Formation of Star Clusters

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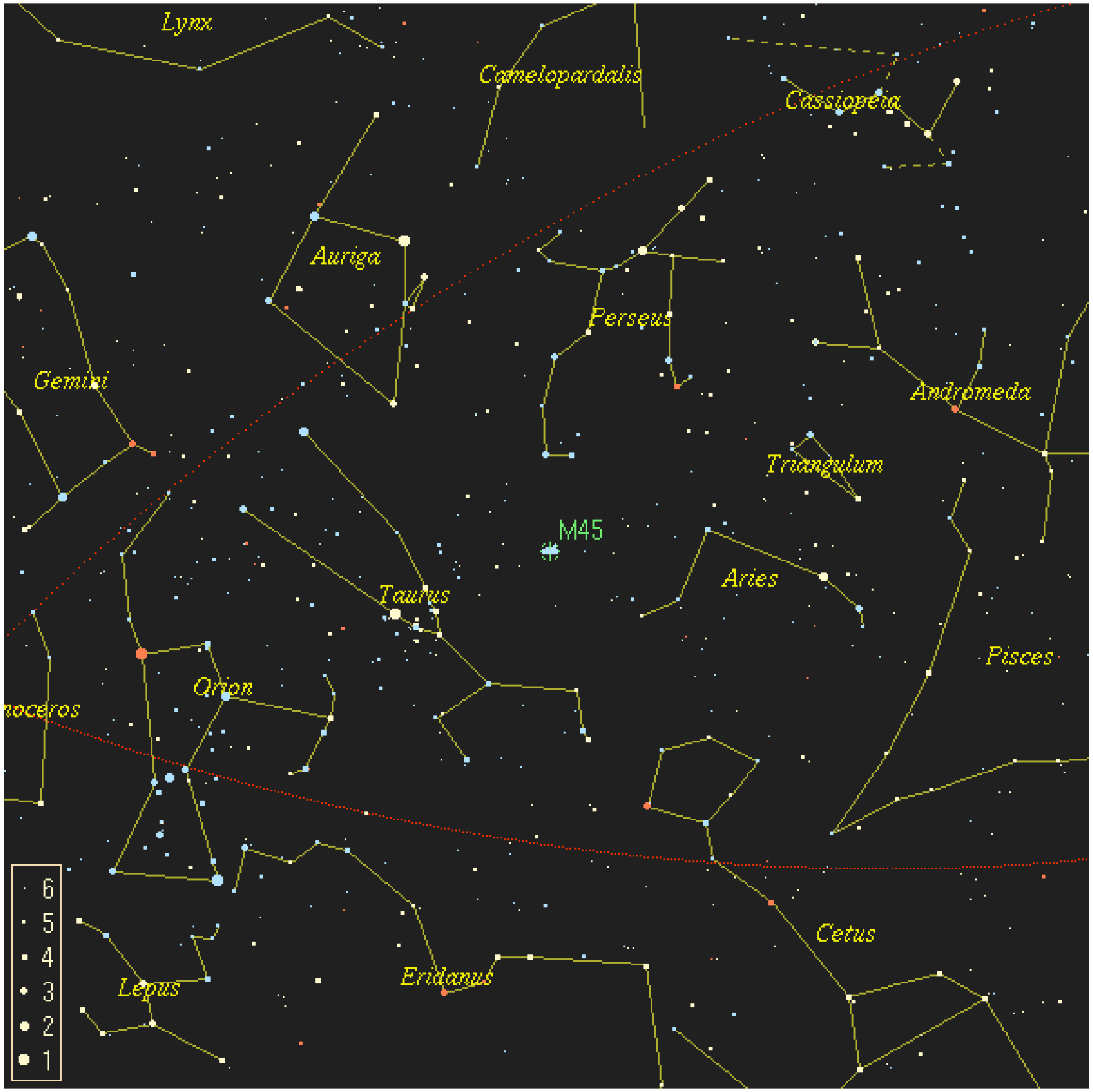
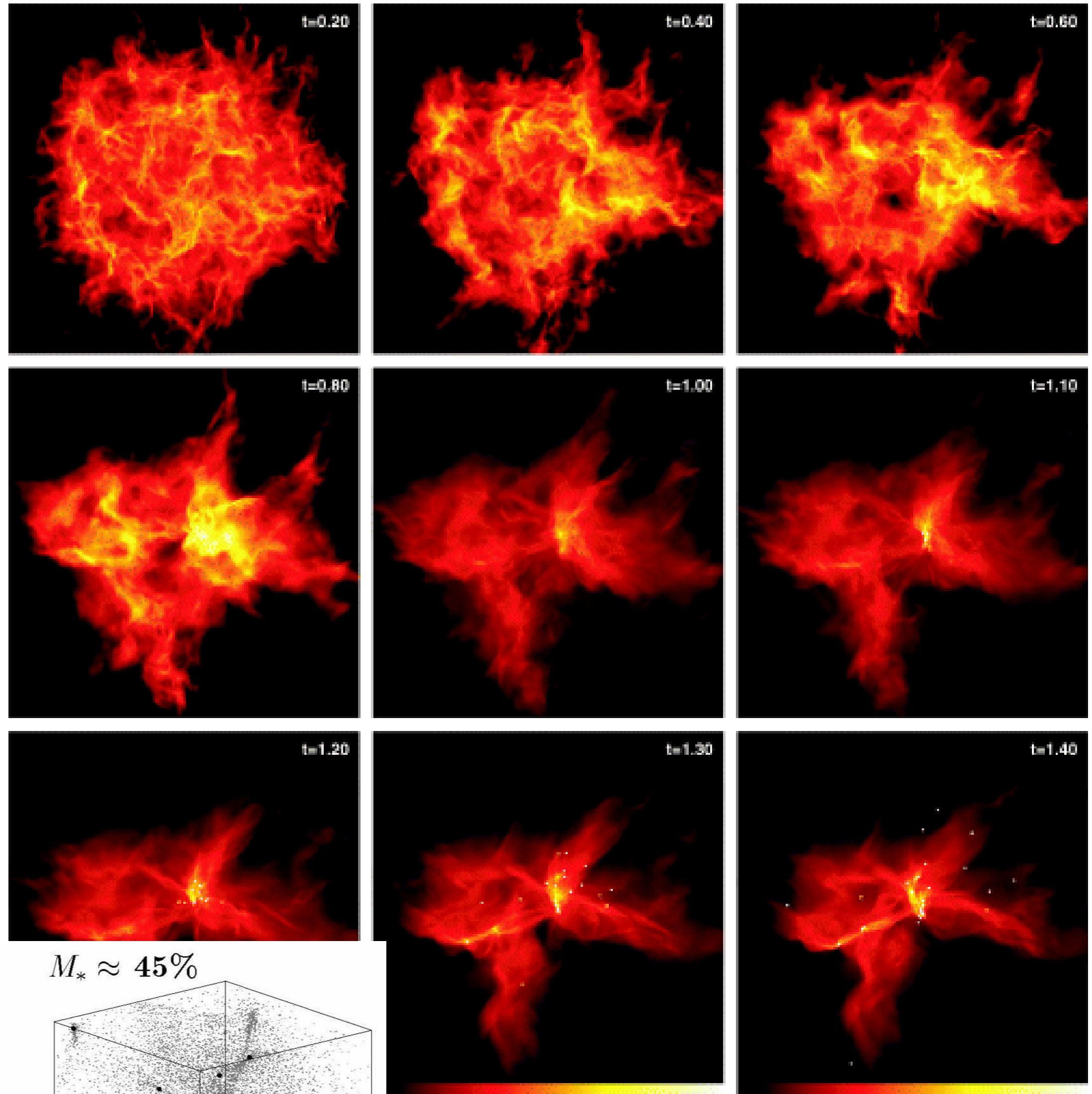
The Pleiades
star cluster
© Christopher J. Picking

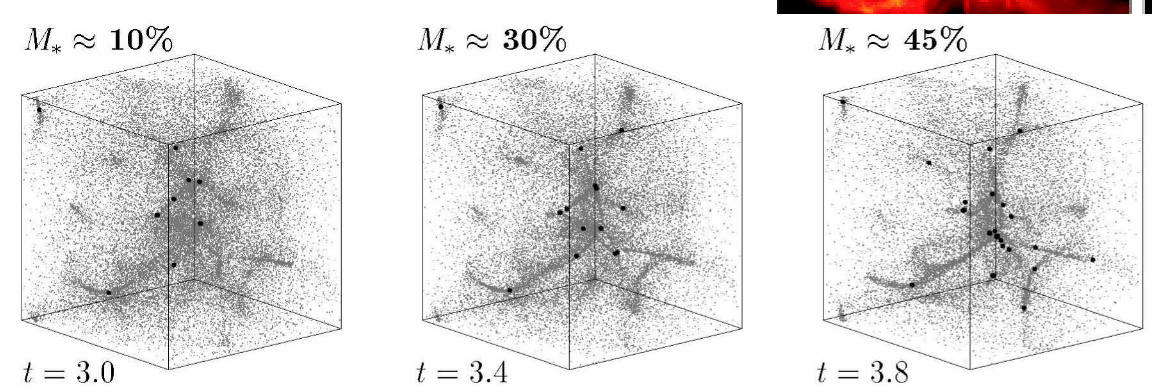

Lynx
Camelopardalis
Cassiopeia
Auriga
Perseus
Gemini
Andromeda
Triangulum
M45
Aries
Taurus
Pisces
Orion
noceros
Cetus
Lepus
Eridanus
6
5
4
3
2
1

Star formation occurs when parts of a gas cloud collapse into stars.

Cluster formation occurs when the stars mix.

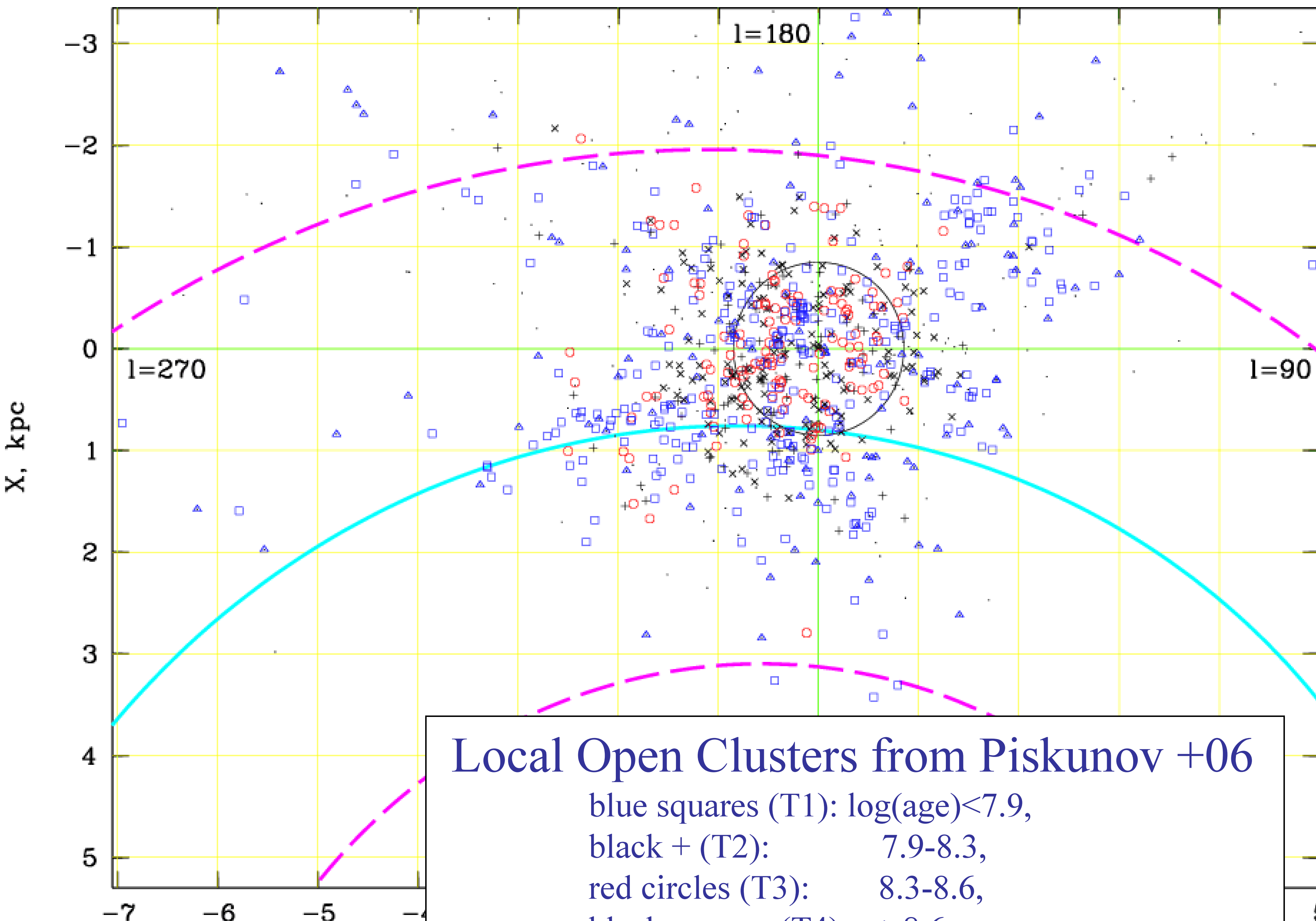
A bound cluster remains after gas leaves if the stellar mass fraction is high.





Bate, Bonnell, & Bromm 2003

Klessen & Burkert 2001

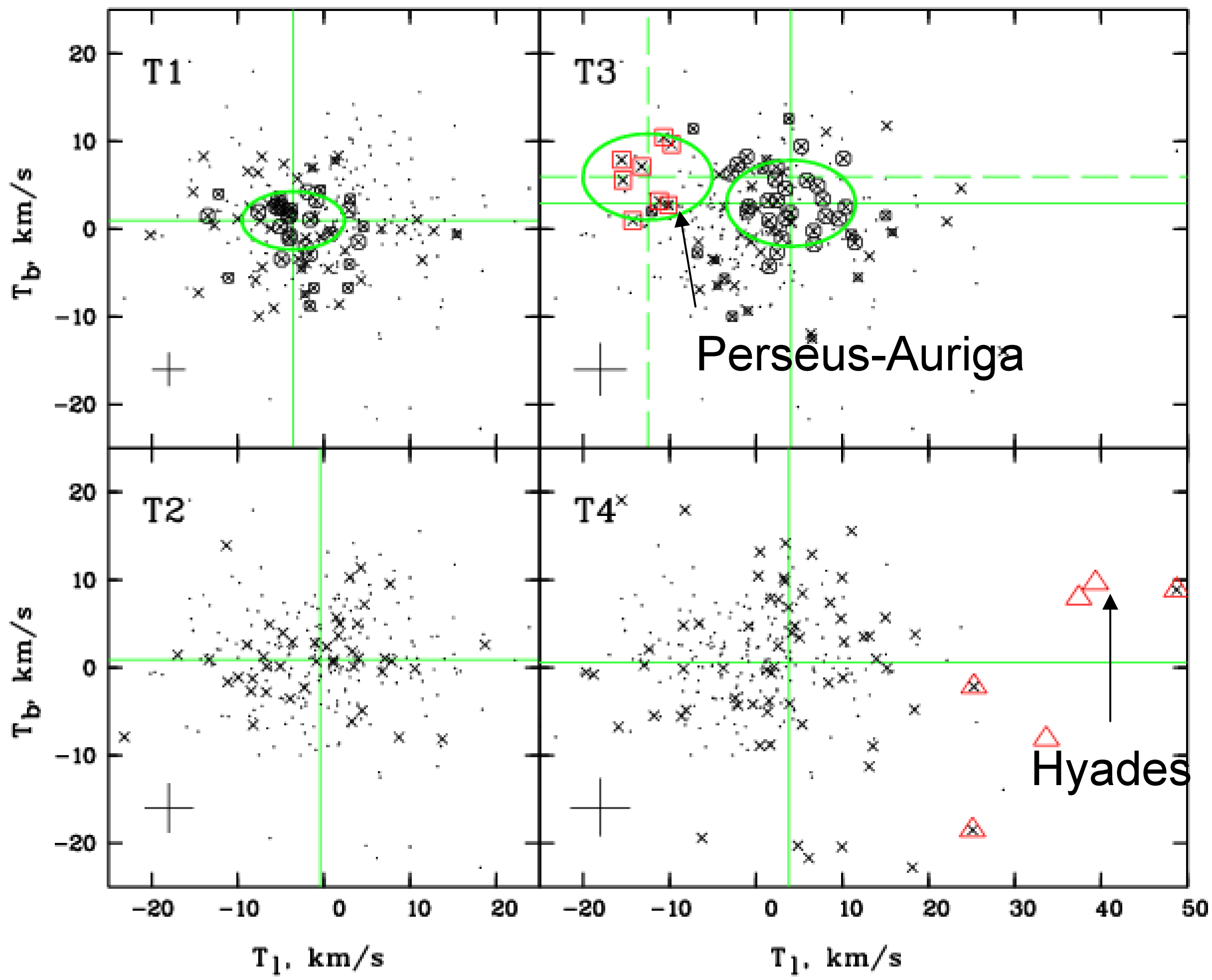


Local Open Clusters from Piskunov +06

blue squares (T1): log(age)<7.9,
black + (T2): 7.9-8.3,
red circles (T3): 8.3-8.6,
black crosses (T4) >8.6

"Open Cluster Complexes"

Tangential velocities sorted by age (T1 young, T4 old)

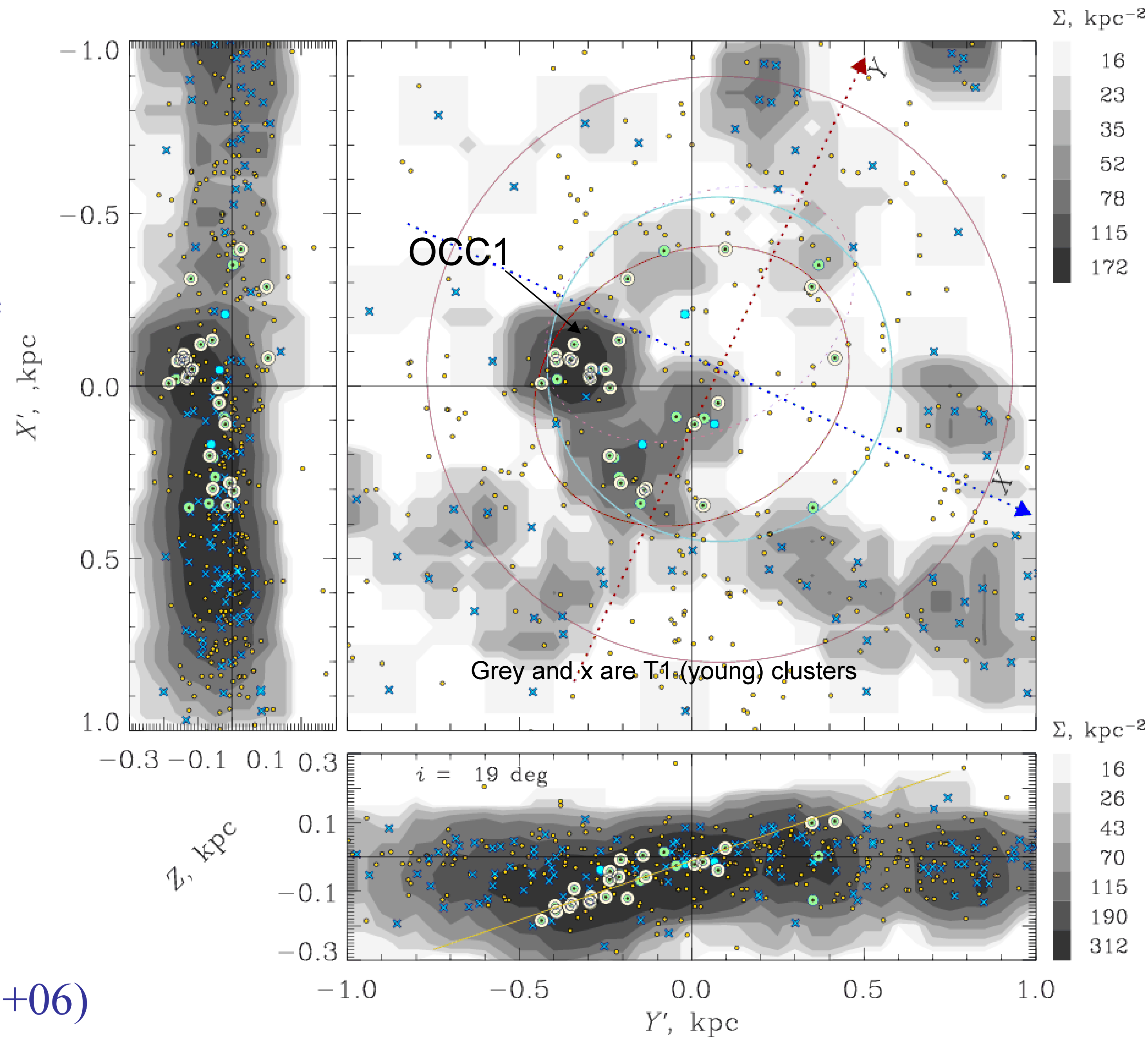


(Piskunov +06; see also Kharchenko et al. 05)

Gould's Belt

Filled circles are Gould Belt members .

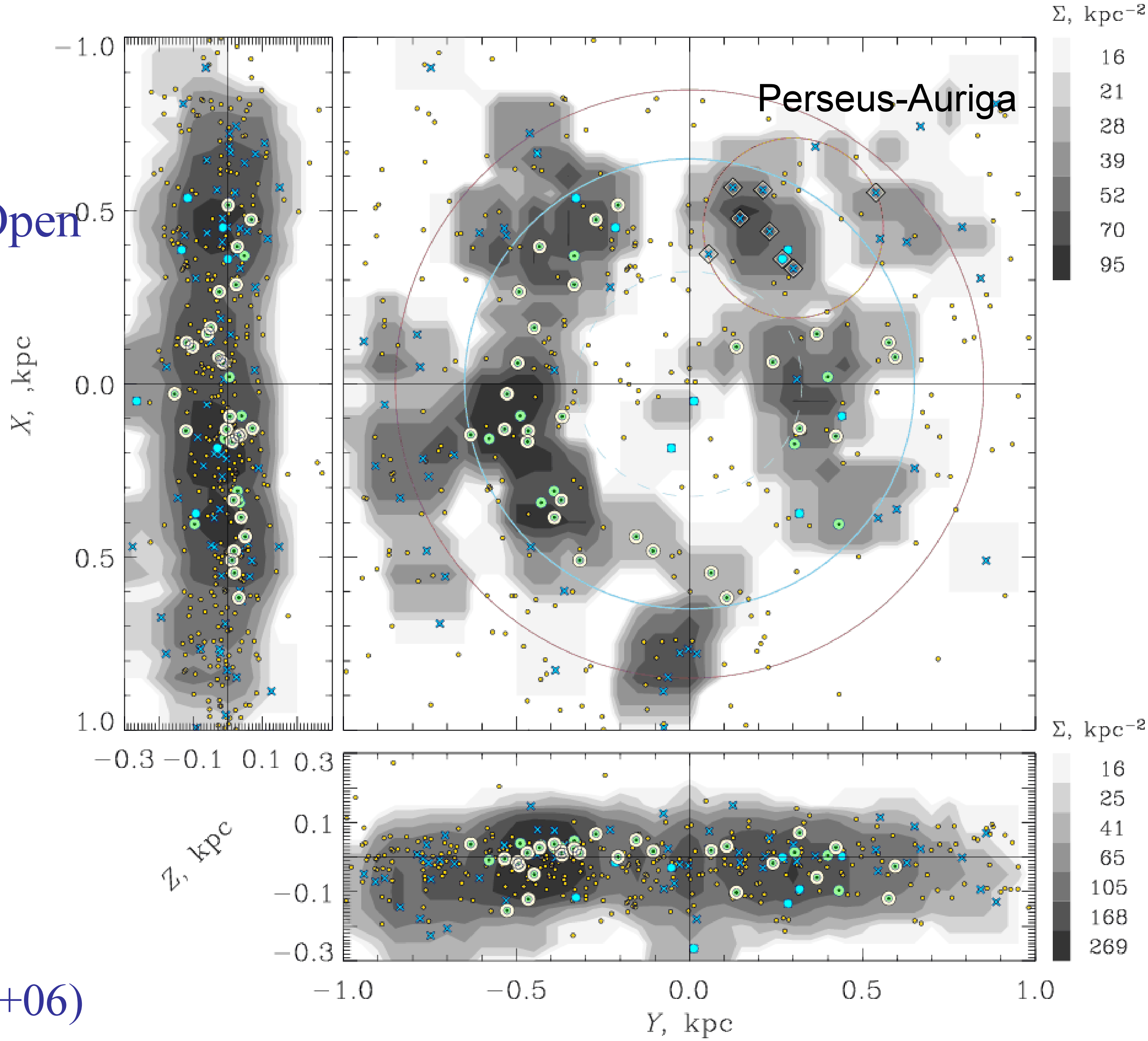
Gray scale is T1 clusters: log(age)<7.9



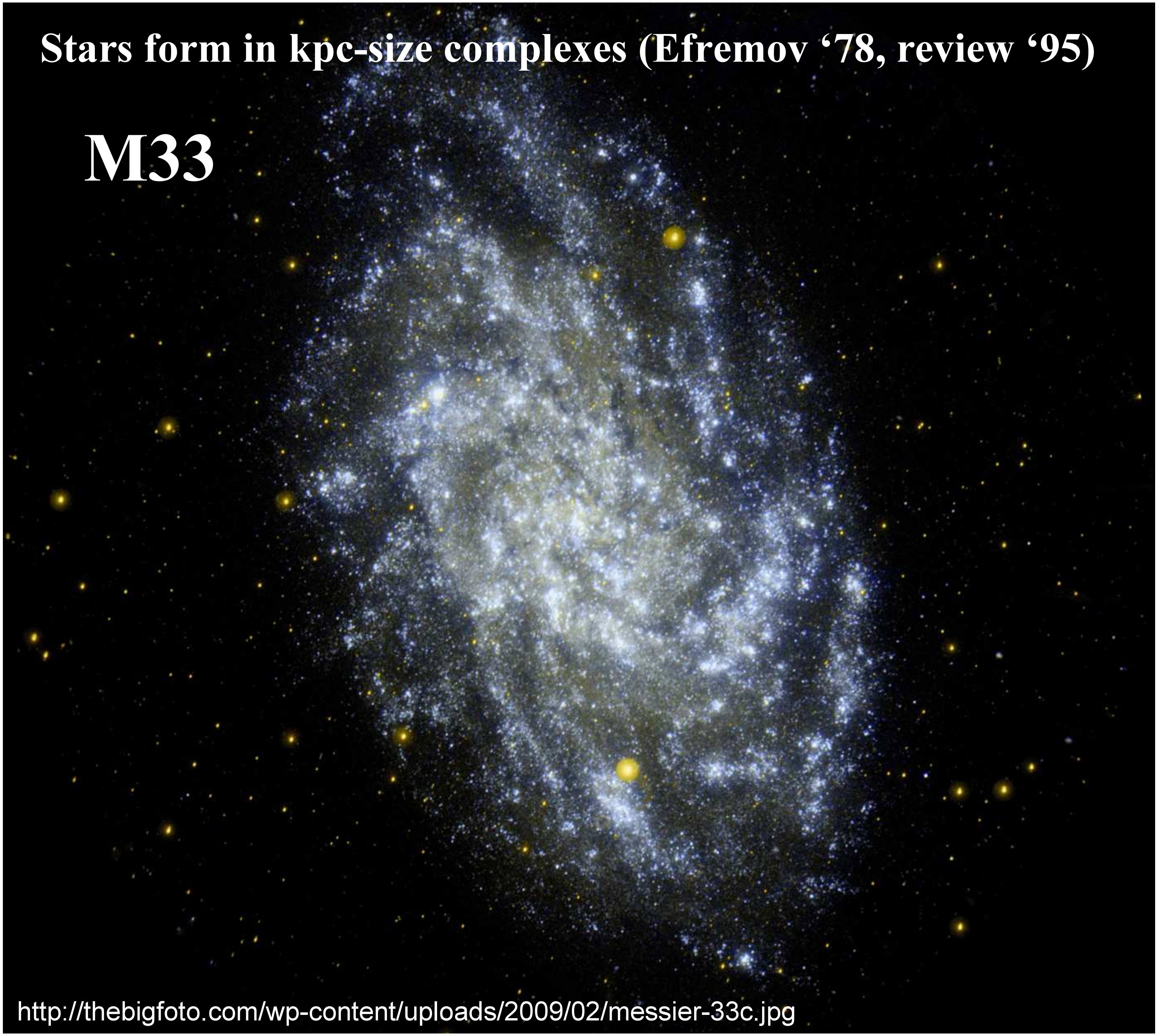
(Piskunov +06)

Perseus-Auriga Open Cluster Complex (filled circles)

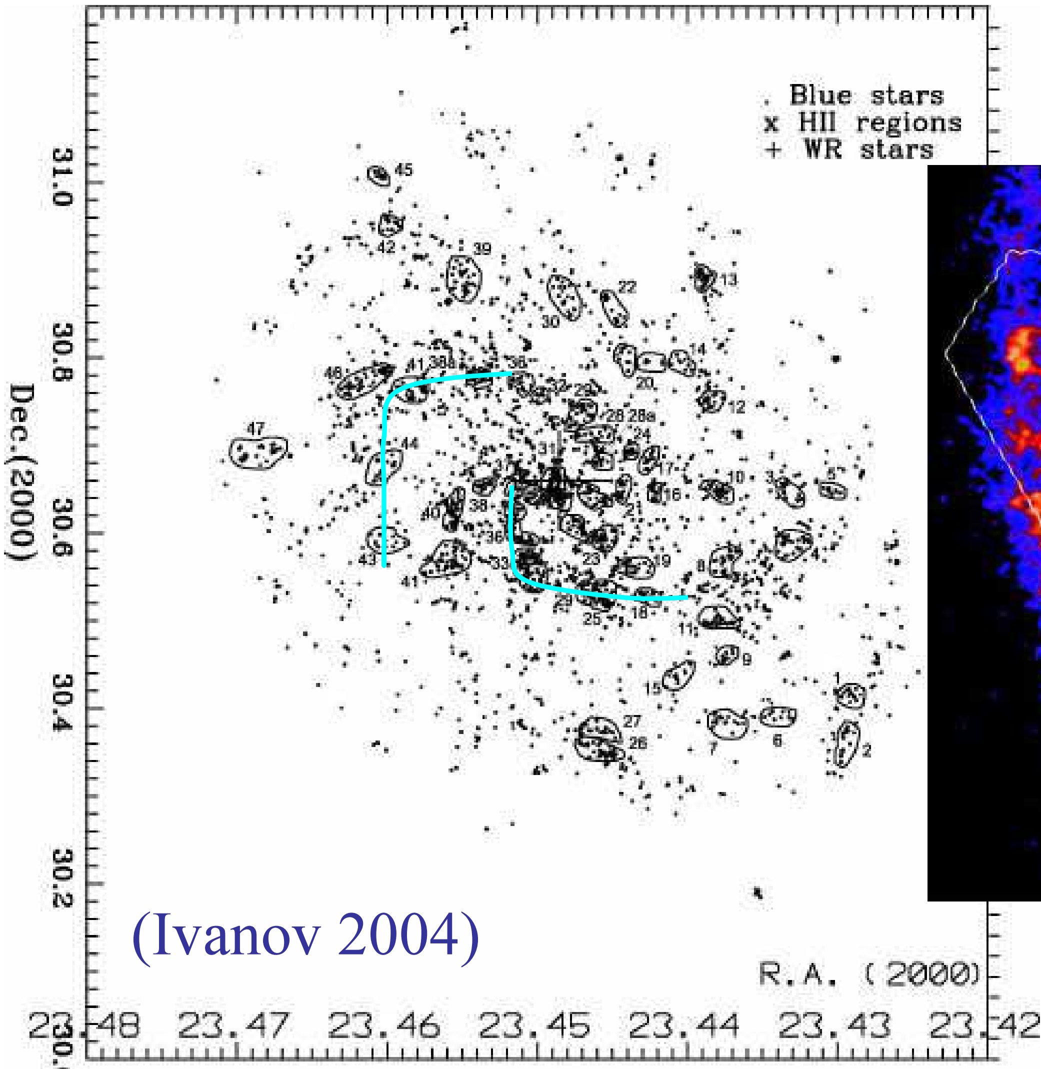
Gray scale is T3 clusters: log(age)=8.3-8.6



(Piskunov +06)

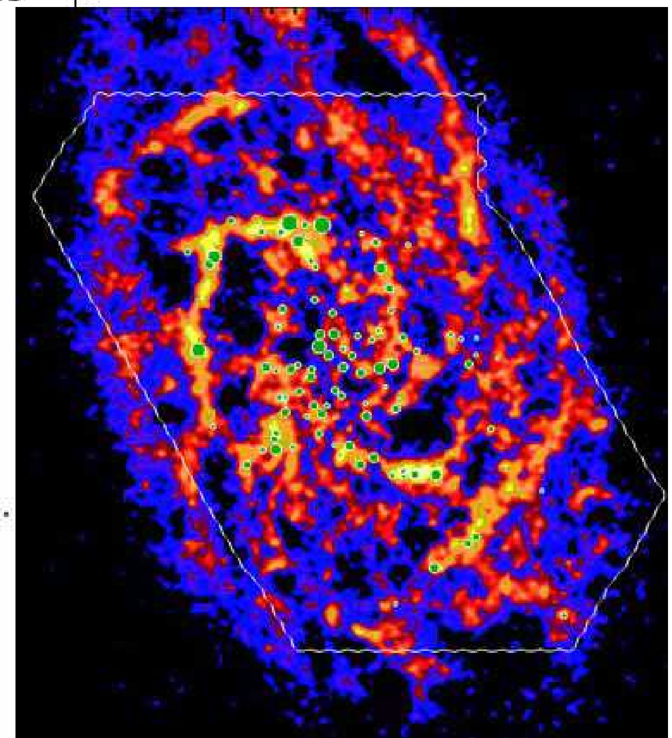

Stars form in kpc-size complexes (Efremov '78, review '95)
M33
http://thebigfoto.com/wp-content/uploads/2009/02/messier-33c.jpg

M33: complexes & CO



(Ivanov 2004)

Figure 1: The stellar complexes in M33.



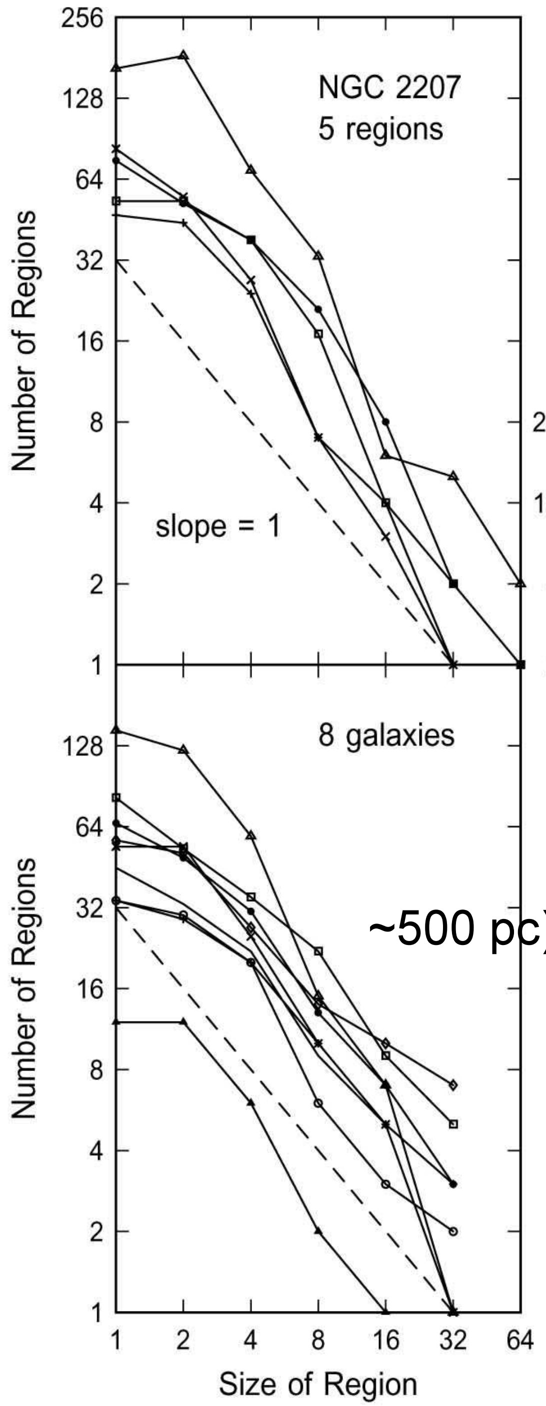
CO & HI

Engargiola et al. (2004)

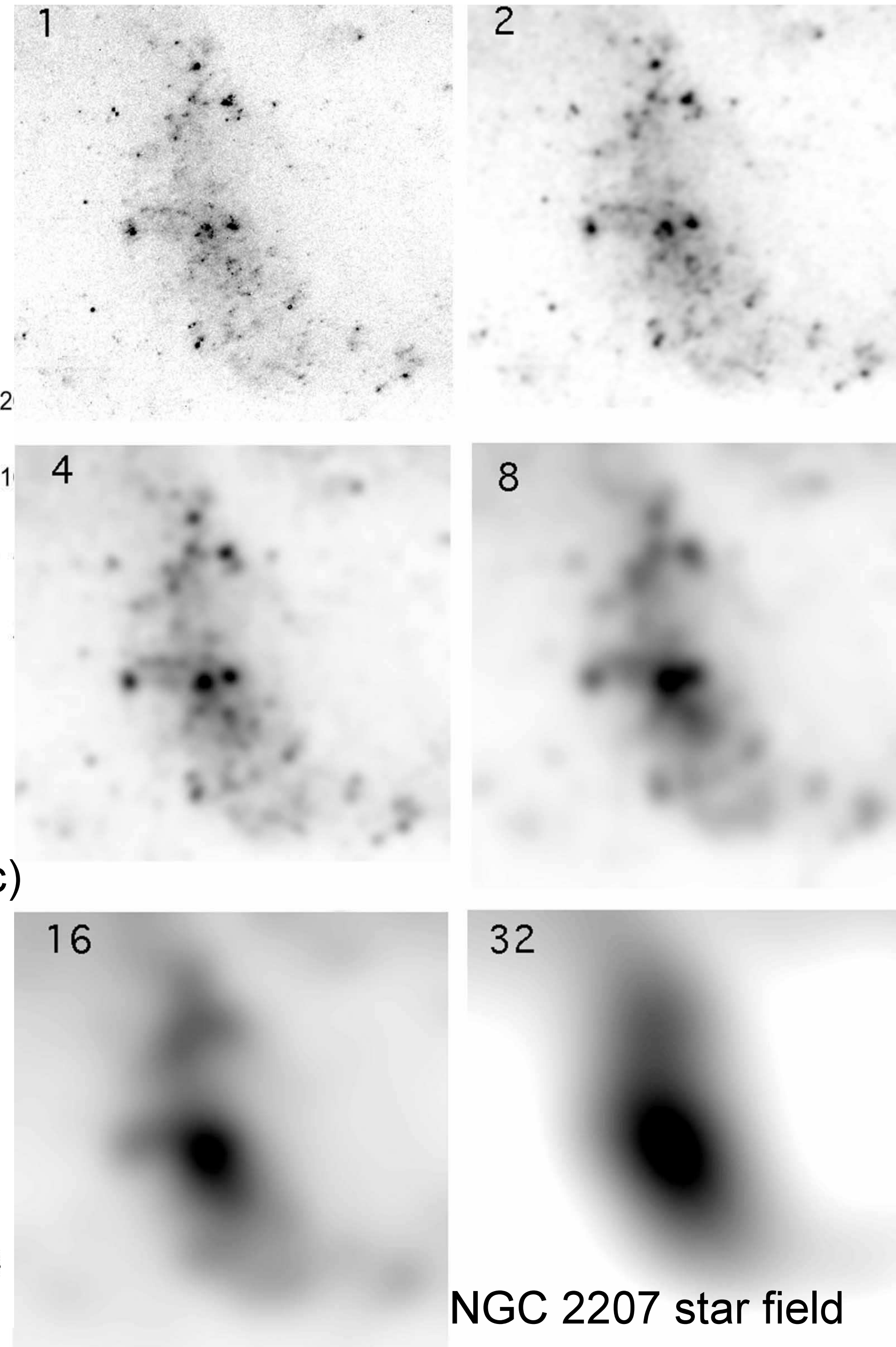
GMCs are shielded cores inside HI clouds; star complexes form in GMCs.

EE 2001 studied 10 galaxies with HST images and looked at fractal properties of young star fields.

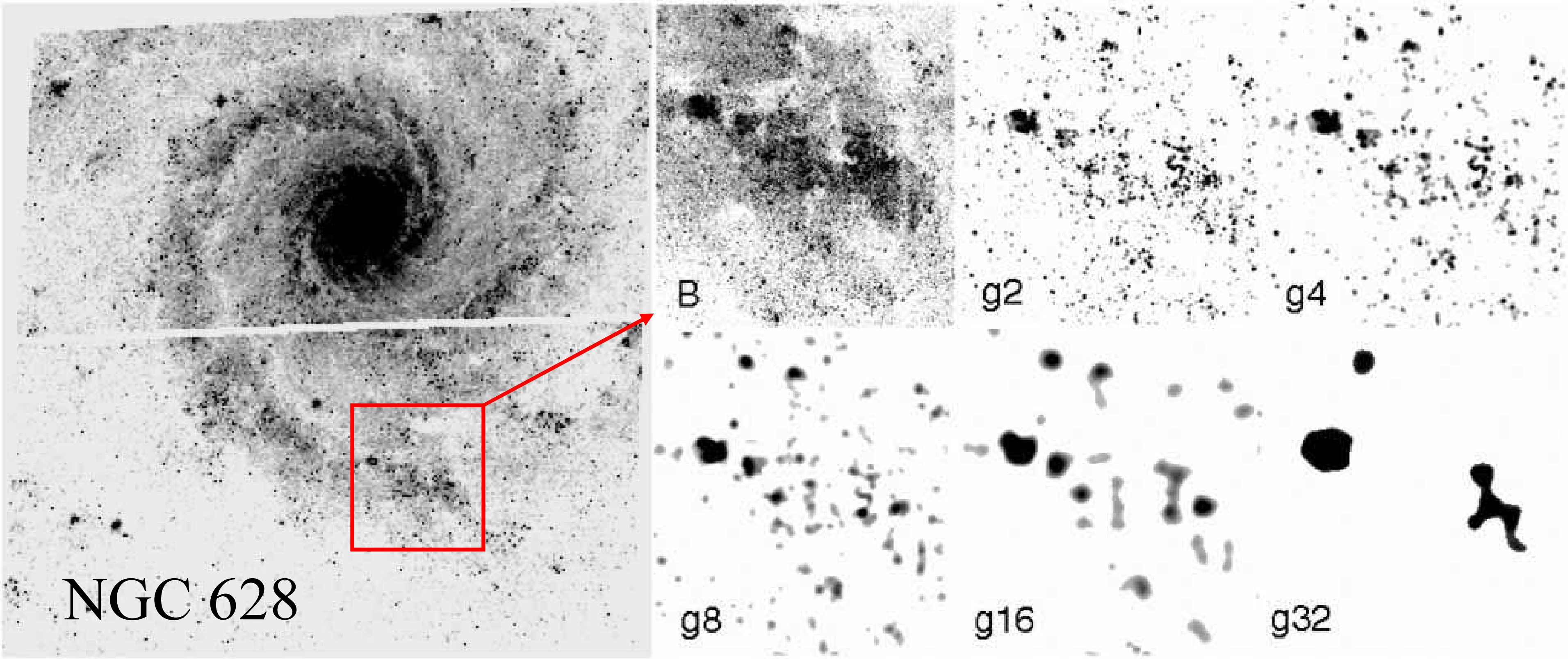
Found power law distributions of subregion size.



~500 pc)



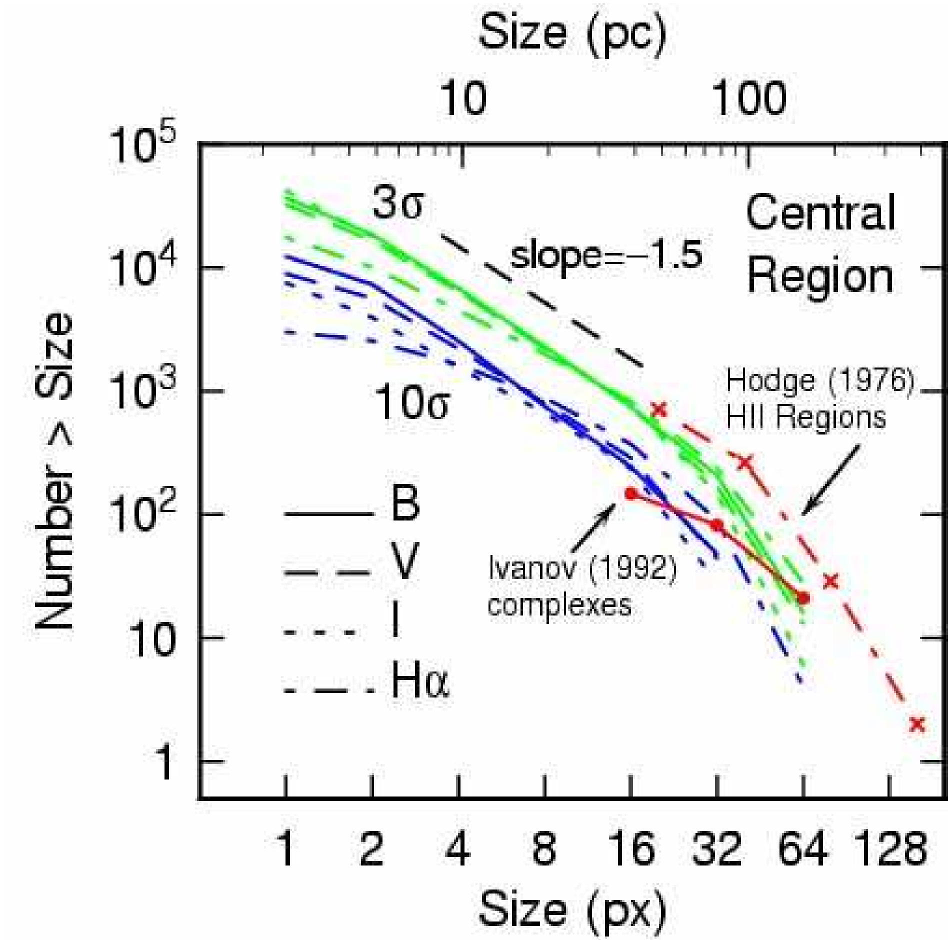
NGC 2207 star field

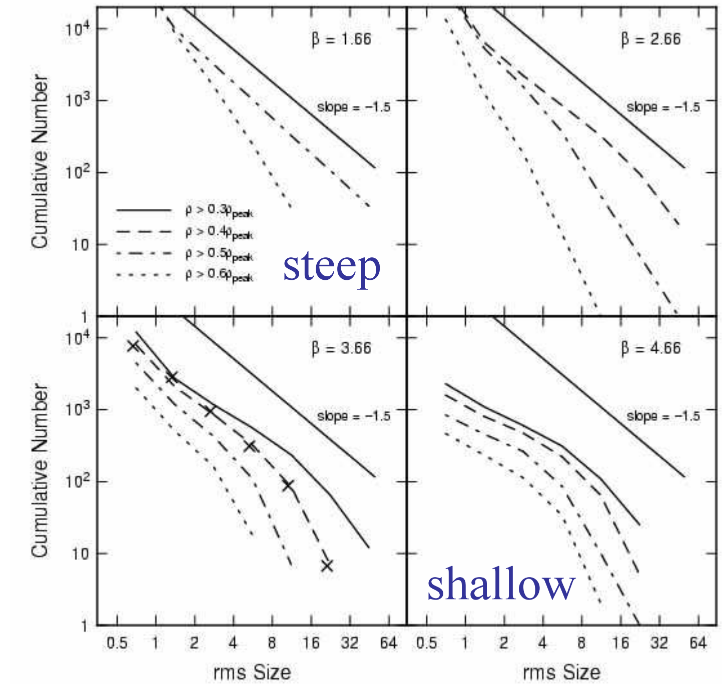


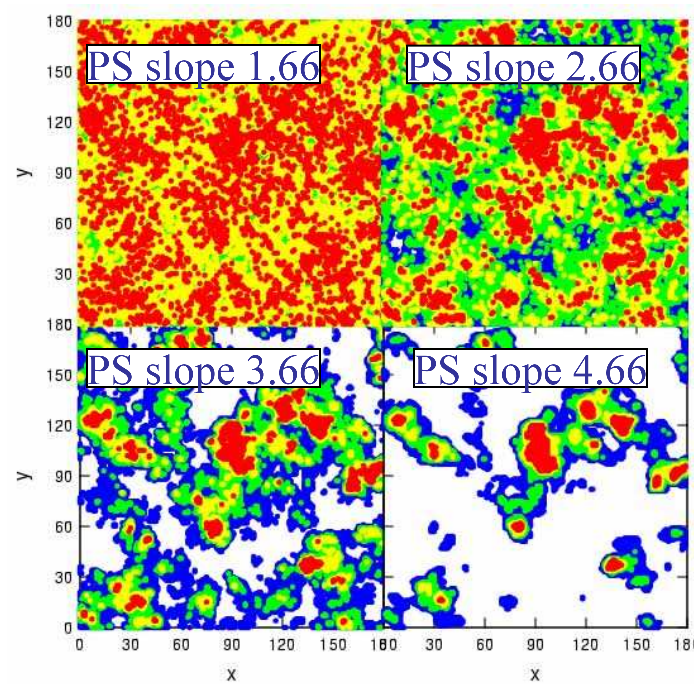
Size distributions of star-forming regions can also be found by "box-counting."

Here an HST/ACS image is blurred in successive stages and all sources are counted with SExtractor.

(Elmegreen +06)





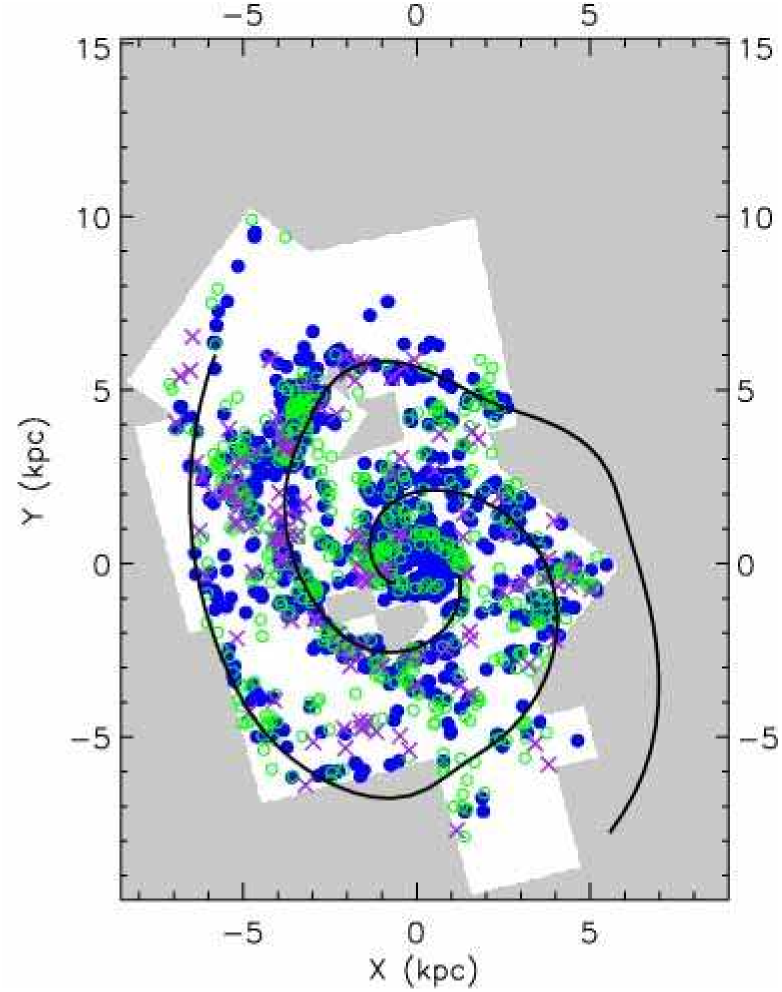


NGC 628: Cumulative Size Distribution

$$n(R)dR \sim R^{-2.5}\,dR$$

fits projected fBm 3D power spectrum with slope of 3.66 (same as Kolmogorov turb.)

M51, HST/ACS clusters



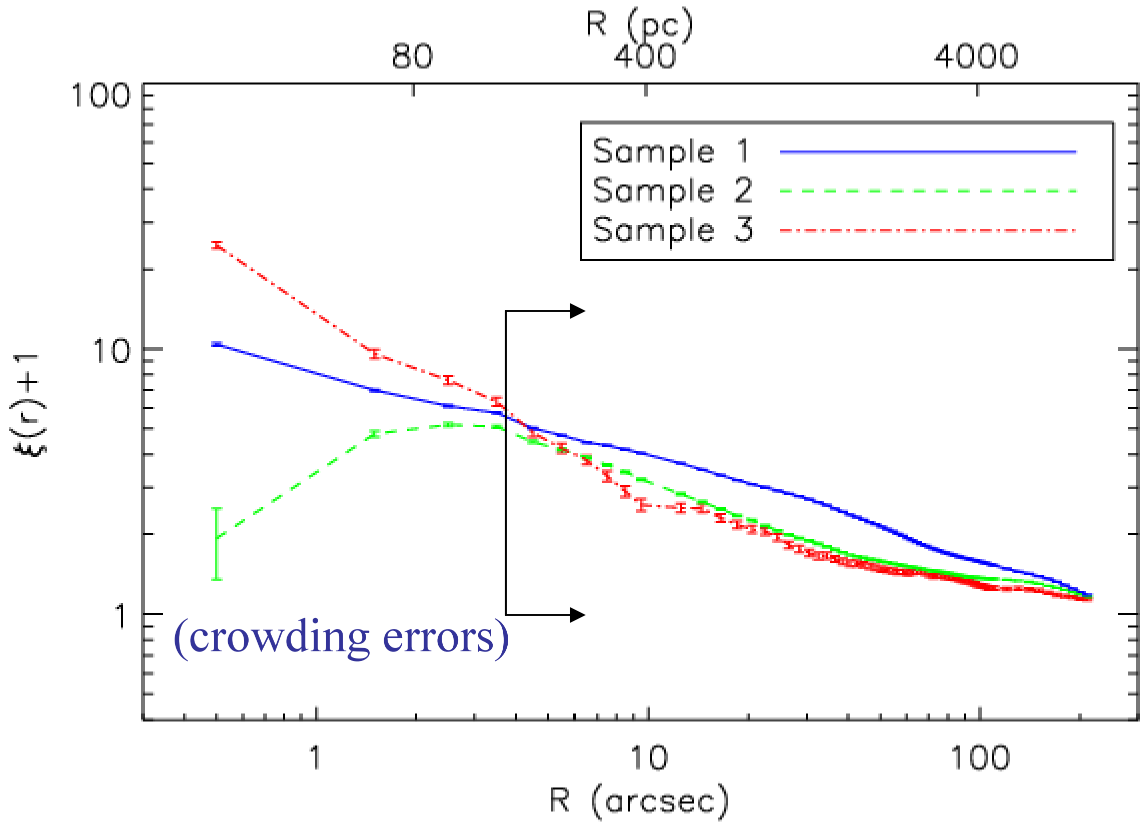
Scheepmaker+09

blue log(age)<7.0, green 7-7.5, purple 7.5-8.6

M51 clusters

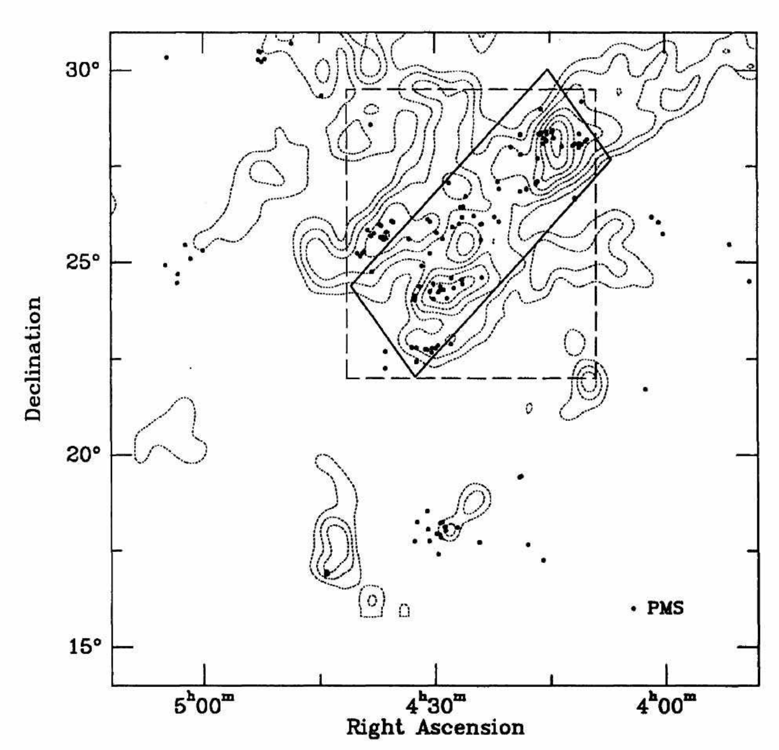
Autocorrelation functions for 3 age bins show the youngest sample (#1) is well correlated:

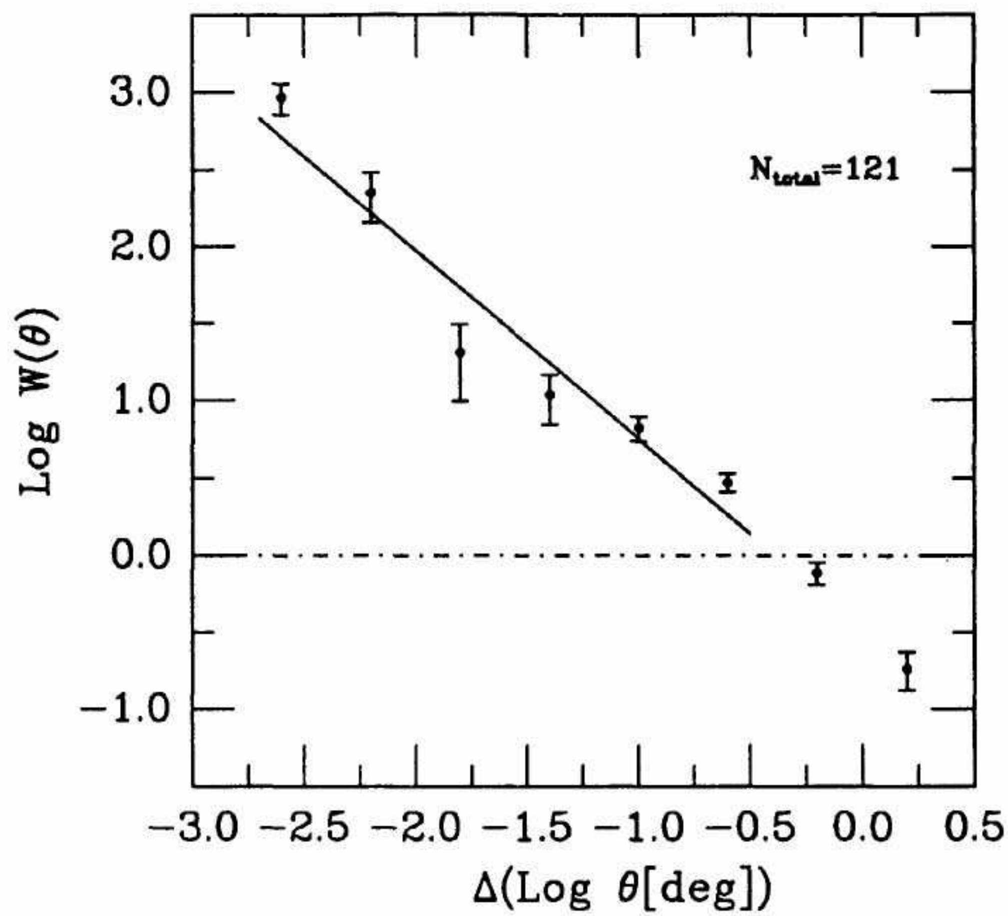
It is hierarchical with a fractal dimension ~1.6



Scheepmaker +09

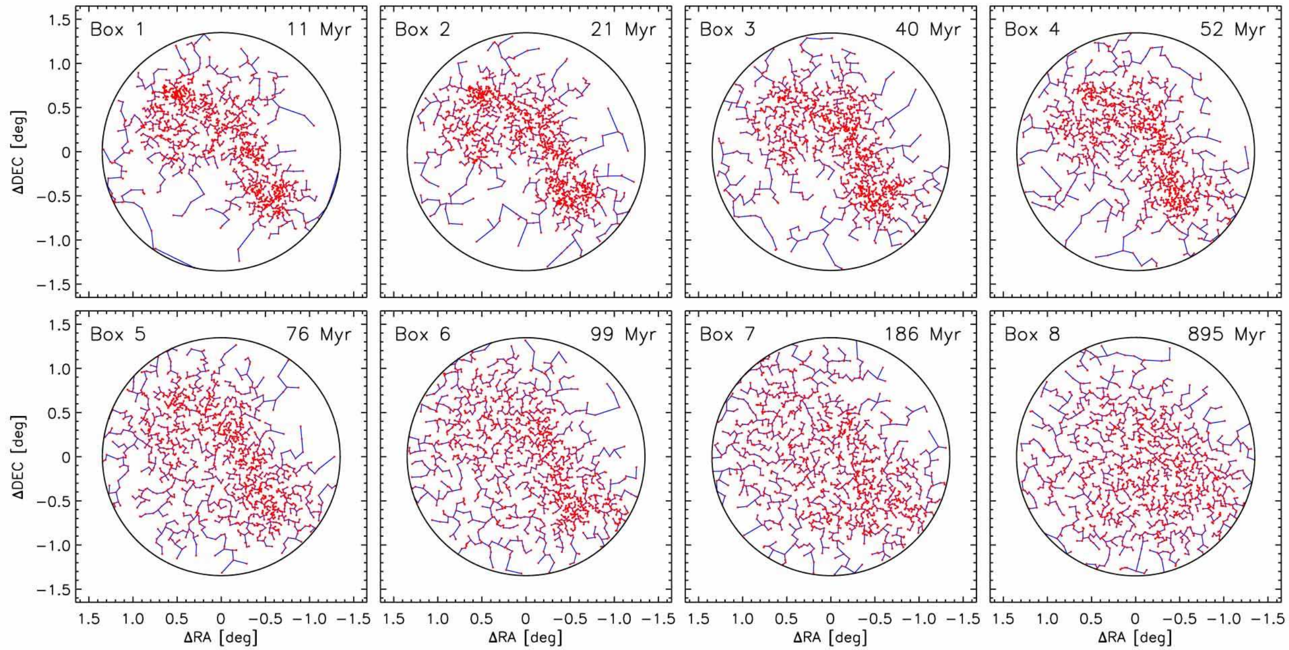
Clusters inside cluster pairs and triplets inside clusters complexes, up to > 1 kpc

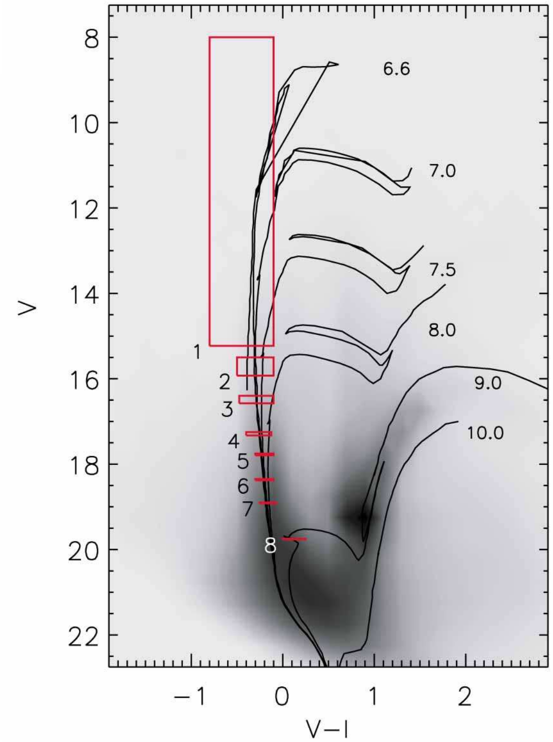


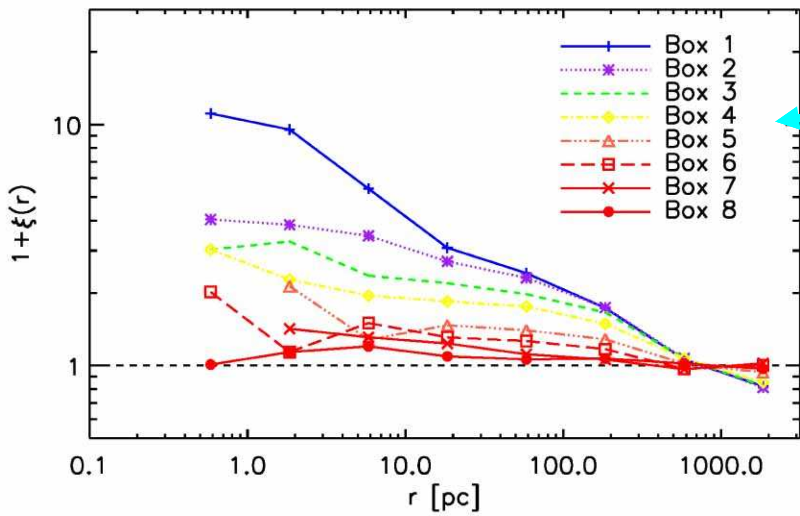


Individual stars are correlated too:
2 point correlation function for stars in Taurus
(Gomez et al. 1993)

Gieles, Bastian, & Ercolano 08: SMC stars

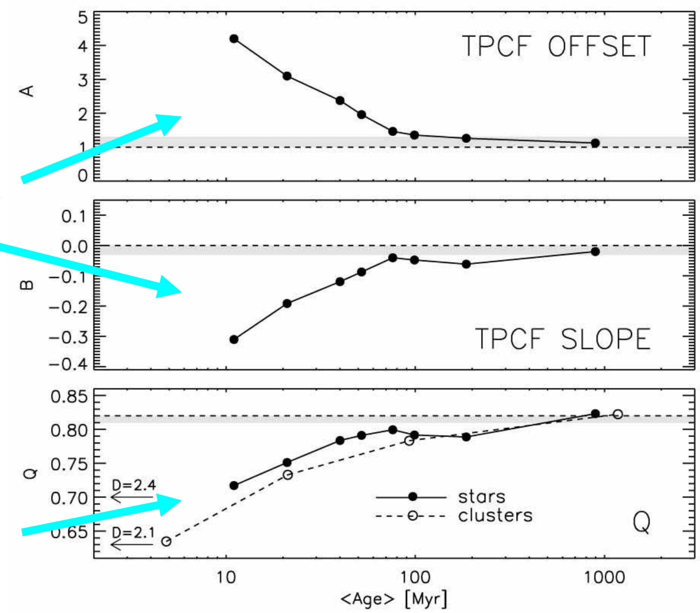






2-pt correlation

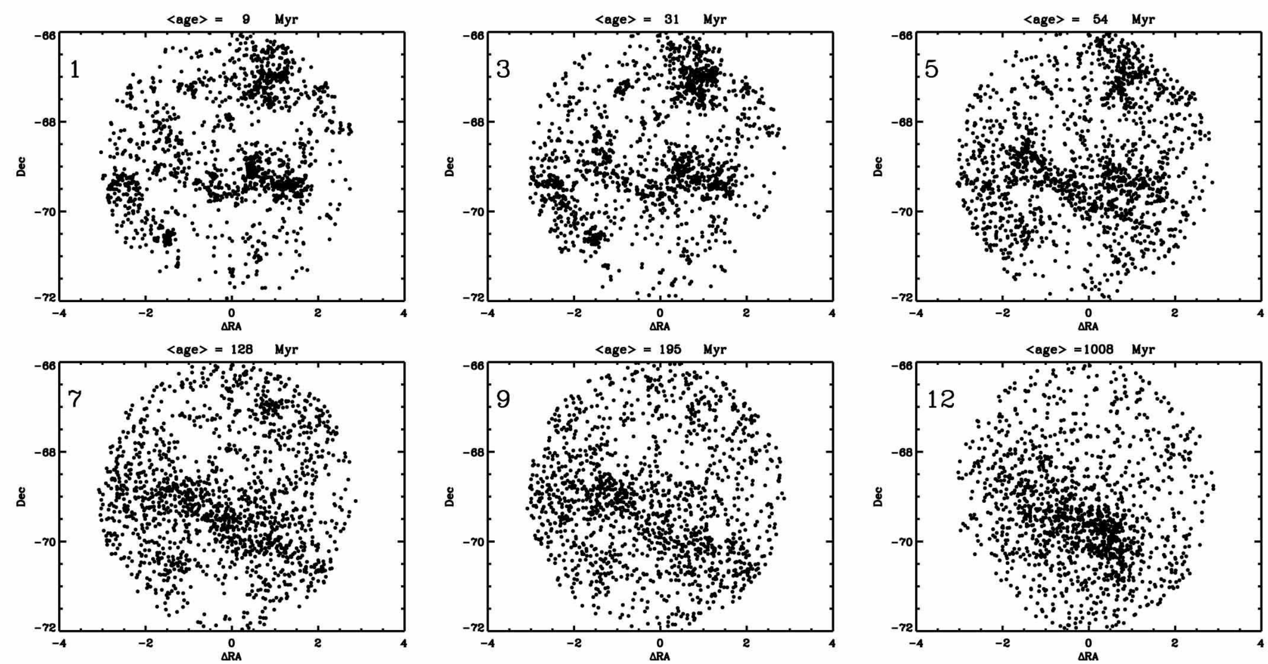
2-pt correl. offset and slope vs age

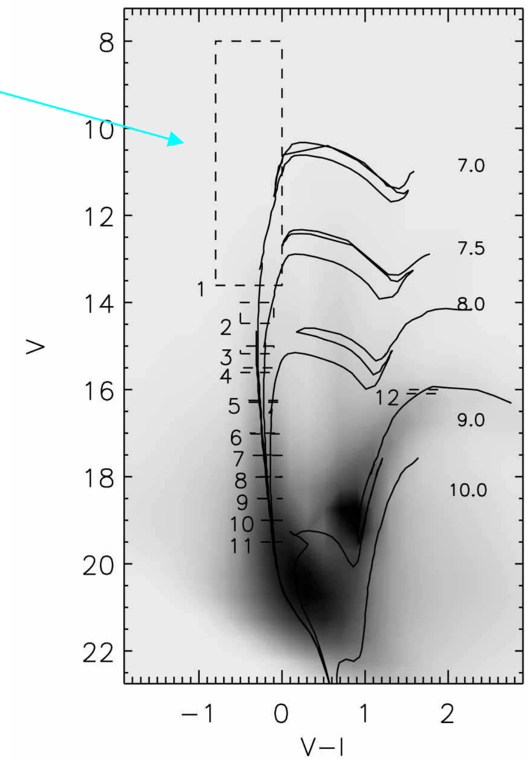


Cartwright & Whitworth 04 Q parameter (= ratio of average mininum spanning tree length to average correlation length).

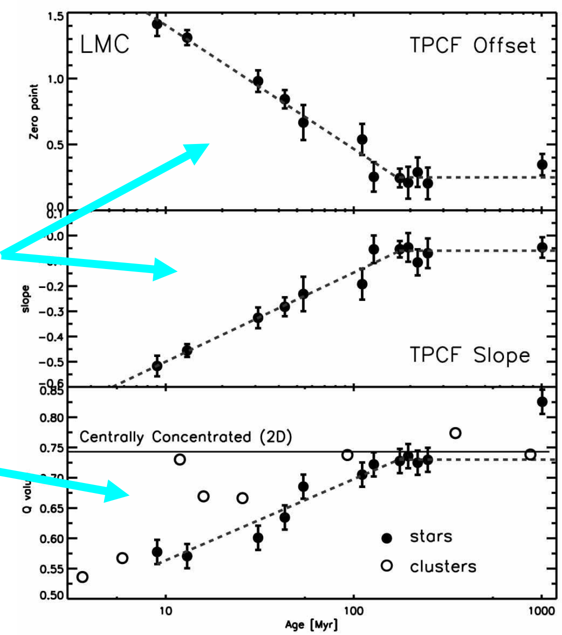
Bastian +09: stars in the LMC (Zaritsky +04)

2000 sources in each CMD age box +
Padova isochrones (Girardi et al. 2002)





Spatial positions in boxes 1, 3, 5, 7, 9 and 12

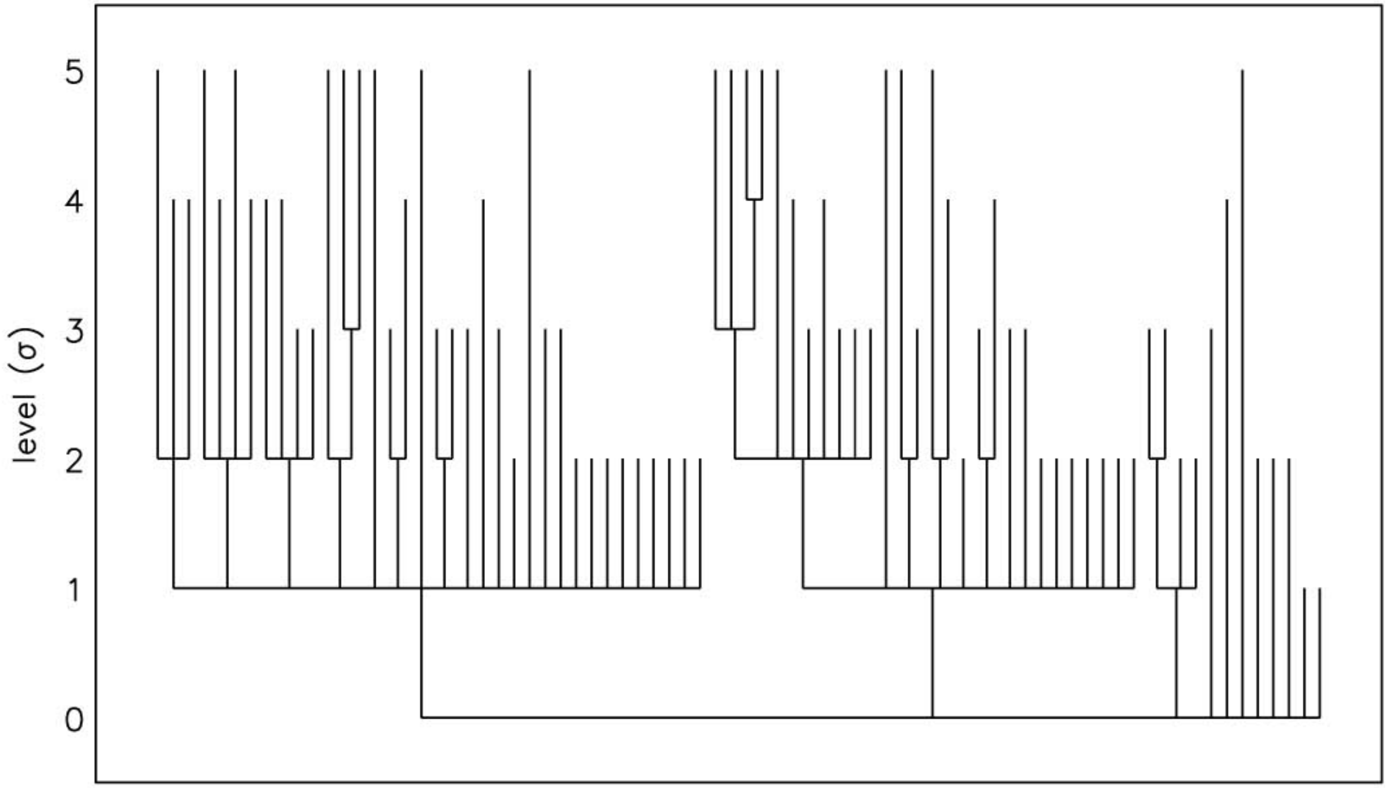


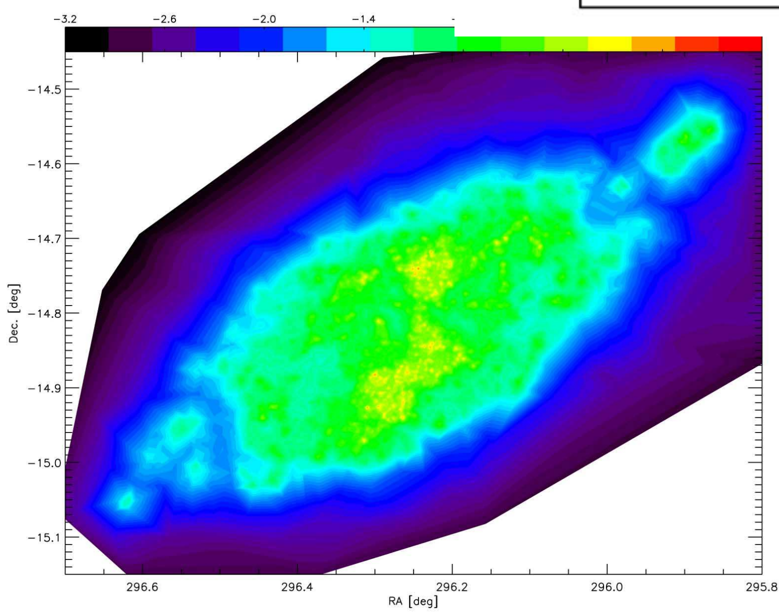
Zero-points and slopes of the TPCF for all age boxes. Younger regions have more substructure. Most substructure erased by 175 Myr.

Cartwright & Whitworth 04 Q parameter (= ratio of average mininum spanning tree length to average correlation length).

Gouliermis +10

NGC 6822



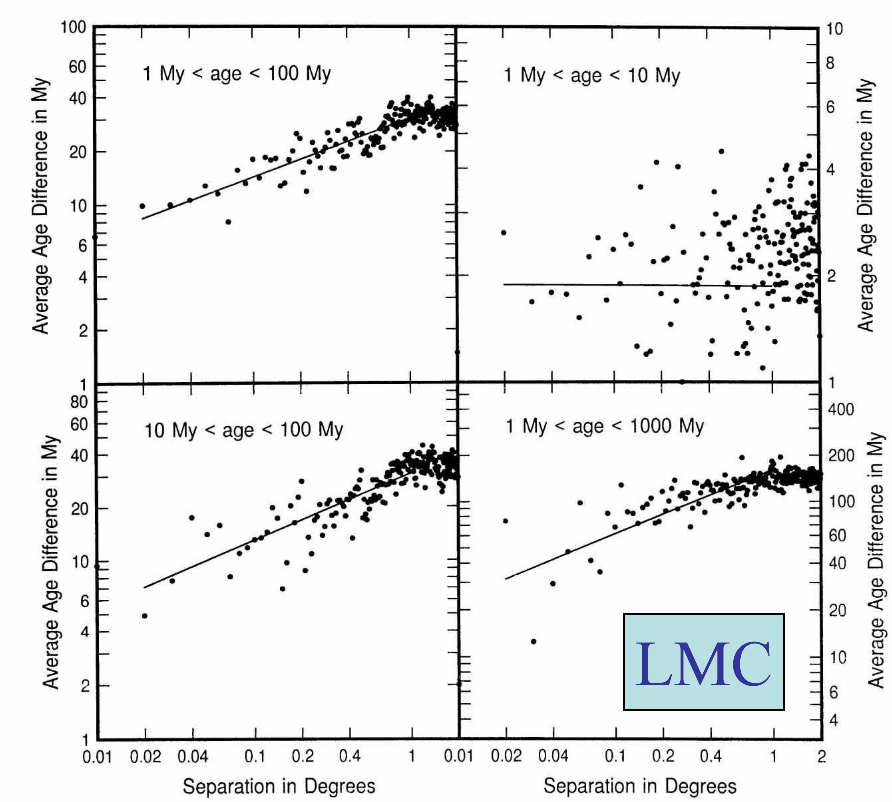


Dendogram of stellar structures
in steps of 1-sigma

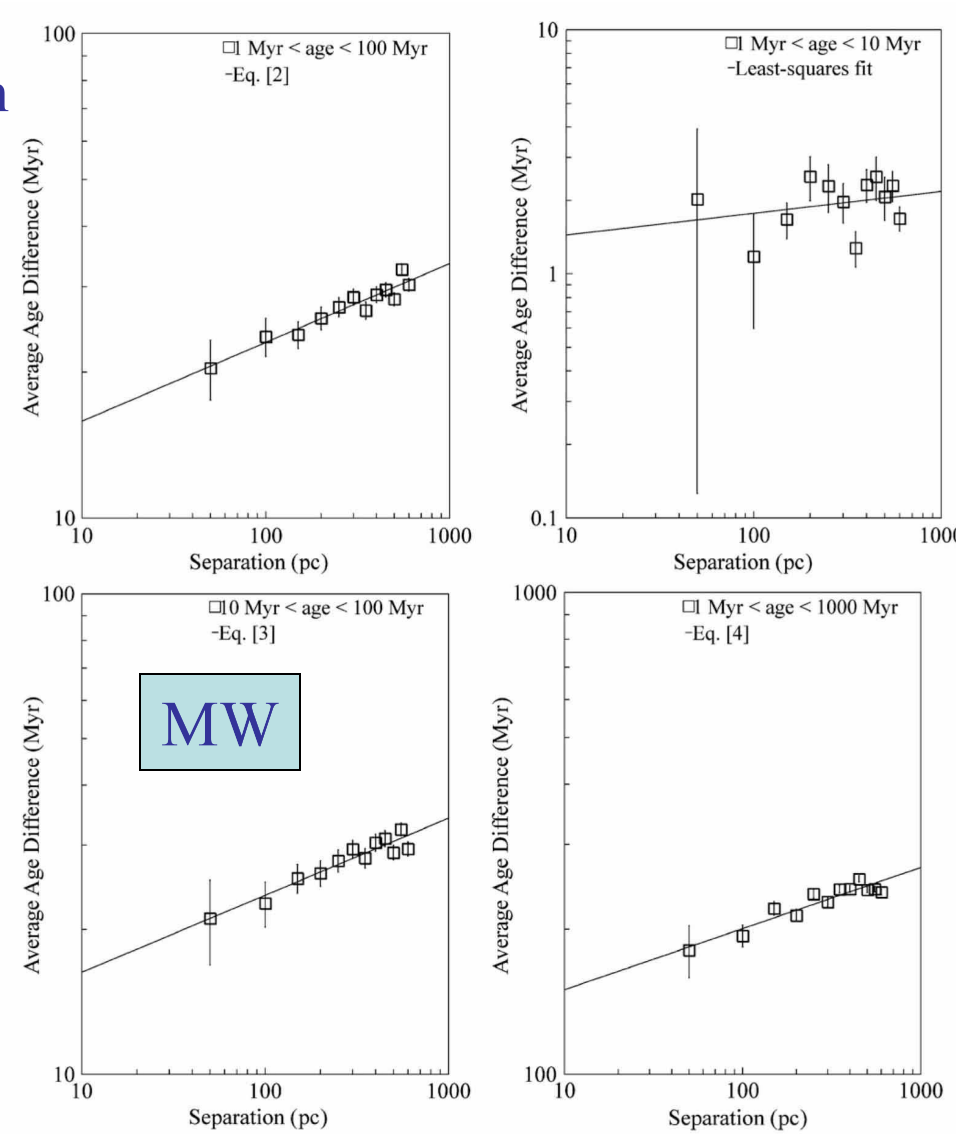
10th nearest neighbor density map of young stars

No break in scale indicates turbulence driven
by large scales

Clusters are also correlated in time: age difference increases with separation



Efremov & Elmegreen '98



LMC clusters from Bica '96.
MW clusters from the *Open Cluster Database* (WEBDA; Mermilliod & Paunzen 2009).

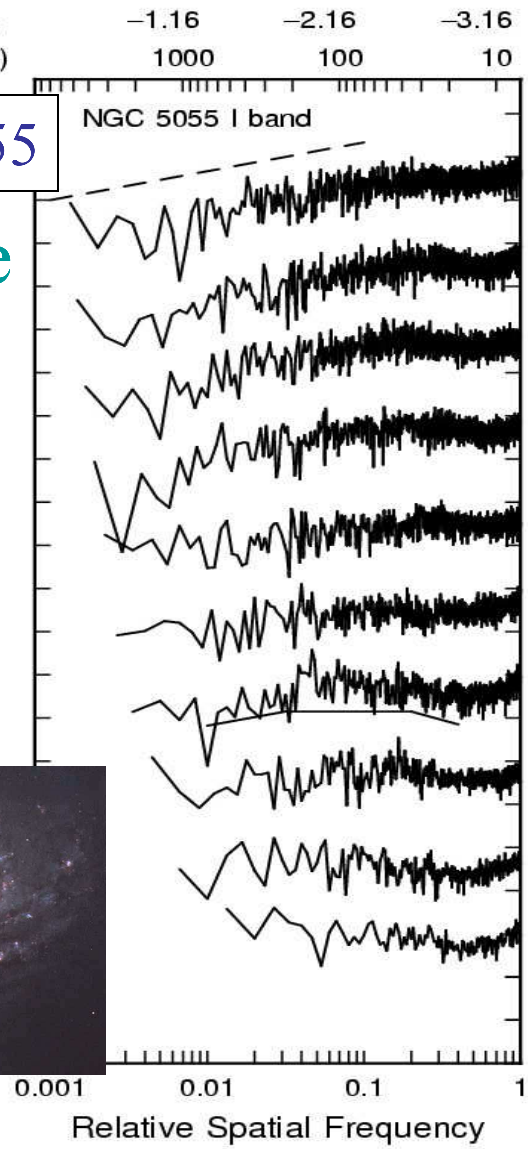
de la Fuente Marcos & de la Fuente Marcos 09

Azimuthal intensity profiles of ***optical*** light from galaxies have power law power spectra.

(Elmegreen etal. 03)

NGC 5055

1D PS slope
~ -1.66



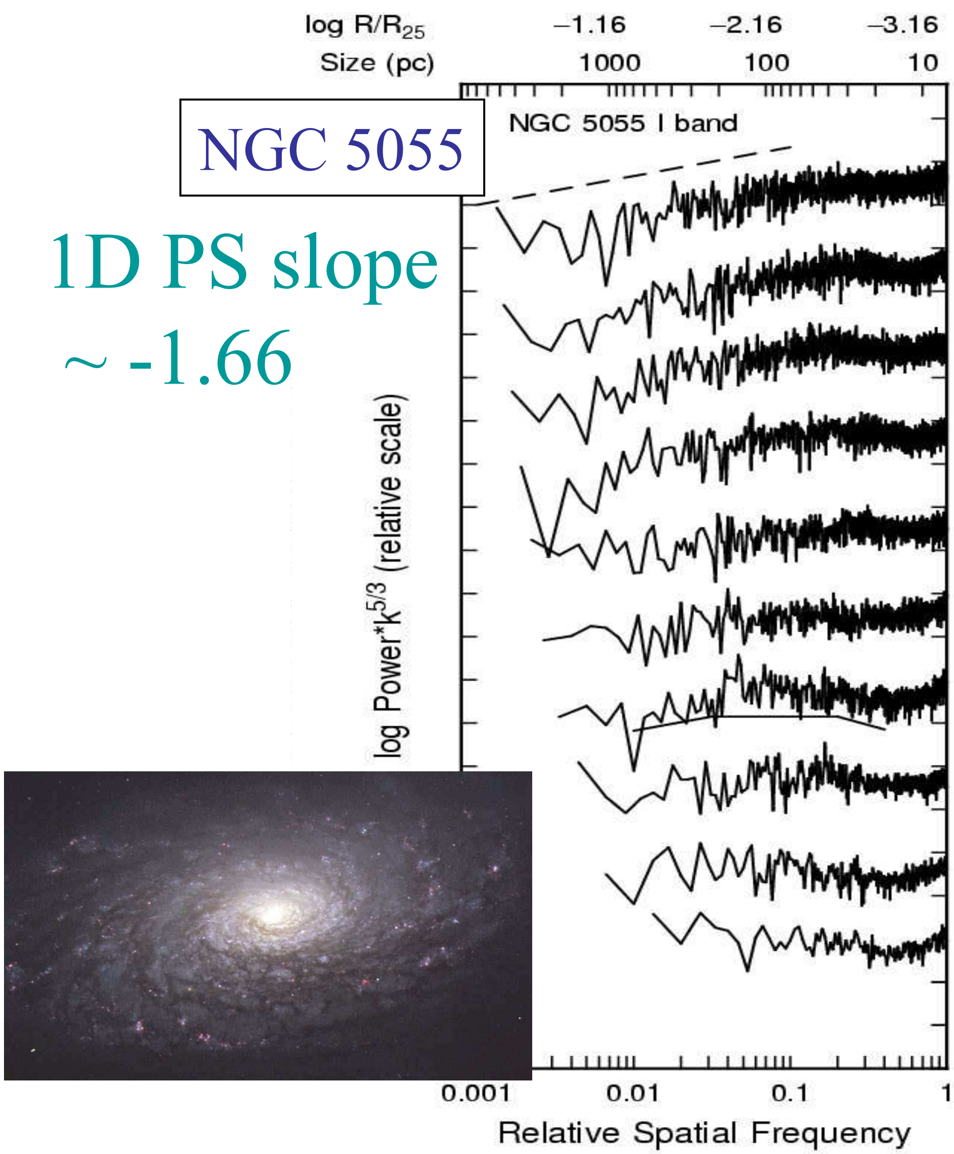
Power spectrum normalized to $k^{-5/3}$, the PS for 1D motions (and tracer particles) in a Kolmogorov turbulent fluid.

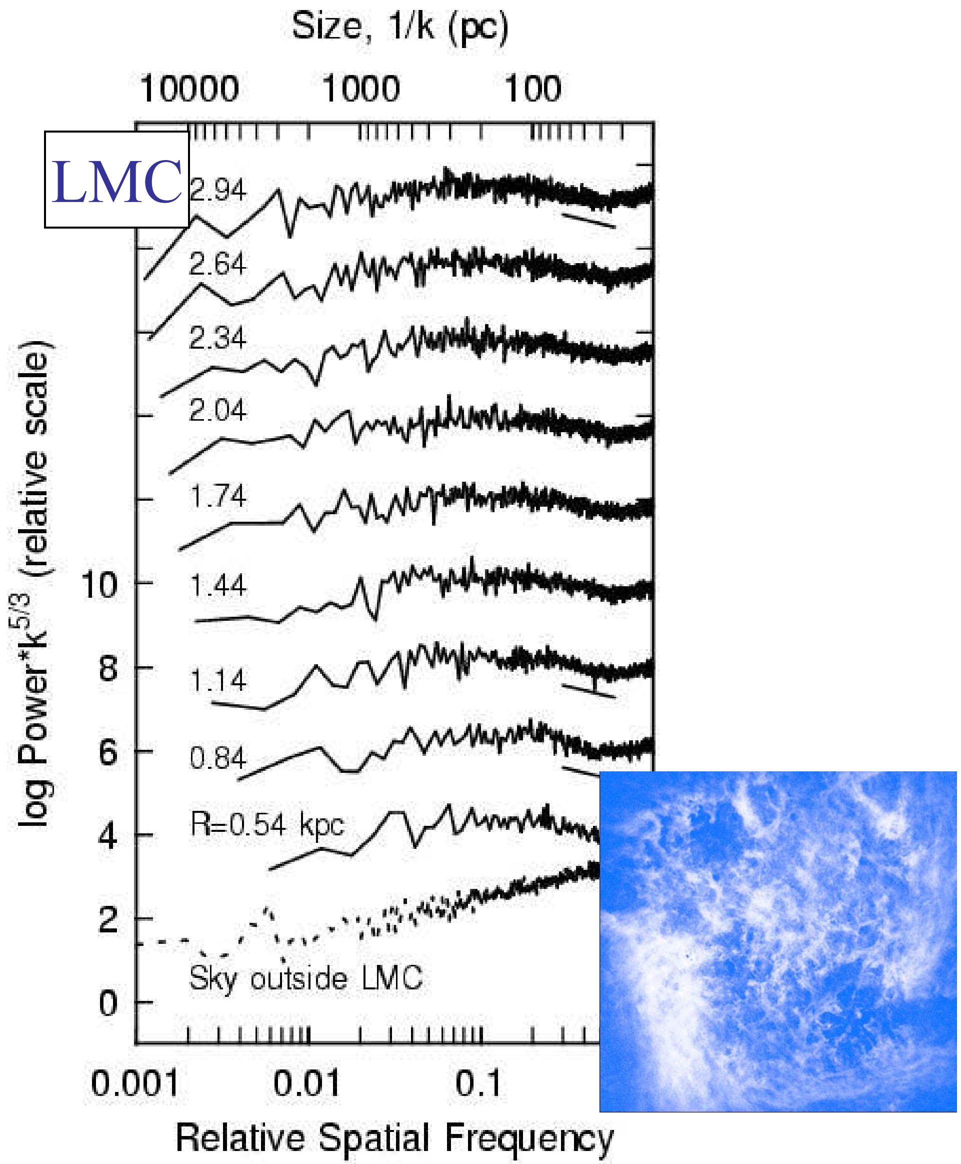
Increasing radius

(Elmegreen etal. 03)

Optical in NGC 5055

1D PS slope
~ -1.66



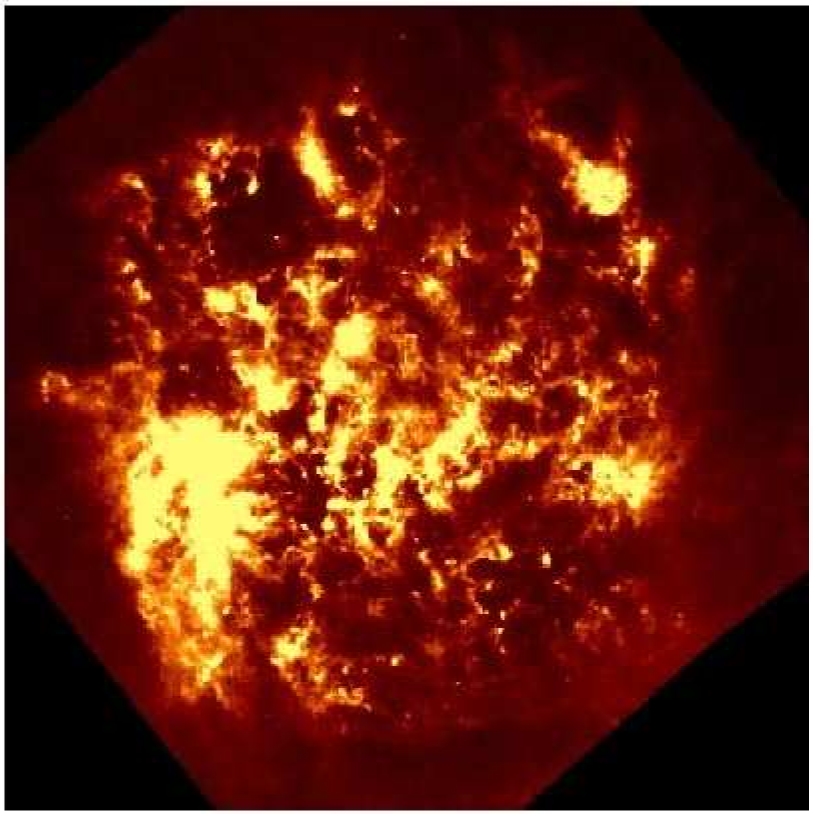


(Elmegreen etal. 03) Optical in NGC 5055 HI in LMC (Elmegreen etal. 01)

Young stars and dust clouds in NGC 5055 have the same scale-free distribution as HI gas in the LMC, both of which resemble a Kolmogorov power spectrum

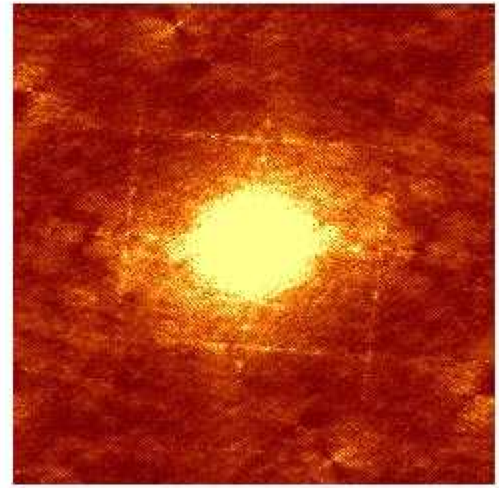
Power spectrum of whole LMC galaxy

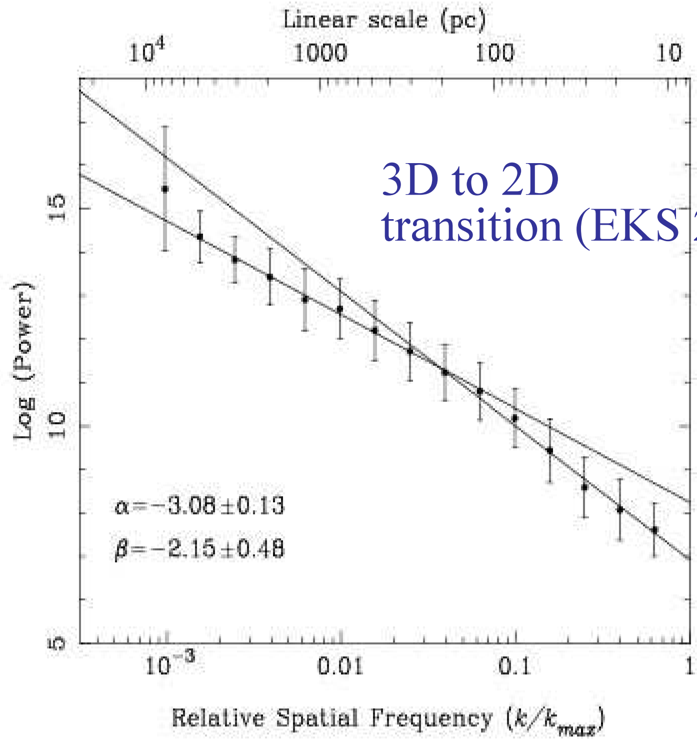
LMC – 160 microns



|← **8.16 degrees** →|

Fourier Transform



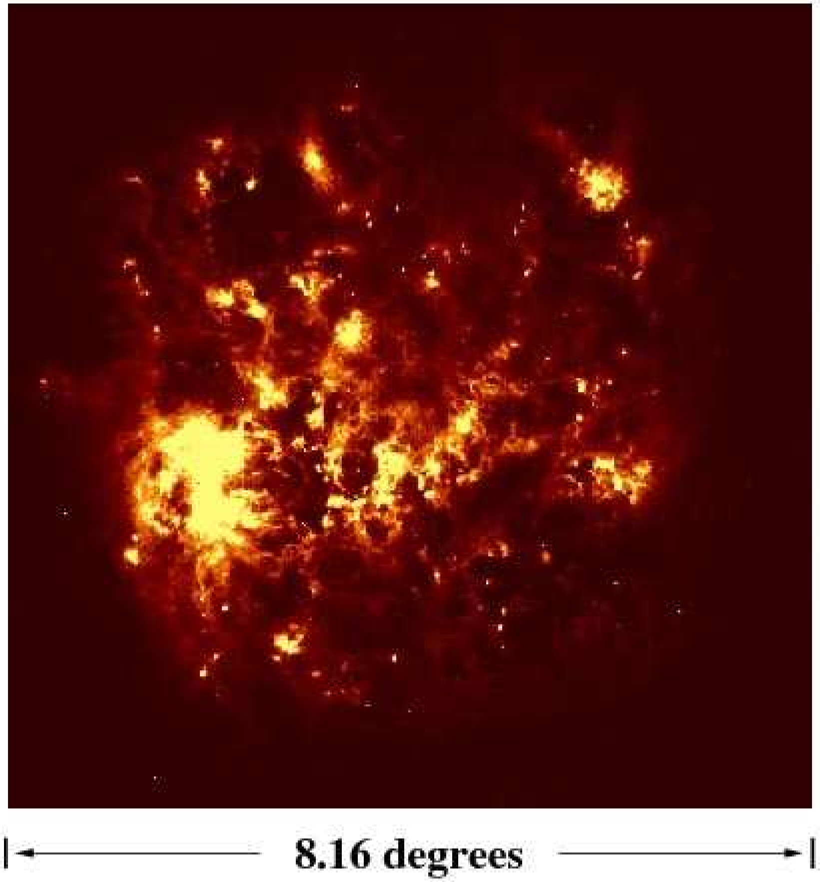


3D to 2D transition (EKS 2001)

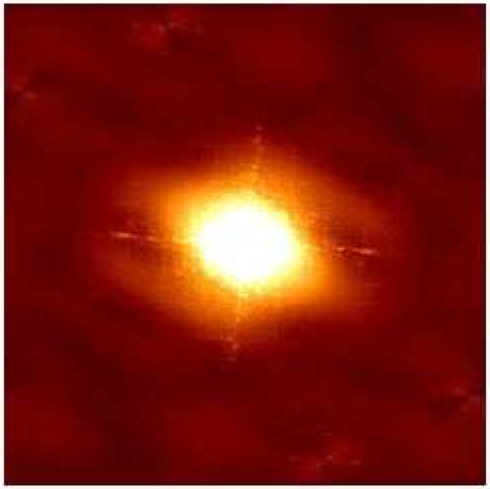
Block +10

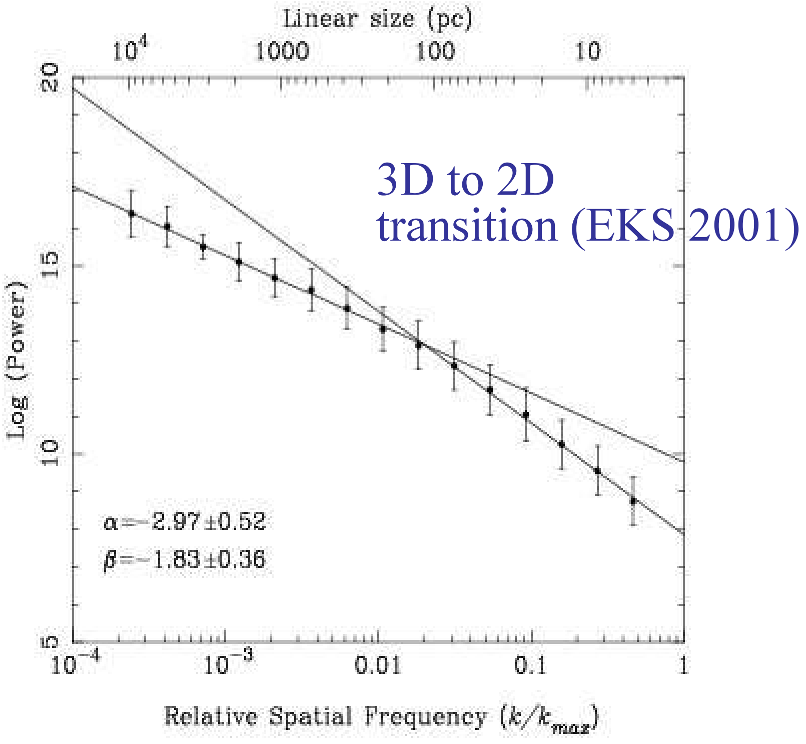
Power spectrum of whole LMC galaxy

LMC – 70 microns



Fourier Transform

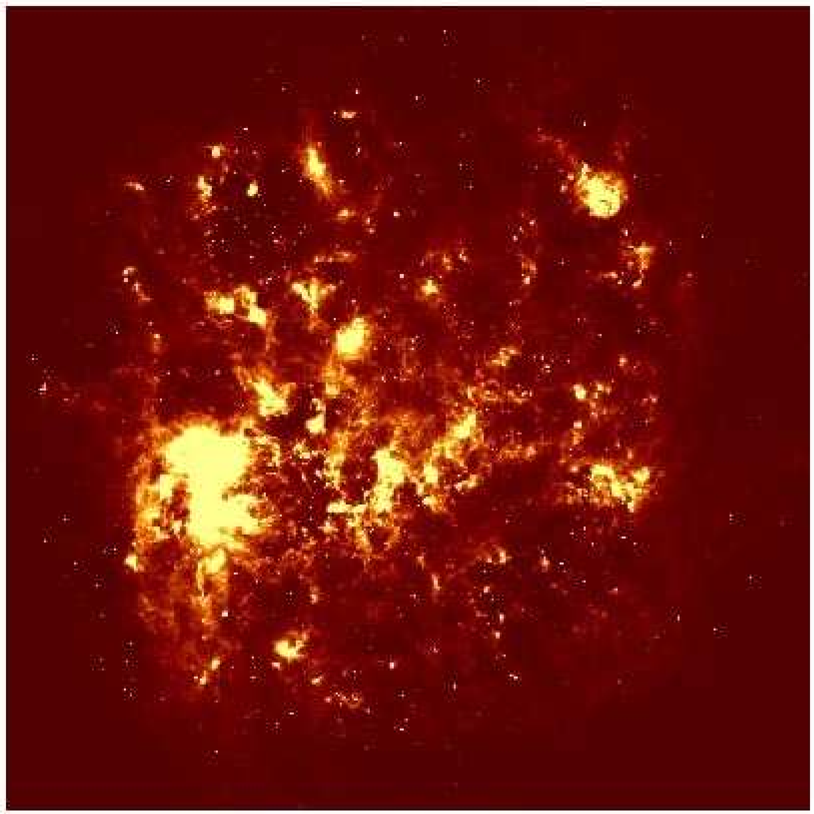




Block +10

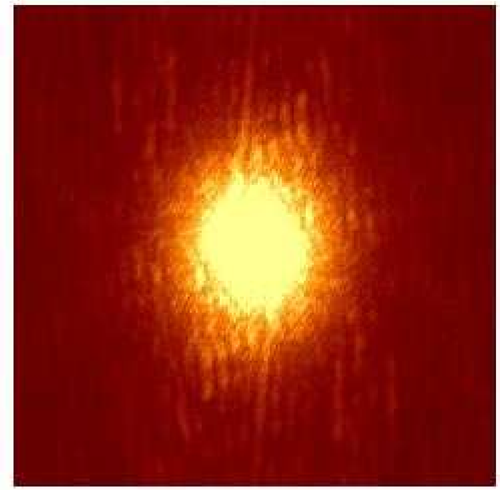
Power spectrum of whole LMC galaxy

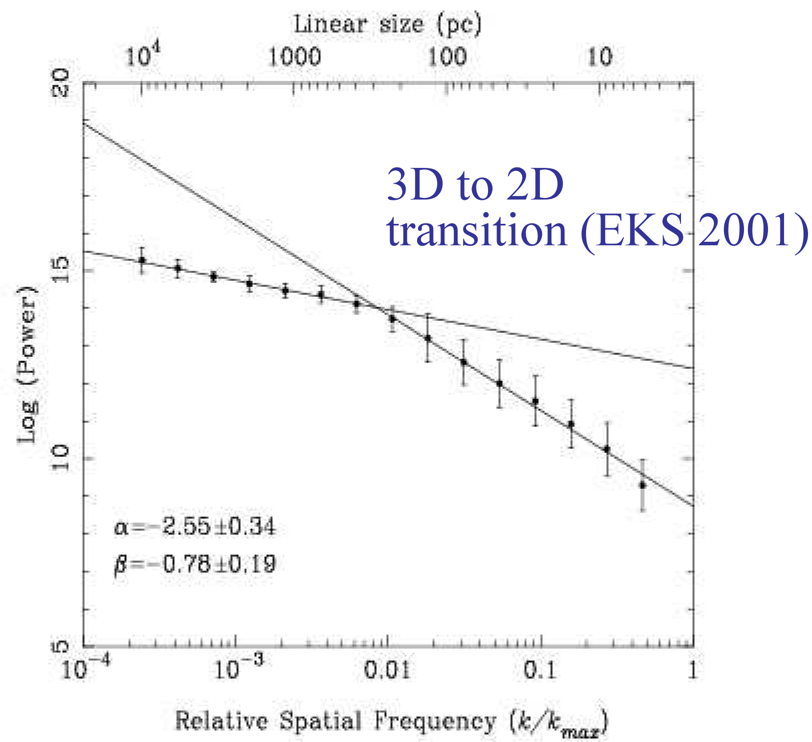
LMC – 24 microns



8.16 degrees

Fourier Transform





Block +10

Bournaud +10 simulations:

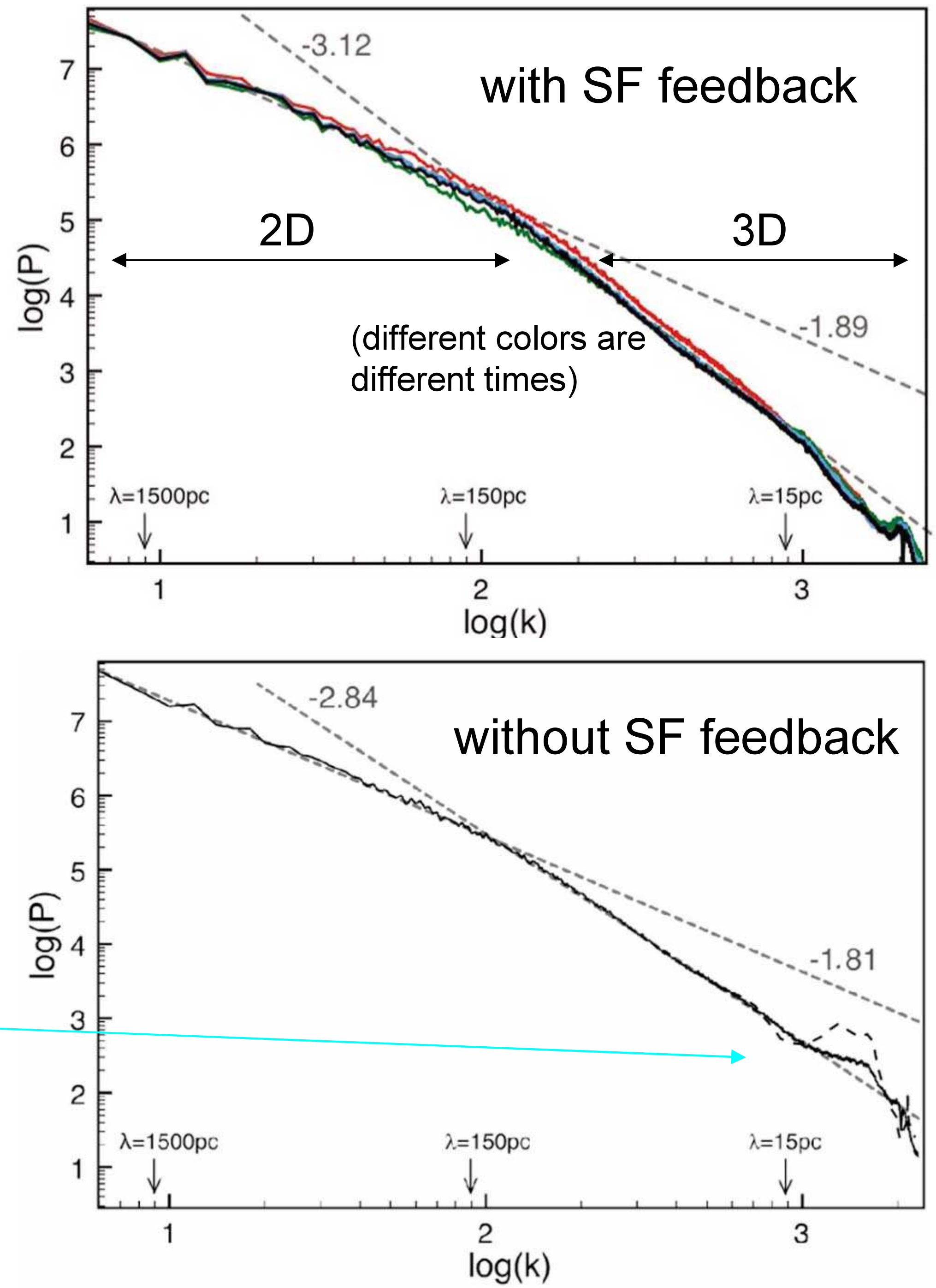
Spirals (gravity) cause 2D turbulent power spectrum at large scales

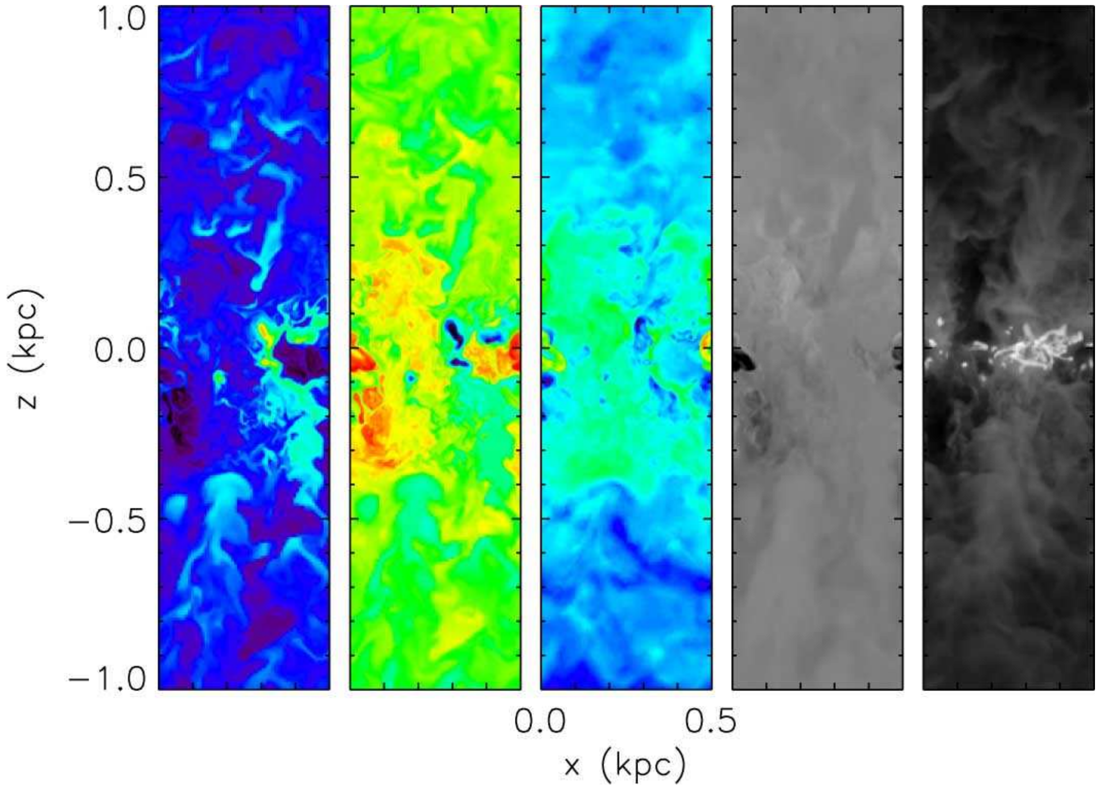
Gravity + feedback cause 3D power spectrum on small scales.

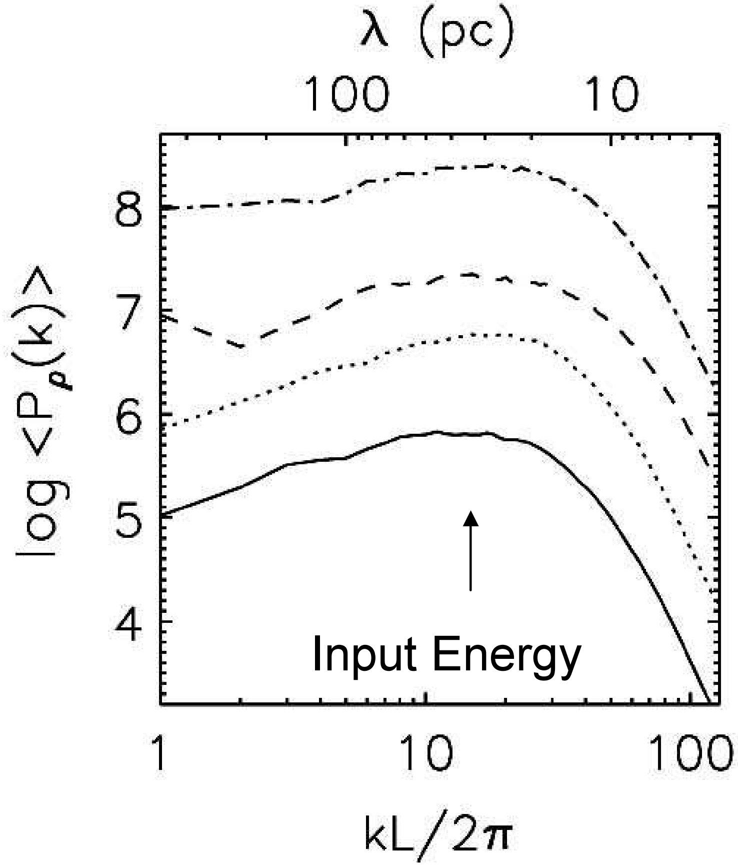
However, feedback does not affect the power spectrum much:

Feedback+gravity maintain Q~1 on scales k^{-1} = thickness

(Feedback is important to break apart clouds)

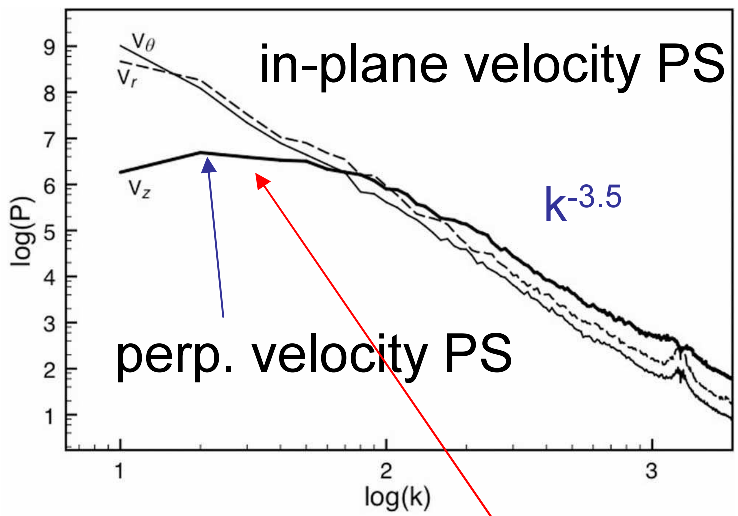






Joung, MacLow & Bryan 09: SN driven ISM: Feedback only.

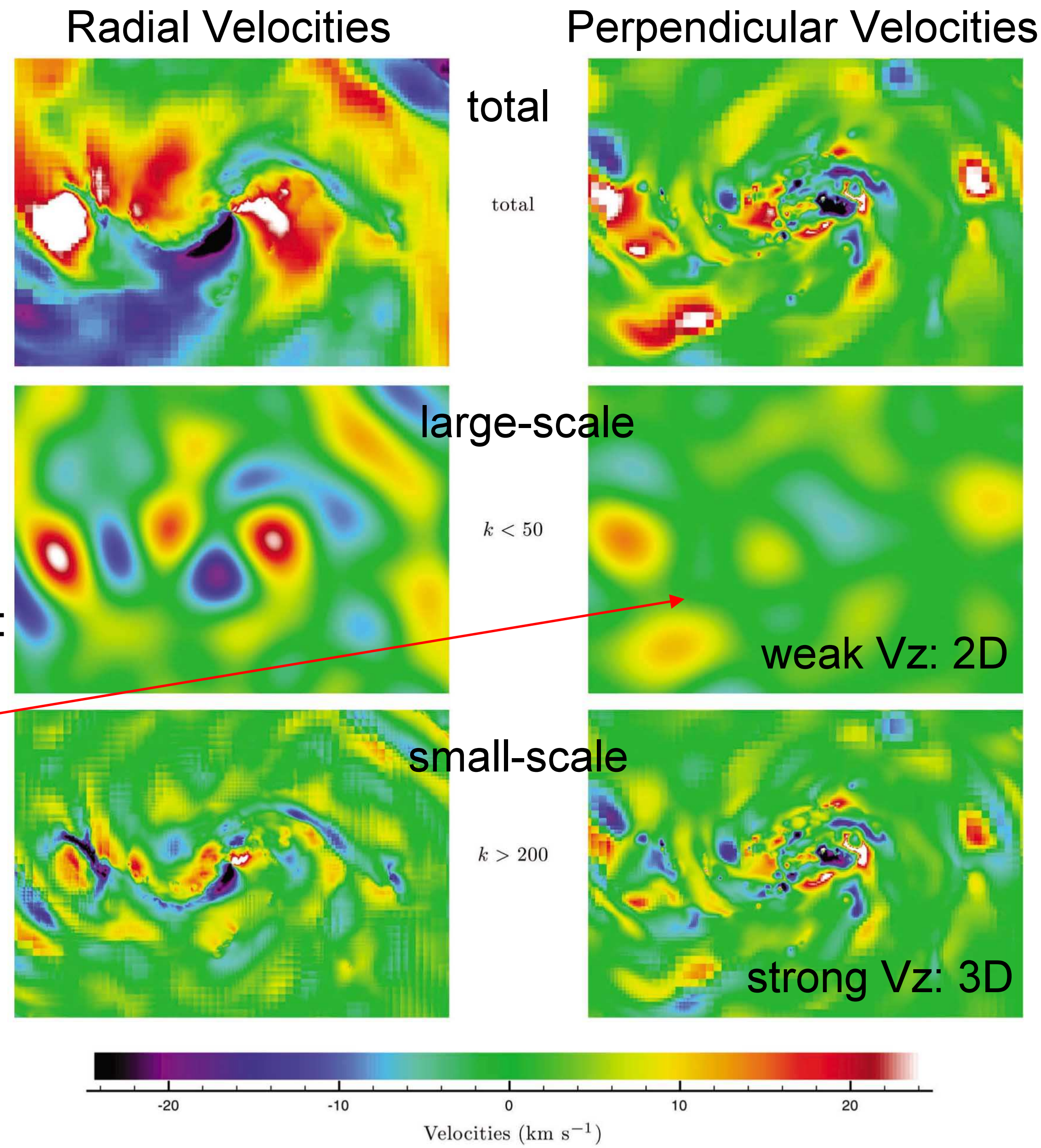
Density power spectrum is a power law only on scales smaller than the energy injection scale.



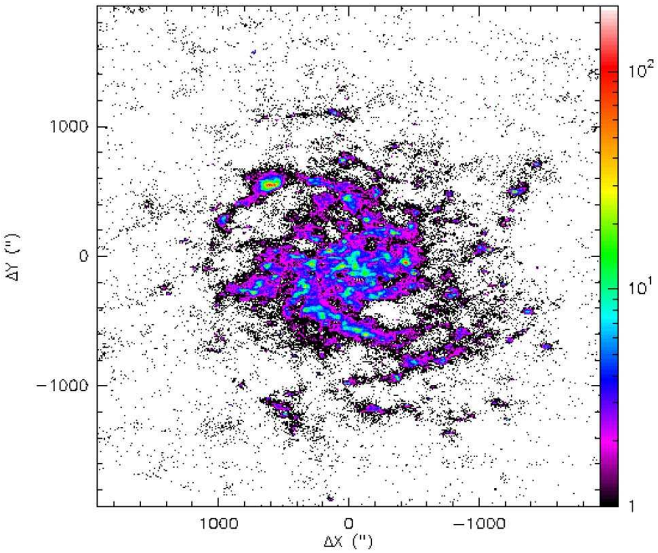
Bournaud +10 same as Joung +09:

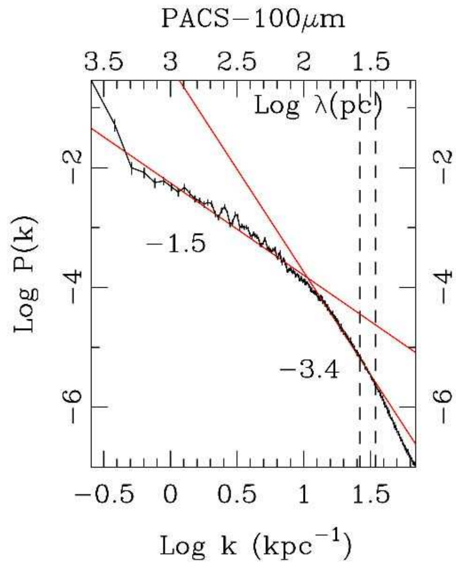
Vz (from SF) lacks energy on large scales.

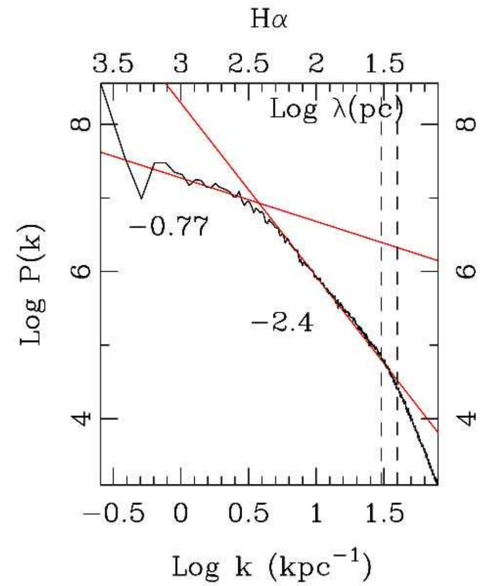
Spiral energy is 2D.



Mass-weighted velocities along the line of sight: Vr (left), Vz (right).

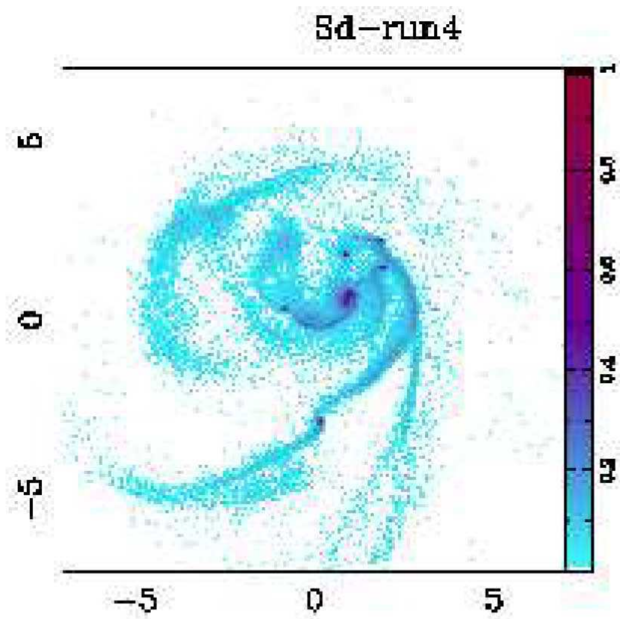


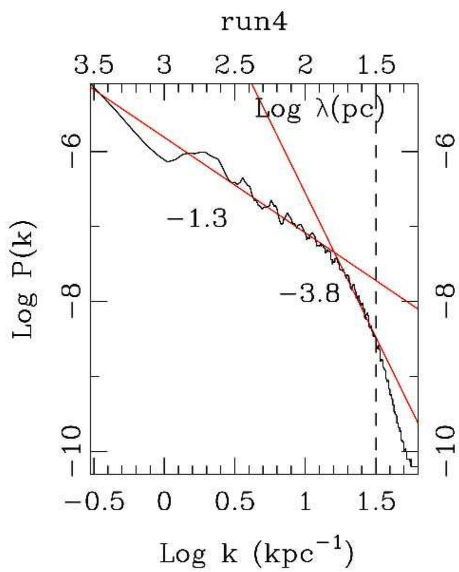




Combes +11: M33 power spectra from Herschel 100 mm
(similar results for other Herschel and Spitzer bands)

Hα PS thicker disk



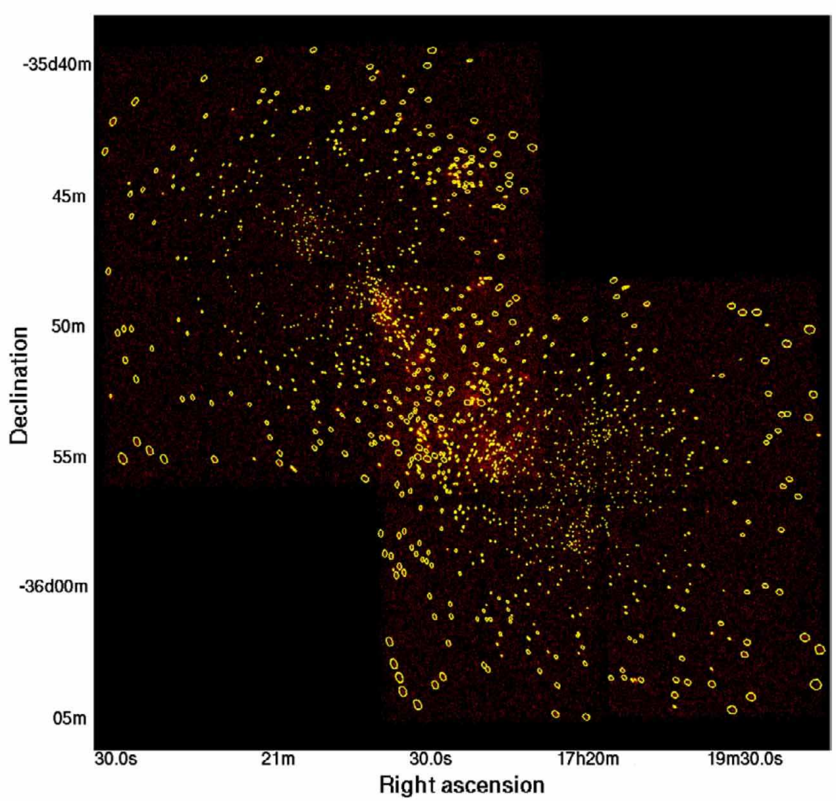


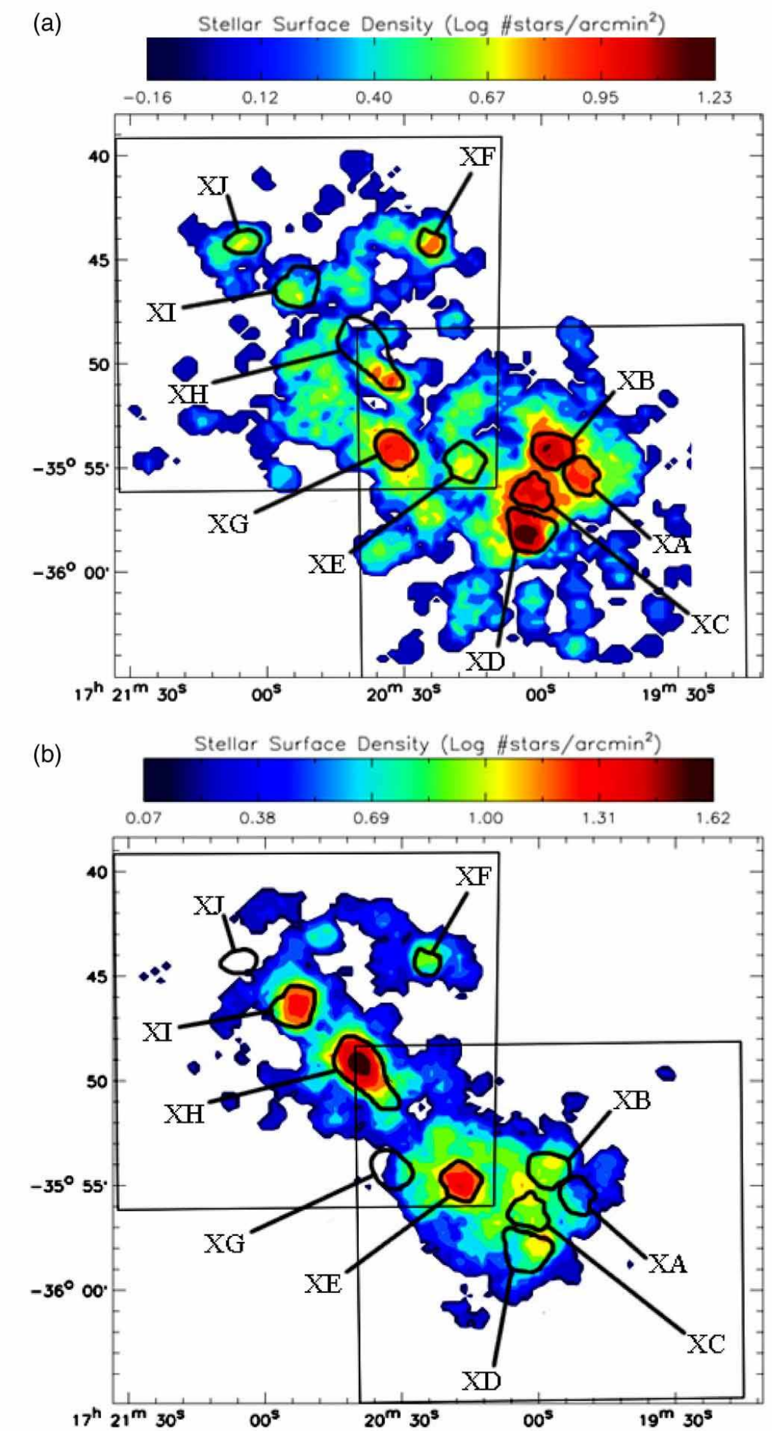
Simulations:
break size = scaleheight

Feigelson +09: X-rays from young stars in NGC 6334

top: soft X-ray source map (A_V<10 mag)
bottom: hard X-ray source map (A_V>10 mag)

X-ray maps nearly complete for $M>1M_O$ stars.

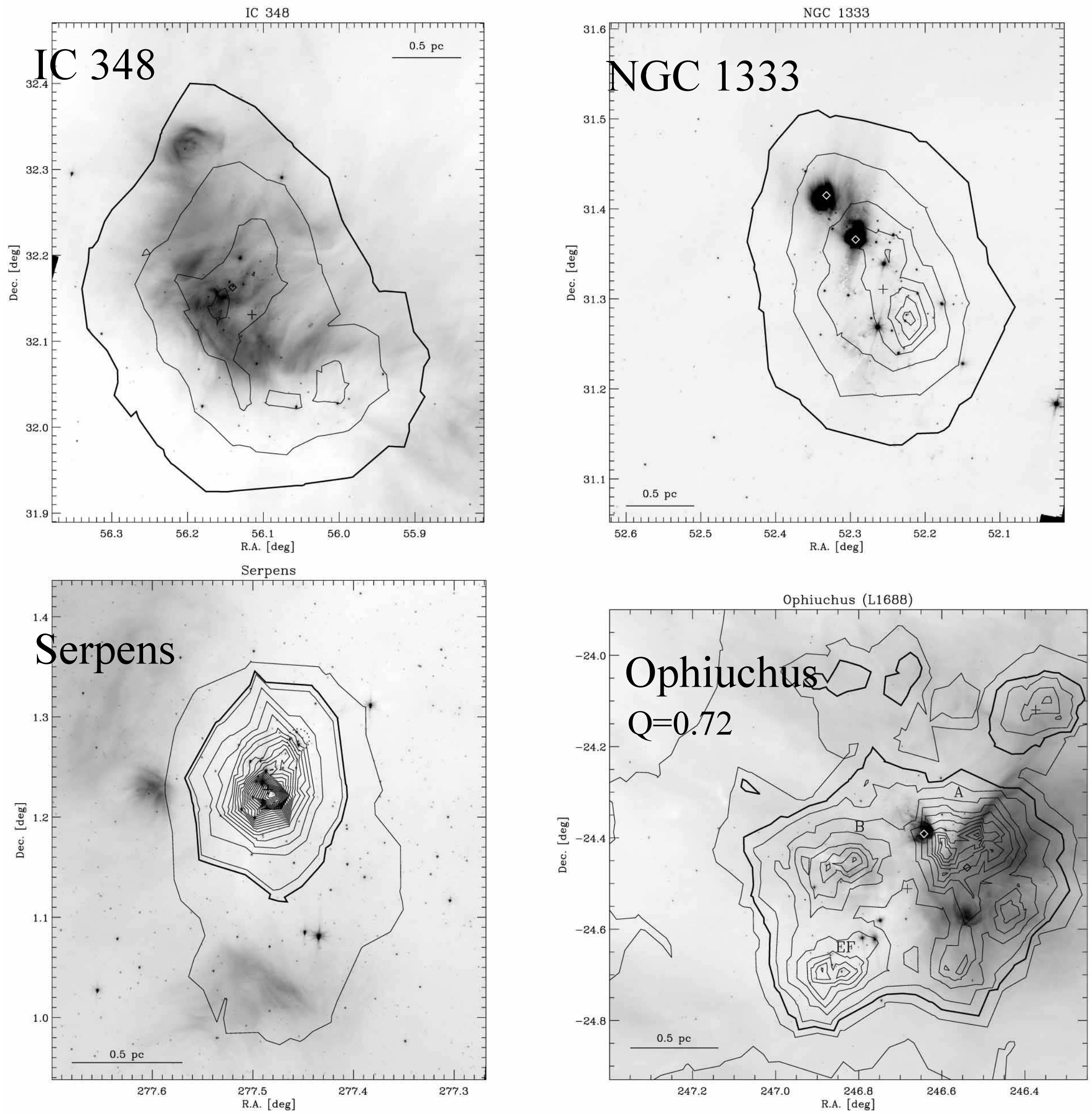




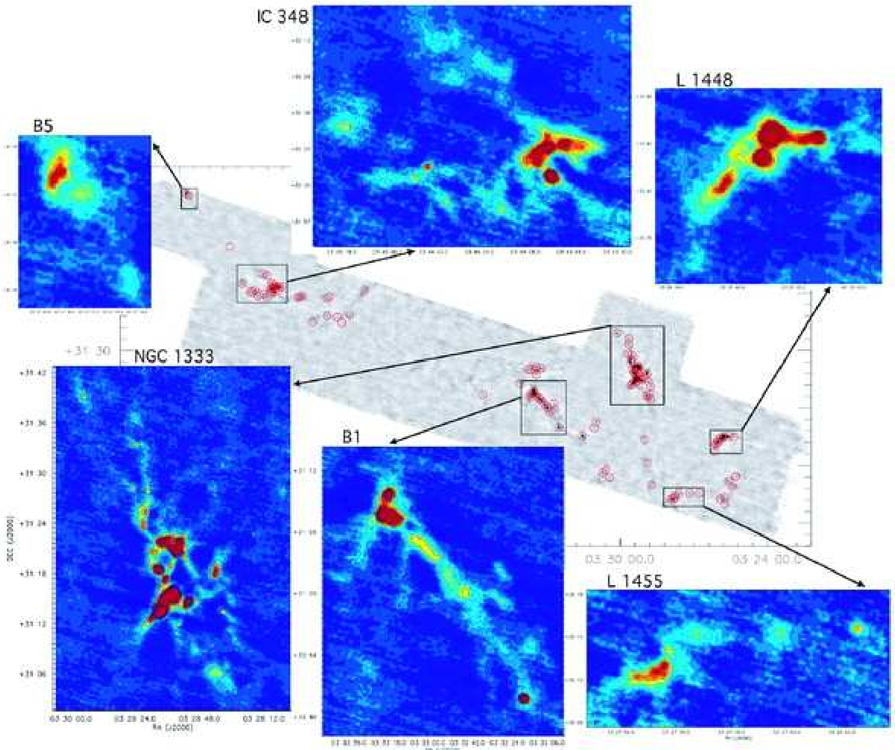
Schmeja, Kumar, Ferreira 08

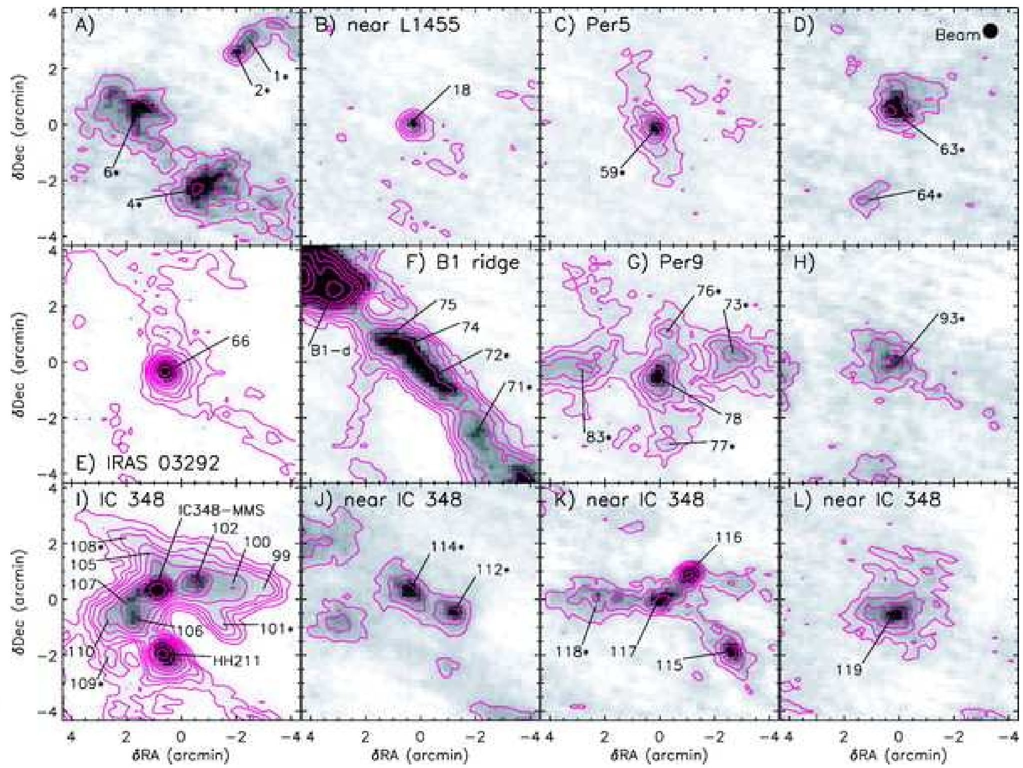
For IC 348, NGC 1333, and Oph, Q is lower (more clumpy) for class 0/1 objects (young) than class 2/3 (old).

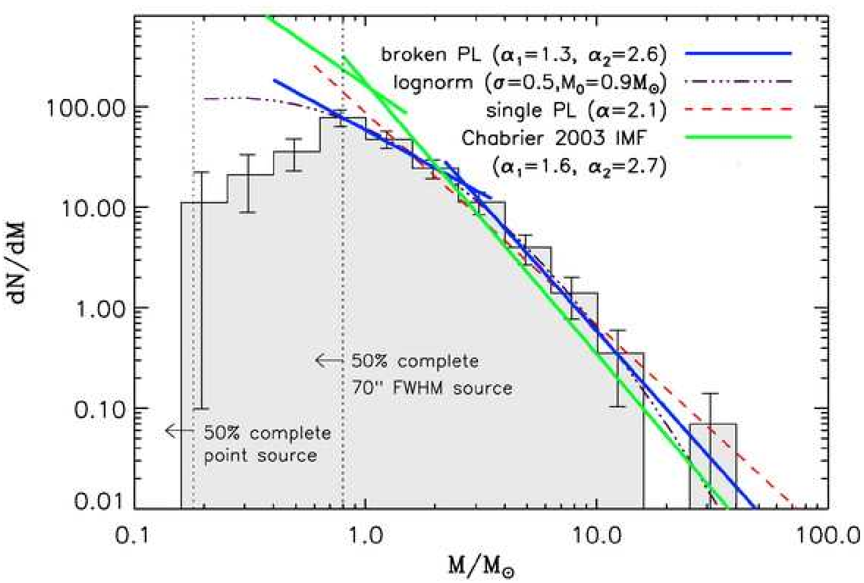
Among 4 subclumps in Oph, Q is lower and it is more gaseous where class 0/1 dominates, and Q is also lower for class 0/1 alone than for class 2/3.

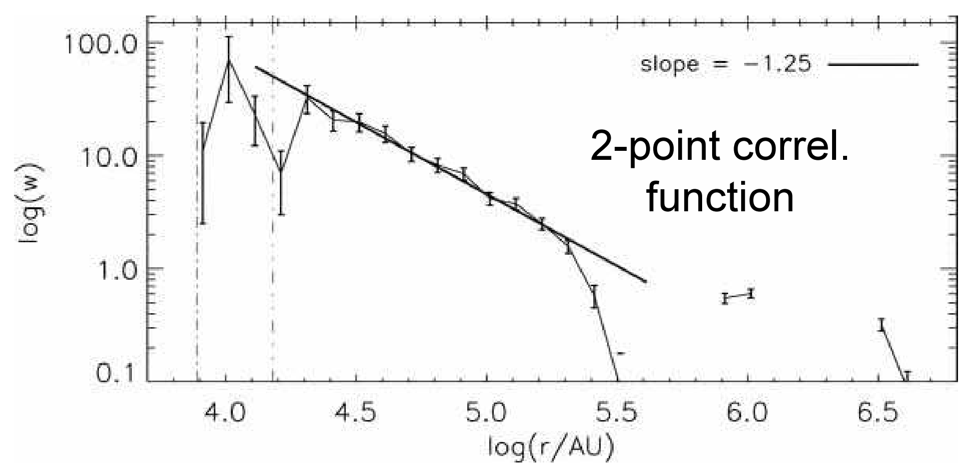


Q parameter (= ratio of average mininum spanning tree length to average correlation length).









Enoch +06: Perseus 1.1 mm cores are spatially correlated

Point 1: Clusters are hierarchical in space and time up to ~1 kpc and ~100 Myr

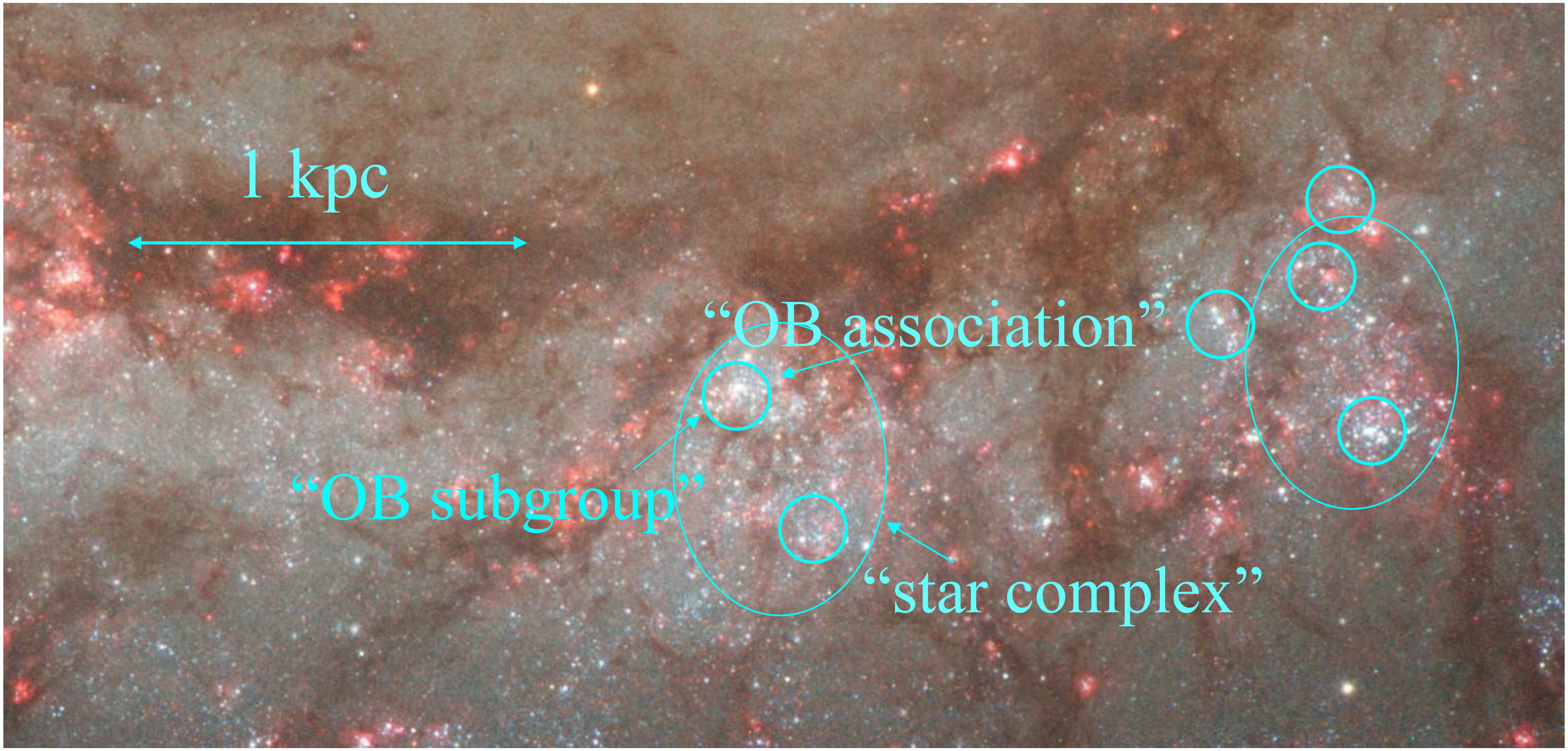
Point 2: Pre-stellar cores and individual stars are also hierarchical.

Clusters = cores of ISM hierarchy

- ISM hierarchy comes from turbulence
  - continues to sub-stellar masses
- The densest regions (where individual stars form) are clustered into the next-densest regions, …
- Stars form in the densest regions, move around, and mix together inside the next-densest regions
- More subclusters mix over time until the cloud disrupts
- The <u>mixture</u> that remains at disruption is the "cluster"
  - need critical efficiency (star mass/total mass) ~ 20%-30% for stars to remain bound after the gas leaves

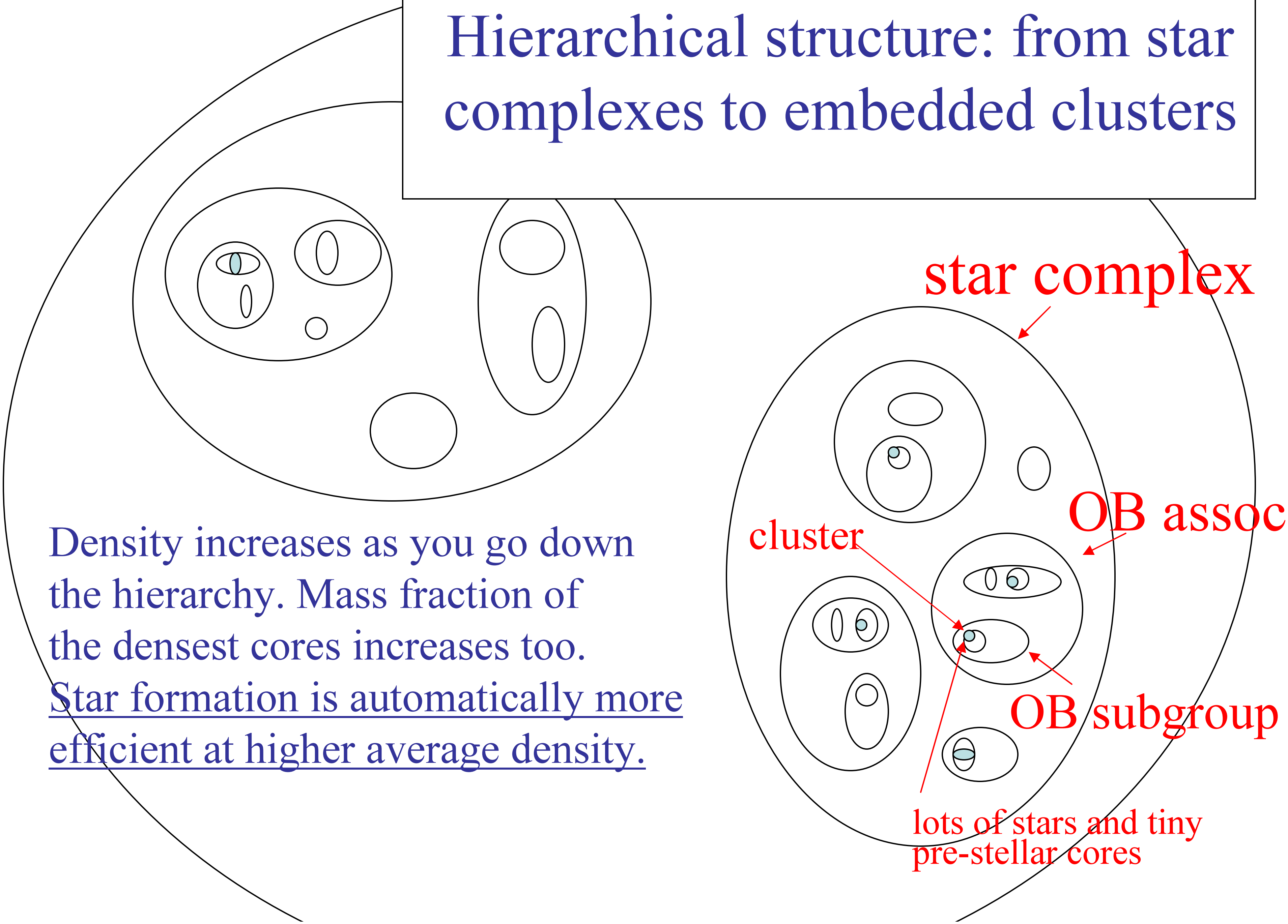
M51, HST/ACS

M51 Southern Inner Arm

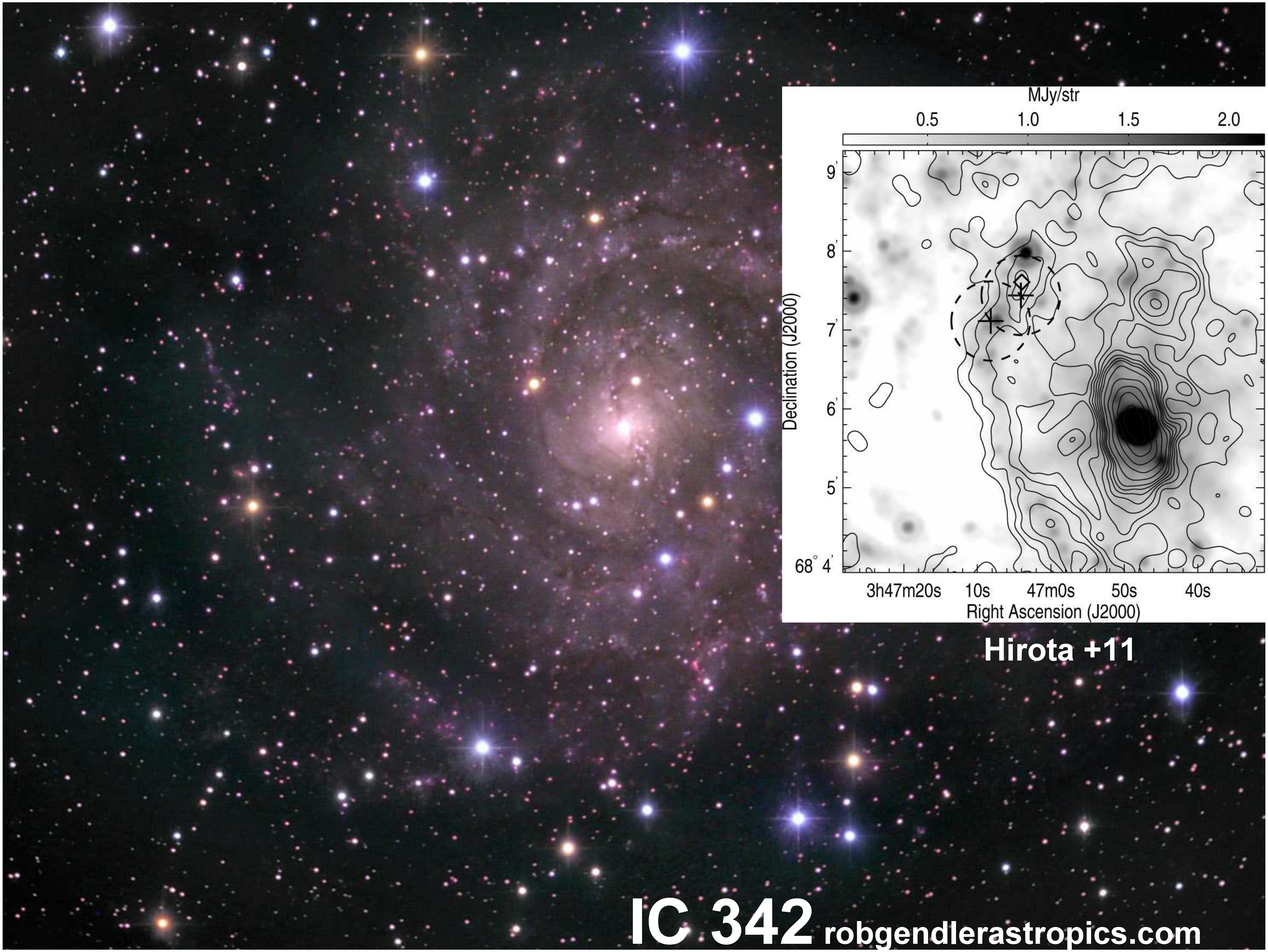


3.49 x 1.65 kpc image

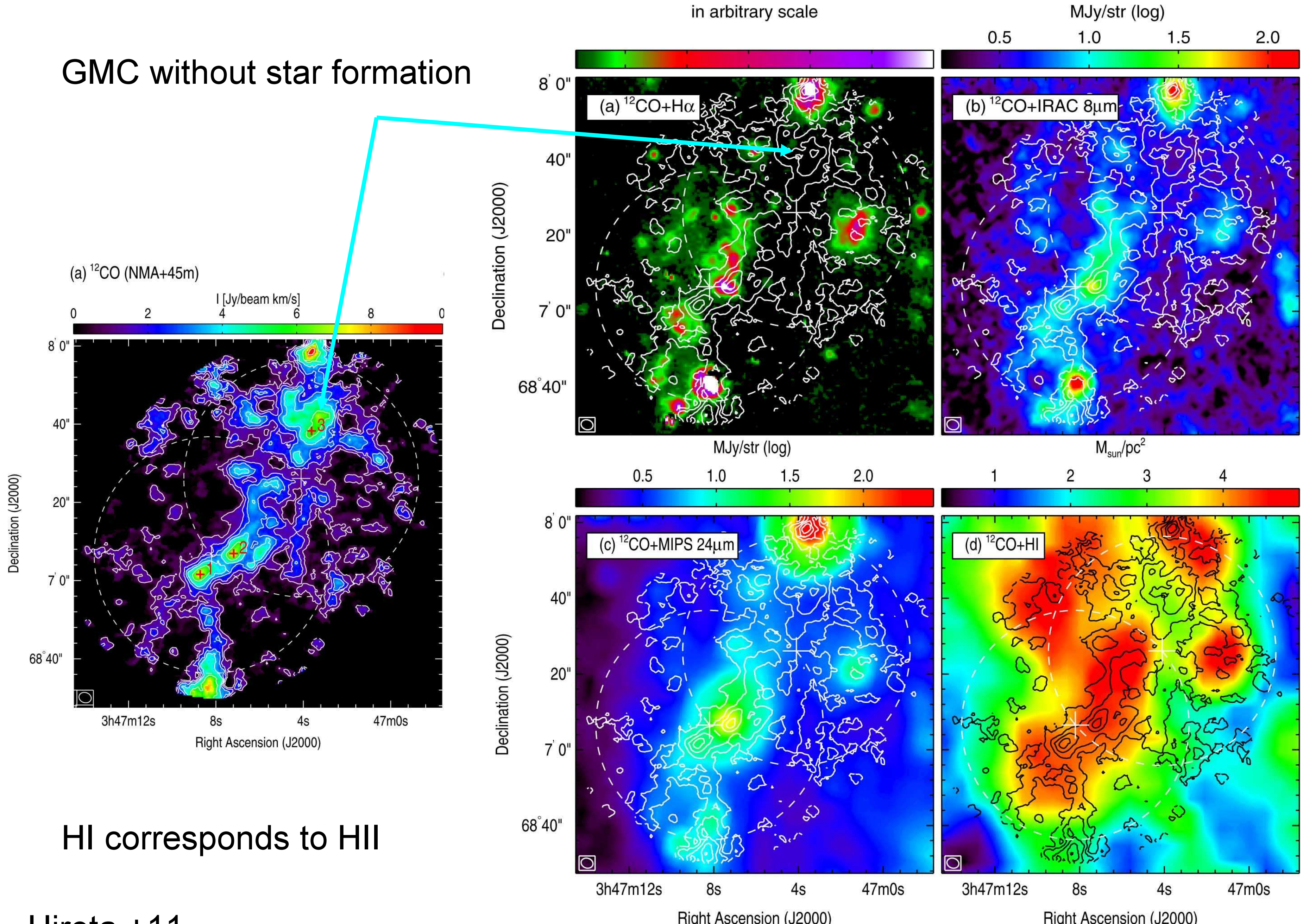
Hierarchical structure: from star complexes to embedded clusters



Density increases as you go down the hierarchy. Mass fraction of the densest cores increases too. <u>Star formation is automatically more efficient at higher average density.</u>


MJy/str
0.5
1.0
1.5
2.0
9'
8'
7'
6'
5'
68° 4'
Declination (J2000)
3h47m20s
10s
47m0s
50s
40s
Right Ascension (J2000)
Hirota +11
IC 342
robgendlerastropics.com

GMC without star formation

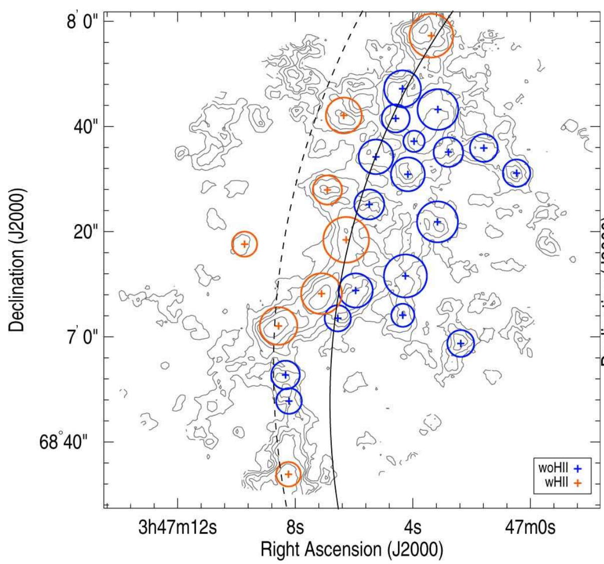


HI corresponds to HII

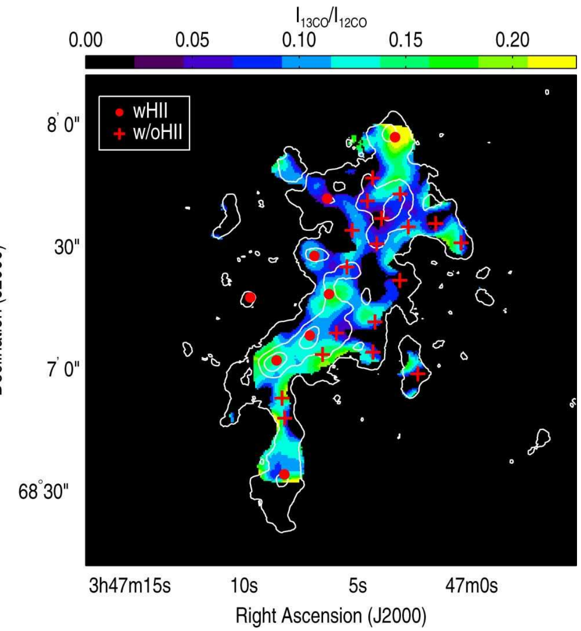
Hirota +11

Hirota +11

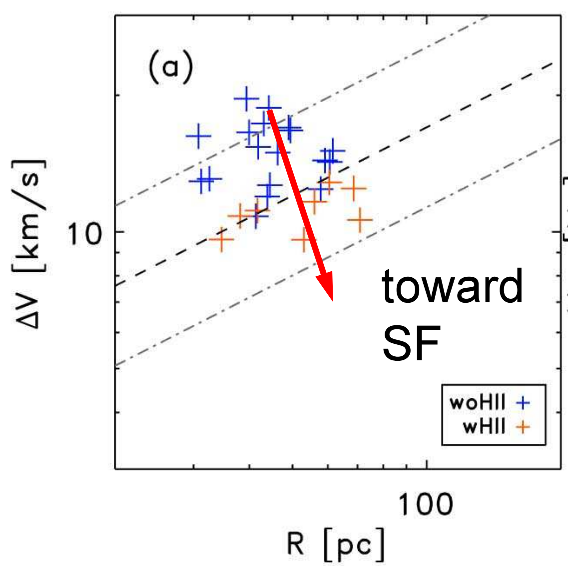
A GMC's density increases, its self-gravity strengthens, and its linewidth decreases as it passes through the arm.



red = with HII,
blue = without HII



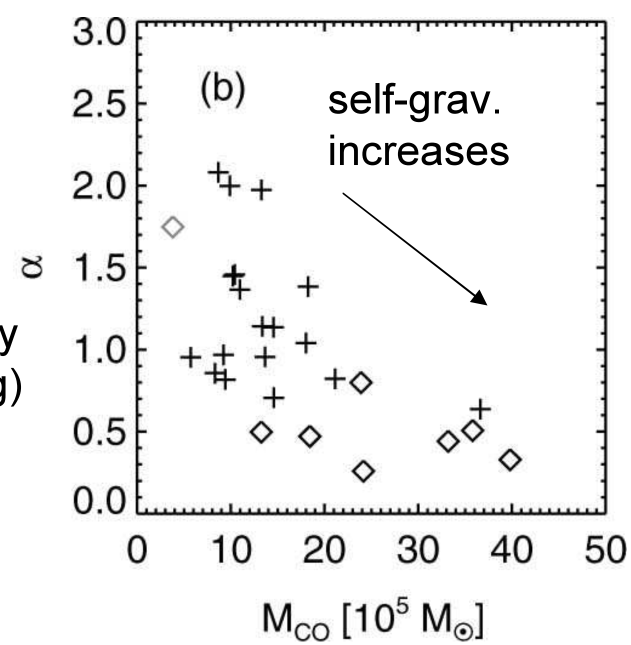
^{13}CO /^{12}CO indicates diffuse CO in GMCs without HII regions



toward SF

(α=M_{virial}/M
large α: weakly self-gravitating)

+ = without HII



self-grav. increases

Basic ingredients for bound cluster formation:

- GMC formation
  - spiral turbulence on large scales, shells and various feedback processes on small scales
  - weakly self-gravitating at formation
  - turbulence compression makes weakly SG sub-structure
    - GMCs defined by uv-shielding, not gravity

- formation of self-gravitating cores
  - turbulent energy dissipation, increasing mass, magnetic diffusion, …
- continued turbulence in self-gravitating cores
  - turbulence-compression makes strongly SG sub-structure
  - continued gravity-driven accretion into core

Basic ingredients for bound cluster formation:

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  - spiral turbulence on large scales, shells and various feedback processes on small scales
  - weakly self-gravitating at formation
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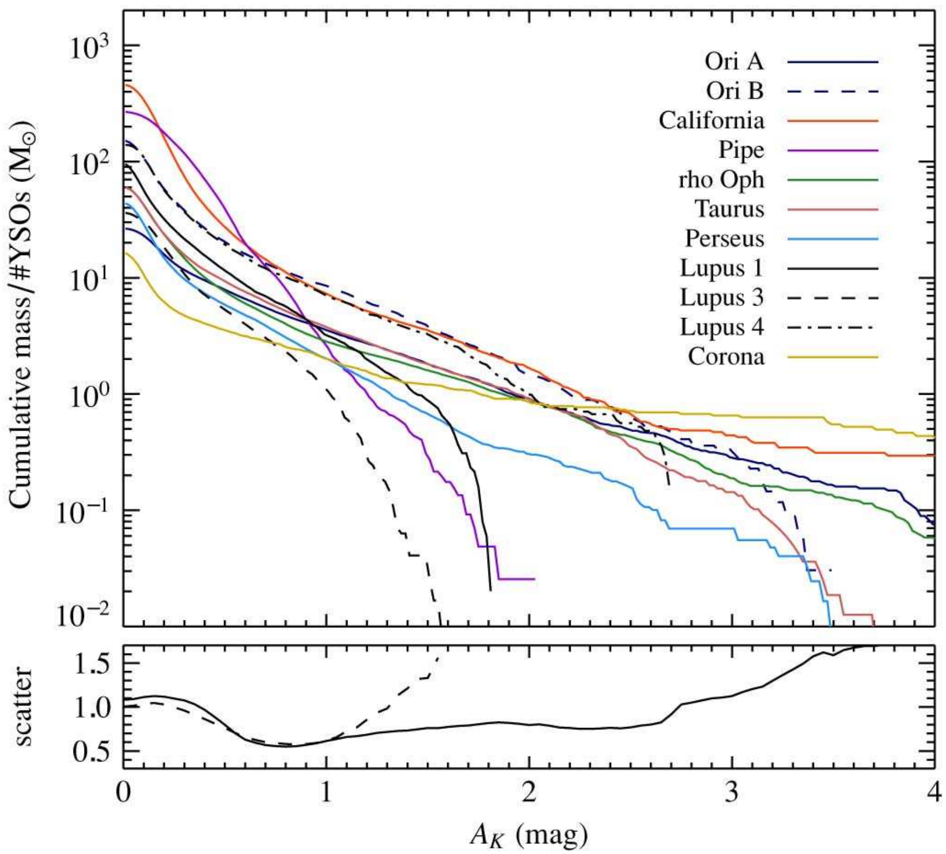
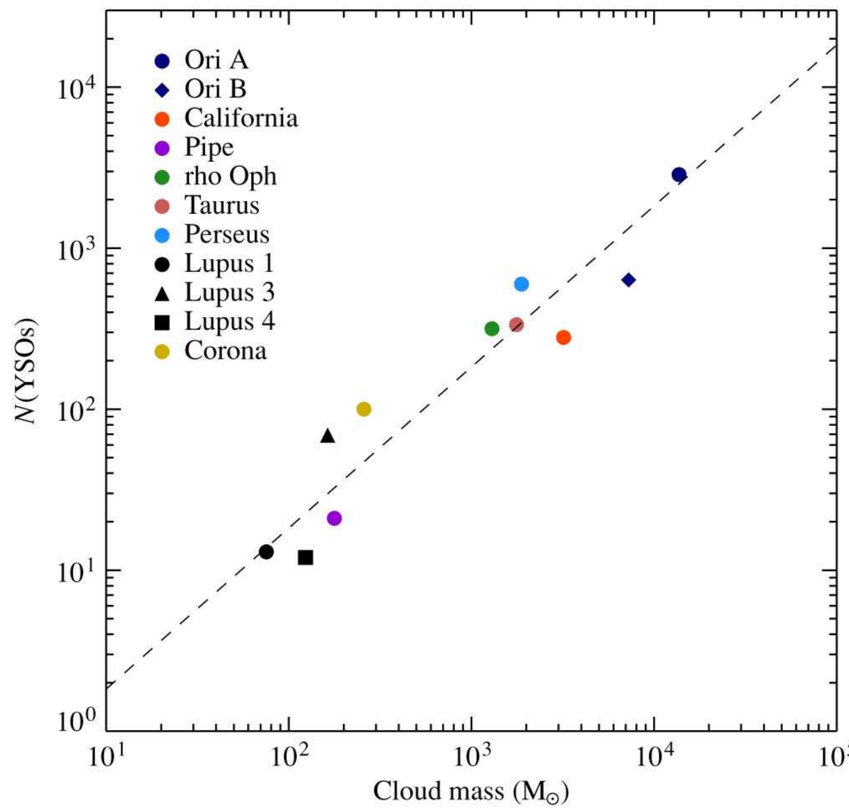
Hierarchical ISM & stellar groupings

- formation of self-gravitating cores
  - turbulent energy dissipation, increasing mass, r diffusion, …
- continued turbulence in self-gravitating cor
  - turbulence-compression makes strongly SG sub-structure
  - continued gravity-driven accretion into core

Collapse simulations with cluster formation

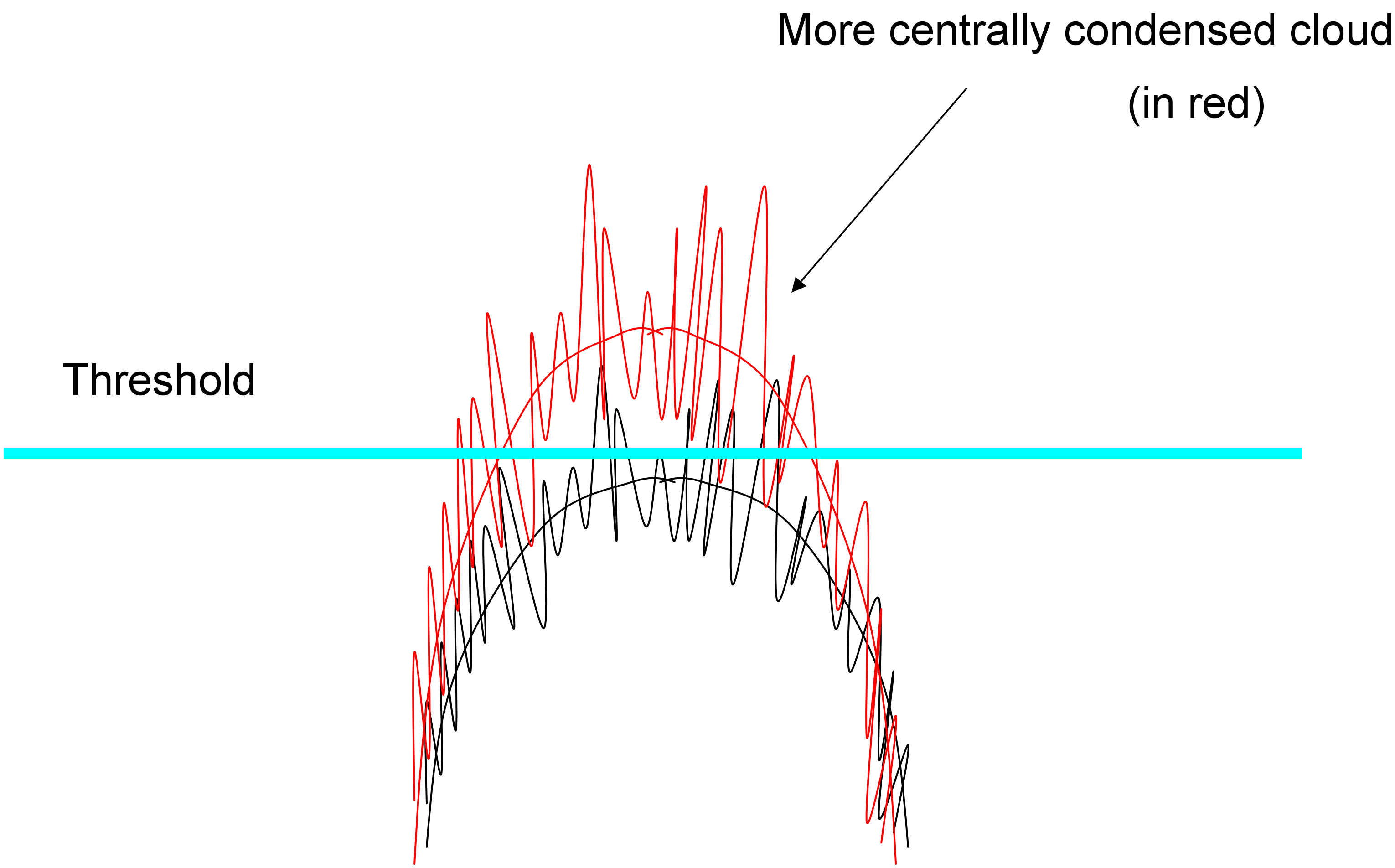


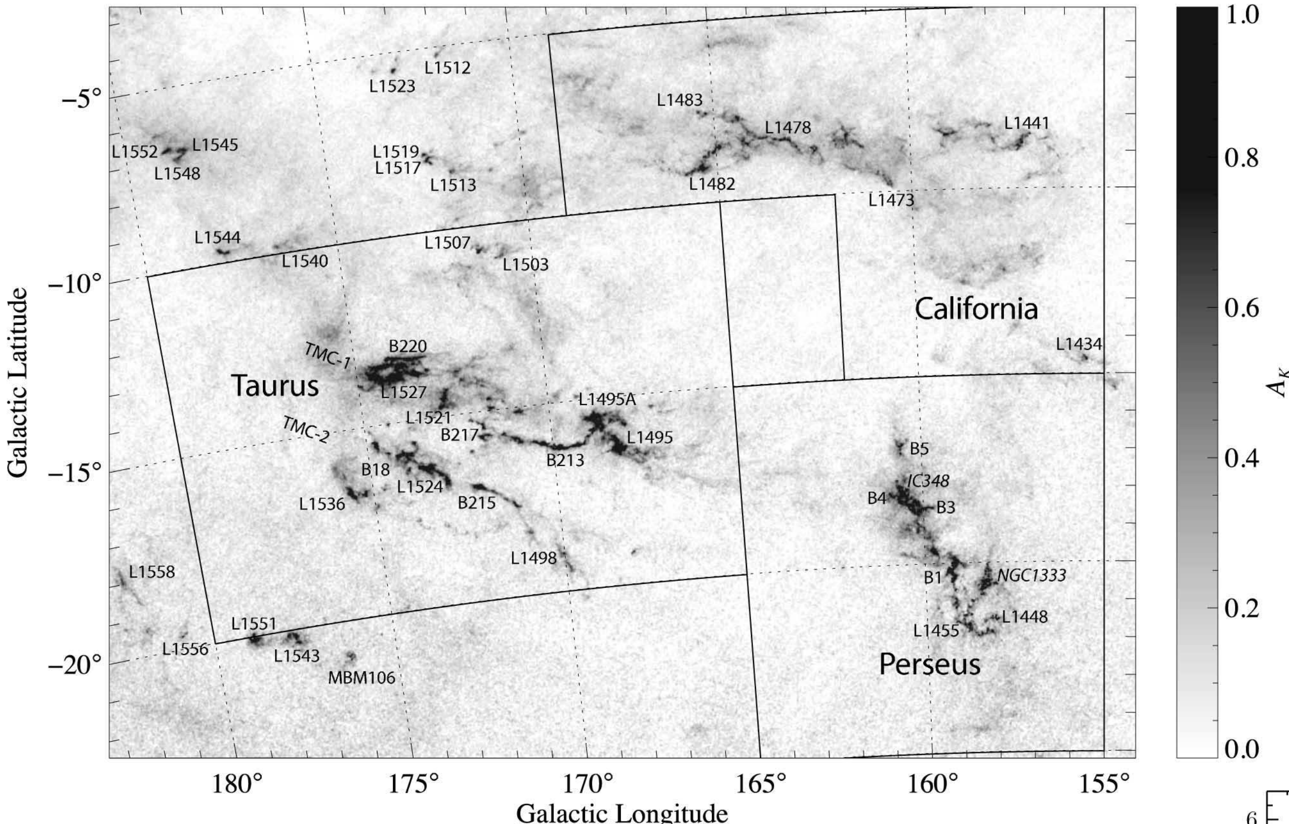


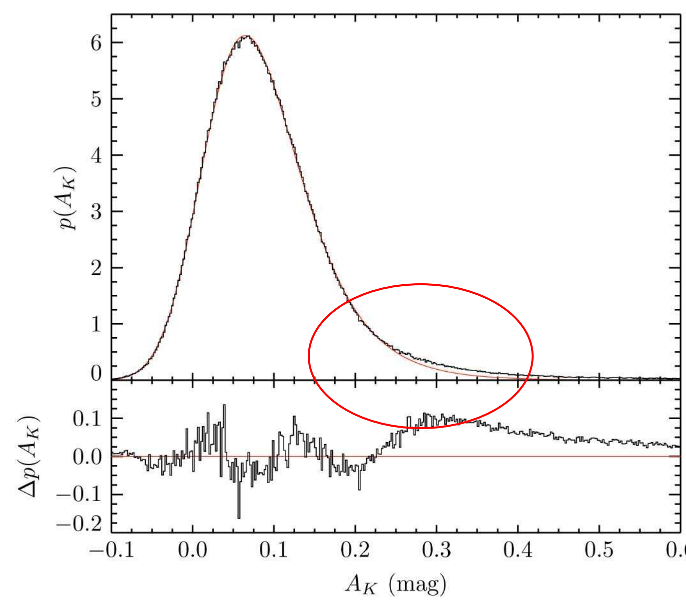
Lada et al. 2010: the cumulative mass <u>per YSO</u> has a similar form for all clouds, and is close to a universal ratio at A_K ~ 0.8 mag

The number of YSOs in a cloud scales directly with the total mass of gas at a <u>column density greater</u> than A_K ~ 0.8 mag. Lada et al. suggest this corresponds to a threshold density of $n \sim 10^4$ cm^{-3}.

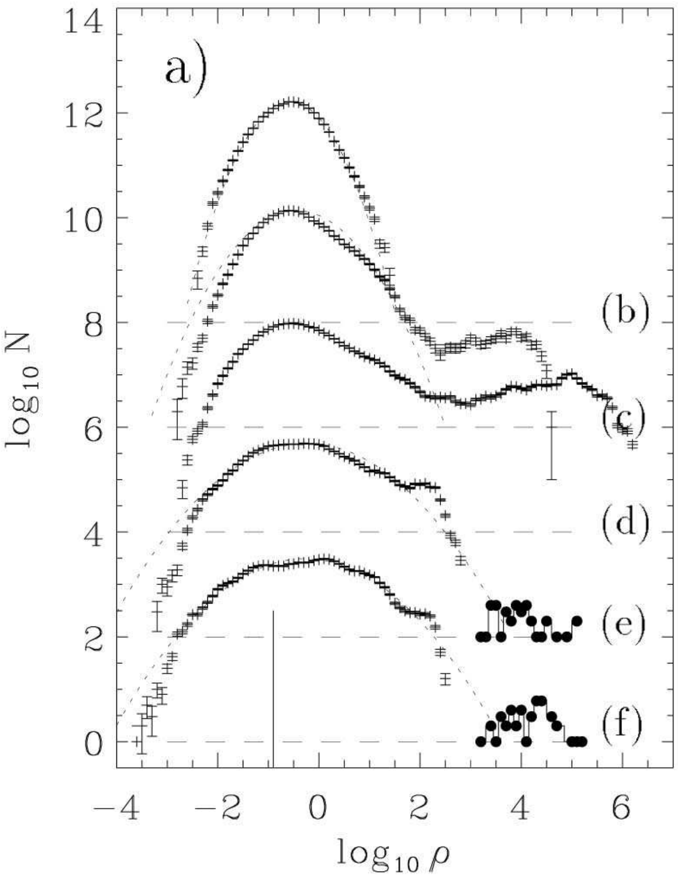
Similar results for a threshold column or volume density with a linear SF relation above are in Gao & Solomon 04, Wu +05, Heiderman +10, ...


More centrally condensed cloud
(in red)
Threshold

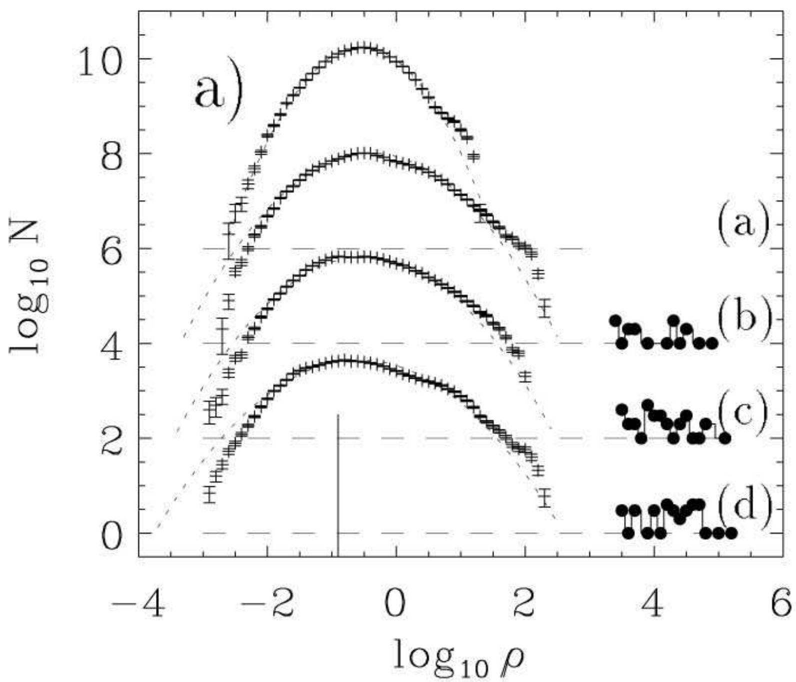




Lombardi + 2010: distribution of column density in the Taurus-Perseus region is log-normal. Deviates at A_K>0.2, suggestive of a high-density tail from self-gravity.



Decaying turbulence
with self-gravity



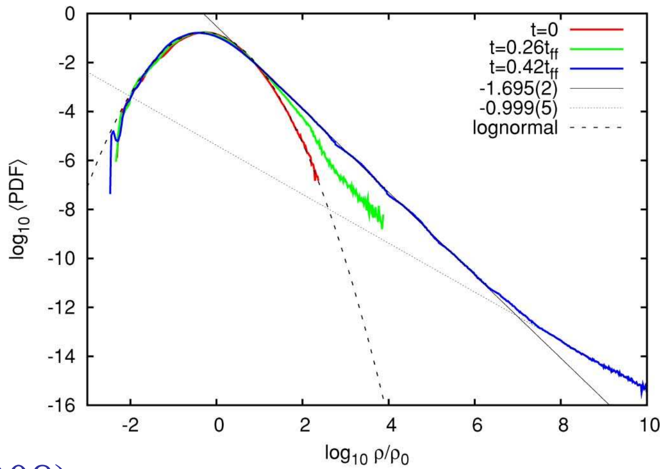
Driven turbulence
with self-gravity

Klessen 2000: Tails in density PDF from self-gravity

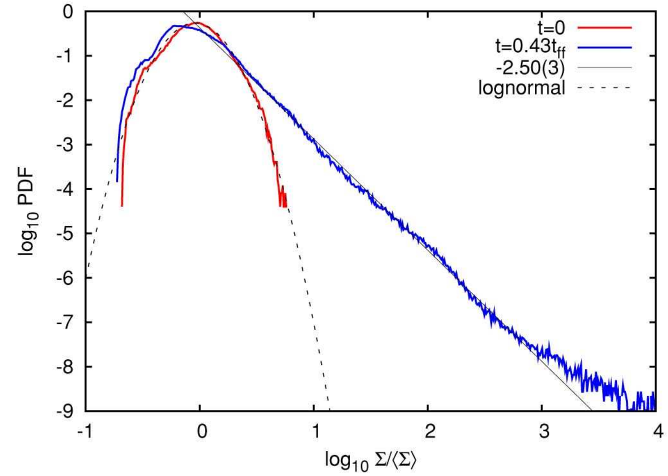
Kritsuk +11

density pdf in self-gravitating gas

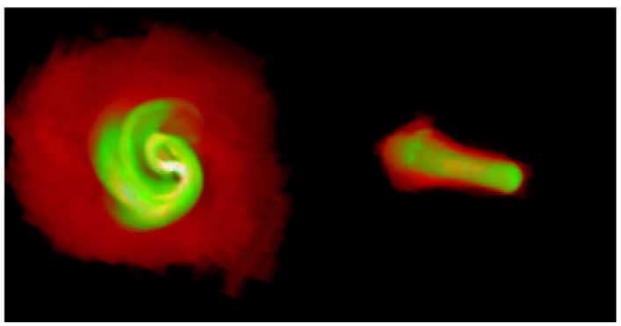
(see also
Vazquez-Semadeni et al 2008)

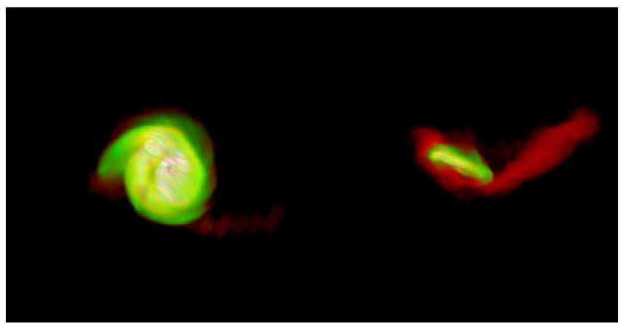


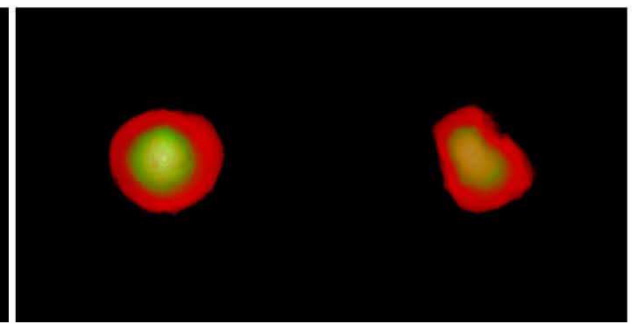
gas density: red: t=0 No Grav,
green: t=0.26tff, blue: t=0.42tff

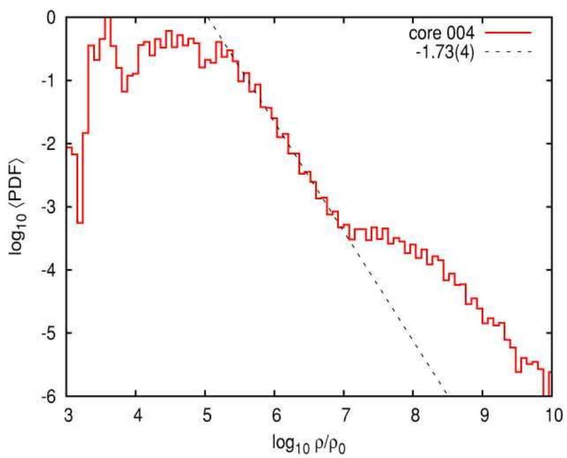


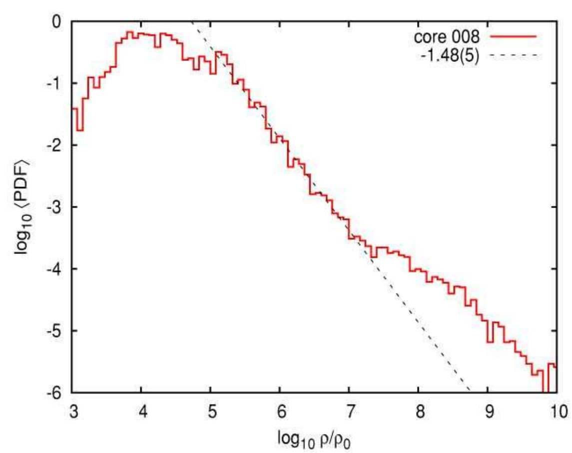
projected density

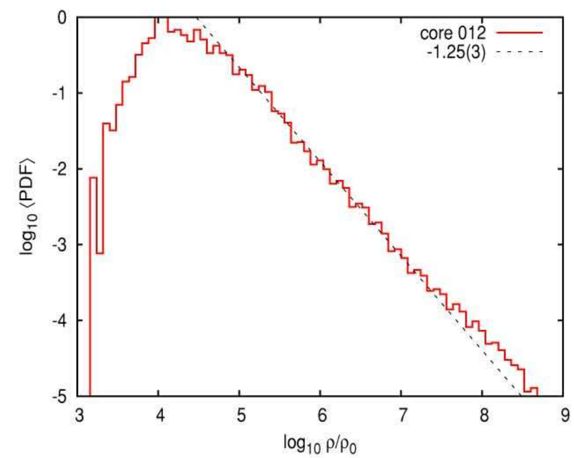




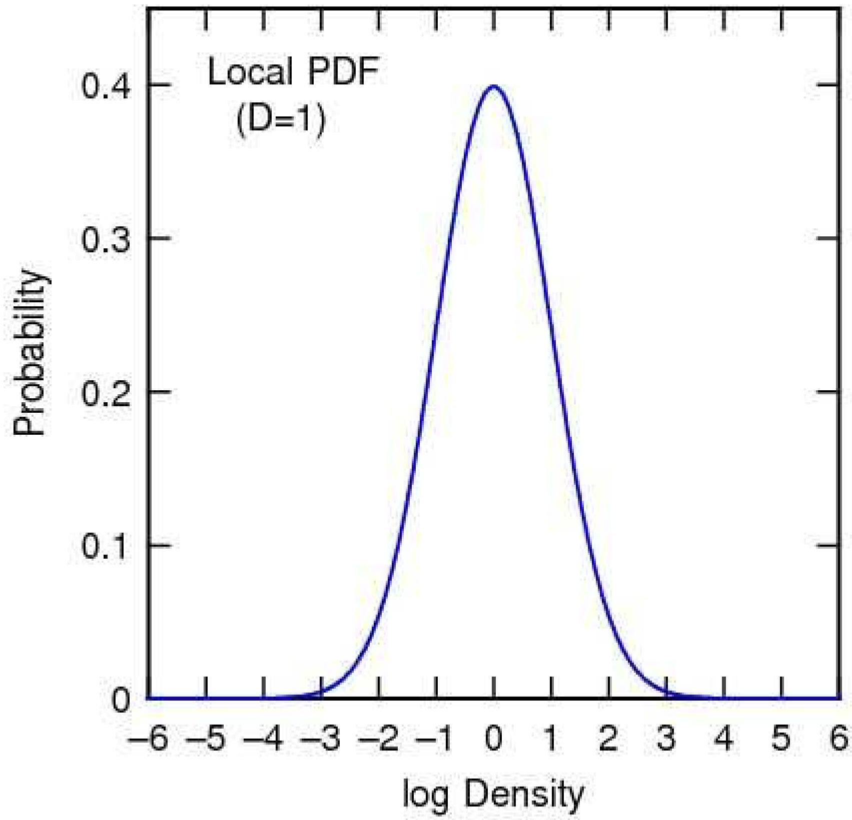


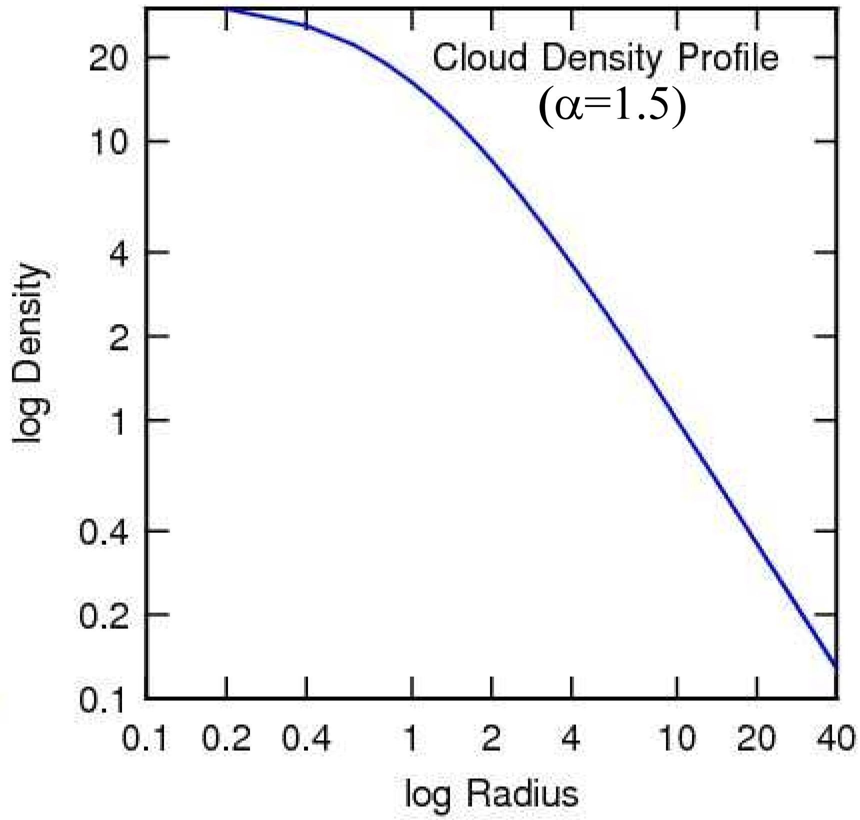






A simple model of cloud structure (Elmegreen 2011)





Density probability distribution function in a turbulent region

Average density profile in a self-gravitating cloud

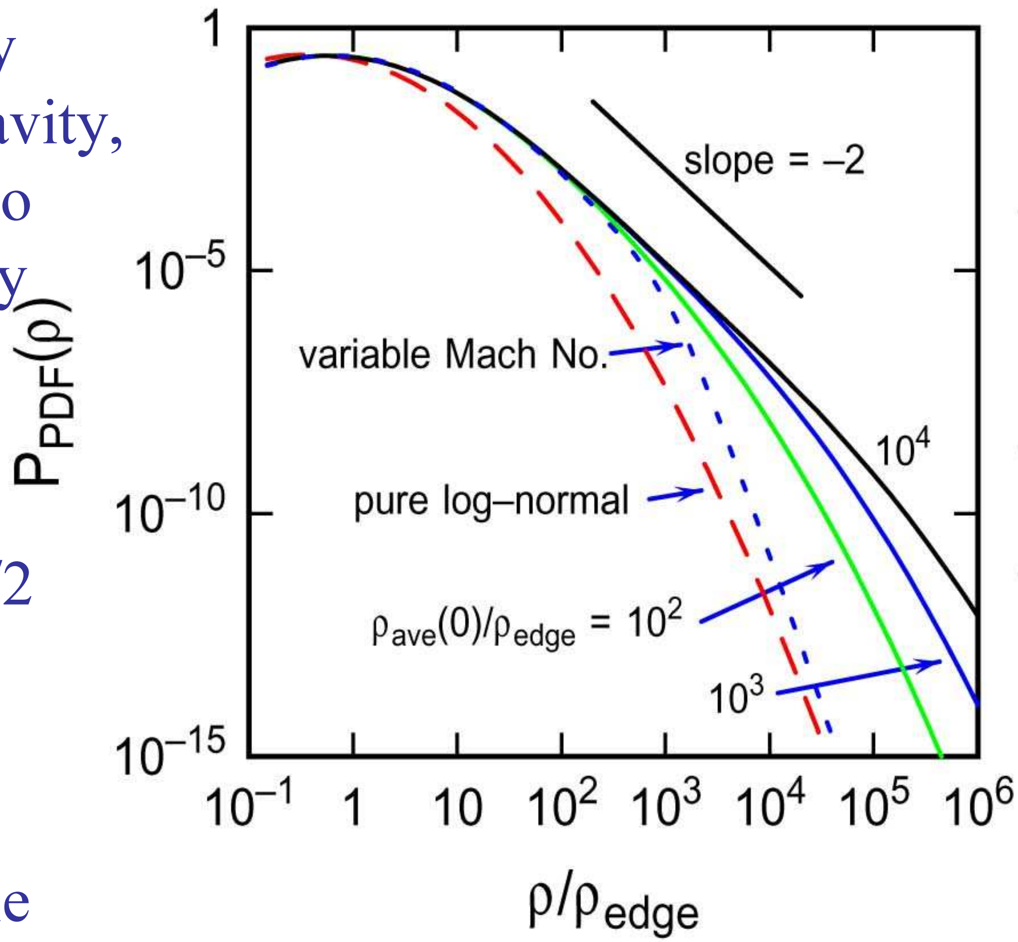
Density PDFs in Self-Gravitating Clouds

- Density PDF in a whole cloud is a convolution:
  - $P_{total}(\rho)$= integral $P_{local}(\rho|\rho_{ave},D)P_{ave}(\rho_{ave})d\rho_{ave}$
    - where ρ_{ave} = function of position, such as

$$\rho_{ave} = \rho_{edge} (r_{edge}^{\alpha} + r_{core}^{\alpha}) / (r^{\alpha} + r_{core}^{\alpha})$$

- Density PDF in local turbulent region is log-normal:
  - $P_{local}(\rho)=(2\pi D^2)^{-1/2} \exp(-0.5[\ln\{\rho/\rho_{peak}\}/D]^2)d\ln\rho$
  - D=width of distribution, ρ_{peak}=density at peak
    - where $\rho_{peak}=\rho_{ave}\exp(-0.5D^2)$
    - and $D^2 \sim \ln(1+0.25M^2)$ for M=Mach number (Padoan +97)

As the center-to-edge density contrast increases by self-gravity, a log-normal pdf changes into power law pdf at high density



Power law slope = -3/α = -2 for core profile $r^{-\alpha}$ with α=3/2

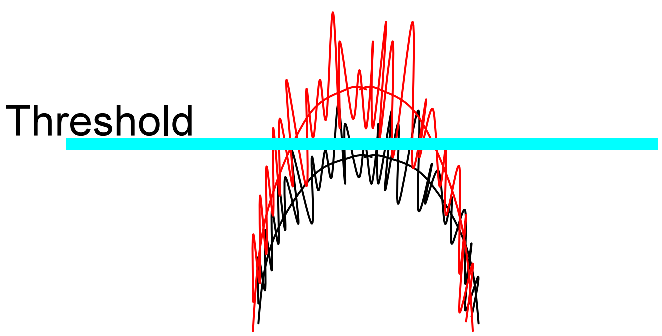
Dotted line assumes variable Mach number, where Mach ~ sqrt(M/r):

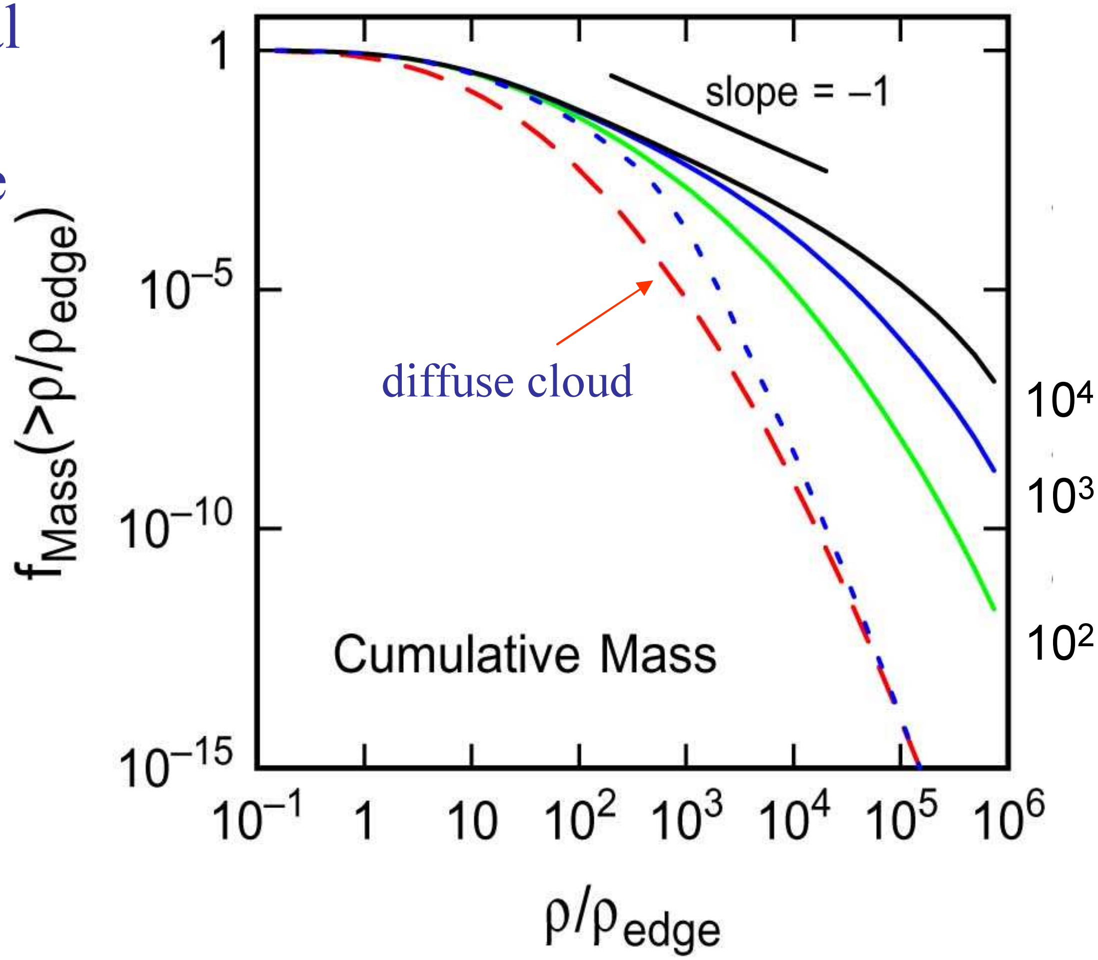
$$\mathsf{M}(r) = \mathsf{M}_{\rm edge}\left(M[r]r_{\rm edge}/M_{\rm total}r\right)^{1/2}.$$

$$M(r) = \int_0^r 4\pi r^2 \rho_{\rm ave}(r)dr.$$

Elmegreen 2011

Mass fraction above a critical density for star formation is much larger (x100) when the cloud is self-gravitating than in a diffuse cloud.





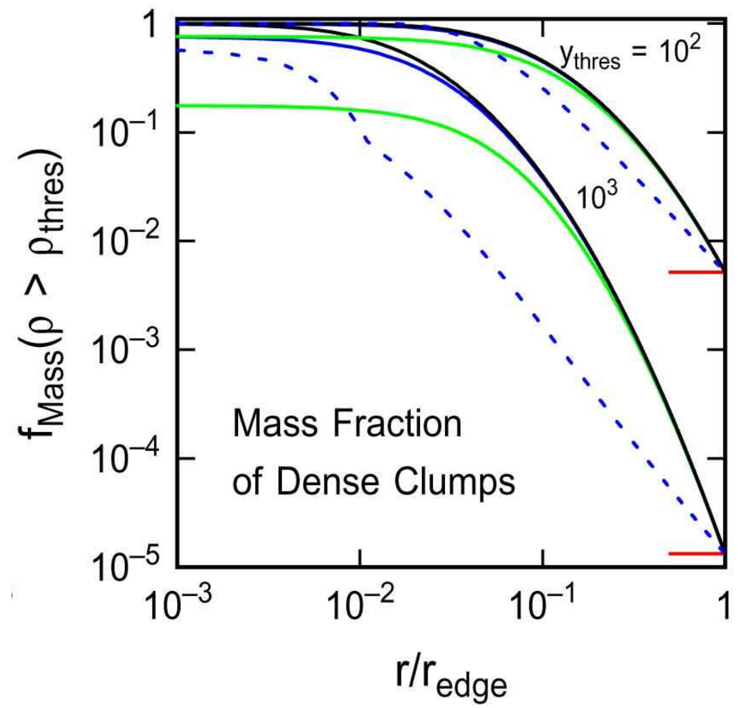
Elmegreen 2011

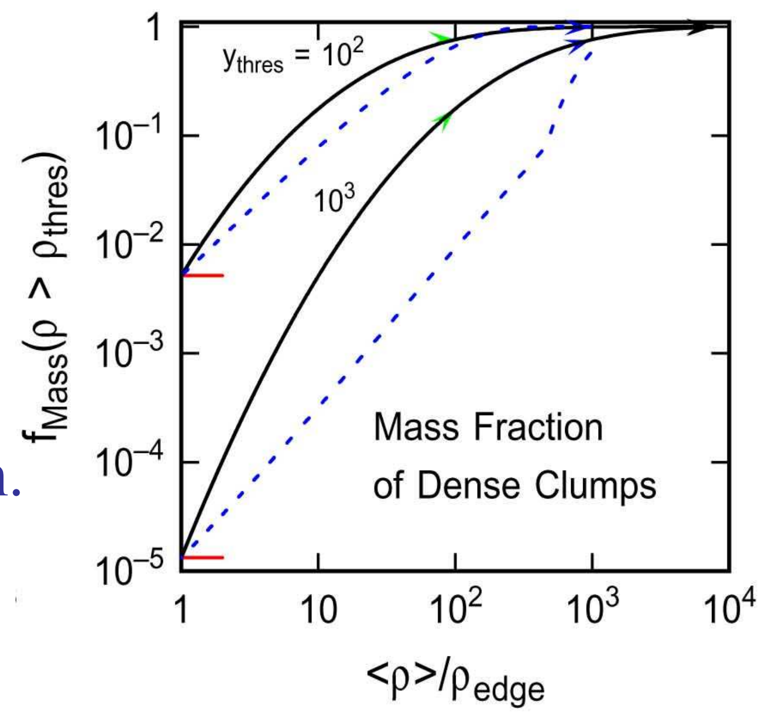
Mass fraction above a critical density ($y = \rho/\rho_{edge} = 10^2$ and 10^3) versus position (top figure) and versus the mean density in the cloud (bottom fig.).

The mass fraction of sufficiently dense clumps in a <u>local</u> region increases with the average region density.

If these clumps turn into stars, then this means the “efficiency” of star formation increases with the average region density (or near the cloud center).

This is the key to <u>bound</u> cluster formation.

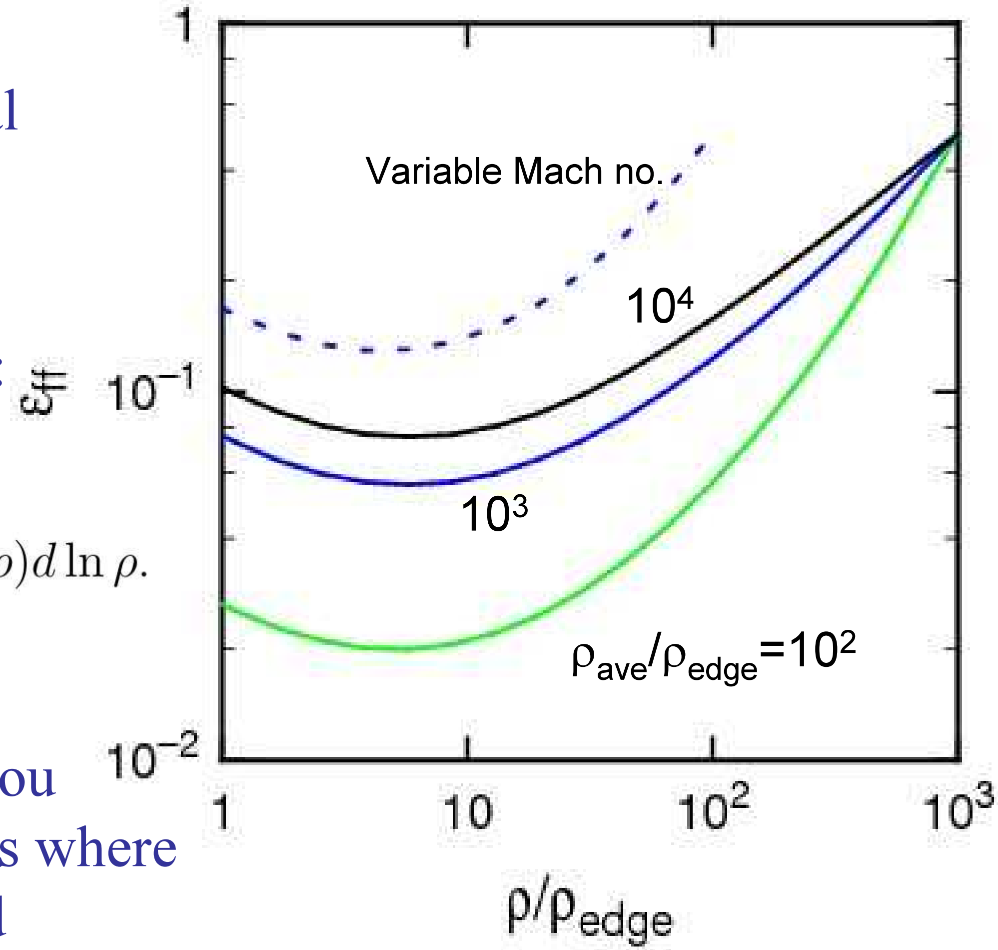




Local efficiency per unit dynamical time versus local average density.

Model of star formation rate/volume:

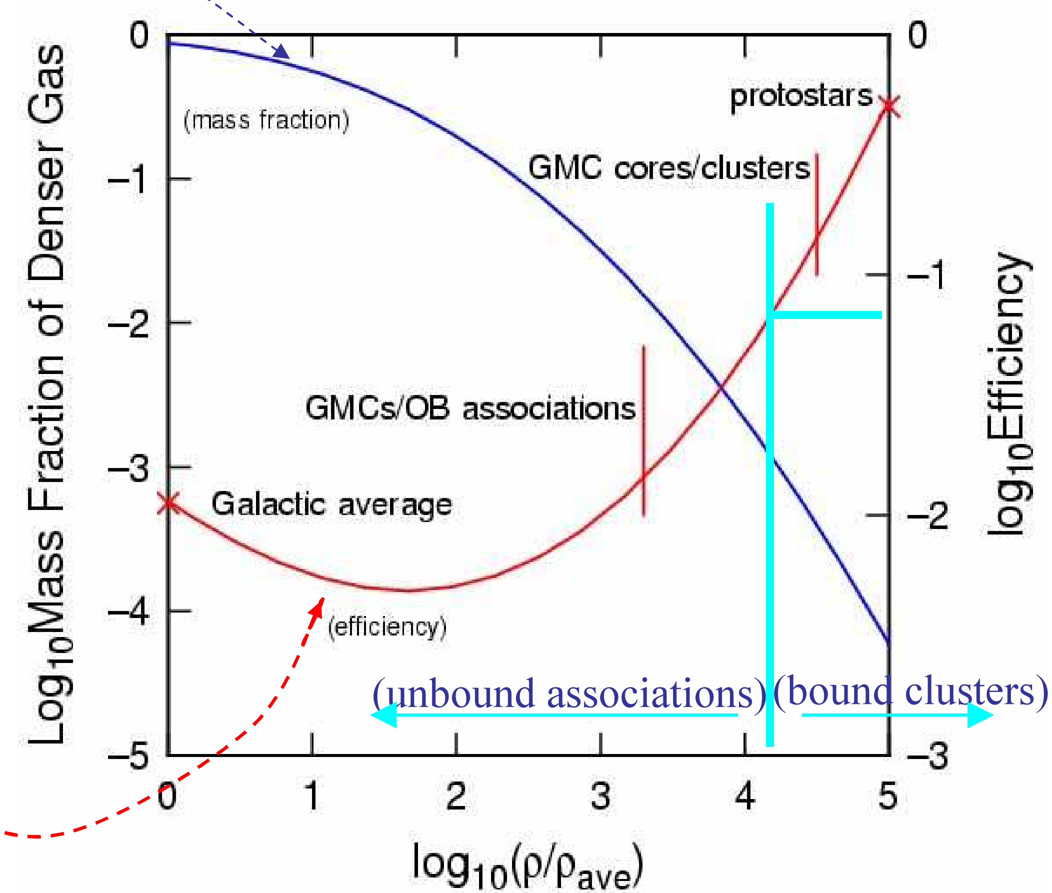
$$\mathrm{SFR} = \epsilon_{\mathrm{dyn}}(\rho)(G\rho)^{1/2} \int_{\rho}^{\infty} \rho P_{\mathrm{PDF,tot}}(\ln\rho) d\ln\rho.$$



As the average density increases, you zero-in on the individual SF clumps where the density exceeds a threshold and the efficiency is high, like 0.5. Then

$$\epsilon_{\mathrm{dyn}}(\rho) = 0.5 \left(\frac{\rho_{\mathrm{thres}}}{\rho}\right)^{1/2} \left(\frac{f_{\mathrm{Mass}}[\rho_{\mathrm{thres}}]}{f_{\mathrm{Mass}}[\rho]}\right).$$

E.g., a log-normal
cumulative mass fraction f_M (ρ).

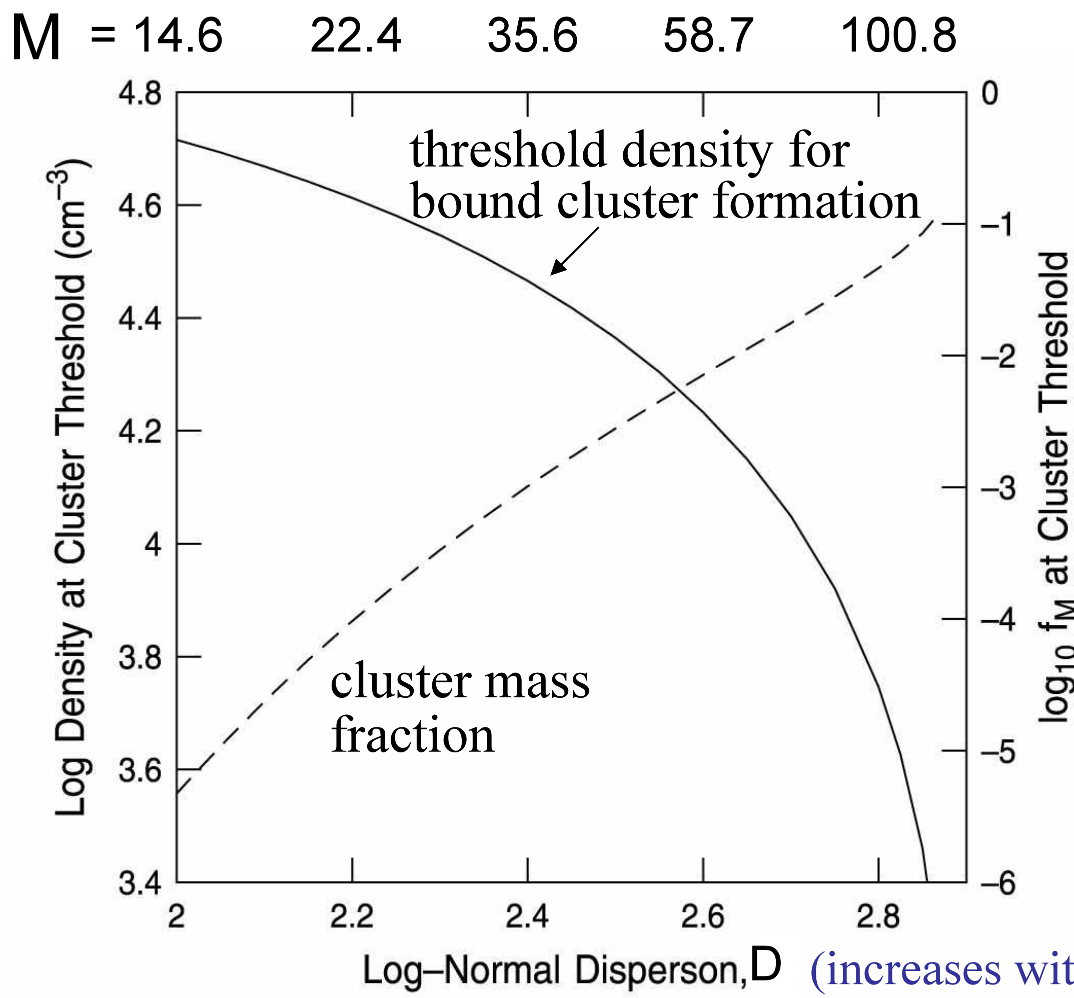


The mass fraction of the densest
clumps ρ_c inside a region of
average density ρ is

$$\varepsilon(\rho) = \varepsilon_c(\rho_c/\rho)^{1/2}\ \ [f_M(\rho_c)/f_M(\rho)]$$

Elmegreen 08

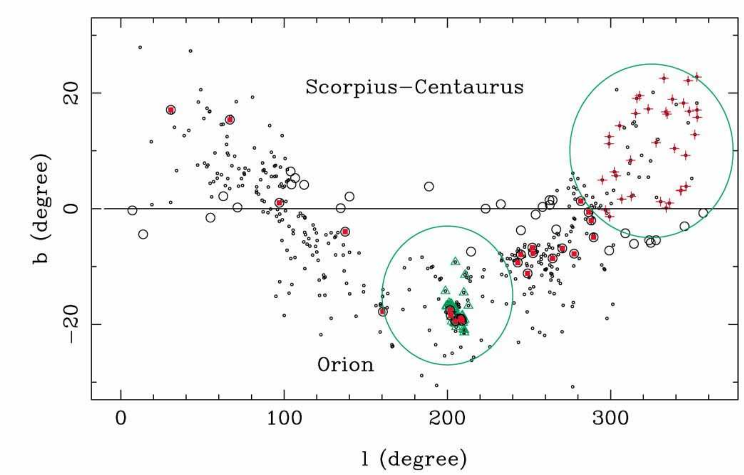
$\varepsilon(\rho)$ is the efficiency of SF. Bound clusters form where the efficiency is highest, which is where the <u>average</u> density is highest.

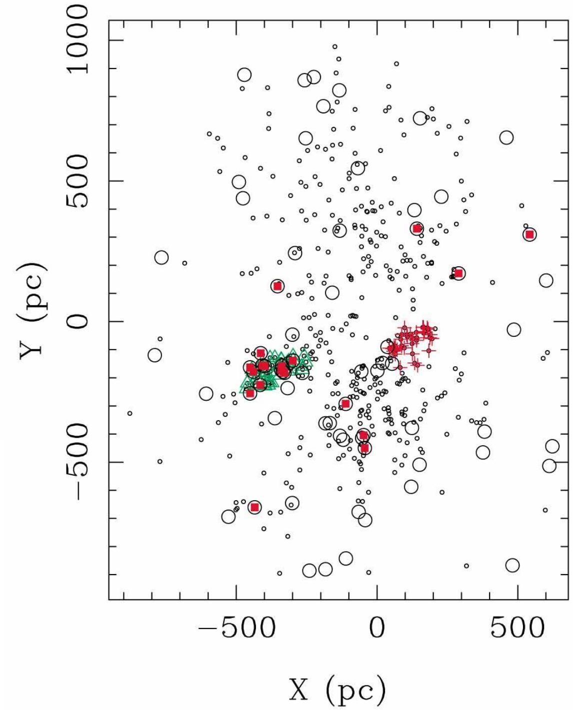


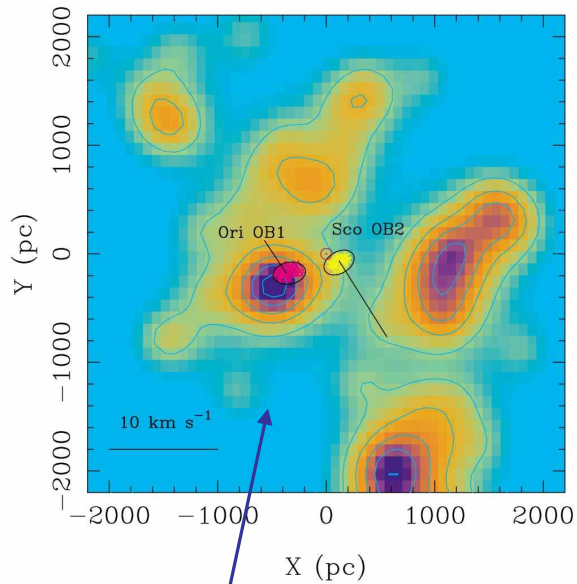
(increases with Mach number)

The fraction of gas that ends up in bound clusters equals the fraction that has a high efficiency $\varepsilon(\rho)$. For a fixed ρ_c, this fraction increases with the breadth of the density probability distribution function.

Elmegreen 08

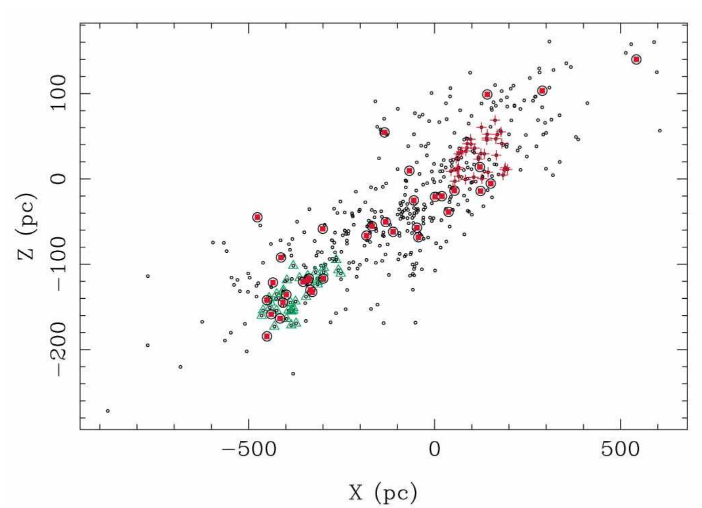


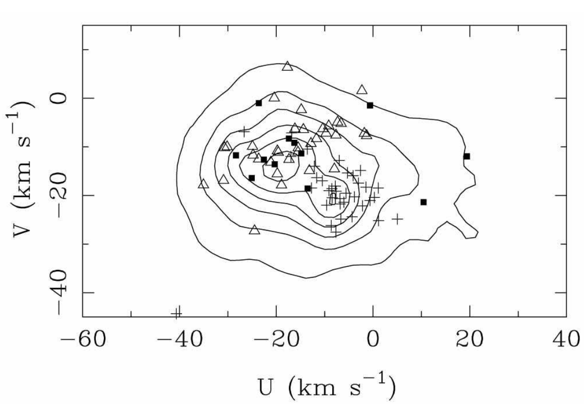




red circles = GB clusters
dots = GB stars
red +'s = ScoCen stars
green triangles = Ori stars

Young cluster (<10Myr) density:

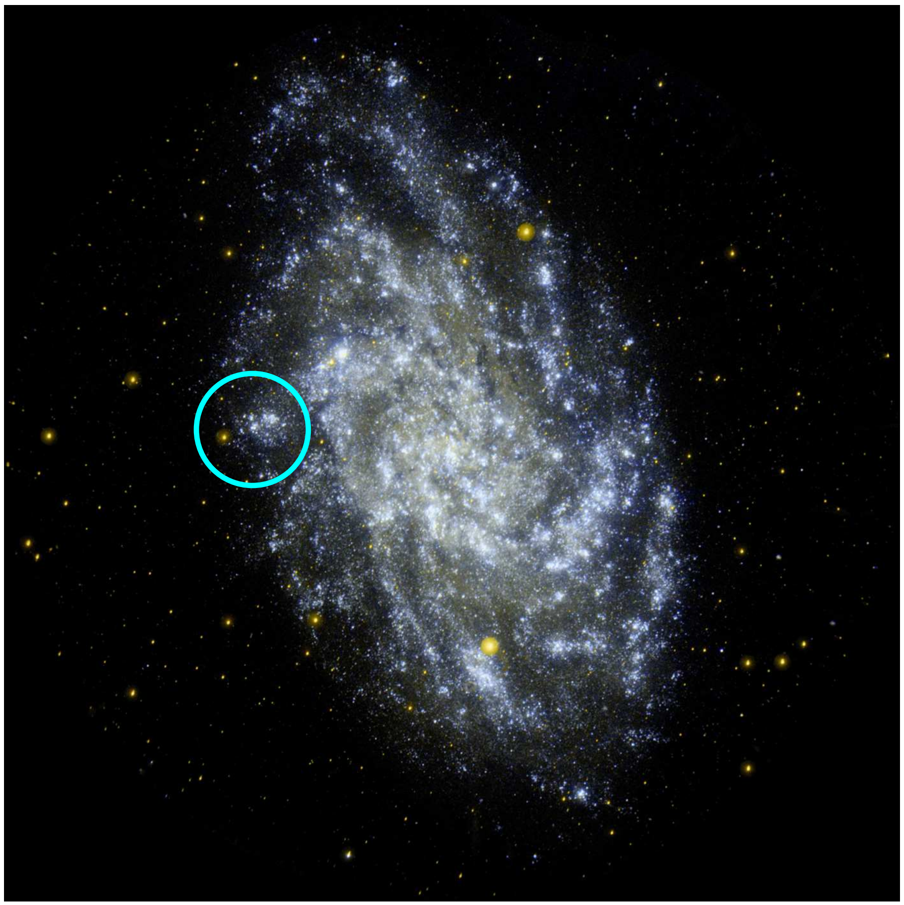


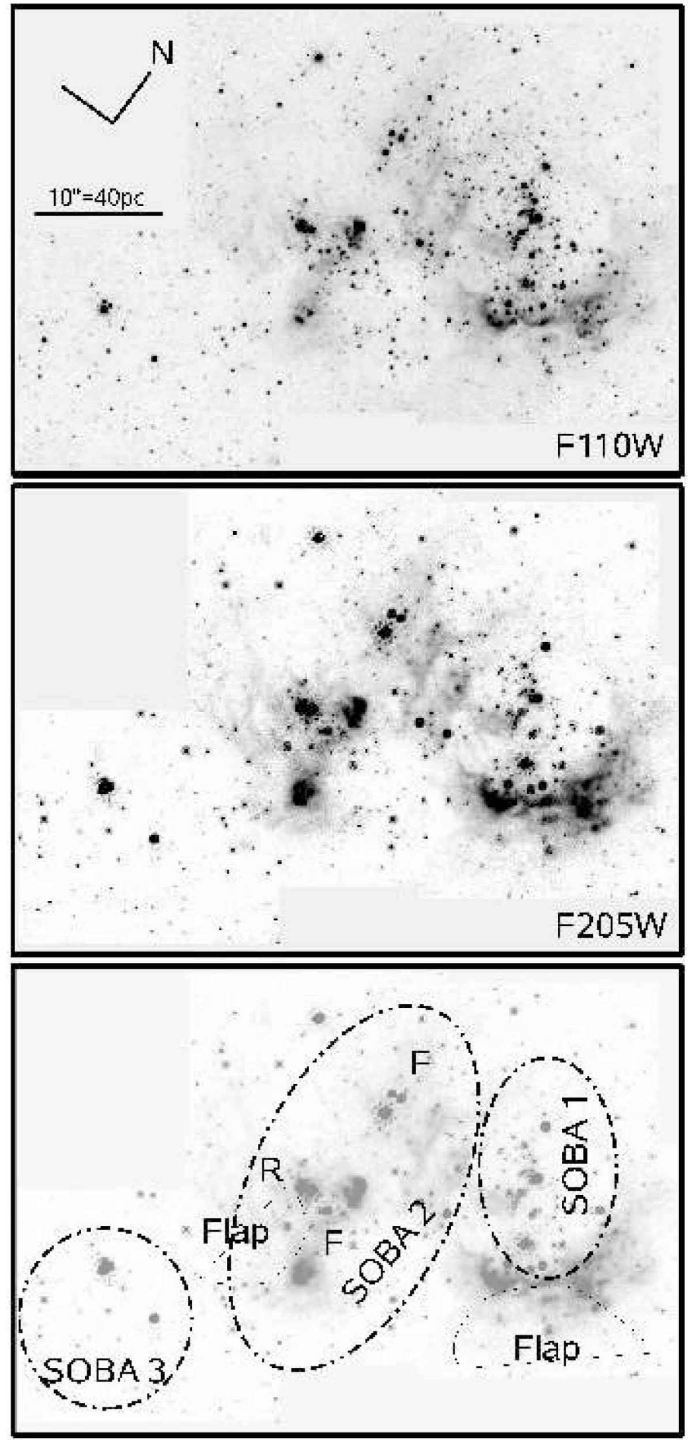


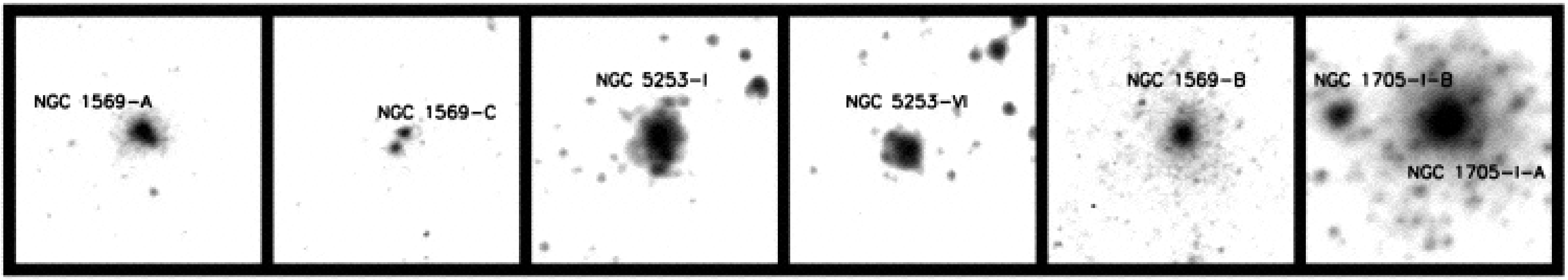
Cluster fraction large for Orion and small for Sco Cen.

Elias, Alfaro & Cabrera-Cano 09: Gould's Belt Catalogue of Open Cluster Data (Kharchenko +05).

Barba +09 NGC 604 in M33 with NICMOS: mostly unclustered stars



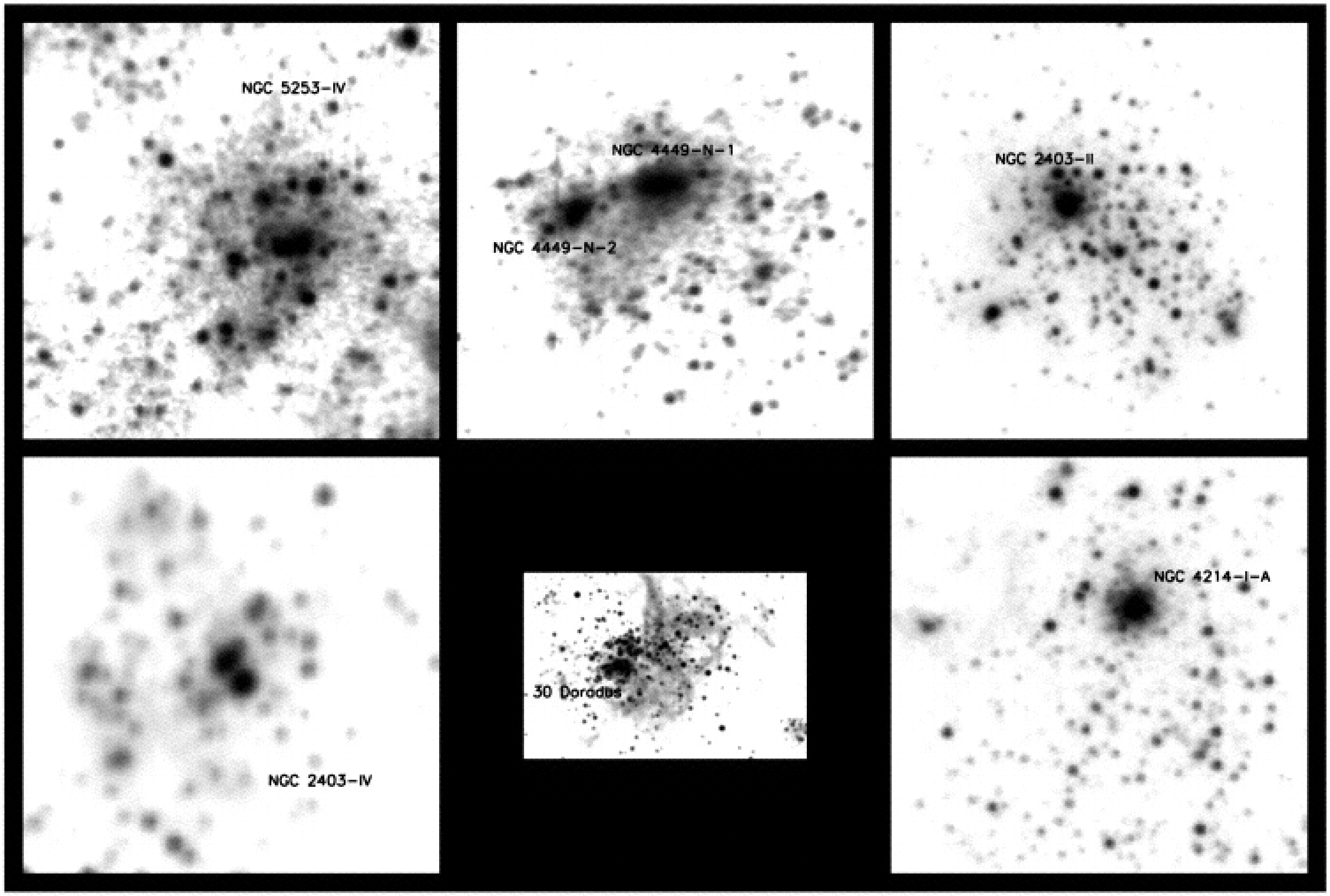




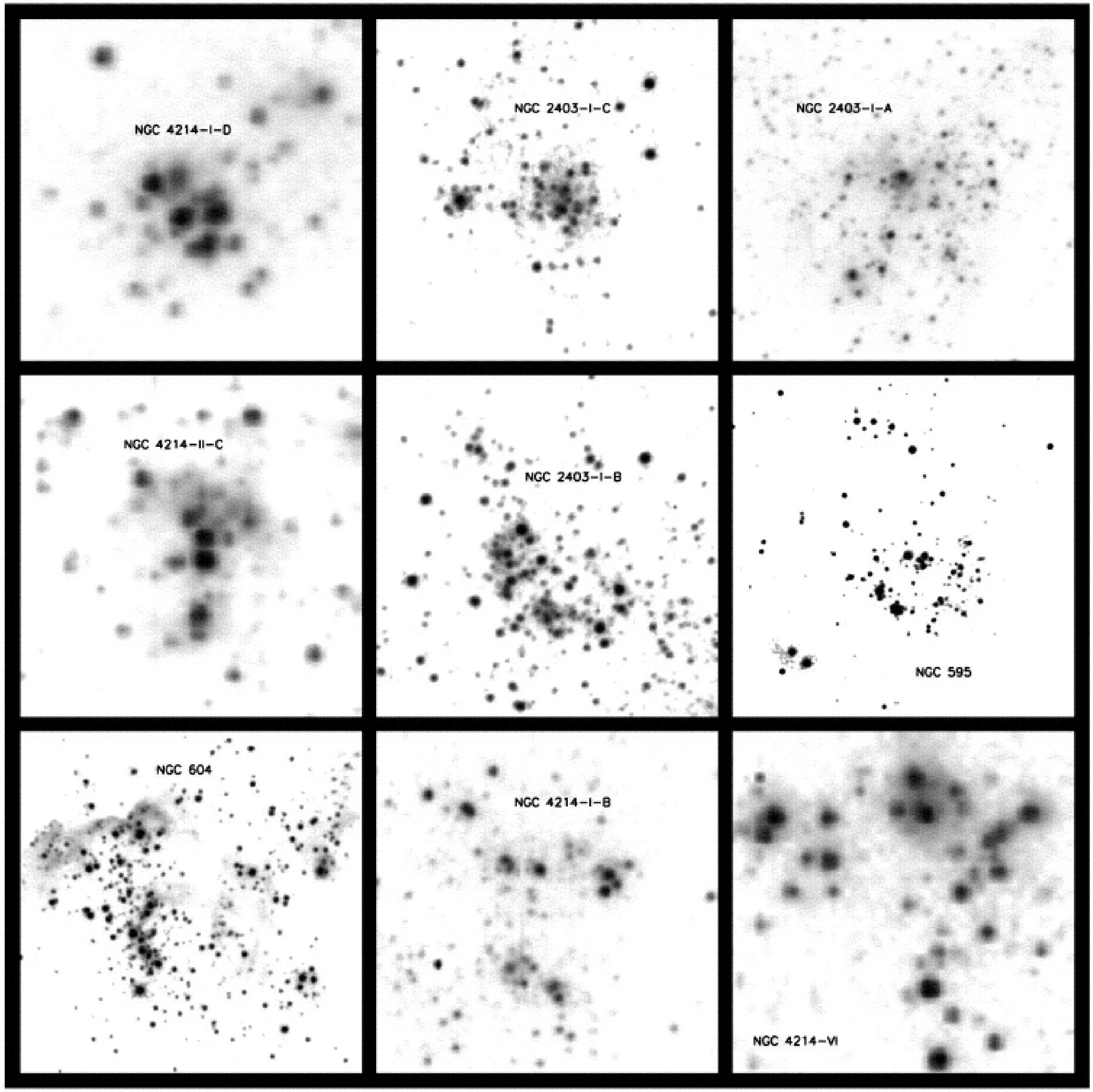
1. compact clusters with weak halos, 50x50 pc^2

Maiz-Apellaniz 01:
Three types

2. compact clusters with strong halos, 100x100 pc^2



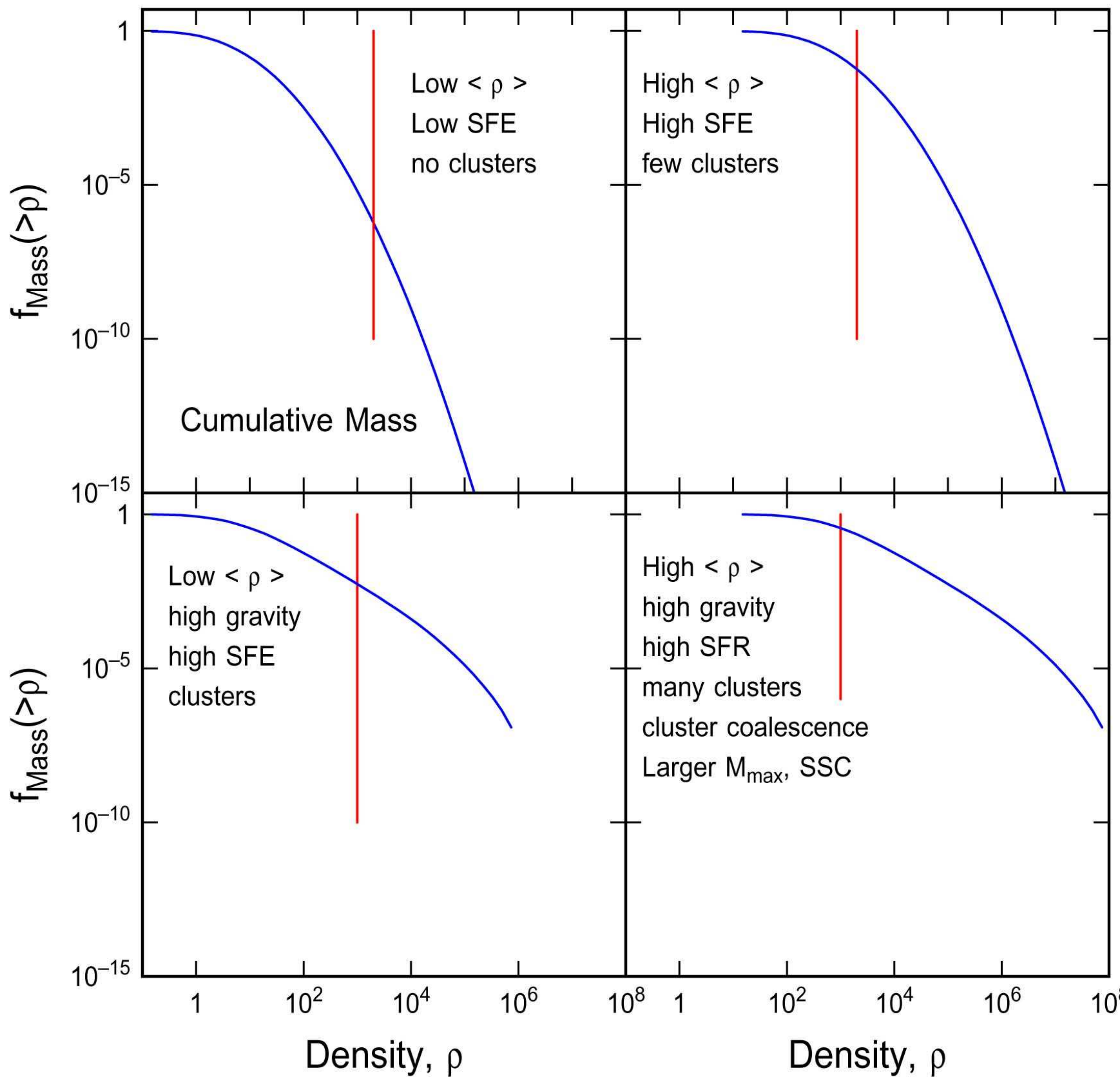
3. Hierarchical, but no clusters



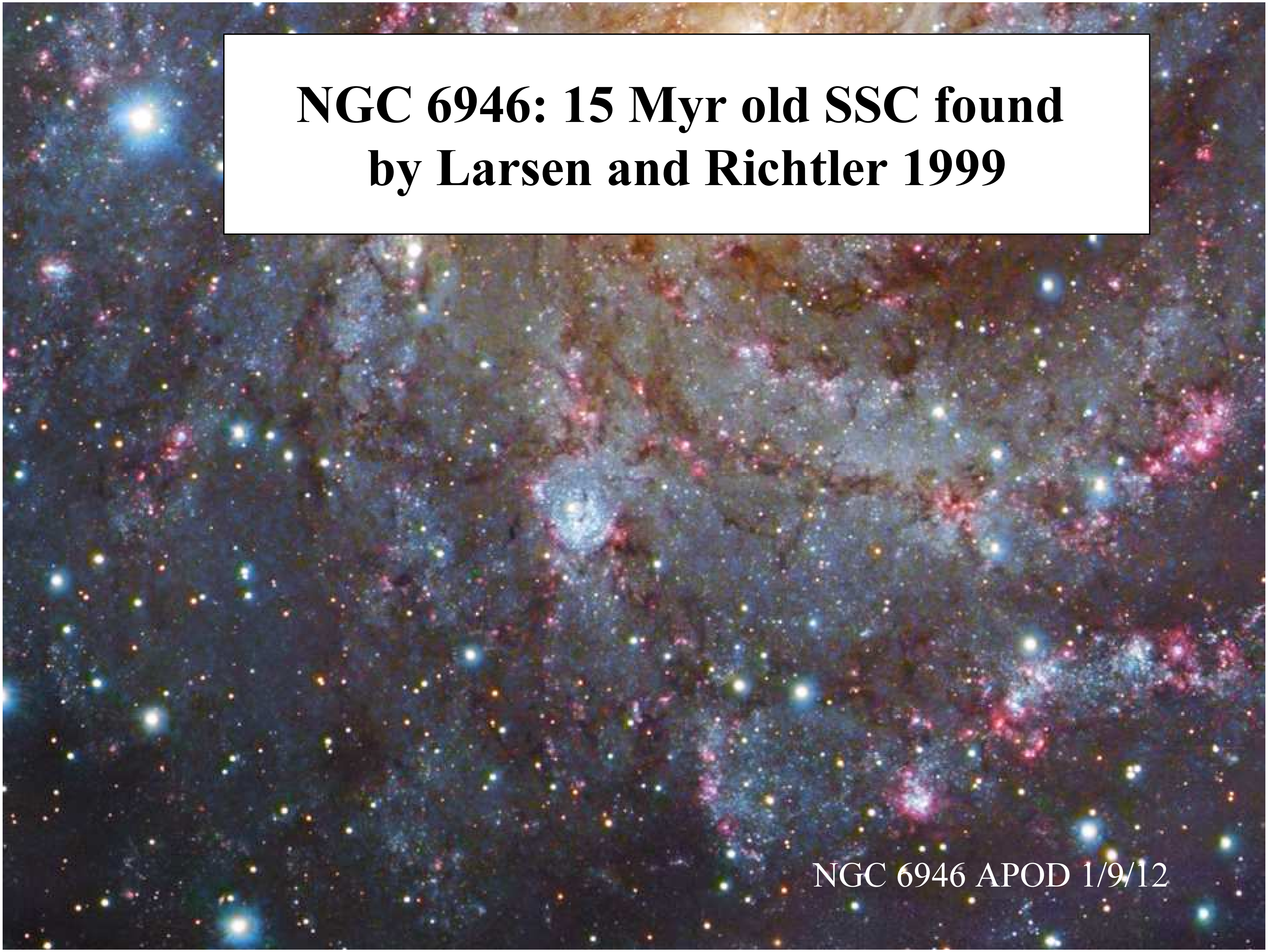
(Maiz-Apellaniz 01)

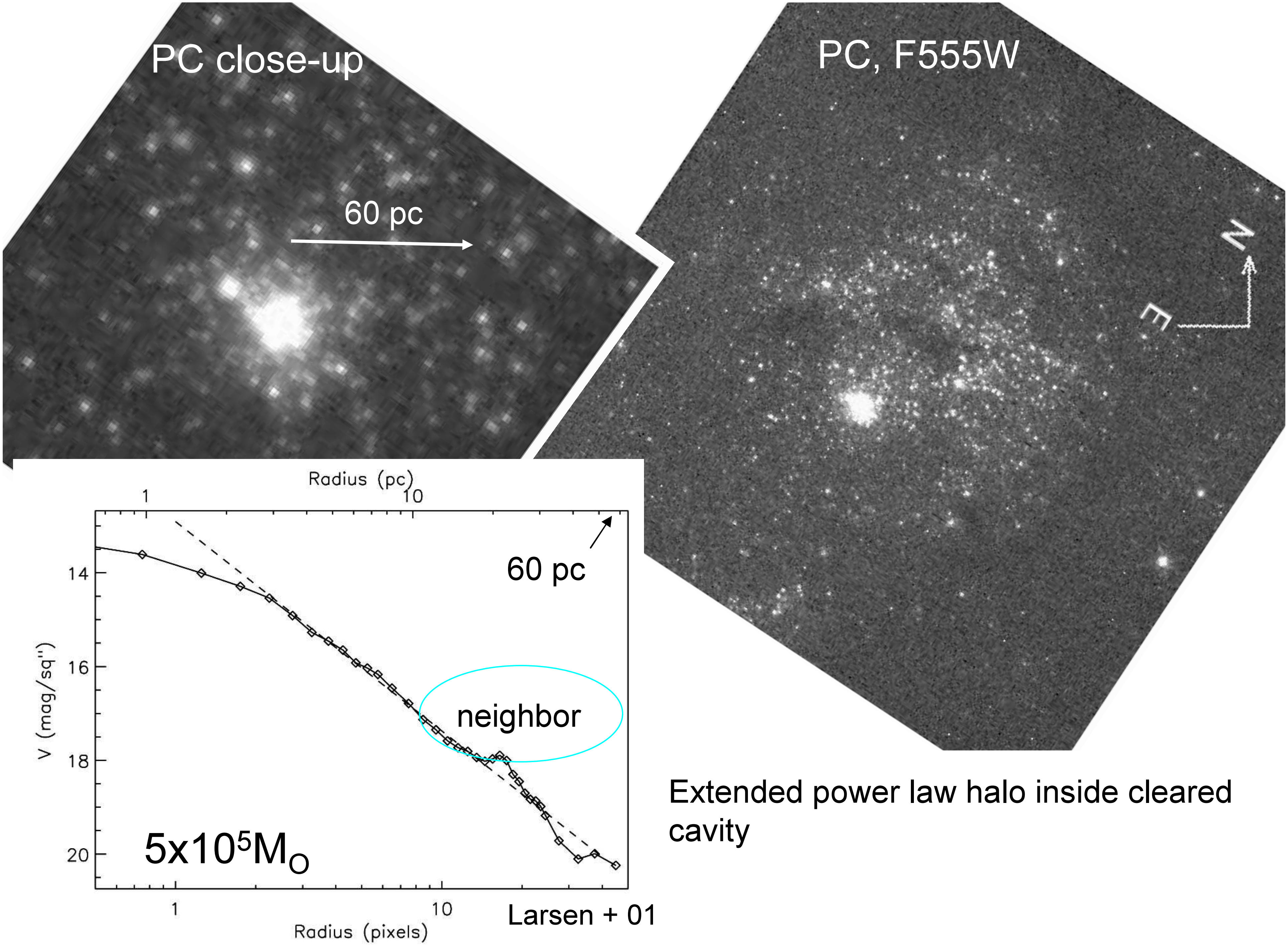
SOBAs
100 x 100 pc^2

Schematic of four regimes for clustered star formation

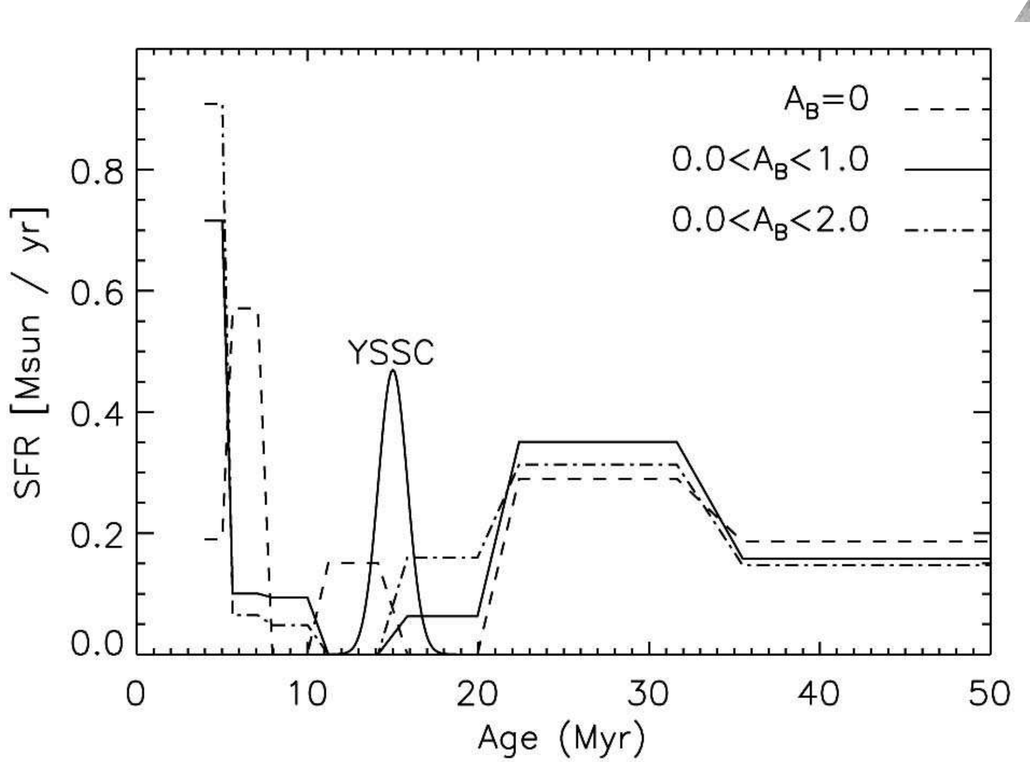


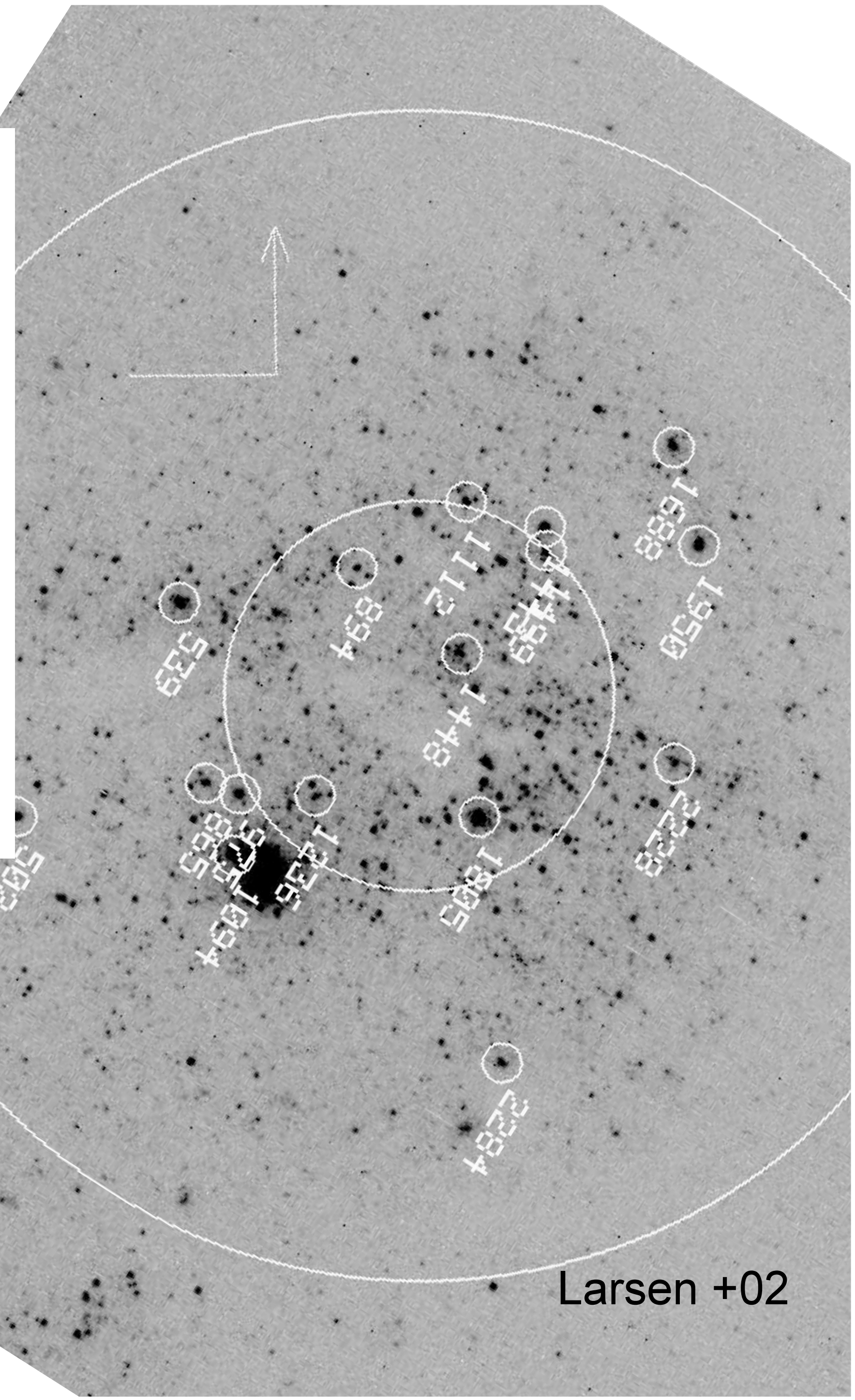
NGC 6946: 15 Myr old SSC found by Larsen and Richtler 1999





Extended power law halo inside cleared cavity



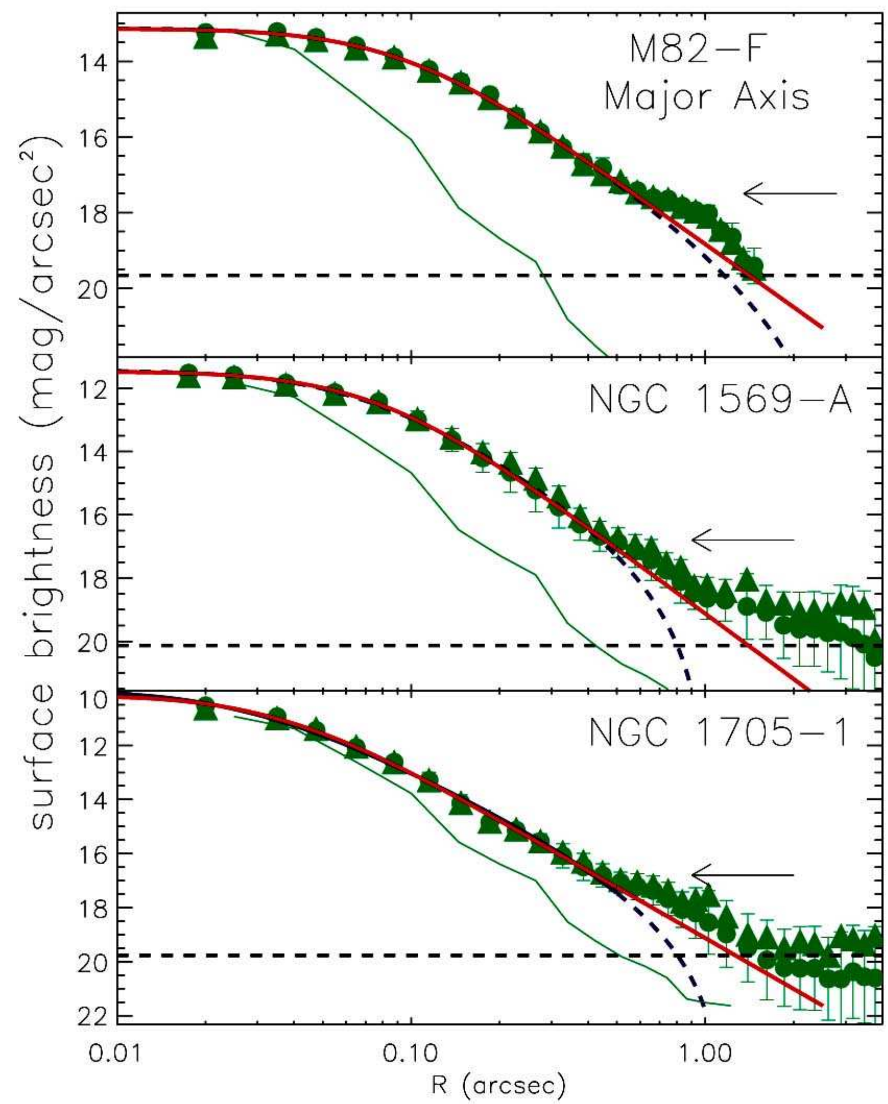


Age of SSC is the average of other clusters in the region and in a gap of other cluster ages

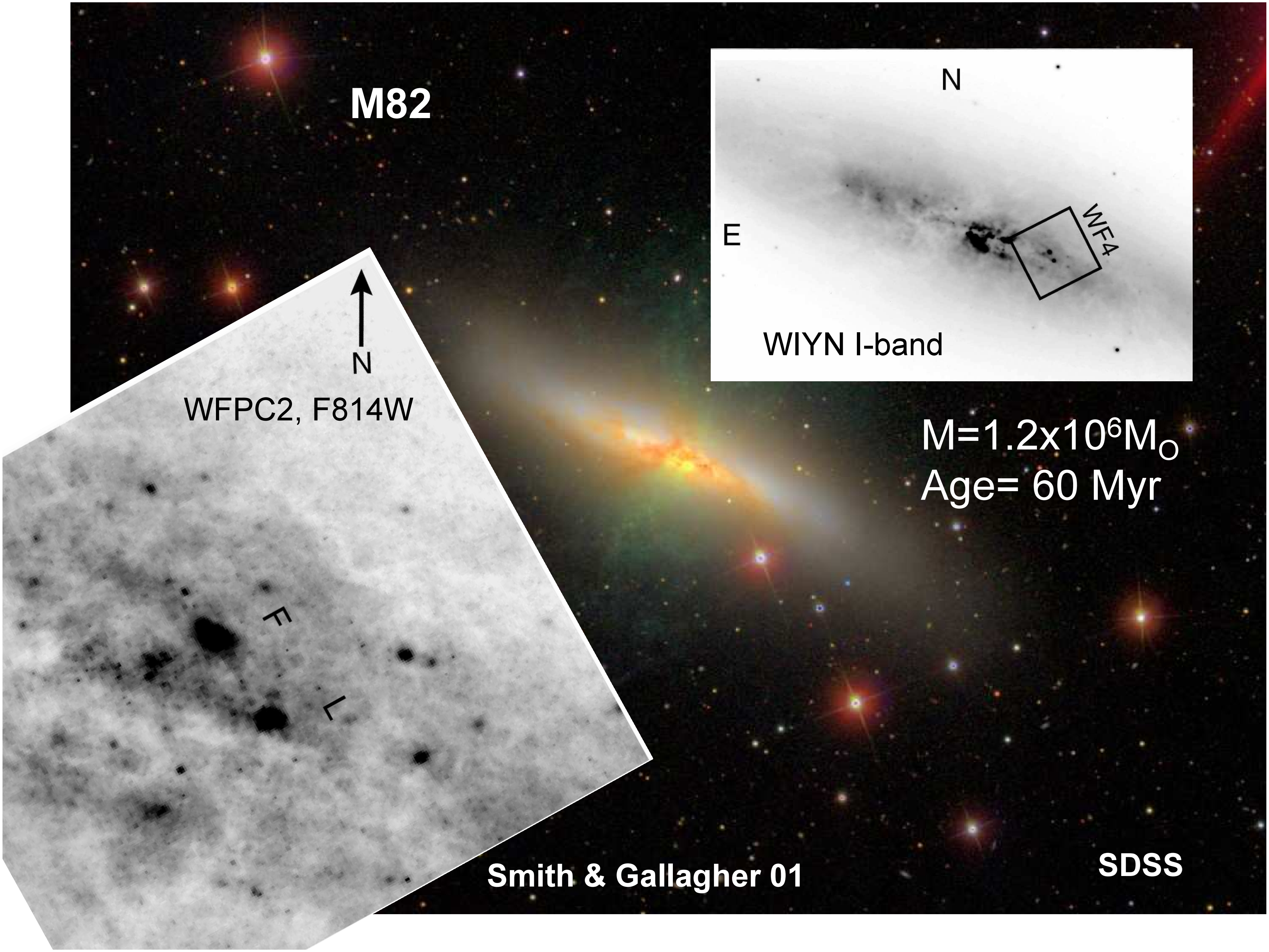
M_V =-13.2, next brightest clusters are -10.3 and -10.2 mag (factor of 15 fainter)

Larsen +02

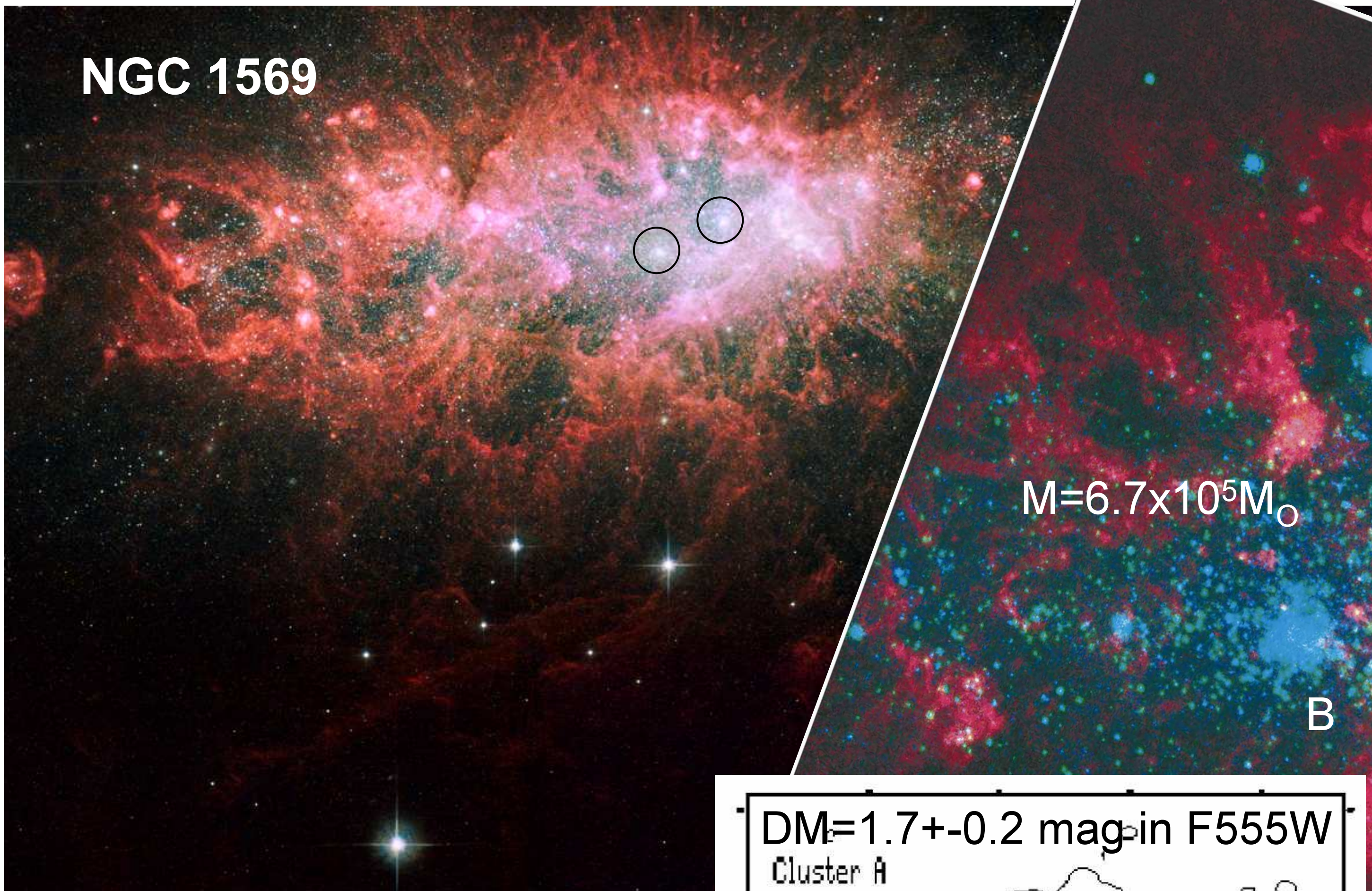
Other nearby SSCs with power law halos have outlying irregularities, as first seen by Elson, Fall & Freeman ’87:

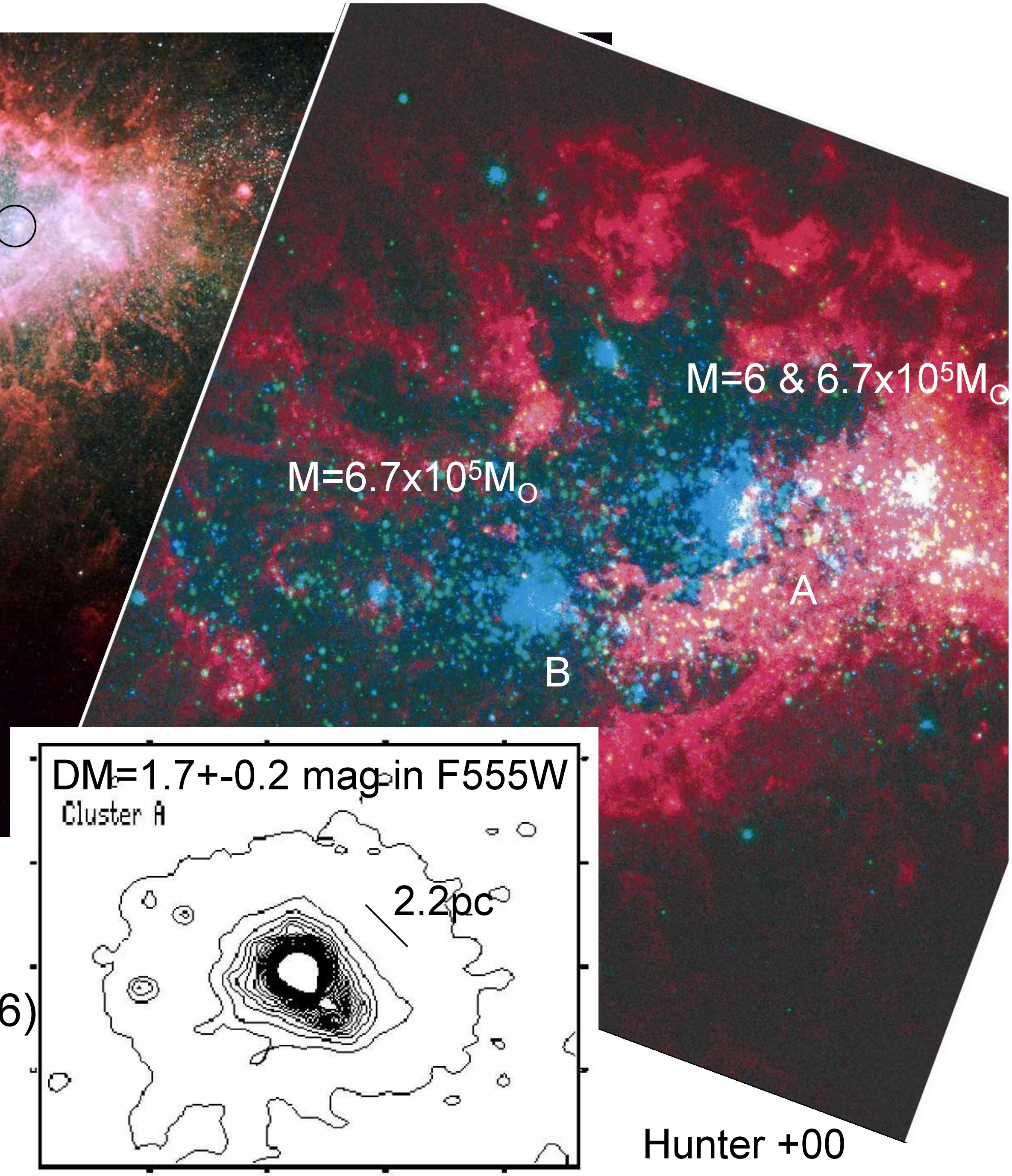


Bastian & Goodwin 06



M82
N
E
WF4
WIYN I-band
N
WFPC2, F814W
F
L
$M=1.2x10^6 M_O$
Age= 60 Myr
Smith & Gallagher 01
SDSS





Cluster A age ~ 7 Myr
3.3x10^{5}M$_O$ (Ho & Filippenko '96)

Cluster B age 10-20 Myr

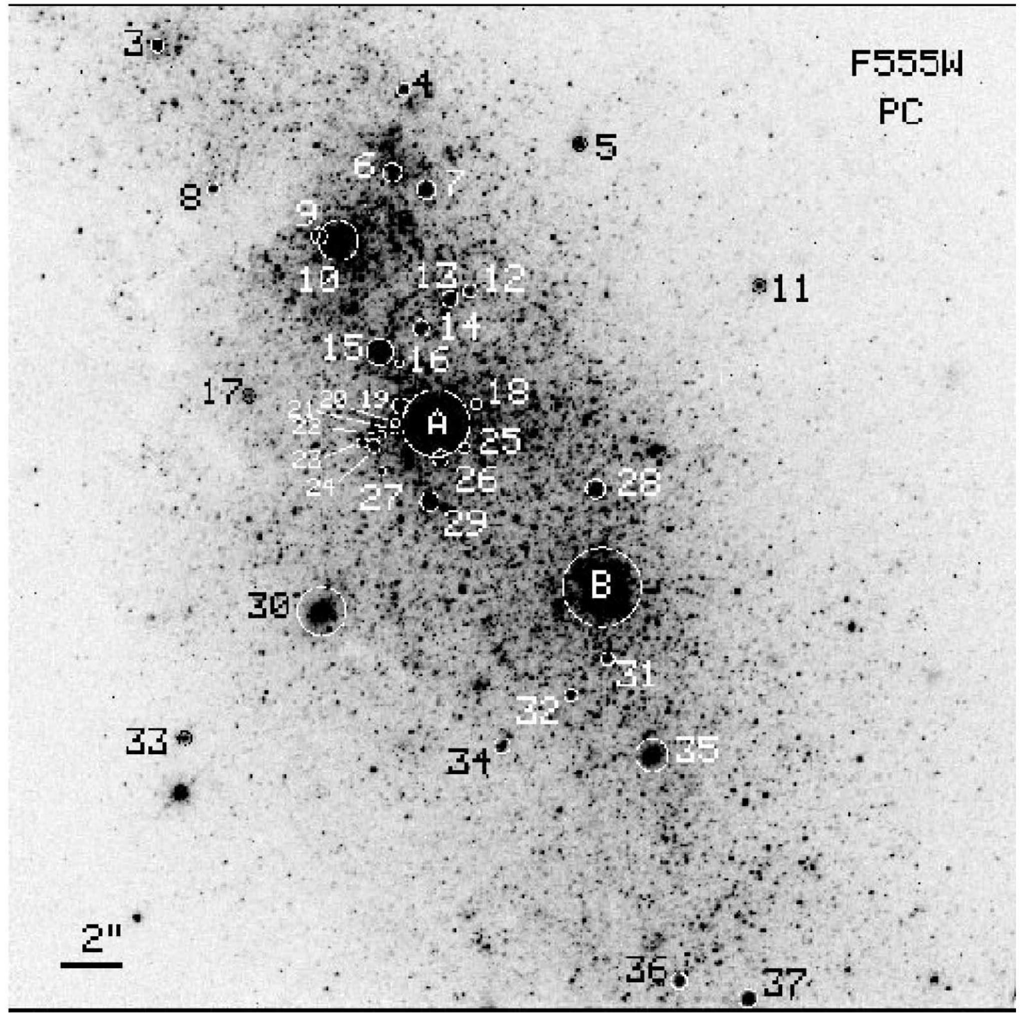
Hunter +00
Grocholski +08

NGC 1569

Neighboring clusters
with M_V up to -11mag
(like R136 in 30 Dor)

whereas
A has M_V = -13.97 mag
B has M_V = -13.05 mag

A,B = factor of 40 larger than
next largest clusters.



Hunter +00

NGC 1705

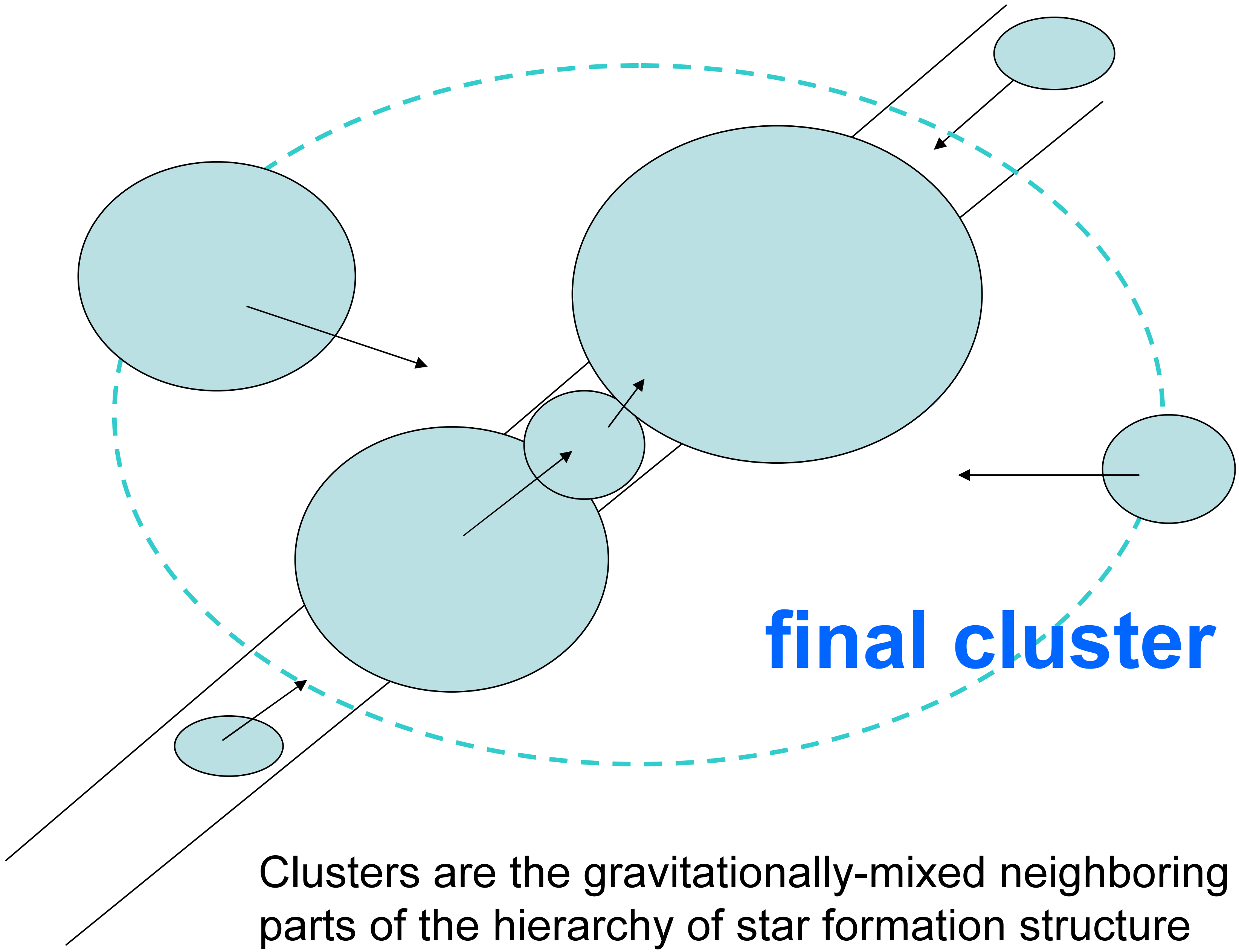
M ~ 5×10^5 M_O

M_V ~ -14 mag

(Smith & Gallagher 01)

Age ~ 13 Myr (Meurer +92)

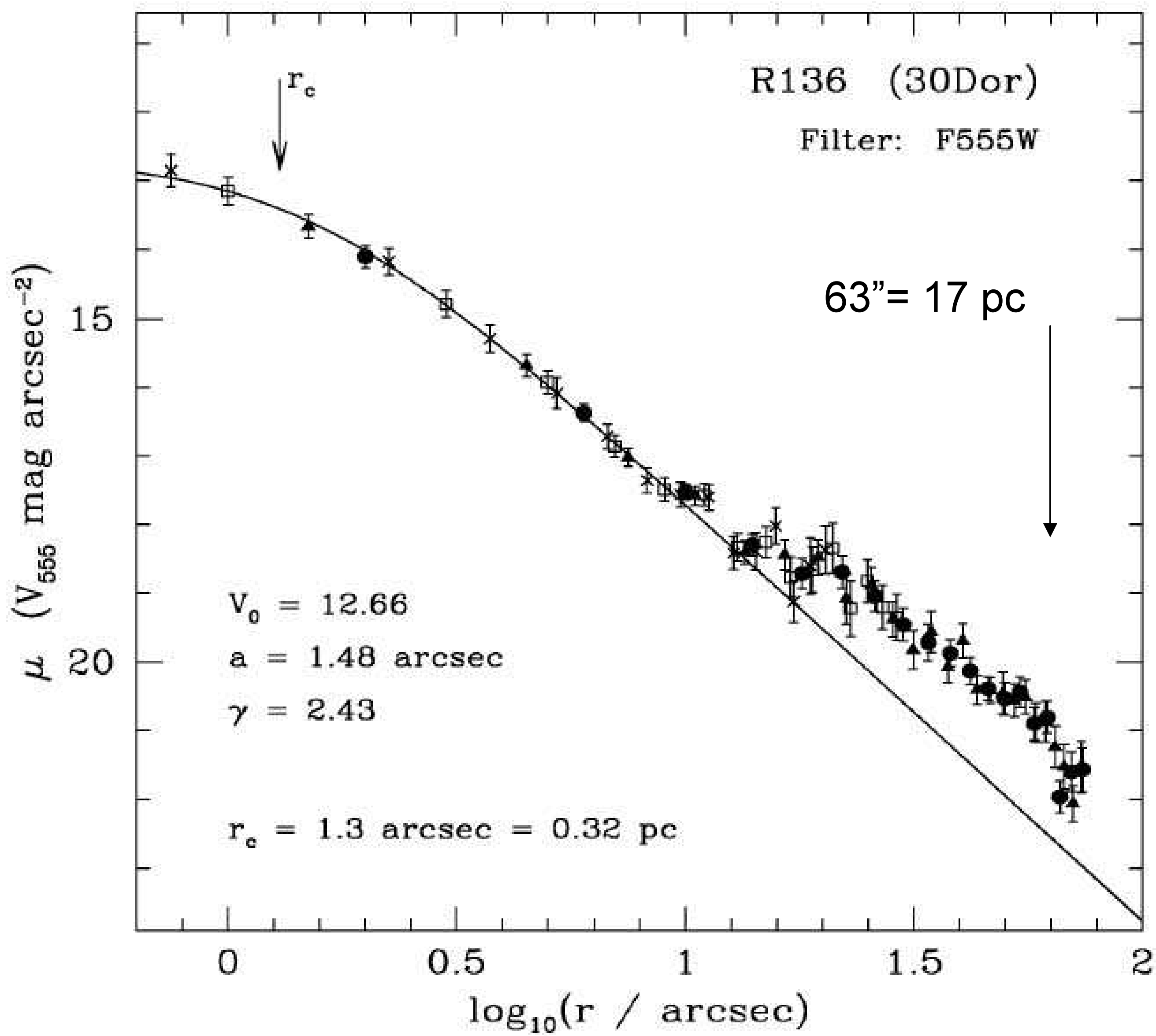
HST: NED

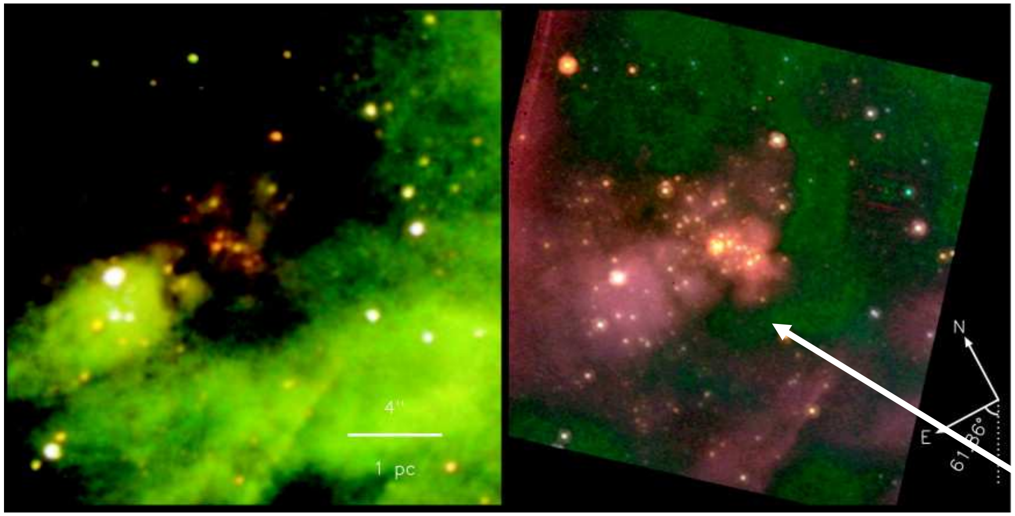


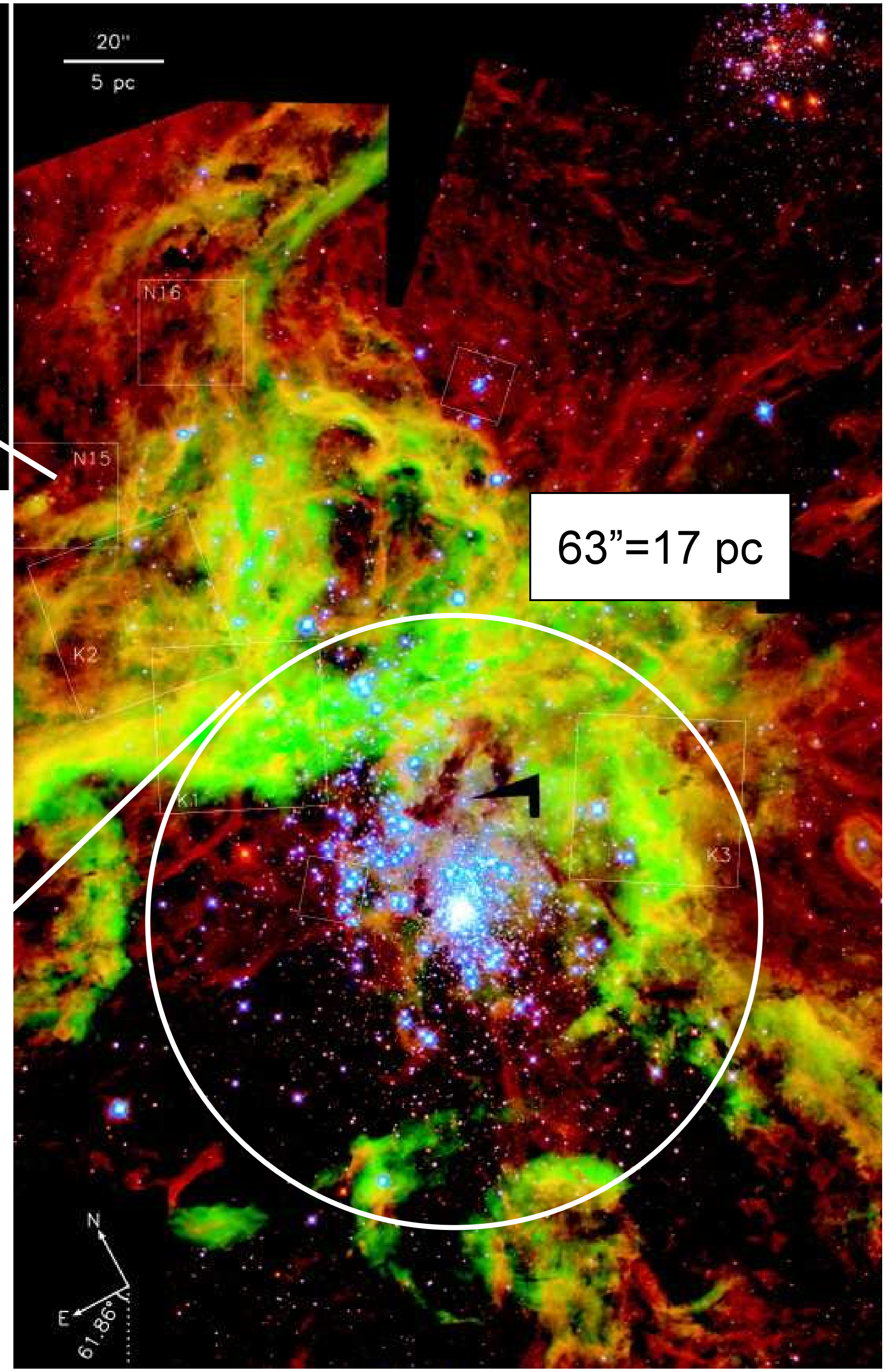
Clusters are the gravitationally-mixed neighboring parts of the hierarchy of star formation structure

Mackey & Gilmore 03

R136 in the LMC

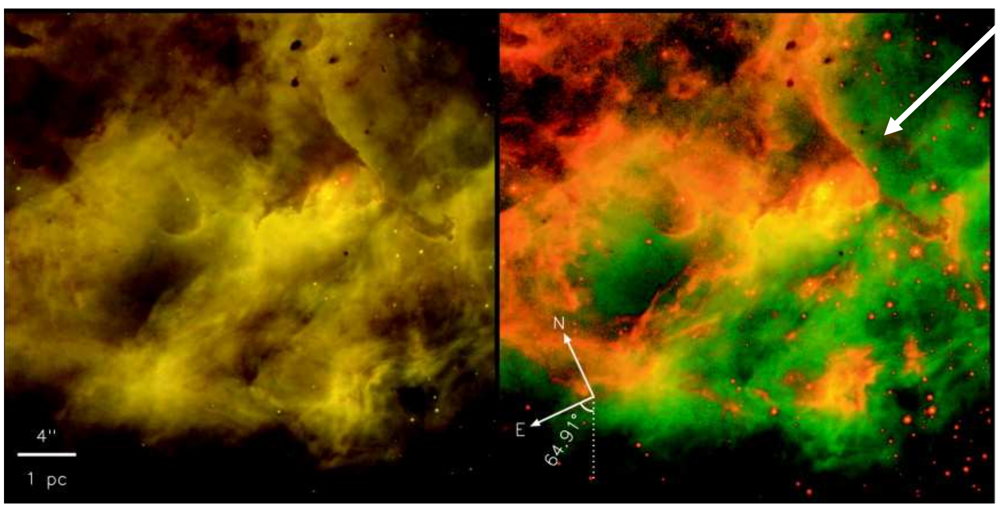






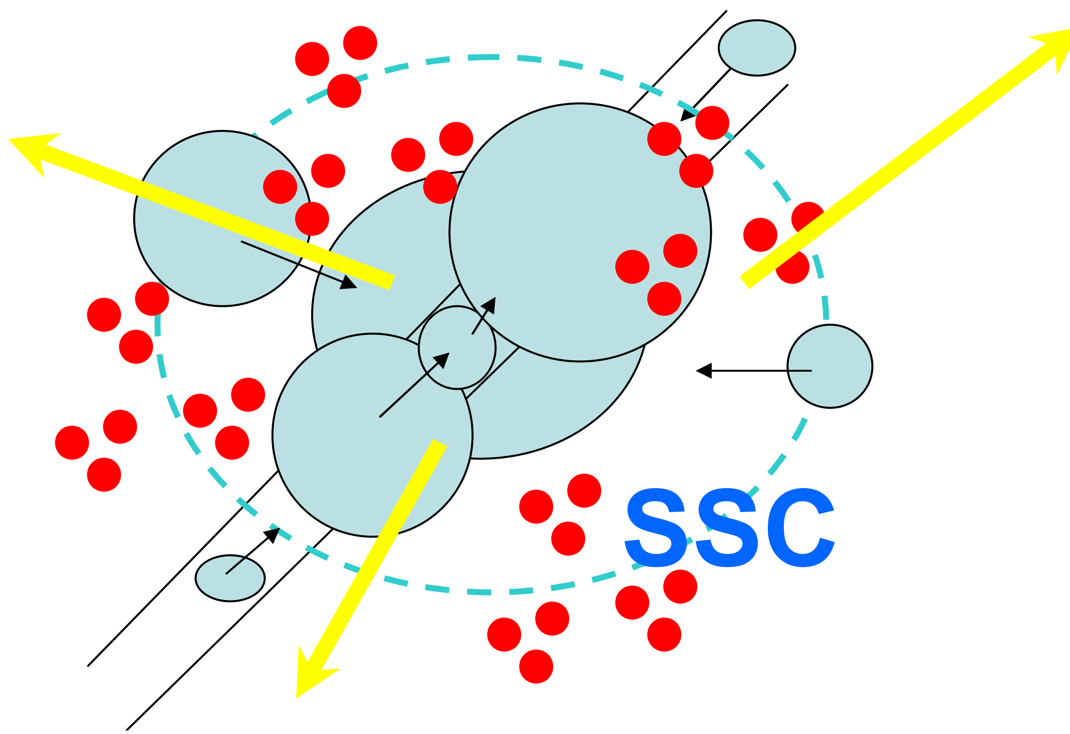
Triggering in 30 Dor

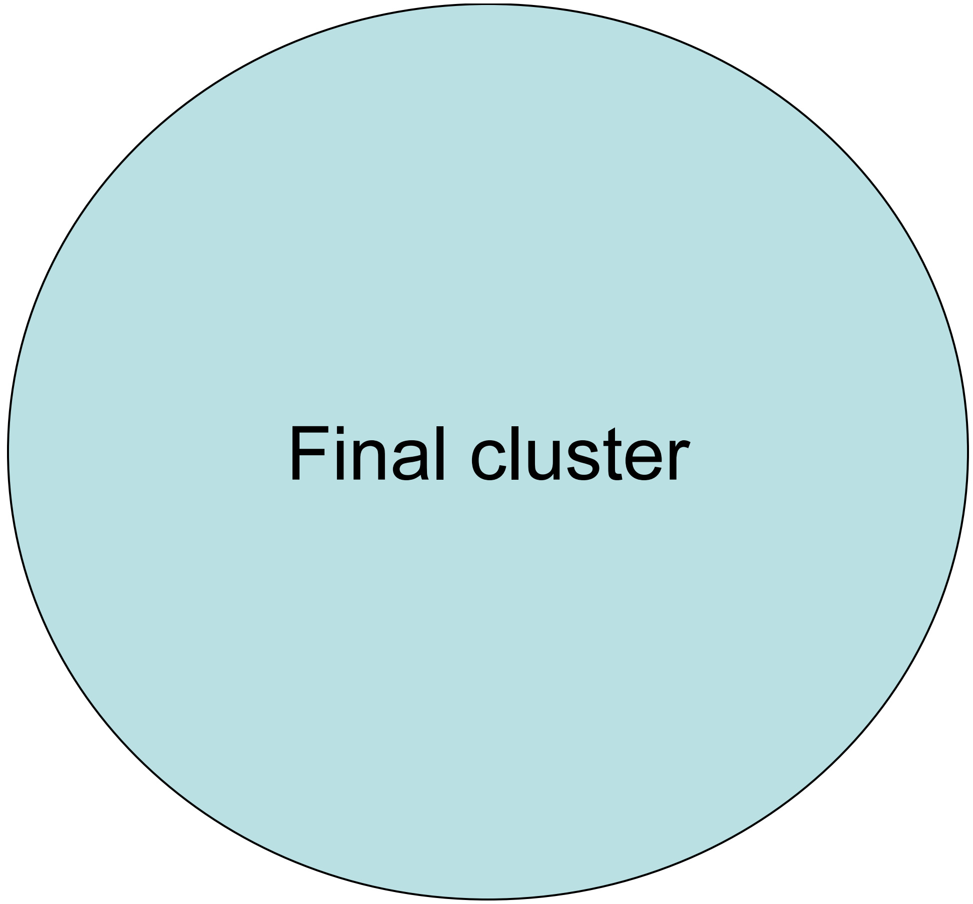
Walborn et al. 2002



~20-60 pc Cluster Halos Probably Contain:

- younger triggered stars in bright rims
- infalling stars and clusters from separate birthsites
- evaporating stars from central birthsite



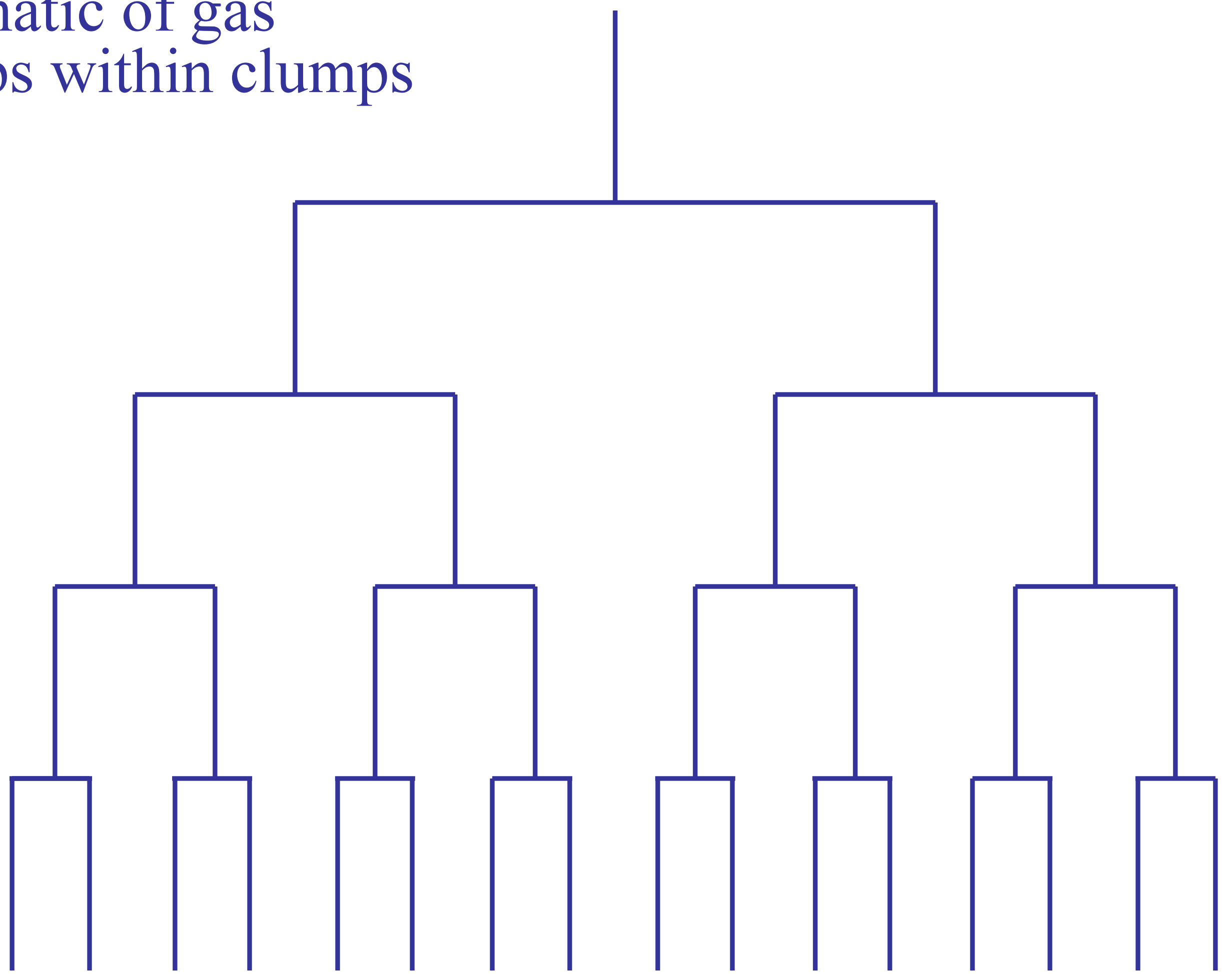


Implications of sub-clump coalescence:

many stars formed outside the final cluster volume,
a range of ages is possible,
the “final” IMF is the sum of local IMFs,
the final “efficiency” can exceed 100%,
mass segregation can be fast (McMillan +07).

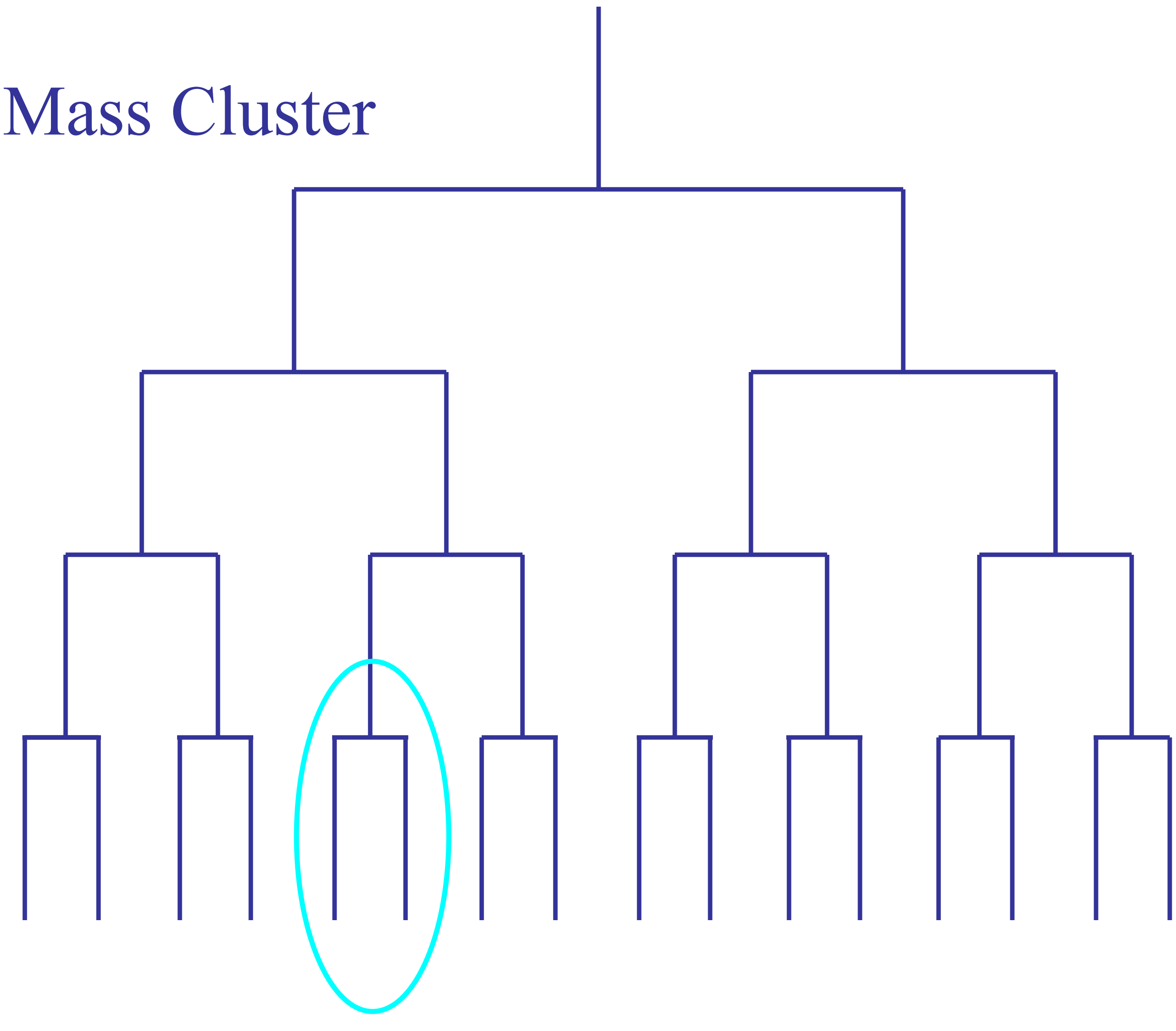
Mass Functions in Hierarchical Clouds

schematic of gas
clumps within clumps



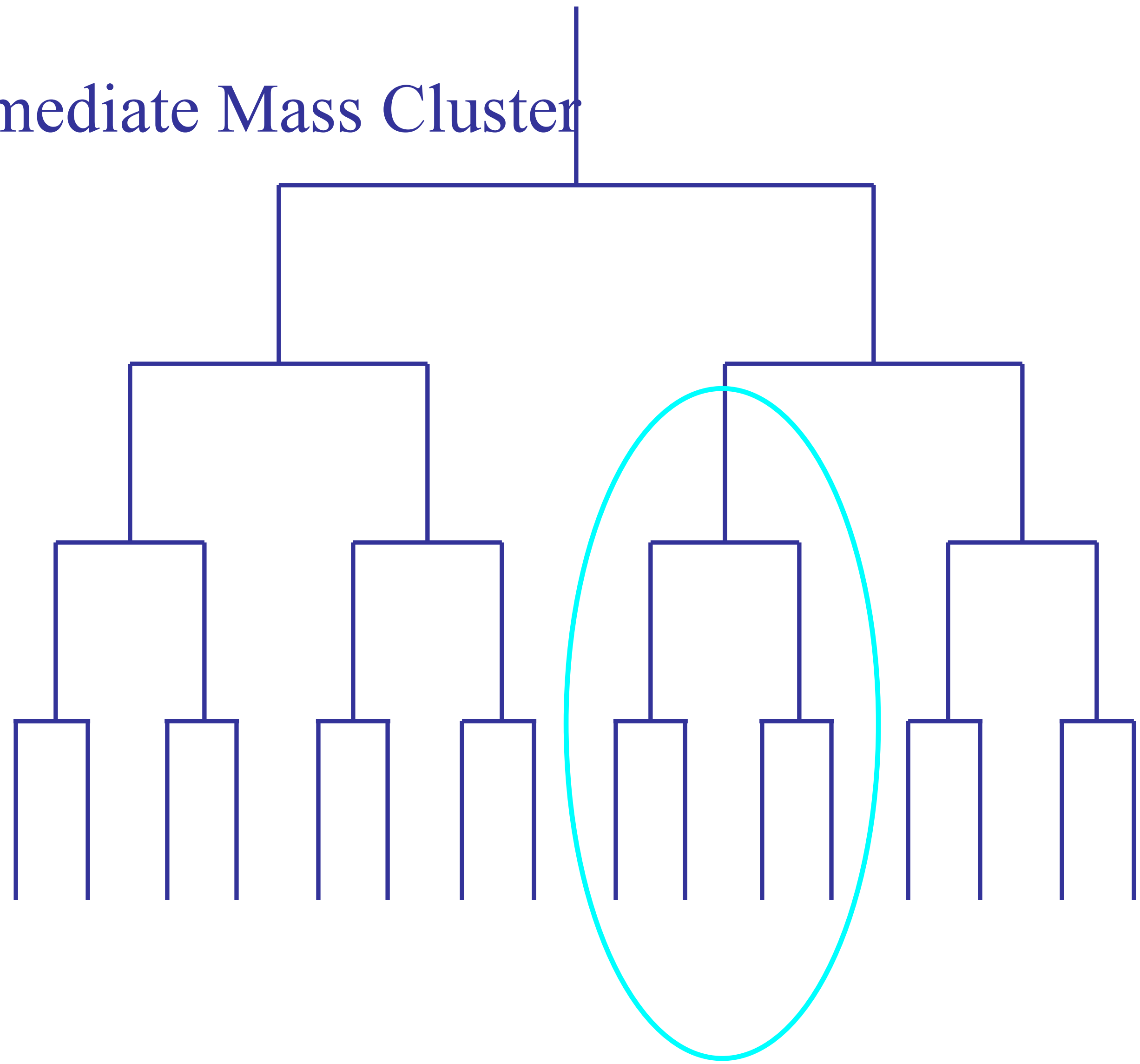
Mass Functions in Hierarchical Clouds

Low Mass Cluster

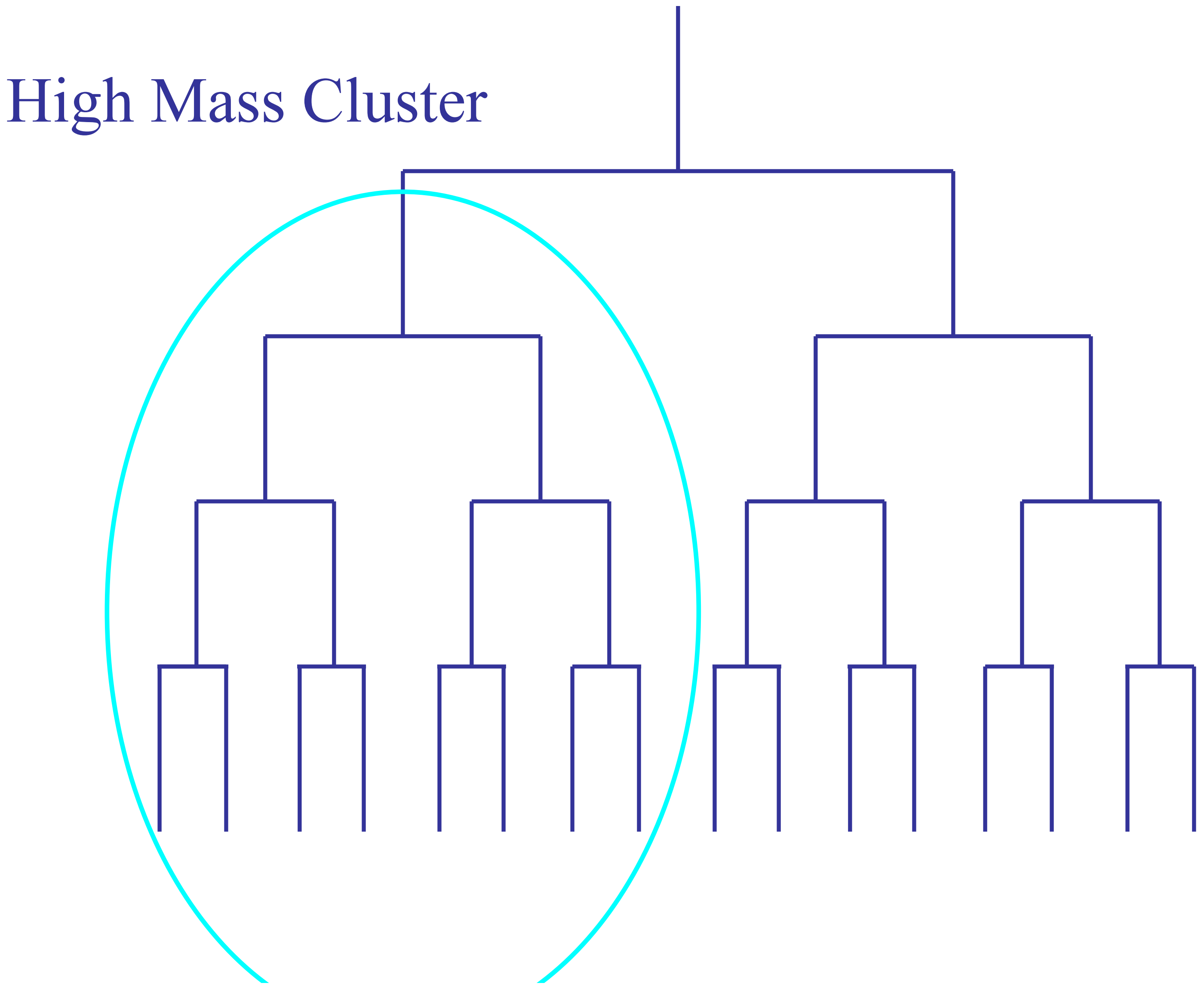


Mass Functions in Hierarchical Clouds

Intermediate Mass Cluster

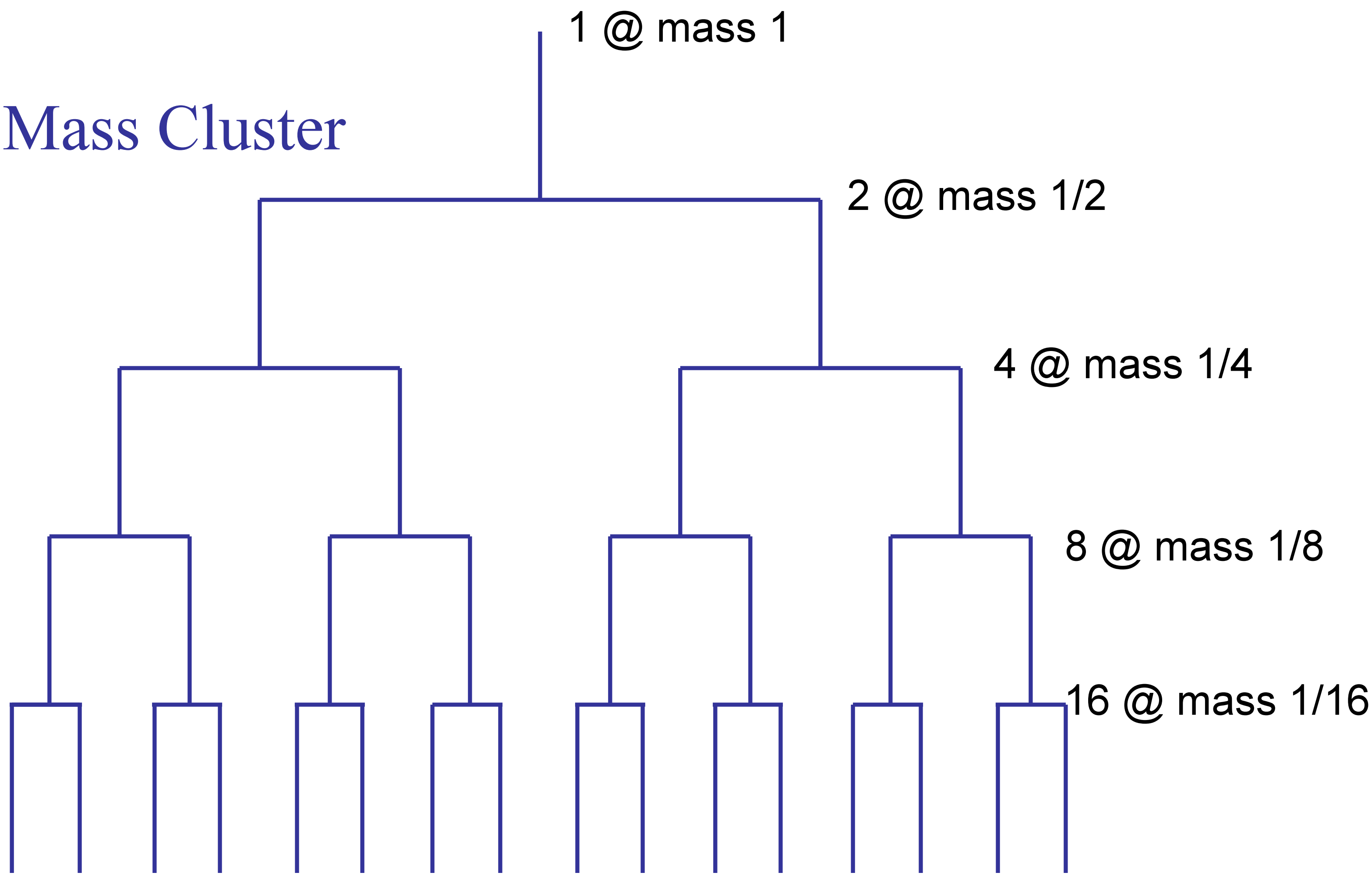


Mass Functions in Hierarchical Clouds



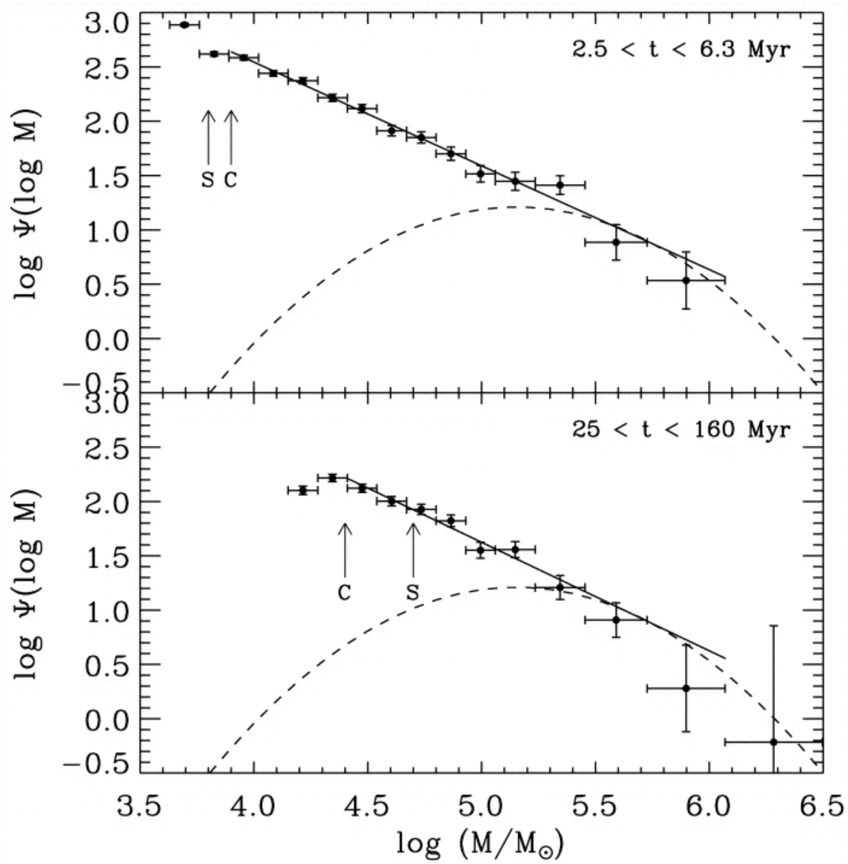
The mass distribution function of nodes in a hierarchy is $dN/d\log M \sim 1/M$, or $dN/dM \sim 1/M^2$, the same as star clusters

High Mass Cluster



probability you pick a mass between M and 2M is proportional to 1/M

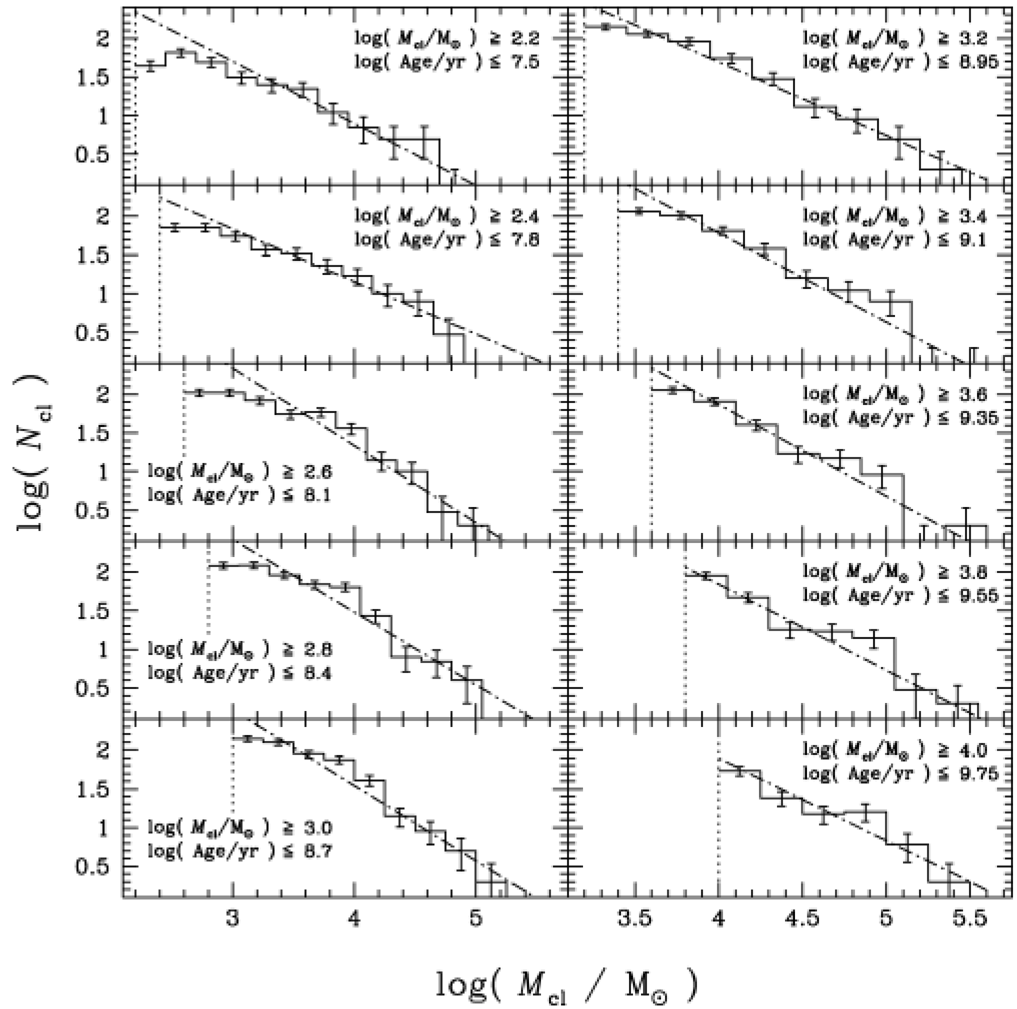
Cluster mass functions have slope β~2



Antennae: Zhang & Fall 99

β=1.95pm0.03 (young)

β=2.00pm0.08 (old)



LMC: de Grijs & Anders 06

β=1.85pm0.05

Summary

- Clusters and young stars are hierarchical in space and time up to ~1 kpc and ~100 Myr and down to unresolved sizes & ages
- Hierarchical structure has characteristics of turbulence
  - spiral turbulence on large scales,
  - cascade from spiral turbulence + feedback on small scales
- GMCs form highly turbulent and bound by ram-pressure (from accretion in spirals and turbulent flows)
- After energy dissipation and with continued accretion, they develop self-gravitating cores
  - perhaps at a threshold density or column density
- Continued turbulence compression, but now with a central gas concentration from gravity, produces gravitating pre-stellar cores (stars) at high efficiency.
- Hierarchical groupings of these stars mix together by gravity
- Bound clusters are the mixtures that remain when the gas leaves
- M^{-2} cluster mass function follows & maybe an $M_{max}(P)$ relation