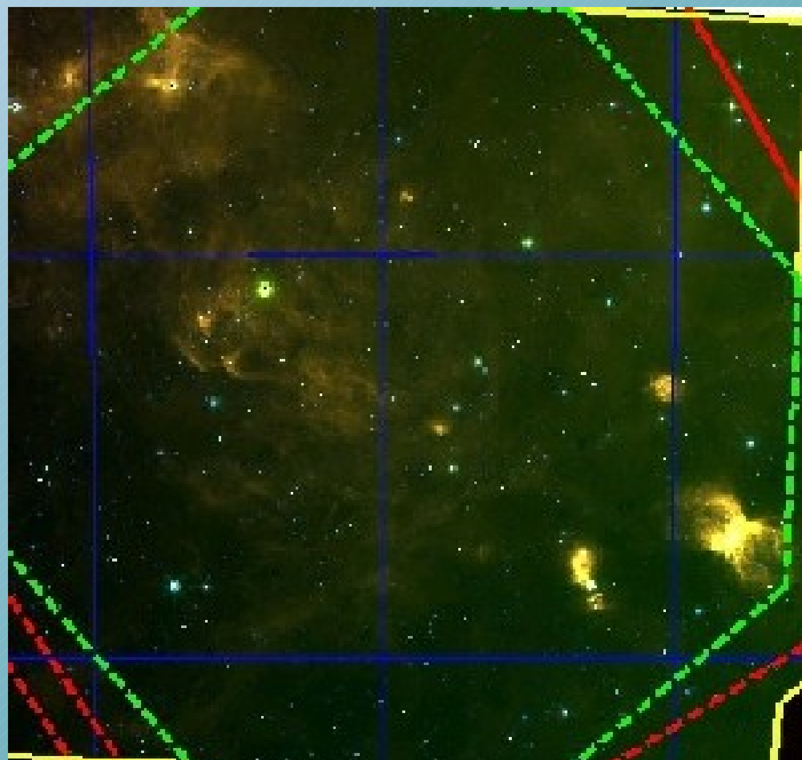
High Mass End of the Initial Mass Function



F. Massi
INAF - Osservatorio astrofisico di Arcetri

(Prague, September 14, 2009)

Star Formation: clustered vs. isolated

A widely accepted theoretical picture describes the birth of isolated low-mass stars (overviewed by Shu et al. 1987)

But, based on the observational evidence:

Most of the star formation in Giant Molecular Clouds occurs in clusters;

According to Adams & Myers (2001), most stars form in embedded star clusters with ~ 10 – 100 members;

Lada & Lada (2003) suggest that 90 % of stars that form in embedded clusters occur in rich clusters with > 100 members, but only< 4-7 % of embedded clusters emerge from molecular clouds to become bound clusters of Pleiades age.

The Initial Mass Function (IMF)

Throughout this talk the IMF is defined as the number of stars per unit stellar mass that form in a given volume:

$$f(M) = dN/dM$$

There is a case for a UNIVERSAL functional form of the IMF, meaning that Stellar populations in the field, in open clusters and in young embedded clusters all appear to have evolved from a same IMF.
But there are also hints of differences in different regions (see reviews Scalo 1998 and Kroupa 2007).

From observations, the IMF can be approximated by power-law segments:

$$f(M) = k\, M^{-\alpha} \quad \text{(E.g., Salpeter } \alpha = 2.35\text{)}$$

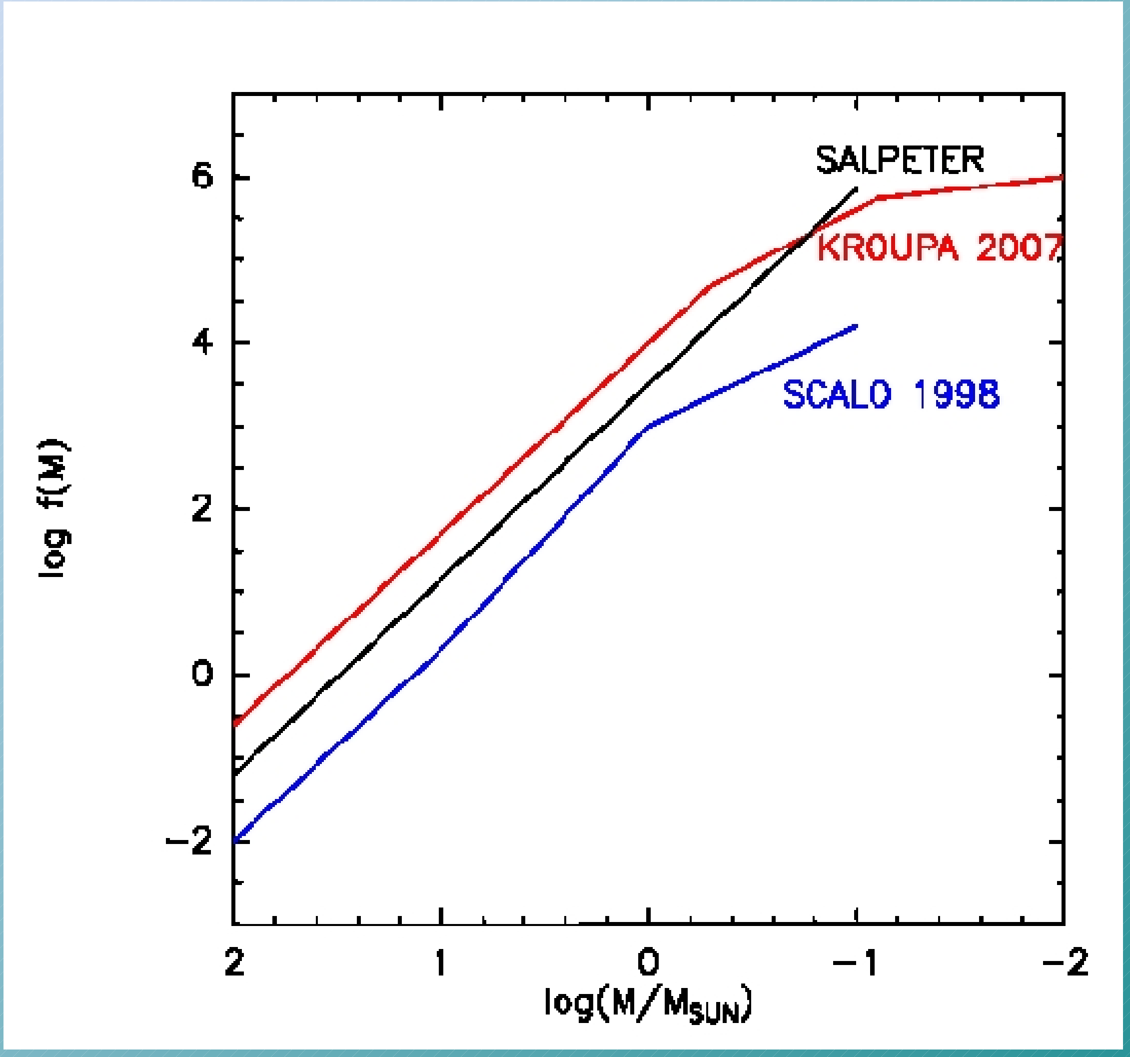
Normalization:

$$k = N_{TOT} / \int f(M)dM$$

.

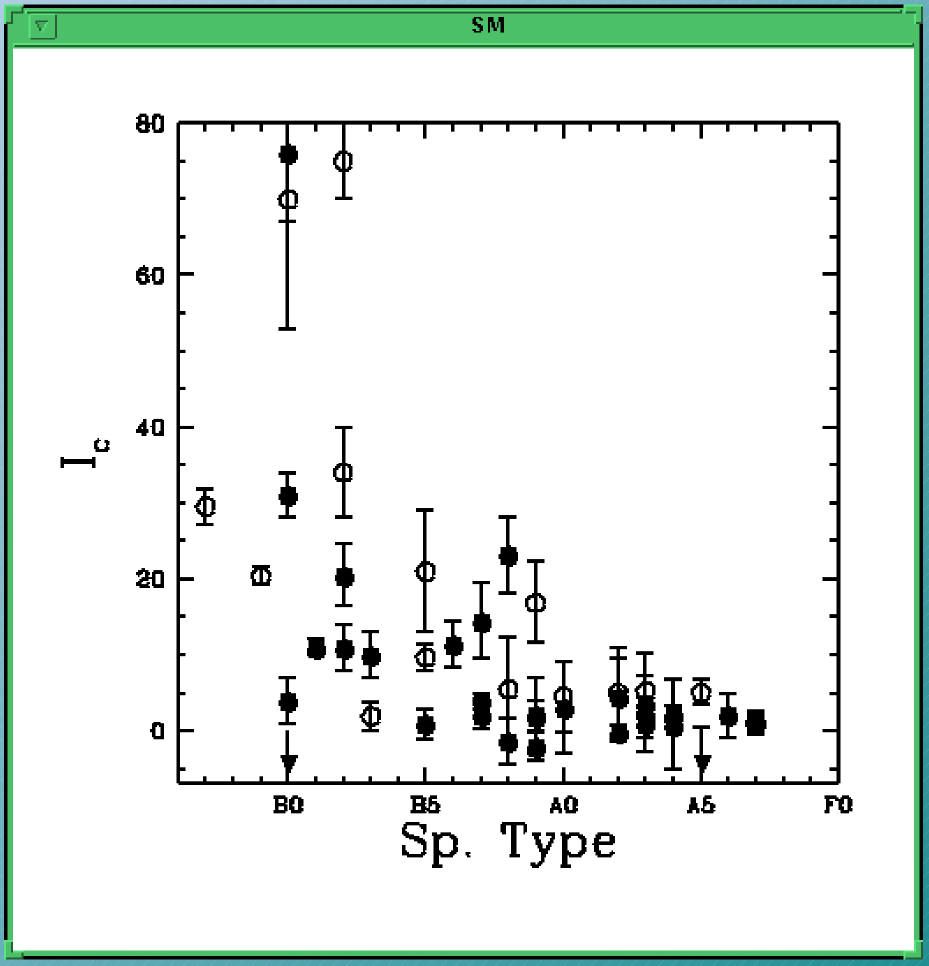
The Initial Mass Function (IMF)

Examples of widely adopted average IMFs from field stars and clusters



Do MASSIVE STARS form ONLY in clusters?

E. g., see the results of Testi et al. (1997, 1998, 1999) on Herbig AeBe stars



Do MASSIVE STARS form ONLY in clusters?

One fundamental problem with the results of Testi et al. (1997, 1998, 1999):

They selected massive stars and then searched for associated star clusters

More massive stars are more likely to be found in richer clusters, since richer clusters better sample the IMF (Bonnell & Clarke 1999).

Therefore: just a statistical bias?

More on the relation between the most massive star and the parental cluster size in Maschberger & Clarke 2008 and Weidner et al. 2009

Do MASSIVE STARS form ONLY in clusters?

An unbiassed test:

If small clusters cannot produce massive stars, the composite IMF of a large sample of young embedded star clusters should exhibit a break or be much steeper at the high mass end (Kroupa 2007)

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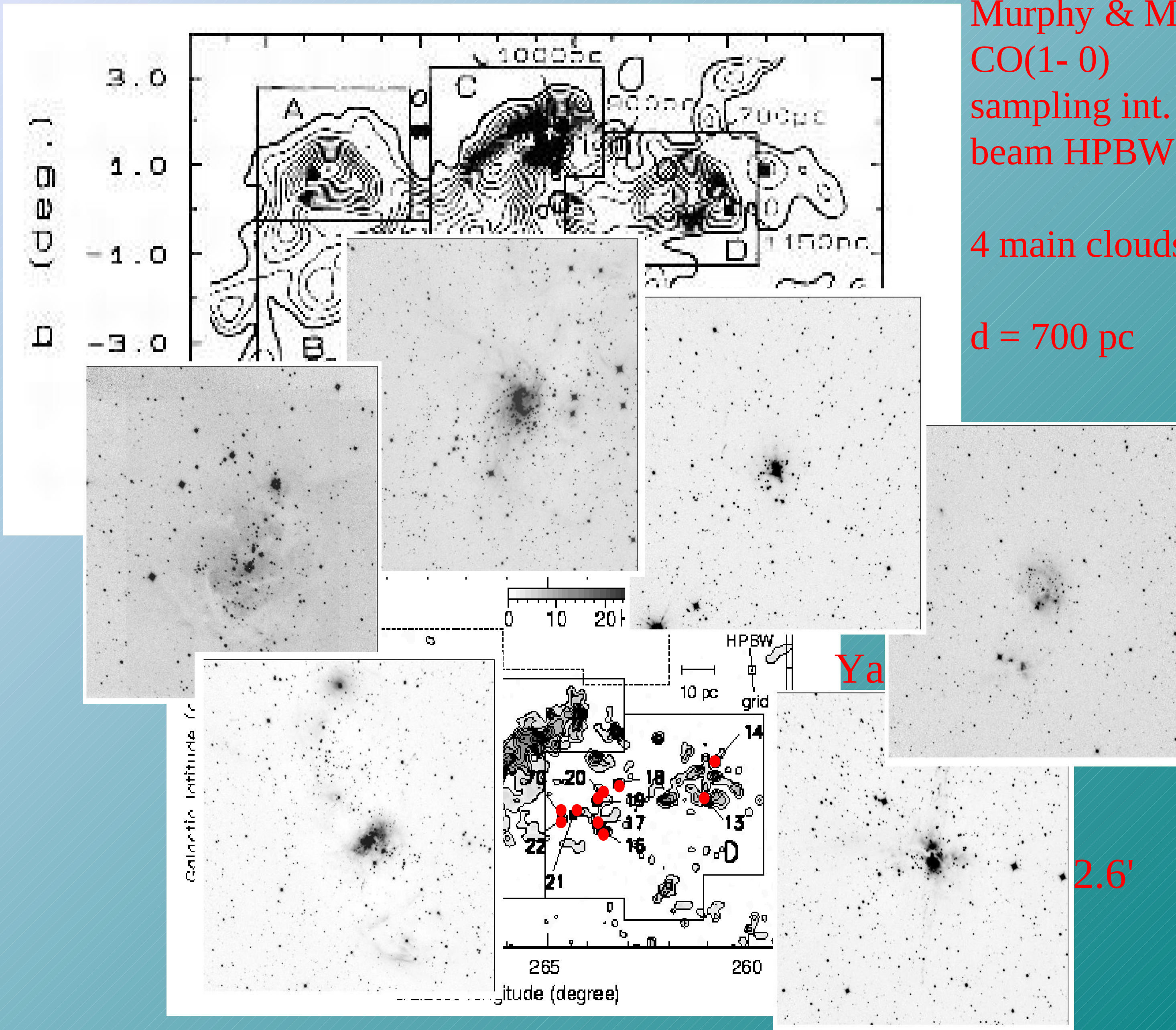
The Vela Molecular Ridge: a Suitable Laboratory to Study Star Cluster Formation

Vela Molecular Ridge: ~18x6 deg^2

Murphy & May (1991)
CO(1- 0)
sampling int. 30'
beam HPBW 8.8‘

4 main clouds: A,B,C,D

d = 700 pc



galaxy

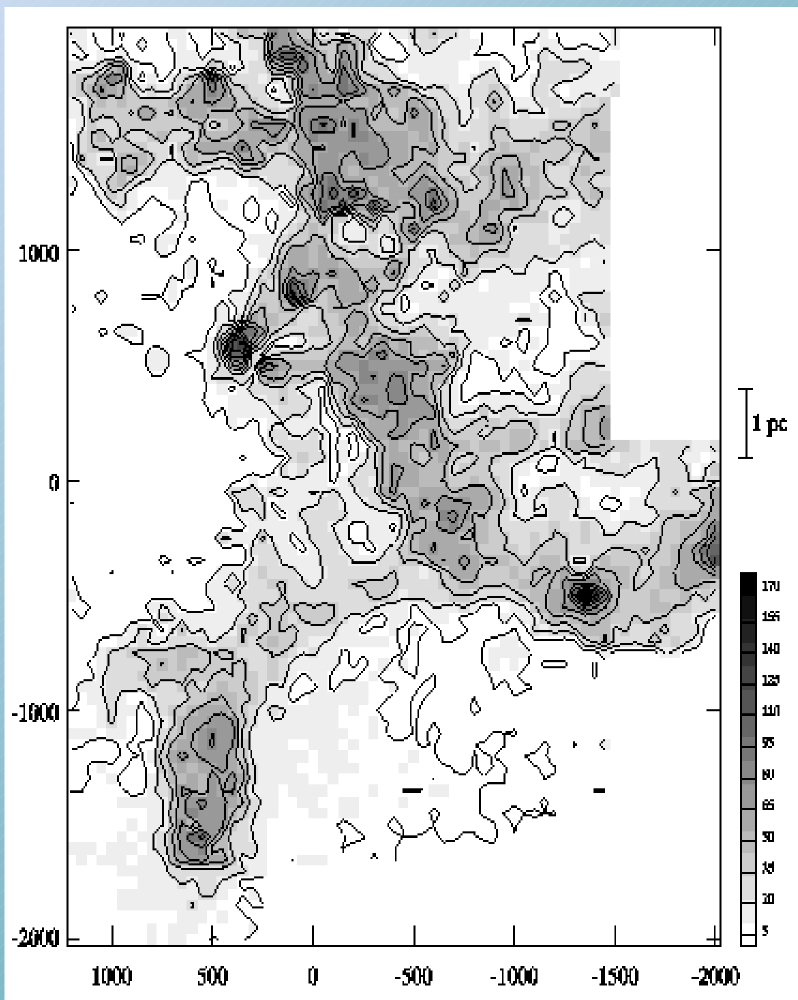
Ya

999)

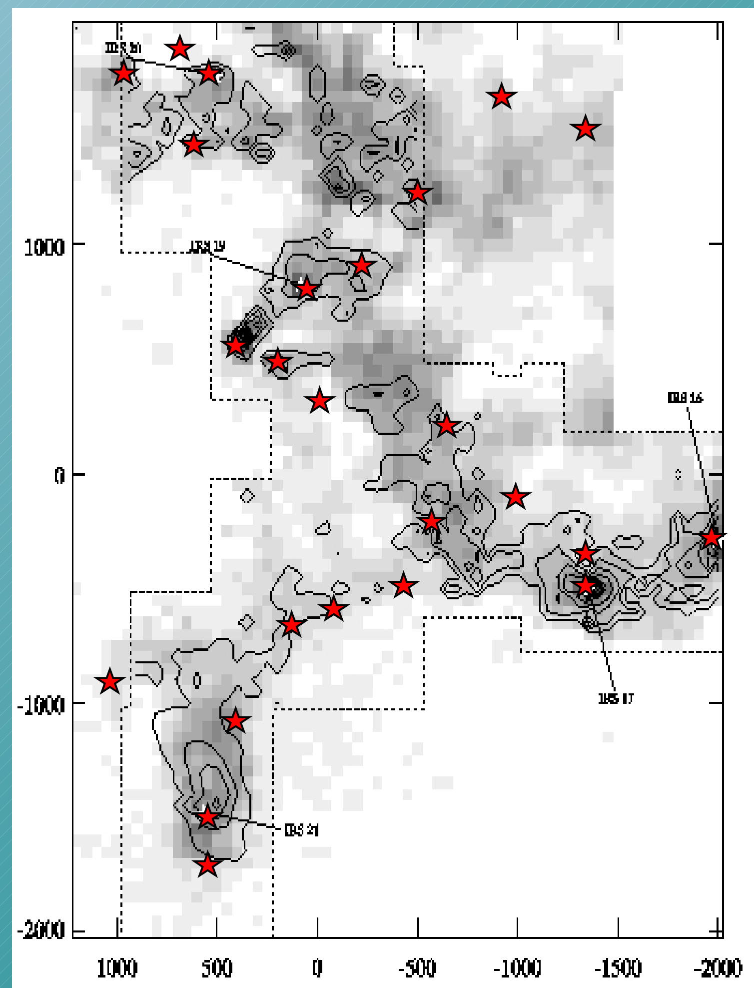
2.6'

The molecular cloud: ~1x1 deg^2 (~12 x 12 pc^2 @ d=700 pc)

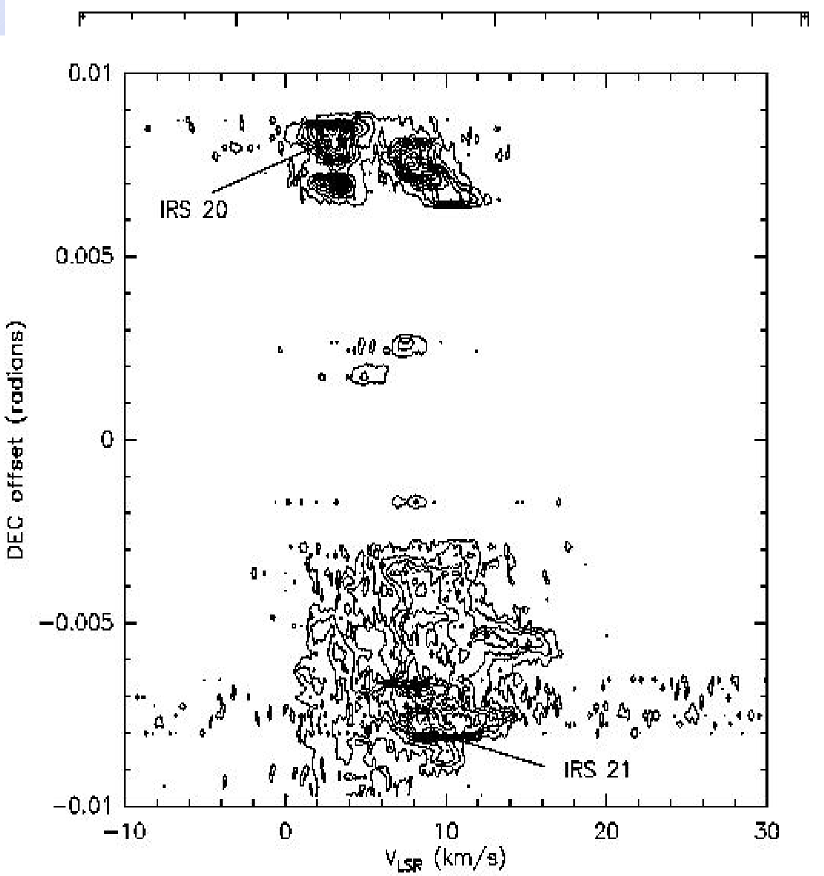
2.6 mm: CO(1-0) map (SEST)
Elia et al. 2007



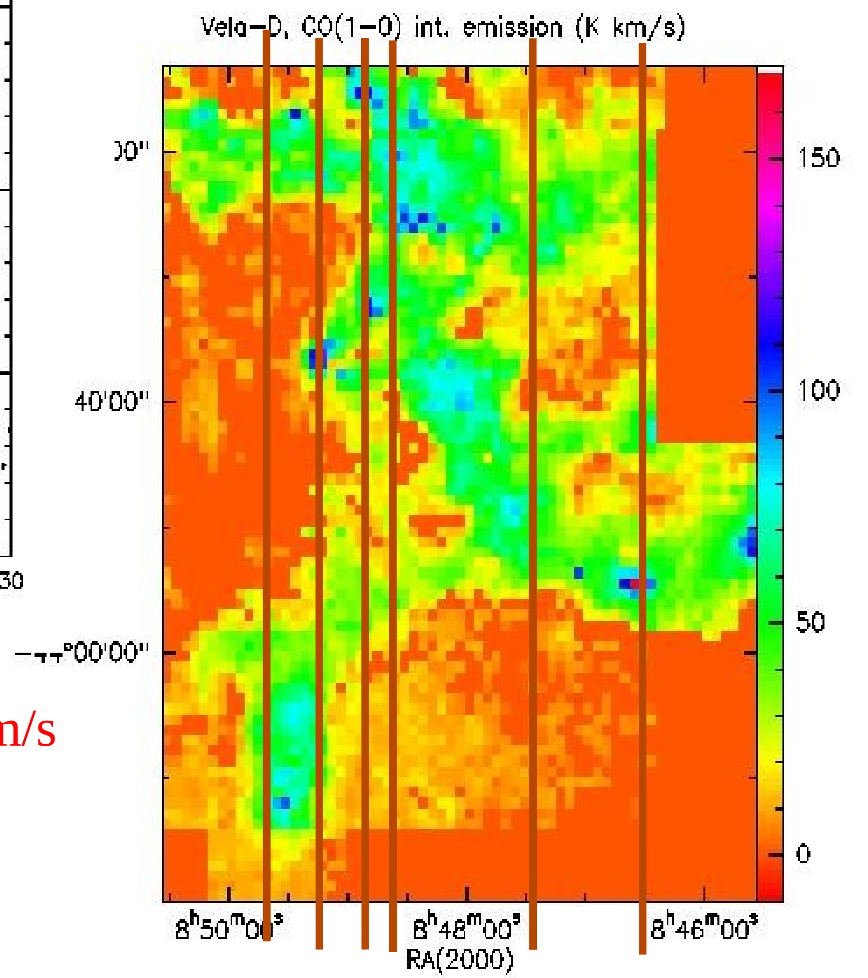
1.3 mm : ^{13}CO(2-1) map (contours) overlaid with CO(1-0) (grey scale)



Close- up on Vela D: ~1x1 deg^2 (~12 x 12 pc^2 @ d=700 pc)



Filaments or shells ?



CO(1- 0), int. from 0 to 12 km/s
sampling 50"
beam 43"
(0.15 pc @ d=700 pc)

Expanding Shells?

$R \sim 5$ pc

$V \sim 5$ km/sec

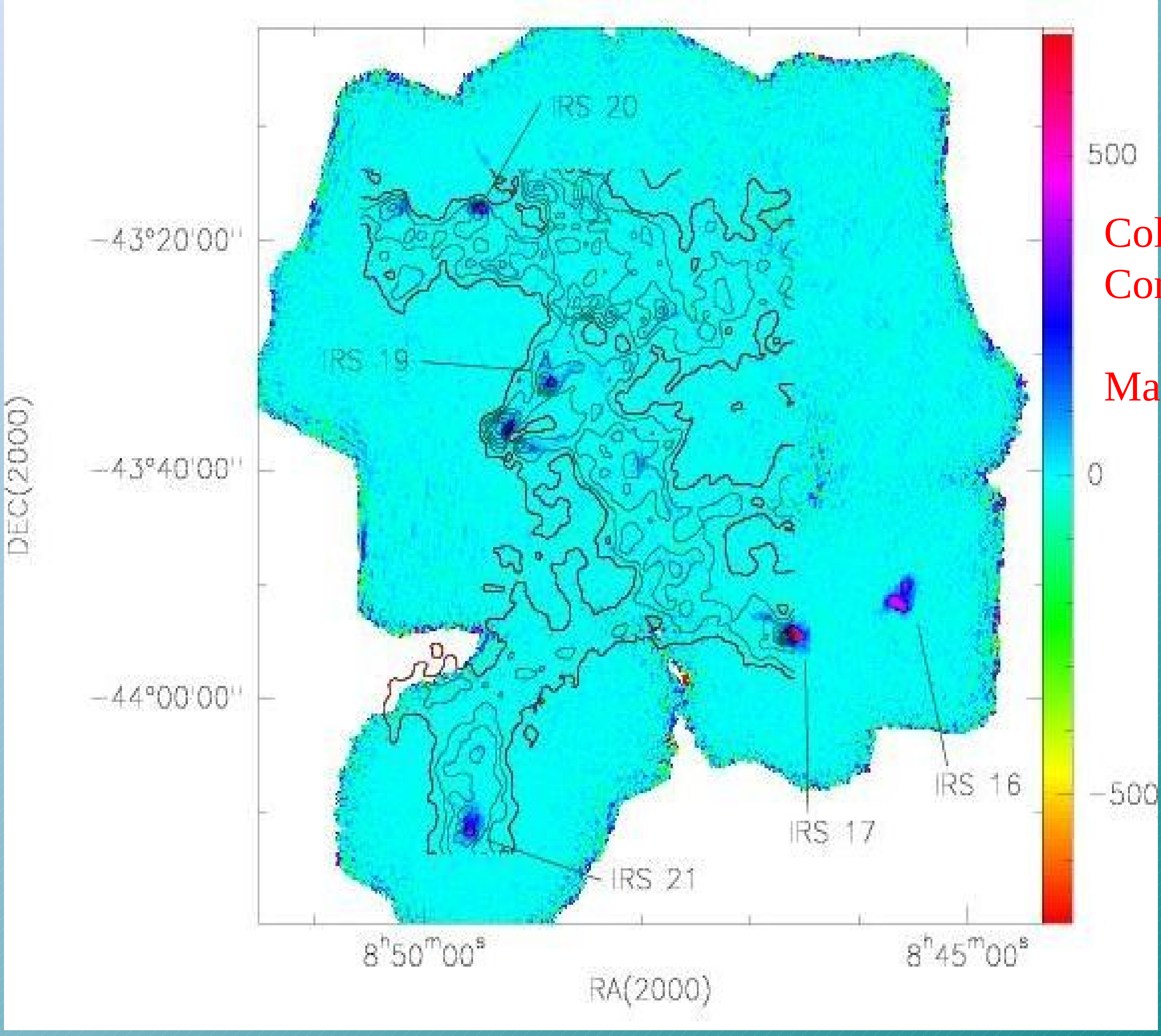
$E_{kin} \sim 10^{47}$ erg

Age $\sim 10^{6}$ yr

Driving sources: HII regions? Winds from young stars?

Vela- D: dense cores

SIMBA@SEST, 1.2 mm continuum, beam HPBW 24" (0.08 pc @ d=700 pc)

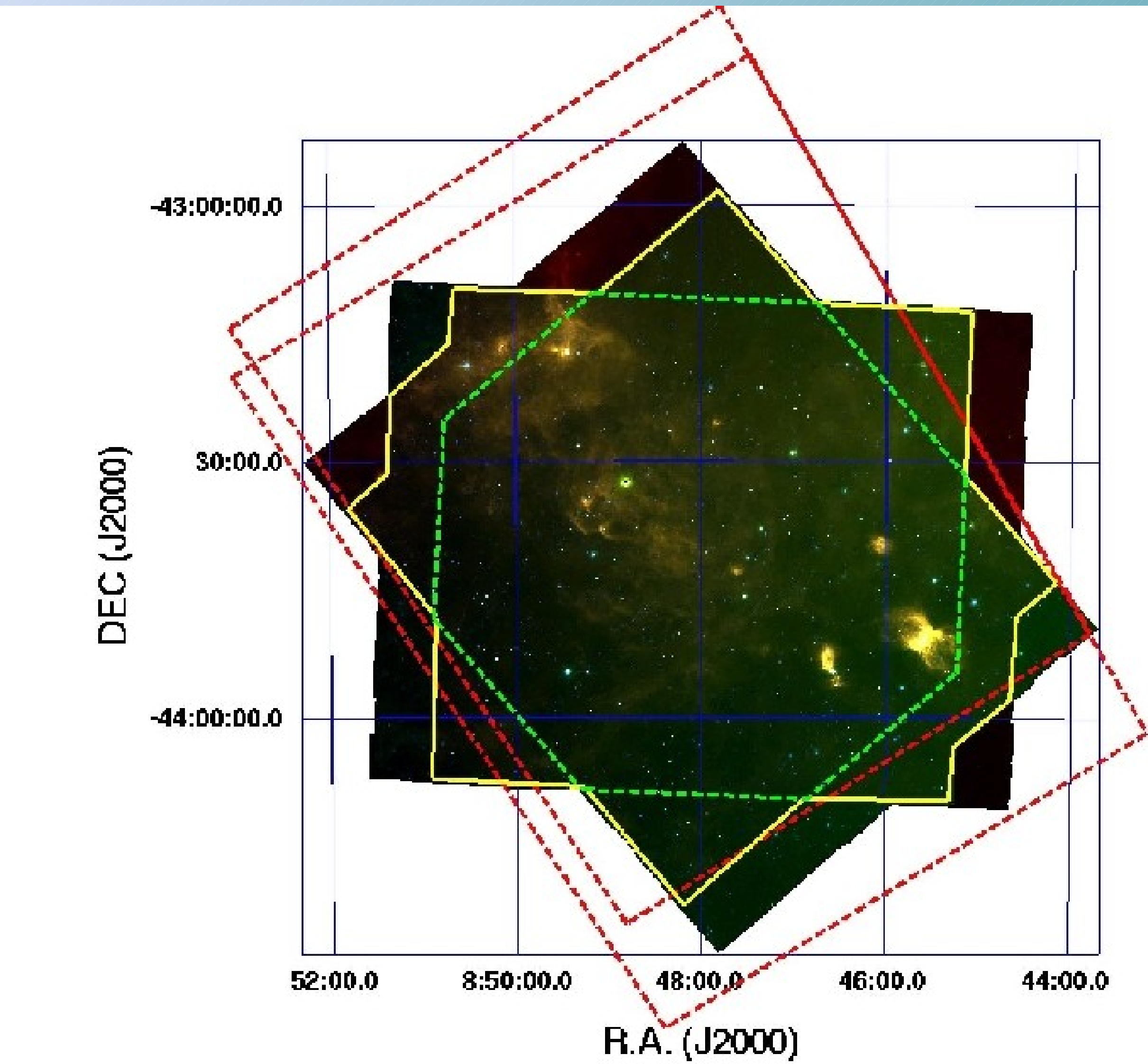


Colour map: 1.2 mm
Contours: CO(1- 0)

Massi et al. 2007

Vela- D: Mid-Infrared

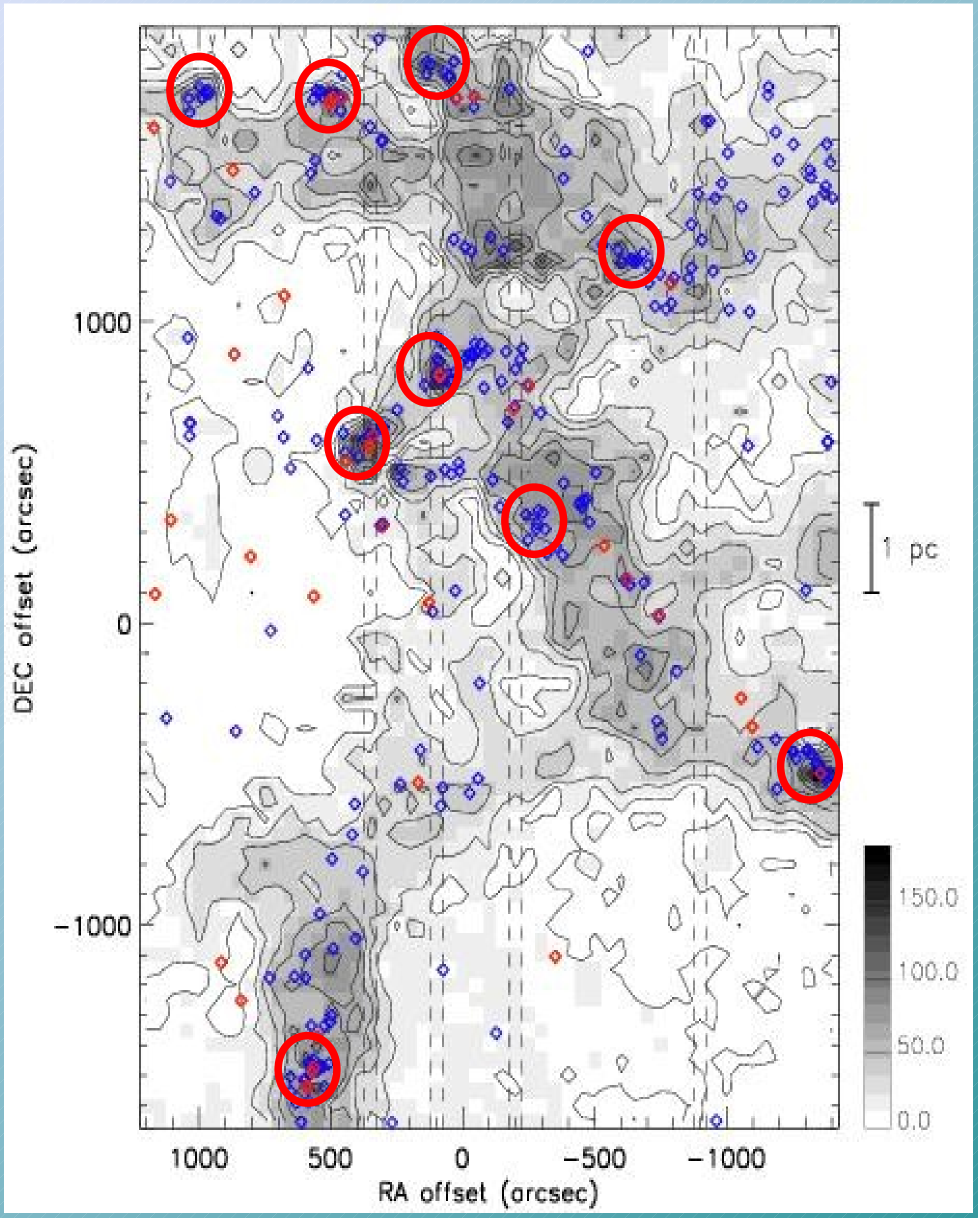
Spitzer/IRAC, three colour: 3.6, 5.8 and 8.0 micron 24"



MIPS observations:
Giannini et al. 2007

IRAC observations:
Strafella et al.
in preparation

Vela- D: stellar populations

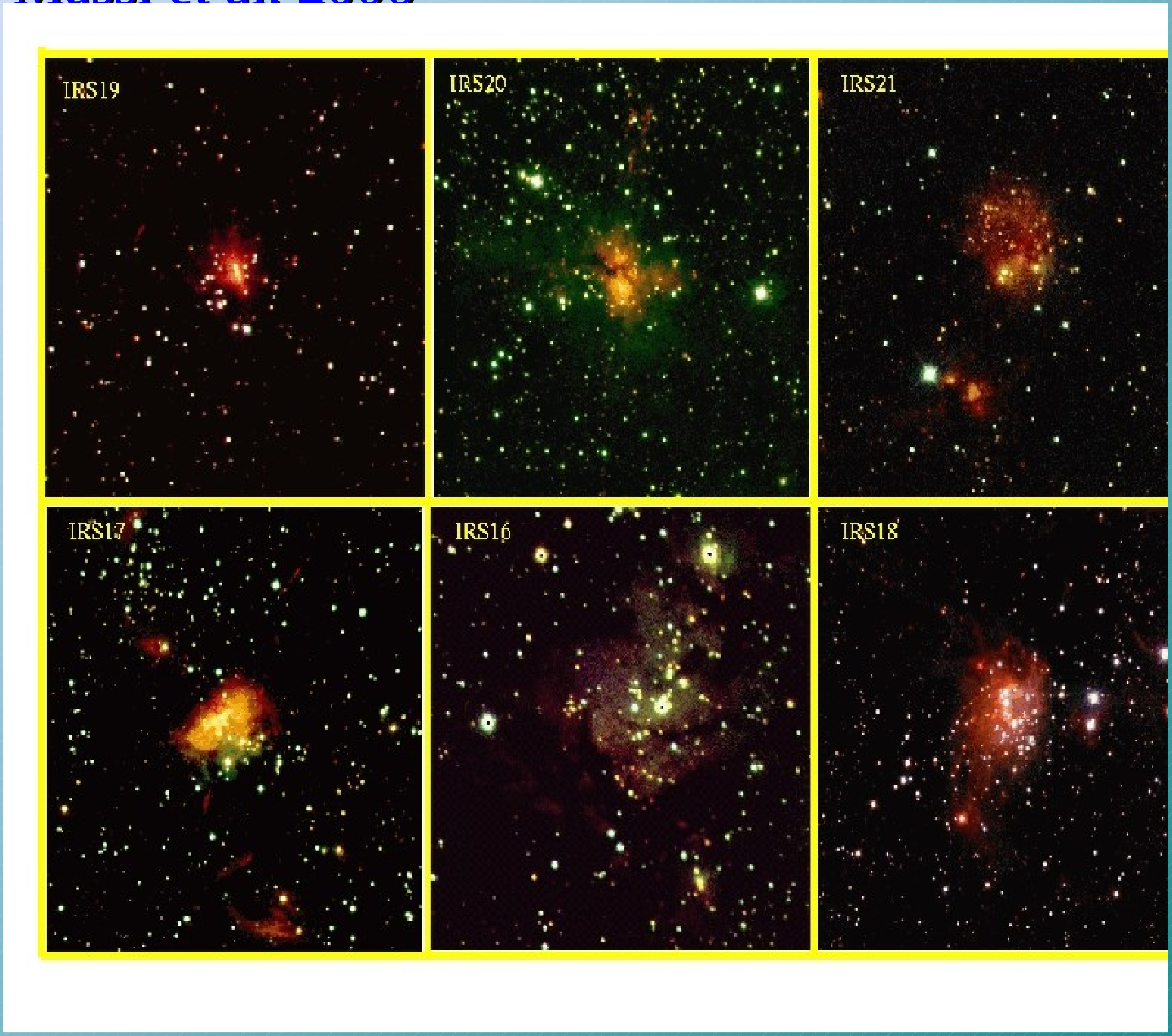


NIR (2MASS) sources:
red H - K > 1
blue H - K > 2

Young embedded star clusters towards CO(1- 0) peaks

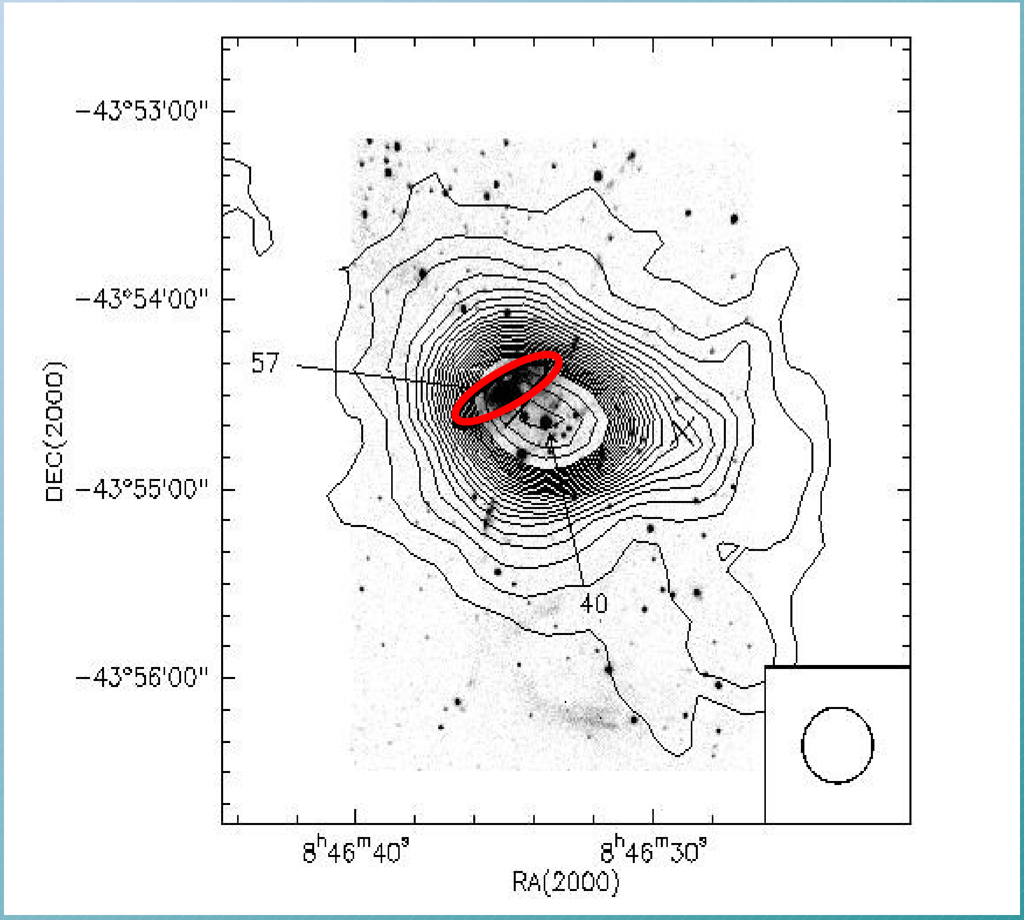
Also, more diffusely distributed stars

True colours images of the six clusters (JHK): SofI@NTT
Massi et al. 2006



Close up on the clusters: IRS 17

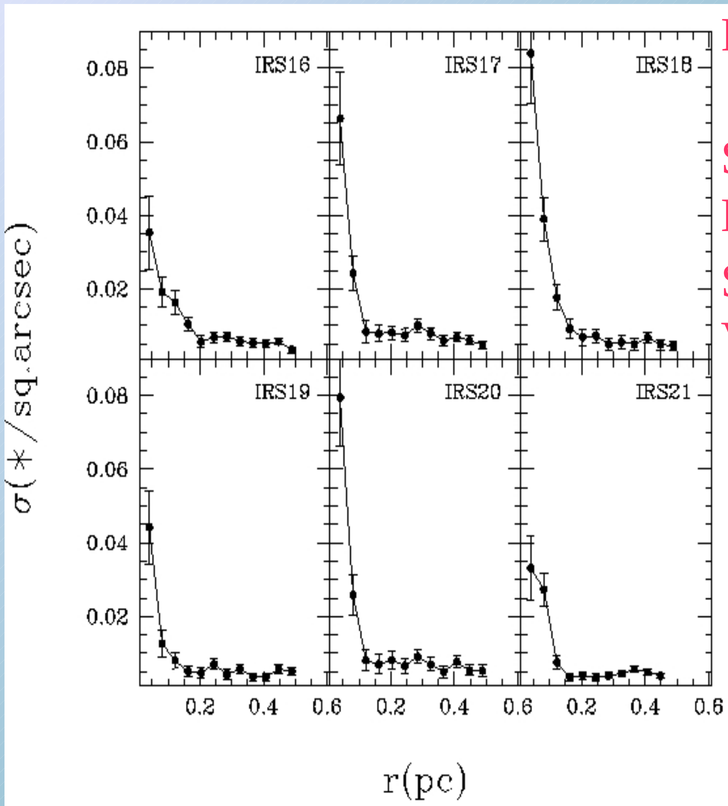
1.2-mm map (contours)
K image (SofI@NTT)



#57 is the NIR counterpart of the IRAS source

#40 has been resolved with the VLT into a subcluster at the centre of a jet

Vela- D: properties of the embedded clusters



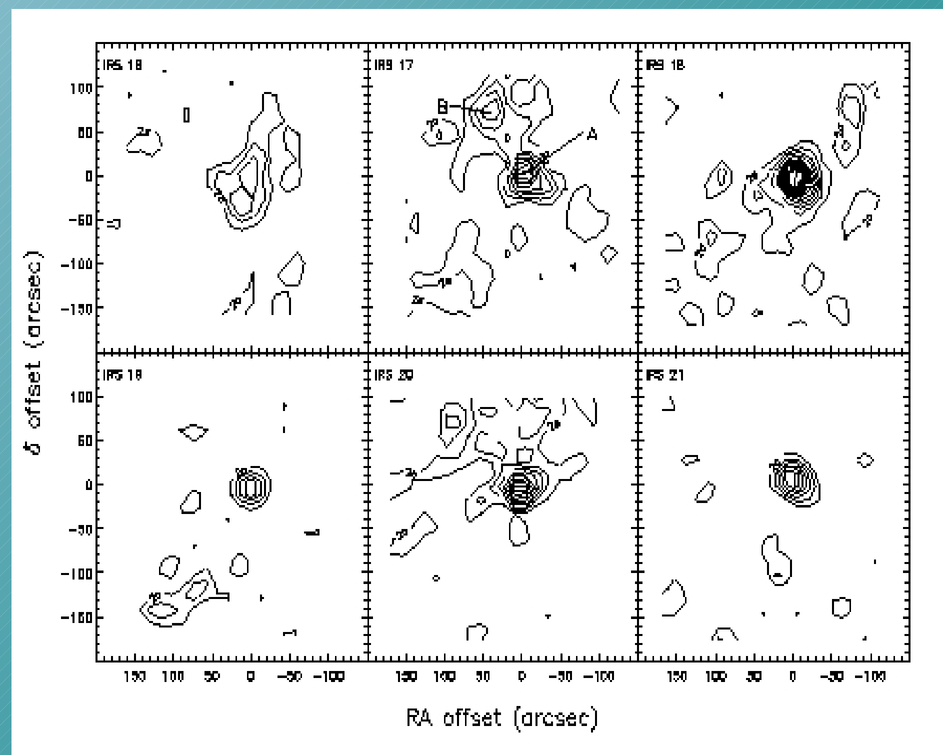
Radial surface density maps (of K_s sources)

Size (radius): 0.1-0.2 pc

Members: 50-150 (down to 0.1 - 0.3 M_{sun})

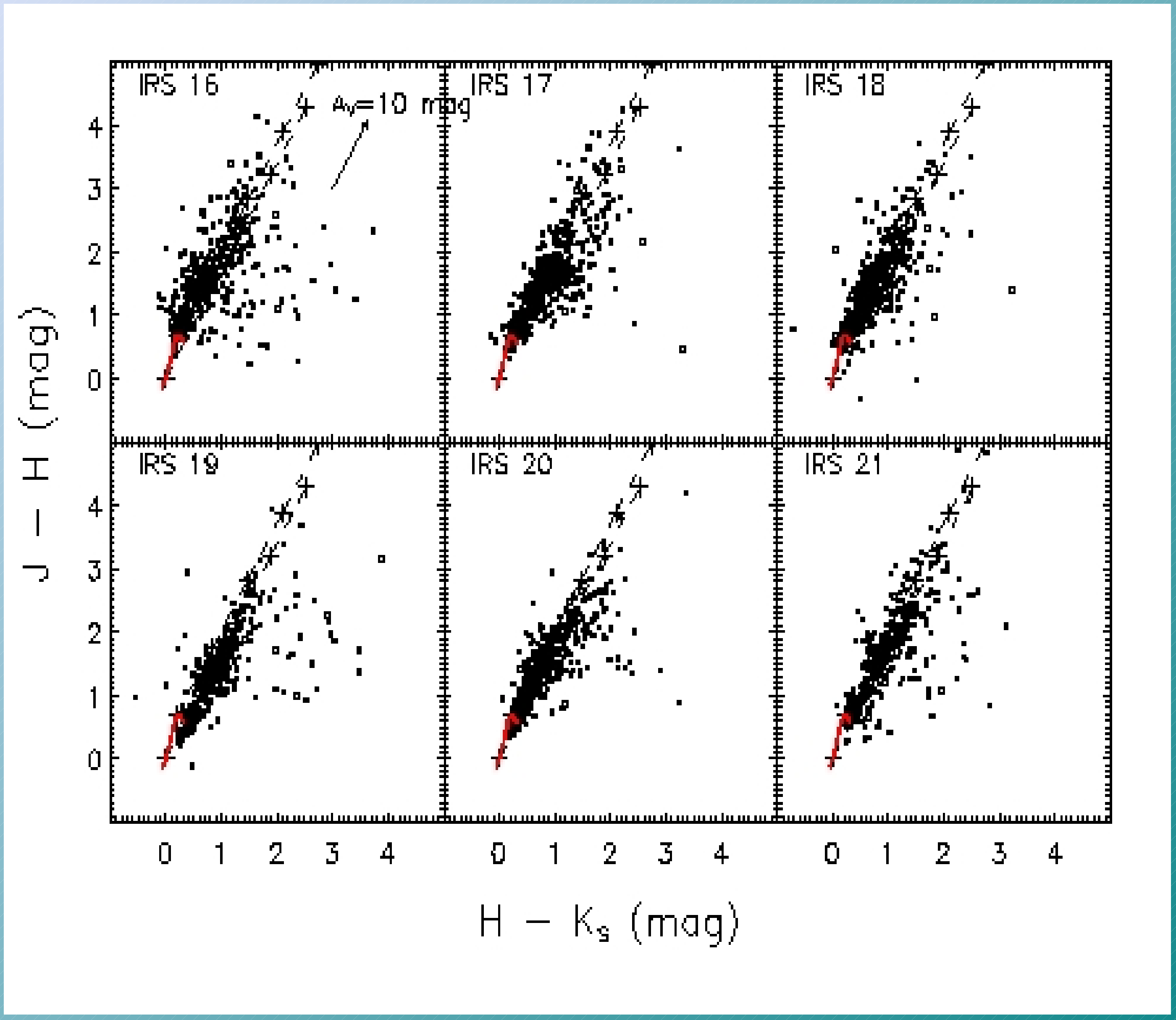
Star formation efficiency: <30 %

Volume density of stars: 10^3 pc^{-3}

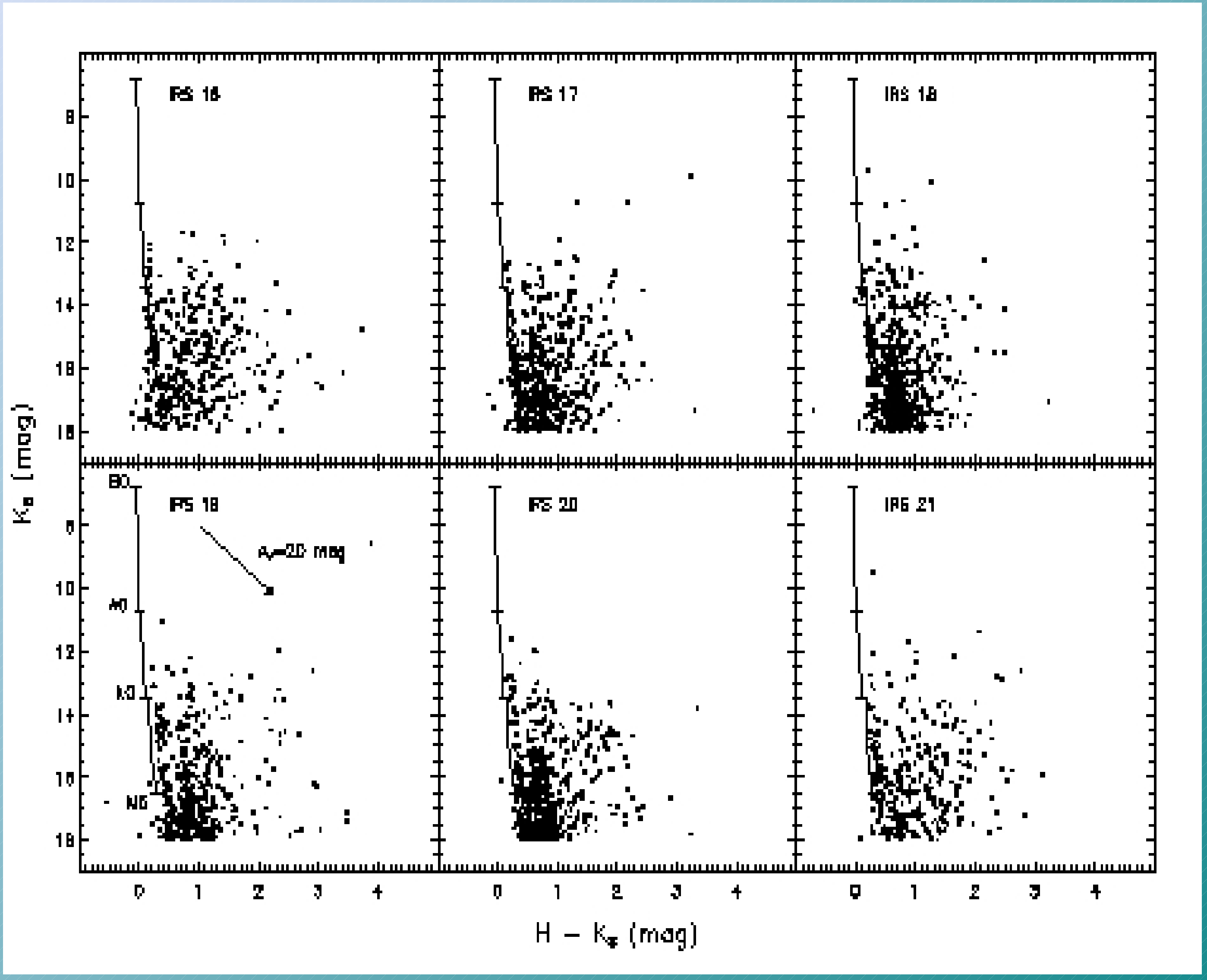


Surface density maps (of K_s sources)

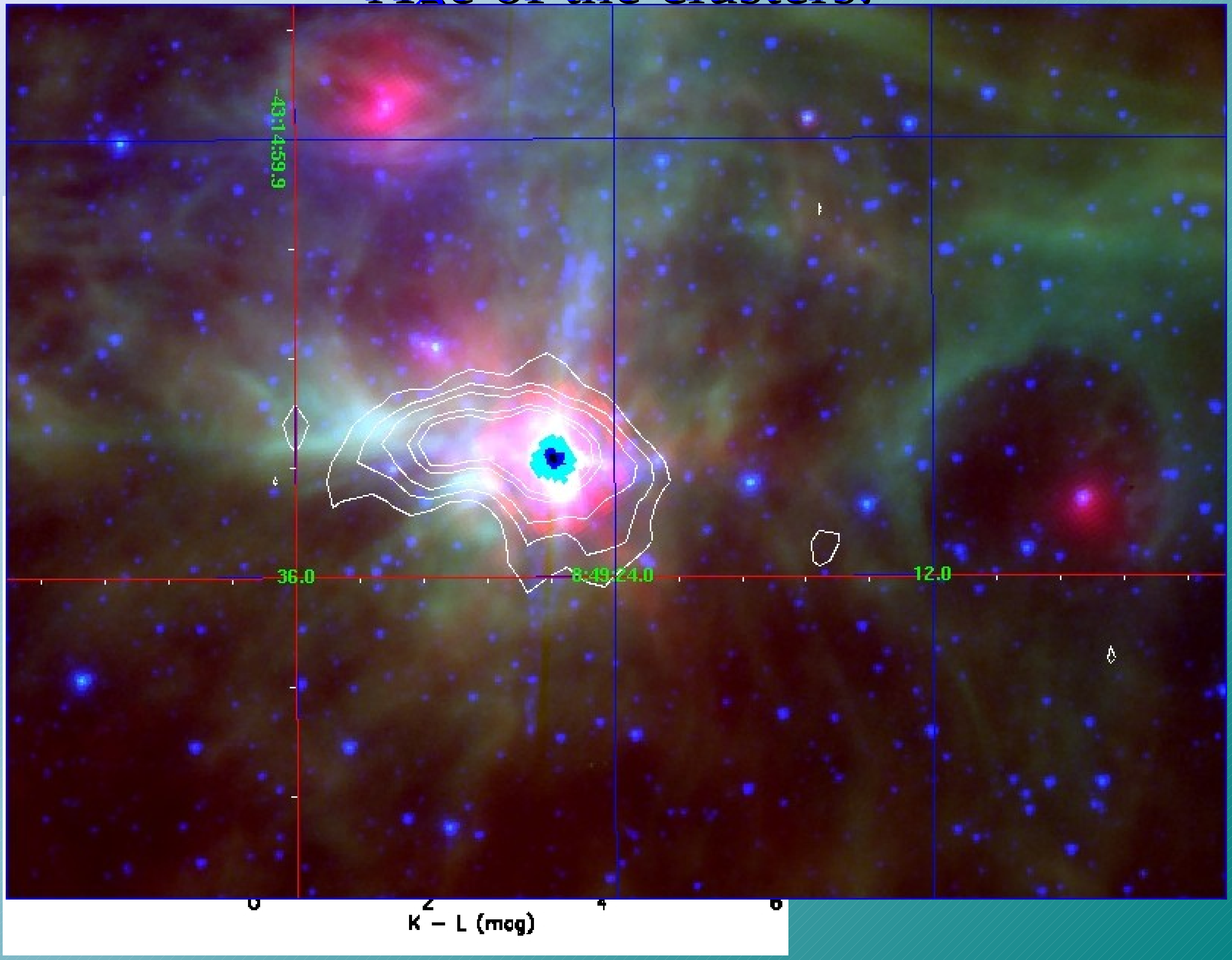
Vela- D: clusters' star population



Vela- D: clusters' star population



Age of the clusters:



Deriving the IMF from the K luminosity function

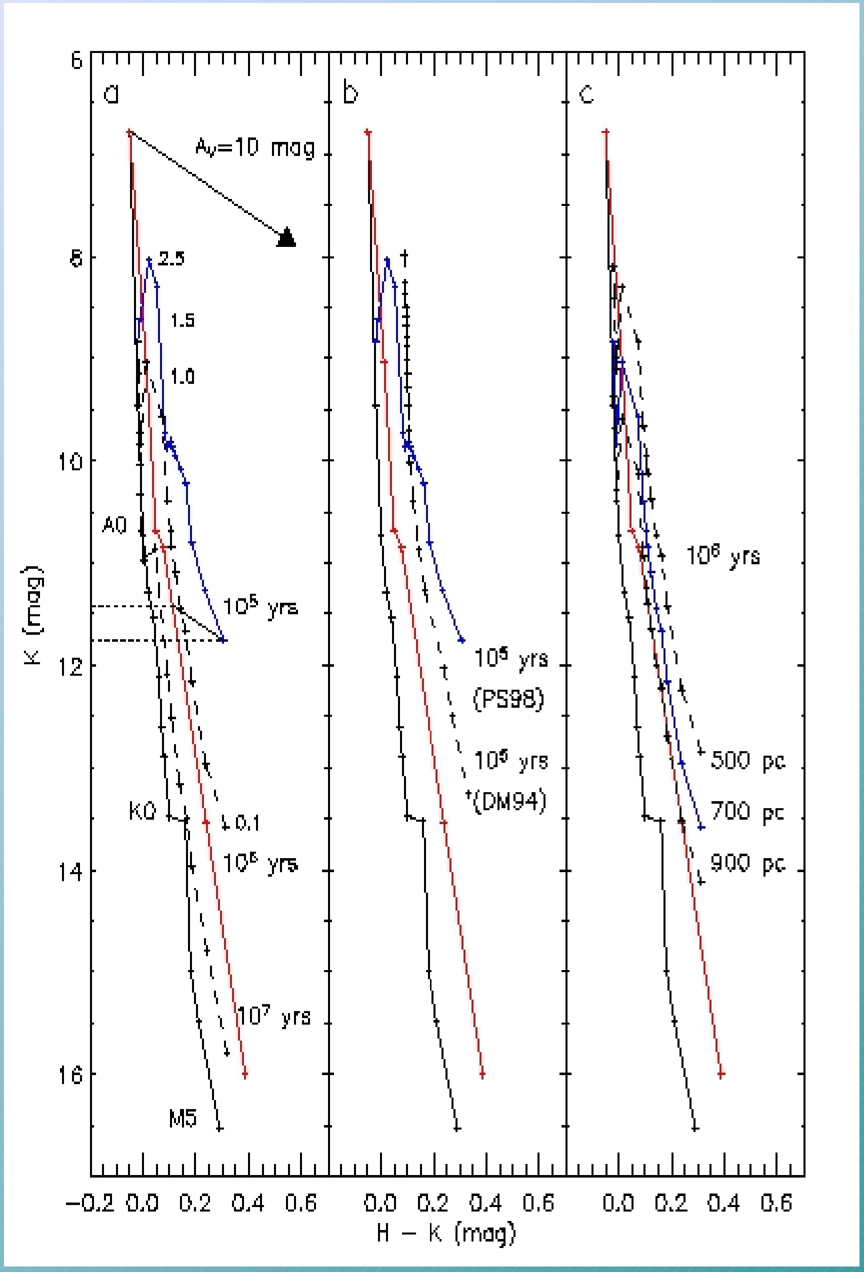
The flux of a star at a given wavelength (e.g., in the K band @2.2 micron) depends on the star mass

Then, we can construct a K Luminosity Function (KLF) of the cluster and convert it into an IMF

Problems:

Distance
Extinction
NIR excess above photospheric flux in young stars
Mass-K relation model-dependent
Mass-K relation also depends on age for PMS stars
KLF contamination from foreground-background stars

Dereddening K luminosity functions



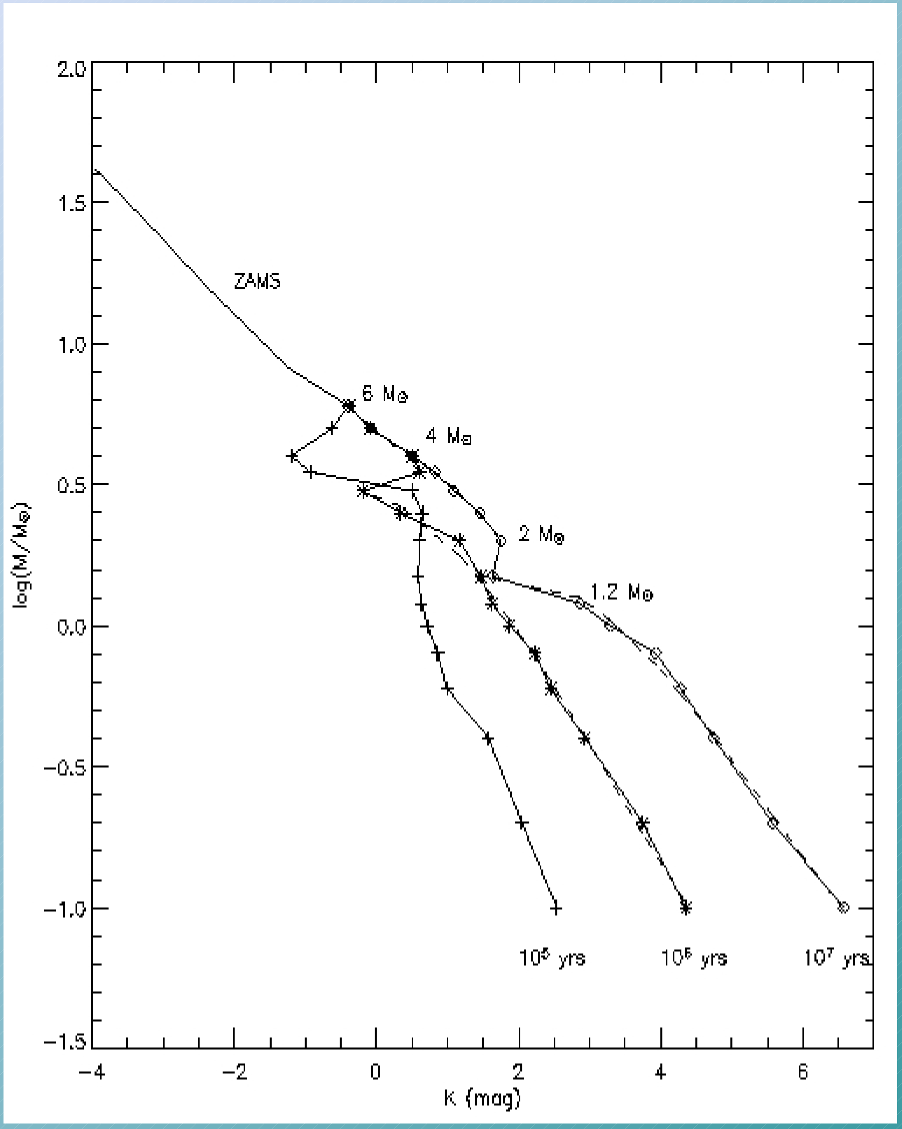
The cluster KLF depends on the IMF

Once the KLF is derived for each image in K, one has to correct it for field stars contamination

The dereddening procedure is shown on the left

The dereddened KLF is, however, still affected by the NIR excess of many young stars

Deriving an IMF from the KLF



The KLF is:

dN/dK = (dN/dM)x(dM/dK)

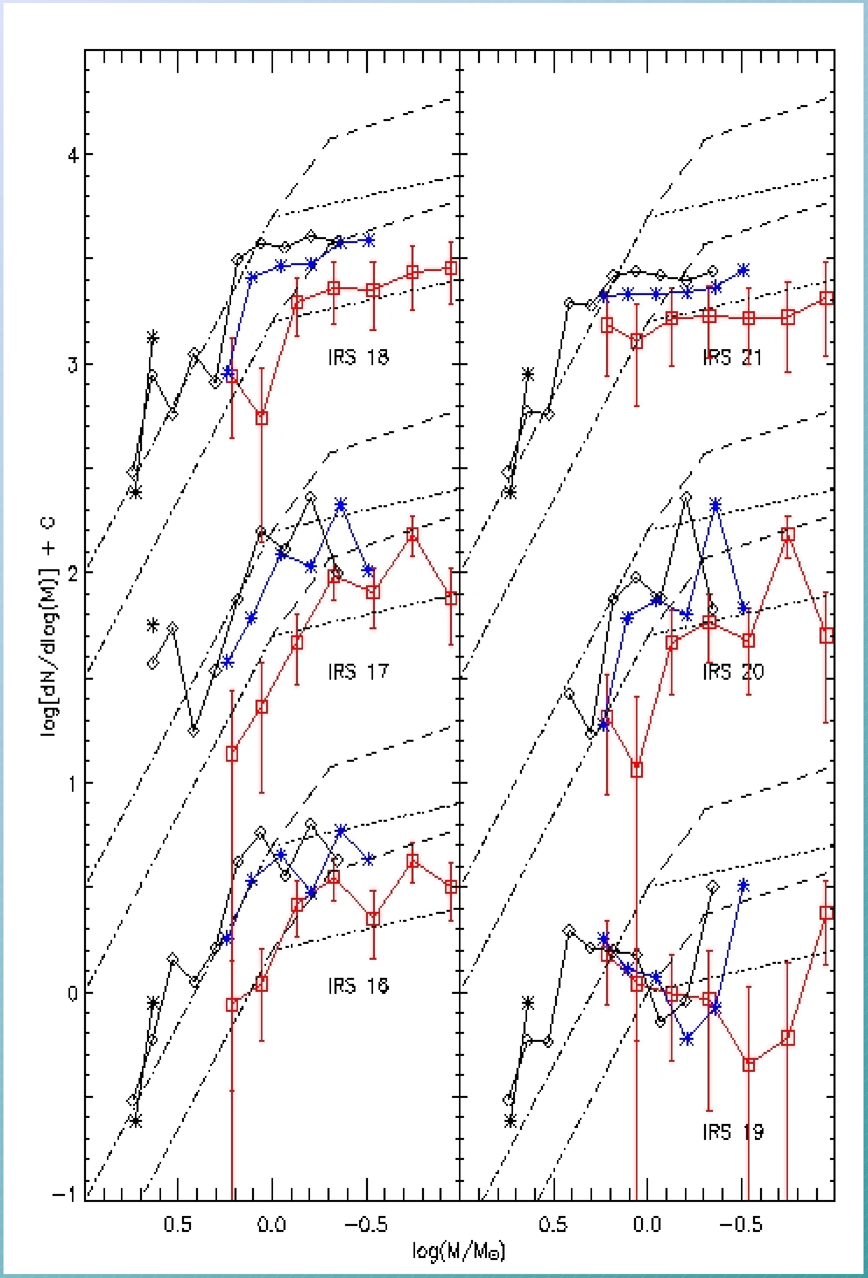
dN/dM is the IMF
---> to derive the IMF one has to know the mass-luminosity relation dM/dK

This can be obtained from theoretical evolutionary tracks
We used those of
Palla & Stahler (1999) for pms stars

The mass-luminosity relation depends on the age

Age of clusters < $5x10^6$ yr

nitial Mass Function of the embedded clusters

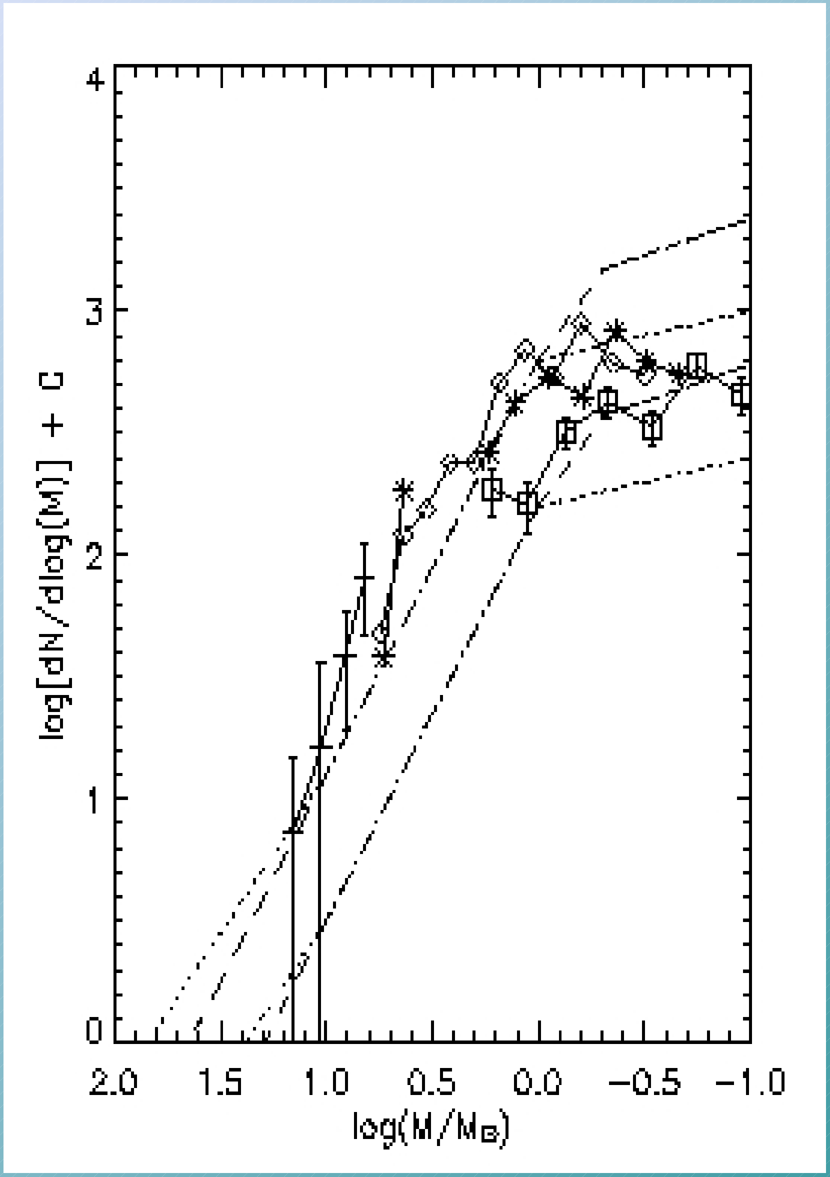


Obtained from the KLF assuming Coeval star formation and three possible ages:

10^6 yr (red line)
$3x10^6$ yr (blue line)
$6x10^6$ yr (black line)

Also drawn:
Scalo's (1998) IMF (dotted line)
Kroupa's IMF (dashed line)

TOTAL Initial Mass Function of the six clusters



Does the mass of the most massive star in a cluster depend on the number of cluster's members?

The total number of stars within the six clusters is > 650. Scalo's IMF predicts a star with M > 22 M_{SUN} in one of the clusters, that is not found.

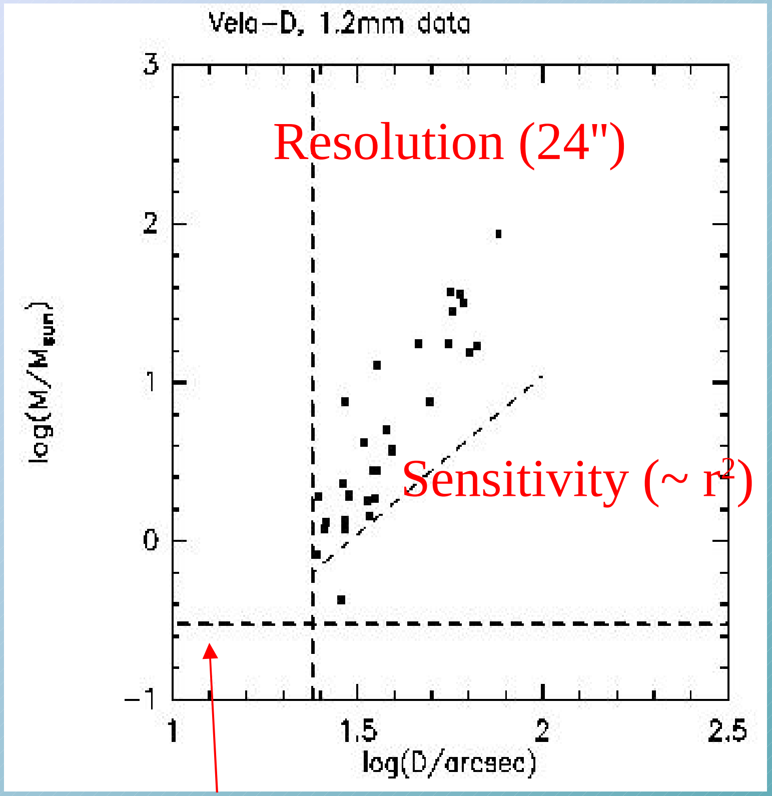
Part III: Conclusions

An analysis of 6 young clusters of VMR-D suggests a break at the high mass star, at the border between intermediate and high mass stars.

Available JHK deep images (SofI@NTT) for 16 more clusters in the D and C clouds (photometry under way), taken in 2005/2006 and 2007/2008!

More robust estimators for the IMF functional form and the mass upper limit are discussed in Maschberger & Kroupa (2009)

Vela- D: properties of the dense cores



3σ ~ 60 mJy/beam

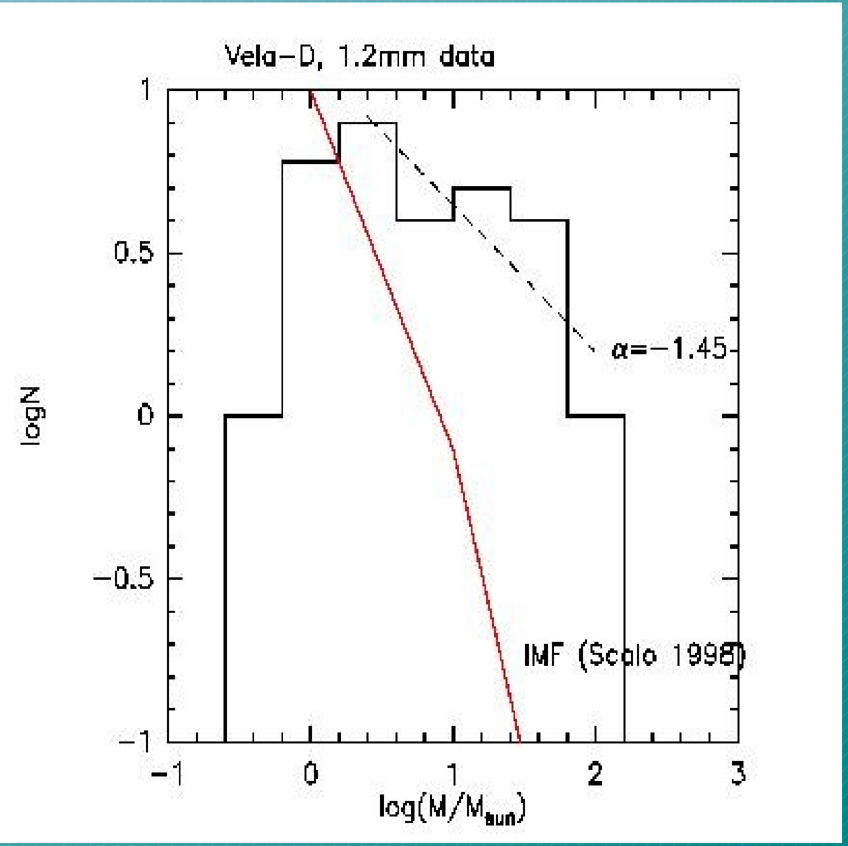
CLUMPFIND

Mass: assuming T=30 K, k = 0.005 g cm^{-3}

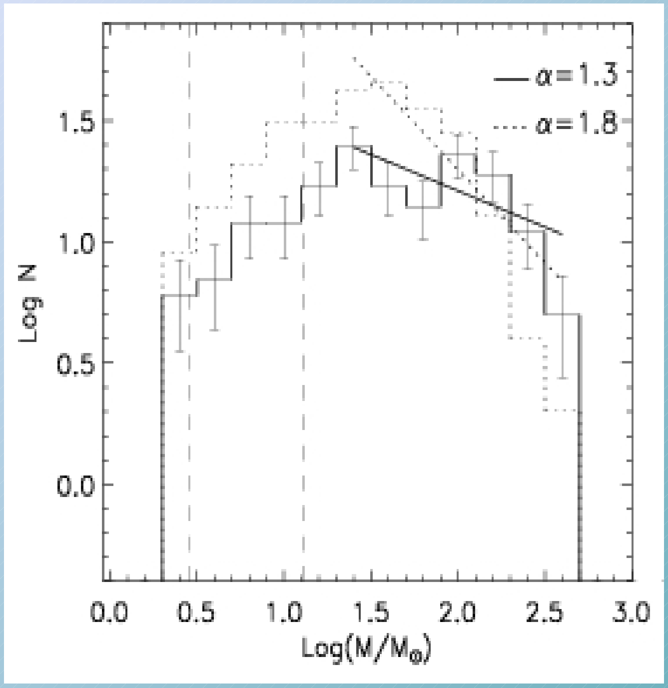
(dust/gas = 0.01)

Cores mass spectrum: dN/dM~M$^{\alpha}$

mass-size relation: M ~ r$^{1.74}$

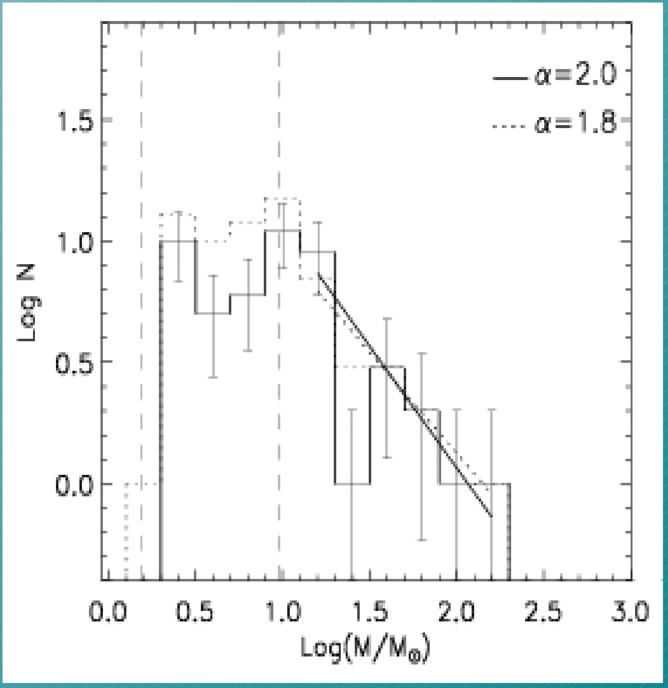


Vela- D: properties of the molecular clumps



CLUMPFIND
Mass: scaling $^{12}CO(1-0)$ int. emission (left)
LTE, from $^{13}CO(2-1)$ (bottom)

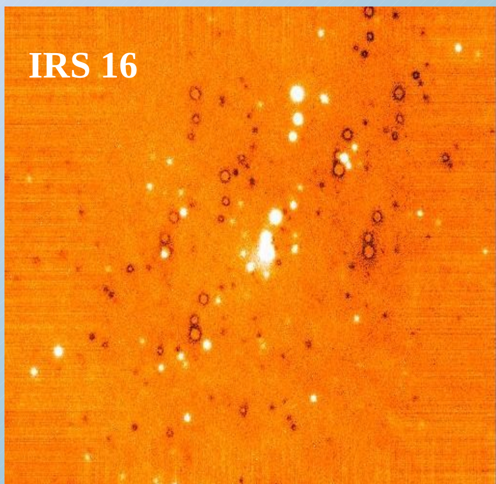
Cores mass spectrum: $dN/dM \sim M^{-a}$

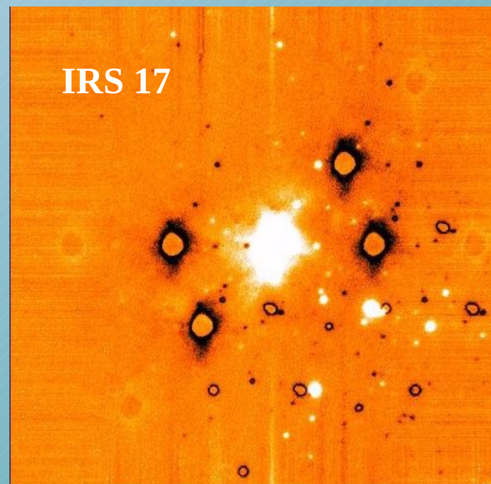


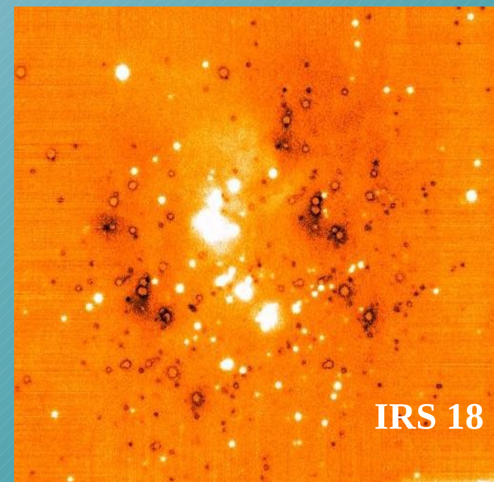
But:
$^{12}CO(1-0)$ is optically thick
$^{13}CO(2-1)$ is undersampled!

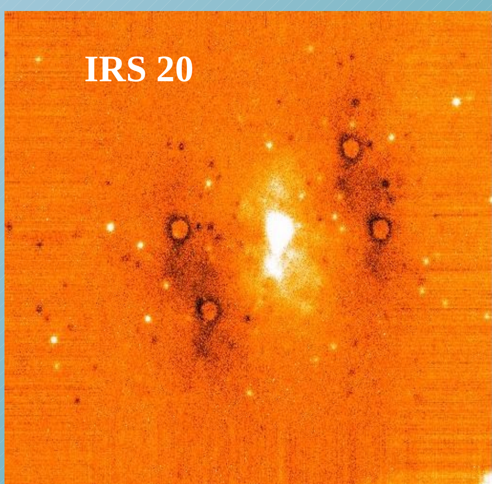
Determining the age of clusters and the fraction of members with disk (work in progress!)

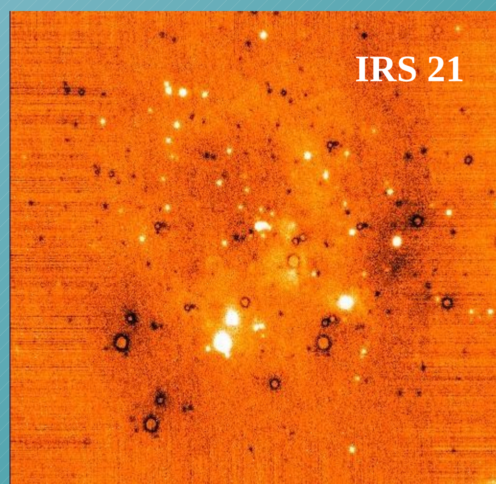
ISAAC@VLT L-band (3.5 μm)

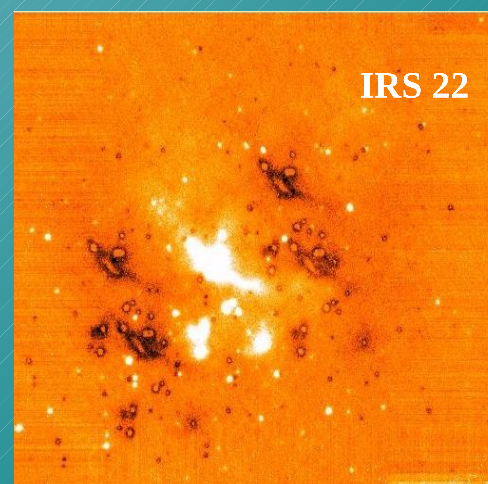




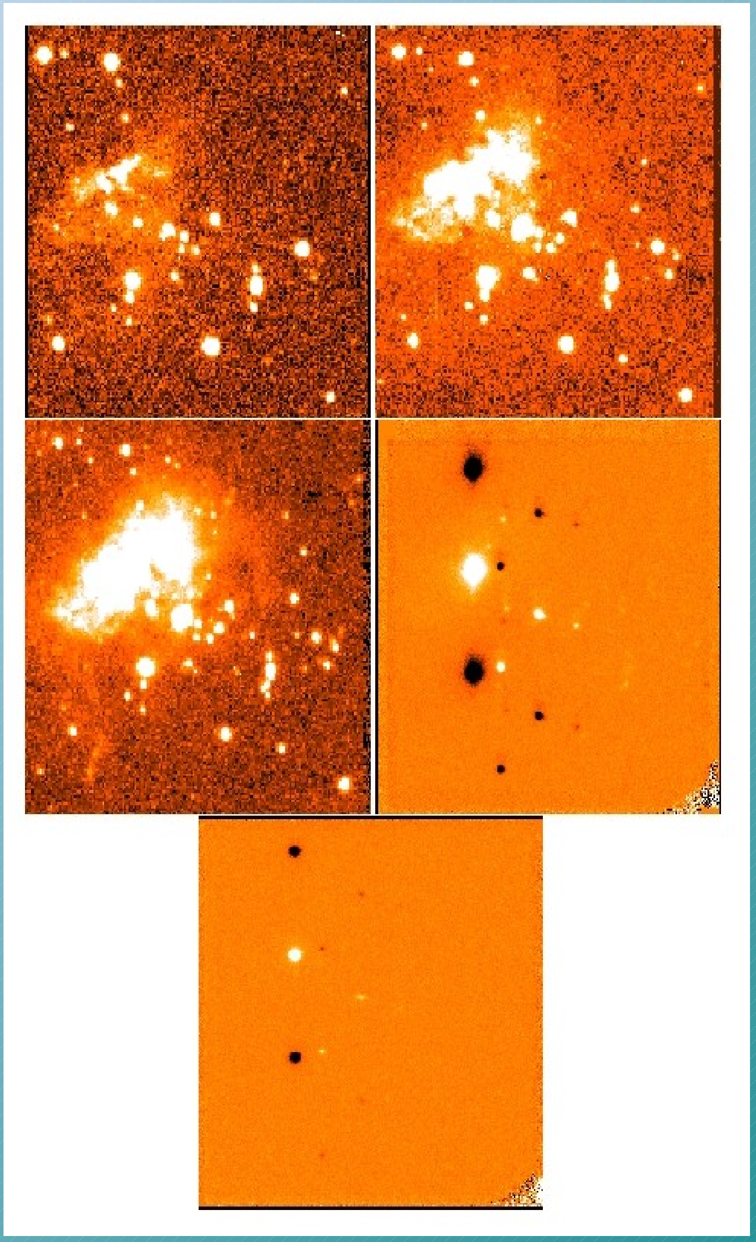








IRS17: from the NIR- to the Mid-IR



VELA: other embedded star clusters