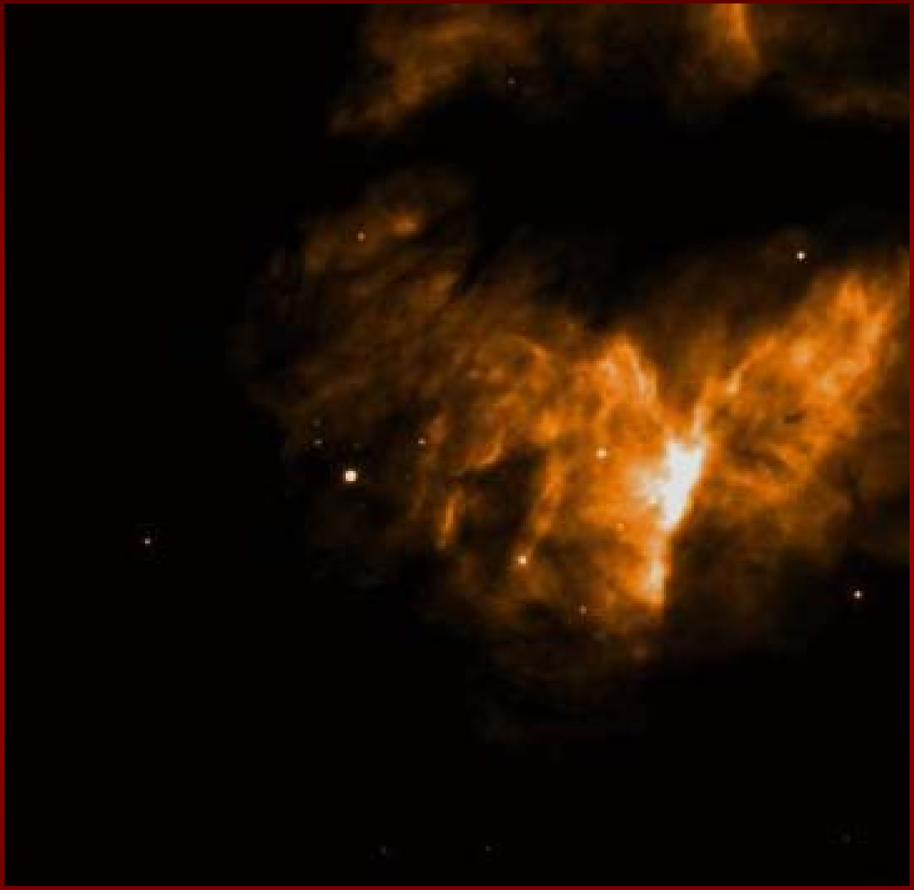
# Measuring The Initial Mass Function in Embedded Clusters

Form Cores to Clusters, Porto Portugal, Oct. 2004



Optical Image

Infrared Image

Team: Charles Lada (CfA), Gus Muench (CfA), Liz Lada (Florida), Joao Alves (ESO)

# Young Embedded Clusters and the IMF

Advantages:

- Present day mass function = IMF
  few stars lost due to stellar evolution;
  few stars lost due to dynamical evolution.
- Most members are PMS stars and are brighter than any other time in their subsequent evolution.
- Richness: statistically significant sampling of entire range of stellar mass. Membership issues also minimized.

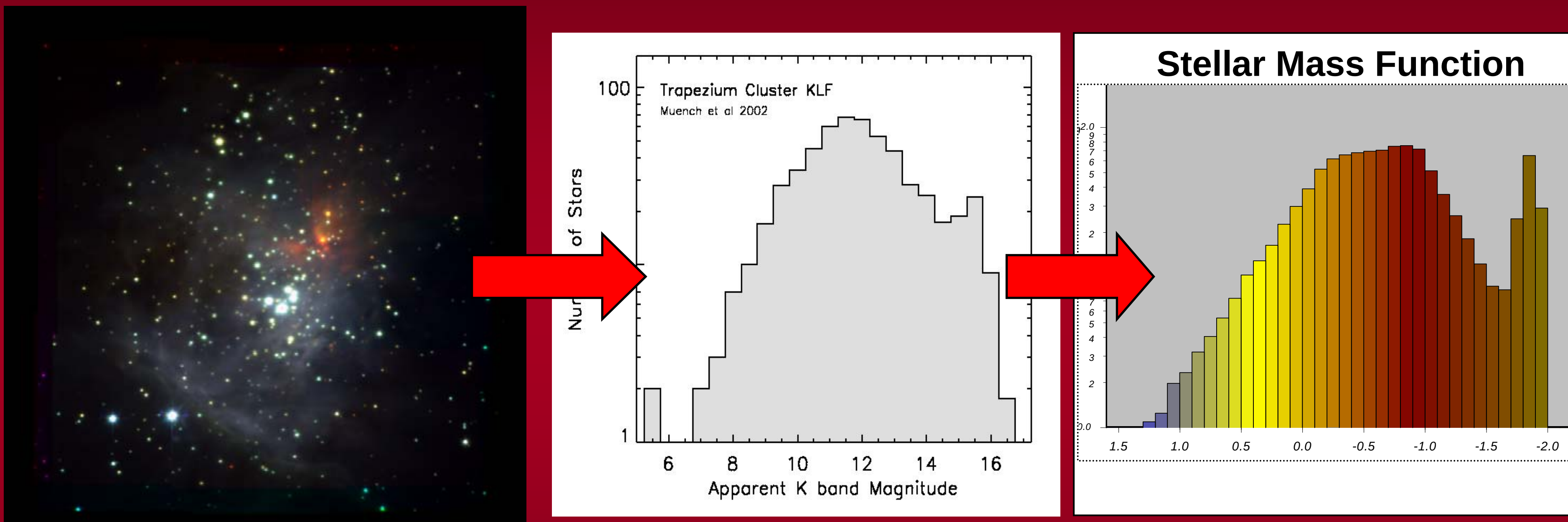
Disadvantages:

- PMS = nonunique mass-luminosity relation.
- Extinction (variable).
- Contamination from circumstellar matter

# *Why Infrared ?*

# *Why Infrared ?*

# Modelling The IMF in Young Embedded Clusters



# *From Luminosities to Masses: Defining the Initial Mass Function*

***A mass-luminosity relation is needed to convert stellar luminosities into masses.***

***For main sequence stars:***

$L_{bol} \sim m_*^p$ ***so:***

$M_{bol} \sim \log(L_{bol}) \sim \log(m_*)$

**Therefore it is appropriate and useful to define an *Initial Mass Function* (IMF) $\xi(\log m_*)$ = # of stars per unit volume per unit *logarithmic* mass**

***The IMF and the ILF are related as:***

$$\Psi\,(M_\lambda)\,dM_\lambda = \xi\,(\log m_*)\,d\log m_*$$

# From Luminosities to Masses:

$$\Psi(M_\lambda) = \xi(\log m)\,\frac{d\log m}{dM_\lambda}$$

ILF

IMF

Mass-to-luminosity relation

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**Notes:**

**A-** ***The IMF is often expressed in the form:***

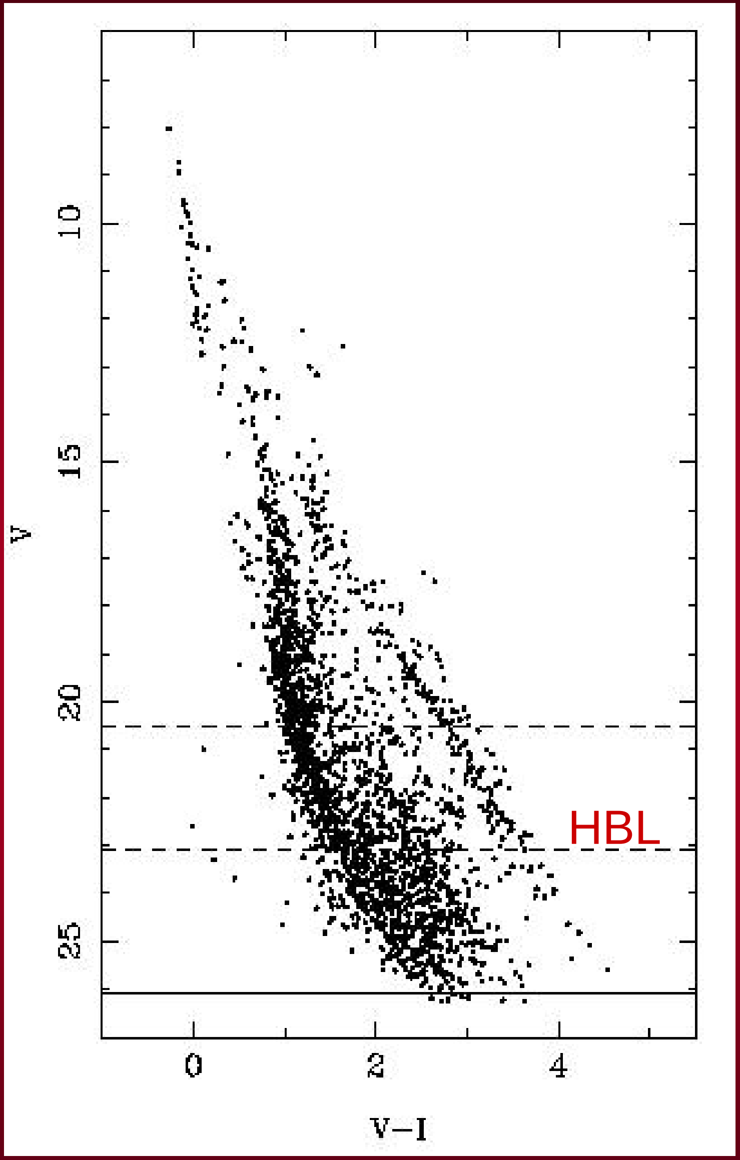
$$dN = \xi(\log m_*)\,d\log m_* = K\, m_*^{-\gamma}\, d\log m_*$$

**B-** ***The IMF and the initial mass spectrum (IMS) are related by:***

$$\xi(\log m_*) = m_*\, f(m_*) / 0.434$$

# NGC 2362

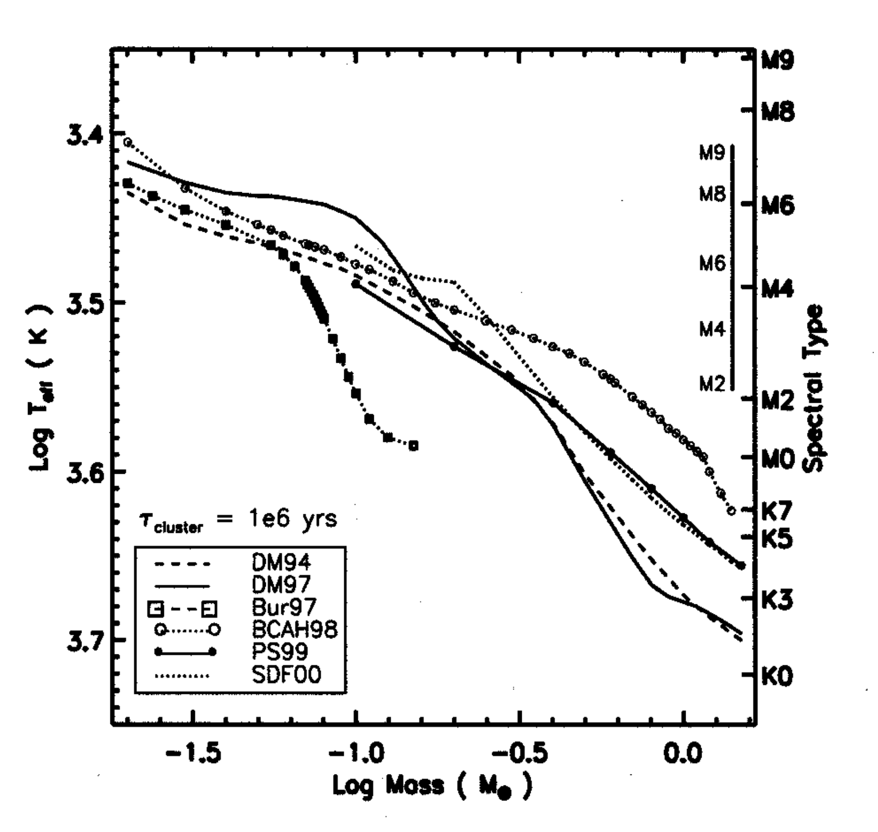
Alves, Moitinho, Lada, Lada, Muench 2004



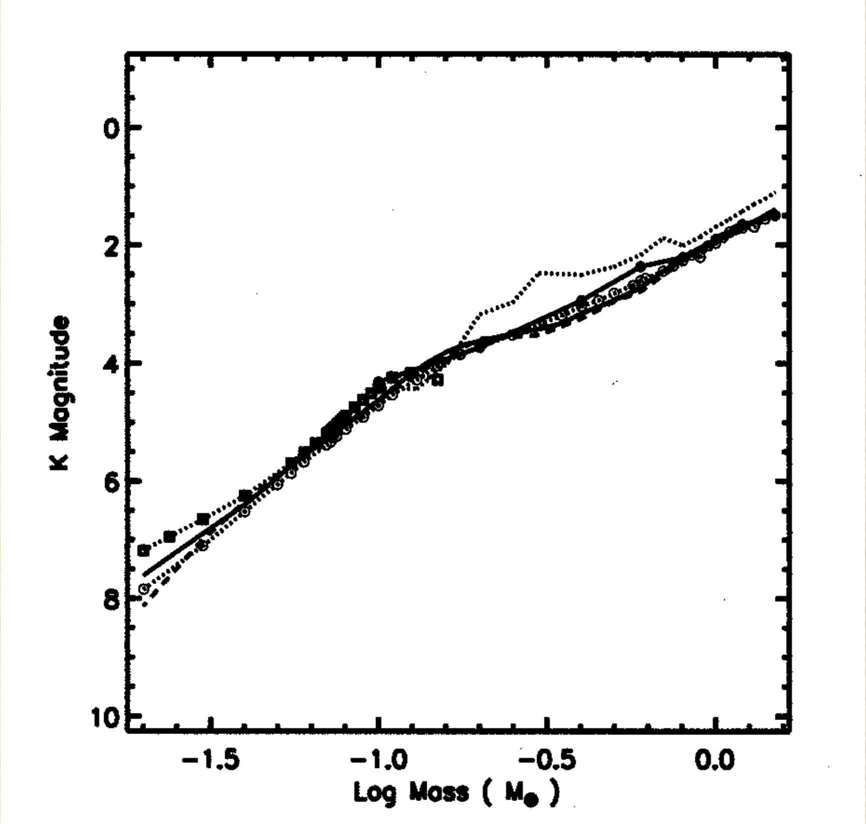

**Stellar and PMS luminosities very sensitive to stellar mass!!**

# PMS Effective Temperatures and Luminosities

**PMS luminosities are very sensitive to stellar masses. Model KLFs are relatively insensitive to input PMS tracks!**



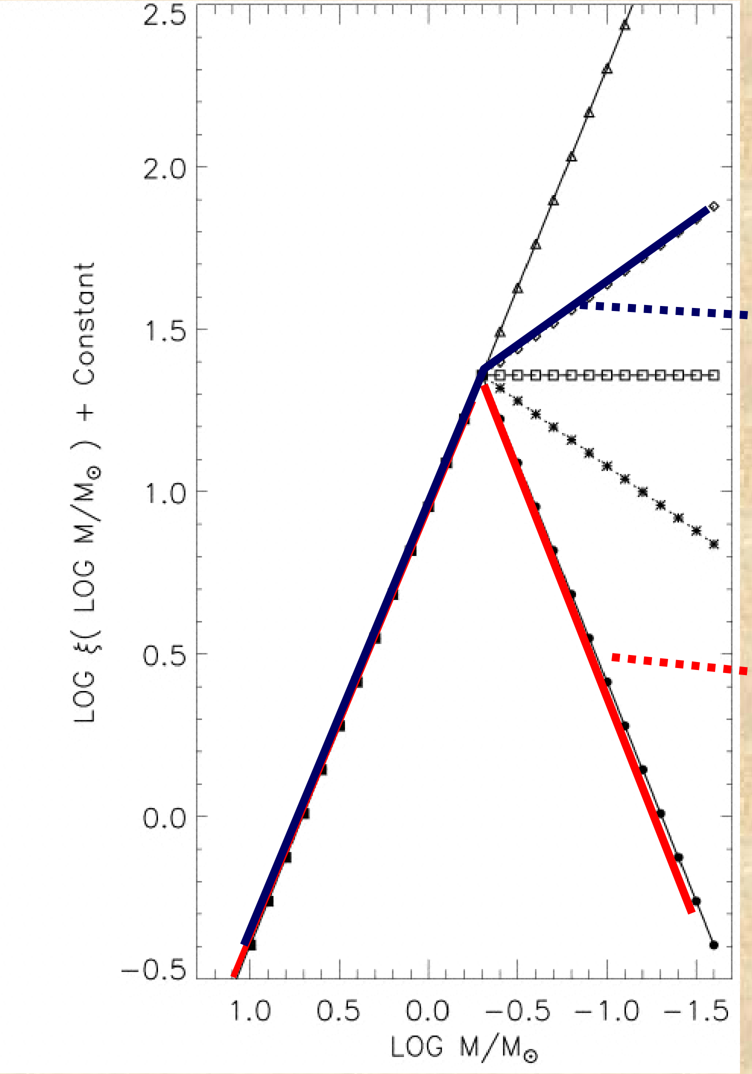

*Predicted Effective Temperatures*



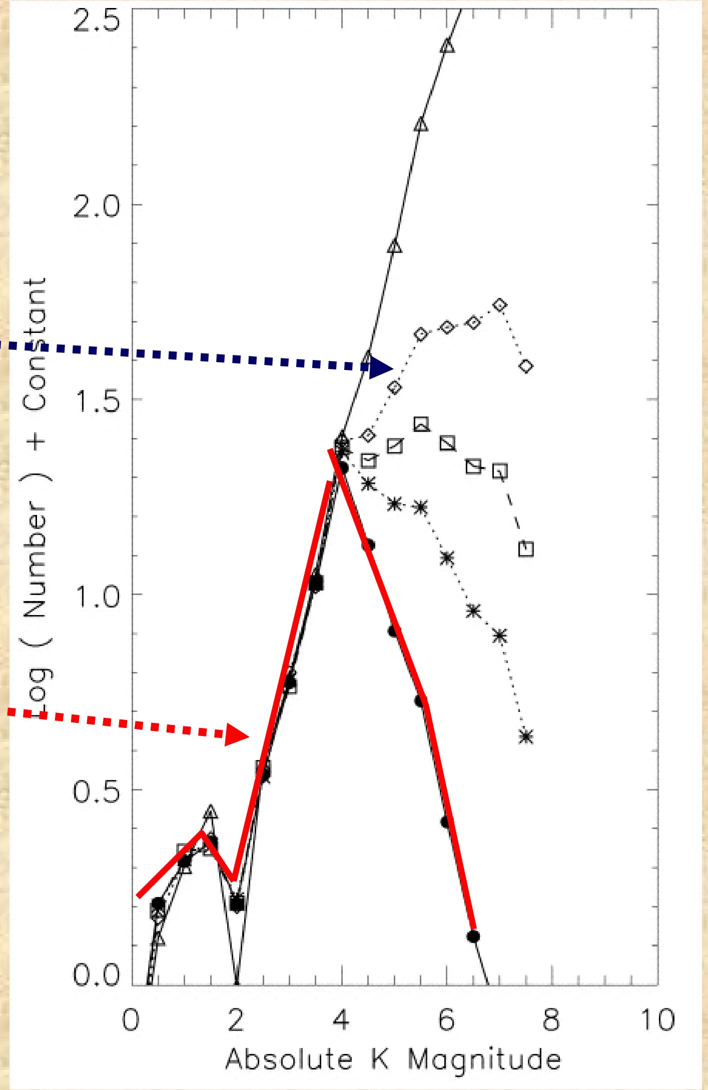

*Predicted Luminosities*

# KLF Sensitivity to Underlying IMF

## Form of KLF very sensitive to form of IMF!



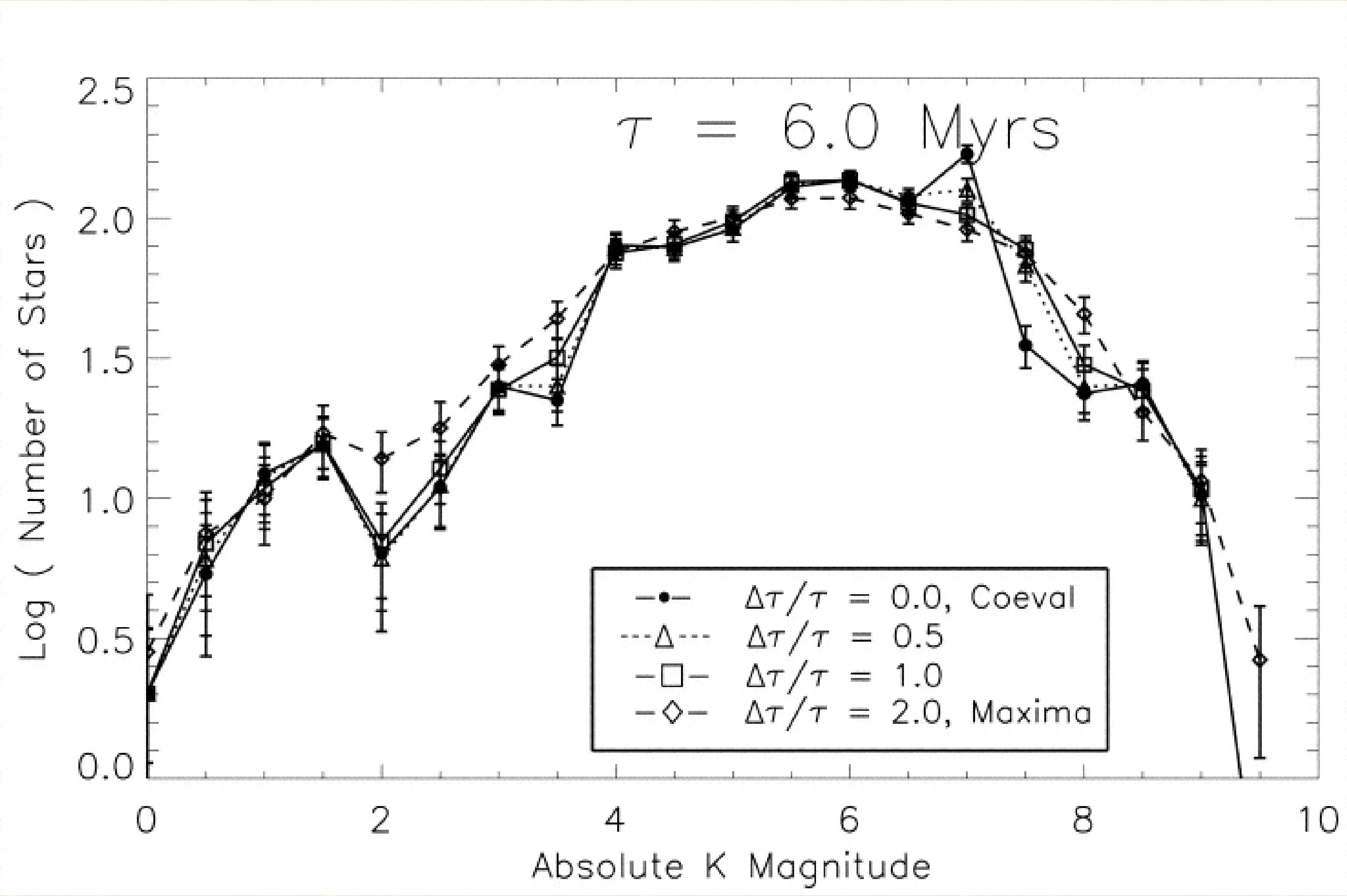

**Input IMFs**




**Predicted Luminosity Functions**

# KLF Sensitivity to Ages

**KLF depends on mean age but not age spread**




**Luminosity Evolution**

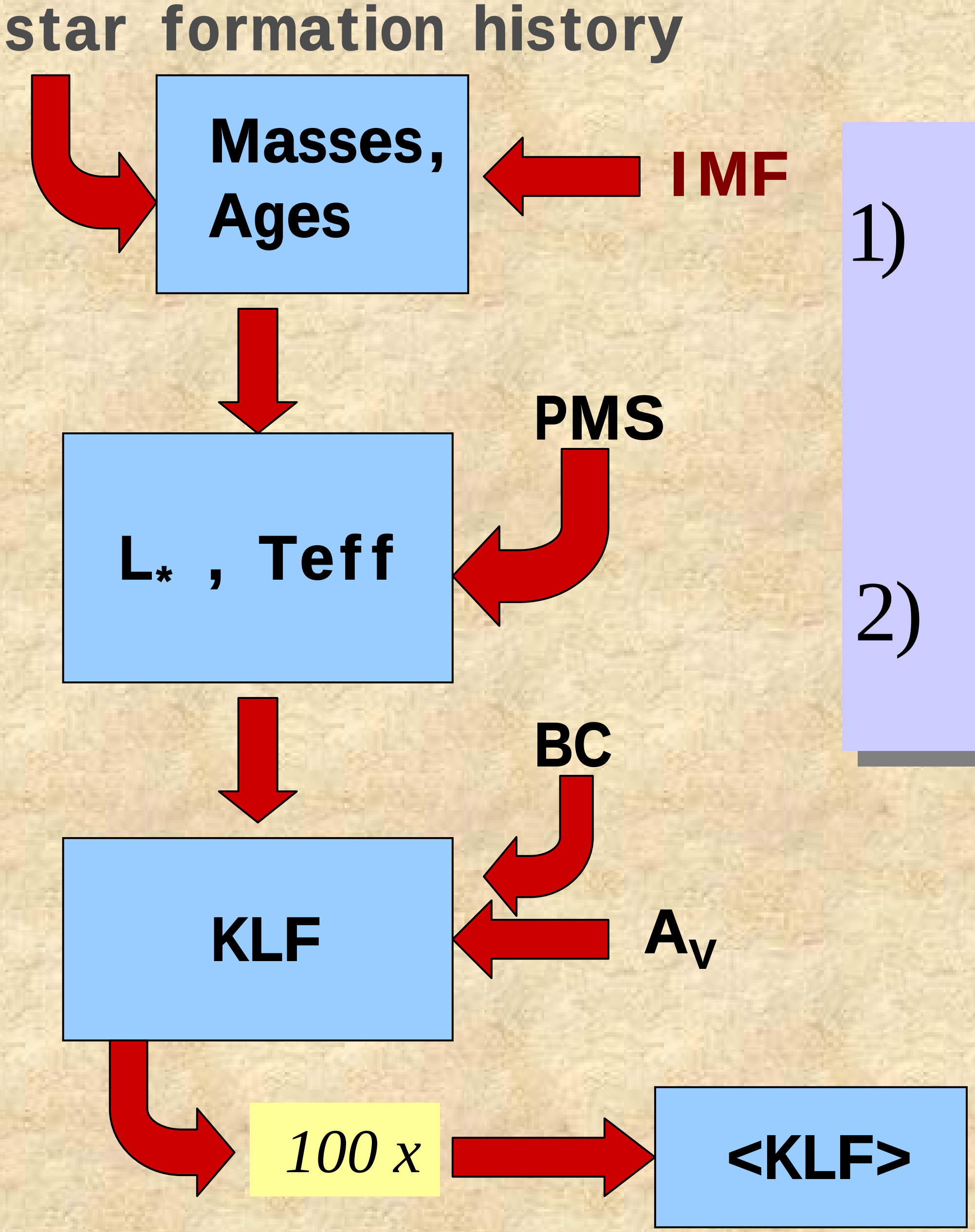
*Muench, Lada & Lada 2000*

# Method: Population Synthesis Models of Pre-Main Sequence Stellar Populations

- Monte Carlo based FORTRAN population synthesis models for pre-main sequence stars;
- Allows rapid changes to the fundamental parameters;
- Allows statistical tests;
- Allows for the inclusion of many physical inputs such as extinction, excess ir emission, and binarity;
- Produces model luminosity functions, color-color and color-mangitude diagrams as well as samples of any of the synthetic star's parameters.

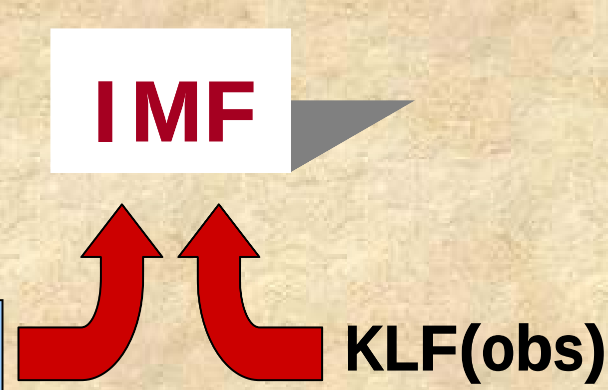
*Gus Meunch: 2002 PhD Thesis UF*

# Monte Carlo Modeling of the KLF

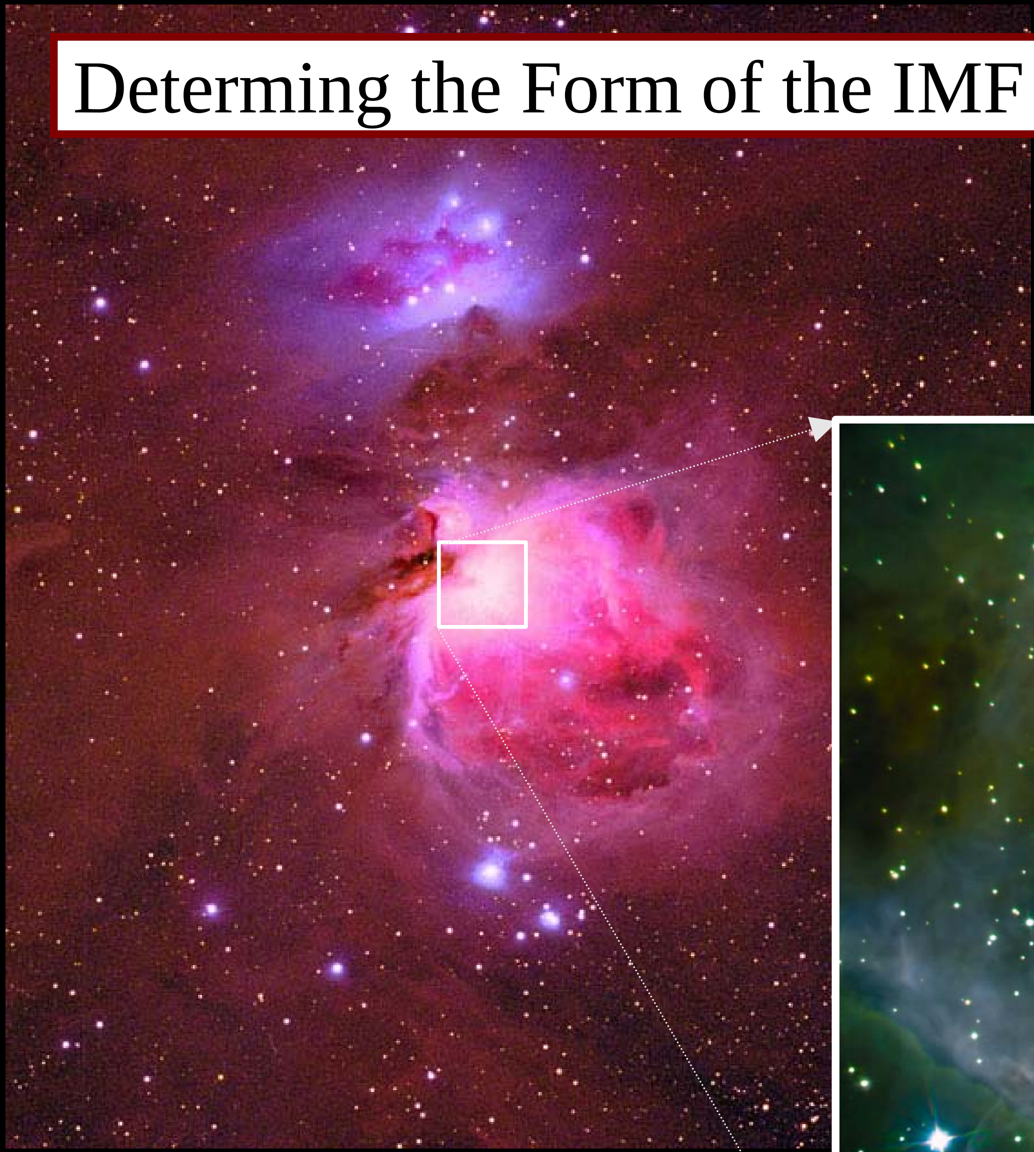



1) $$\frac{dN}{dM_K} = \frac{dN}{d\log m} \times \frac{d\log m}{dM_K}$$

2) $$\frac{d\log m}{dM_k} = f(t)$$



# Determing the Form of the IMF in the Trapezium Cluster

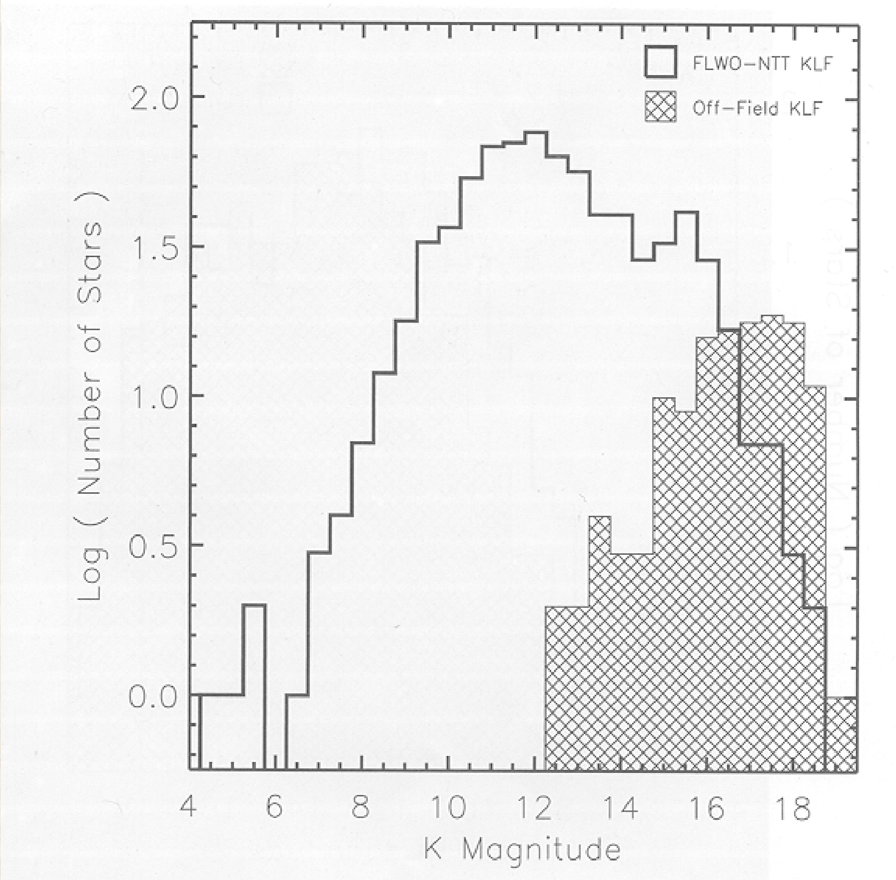


*Photograph of Orion Cluster courtesy George Greaney*

*ESO NTT JHKs Image of the Trapezium Cluster*
*Muench et al 2002*

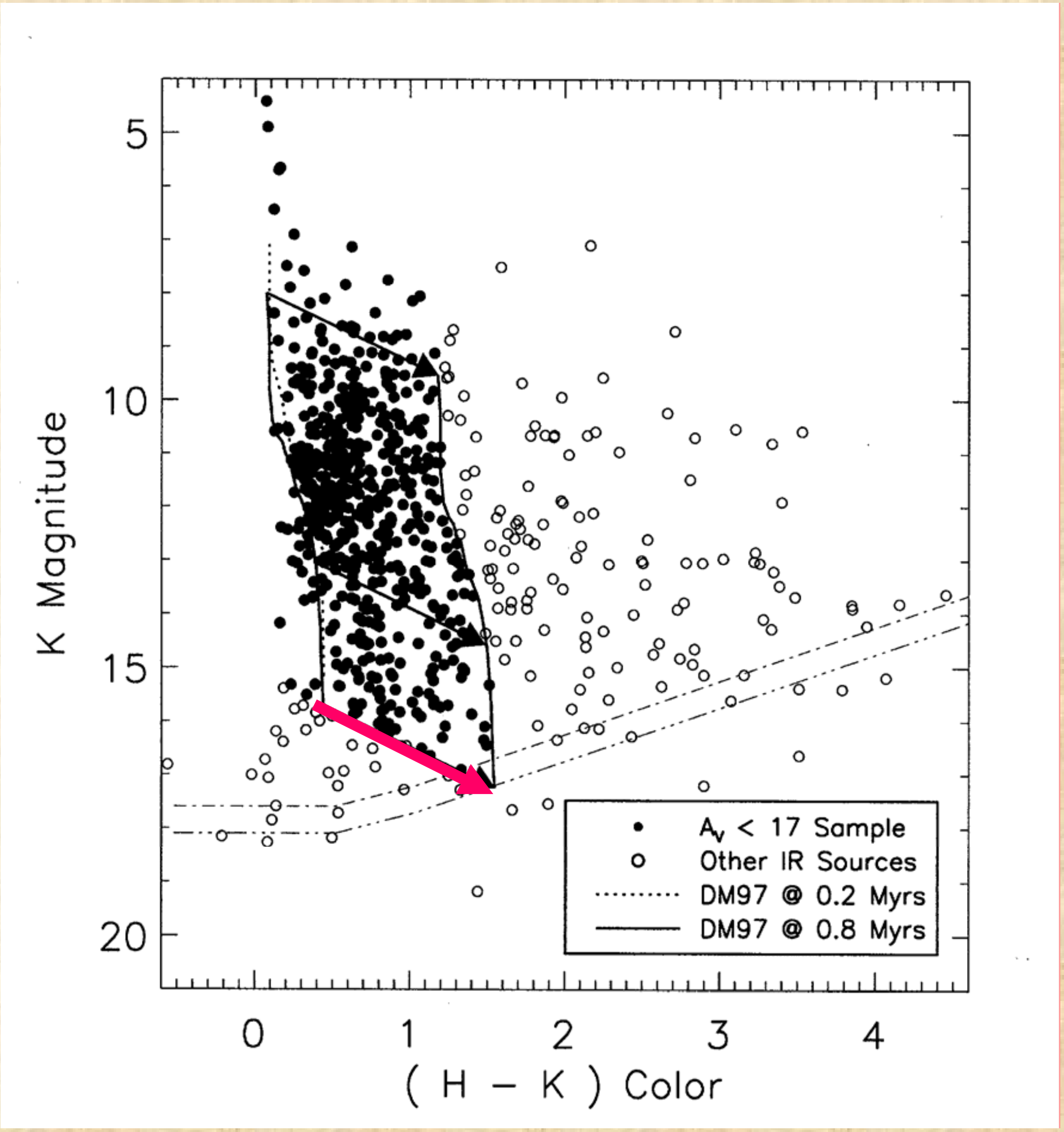
# *Stellar Luminosity Functions*

- **Stellar Mass is not an observable quantity**
- **Stellar radiant flux or luminosity is the observable quantity**
- **Constructing the appropriate luminosity function is the starting point for determining the IMF**



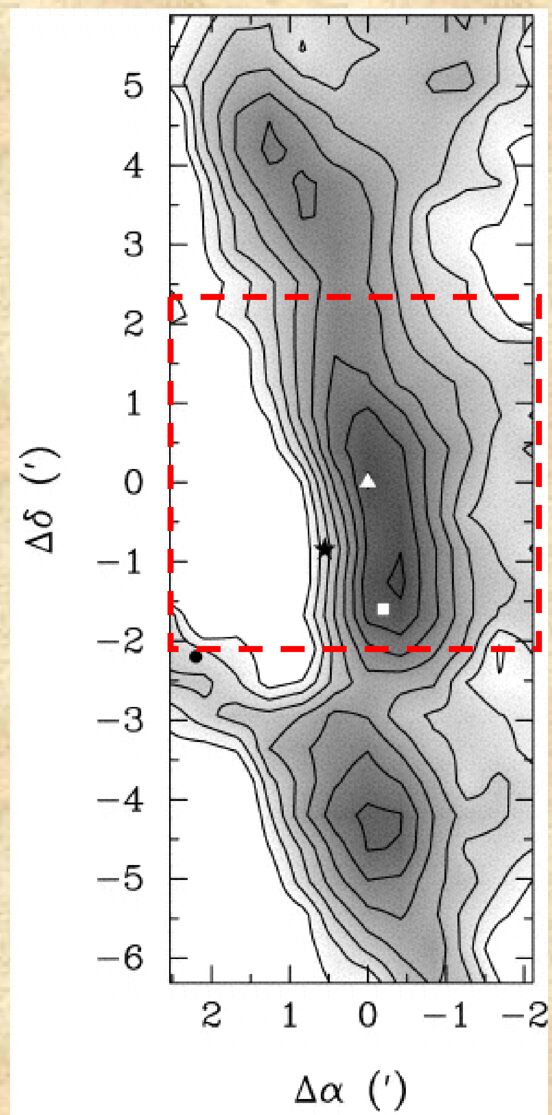

Infrared K-band luminosity function of the Trapezium cluster (Muench et al 2002).

# Complete Magnitude-Limited KLF

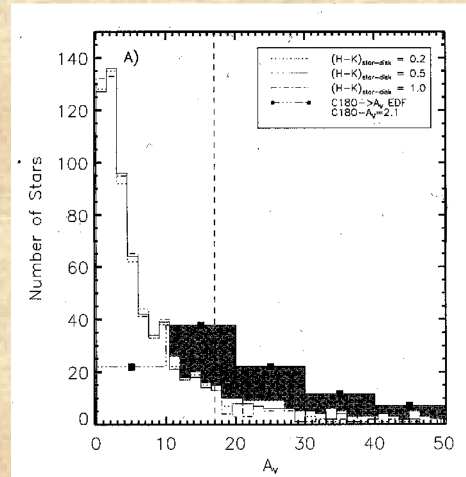


# Field Star Correction

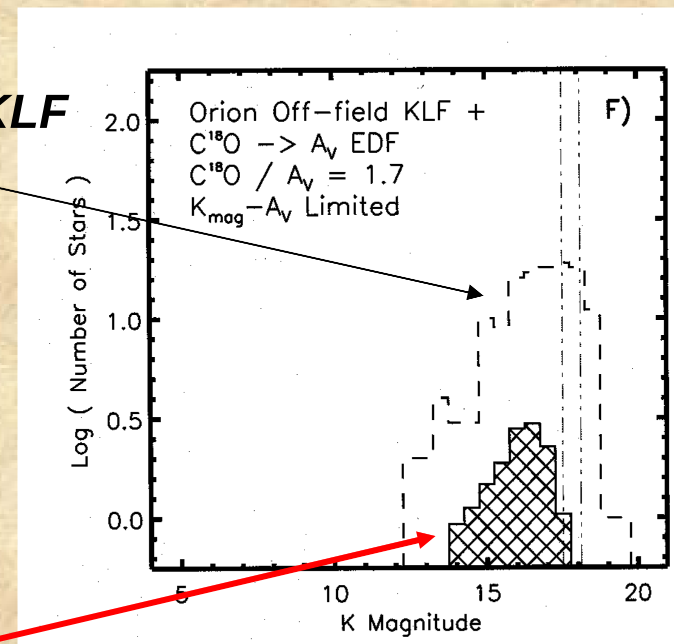
*N(C$^{18}$O )*




***A$_V$***




***Unextincted control field KLF***

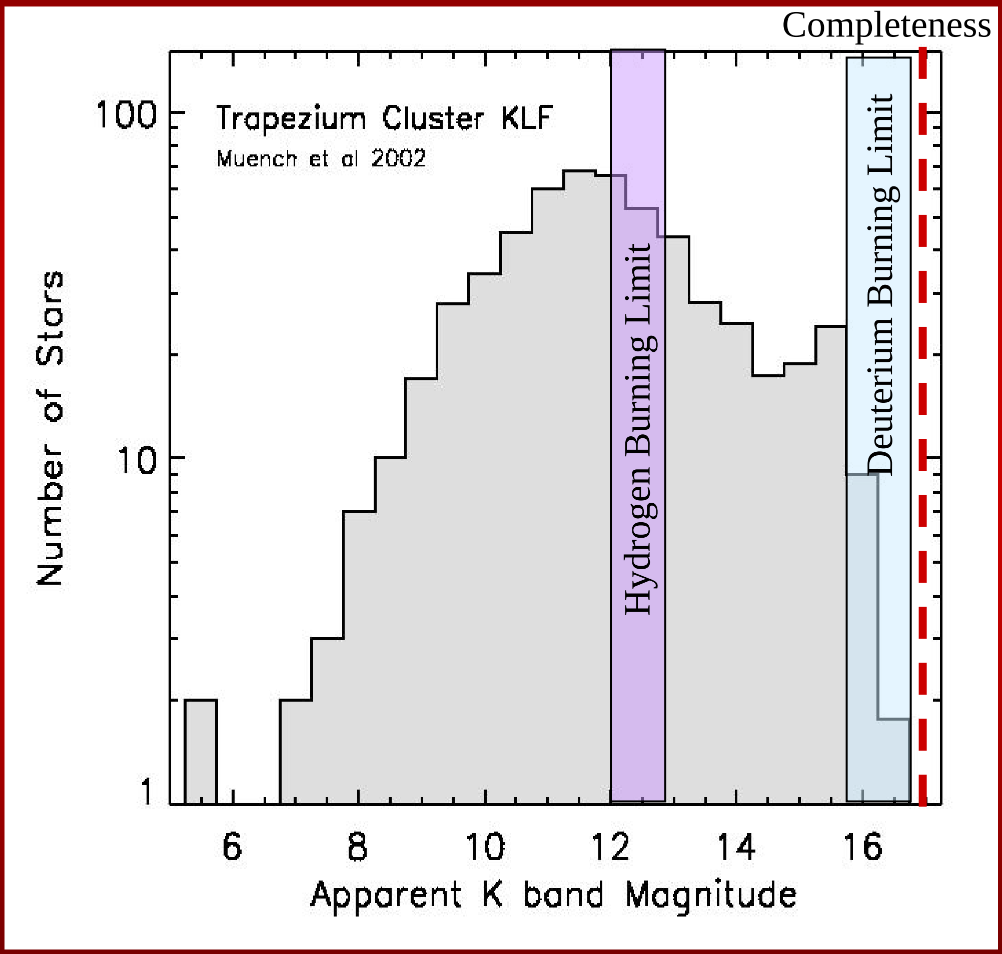



***Extincted control field KLF***

***Goldsmith, Bergin & Lis 2000***

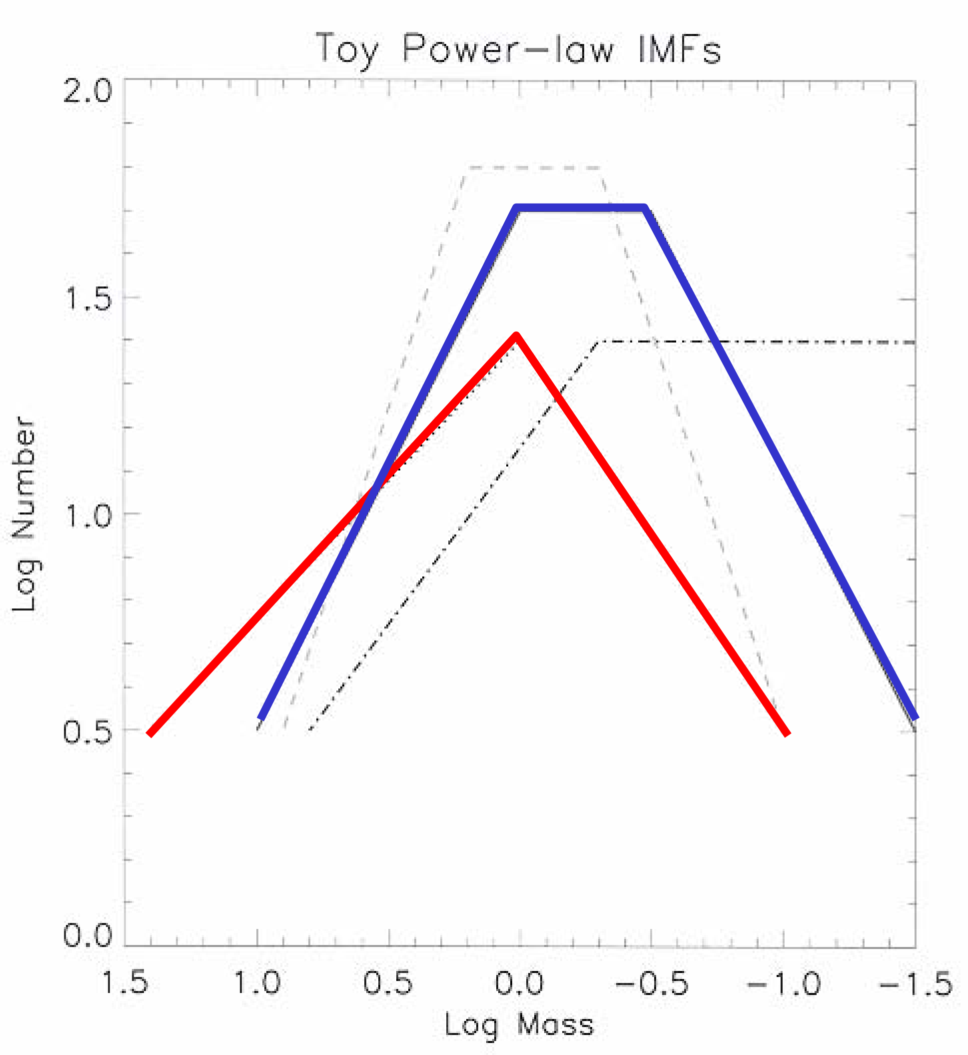
# *Embedded Clusters: Astrophysical Laboratories*

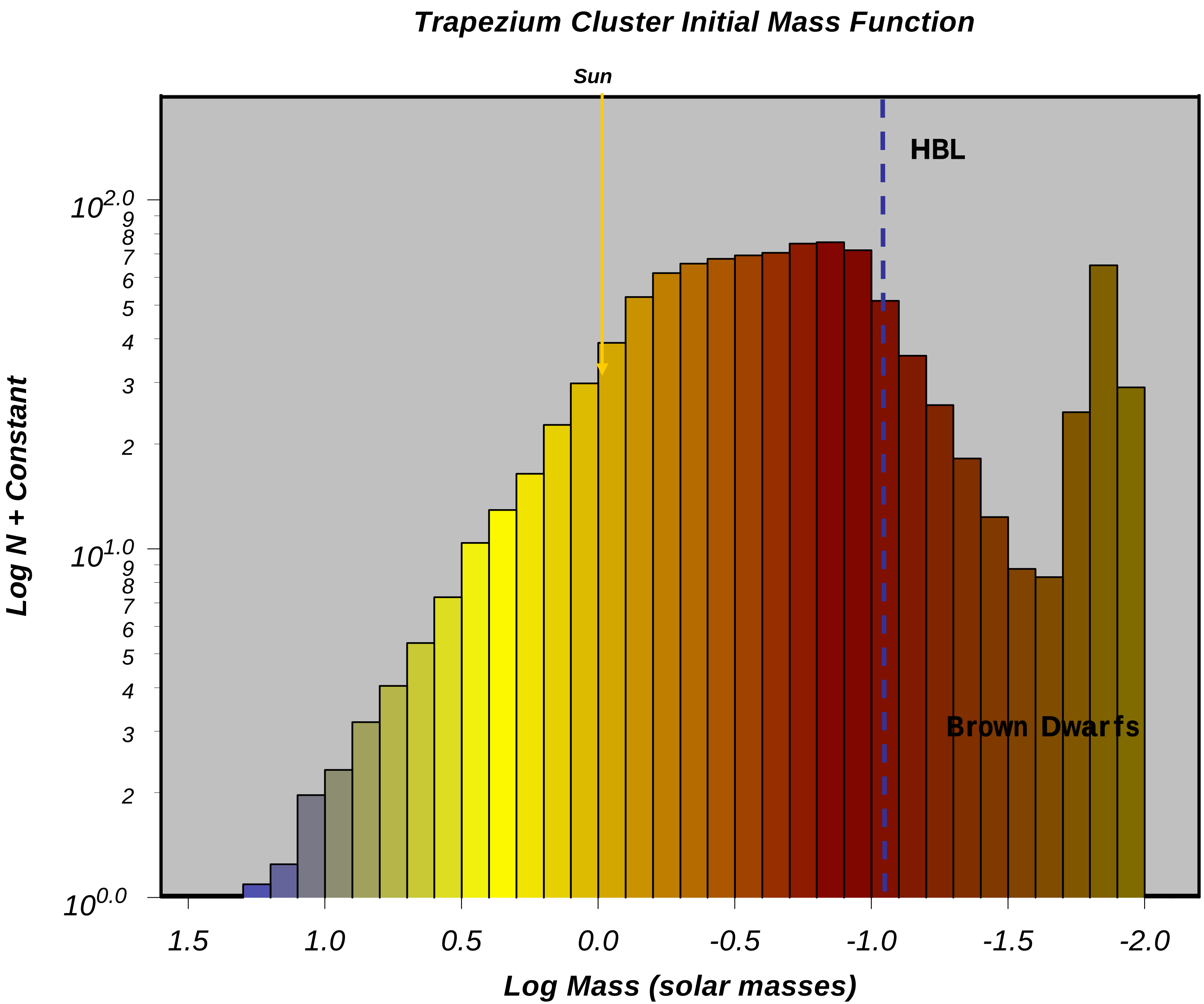
## The Initial Mass Function



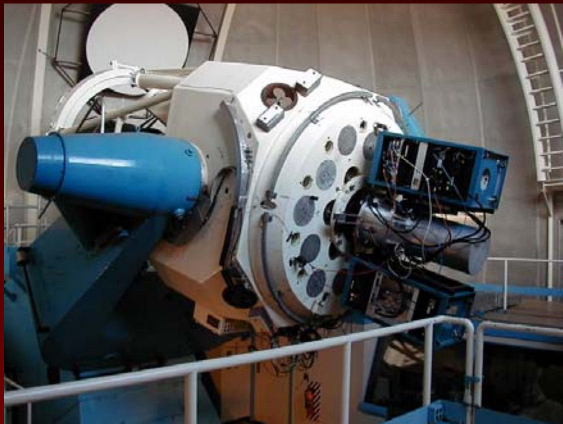

Muench, Lada, Lada & Alves (2000)

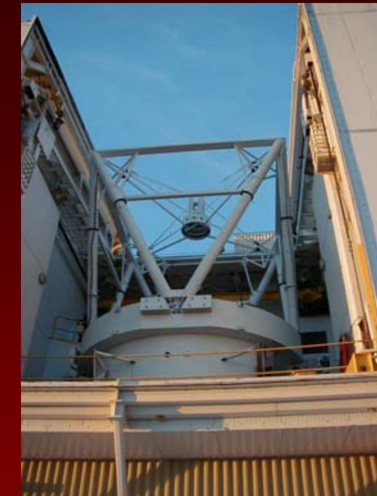
# *Synthetic IMFs*



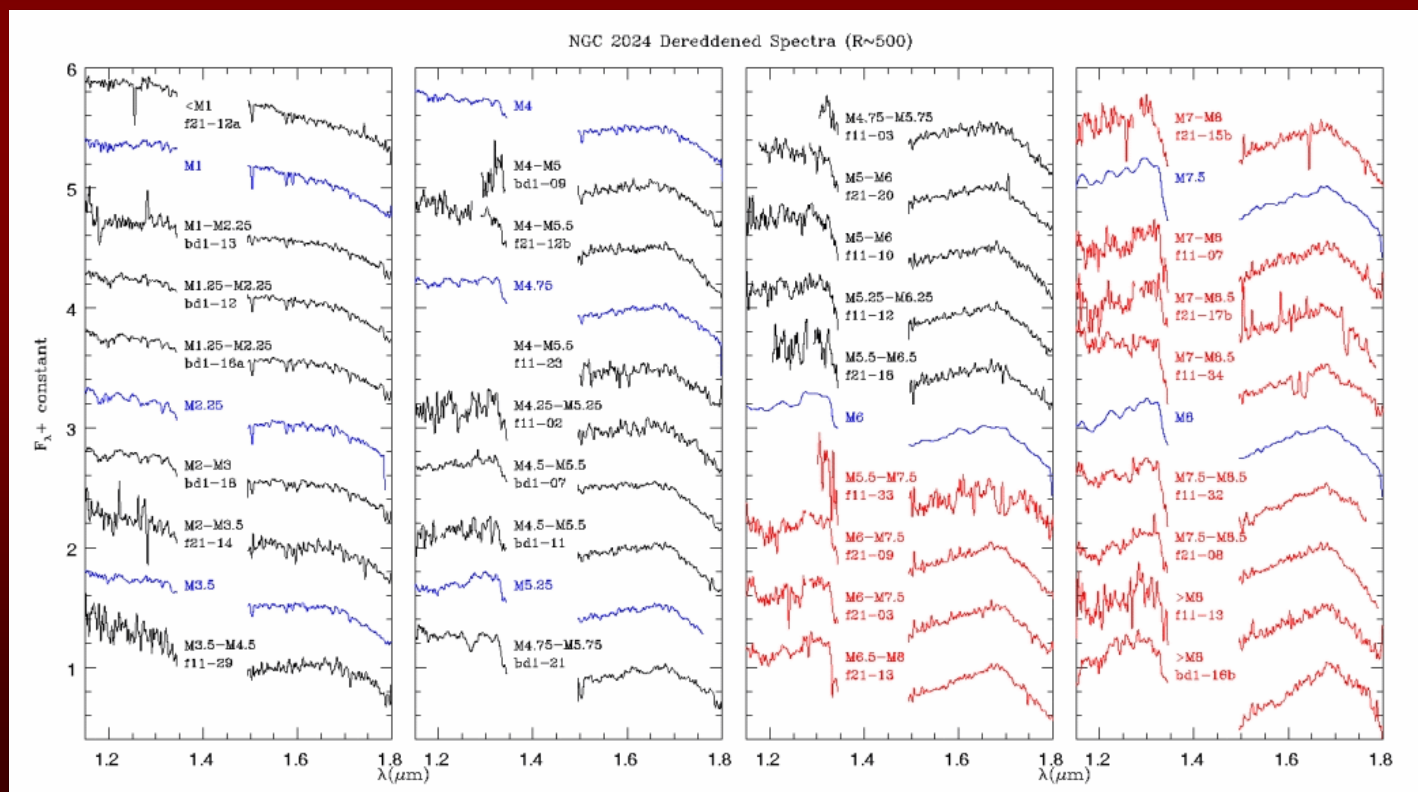


Trapezium Cluster Initial Mass Function
Sun
HBL
Brown Dwarfs
Log N + Constant
Log Mass (solar masses)
$10^{2.0}$
$10^{1.0}$
$10^{0.0}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0

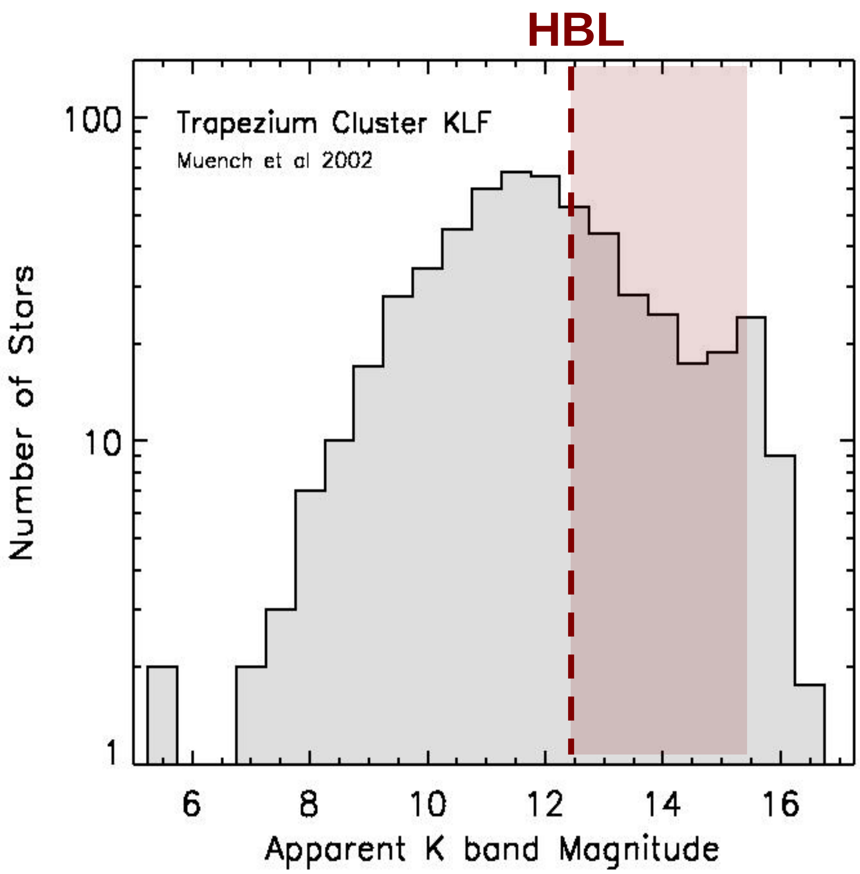


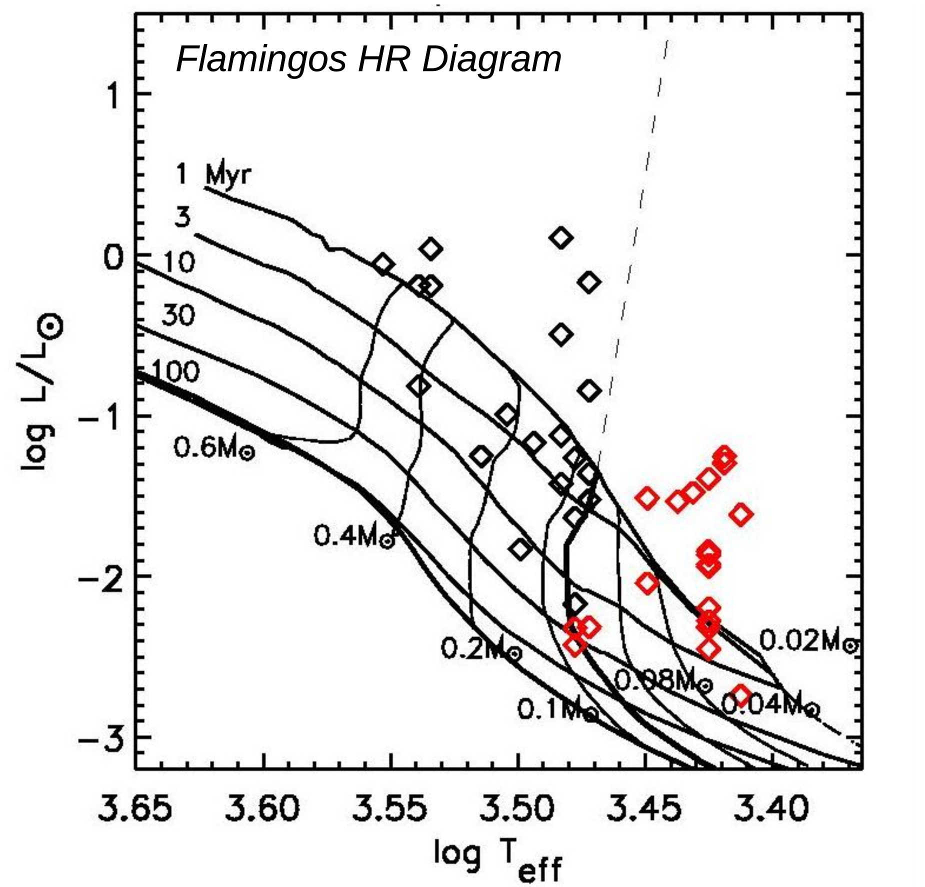


# *FLAMINGOS: Florida's Infrared Multi-Object and Imaging spectrometer*



# *Brown Dwarfs in the Trapezium:*
## *Flamingos Spectroscopic Survey*

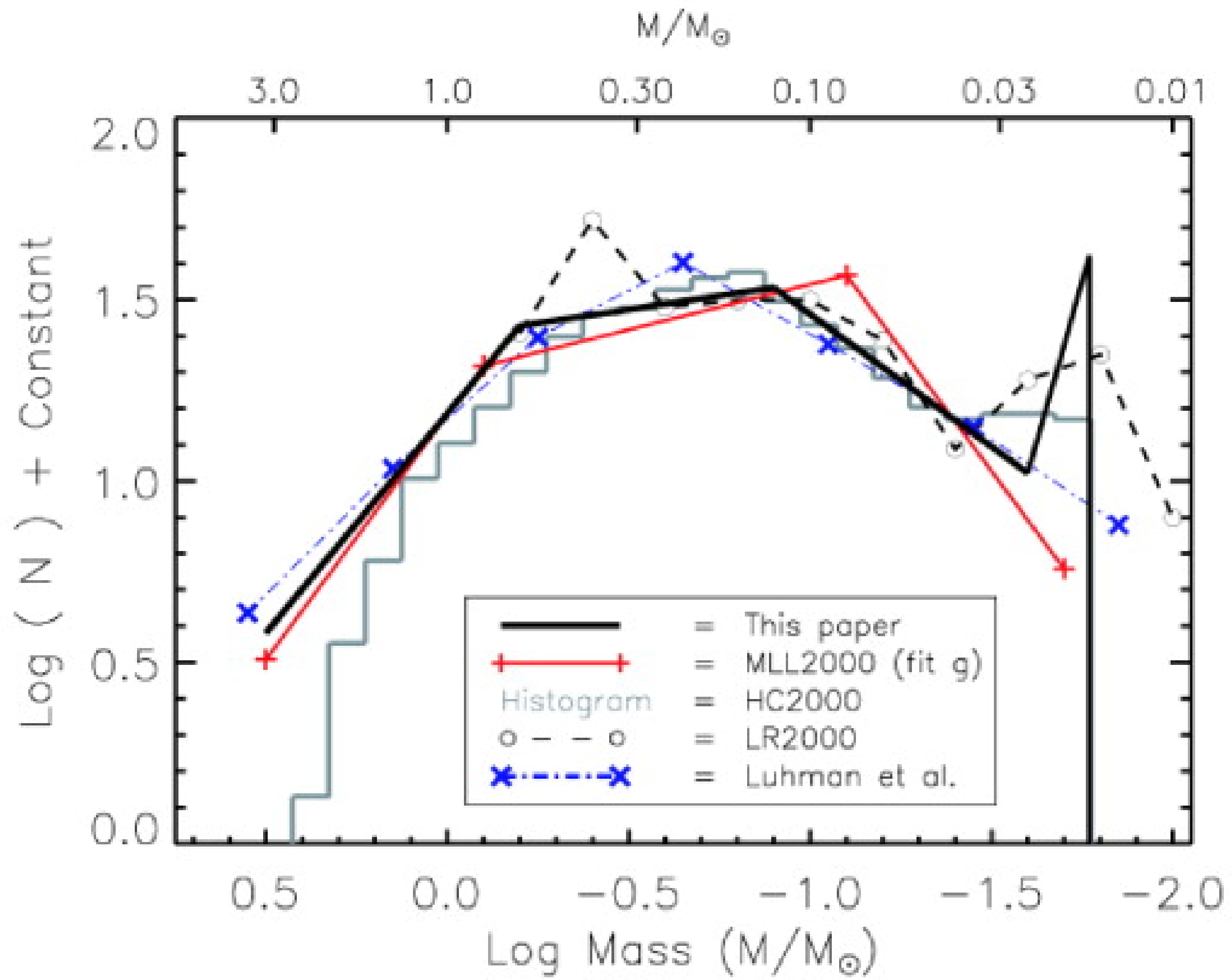



Steinhauer et al. 2004

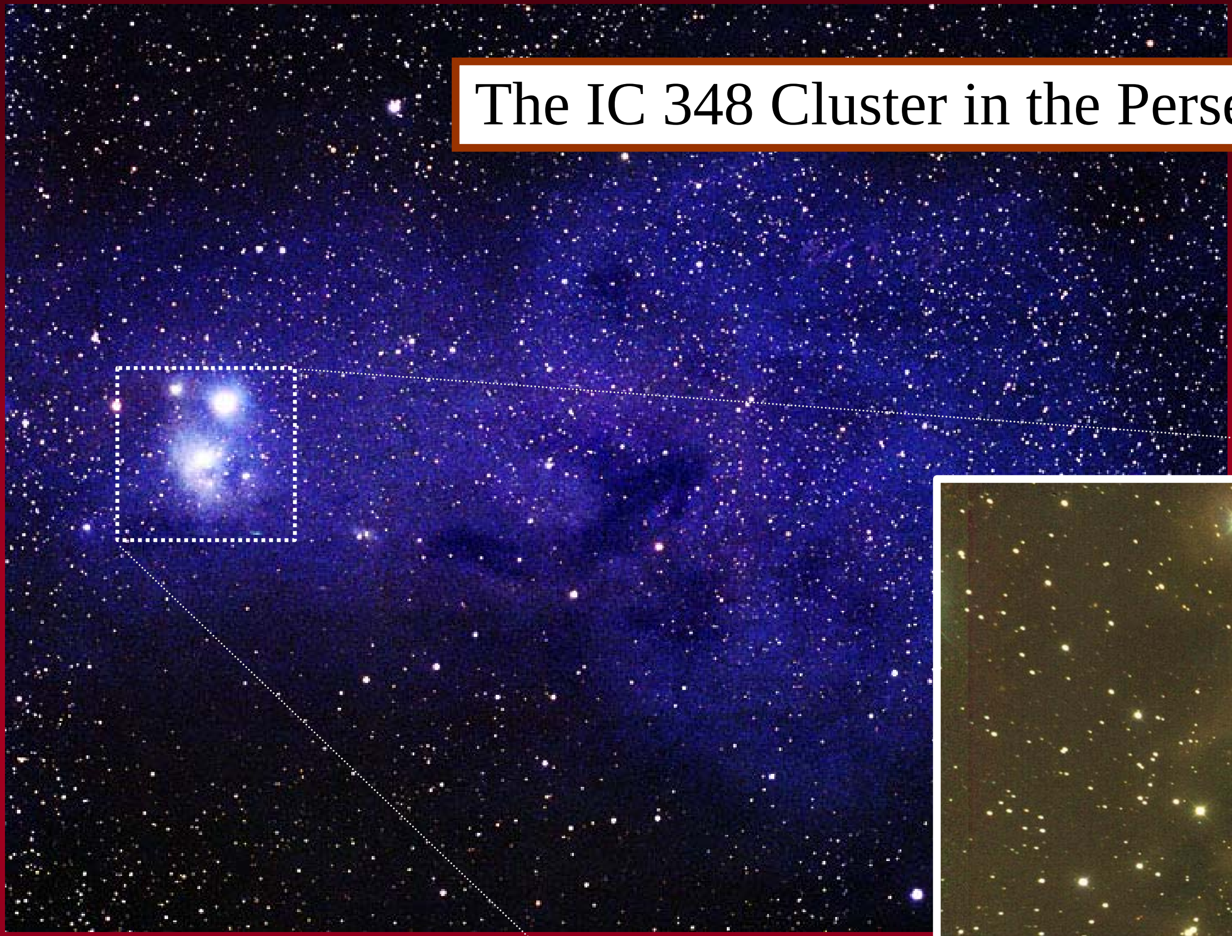
**18/30 (60%) sources with K > 13 are substellar (BDs)!**

# Comparison of Derived IMFs for the Trapezium Cluster



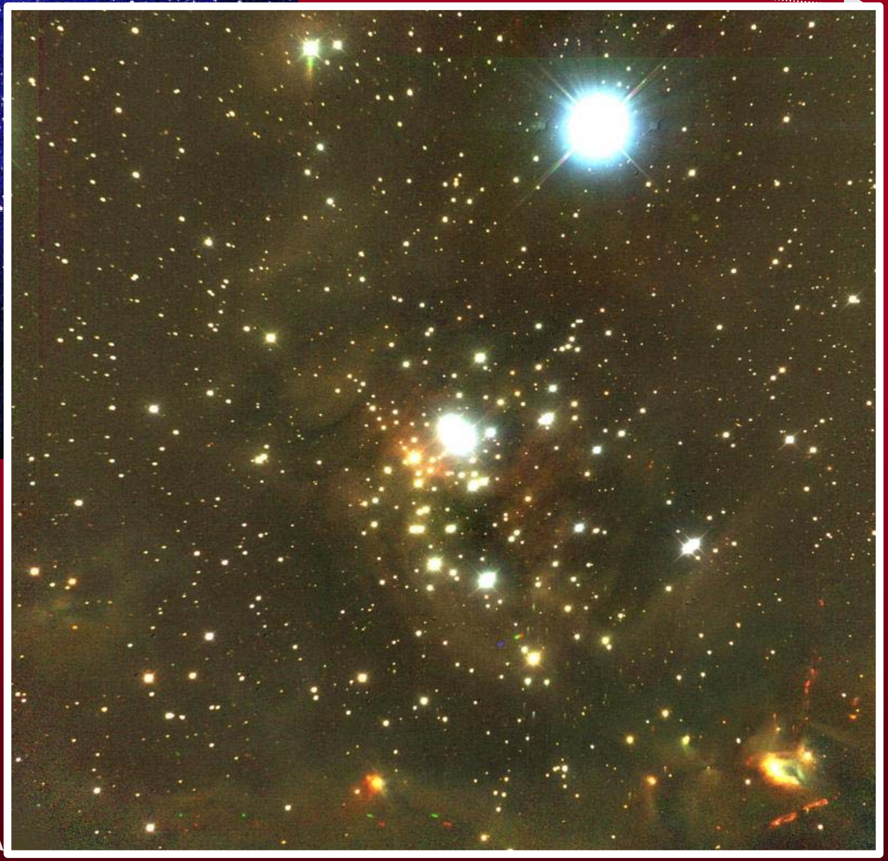
# *On The Universality of the IMF*

# The IC 348 Cluster in the Perseus Molecular Cloud



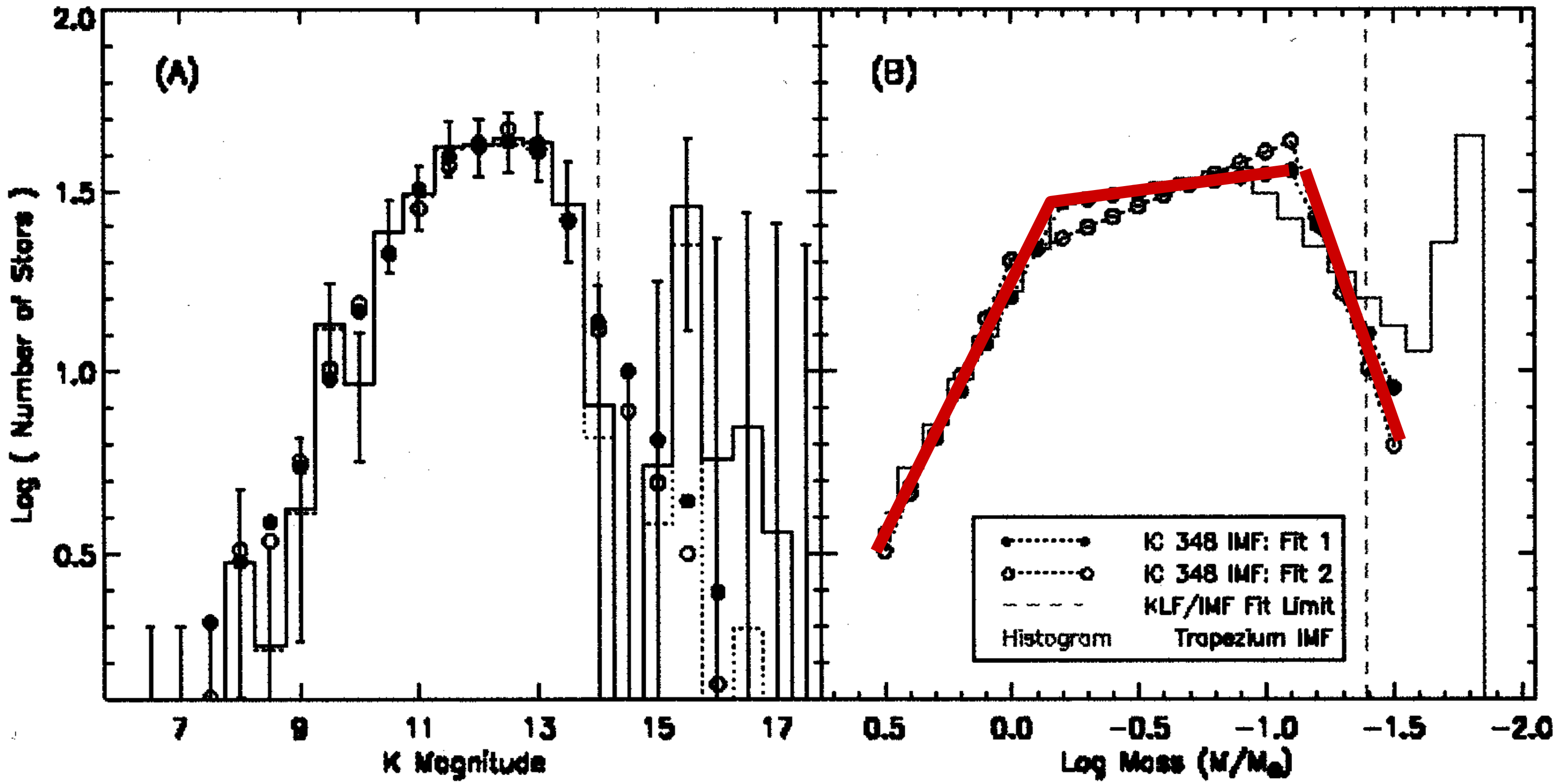
*Photograph of Perseus courtesy George Greaney*

***FLAMINGOS JHKs Image of IC 348***
***Muench et al 2003***



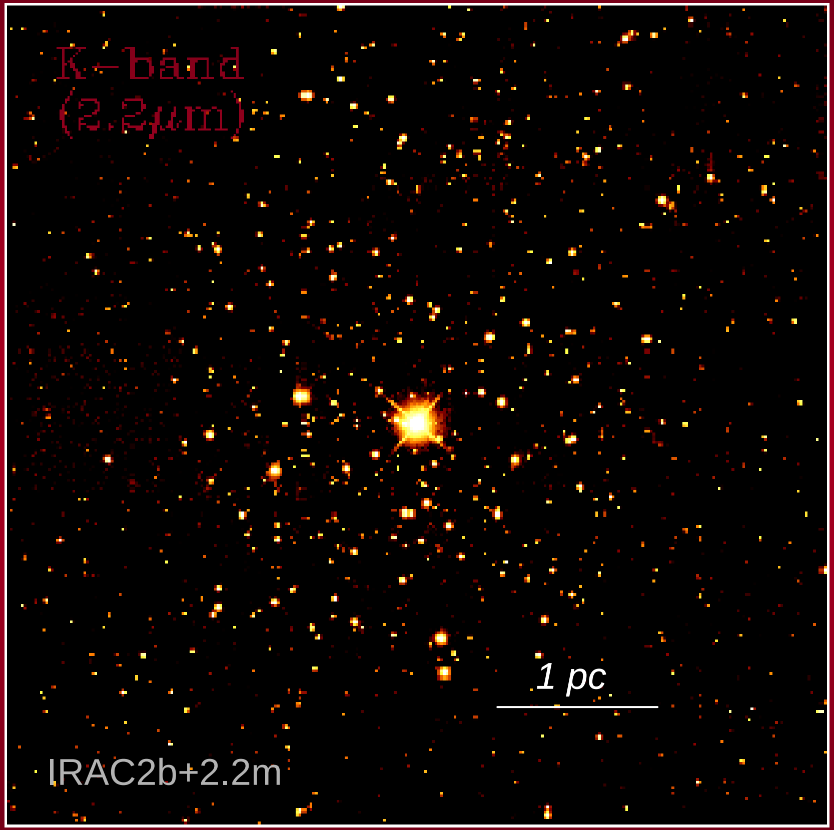
# IMFs: IC 348 vs the Trapezium

***Luminosity Function*** ***Mass Function***

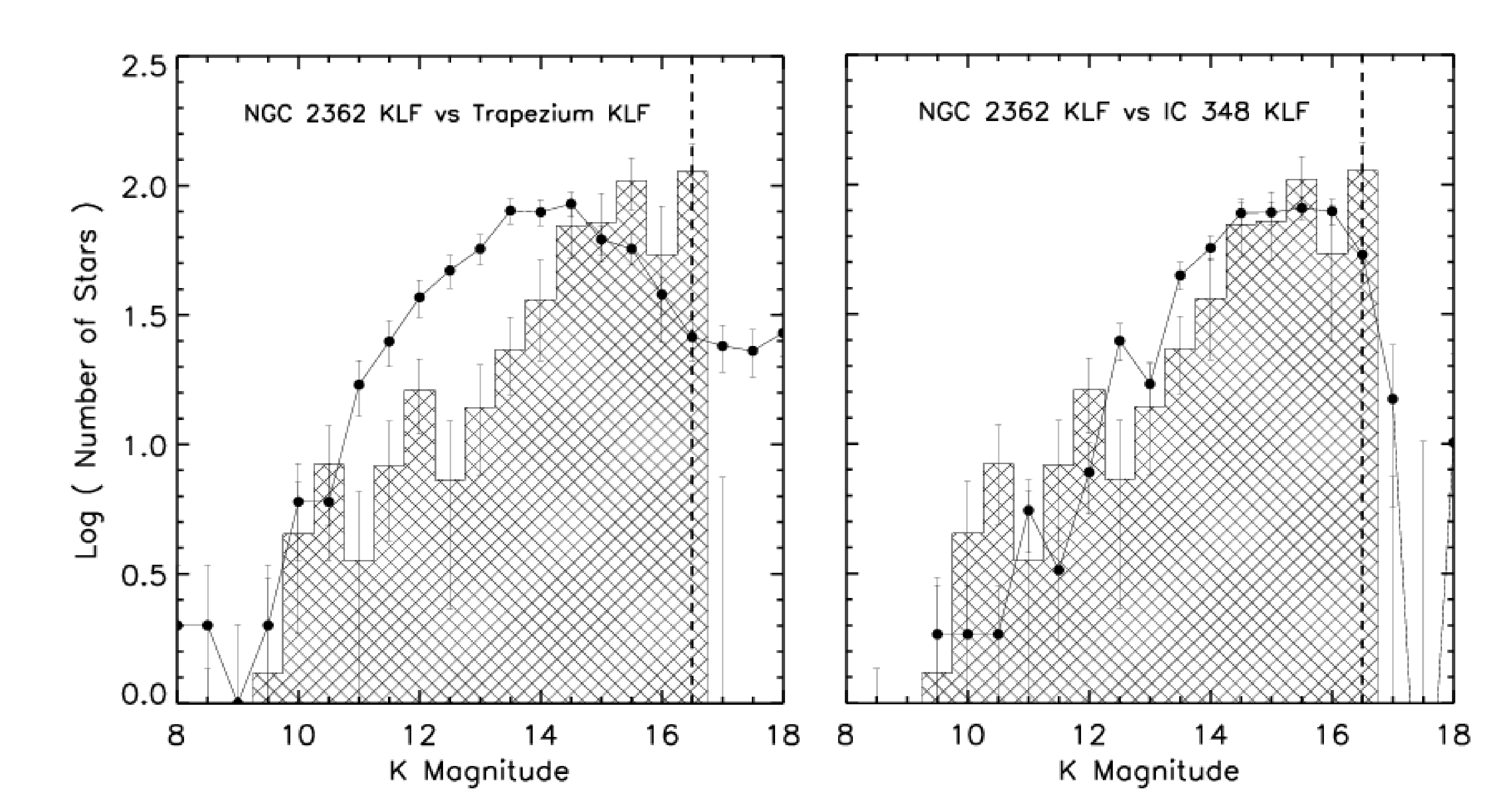



***Muench et al. 2003***

# NGC 2362



# NGC 2362

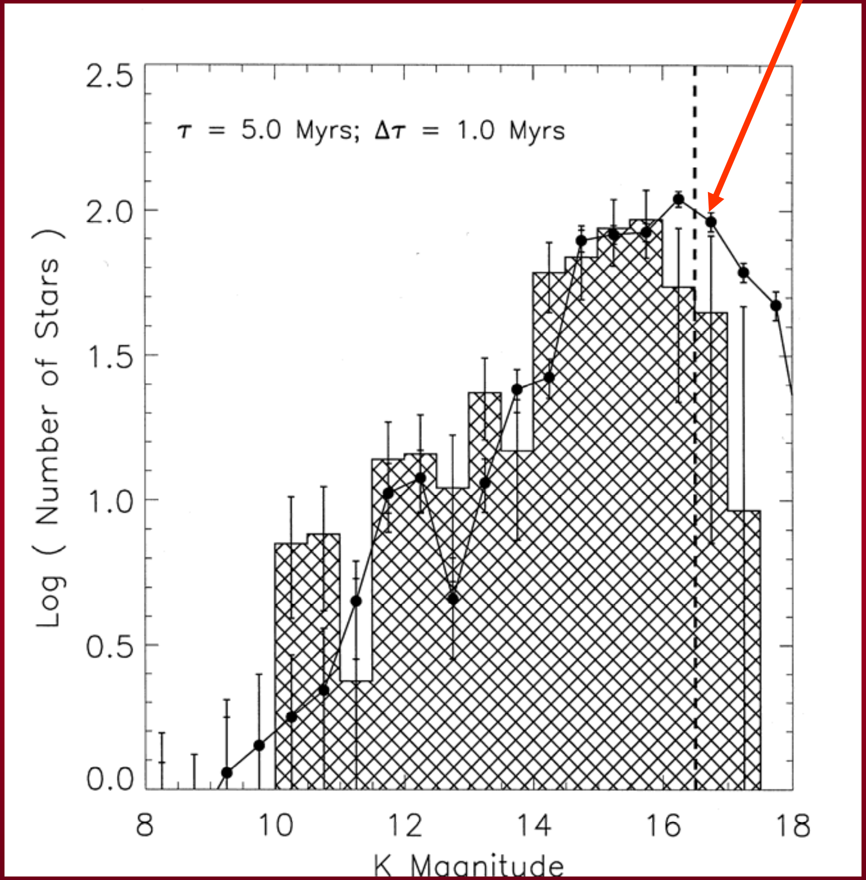


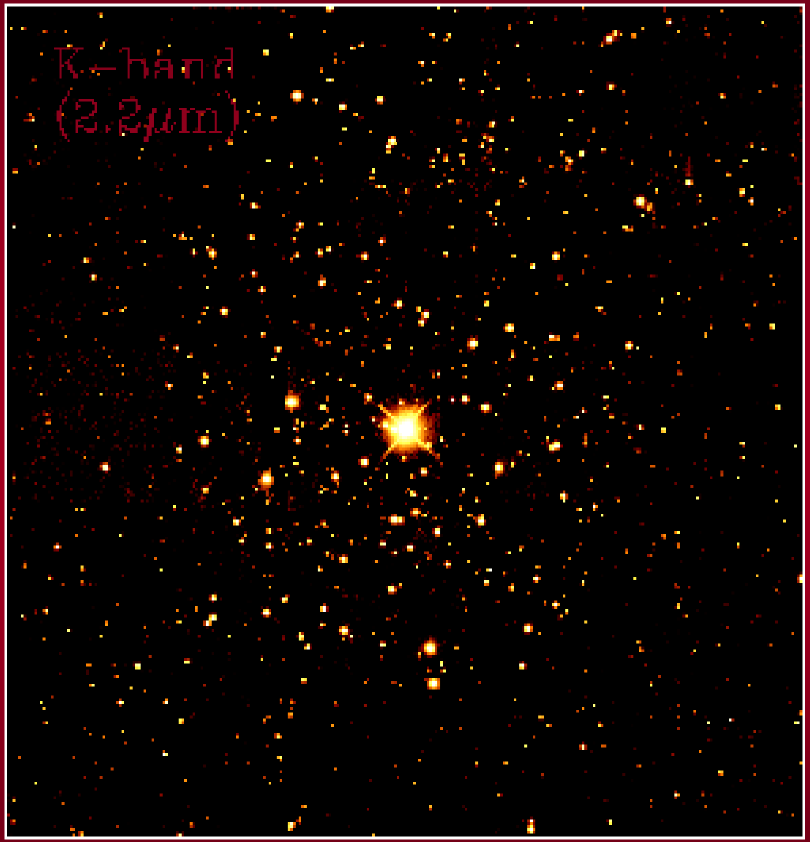

- Comparison of NGC 2362, Trapezium and IC 348 KLFs.
- Clear evolution of the cluster KLFs to fainter magnitude with age.

# NGC 2362

***Universal IMF?***

***Trapezium IMF***

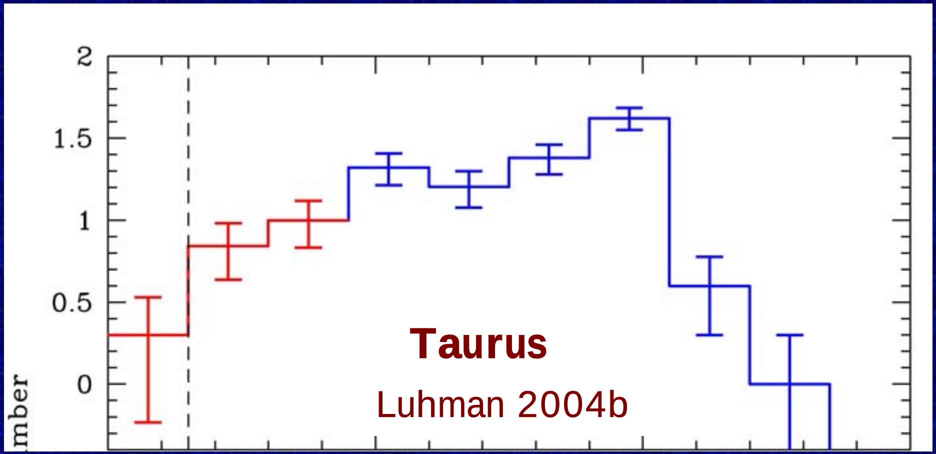



Alves, Muench, Lada & Lada 2000

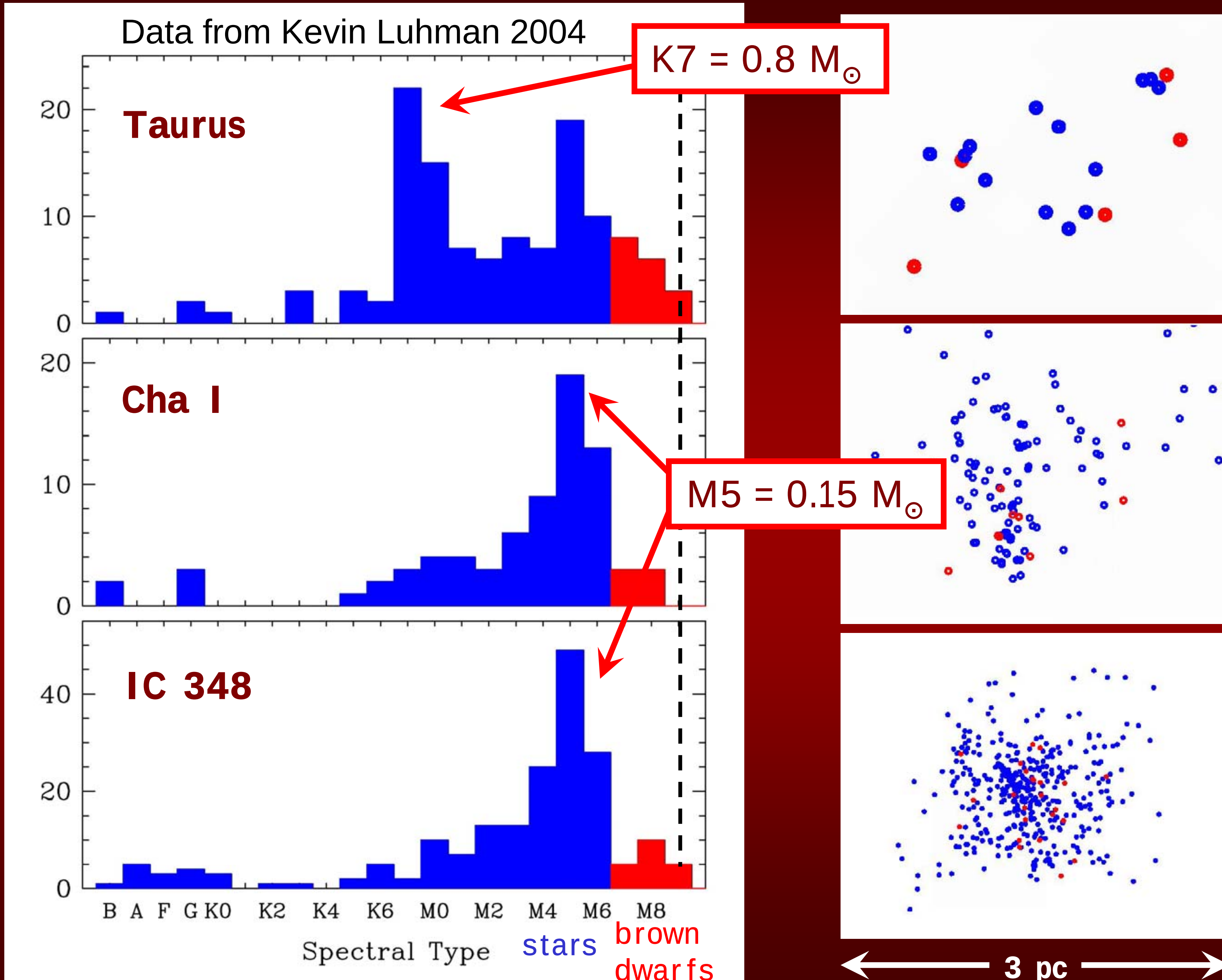
Luhman 2000
Briceno et. al. 2002
Luhman et al. 2003

Comeron et al. 1999
Luhman 2004a




Herbig 1998
Luhman 1999, Luhman et al. 1998, 2003
Lada & Lada 1996, Muench et al. 2003

Hillenbrand 1997, Hillenbrand & Carpenter 2000
Slesnick, Hillenbrand, & Carpenter 2004
Luhman et al. 2000


Data from Kevin Luhman 2004
K7 = 0.8 M⊙
Taurus
Cha I
IC 348
M5 = 0.15 M⊙
20
10
0
20
10
0
40
20
0
B A F G K0 K2 K4 K6 M0 M2 M4 M6 M8
Spectral Type
stars
brown dwarfs
3 pc

# *Comparison with The Field Star IMF*

# *The Field Star Initial Luminosity Function*

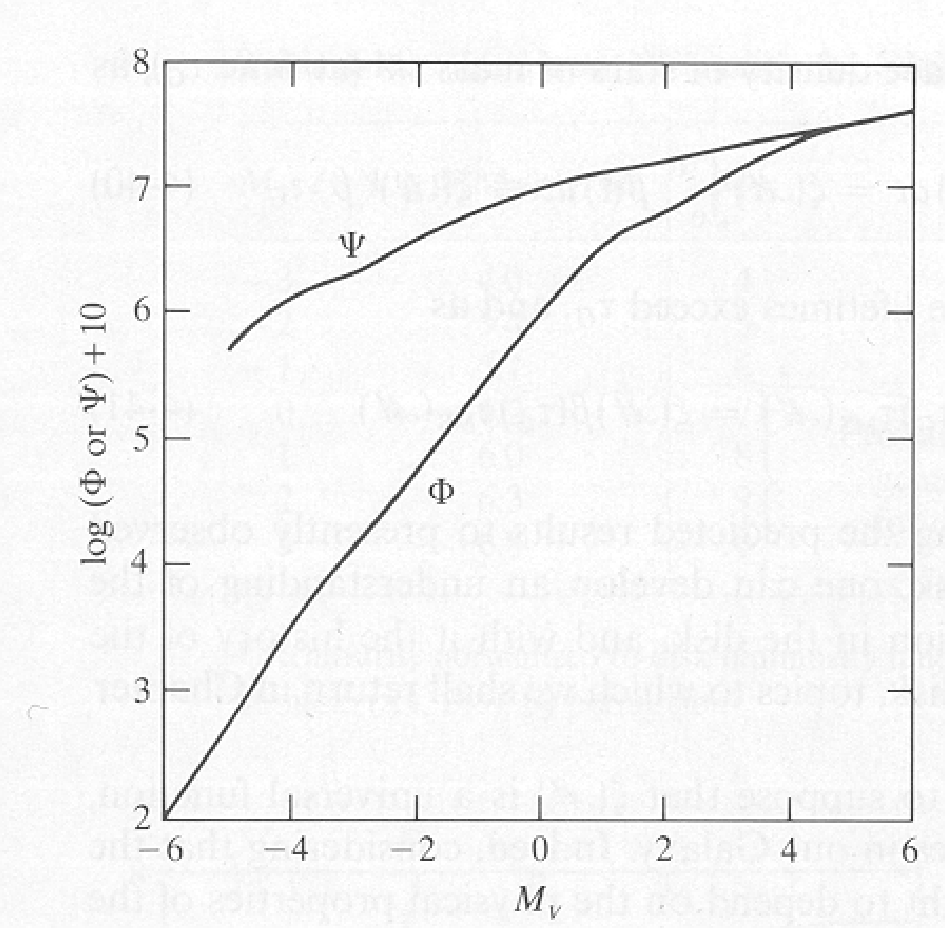
**A complete luminosity function, Φ(M), must be constructed and adjusted for stellar evolution to derive the initial luminosity function, Ψ(M):**

$$\Psi(M_\lambda) = \Phi(M_\lambda) \;\; \textit{for} \;\; \tau_{ms} \geq \tau_G$$

*and*

$$\Psi(M_\lambda) = \frac{\tau_G}{\tau_{ms}} \Phi(M_\lambda) \;\; \textit{for} \;\; \tau_{ms} < \tau_G$$

*(e.g. Salpeter 1955)*



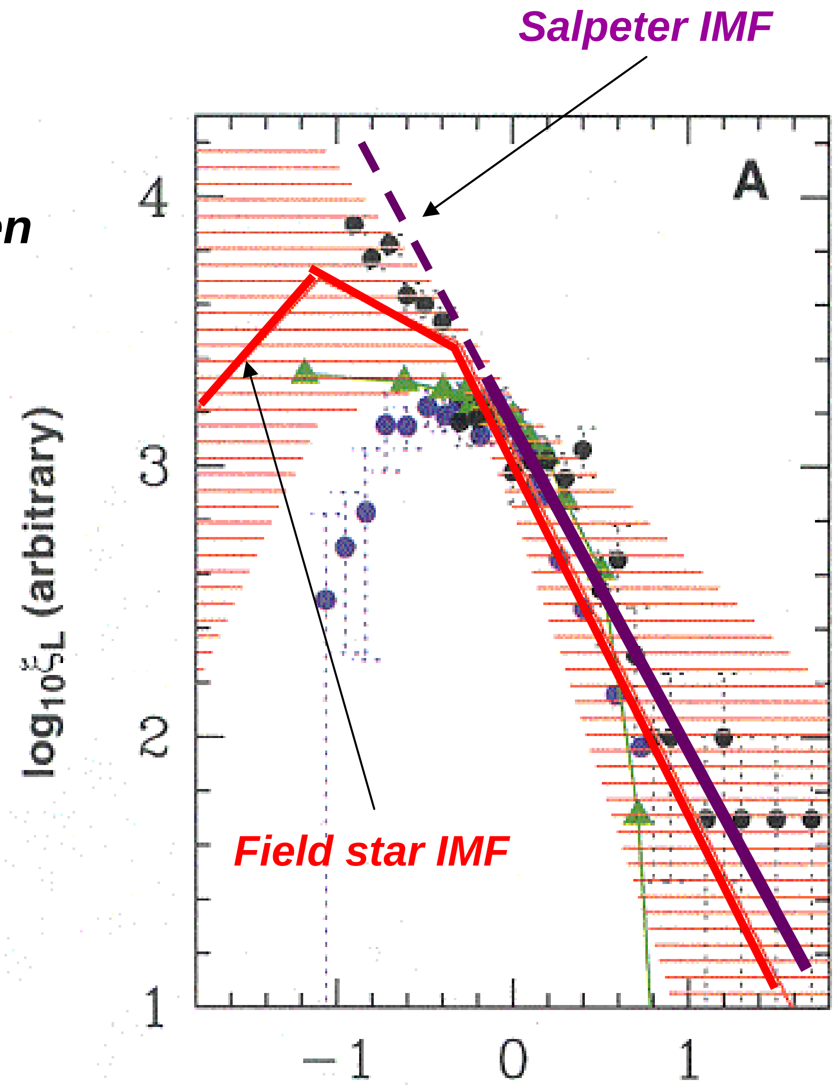

Mihalas & Binney 1981

# The IMF for Local Field Stars

***Salpeter (1955) found a single power-law characterized the IMF with $\gamma = 1.35$ between roughly 1—10 solar masses.***

***Scalo (1977) found IMF to depart from a single power-law near 1 $M_\odot$ and proposed lognormal form with peak near 0.1 $M_\odot$***

***Current consensus favors multiple (3-4) power-law form.***




*Kroupa: 2002 Science **295,** 82*

# SUMMARY

1.- The IMF is populated by objects which continuously span a range of mass from the most massive stars to substellar objects near the deuterium burning limit (DBL).

2. - The IMF is characterized by a broad peak near 0.2 $M_{\odot}$ suggesting a characteristic mass for star formation near 0.1-0.3 solar masses.

3.- Substellar objects account for only 20-25% of all sources produced by the IMF. The IMF declines from the HBL to the DBL. Freely floating objects of planetary mass are very rare.

4.- The IMF in clusters appears universal in form and very similar to the field star IMF.*

*However observations of Taurus suggest that significant variation can occur.

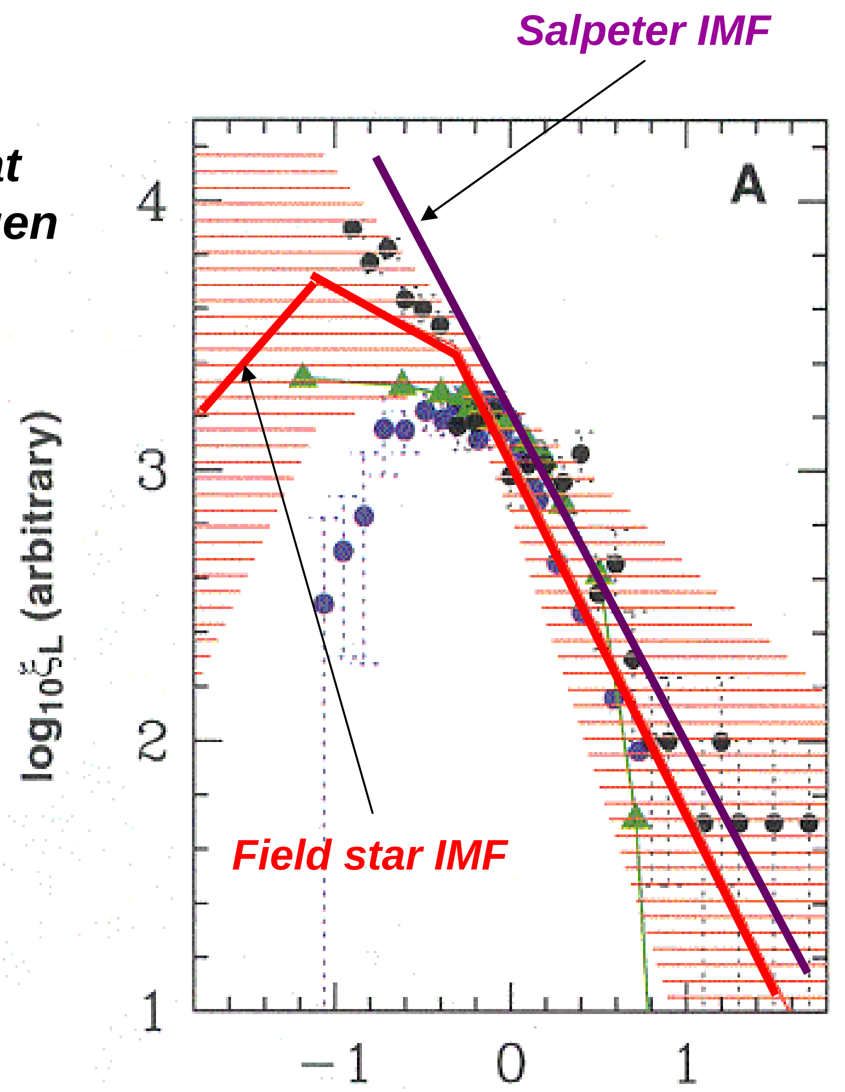
# *The End*

# The IMF for Open Clusters

*However, field star IMF is very uncertain at high stellar masses and below the hydrogen burning limit.*

*Open clusters offer advantages of coeval star formation and statistically significant samples of stars over a large range of masses.*

*Significant limitations arise due to issues of membership and loss of members due to stellar and dynamical evolution.*




Kroupa: 2002 Science **295,** 82