Star formation

The Initial Mass Function

Clusters

Almost all stars form in clusters, isolated star formation is exception.

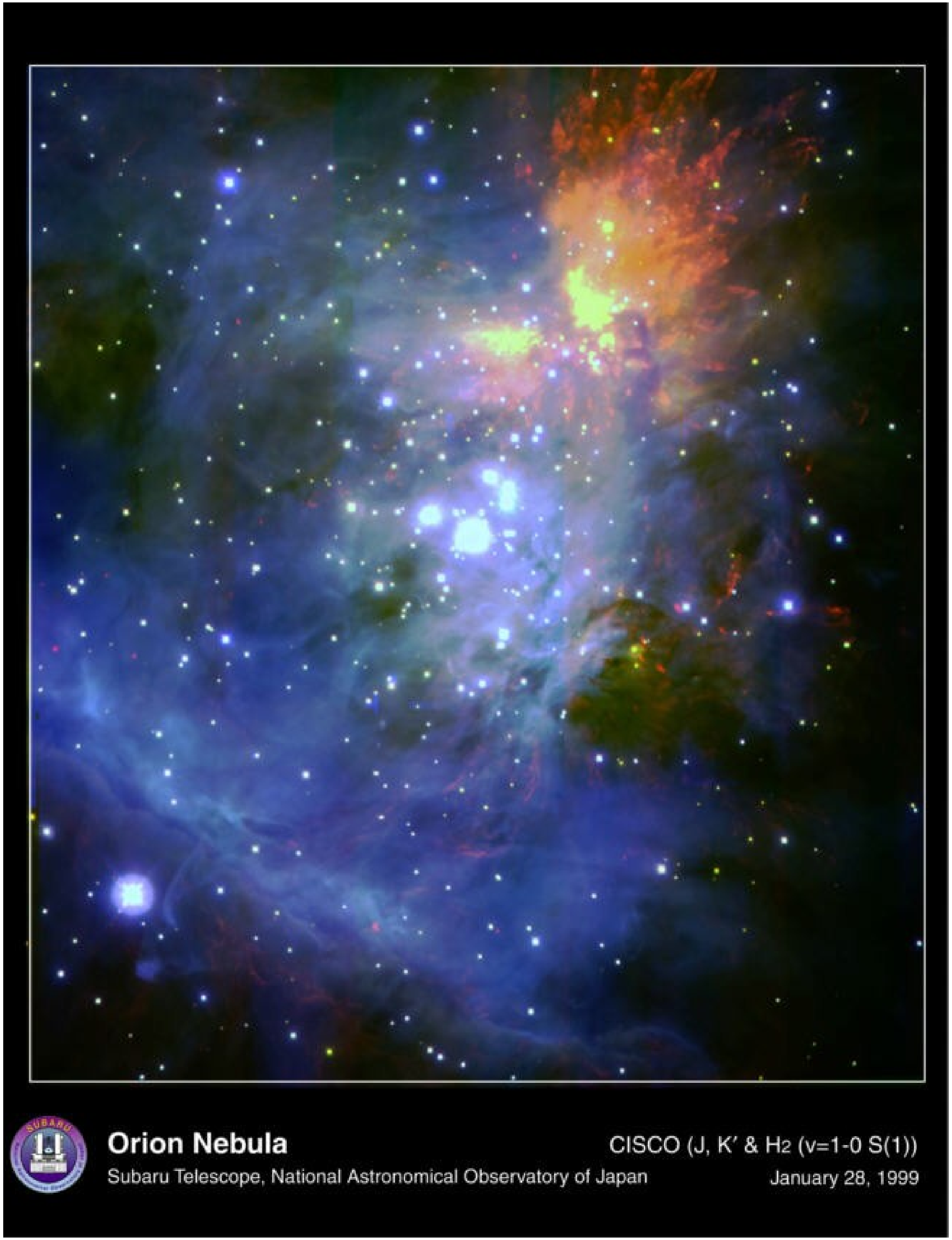
NGC3603
6 x 6 pc
1 pc diameter
10 000 stars:
 0.5-120 M_{sun}

Stolte et al. 2006

Clusters

In clustered mode stars of different masses are produced at the same time

→ Initial mass function (IMF)



Orion Nebula

Subaru Telescope, National Astronomical Observatory of Japan

CISCO (J, K′ & H2 (v=1-0 S(1))

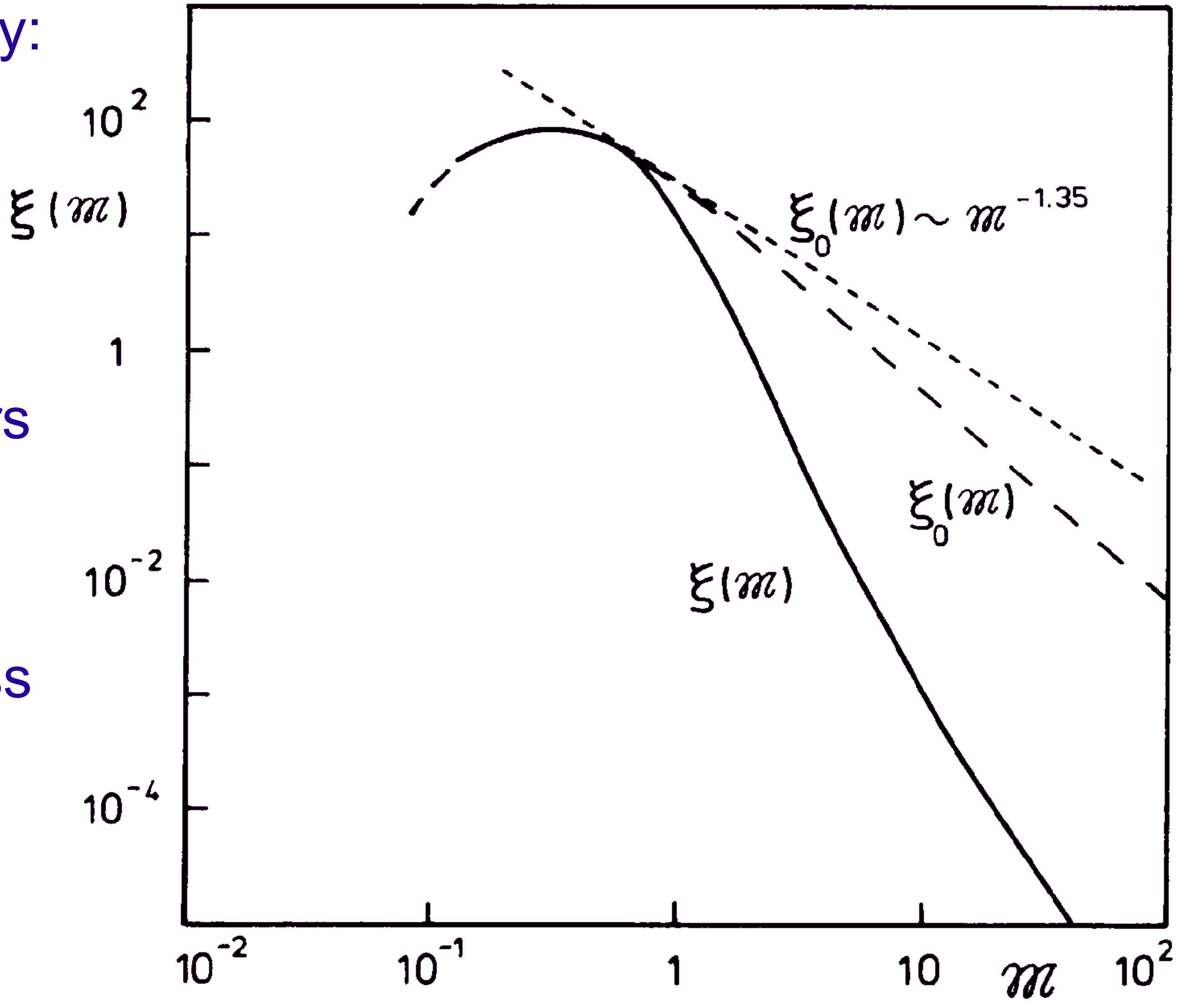
January 28, 1999

Deriving the IMF

Only observable quantity:

Present stellar mass function

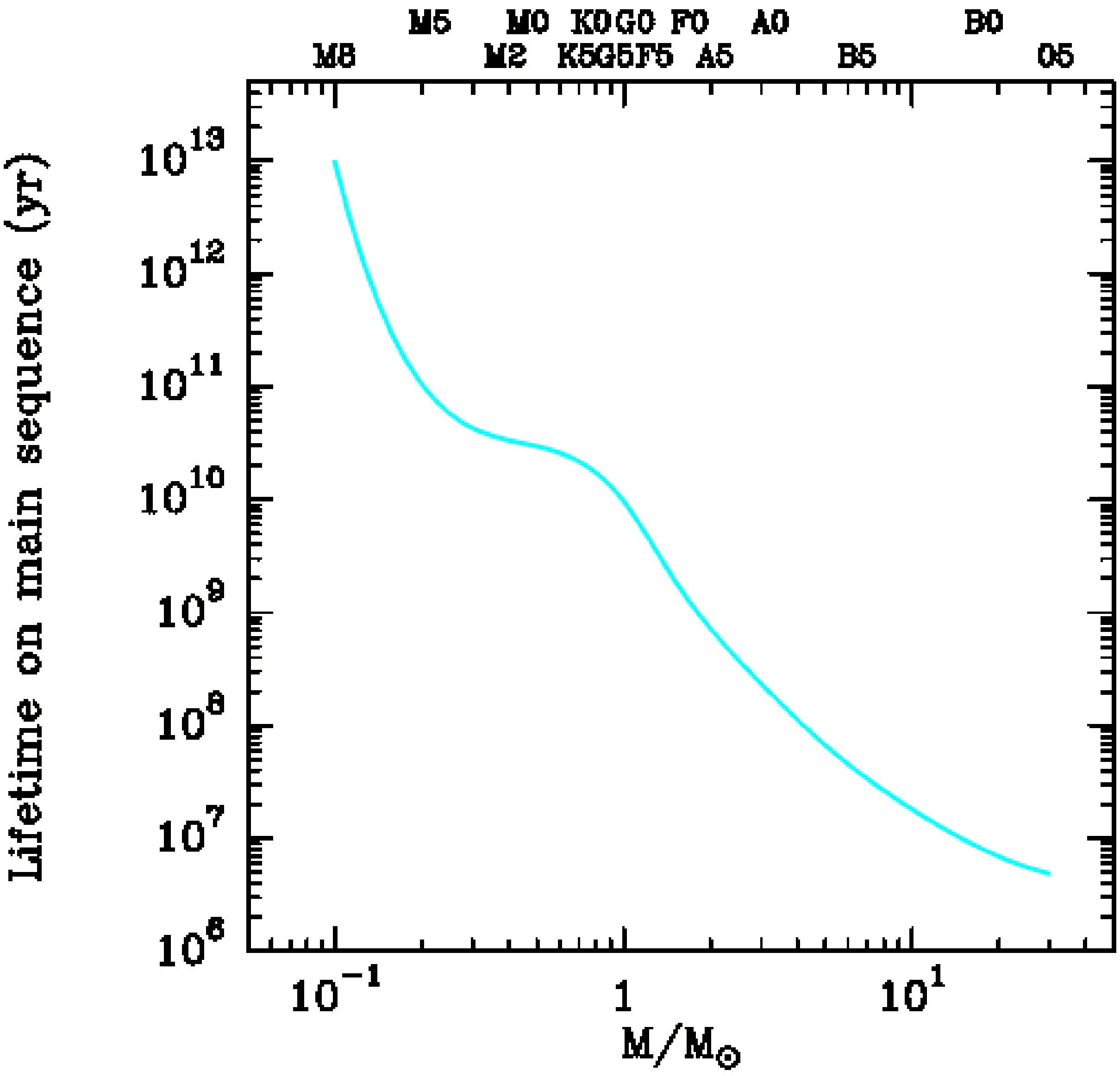
- Dynamic range problem:
  - In high mass clusters low mass stars are not seen
  - Low mass clusters don't have high mass stars
- Aging problem
- Has to be patched together



Deriving the IMF

Correction for lifetime

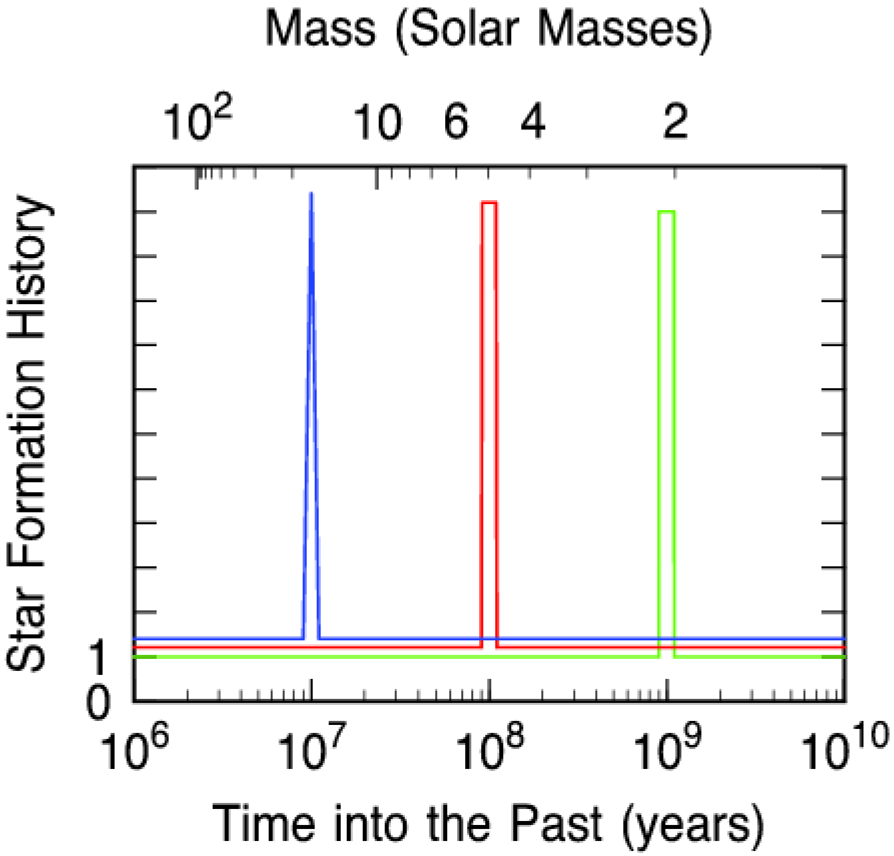
- In older clusters the most massive stars have disappeared already
- Assumes sporadic (short) star-formation periods



Deriving the IMF

Correction for lifetime

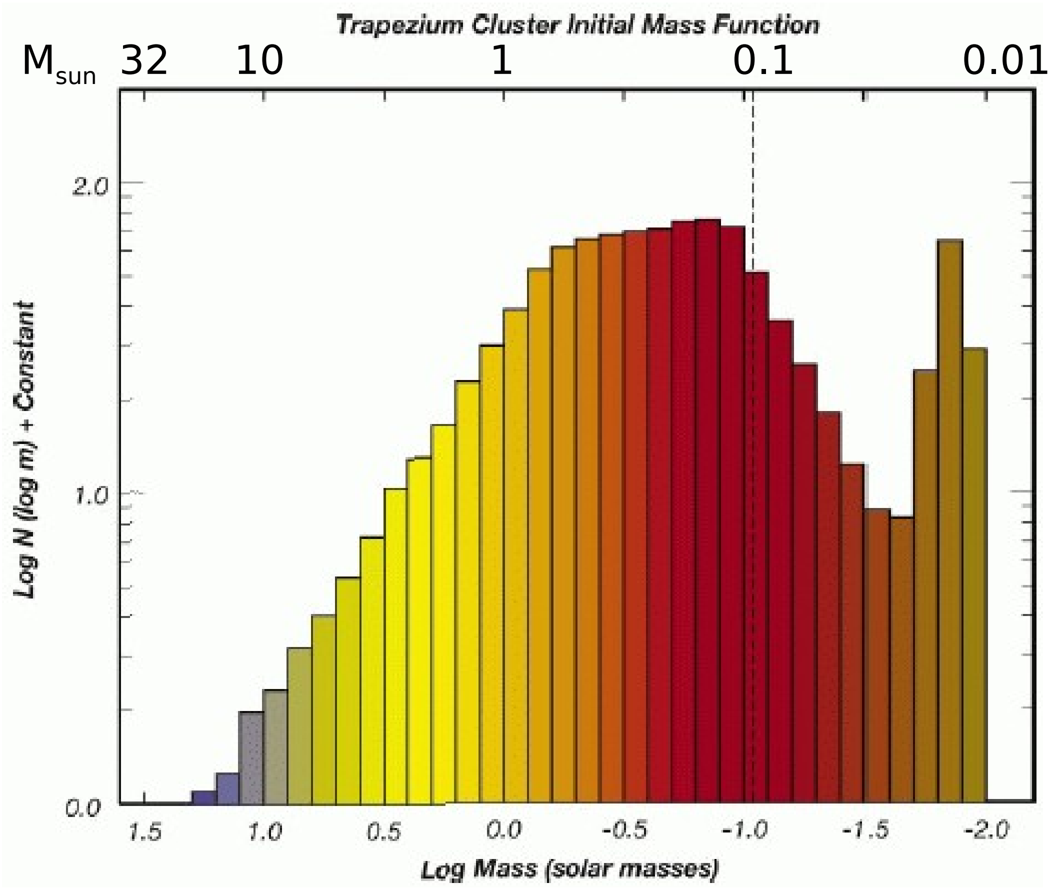
- Assumes sporadic (short) star-formation periods



Starburst episodes

triggered e.g. by spiral density wave

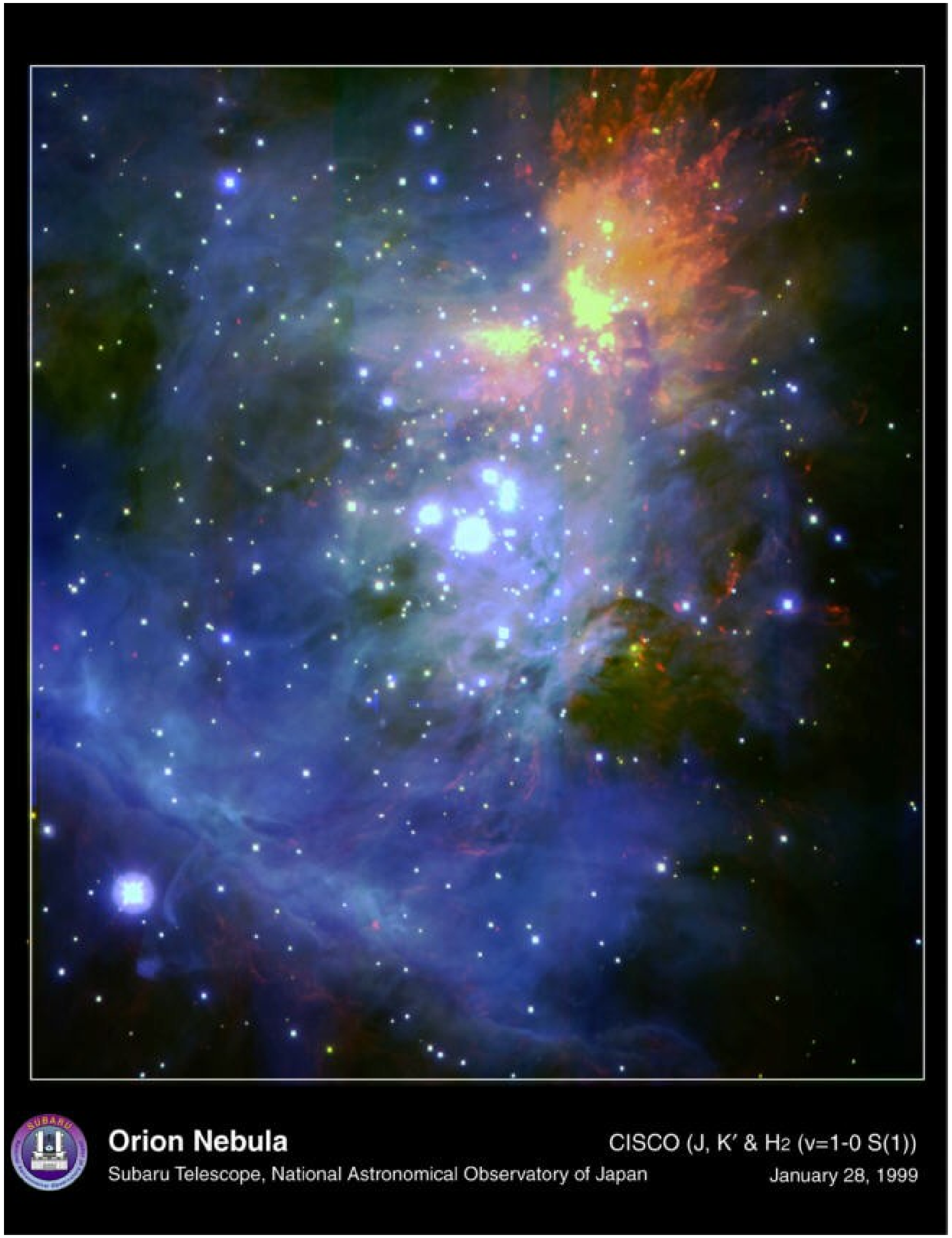
Initial Mass Function (IMF)



Muench et al. 2002

Over-abundance of low-mass stars

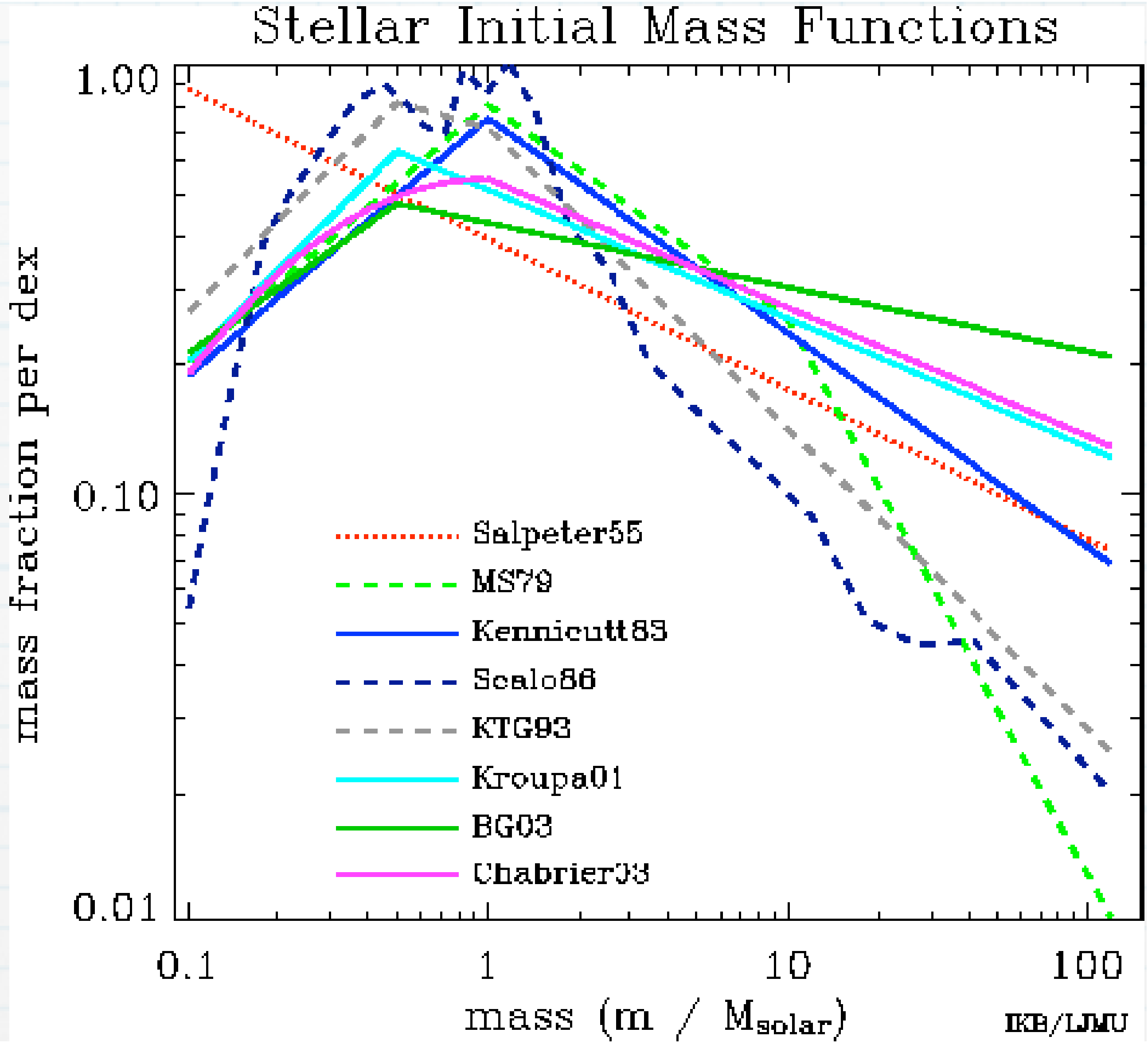
Very few stars with $M > 7M_\odot$



Initial Mass Function (IMF)

- Still relatively large error bars

- Many indications for a universal IMF



Muench et al. 2002

General properties of the IMF

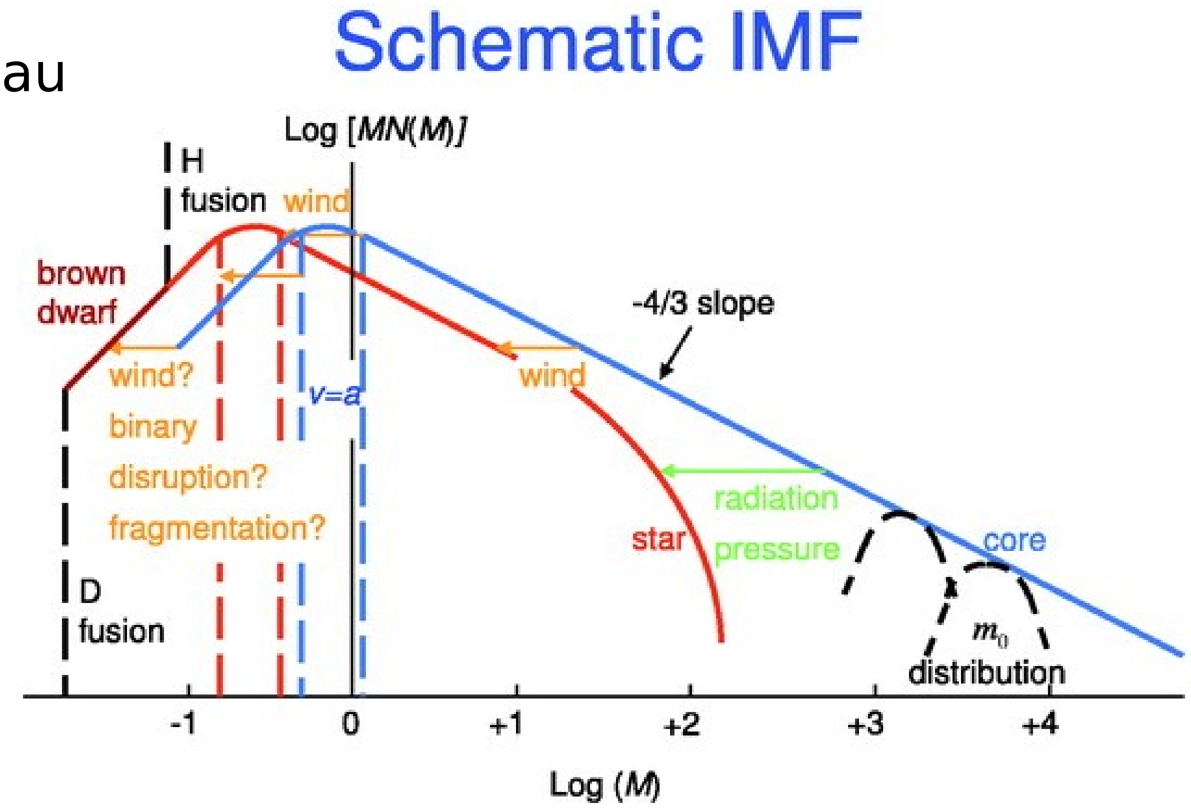
E. Salpeter (1955):

$$\frac{dN(M)}{d\log M} \propto M^{-1.35}$$

$$\frac{dN(M)}{dM} \propto M^{-2.35}$$

derived for stars approximately larger than $1M_{sun}$.

- Characteristic mass plateau around $0.5\ M_{sun}$
- Brown-dwarf desert
- Upper mass limit unknown (~ $150M_{sun}$?)


Schematic IMF

Shu et al. 2004

General properties of the IMF

More detailed current description of the total IMF (Kroupa 2001,2005):

$$\xi(m) \propto m^{-\alpha_i} = m^{\gamma_i},$$

where

$$\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \le m/\mathrm{M}_\odot < 0.08,$$

$$\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \le m/\mathrm{M}_\odot < 0.50,$$

$$\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \le m/\mathrm{M}_\odot < 1.00,$$

$$\alpha_3 = +2.3 \pm 0.7, \quad 1.00 \le m/\mathrm{M}_\odot,$$

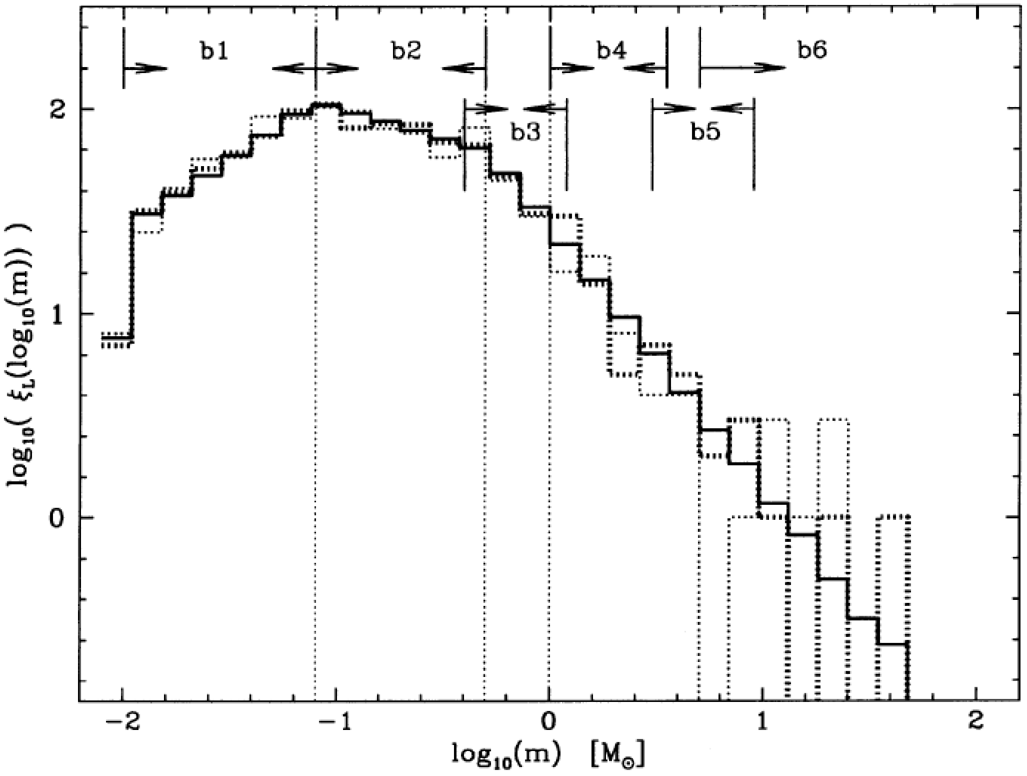


Figure 2. The adopted logarithmic IMF (equations 2 and 3), $\xi_L/10^3$, for 10^6 stars (solid histogram). Two random renditions of this IMF with 10^3 stars are shown as the heavy and thin dotted histograms. The mass ranges over which power-law functions are fitted are indicated by the arrowed six regions (equation 4), while thin vertical dotted lines indicate the masses at which α_i changes.

Largely universally valid, in clusters and the field in our Galaxy as well as in the Magellanic Clouds .

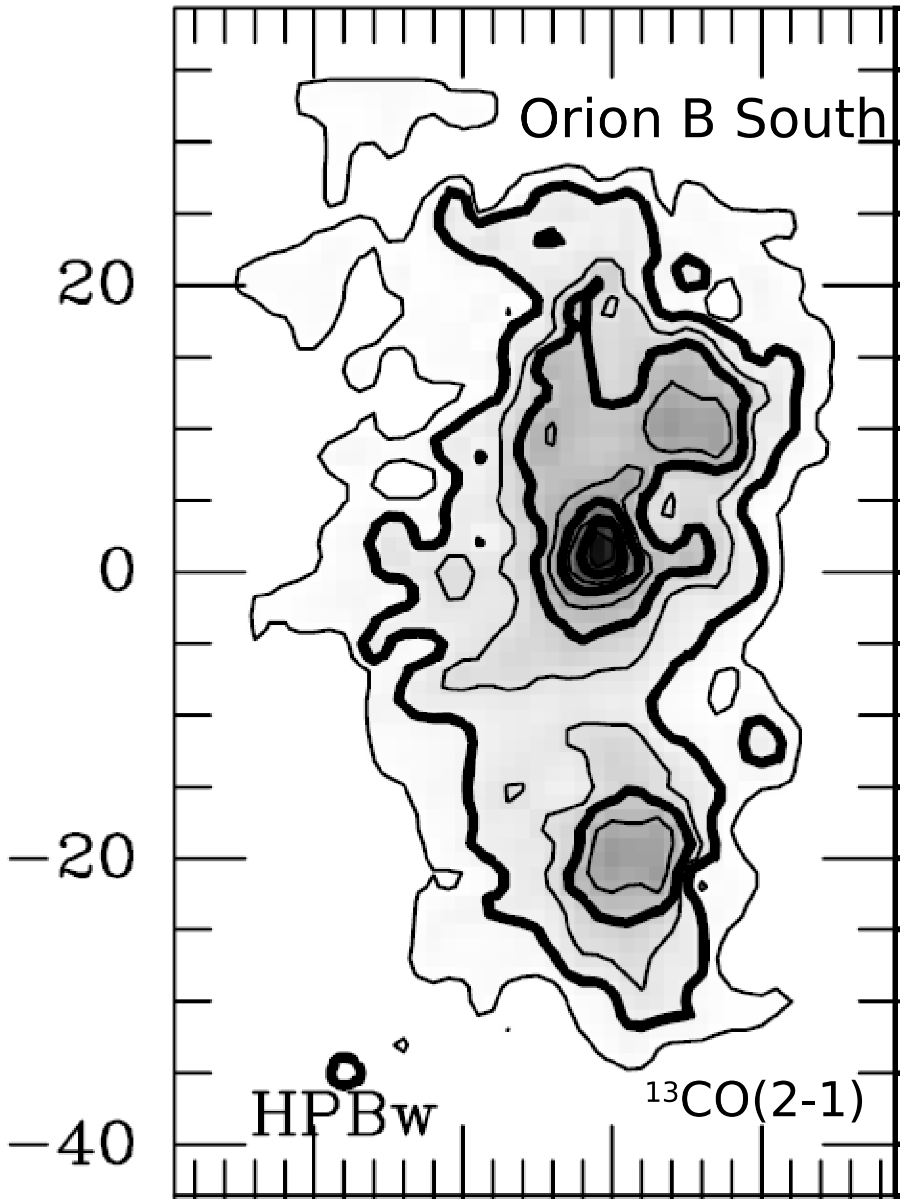
Origin of IMF

- Does the IMF originate during
  - cloud fragmentation
  - collapse to protostellar cores
  - final collapse to star ?
- How is mass redistributed?

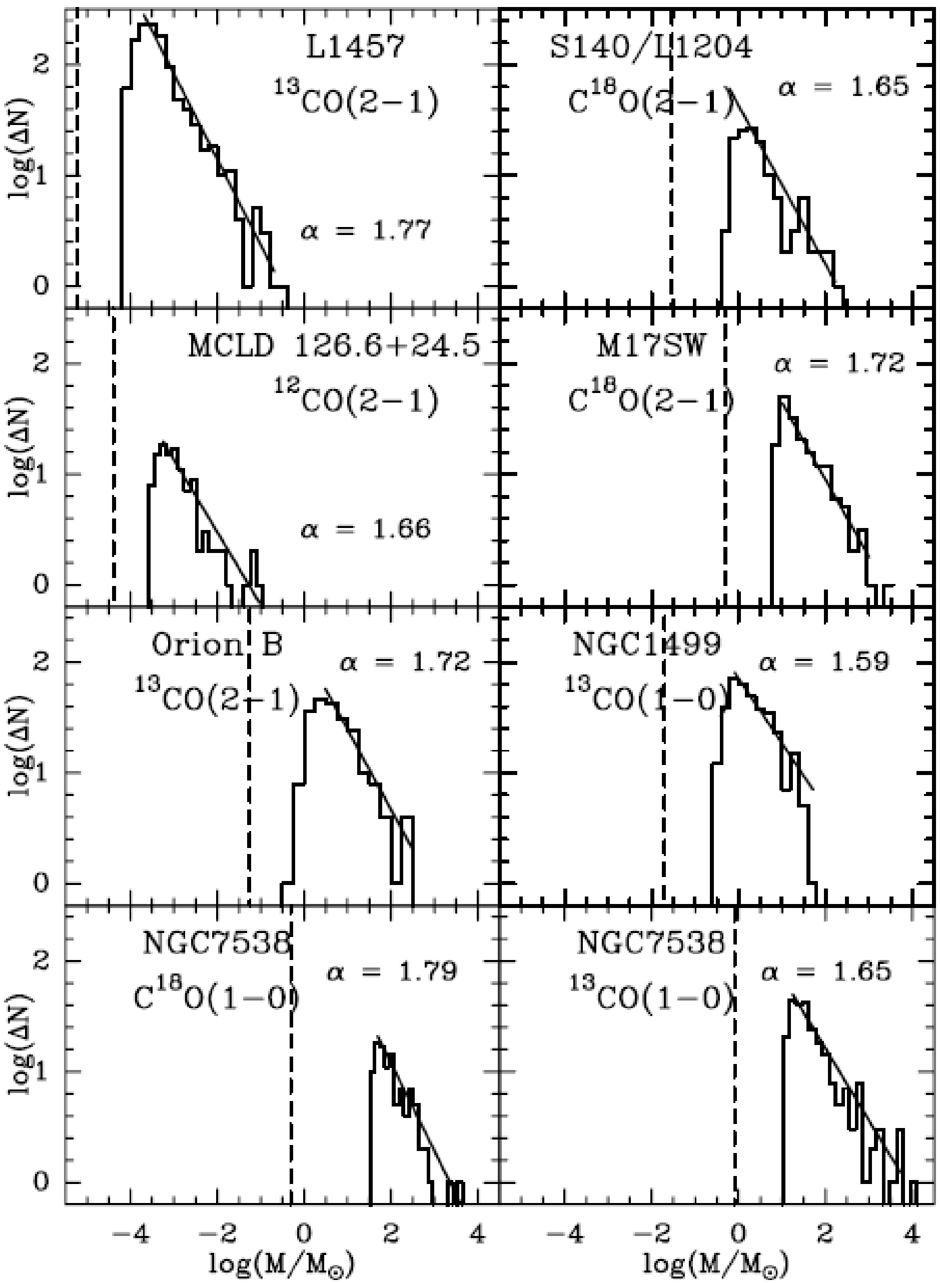
- Observational evidence

- Theoretical models

Clump mass distributions



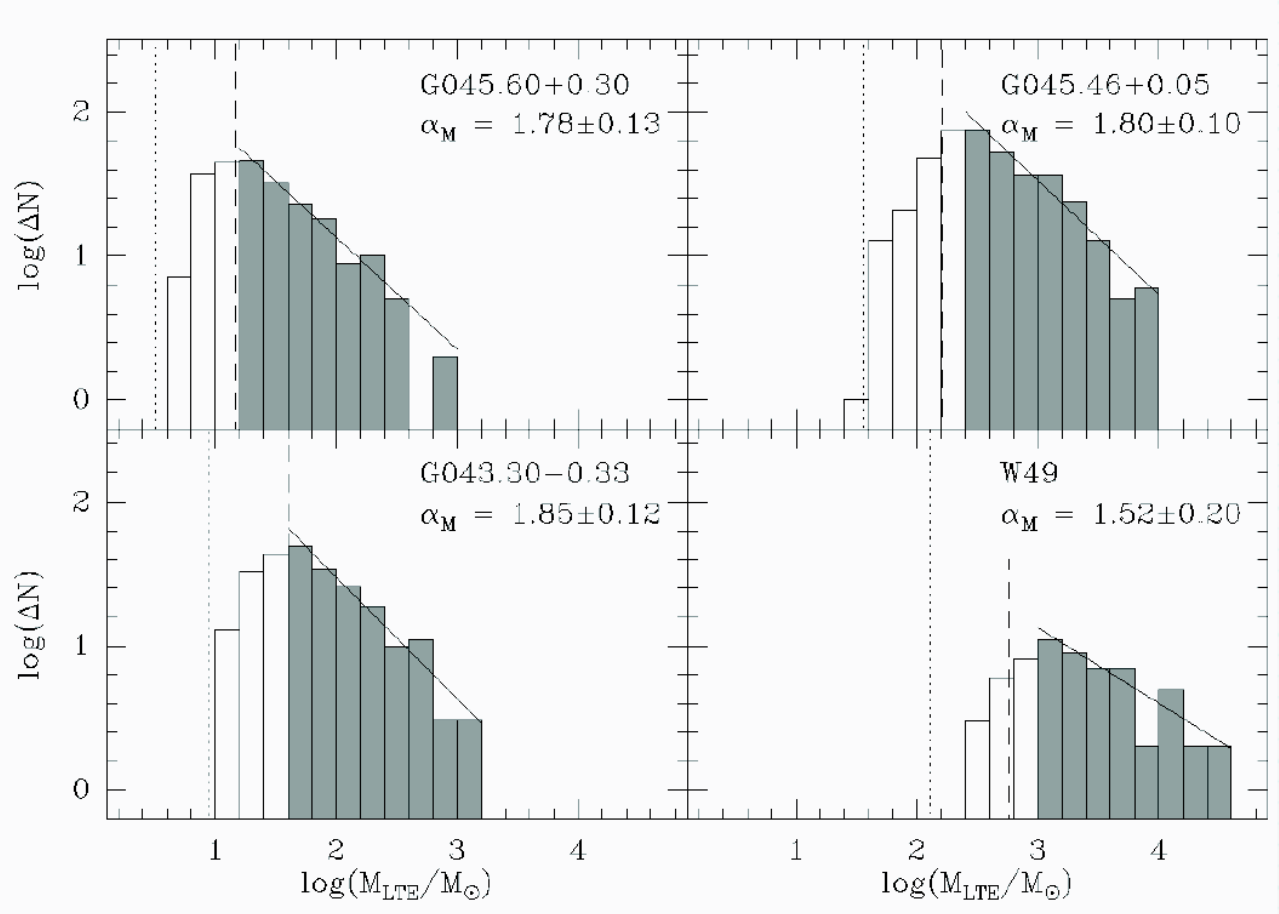
Kramer et al. 1996



Clump mass distributions

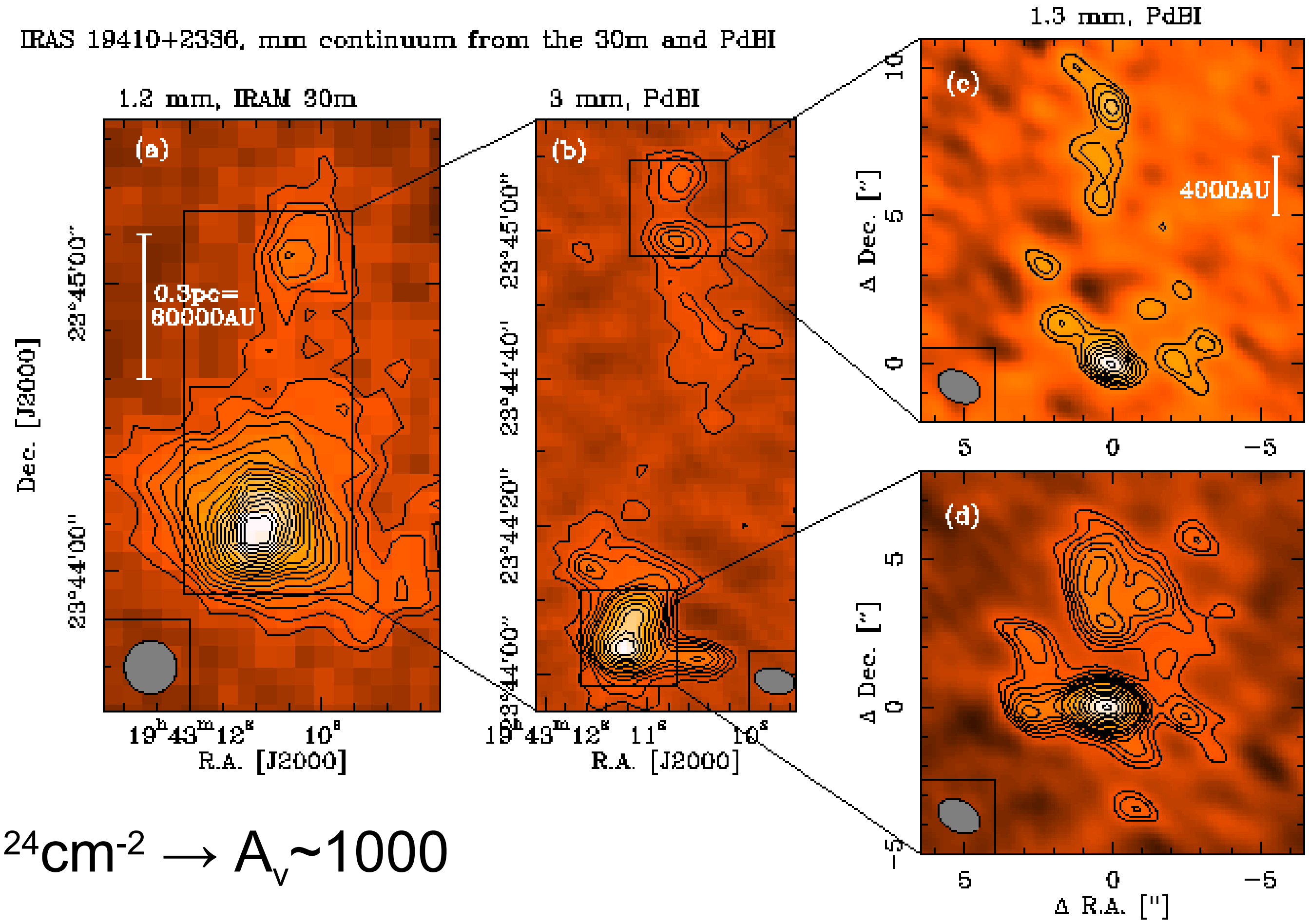
- Spectral index shallower than IMF index
- No significant difference between non-star-forming clouds and star forming clouds

→ The IMF must be created by further fragmentation or coalescence during gravitational collapse



Observation of the fragmentation of a massive protocluster

Beuther & Schilke (2004):



- 12 clumps within each core (80 to 90% of the gas in halo)
- Clump masses: 1.7M_{sun} to 25M_{sun}
- Column densities: 10^{24}cm^{-2} → A_v~1000

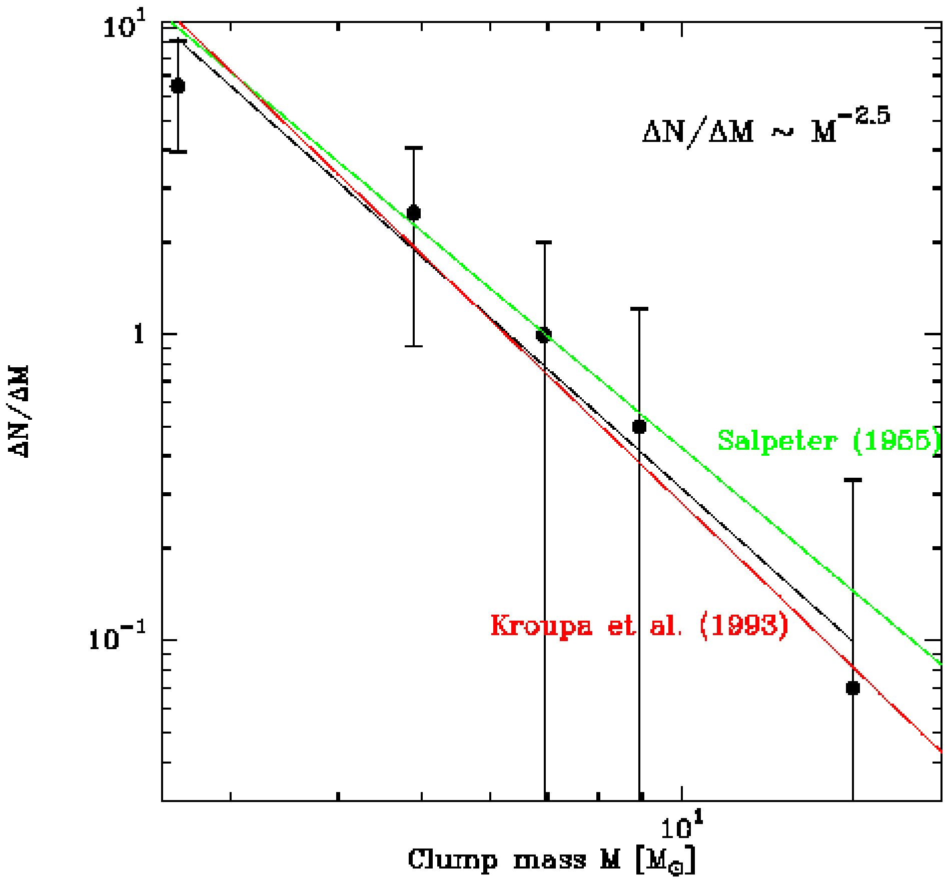
Observation of the fragmentation of a massive protocluster

Beuther & Schilke (2004):

Assumptions: - All emission peaks of protostellar nature (e.g. no HH obj.)
- Same temperature for all clumps (46K, IRAS)
(both assumptions questionable!)

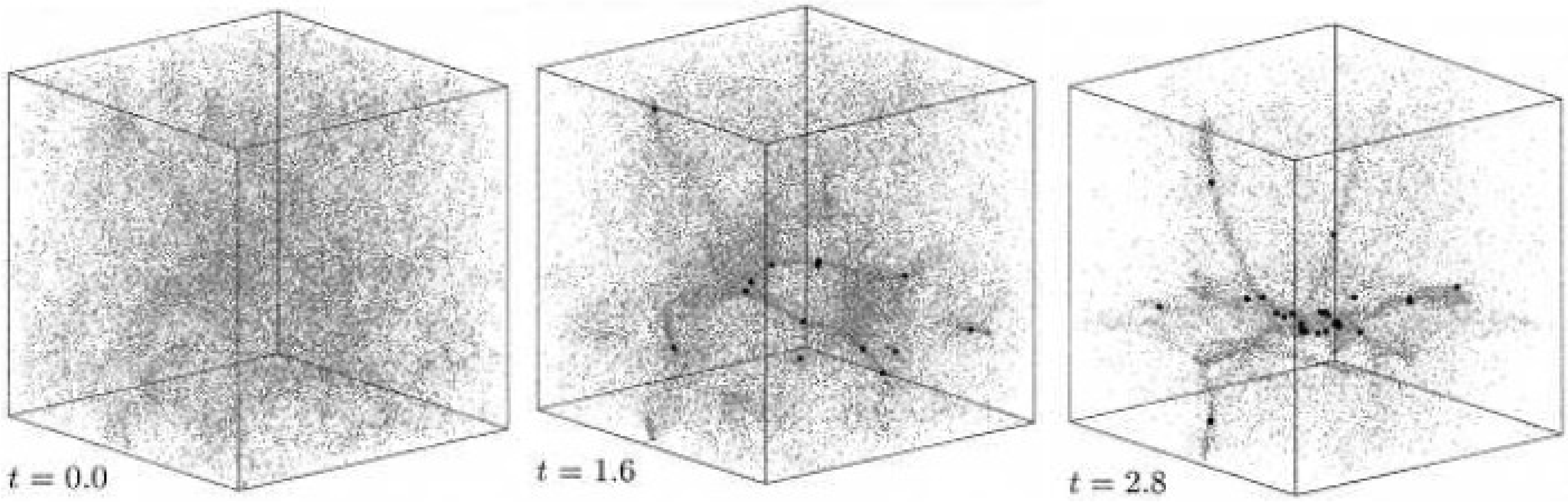
→ Resulting core spectrum matches IMF

But: Huge error bars



Theory: Gravitational fragmentation

HD simulation of gravitational collapse of cloud with initial density fluctuations:



Klessen et al. 1998

Created structures determined by Jeans mass

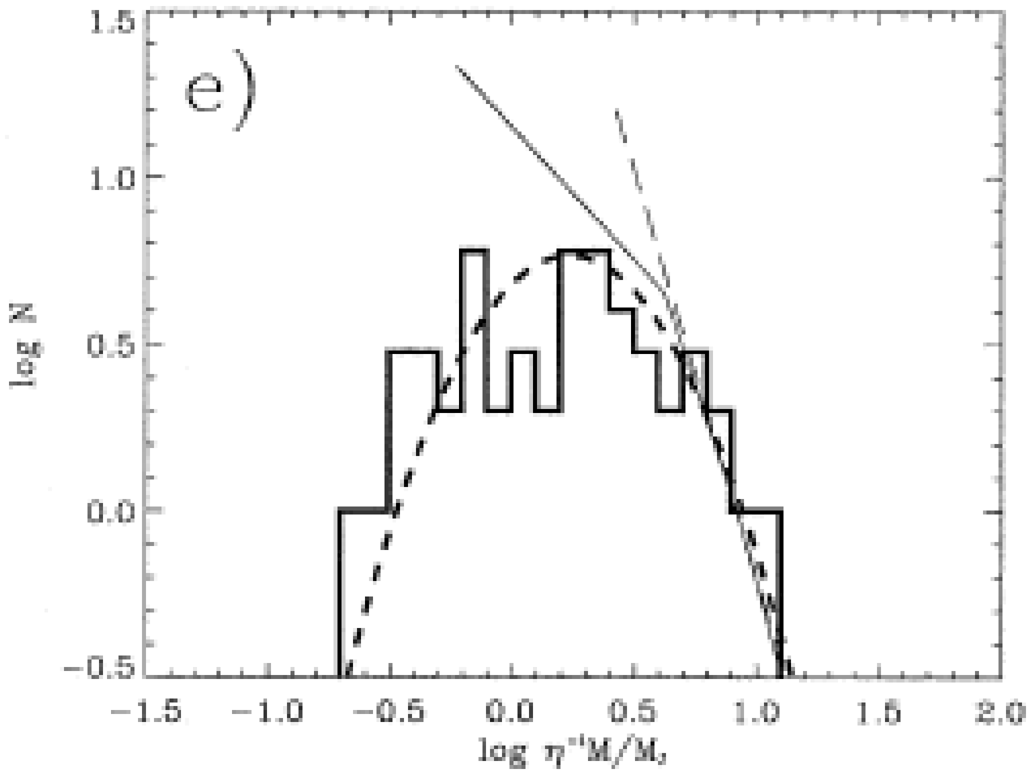
$$M_J \approx 1 M_\odot \left(\frac{T}{10\mathrm{K}}\right)^{3/2} \left(\frac{n_{\mathrm{H}_2}}{10^4 \mathrm{cm}^{-3}}\right)^{-1/2}$$

one can in principal obtain all masses.

Theory: Gravitational fragmentation

Resulting core spectrum:

No power-law scaling relation.



Klessen et al. 1998

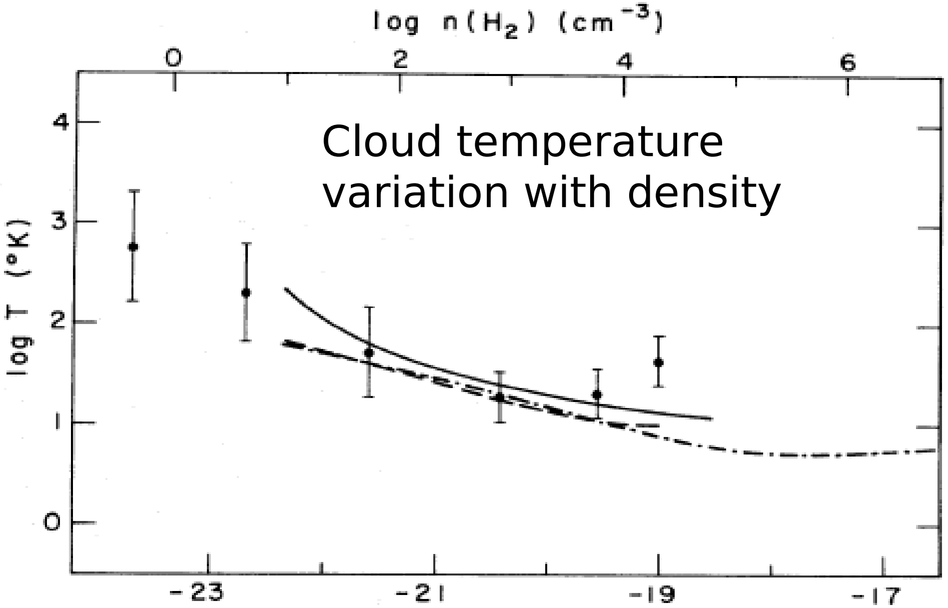
Unlikely to be the main driver for IMF:

- Scale set by density and temperature
- Number of bound fragments ≈ number of Jeans-masses within the cloud.
- With the usual temperatures and densities, massive fragments are hard to produce.

Theory: Gravitational fragmentation

Characteristic mass defined by thermal physics

Non-monotonous density-temperature dependence:



Cloud temperature variation with density

Larson 1985

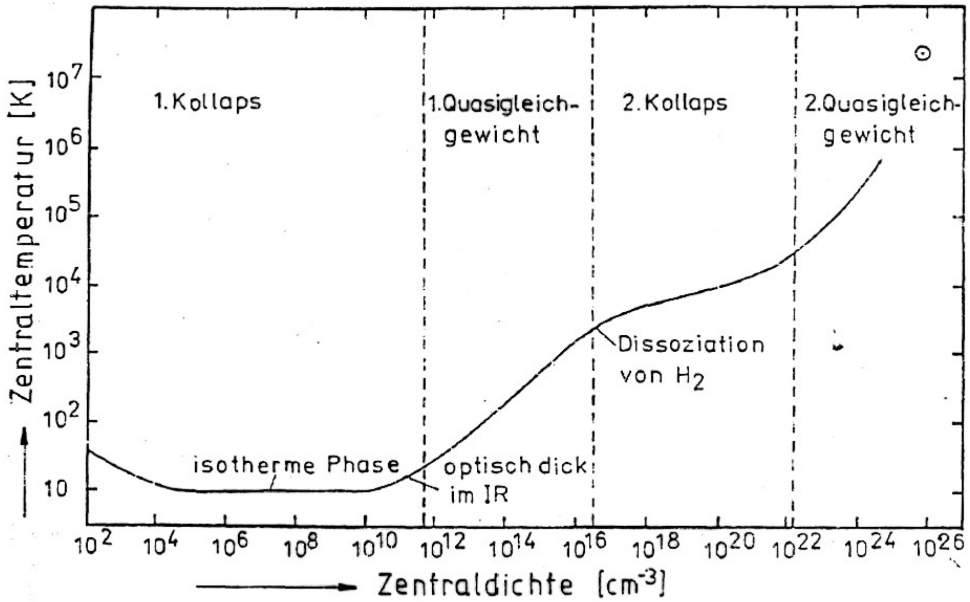


Abbildung 6.3: Zusammenhang zwischen Temperatur und Dichte im Zentrum einer kugelsymmetrischen Wolke während des protostellaren Kollaps'.

- Low densities: cooling not efficient → warm
- Dense clumps: efficient cooling through dust, atomic and molecular lines → cold
- Protostellar cores: optically thickness prevents cooling → hot

Theory: Gravitational fragmentation

Characteristic mass defined by thermal physics:

- Low densities:
  - temperature decreases with increasing density
    → decreasing M_J → fragmentation

- High densities:
  - temperature increases with increasing density
    → increasing M_J → inhibits further fragmentation

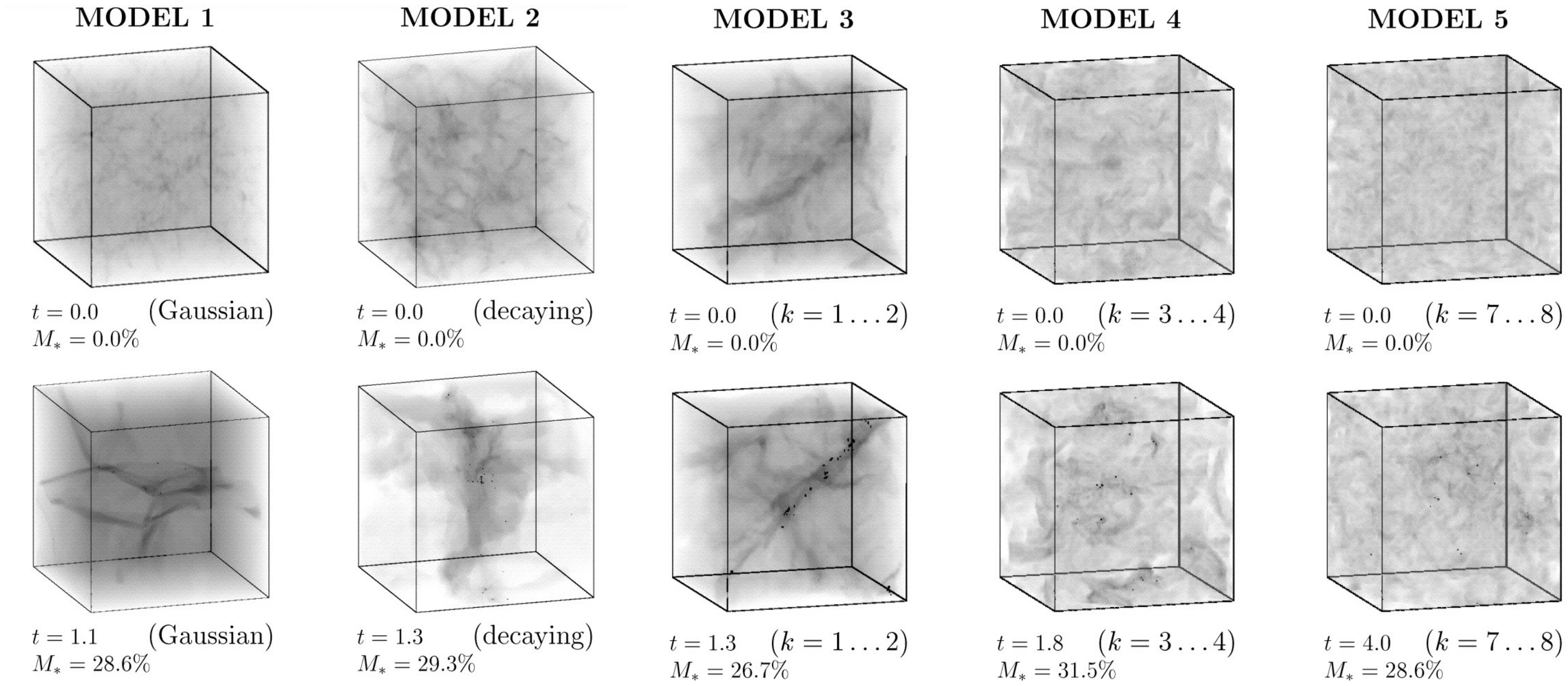
- Regime with lowest T corresponds to the preferred fragmentation scale.
  - The Bonnor-Ebert mass at this point is about 0.5 $M_\odot$.

→ **Turn-over in IMF**

(Gravo)-turbulent fragmentation

Introduce turbulent motions into the simulations:

Klessen (2001)



Pure gravitational collapse

Freely decaying tubulence field

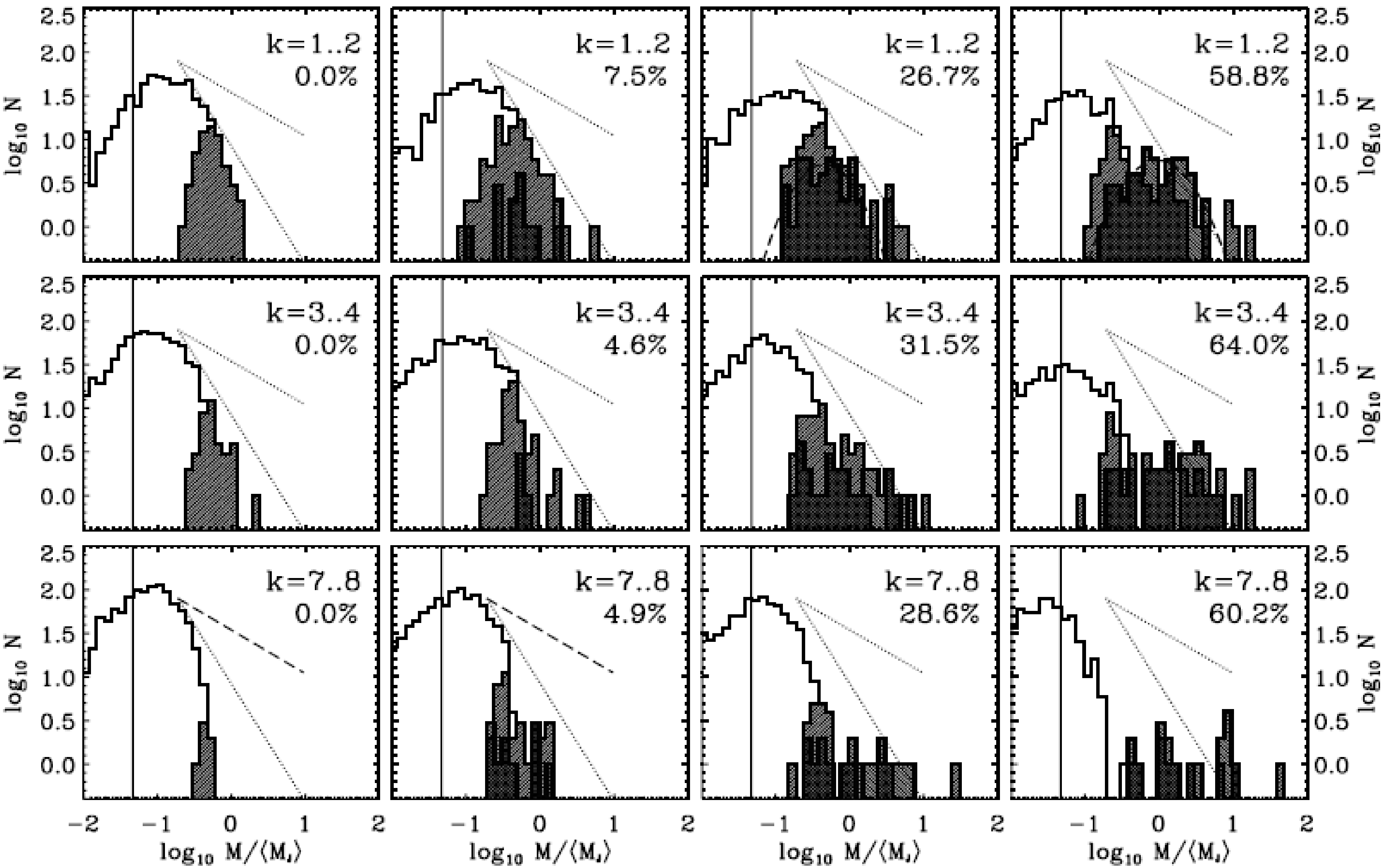
Continuously driven turbulence. Pertubations given by wavenumber k.
Small k, large scale → large k, small scale

(Gravo)-turbulent fragmentation

- Turbulence produces network of filaments and interacting shocks.
  - Converging shock fronts generate clumps of high density.
  - Collapse when the local Jeans-length gets smaller than the size of fluctuation.
  - Have to collapse on short time-scale before next shock hits the region.

→ Efficiency of star formation depends on the wave-number and strength of the turbulence driving.

(Gravo)-turbulent fragmentation



Histogram: Gas clumps
Grey: Jeans unstable clumps
Dark: Collapsed cores

(Gravo)-turbulent fragmentation

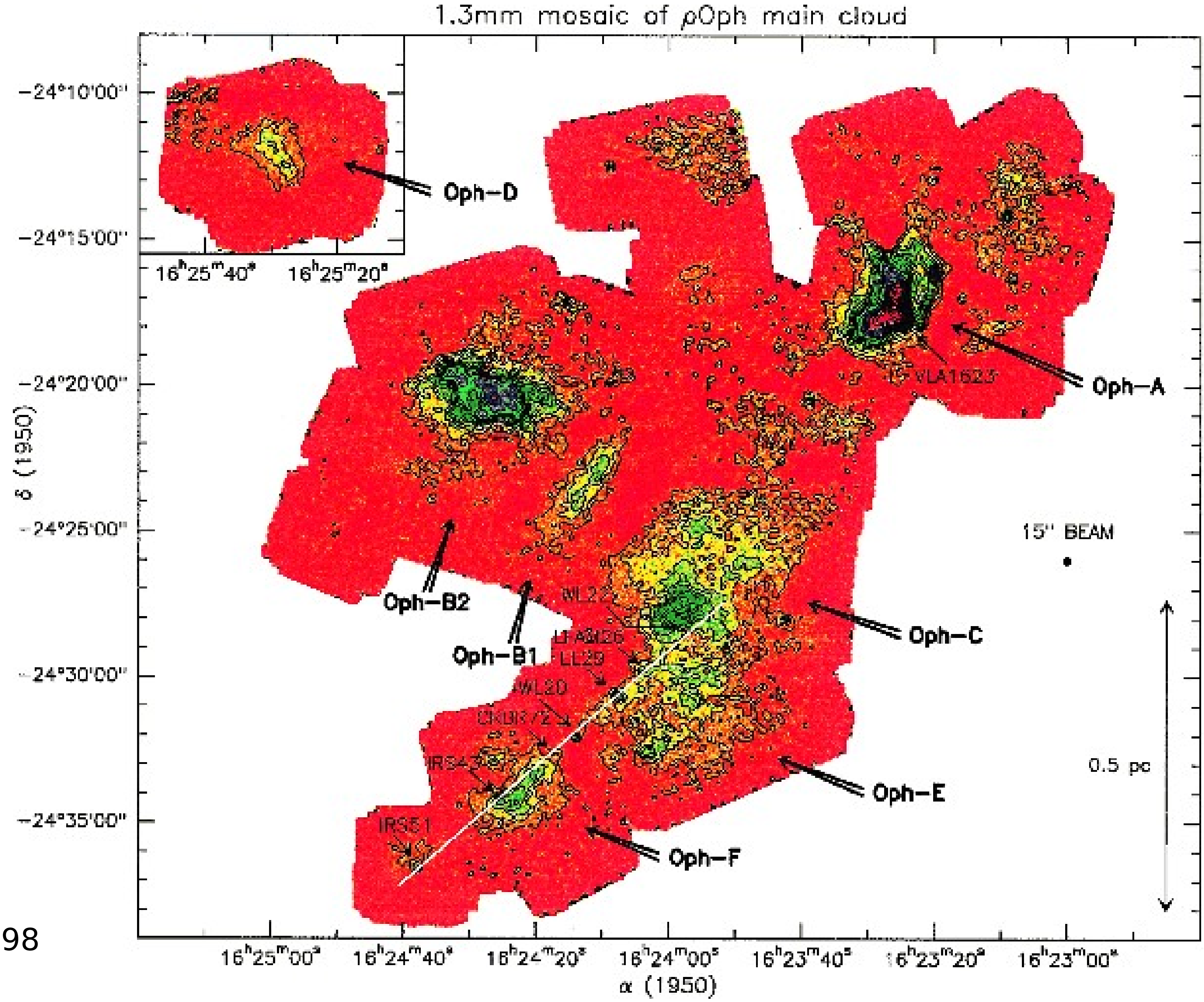
Preliminary reproduction of IMF formation process:
1.) Turbulent fragmentation
2.) Collapse of individual core → needs higher resolution

- Large-scale less strongly driven turbulence results in clustered mode of star formation.
- Small-scale strong driving results in more low-mass protostars and more isolated star formation.

- Large-scale driving roughly reproduces shape of IMF.
  - Dynamic range still insufficient
  - unclear whether largest fragments remain stable or whether they fragment further …

Pre-stellar core mass functions

Mass
spectrum
of ρ Oph:



1.3mm mosaic of ρOph main cloud

Motte et al. 1998

Pre-stellar core mass functions

Mass spectrum of ρ Oph:

- Similar to IMF
- But two fitting slopes
- No direct match

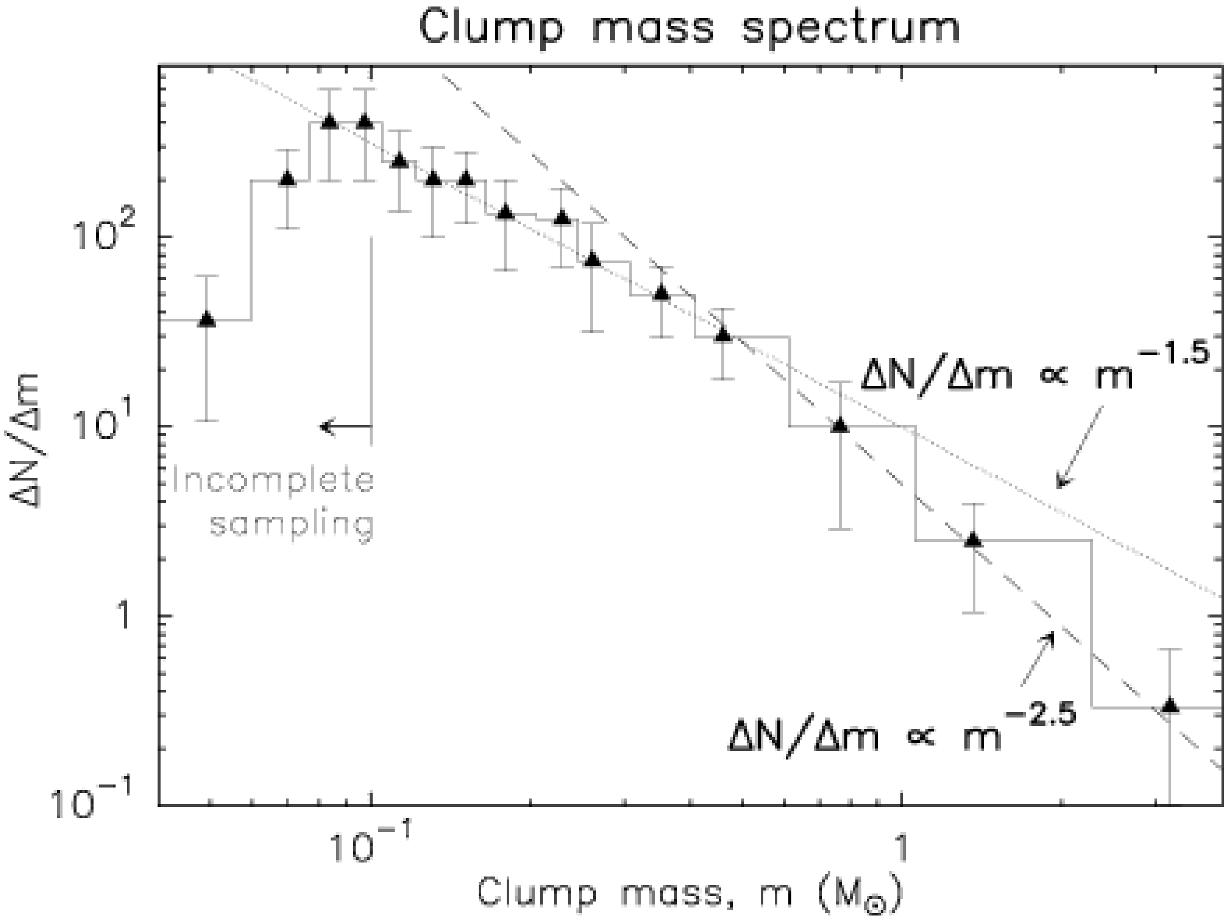
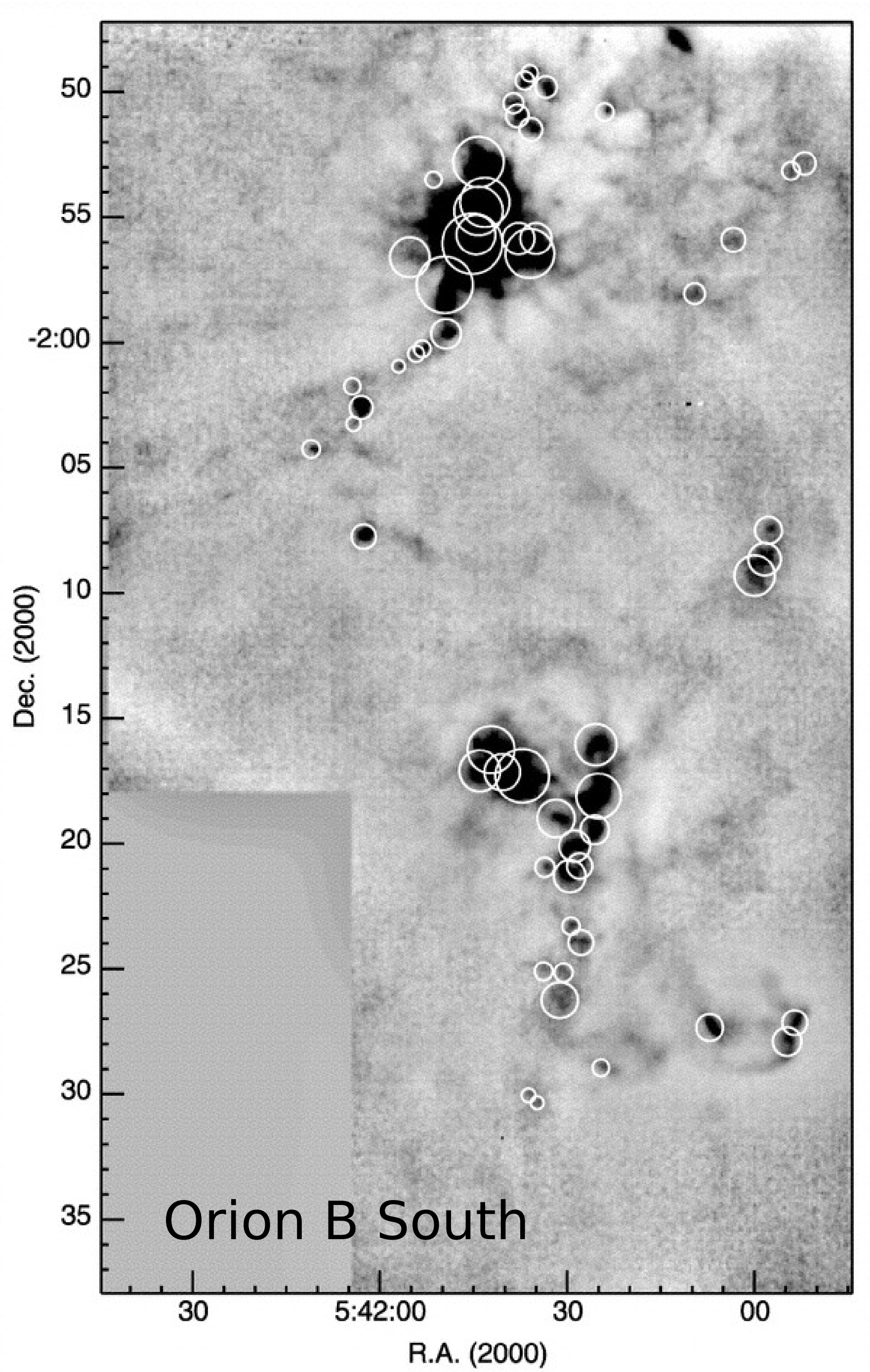
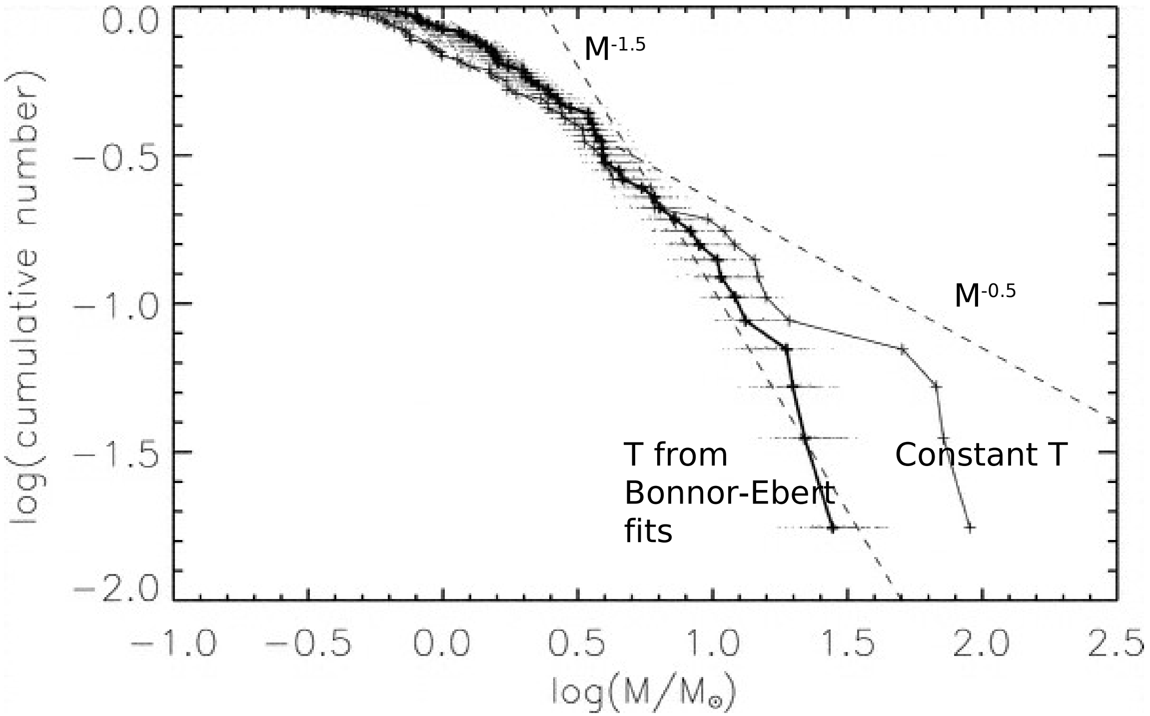


Fig. 5. Frequency distribution of masses for 60 small-scale clumps extracted from the mosaic of Fig. 1 (solid line). The dotted and long-dashed lines show power laws of the form $\Delta N/\Delta m \propto m^{-1.5}$ and $\Delta N/\Delta m \propto m^{-2.5}$, respectively. The error bars correspond to $\sqrt{N}$ counting statistics.

Motte et al. 1998

Pre-stellar core mass functions



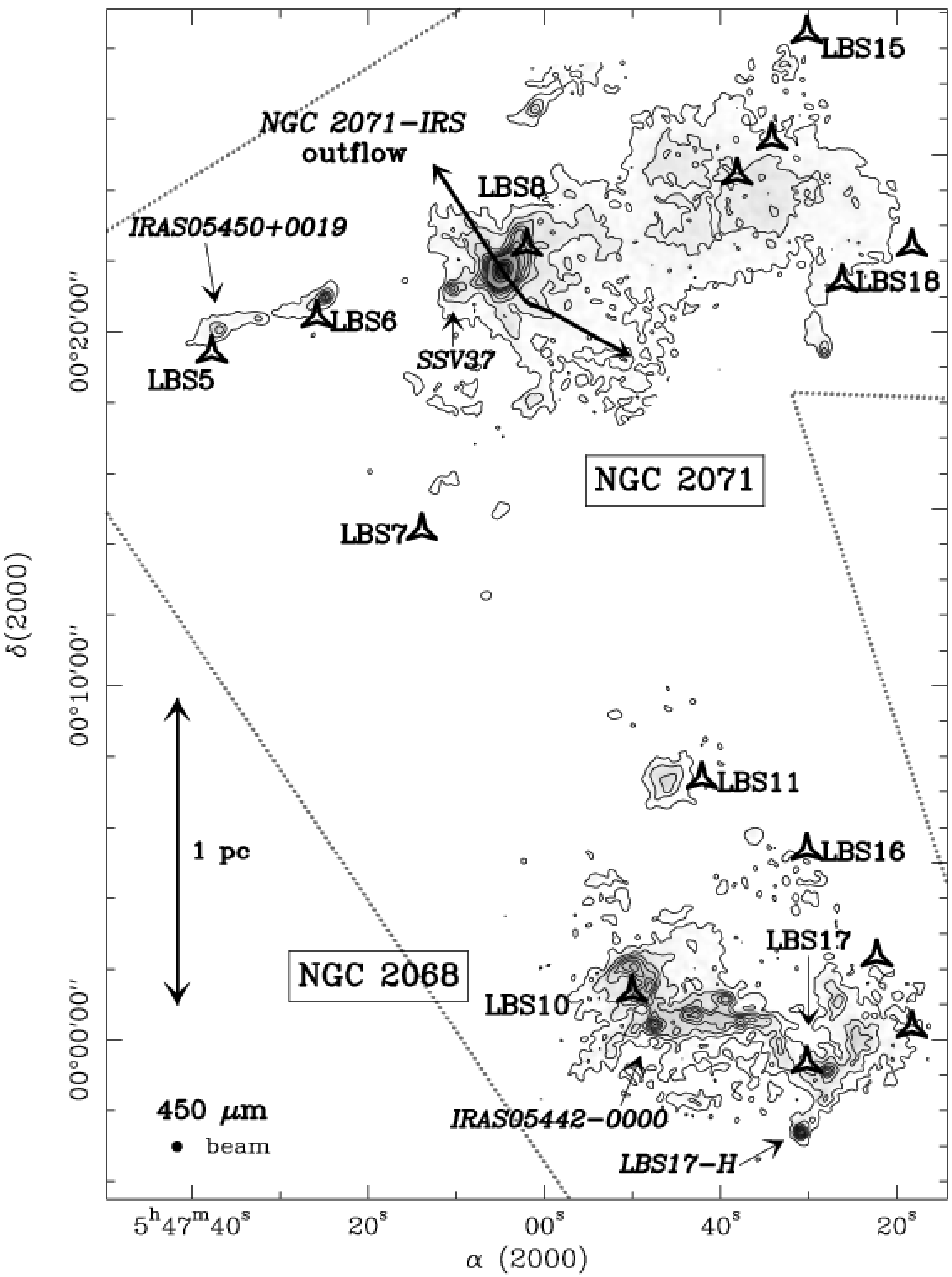


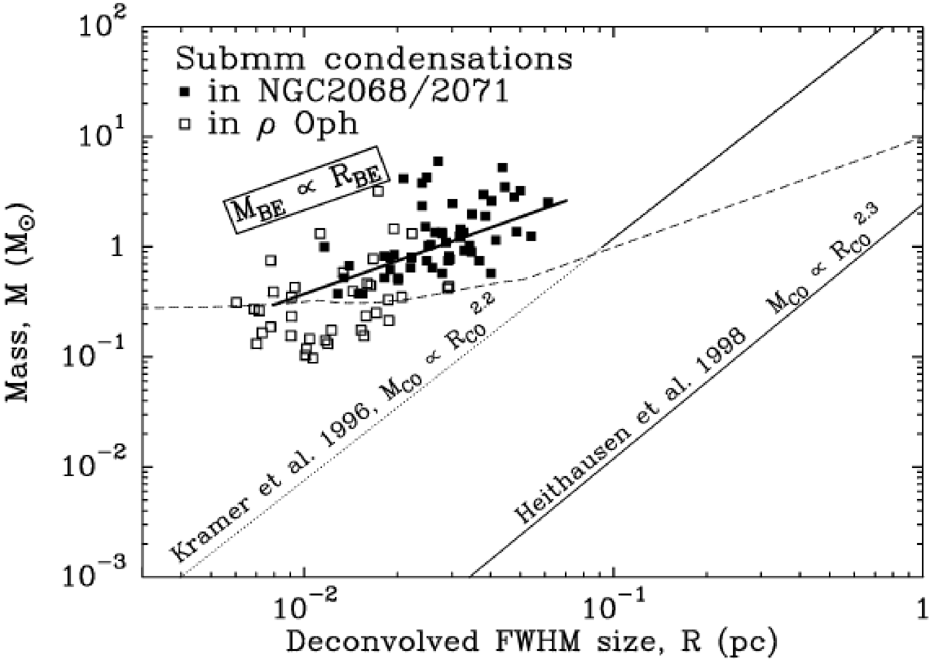
Johnston et al. 2006

- Core parameters hard to determine
  - Uncertainties from temperature and decomposition
- No power-law

Pre-stellar core mass functions

NGC2067/2071:



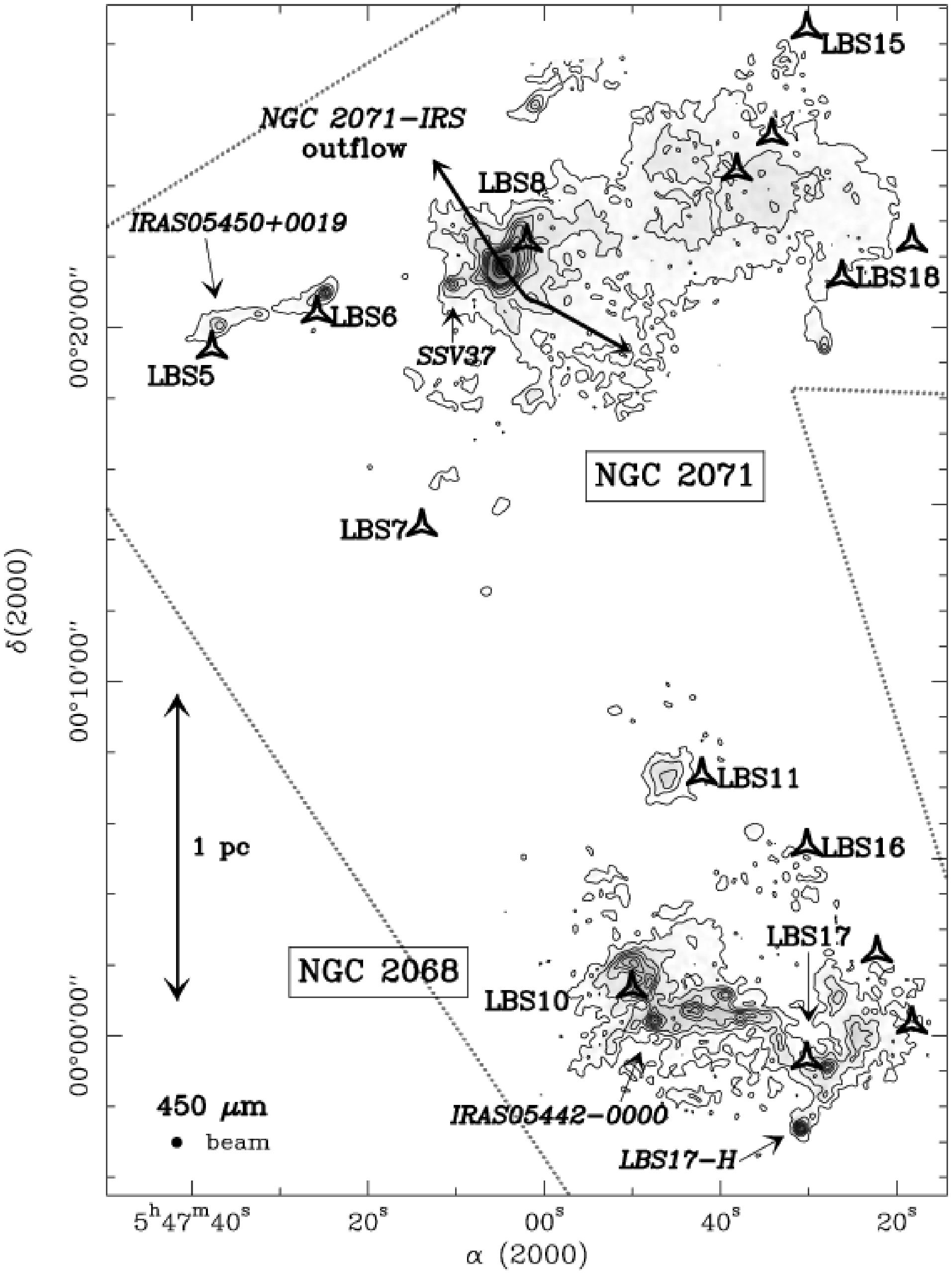


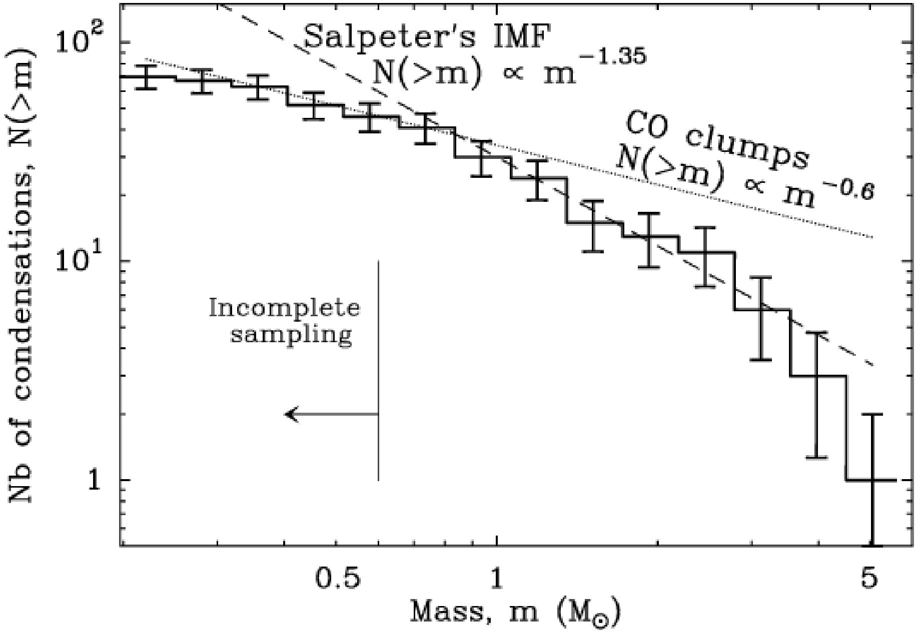
- Most cores gravitationally bound (critical Bonnor-Ebert spheres)
- Protostellar nature probable

Motte et al. 2001

Pre-stellar core mass functions

NGC2067/2071:

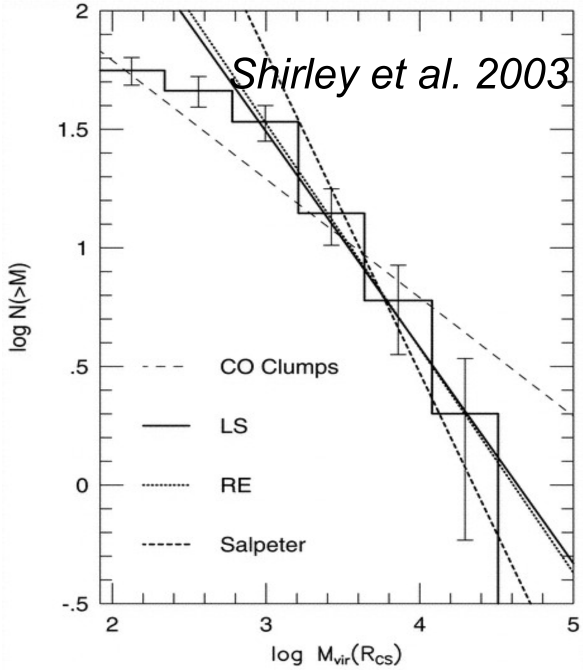


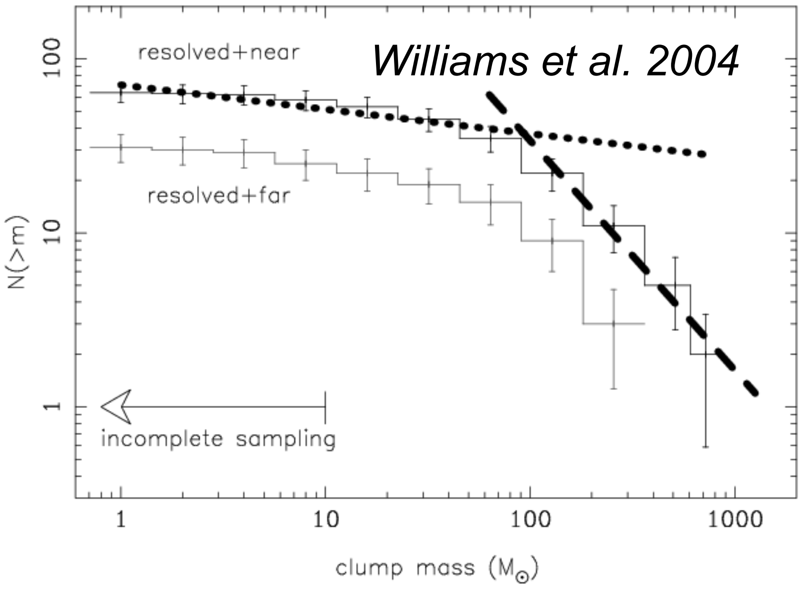


- Again two-slope CMF
- Reasonable match to IMF for $M > 1\ M_\odot$

Motte et al. 2001

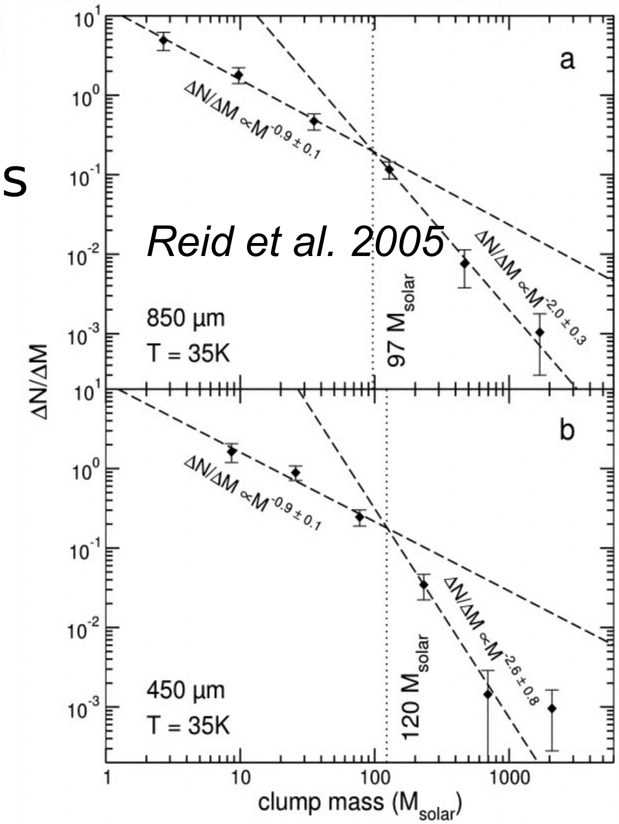
Going to high-mass star formation

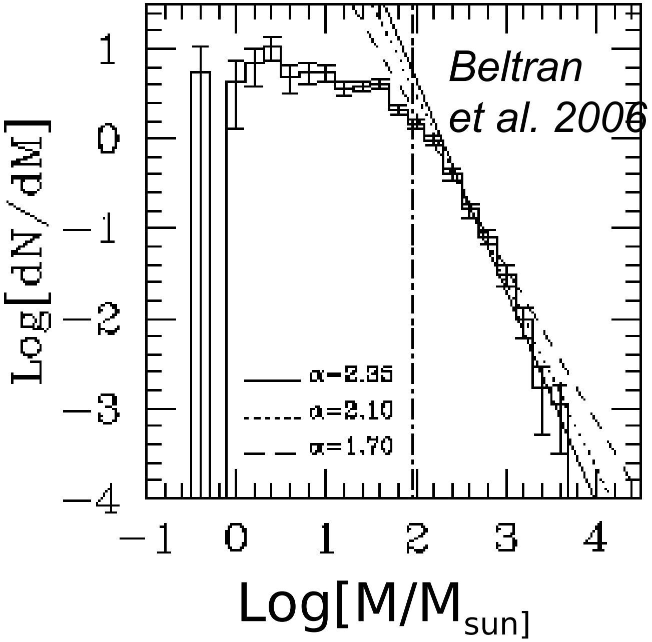

Shirley et al. 2003


Williams et al. 2004

Cumulative mass functions from single-dish surveys of massive star-forming regions resemble Salpeter-IMF.

But regions sample evolving clusters?!


Reid et al. 2005


Beltran et al. 2006

Pre-stellar core mass functions

New statistics from Herschel observations (2010):

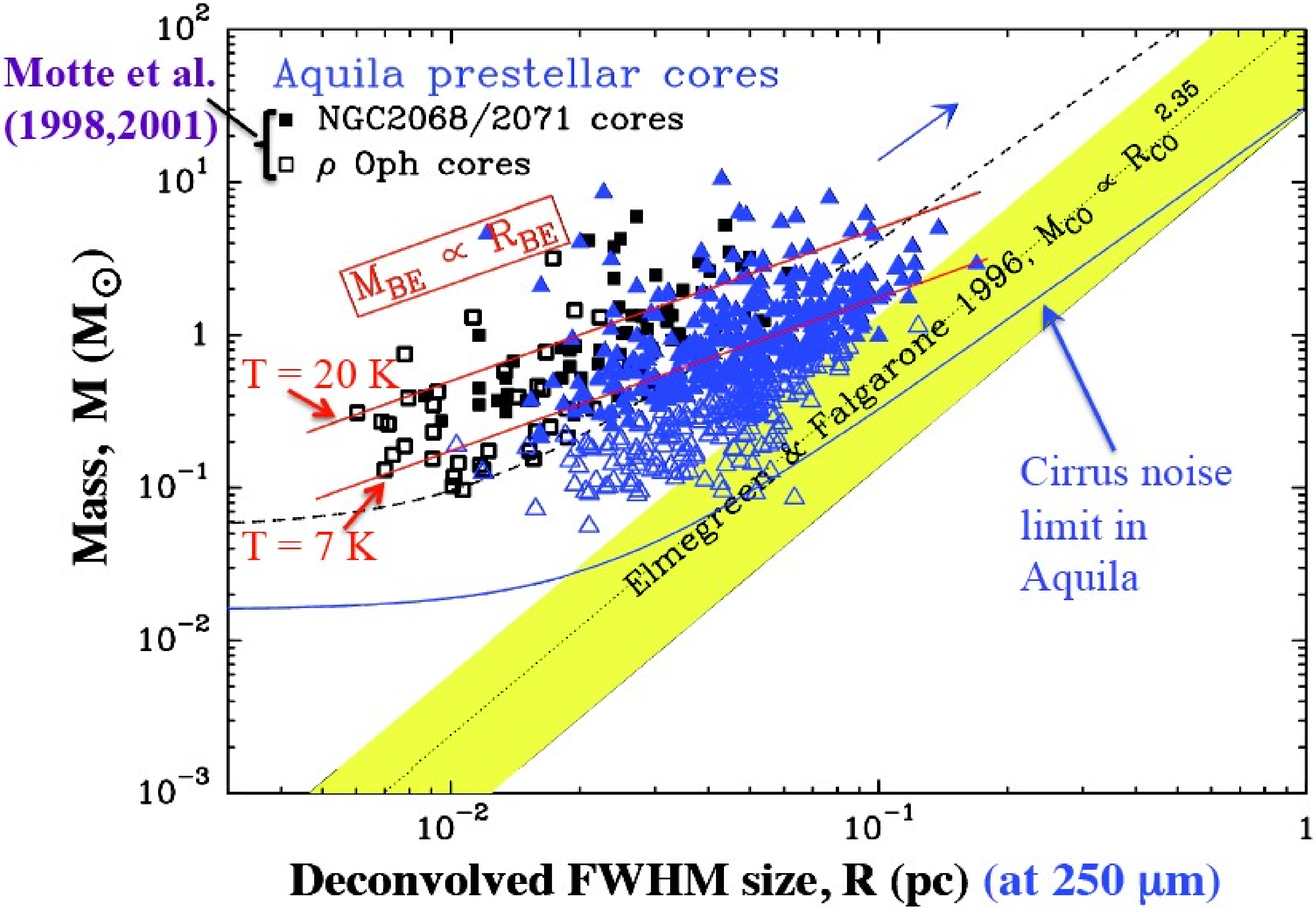
Aqulia rift (star-forming cloud)

- Red: 500μm
- Green 160μm
- Blue: 70μm

Factor 2-9 better core statistics than earlier core-mass-function studies

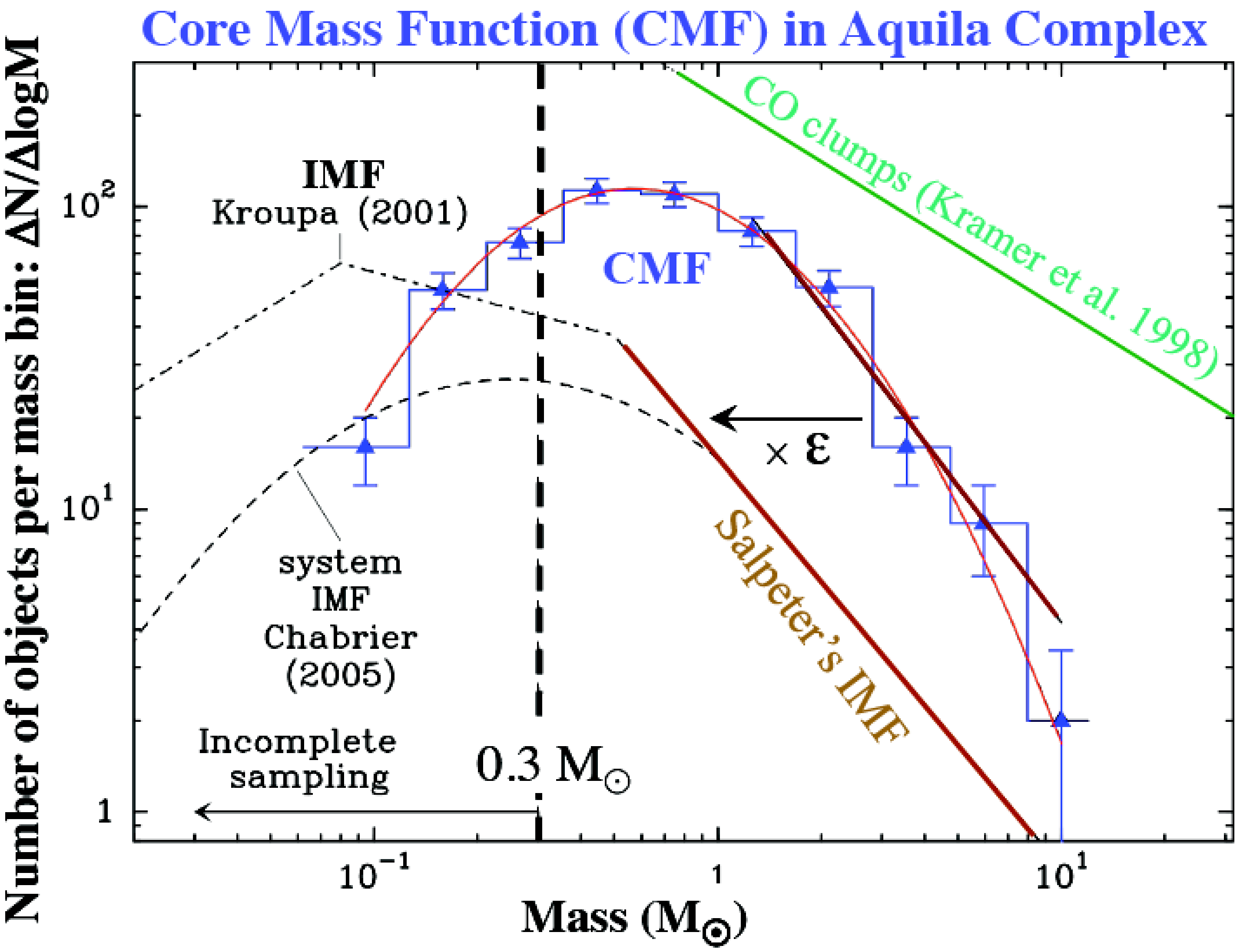
Andre et al. 2010,
Könyves et al. 2010

Pre-stellar core mass functions



- Most cores gravitationally bound (critical Bonnor-Ebert spheres)
- Probably more than 60% prestellar

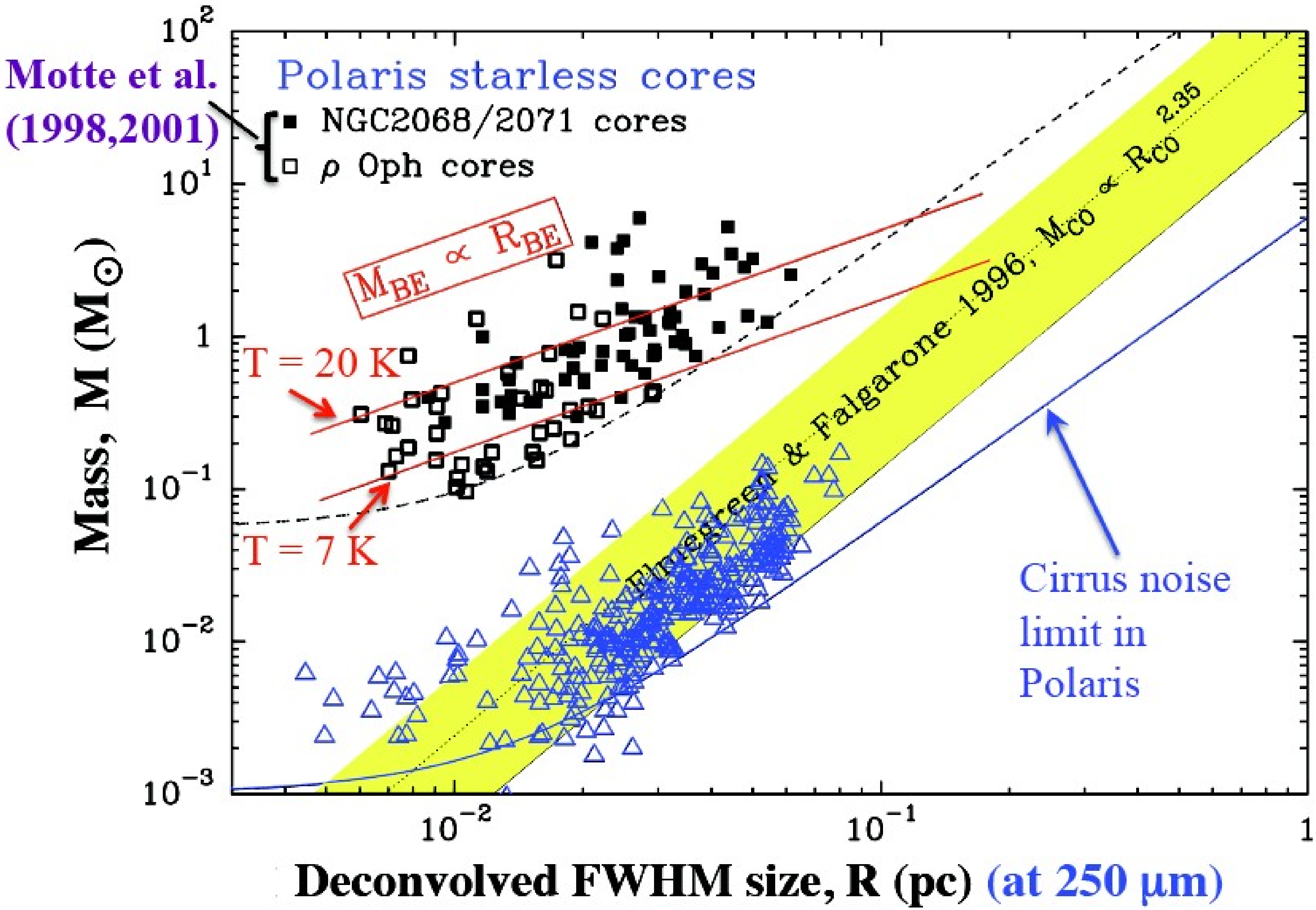
Pre-stellar core mass functions



Könyves et al. 2010

- Very good match between CMF and IMF
- Constant efficiency factor 0.2-0.4

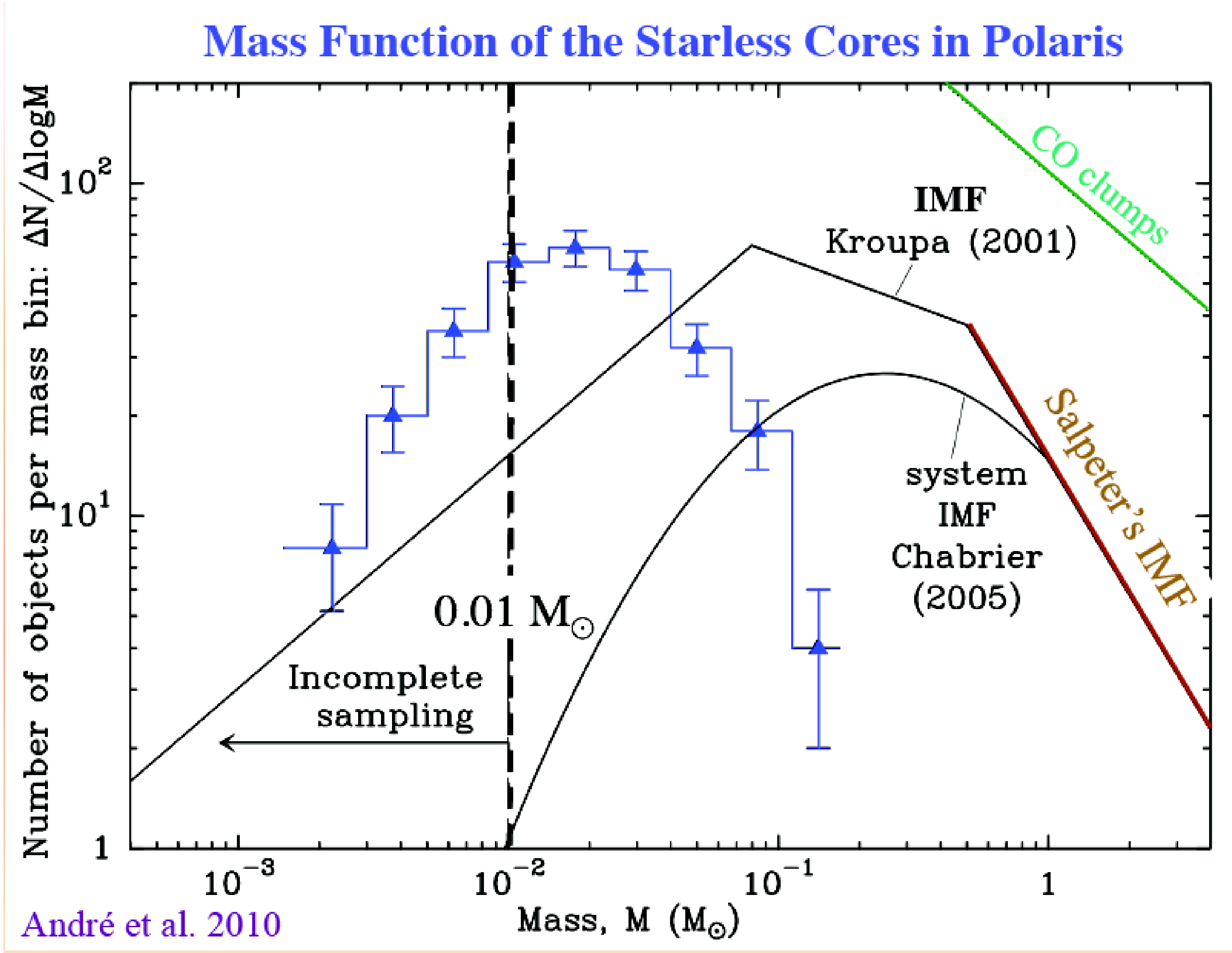
Compare: clump mass function



- Most clumps in Polaris Flare gravitationally unbound
- not prestellar (yet?)

Ward-Thompson et al. 2010

Compare: clump mass function



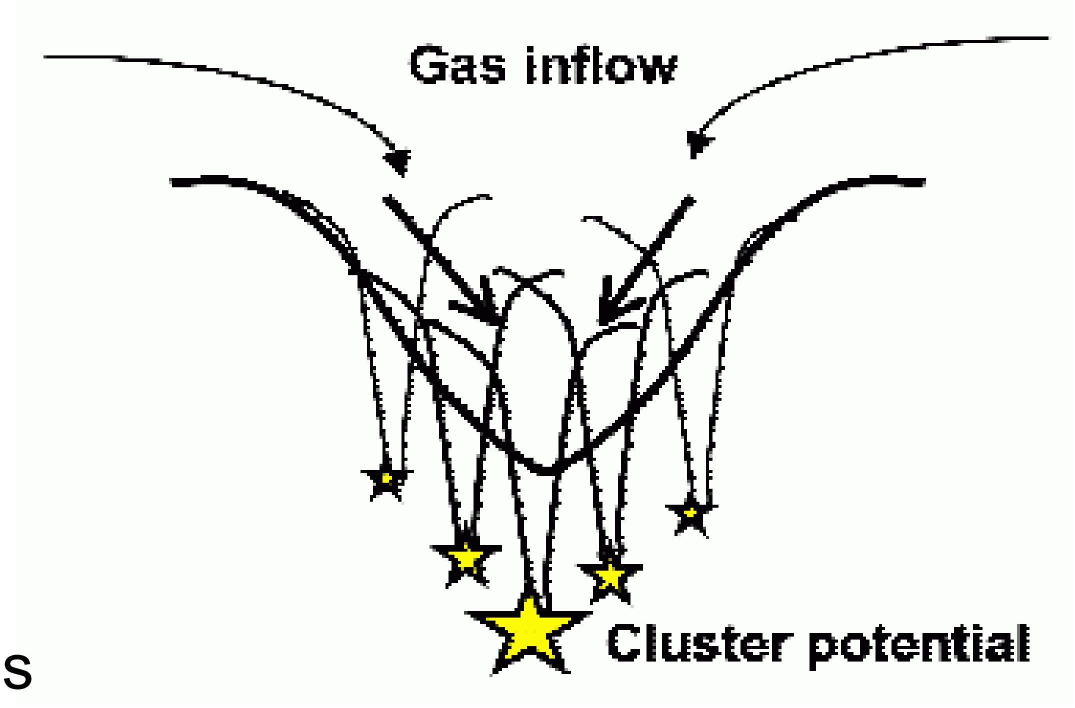
- Not massive enough to form stars (factor 3 in mass lacking)
- Still different spectrum from larger-scale clumps

From CMF to IMF

- Transition from clumps to protostellar cores
  - Through fragmentation
  - Clump-mass spectrum → Core-mass function
  - Massive change of slope
    - Clump mass function is too flat
      - Small clumps can form individual stars
      - Massive clumps have to fragment into multiple cores

- Transition from protostellar cores to protostars
  - Gravitational collapse
    - Competetive accretion, further fragmentation (?)
  - Core-mass function → “pre”-IMF
  - Seems to retain general shape
    - Individual cores form individual protostars
    - Efficiency factor (~0.3) to form protostars from cores
    - What happens to the rest of the cores?

Competitive Accretion

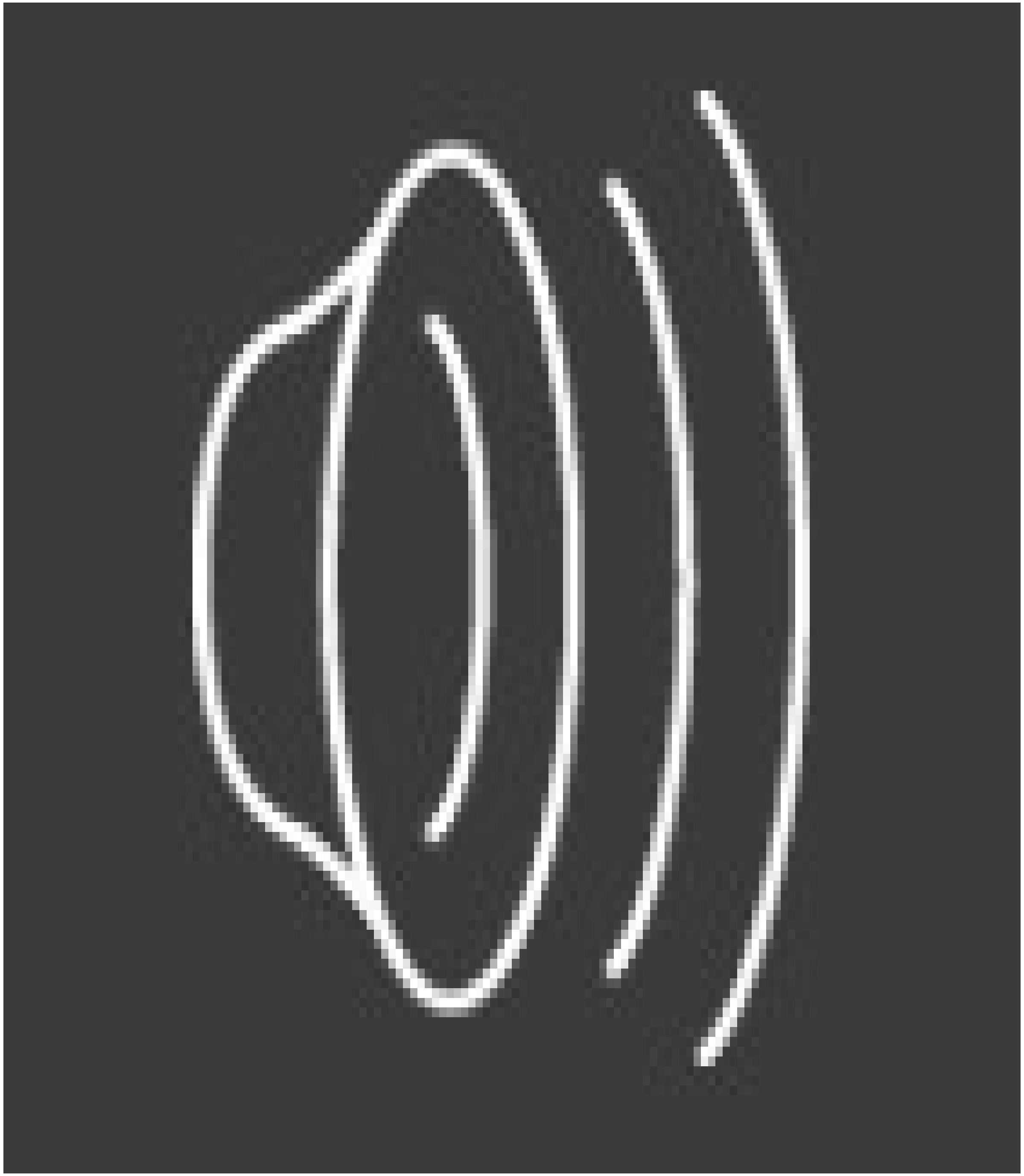


- Gas fragments into a large number of clumps with approximately one Jeans mass.

- Then each clump accretes gas from the surrounding gas potential.

- Clumps at different positions in the cluster and with different mass compete for the remaining gas.

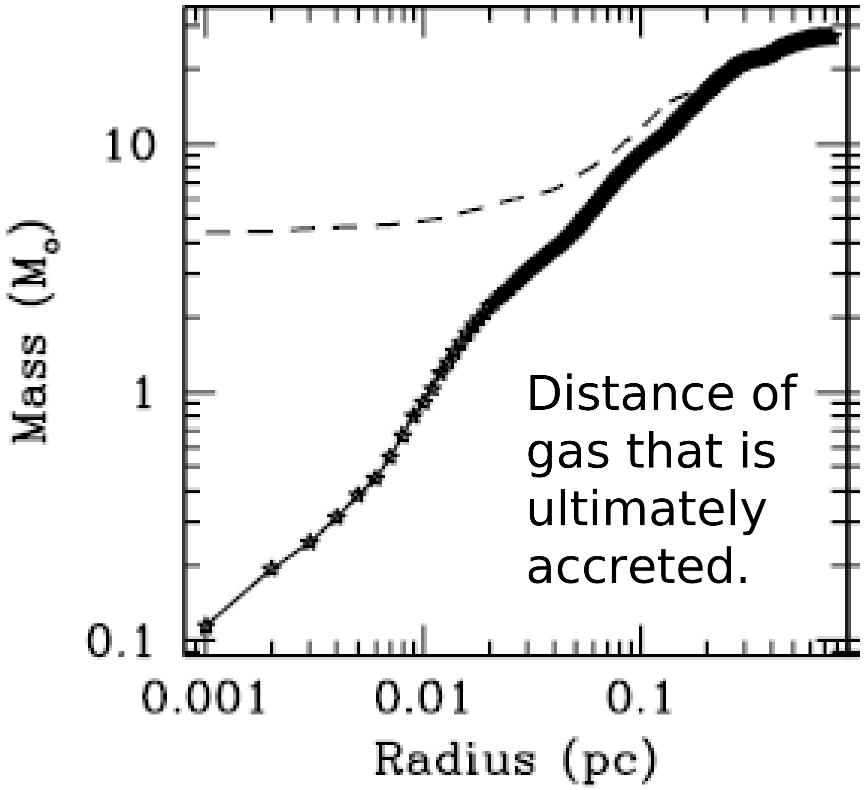
Competitive Accretion



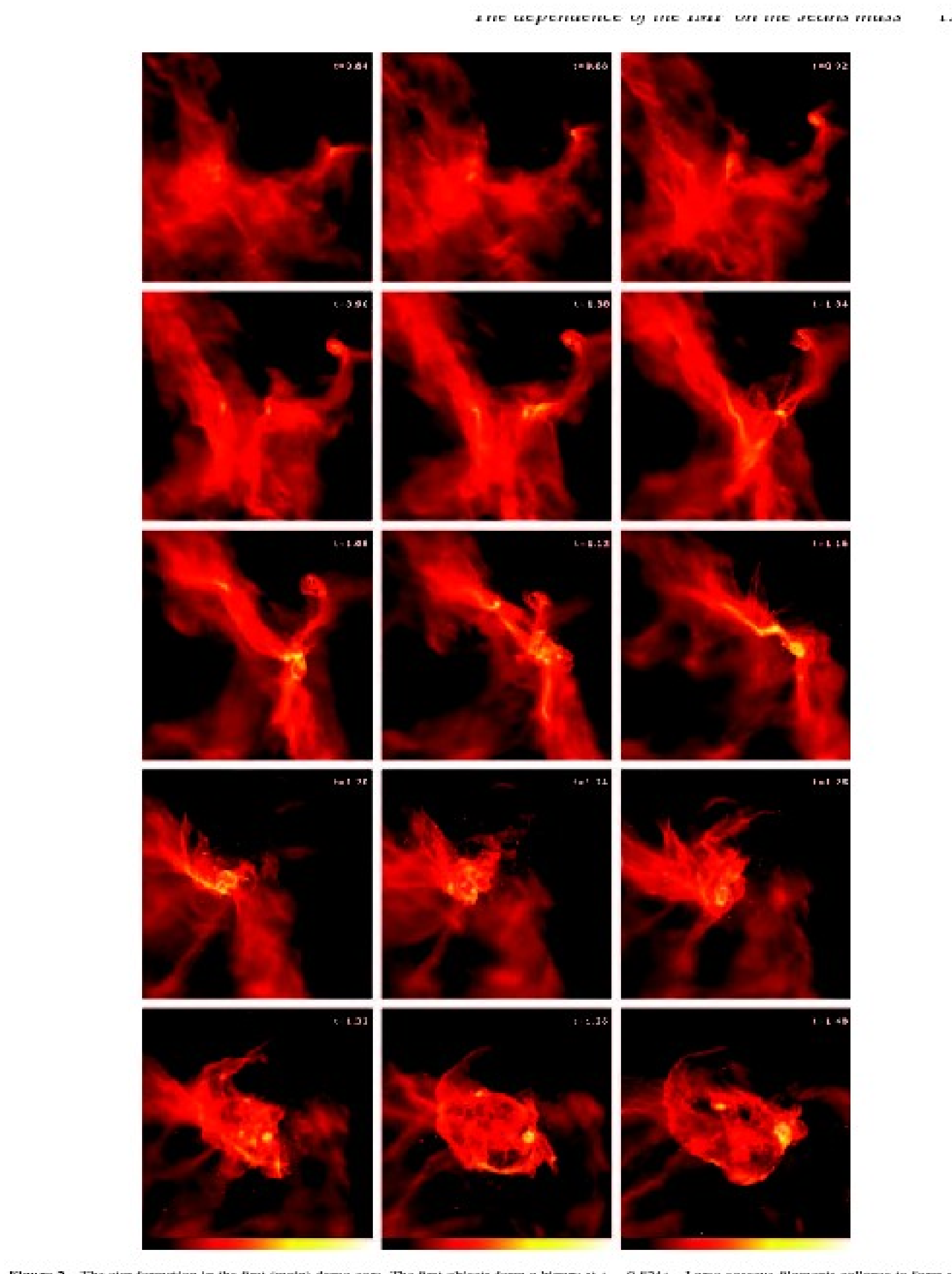
Continuation: see `flythrough.avi`

Competitive Accretion

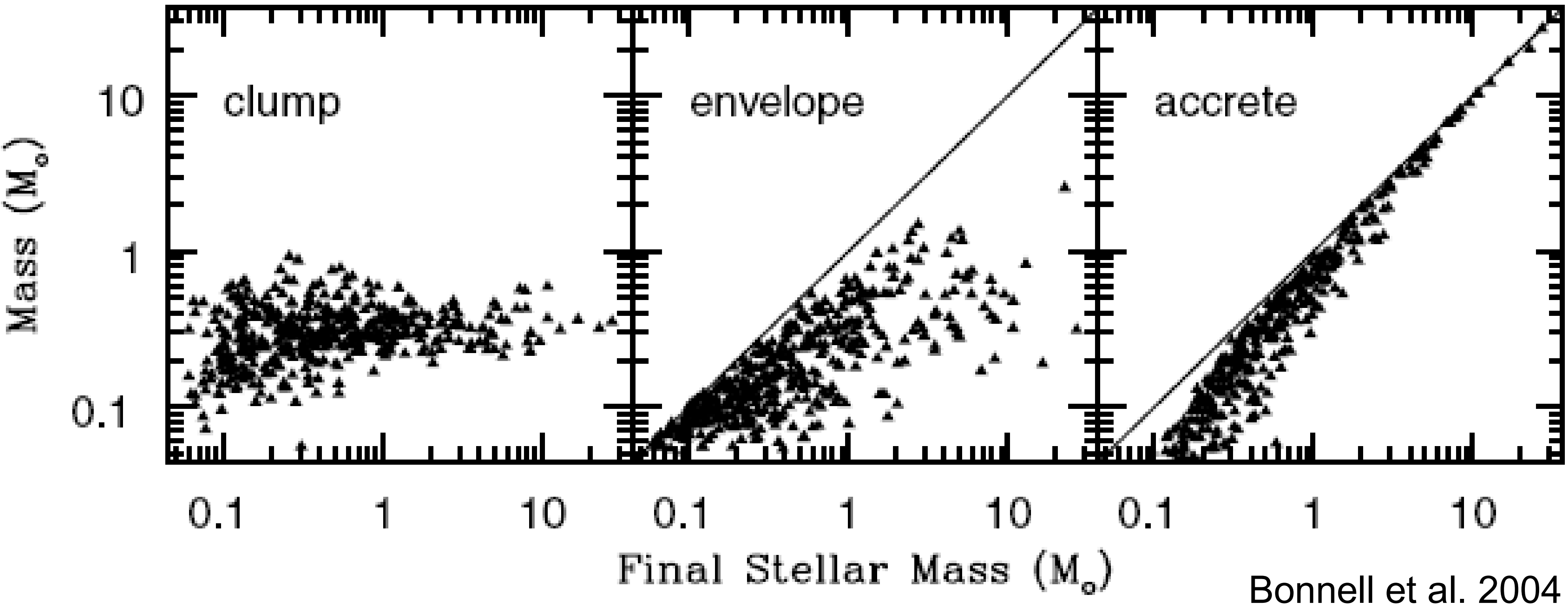
- Gas that was originally far away may finally fall onto the protostar.
- Higher mass protostars can sweep up gas from a bigger surrounding.



Distance of gas that is ultimately accreted.



Competitive Accretion

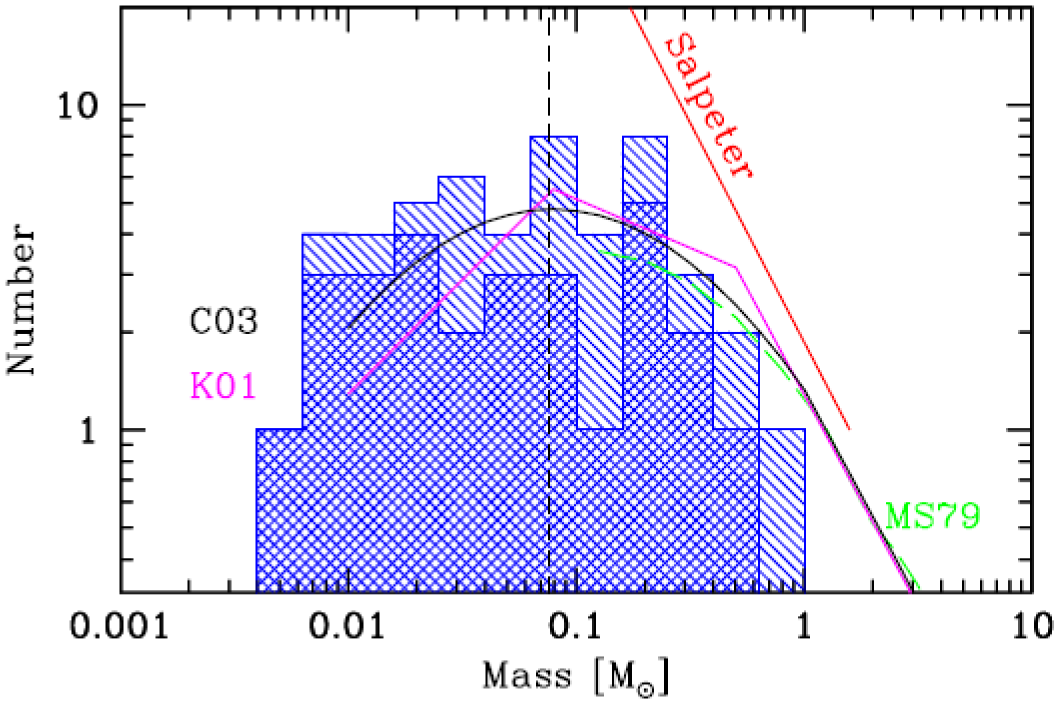


Bonnell et al. 2004

- Small clumps lose mass from competetive accretion.
- Large clumps win. Most of their protostellar mass is accreted.
- Creates a shallower IMF from the CMF
- But probably only way to explain high mass stars (next lecture).

Ejection

- Stars accrete at constant rate
- Until they are ejected by close enounter
  - Cannot further grow
  - Do no longer compete for reservoir
- Low-mass protostars are preferentially ejected

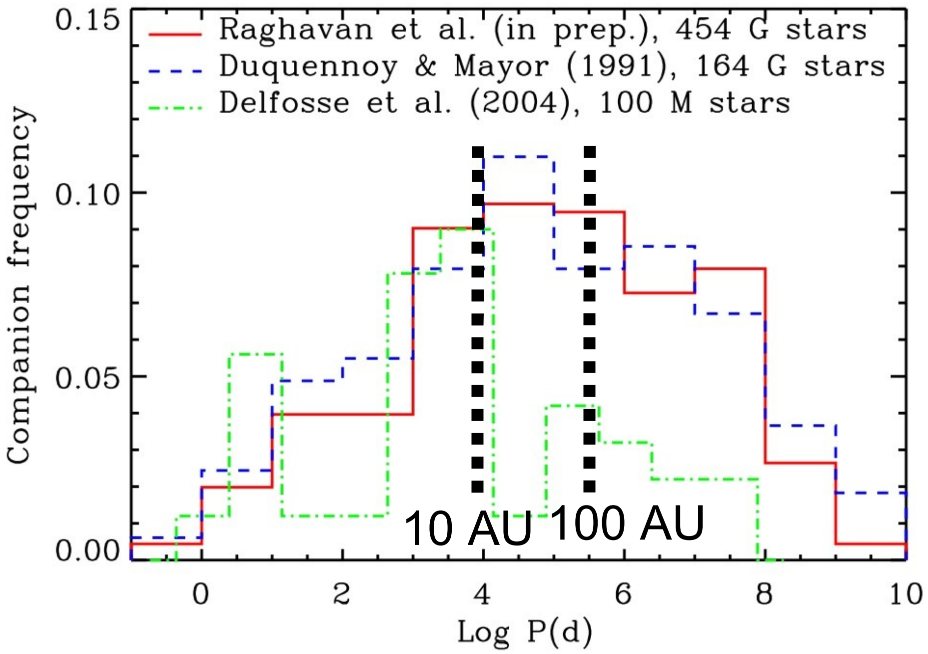


- Shape of IMF reproduced
- Size of simulation insufficient to create massive stars
- Very small dynamic range

Bate & Bonnell (2005)

Multiplicity

- Most stars are in binary (multiple) systems



G stars in binary systems (Duchene et al. 2009)

> 50% have companions

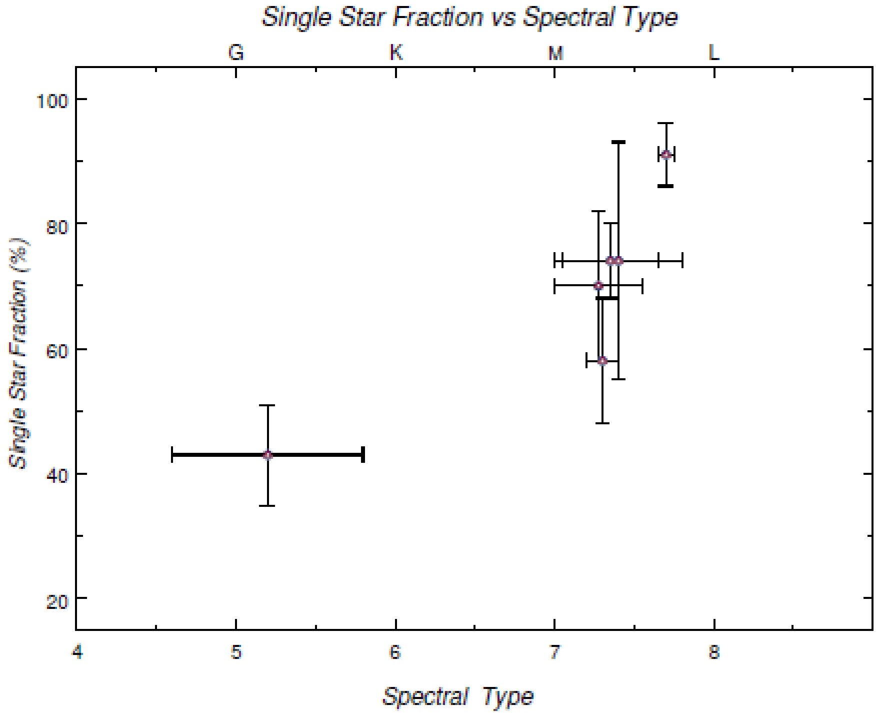


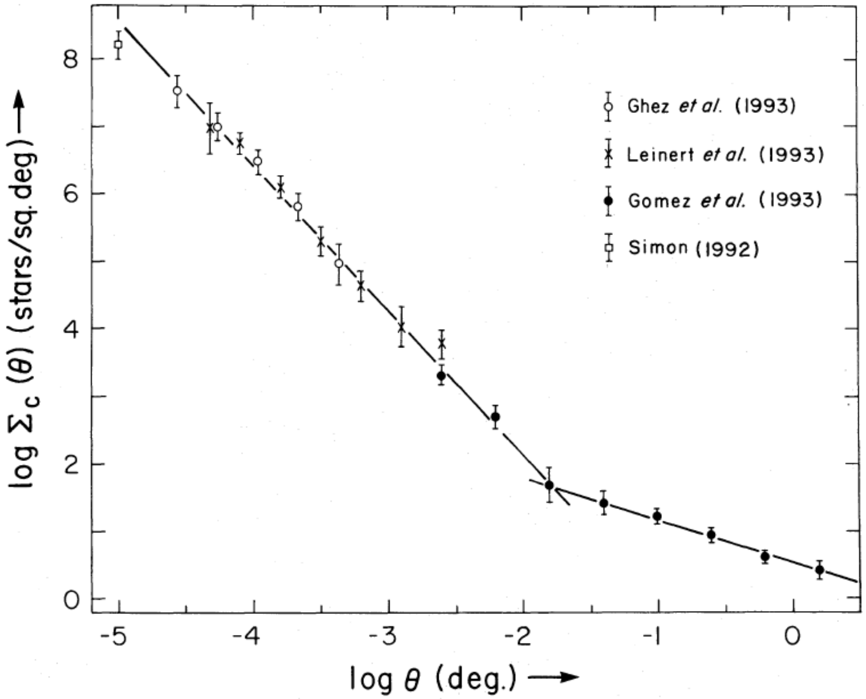
FIG. 1.— The single star fraction vs spectral type. The single star fraction increases significantly with spectral type reaching values of ∼ 75% for M stars, the most populous stars in the IMF and the field. Vertical error bars represent statistical uncertainties

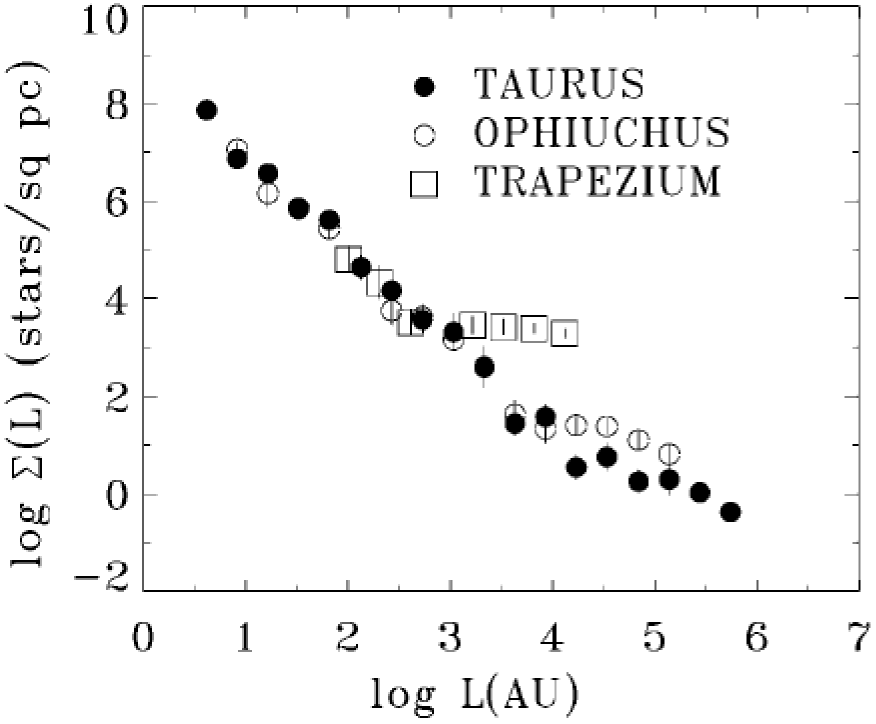
Lada (2006)

- Massive stars have less companions
- Most brown dwarfs are in multiple systems

Multiplicity

- Transition from clustered star formation to binaries in clusters





Larson (1995): Turn-over at 0.04pc ~ M_J=0.8$M_\odot$ ~ turn-over in IMF
Simon (1997): Different turn-over in different clusters → excludes M_J relation

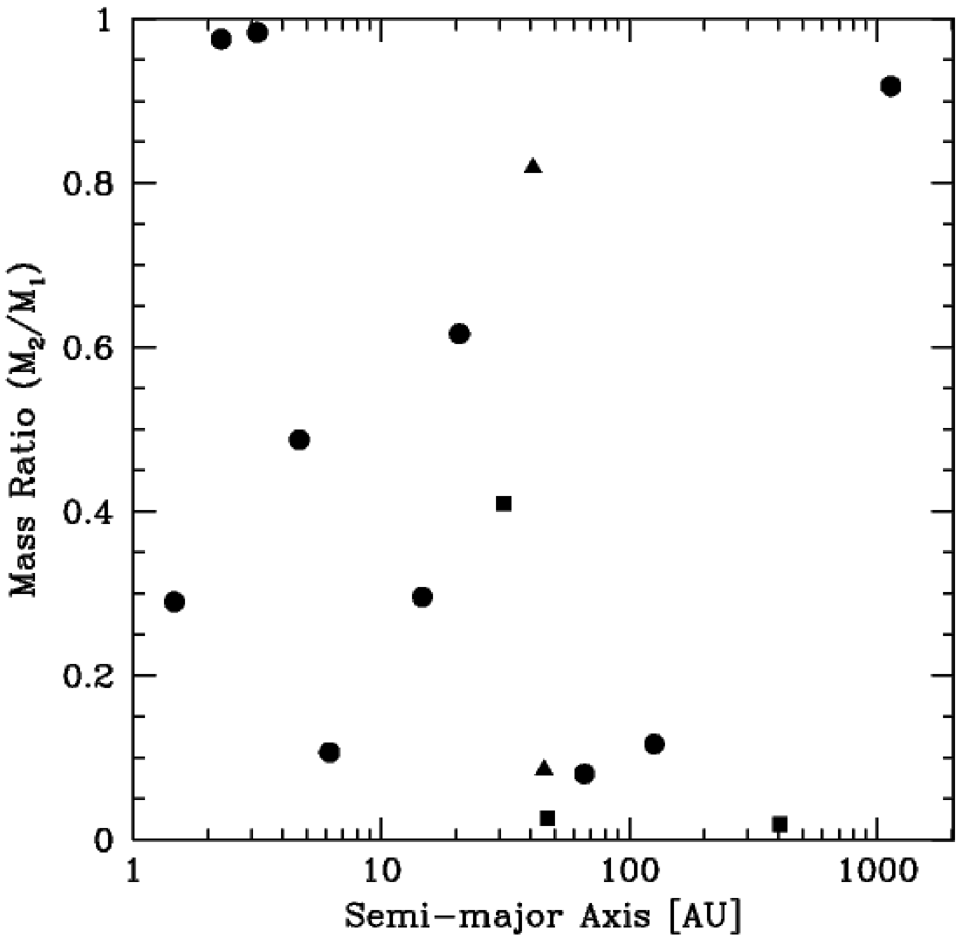
- Models need to reproduce wide range of semi-major axes in binary systems

Multiplicity

Competitive accretion-ejection model:

- Ejection typically kicks out brown dwarfs
- Preference of equal-mass systems

- Fraction of multiple systems too small
- Fraction of BD binaries grossly underestimated



Bate et al (2003)

From CMF to IMF

- Transition from protostars to stars
  - Competetive accretion
  - Ejection
  - Coalescence (?)
  - Role of multiplicity not understood

Contradicting results from observations and theory:

- Observations:
  - Clump mass spectrum shallower than IMF
  - Core-mass-spectrum = shifted IMF

    → Critical step for IMF is formation of gravitationally bound cores (Bonnor-Ebert cores)

    → Pre-collapse CMF determines IMF

From CMF to IMF

Contradicting results from observations and theory:

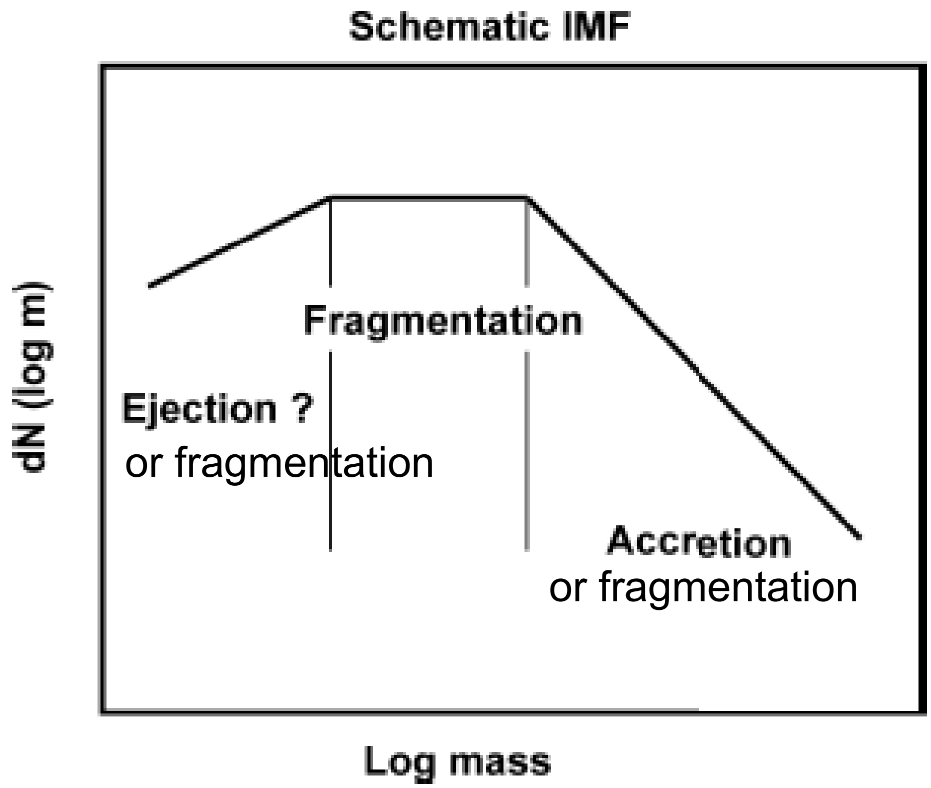
- Theory:
  - Core mass spectrum narrow, determined by Jeans mass
  - Broad power law IMF created by competetive accretion

    → Jeans mass determines core mass spectrum
    → Competetive accretion and its termination by ejection determine IMF

- Both approaches give consistent explanation for the IMF!

- But:
  - Why is the IMF universal?
  - Hidden mass not traced by clump/core observations
  - Multiplicity

General conclusions



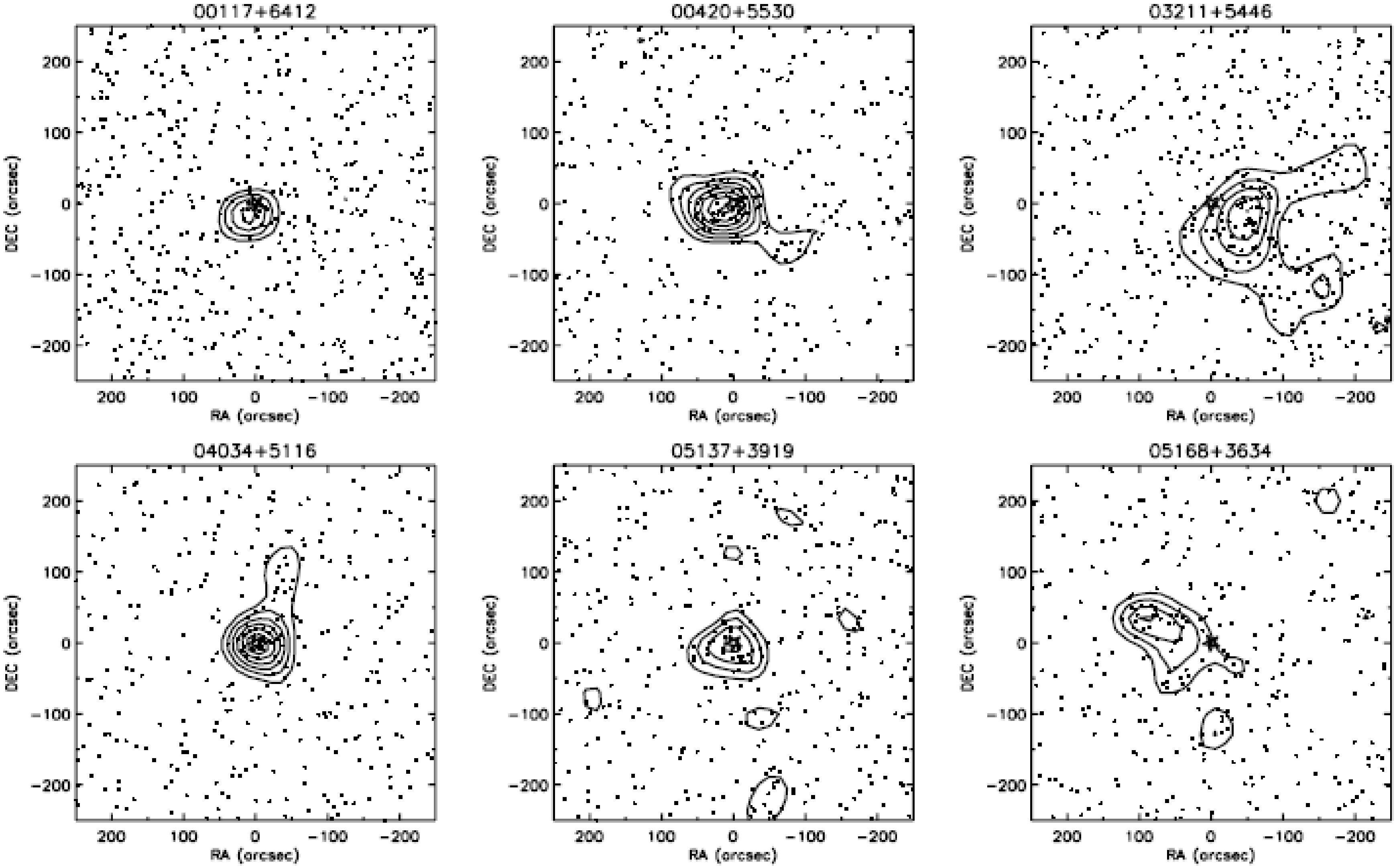
Agreement that:

- Characteristic plateau must be due original fragmentation processes.
- At the low-mass end, fragmentation is not efficient enough and dynamical ejection is important.

Dispute wether:

- Large, massive fragments are stable to form the Salpeter tail
  - Models favour fragmentation down to M_J at minimum temperature
  - Observations suggest that heating from first protostars could increase M_J so that fragmentation results in power-law CMF
- Competetive accretion creates the tail or is insignificant

Order of star formation



Kumar et al. 2006

- Detection of a clusters of class I and II objects around young High-Mass Protostellar Objects.
- Since the the massive HMPO are still forming, this may indicate that low-mass sources form first and high-mass sources later.

The uniformity of the IMF

The IMF is surprisingly uniform, it does not change significantly with

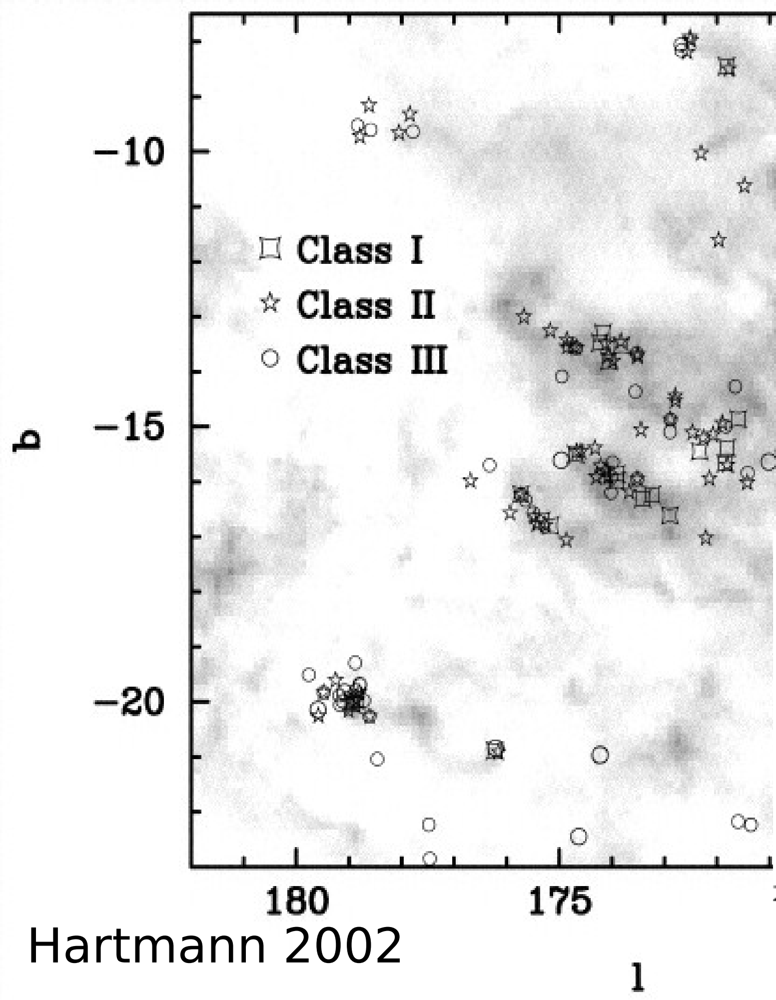
- pressure,
- temperature,
- metallicity

of the star forming clouds – in our Galaxy.

This contradicts theories of fragmentation, because the Jeans-length of fragmentation **does** depend on these quantities.

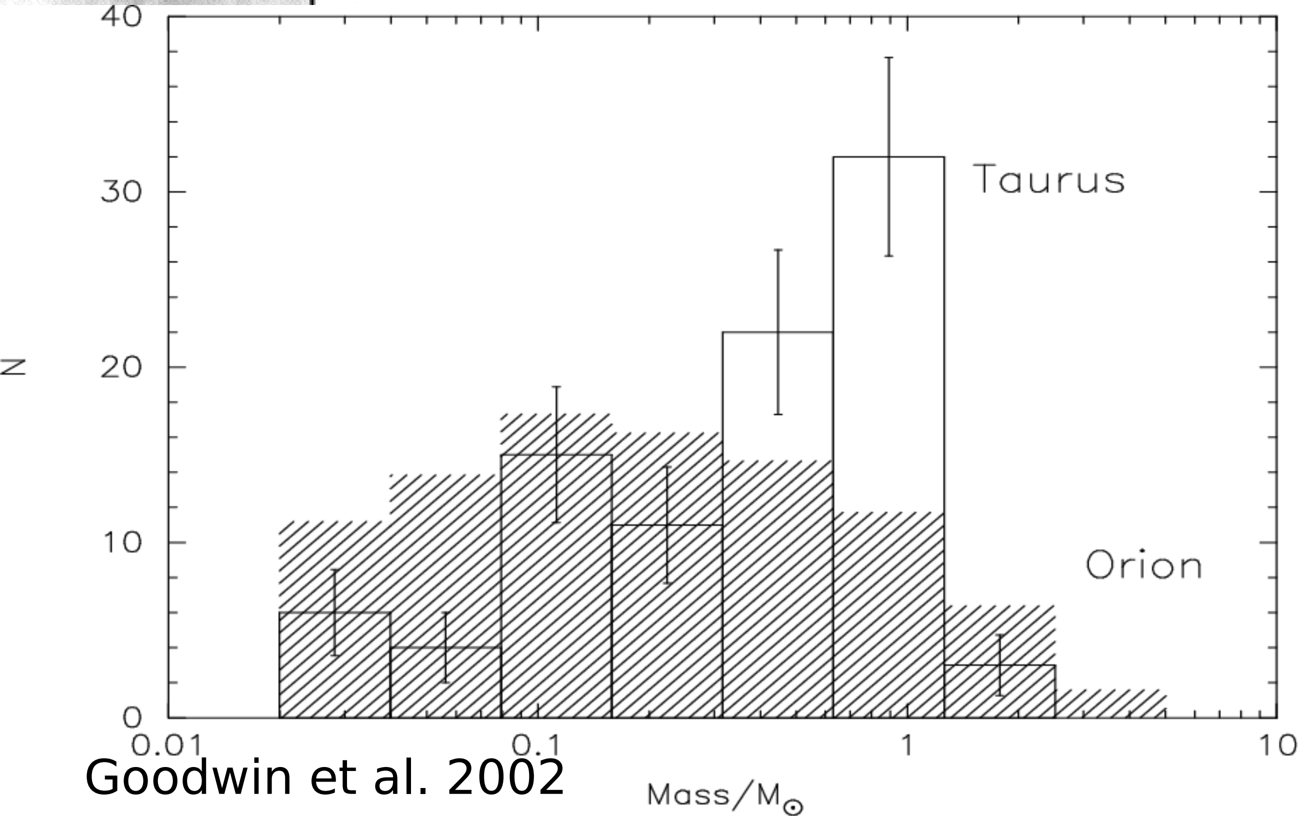
- There is some evidence that the IMF does change in extremely metal-poor environments.
- There is some evidence that the IMF in super star clusters (in starbursts) is top-heavy, but not for starbursts in general.

Deviations from the IMF: Taurus



Hartmann 2002

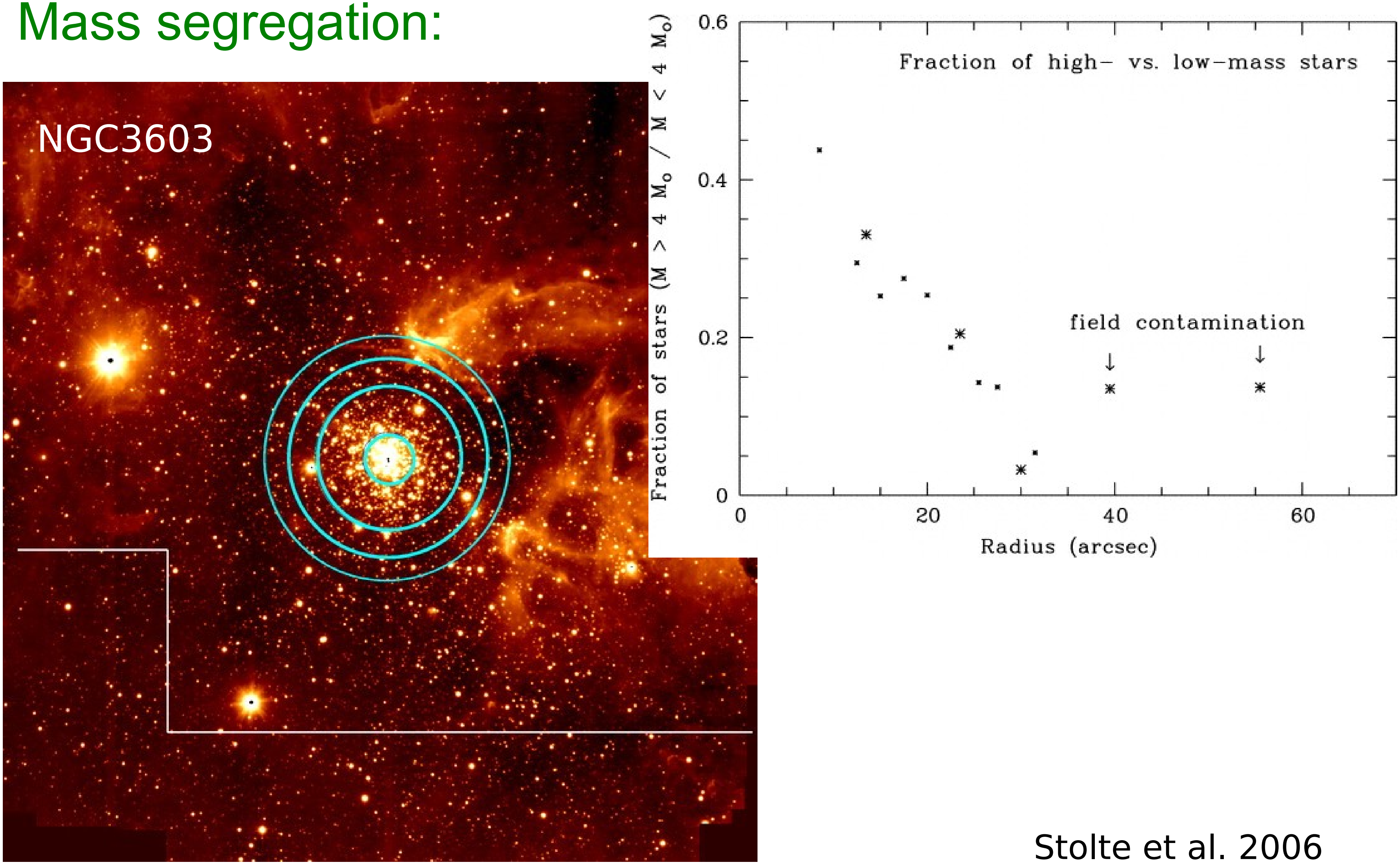
- Taurus: filamentary, more distributed mode of star formation.
- The core-mass function already resembles a similar structure.



Goodwin et al. 2002

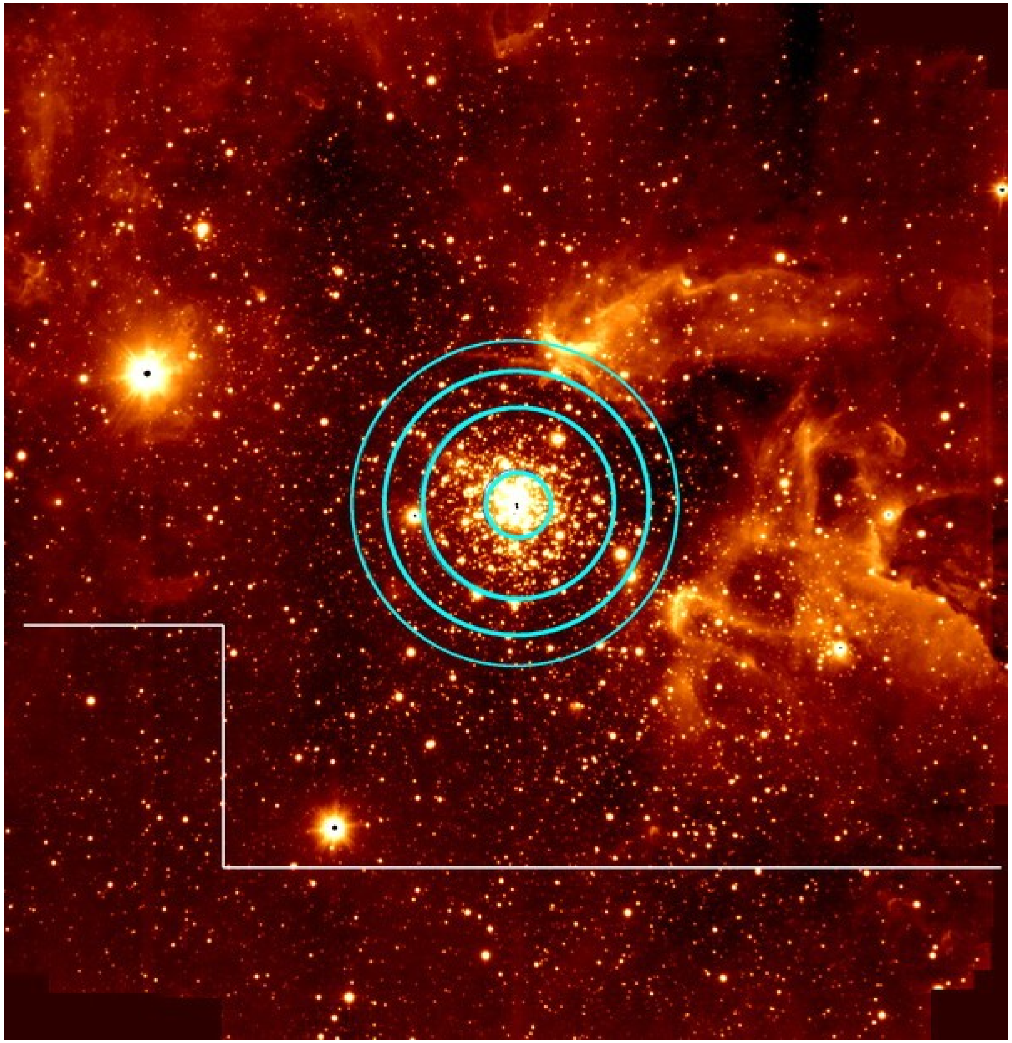
The uniformity of the IMF

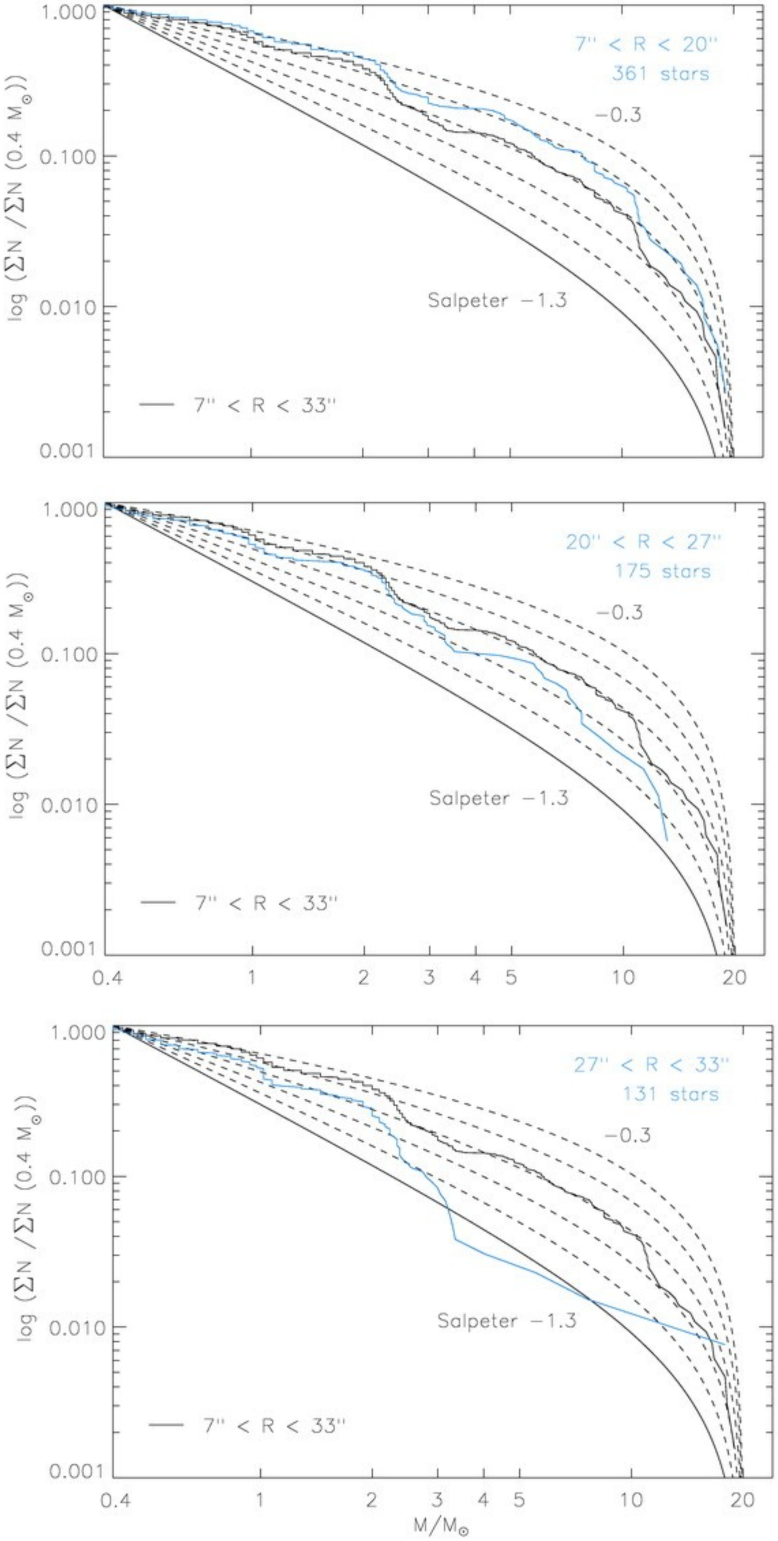
Mass segregation:



Stolte et al. 2006

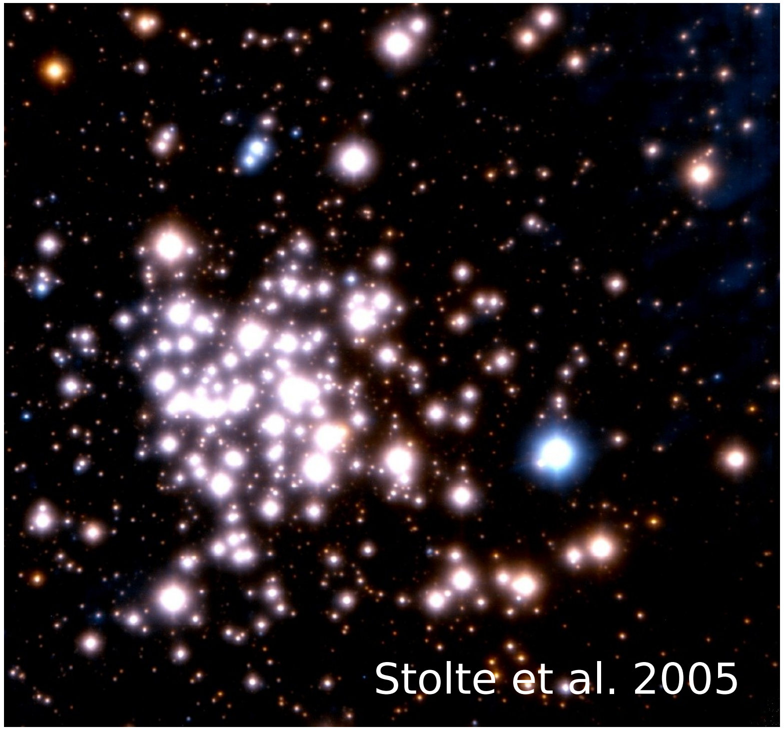
Mass segregation

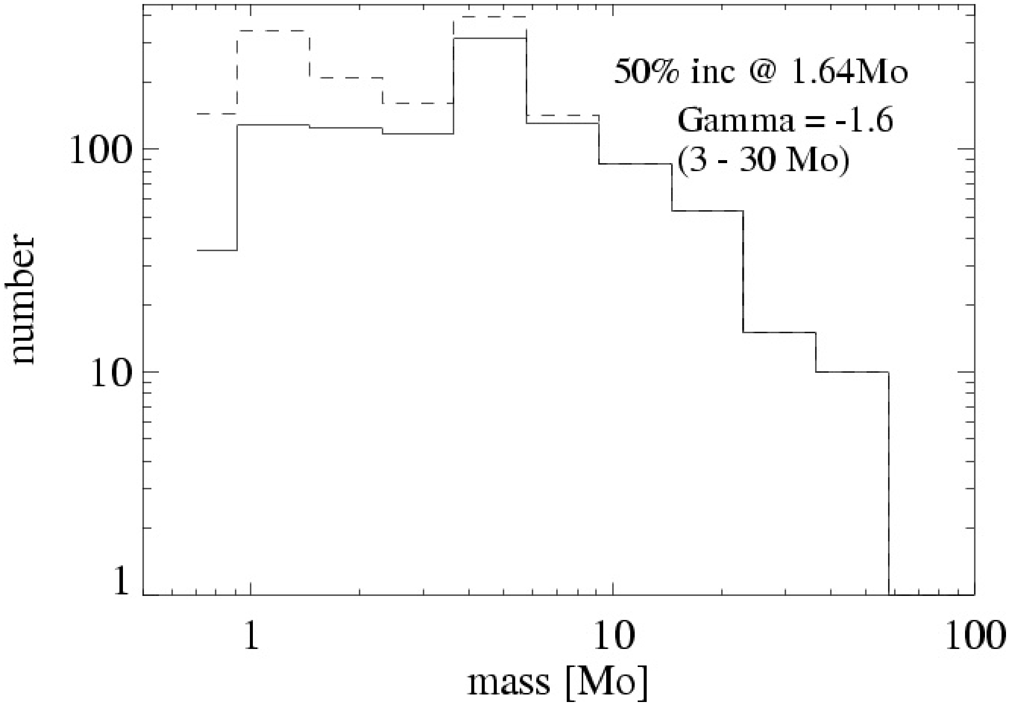




Variations of the stellar mass function:
→ IMF variation or posteriori change?

The IMF in extreme environments


Stolte et al. 2005



Low-mass deficiency in Arches cluster near Galactic center.
The average densities and temperatures in such an extreme environment close to the Galactic Center are much higher
→ Gas and dust couples at higher temperatures.
→ Clouds become earlier opaque for own cooling.
→ Larger characteristic mass for the fragmentation process!