Star Formation

Melvin Hoare
University of Leeds

Overview

- Sites of star formation
- Gravitational collapse
- Disks and Outflows
- Evolutionary Stages
- Massive star formation

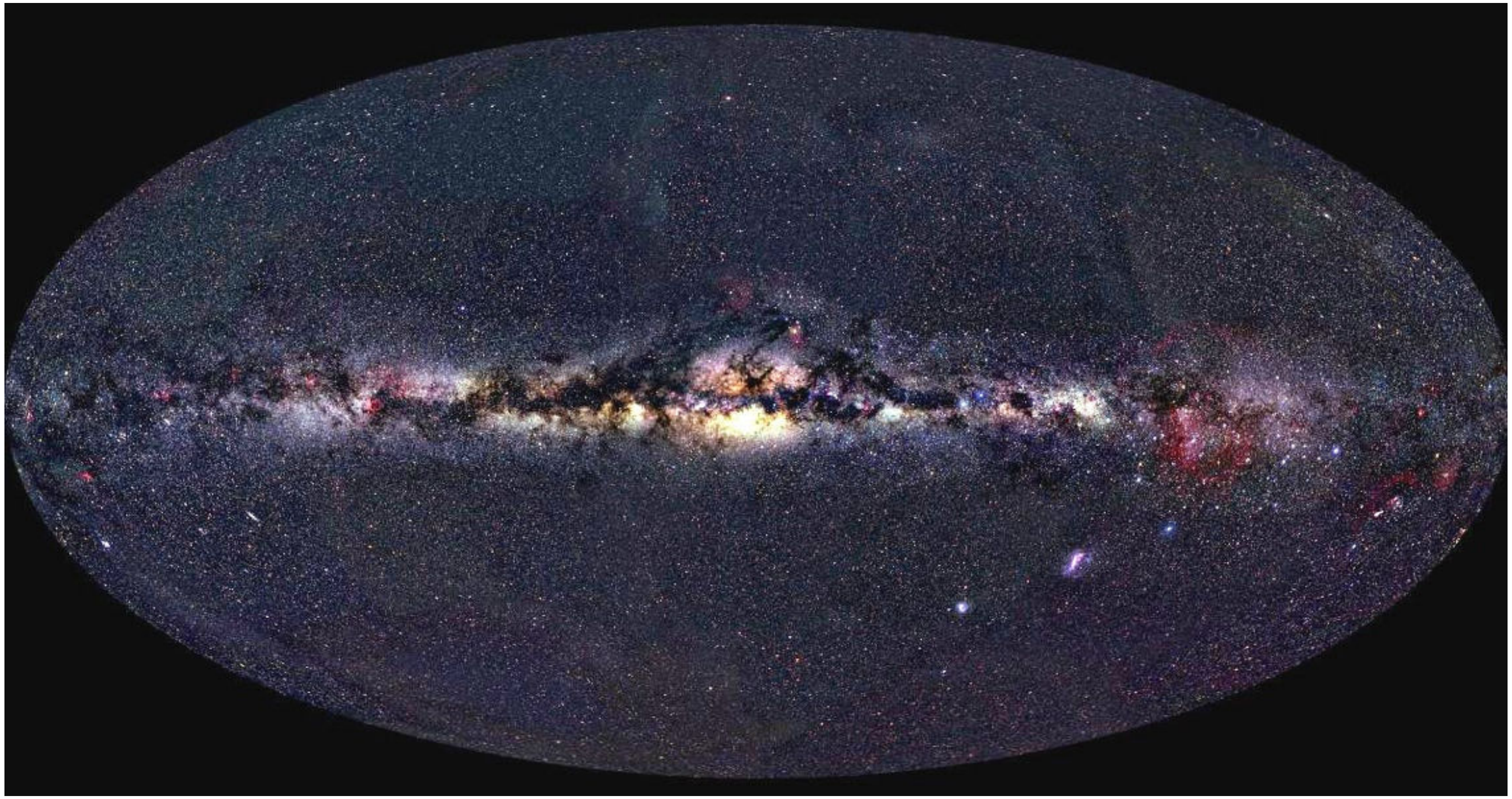
Sites of Star Formation

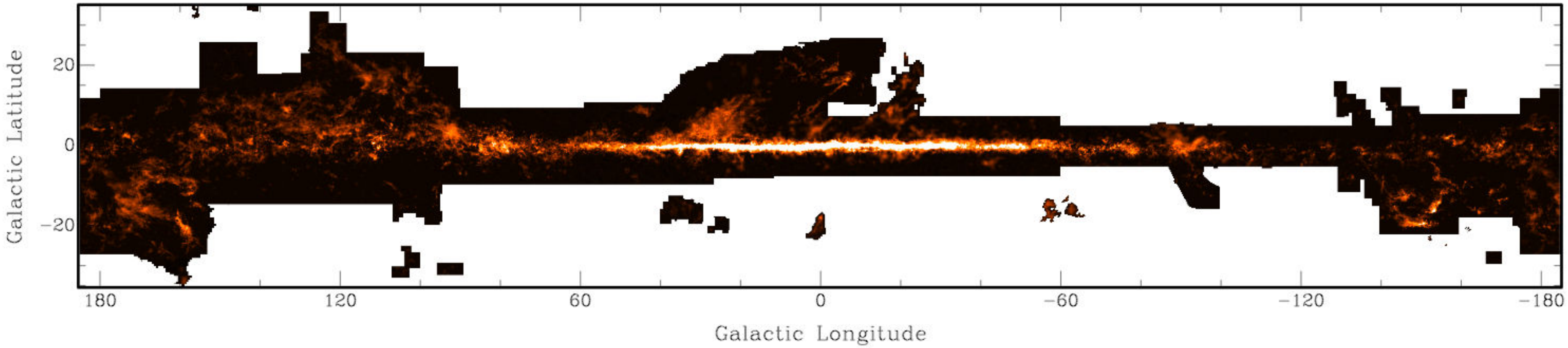
- *Stars for in spiral arms*
- *Compression of H I gas via spiral density wave*
- *Forms Giant Molecular Clouds GMCs*

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

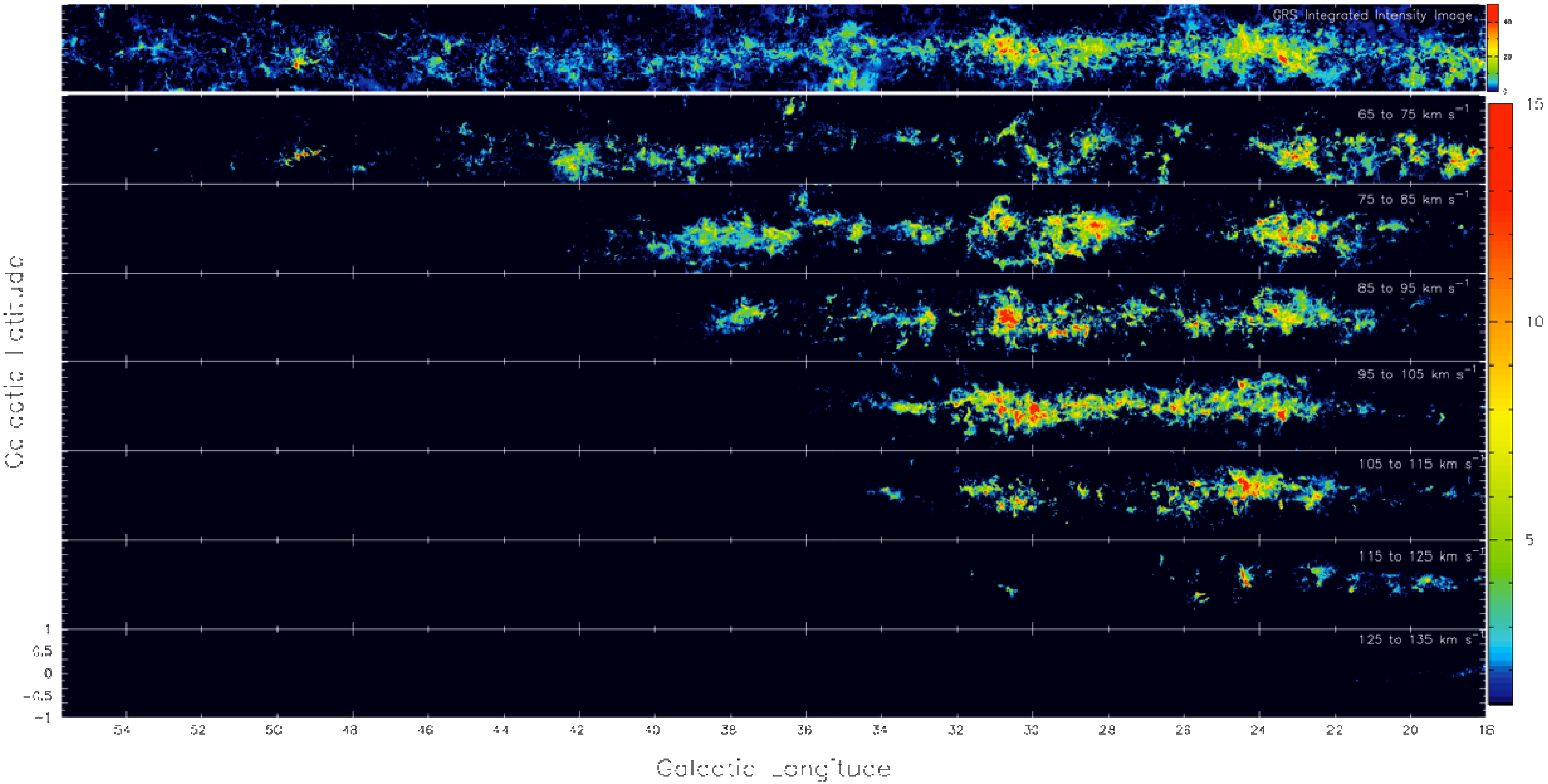
Molecular Clouds

The Milky Way as seen in Integrated ^{13}CO Maps





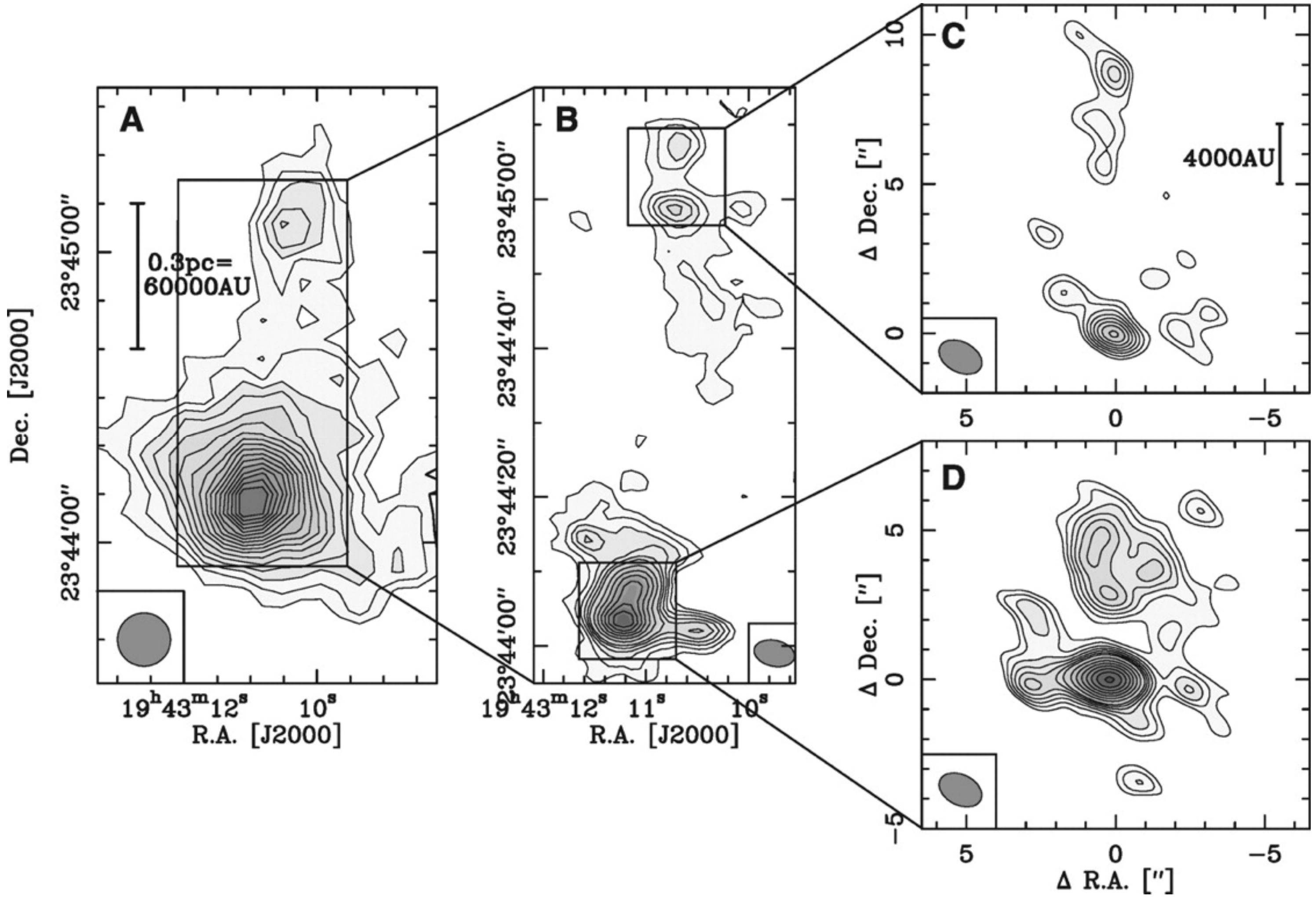
Molecular Clouds



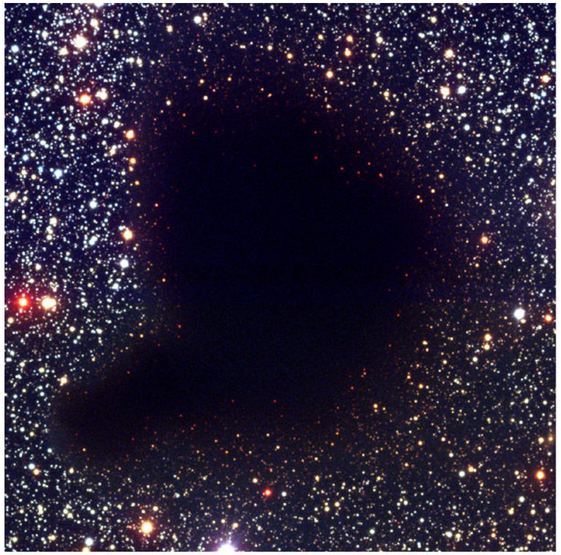
Courtesy of the Galactic Ring Survey (http://www.bu.edu/galacticring)

Molecular Clouds

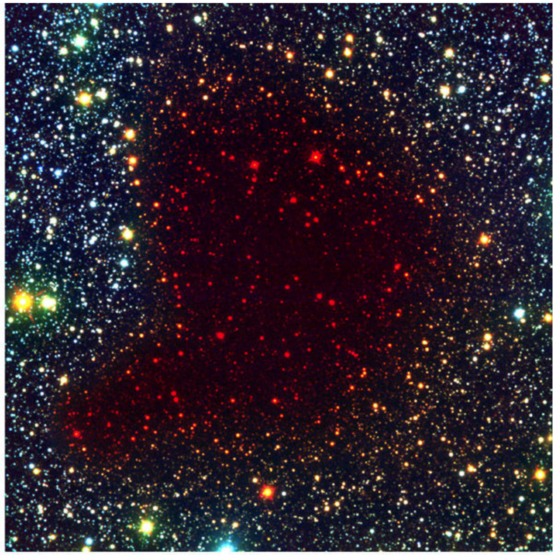
- Filamentary, clumpy, hierarchical on wide range of scales:
- massive clumps, several pc and masses ~1000 Mo
- small dense cores , 0.1 pc and masses of order 1 Mo,



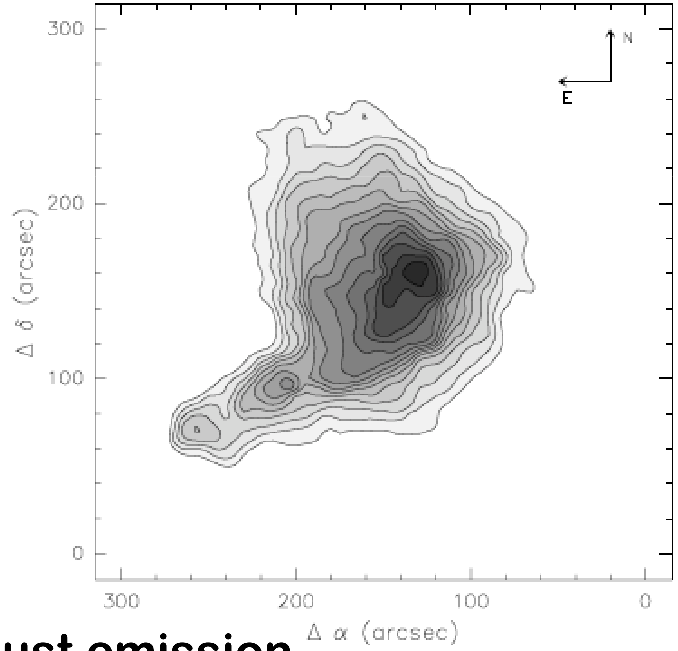
Initial Conditions



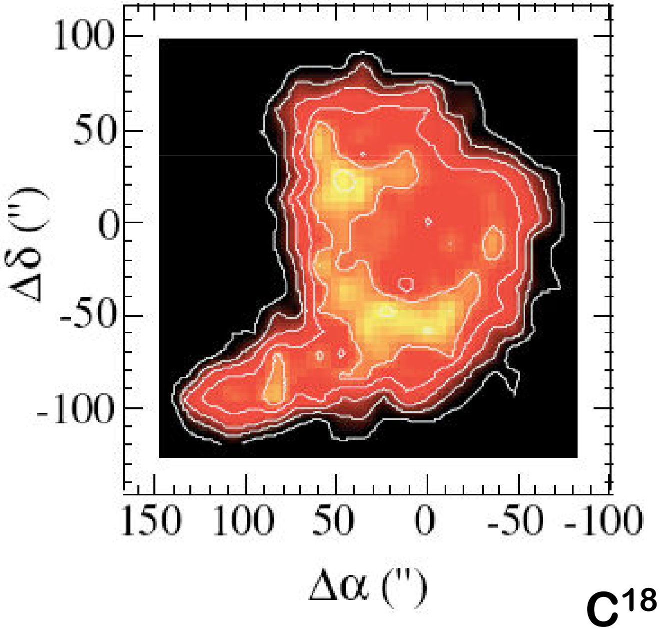
B, V, I



B, I, K



Submm Dust emission



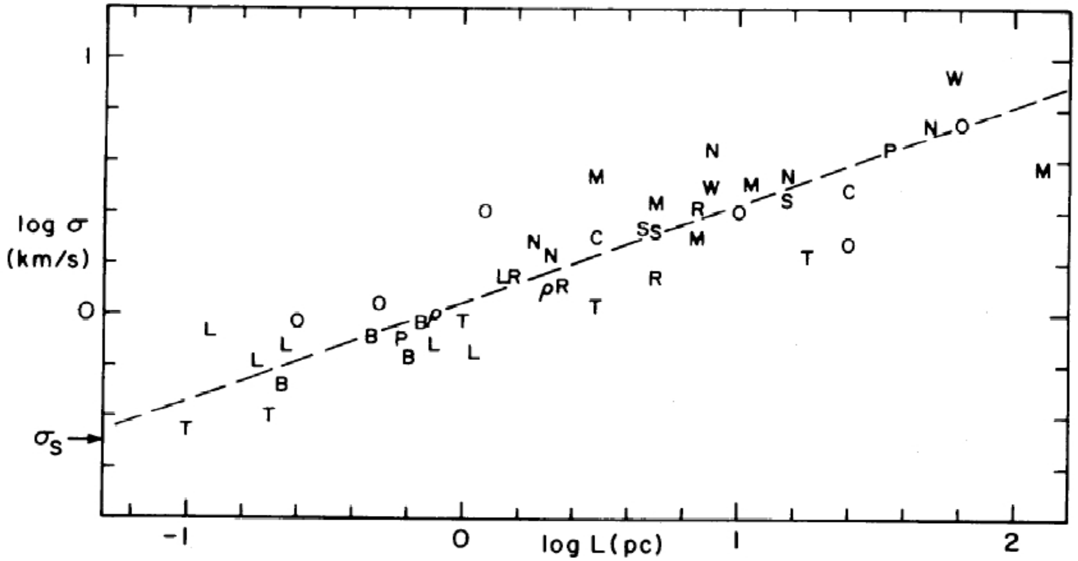
$C^{18}O$ emission

Cloud Support

- ***Clouds are dominated by non-thermal motions***

- Turbulence

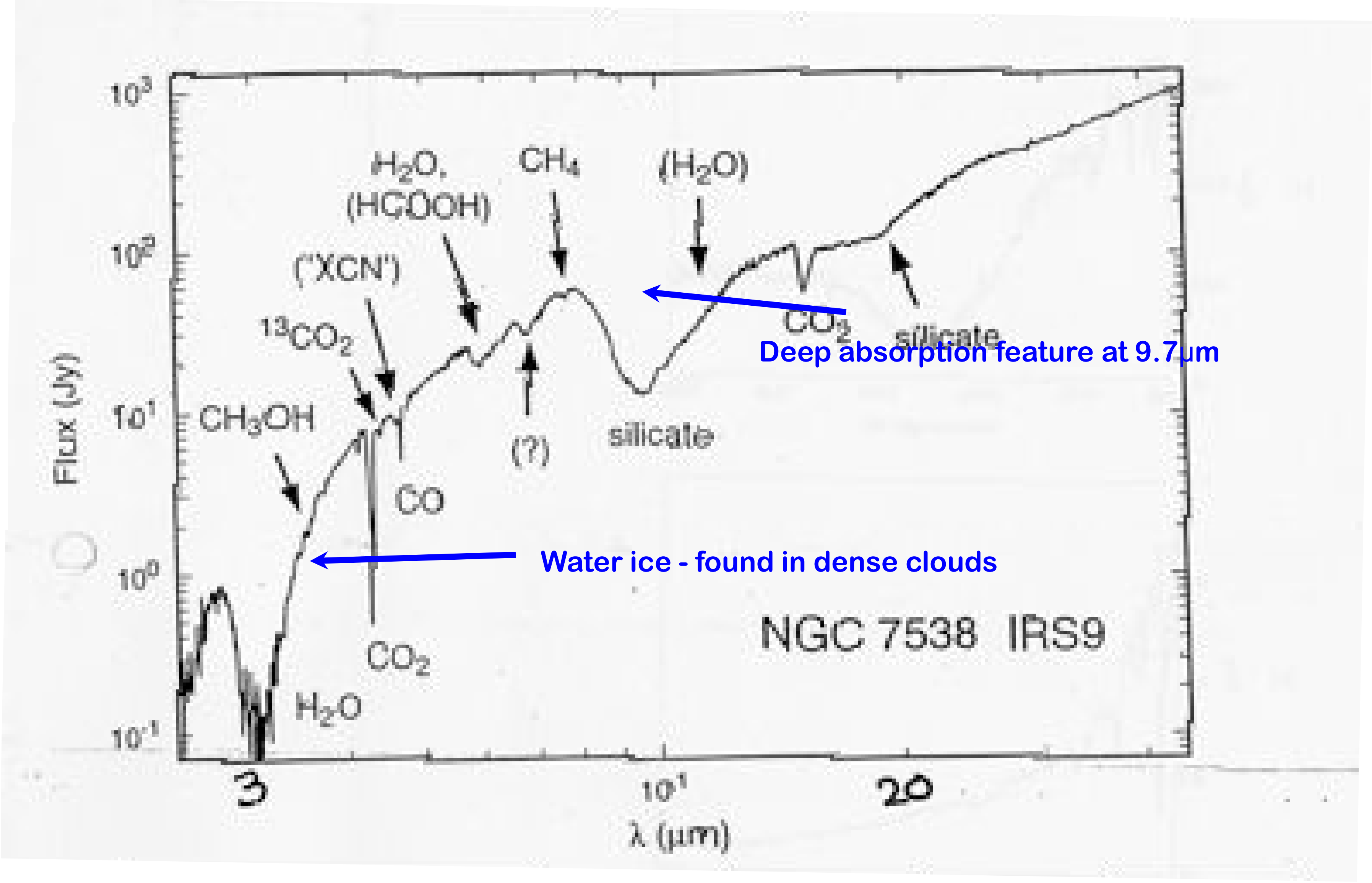
- Magnetic support



$v \sim R^{0.4}$ $\langle n \rangle \sim R^{-1.1}$

Physical Conditions

- Cold (20 K), dense 10^4 cm^{-3}, ice forms on grains



Deep absorption feature at 9.7μm

Water ice - found in dense clouds

Gravitational Collapse

The balance between thermal support and gravity leads to

The critical mass is known as the Jeans criterion i.e.

$$M_{\mathrm{C}} > M_{\mathrm{J}} \simeq \left(\frac{5kT}{G\mu m_{\mathrm{H}}}\right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho_{\mathrm{C}}}\right)^{\frac{1}{2}}$$

Free-fall time

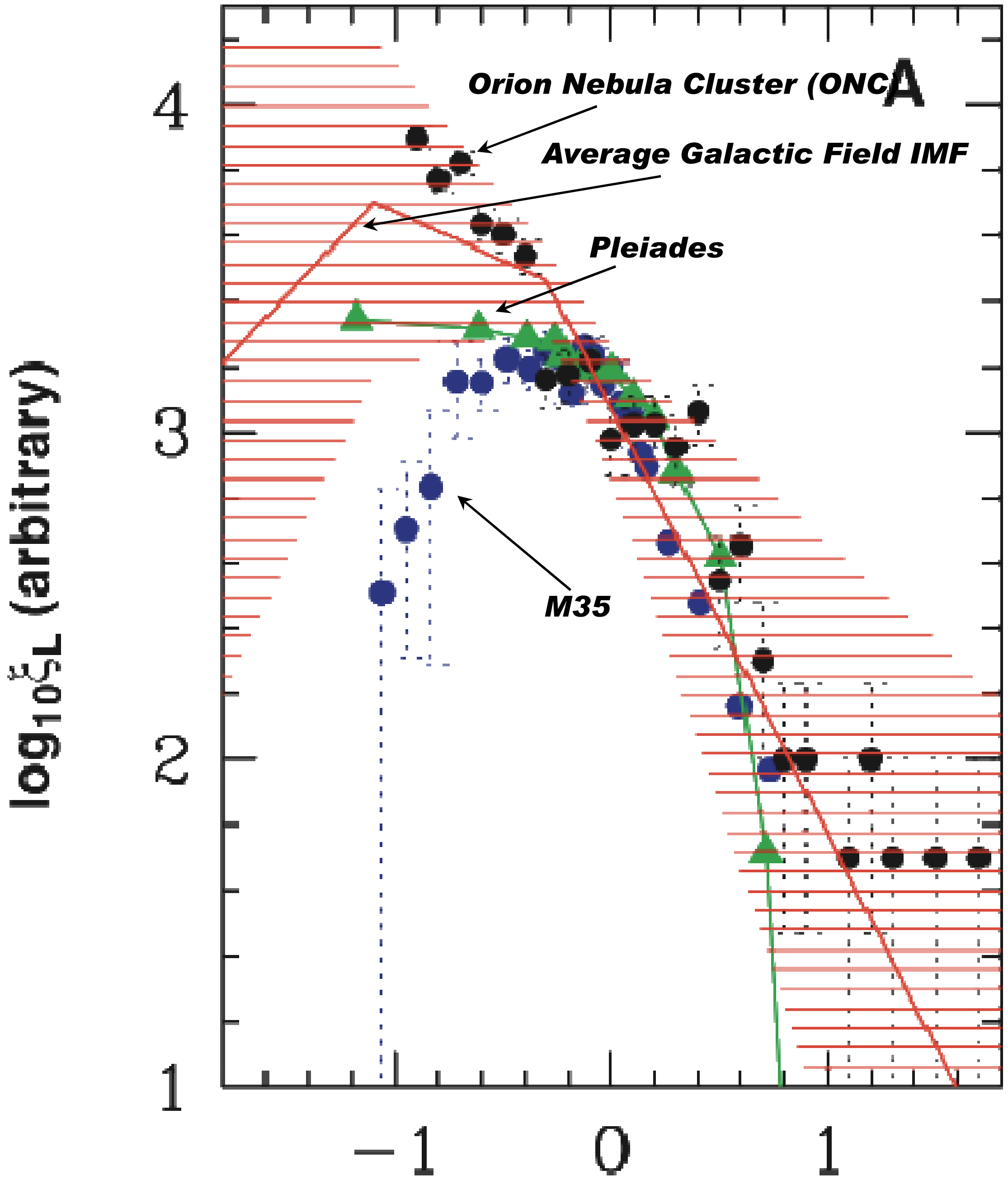
$$t_{ff} = \sqrt{\frac{3\pi}{32G\mu m_{\mathrm{H}}} n} \sim \frac{5 \times 10^{10}}{\sqrt{\mu n}} yr$$

8 Mo cloud collapse in ~10^5 yr

Fragmentation

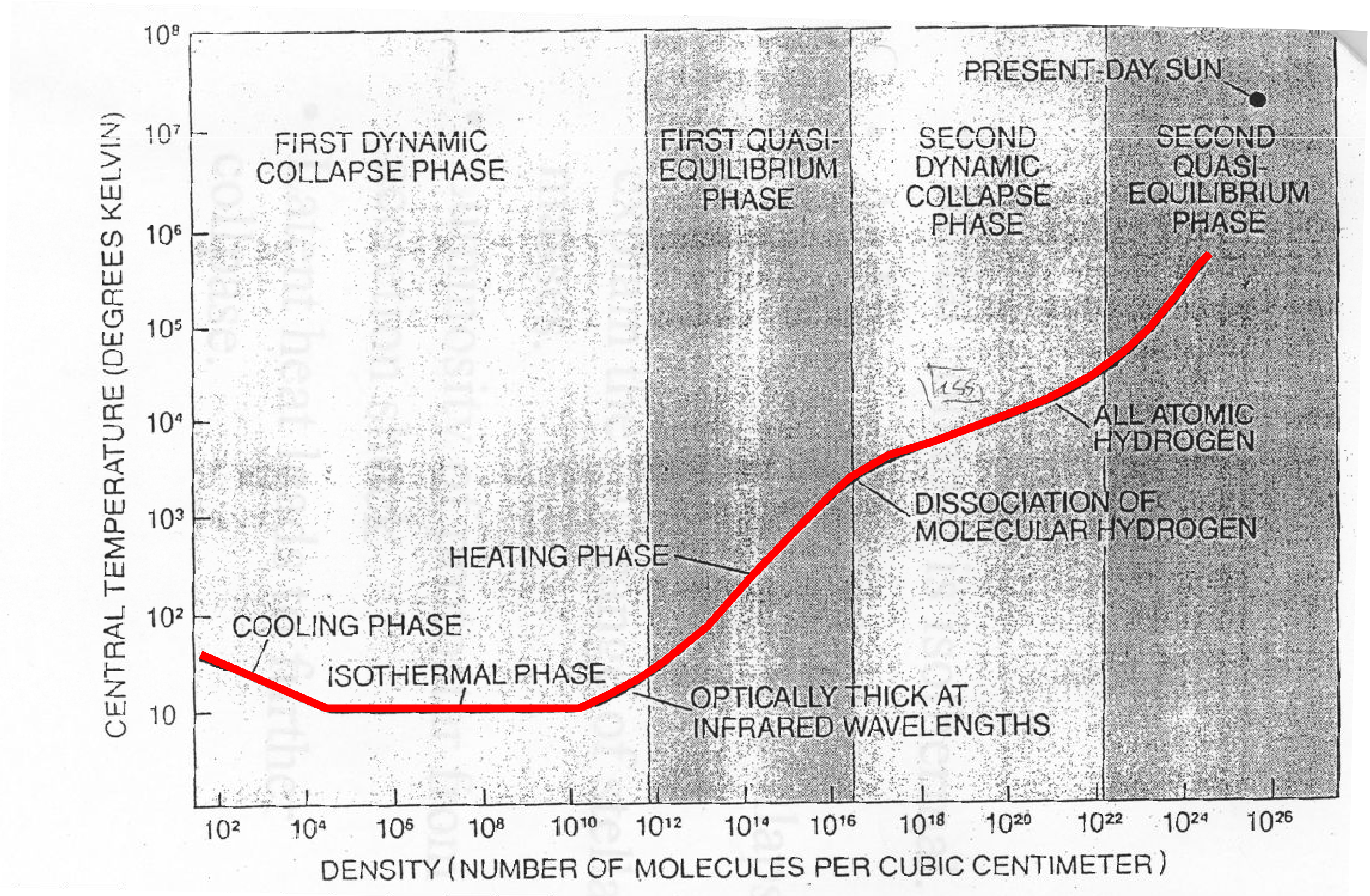
The Initial Mass Function

- ***Initial collapse is isothermal***
- ***Jeans mass decreases***
- ***Smaller fragments become unstable***
- ***Stops when clumps become optically thick and no longer isothermal***



Kroupa 2002, Science, 295, 8

Progress of collapse



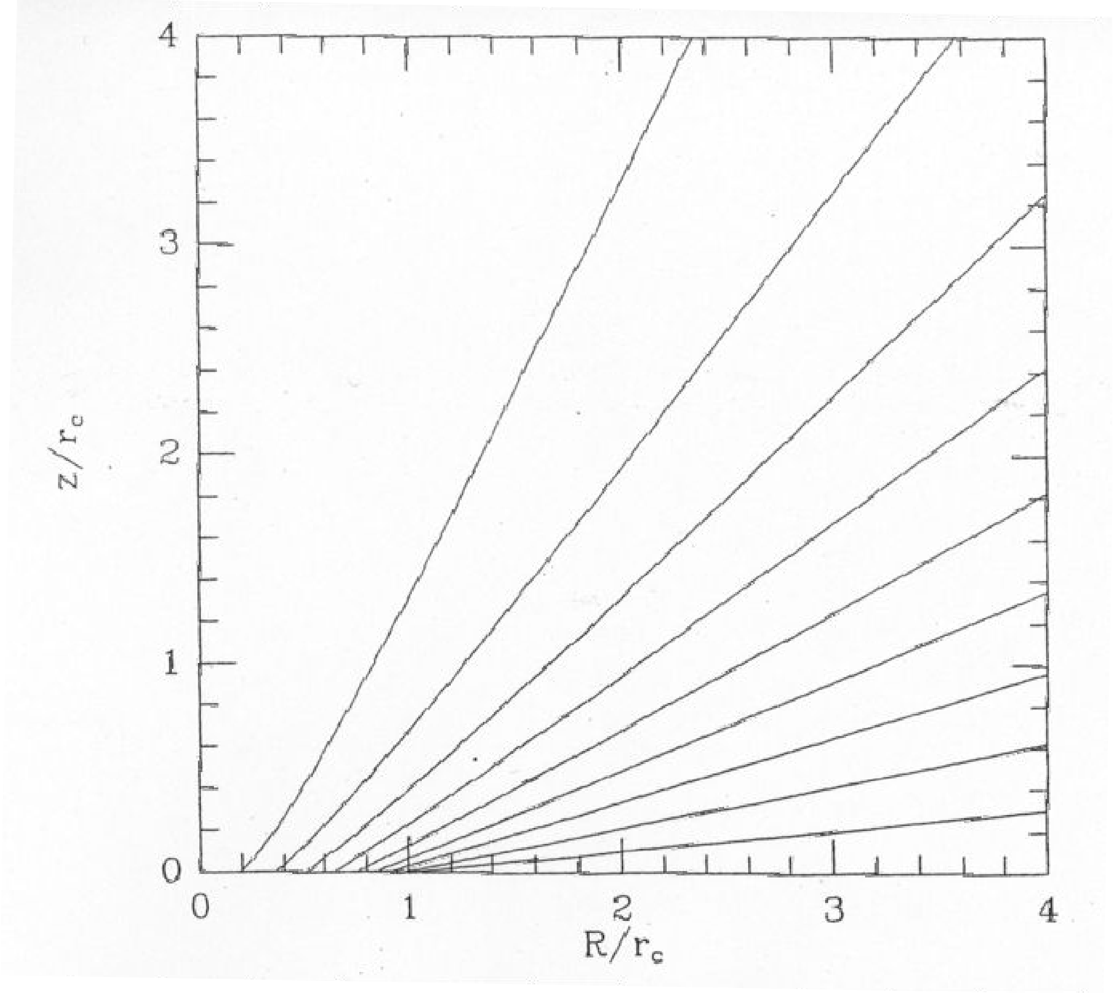
Effects of Rotation

- We can determine the radius where $F_C = F_G$

$$R_C = \frac{\Omega^2 R^4}{GM}$$

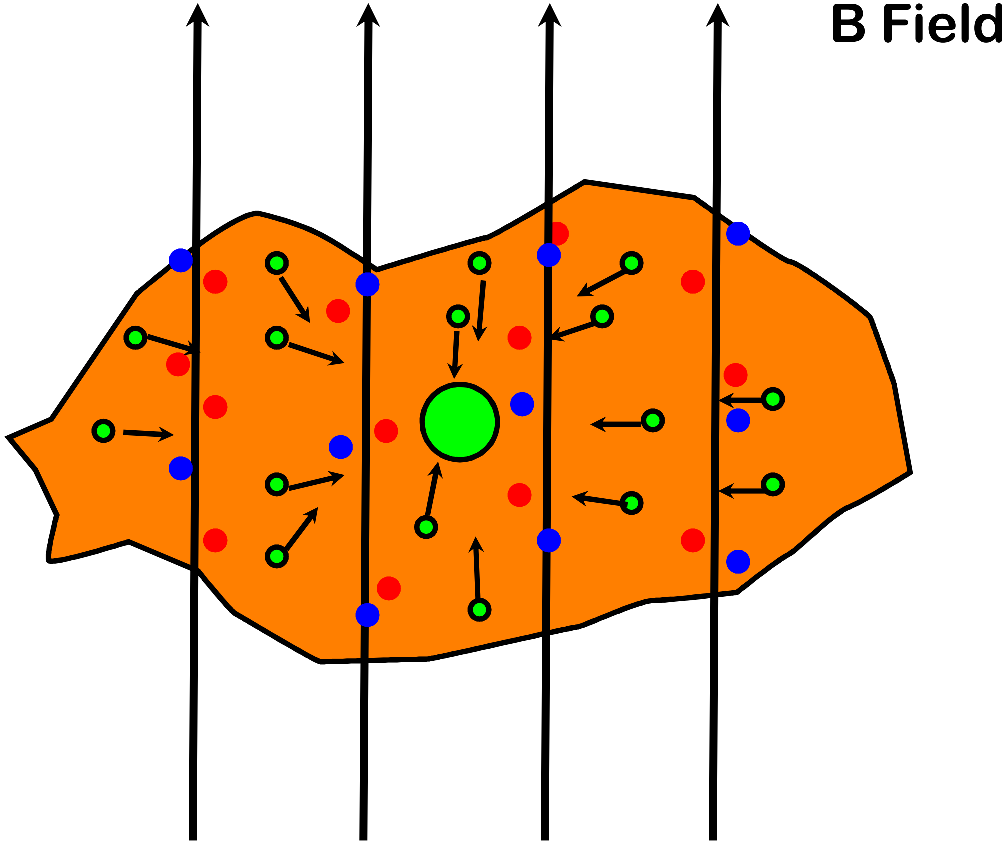
  - this is referred to as the centrifugal radius

$$R_C = 0.004 \text{ pc} \sim 1000 \text{ AU}$$



Effects Magnetic Fields

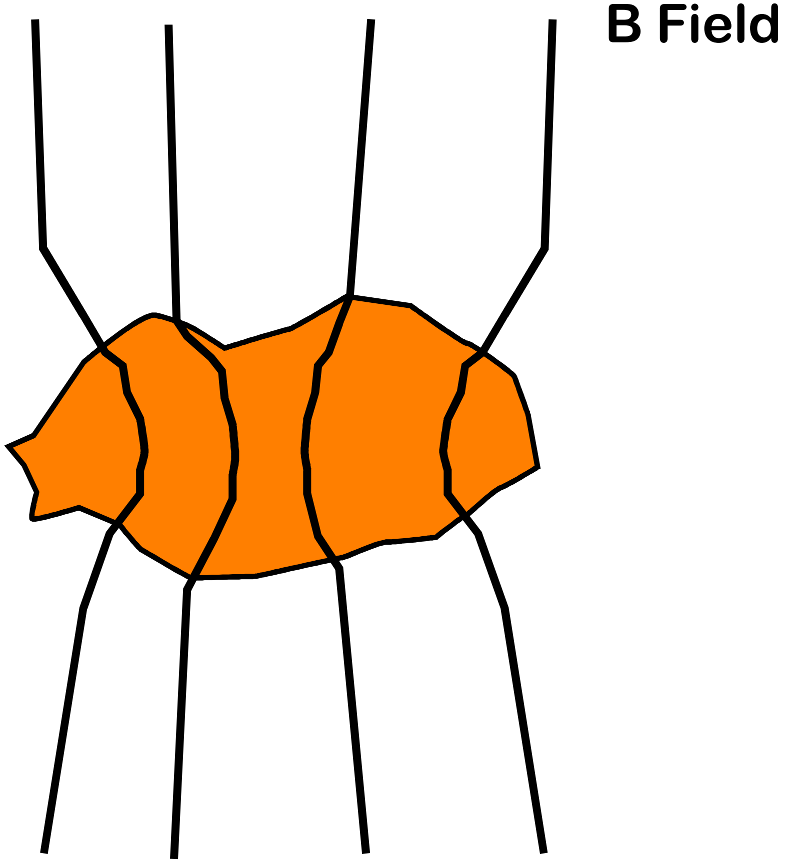
Ambipolar Diffusion



- Neutrals can drift relative to the magnetic field opposed by only collisions with ions
- Timescale for this process is typically longer than t_{ff}

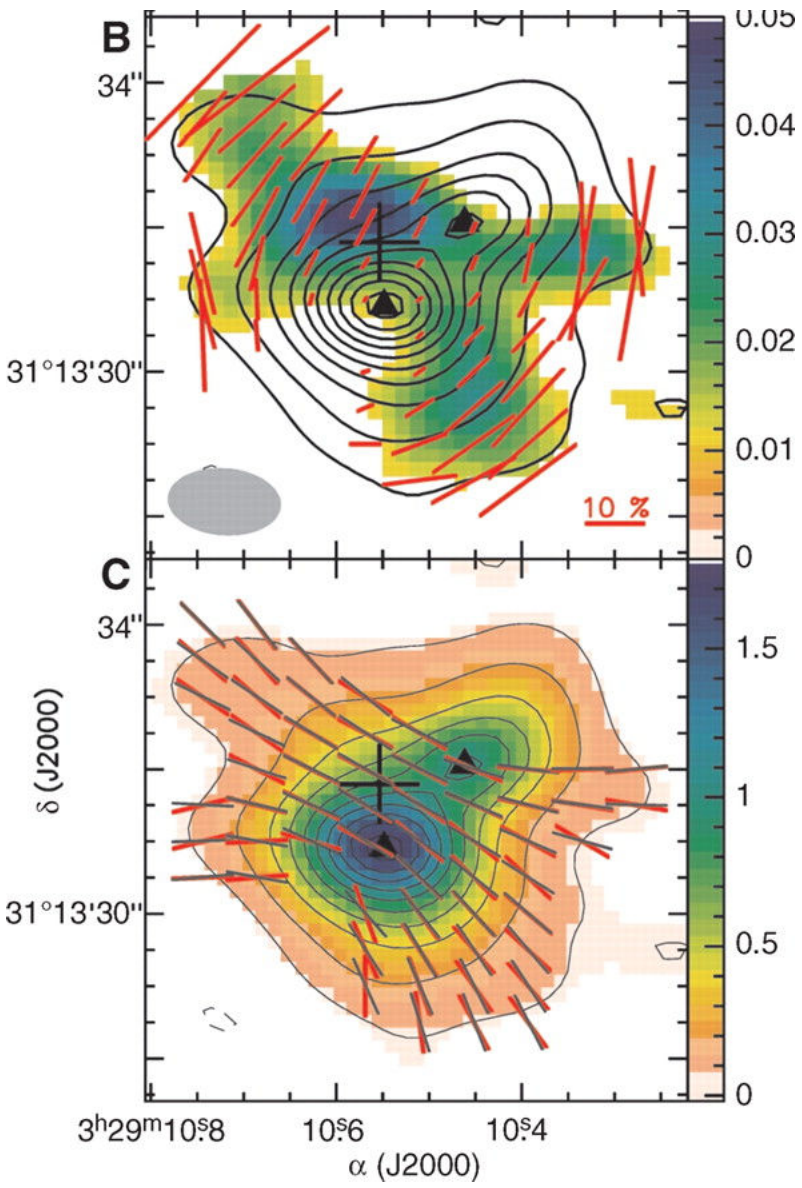
Effects of Magnetic Fields

Magnetic Fields



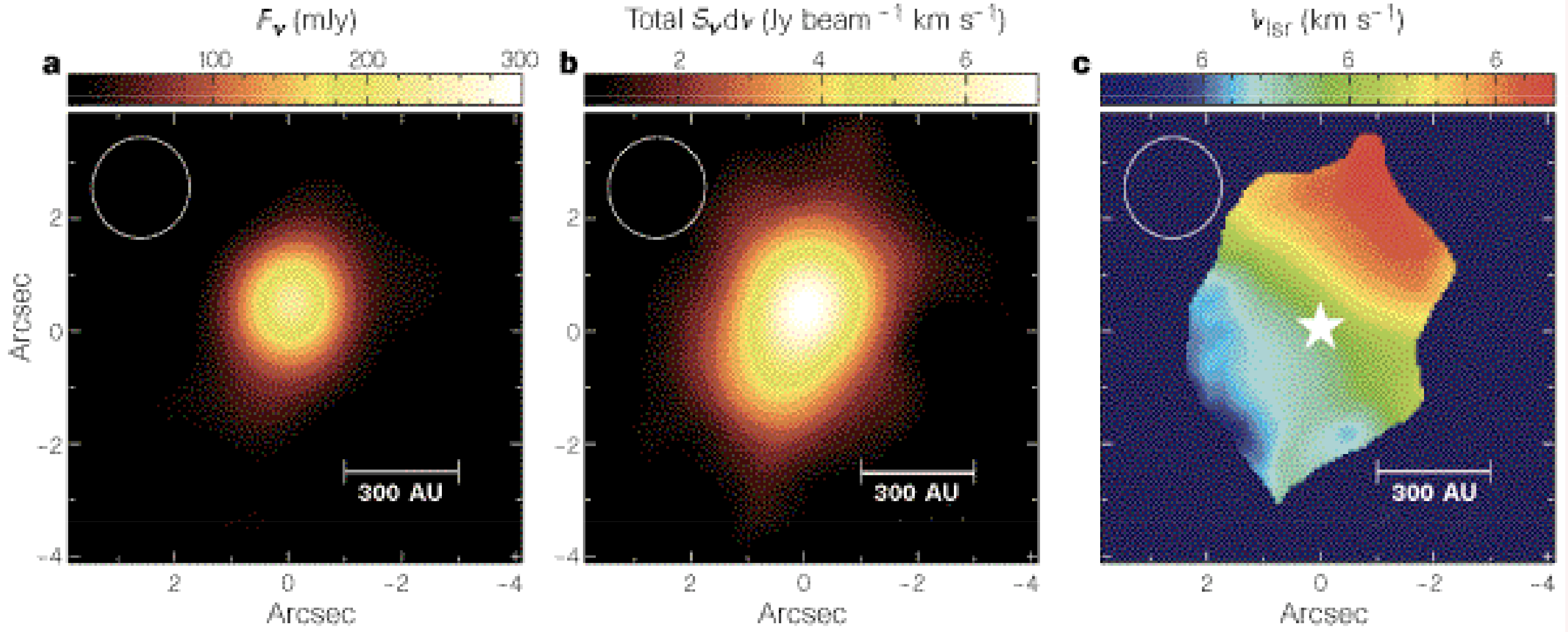
- Collapse of magnetically supported cloud should lead to hourglass shape
- Need to loose large amount of magnetic flux during collapse

- ***SMA observations of polarized sub-mm emission (Girat et al 2006)***
- ***Shows hourglass field***



Accretion Discs

Rotation leads to accretion via a disc



Mannings Nature 388, 555-557 (7 August 1997)

Accretion Disc Spectrum

Viscous dissipation in disc in optically thick disc gives $T = \left(\frac{GM\dot{M}}{8\pi\sigma r^3}\right)^{\frac{1}{4}}$

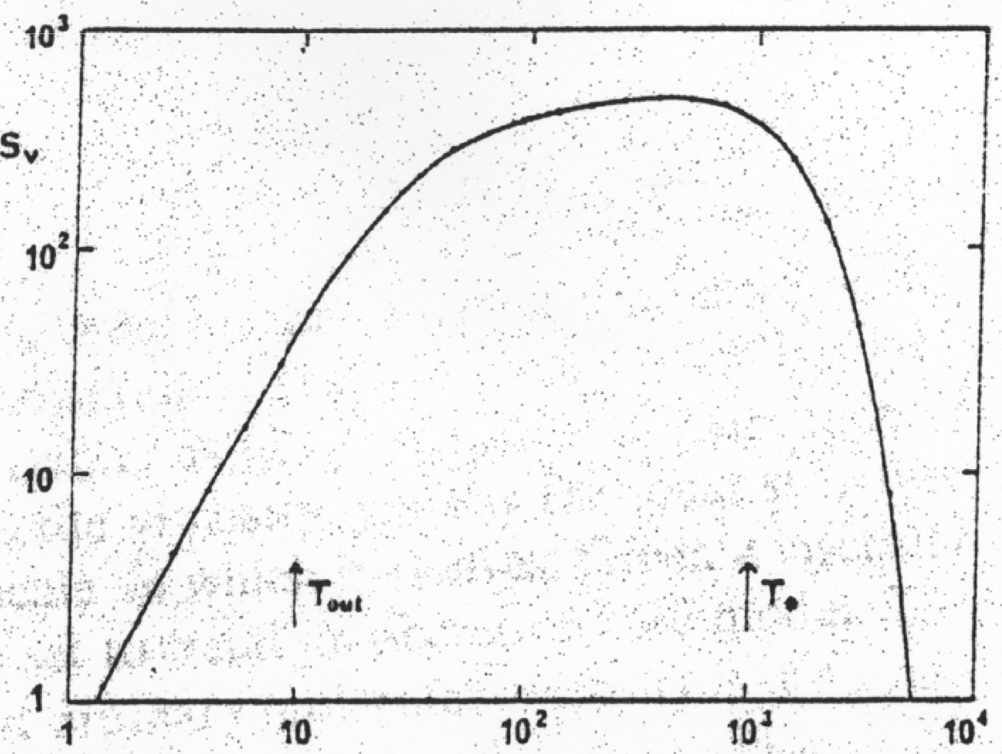
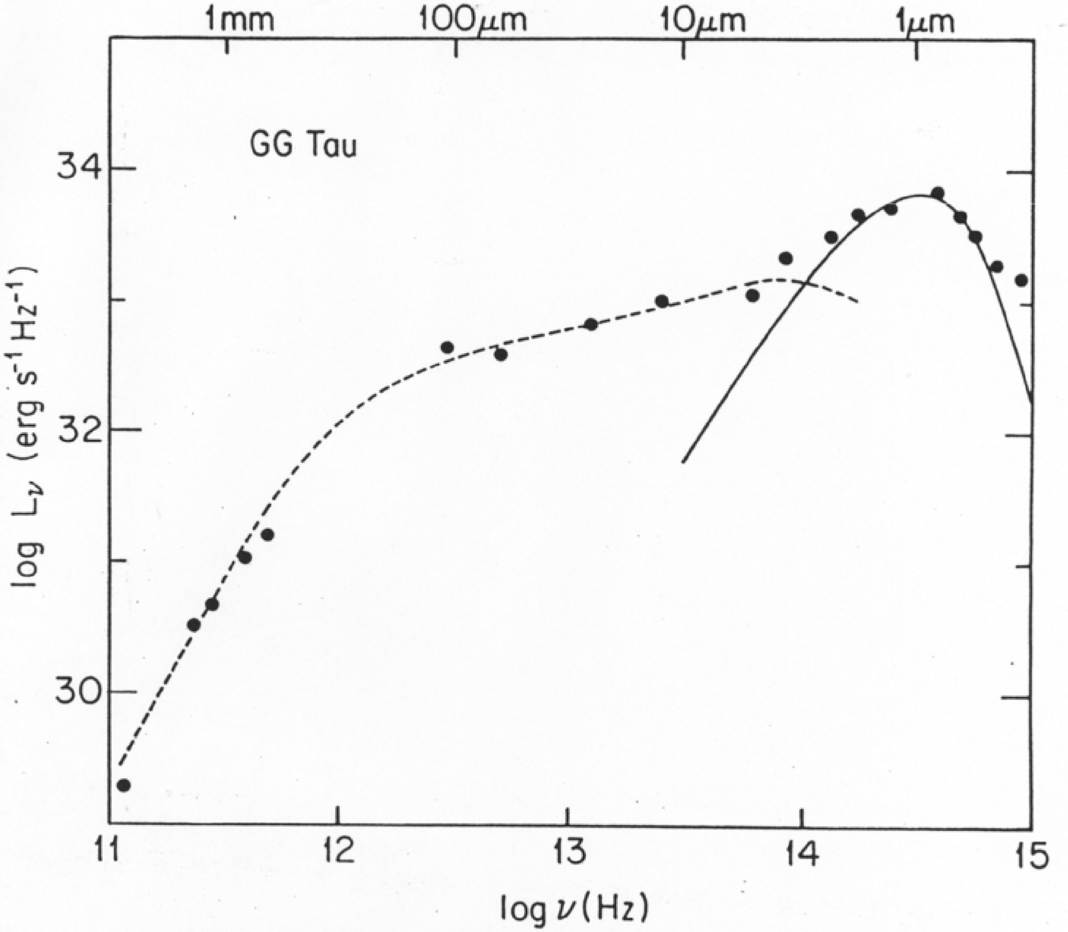


Figure 2 The integrated spectrum of a steady accretion disc that radiates a local blackbody spectrum at each point. The units are arbitrary, but the frequencies corresponding to T_{out}, the temperature of the outermost disc radius, and to T_*, the characteristic temperature of the inner disc, are marked.

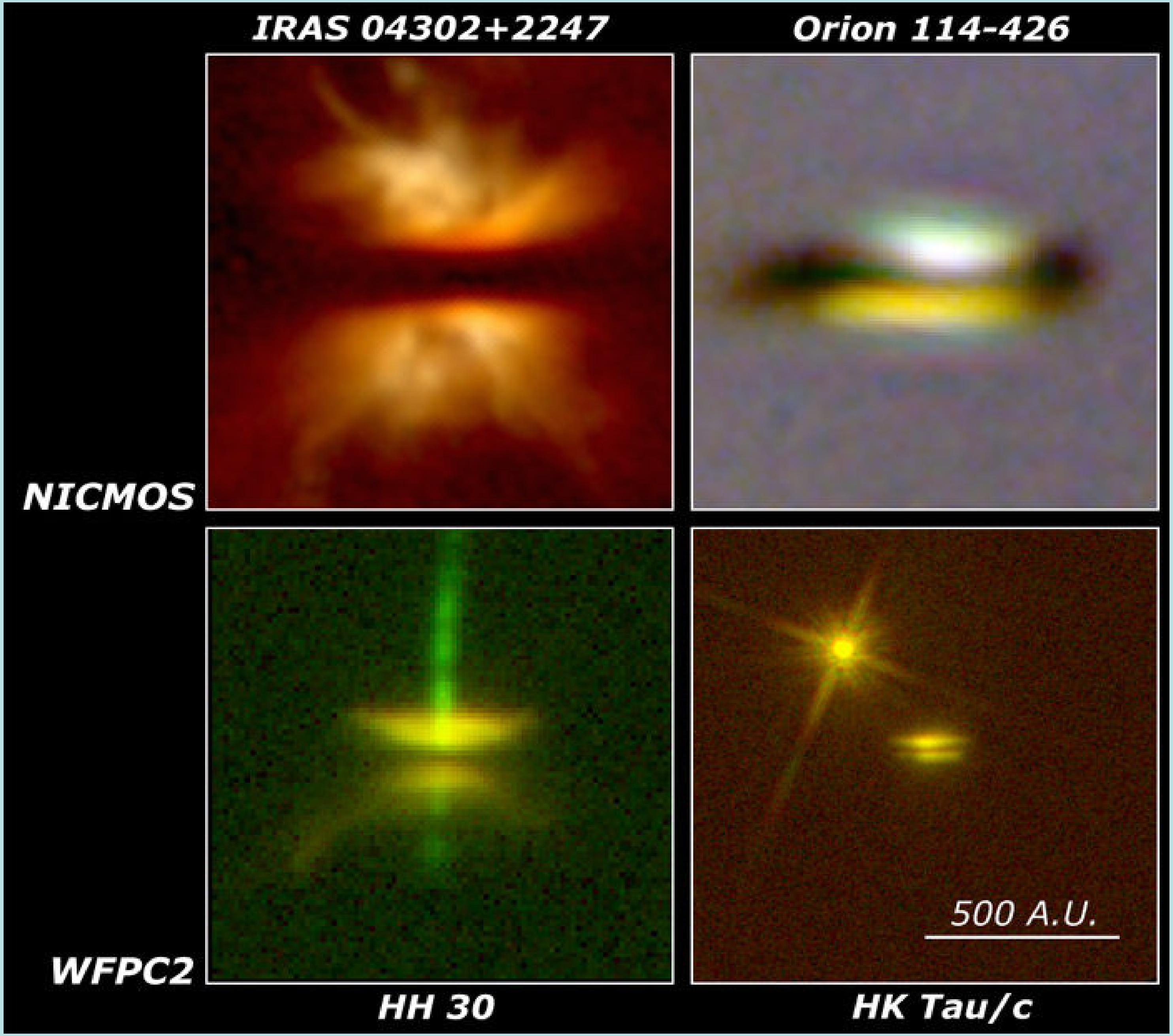
MM IR OPT/UV

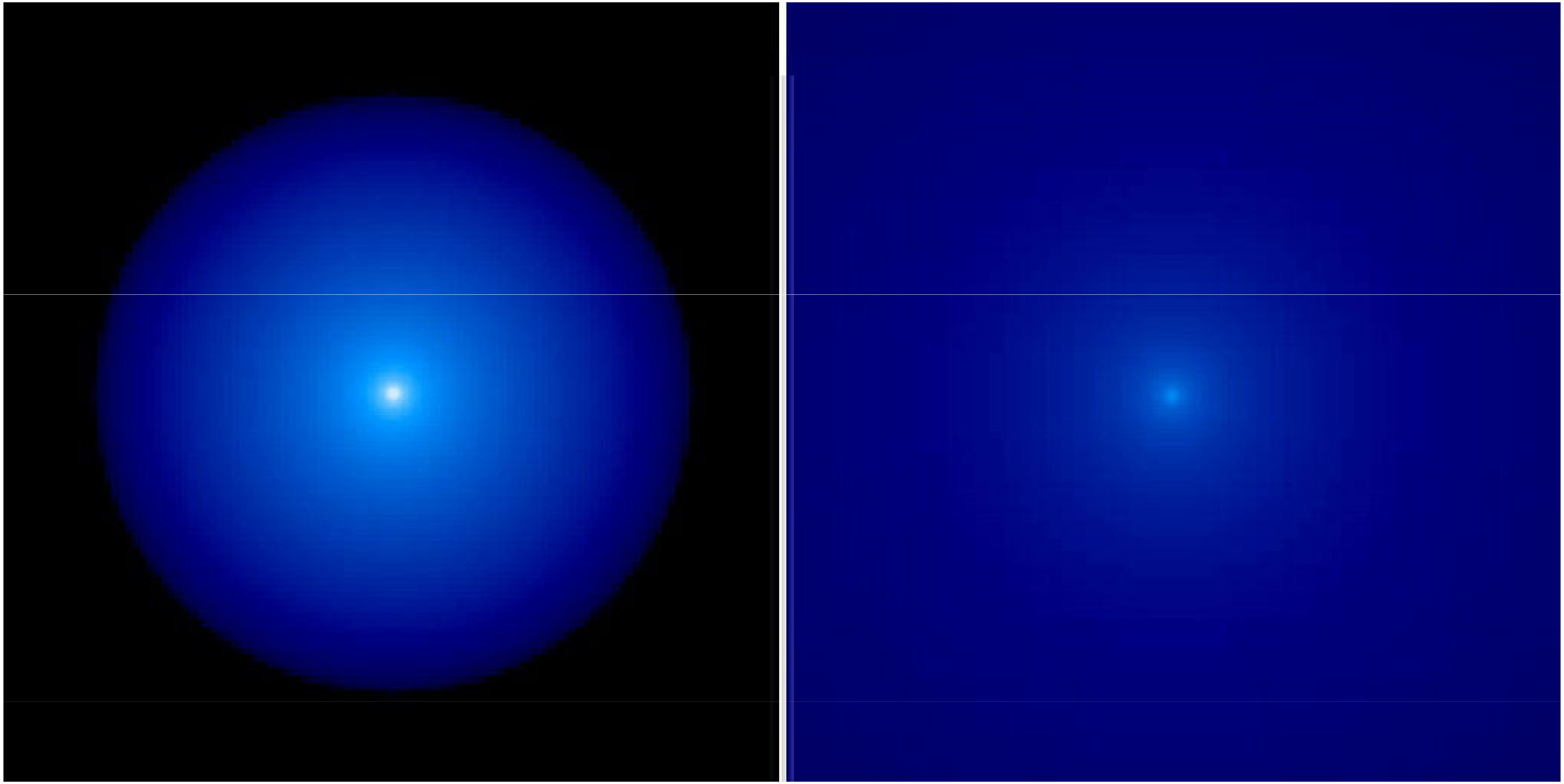
Accretion Discs Observed



The spectral energy distribution ($L_\nu \equiv 4\pi D^2 F_\nu$) is shown for the T Tauri star GG Tau. The solid line is Planck function at the temperature of the stellar photosphere; the dashed line is calculated emission from a flat disk with a power-law temperature distribution.

Accretion Discs Observed

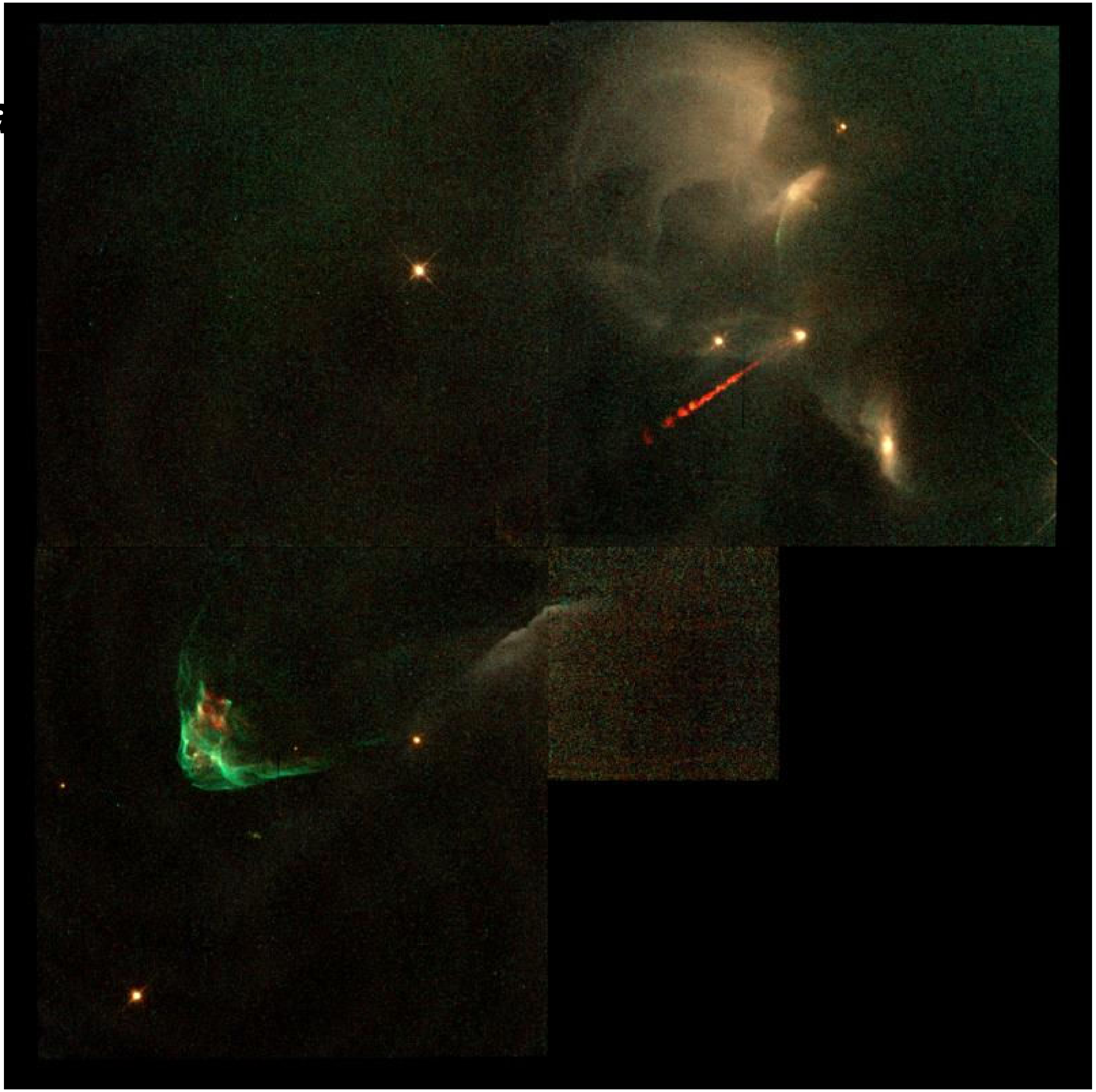




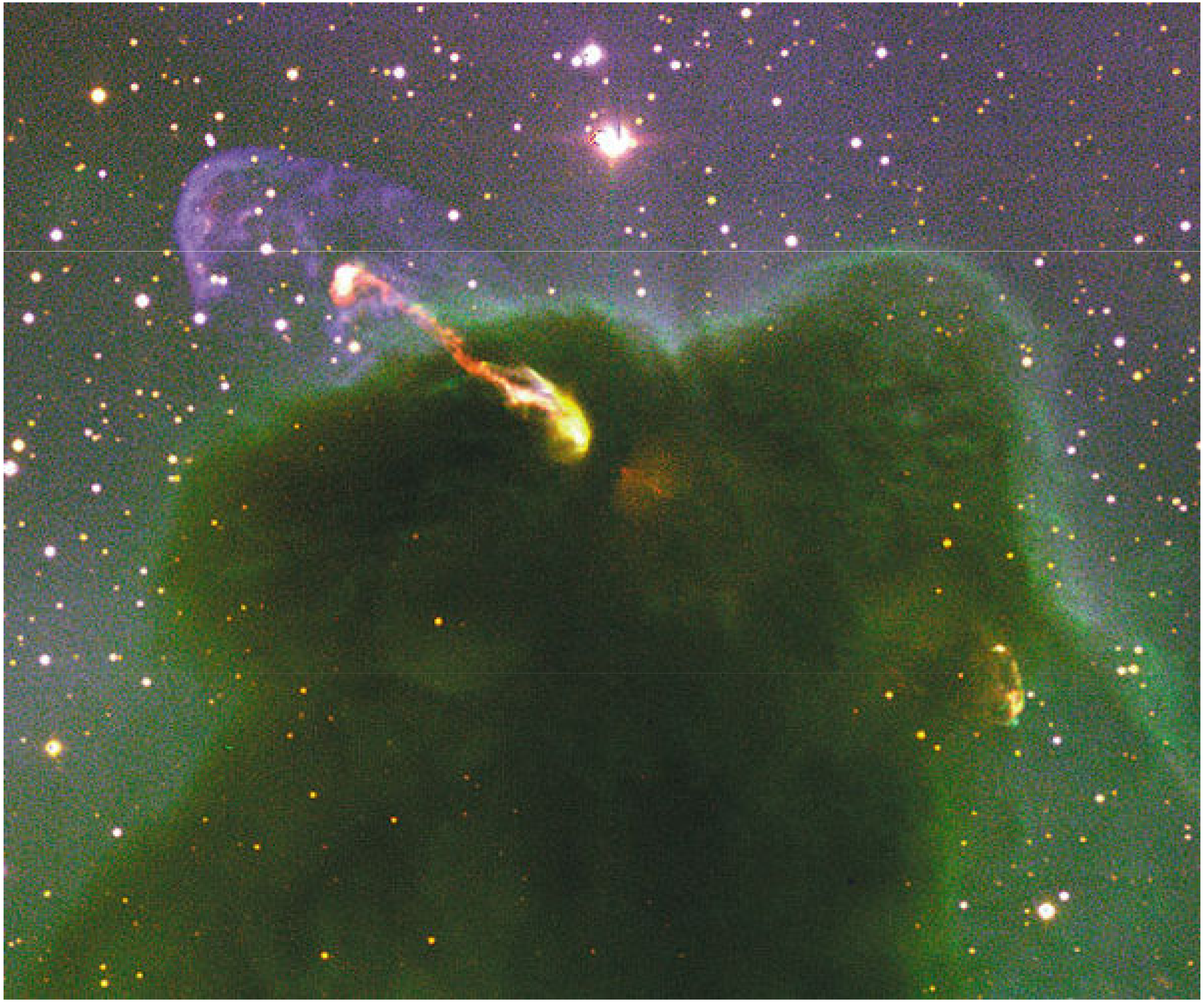
Collapse of a 100 solar mass protostellar core to a massive star (Krumholz, Klein, & McKee 2007)

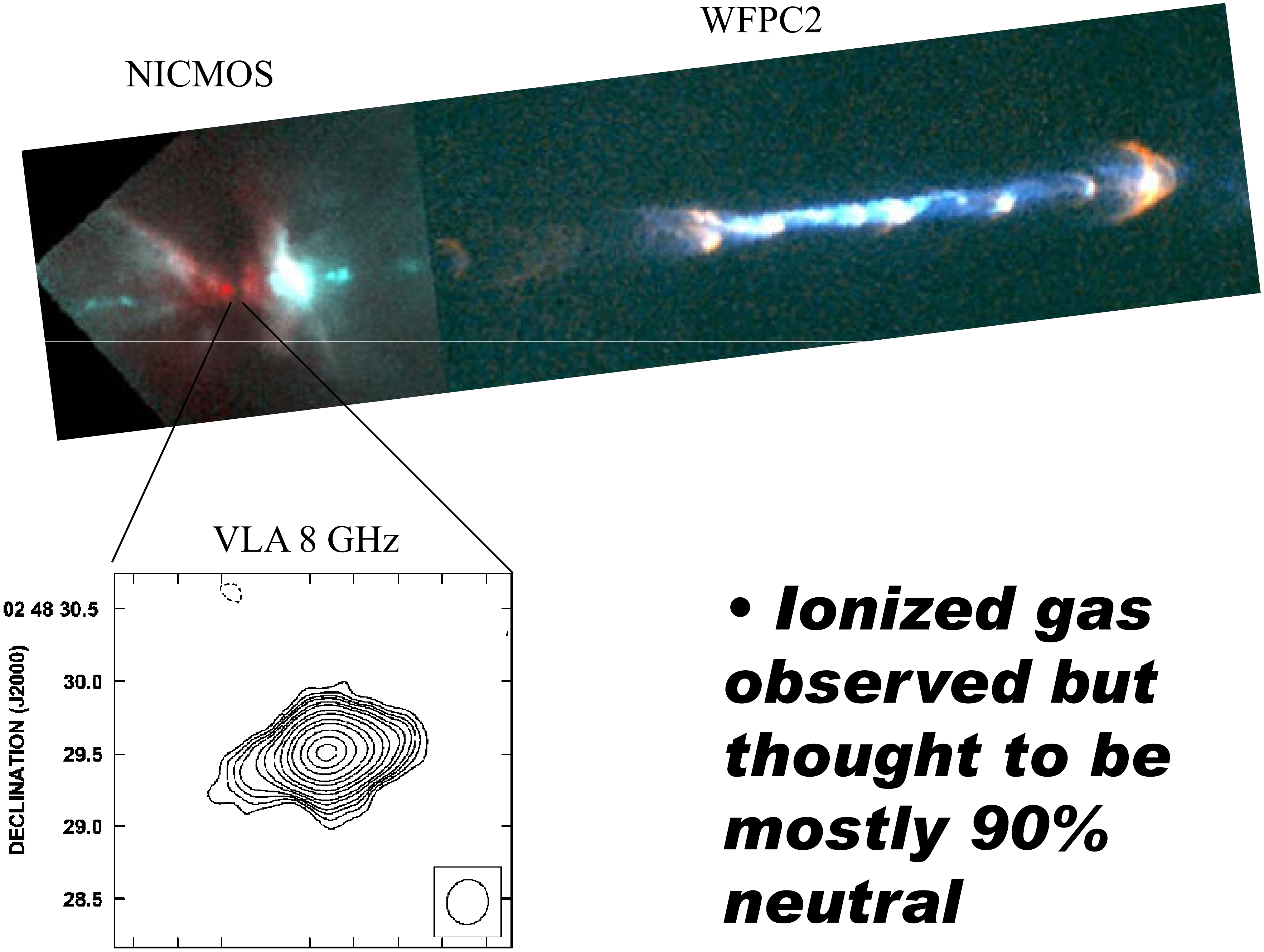
Jets and Outflows

- ***Highly collimated jets are invariably a part of star formation***
- ***Extend over pc distances and end in a bow shock - Herbig-Haro emission***
- ***Some episodic and precessing***



Jets and Outflows

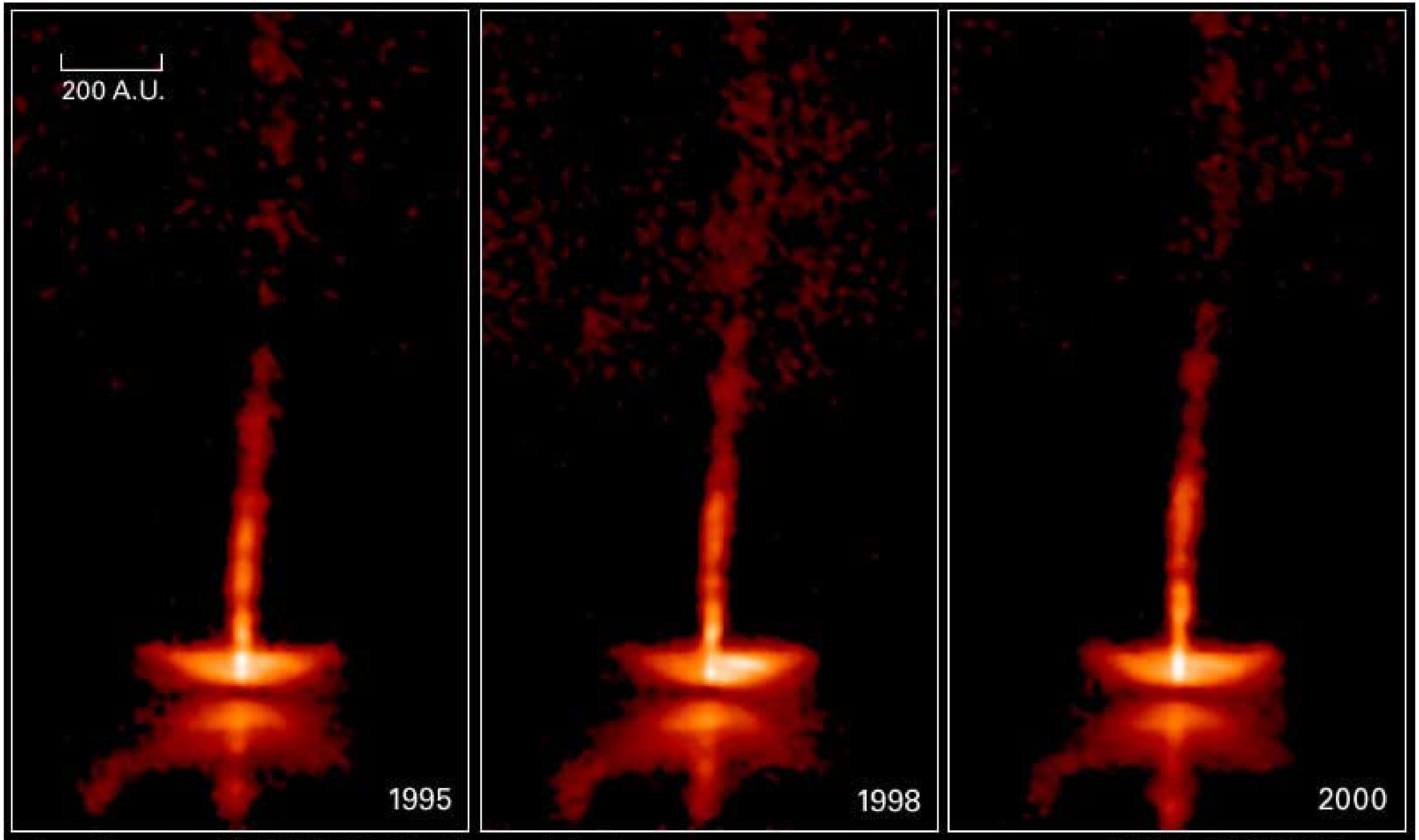




- ***Ionized gas observed but thought to be mostly 90% neutral***

Jet Proper Motions

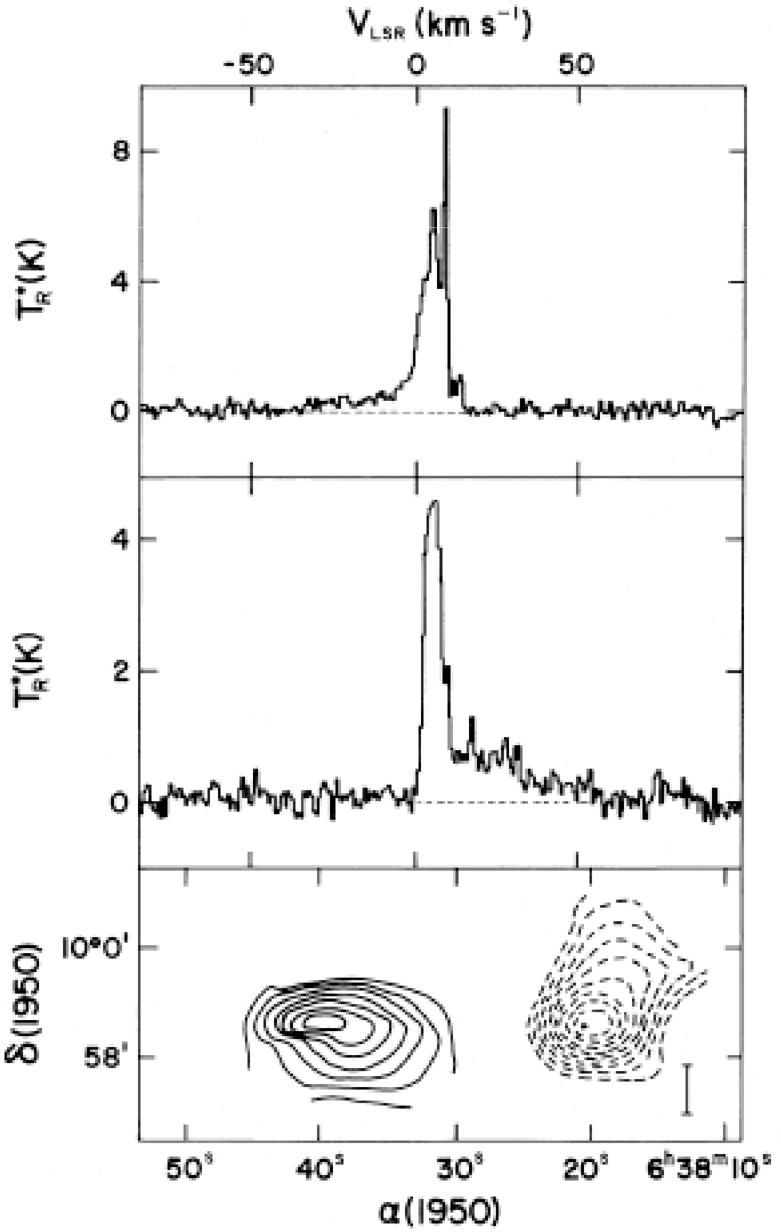
Material moving at around 500 km s^{-1}



The Dynamic HH 30 Disk and Jet HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

Bipolar Molecular Outflows



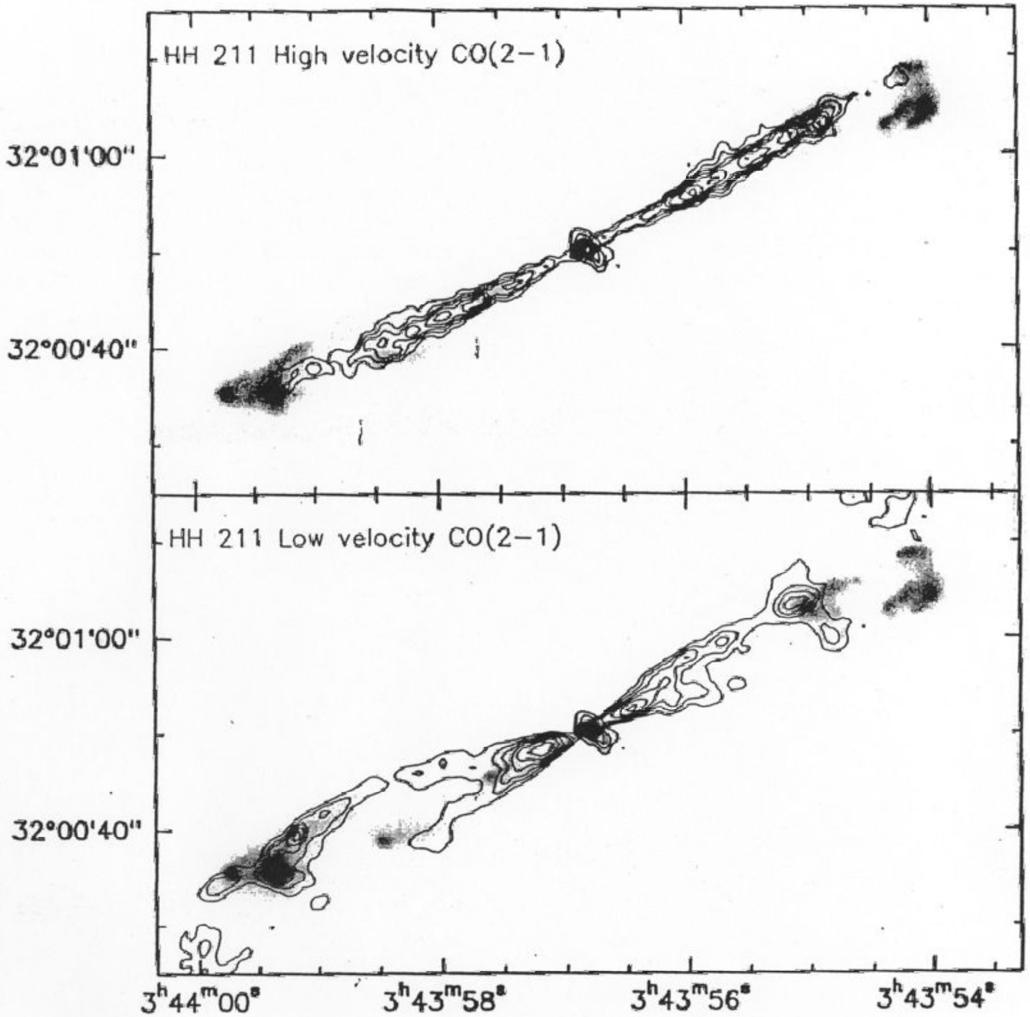
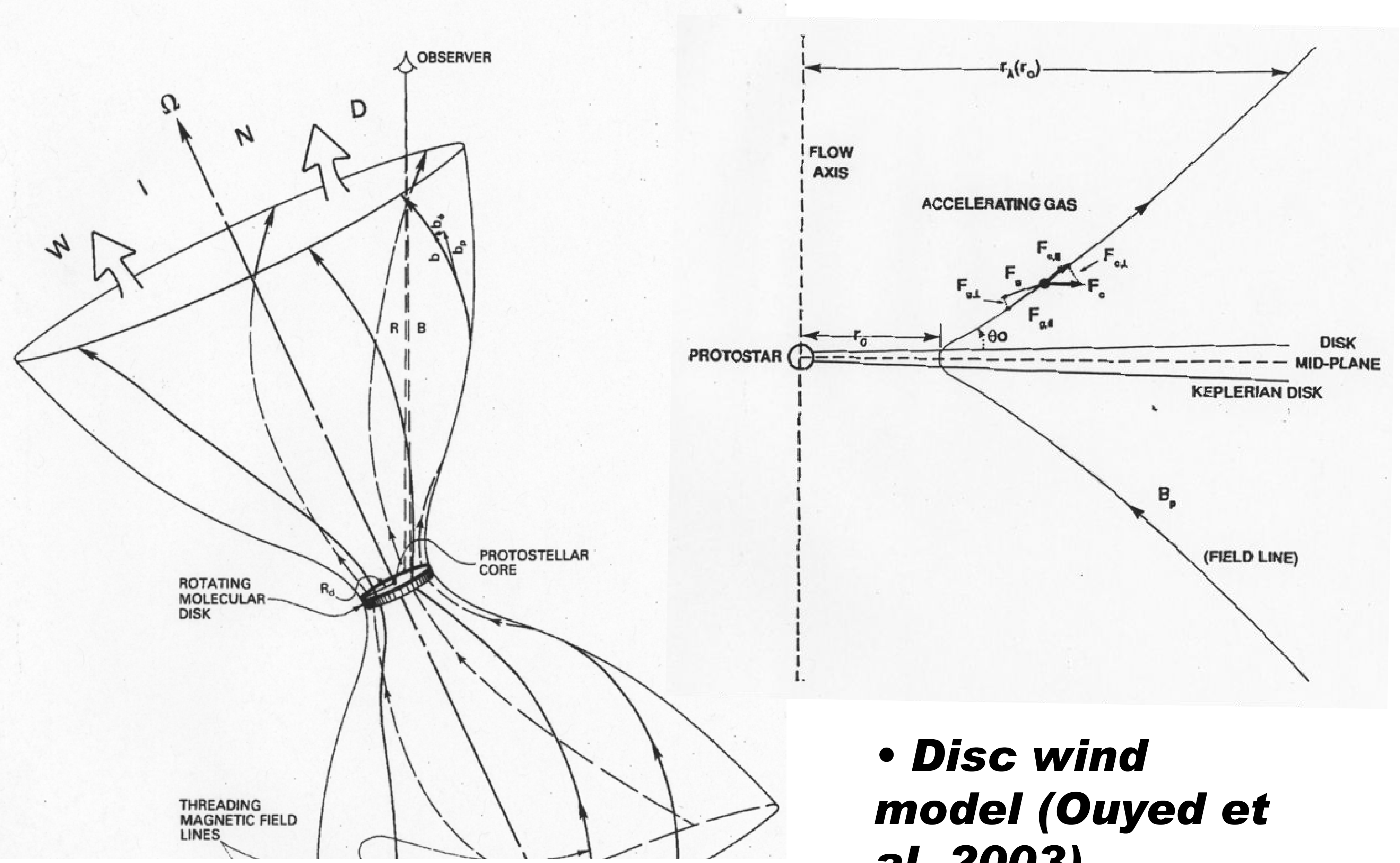


Figure 3. Contour map of the high and low velocity ^{12}CO(2-1) emission in HH 211, superimposed on the H_2 2.2 μm image in greyscale from McCaughrean et al. (1994). The thick contours indicate the 1.3 mm continuum emission. Angular resolution is $1.4 \times 1.1''$ at PA 83°.

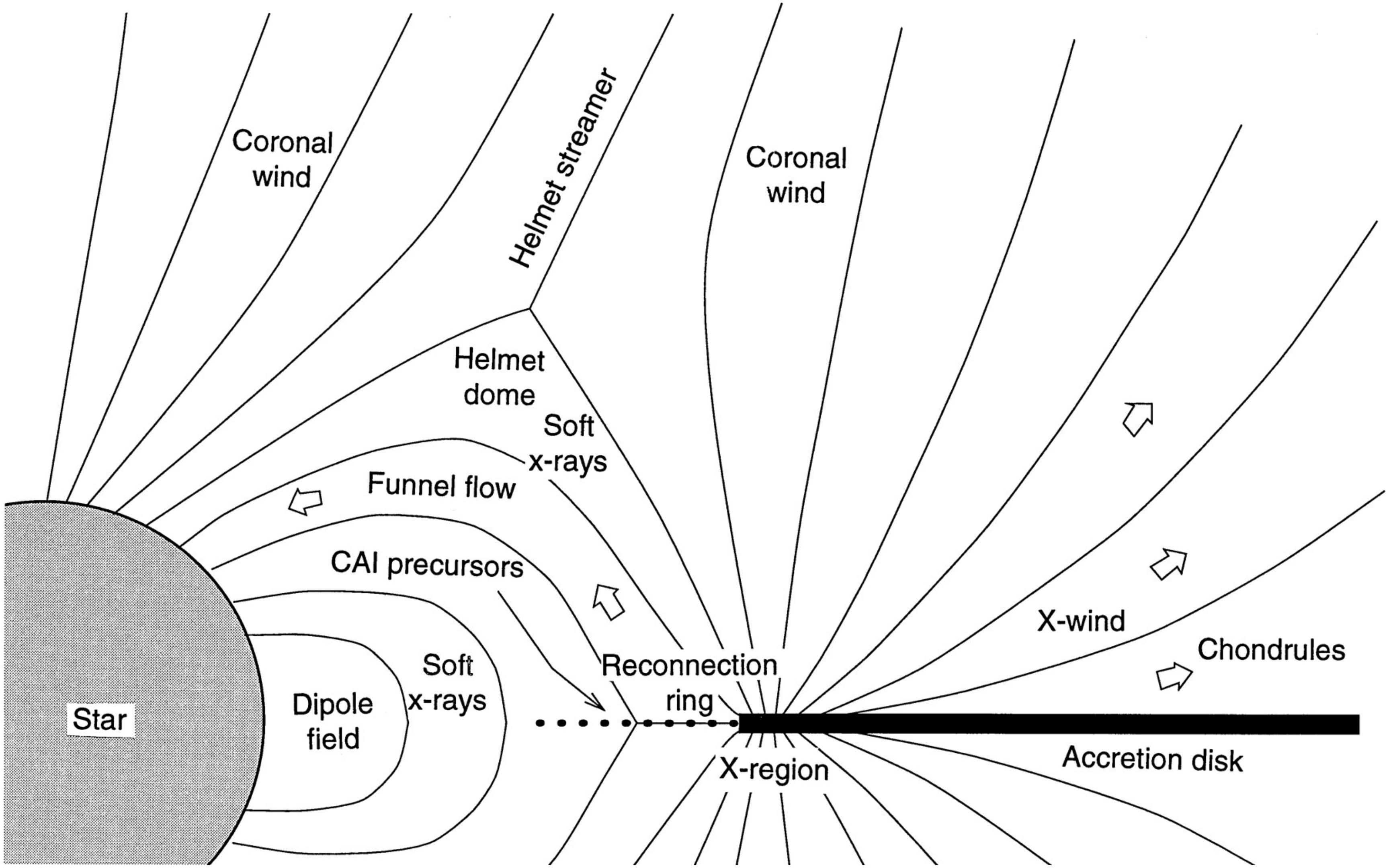
MHD Driving and Collimation Mechanisms



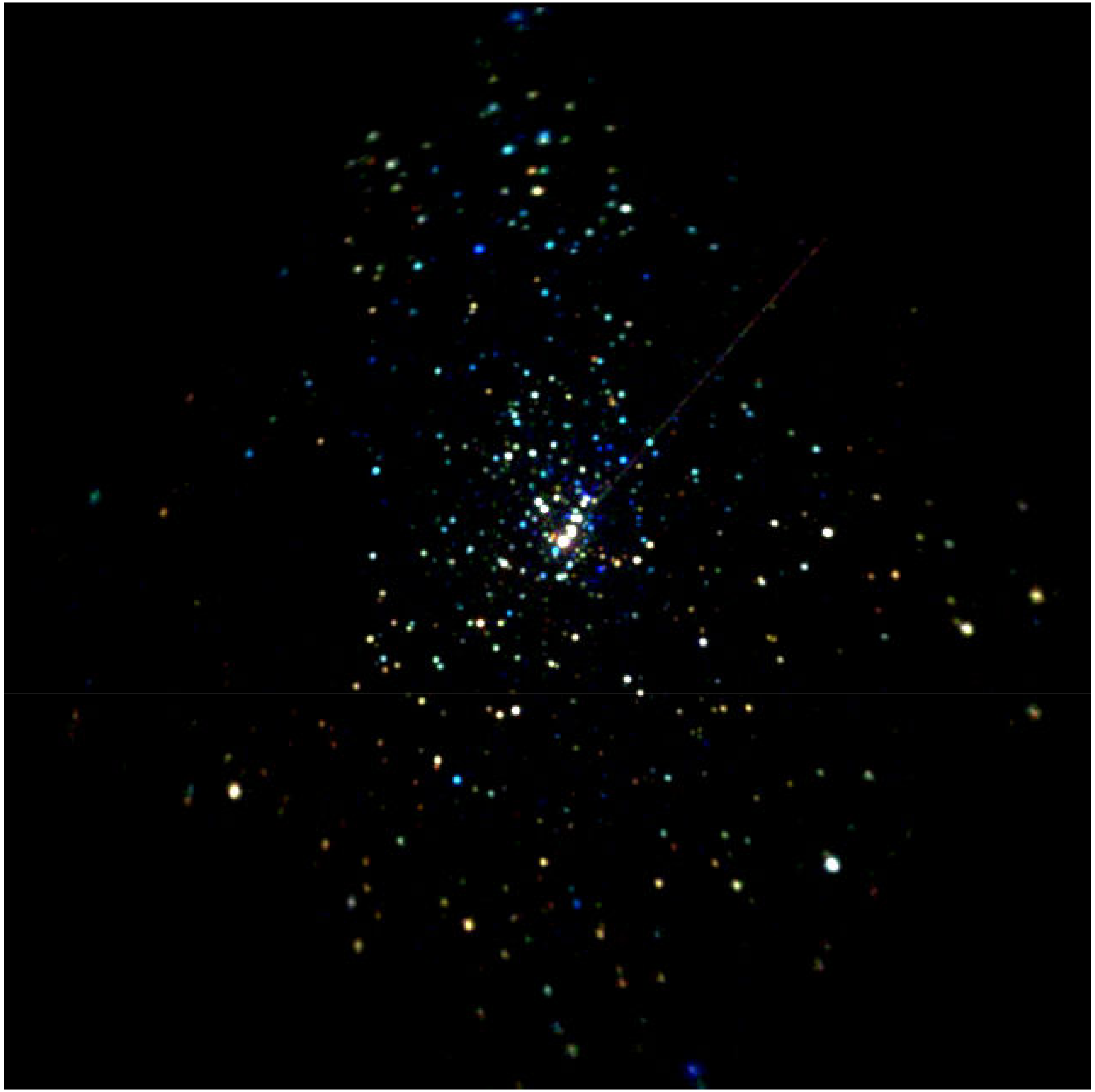
- ***Disc wind model (Ouyed et al. 2003)***

X-wind model (Shu et al. 1997)

- X-wind interaction between rotating stellar field and disc
- Infall channelled along magnetic fields

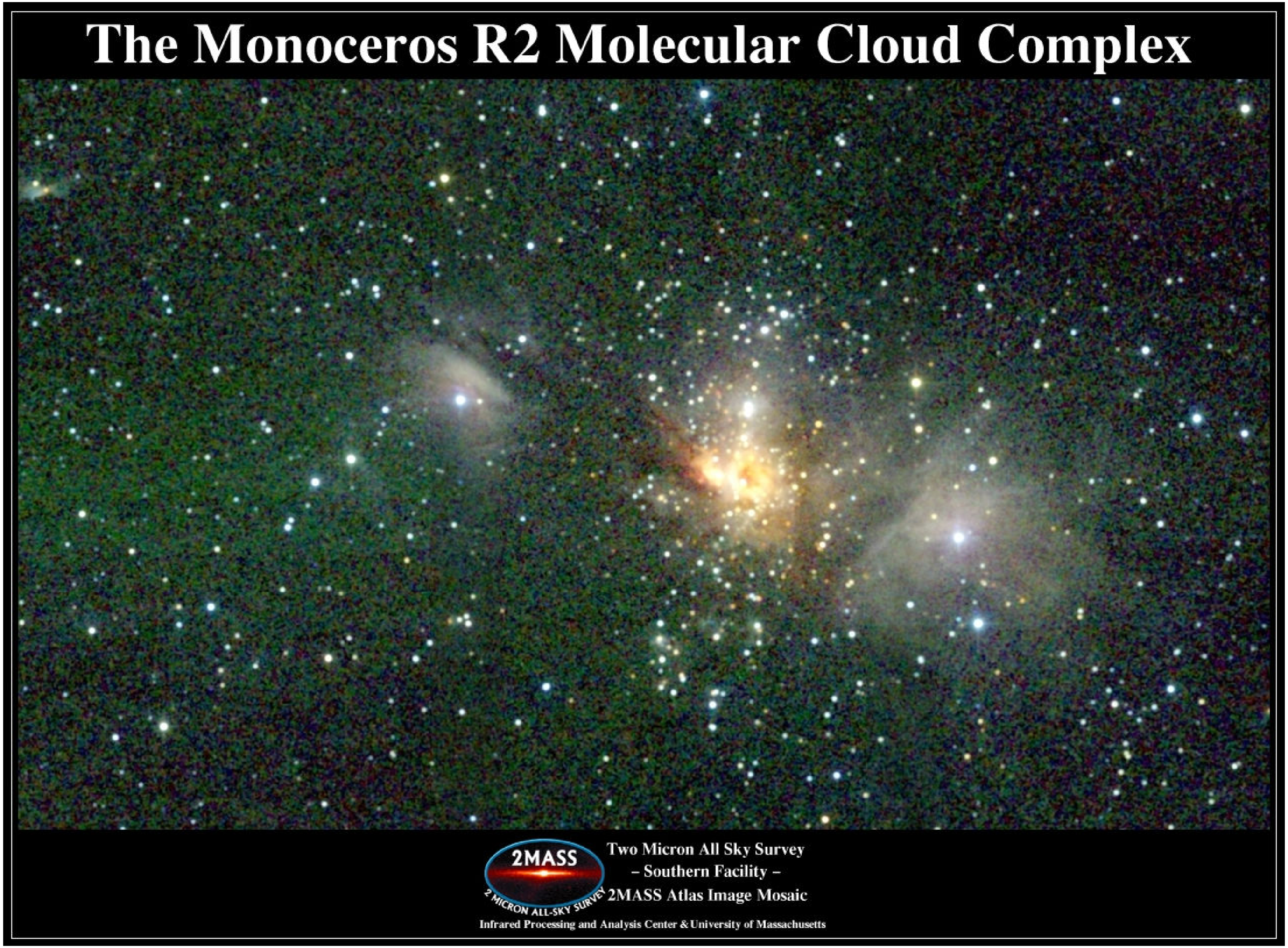


X-ray Activity in Orion Cluster



www.astro.psu.edu/coup

Most (all?) stars form in clusters

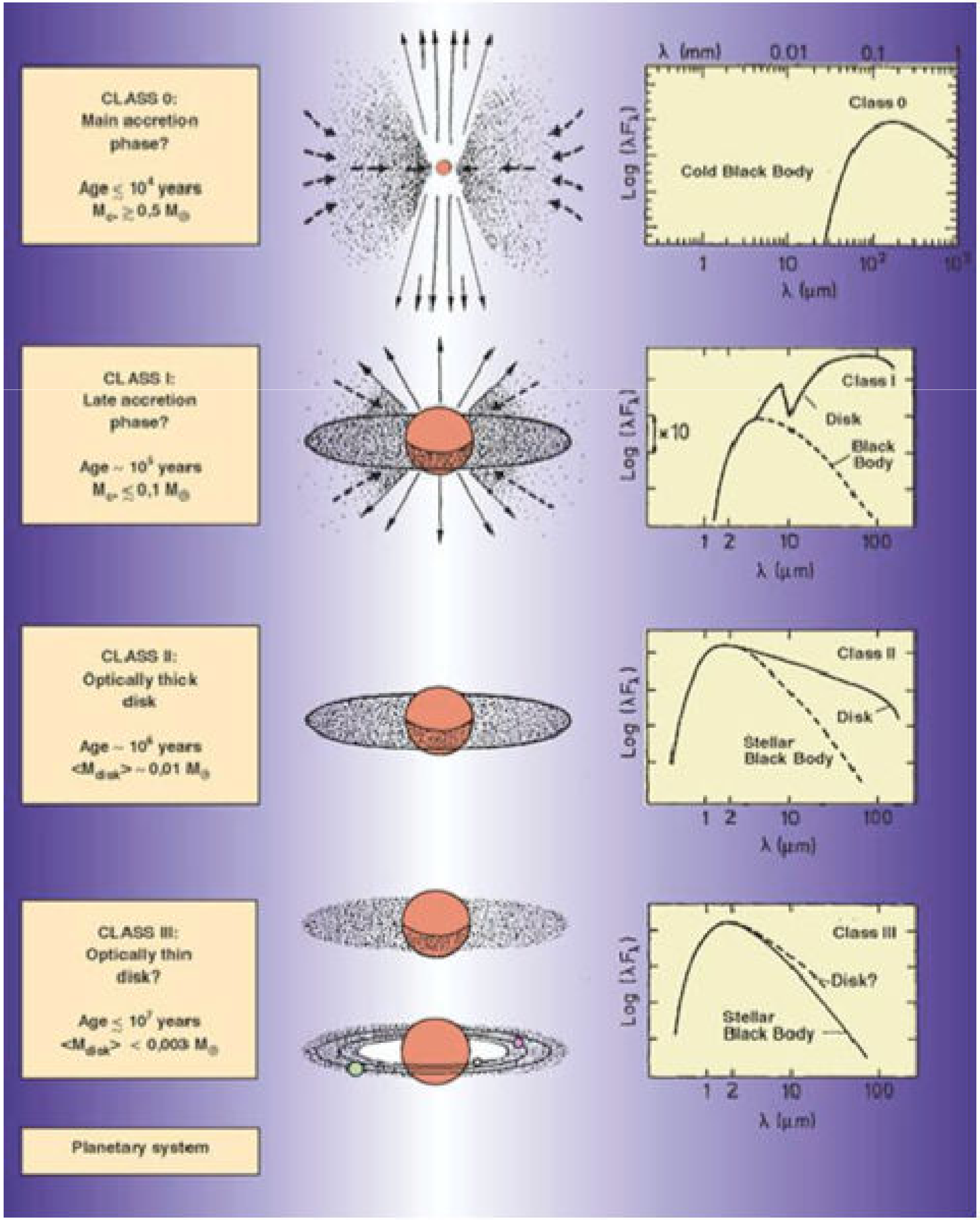


The Monoceros R2 Molecular Cloud Complex

Two Micron All Sky Survey
– Southern Facility –
2MASS Atlas Image Mosaic
Infrared Processing and Analysis Center & University of Massachusetts

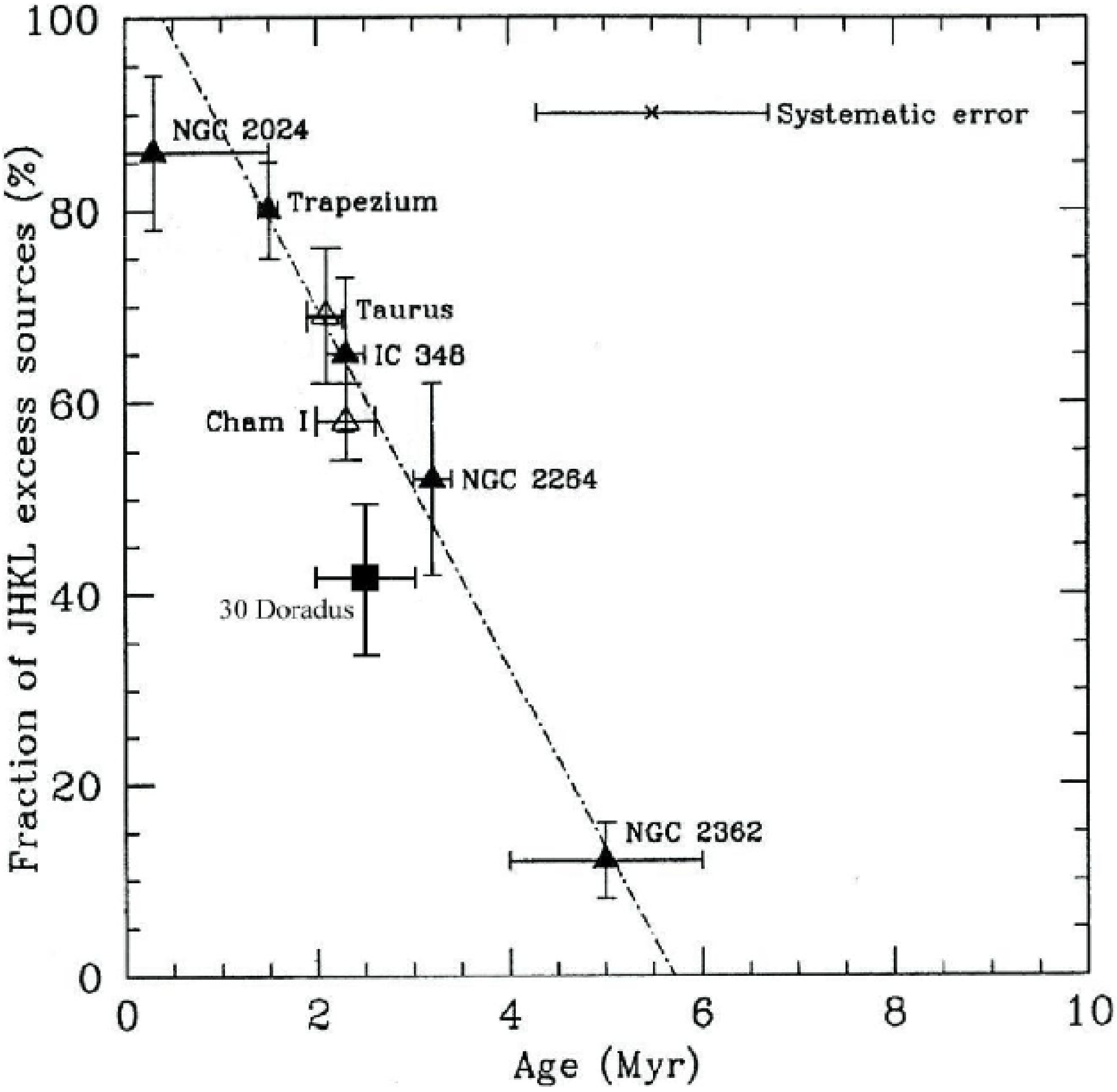
Evolution

- ***Forming stars evolve from deeply embedded phases to optically visible***
- ***Adams et al (1987), Andre et al. (1993) classification scheme Class 0, I, II, III***



Disc Dispersal

- ***Disc disperses over time as fraction of objects with IR excess due to discs decreases with age of cluster (Haisch et al. 2001)***
- ***Likely due to planet formation***

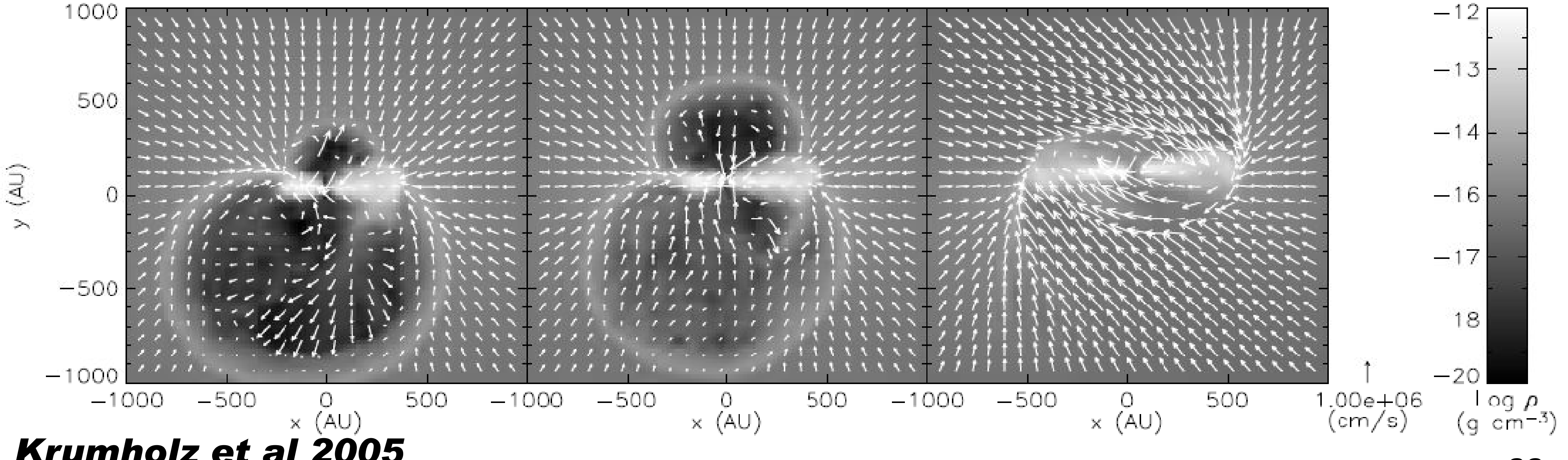


Massive Star Formation

Kelvin-Helmholtz Timescale

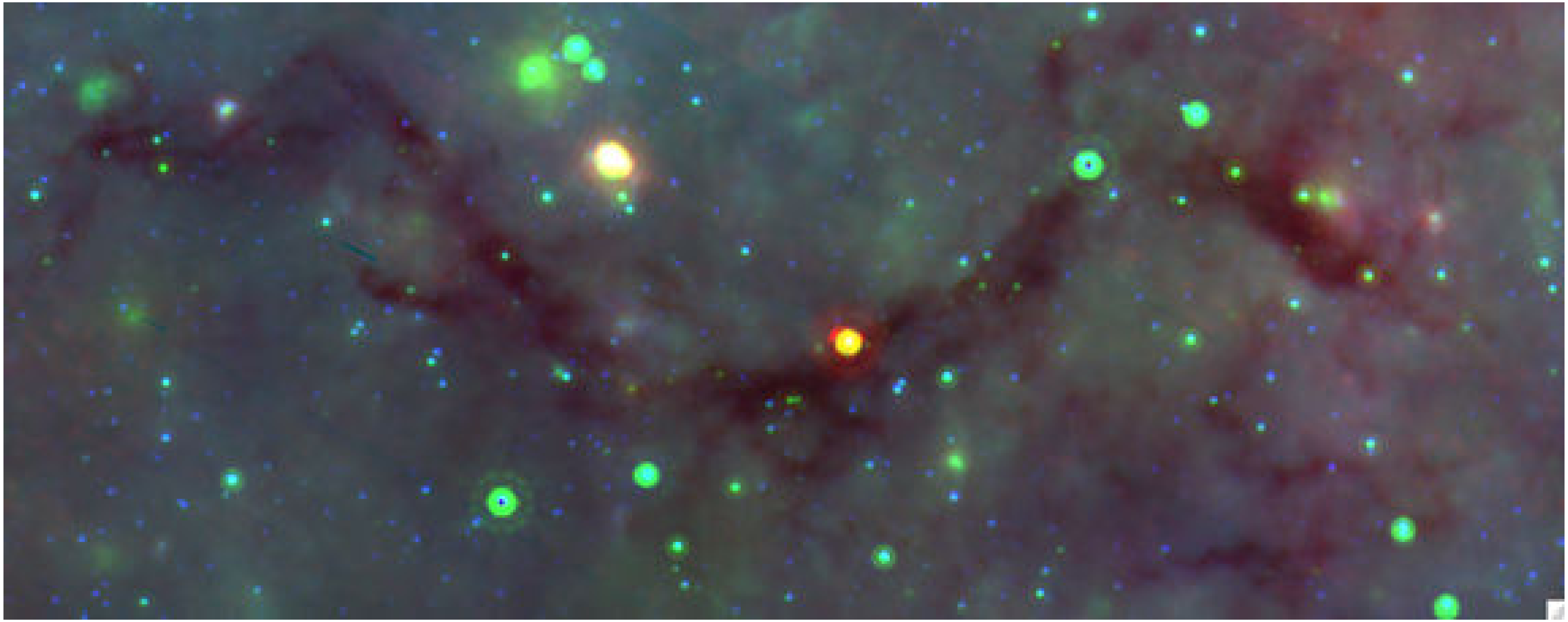
$$\tau_{\mathrm{K-H}} \sim \frac{GM^2}{RL} \qquad \tau_{\mathrm{K-H}} \propto M^{-2} \qquad \tau_{\mathrm{K-H}} << \tau_{\mathrm{ff}}$$

- ***Massive star starts core hydrogen burning whilst still deeply embedded and accreting***
- ***Radiation pressure on infalling dust is very high***
- ***Accretion at high rates via a disc overcomes this***



Krumholz et al 2005

Evolution in Massive Star Formation

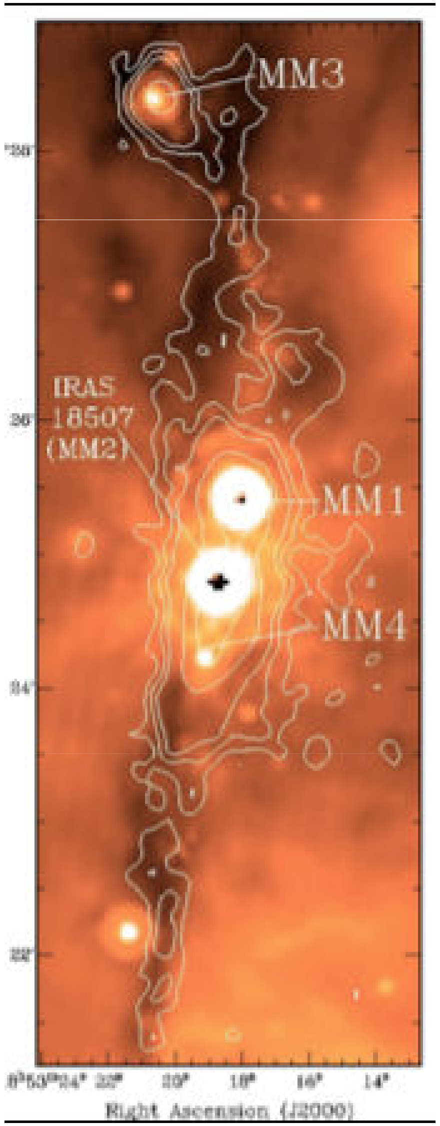


Infrared dark clouds – opaque at 8 microns

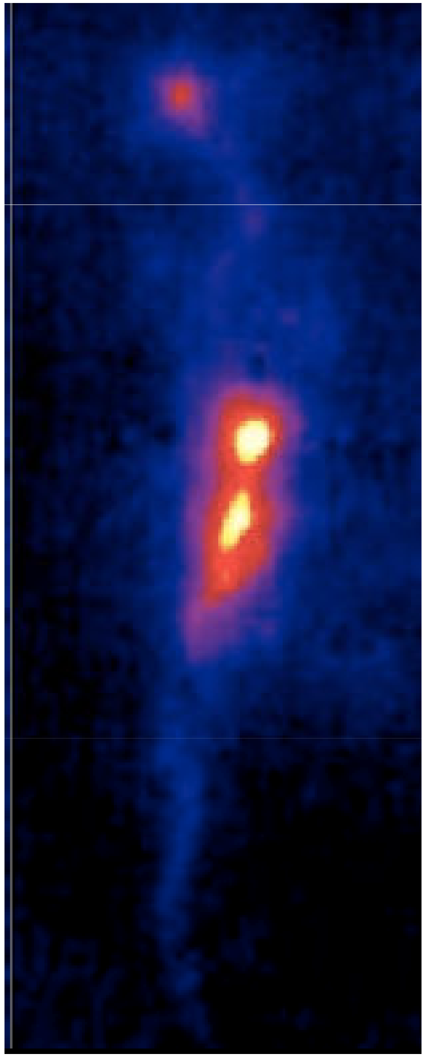
(Rathborne et al. 2005)

IRDCs

Spitzer IRDC



24 µm



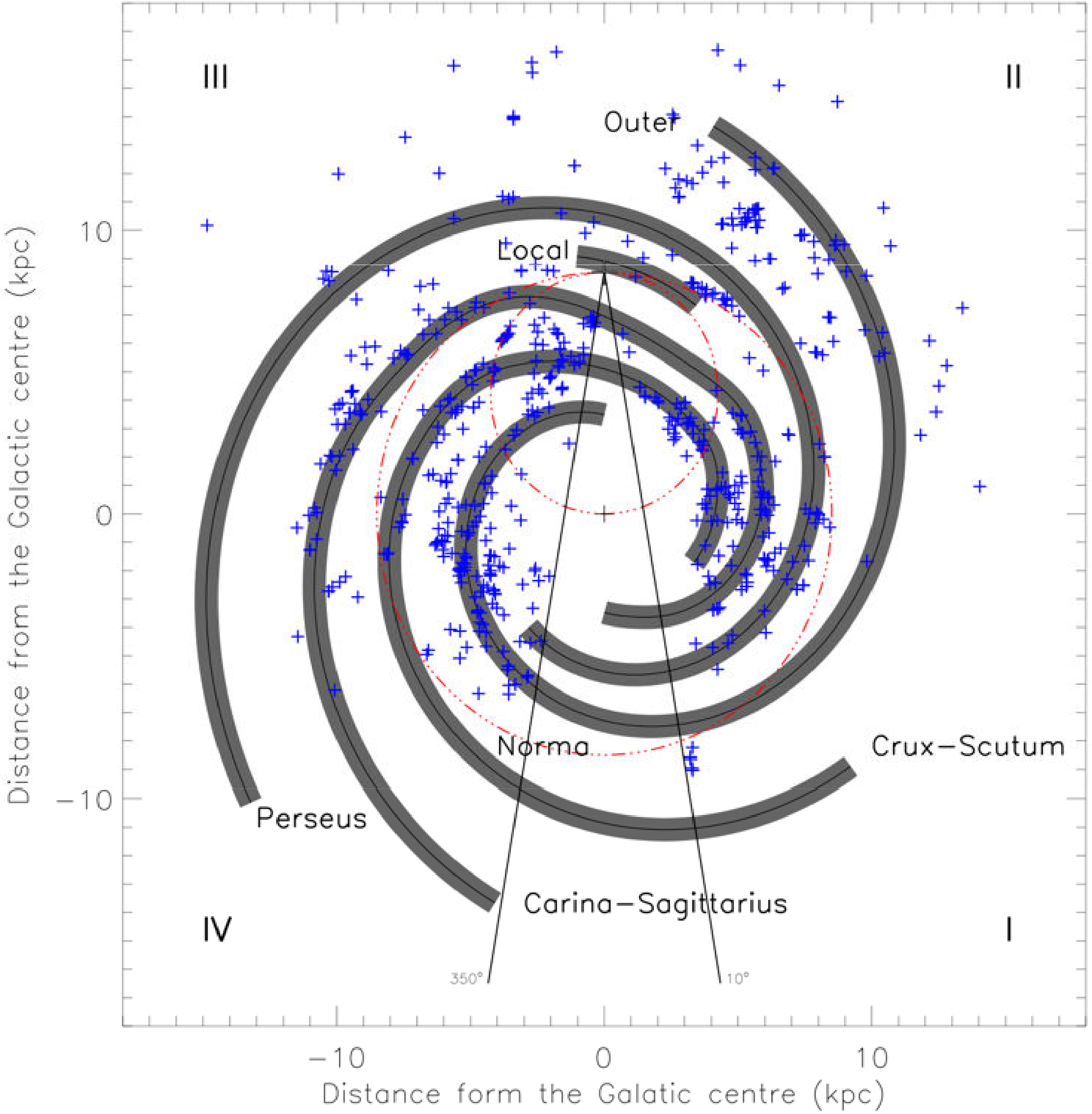
450 µm

Rathborne et al. 2005

Massive Young Stellar Objects

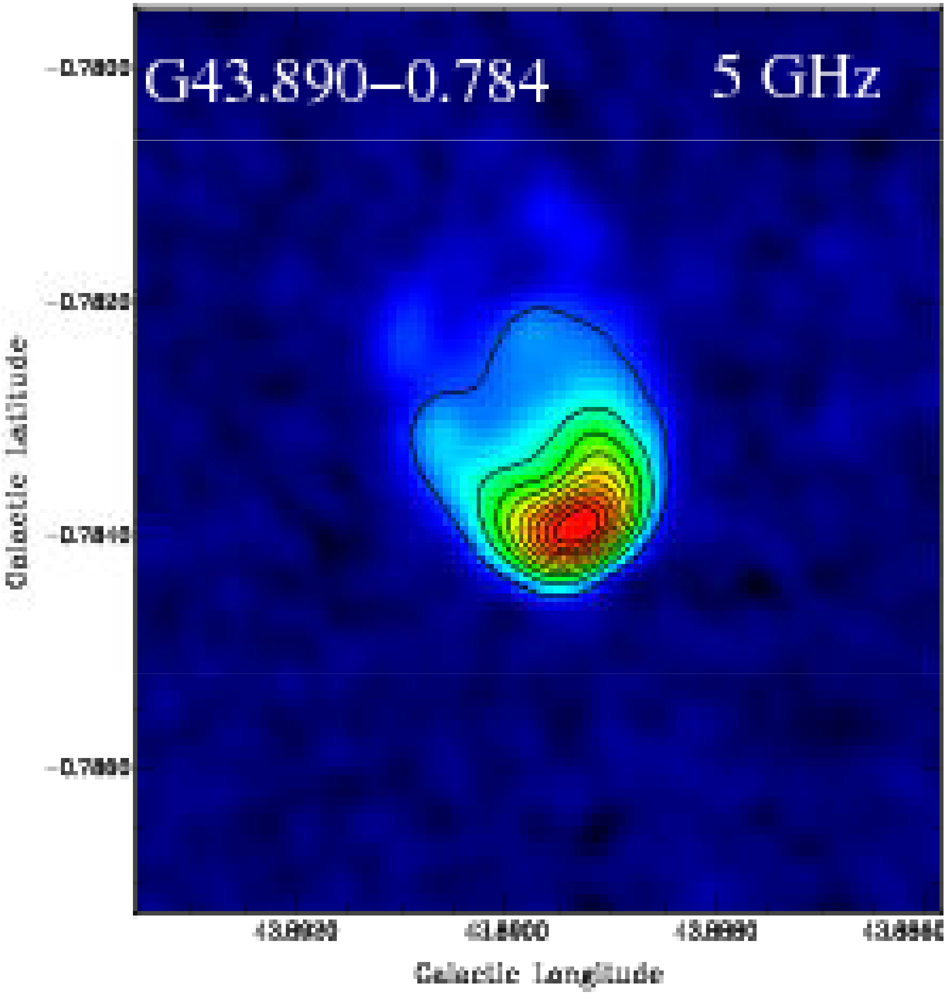
- *Mid-IR bright point sources*
- *Luminous but not yet ionizing surroundings*
- *Bipolar outflows*

Gemini Observatory/Colin Aspin



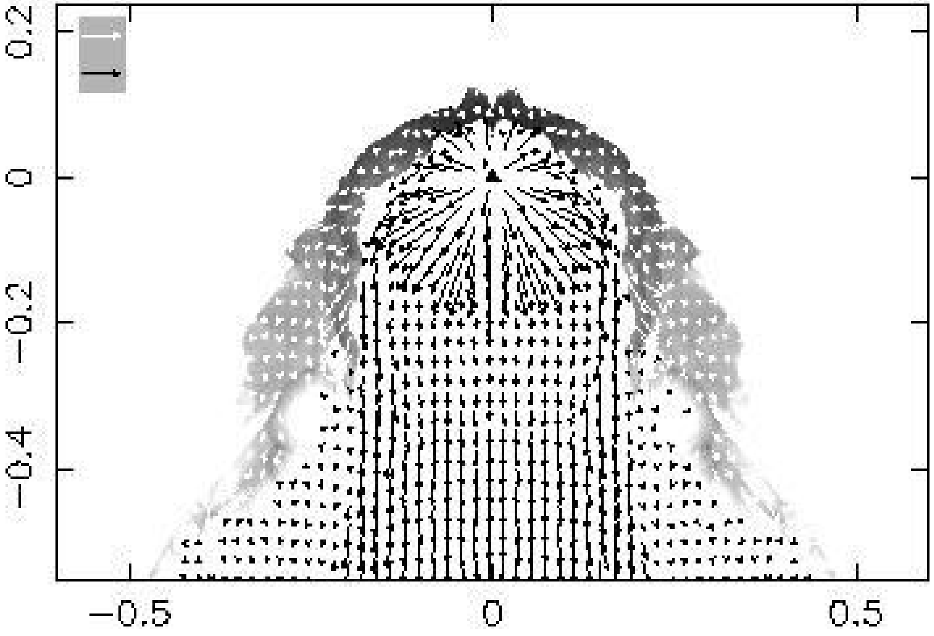
www.ast.leeds.ac.uk/RMS

UCHII regions



www.ast.leeds.ac.uk/Co rnish

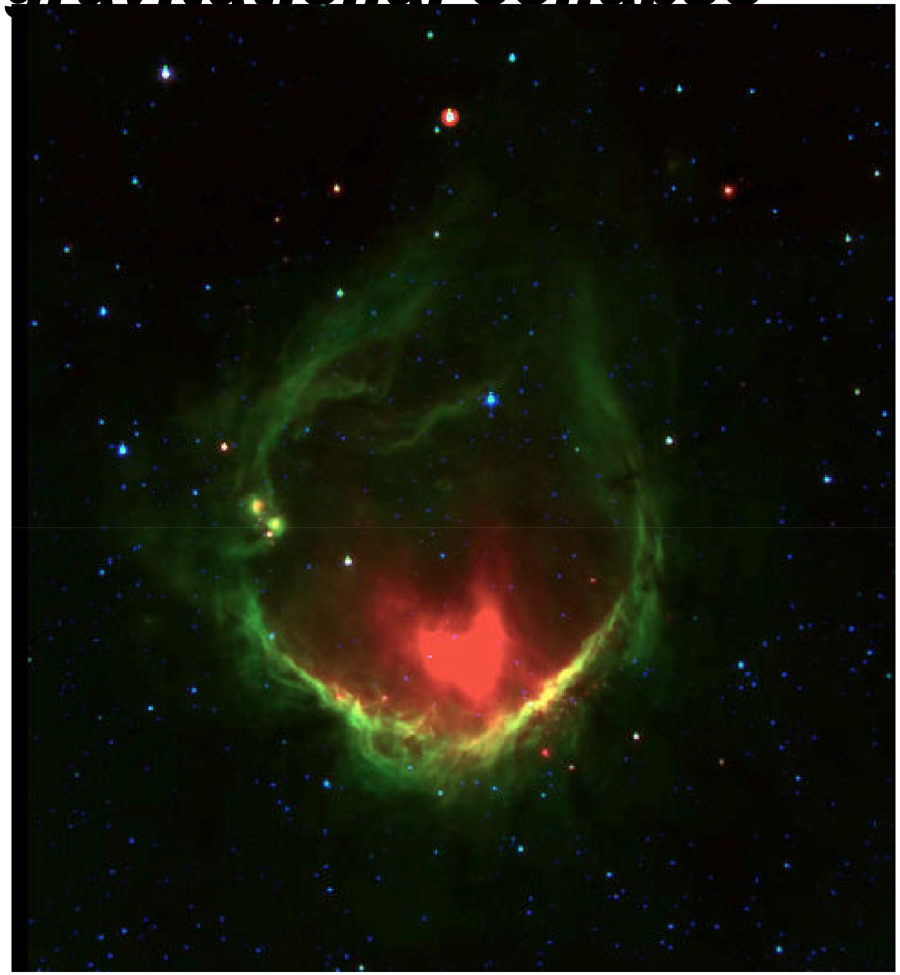
- Cometary UCHIIs imply stars born in density gradient ie off-centre

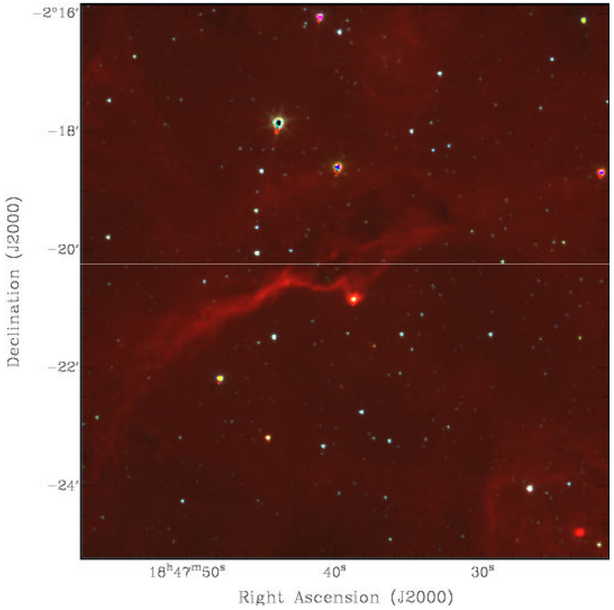


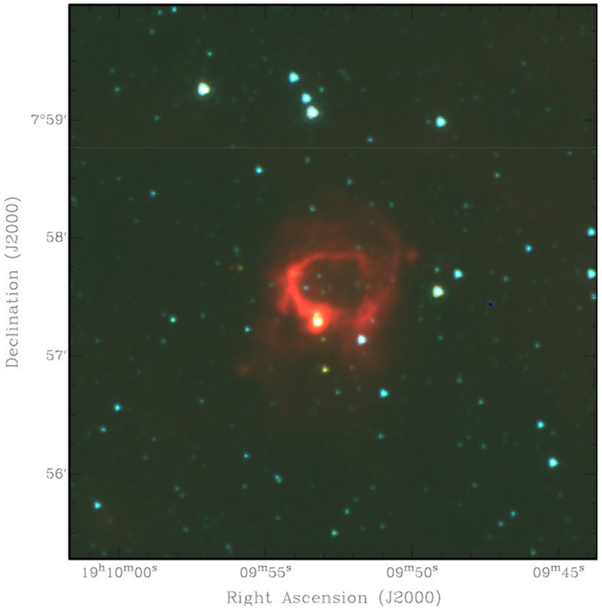
Arthur & Hoare 2006

Triggered Star Formation

- *Expanding H II regions compress surrounding cloud triggering further gravitational collapse*







Danger: Massive stars about