Star formation and ISM on parsec scales

Hony, Gouliermis, Cormier, Dib, Galametz, Galliano, Klessen et al.

N66 in the Small Magellanic Cloud

Catalogue of PMS stars from Hubble ST photometry
(PI: Nota)
ISM properties from dust continuum data
(PIs: Gordon, Meixner, Hony)

Simple and direct methods

- Auto-correlation function of PMS stars
- Counting PMS stars → SFR
- Dust SED radiative transfer modeling → dust mass

With some **care** one can obtain

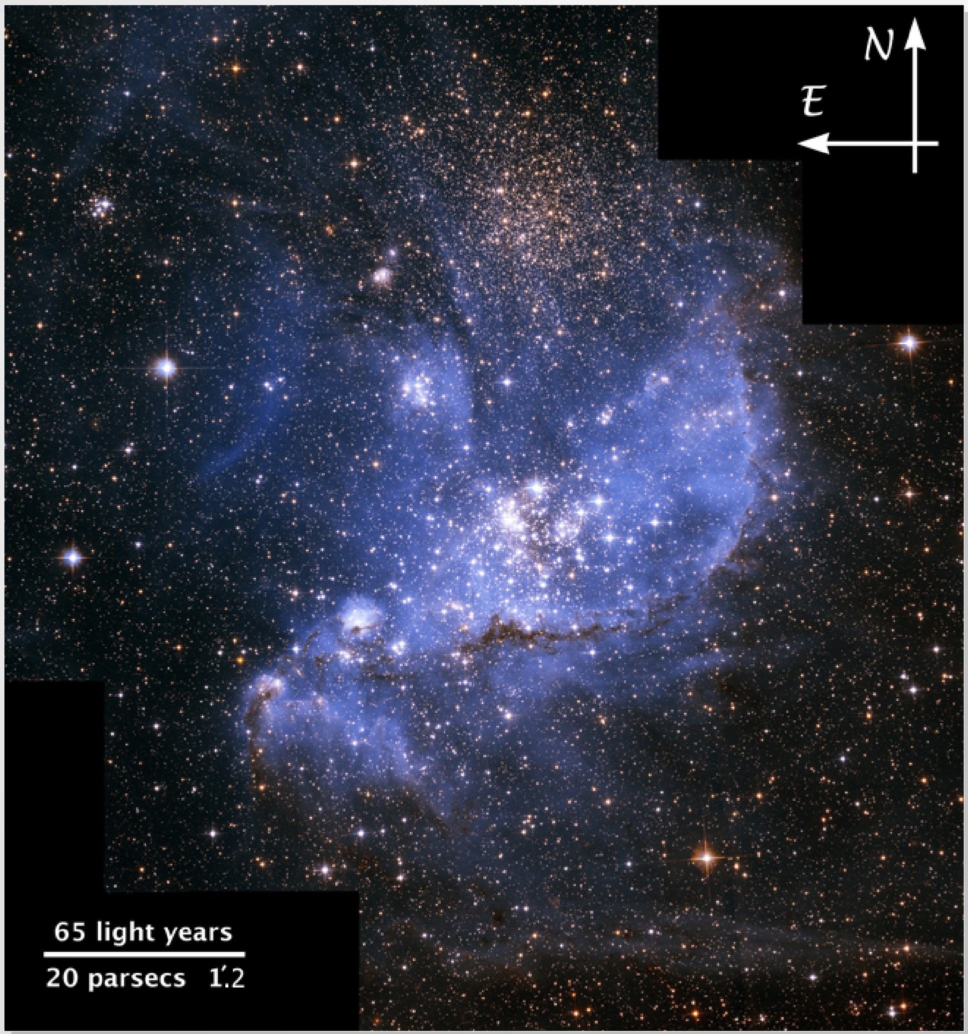
- Quantitative information on the distribution of young stars
- Relation of stars and ISM on otherwise inaccessible scales

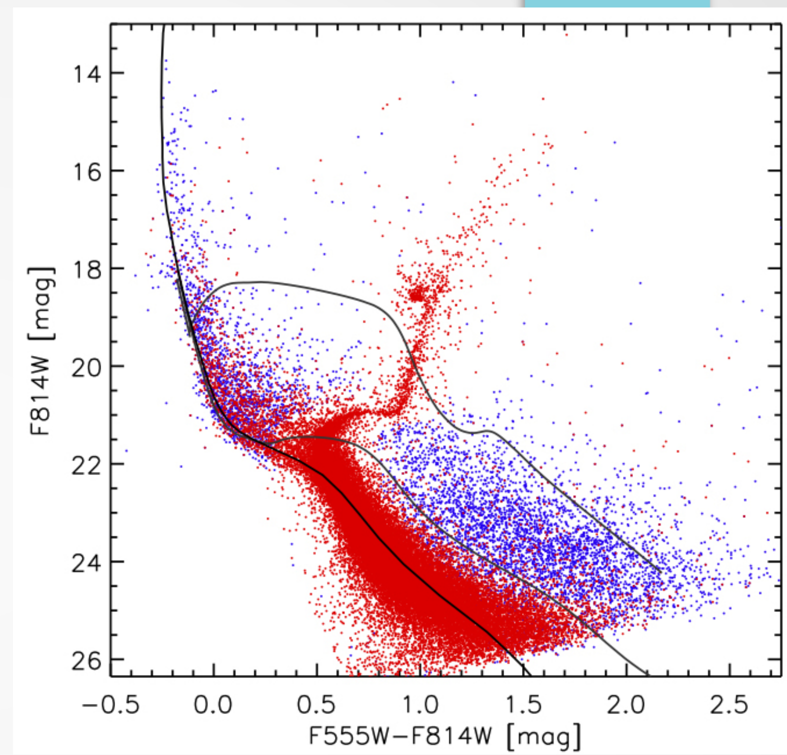
Methodology to bridge galactic and extragalactic SF

- *New physical insights for N66*

The Star-Forming Complex N66

NGC 346 (N66) in the SMC HST (PI: A. Nota)

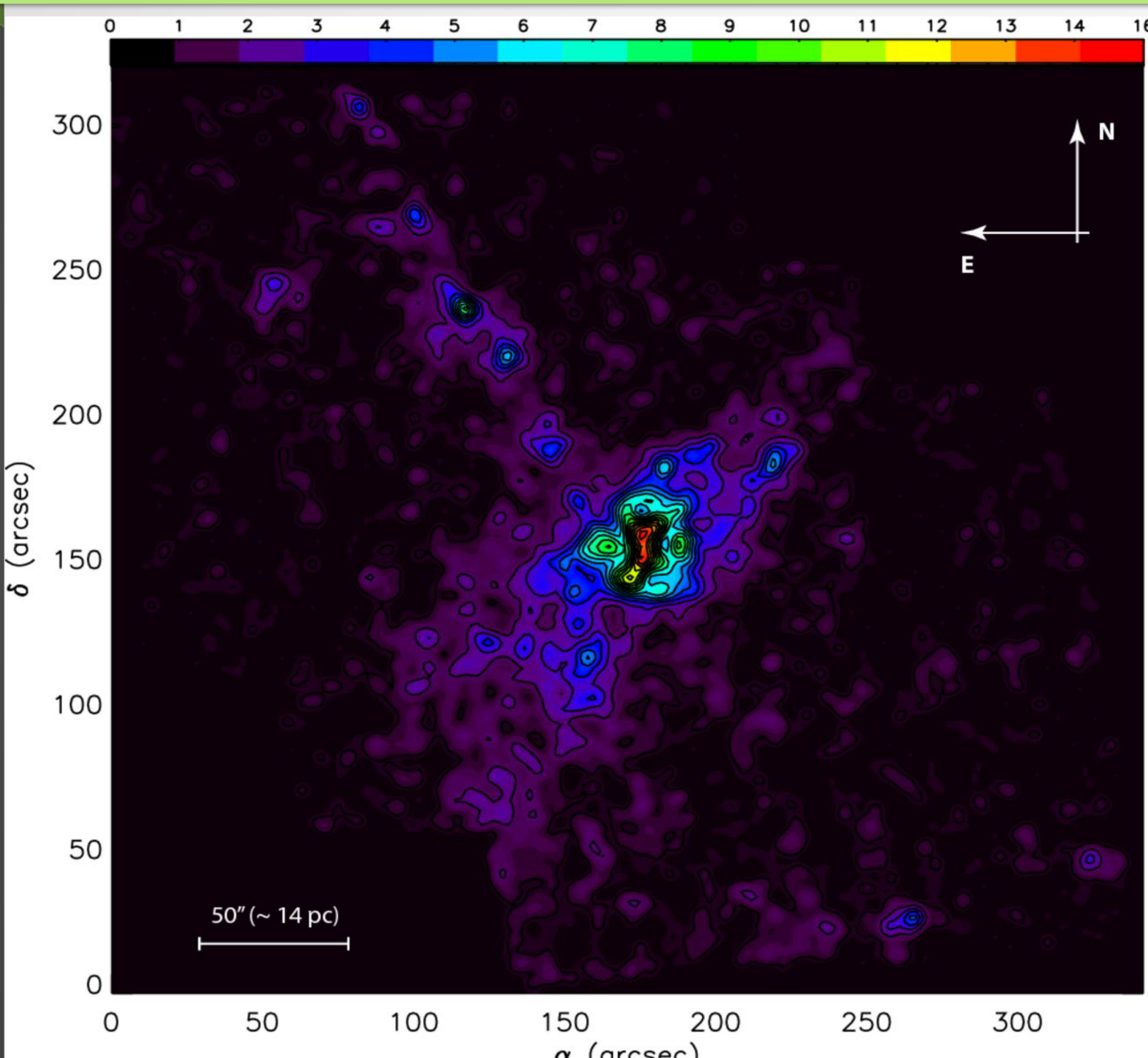




Photometric Catalogs:
> 5000 PMS stars
Ages 0-5Myr
Very rich central part
PMS detected everywhere
(Nota et al, Gouliermis et al. 2006)

Credit: NASA/ESA HST & A. Nota (STScI)

Stellar Clustering in N66



Kernel Density Estimator map: Convolution with 5” Gaussian kernel

- Clear central concentration of PMS stars
- Non-spherically symmetry
- Secondary over-densities

- Use autocorrelation function to characterise the distribution

Gouliermis, Hony & Klessen 2014

The Autocorrelation Function (ACF)

Definition from Peebles & Hauser, 1974

$$1 + \xi(r) = \frac{1}{\bar{n}N} \sum_{i=1}^{N} n_i(r)$$

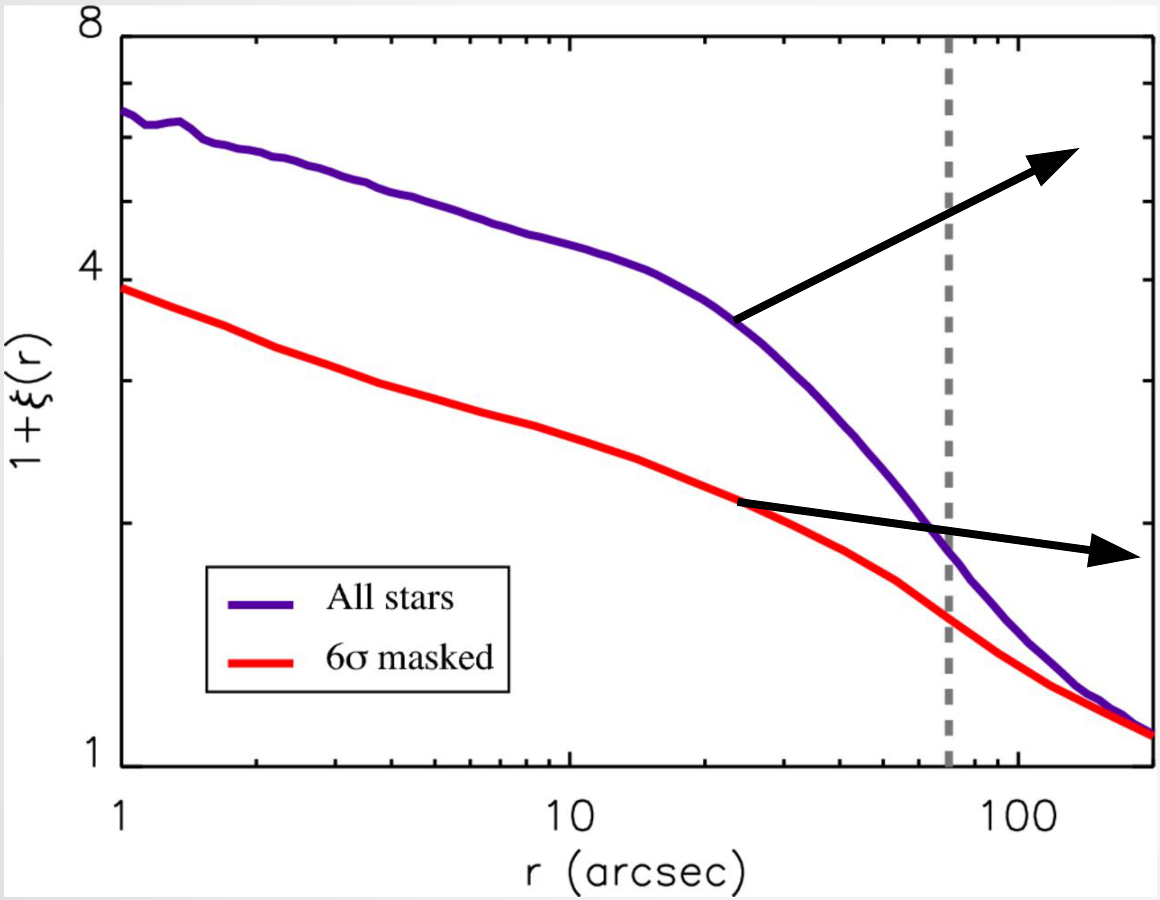
Surface density of stars (n) around star i as a function of distance (r)

Normalised to average surface density

Average over all stars

- Slope is a measure of how “clustered” the distribution is
- Power-law exponent(η) of 1+ξ(r) is related to the fractal index (D_2) for hierachical distributions ($\eta = D_2 - 2$; Mandelbrot 1983)
- Typical values for turbulence driven ISM: D_2 = 1.3-1.5 (Sreenivasan 1991, Elmegreen & Scalo 2004)

Observed ACF



Full ACF has a break around 20”

→ Not a single type of distribution

Without central concentration: power-law behaviour

→ Cluster on top of dispersed distribution

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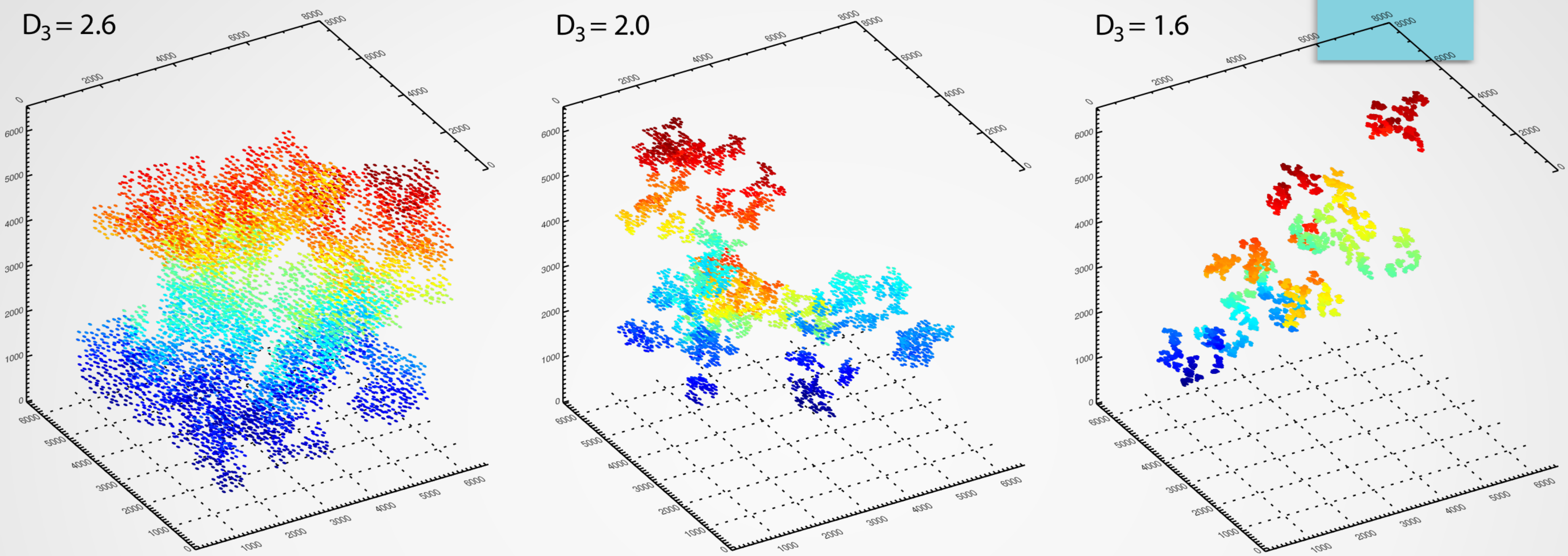
Synthetic distributions



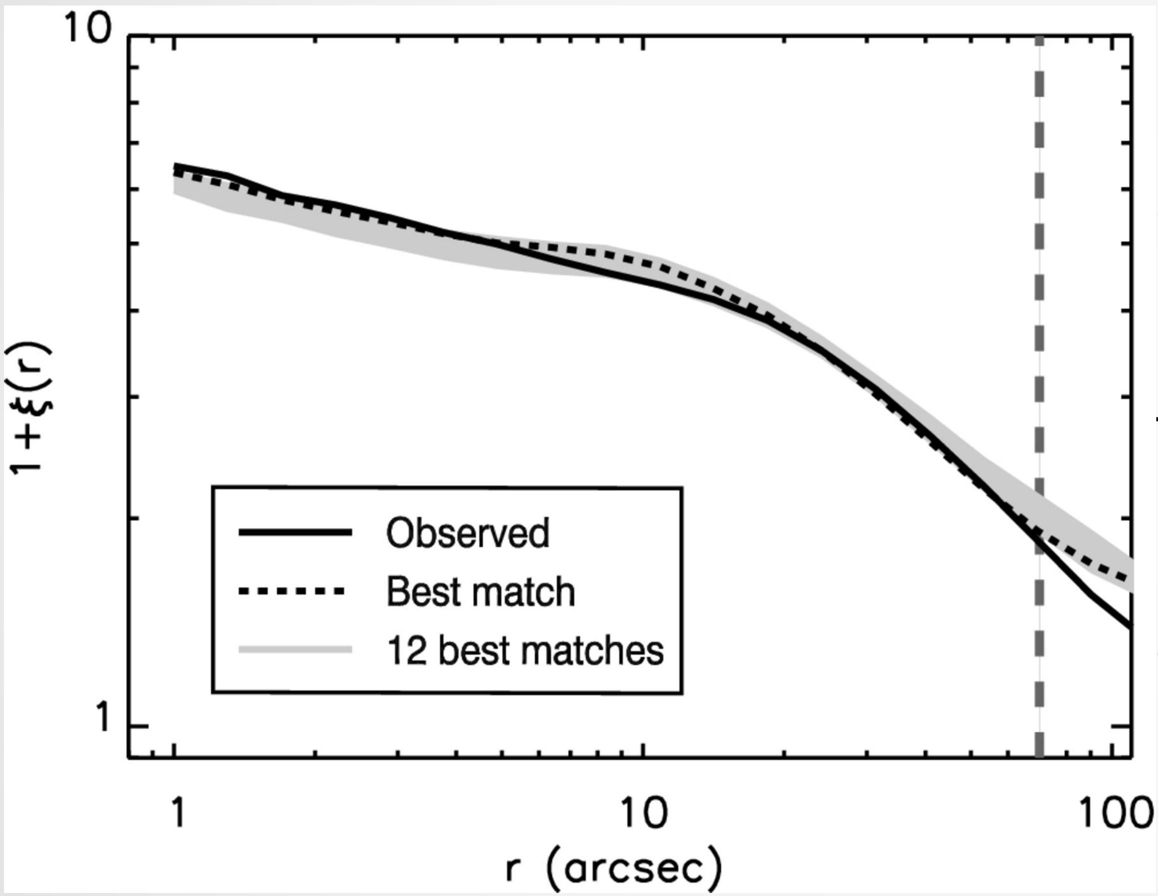
Populations following probabilities given by

+ Clusters (**Elson, Fall & Freeman 1987**)
  not tidally truncated [core radius, central density, outer powerlaw]
+ Random fields
+ 3D Fractal distributions (Cartwright & Whitworth 2004) [fractal dim.]
+ And **combinations** of the above

3D → 2D projection → ACF

(IDL suite available upon request)

A condensed cluster embedded in a fractal stellar distribution



Matching parameters:

Cluster:
Core radius ~9'' (2.5 pc)
Fraction of stars belonging to cluster ~40% (~2000)

"Field":
3D fractal dimension ~2.3
(similar to turbulence)

Gouliermis, Hony & Klessen 2014

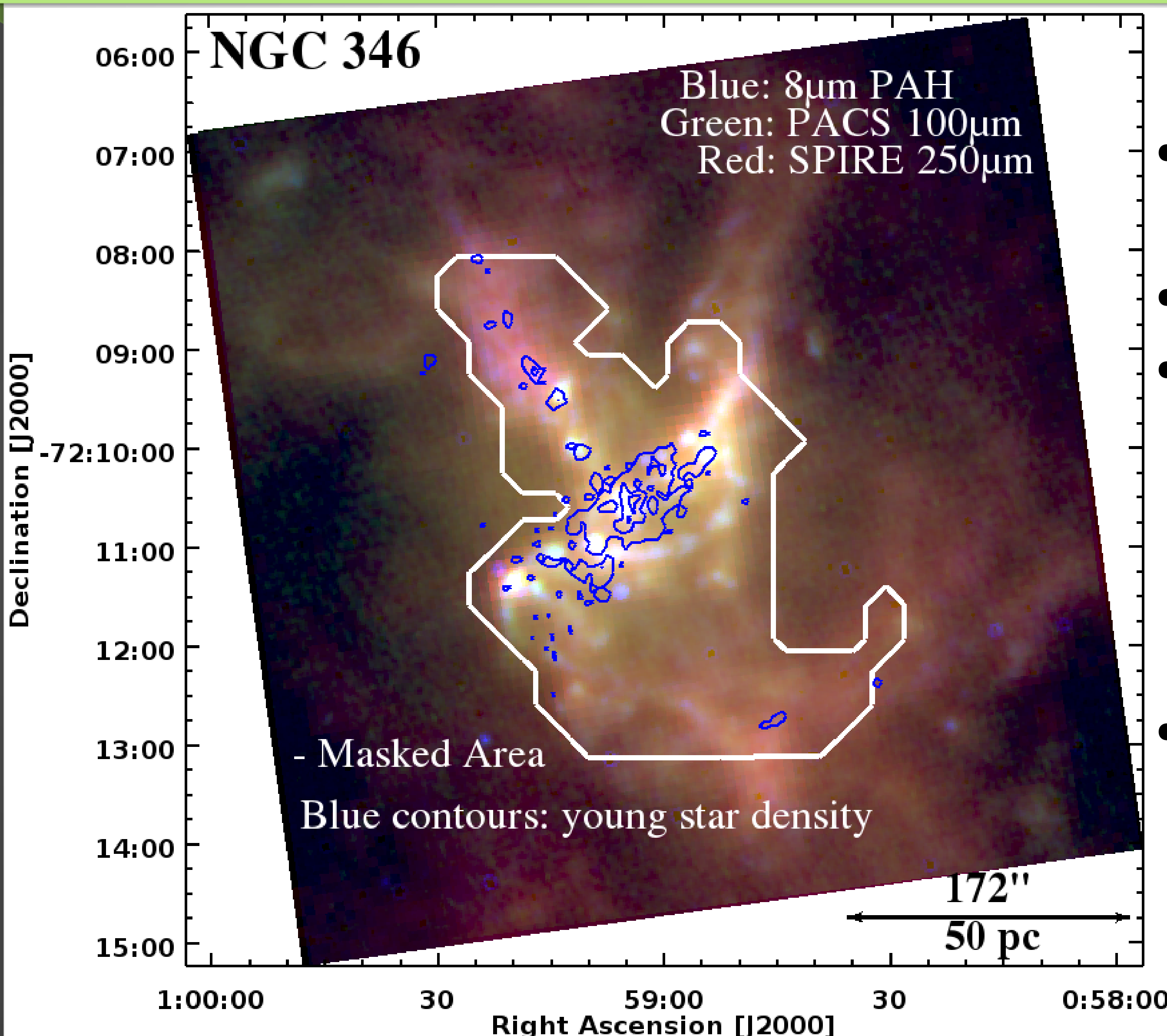
What about the ISM?

Q: How well do the young stars follow the ISM?

Is this bimodal distribution reflected in the ISM?

• SAGE, HERITAGE, Laboca to constrain dust column densities (3.6 - 870 μm)
• Convolved to 20”x20” independent beams
• SED fits → **Dust column density**, Temperature, etc (Galliano Model; Galametz et al. 2009)
• Stellar density map using same beam

N66 in ISM tracers



- 115 independent pixels
- ~50 pc radius
- Covering main cluster but also field and northern molecular "spur"

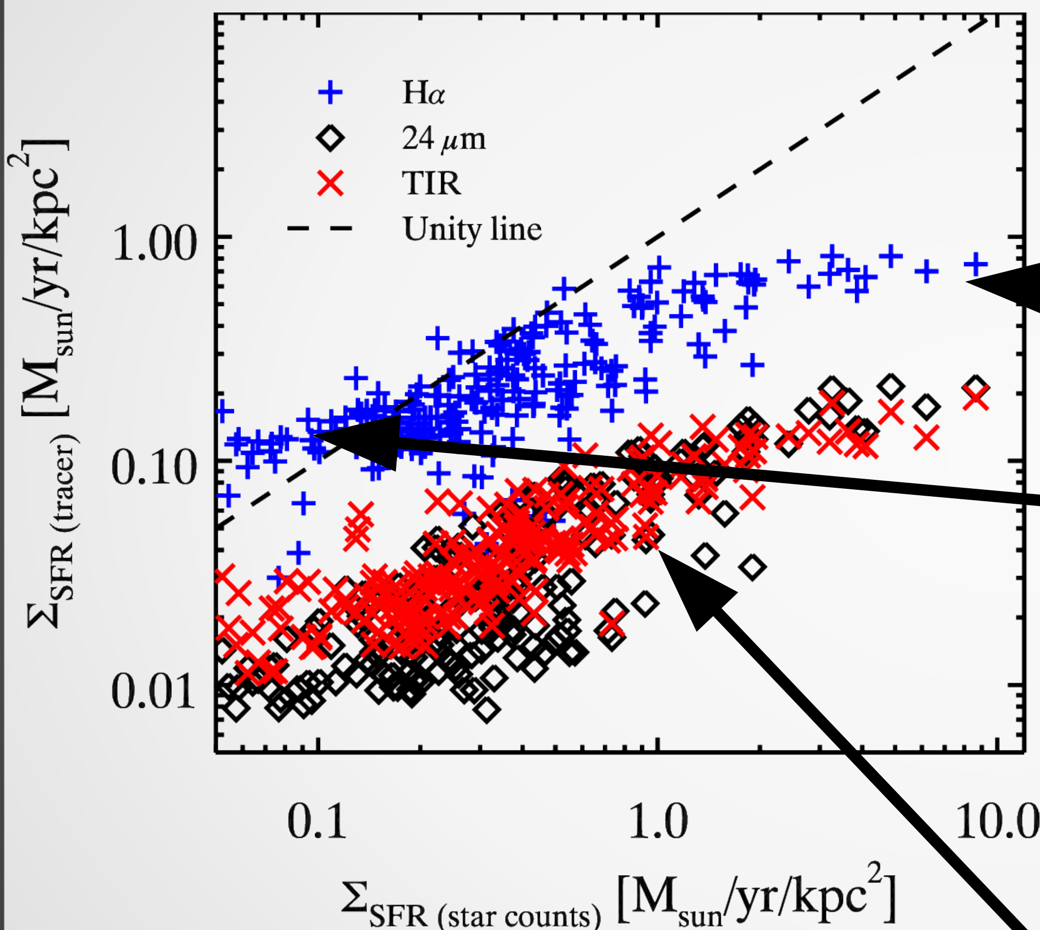
- Masked area is where stars and Laboca are well defined

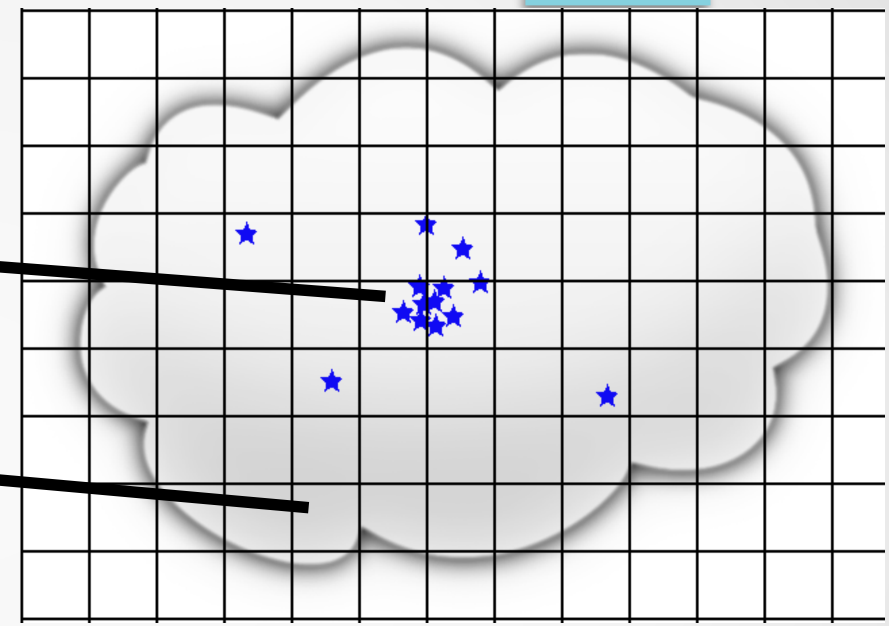
Conversion factors

Quantitiy	Symbol	Value	Comments/Refs
SMC distance	d_{SMC}	60 kpc	Harries et al. (2003)
Detected young stars[a]	$N_{\rm star}$	5150	Gouliermis et al. (2006)
Total young stellar mass[b]	$M_{\rm tot}$	$2.2{\cdot}10^4$ M$_\odot$	Sabbi et al. (2008)
Mass per catalog source[b,c]	$M_{\rm cat}$	4.3 M$_\odot$	$= M_{\rm tot}/N_{\rm star}$
SF duration[b]	$\Delta t_{\rm SFR}$	$5{\cdot}10^6$ yr	Mokiem et al. (2006)
Gas-to-dust mass ratio	$r_{\rm gd}$	1740	Gordon et al. (2014)
Derived Quantity			
Stellar surface density	$\Sigma_\star$		from star catalog
Stellar mass surface density	$\Sigma_{\rm M\star}$	$= \Sigma_\star M_{\rm cat}$	
SFR surface density	$\Sigma_{\rm SFR}$	$= \Sigma_{\rm M\star}/\Delta t_{\rm SFR}$	
Dust column density	$\Sigma_{\rm dust}$		from SED fitting
Gas column density	$\Sigma_{\rm gas}$	$= \Sigma_{\rm dust} r_{\rm gd}$	
Stellar mass fraction	$frac_{\rm M\star}$	$= \Sigma_{\rm M\star}/(\Sigma_{\rm M\star} + \Sigma_{\rm gas})$	

[a] See Sect. 2.1. [b] See Sect. 2.5. [c] This mass is *not* the mean mass of the *HST* detected sources but the mass each source represents after correcting for completeness. The mean mass of the young stars in the *HST* catalog is ~2 M$_\odot$.

SFR compatible with Hα or TIR?





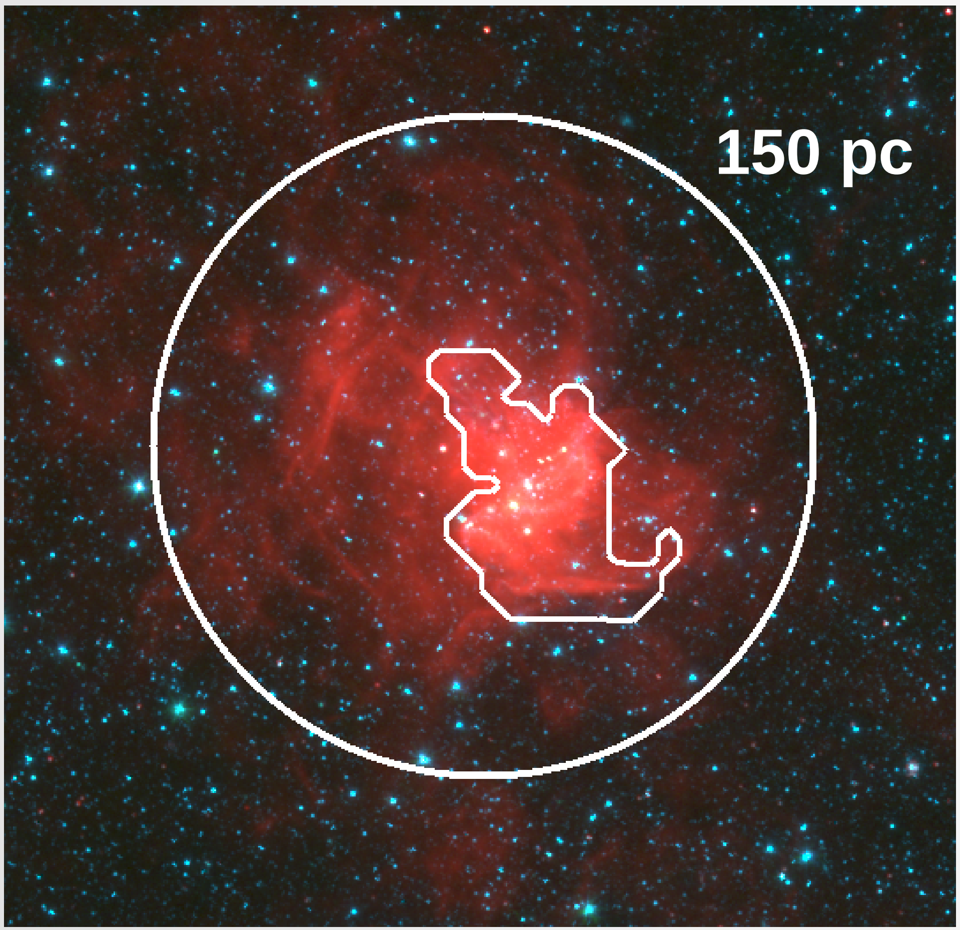
These tracers are not local on ~10 parsec scales

Would break SK even if stars follow ISM

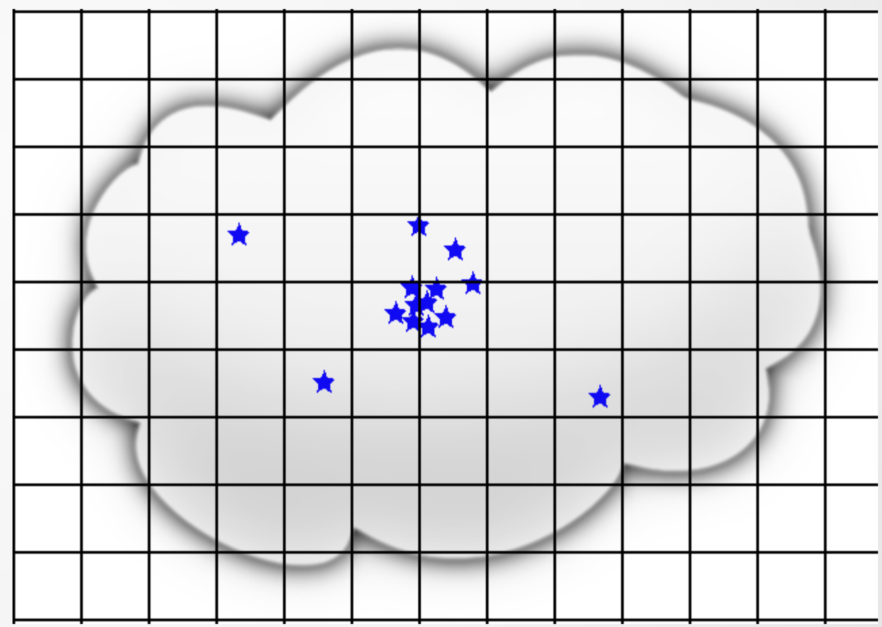
Not locally and not with dust because of little dust

(Direct effect of low metallicity and low dgr of SMC)

The Hα nebula is large

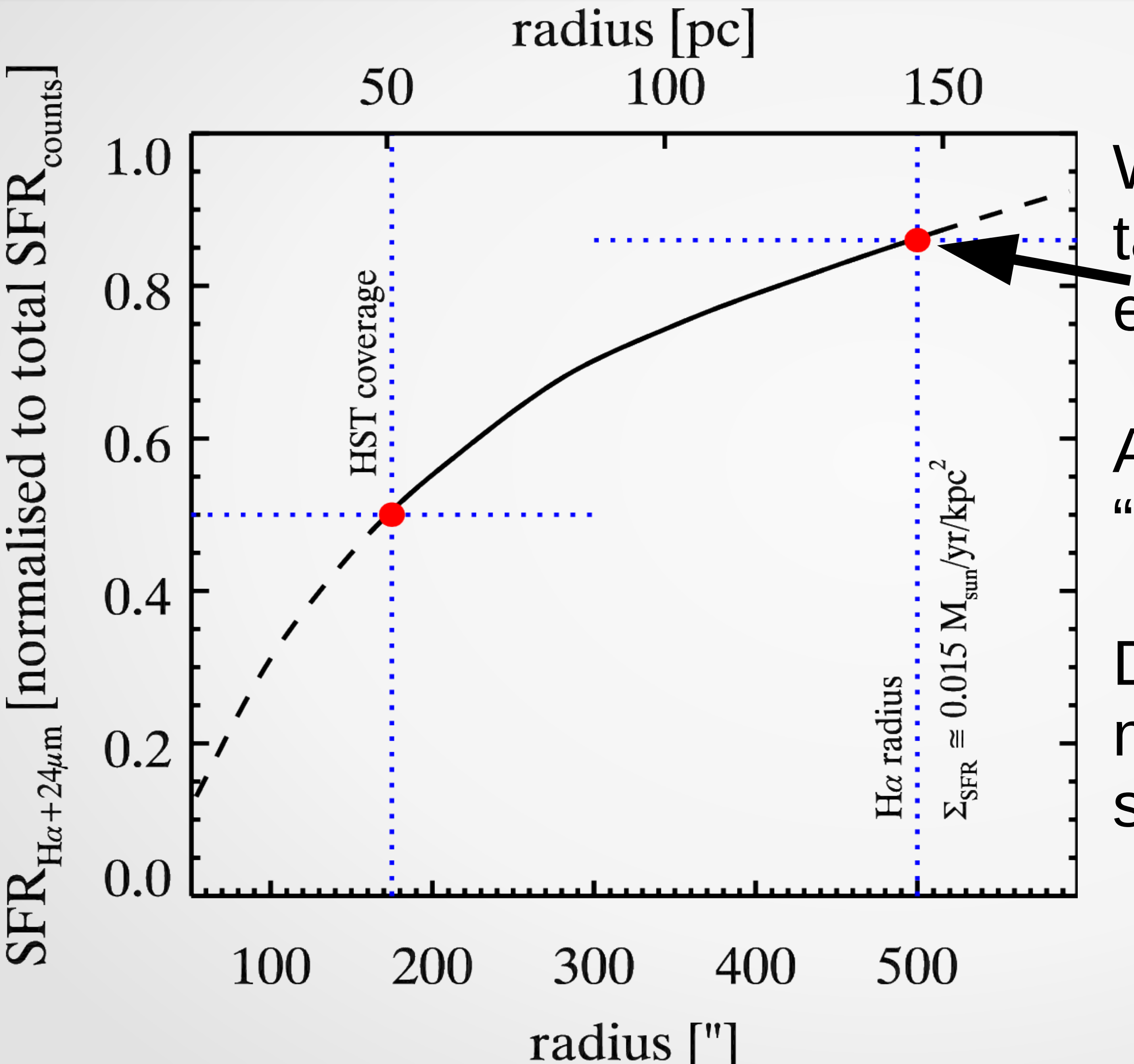


Cartoon is quite accurate



Hα MCELS (Smith et al 2000, Points priv comm.)
Stars (Sage-SMC Gordon et 2011)

Remission tracers require averaging



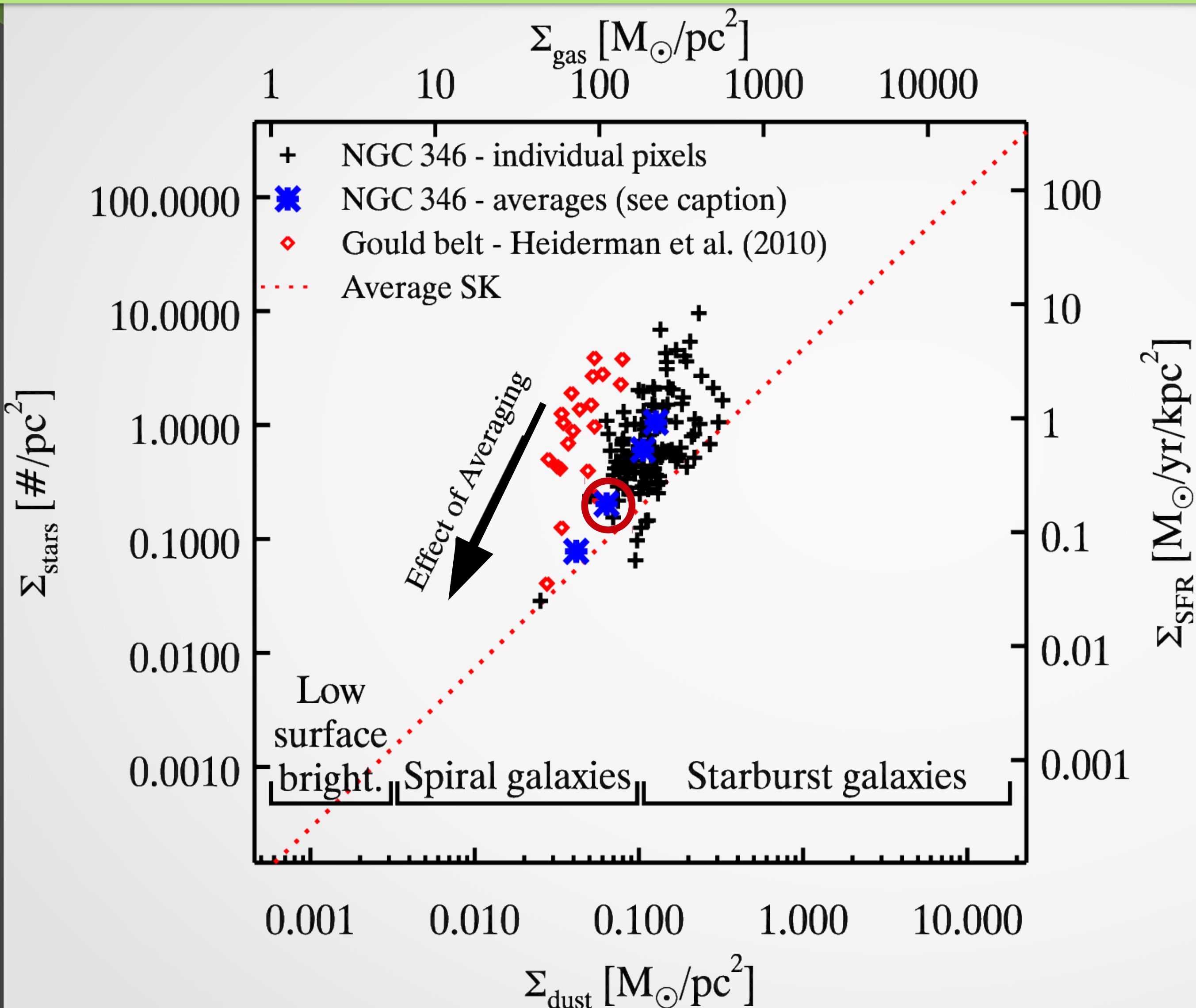
Works globally when taking into account the entire Hα nebula

Absolute calibration is "correct"

Direct SFR tracers needed to study small scale variations

Hony et al, in prep

Comparing to SK

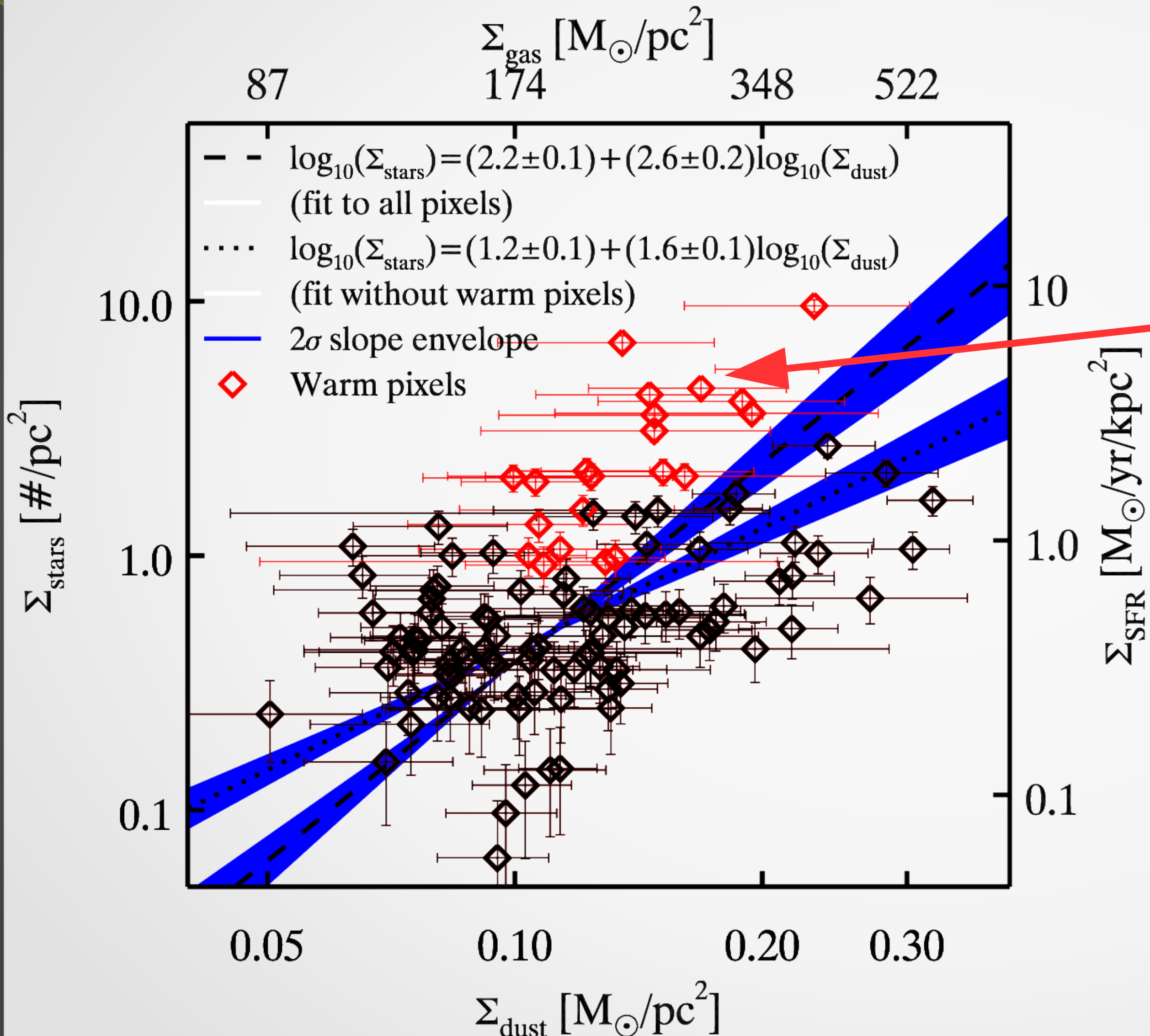


Individual points lay systematically above SK

- **Averaging** over Mask, 50, 90 and 150 pc brings points closer
- Similar to Heiderman et al 2010.
- *Not the most instructive comparison.*

Hony et al, in prep

Zoomed in view



- Some correlation with a lot of scatter
- Highest points are all warm (near the main cluster): $(\Sigma_{24\mu m}/\Sigma_{250\mu m}>0.3)$ [(Mjy/sr)/(Mjy/sr)]

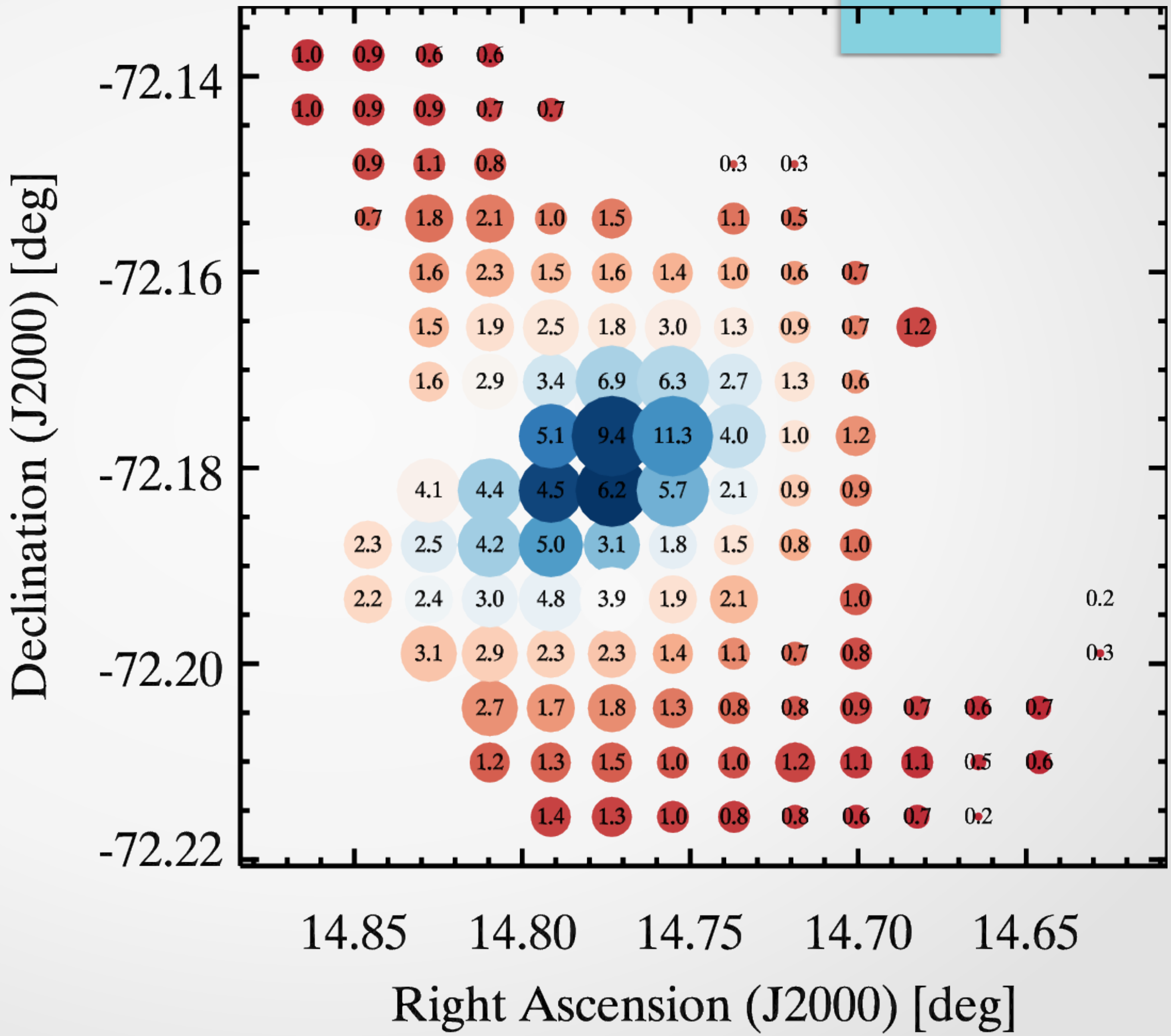
Stellar mass fraction map

Variations (scatter) is **not random**!

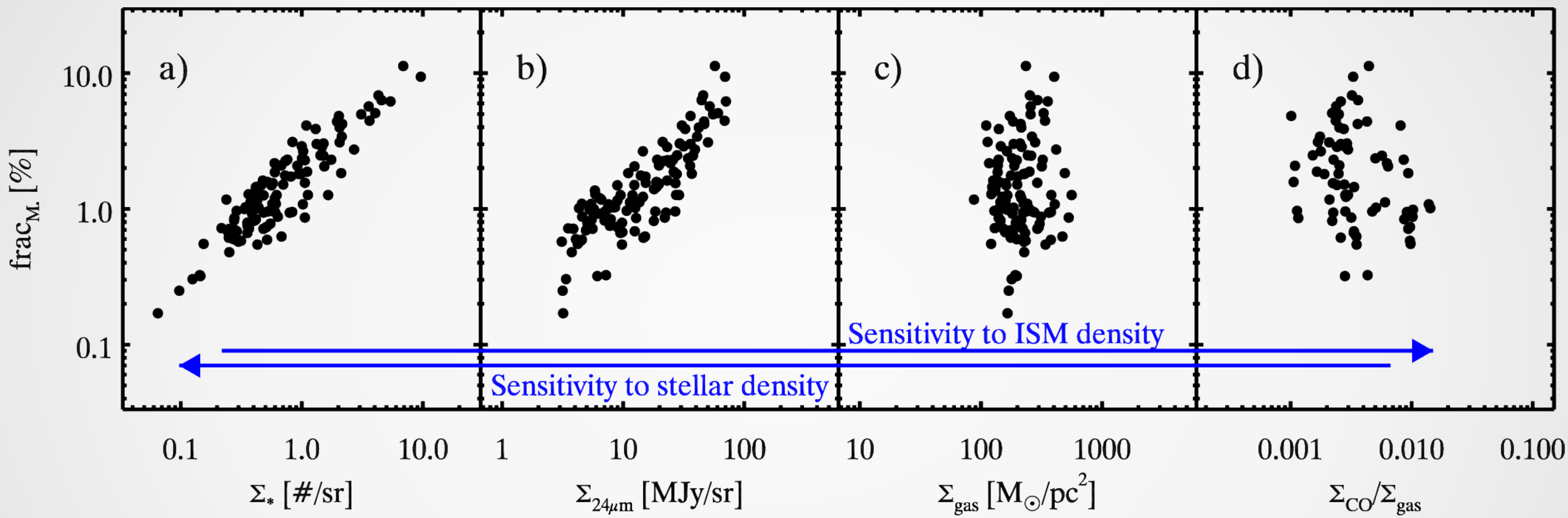
Mostly between 0% and 2% (size of points)

High tail to ~10% towards the cluster

High values correlate with 24μm emission (colour of points)



Stellar mass fractions vs X



Correlates best with **direct stellar tracers** (radiation field, stellar density) and much less with **ISM conditions**.

Interpretation: *ISM conditions that led to cluster formation have already been erased*

Conclusions

ACFs and PMS star counts are **powerful tools** to study star formation

N66:

Rich cluster (>2000 PMS) **embedded** in fractal distribution

N66 averaged SFE over 90 pc is high compared to SK by a factor of 2

Stars and ISM correlate **even on small scales** (6pcx6pc) with scatter

Variations are **not random** but highest values (by factor of 3-5) are **all** cluster environment

Suggestive*: High SFE in clustered environment*

Advantages and pitfalls

ACF (or Δ-variance):

- Compared to nth-nearest neighbor or Q-parameter: can detect change of behavior at specific spatial scale
- Requires careful treatment of **edge effect** and **absolute number** of sources

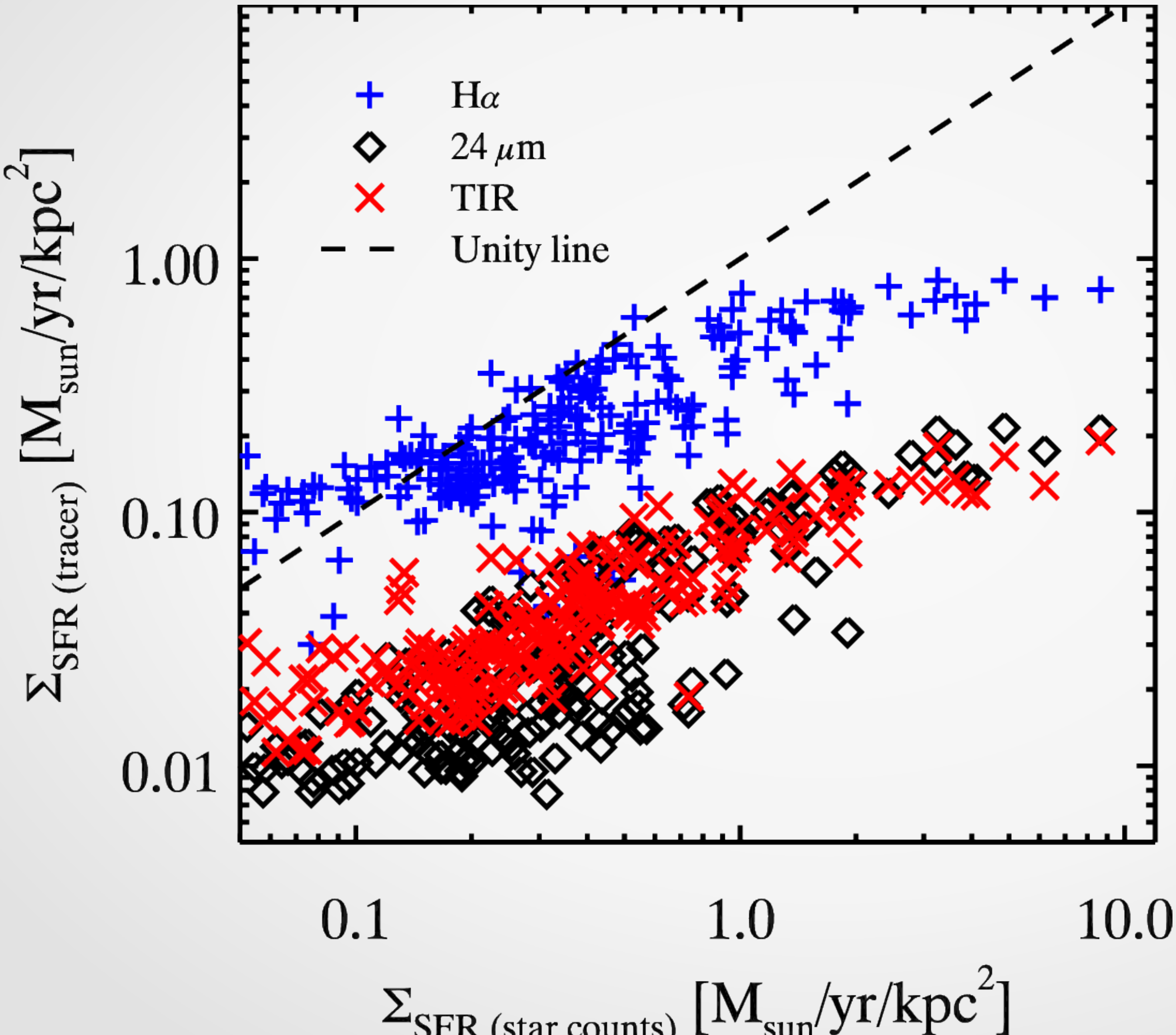
Star counts:

- Does not require assumed **mass function** or **ages**
- Access to **smaller spatial** scales (~pc) than traditional tracers

Dust method:

- Large/Complete coverage
- Not sensitive to gas state or X_{CO}
- Assumes gas and dust are **well mixed** and **constant gas-to-dust mass ratio** (appears valid in this case)

Dust emission and Hα are tightly correlated



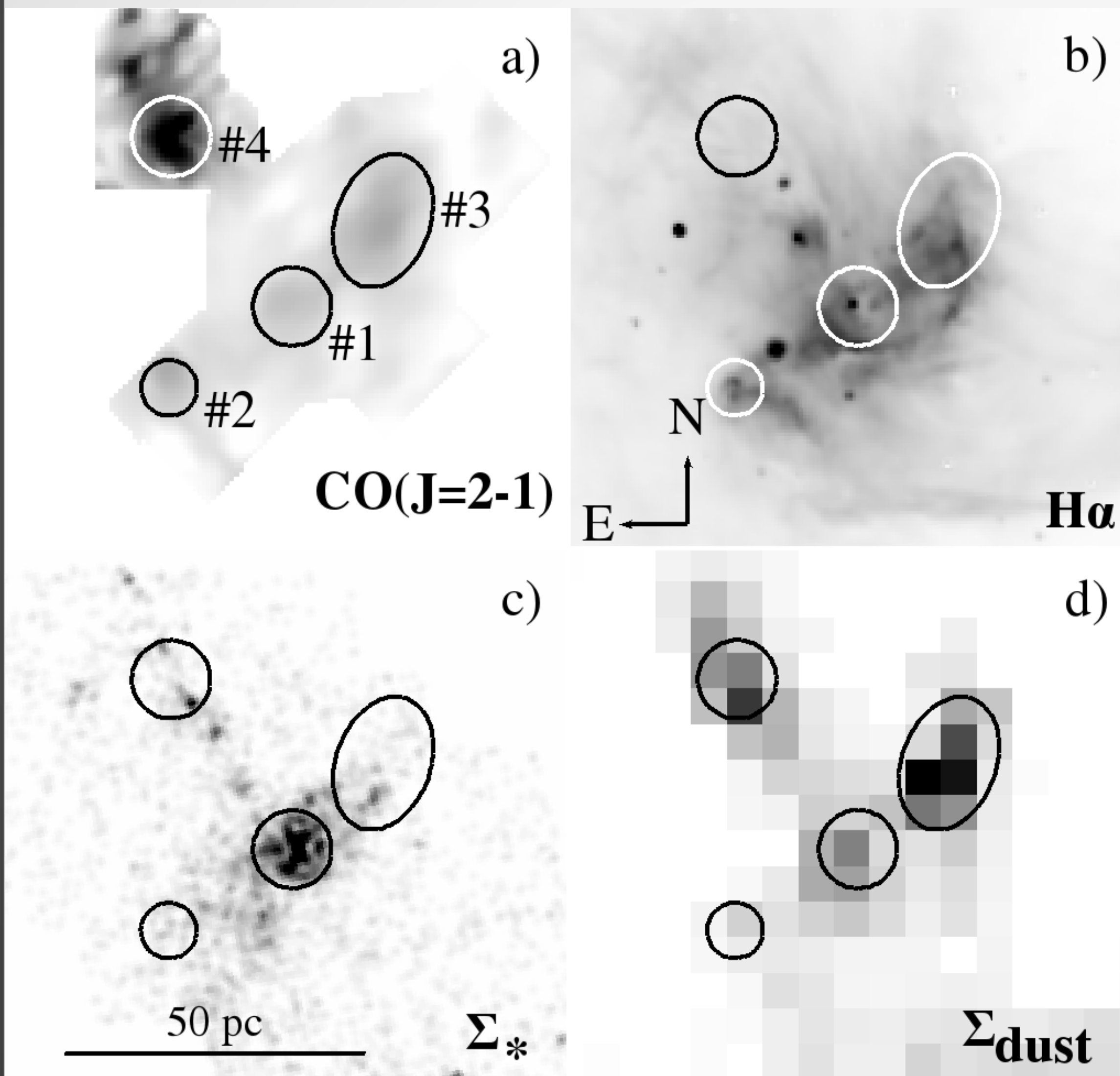
Less than 20% variations in their ratio

Variations do not resemble SFE map

If ~optically thin, ratio measures the chance to be absorbed by gas or dust

→ no **strong** variations in gas-to-dust

Variety of environments



#1: many stars, little CO, highest SFE

#2: intermediate SFE

#3: lots of dust, little CO, low SFE

#4: lots of dust, strong CO, low SFE

#4 could become like #1 if strong new SFE will occur

#2 and #3 will probably not

Importance of 3D simulations

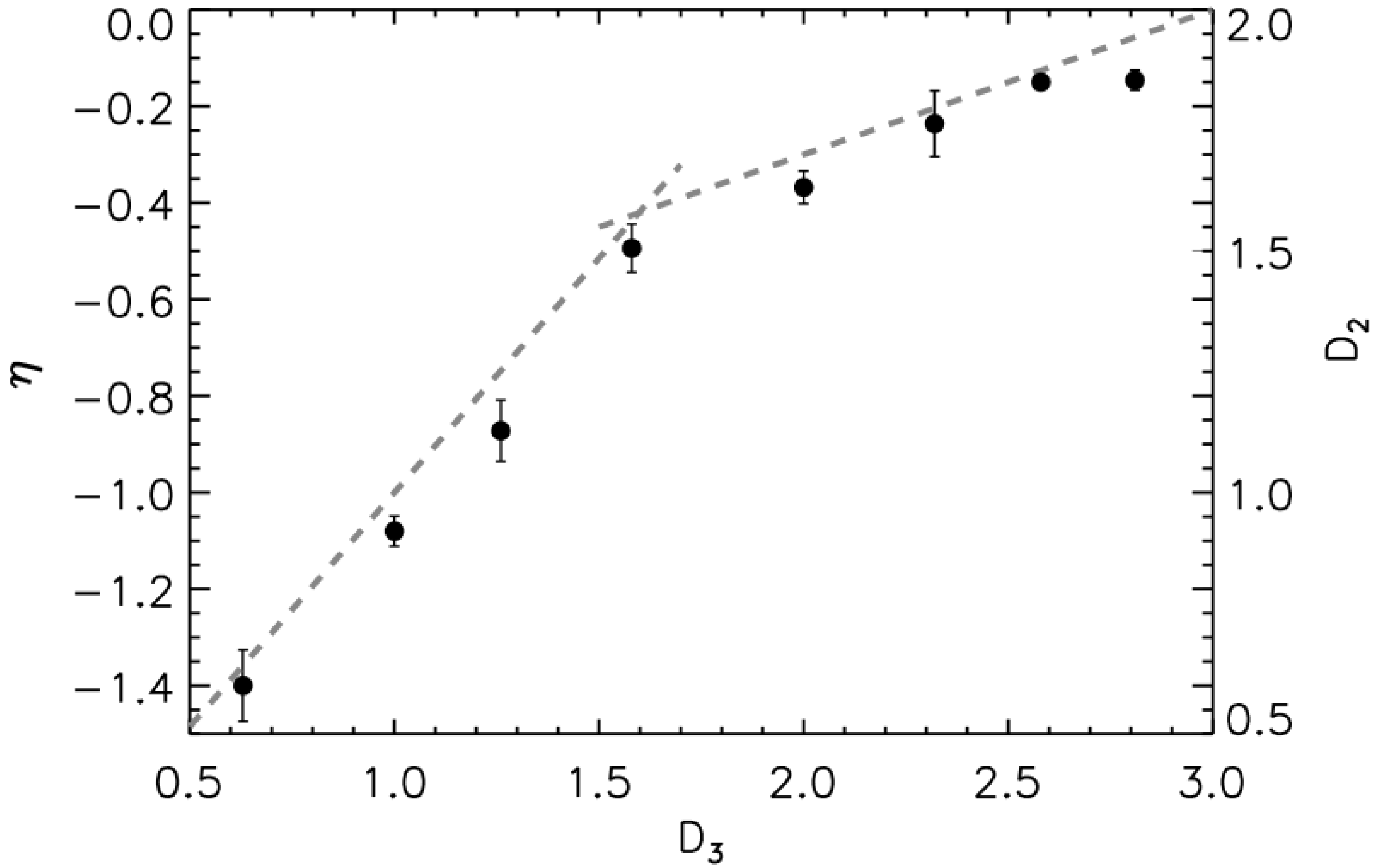


Figure B1. Calibration relation between the three-dimensional fractal dimension D_3, the ACF index η, and the corresponding two-dimensional fractal dimension D_2, derived from our simulated self-similar stellar distributions.

Importance of 3D simulations