Properties of Embedded Clusters

Models versus Observations

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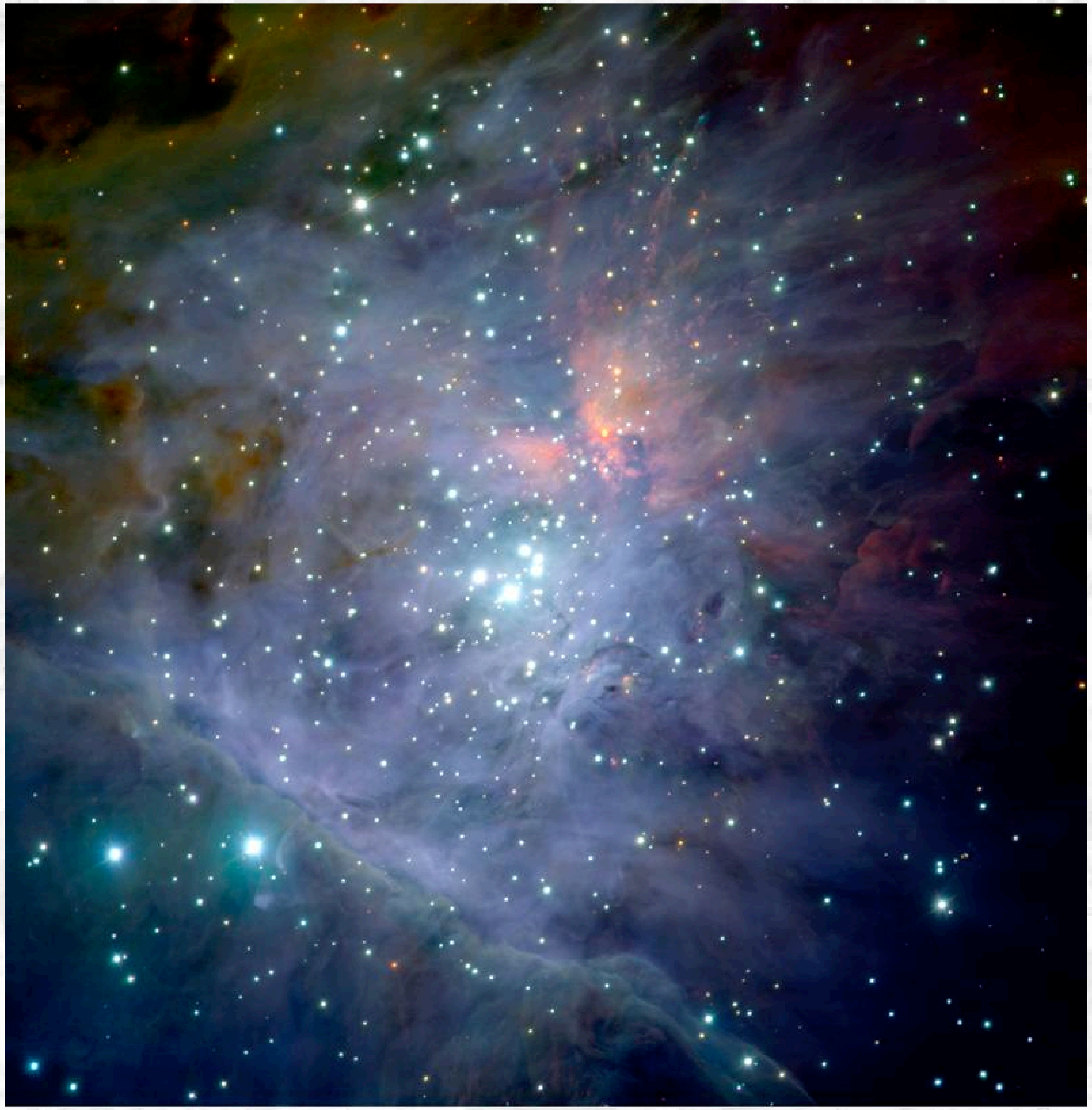
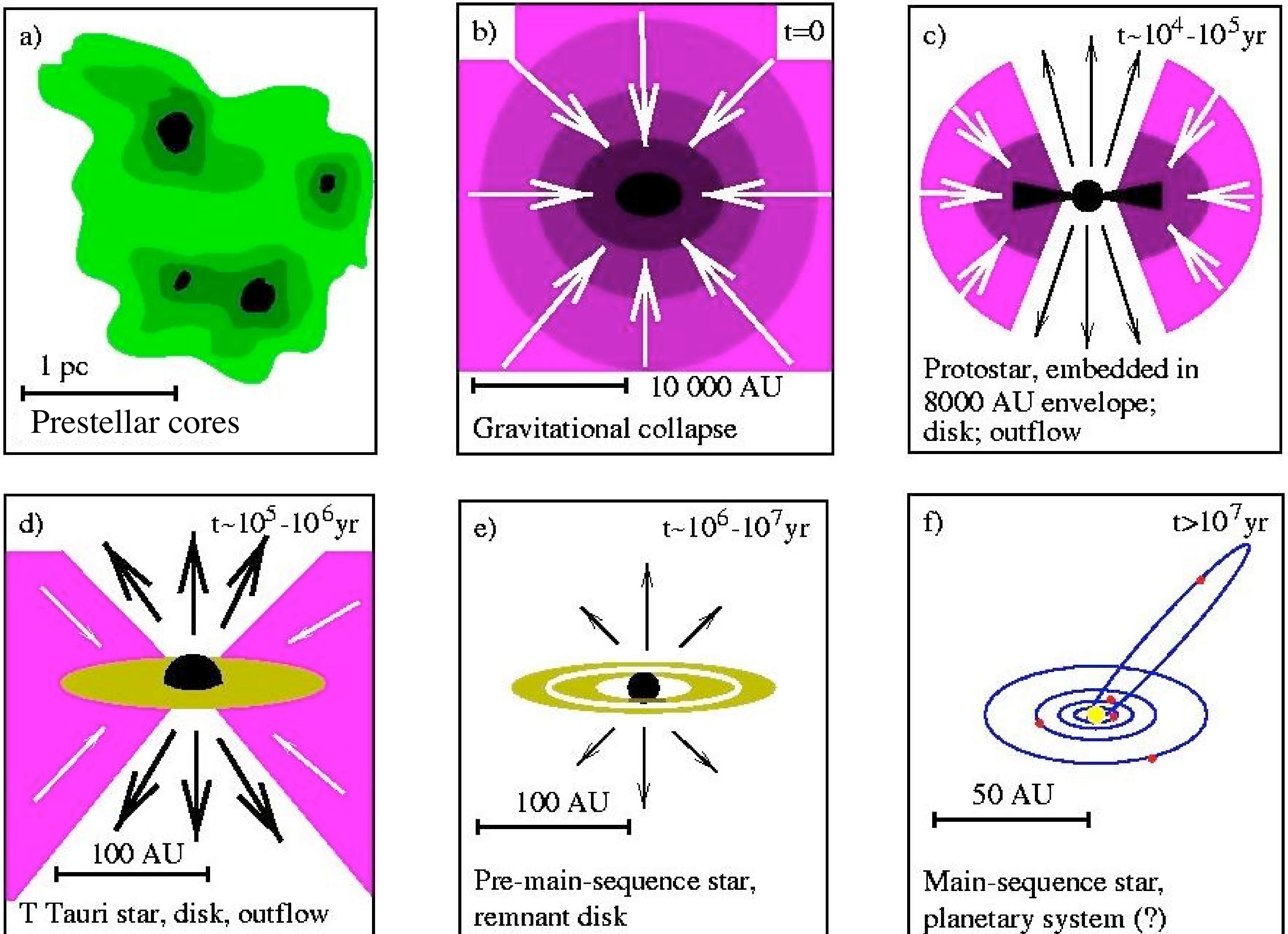
Stars form...



M. McCaughrean, ESO

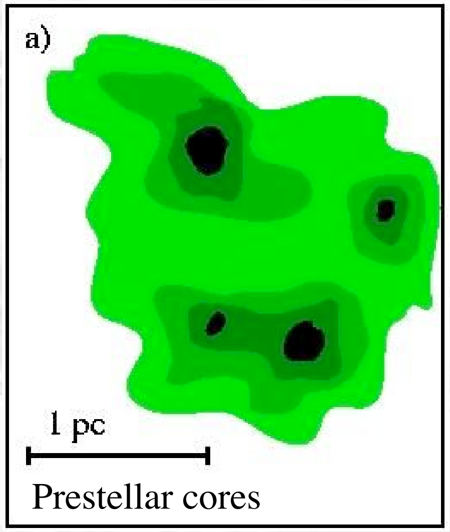
- in the dense cores of molecular clouds
- in clusters
- continuously
- with an efficiency $\lesssim 30\%$

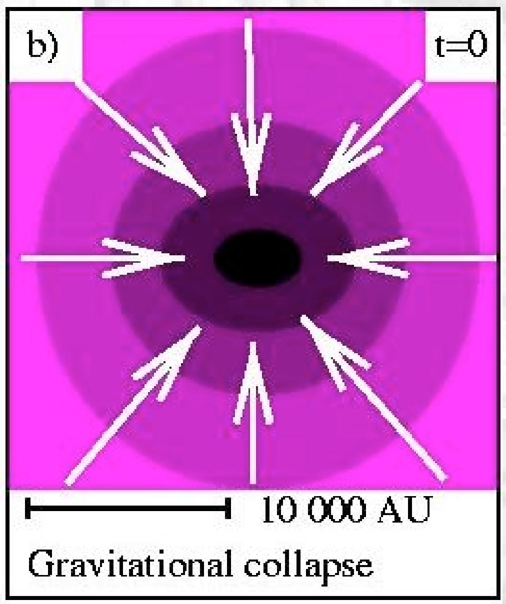
From Clouds to Stars

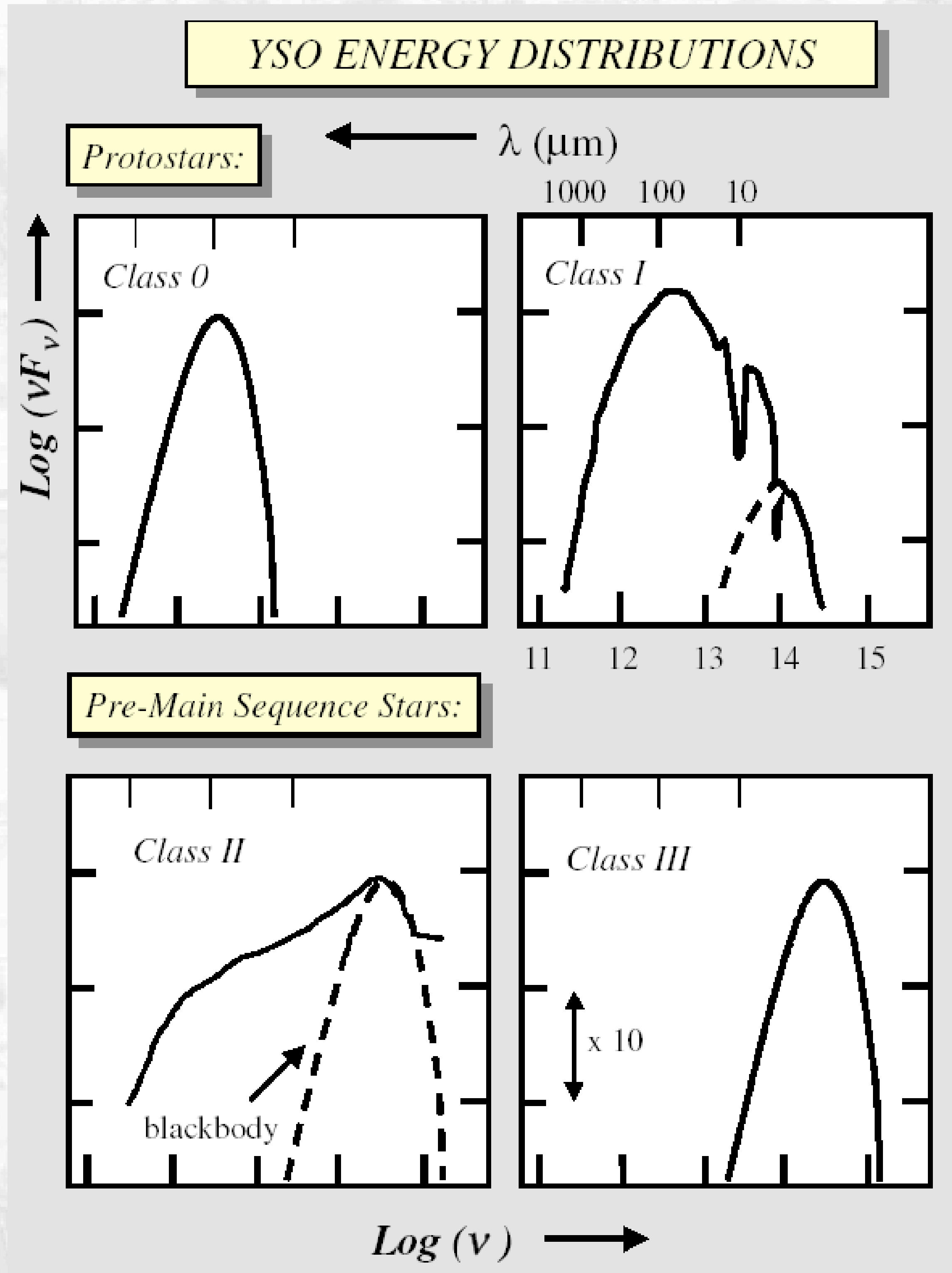


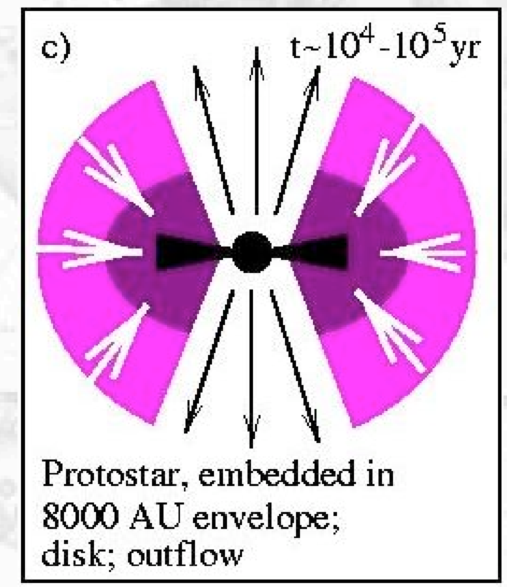
(Hogerheijde 1998, after Shu et al. 1987)

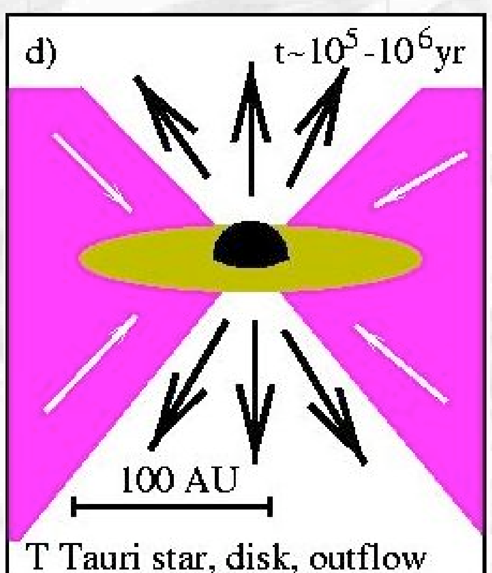
YSO Classification

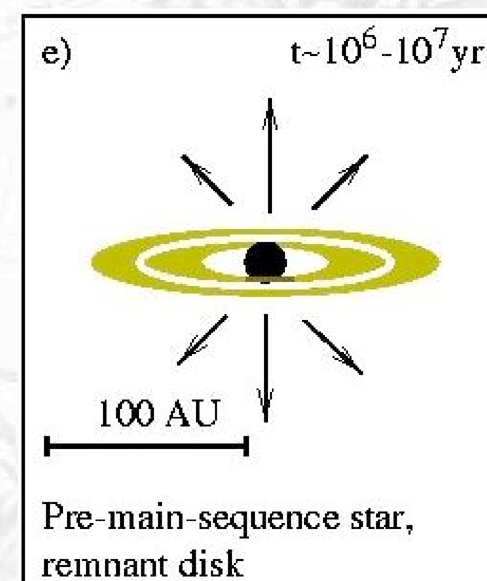












(Hogerheijde 1998, after Shu et al. 1987; Lada 2001)

"Standard Model" of SF

"Standard model" of star formation (Shu 1977):
stars form by inside-out collapse of a singular isothermal sphere (SIS), initially in quasistatic equilibrium,
supported against gravity by magnetic and thermal pressure
evolution only due to ambipolar diffusion processes

problems:

- only applicable to isolated stars
- observed magnetic fields probably not strong enough
- long timescale
- constant mass accretion rates

➡ Star formation controlled by interplay between gravity and supersonic turbulence

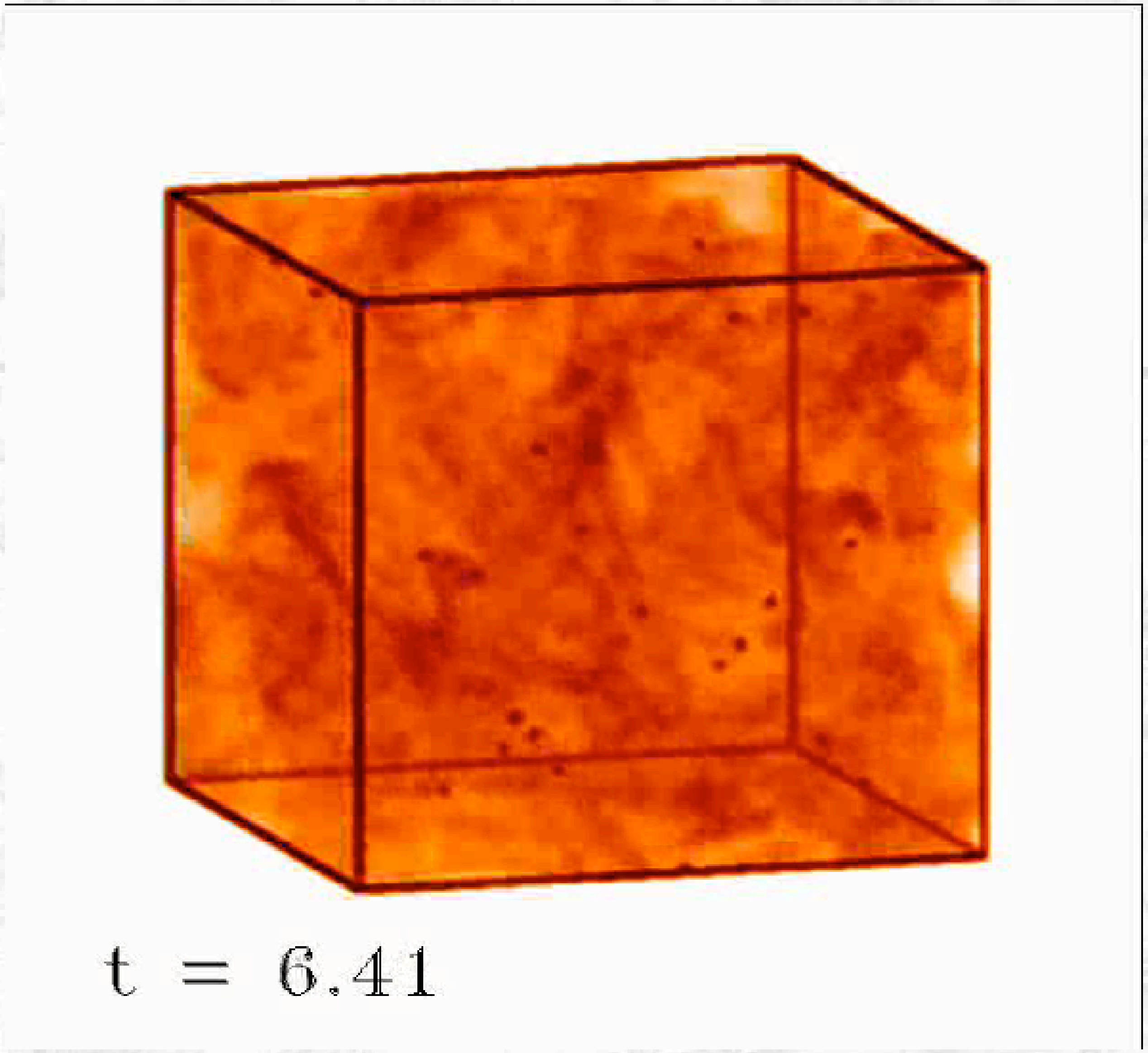
Supersonic Turbulence

- observed ubiquitously within the Galaxy
- Mach numbers $\mathcal{M} \approx 10$ $(\mathcal{M} = v/c_s)$
- counterbalances gravity on global scales
- produces strong density fluctuations → local collapse
- hierarchical and complex (clumpy) density and velocity structure
- moderates the star formation process (Mac Low & Klessen 2004)

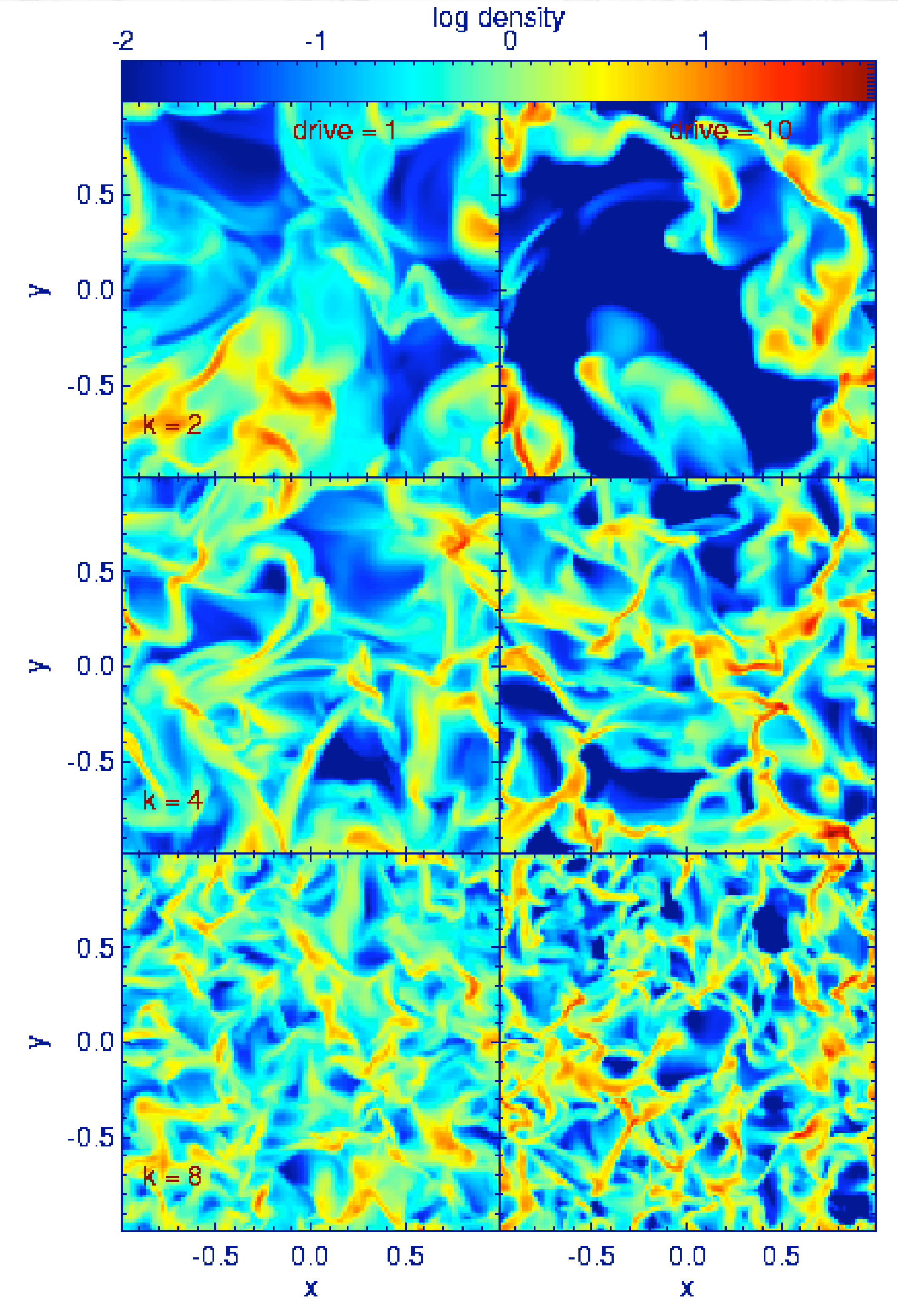
Turbulence plays a dual rôle!

Numerical Simulations

- smoothed particle hydrodynamics (SPH) (Lagrangian method)
- periodic boundaries
- sink particles
- resolving large density contrasts, long timescale



Numerical Simulations



(Mac Low 1999)

- isothermal equation of state
- two models contracting from initial Gaussian conditions without turbulence
- different turbulent environments: $0.1 \leq \mathcal{M} \leq 10$, $k = 1..2, 3..4, 7..8$
- initial conditions typical for observed star-forming regions
- magnetic fields, feedback mechanisms neglected

Properties of Embedded Clusters

- **local properties** (properties of individual objects):
  - properties of individual clumps (e.g. shape, radial profile)
  - accretion history of individual protostars
  - SEDs of individual protostars
  - T_{bol}-L_{bol} evolution, evolutionary tracks
- **global properties** (statistical properties):
  - SF efficiency
  - SF time scale
  - initial mass function (IMF)
  - number ratios of YSOs
  - structures of young star clusters

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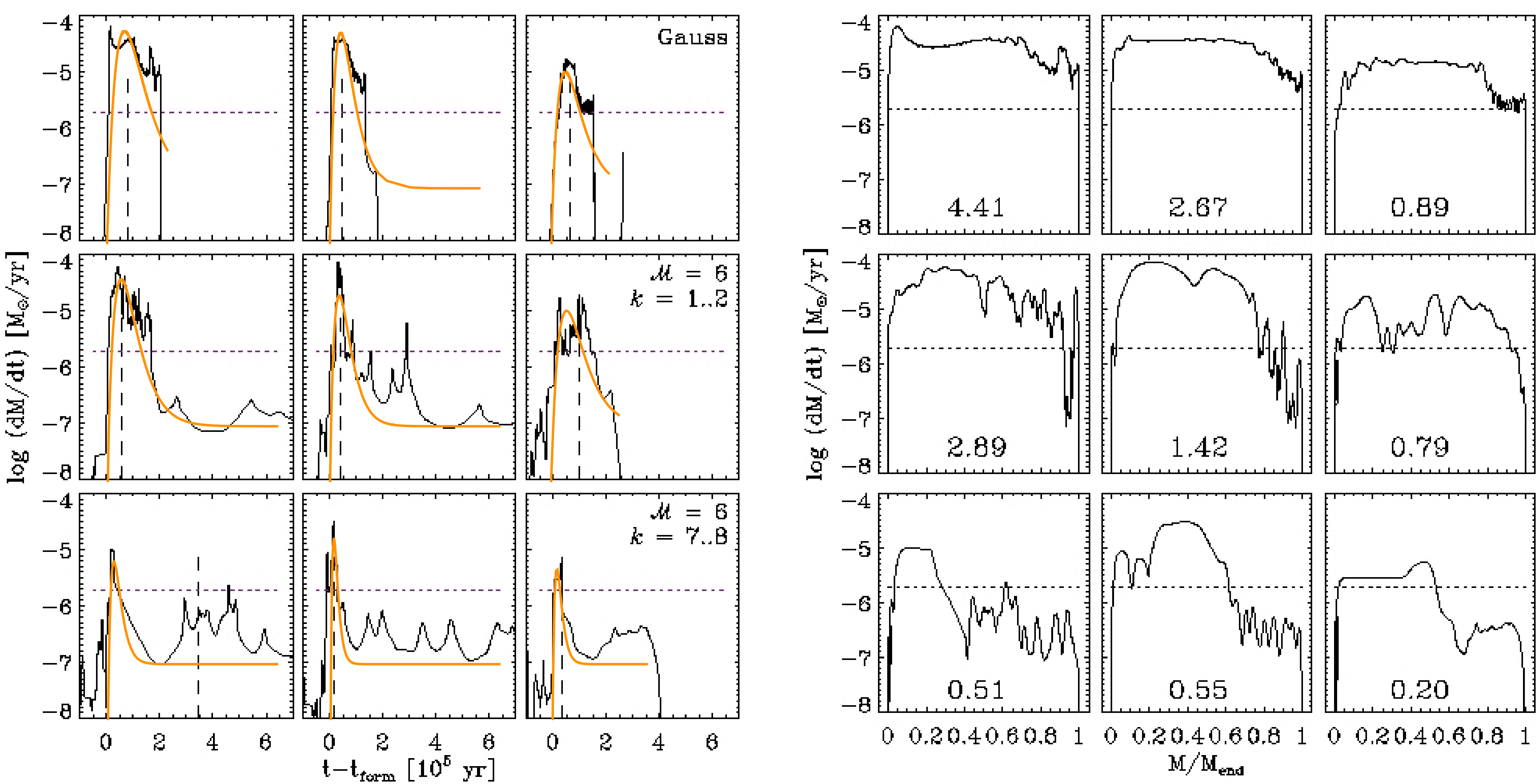
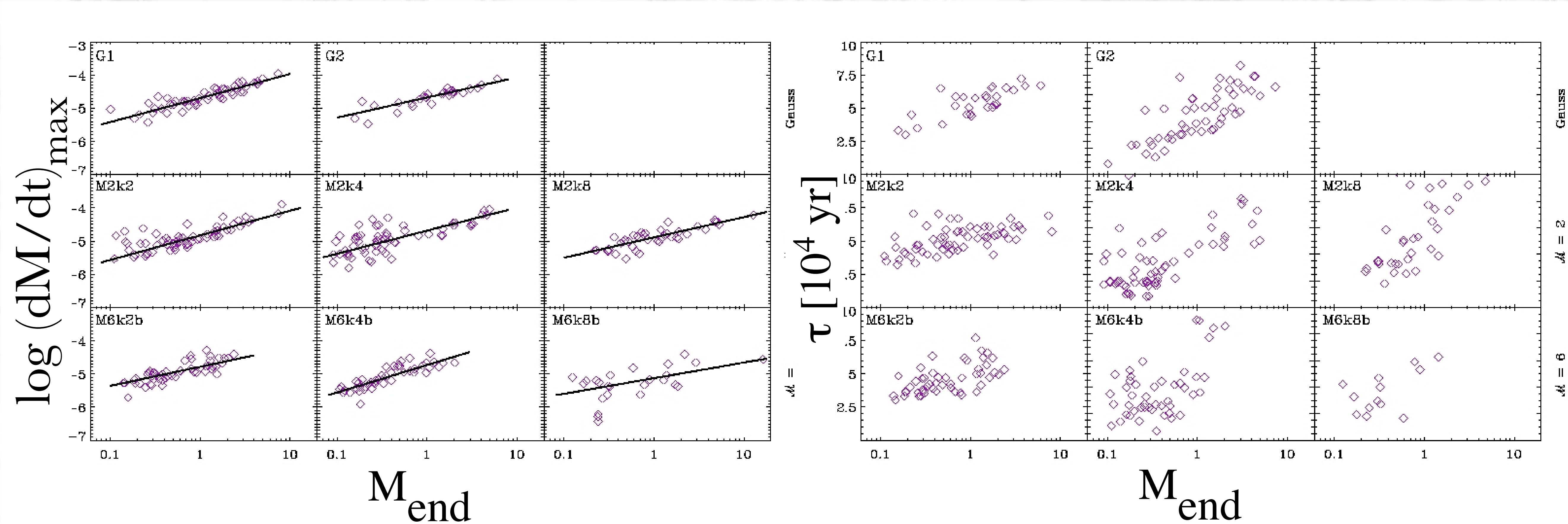
Mass Accretion History



$$\log \dot{M}(t) = \log \dot{M}_0 \frac{e}{\tau}\, t\, e^{-t/\tau}$$

(Schmeja & Klessen 2004)

Fit Parameters



$\log \dot{M}_0$: $\log (dM/dt)_{max}$

τ: time of $(dM/dt)_{max}$
related to local free-fall time/local density at onset of collapse

Observations

Mass accretion rates cannot be measured directly from observations → estimated from SEDs or outflow strengths

Class 0 protostars: $\sim 10^{-5} \ldots \sim 10^{-4}\ M_{sun}/yr$

Class I protostars: $\sim 10^{-7} \ldots \sim 5 \times 10^{-6}\ M_{sun}/yr$

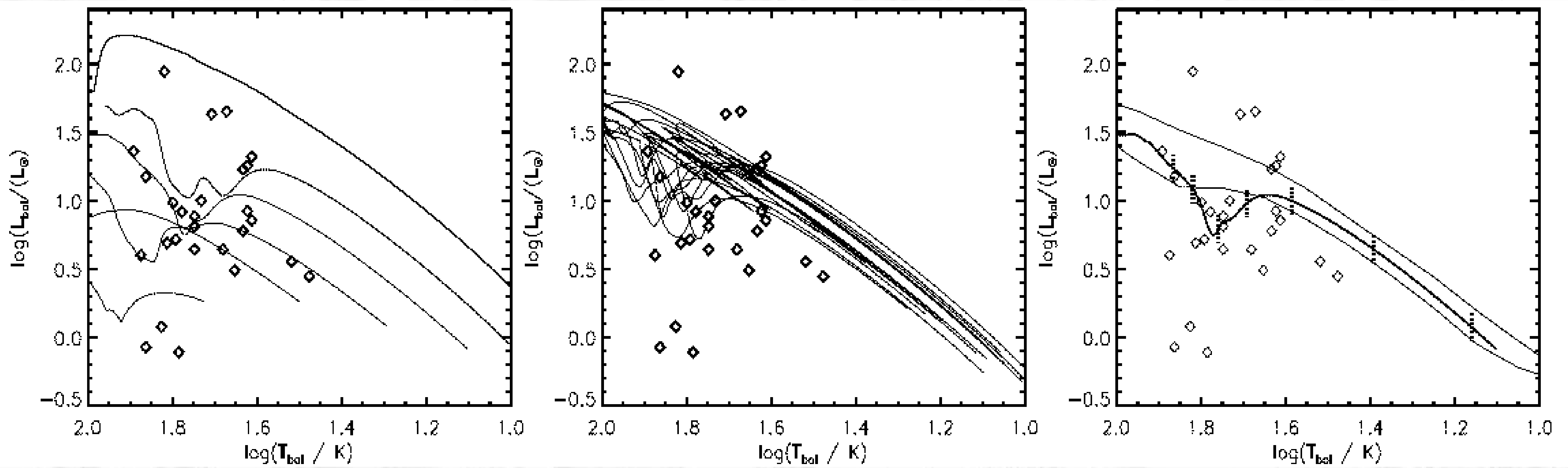
dM/dt ~ one order of magnitude higher in Class 0 phase: good agreement with our values

dM/dt hard to observe → conversion of dM/dt into easier observable quantities like T_{bol}, L_{bol}

Evolutionary Tracks

combination of mass accretion rates from gravoturbulent models with evolutionary code (Smith 2000) → L_{bol} - T_{bol} diagram

Can we predict final masses, ages...?



tracks for averaged dM/dt in six mass bins

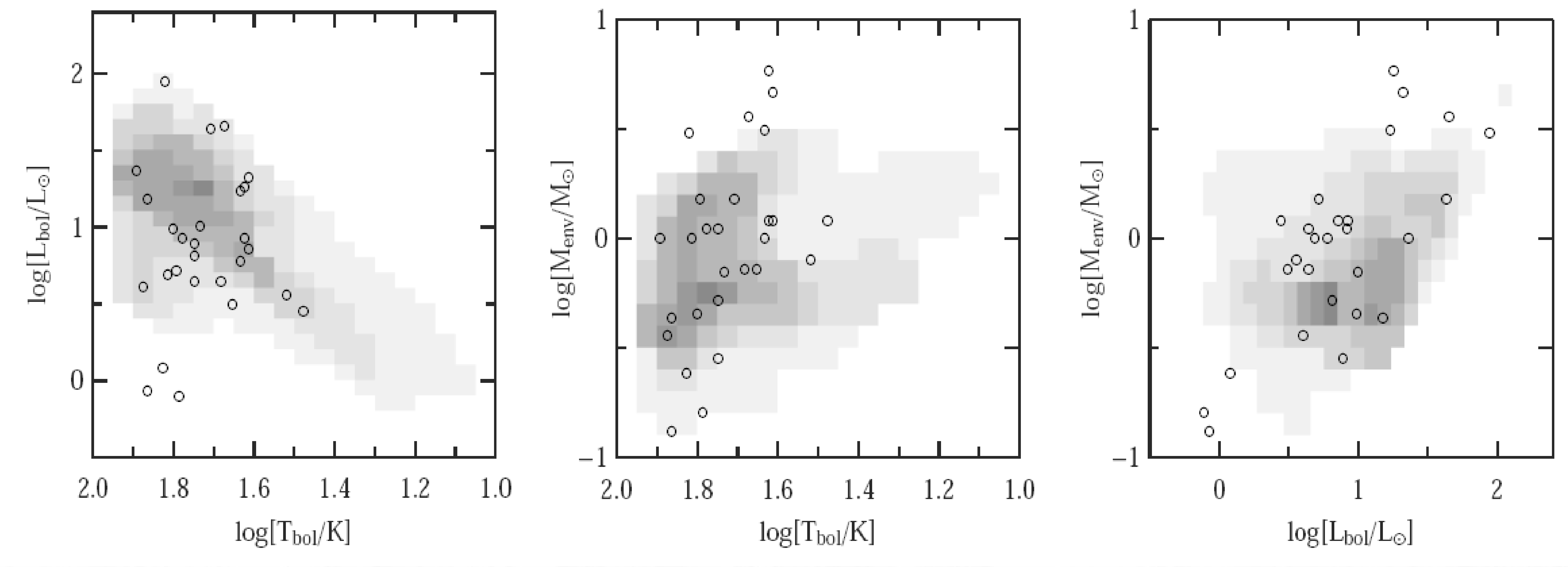
all individual tracks in mass bin 0.8-1.6 M_{sun}

average dM/dt in mass bin 0.8-1.6 M_{sun}, 1σ scatter

(Froebrich, Schmeja, Smith & Klessen 2006)

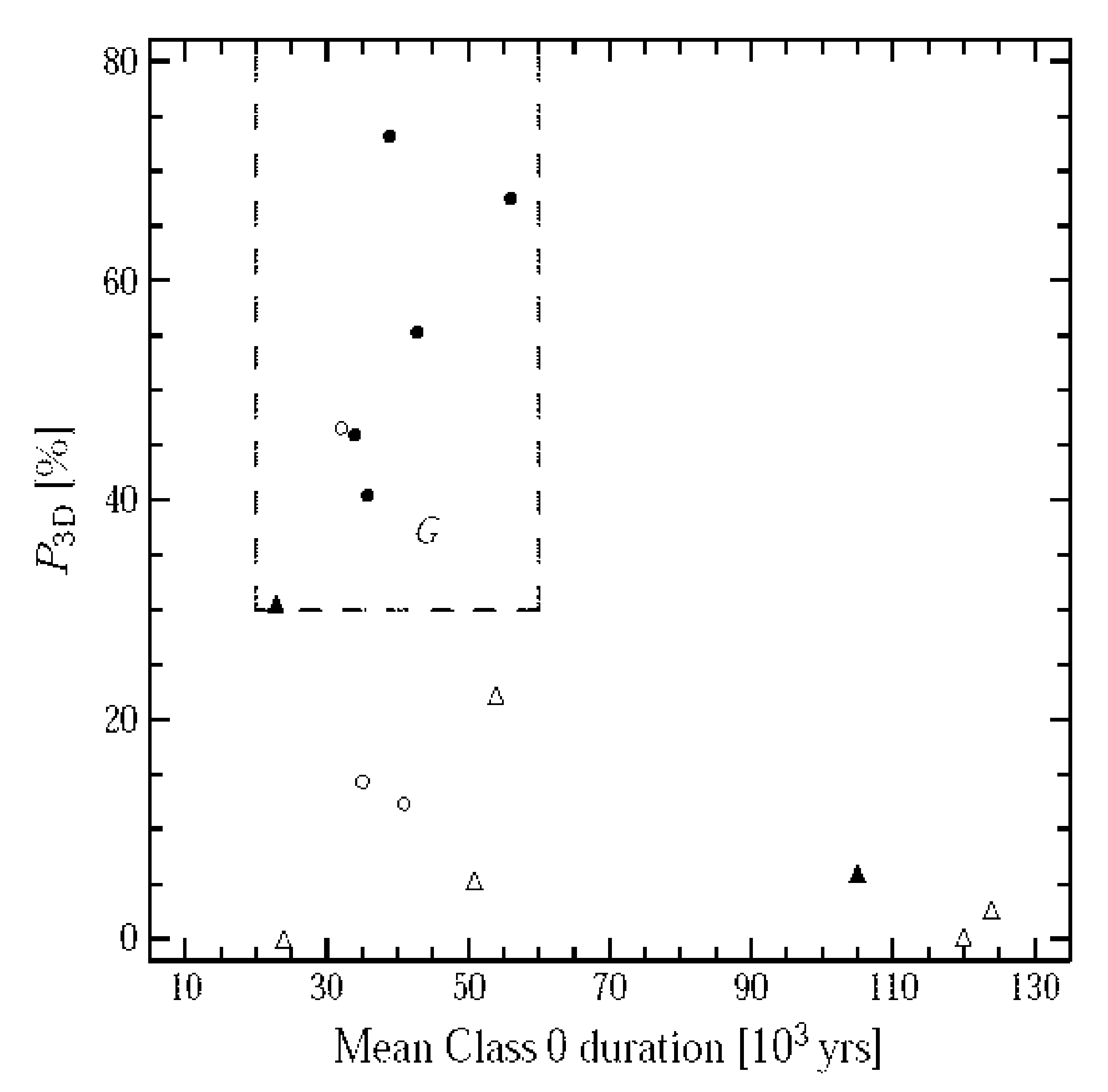
Comparison with Observations

- All tracks of one model → 3D probability diagram (L_{bol}, T_{bol}, M_{env}): comparison with sample of observed Class 0 sources (Froebrich 2005) by 3D Kolmogorov-Smirnov test



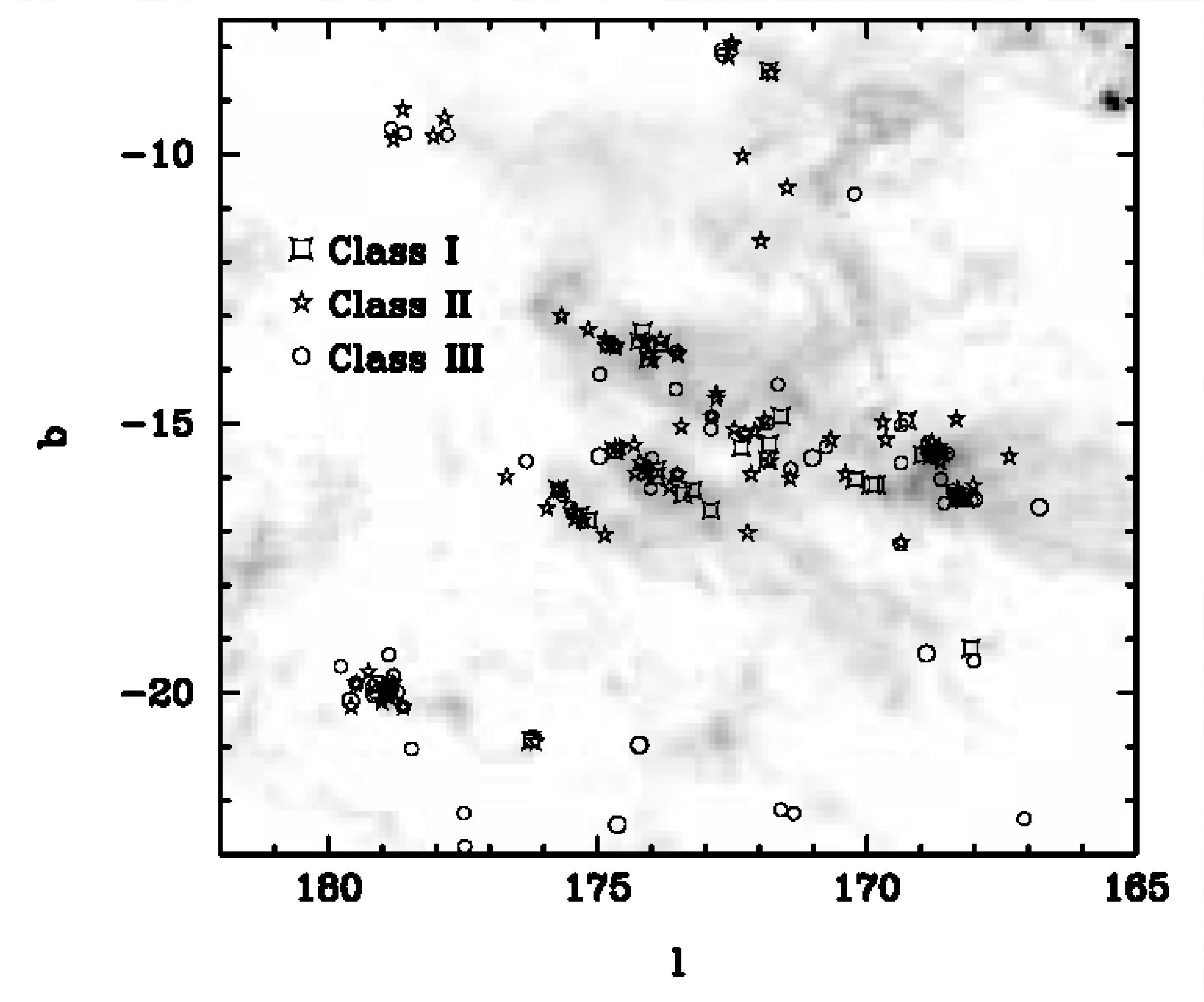
Comparison with Observations

- max. 70% probability
- best agreement for Class 0 duration of 2 ... 6 × 10^4 yr
- no correlation with turbulent environment ($\mathcal{M}$, k)
- all sources in Taurus: under-luminous, worse correlation → other mechanism than turbulence?



Structures of Embedded Clusters

- (almost) all stars form in clusters
- quantitative statistical measure of structure important for understanding the formation and evolution of young star clusters

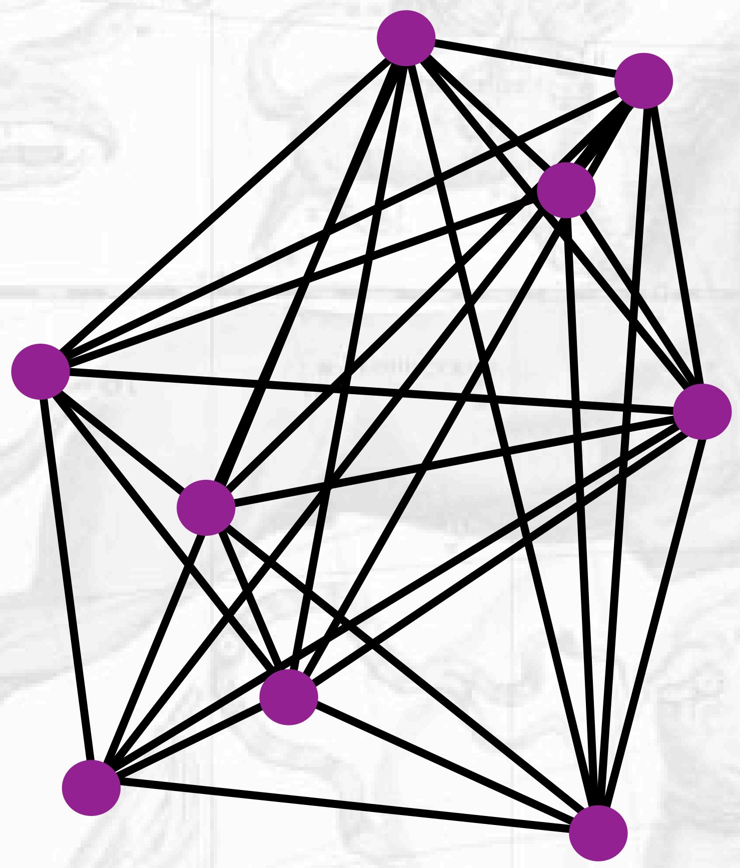


(Hartmann 2002)

Statistical Methods

- Distribution of source separations
- Mean surface density of companions (Larson 1995):
  - average number of neighbours per square degree on the sky at an angular separation ϑ
- Normalised correlation length (Cartwright & Whitworth 2004)
- Minimum spanning tree (MST) (Cartwright & Whitworth 2004)

Normalised Correlation Length

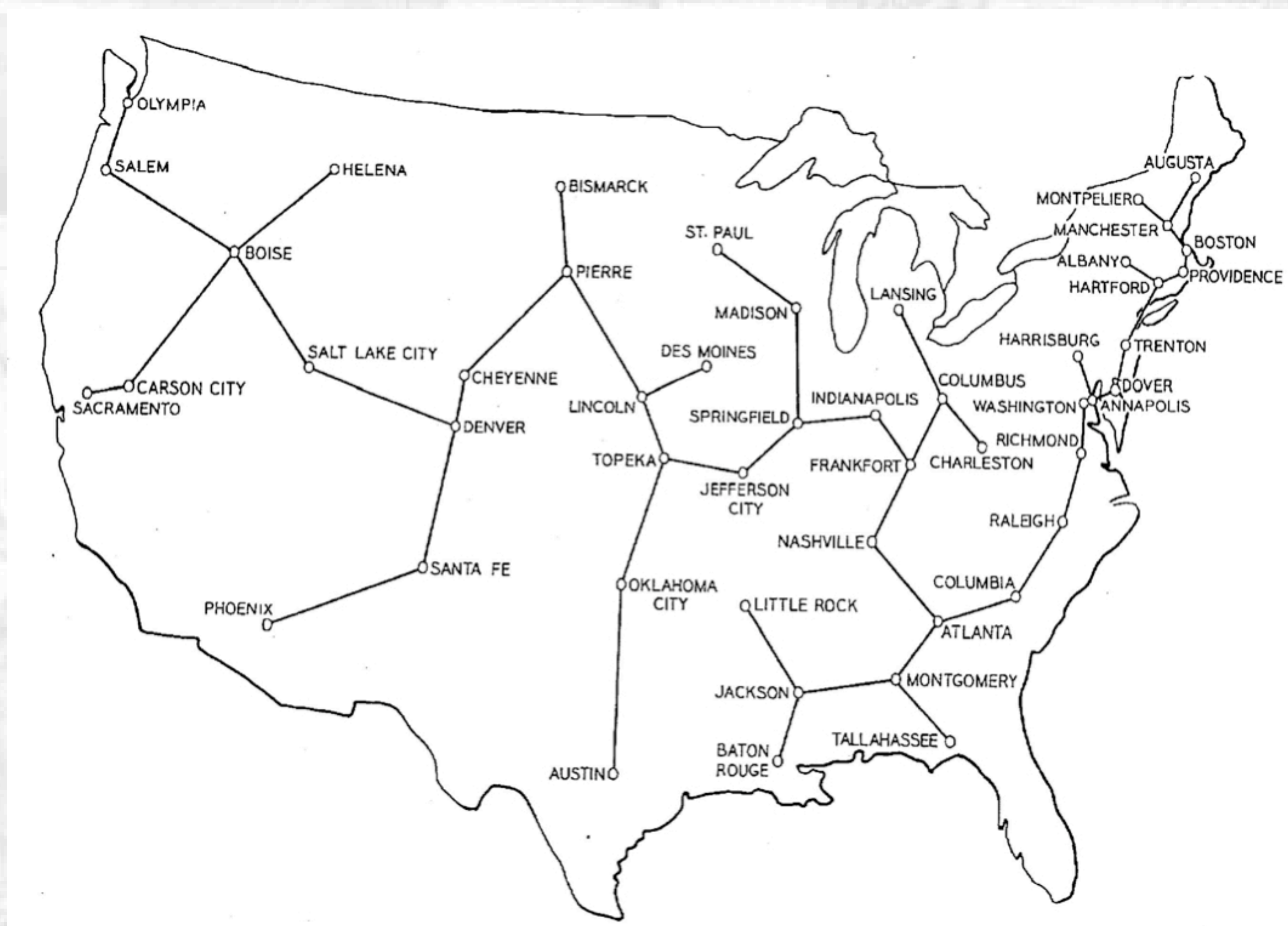


- mean separation between stars in the cluster, normalised by cluster radius
- better indicator for cluster behaviour than MSDC
- independent of the number of stars

→ normalised mean correlation length $\bar{s}$

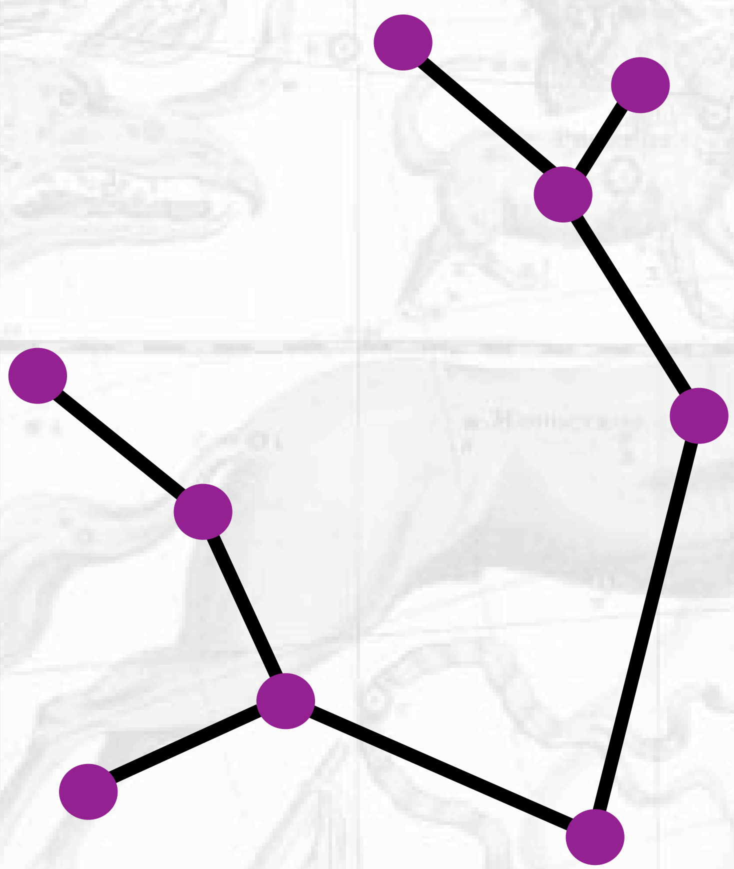
Minimum Spanning Tree

- construct from graph theory (Kruskal 1956; Prim 1957)
- unique set of edges connecting a given set of points without closed loops, such that the sum of edge lengths is a minimum
- used in many fields (telecommunications, genetics, biology...); astrophysics: structures of galaxy clusters



(Prim 1957)

Minimum Spanning Tree



MST → mean edge length m

m not independent of number of points → normalised with factor $\sqrt{A/n}$ (Marcelpoil 1993)

A ... area
n ... number of points

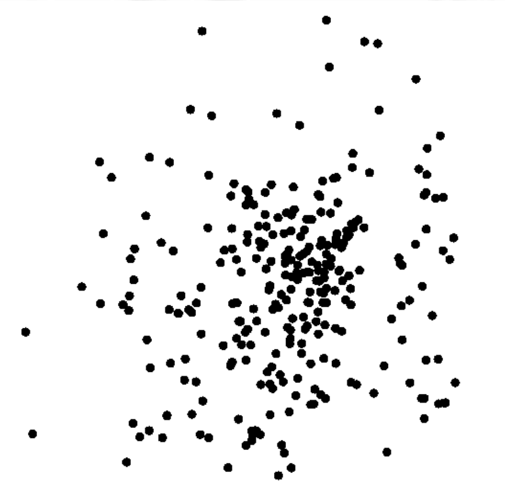
→ normalised mean edge length $\bar{m}$

Q

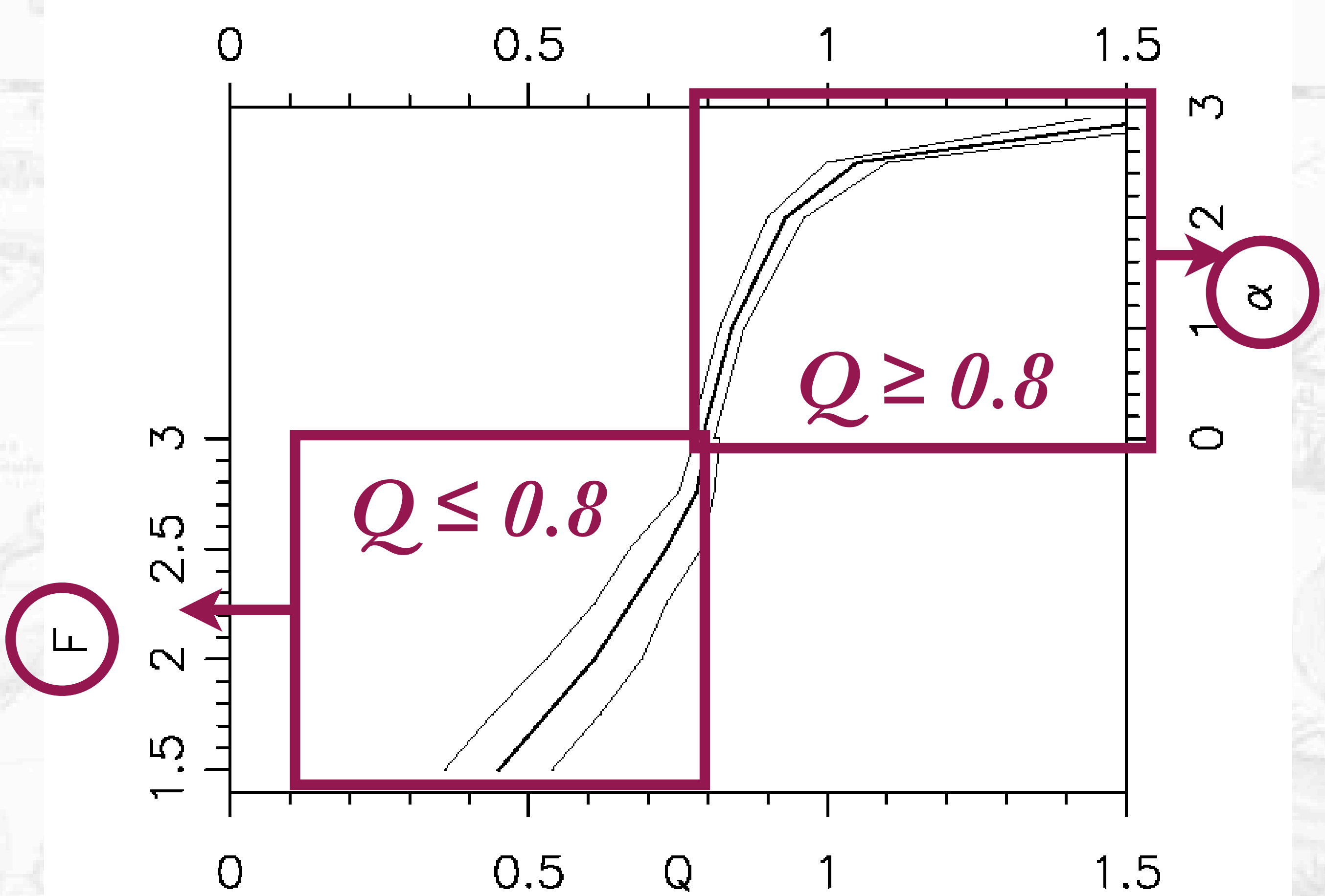
Q (Cartwright & Whitworth 2004): distinction between smooth large-scale density gradient and fractal subclustering

$$Q = \frac{\bar{m}}{\bar{s}} = \frac{\text{normalised mean edge length}}{\text{normalised correlation length}}$$

$Q \geq 0.8$:
centrally concentrated clusters with volume density $n \propto r^{-\alpha}$



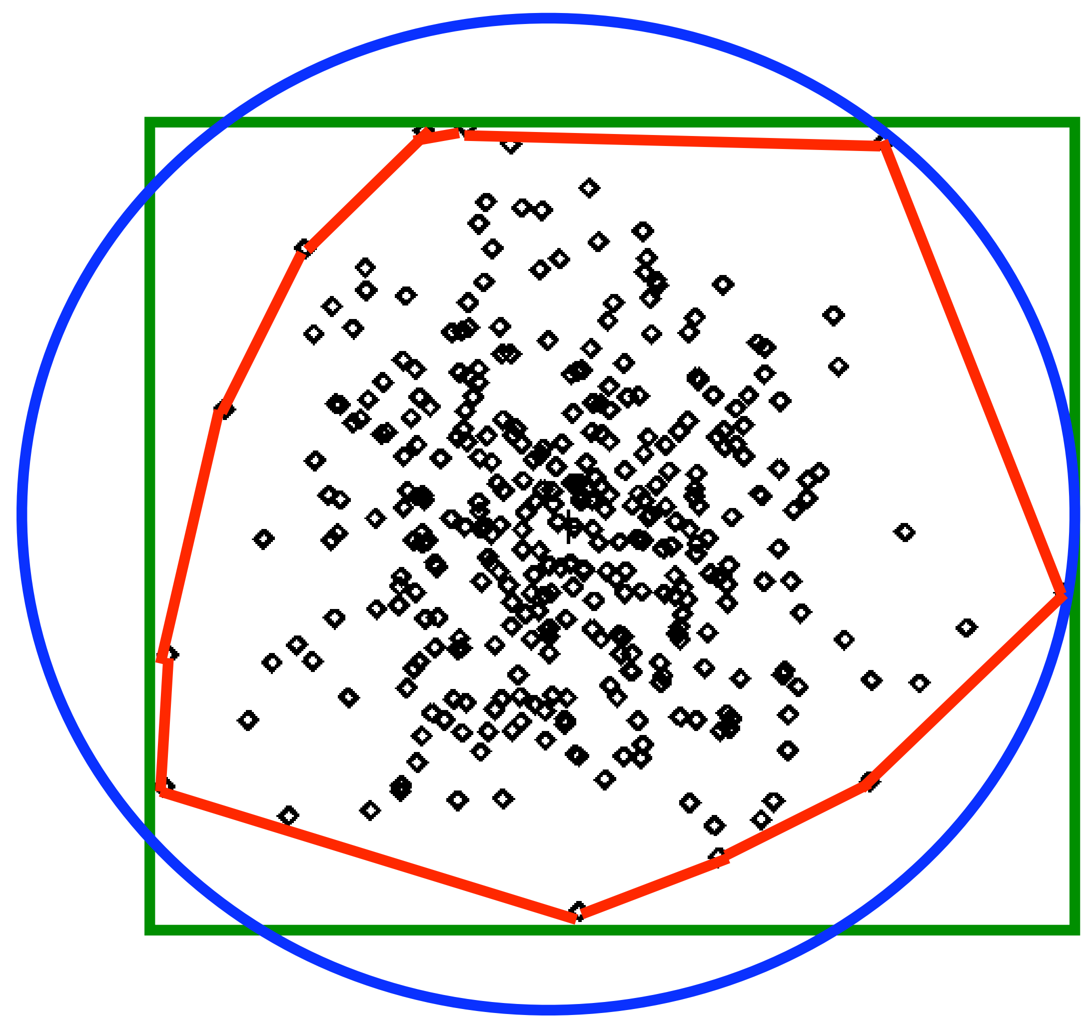
$Q \leq 0.8$:
clusters with fractal substructure, fractal dimension F



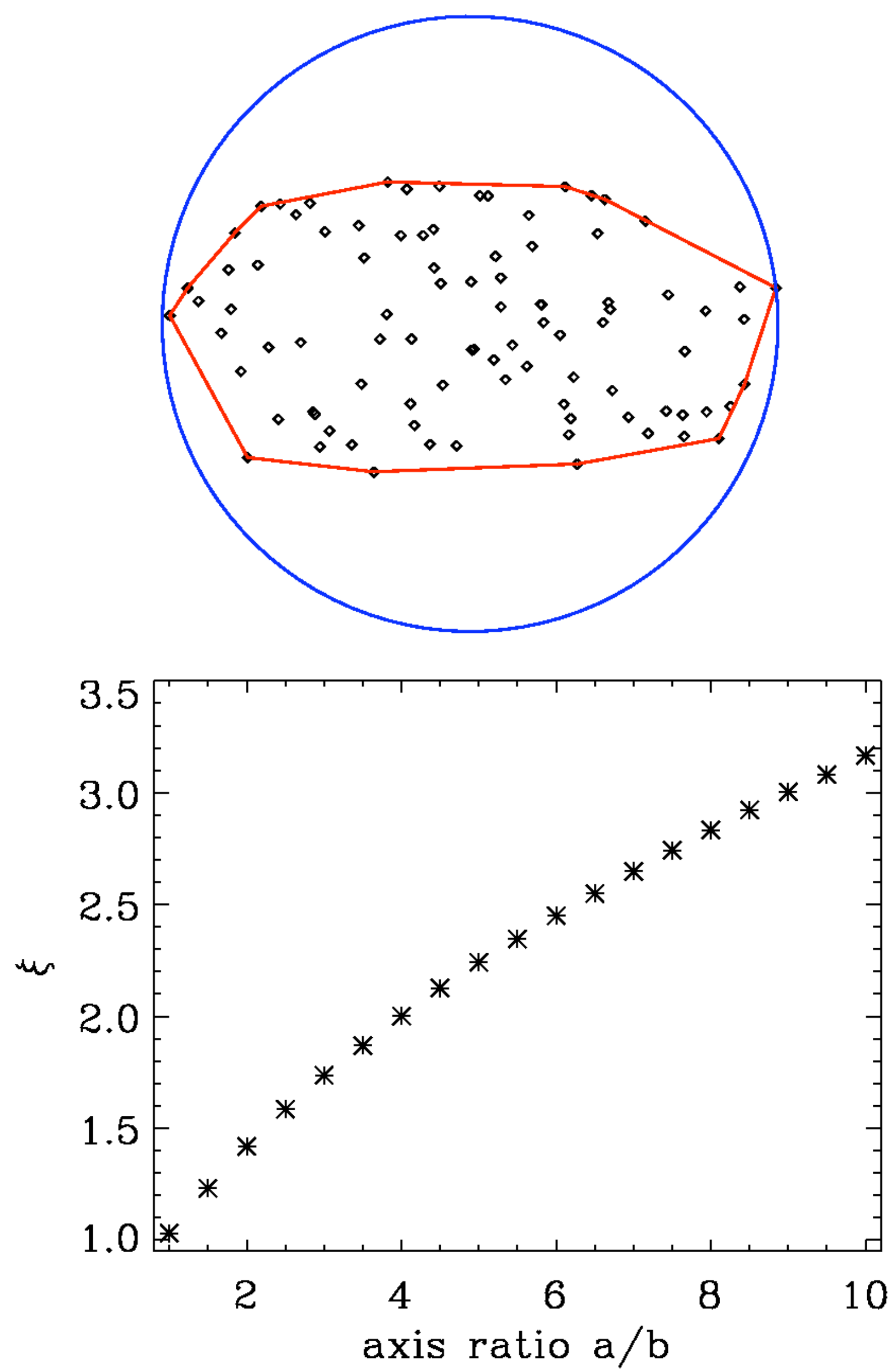
(Cartwright & Whitworth 2004)

Area of a Cluster

- m, s normalised by cluster radius/area
- How to define the cluster area?
- different approaches: circle, rectangle, convex hull
- definition crucial, can differ by factor of 2 or more
- $Q = \bar{m}/\bar{s}$ independent of radius/area!



Elongation of a Cluster

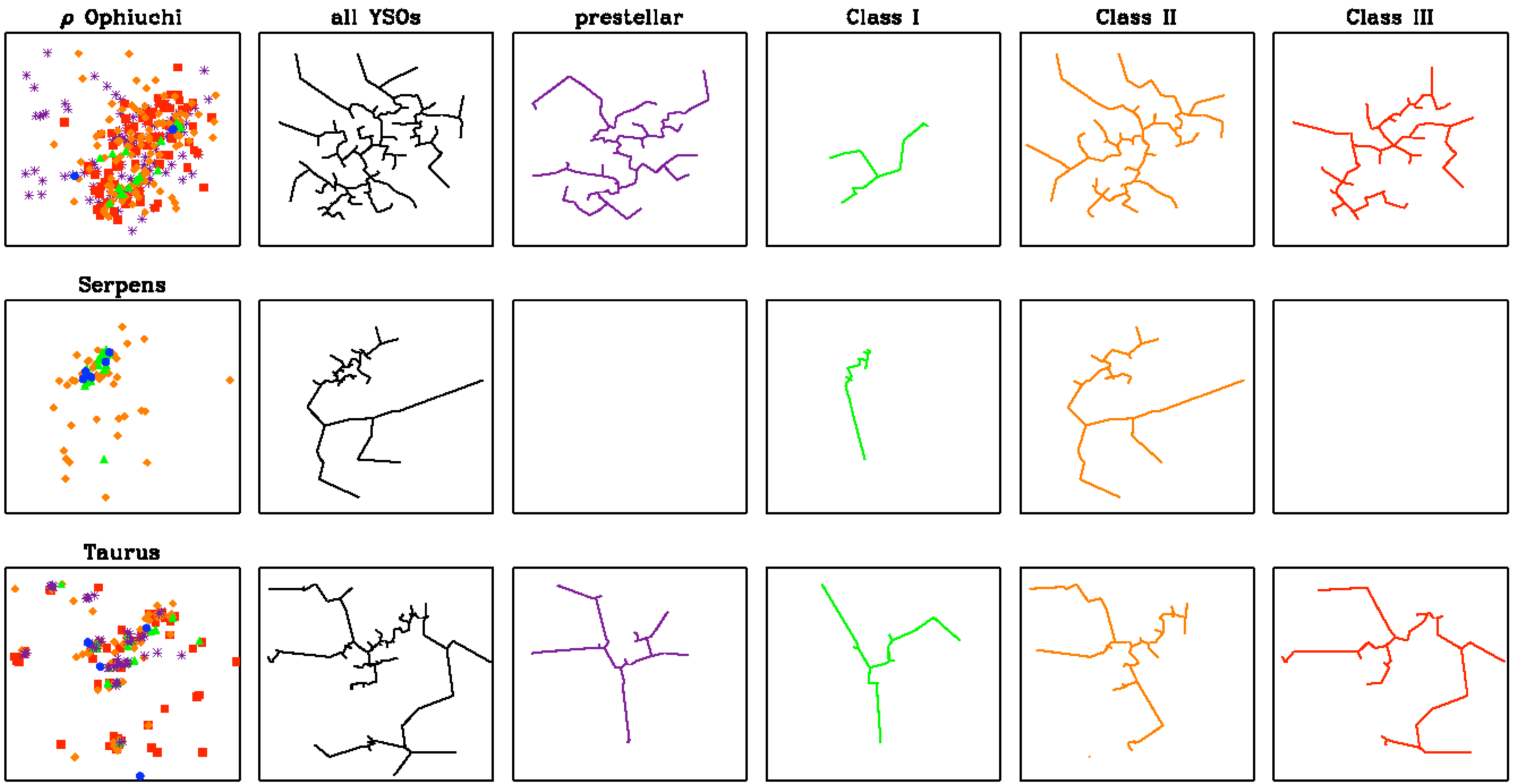


- elongation ξ of a cluster:
-
- $$\xi = \frac{R^{\mathrm{circle}}_{\mathrm{cluster}}}{R^{\mathrm{conv.hull}}_{\mathrm{cluster}}}$$
-
- ξ ≈ 1: spherical cluster, ξ ≈ 3: elongated elliptical cluster with axis ratio of $a/b \approx 10$

Observations

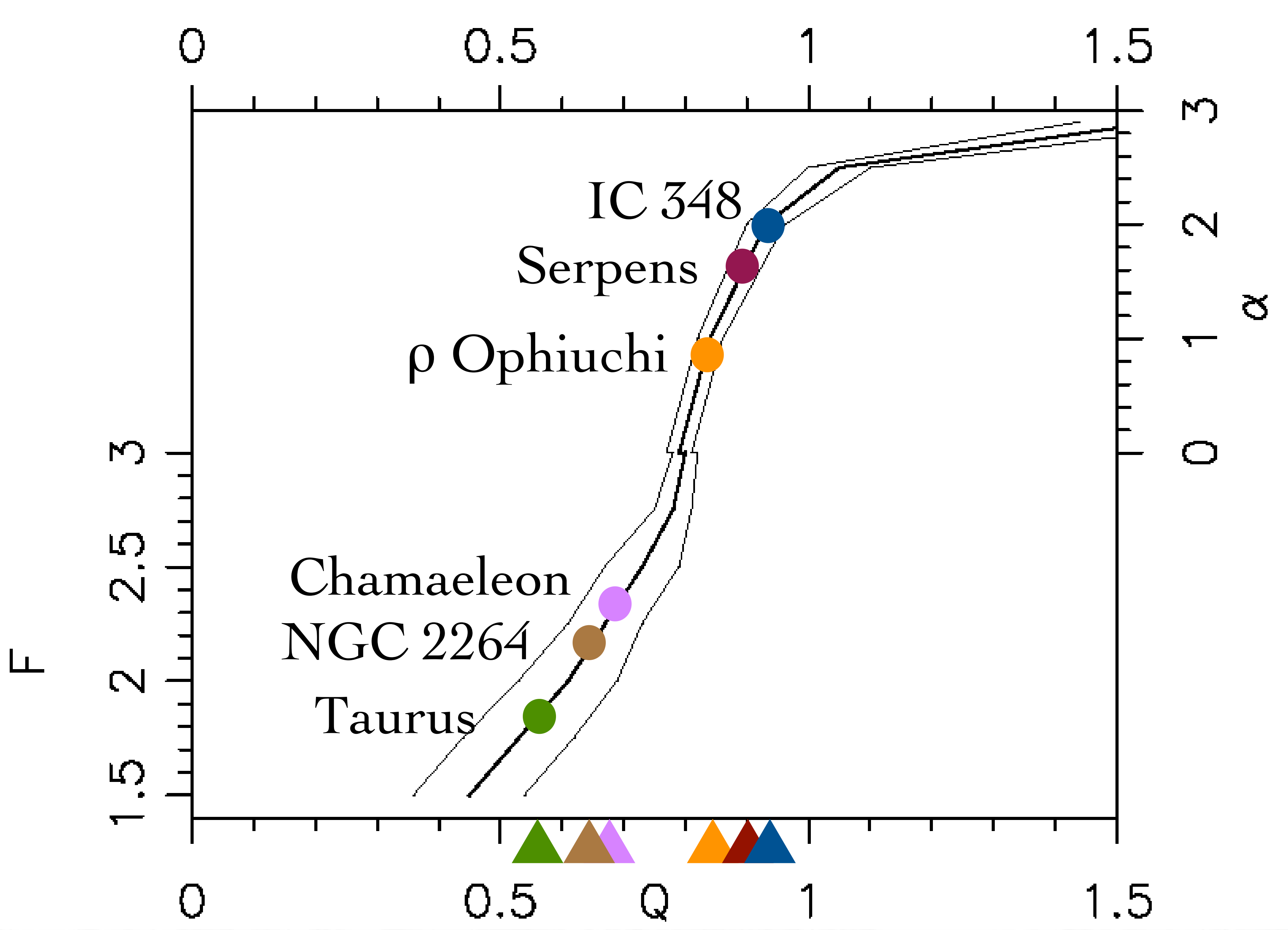
- data: sample of YSOs and prestellar cores constructed from various published sources (Schmeja et al. 2005)
- ρ **Ophiuchi, Serpens, Taurus:** all classes
- **Chamaeleon I, IC 348:** no information on individual classes
- Caveat: different samples → different completeness limits
- Caveat: 2D projections, not 3D structure!

Observations: MST



(Schmeja & Klessen 2006)

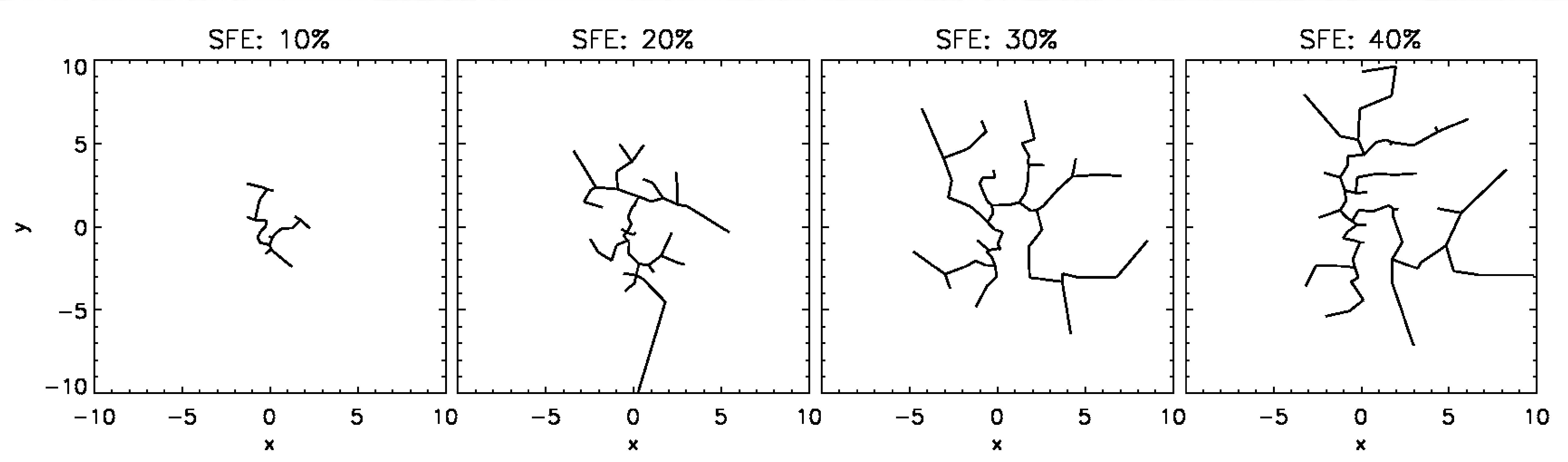
Observations: Q



(Cartwright & Whitworth 2004)

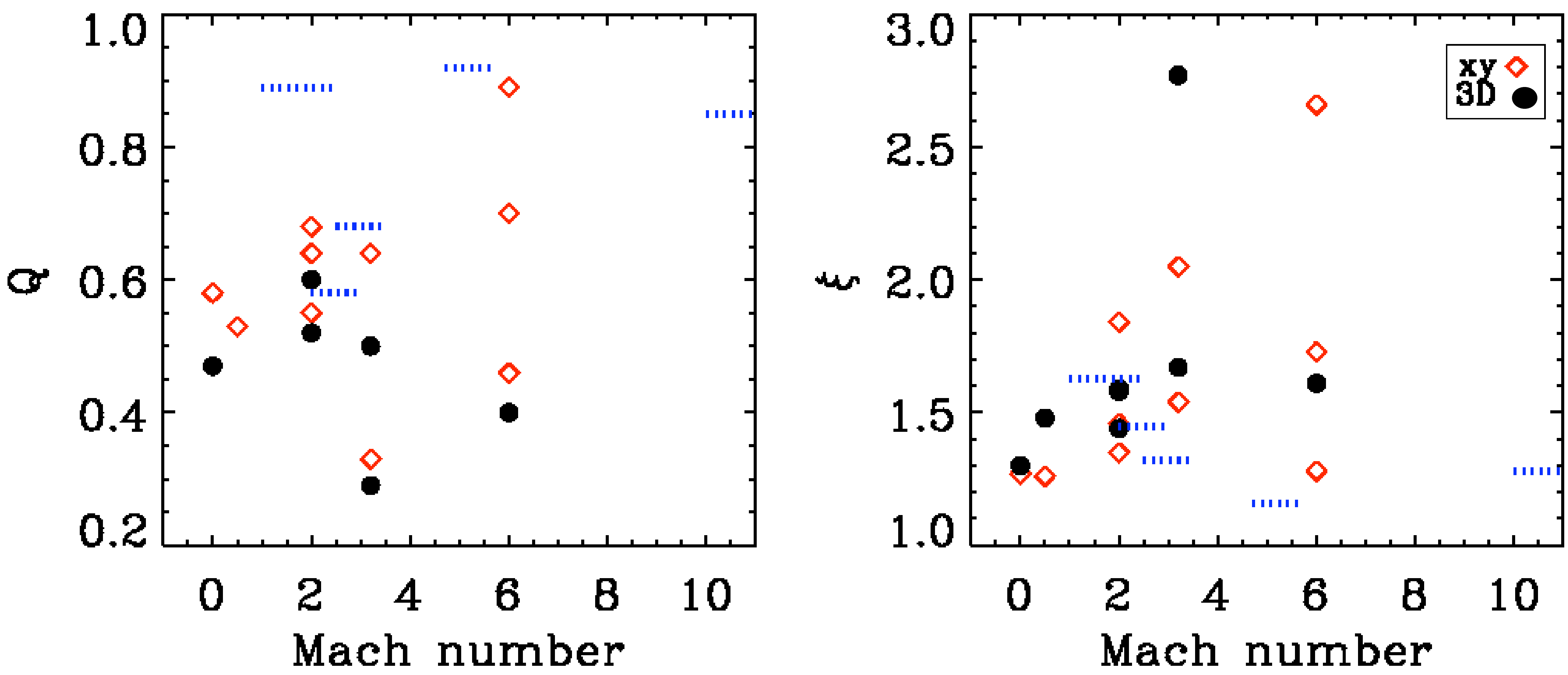
Models: MST

Models: 3D, projection into 2D planes



MST of one model ($\mathcal{M} = 6$, $k = 3..4$) projected into the xy-plane at different times (SFEs): expansion of the cluster

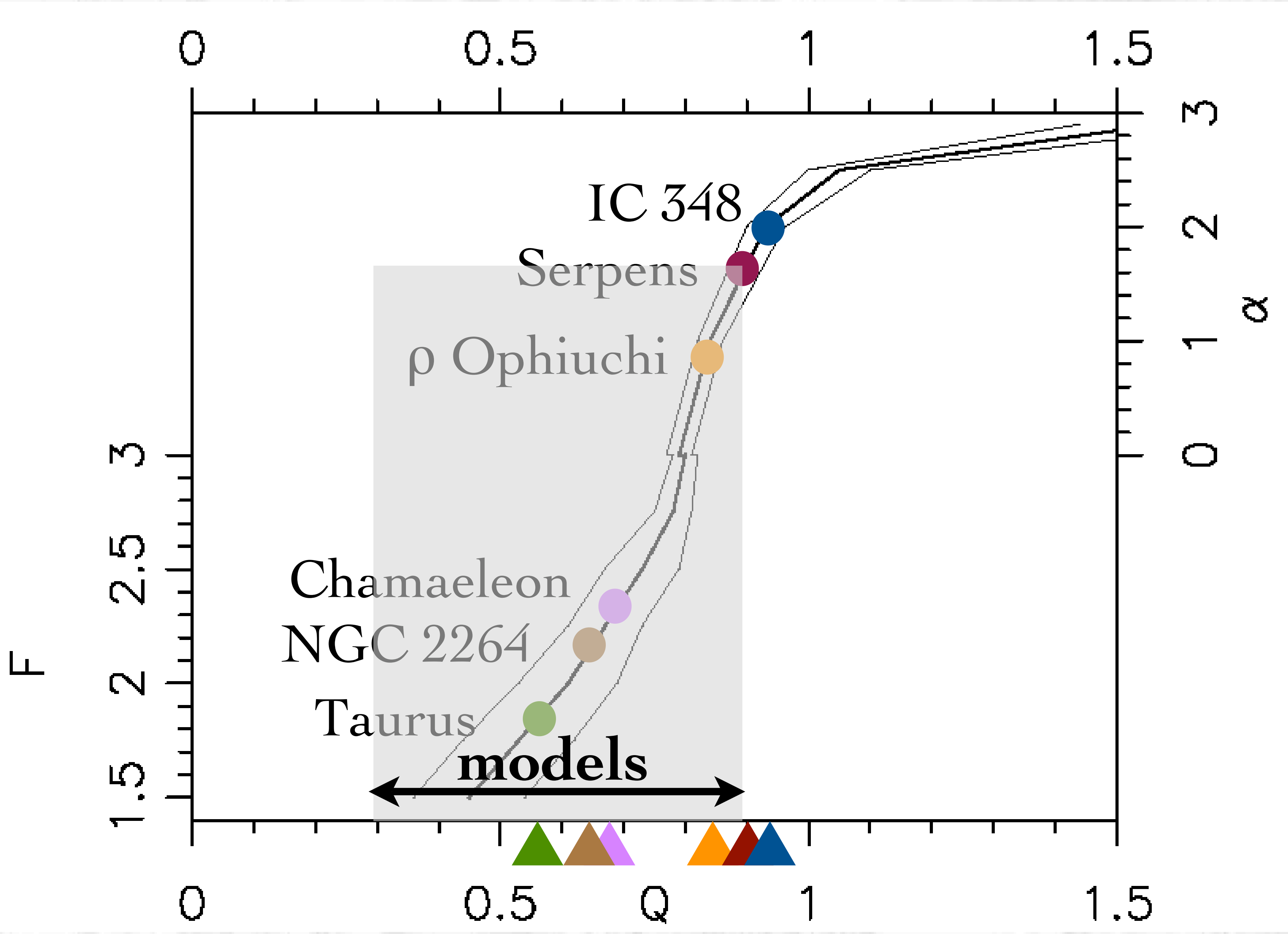
Models: Parameters



•••• Serpens - Taurus - Cha I - IC 348 - ρ Oph

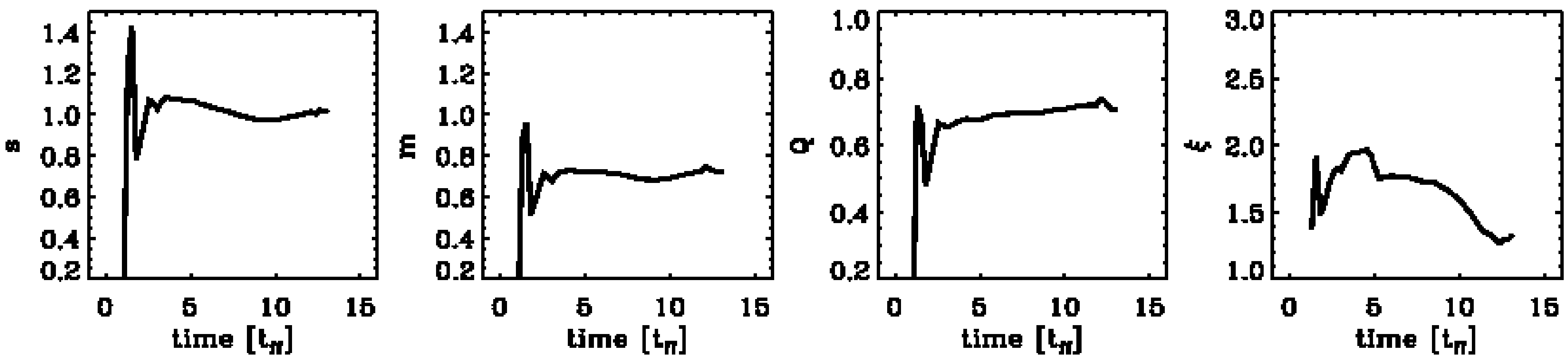
- no correlation with $\mathcal{M}$ or k
- good agreement between models and observations when similar ξ values

Models: Q



(Cartwright & Whitworth 2004)

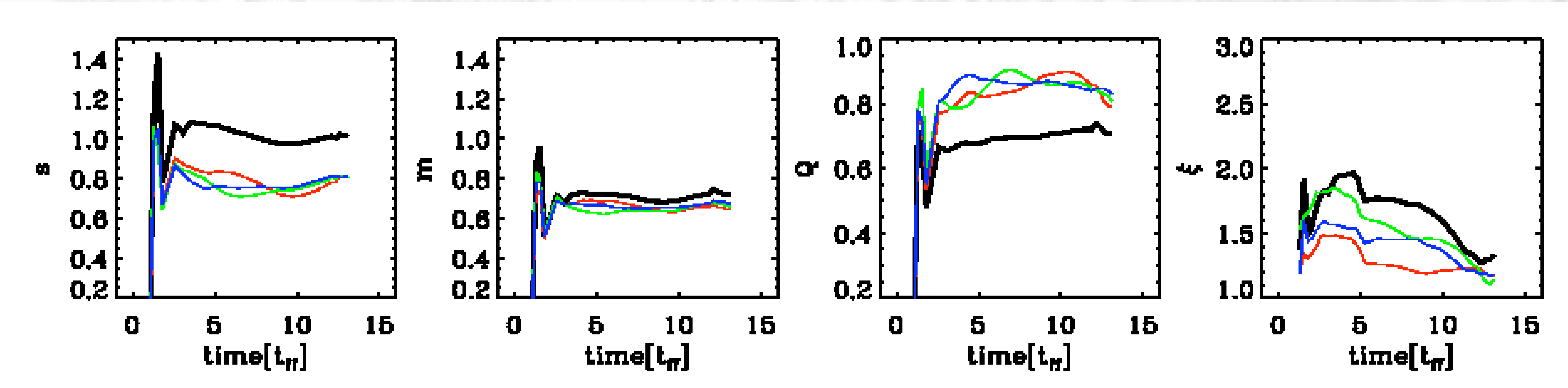
Models: Temporal Evolution



- similar behaviour of all models
- $\bar{s}$, $\bar{m}$ decline slightly, Q increases
- star formation sets in in different regions, cluster becomes more centrally concentrated as more and more gas is turned into stars

Models: Effect of Projection

models: 3D distribution projected into xy-, xz-, yz-plane

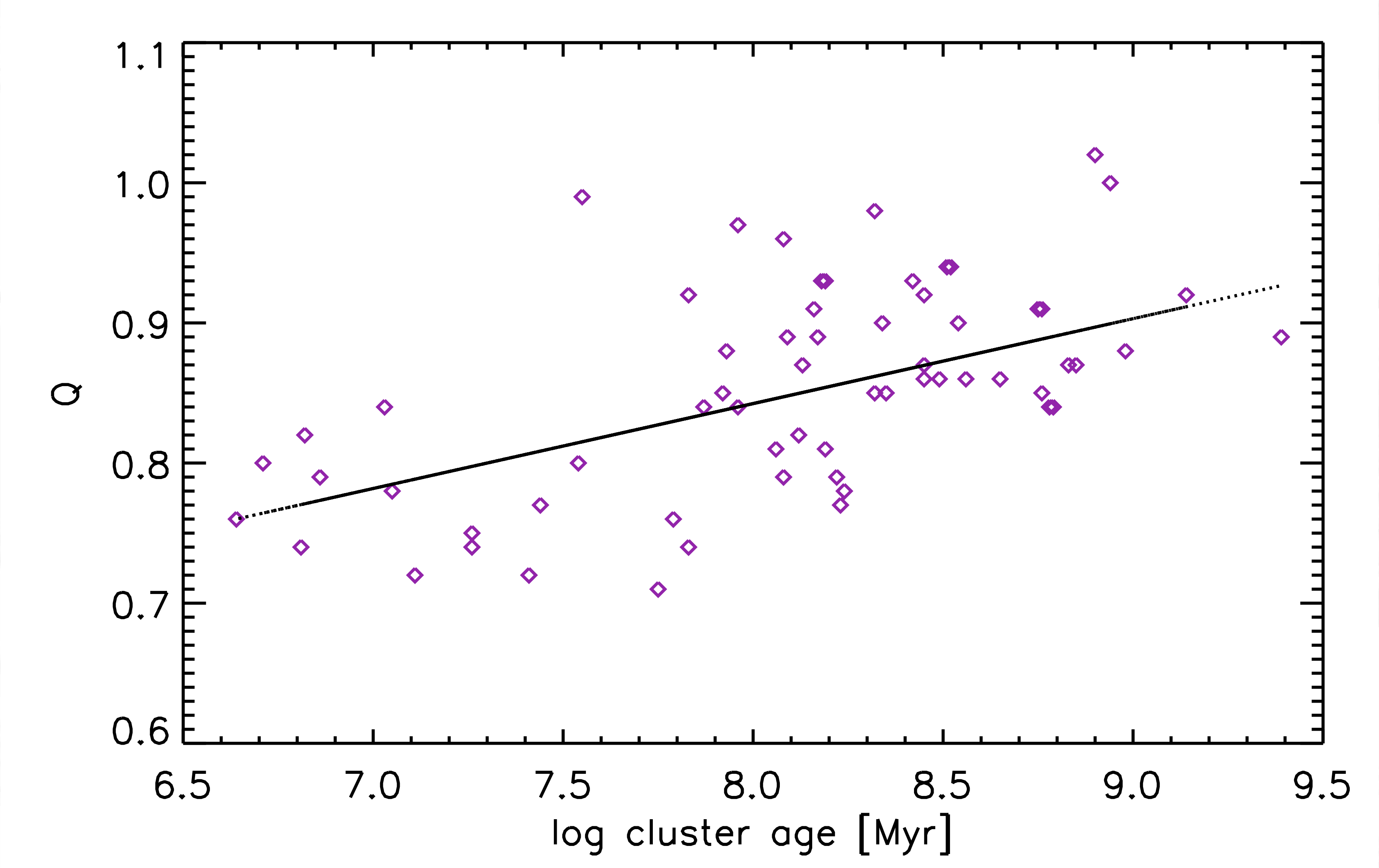


$\bar{s}_{\mathrm{3D}}/\bar{s}_{\mathrm{2D}} \approx 1.2, \bar{m}_{\mathrm{3D}}/\bar{m}_{\mathrm{2D}} \approx 1.1$

individual values can change, but qualitative behaviour of evolution similar

Evolution: Open Clusters

sample of 63 open clusters (Kharchenko et al. 2004, 2005):



correlation of Q with cluster age?

Summary

- gravoturbulent models of SF predict many observed properties
- mass accretion rates highly time-dependent
- no unique protostellar evolutionary tracks
- Class 0 duration: 2 ... 6 × 10^4 yr
- protostars in Taurus: anomalous accretion history → other control mechanism?
- not all prestellar cores may form stars
- clusters build up from several subclusters, evolve to more centrally concentrated state