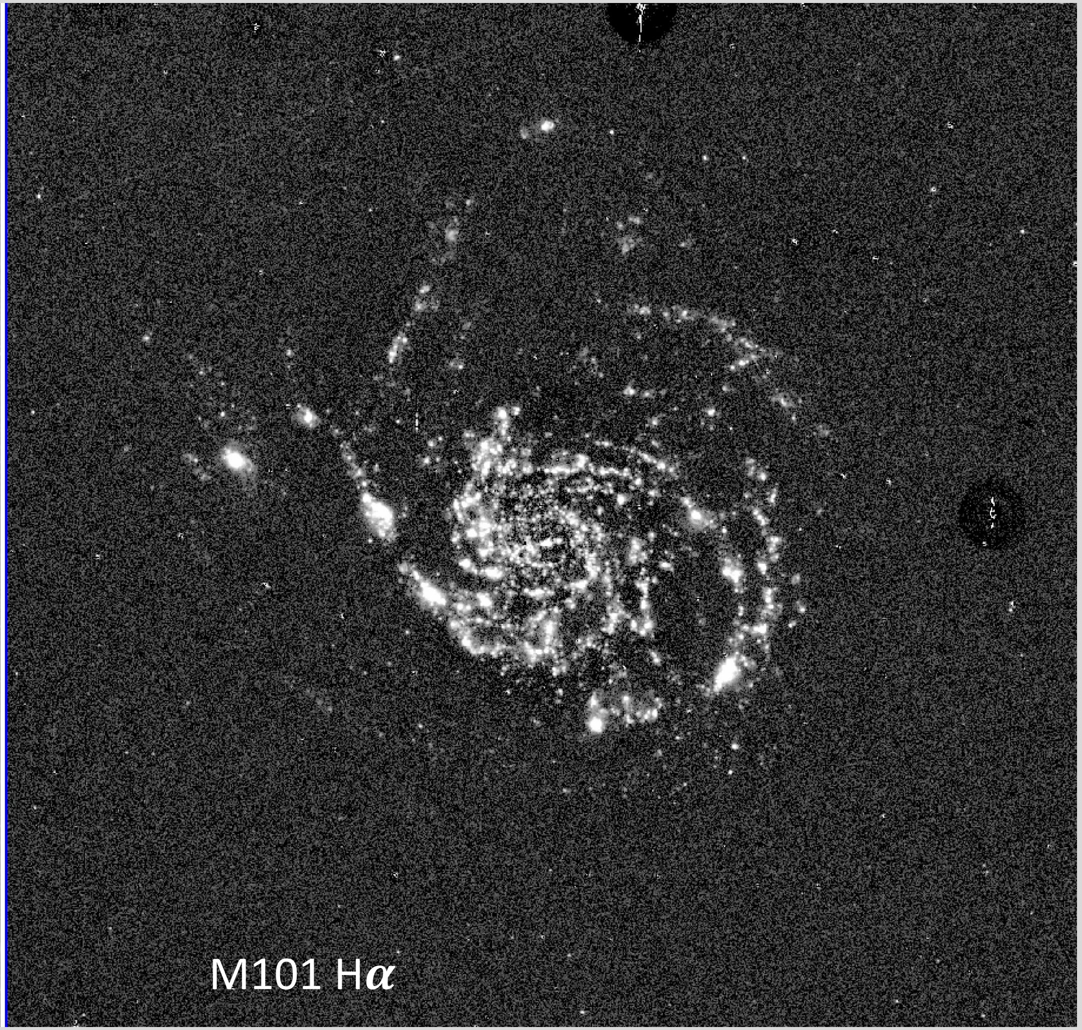


Schweizer+13

The Great Nebula in Orion (or just "Orion")

Ionized Gas





Ionized Gas: Line Nomenclature

Forbidden lines: At higher densities, atoms can de-excite collisionally rather than through a radiative cascade. Emission lines coming from transitions which are collisionally suppressed at higher densities (ie in the lab) are called "forbidden" and are usually denoted with brackets.

Ionization state: denoted via roman numerals: I=neutral, II=once ionized, III=twice ionized, etc.

Wavelength: if included, written as λxxxx at the end.

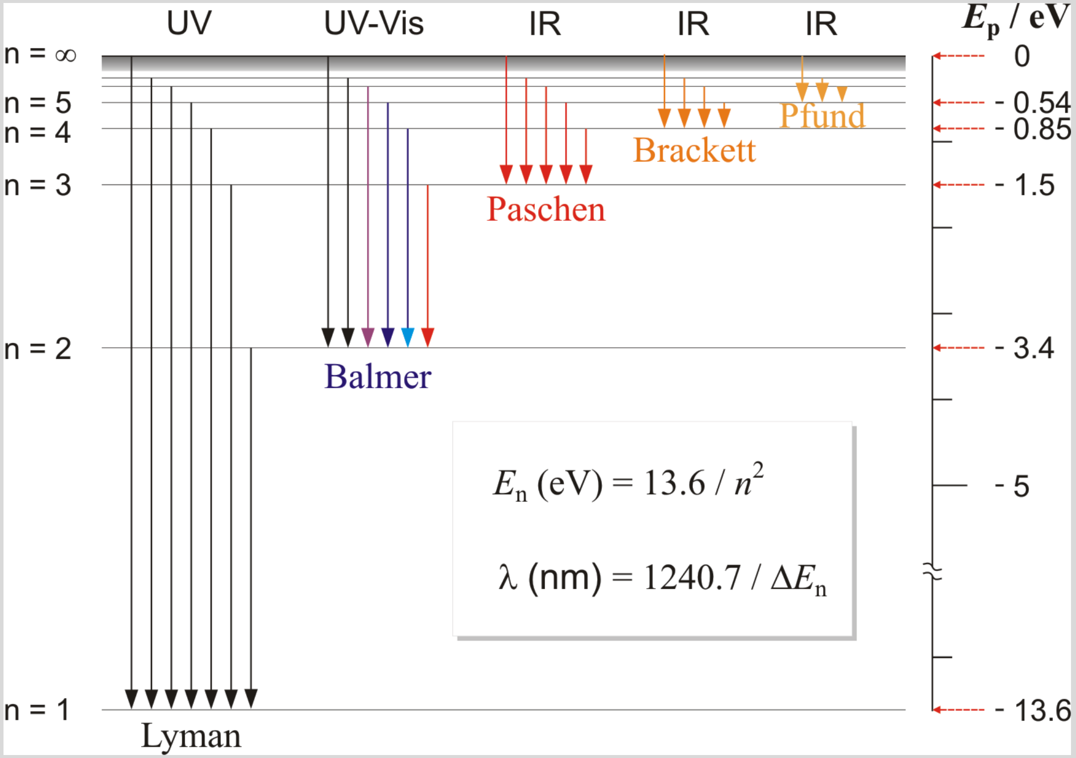
So:

- **[OIII]** : a forbidden line from twice-ionized oxygen.
- **[SII]λ6718** : forbidden line at 6718Å from once-ionized sulfur.

Hydrogen series use special notation:

Lyman (transitions to n=1: Lyα, Lyβ, Lyγ, etc, in UV)
Balmer (transitions to n=2: Hα, Hβ, Hγ, etc, in optical)
Paschen (transitions to n=3: Paα, Paβ, Paγ, etc, in IR)

Hydrogen transitions



Emission Line Diagnostics

Emission lines sensitive to temperature, density, metallicity, ionization source.

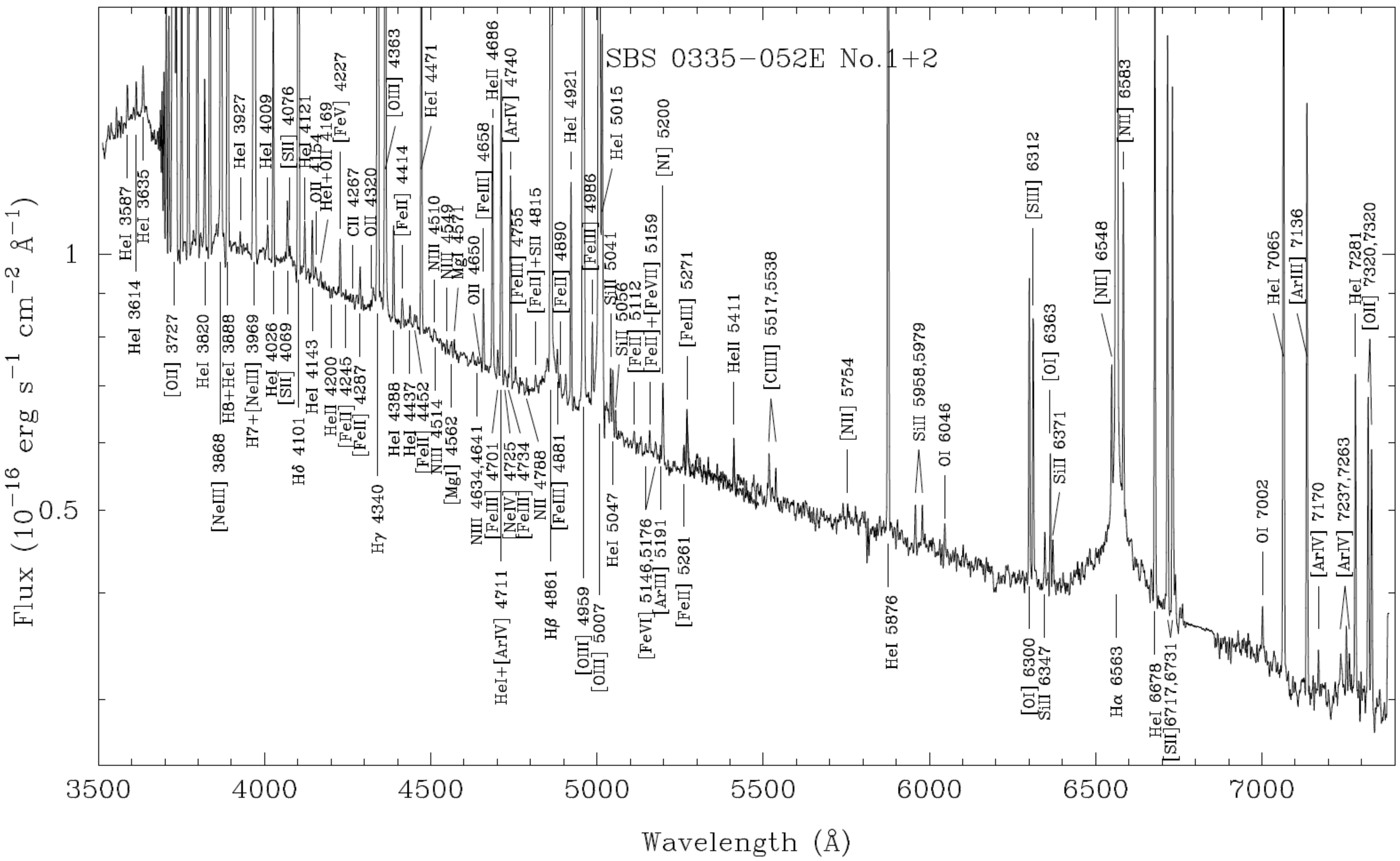
Reddening by Dust: Transition probabilities in Hydrogen are purely a quantum mechanical property of the atom, rather than the environment, and under most situations the line ratios reflect these probabilities. Common conditions ("Case B approximation") give Hα/Hβ flux ratio ≈ 2.7. If the observed ratio is different, it is because dust is preferentially extincting the bluer Hβ line.

Gas temperature: line ratios for ions with different ionization potentials give information on the gas temperature and/or the ionization mechanism (stars/AGN/shocks).

Gas density: Consider doublet lines (eg [SII]λλ6717,6731). The have same ionization potential, but different sensitivity to collisional de-excitation. These line ratios give information on the density of the gas.

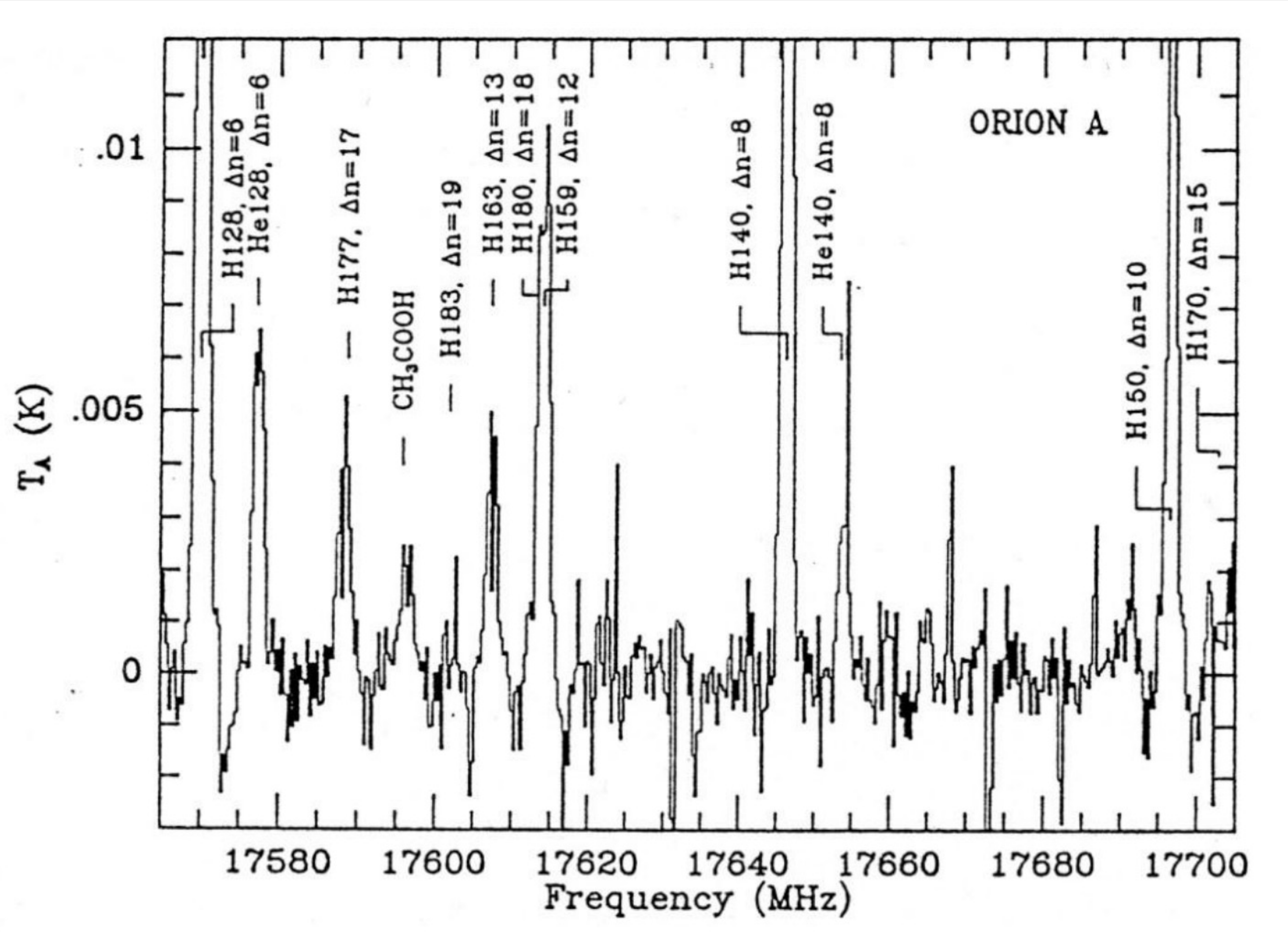
Optical Emission Lines

4 Y.I.Izotov et al.: SBS 0335-052E+W: deep VLT/FORS+UVES spectroscopy



Radio Emission Lines

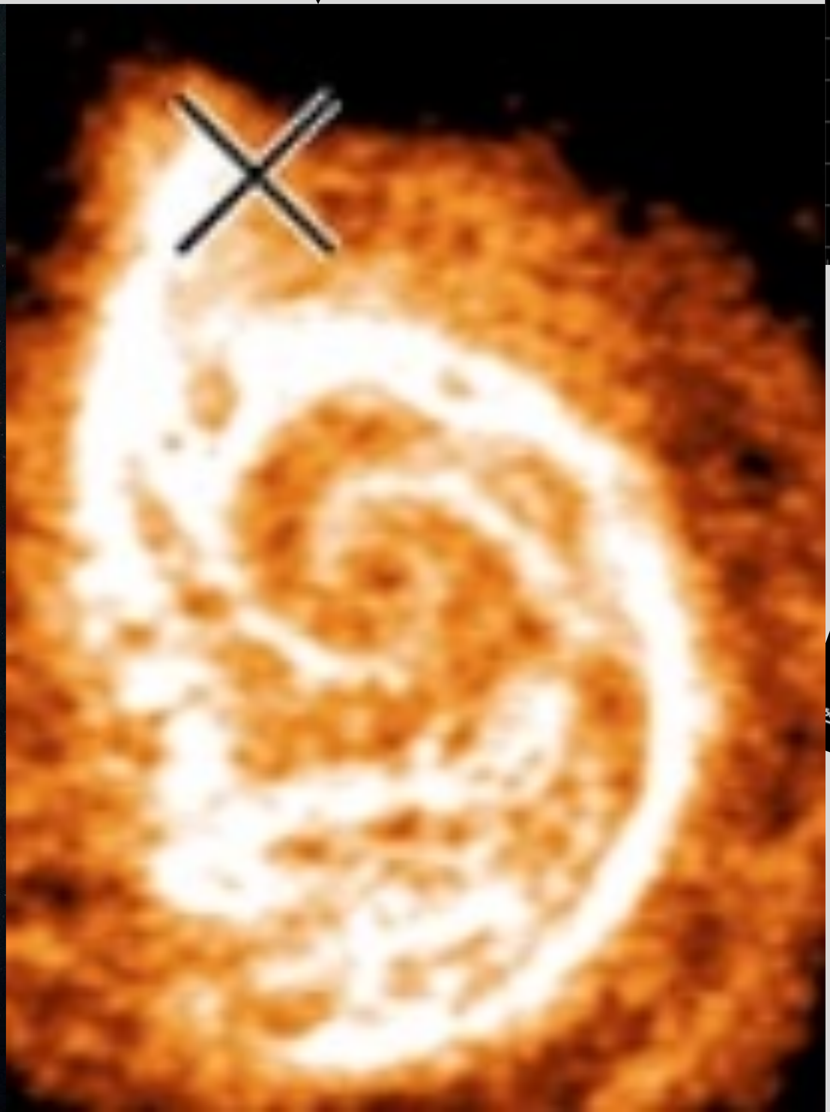
(also called "Radio recombination lines")

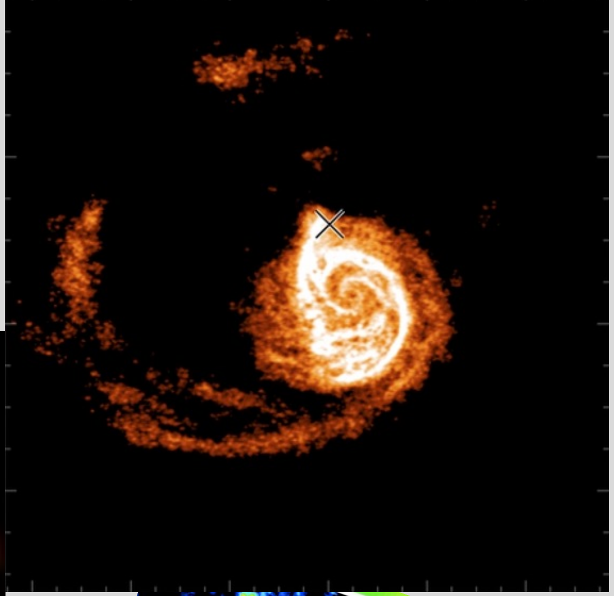


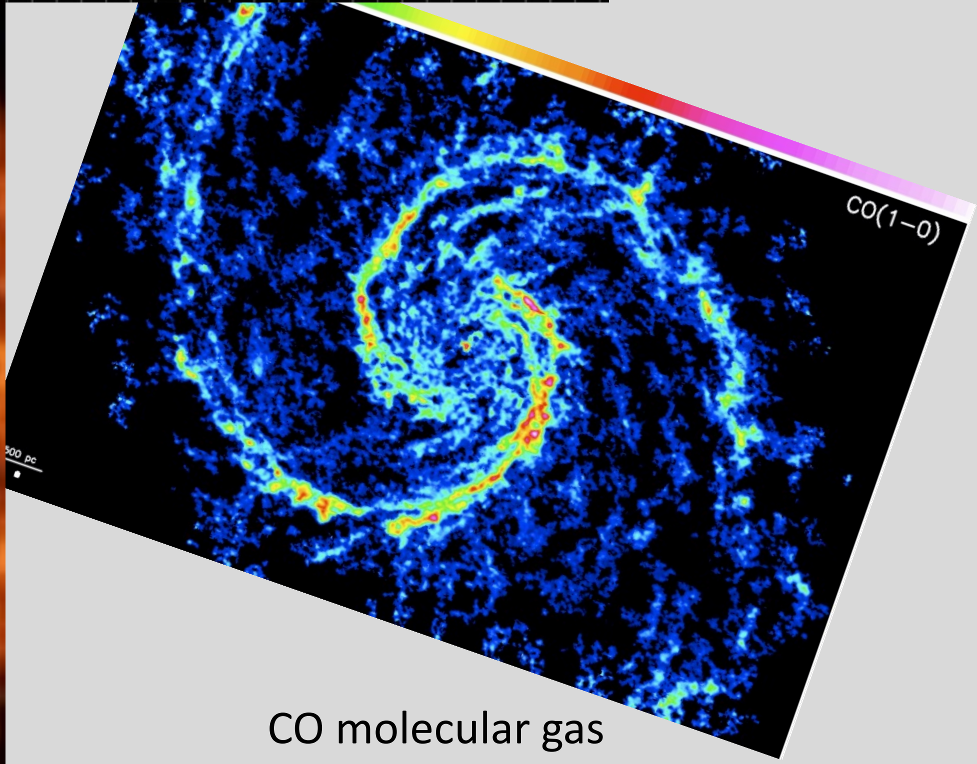
M51: The Whirlpool Galaxy

21 cm neutral hydrogen

Optical with Hα

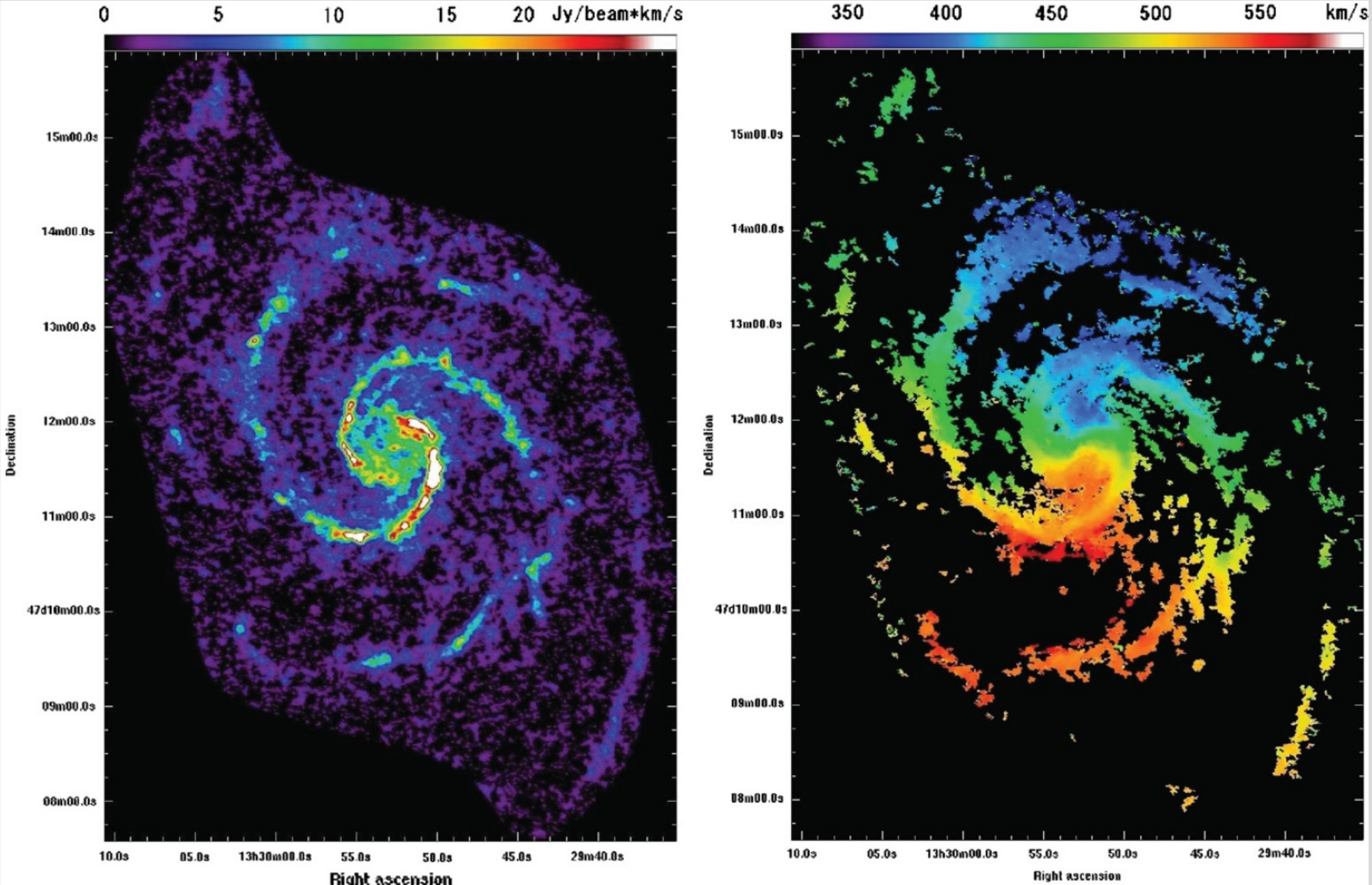




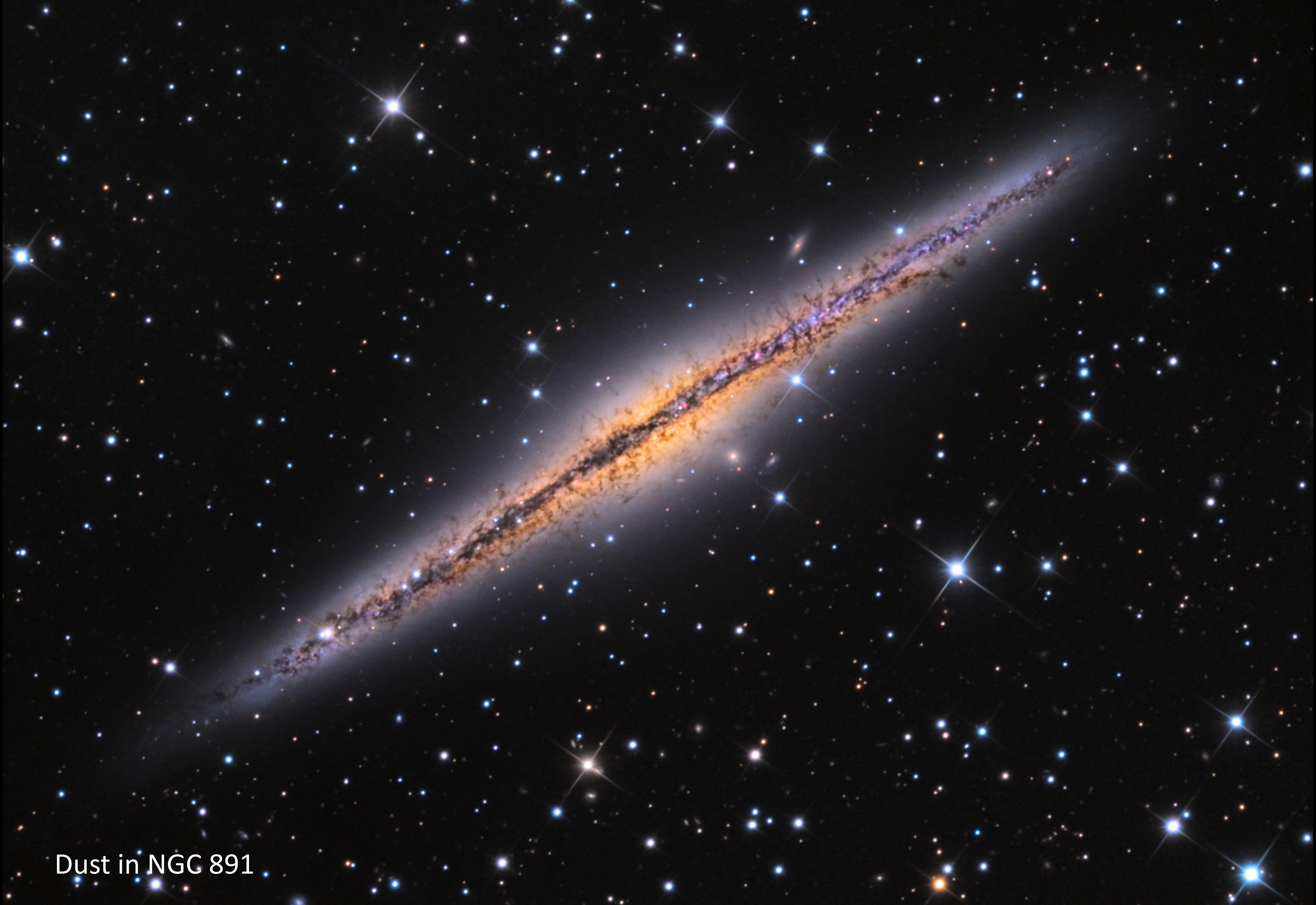


CO molecular gas

M51: CO and CO velocity field



Dust in the Milky Way



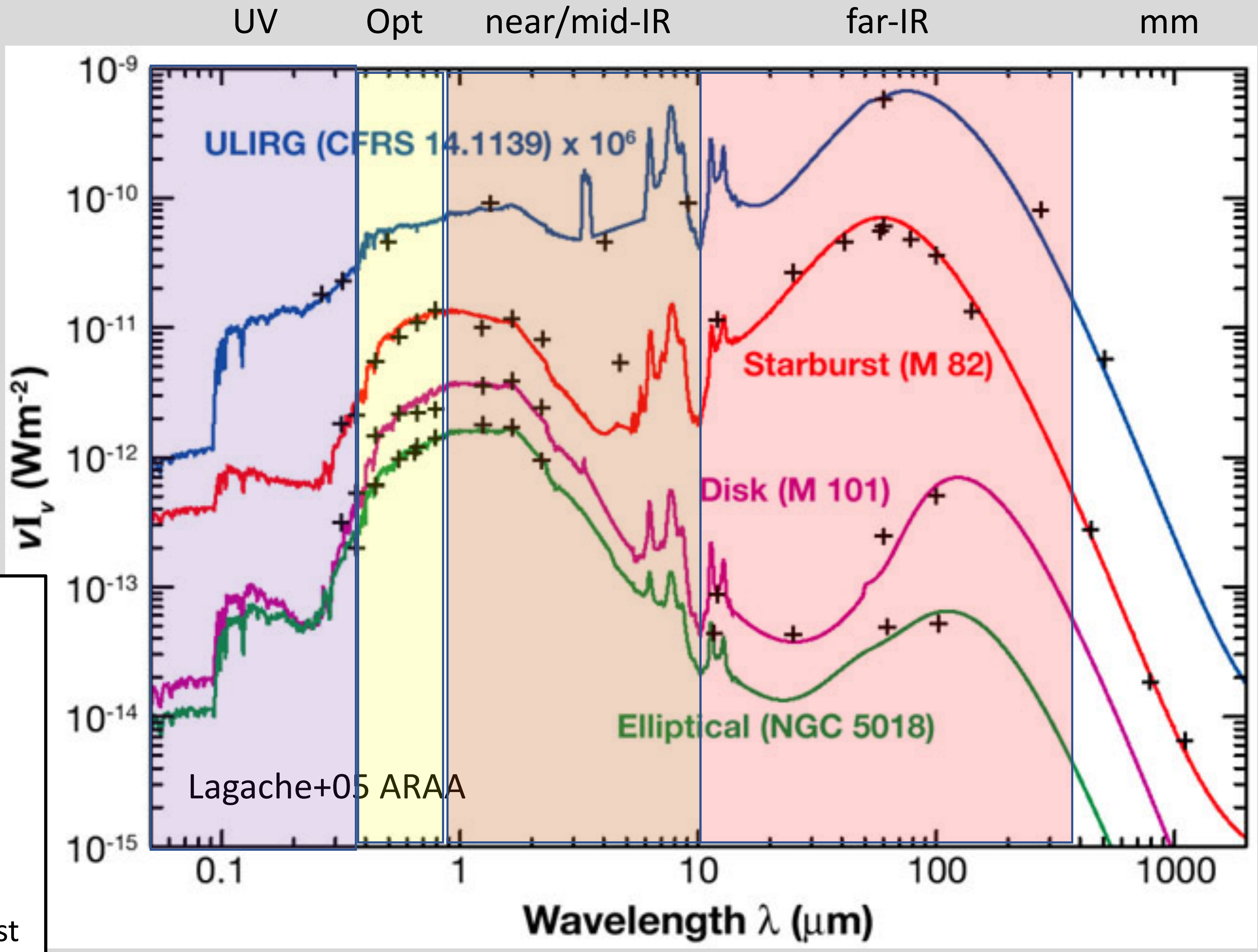
Dust in NGC 891

Dust in NGC 891

Thermal emission from dust

Dust absorbs radiation from stars and AGN, heats up, reradiates **blackbody emission** in the far infrared.

Far-IR emission traces starburst/AGN activity



Example spectra ⇒

- **Elliptical:** very little dust /star formation
- **M101:** normal spiral galaxy
- **Starburst:** High star formation rates
- **ULIRG** (ultra-luminous infrared galaxy): dust heated by intense starburst and/or AGN.

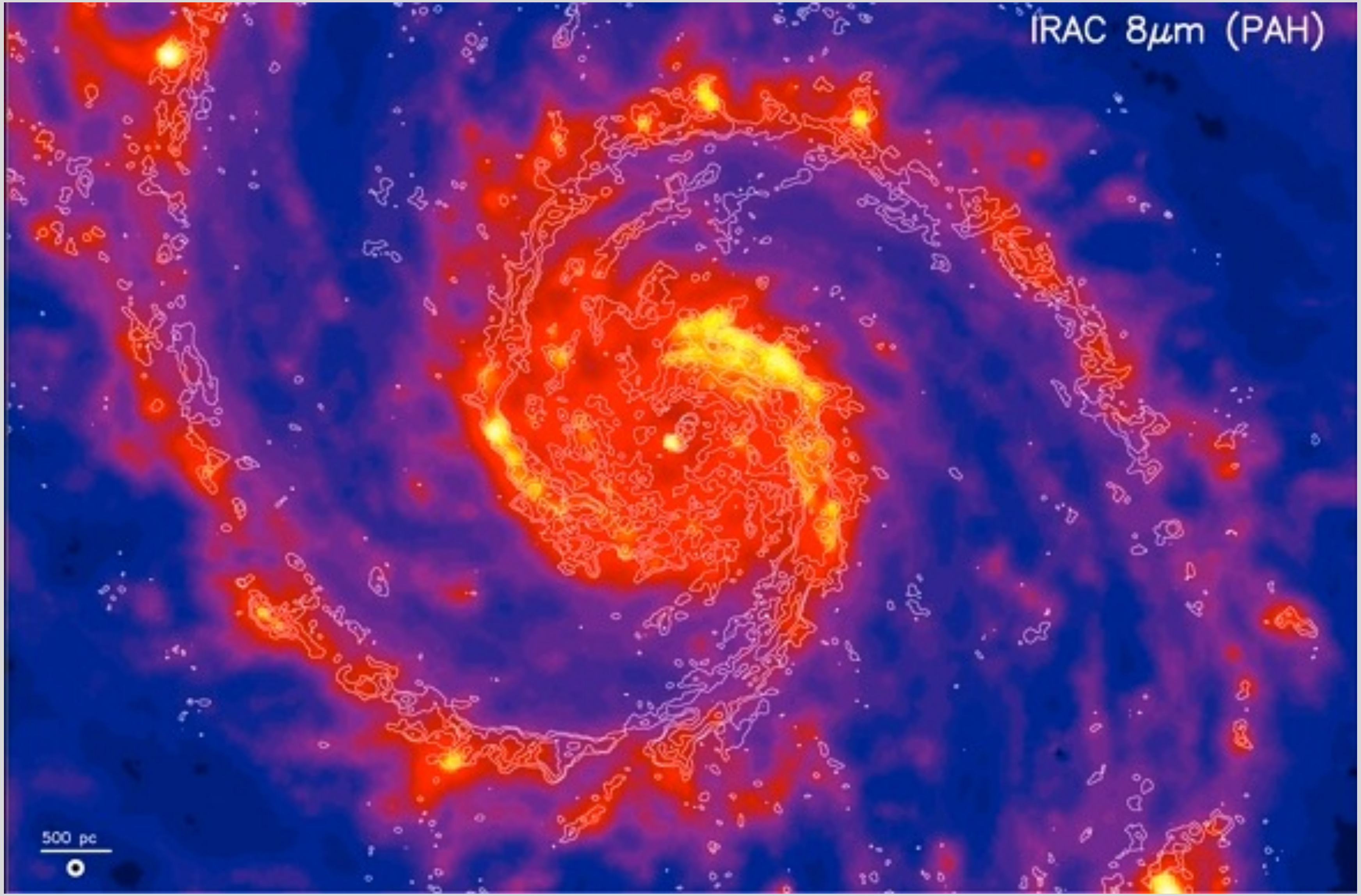
Thermal emission from dust

Dust grains also produce broad **emission lines** in the mid-IR.

PAH emission: “Polycyclic Aromatic Hydrocarbons”

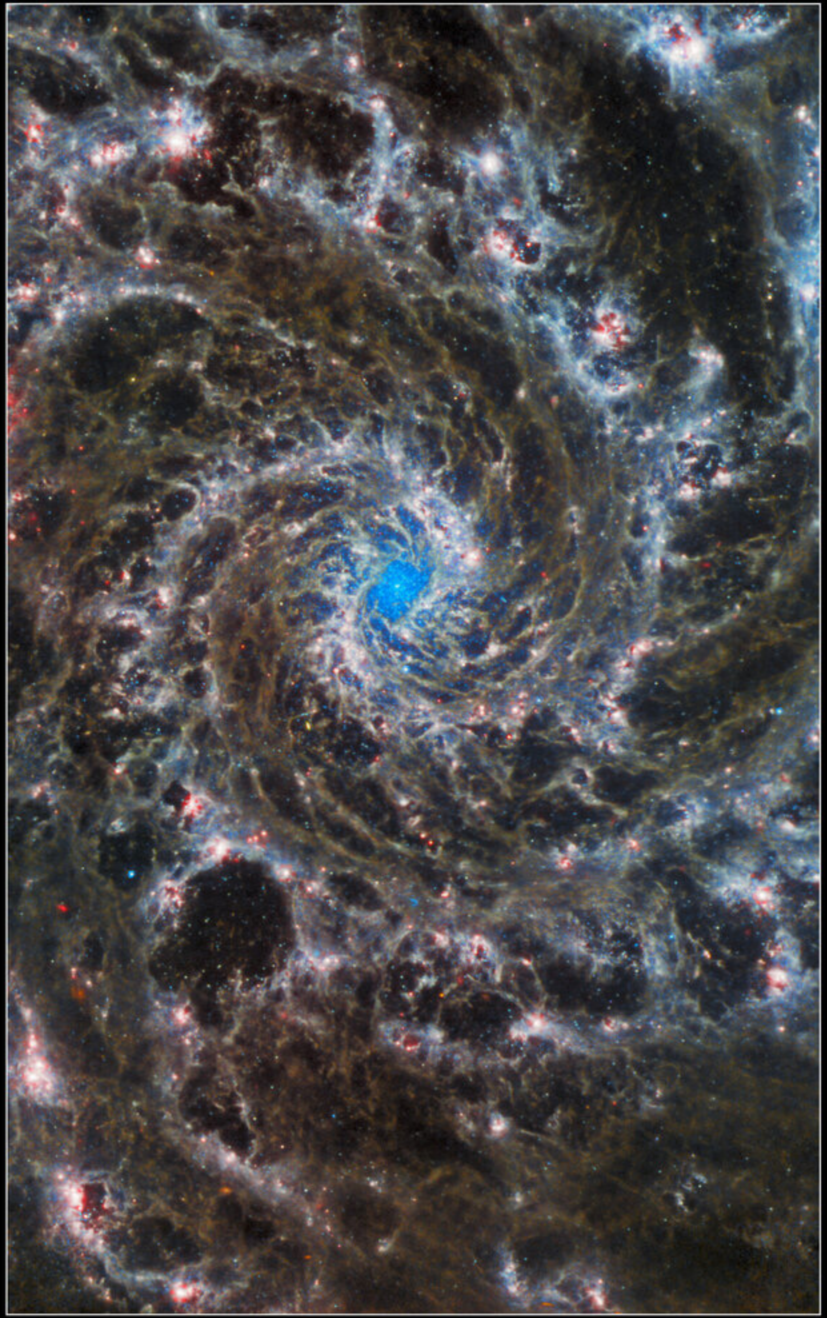
This emission traces warm dust in the spiral arms and nucleus.

PAH emission in M51



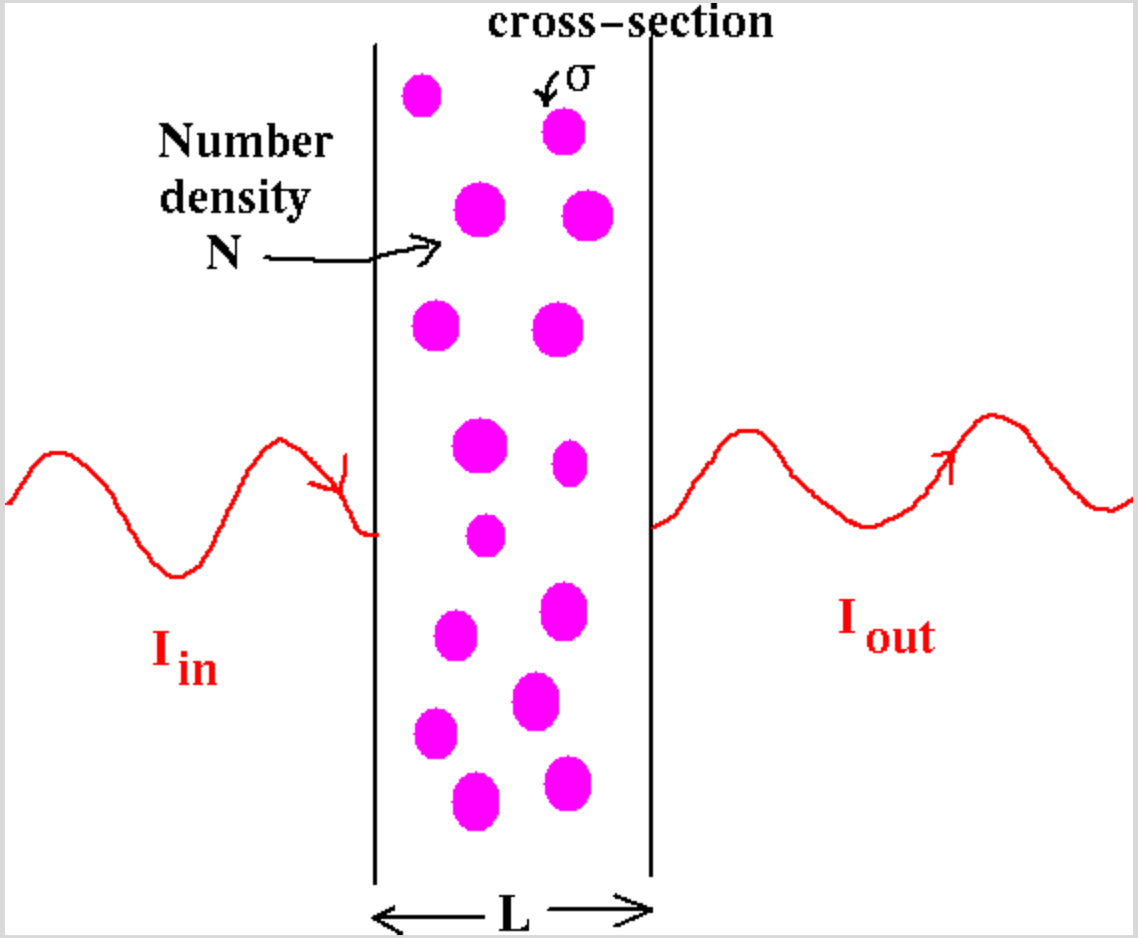

Hubble / Optical


Hubble & Webb


Webb / Infrared

Dust Extinction

Imagine light going through a slab of dust particles



Define optical depth: $\tau = N\sigma L$

then $I_{out} = I_{in}e^{-\tau}$

Working out the extinction in magnitudes

The light is extincted by a factor

$$I_{out}/I_{in} = e^{-\tau}$$

Converting this to magnitudes:

$$\begin{aligned} m_{out} - m_{in} &= -2.5\log(e^{-\tau}) \\ &= -2.5(-\tau)\log e \\ &= 1.086\tau \end{aligned}$$

We define the extinction term in magnitudes as

$$A = 1.086\tau$$

so $m_{out} - m_{in} = A$

In other words, the true apparent magnitude (if there had been no dust) is related to the observed apparent magnitude by

$$m_{true} = m_{obs} - A$$

Reddening and Extinction

Dust extincts more at bluer wavelengths, so it also reddens the light. Define redding as:

$$\underbrace{E(B-V)}_{\text{reddening}} = \underbrace{(B-V)}_{\text{observed color}} - \underbrace{(B-V)_0}_{\text{true color}}$$

More reddening, more extinction

$$A = R \times E(B-V)$$

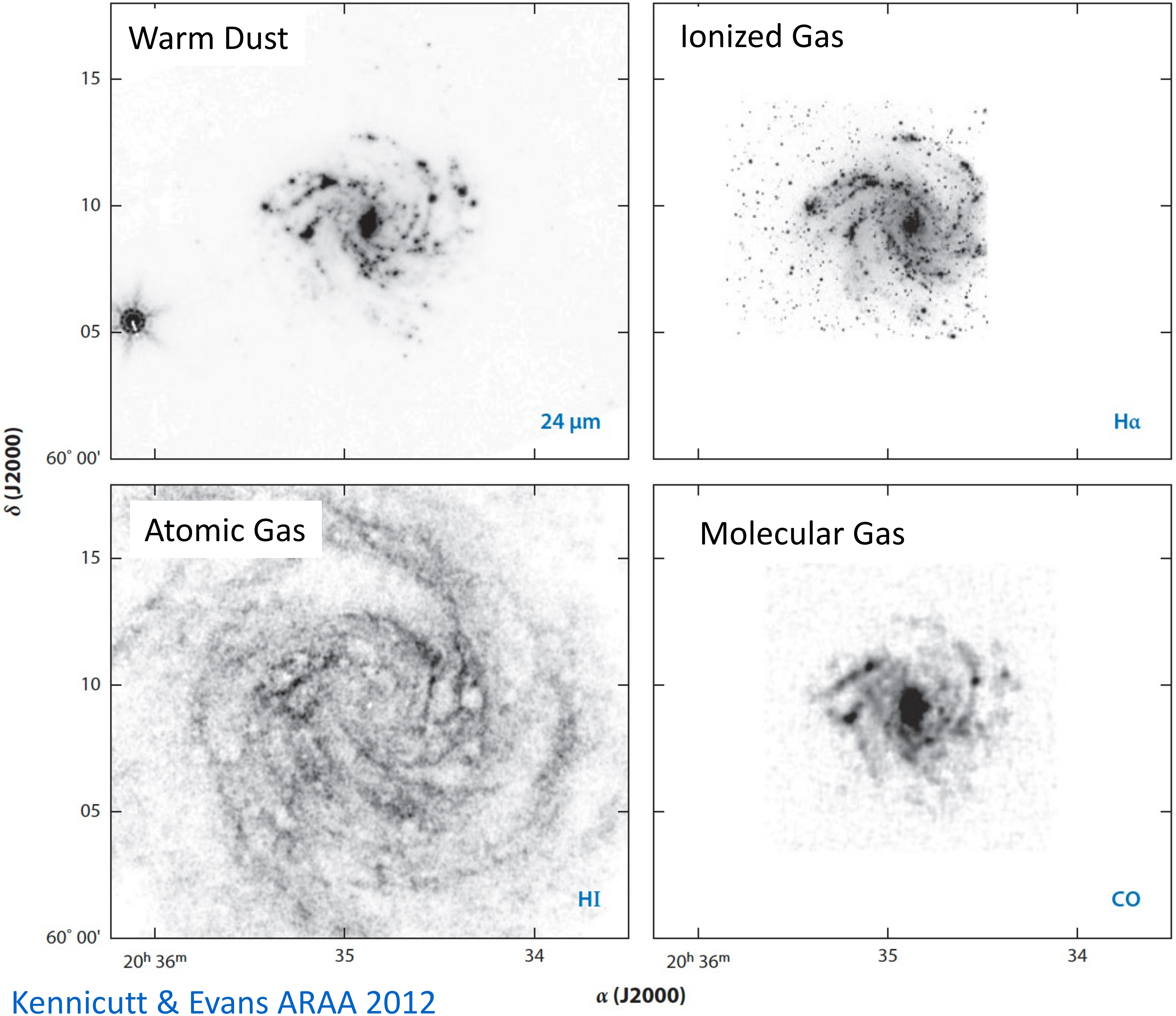
Spatial Distribution of ISM in Spiral Galaxies

Atomic gas (HI) is generally quite extended, outer regions are HI gas-rich.

Molecular gas more centrally concentrated.

Ionized gas (i.e., star formation) follows molecular gas.

Warm dust follows star formation.



Kennicutt & Evans ARAA 2012

Hot gas: X-rays

Gas heated to $10^5 - 10^6$ K by supernovae, stellar winds, shocks.

Highly ionized, so no emission lines in the optical/UV. Largely radiates via **Bremstrahhlung** or **free-free** radiation from charged particles (e^-).

Connect thermal energy and photon energy: kT ≈ hν, gives emission in X-ray.

Some line emission from highly ionized atoms (typically Fe).

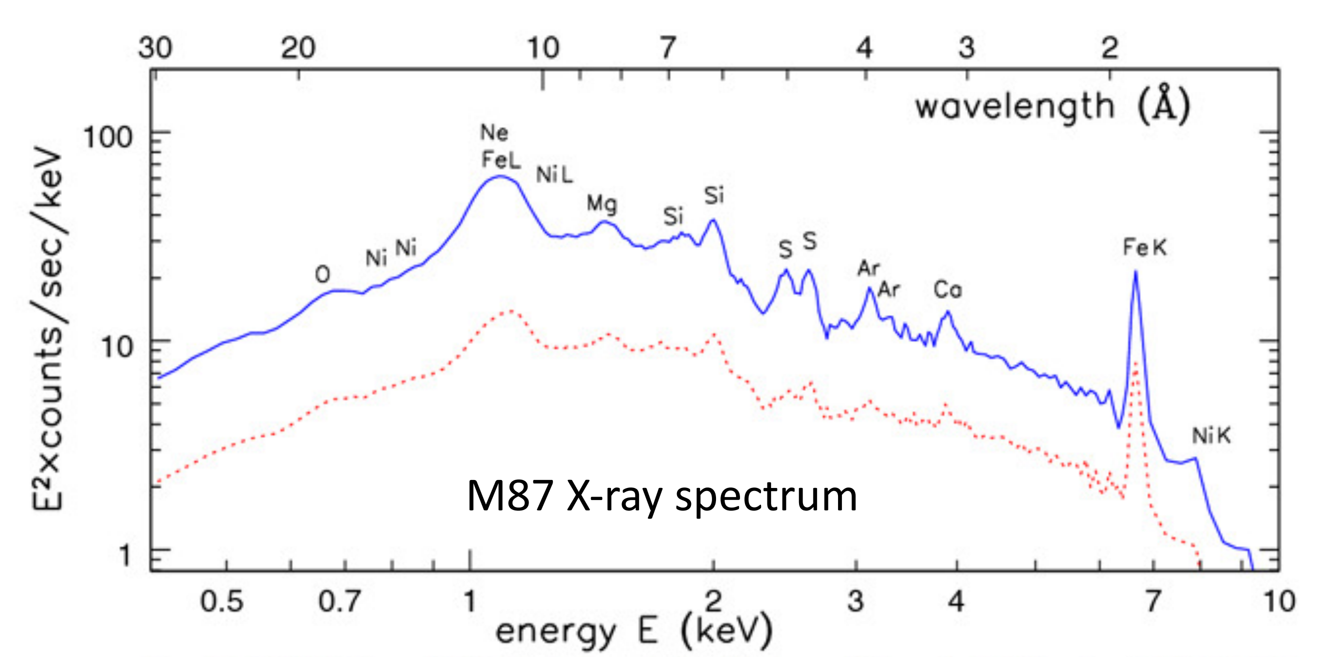
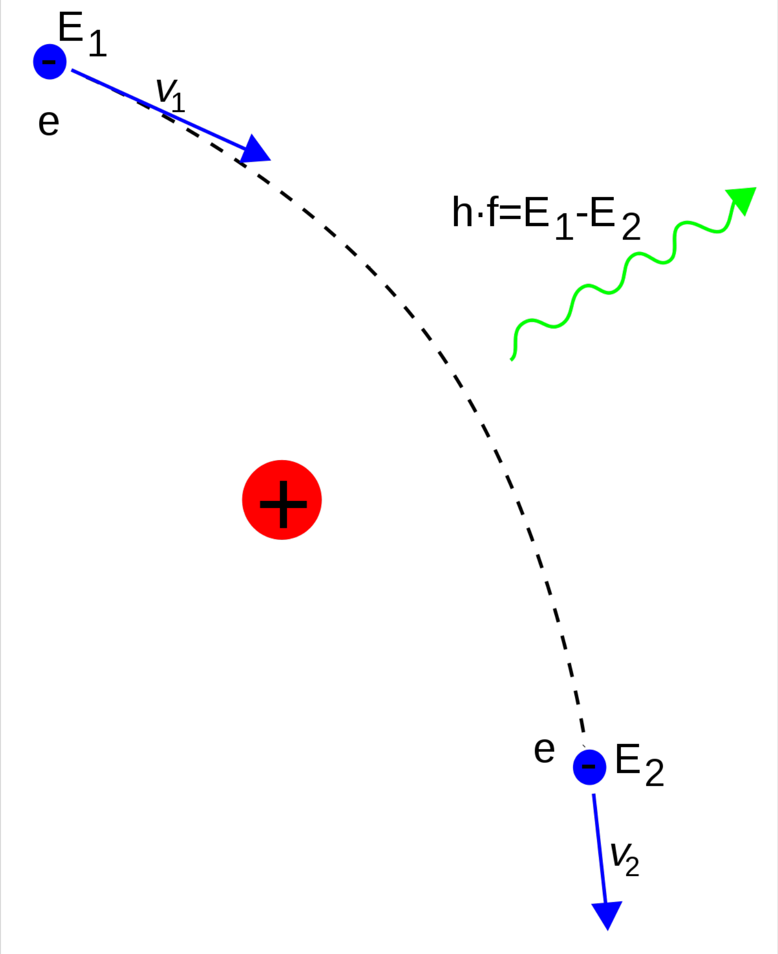


Fig 6.21 (K. Matsushita) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Bremstrahhlug / free-free emission



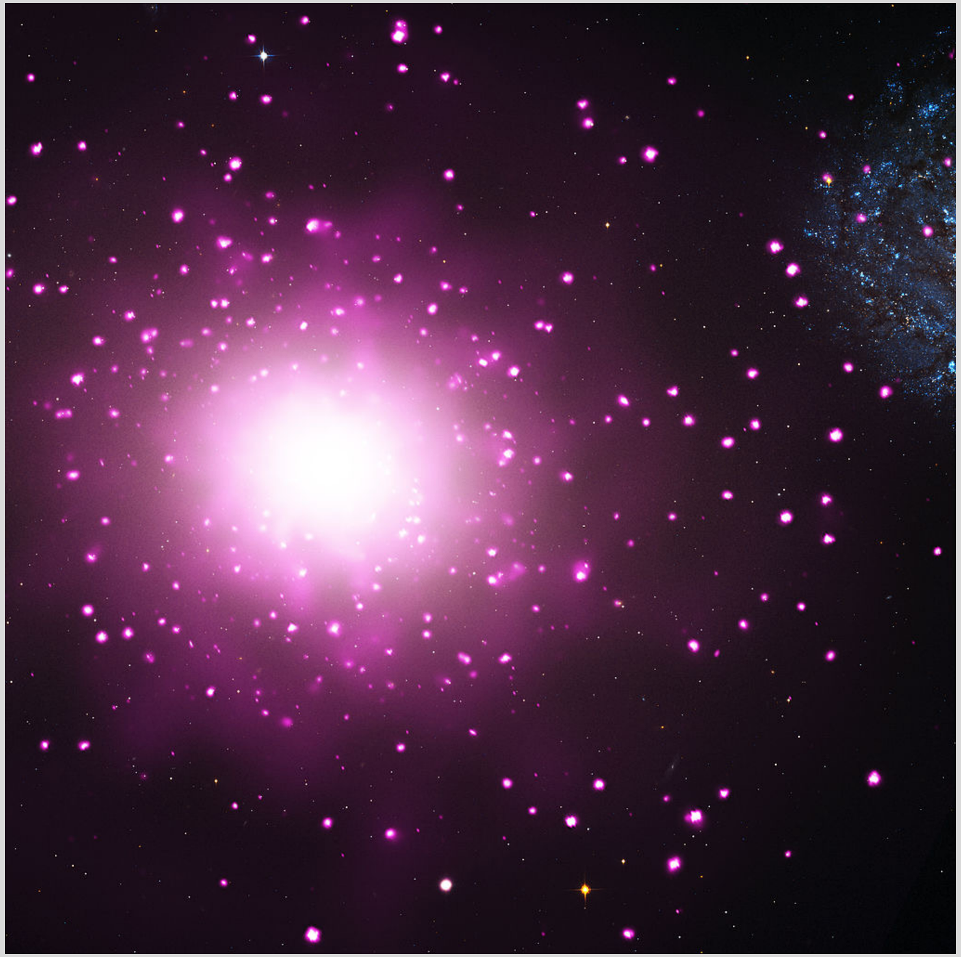
Hot gas in elliptical galaxies (NGC 4649, Strader+)

Optical Starlight

X-ray Emission

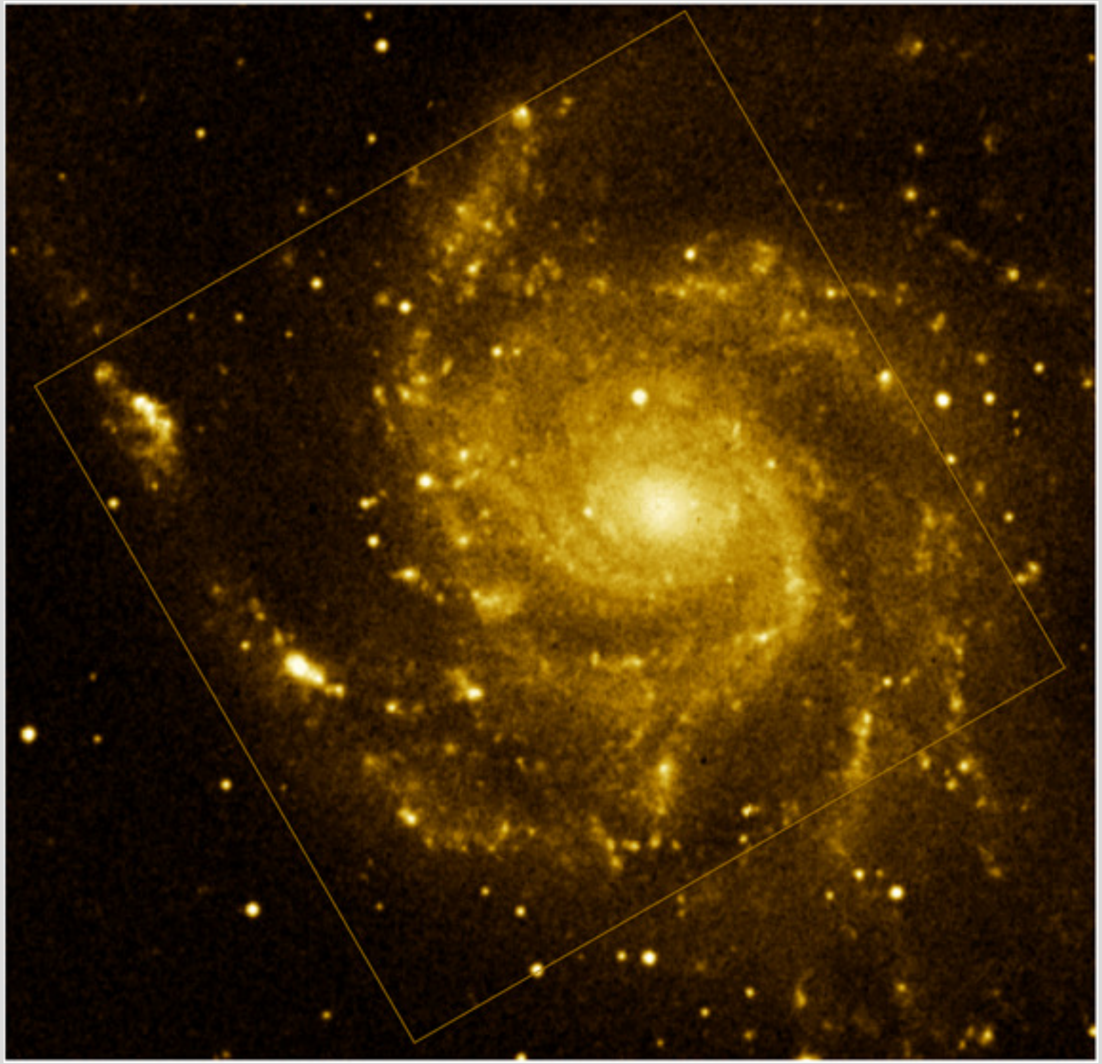
Smooth diffuse emission: free-free emission from hot gas

Point sources: accreting neutron star or black hole (not free-free emission!)



Hot gas in spiral galaxies (M101)

Optical Starlight



X-ray Emission

Smooth diffuse emission: free-free emission from hot gas
Point sources: accreting neutron star or black hole (not free-free emission!)