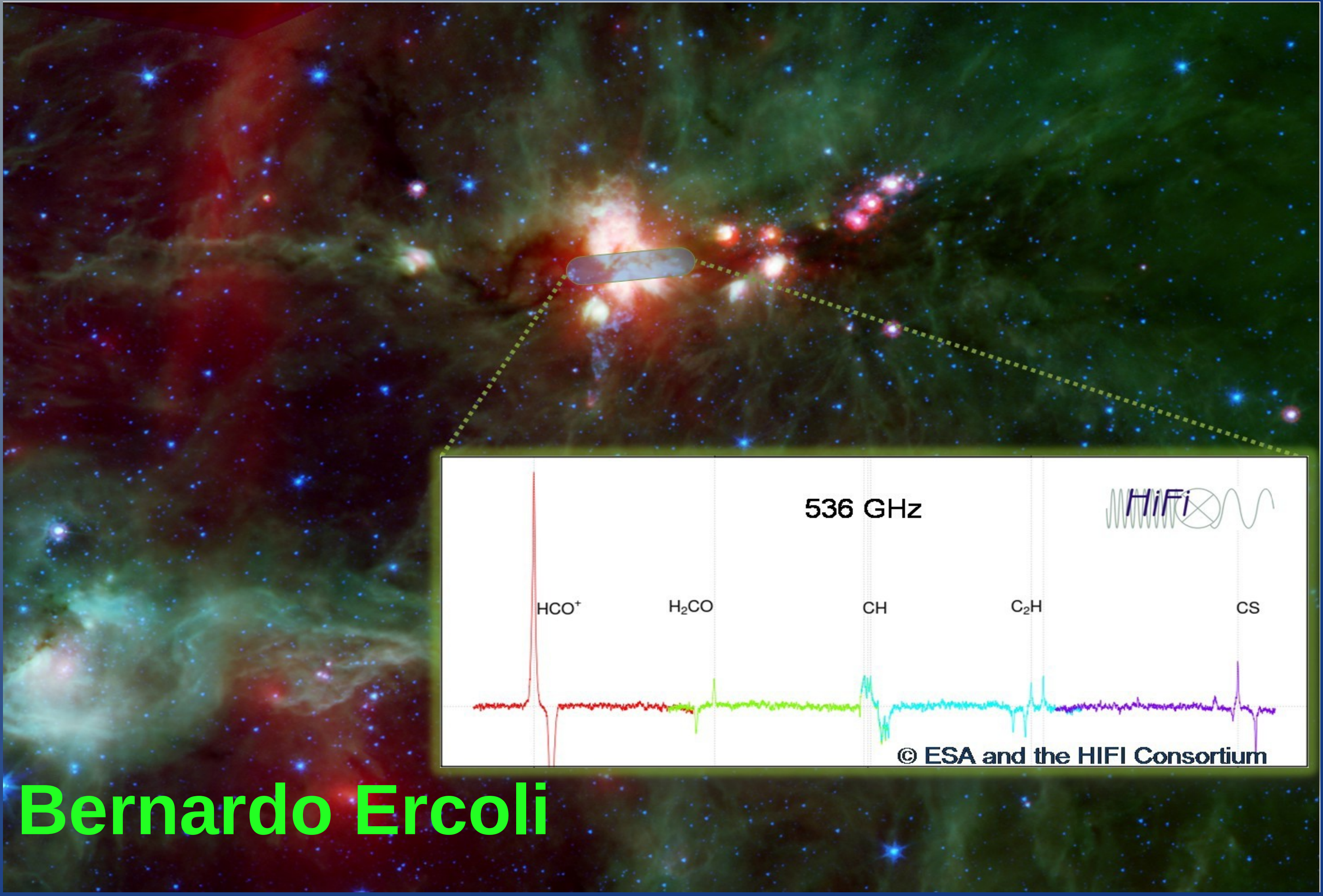
Molecular Line Emission in Star-Forming Regions



Bernardo Ercoli

GENERALITY

Astrochemistry is the study of the molecules and
the reactions of chemical elements in the universe.

The aim of this work is to show its application in star birth regions.

INDEX

1.1 Molecular spectral lines

Molecular spectra can be due to:

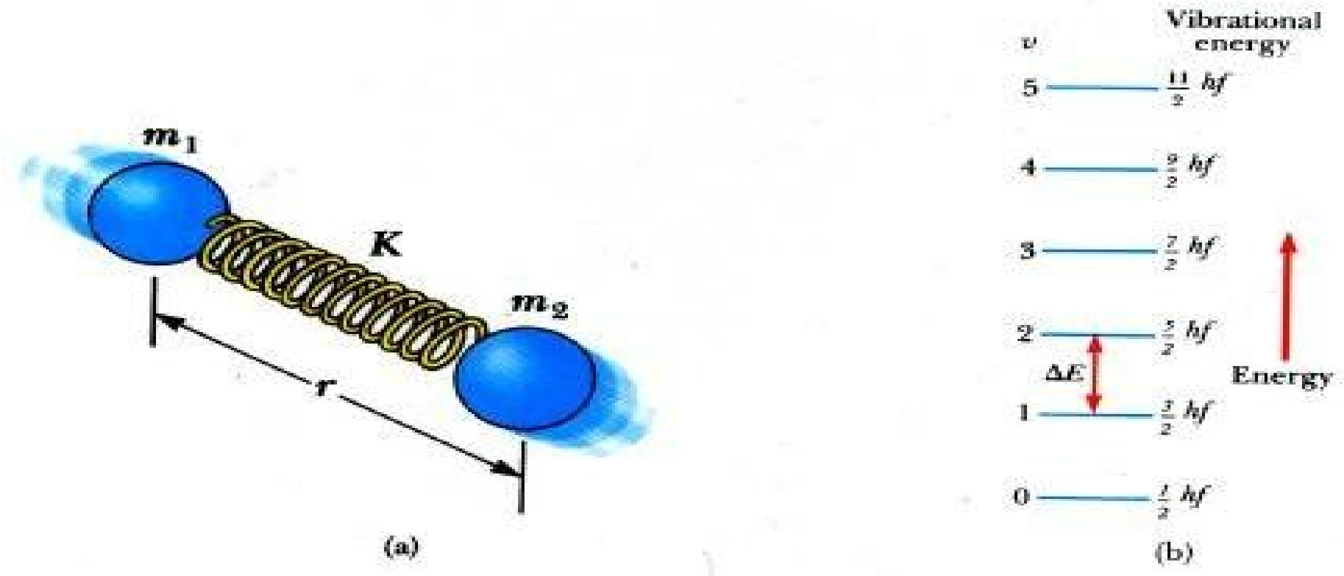
- Molecular rotations
- Molecular vibrations
- Electronic states

Rotations are collective motions of the atomic nuclei and typically lead to spectra in the **microwave and millimeter-wave** spectral regions.

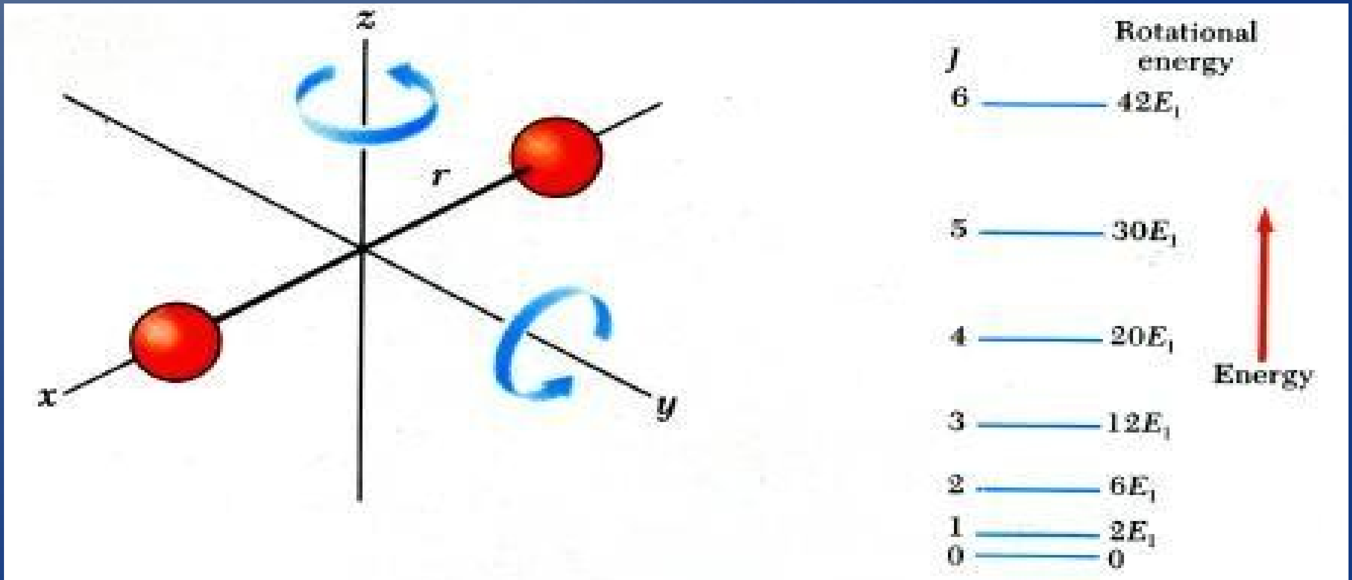
Vibrations are relative motions of the atomic nuclei and are studied by infrared spectroscopy.

Electronic excitations are studied using visible and ultraviolet spectroscopy.

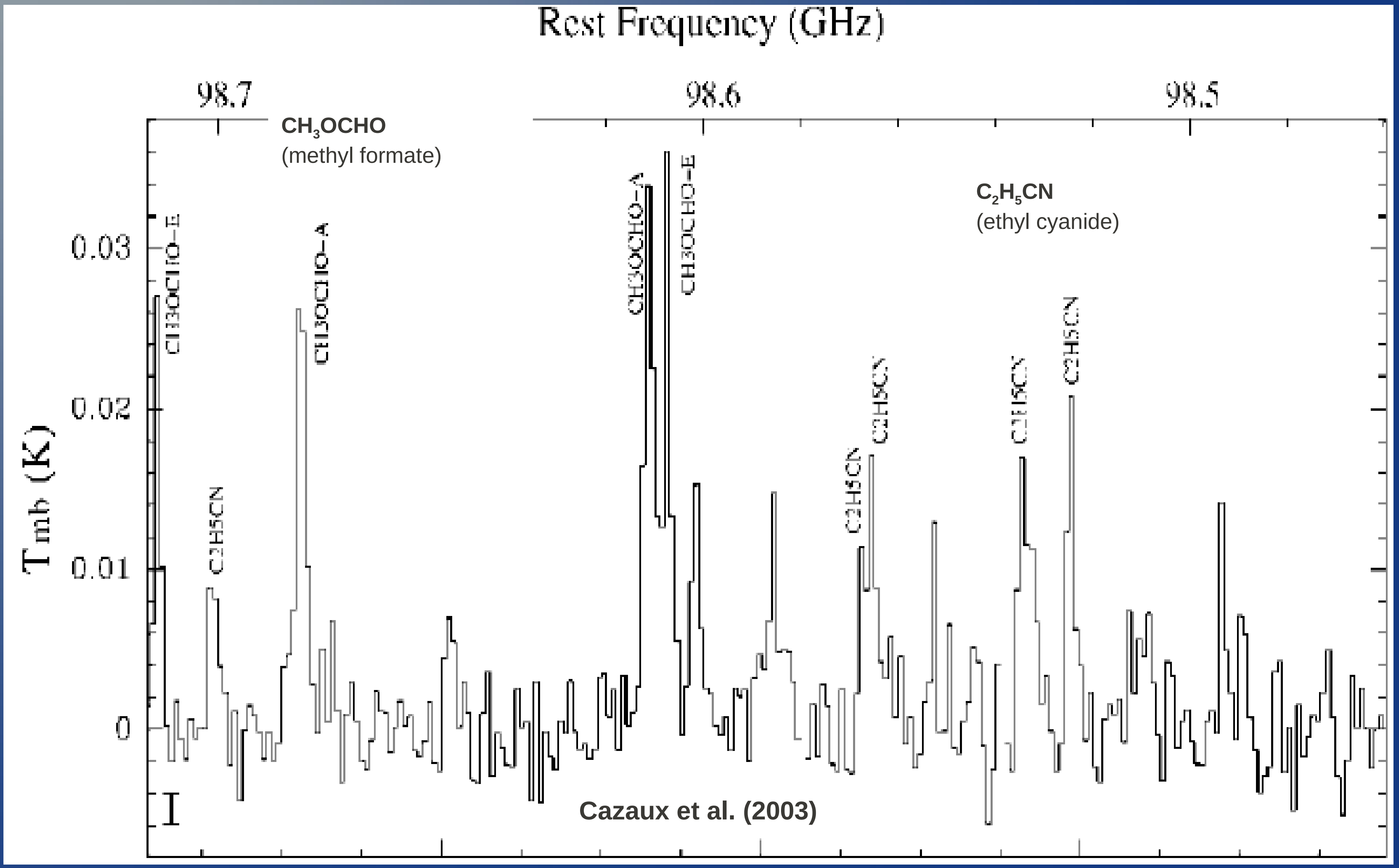
vibrational



rotational



The combination of atoms into molecules leads to the creation of unique types of energetic states and therefore unique spectra of the transitions between these states: we can recognize the molecules from their lines!



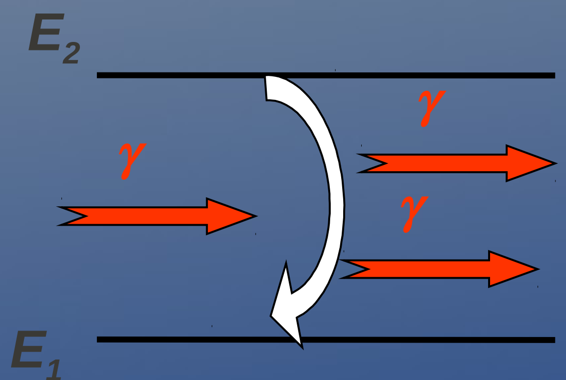
1.2 Masers

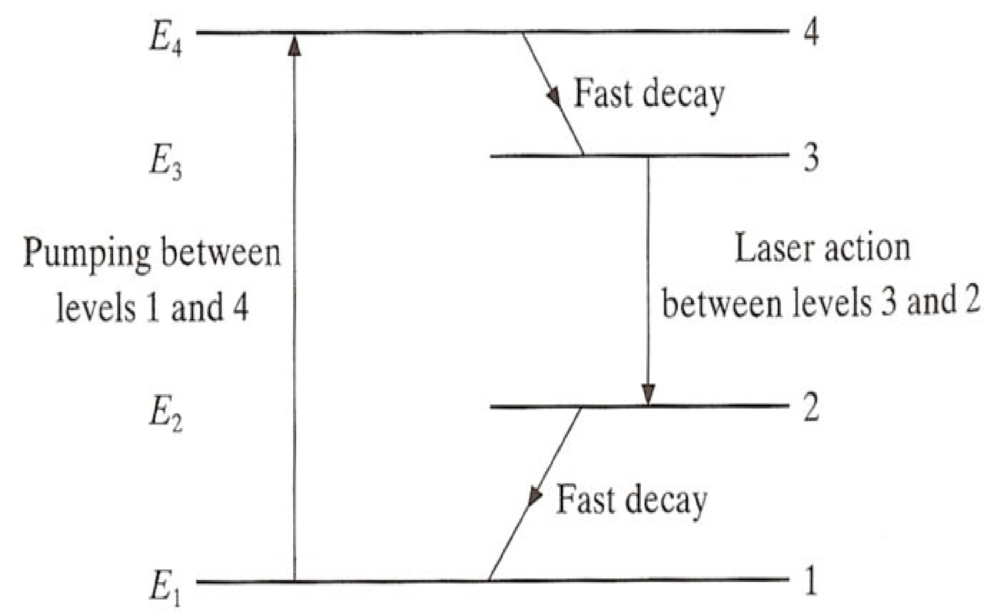
A particular case of molecular lines are Masers (*Microwave Amplification by the Stimulated Emission of Radiation*):

Under normal conditions of thermal equilibrium, the number of particles in lower energy levels is always greater than the number in higher energy levels, this leads to radiation being absorbed rather than amplified; otherwise we assist at a population inversion.

One requirement in creating an inversion is "pumping", either collisionally or radiatively.

Interacting with an another incident photon the molecule returns in ground state of energy (stimulated emission)





Principle of the four-level laser.

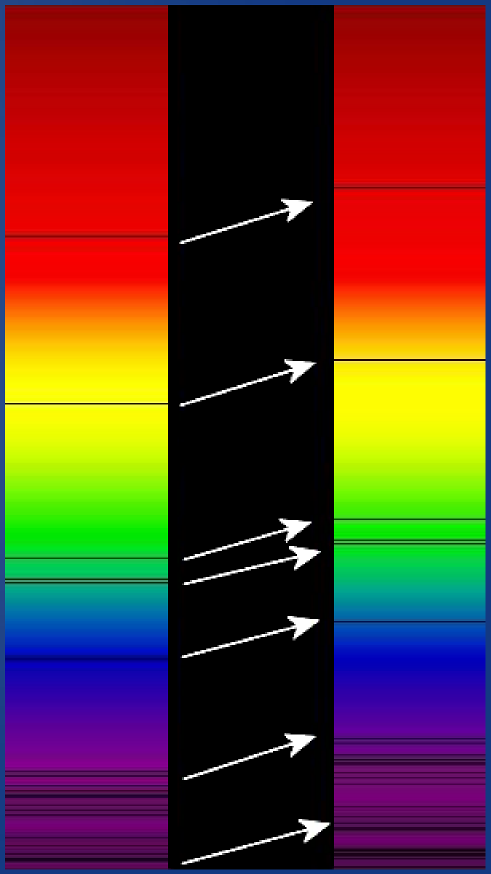
1.3 Doppler effect

The Doppler effect is the relationship between an observed frequency and the radial velocity of the emitting source.
Velocities are usually calculated respect to the **Local Standard of Rest (LSR)**, an ideal point in rotation around the Galactic centre as far as the Sun.

The relationship between velocity and frequency is:

$$\frac{\Delta \nu}{\nu_0} = \frac{\nu_0 - \nu}{\nu_0} = \frac{V_{LSR}}{c}$$

The doppler effect determins in this spectrum a redshift.



2 S**tar Forming Regions**

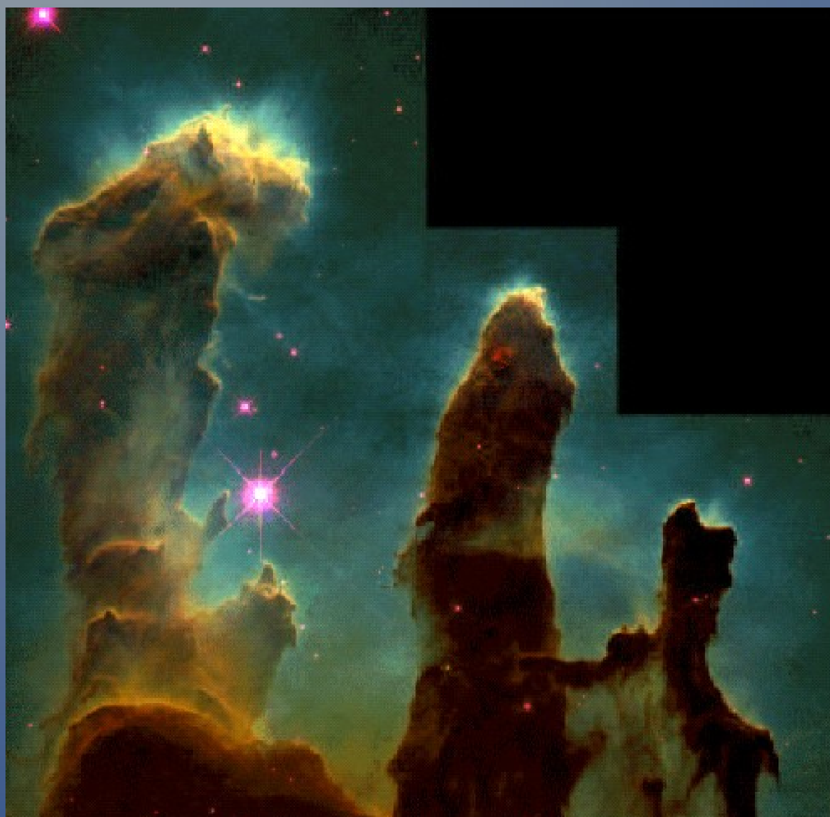
2.1 Molecular clouds

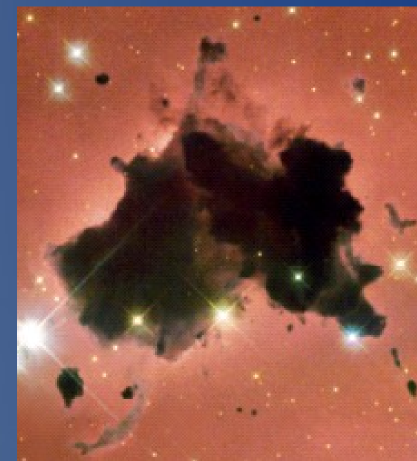
Stars are formed within extended regions of higher density in the interstellar medium.

These regions, called **molecular clouds, observationally can be traced with carbon monoxide (CO) whereas their dense cores can be traced with ammonia (NH3).**

The concentration of dust is normally sufficient to block light from background stars so that there appear "dark nebulae".

The Eagle Nebula, Hester et al. (1995)

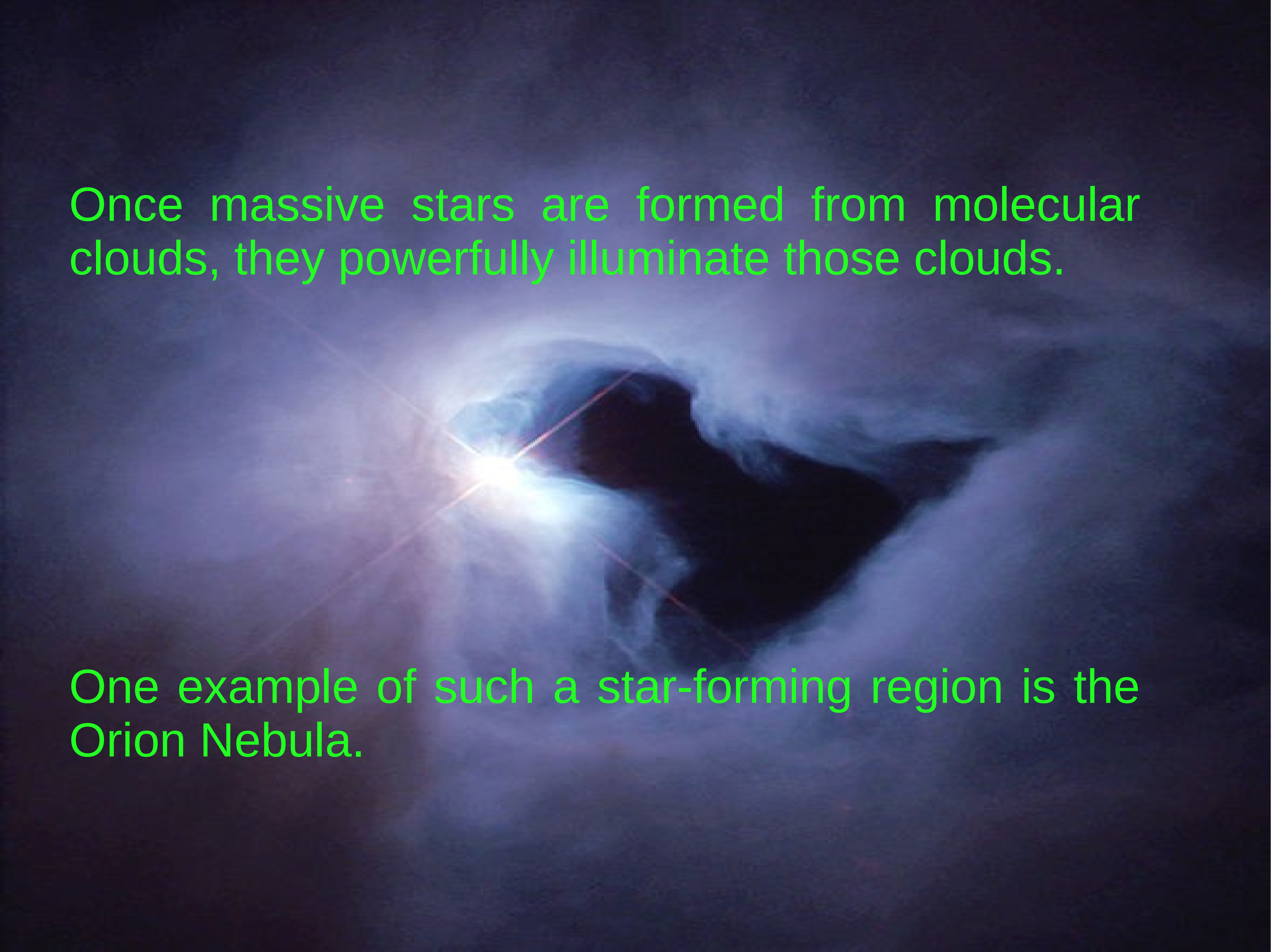




Thackeray’s Globule in IC 2944, Reipurth et al. (2002)

The Horsehead Nebula, HST Heritage project

Stars form within dense interstellar clouds of gas and dust



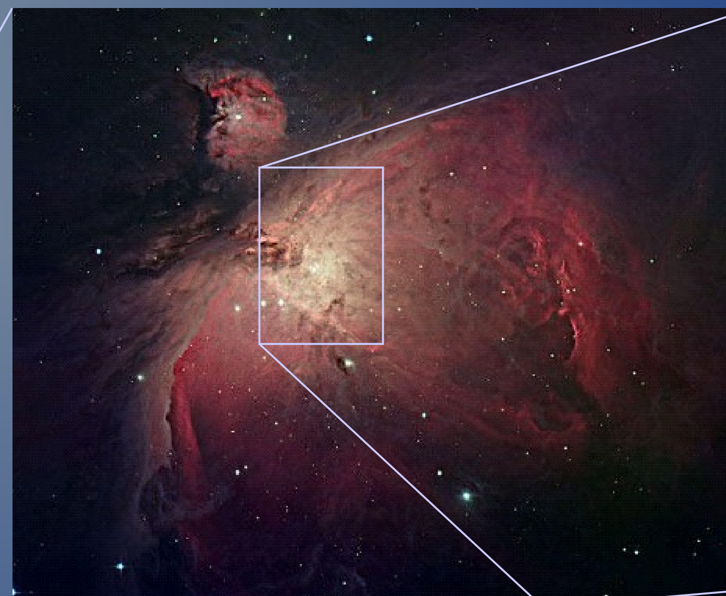
Once massive stars are formed from molecular clouds, they powerfully illuminate those clouds.

One example of such a star-forming region is the Orion Nebula.

2.2 Orion molecular cloud

Akira Fujii

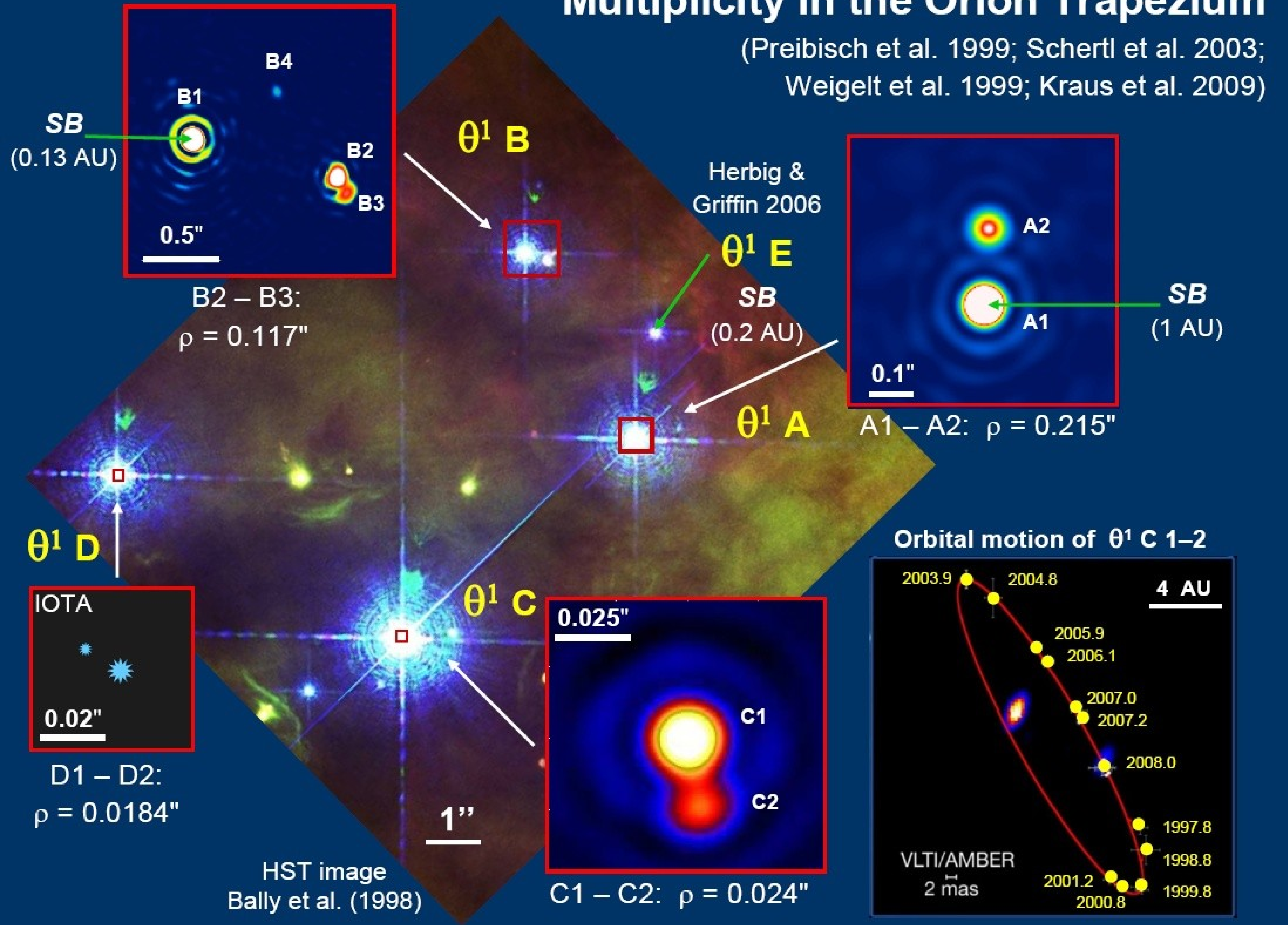
David Malin



HST image (O’Dell 1995)

Multiplicity in the Orion Trapezium

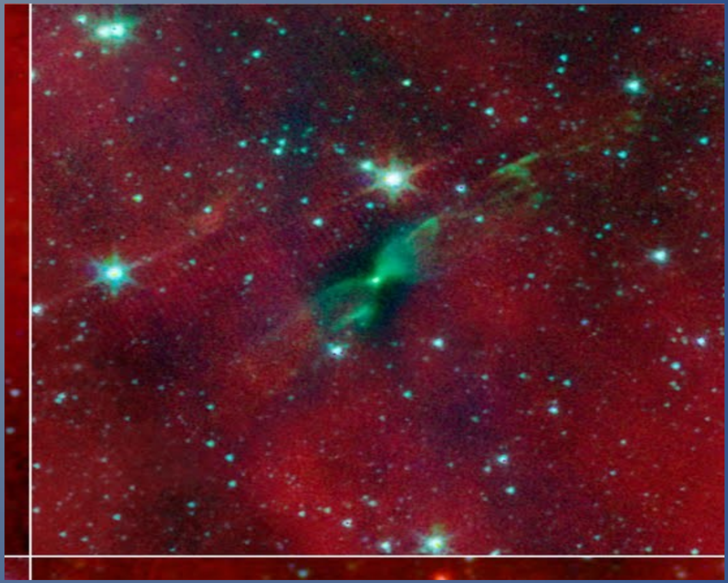
(Preibisch et al. 1999; Schertl et al. 2003;
Weigelt et al. 1999; Kraus et al. 2009)



2.3 Outflows and disks

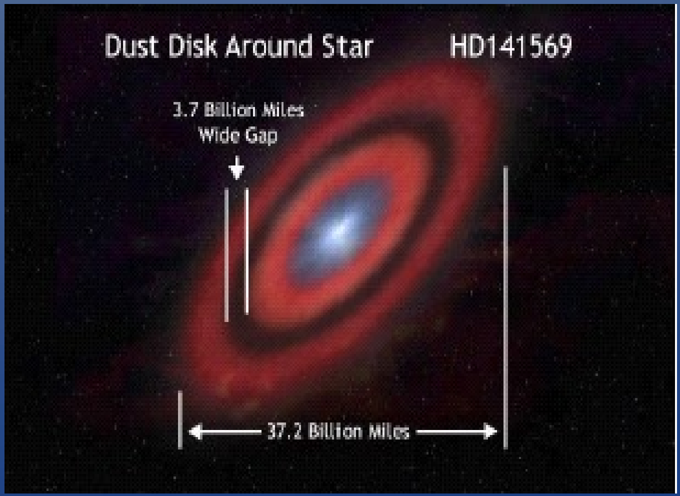
Associated to young stellar objects are:

- **Outflows**, wich provide critical angular momentum transport from the disk, allowing accretion to proceed

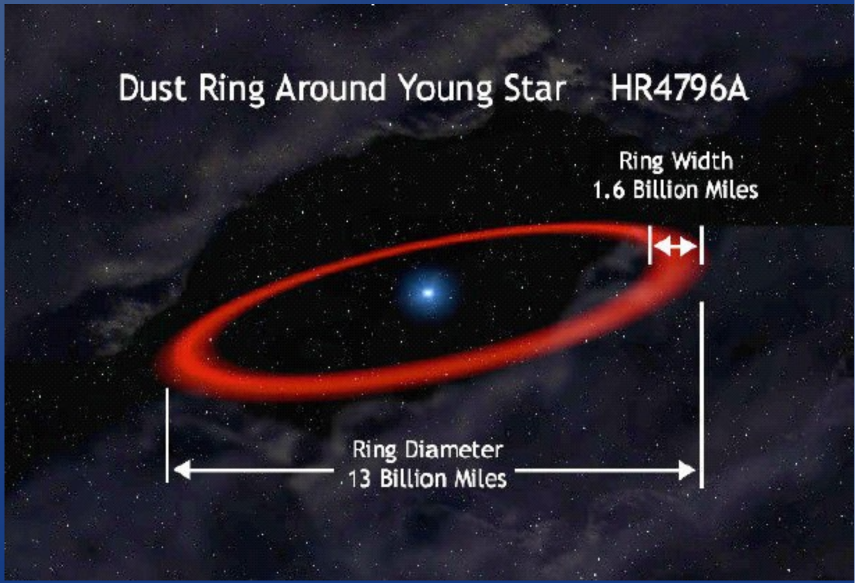


NASA's Spitzer Space Telescope

- **Accretion disk** (Protoplanetary Disk, *proplyd*)



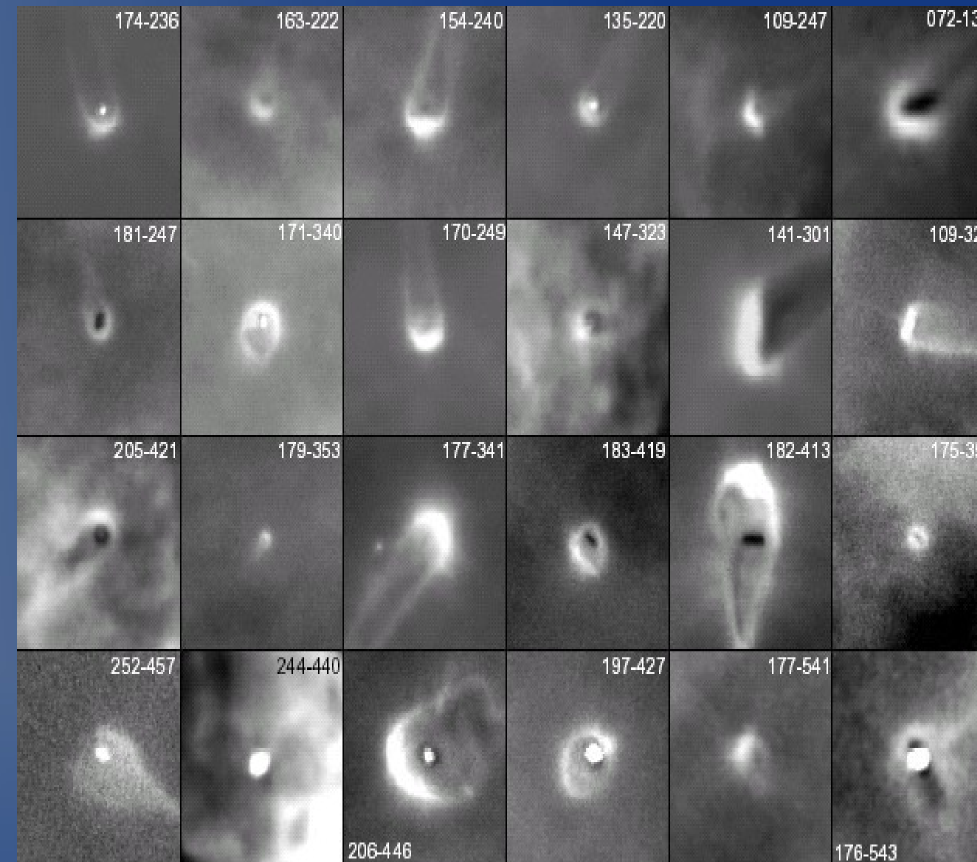
Schneider et al. (1999)



HH 111

Forming stars and disks

HH 111. IR and visible light (HST) showing jet and nebula above edge-on accretion disk (Reipurth et al. 1997, Reipurth & Bally 2001).



Disk irradiated by the Trapezium stars and in silhouette against bright nebular emission. Bally, O’Dell, McCaughrean 2000

3. Molecular lines emission in star-forming regions

Physical conditions:

- The excitation conditions depend on T_K, n $_{H2}$ and the radiation field.
    - Molecular clouds:
      $T_K \sim 10$ K $\rightarrow$ excites lowest rotational transitions
    - From line intensities: Tex, N

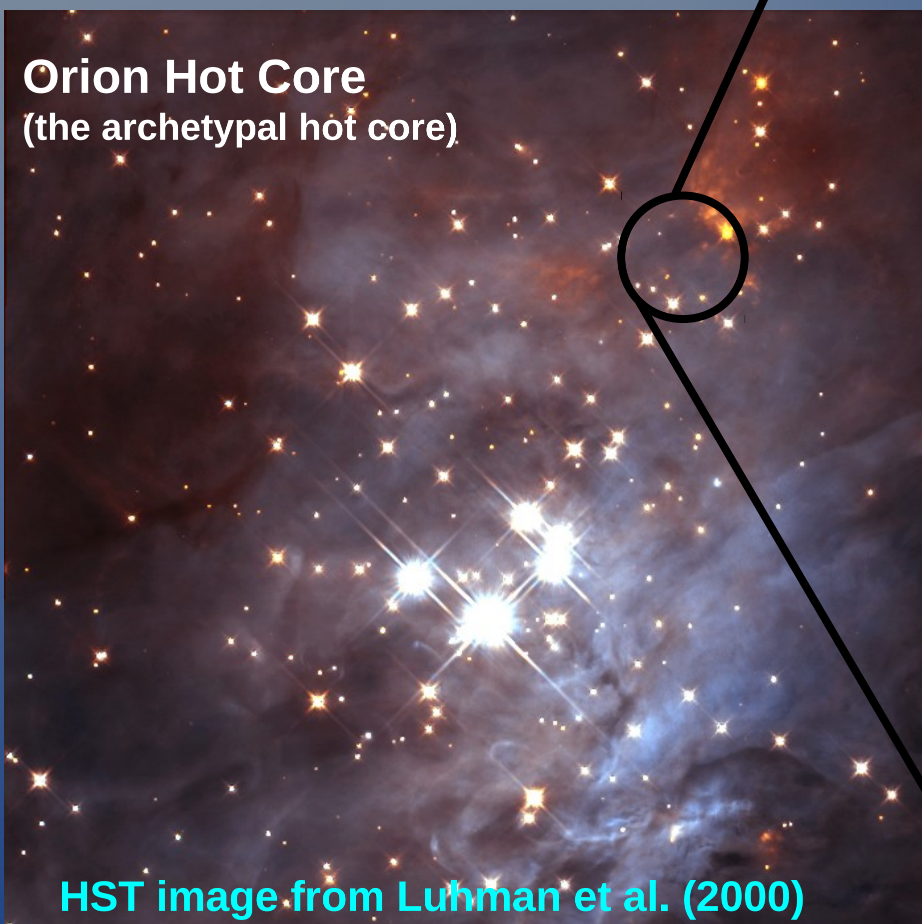
Kinematics:

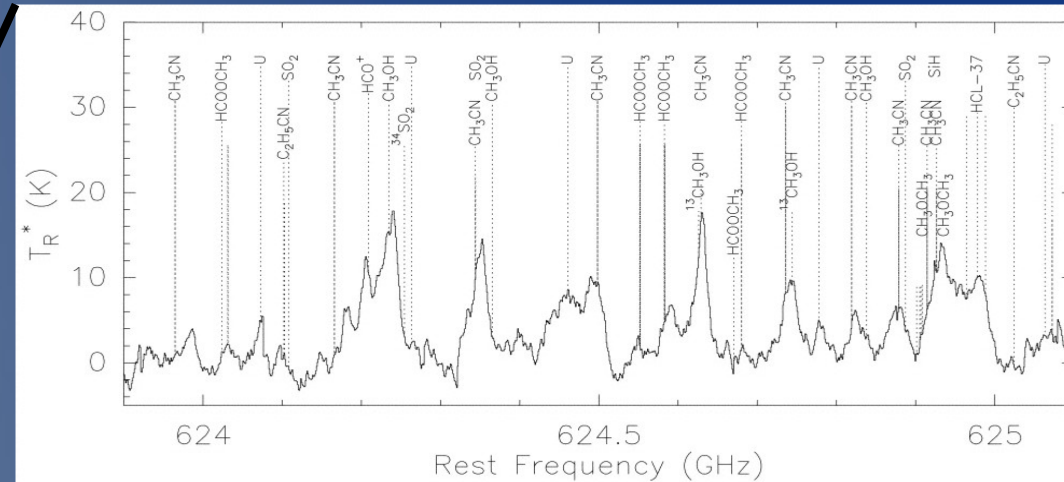
- Linewidths and shapes $\rightarrow$ turbulent and systemic motions of the gas

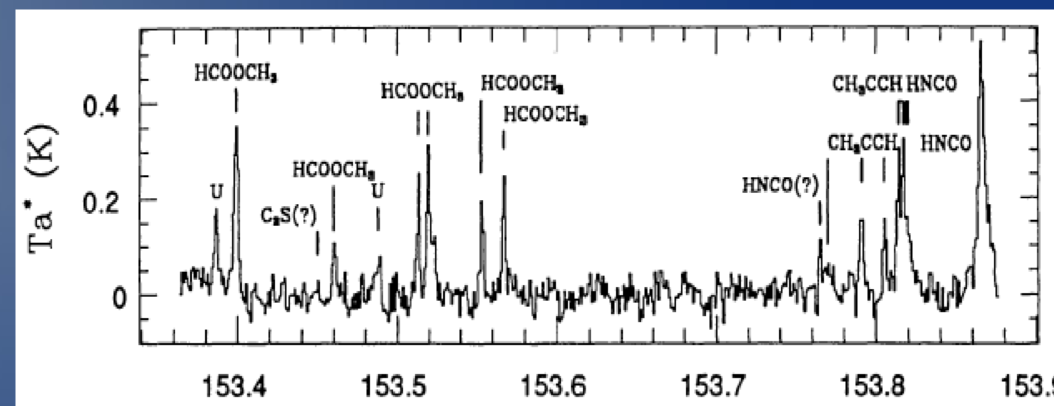
Stage of evolution:

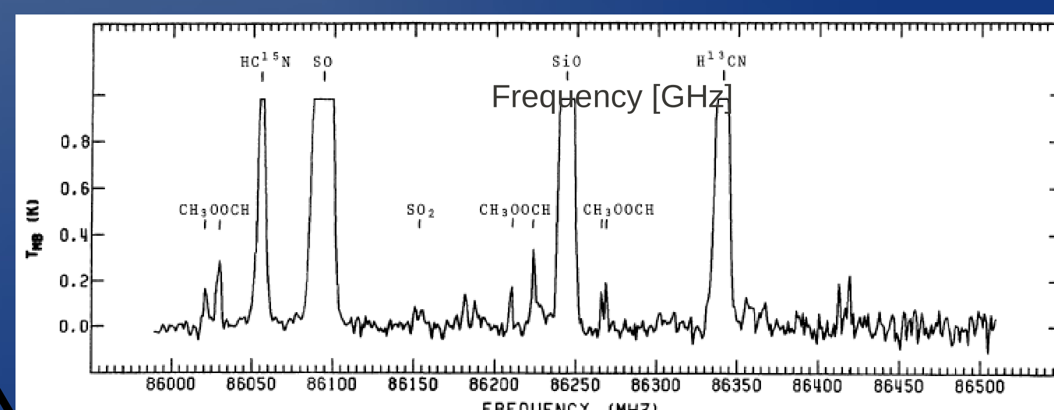
- Time-dependent chemistry and the spatial distribution of some species (e.g. NH_3 (late-type molecule) and CCS (early-type molecule)).

3.1 Hot cores



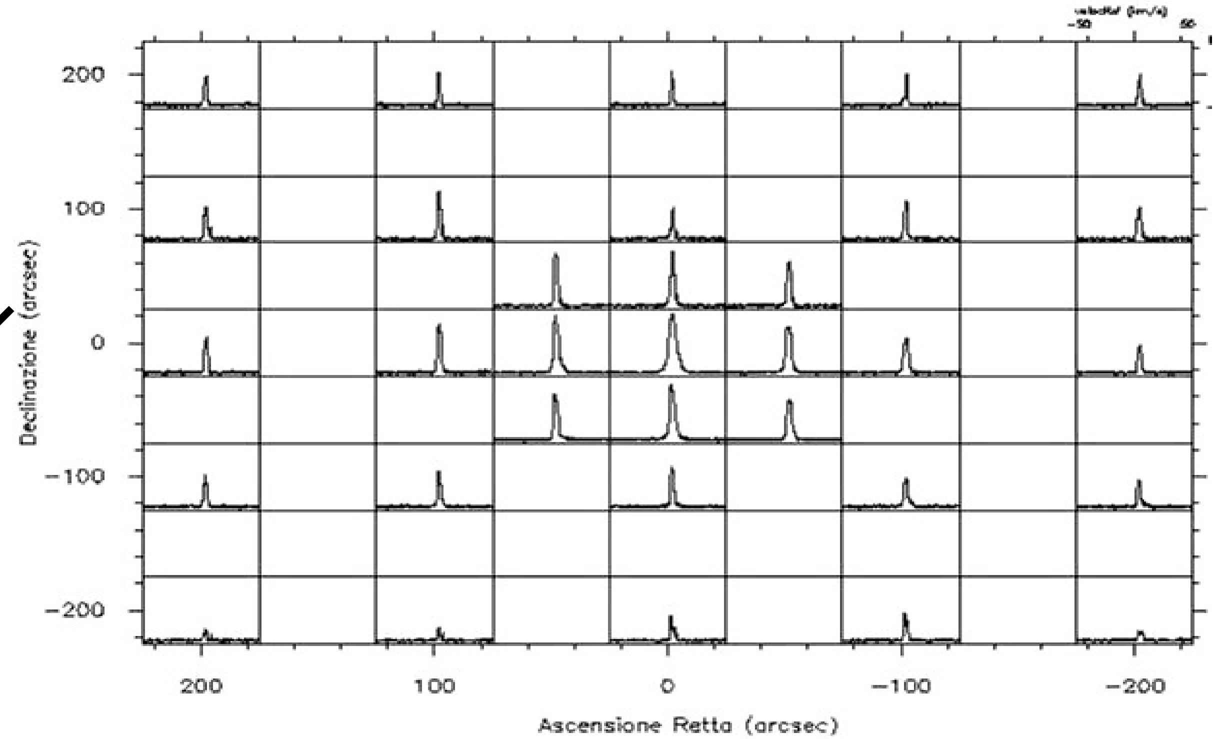


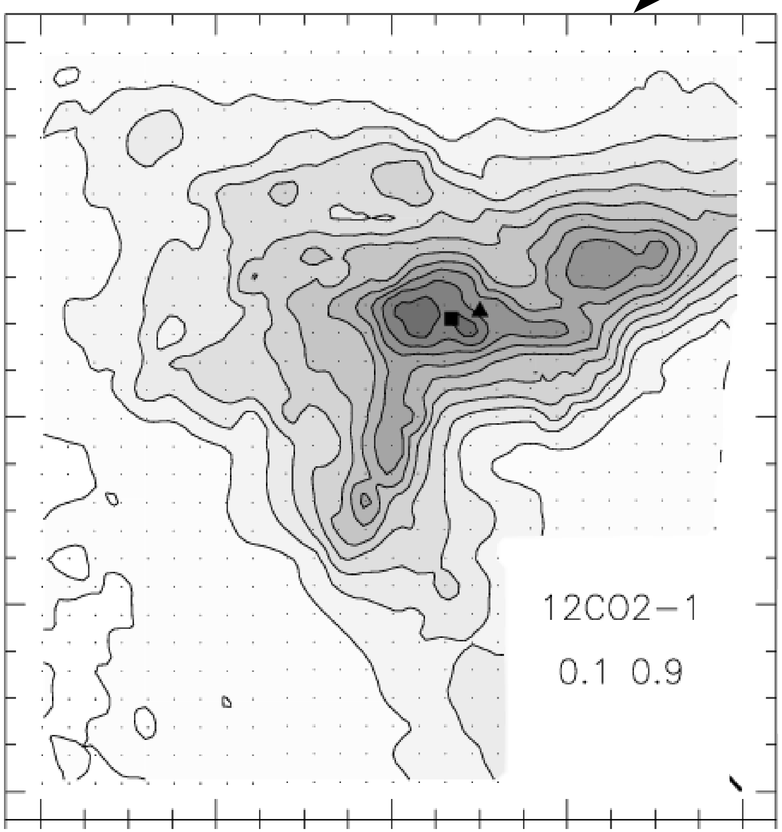




Spectral line surveys:
Schilke et al. (2001); Ziurys & McGonagle (1993) Johansson et al. (1984)

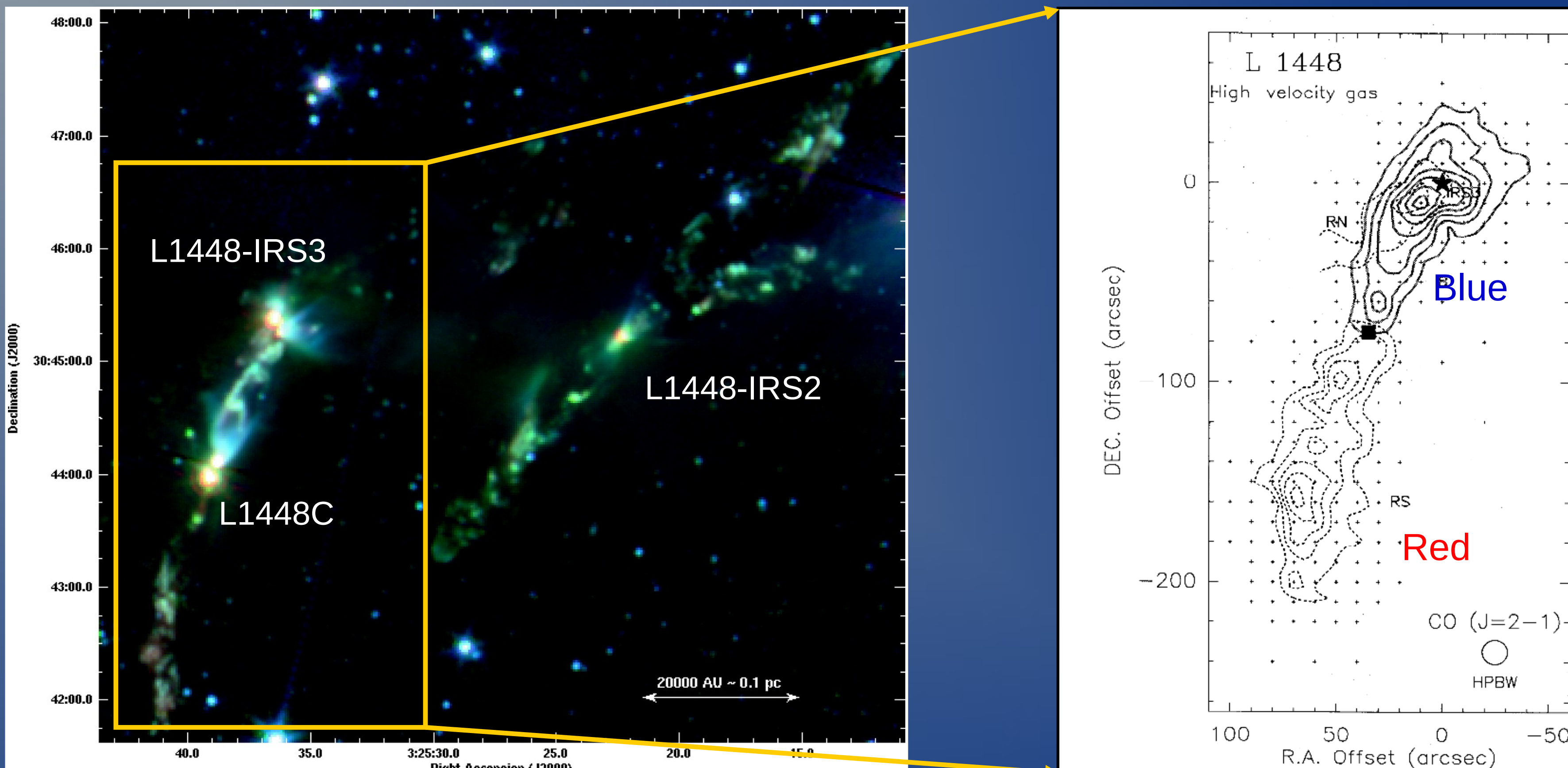
Maps


Declinazione (arcsec)
Ascensione Retta (arcsec)
200
100
0
−100
−200
200
100
0
−100
−200


12CO2−1
0.1 0.9

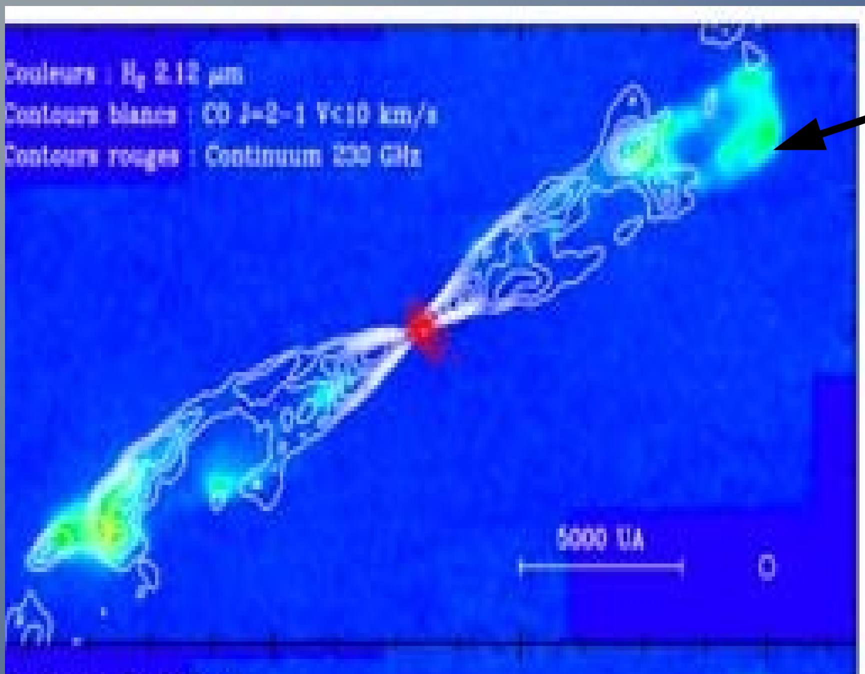
3.2 Outflows

Doppler effect:
Blue (approaching) and Red (receding) part of the outflow



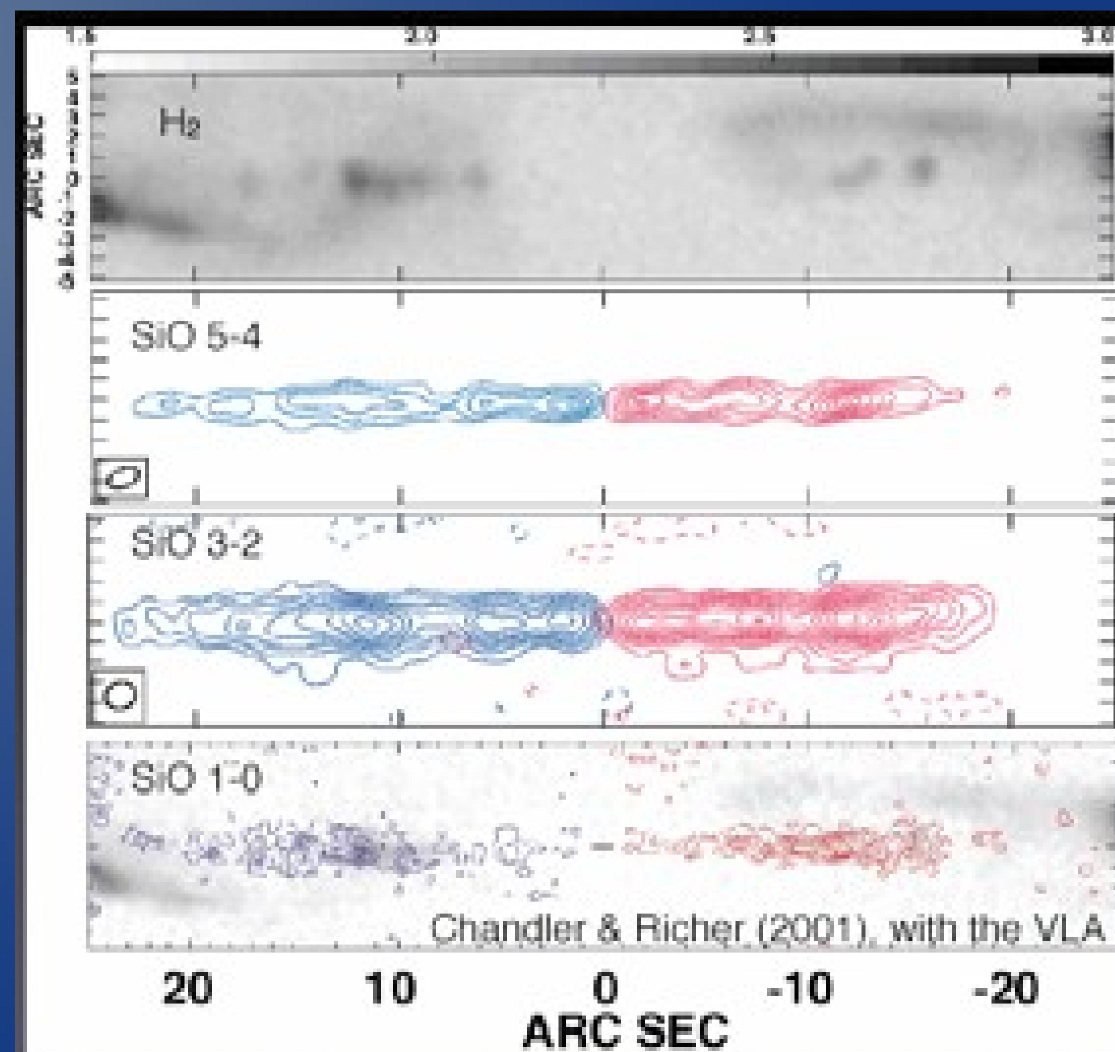
- Located in Perseus molecular cloud (250 pc; Enoch et al. 2006).
- L1448-C (Class 0 source) and L1448-IRS3 (Class0/I source).
- Spectacular molecular outflow (Bachiller et al. 1990)

CO (white contours) and 1 mm continuum (red contours).



Shock-excited molecular hydrogen , H2 in green color.

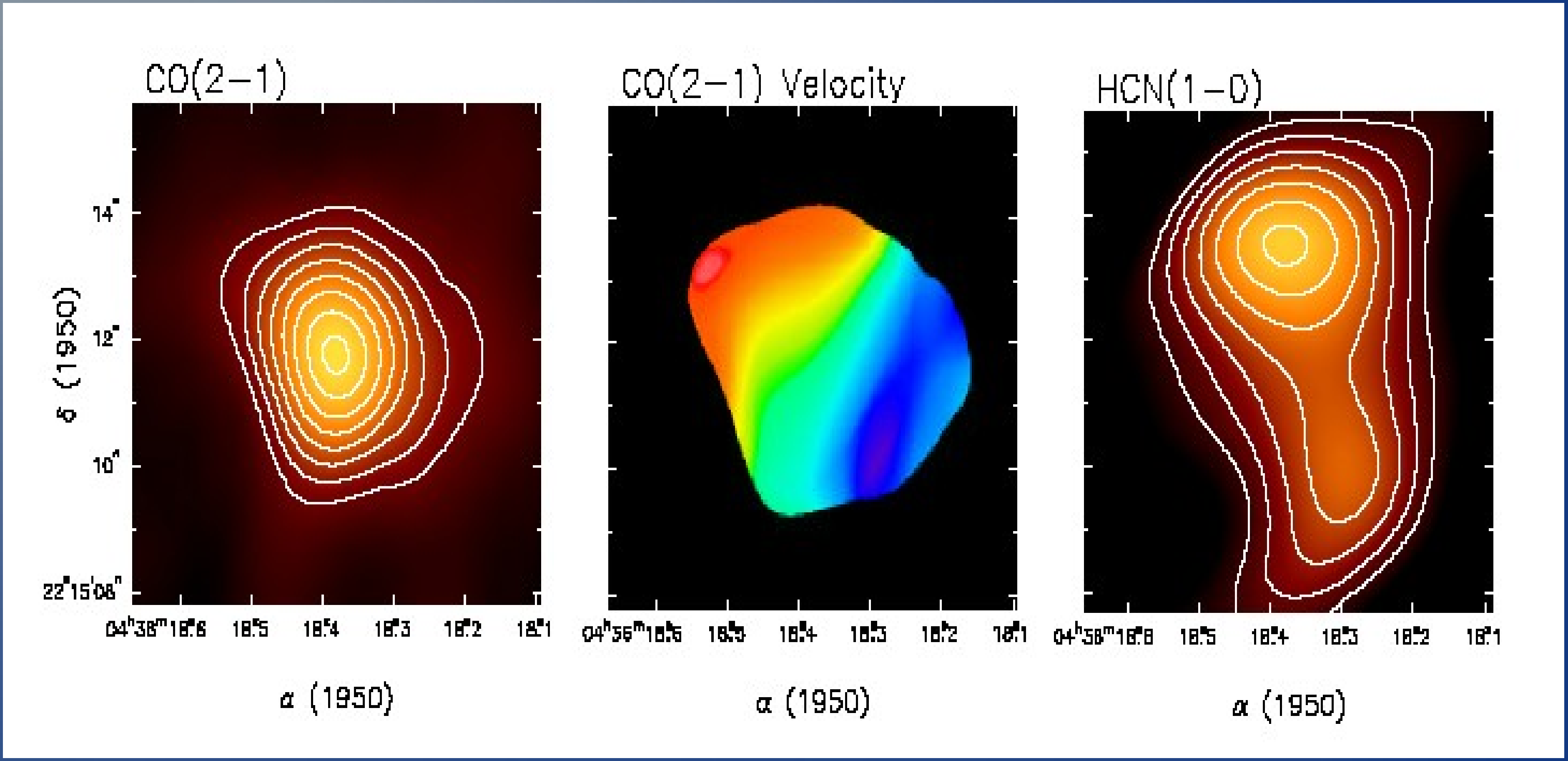
(McCaughrean et al. 1994, Gueth & Guilloteau 1999).



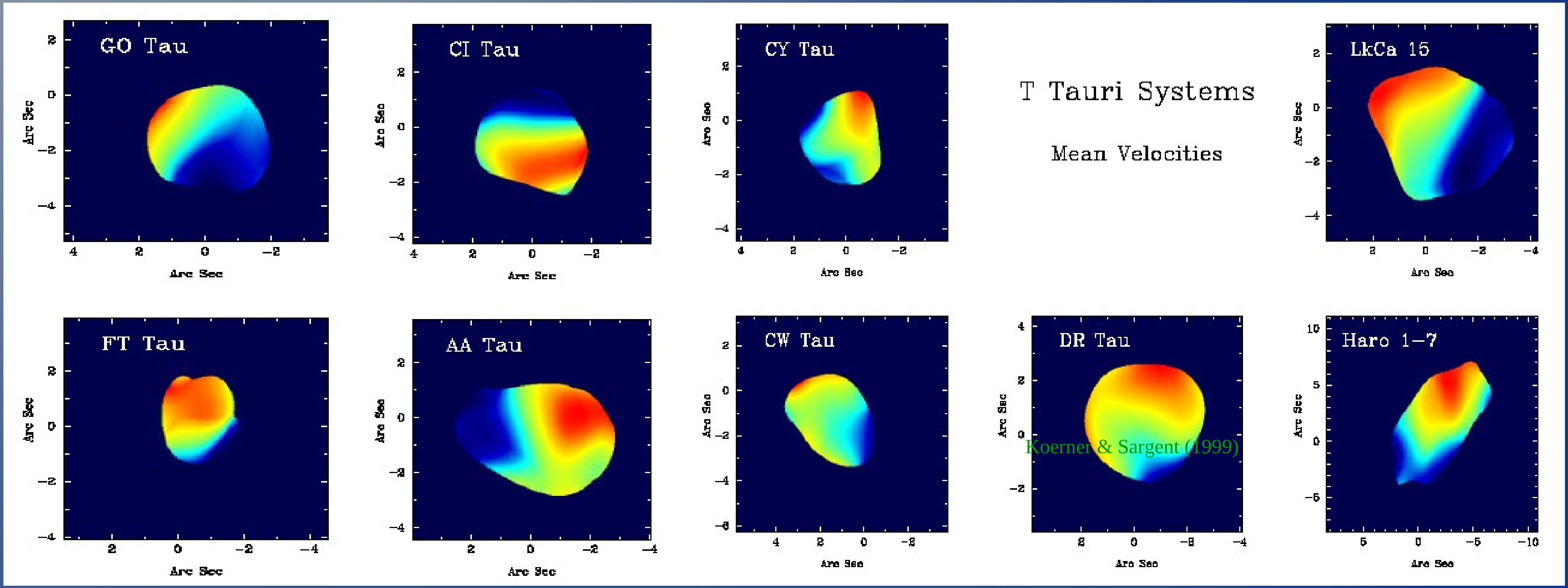
Higher transition SiO more highly collimated
(Hirano 2005, Chandler & Richer 2001)

3.3 Accretion disk

Through the redshift we can study the kinematic of the disk. The disk velocity in LkCa 15 traced by CO and chemistry traced by HCN, Owens Valley Interferometer (Qi et al. 2001)



LkCa 15 disk

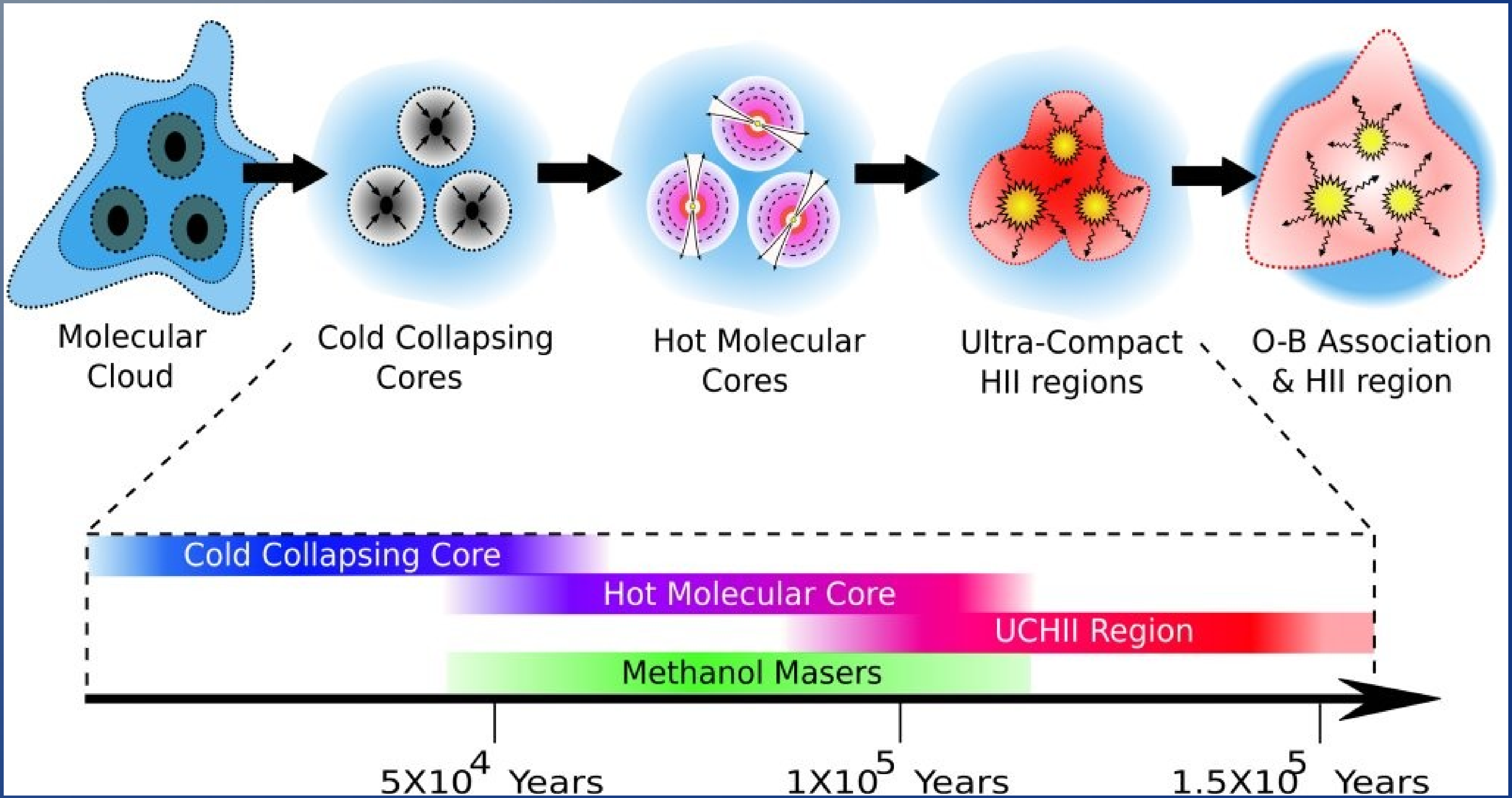


Disk sizes ~100 AU, M_d ~.03 M_{sun}

(Sargent et al. 1986, Dutrey et al. 1997, Looney et al. 2000)

3.4 Masers

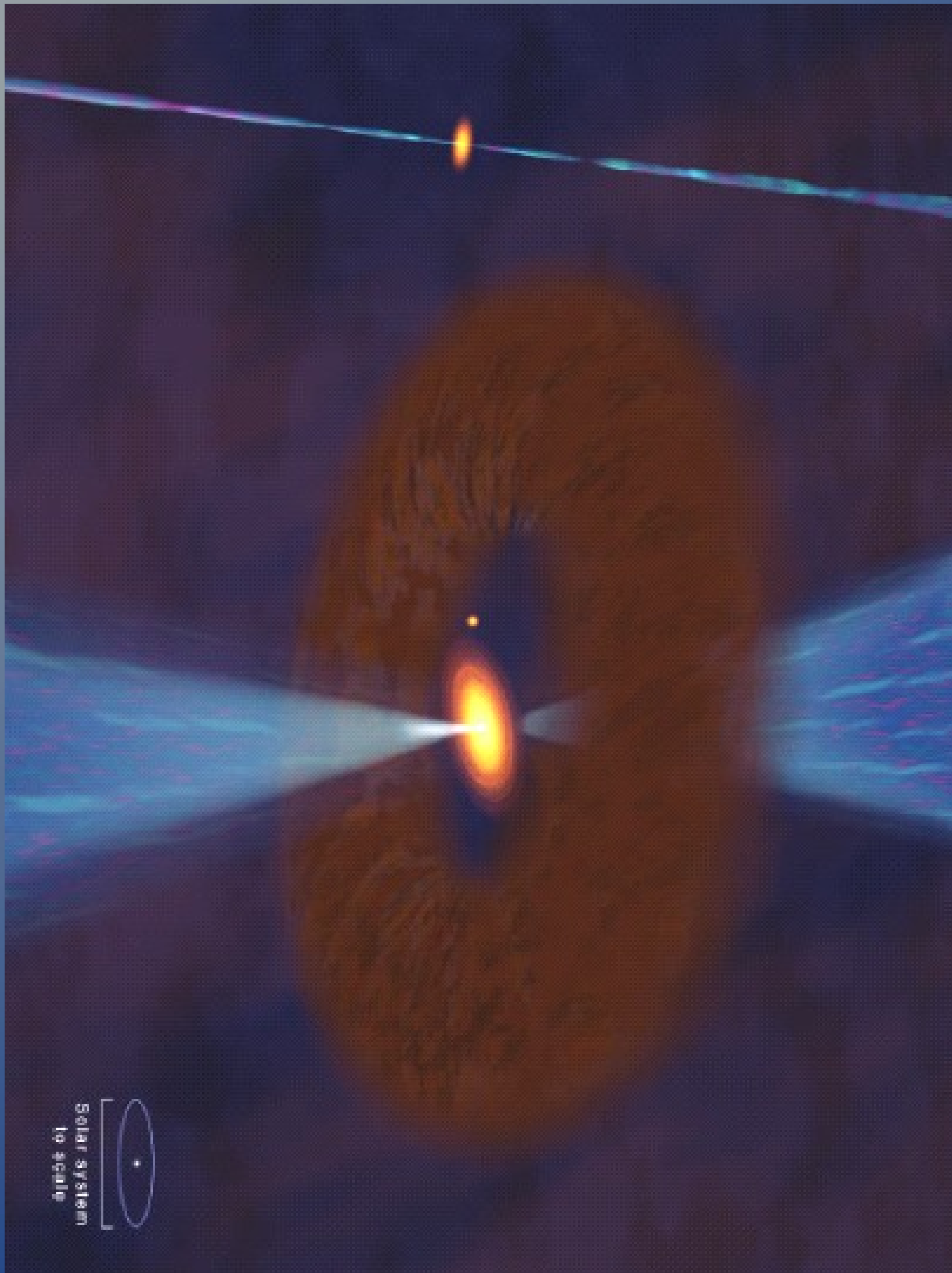
Masers are associated to some phases in the evolution process of protostars.



Known maser lines:

Species	Frequency (GHz)
OH	1.612, 1.665, 1.667, 1.720, 6.035
H_2O	22.235, 187, 233, 658
NH_3	20.719, 21.071, 23.870, 24.533, 25.056
SiO	42.820, 43.122, 85.640, 86.243
CH_3OH	(many)

Other maser species: H, CH, H_2CO, HCCCN, HCN, SiS



Credit: B. Starosta, NRAO/AUI/NSF

G192.16-3.82 – Artist view

Massive protostar with 130 AU diameter accretion disk and wide-angle outflow.

Circumbinary torus – <u>inferred from water maser emission.</u>

Well-collimated jet (mixed thermal and synchrotron emission)

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