Massive Star Formation in Giant Molecular Clouds

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Rosette Nebula

Ionized region, called an H II region.
Red light comes from H   as H^+ recombines.
Hot stars (> 13.6 eV) in central cluster cause the ionization.
Stars about 4 My old → signpost of recent star formation.
Large region, 30 pc across (c.f. smaller size on SNR).

Stromgren sphere

How large a region can be ionized by a hot star, which emits Q(H) ionizing photons s^{-1} ?

Gas near star is highly ionized, then makes a sharp transition to neutral (mean free path of an ionizing photon is quite short). Look for ionization equilibrium:

$$Q(H) = 4/3\,\pi\,R_s^3\,n_e^2\quad{}_r\ .$$

When density is low, a larger region can be kept ionized.

Exercise: Verify that this lower density case has:

- more mass ~ $R^3\,n$
- lower surface brightness ~ $R\,n^2$

Stromgren sphere expansion

The ionization front expands rapidly, establishing a Stromgren sphere of size corresponding to the initial density.

Gas pressure $p = n\,k\,T$.

The temperature, established by heating-cooling equilibrium, is 8000 K, much larger than the initial temperature of the molecular cloud. → Over-pressured. Region expands, lowering density, until pressure equilibrium is established. Ends up with low surface brightness.

Exercise: work out by what factor R_s increases, using $Q(H) = 4/3\,\pi\,R_s^3\,n_e^2\quad_r$ (assuming star does not evolve).

Some Motivation, High Mass SF

GMCs are the most representative star-forming environments, yet are poorly understood.

- In what conditions do massive stars form?
- Can they form spontaneously?
- Does IMF depend on molecular cloud mass?
- Is star formation coeval?

Galactic Ecology:

Feedback:

- triggered star formation
- disruption of the parent cloud, even without SNe

Examining the details of how things work:

Energetics. Structure: ionization fronts, blisters, and PDRs. Evolution of dust and PAHs.

Reality

- Diffuse H II region has enveloped dense neutral regions that were present in the parent molecular cloud.
- There is a central hole, from radiation pressure on dust and/or stellar winds.

Perseus Chimney

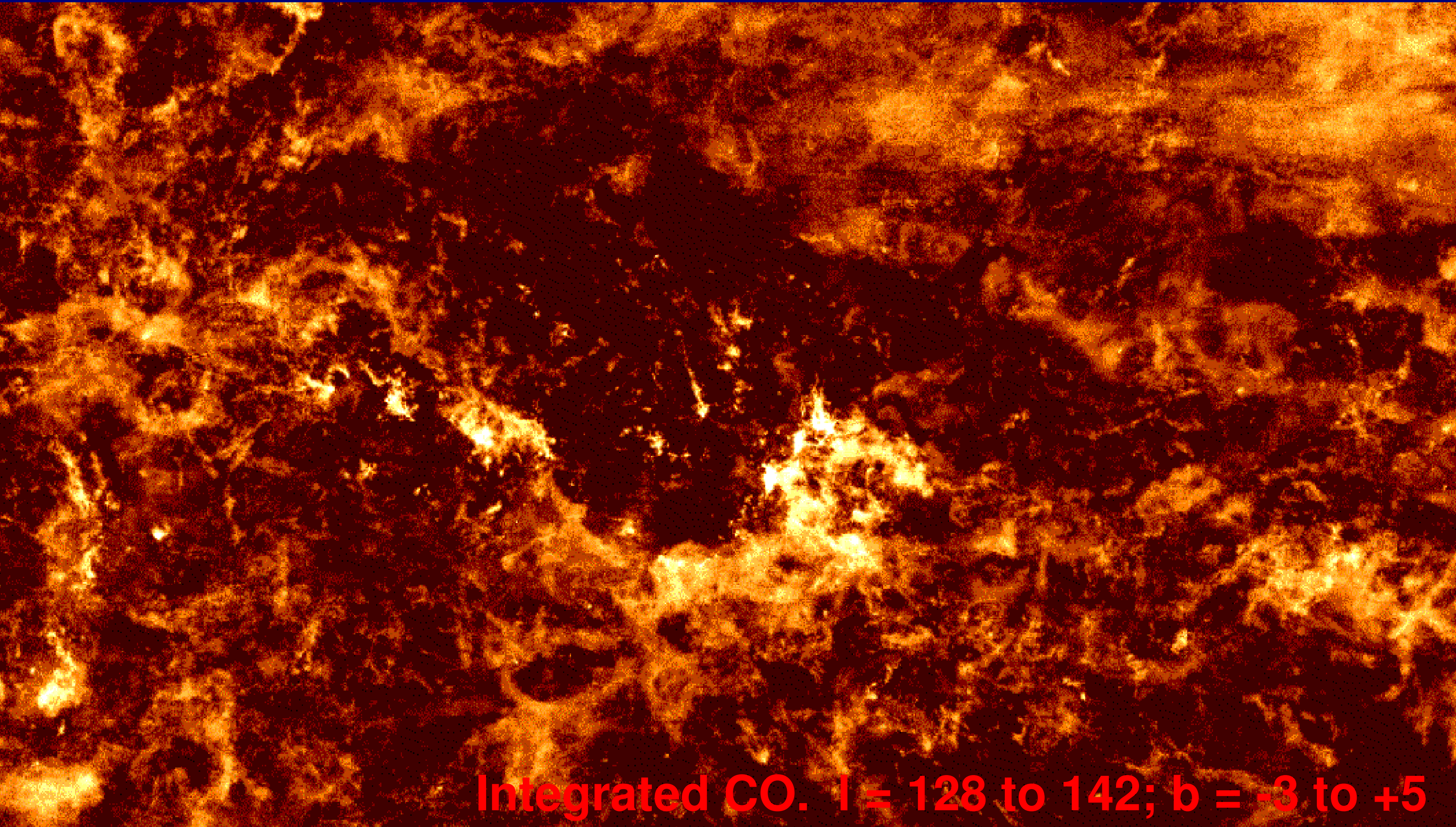
Winds from cluster of hot stars in W4 create a chimney out of disk to halo.

Parent cloud largely gone (see CO map).

Trigger new star formation in W3 GMC.

CO (1-0) FCRAO OGS: W3, W4, W5

At W4, the parent molecular cloud has been destroyed, except for some dense regions. SNe not needed?



SFE: Cluster survival

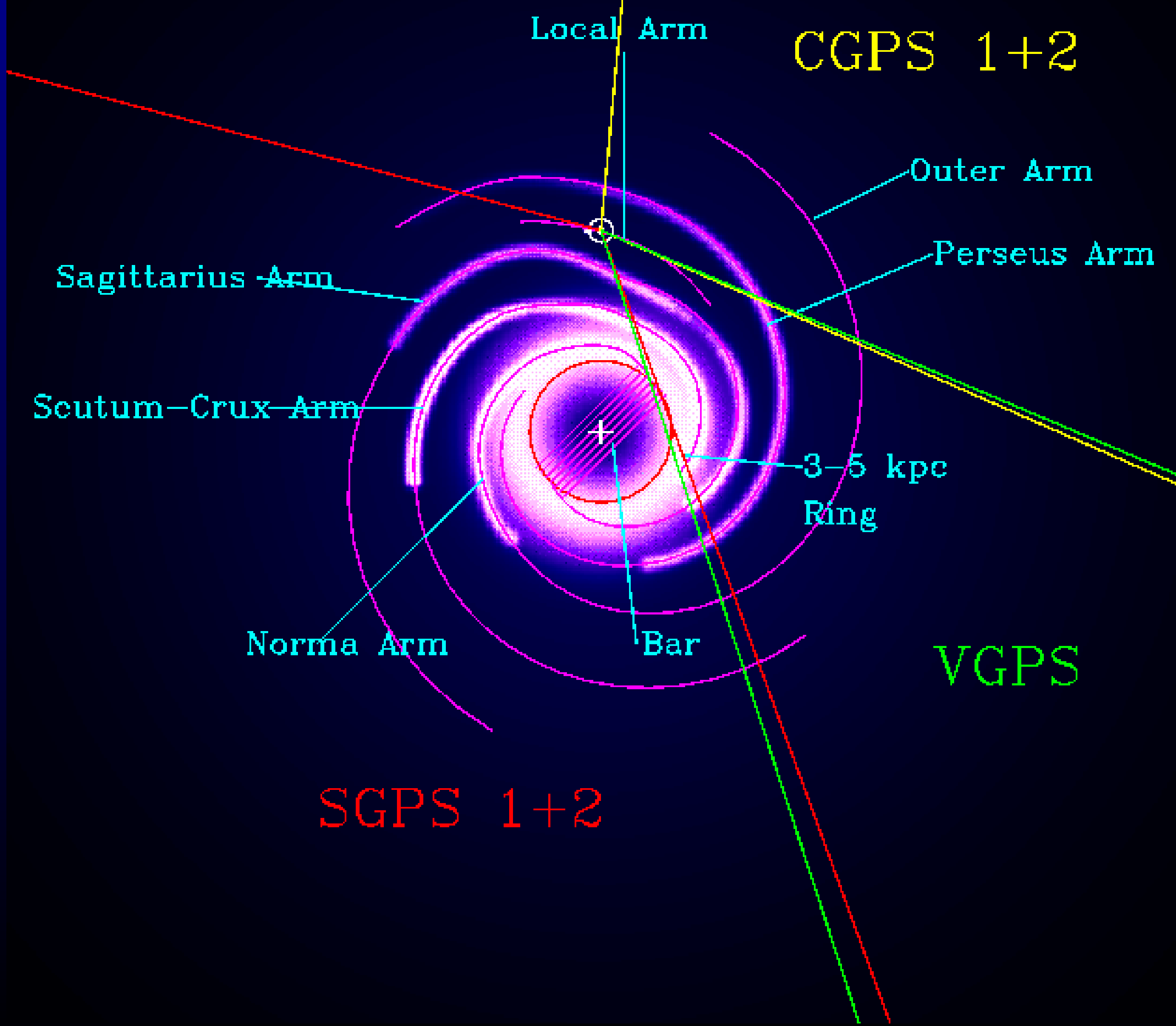
GMCs (gas) are gravitationally bound.
Stars form, usually a whole cluster.
Stars disrupt the cloud and expand the gas, but leave the stars behind.
Is the stellar cluster still gravitationally bound?
Depends on the star formation efficiency (SFE), which is low → usually unbound.
Expanding "associations" of stars are seen. These are clusters in the process of dissipating, becoming "field stars". (Evidence for low SFE.)
GMCs contain most of the molecular mass, and so statistically the sun would have formed in a GMC; now the sun is a field star.

Perseus arm context

Distance 2 kpc (c.f. GC at 8 kpc).

Easier to see “nearby” regions; also better linear resolution.

Previous CO map extends 14 degrees along the plane.



Orion Nebula: closest massive SF

Dust obscuration from molecular cloud.

Trapezium of hot stars exposed.

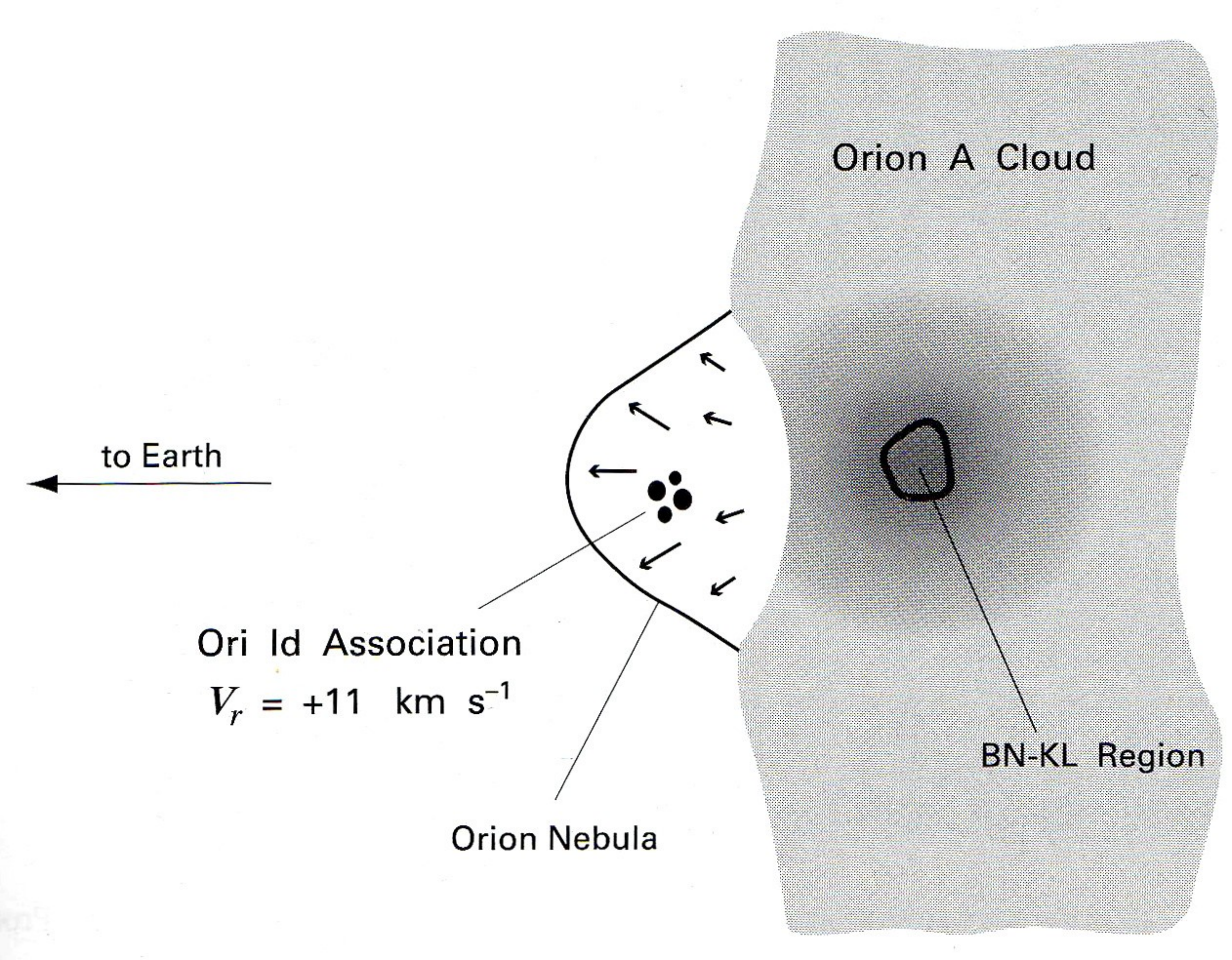
Hubble heritage: Bally and O'Dell

Orion Nebula

Ionized by massive stars near the front surface of the closest (450 pc) GMC.

Thus we can see it in the optical.

(comments on blister depth)



Cartoon after Stahler and Palla.

Oxygen ionization structure from CLOUDY

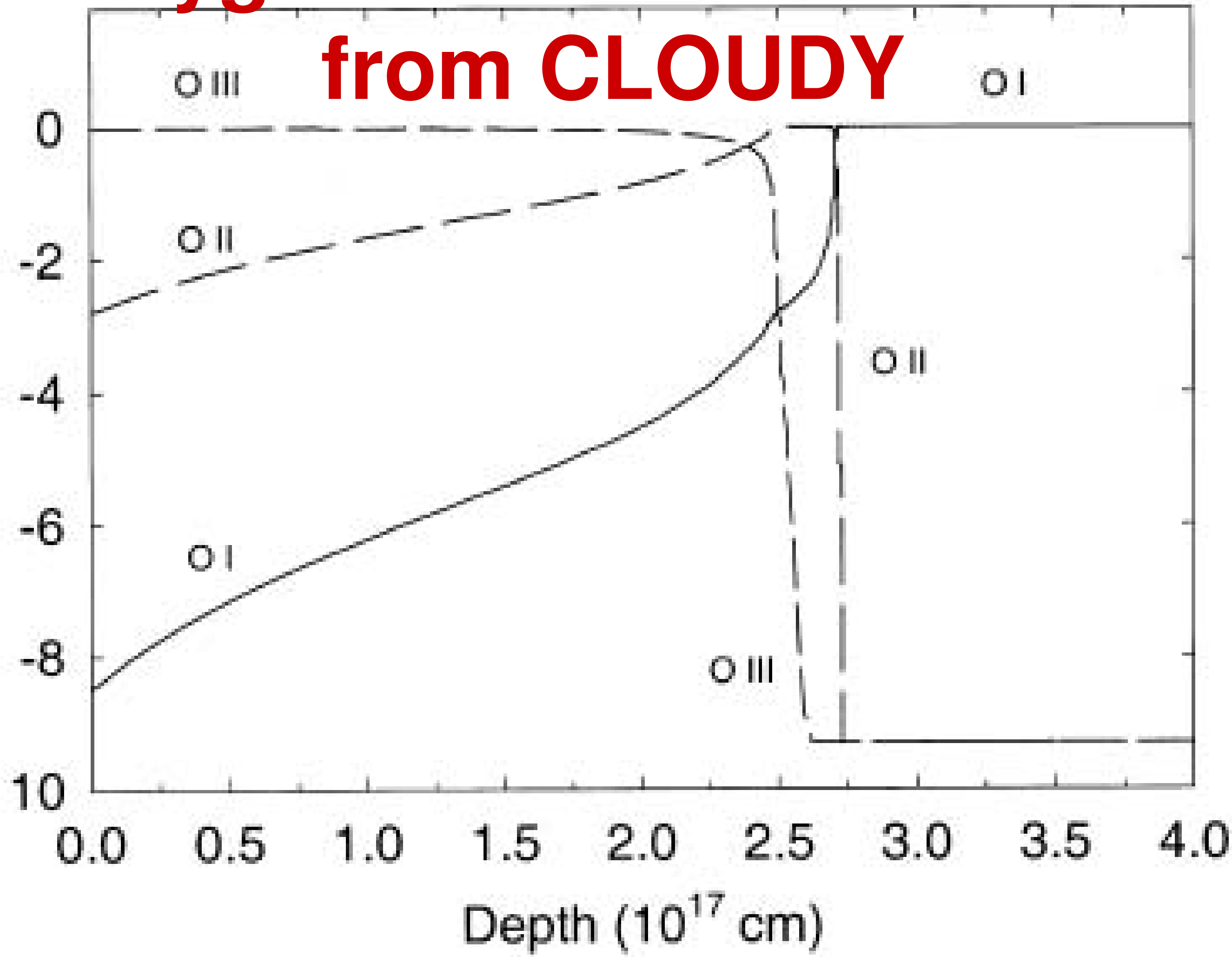


FIG. 4.—Log of the O^0 to O^{2+} ionization fractions vs. depth in cloud

Blister outflow (destroying cloud)

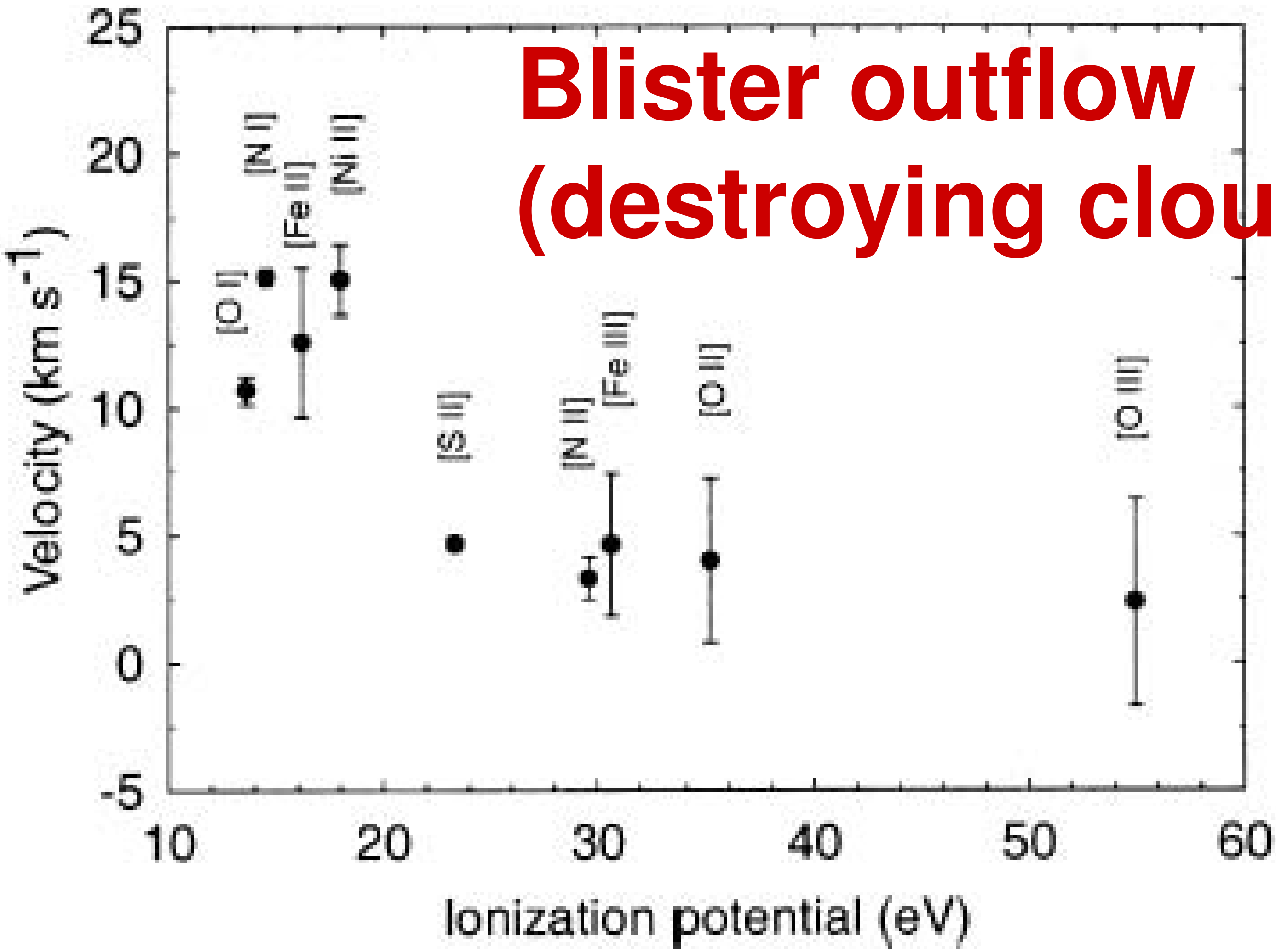
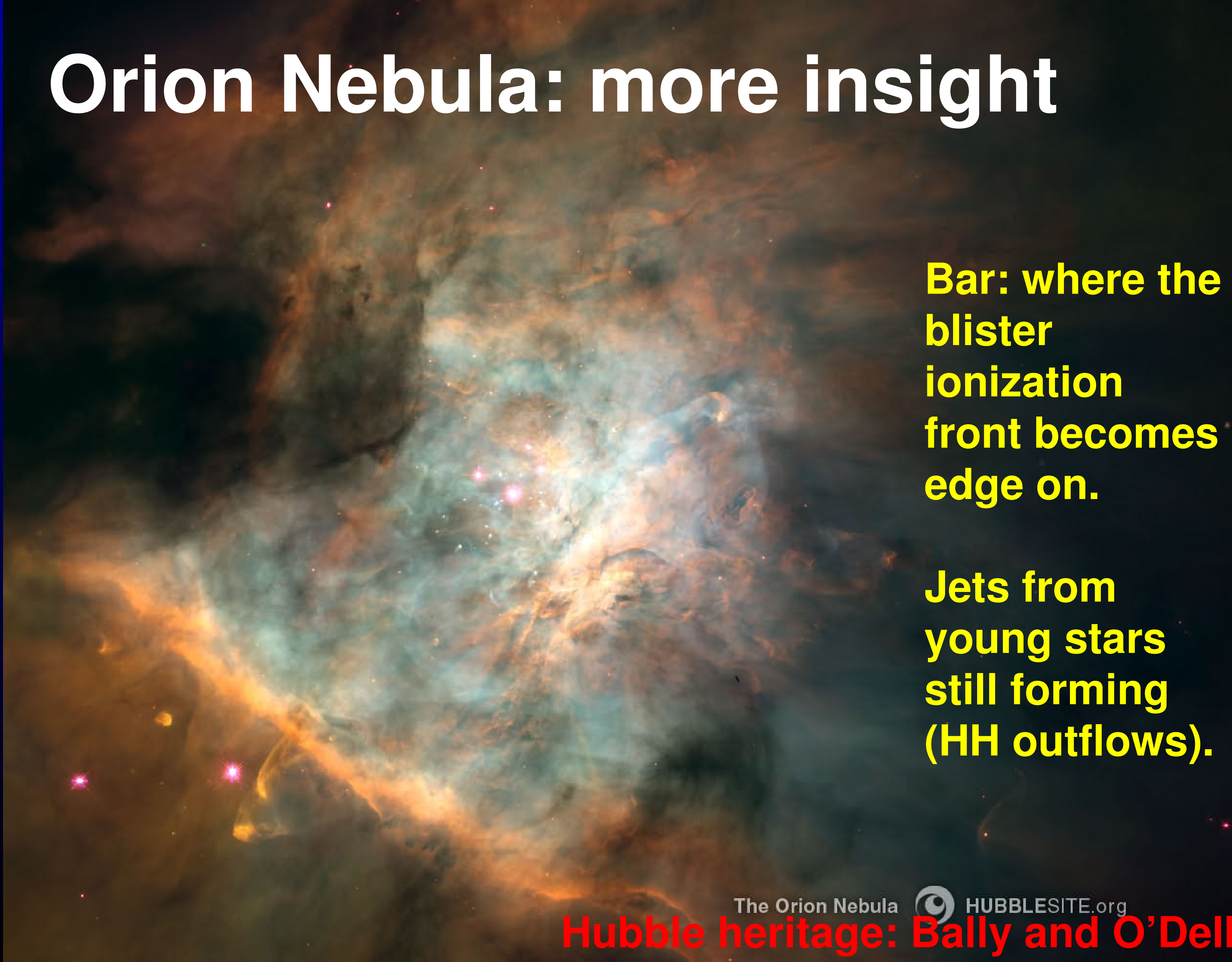


FIG. 11.—Velocities of forbidden lines vs. the ionization potential. Errors are standard deviations of the distribution of velocities from several lines for a given ion. Other ions such as [Ne III], [S III], [Ar III], and [Ar IV] are not shown because the rest wavelengths of their lines are less accurately known. Generally, they show the same trend.

Orion Nebula: more insight



Bar: where the blister ionization front becomes edge on.

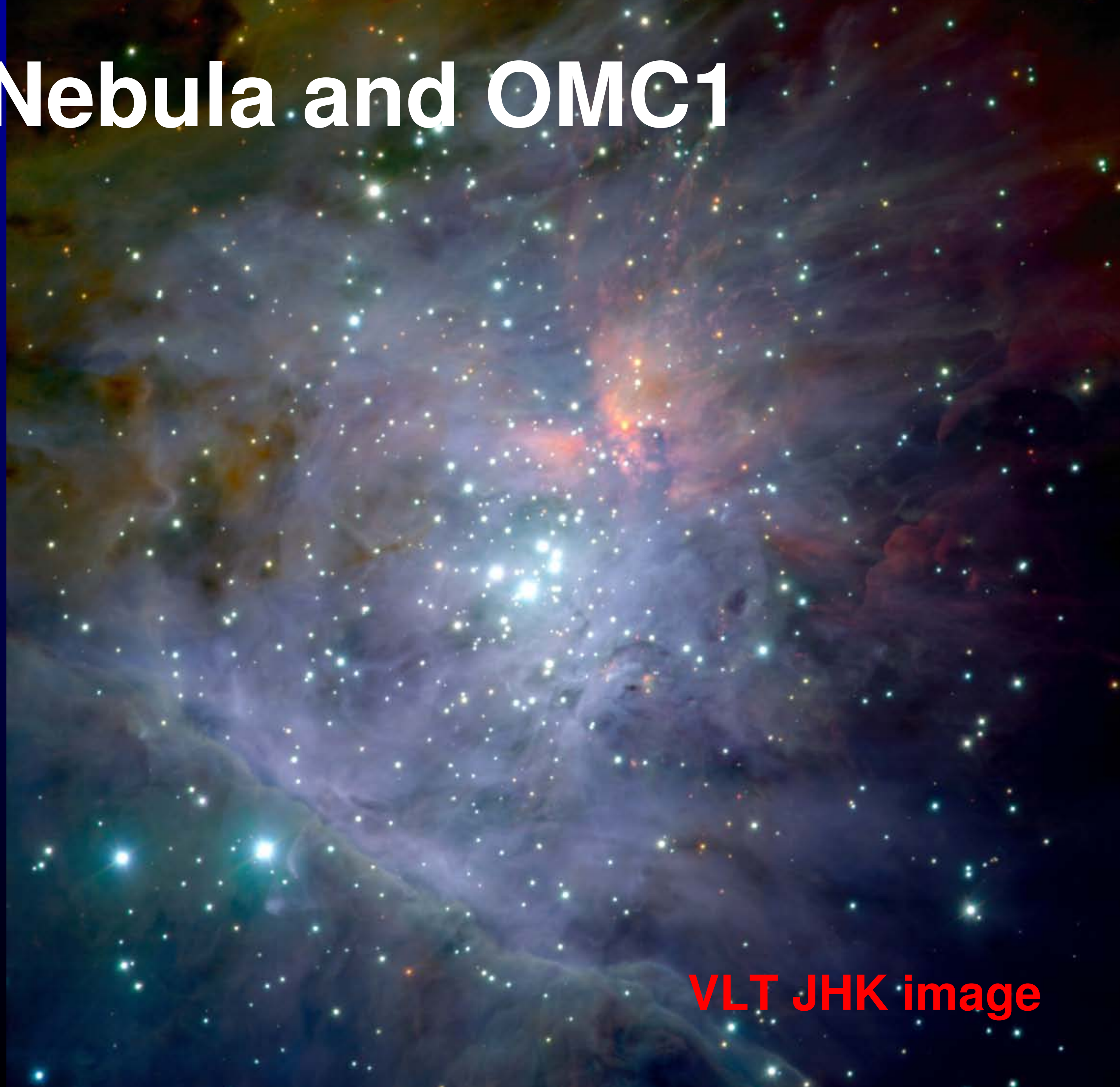
Jets from young stars still forming (HH outflows).

Hubble heritage: Bally and O’Dell

Orion Nebula and OMC1

JHK image.

Red hue is from shock-excited H_2 in the background molecular cloud OMC1 where there is on-going star formation.



A large cluster has formed

While the massive hot stars are causing the ionization, there are many more lower mass young stars.

Some of these have very interesting features, e.g., disks of gas and dust (like around other young stars, and like the disk from which the planets in our Solar System formed).

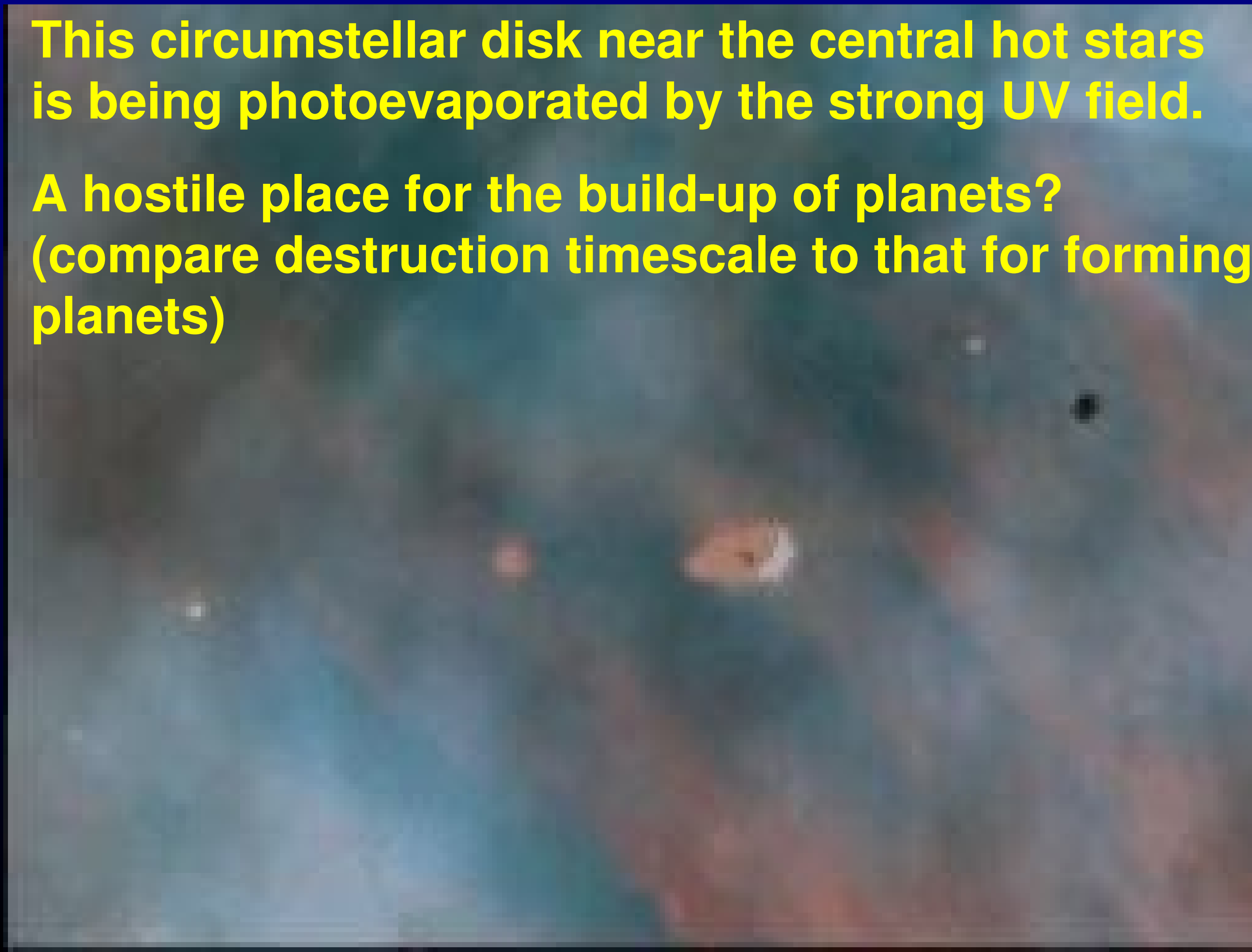
Low mass stars with disks

This young lower mass star has a “protoplanetary disk” whose dust is blocking out the background nebular glow.

Photoevaporation of disks

This circumstellar disk near the central hot stars is being photoevaporated by the strong UV field.

A hostile place for the build-up of planets? (compare destruction timescale to that for forming planets)



Why is the Orion nebula green?

Seen visually through a telescope, the nebula looks green. Why?

It is certainly not red, as it might be from the strong red recombination line H   at 6563 Å.

Instead there is also a strong green line at ~ 5000 Å, near the peak of the sensitivity of the human eye.

This line was not identified with a particular element at the time it was first recorded, and so the originating “mystery” element was called “nebulium” (c.f., “helium” in the sun).

Heating – Cooling Equilibrium

Heated by photoelectrons from atoms and ions as the gas (largely H) is ionized.

Cooled by collisional excitation of transitions of several ions. A large fraction of the cooling comes out in the [O III] line at 5007 Å.

This is a so-called "forbidden line" of the O^{++} ion, with a low transition probability so that it had never been seen in the laboratory (hence "nebulium"; but this name did not stick, like helium, which was a "new" element).

Equilibrium at T ~ 8000 K.

Other famous H II regions

Lots of surrounding molecular gas and dust.

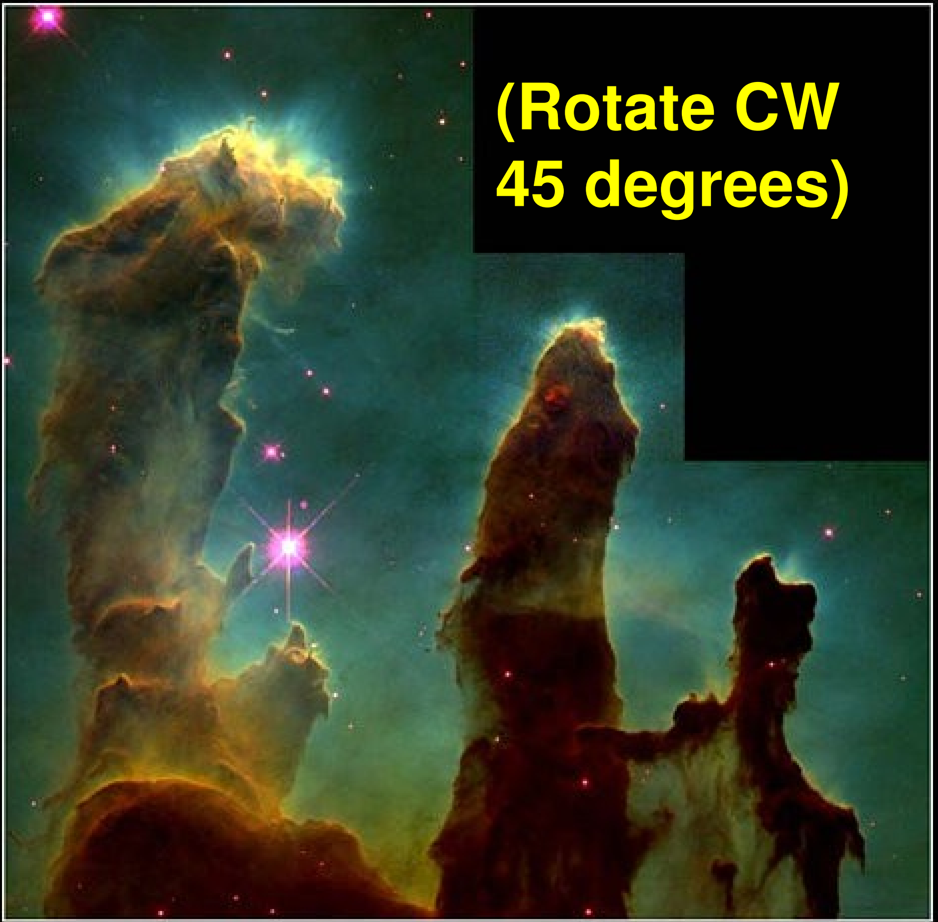
Dense regions are highlighted by silhouette and ionization fronts. These have the potential to form more stars (again note that the GMC did not all collapse at once).

But these molecular clouds are being severely disrupted by the hot stars that have formed, which will terminate star formation at least locally (range of influence an interesting issue).

Eagle Nebula (M 16)

Star cluster with massive stars. Residual molecular material nearby and dense regions engulfed within H II region (more stars could form, but these are being photoevaporated too).

M 16 detail



Gaseous Pillars · M16 HST · WFPC2
PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

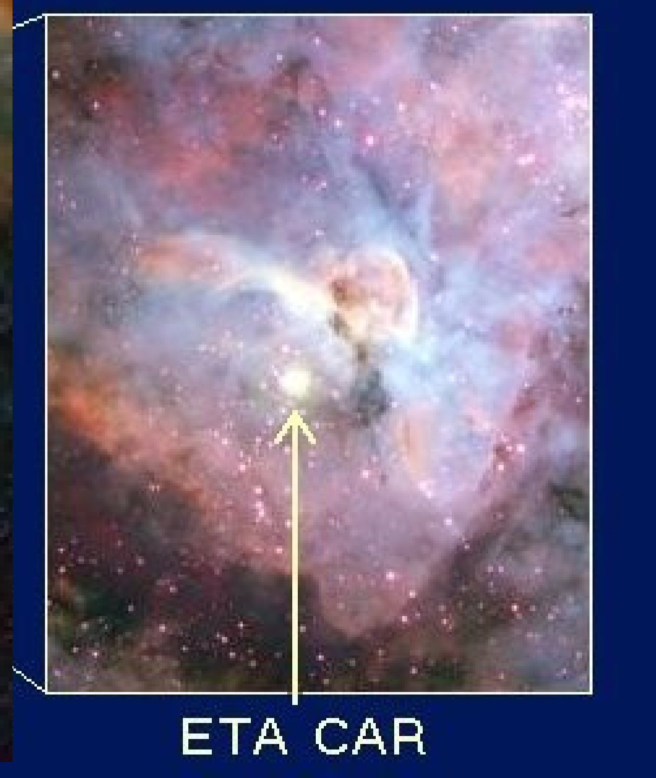
Great nebula in Carina

Contains many of the most massive stars known in the Galaxy (O3 stars).

η Carina

Massive star which has had a major eruption and mass loss in the last 200 years.

Like other massive stars, it will become a core-collapse SN, this one sooner than later ($< 10^5$ y). Will be very bright!



High-mass star formation

Conclusion: This is quite complicated!   Turbulence and magnetic fields as well as thermal pressure and gravity.

It is hard to observe the theoretical 0.01 M_{sun} fragments, even if they exist. But there certainly is structure on larger scales. Often this is stable (i.e., not in free-fall). The GMC does not collapse as a whole.

An H II region is a signpost of recent star formation. In the surrounding (remaining part of) the molecular cloud are there stars yet to form?

Are there any simple regions with a single ionizing star that look like a Stromgren sphere?

Case study: Vignettes of Massive Star Formation in a Molecular Cloud in the Perseus Arm

Spontaneous (i.e., non-triggered) formation of low mass stars seems common-place in nearby clouds.

But does this happen for high mass stars (as opposed to triggering by previous generations of massive stars)?

We found an example, in a molecular cloud in the Perseus arm, where a massive 25 M_{sun} star appears to have formed spontaneously, well away from the nearest major star-forming activity in W3 (which is influenced by W4).

Cold cores

With SCUBA imager on JCMT we discovered a number of relatively cold submillimetre sources not visible in the IRAS data, ranging in size from 0.2 to 0.7 pc and in mass from 0.5 to 130 M_{sun}.

Many are gravitationally bound and if in virial equilibrium require non-thermal pressure support.

Upon loss of such support they could be sites of future star formation, i.e., they could be the long-sought cold pre-stellar cores.

Not coeval

Several embedded protostars have in fact been found in this field too.

Thus there are simultaneously:

- A massive O star with a fully developed H II region
- Embedded protostars
- Pre-stellar cores.

Star formation in this region is not completely coeval, spanning several million years. Not efficient initially.

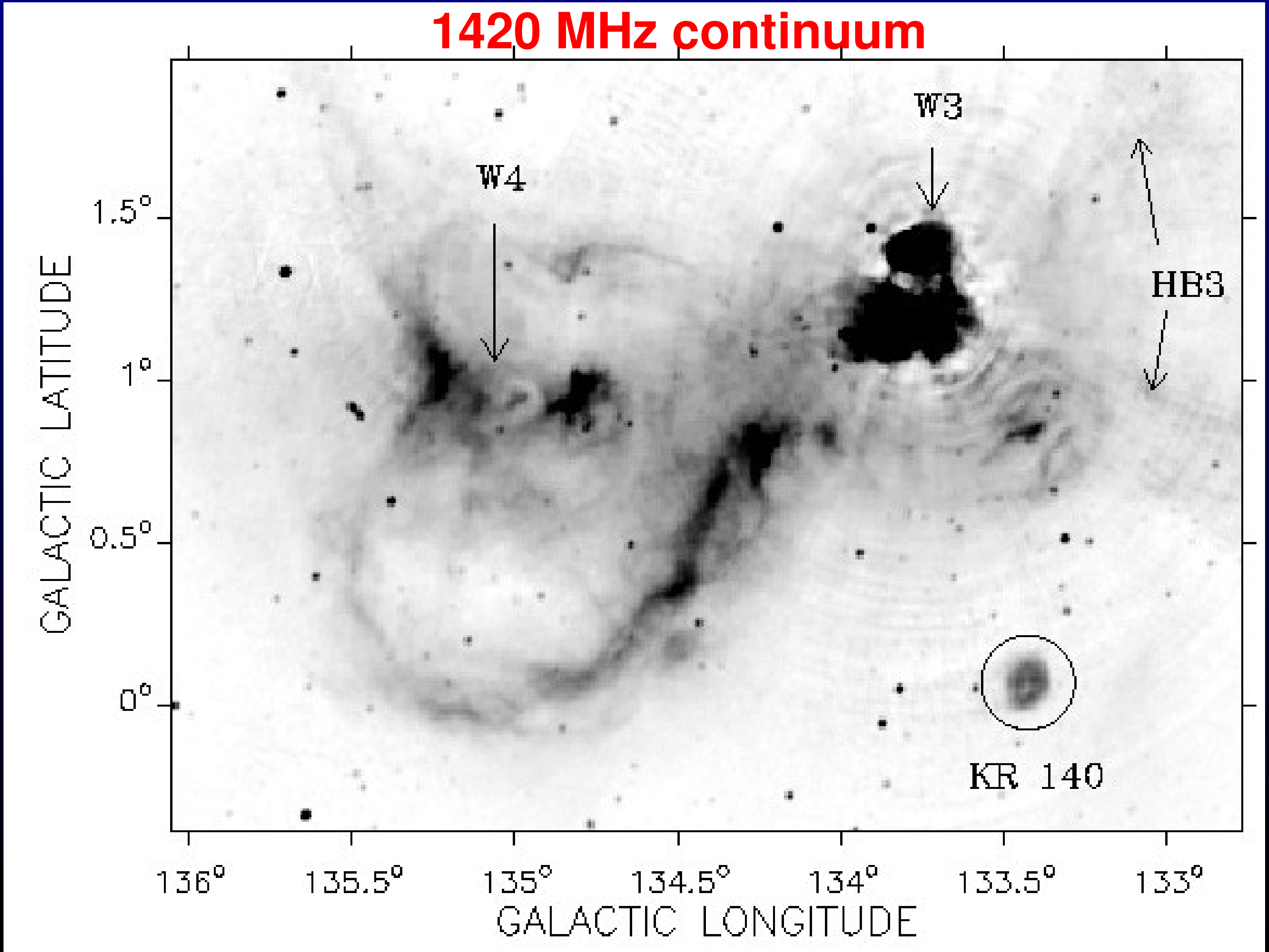
Sets the stage for feedback to terminate star formation before entire cloud is transformed into stars.

Astronomical data bases

This is an example of a multifrequency study of the interstellar medium (ISM) using (largely) the CGPS data base, an archival (on-line) suite of high dynamic range images of the major components and phases of the ISM, on scales from pc to kpc (data bases described in next lecture).

It provides the “big picture” context for this particular investigation of a localized region of size 10 pc.

KR 140 and Friends



Perseus Chimney

W4 wind bubble appears to trigger star formation in W3, at the edge of the cloud, but not at KR 140.

W4 – W3 interface and KR 140

Red: 1420 MHz radio continuum I-front.
Green: 60 micron warm dust
Blue: 12 micron PAH outside H II region.

[Conclusions come first – then explanation.]

Conclusion: 1 – The Nebula

KR 140 is a small (5.7 pc diameter) H II region located in the Perseus arm of the Galaxy at a distance of 2.3 kpc.

The nebula is kept ionized by one O8.5 V(e) star, VES 735, which is less than a few million years old.

The ionized region is surrounded by warm dust, which absorbs and then re-radiates (FIR) most of the luminosity of the star.

Spectrum of Central Star

Red star: $E_{B-V} \sim 1.6$.

Classified in the yellow-green using He I and He II lines as T indicator → O 8.5 V.

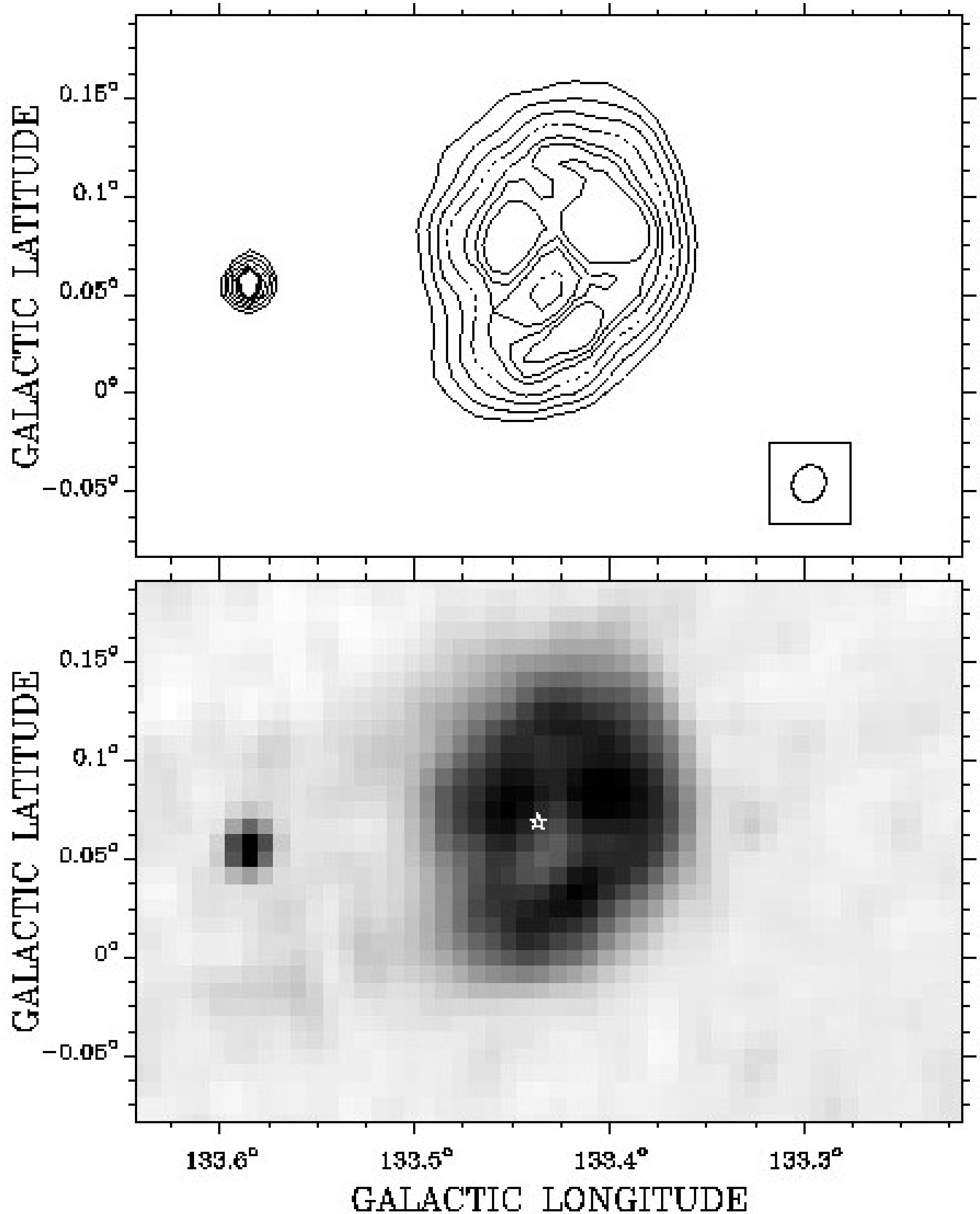
Mass $\sim 25\ M_{sun}$.

Velocity of star and of nebular emission in same spectrum → co-located and at distance of Perseus arm.

Radio Image and Contours

Size ~ 5.7 pc
Mass ~ 160 M_{sun}
n_e ~ 30 cm^{-3}

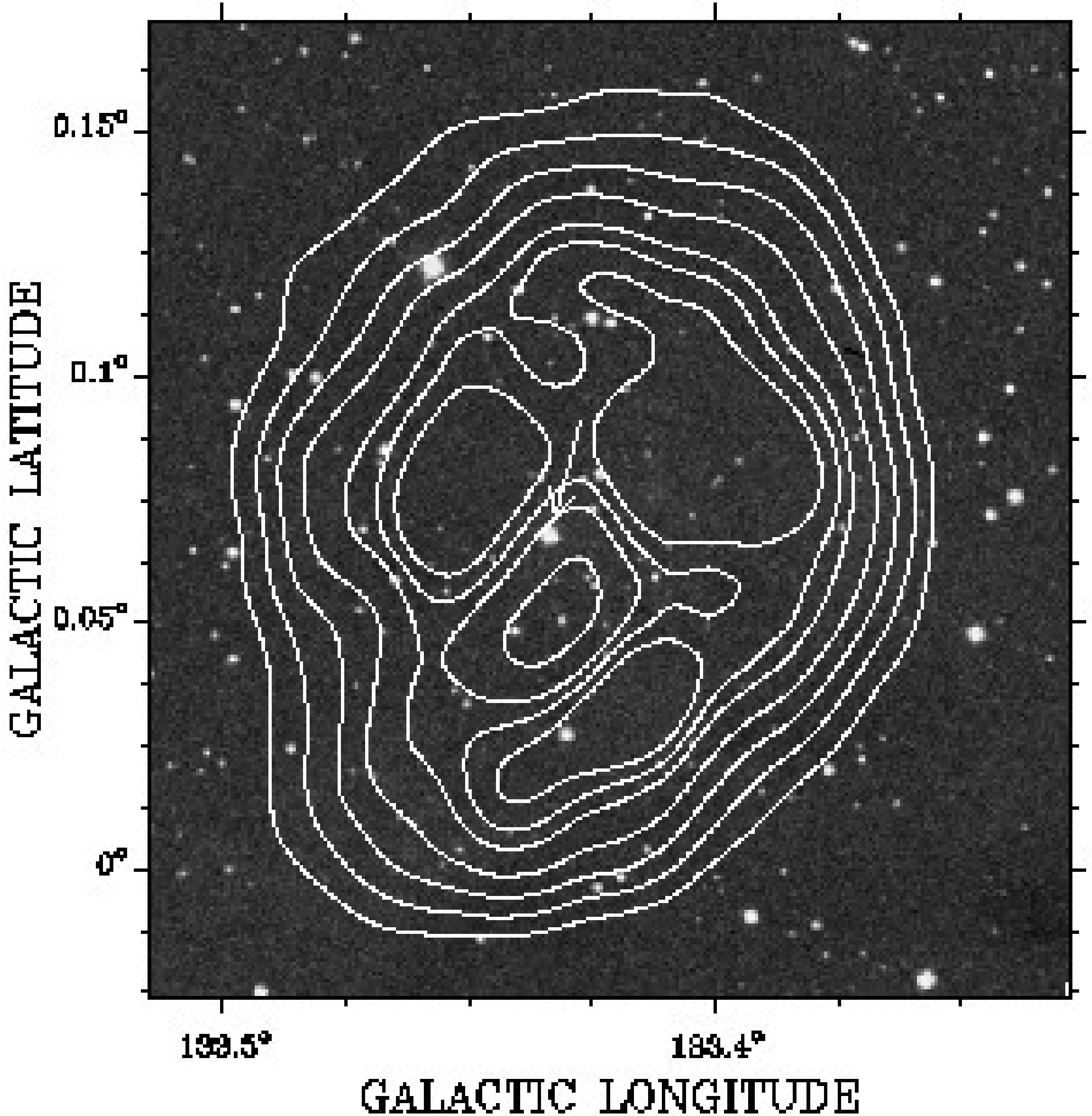
Ionizing star marked



H Nebula (not!)

Red DSS

Ionizing star marked – VES 735

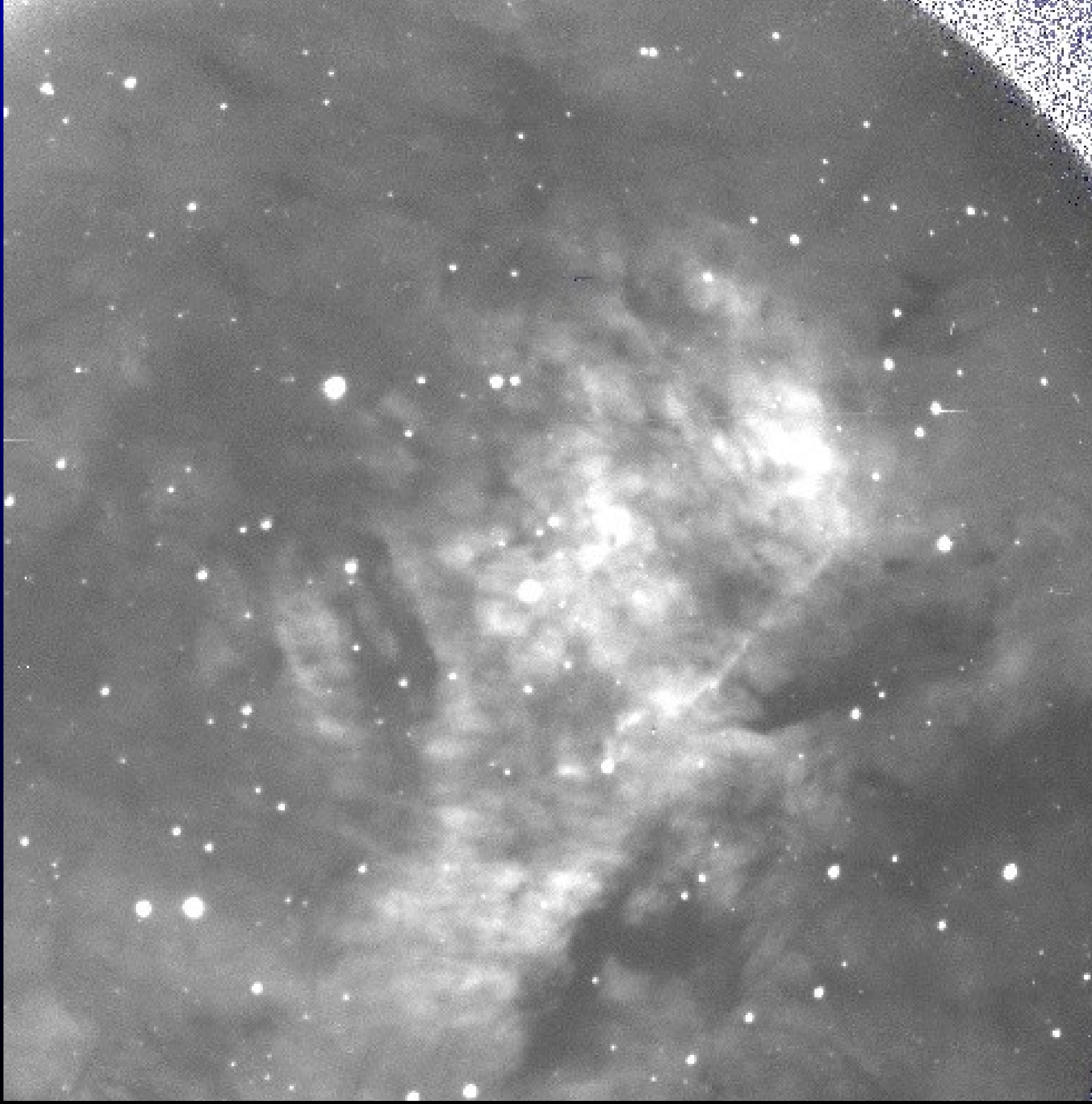


Try Harder!

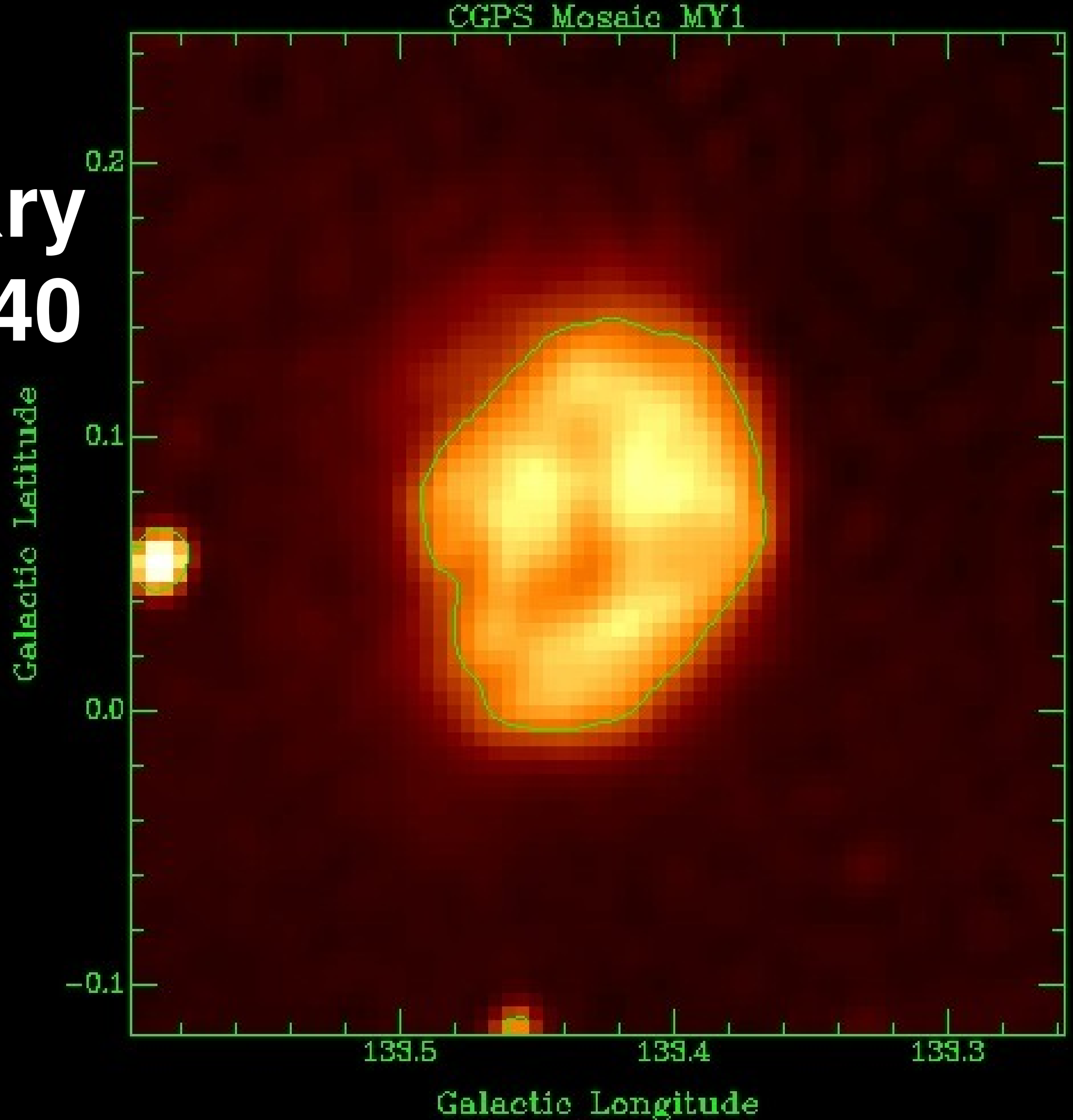
High and patchy extinction.

A_V ~ 6 mag.

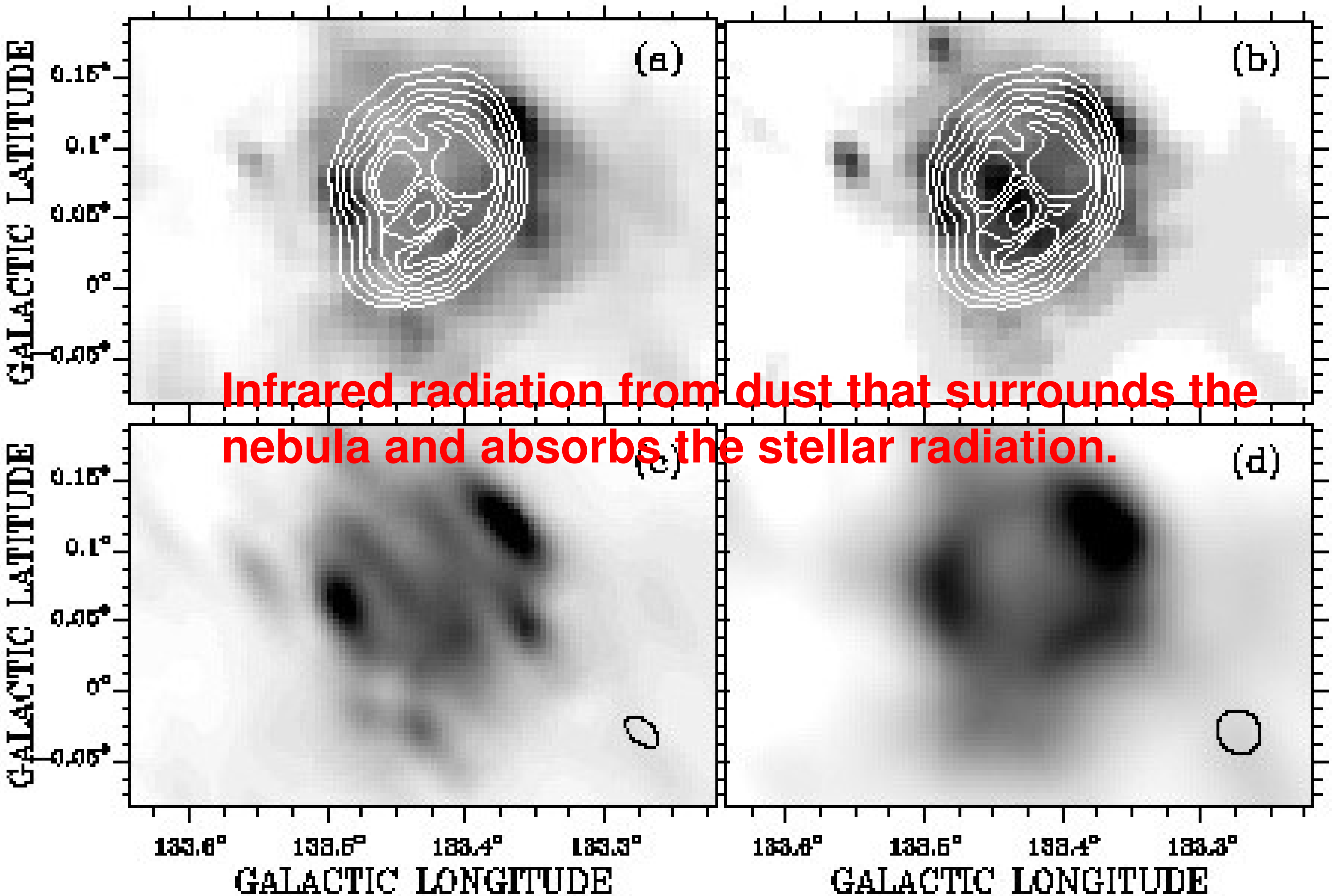
(Image: Gilles Joncas)



Boundary of KR 140



Multifrequency IR Gallery – dust



Infrared radiation from dust that surrounds the nebula and absorbs the stellar radiation.

Energetics

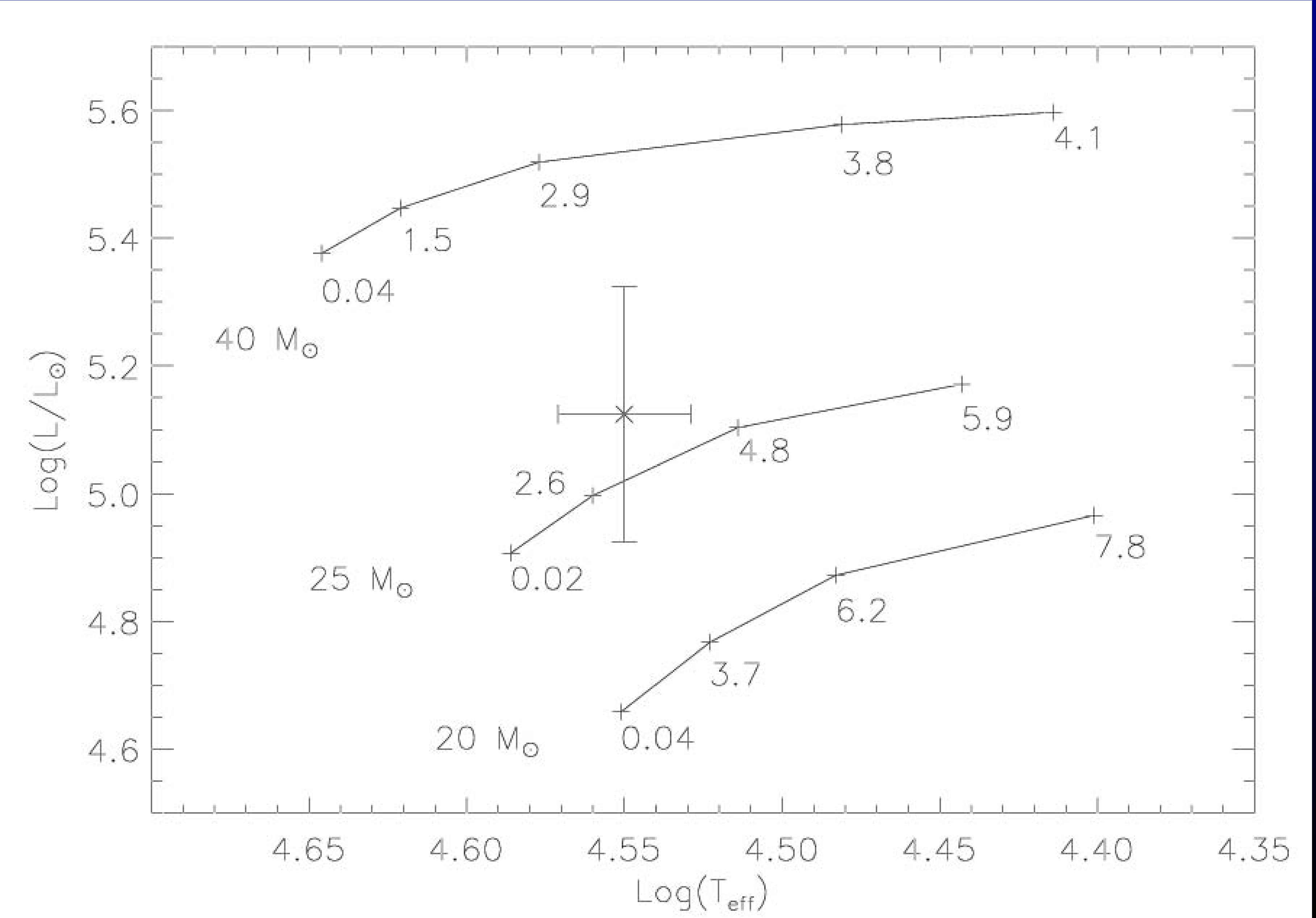
Total radio free-free emission measures Q(H), the total number of ionizing photons.

Total infrared emission re-radiated by dust measures L_{bol}, the total incident radiation.

Compared to what is expected from an O 8.5 V star, both indicate a covering factor of about a half.

→ geometry: a bowl opening more or less toward us – not quite a perfect Stromgren sphere!

Evolutionary Status of VES 735



Conclusion: 2 – Molecular Cloud

KR 140 is isolated from the nearest major star forming activity, in W3.

VES 735 is an example of spontaneous formation (i.e., non-triggered) of, unusually, a high mass star.

CO data show that VES 735 has disrupted the original molecular cloud (localized part) for which the estimated mass and density are about 5000 M_{sun} and 100 cm^{-3}, respectively.

A stellar cluster of $\sim 10^3$ M_{sun} is expected, given an O star and standard IMF (would be ~ 20% efficient → unbound).

The Raw Material – CO Tracer

CO can be mapped using the 1 – 0 line in emission. This traces molecular hydrogen and the sites of potential star formation.

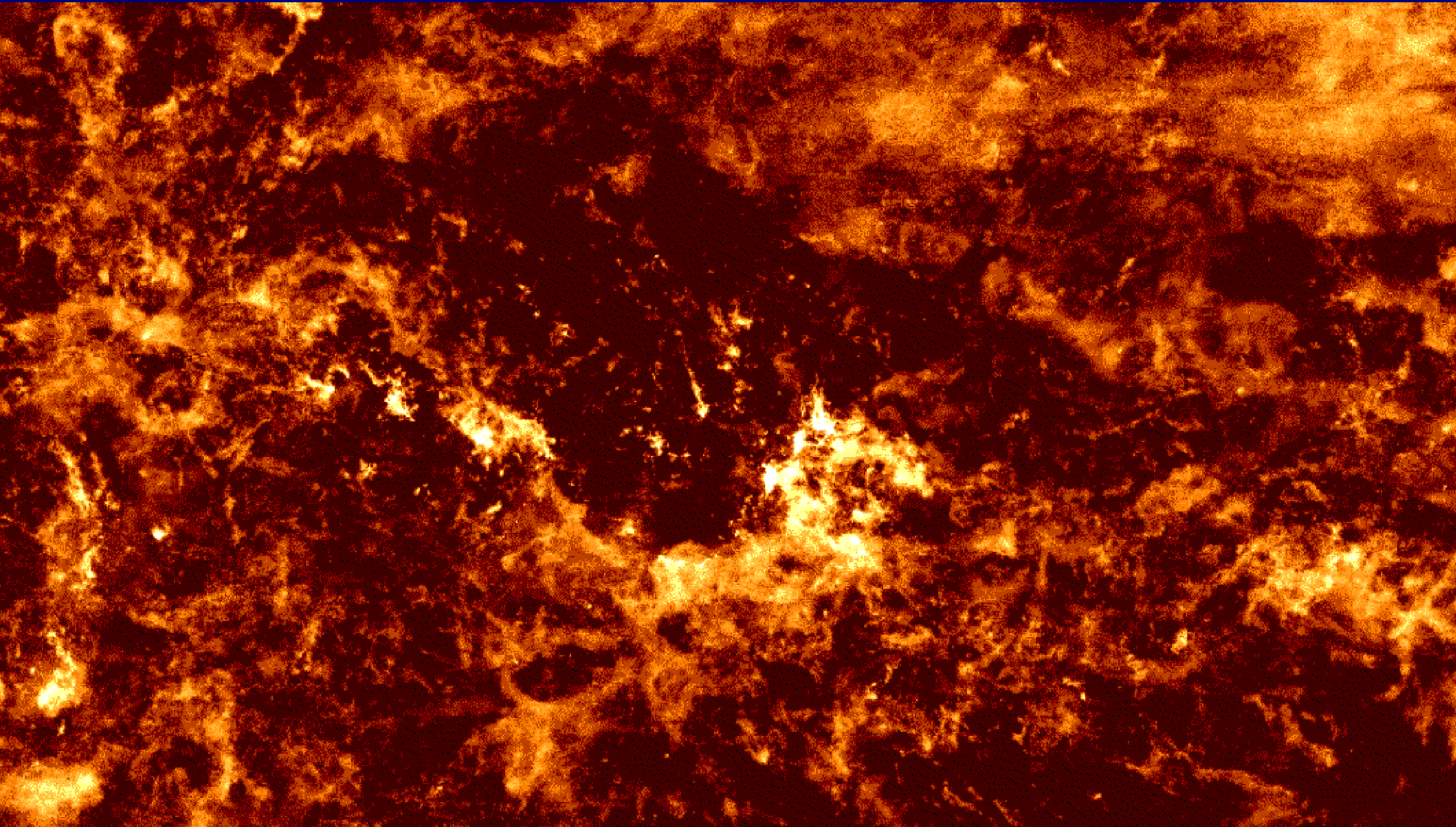
Spectrum reveals systematic motions, and turbulence.

Clumpy spatial structure more reminiscent of clouds.

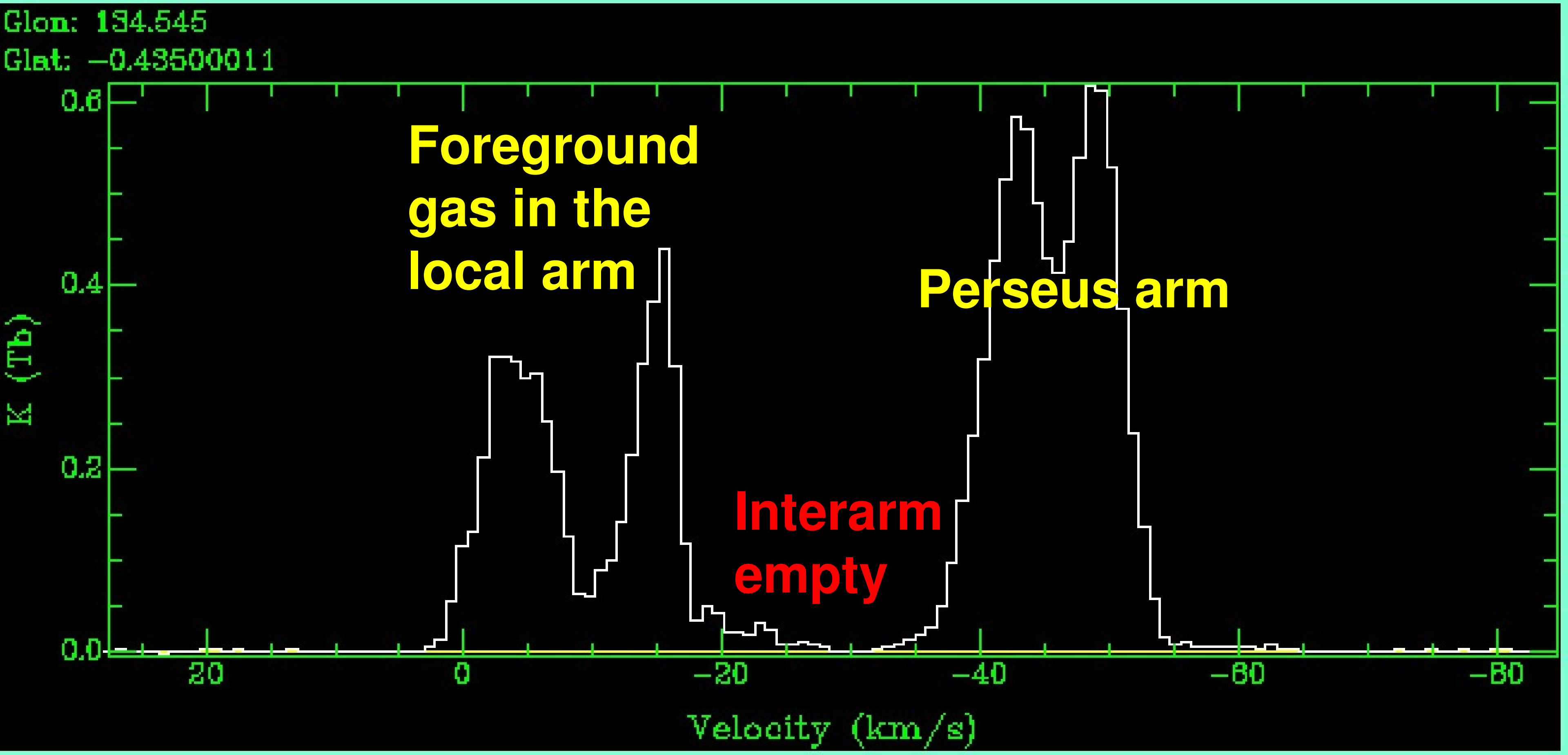
Large arm-interarm contrast.

CO (1-0) FCRAO OGS

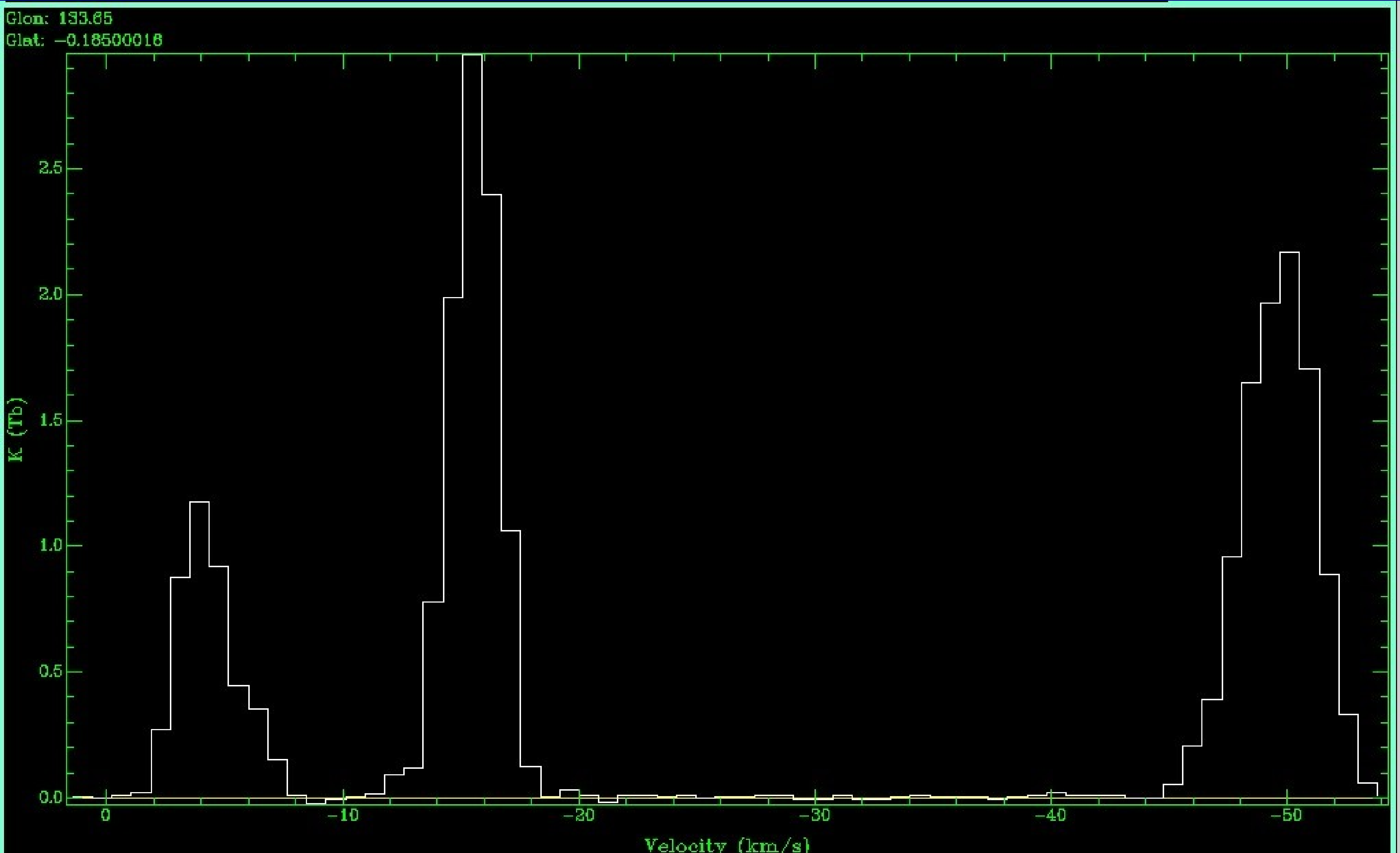
Integrated CO. l = 128 to 142; b = -3 to +5
(chimney clearer still if only Perseus-arm gas is included)



CO Spectrum toward the W3 GMC

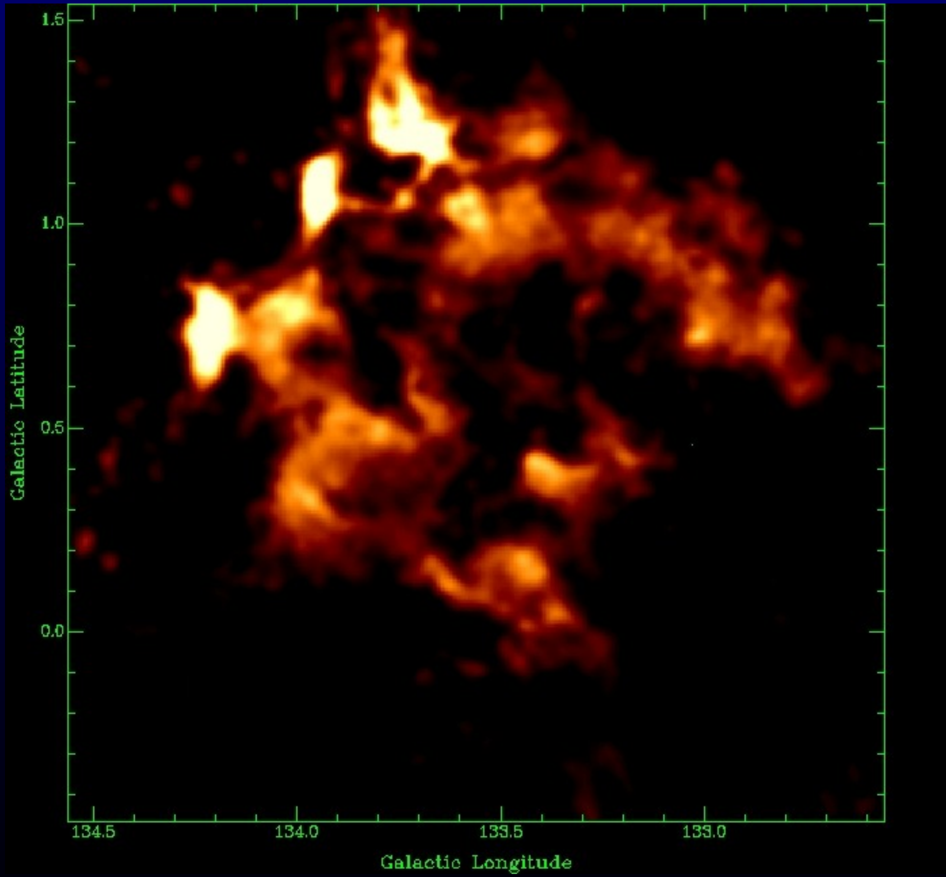


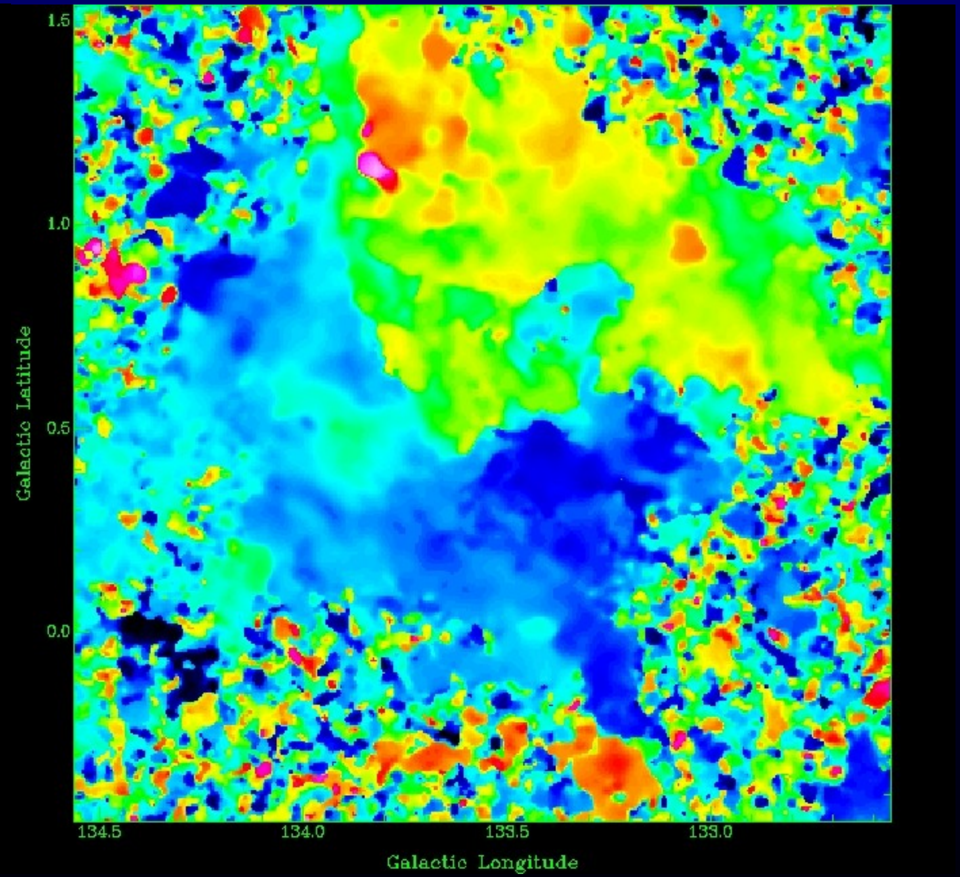
CO Spectrum toward KR 140



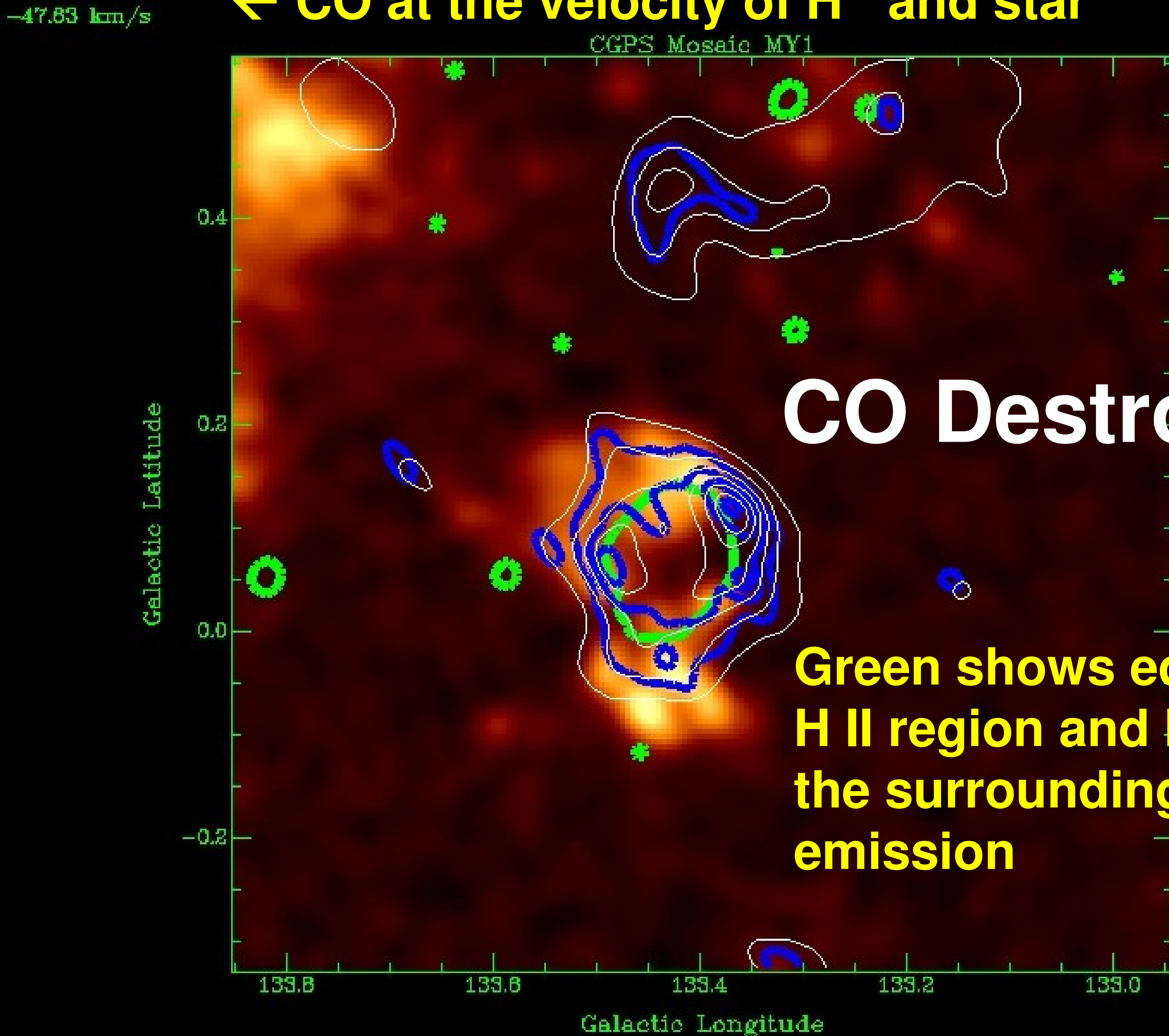
CO

Left: CO integrated over Perseus arm velocities
[movie of cube shown] **Right: 1st moment with velocity.**





← CO at the velocity of H and star



CO Destroyed

Green shows edge of H II region and blue the surrounding dust emission

Conclusion: 3 – FIR Point Sources

Infrared point sources seen by IRAS located near the periphery are of interest because they might be associated with the formation of other stars, perhaps even induced by the expansion of the H II region.

We have made use of SCUBA submillimetre data to reveal the varied nature of the IRAS infrared sources.

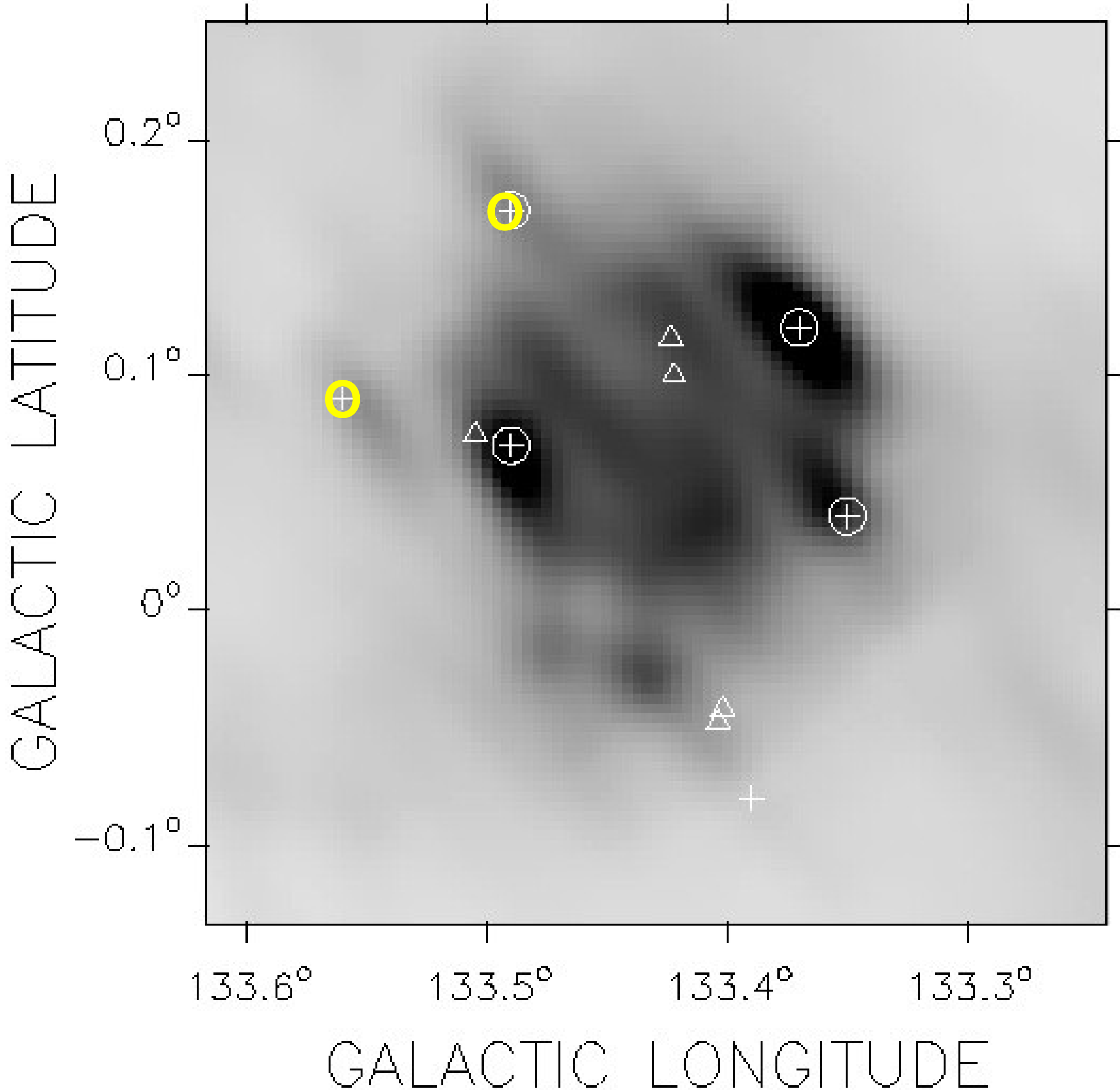
Three IRAS "point" sources are actually pieces of the limb-brightened edge of KR 140.

Two IRAS sources outside the H II region are internally heated and have B-star luminosities. They are younger than VES 735 (not all star formation is coeval).

HIRES 60 micron image

IRAS PSC sources (plus)

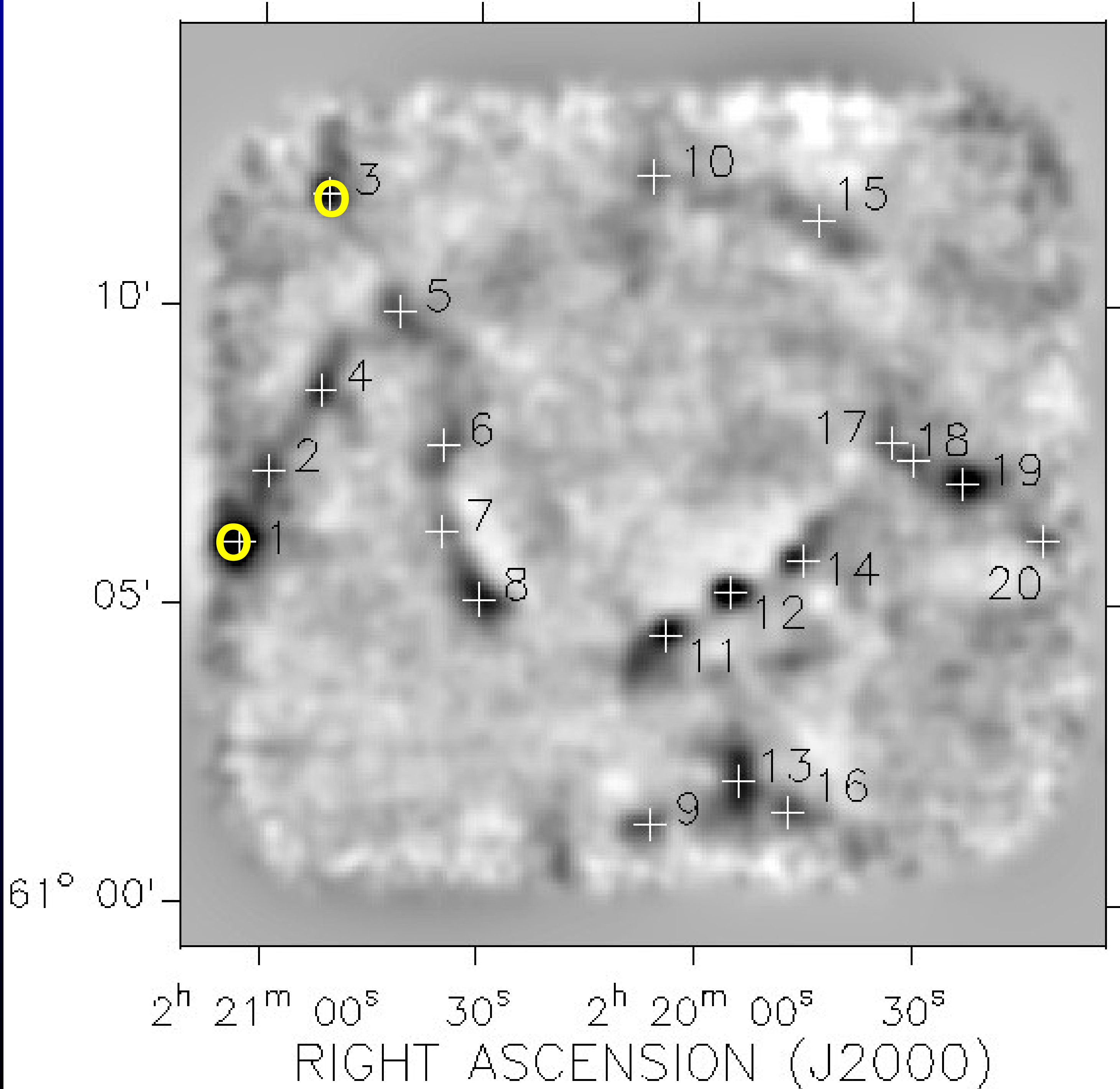
BIRS stars (triangles)



Scuba Sources at 850 microns

Low spatial frequencies suppressed!!

(Note equatorial coordinates.)

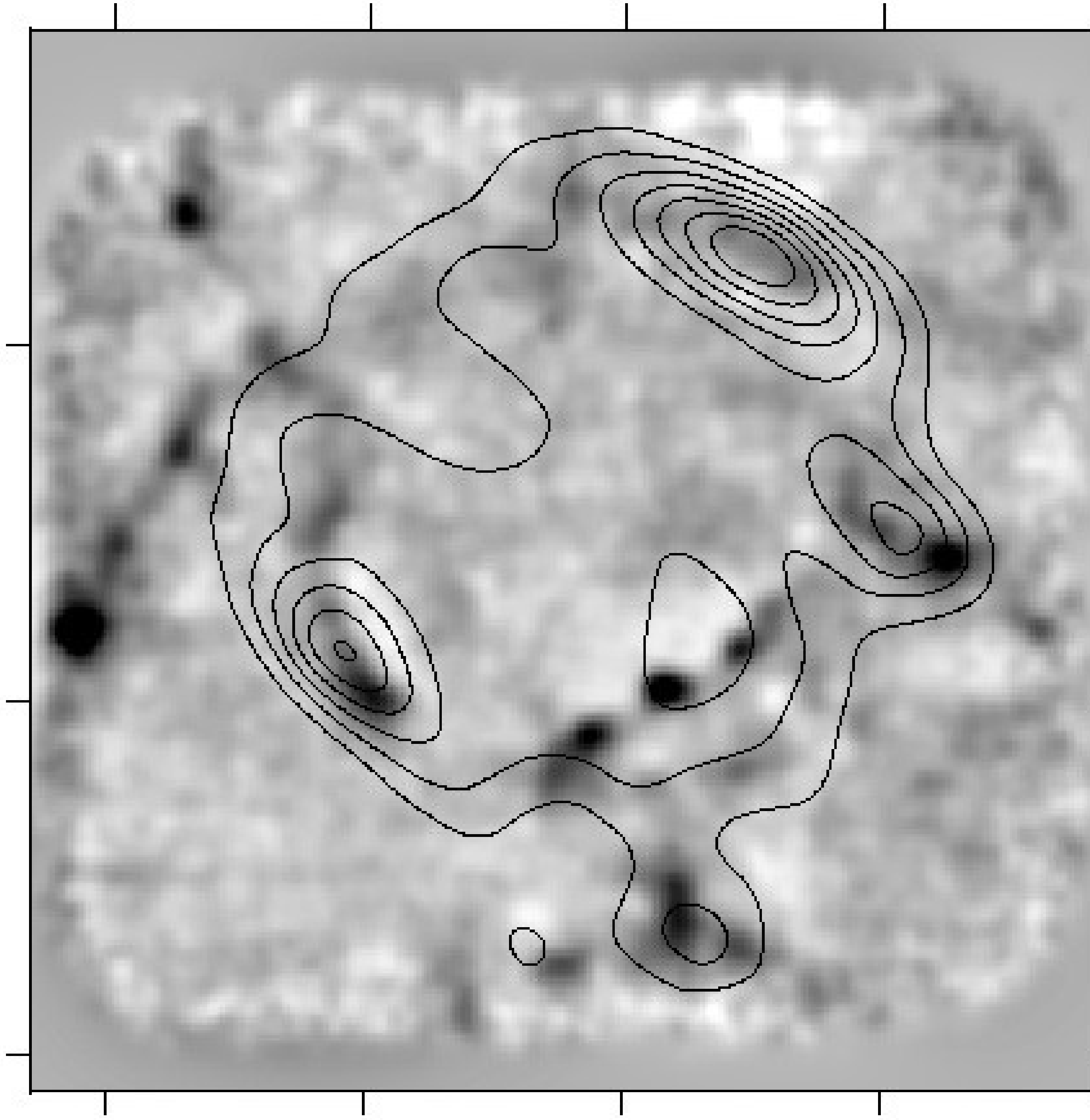


Contrast: 60 micron Contours

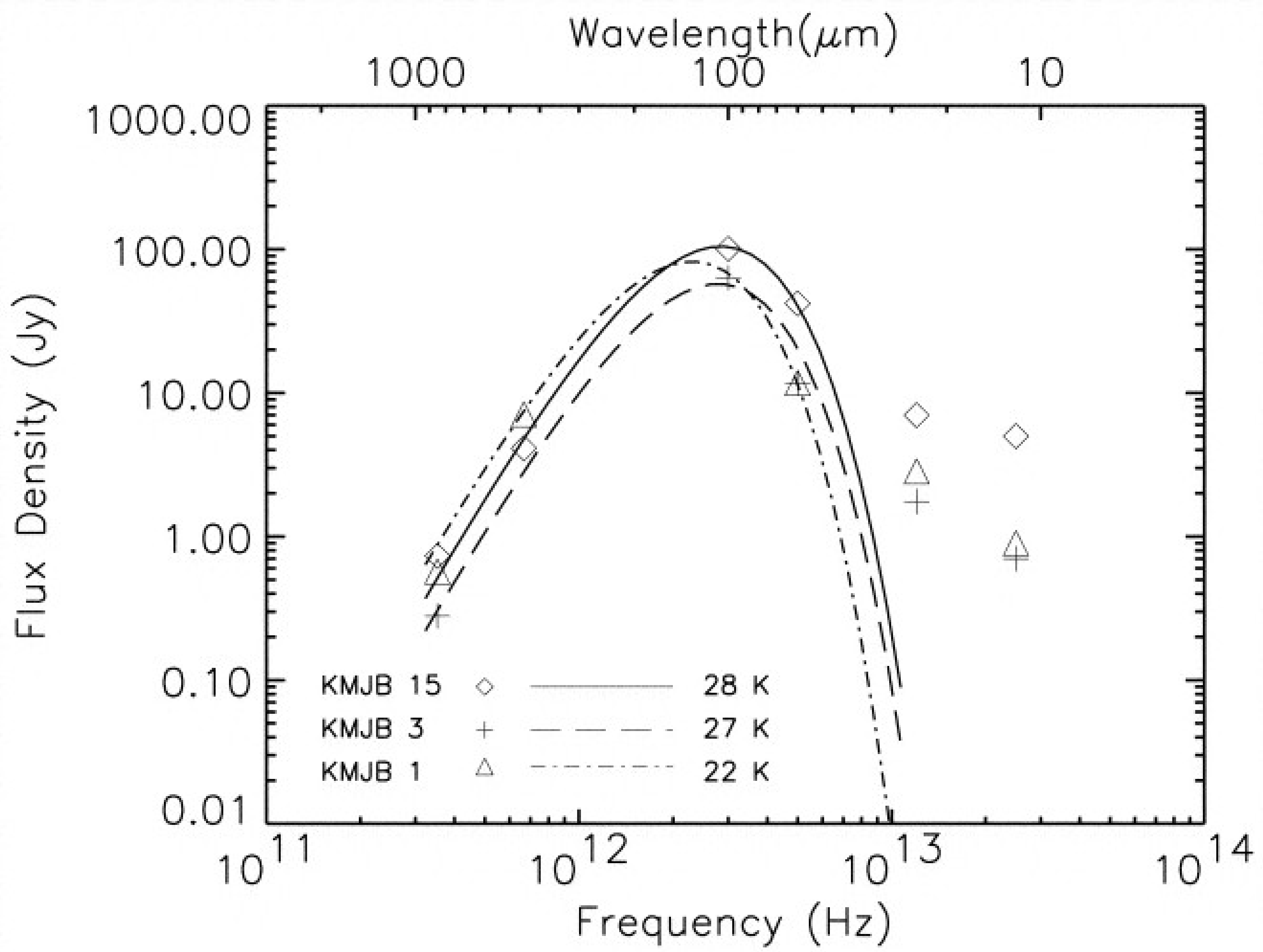
Appearance depends on T and column density.

60-micron shell to NW is barely seen at 850 microns.

Two sources to left (E) are warm and have B-star luminosities.



Spectral Energy Distributions

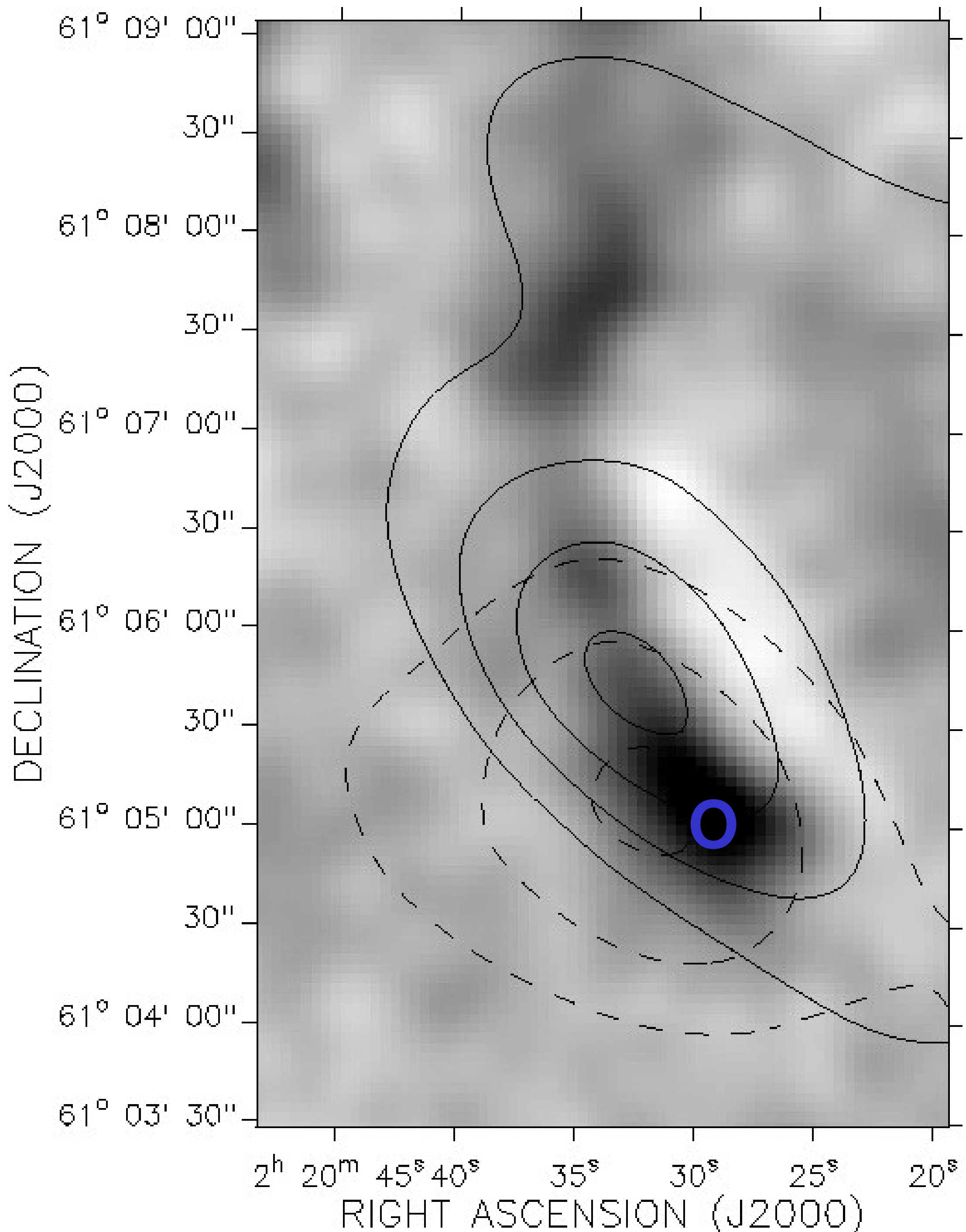


Detail: Scuba Eastern Ridge

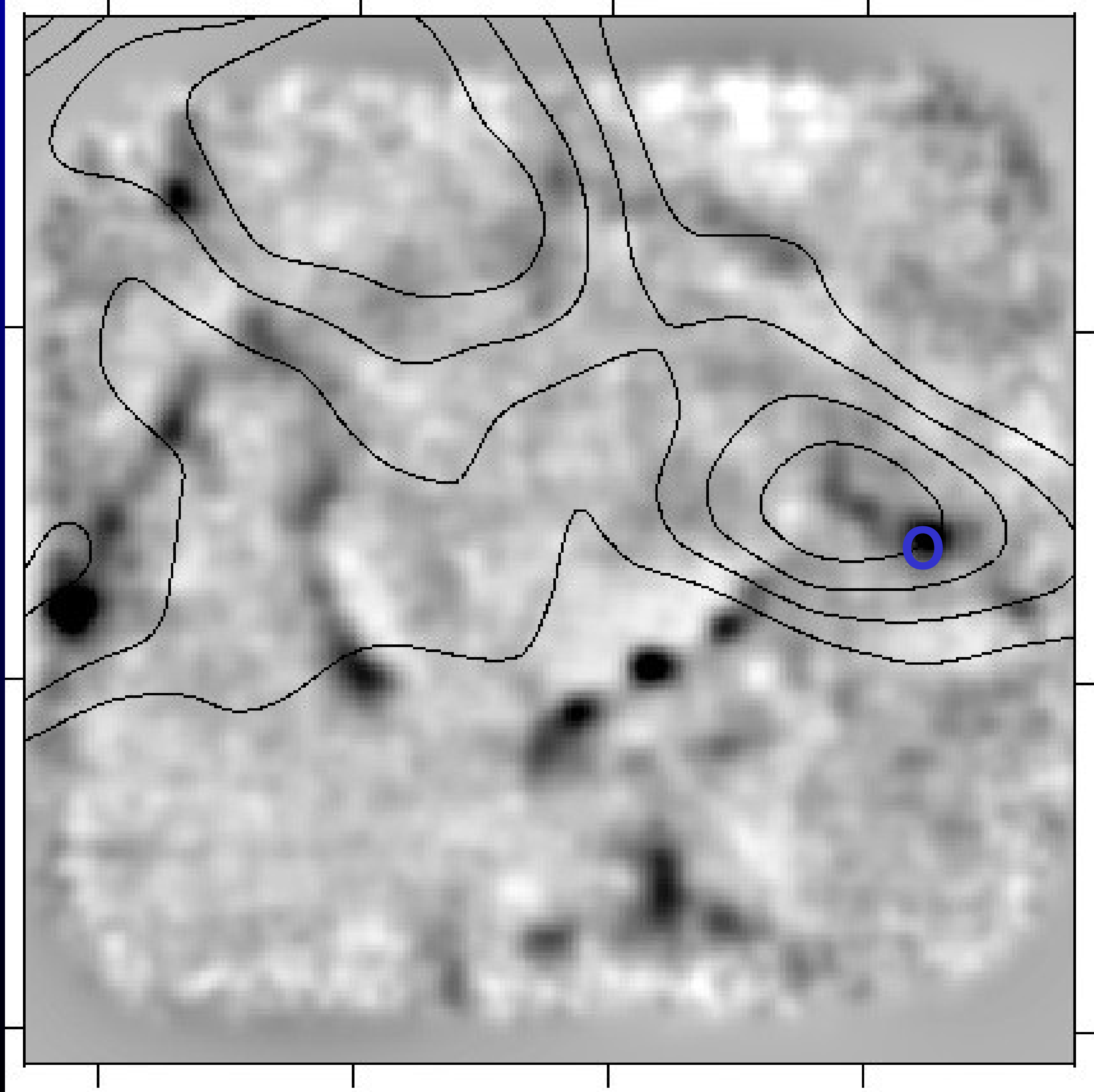
CO contours at systemic velocity (dashed - - -)

60-micron contours of KR 140 shell (IRAS "point" source)

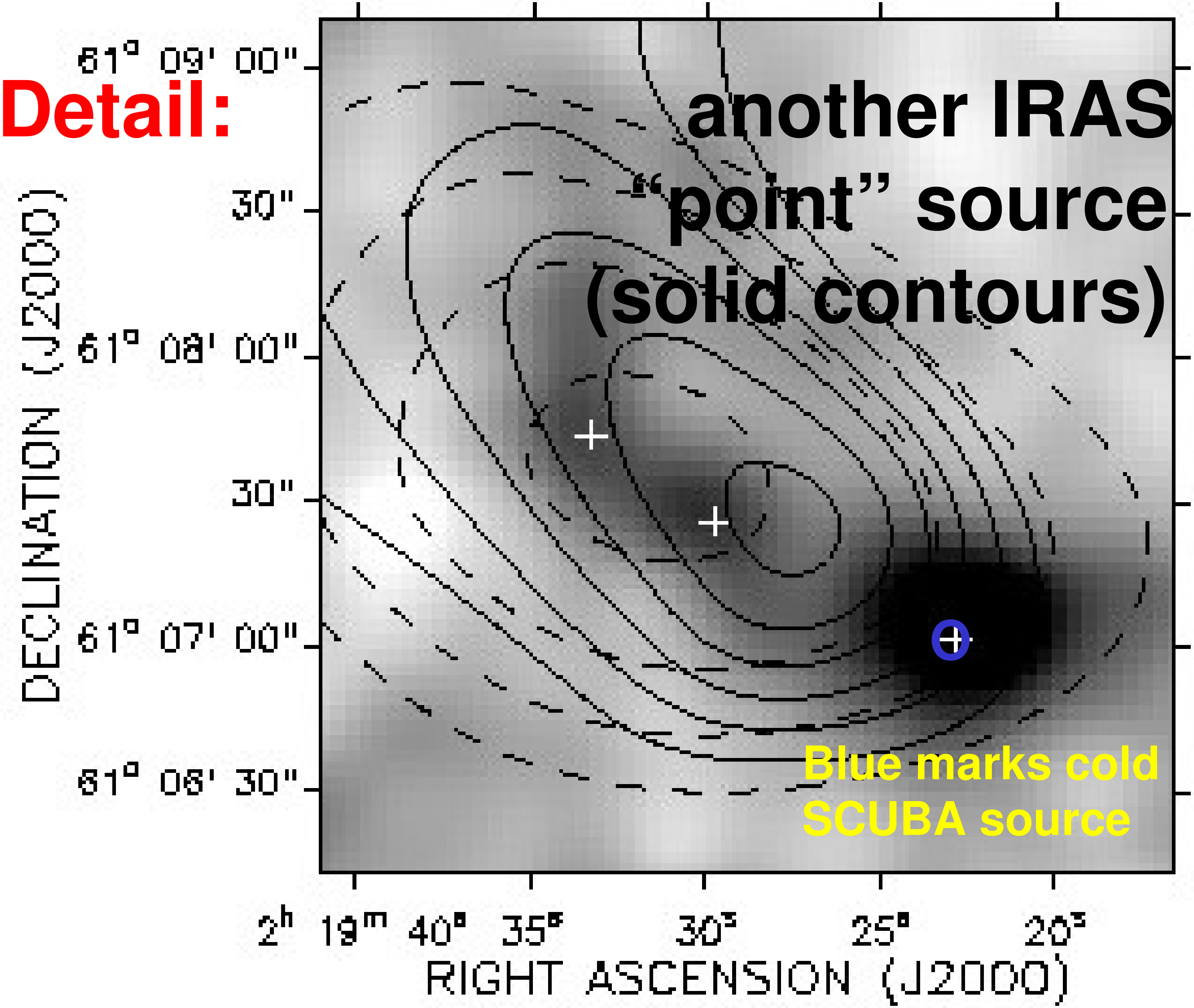
Blue marks cold SCUBA source, near CO peak, not IR.



CO Slice at Velocity of Back-ground Cloud



SW Detail:


another IRAS
"point" source
(solid contours)
Blue marks cold
SCUBA source
61° 09' 00"
30"
61° 08' 00"
30"
61° 07' 00"
61° 06' 30"
DECLINATION (J2000)
2h 19m 40s
35s
30s
25s
20s
RIGHT ASCENSION (J2000)

Conclusion: 4 – Cold Clumps

With SCUBA we had sufficient resolution and sensitivity to probe down to the large molecular core scale (0.1 pc) near KR 140.

We discovered a number of relatively cold (< 10 K) submillimetre sources not visible in the IRAS data, ranging in size from 0.2 to 0.7 pc and in mass from 0.5 to 130 M_sun.

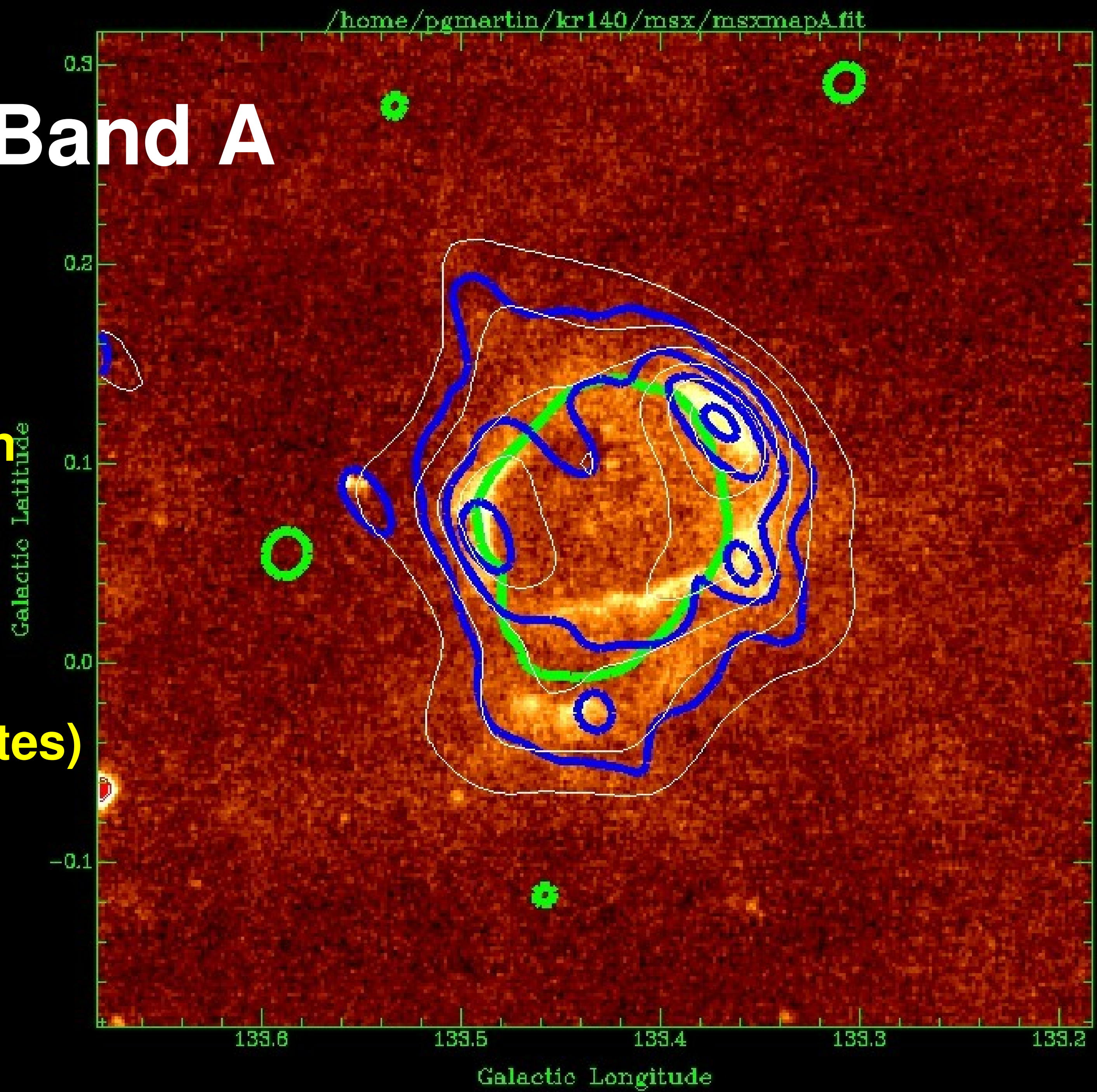
Many are gravitationally bound and if in virial equilibrium have non-thermal pressure support.

Upon loss of this support they could be sites of future star formation.

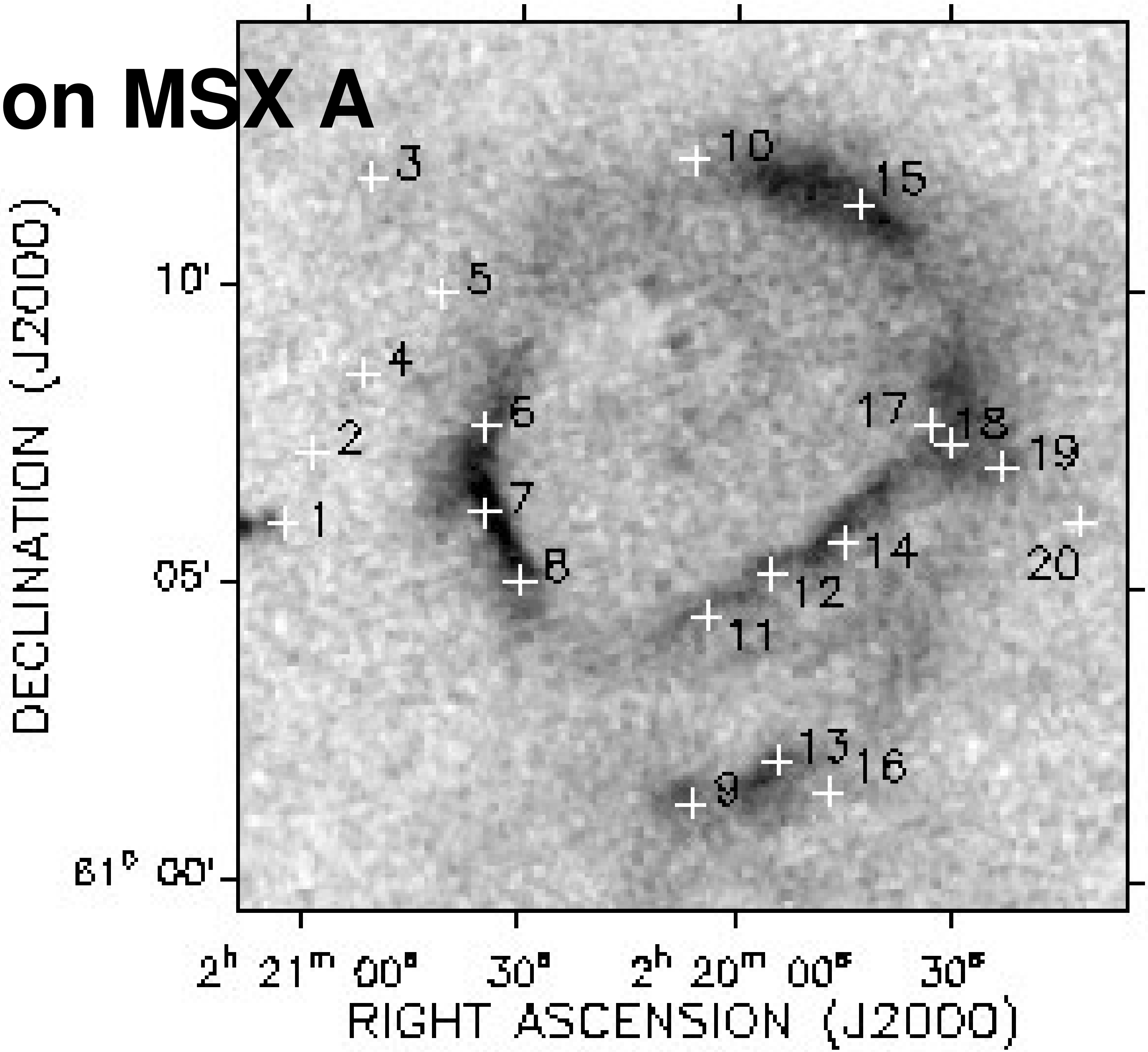
MSX Band A

PAH emission marks ionization fronts.

(Note: Galactic coordinates)



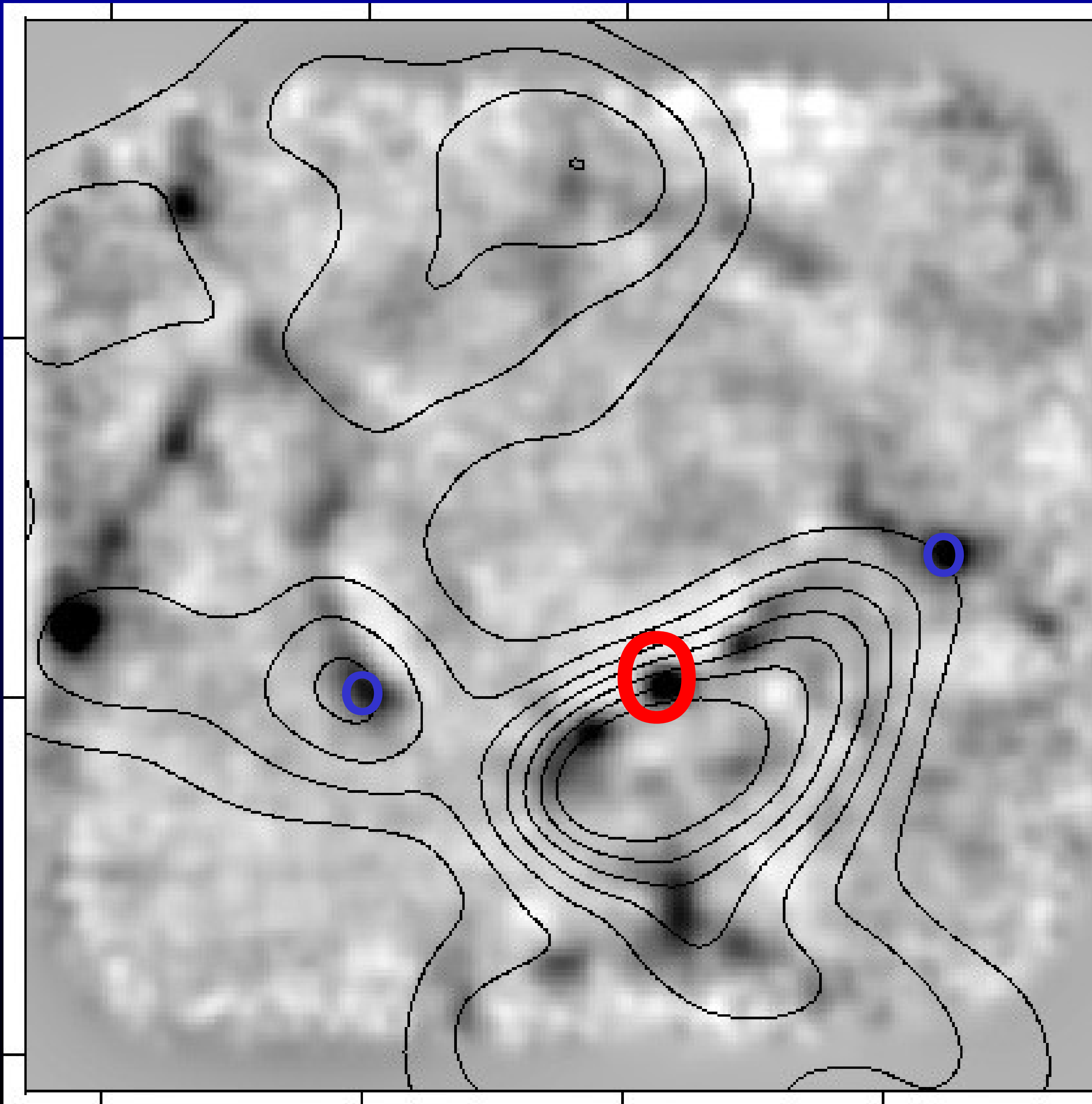
Scuba on MSX A



CO Cloud at Systemic Velocity

Clumps and 8-micron ridge aligned along edge of CO cloud.

Source 12 marked for future reference.



Gravitational instability?

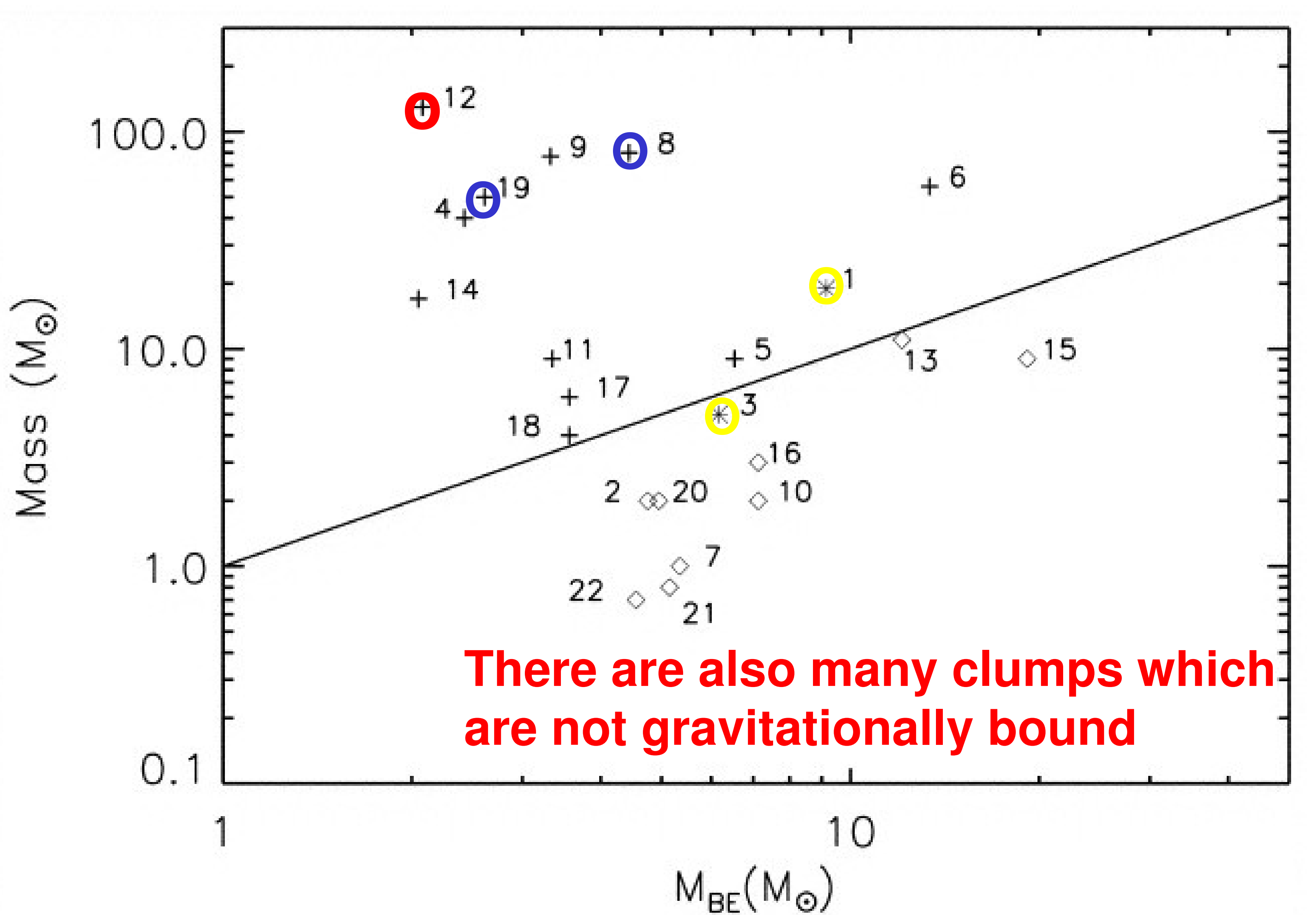
$M_J = M_{BE} = 3200\ M_{Sun}\ (T/80\ K)^{3/2}\ (n_H/1\ cm^{-3})^{-1/2}$.

Typical n_H (from column density) is $10^4\ cm^{-3}$ in these clumps, and
$T \sim T_{dust}$ is typically 10 K,
→ $M_{BE} \sim 1.4\ M_{sun}$.

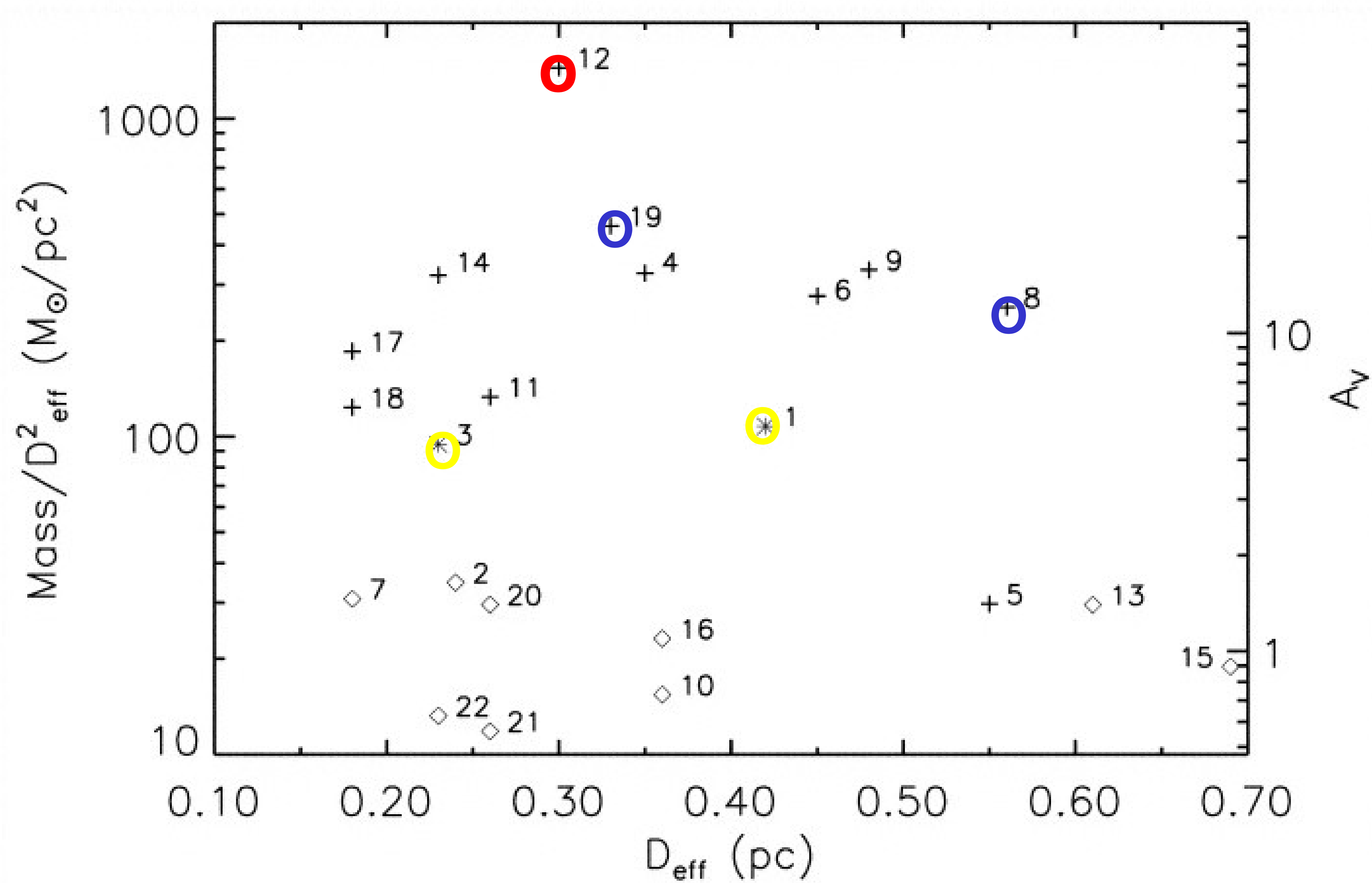
Unstable for $M_{clump} > M_{BE}$, in the sense that the clump can fragment if thermal gas pressure is the only force counteracting gravity.

M_{clump} is obtained from the brightness of the clump, its temperature, and size, plus a gas to dust ratio (dust is detected, mass is mostly gas).

Instability (above line)



Column Density of Clumps



Comments

Clump mass spectrum (regardless of whether gravitationally bound) has a slope like the IMF for stars (similar results in other molecular clouds).

But what does this mean? Would each clump form one and only one star? With what efficiency?

This SCUBA survey also does not probe much below 1 M_{sun} , and so does not probe a potential turnover in the IMF near the theoretical minimum fragment size.

What next? – High mass Star Formation

GOALS

Pre-stellar core mass function. Confirm indication that the clump mass spectrum is like the IMF rather than like the GMC mass spectrum; explore at lower mass.

Lifetimes (timescales) of various stages. This is directly related to the numbers of various classes of sources that one expects to detect. For the earliest stages (yet to be characterized) this number is probably uncertain by a factor ten.

SPIRE GTO Science Objectives (F. Motte et al.)

Open issues on the earliest phases of high-mass star formation

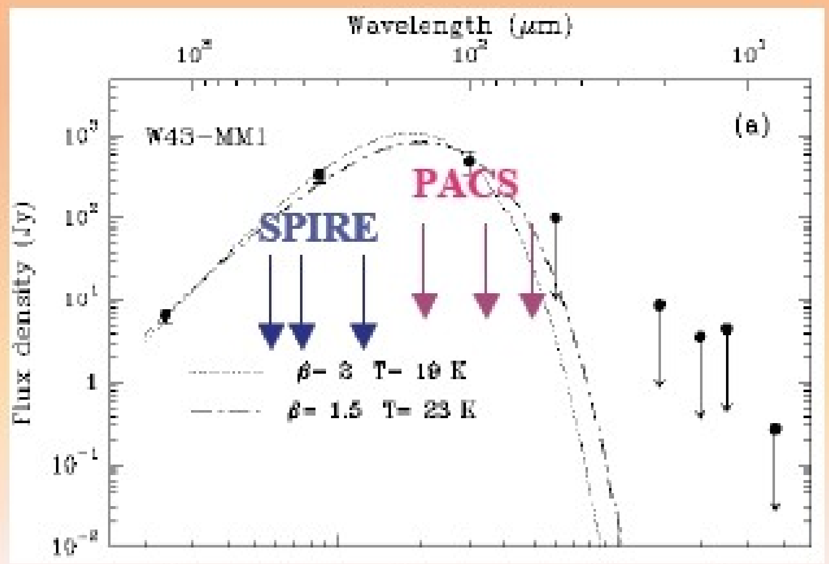
- Basic formation mechanism: accretion or coalescence ?
- Do high-mass pre-stellar cores exist ? Are they warmer, denser than low-mass pre-stellar cores ?
- Detailed evolutionary sequence ? Relative lifetimes of high-mass pre-stellar cores, Class 0 protostars, hot cores, and infrared UC HII regions ?

→ Unbiased search for high-mass pre-stellar cores and Class 0 objects

in nearby complexes (d ~ 2 kpc) => Herschel @200 µm HPBW ~ 0.1 pc
ground-based submm

through multi-λ submm observations

Temperatures expected to span a wide range from < 10 K (cold pre-stellar cores) to > 100 K (hot cores)



Tdust ~ 20 K (Motte et al. 2003)

COLD DUST

10 K

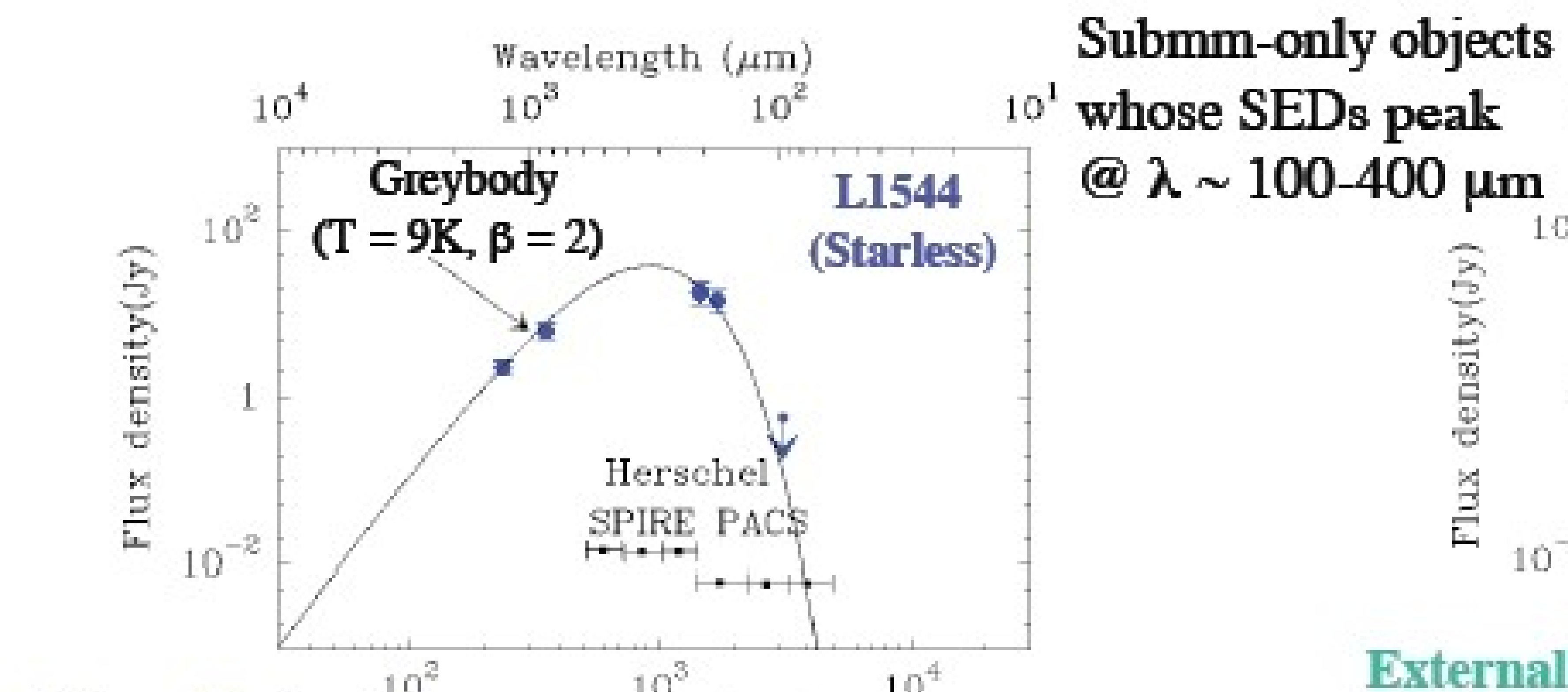
Need to measure the cold pre-stellar cores over the peak in the emission spectrum

→ Sub-mm or THz astronomy

BLAST/SPIRE spectra

Sub-mm: 250, 350, 500 microns like SPIRE

Optimal wavelengths for constraining temperature (and beta)



Many New Galactic Plane Surveys

BLAST (balloon-borne precursor of SPIRE): several regions of plane surveyed; more from Antarctica.

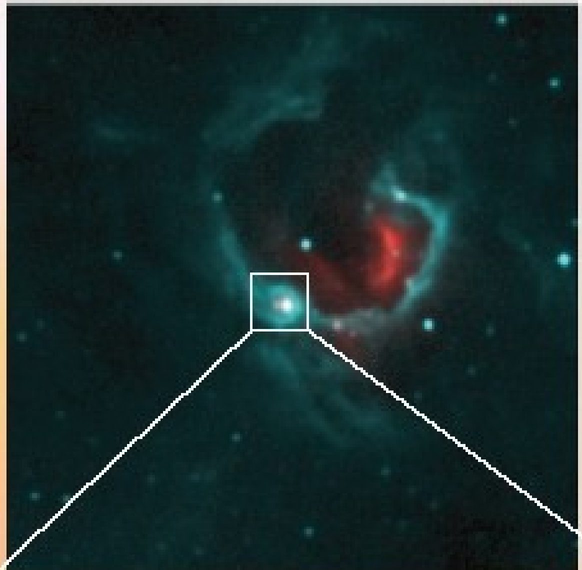
Spitzer: MIPS-GAL (25, 70, and 160 microns). Underway

JCMT: JPS with SCUBA-2 (850 microns). Approved

Herschel: SPIRE GT (approved**) and HI-GAL Open Time KP (**planned**)**

Hot PDRs (F. Motte et al.)

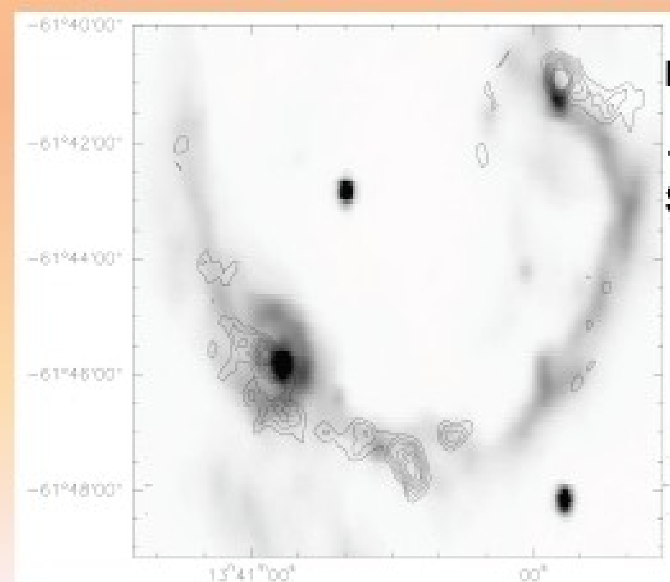
Zones of triggered massive-star formation



MSX-A (blue)
8μm
MSX-E (red)
21μm

DSS-R (blue)
MSX-A (red)

JHK
NTT



MSX-A (black)

1.3mm (contours
SEST-SIMBA)

Future

Many unanswered questions!

Theoretical progress will require numerical simulations involving turbulence and magnetic fields and feedback.

Some further observational guidance is on the horizon.

The End

Low mass star formation

Some lessons learned in nearby molecular clouds:

Stars form in molecular clumps and initially are completely enshrouded in the dusty material. We cannot see the star, only the radiation re-emitted by the dust.

These stars have disks, and fire out jets along the rotation axis at speeds of 100 km s^{-1}.

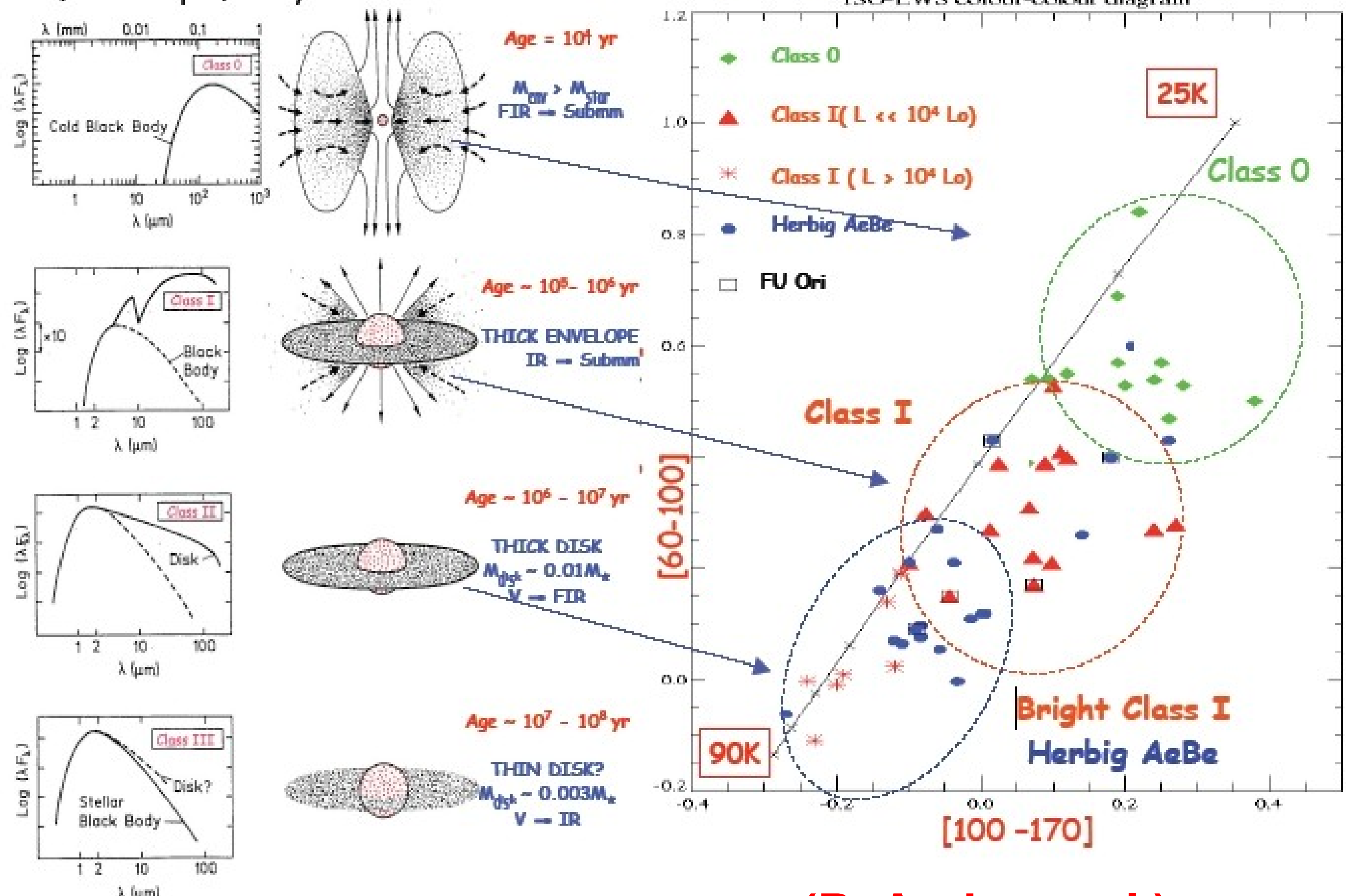
Gradually the surrounding material dissipates (accretes onto the protostar); young star is revealed.

As a result, the spectral energy distribution changes dramatically.

LOW MASS YSO EVOLUTION ISO LWS colour colour diagram

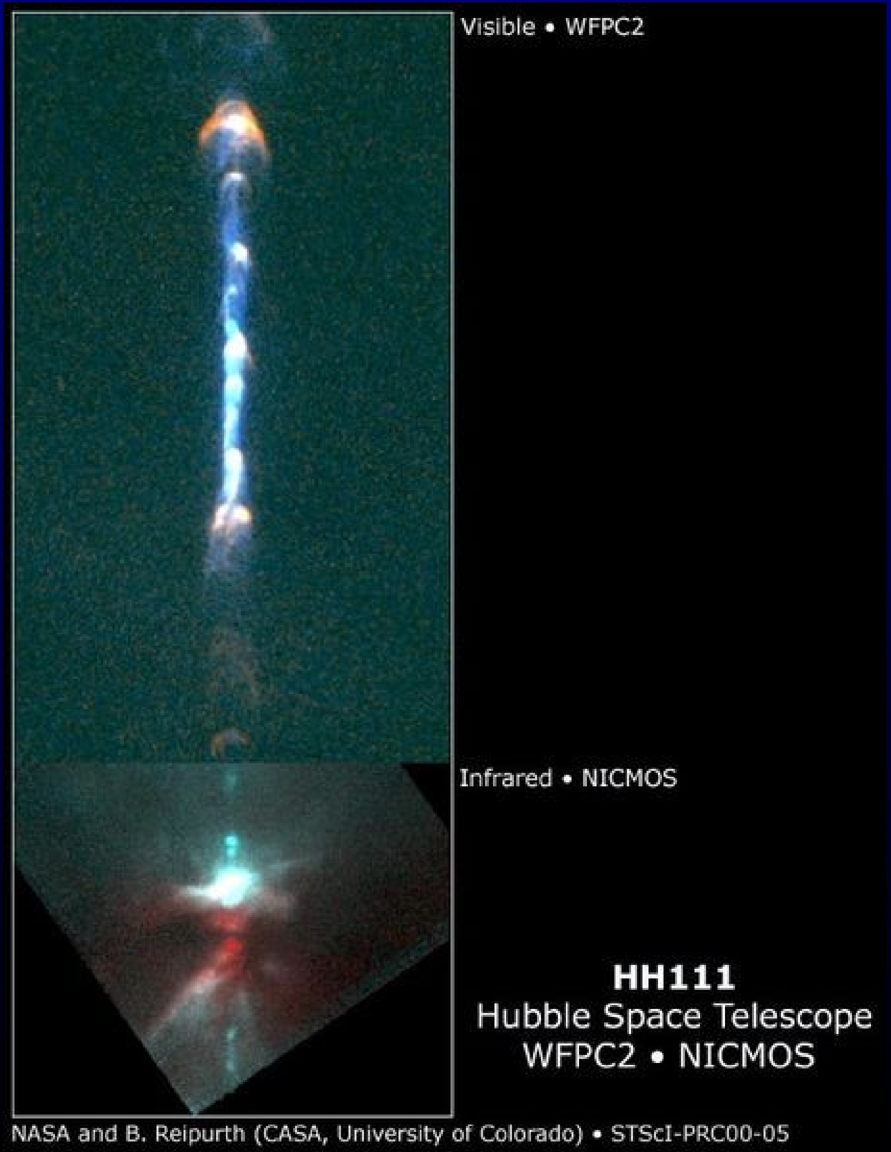
(Pezzuto et al. 1998, 2002)

Lada & Wiking 1984
André, Ward-Thompson, Barsony 1993



(P. Andre et al.)

A jet leading to a Herbig-Haro outflow.



Context of star formation

Make use of multi-wavelength data from optical, IR, through radio continuum