Hierarchical Star Formation in the Magellanic Clouds as Revealed by the VMC Survey

Speaker: Ning-Chen Sun (Peking University)

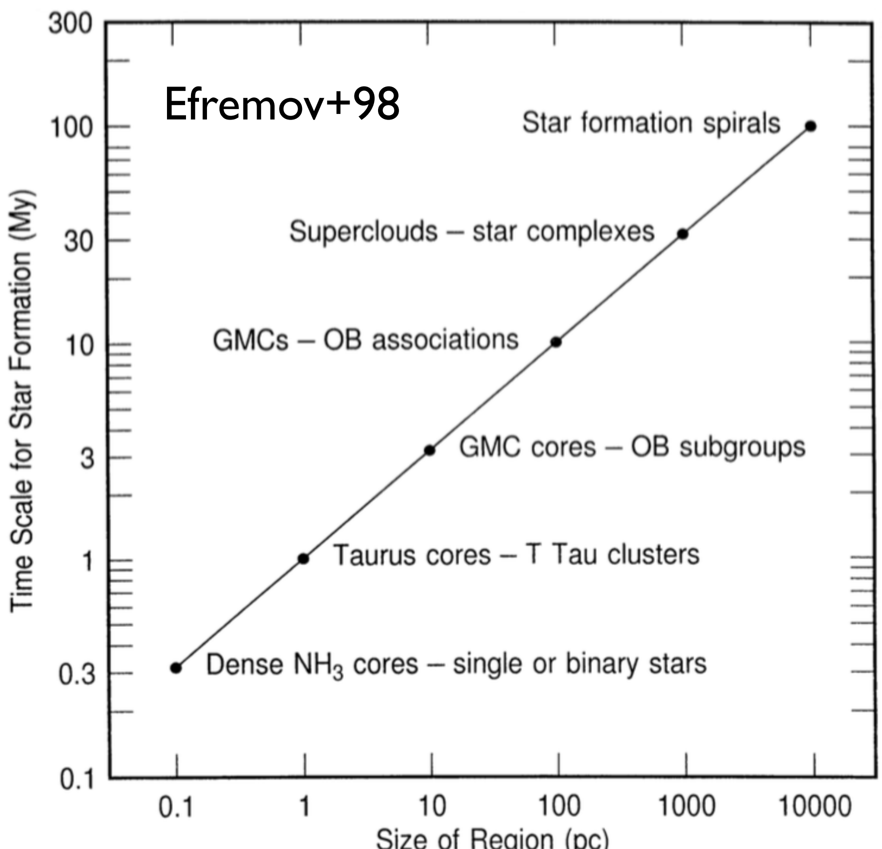
Collaborators: Richard de Grijs (PhD advisor), Smitha Subramanian, Maria-Rosa L. Cioni (VMC PI), Stefano Rubule, Kenji Bekki, Valentin D. Ivanov, Andrés E. Piatti, Vincenzo Ripepi

- Hierarchical Star Formation
- Magellanic Clouds and the VMC Survey
- 30 Dor-N158-N159-N160 Complex
- Summary and Future

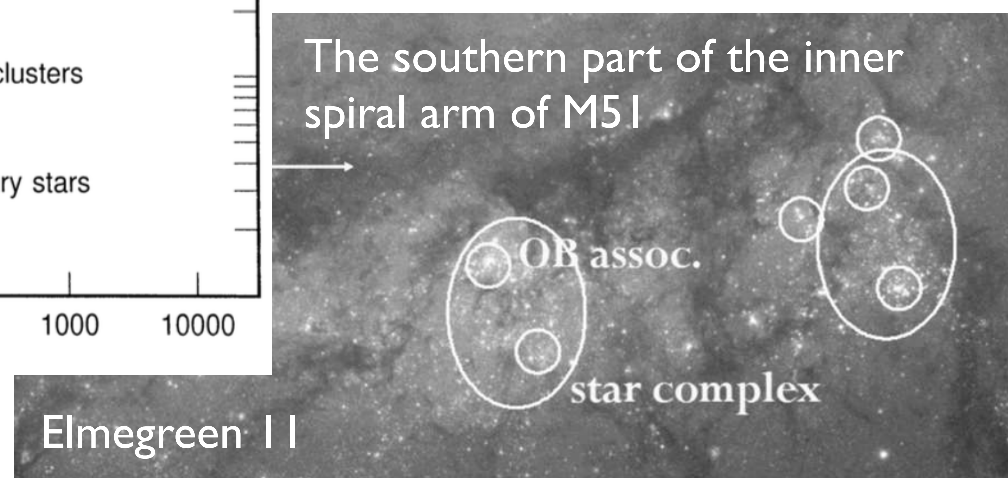
OUTLINE

Hierarchical Star Formation

Galaxies form Jeans-mass cloud complexes, which in turn fragment into clouds and cores in a **sequence** of decreasing size (lifetime) and increasing density



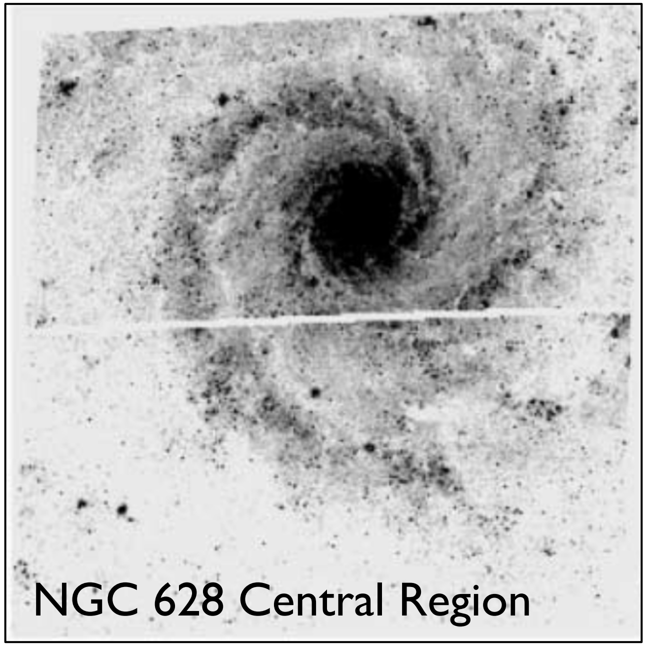
Young stars follow this pattern and form star complexes on the largest scales, OB associations on smaller scales, and so on to clusters and individual stars -- **hierarchical** clustering

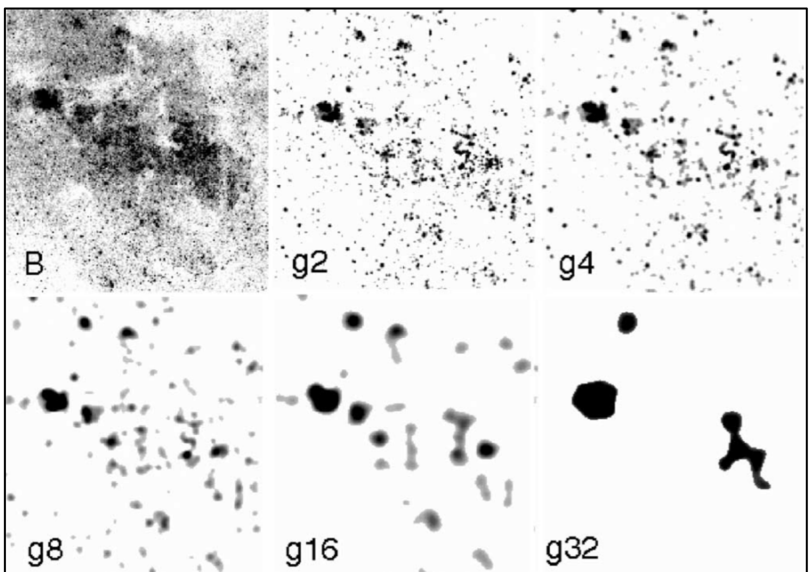


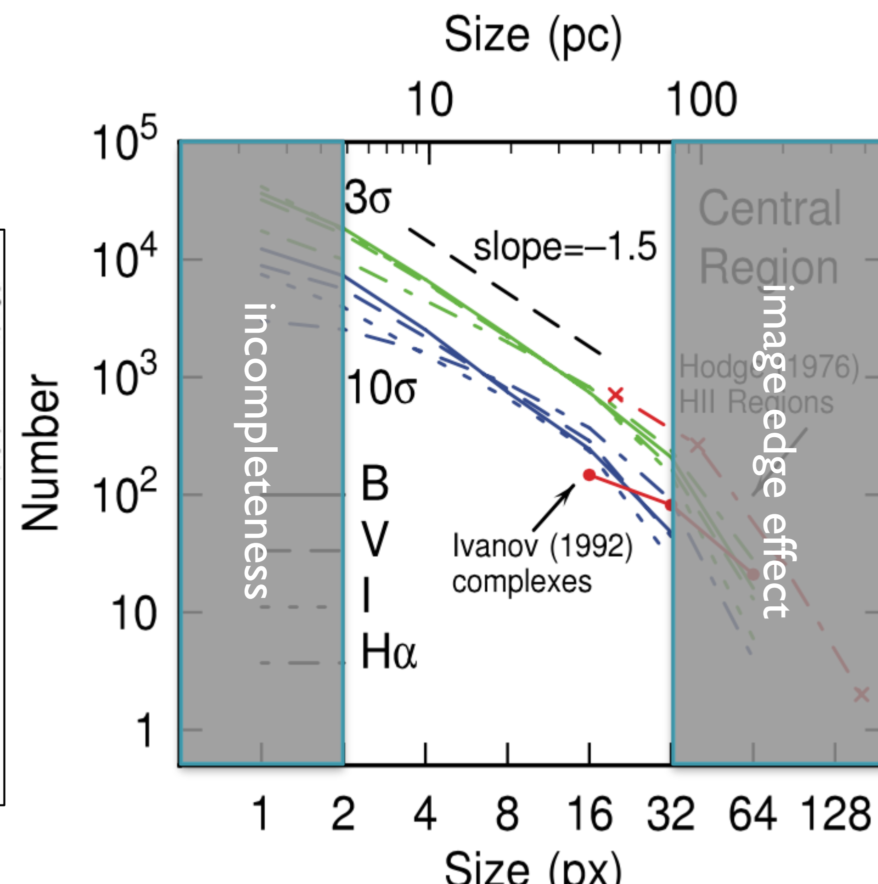
Elmegreen+06

fractal dimension D_2 = 1.5

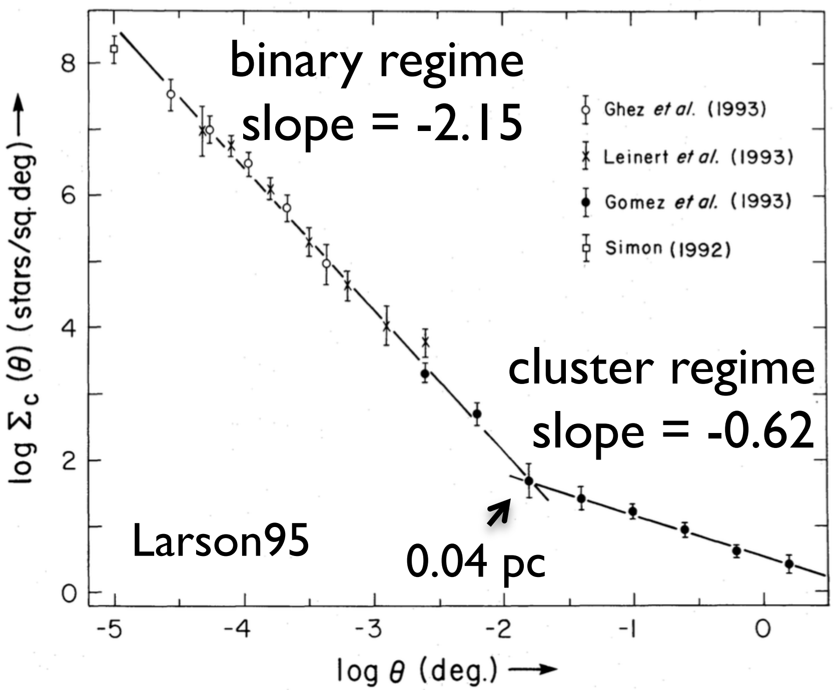
The size distribution is consistent with that of ISM clouds with Kolmogorov **turbulence** (power-spectrum slope 3.66)



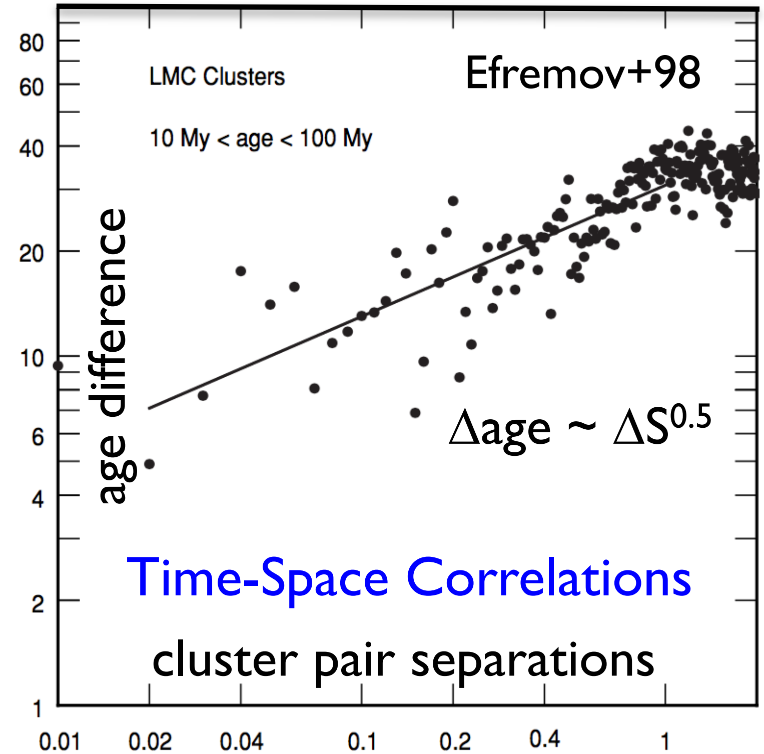




Correlated Star Positions

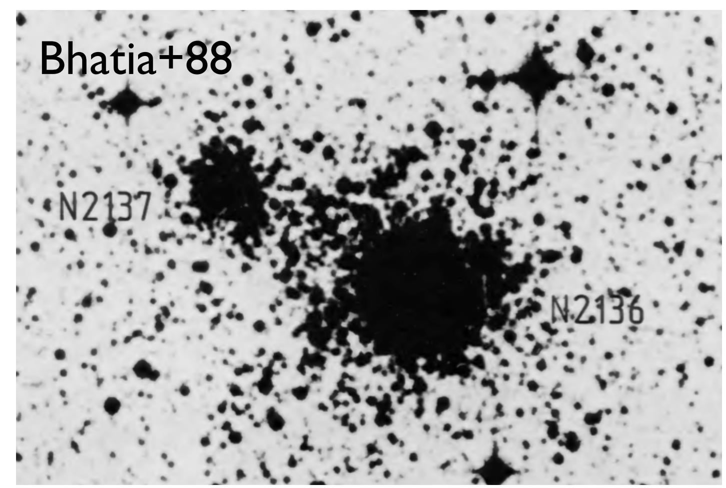


two-point correlation function,
or surface density of companions,
with D_2 = slope + 2.0



Time-Space Correlations

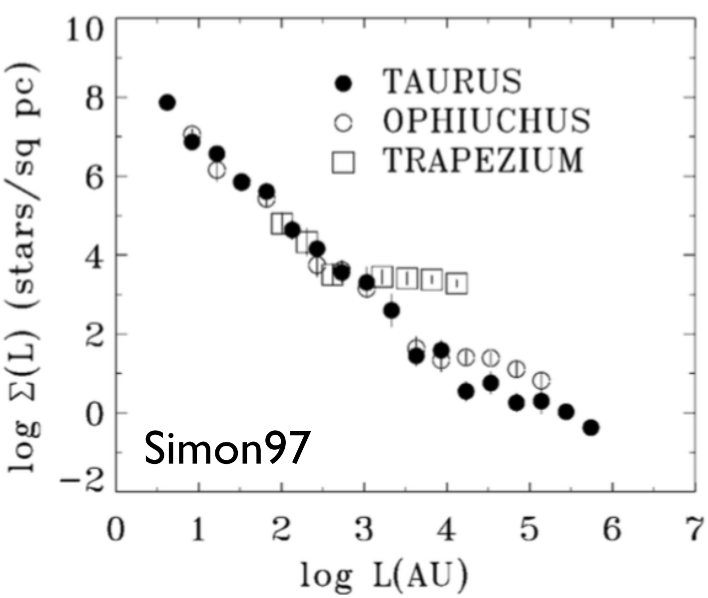
cluster pair separations

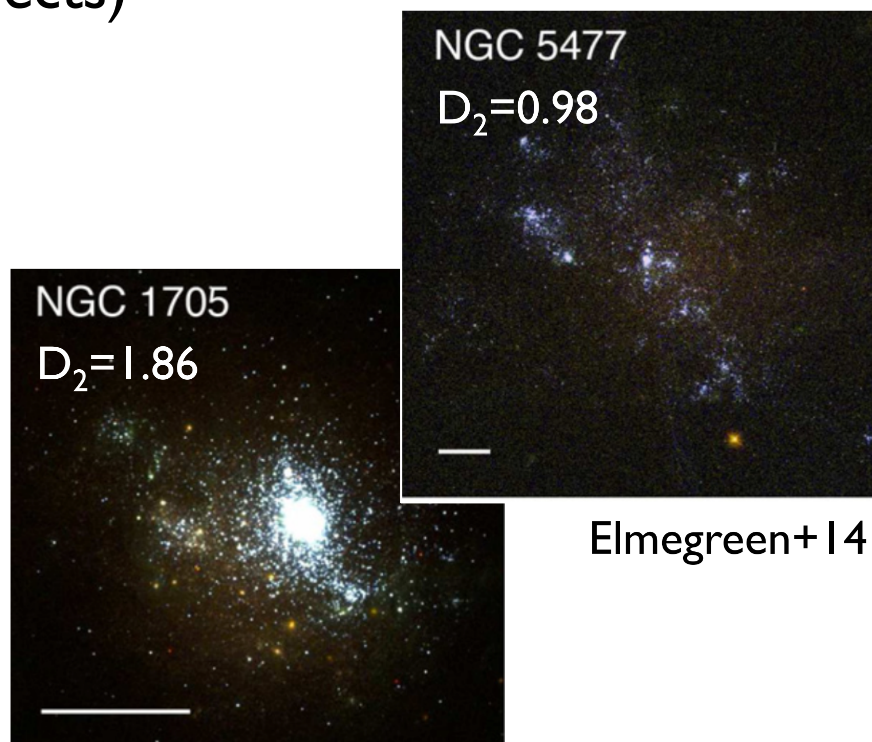


Clusters Forming in Pairs

The hierarchical stellar structures, especially their fractal dimensions, have been investigated for only a few galaxies and individual star-forming regions

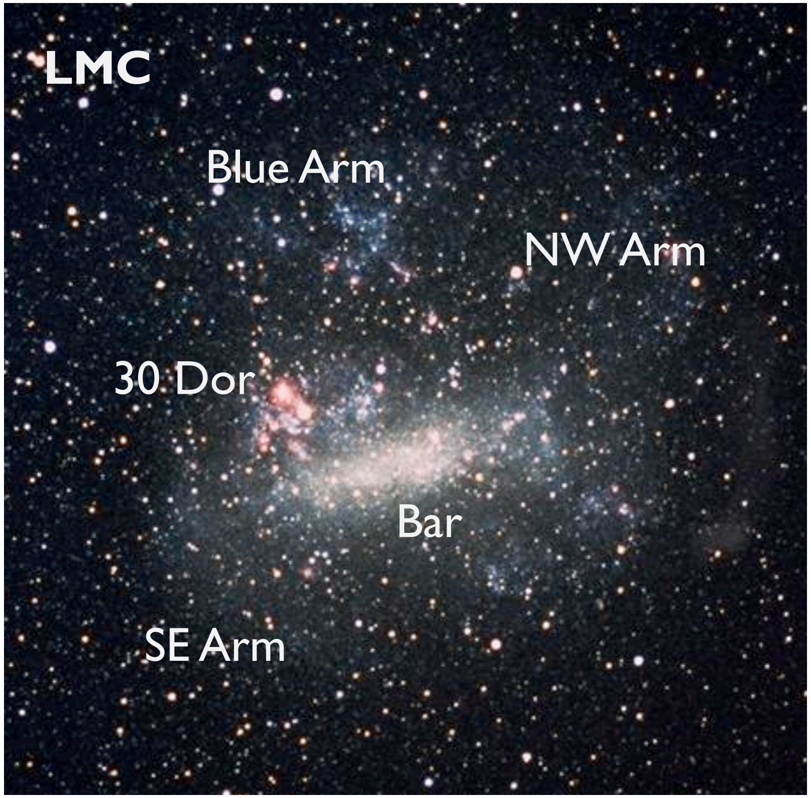
Is there any difference in the stellar clustering properties? If so, what controls them? (stellar feedback, external triggering, evolutionary effects)





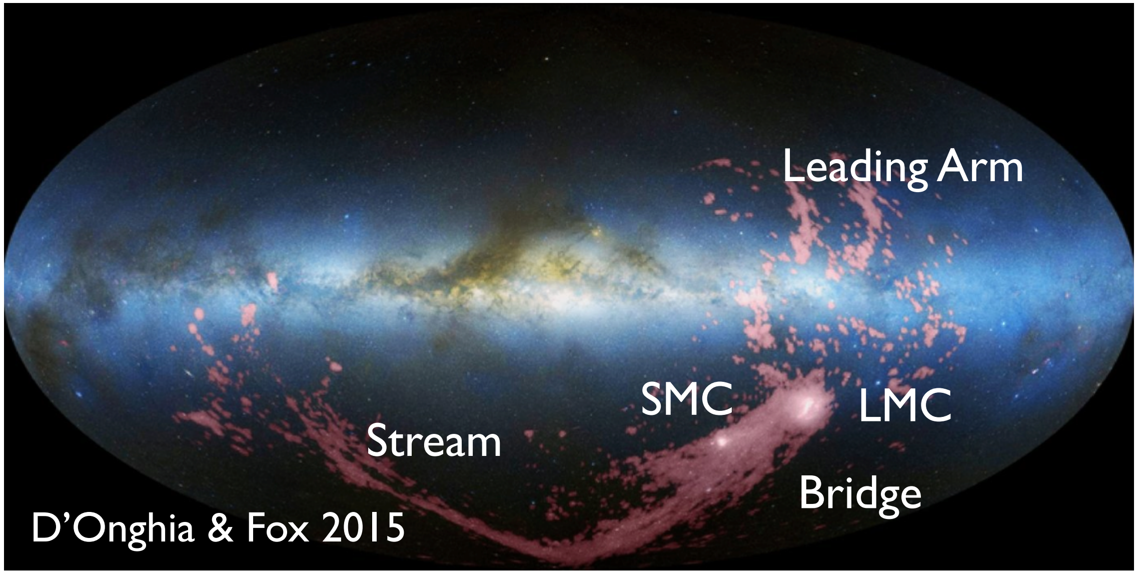
Elmegreen+14

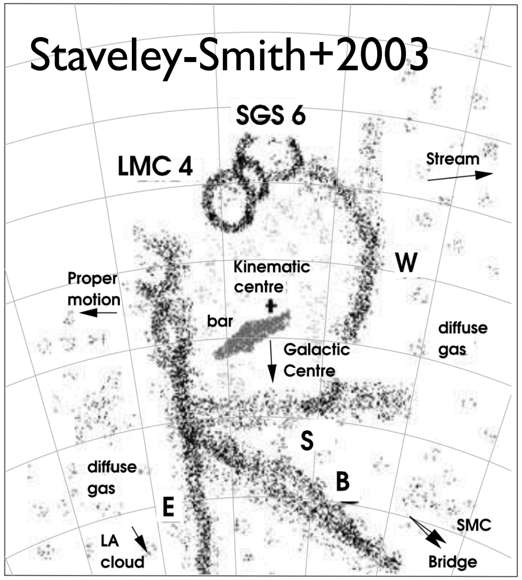
The Magellanic Clouds



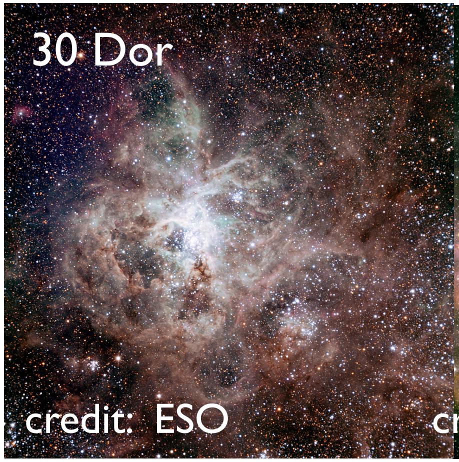
stellar mass $3x10^9$ Msun
halo mass $1.7x10^{10}$ Msun
HI mass $4.4x10^8$ Msun

stellar mass $3x10^8$ Msun
halo mass $2.4x10^9$ Msun
HI mass $4.0x10^8$ Msun





Active ongoing star formation in interacting galaxies



proximity: d = 50 ~ 60 kpc

no distance ambiguity

abundant interesting objects

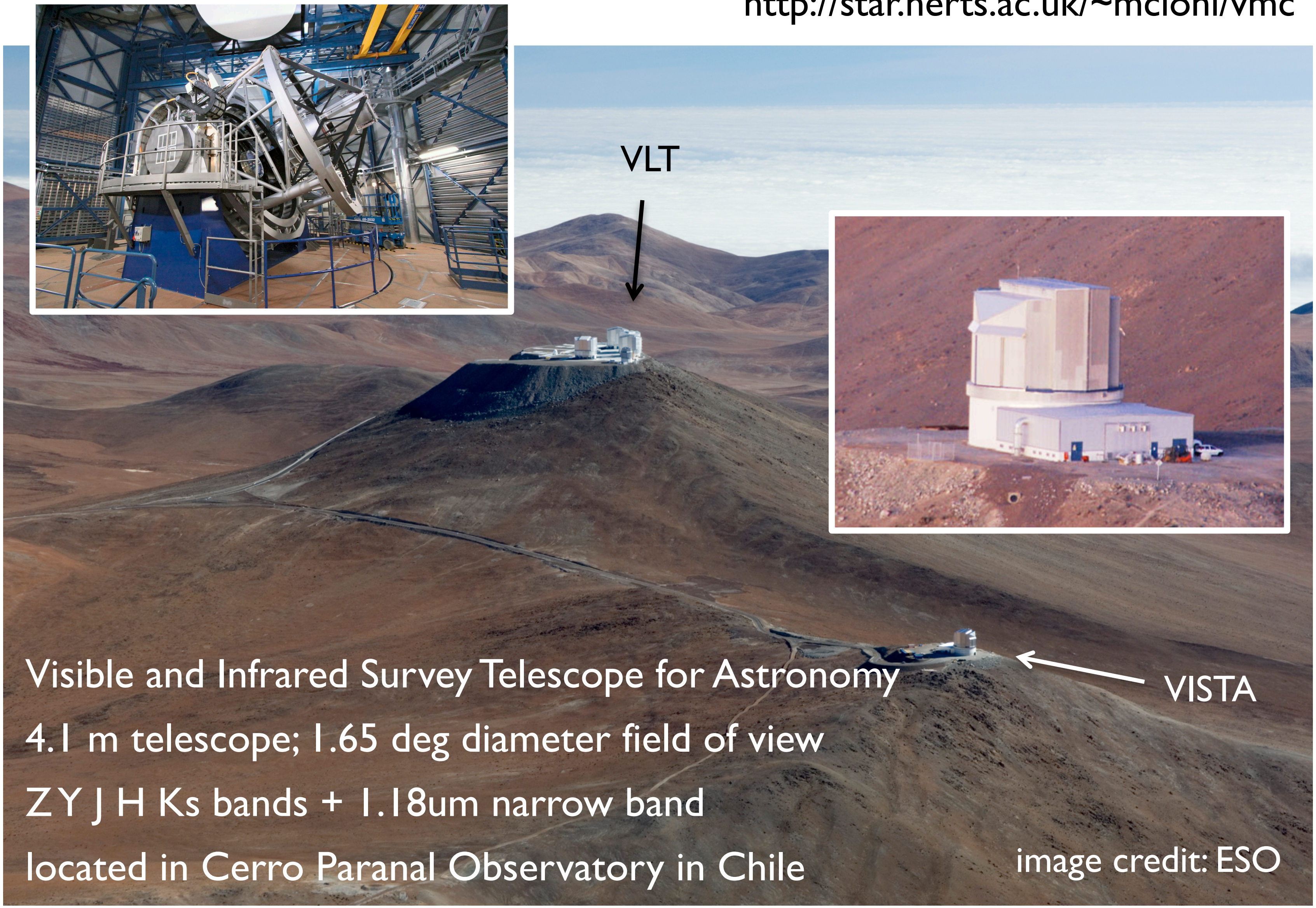
abundant physical processes

abundant observational material

unique Laboratory for this study

The VMC Survey

VISTA Survey of the Magellanic Clouds
PI: Prof. Maria-Rosa L. Cioni
http://star.herts.ac.uk/~mcioni/vmc

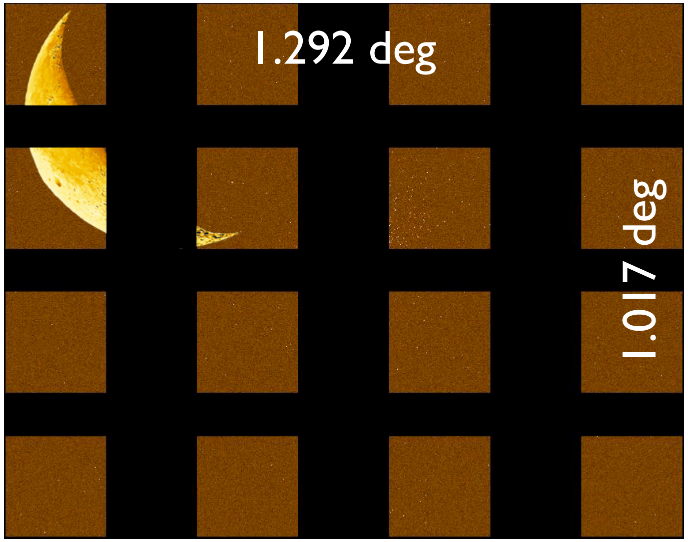


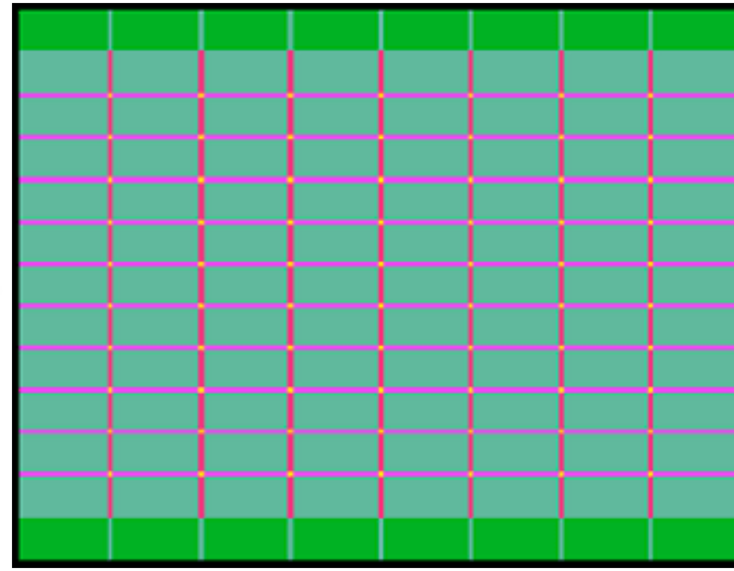
Visible and Infrared Survey Telescope for Astronomy

4.1 m telescope; 1.65 deg diameter field of view

Z Y J H Ks bands + 1.18um narrow band

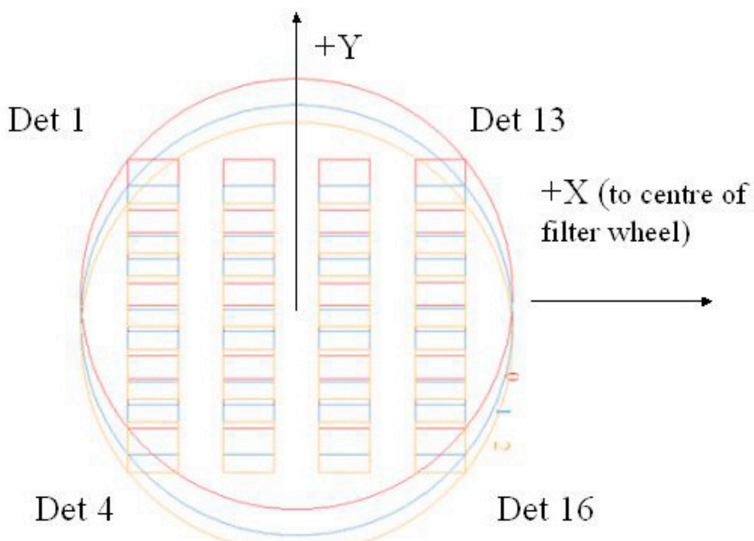
located in Cerro Paranal Observatory in Chile





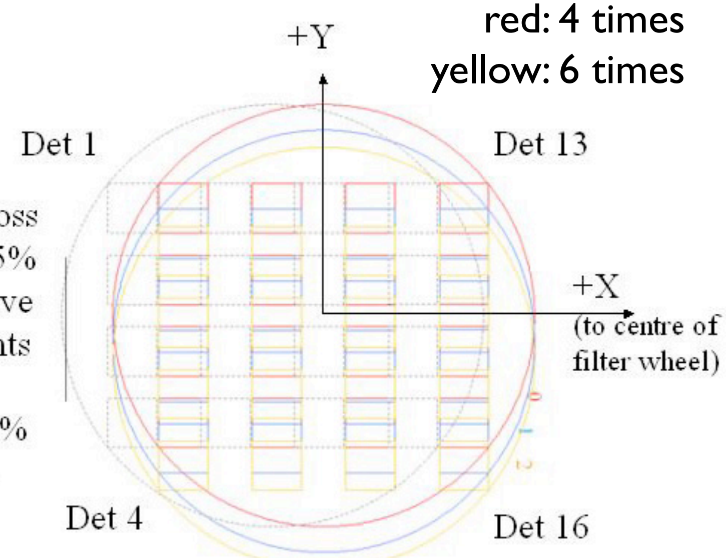
green: once
light green: twice
magenta: 3 times
red: 4 times
yellow: 6 times

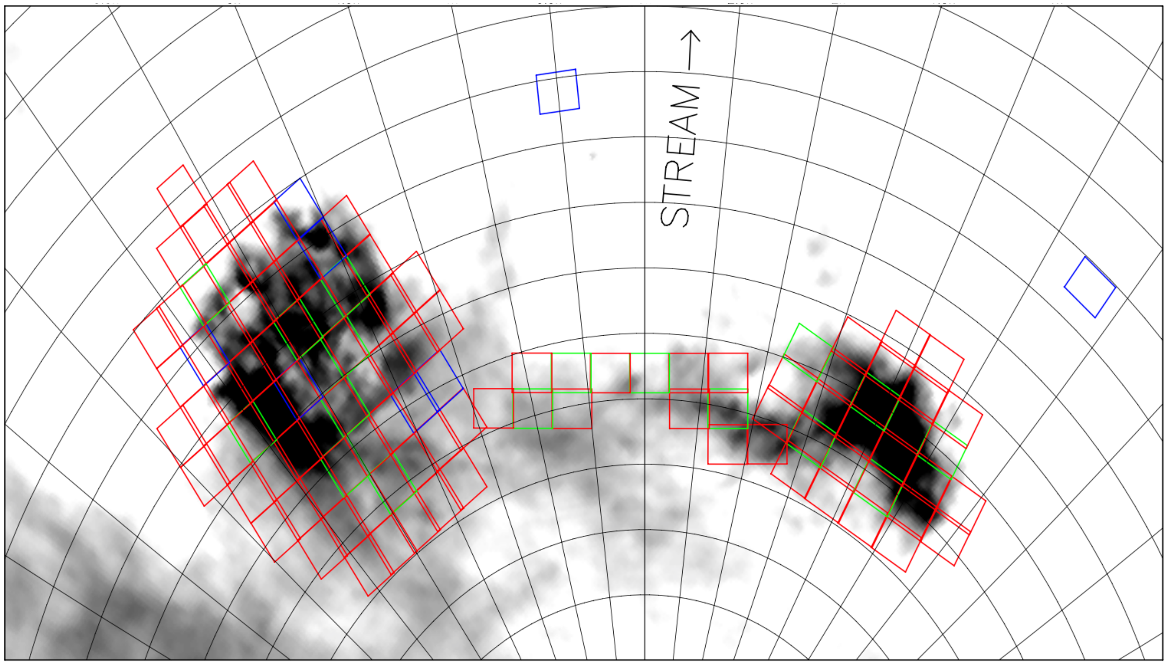
six "**pawprints**" with offsets to form a "**tile**" (1.65 deg^2)



Observe 3 pawprints (0,1,2) separated by ΔY= 47.5% of a detector

Move across by ΔX=95% and observe 3 pawprints with ΔY=47.5% again



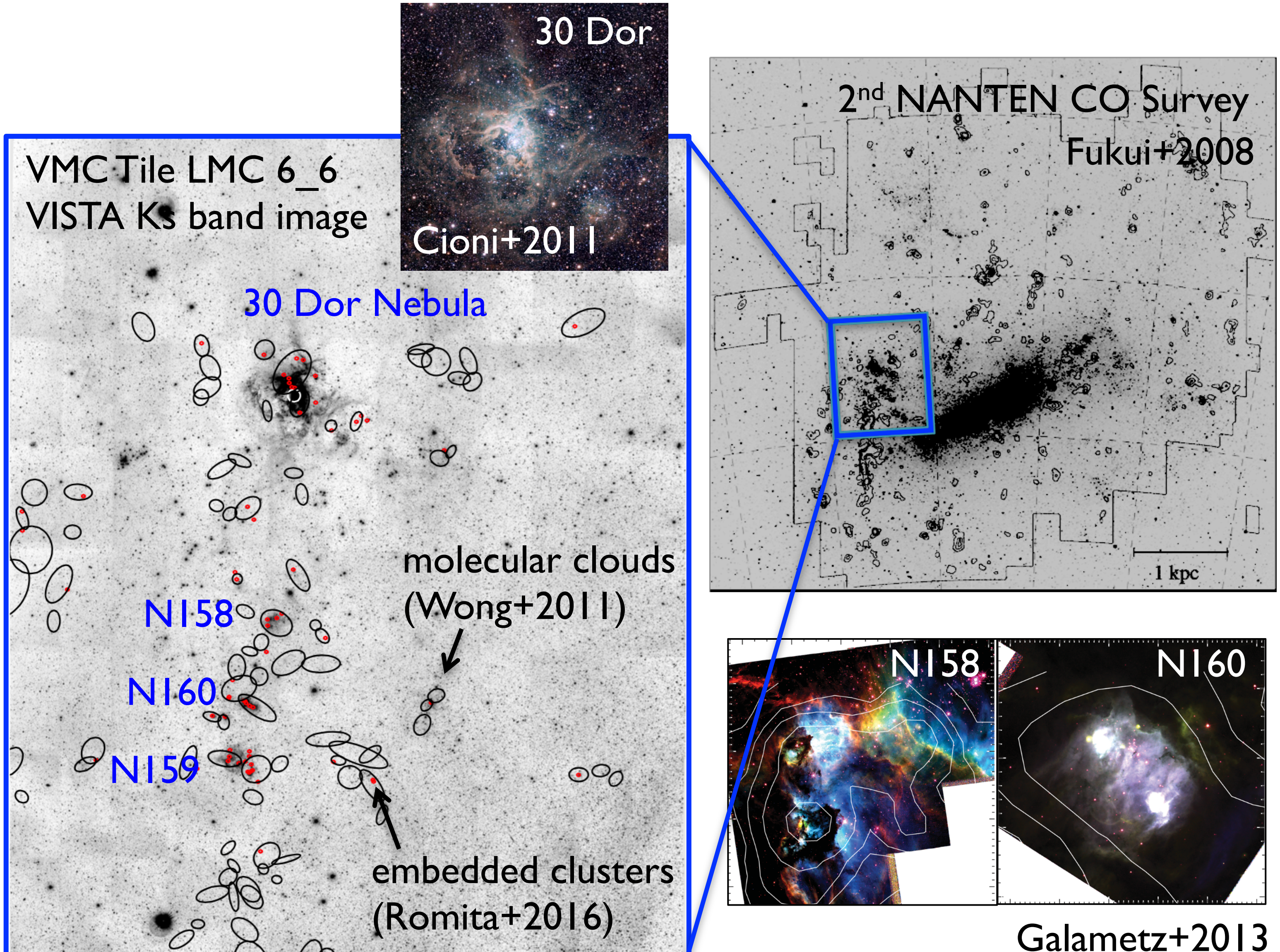


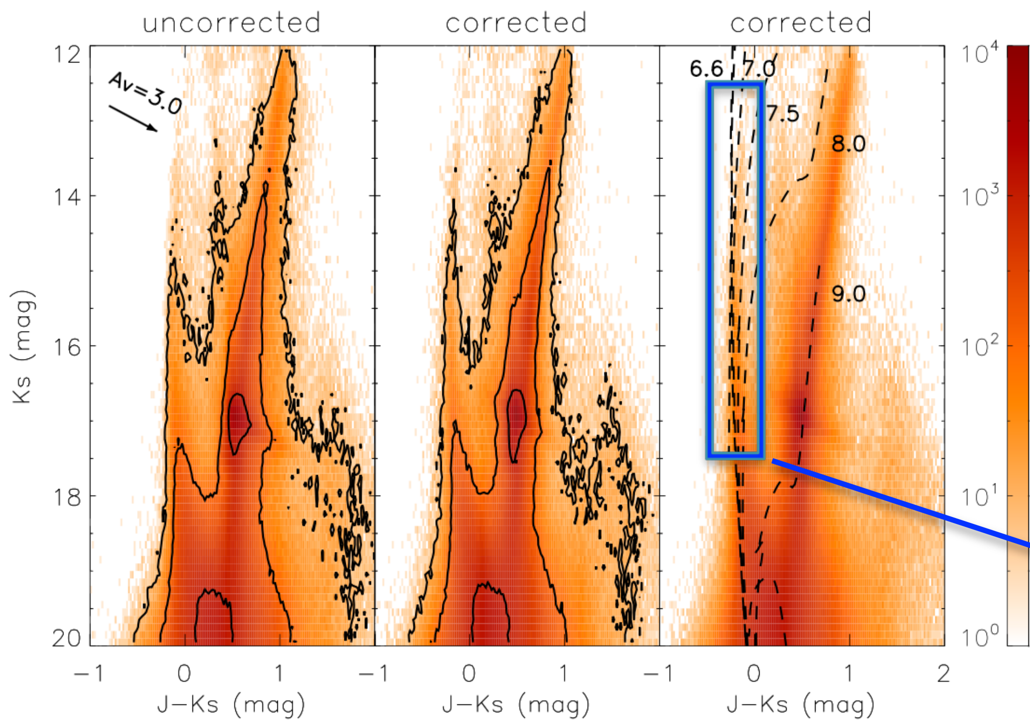
resolution ≤ 1”
large survey area
near-IR wavelengths
deep photometry
suitable for this study

wavelengths :	Y (1.02 um), J (1.25 um), Ks (2.15 um)
exposure times :	800s x 3 (Y), 800s x 3 (J), 750s x 12 (Ks)
saturation limits :	12.9 mag (Y), 12.7 mag (J), 11.4 mag (Ks)
total sensitivities : (at S/N = 10)	21.9 mag (Y), 21.4 mag (J), 20.3 mag (Ks)
number of tiles :	68 (LMC) 27 (SMC) 13 (Bridge) 2 (Stream) 110 (total)
area (deg^2) :	116 (LMC) 45 (SMC) 20 (Bridge) 3 (Stream) 184 (total)

The 30 Dor-N158-N159-N160 Complex

Sun et al., arXiv1611.06508, ApJ accepted

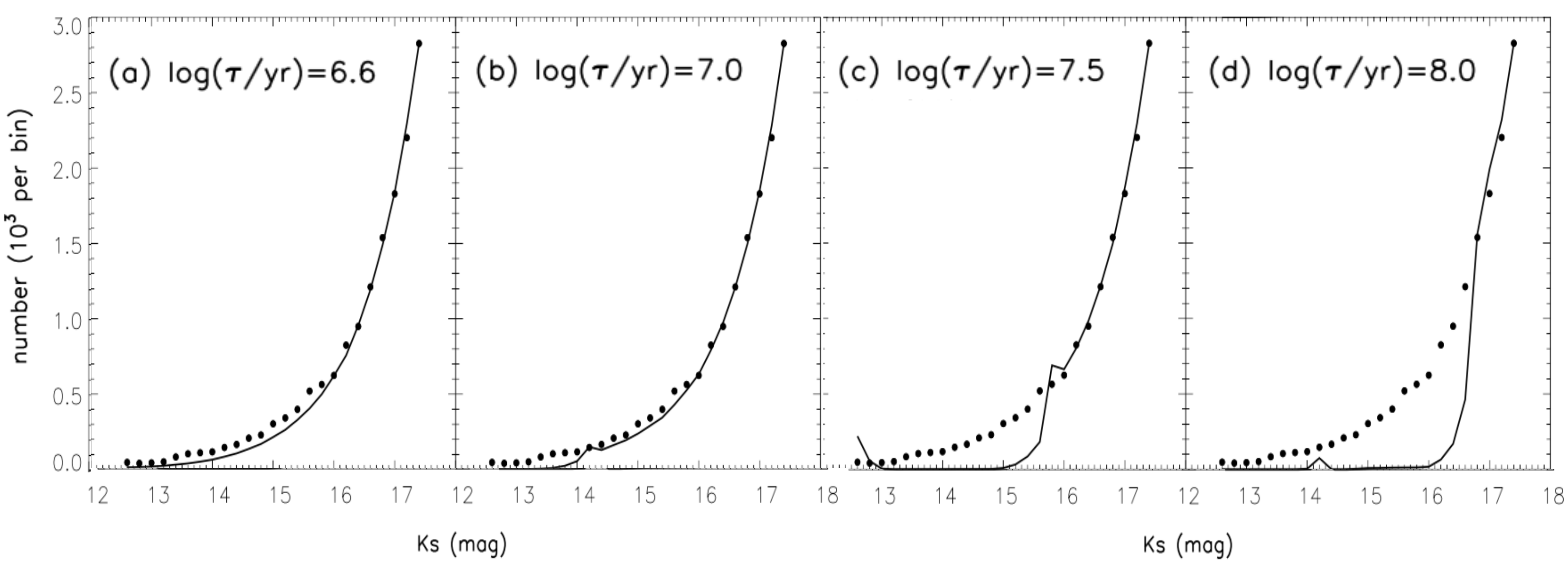




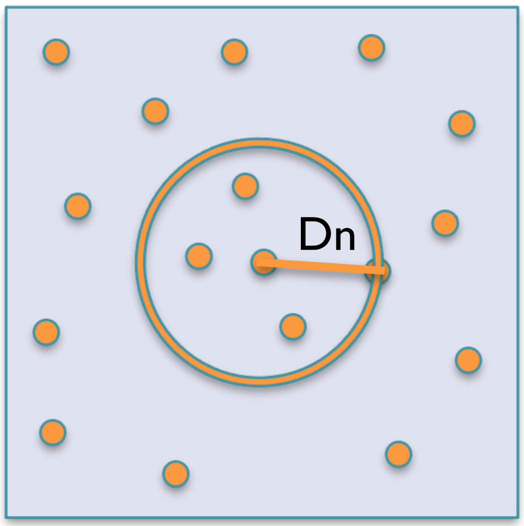
- PSF-phot catalog (Rubele+12)
- RC extinction catalog (Tatton+13)
- Upper-MS stars (1.5×10^4 stars)

$-0.45 < J\text{-}Ks < 0.05$

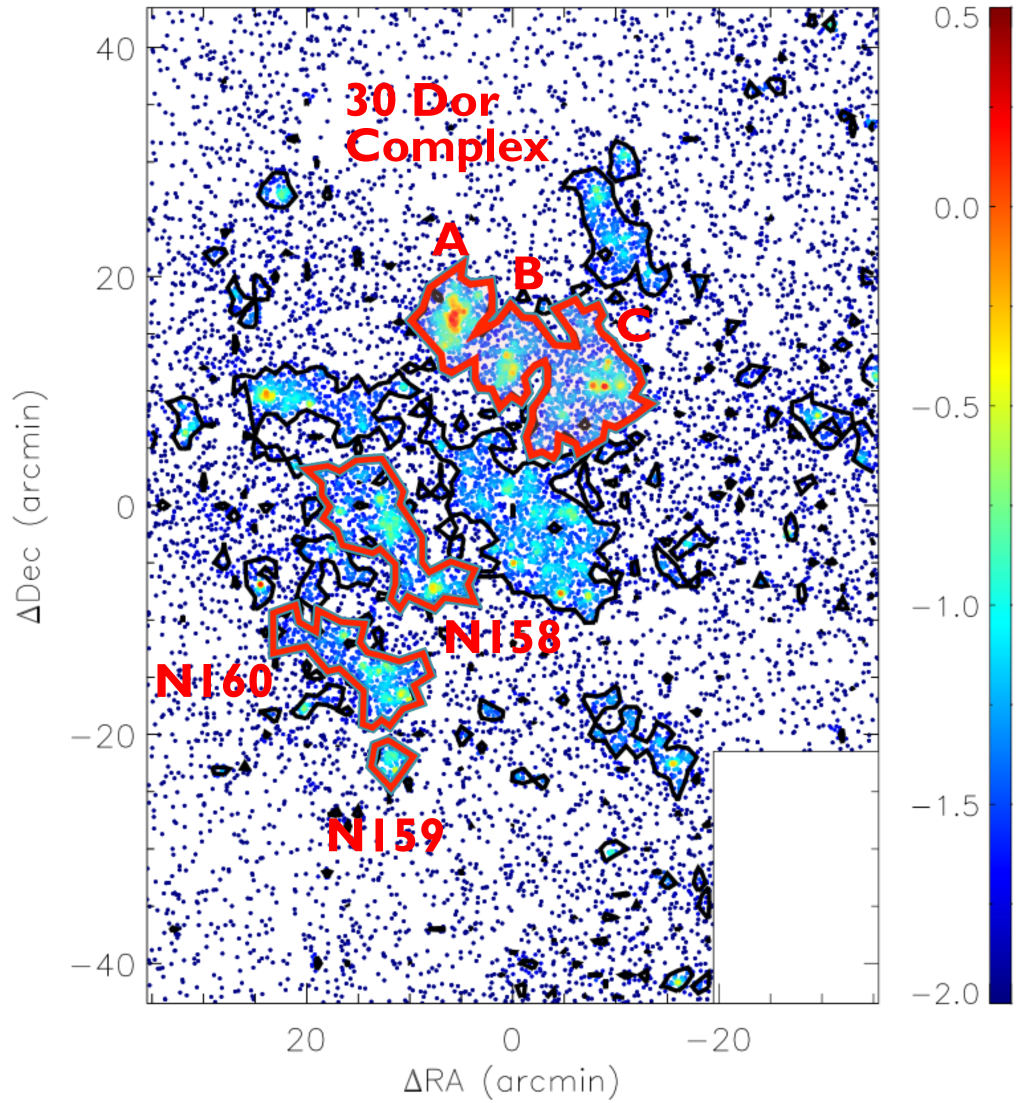
$12.5 < Ks < 17.5$



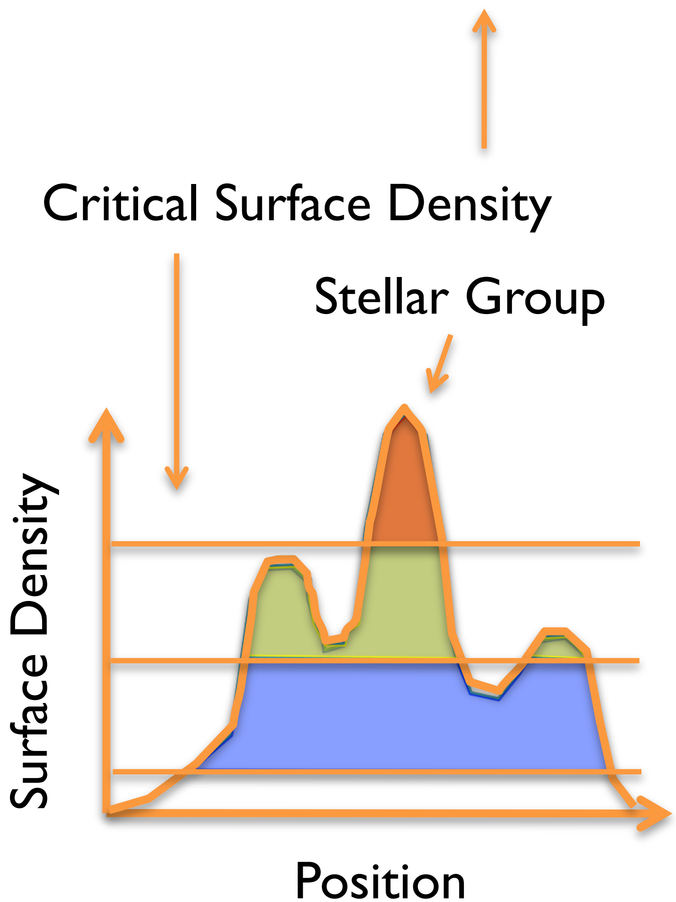
n^{th} nearest-neighbor density estimation

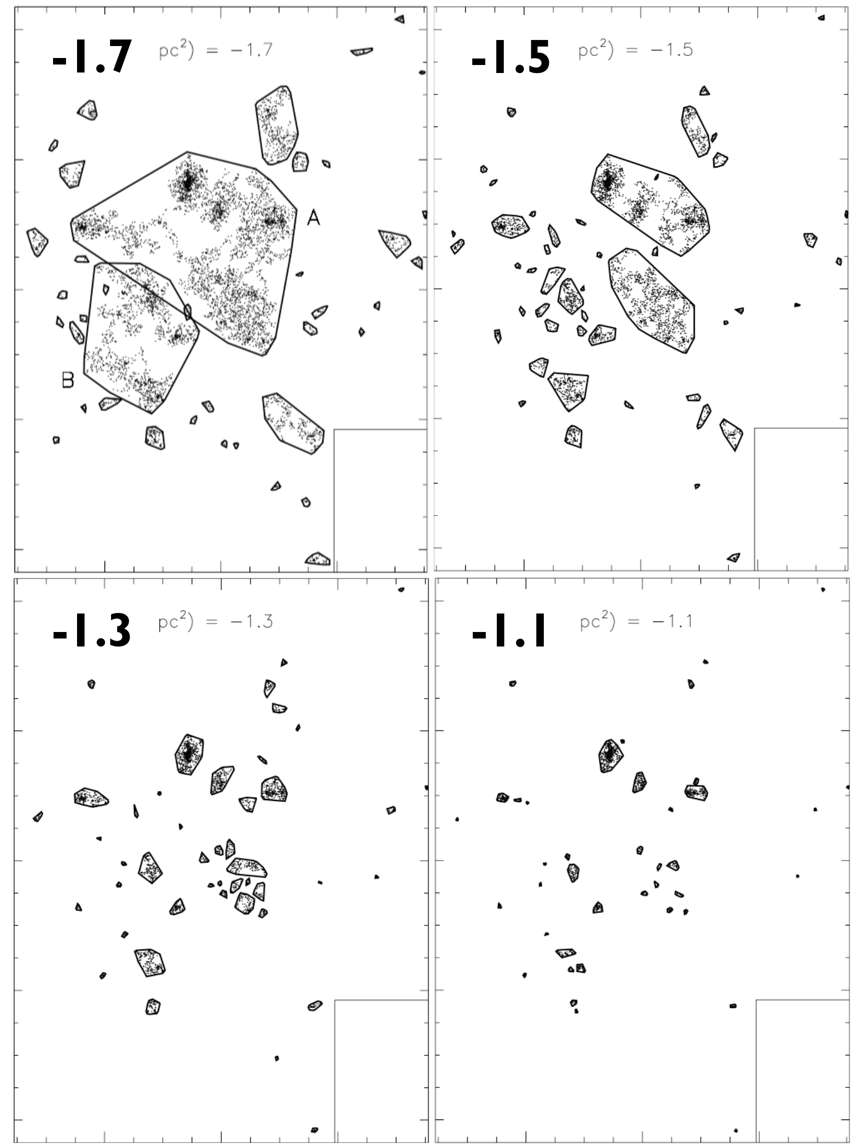


$$\Sigma n = (n - 1) \div (\pi \, Dn^2)$$

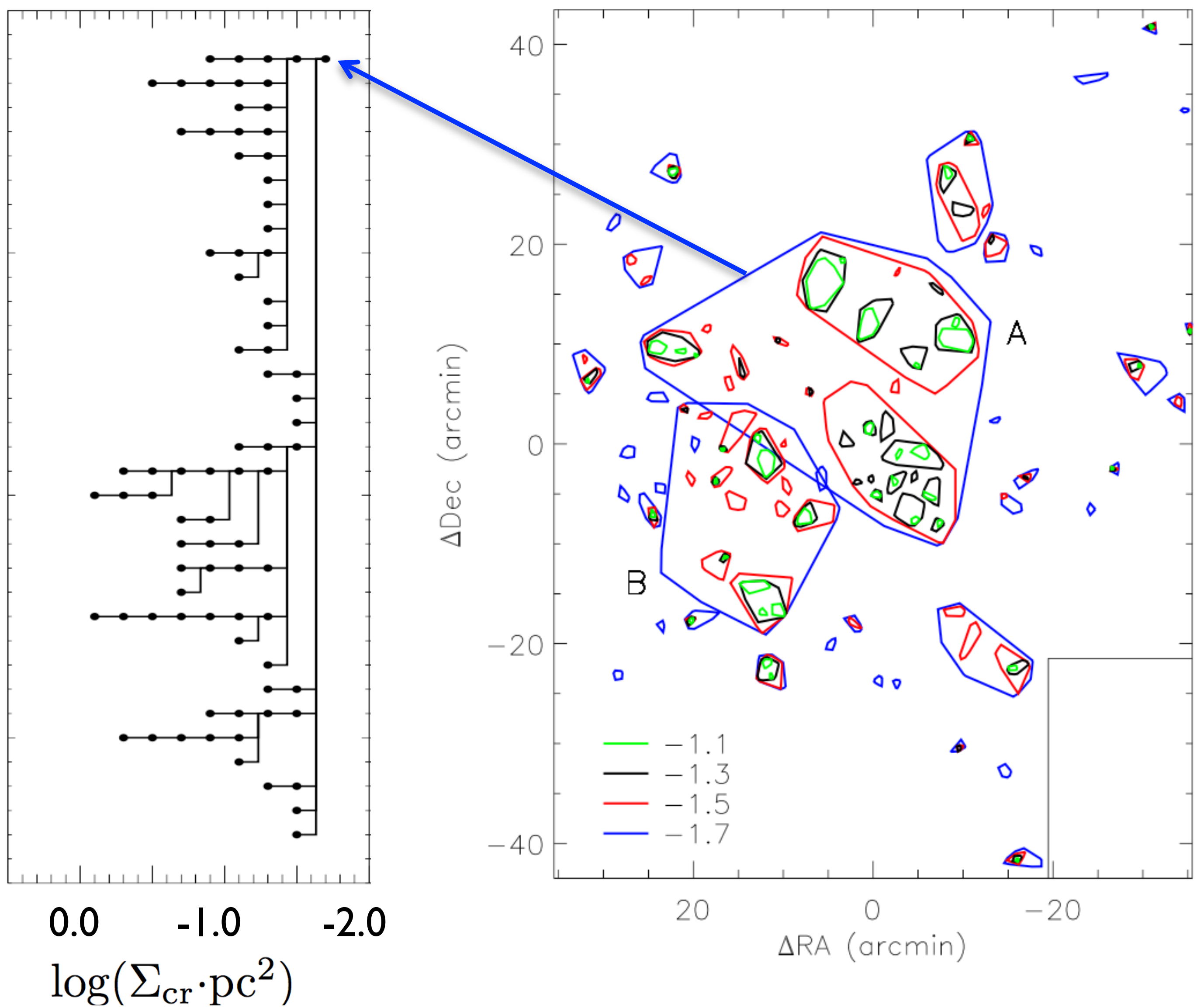


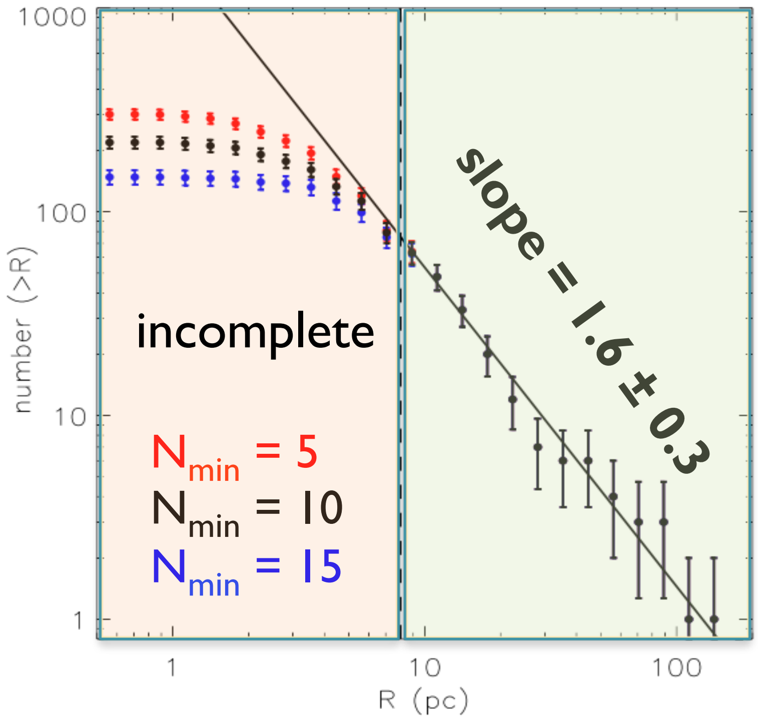
$$\log(\Sigma_{\rm cr}\cdot {\rm pc}^2) =$$





$$\log(\Sigma_{cr} \cdot pc^2) = -1.7\ -1.5\ -1.3\ -1.1$$





- power-law size distribution
- no characteristic scale
- fractal dimension D_2 = 1.6 ± 0.3
- ISM clouds D_3 ~ 2.4 (Roman-Duval+10)
- consistent with hierarchical star formation scenarios

other star-forming regions

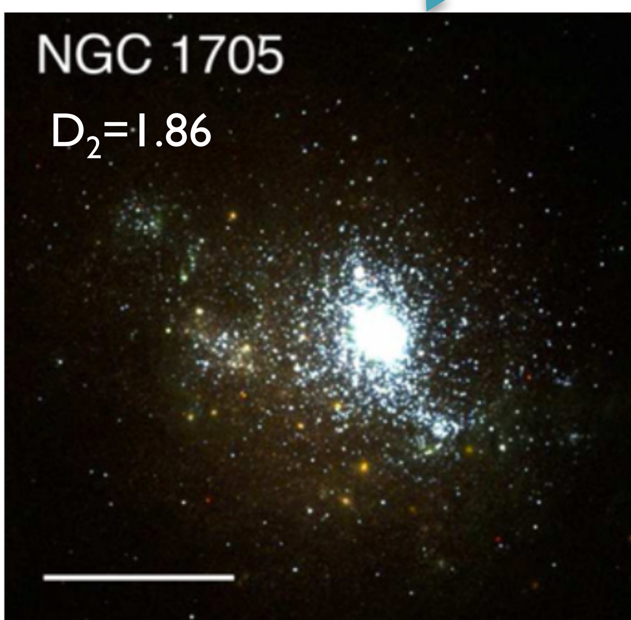
D_2 = 1.4, Taurus (Larson95)
D_2 = 1.5, Taurus, Ophiuchus, Orion (Simon97)
D_2 = 1.4, ngc 346 (hierarchical component, Gouliermis+14)

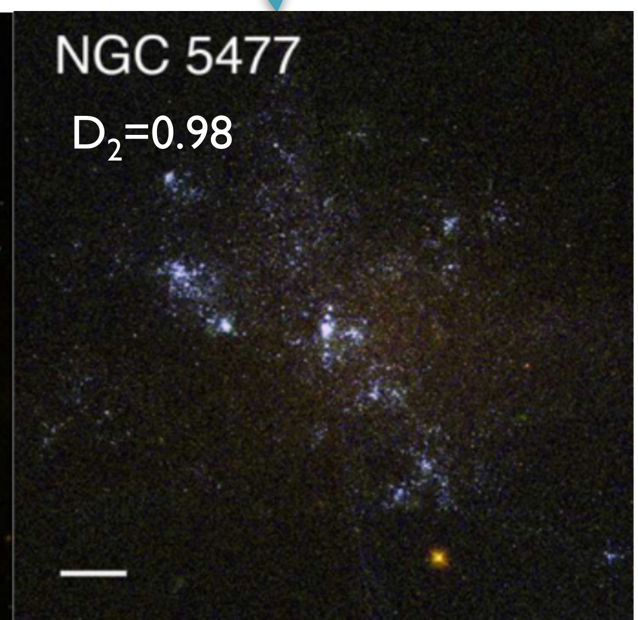
stochastic self-propagating star formation (Feizenger1981)
dynamical perturbation of the off-center bar (Gardiner+1998)
bow-shock due to the Galactic warm gas (de Boer 1998)
Magellanic interaction (Fujimoto 1990, Bekki & Chiba 2007)

Elmegreen+14

Galaxy	Type	D^a (Mpc)	B_{NS}
NGC 1566	SABbc	13.20	-1.34 ± 0.05
NGC 1705	SA0pec [Irr]	5.10	-1.86 ± 0.10
NGC 2500	SBd	10.10	-1.17 ± 0.06
NGC 3738	Im	4.90	-1.39 ± 0.06
NGC 5253	Im pec	3.15	-1.51 ± 0.08
NGC 5477	SAm	6.40	-0.98 ± 0.06
NGC 7793	SAd	3.44	-1.62 ± 0.08
IC 4247	S? [Irr]	5.11	-1.14 ± 0.04
IC 559	Sc [Irr]	5.30	-1.12 ± 0.14
ESO486-G021	S? [Irr]	9.50	-1.47 ± 0.08
UGC 695	S? [Irr]	10.90	-1.83 ± 0.15
UGC 7408	IAm	6.70	-0.76 ± 0.12

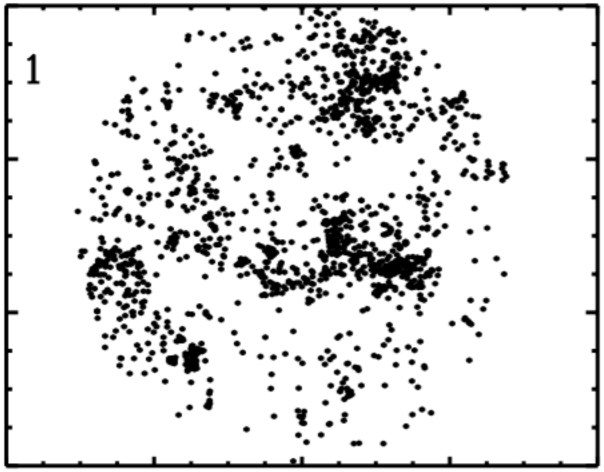
- Galaxies have large range of reported D_2 values
- Consistent with
  ngc 628 (1.5, Elmegreen+06)
  ngc 6503 (1.7, Gouliermis+14)
  some galaxies in Elmegreen+14
- Deviate more than 3σ with some other galaxies



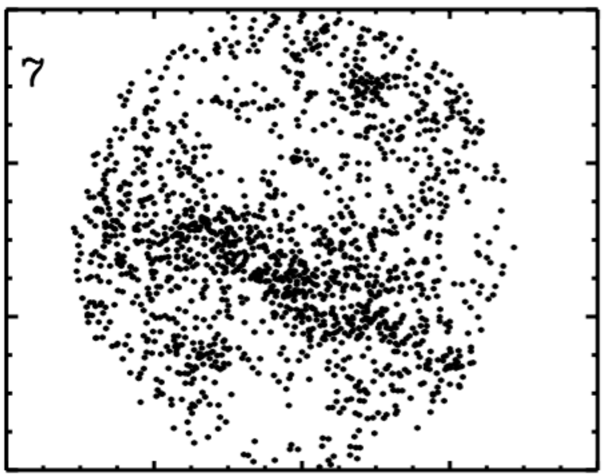


Evolutionary effects may also contribute to the difference in D_2

<age> ~ 9 Myr



<age> ~ 128 Myr

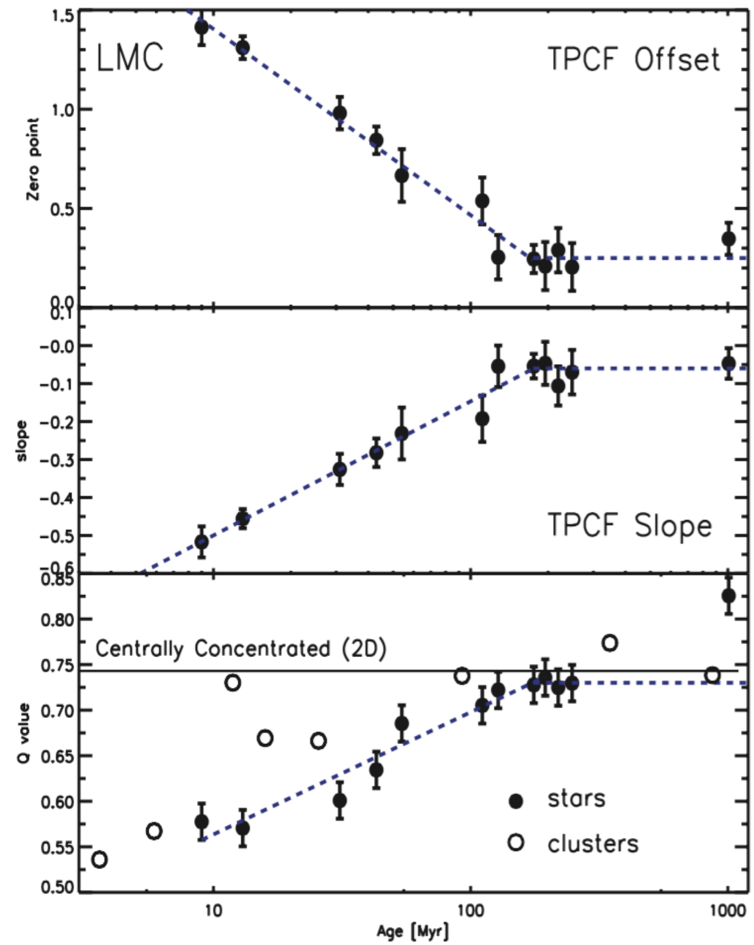


Bastian+09

decreasing amount of substructures

→

increasing age



SUMMARY

- the young upper-MS stars exhibit fractal distributions
- group size distribution is a single power law with $D_2 = 1.6 \pm 0.3$
- support a scenario of hierarchical star formation
- consistent with other star-forming regions and some galaxies

FUTURE