Cluster Formation in Mergers: Theory

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Overview of SF in Mergers

1. ISM is globally shocked

⇒ 2. Gas column density increases

★ Accretion through a galaxy disk via tidally- induced spirals or bars

- (grazing collision)

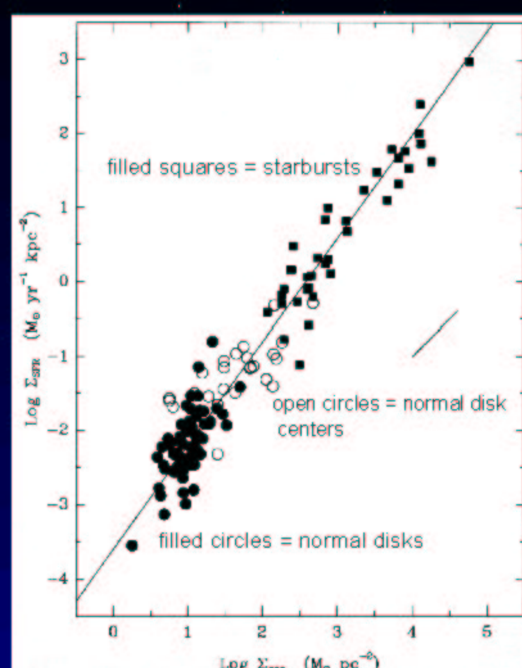
★ Accretion of gas from another galaxy

- (merger)

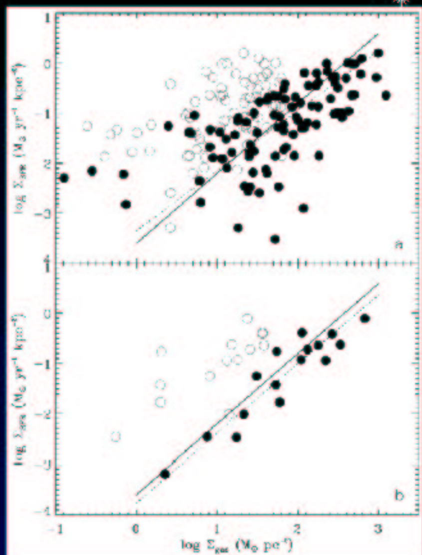
★ SFR/A increases as $\Sigma^{1.4}$

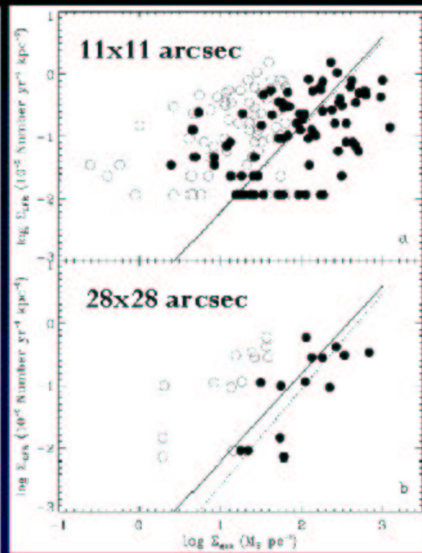
- (the usual Schmidt law)

Why is this law so universal?



Kennicutt 1998 ApJ 498 541



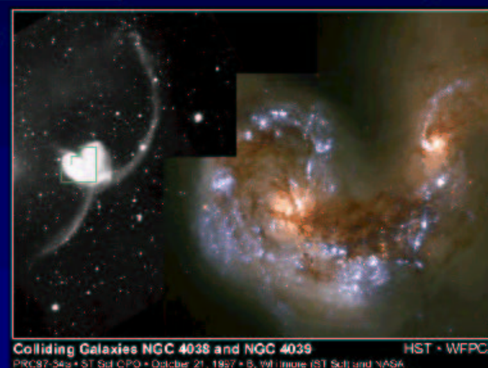


open O = HI
filled O = total

Zhang, Fall, & Whitmore 2001

General Star Formation

Clusters only



The Schmidt-law works in small regions too

Why is there a Schmidt-Kennicutt Law?

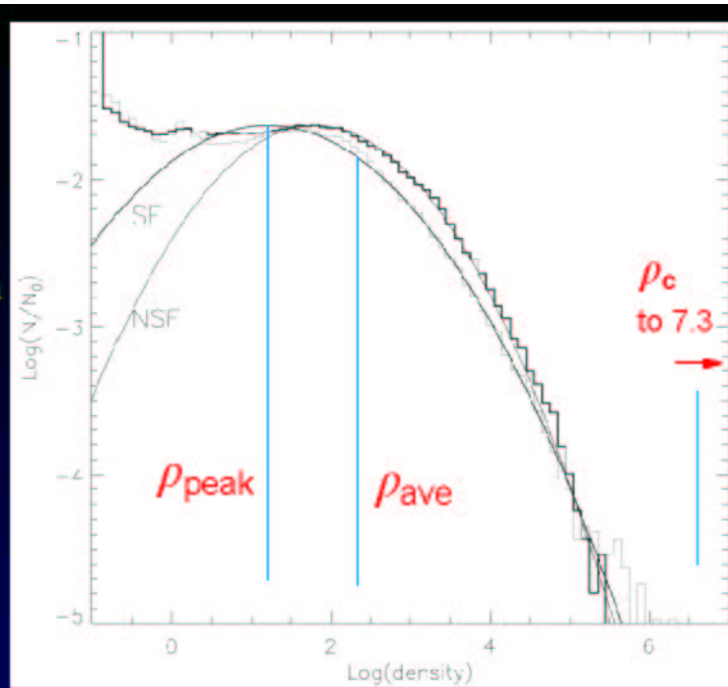
- ★ Stars form only at high density yet the SFR scales with the average density: SFR(M/vol/time)$\sim\varepsilon\,\rho\,(G\rho)^{1/2}$
- ★ In high density cores, the SFR should be
  SFR(M/vol/time)$\sim\varepsilon_c\,\rho_c(G\rho_c)^{1/2}$
- ★ For a threshold core density $\rho_c\sim10^5$ cm^{-3}, and typical $\varepsilon_c\sim0.1$-0.5, the core SFR is constant.
  - ★ at $\rho_c\sim10^5$ cm^{-3}, big grains stop gyrating (Kamaya & Nishi 2000), molecules freeze onto grains (Bergin et al. 2001), the ionization fraction begins to drop (Caselli et al. 2002), and turbulence becomes subsonic (Goodman et al. 1998).
- ★ Schmidt-law $\rightarrow\rho_c/\rho$ const.: $\varepsilon\propto$ fraction of gas at $\rho>\rho_c$
- ★ Constant efficiency (Rownd & Young 1999; Boselli et al. 2002) $\rightarrow\rho_c$ const. ; $\varepsilon\propto$ fraction of gas at $\rho>\rho_c$

What is the predicted fraction f_c of gas at $\rho > \rho_c$?

Wada and Norman 2001 found a log-normal distribution function for density in their whole galaxy models.

The dimensionless width depends on the mean Mach number

The dense gas fraction is the integral above the density threshold.



Wada & Norman 2001 ApJ 547 172

(1) Normalize this pdf to the local density.

(2) Integrate it for $\rho > 10^5\ m_{H2}$. (or $\rho_c/\rho > 10^5$)

(3) Find $f = 10^{-4}$ of the gas mass has $\rho > 10^5\ m_{H2}$.

What is the observed f?

The Kennicutt 1998 relation is: $SFR/A = 0.033\ \Sigma\Omega$ for average Σ and outer galaxy rotation rate Ω.

Integrating over an exponential disk and taking the average density equal to the tidal limit, this converts to a local rate,

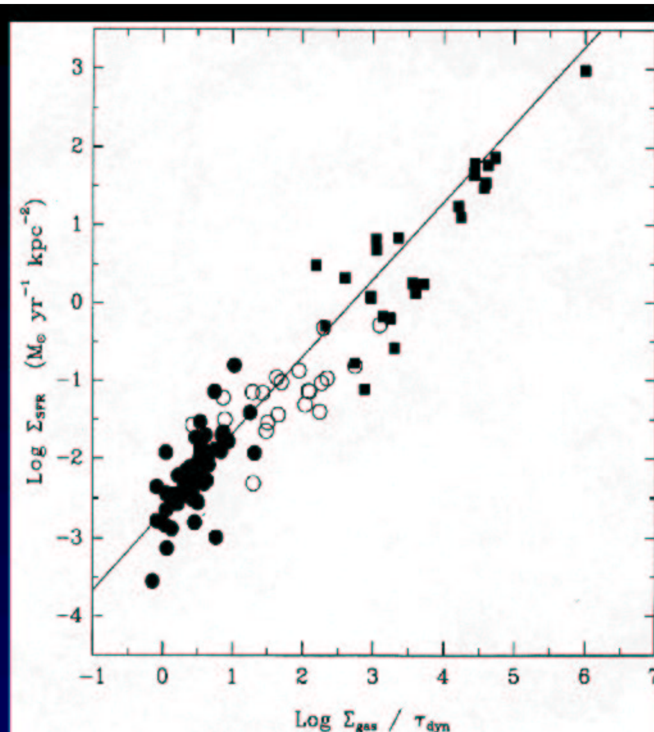
$SFR/V = 0.012\ \rho\ (G\rho)^{1/2}$

But $(SFR/V)_{galaxy} = (SFR/M)_{core}\ (M_{core}/M_{galaxy})\rho = \varepsilon_c\ (G\rho_c)^{1/2}\ f_c\ \rho$

So $\varepsilon_c\ (G\rho_c)^{1/2} f_c = 0.012\ (G\rho)^{1/2}$

and the observed mass fraction is

$f_c = 0.012\varepsilon_c^{-1}\ (\rho/\rho_c)^{1/2} \sim 10^{-4}$

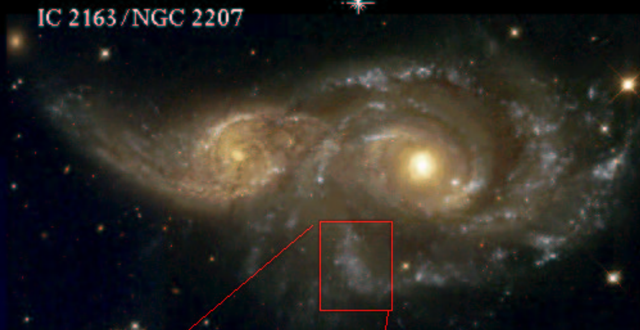


Kennicutt 1998 ApJ 498 541

...or $0.012 \sim \varepsilon_c (\rho_c/\rho)^{1/2} \times 10^{-4}$

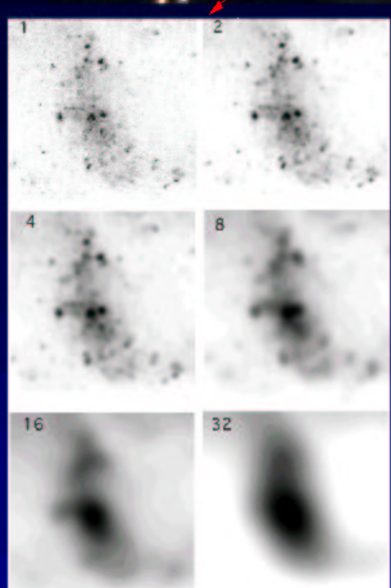
Star Formation acts Saturated, not Fine-Tuned

- SFR depends on the mass fraction in dense gas
  - turbulence may determine this in a universal way, independent of the sources of turbulence
    - Global SFR independent of triggering mechanisms
      - many turbulence-driving processes trigger SF
    - No fine-tuning of SF ("feedback") in the usual sense... only geometrical saturation
      - all the gas that can form stars is doing it already
      - blow-out or heating types of feedback still possible
    - SF halted only by conversion to a pure-warm phase
      - outer parts of galaxies, dwarf galaxies, low surface brightness galaxies, blow-out regions



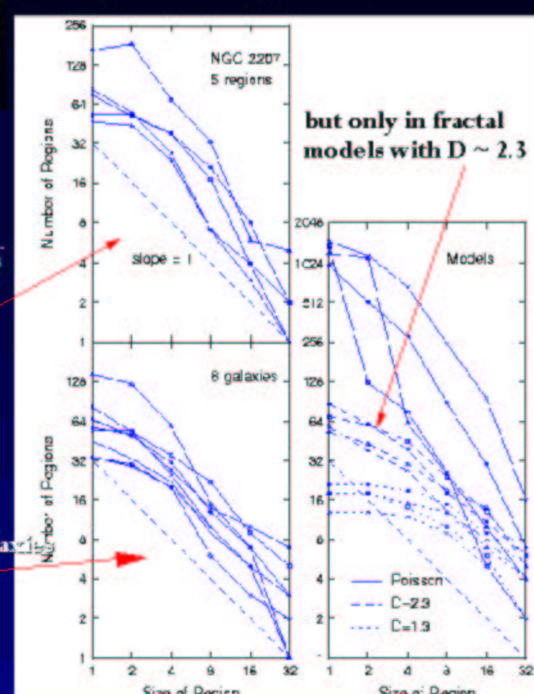
Young stars in many galaxies are arranged in fractal patterns.

(Elmegreen & Elmegreen 2001)

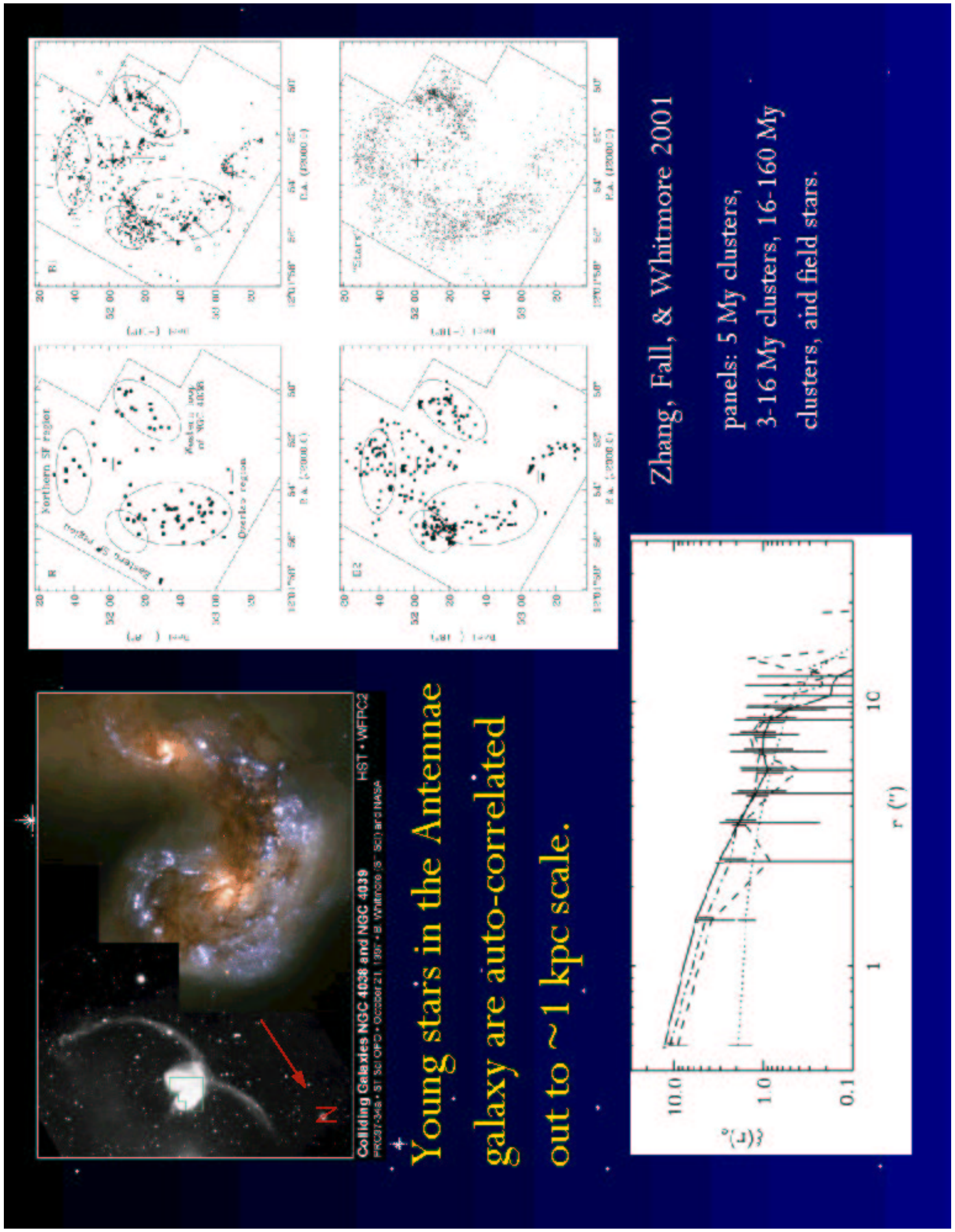


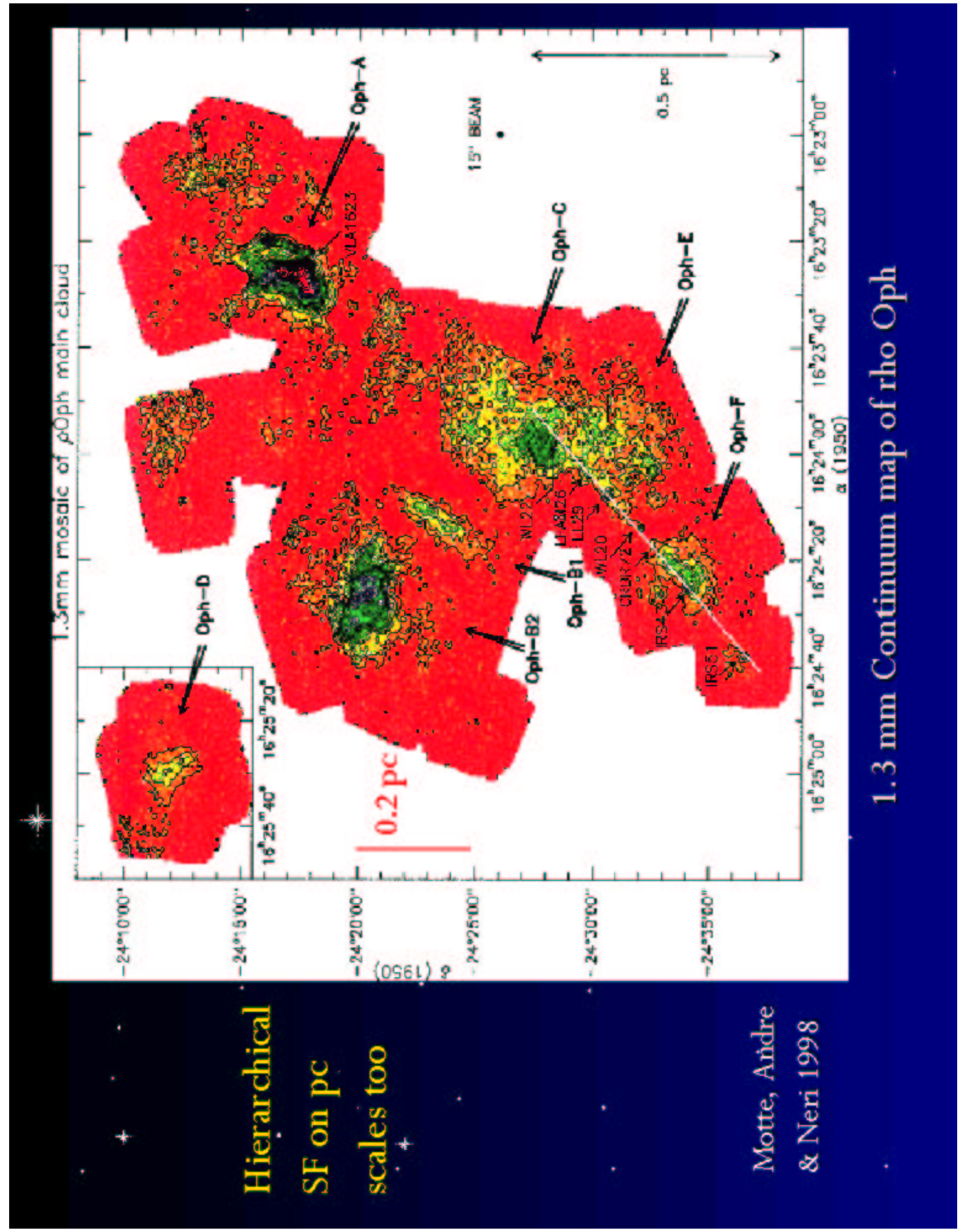
The number of clumps decreases with scale as a power law.

The same power is found in giant SF regions of other galaxies



but only in fractal models with D ~ 2.3


Young stars in the Antennae galaxy are auto-correlated out to ~1 kpc scale.
Zhang, Fall, & Whitmore 2001
panels: 5 My clusters, 3-16 My clusters, 16-160 My clusters, and field stars.
Colliding Galaxies NGC 4038 and NGC 4039
HST • WFPC2
r (")

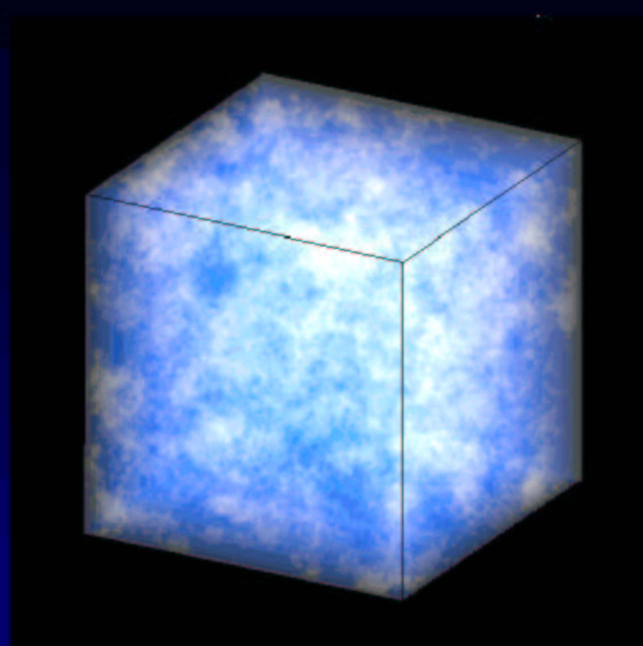

1.3 mm Continuum map of rho Oph
Hierarchical SF on pc scales too
Motte, Andre & Neri 1998
1.3mm mosaic of ρOph main cloud
Oph-A
Oph-B1
Oph-B2
Oph-C
Oph-D
Oph-E
Oph-F
0.2 pc
0.5 pc
15" BEAM

Why are there clusters? When does SF make SSC?

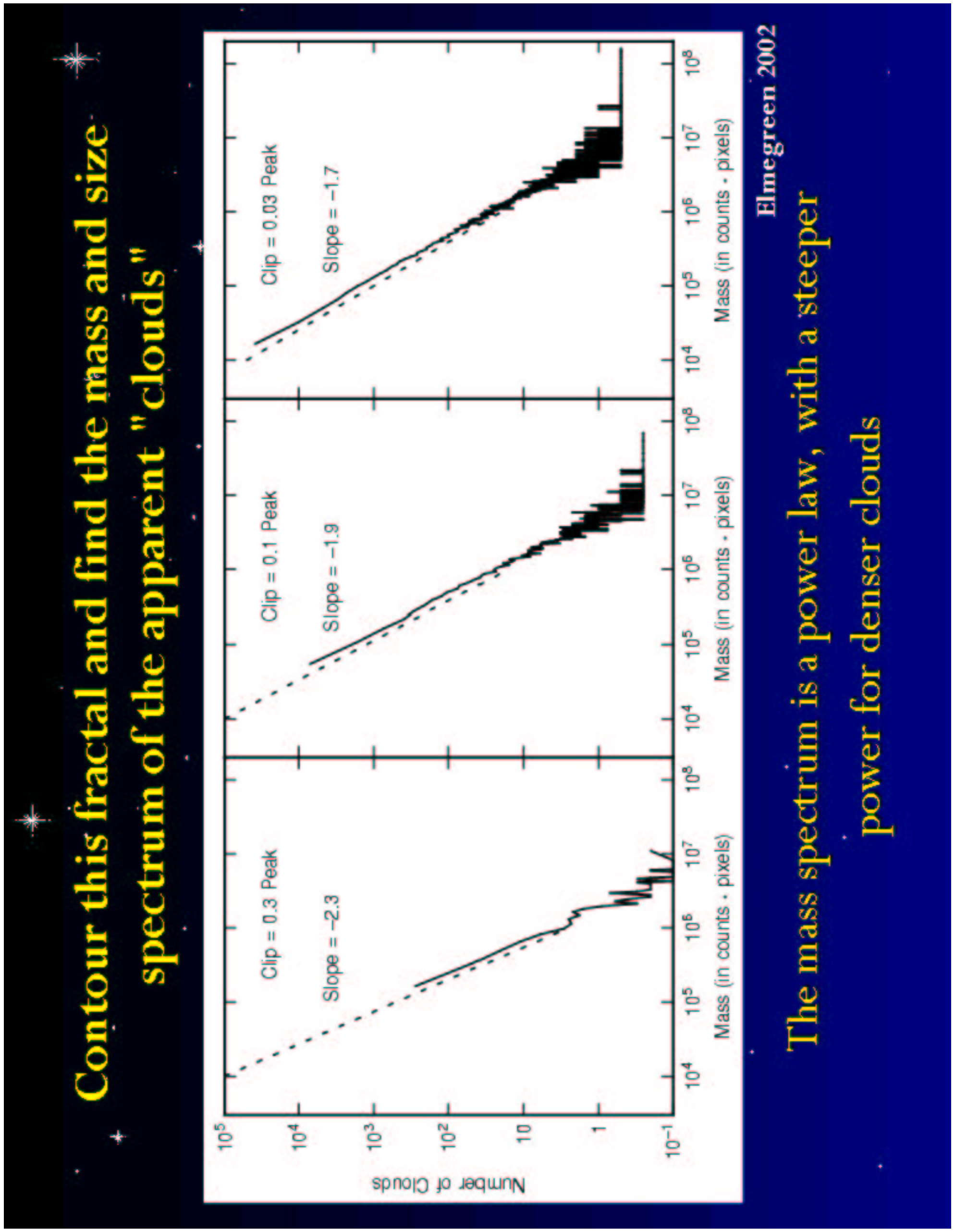
- Turbulence makes the gas fractal
- SF regions are fractal and time-correlated too
  - hierarchically clumped
  - large regions take longer to form
- Mass spectra of clusters in a hierarchically clumped medium is $\sim M^{-2}dM$
- This is about the observed cluster and OB association mass function in all disk systems
- (although not the "cloud" MF, which is shallower)

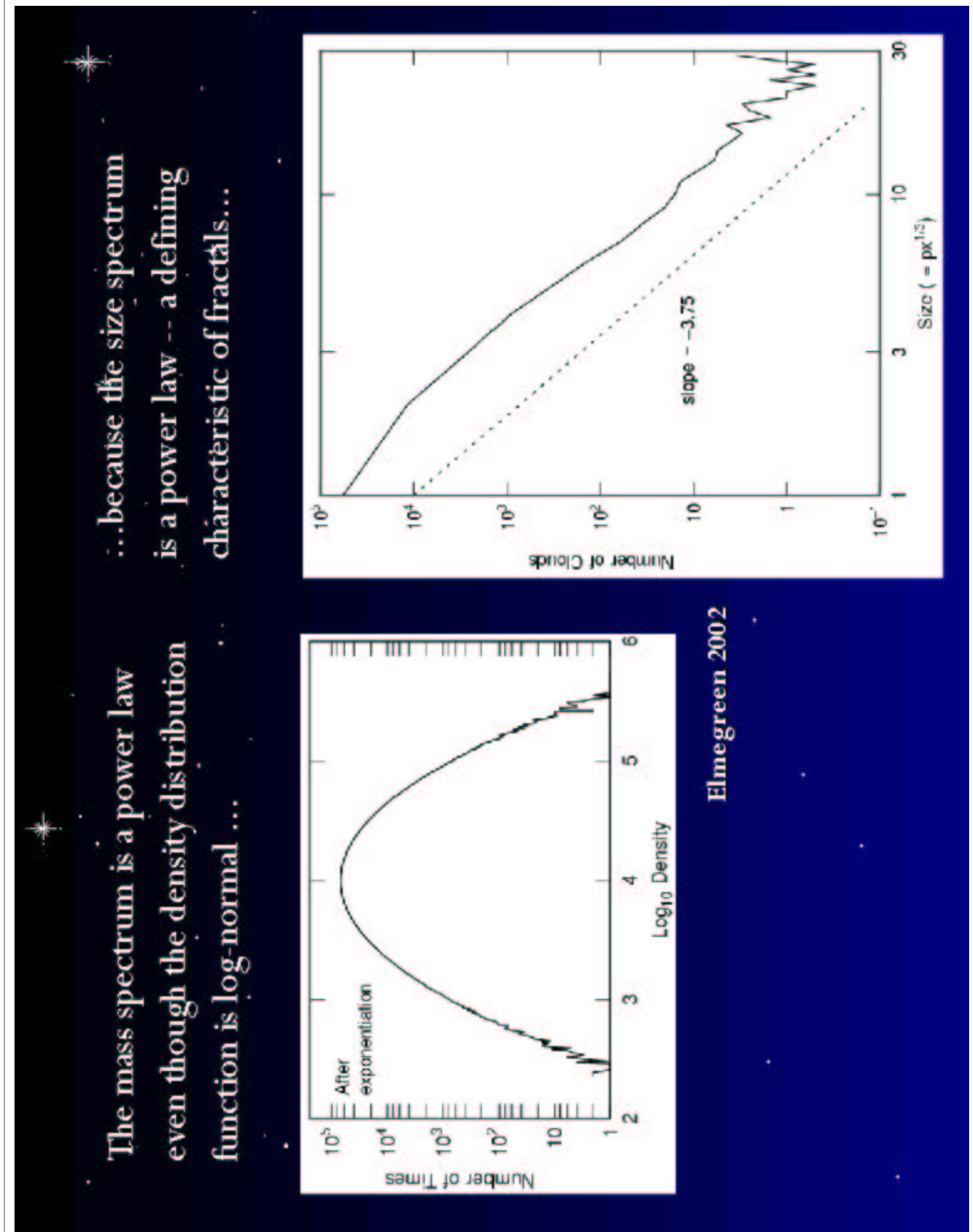
Turbulent motions <u>compress</u> and <u>push around</u> gas, and the velocity-distance correlation produces hierarchical structure in density

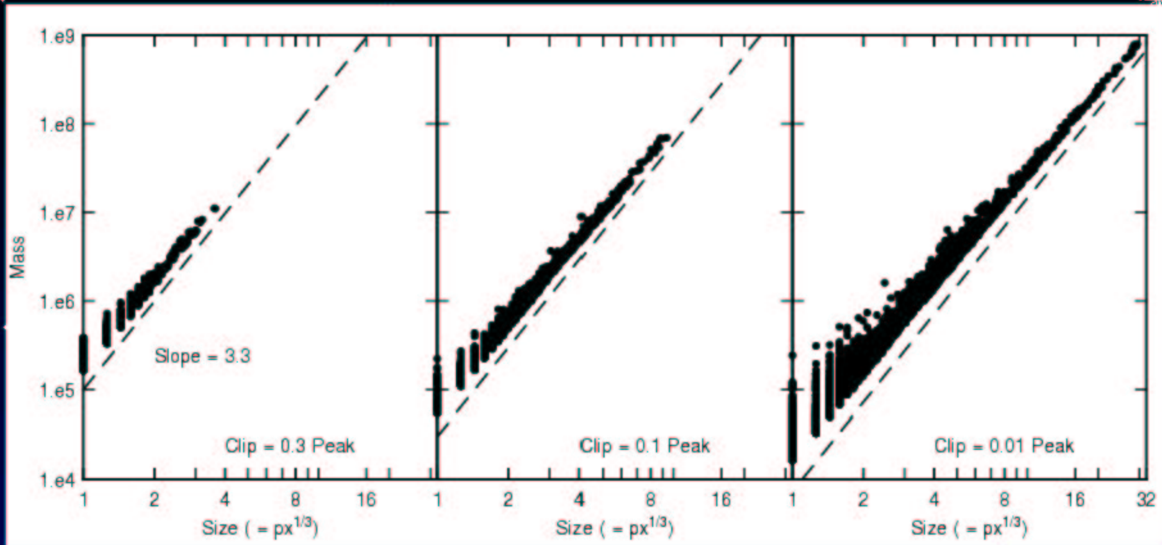
A fractal cube with a power spectrum and log-normal density distribution typical of turbulence.



Elmegreen 2002


Contour this fractal and find the mass and size spectrum of the apparent "clouds"
Clip = 0.3 Peak
Slope = −2.3
Clip = 0.1 Peak
Slope = −1.9
Clip = 0.03 Peak
Slope = −1.7
Number of Clouds
Mass (in counts - pixels)
Elmegreen 2002
The mass spectrum is a power law, with a steeper power for denser clouds


The mass spectrum is a power law even though the density distribution function is log-normal …
After exponentiation
Number of Times
Log10 Density
Elmegreen 2002
…because the size spectrum is a power law -- a defining characteristic of fractals…
Number of Clouds
slope ~ −3.75
Size (= px^1/2)



Elmegreen 2002

...and most of the mass is near the "cloud" edge, where the column density or density equal the contour value.

SUM: Power-Law Mass Spectra

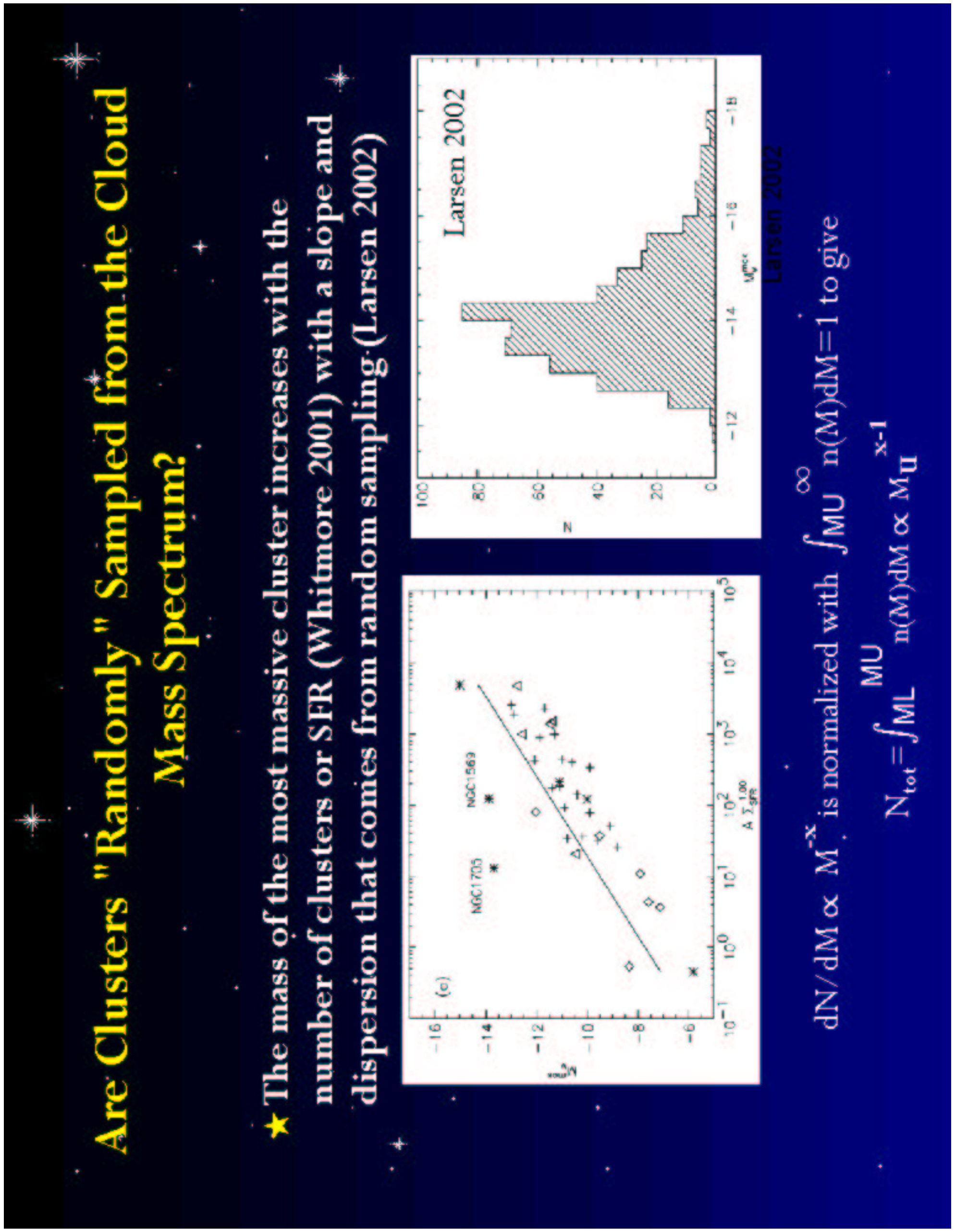
★ Turbulent motions ($v \sim r^k$) produce scale-free density structures and power-law mass spectra.

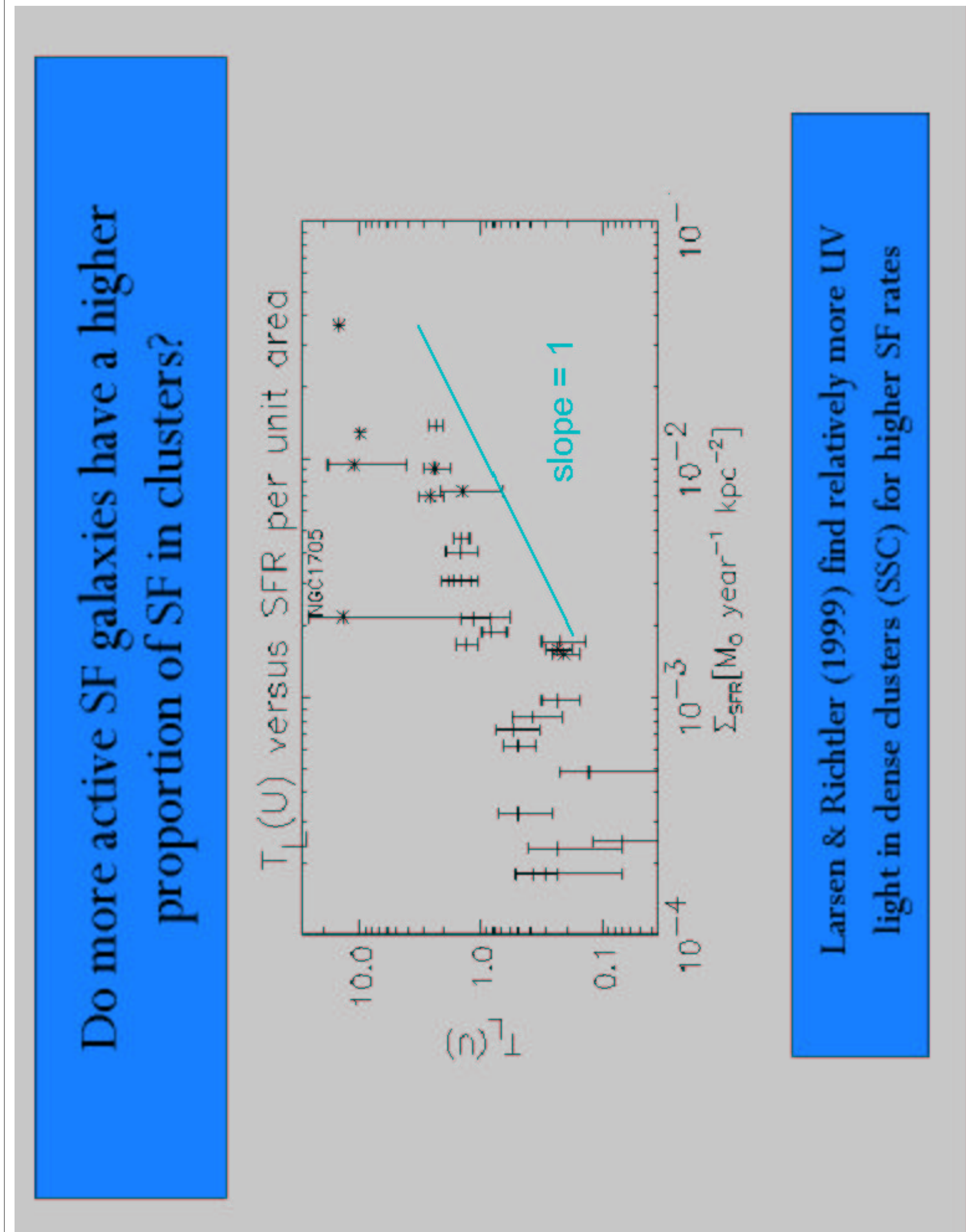
- Hierarchical structure gives $dn/dM = M^{-2}$
  ..... $Mn(M)d\log M$ = constant

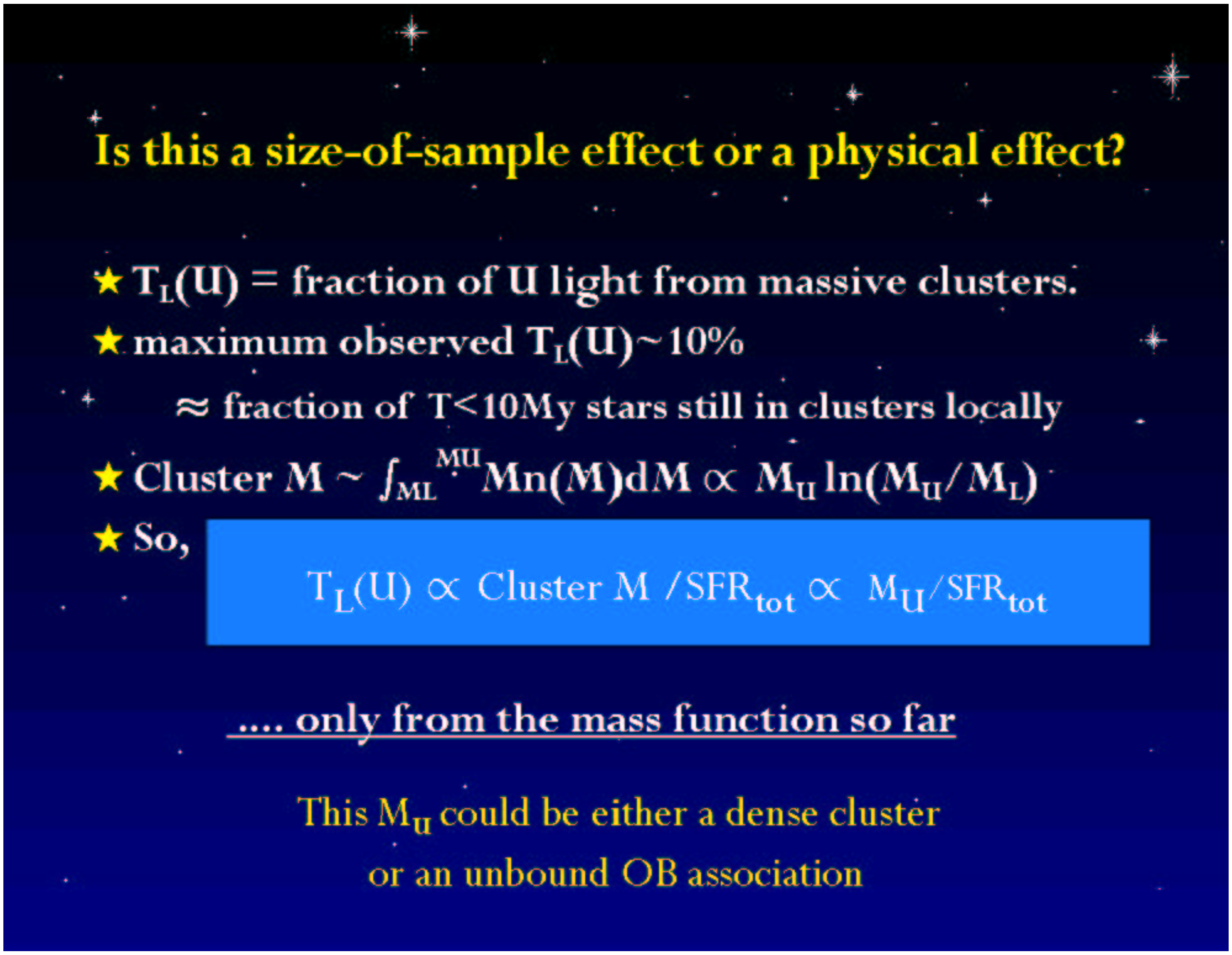
★ The cluster and OB association mass spectra probably result from sampling this gas structure

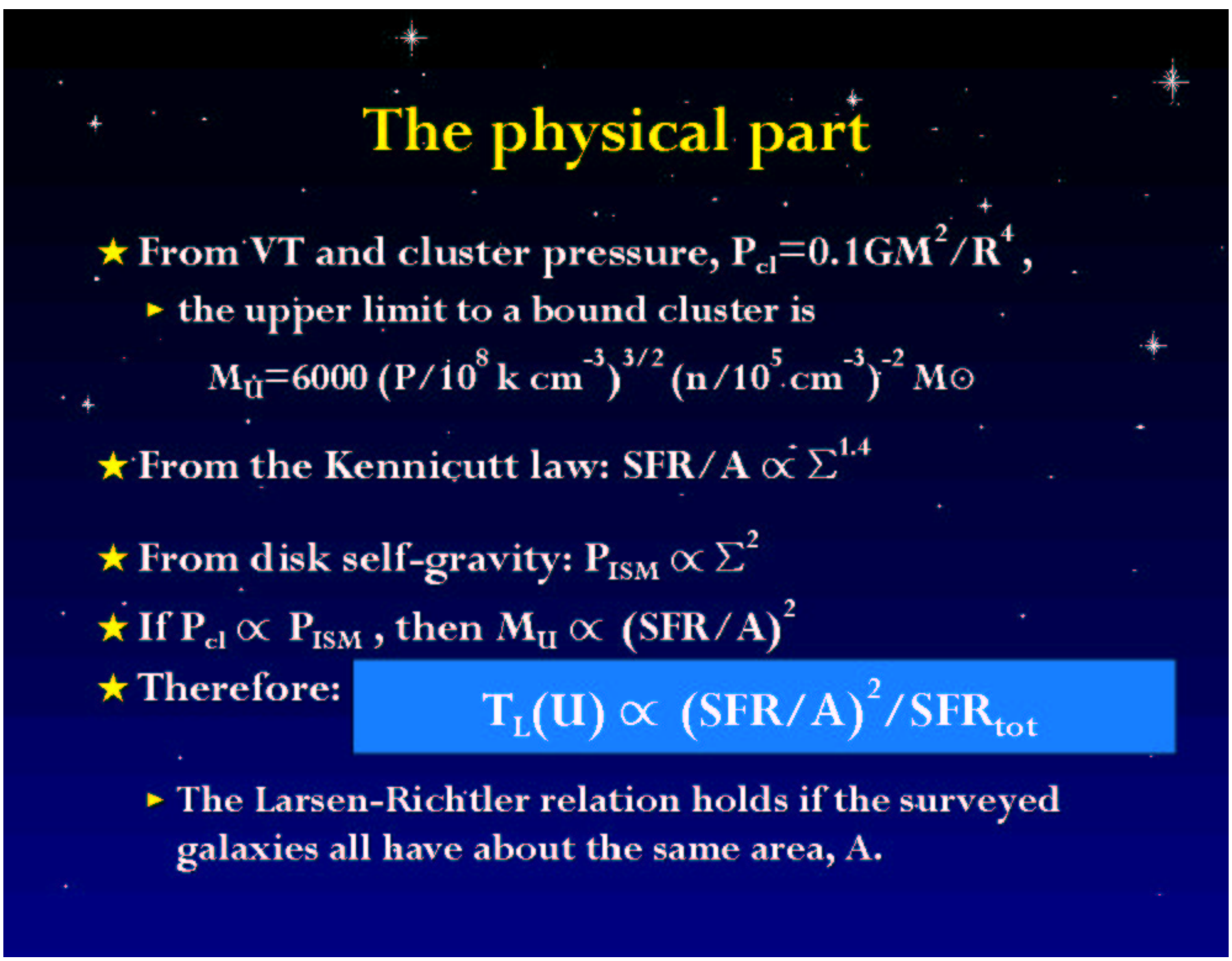
- This does not mean turbulence forms clusters,
- only that clusters form by any triggering processes that operates in a turbulent gas
  - e.g., compression of clouds, collapse of clouds ...

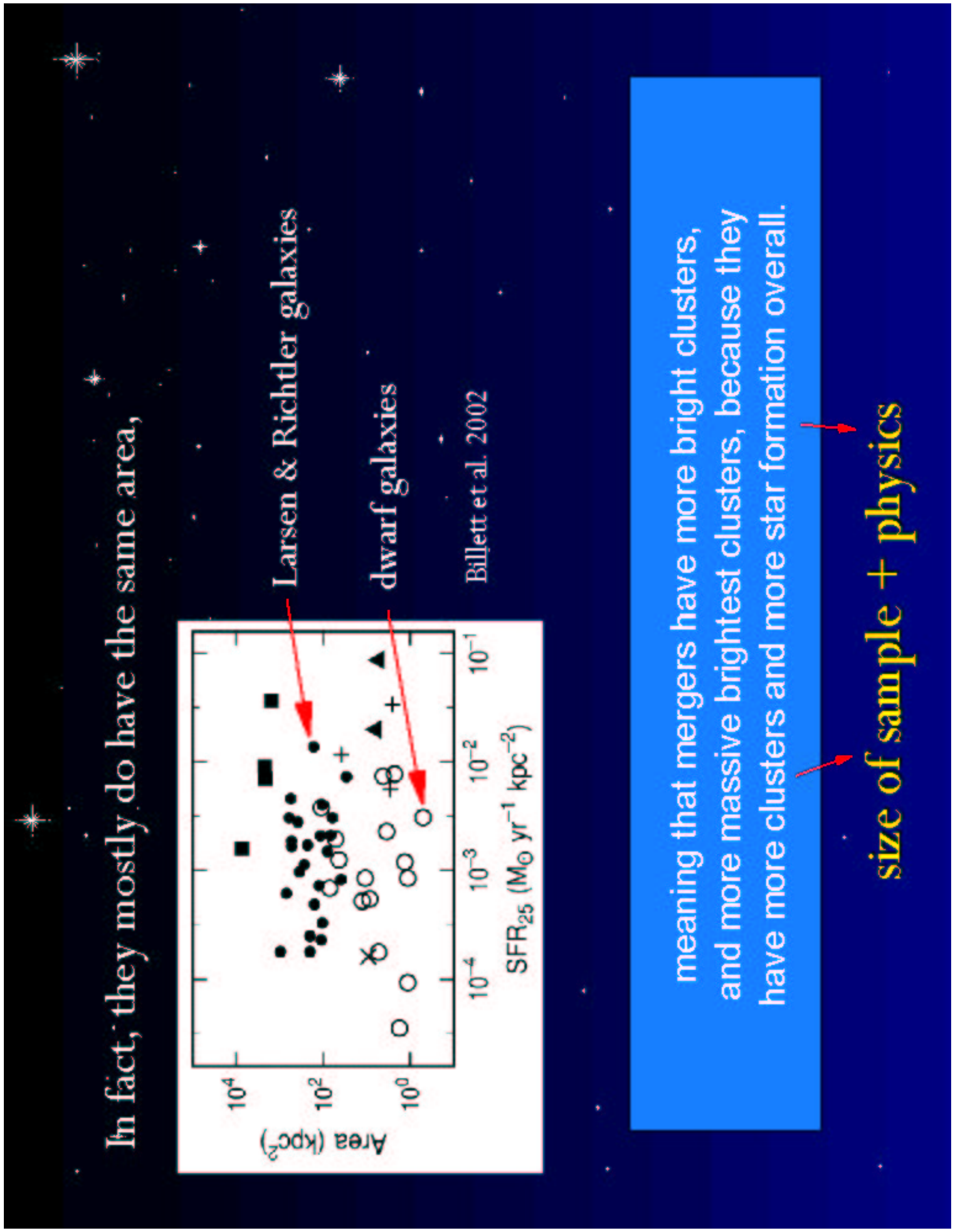
★ The mass spectra do not reveal the SF processes

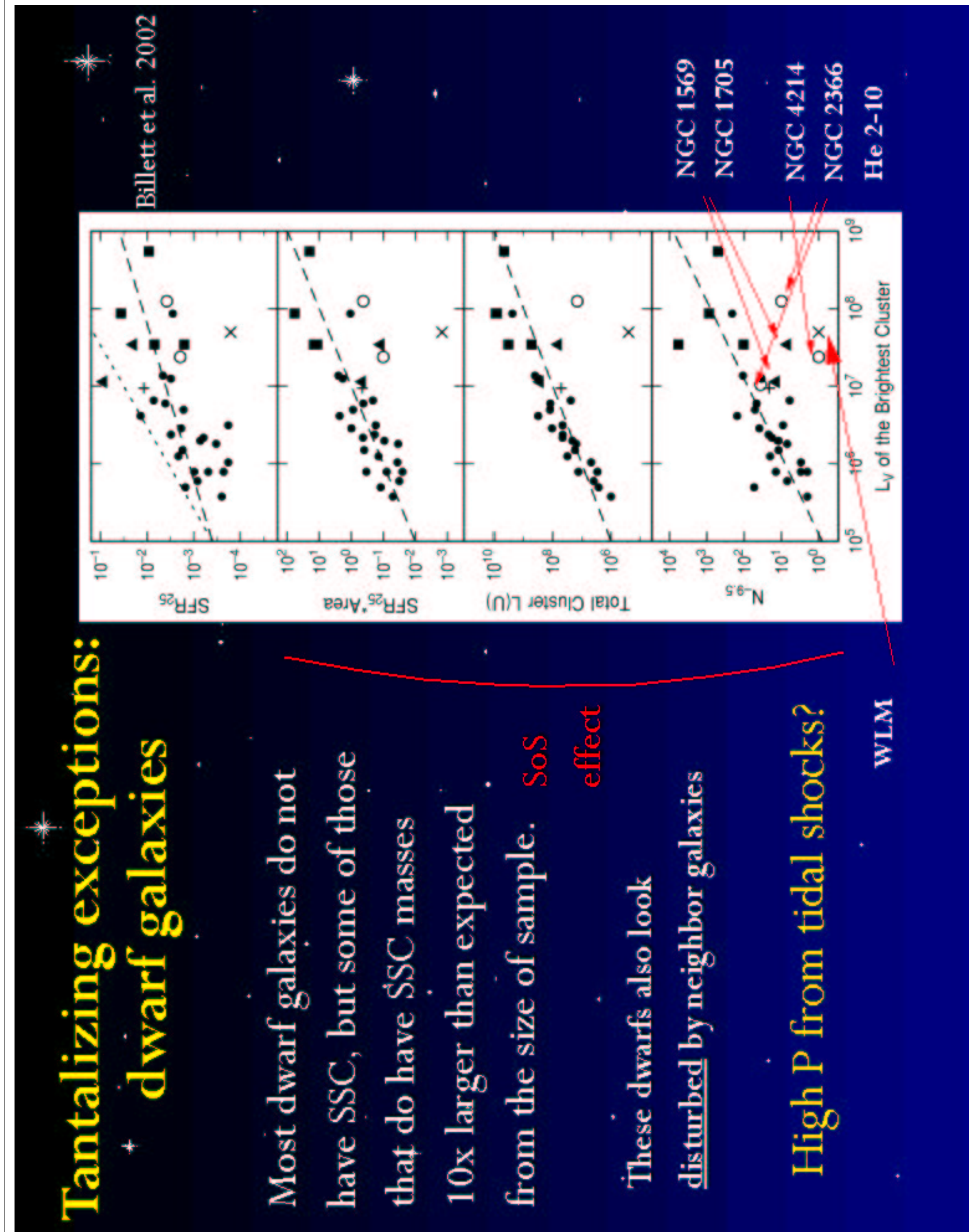

Are Clusters "Randomly" Sampled from the Cloud Mass Spectrum?
The mass of the most massive cluster increases with the number of clusters or SFR (Whitmore 2001) with a slope and dispersion that comes from random sampling (Larsen 2002)
NGC1705
NGC1569
Larsen 2002
dN/dM ∝ M^-x is normalized with ∫_MU^∞ n(M)dM=1 to give
N_tot=∫_ML^MU n(M)dM ∝ M_U^x-1


Do more active SF galaxies have a higher proportion of SF in clusters?
T_L(U) versus SFR per unit area
NGC1705
slope = 1
T_L(U)
Σ_SFR[M_o year^-1 kpc^-2]
Larsen & Richtler (1999) find relatively more UV light in dense clusters (SSC) for higher SF rates


Is this a size-of-sample effect or a physical effect?
★ $T_L(U)$ = fraction of U light from massive clusters.
★ maximum observed $T_L(U) \sim 10\%$
≈ fraction of T<10My stars still in clusters locally
★ Cluster $M \sim \int_{ML}^{MU} Mn(M)dM \propto M_U \ln(M_U/M_L)$
★ So,
$T_L(U) \propto$ Cluster M / $SFR_{tot} \propto M_U/SFR_{tot}$
.... only from the mass function so far
This M_U could be either a dense cluster
or an unbound OB association


The physical part
★ From VT and cluster pressure, $P_{cl}=0.1GM^2/R^4$,
▸ the upper limit to a bound cluster is
$M_U=6000\ (P/10^8\ k\ cm^{-3})^{3/2}\ (n/10^5\ cm^{-3})^{-2}\ M_\odot$
★ From the Kennicutt law: $SFR/A \propto \Sigma^{1.4}$
★ From disk self-gravity: $P_{ISM} \propto \Sigma^2$
★ If $P_{cl} \propto P_{ISM}$, then $M_U \propto (SFR/A)^2$
★ Therefore:
$T_L(U) \propto (SFR/A)^2/SFR_{tot}$
▸ The Larsen-Richtler relation holds if the surveyed galaxies all have about the same area, A.

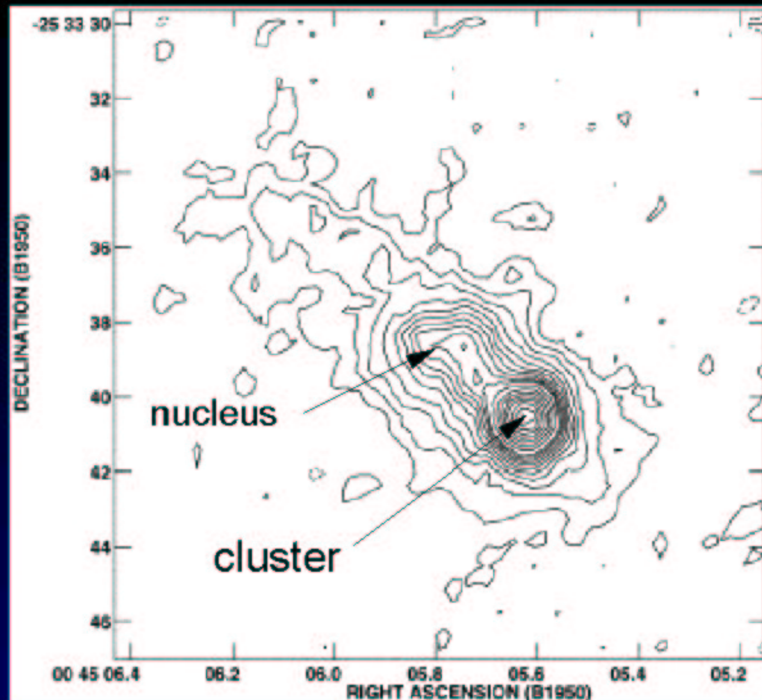

In fact, they mostly do have the same area,
Larsen & Richtler galaxies
dwarf galaxies
Billett et al. 2002
Area (kpc^2)
SFR$_{25}$ (M$_\odot$ yr^{-1} kpc^{-2})
meaning that mergers have more bright clusters, and more massive brightest clusters, because they have more clusters and more star formation overall.
size of sample + physics


Tantalizing exceptions: dwarf galaxies
Billett et al. 2002
NGC 1569
NGC 1705
NGC 4214
NGC 2366
He 2-10
WLM
SFR$_{25}$
SFR$_{25}$*Area
Total Cluster L(U)
N$_{-9.5}$
L$_V$ of the Brightest Cluster
Most dwarf galaxies do not have SSC, but some of those that do have SSC masses 10x larger than expected from the size of sample.
SoS effect
These dwarfs also look disturbed by neighbor galaxies
High P from tidal shocks?

Another exception: Nuclear clusters

12.8 micron image of the bright cluster near the center of NGC 253.

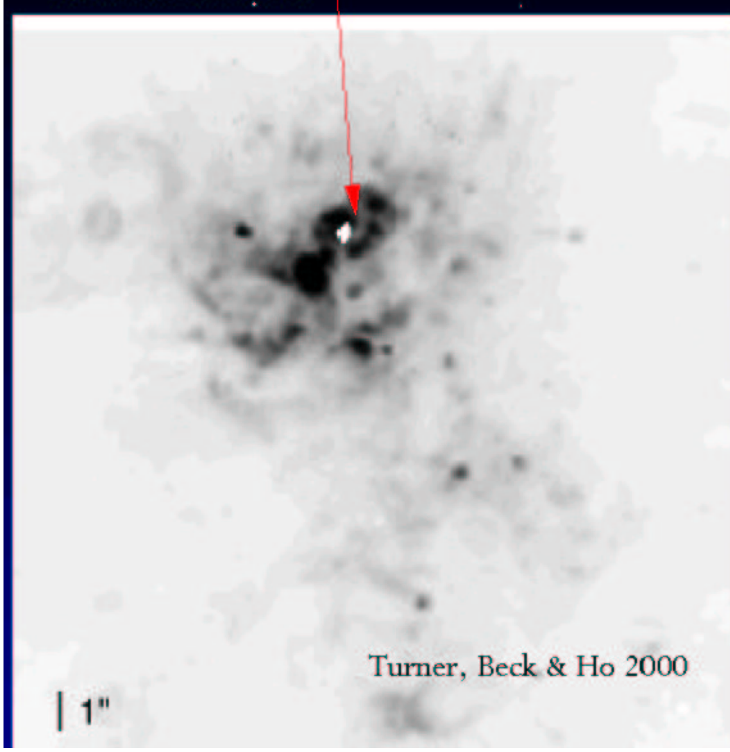
Age < 1My;
several thousand O-stars.



Keto et al. 1999 ApJ 518, 183

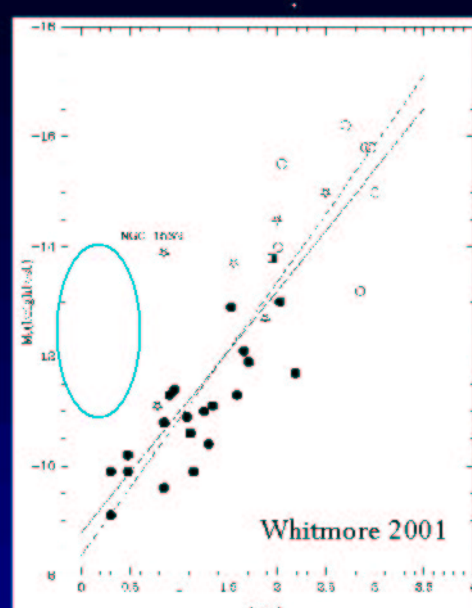
High P from self-gravity?

NGC 5253 nucleus in Hα with radio continuum source from 4000 O7 stars shown in white.

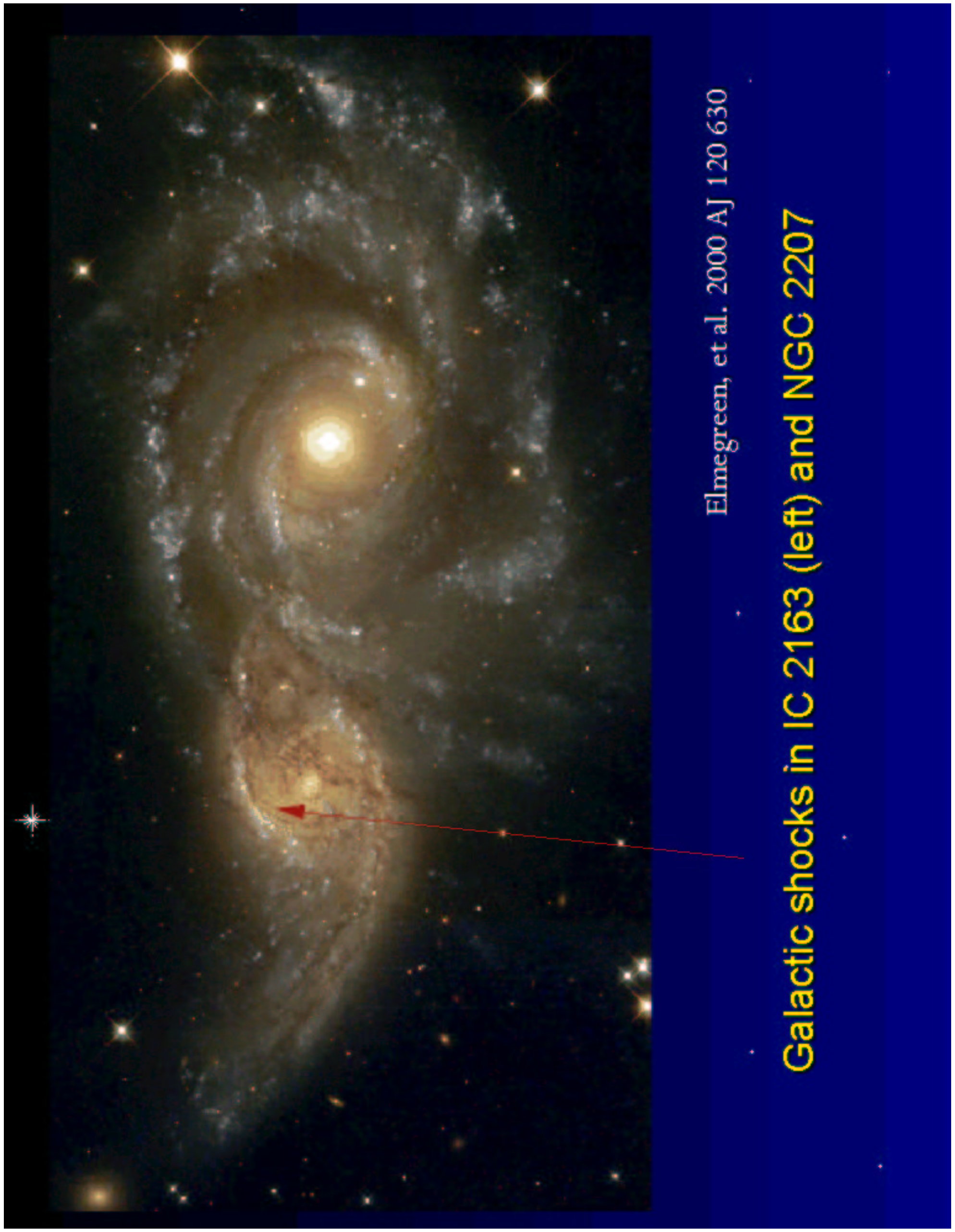


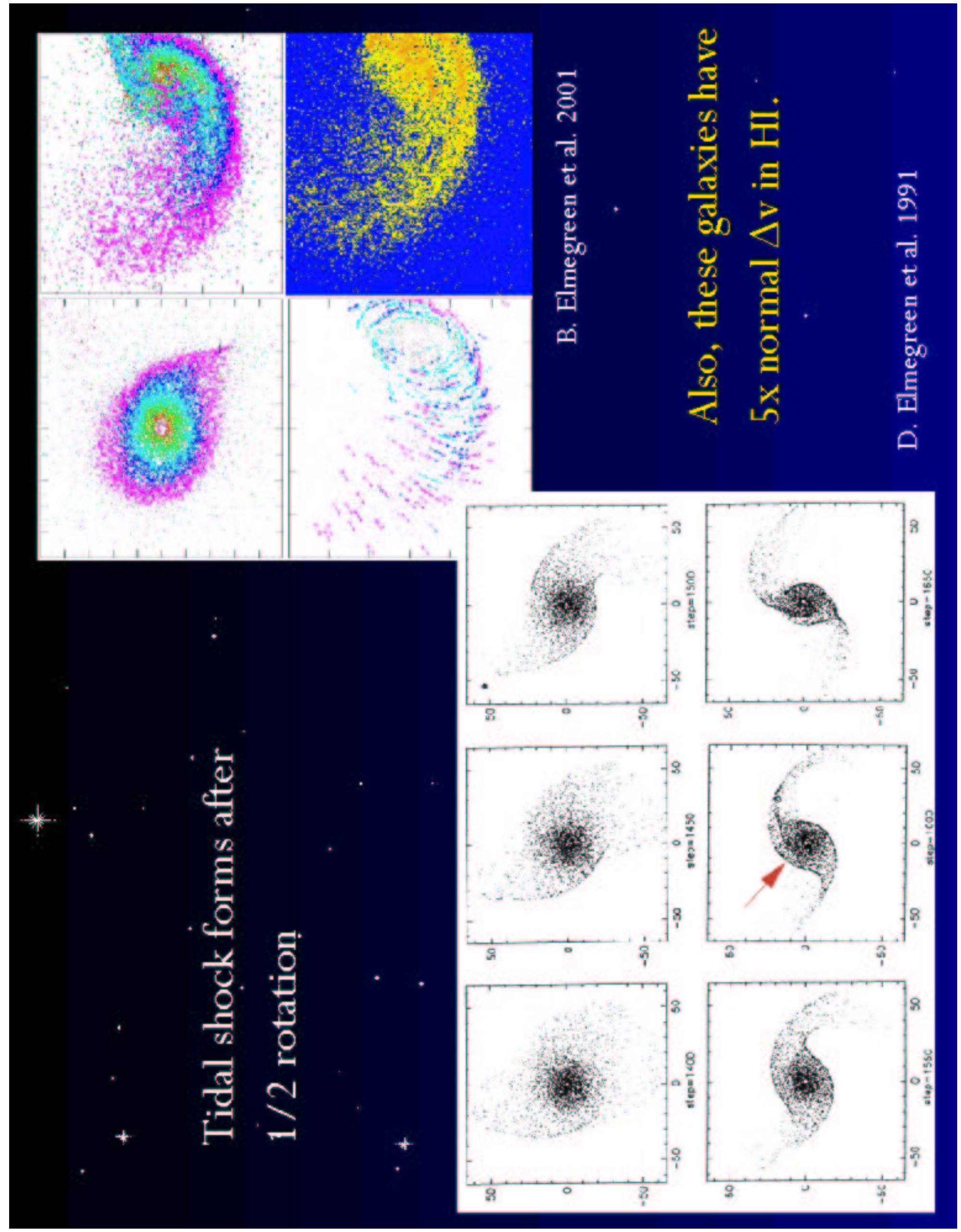
Turner, Beck & Ho 2000

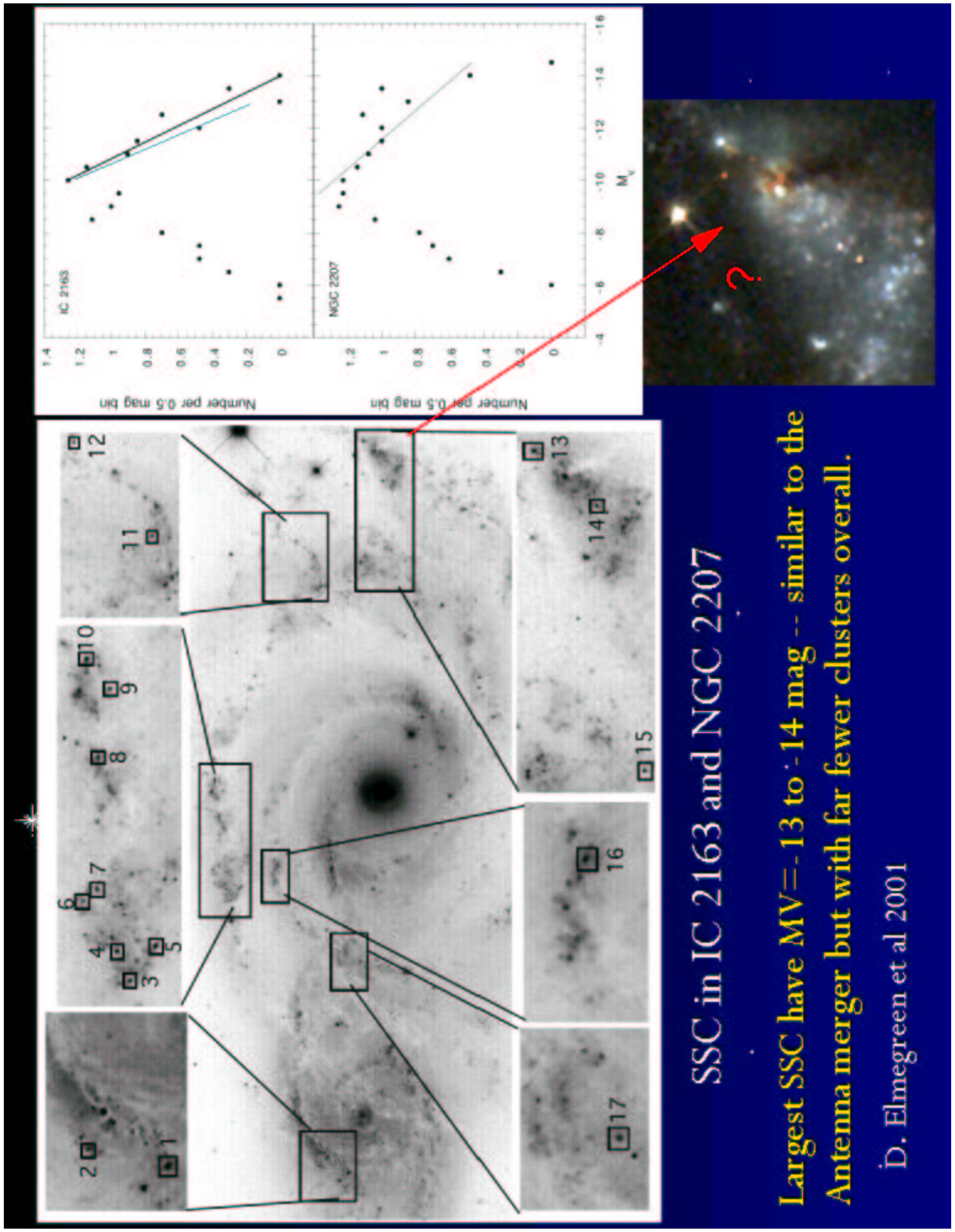
Both nuclear clusters are unusually massive

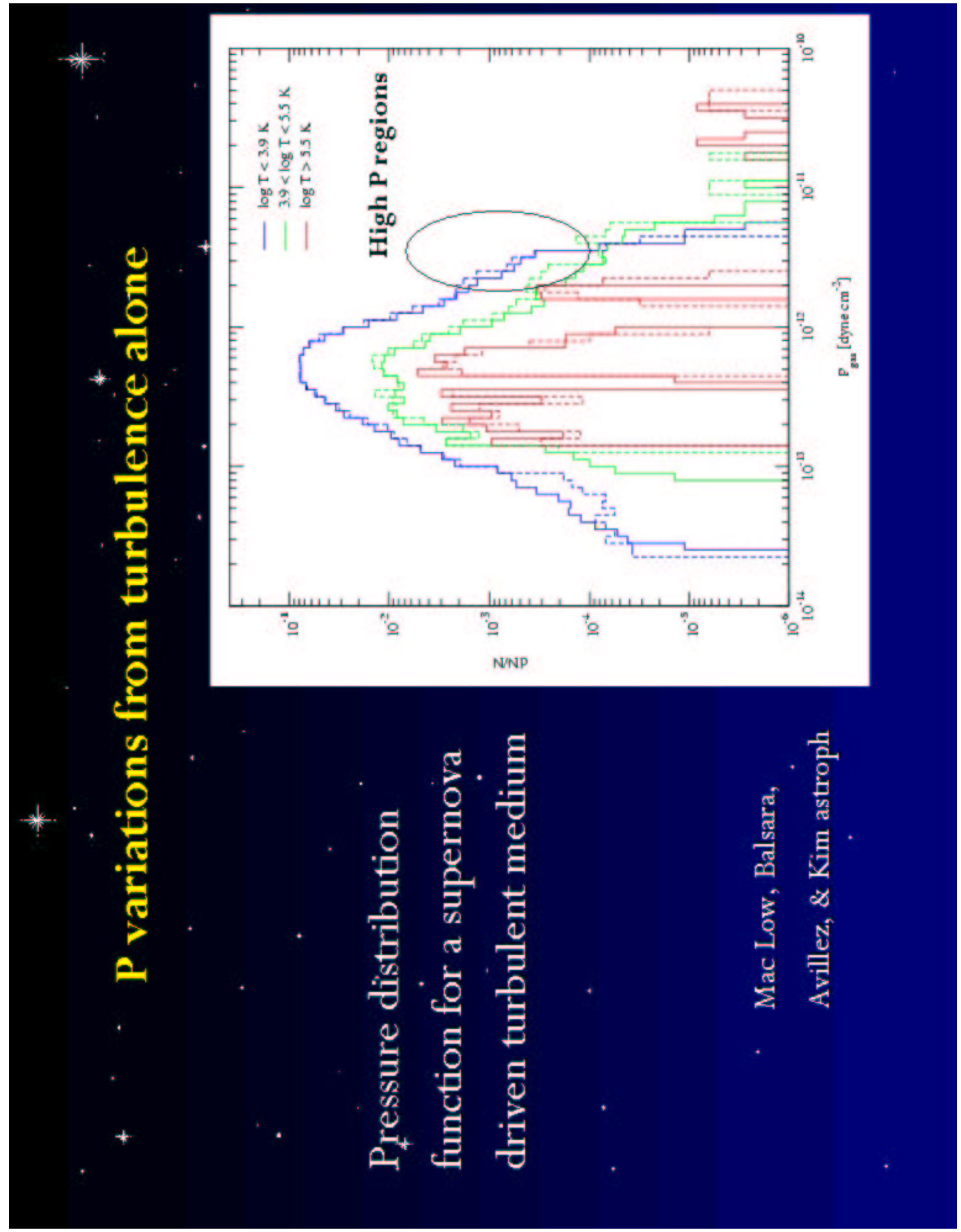


Whitmore 2001

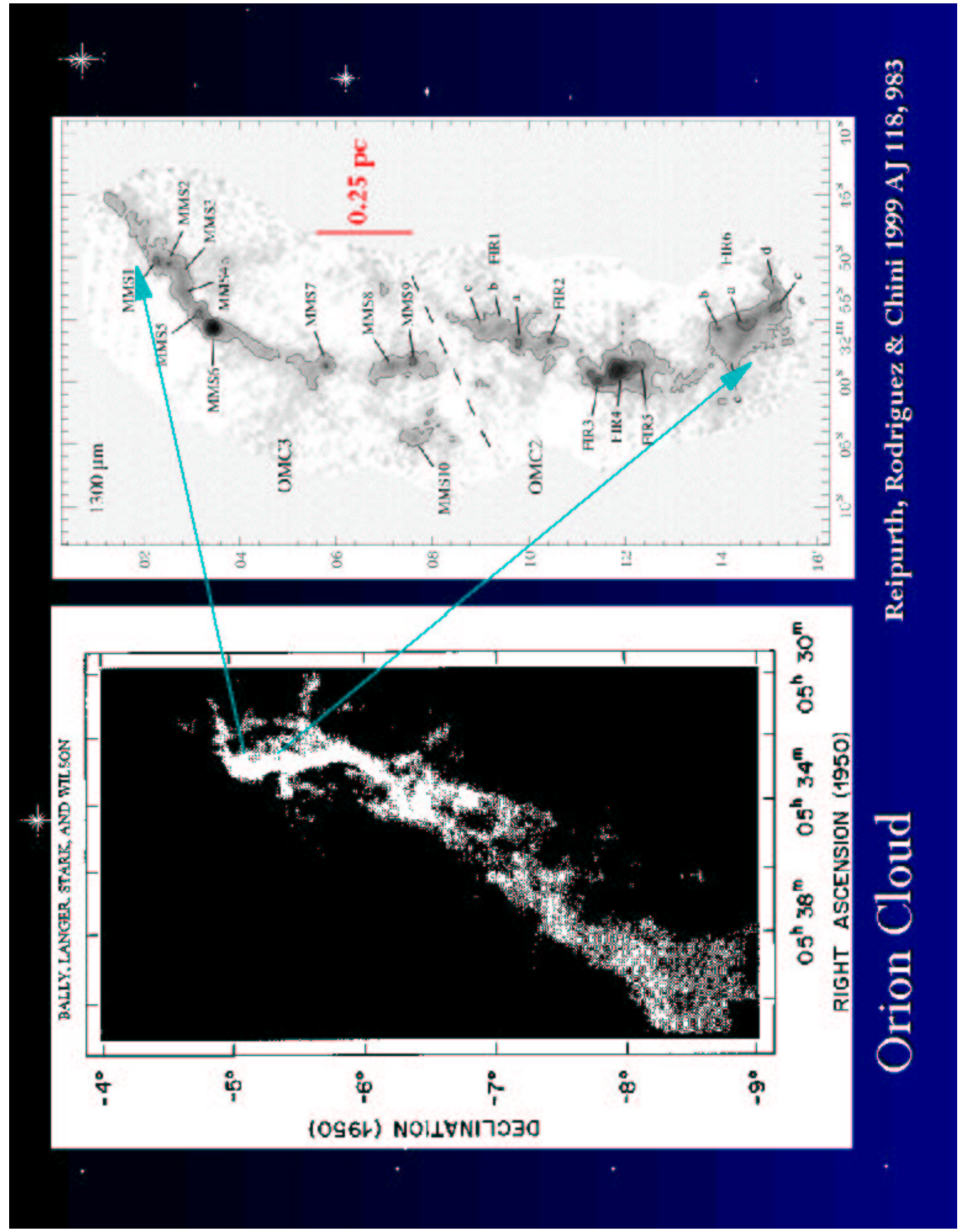

Elmegreen, et al. 2000 AJ 120 630
Galactic shocks in IC 2163 (left) and NGC 2207

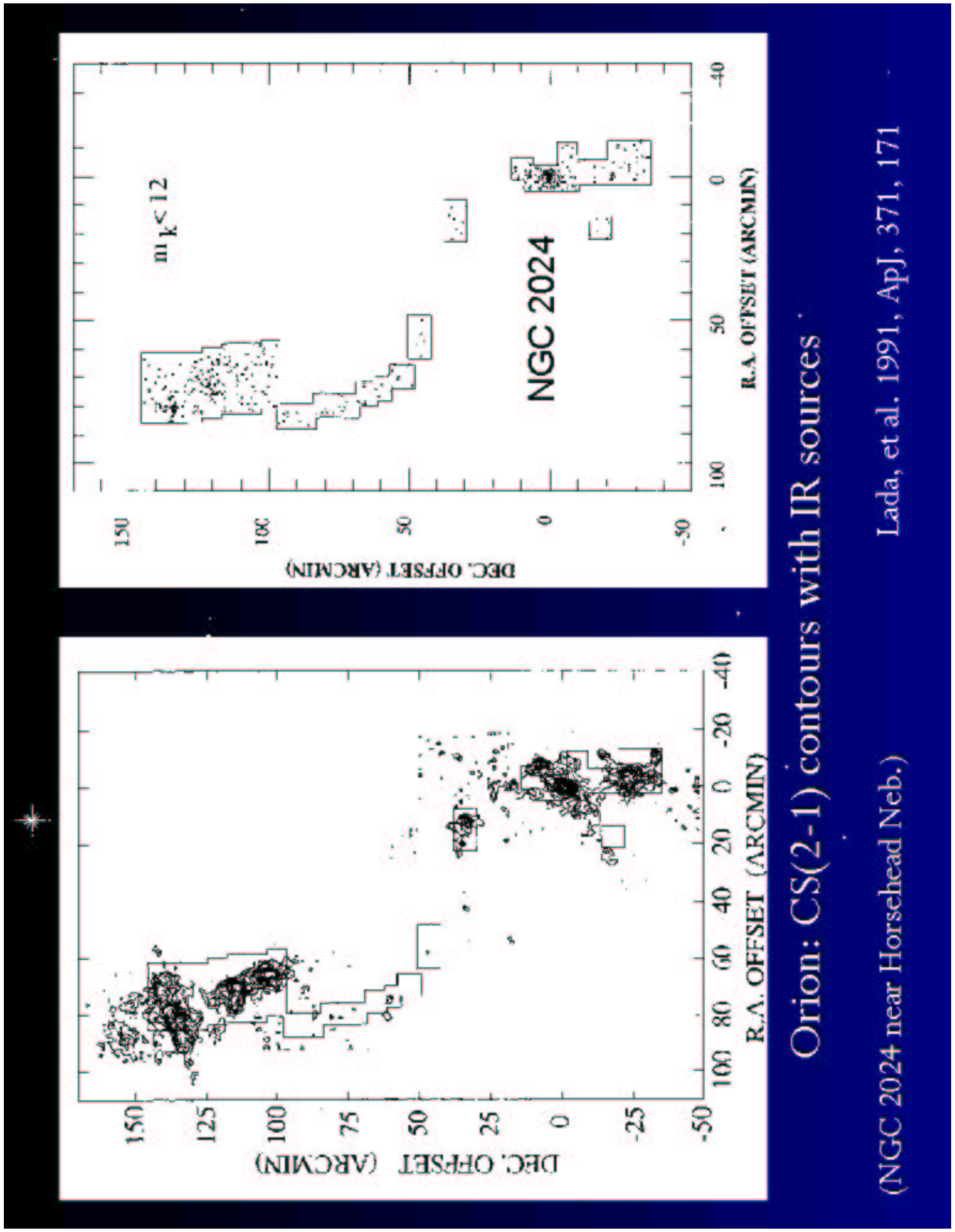

B. Elmegreen et al. 2001
Also, these galaxies have
5x normal Δv in HI.
D. Elmegreen et al. 1991
Tidal shock forms after
1/2 rotation

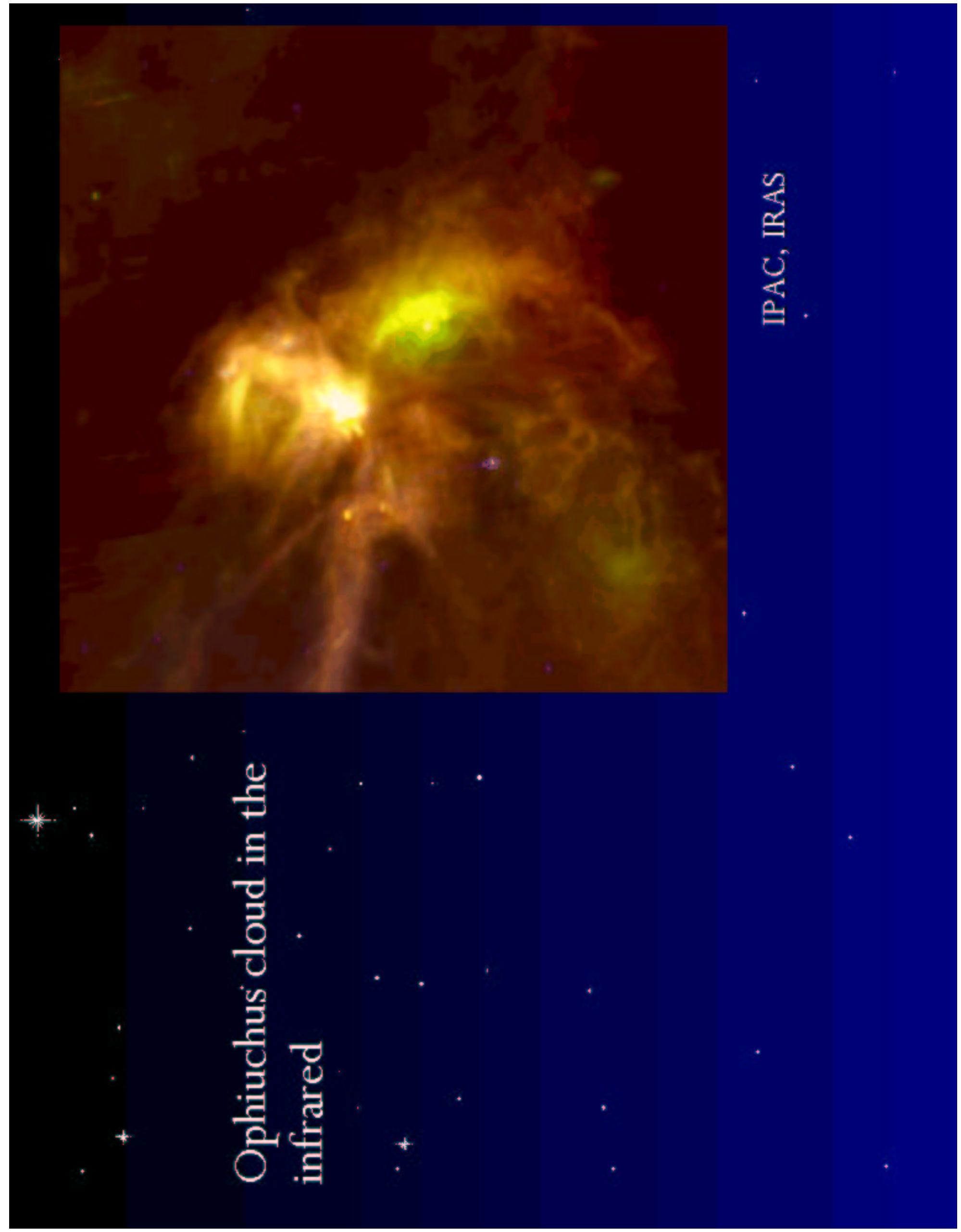

SSC in IC 2163 and NGC 2207
Largest SSC have MV=-13 to -14 mag -- similar to the Antenna merger but with far fewer clusters overall.
D. Elmegreen et al 2001
IC 2163
NGC 2207
Number per 0.5 mag bin
M$_V$
?


P variations from turbulence alone
Pressure distribution function for a supernova driven turbulent medium
Mac Low, Balsara, Avillez, & Kim astroph
High P regions
log T < 3.9 K
3.9 < log T < 5.5 K
log T > 5.5 K
N/NP
P$_{gas}$ [dyne cm^{-2}]


Locally high
pressures trigger
clusters too.
Orion

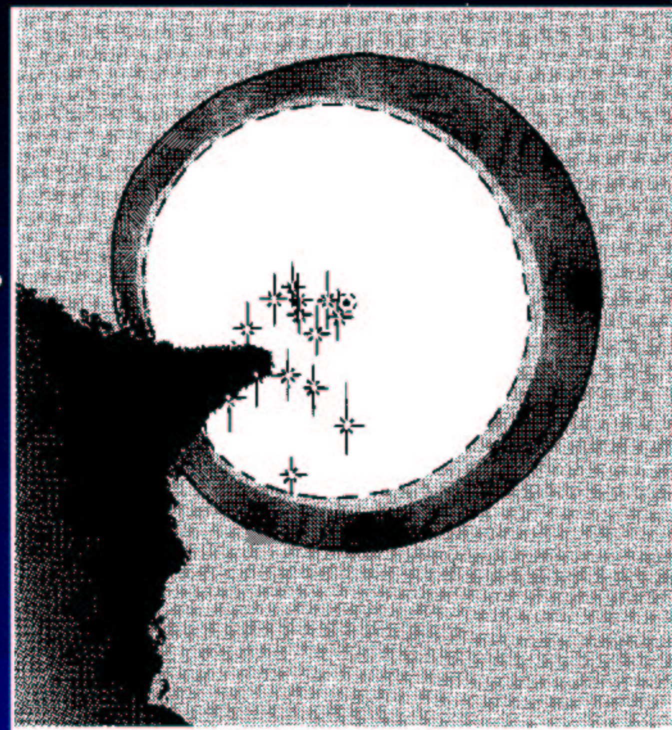

Orion Cloud
Reipurth, Rodriguez & Chini 1999 AJ 118, 983
BALLY, LANGER, STARK, AND WILSON
RIGHT ASCENSION (1950)
DECLINATION (1950)
0.25 pc
1300 μm
OMC3
OMC2


Orion: CS(2-1) contours with IR sources
(NGC 2024 near Horsehead Neb.)
Lada, et al. 1991, ApJ, 371, 171
NGC 2024
m_K < 12
DEC. OFFSET (ARCMIN)
R.A. OFFSET (ARCMIN)

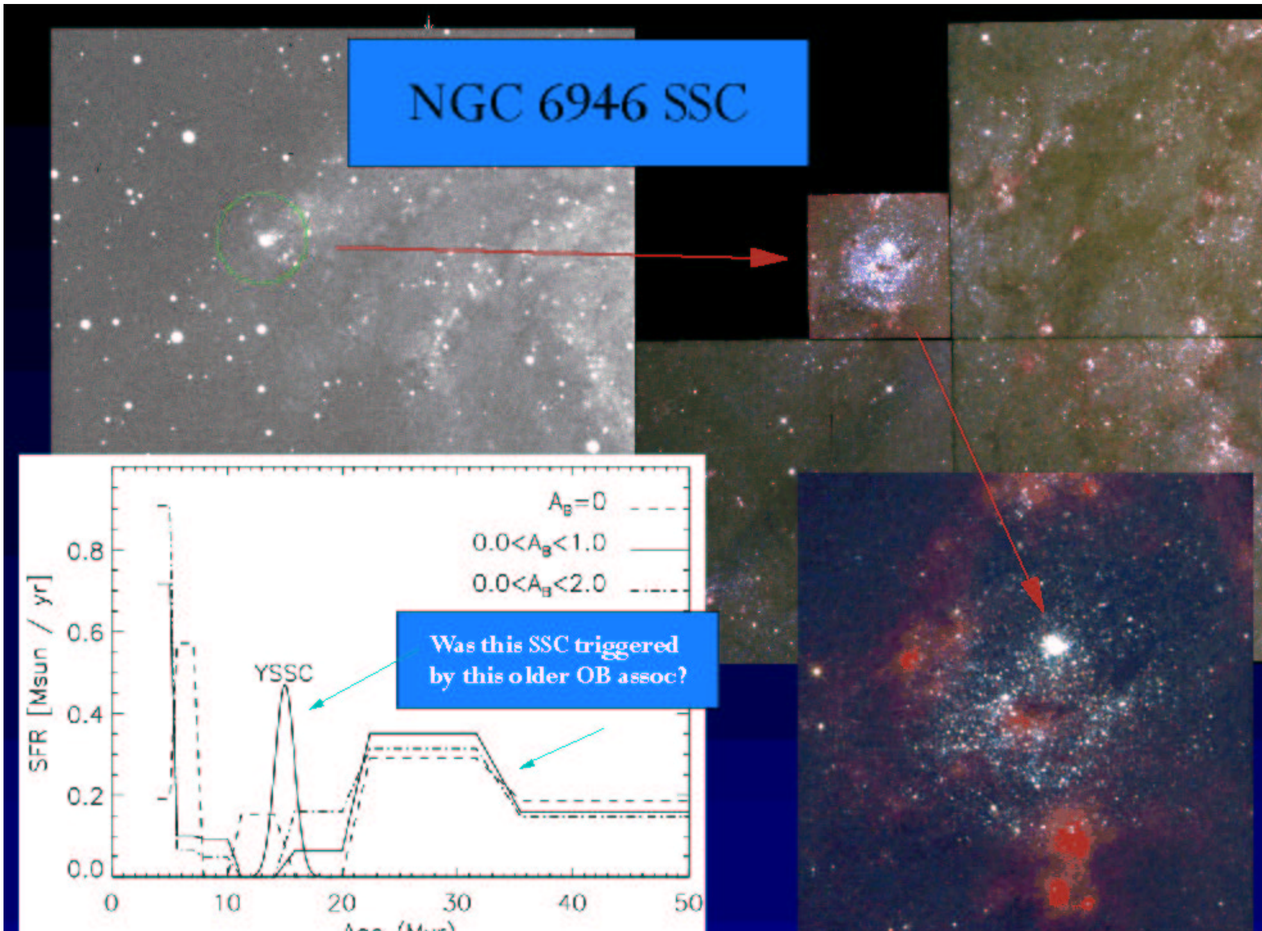

Ophiuchus cloud in the infrared
IPAC, IRAS

Shocks from Upper Sco OB association triggered SF in Ophiuchus (de Geus 1992) and, before this, shocks from upper Cen-Lupus triggered Upper Sco (Preibisch & Zinnecker 1999).

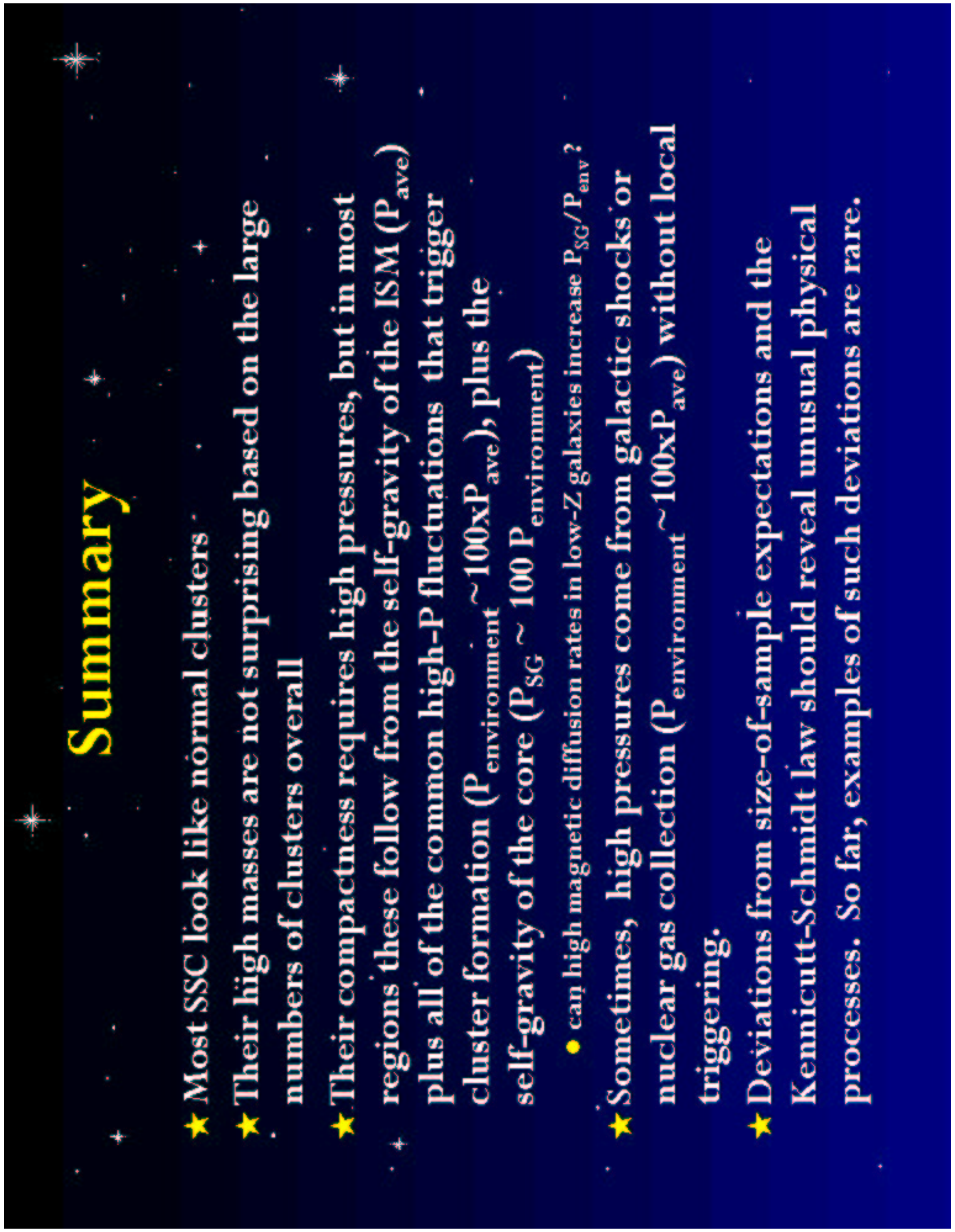
Most local clusters form in cores compressed by HII regions.
10-50% of SF in the inner MW and the LMC adjacent to high-P HII regions
(Yamaguchi et al 2001, 2002)



de Geus 1992 AA 262, 258



Larsen et al. 2001,2002


Summary
Most SSC look like normal clusters
Their high masses are not surprising based on the large numbers of clusters overall
Their compactness requires high pressures, but in most regions these follow from the self-gravity of the ISM (P_{ave}) plus all of the common high-P fluctuations that trigger cluster formation ($P_{environment}$ ~100xP_{ave}), plus the self-gravity of the core (P_{SG} ~ 100 $P_{environment}$)
can high magnetic diffusion rates in low-Z galaxies increase P_{SG}/P_{env} ?
Sometimes, high pressures come from galactic shocks or nuclear gas collection ($P_{environment}$ ~100xP_{ave}) without local triggering.
Deviations from size-of-sample expectations and the Kennicutt-Schmidt law should reveal unusual physical processes. So far, examples of such deviations are rare.