Spatially Resolved Star Formation

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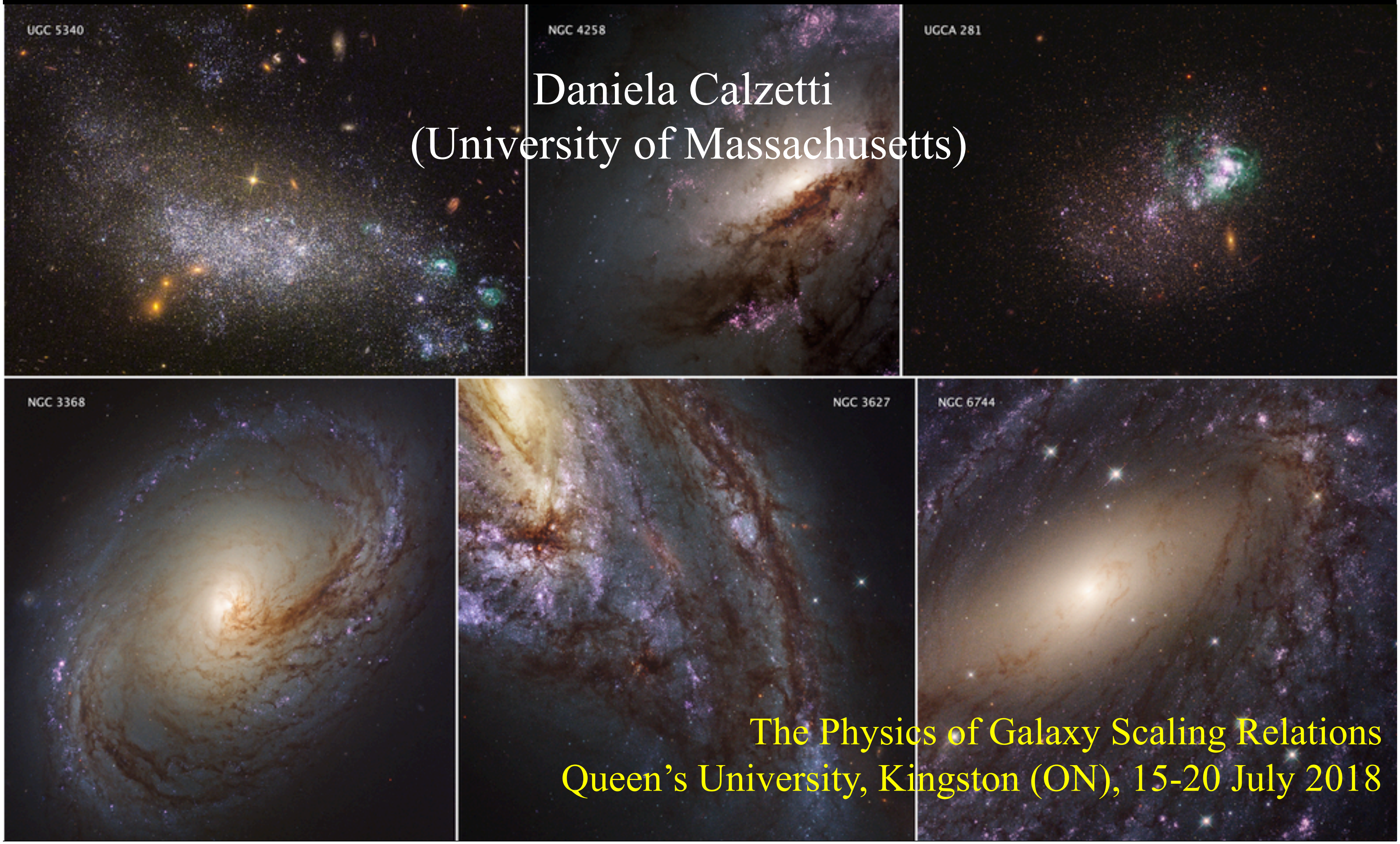
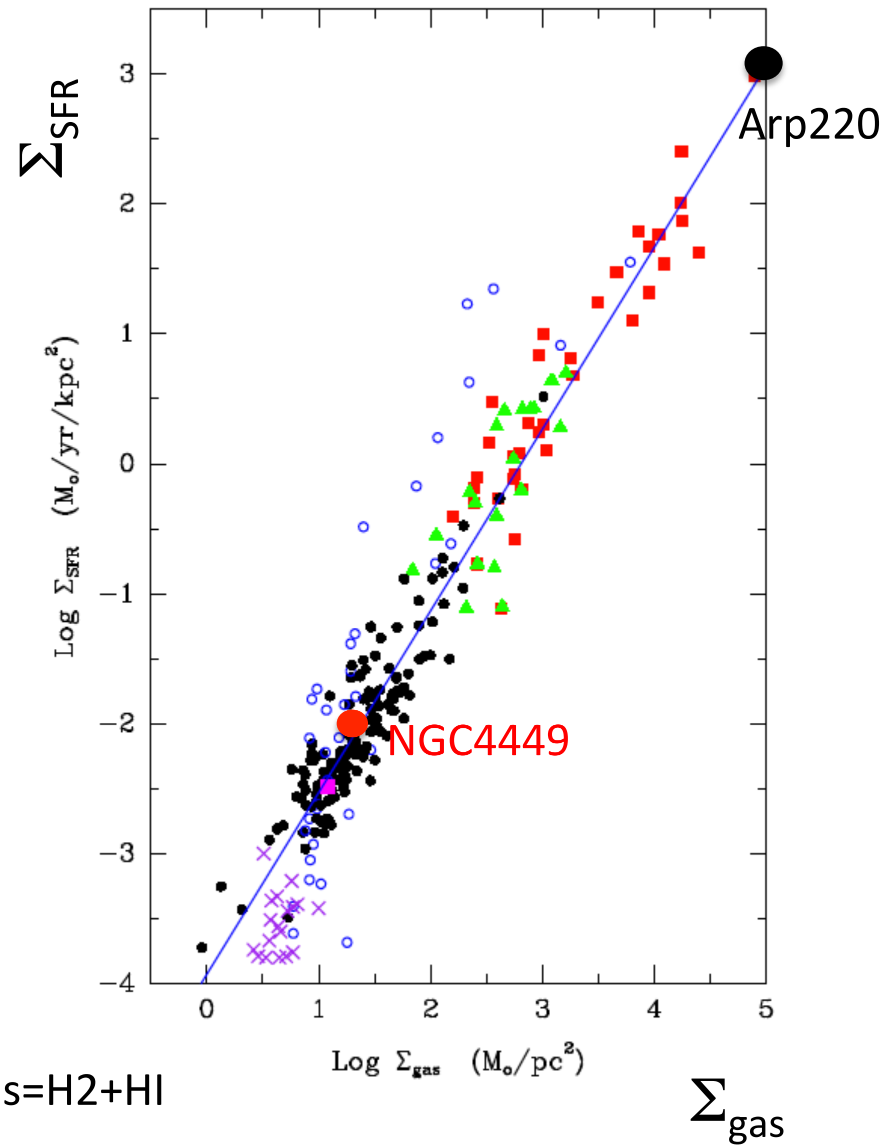


The Physics of Galaxy Scaling Relations
Queen's University, Kingston (ON), 15-20 July 2018

The SK Law: The Gas/SF Scaling Relation

- If Rob had received 1 cent for each time this figure has been shown over the past few years, ….
- He would be a millionaire.

Kennicutt & Evans 2012



gas=H2+HI

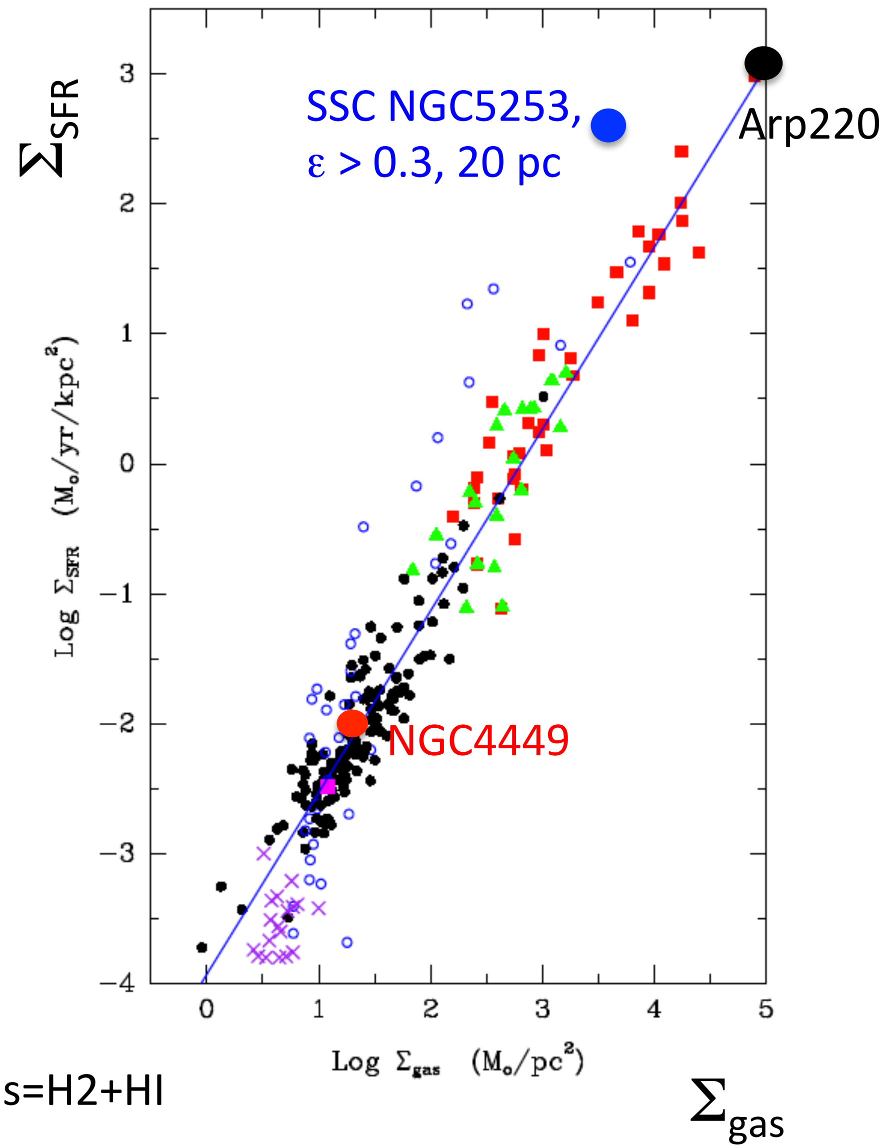
The SK Law: The Gas/SF Scaling Relation

- A tight relationship between the total gas and SFR densities in galaxies.

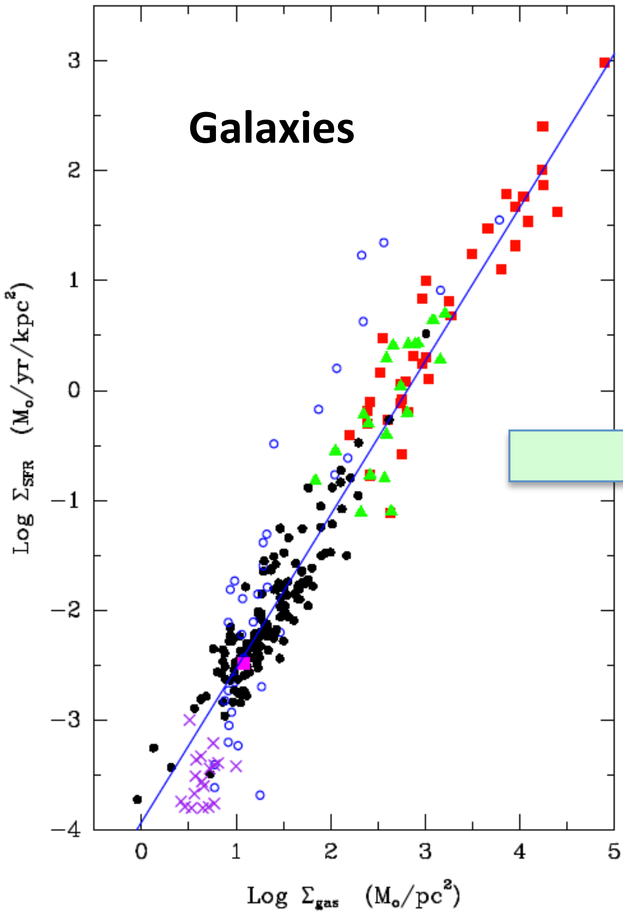
- This implies:
  - An increasing of the efficiency of gas-to-star conversion ε for increasing Σ_{SFR}
  - and/or shorter timescales (e.g., Krumholz+2012).

- How do we discriminate between the two scenarios?

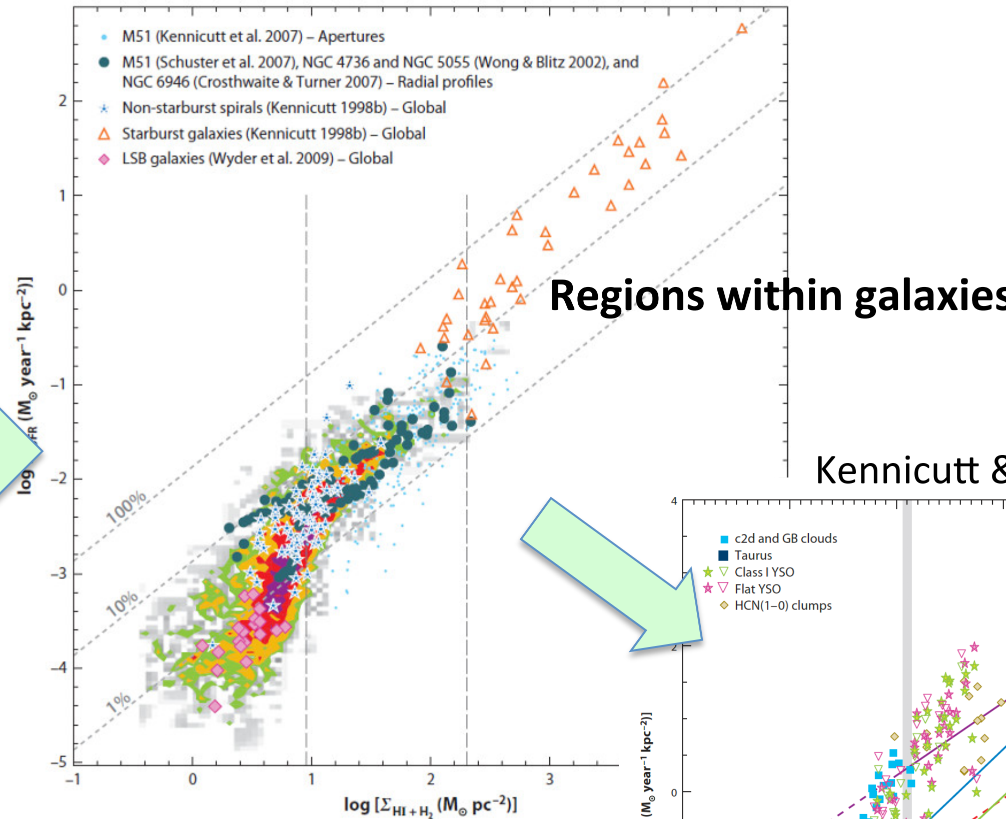
Kennicutt & Evans 2012



gas=H2+HI

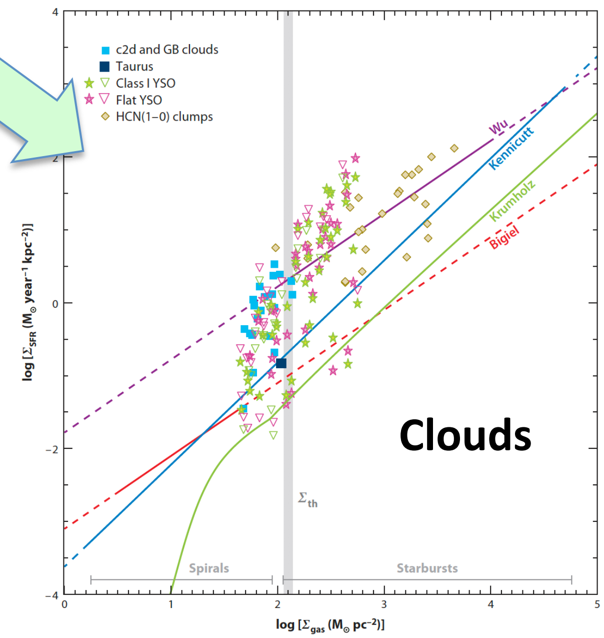


Kennicutt & Evans 2012



Bigiel+2008

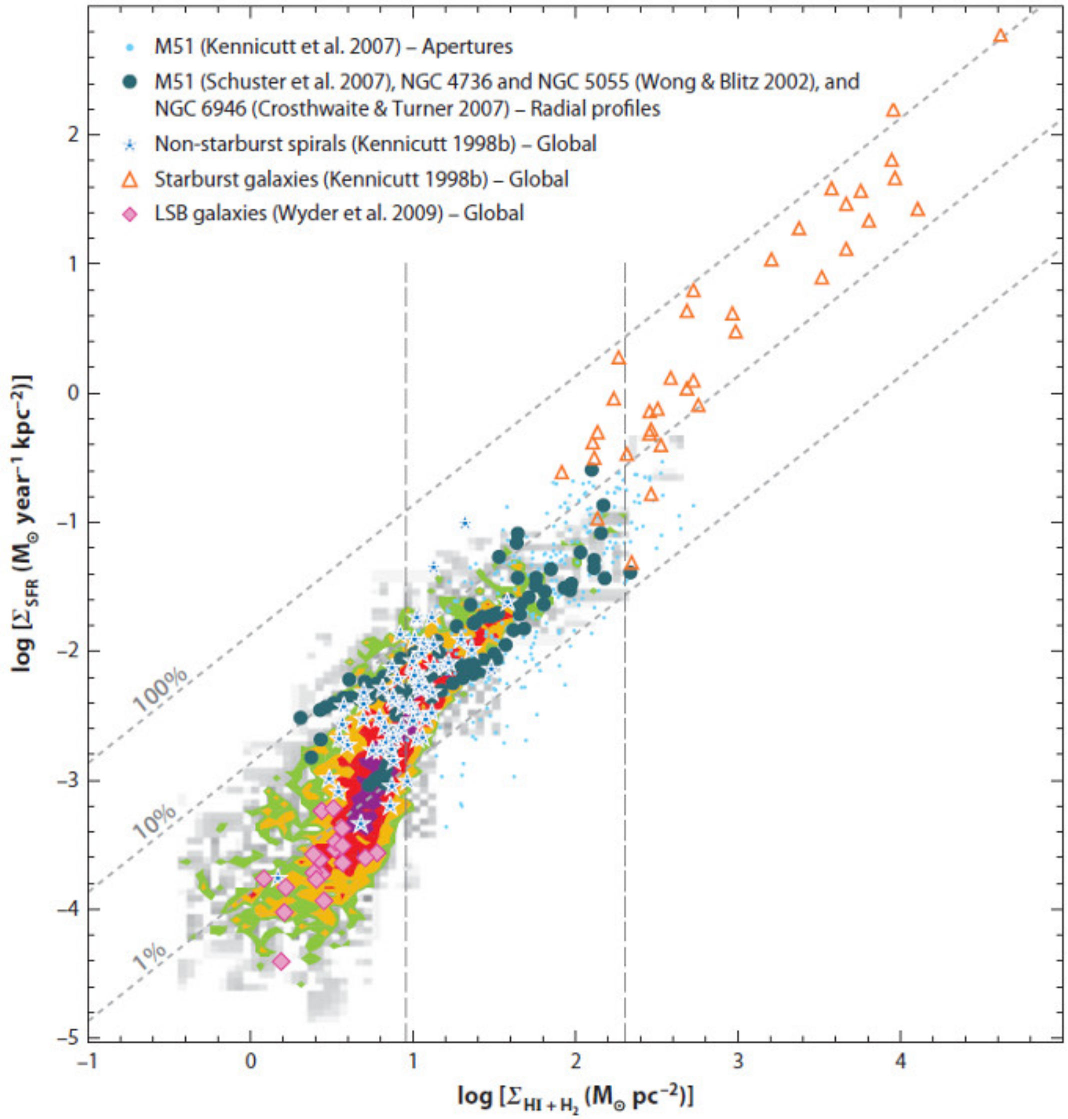
Kennicutt & Evans 2012



The gas-SFR link at large scales t is not recovered at small scales

- What determines the HI -> H2 -> dense gas -> SFR transition fractions?
- Is the scaling at large spatial scales simply due to galaxy feedback (e.g., Hopkins et al. 2011, 2013)?

Non Dissipative = time-integrated tracer

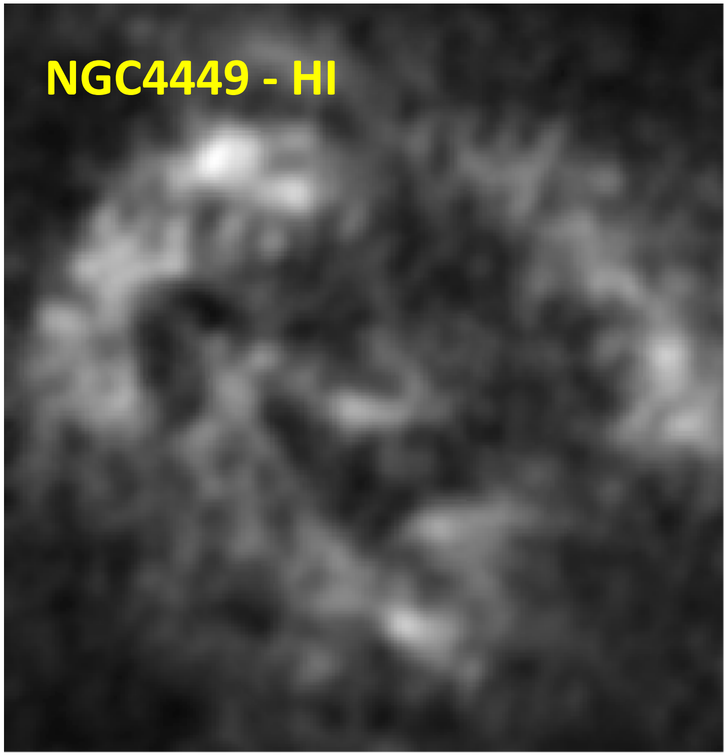


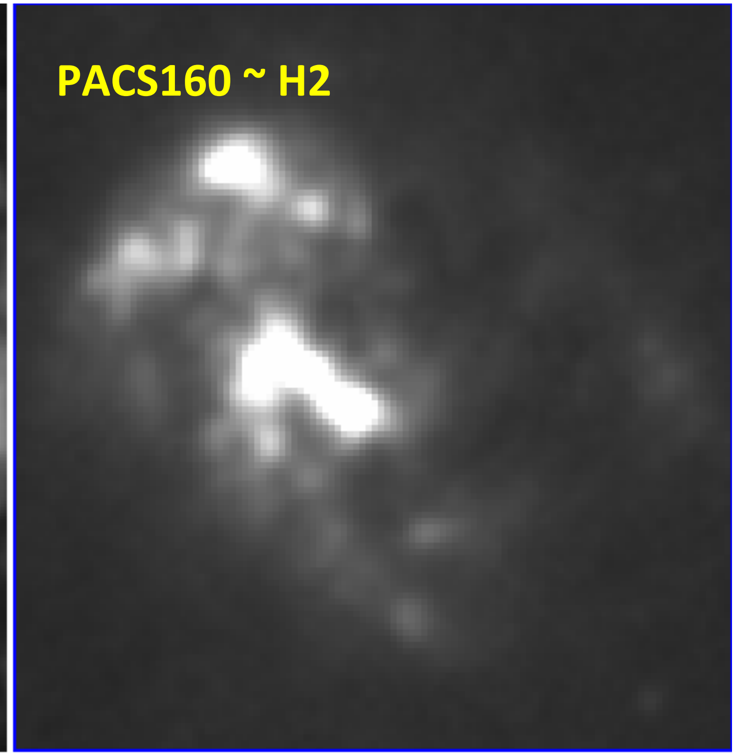
Bigiel+2008

Dissipative = instantaneous tracer

See also: Kennicutt+2007, Daddi+2010, Genzel+2010, 2015, Saintonge+2011, 2016, 2018, Liu+2011, C+2012, Shetty+2013, 2014, Leroy+2013, Tacconi+2018, …

All Gas Phases lead to SF

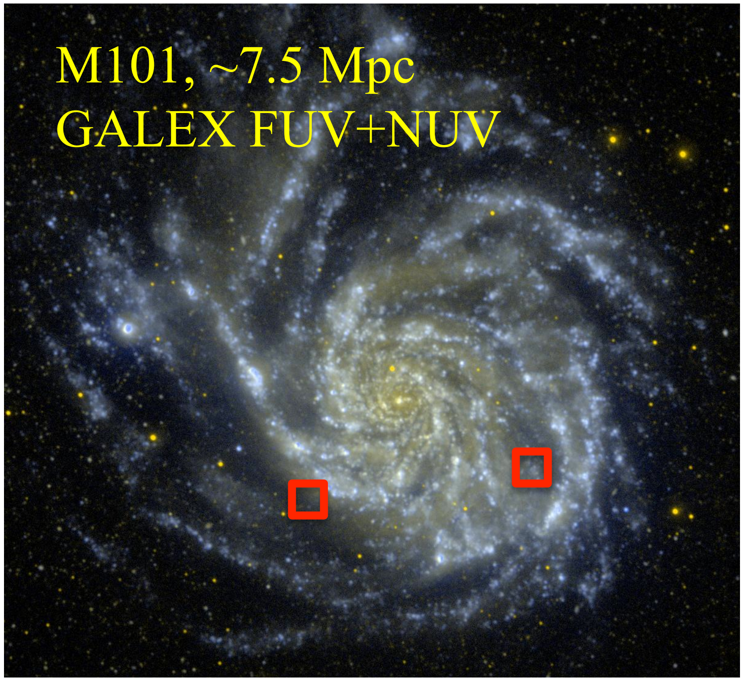




- HI is distributed throughout the galaxy, while H2 tends to be more closely associated with recent star formation (Kennicutt+2007, Bigiel+2008);
- higher density gas is progressively more strongly correlated with SF (e.g., Gao & Salomon, 2004 + a large number of recent papers) – we will reach a point where stars will be correlated with stars

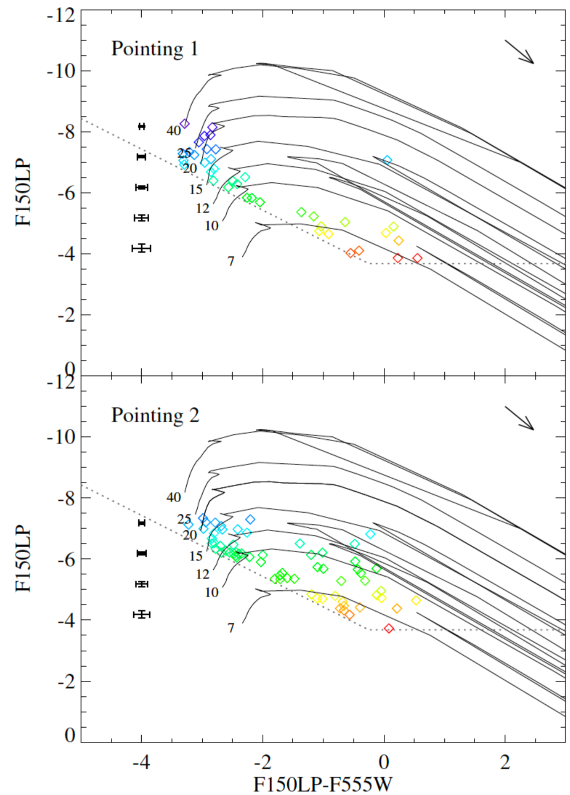
No gas phase can be neglected in a theory of SF

Non-Dissipative = Stellar Pops Diffusion



A common characteristic of local spirals: GALEX FUV-NUV color maps show that interarm regions have redder UV colors than arm regions. This cannot be an effect of differential attenuation.

Interarm regions in M101 do not contain stars younger than ~40 Myr (or more massive than ~10-15 M_o) (Crocker+2015).
Similar results for starbursts (Tremonti+2001, Chandar+ 2005).
No active SF in interarms.



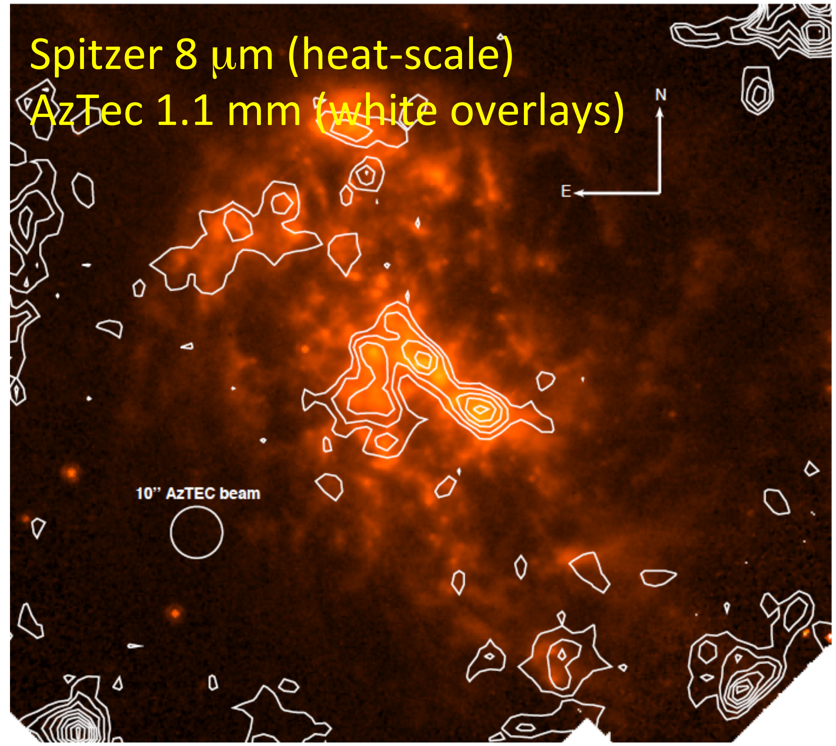
Diffuse light from older populations need to be removed to measure local SFRs
(C+2005, Liu+2011, C+2012, Kumari+2018)

NGC4449

- A dwarf Magellanic Irregular at 4.2 Mpc
- A starburst, about 4-10x above the Main Sequence of SF:

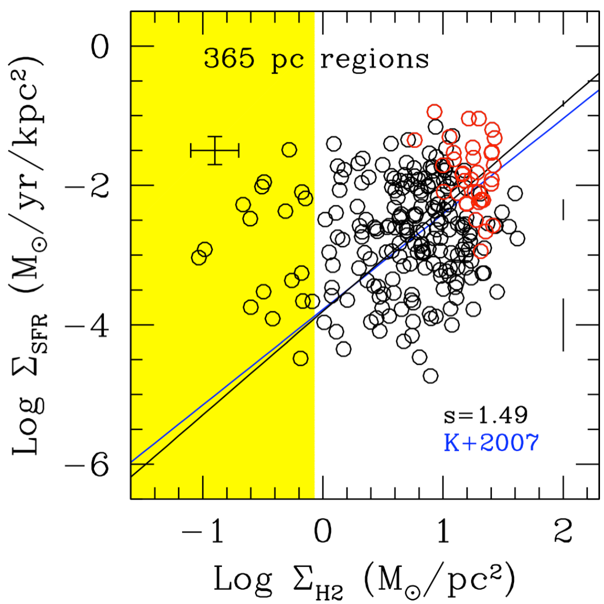
  SFR/mass~ 10^{-9} M_o
- Measure Σ_{SFR} from attenuation-corrected Hα (e.g., using 24 μm emission)
- Measure Σ_{gas} from Σ_{dust} . Derive Σ_{H2} using:

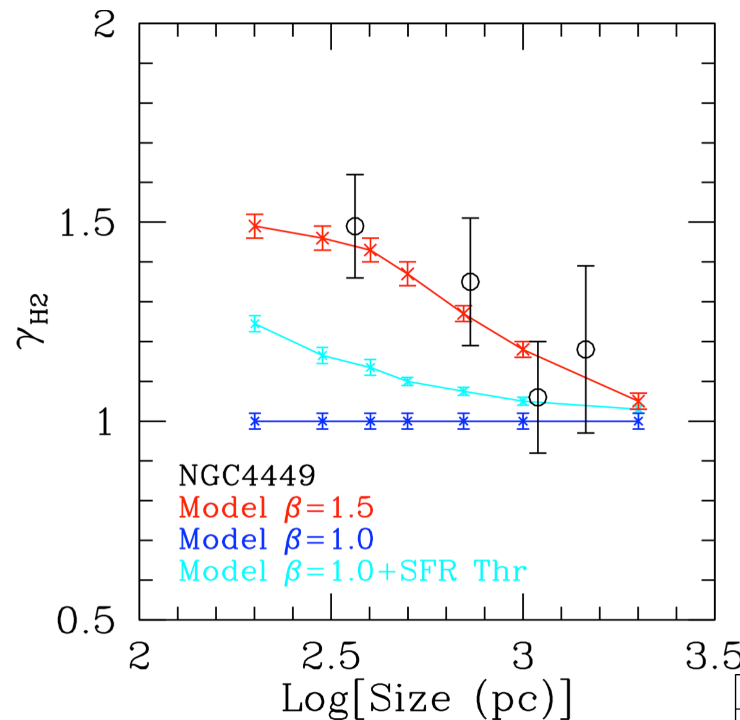
$$\Sigma_{dust} = (D/G)\ [\Sigma_{H2}+\Sigma_{HI}]$$



Mapped at 1.1 mm with the 144-bolometers array AzTec on the LMT in March 2015
- RJ dust emission tail at 8.5" (~170 pc) resolution

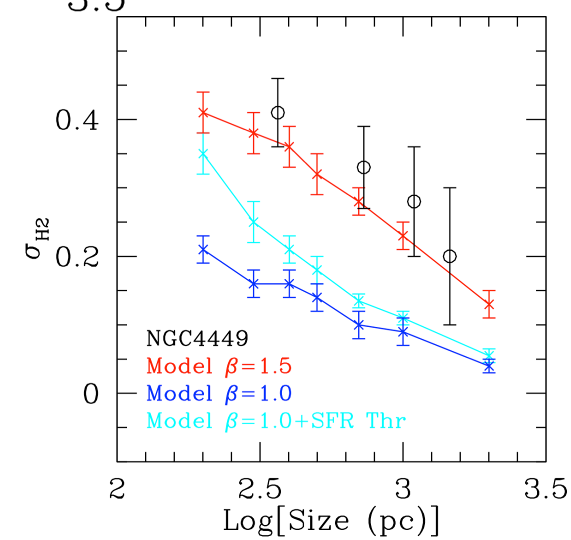
The Molecular SK Law with Spatial Scale





C+2018

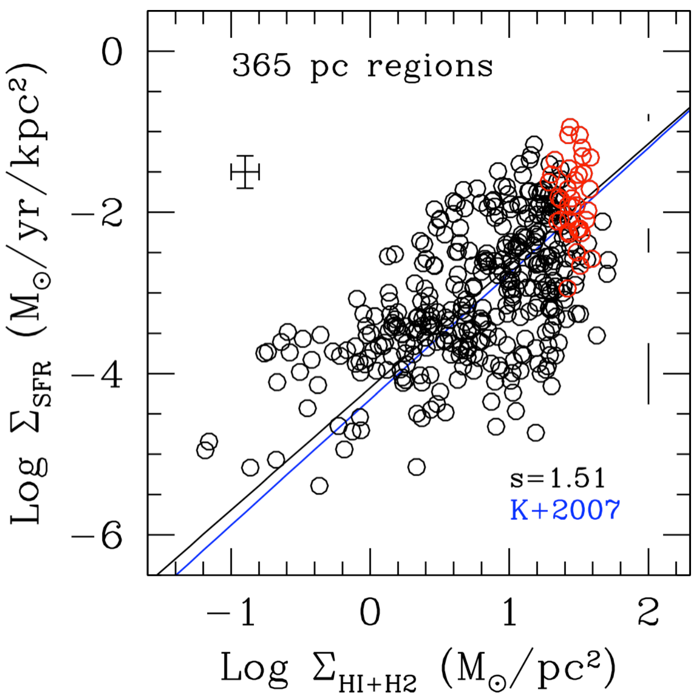
In agreement with results from: Liu+2011 and C.+2012 for 2 massive spirals

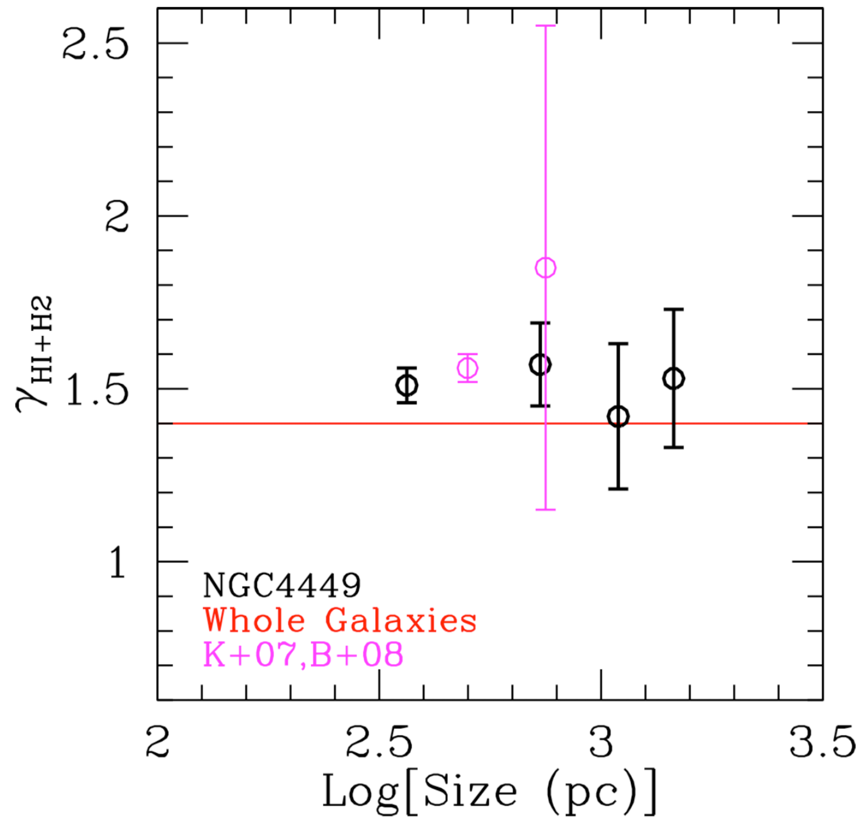


- Model the trend as: $\Sigma_{SFR} = c\, \Sigma_{H2}^{\gamma 2}$, with σ_{H2} scatter.
- Both slope and scatter decrease with increasing spatial scale

The measured trends for the slope and scatter are consistent with `counting clouds'.

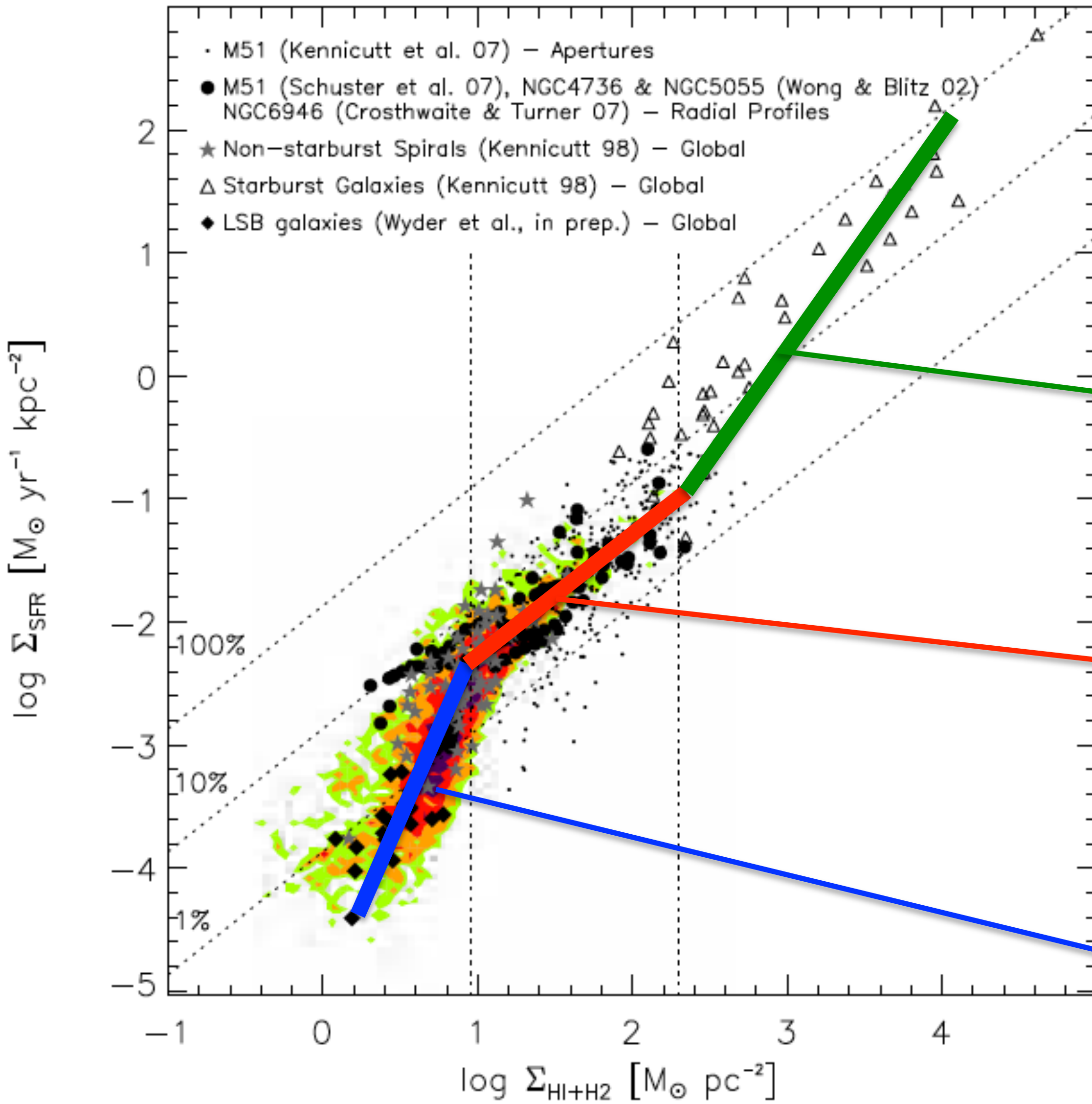
The Total-Gas SK Law with spatial Scale





- The slope and scatter of the scaling SFR-gas relation remains unchanged with spatial scale, when using total gas: HI+H2

Turbulence-induced feedback (e.g. Hopkins+2013, Orr+2017) could be consistent with this picture.



Merging of clouds, physical relation between gas and SF

Cloud sampling and covering factors dominate; geometry rather than physics

HI dominates and SF is in stochastic regime (similar to a threshold)

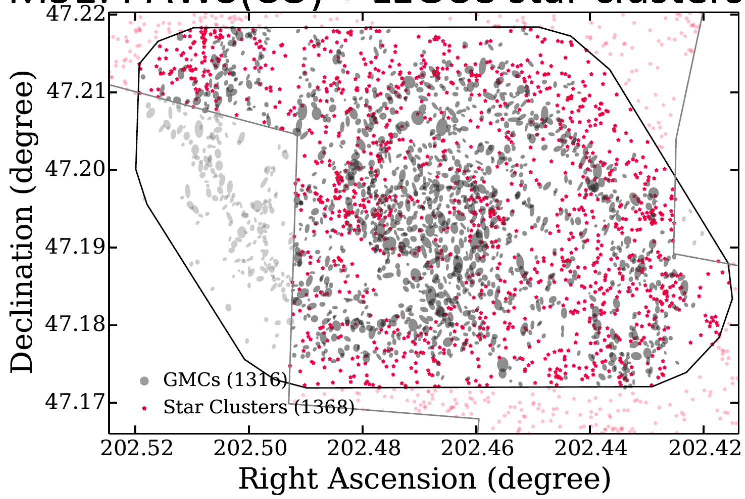
From the IAU 309, July 2014

Legacy ExtraGalactic Ultraviolet Survey

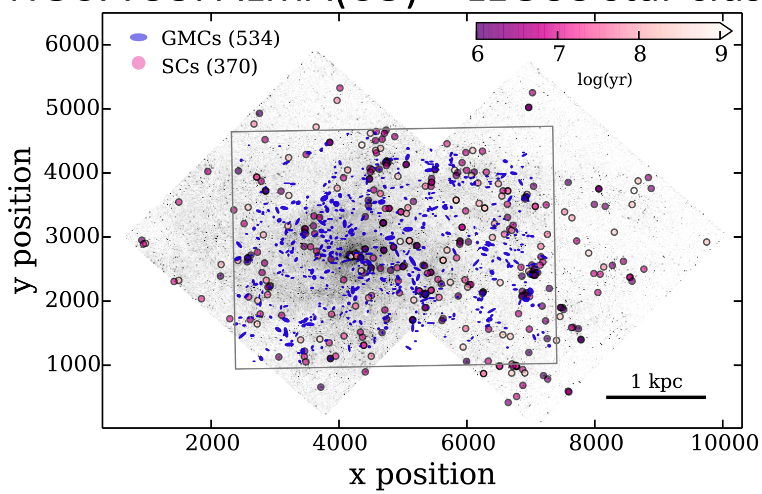
The Hierarchy of SF and Gas

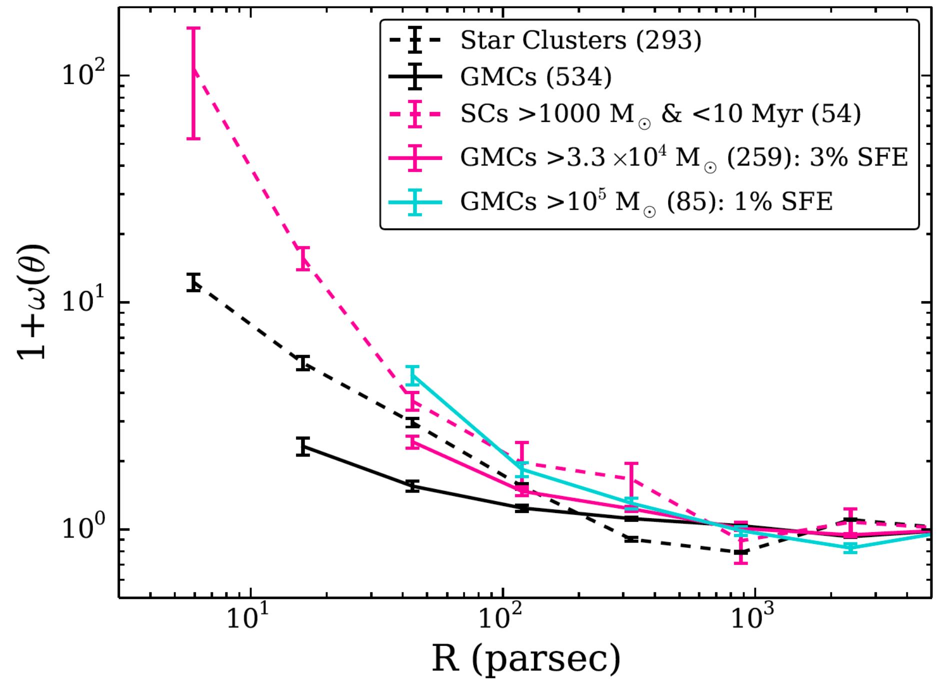
Grasha+2018a,b, subm

M51: PAWS(CO) + LEGUS star clusters



NGC7793: ALMA(CO) + LEGUS star clusters





Massive GMCs have the same clustering properties as the young (<10 Myr) star clusters they produce. The latter can be use to trace the distribution of the former.

(All GMCs are less clustered than SF)

Expectations

If star formation is a random process throughout the galaxy, we expect no correlation between separation and age difference in stars and/or star clusters.

In case of clustered star formation, we can envision several scenarios for:

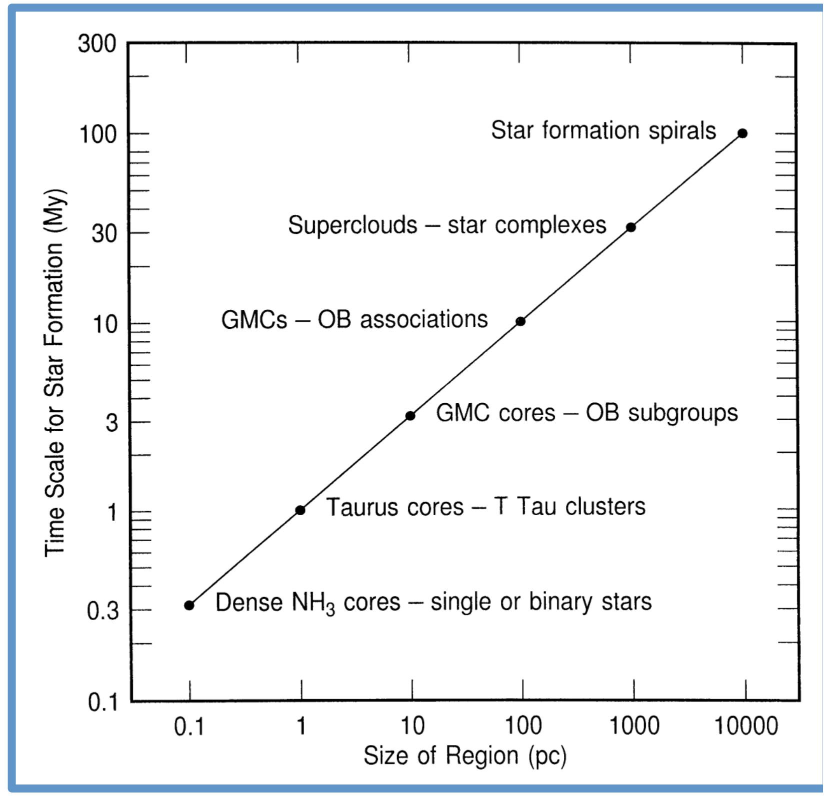
$$\Delta\,\tau(\mathrm{Myr}) \sim S(\mathrm{pc})^{\alpha}$$

With:

$\alpha \sim 1$ for secular evolution-driven expansion of the structure (e.g., stellar drifts);

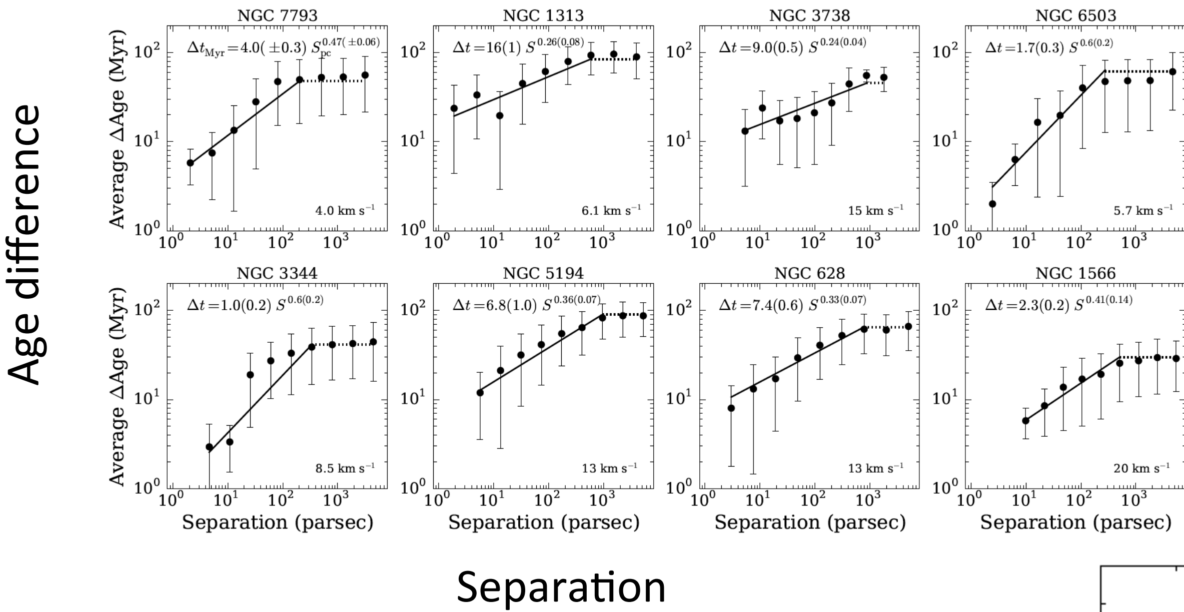
$\alpha \sim 2$ for diffusion-driven expansion (random walk);

$\alpha \sim 0.5$ for turbulence-driven star formation. In this case, $\Delta\,\tau$ is the maximum duration of the star formation within the largest coherent region possible in the galaxy



Only two galaxies measured: LMC and MW, with α~0.3-0.4
(Efremov & Elmegreen 1998, de la Fuentes Marcos & de la Fuentes Marcos 2009)

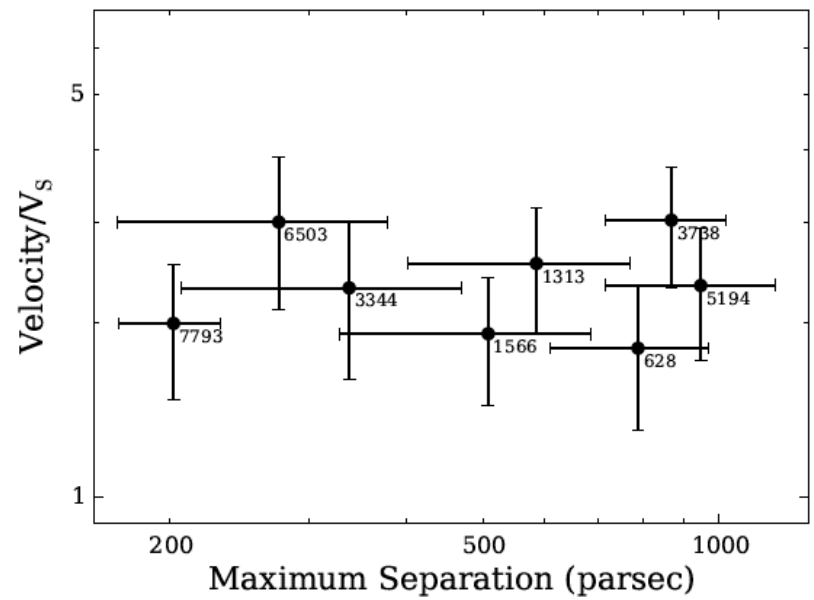
The Star Cluster’s Scale of Coherence



- Slopes in range 0.25-0.6 (closer to 0.5 if only ages<100 Myr included)
- Maximum structure size in range 200-1000 pc; maximum $\Delta\,\tau$ ~30-90 Myr.

Grasha+2017

The maximum velocity at the edge of the largest structure of SF is limited by shear -> Impact of galactic environment



Conclusions

- We are beginning to connect the large to the small scales of star formation within galaxies
- In order to understand star formation, all gas phases need to be considered, while the SFR tracers need to be `cleaned' of diffuse light contamination (contributions from stellar populations older than the relevant timescales)
- Star formation is hierarchically clustered in galaxies over spatial scales > than super-complexes (~200-1,000 pc). The scale could be linked to the galaxy's scale height.
- Massive GMCs clustering closely mirrors that of their children clusters, although the GMC population is less clustered than the star cluster population
- Randomization timescales for the structures are ~30-90 Myr. Structures evaporate within a few tens of Myr, although compact star clusters remain stable for >200 Myr.
- Turbulence is a viable mechanism, but the size of the structures appears to be limited by shear (galaxy dynamics)