The formation of stars in the outer disks of galaxies

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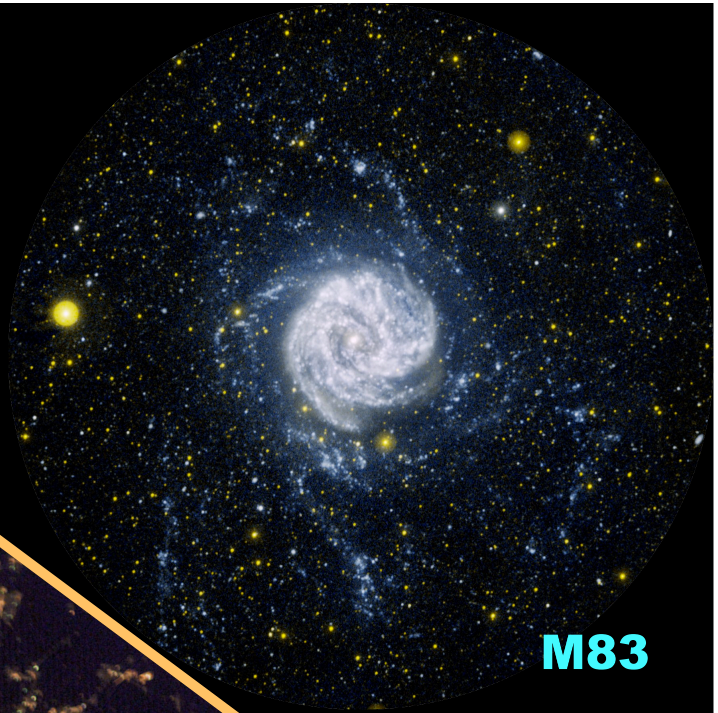
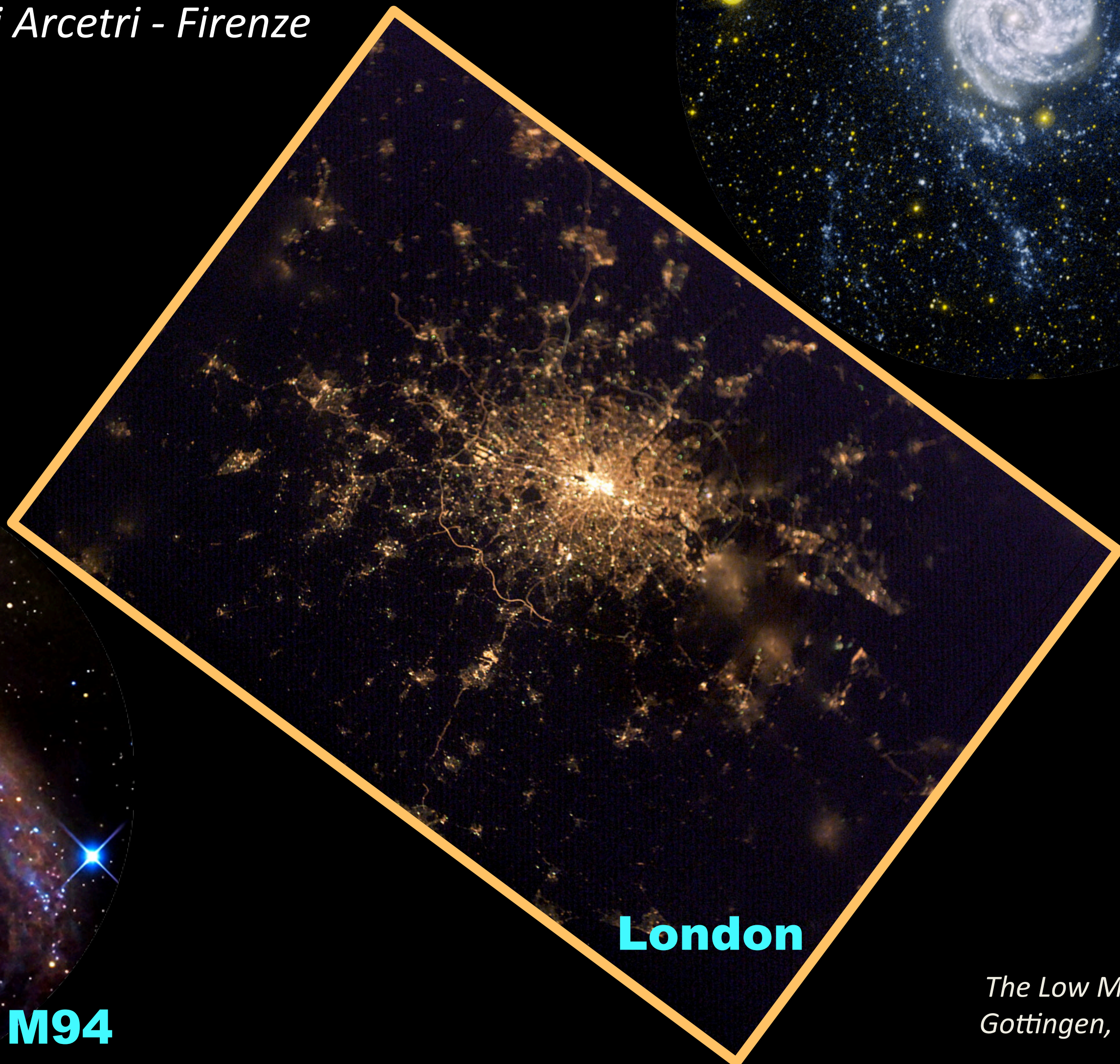




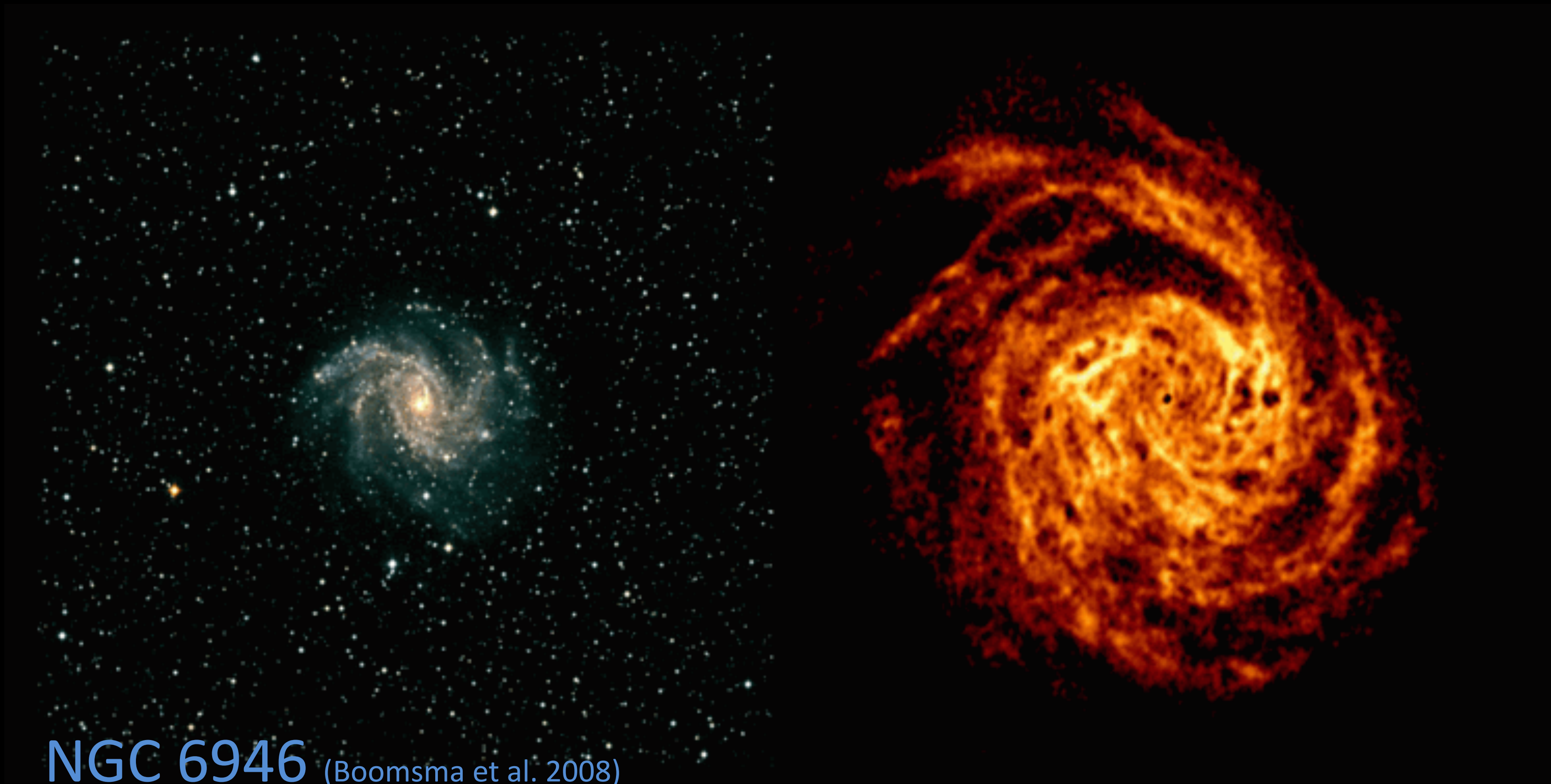
The Low Metallicity ISM
Gottingen, October 2012

Why are outer disks interesting ?

- Lower density, lower metallicity than bright disks: how do they form stars? Do they fuel inner disk SF?
- Possible analogue of high-z objects such as DLAs
- Provide important information on how disks are assembled and on the environment
  - They are dominated by dark matter

Galaxies are more extended than previously thought!

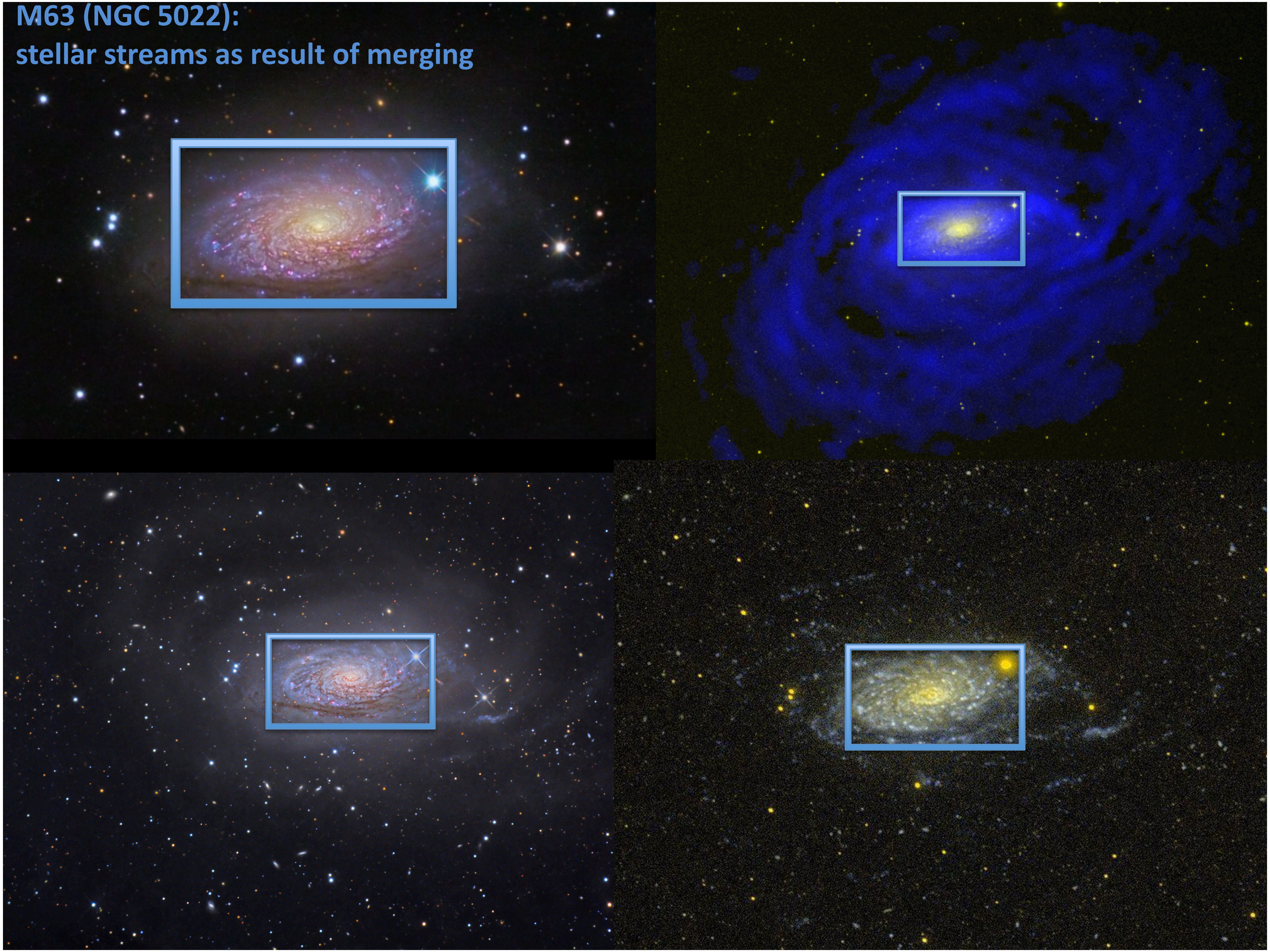
First evidence came from 21-cm surveys

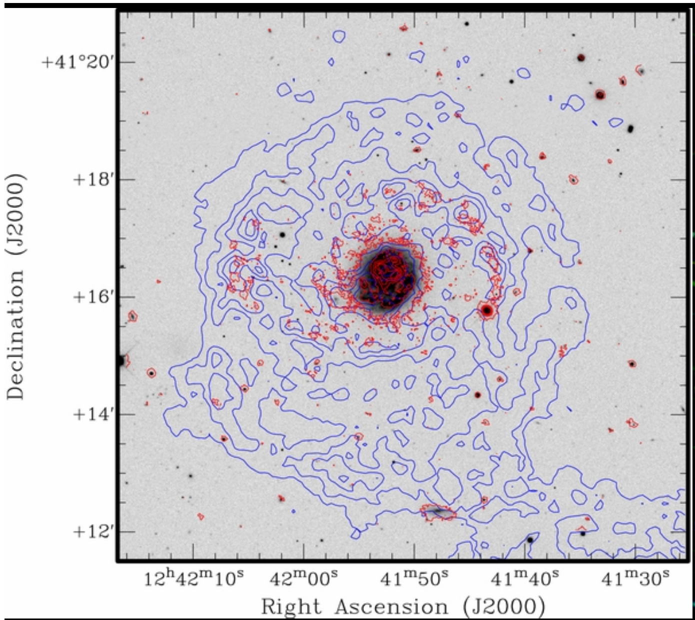


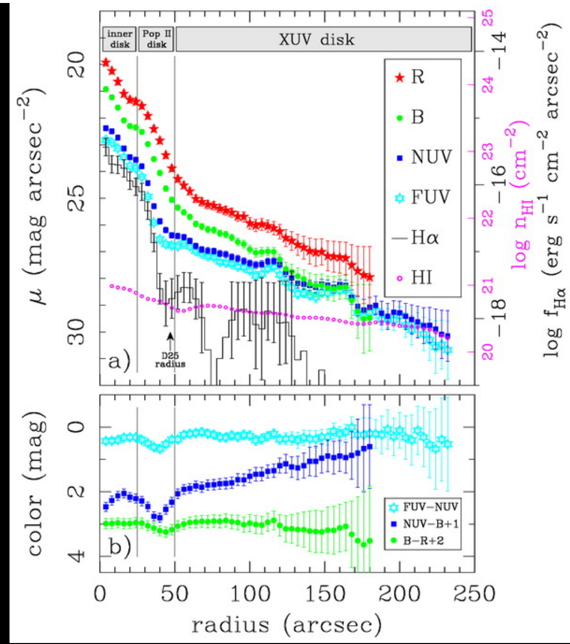
Thanks to GALEX/THINGS and to other nearby galaxy surveys

we know that outer regions have: lower Σ_{gas} - lower SFR - lower Z

M63 (NGC 5022):
stellar streams as result of merging





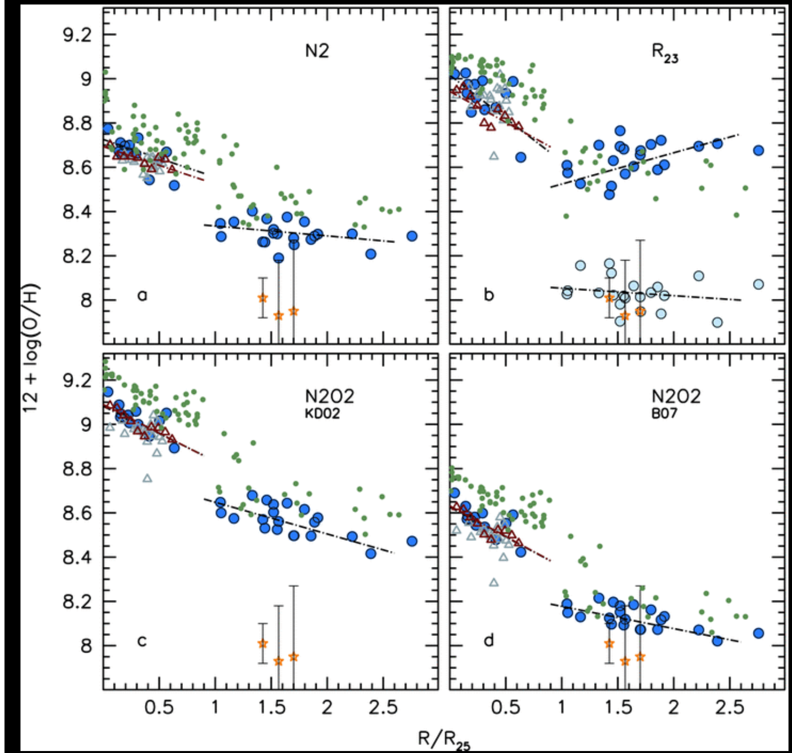


Recent star formation in UV disks: the NGC 4625 case

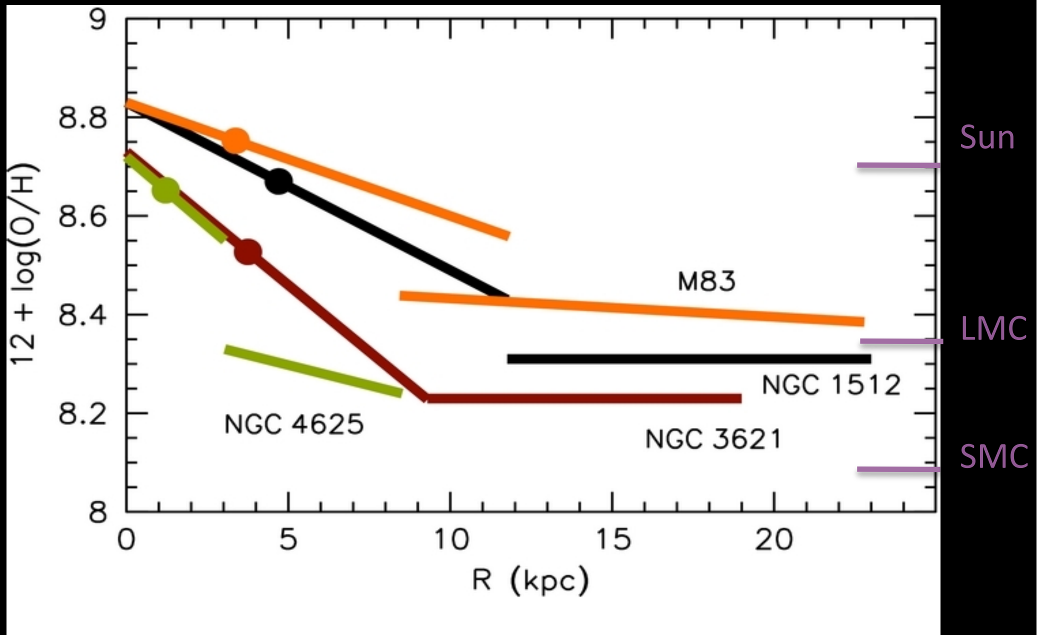
(Kaczmarek & Wilcots 2012, Gil de Paz et al. 2005)

Is galaxy-galaxy interaction always the trigger of SF?

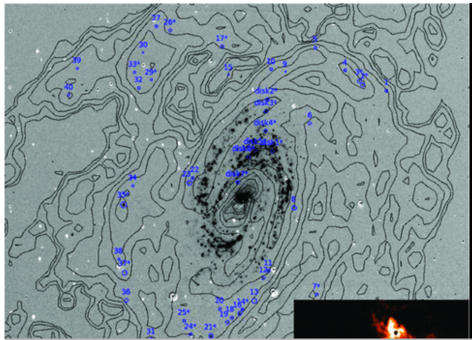
Metallicity in outer disks is lower than innner disk and the gradients observed (in bright regions) are flat



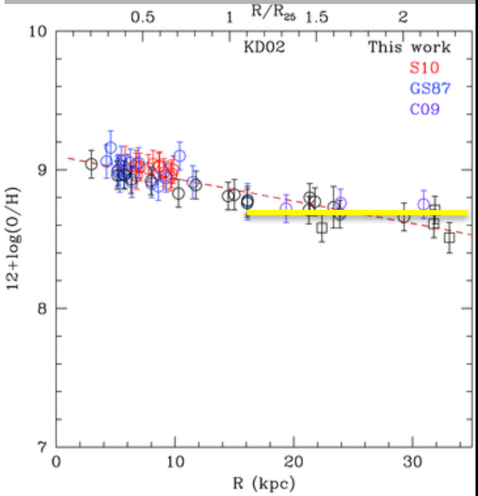
Metallicity values depend on the method of analysis
(Goddard et al. 2011 NGC4625 & M83)

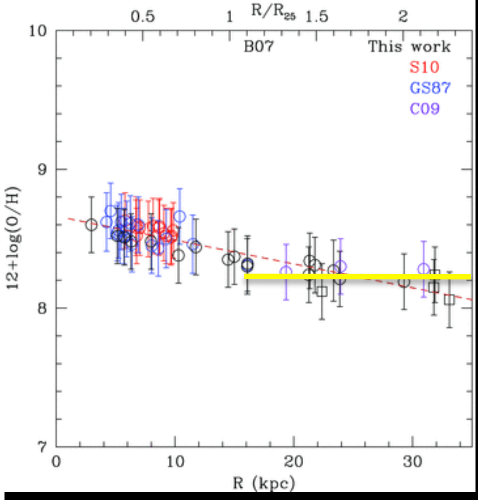


Often the drop between inner and outer disk is about 0.4 in log(O/H) and there seems to be a convergence on the fact that gradients flatten out in outer disks
(Bresolin et al. 2012)



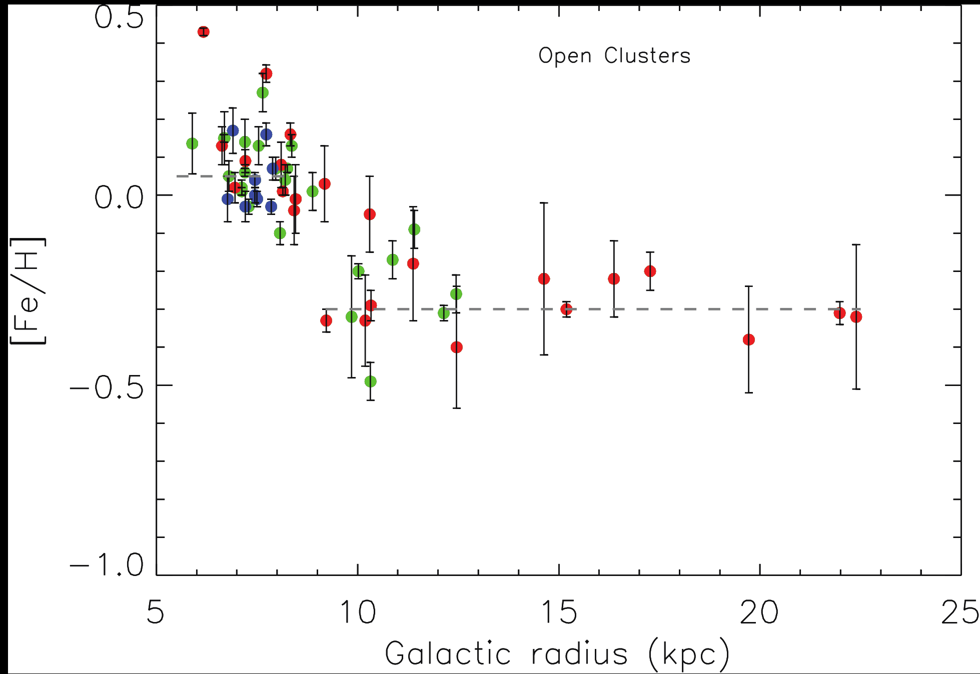
Oxygen abundance gradient of M81 *(Patterson et al. 2012)*





Milky Way open clusters

Lepine et al. 2011



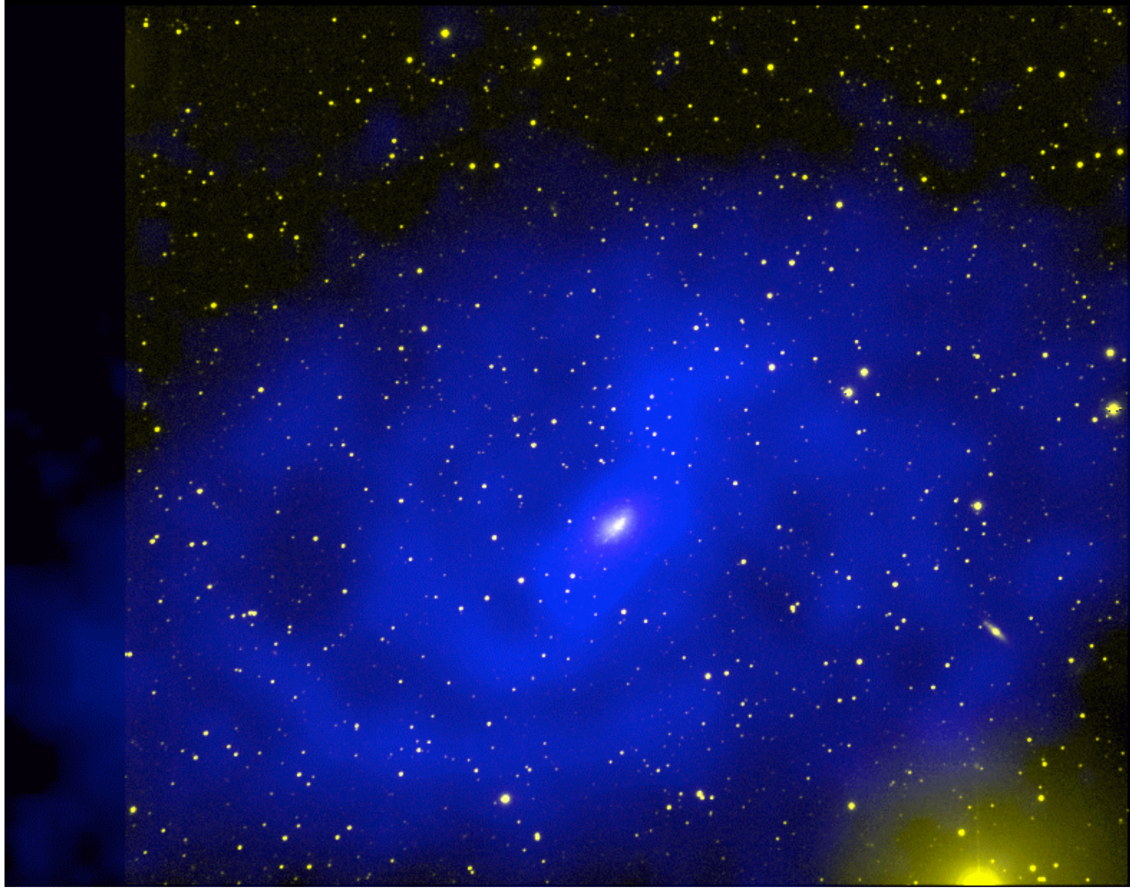
Flatter metallicity gradients in outer disk support the scenario that outer disk form stars by accretion events A steeper gradient in the inner disk supports a possible collapse model.

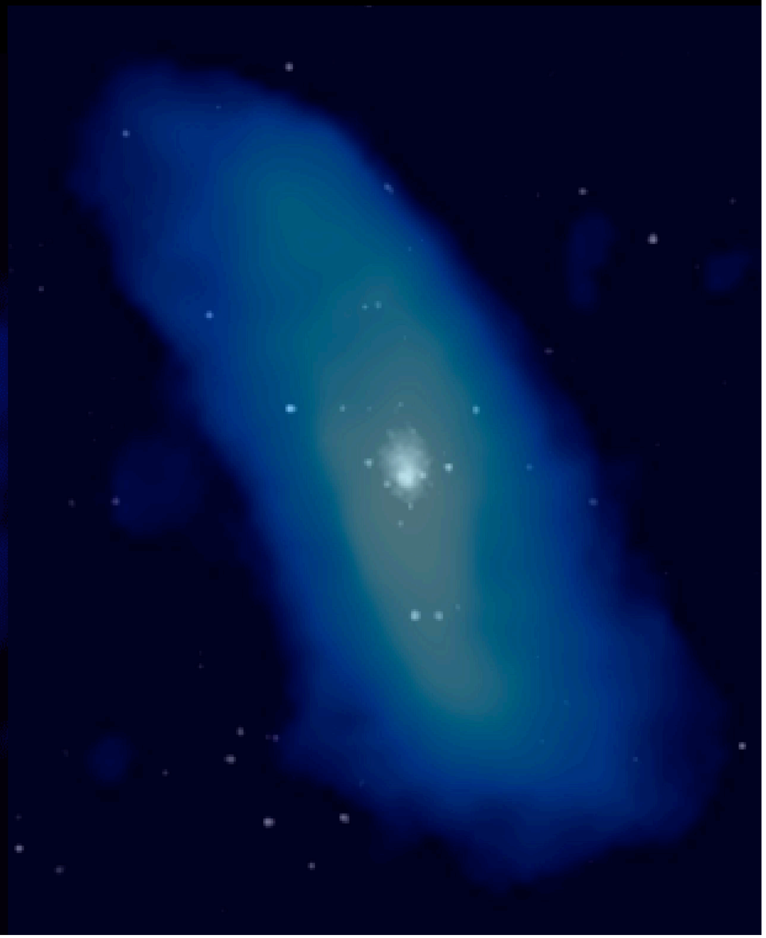
Extremes:

The HI disks of isolated dark dwarf galaxies NGC2915 - NGC3741

(Meurer 1996; Begum et al. 2005)

Are these extended disks polluted by stars ?



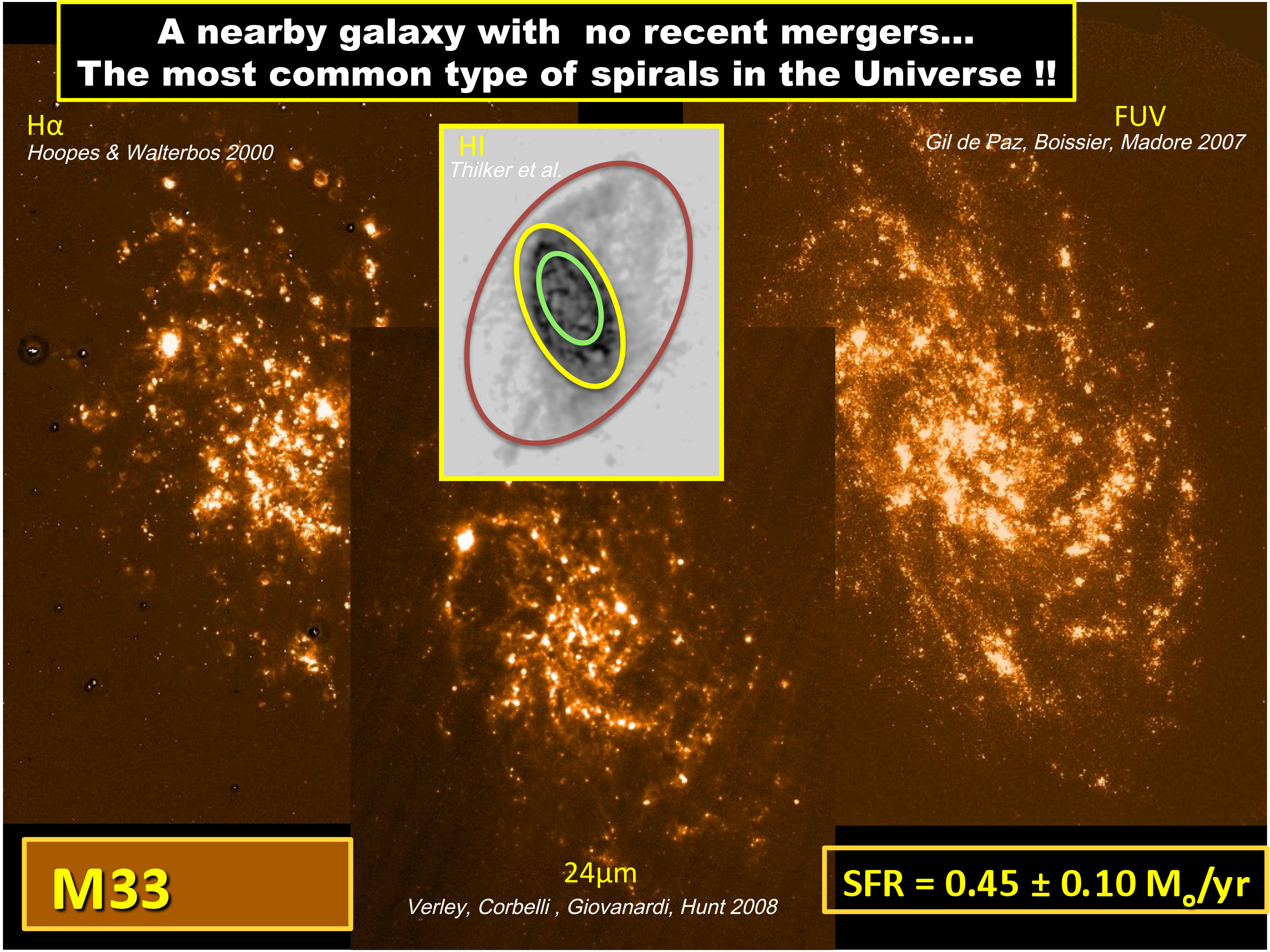


Bright, isolated SF filaments form by Σ_{gas} enhancements due to external perturbations or internal resonances.

These are rich areas!

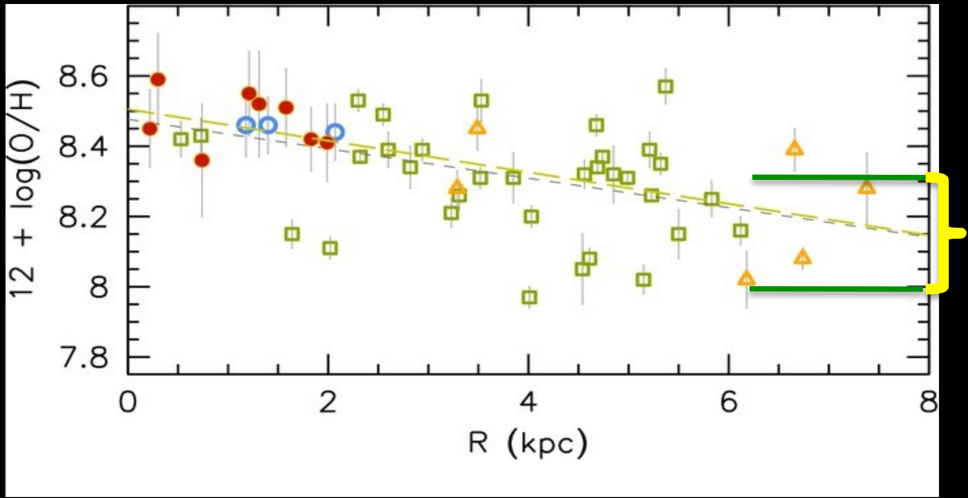
Are these non-residential areas or poor suburbs ?

Is it possible that SF is persistent in small units i.e. low mass young clusters are common in outer disks ?


A nearby galaxy with no recent mergers…
The most common type of spirals in the Universe !!
Hα
Hoopes & Walterbos 2000
HI
Thilker et al.
FUV
Gil de Paz, Boissier, Madore 2007
M33
24μm
Verley, Corbelli , Giovanardi, Hunt 2008
SFR = 0.45 ± 0.10 M☉/yr

Metallicity across M33 is flat and subsolar

(Bresolin et al. 2011, Magrini et al. 2010, Grossi et al. 2011)



Metallicity range
in outer disk 8-23 kpc
from CMD

$$O/H = t \; Y_O \; \Sigma_{SFR} \; / \; \mu \; \Sigma_{HI}$$

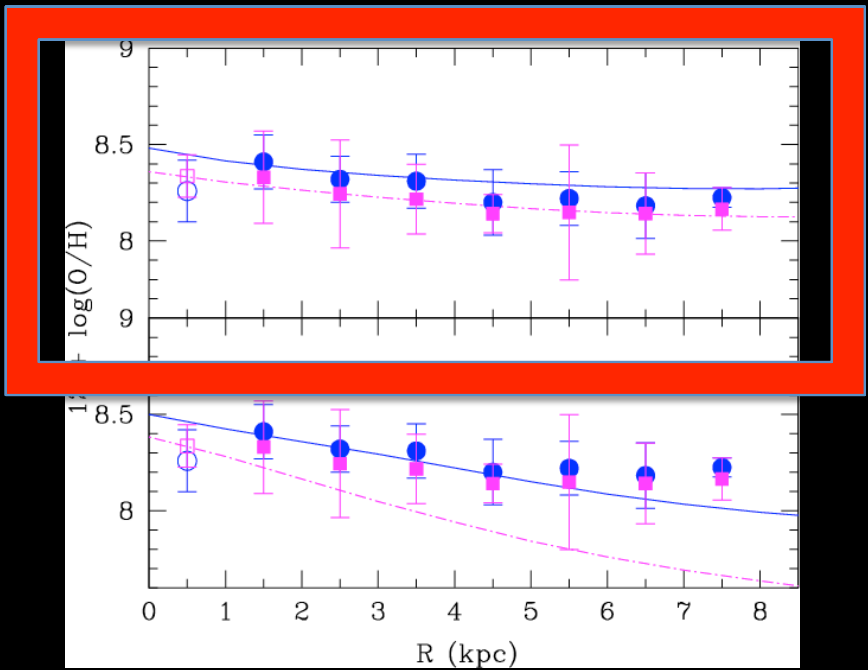
R=1 kpc t = 0.6 Gyrs

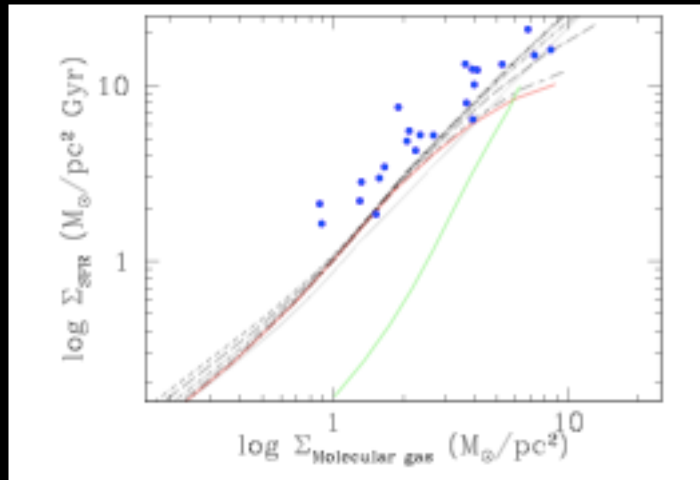
R=5 kpc t = 0.9 Gyrs

R>8 kpc t > 8 Gyrs

Given the low metallicity and the extrapolation of the observed SFR we need some pre-enriched gas accretion in outer disk.

Metallicity gradient and SFR do not change with time



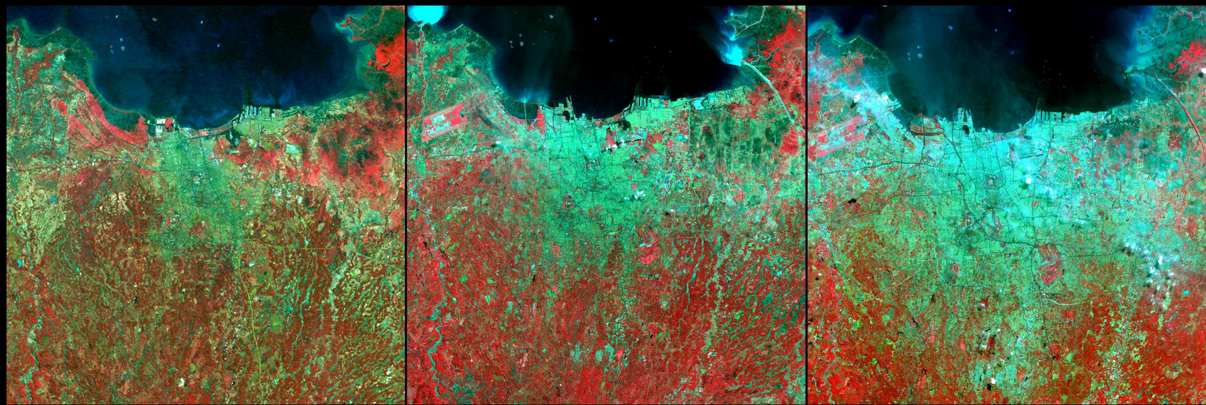


To the left: The M33 O/H gradient 5 Gyrs (pink) ago and now (blue). For a constant SFE (bottom) and for a SFE which increases with radius (top).
To the right: the SFR versus H2 relation for a constant (green) and radially varying (red) SFE at the present time

The SFR has not changed much during the cosmic evolution
slow accretion model of 1 solar mass/year
(Magrini, Stanghellini, Corbelli, Galli, Villaver 2010).

How do outer disks get their gas and convert this into stars?

➢1. Inner disks form and make stars quickly, outer disk have a more quiescent SF mode because of the slow cooling.

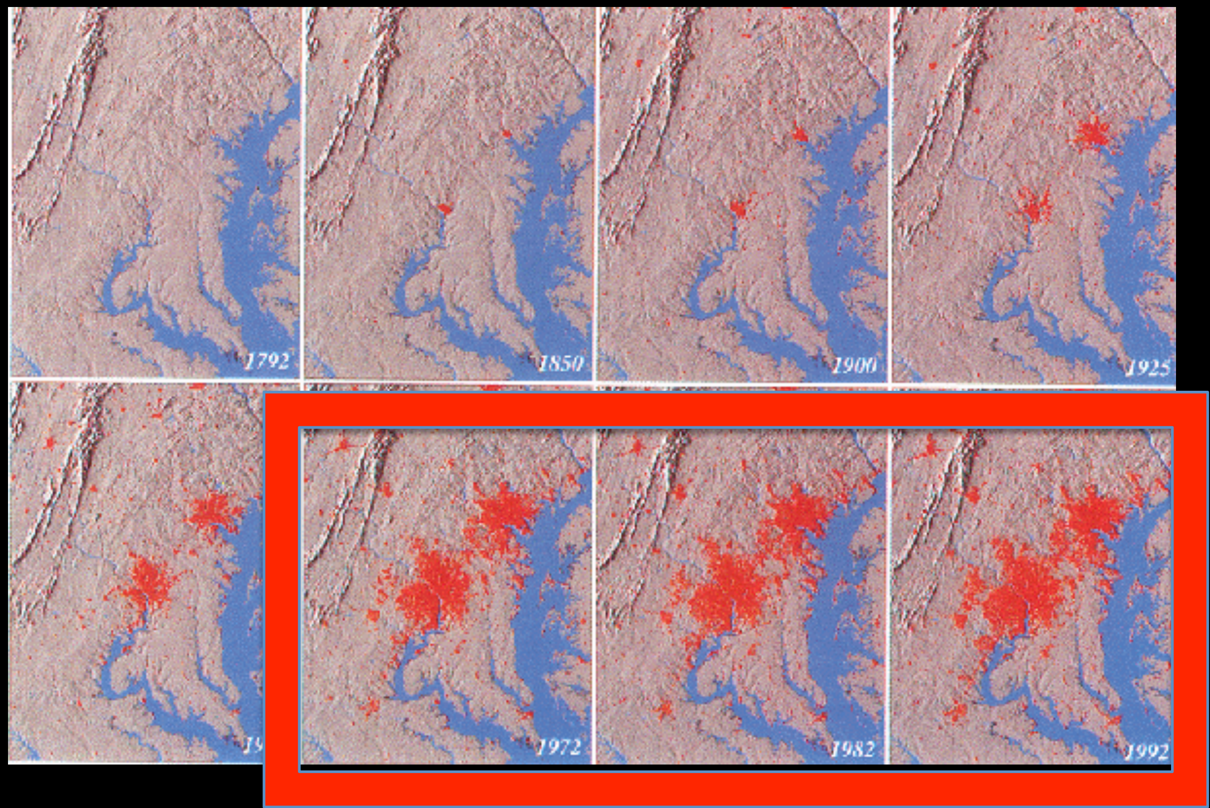


Collapse model for inner disk: metallicity gradient flattens with time

City growth analogue: Jakarta 1976-2004

Everybody gets to the center leaving the poor countryside empty

➢2. Outer disks or M33 like galaxies are accreting gas slowly and continuosly from the IGM   and fuel SF through short bursts

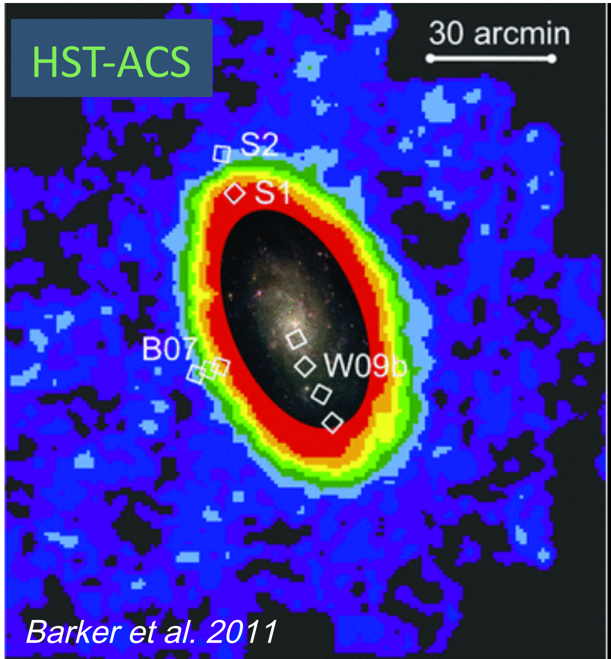


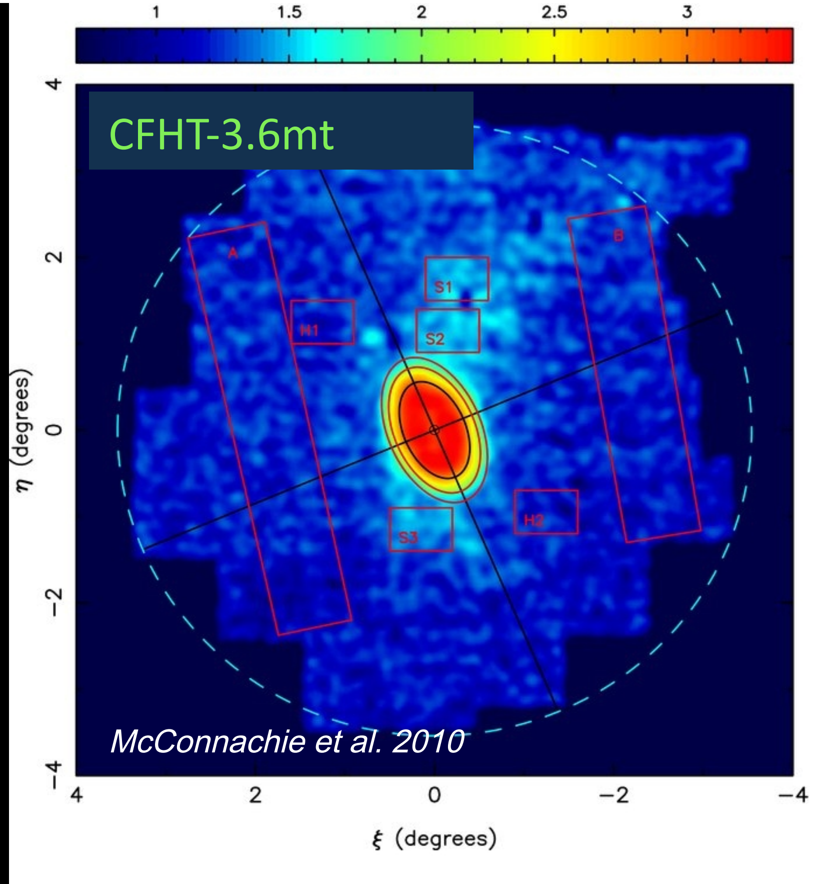
Slow accretion: metallicity gradient changes little with time

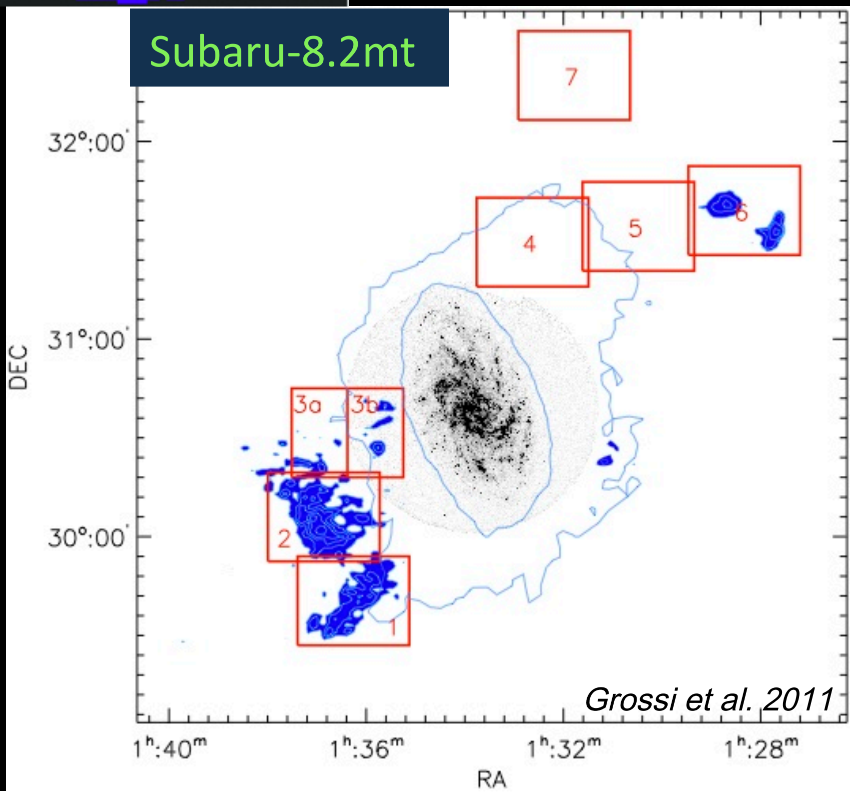
City growth analogue: Baltimora-Washigton

Villages in the surrounding countryside grow as well as centers

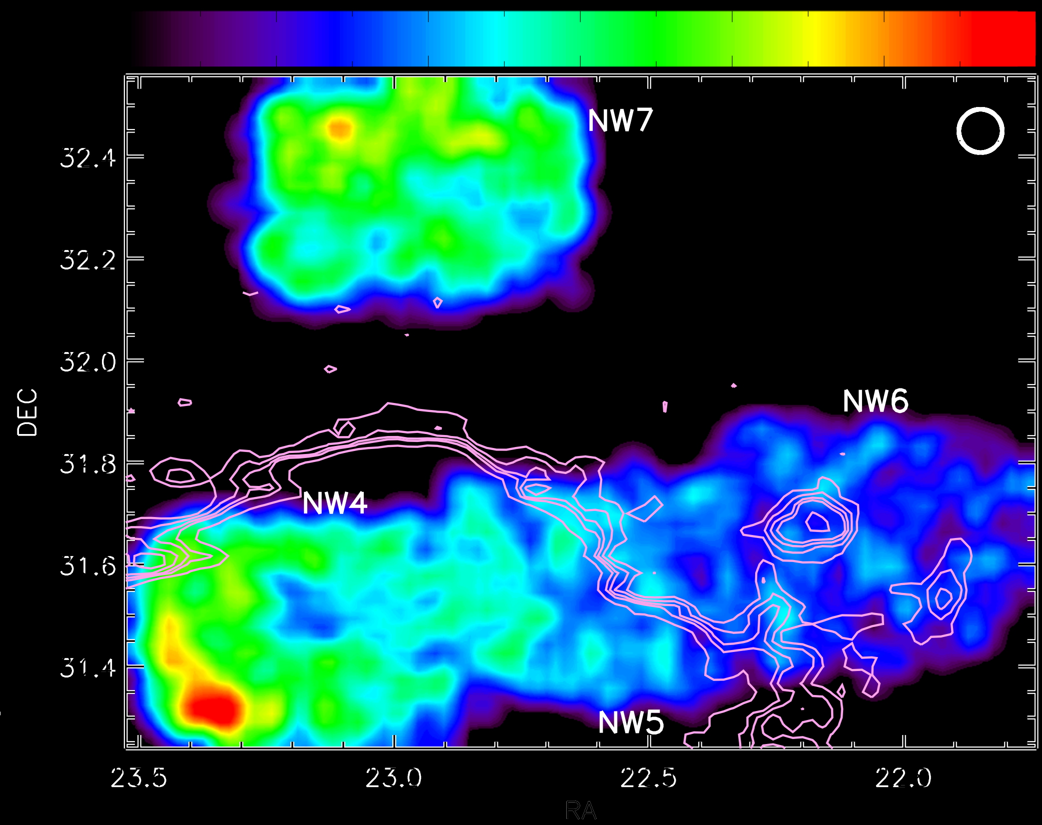
Deep surveys of M33 outer disk





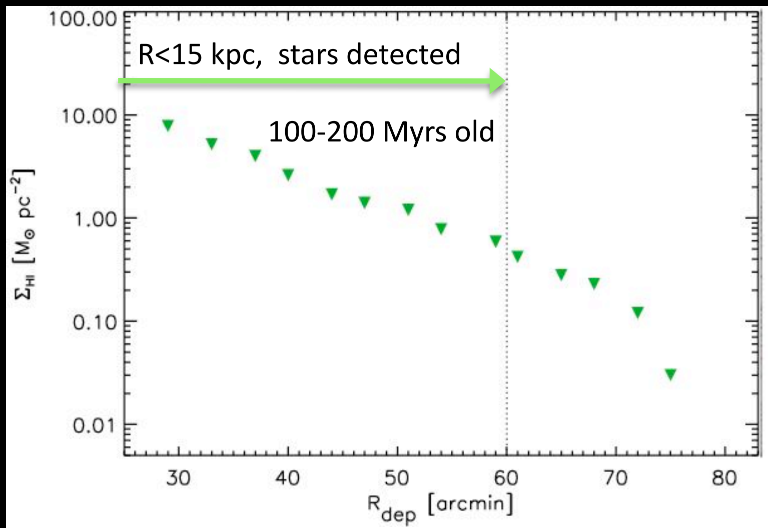


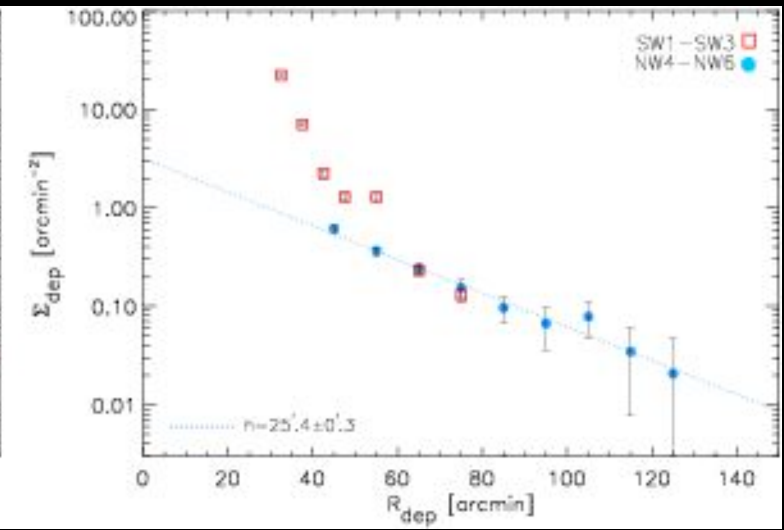
Spatial distribution and surface density of RGB stars in the outer disk of M33 *(in color, contours show the HI gas)*

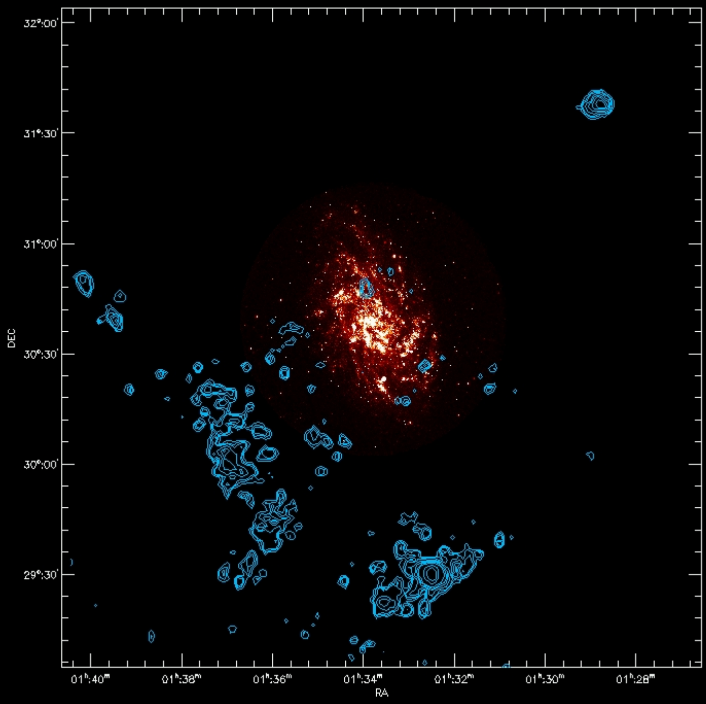


Best fit age= 2.5 Gyrs, log Z= -0.7

(Grossi et al. 2011)



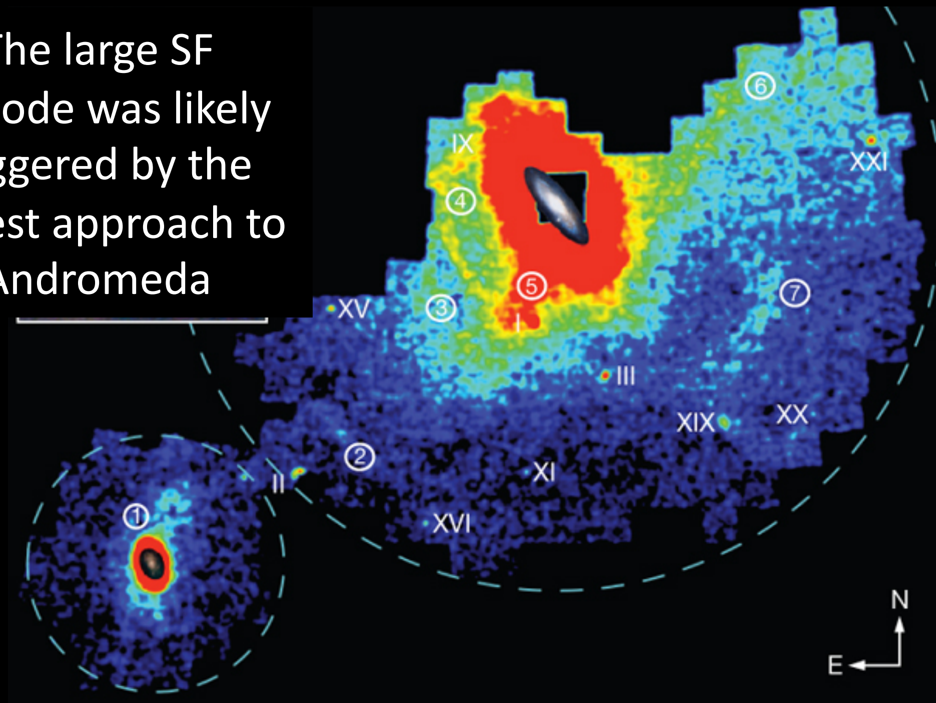




HI Clouds infalling into the outer disk and halo of M33 *(Grossi et al. 2008)*

Clouds have no obvious stellar counterpart. Evidence for cold accretion.
Recent SF episode 200 Myrs ago
Large SF episode 2.5 Gyrs ago

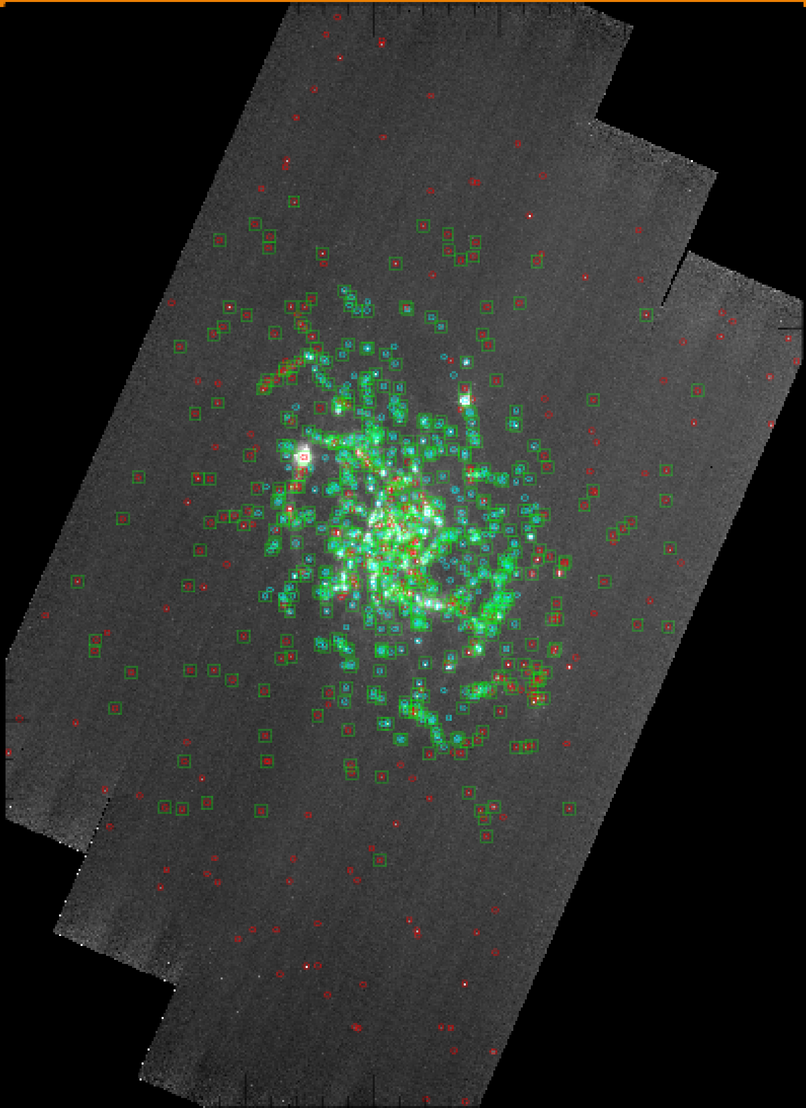
The large SF episode was likely triggered by the closest approach to Andromeda

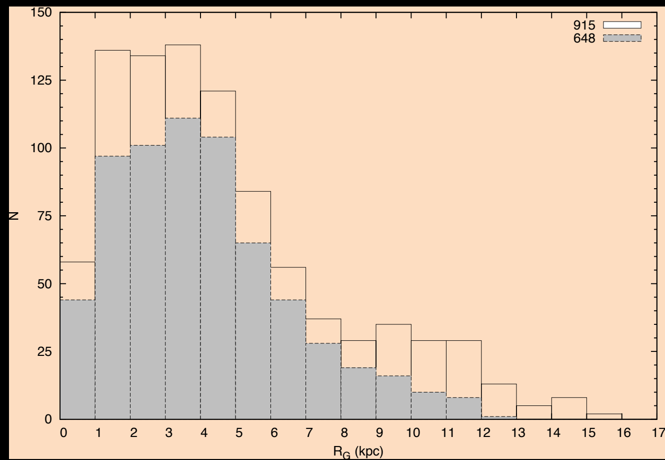


A faint, older (7-12 Gyrs) stellar halo with a lower metallicity ($Z=0.1-0.01\ Z_{sun}$) is in place

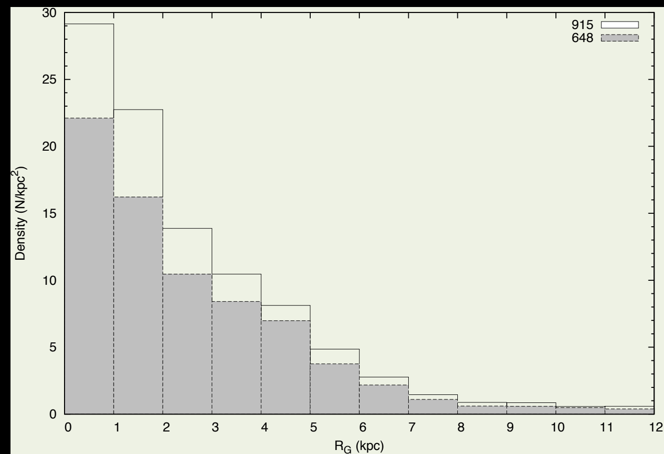
Young star forming clusters: a MIR selected sample

The SFR measured just outside the optical disk is sufficient to support in situ formation of the observed stars during the last 8 Gyrs . Is SF going on right now ???????

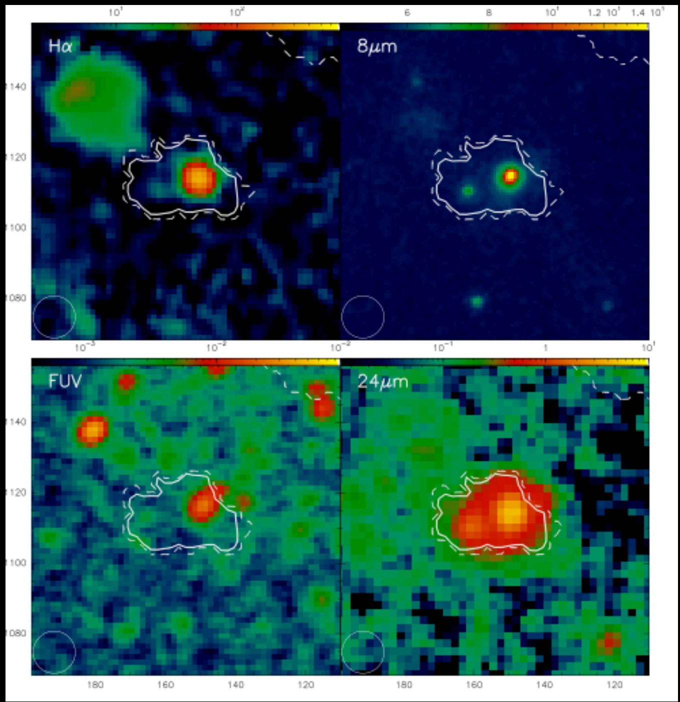




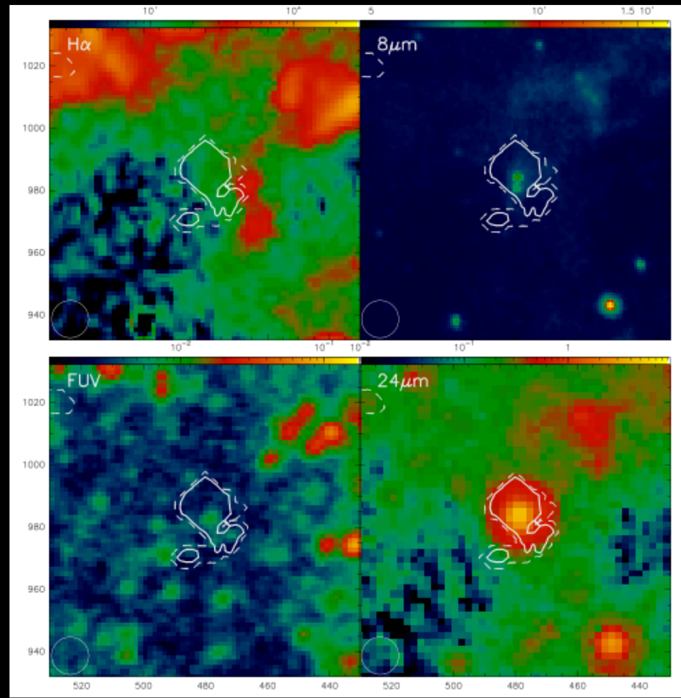
Sharma,Corbelli,Giovanardi,Hunt,Palla 2011

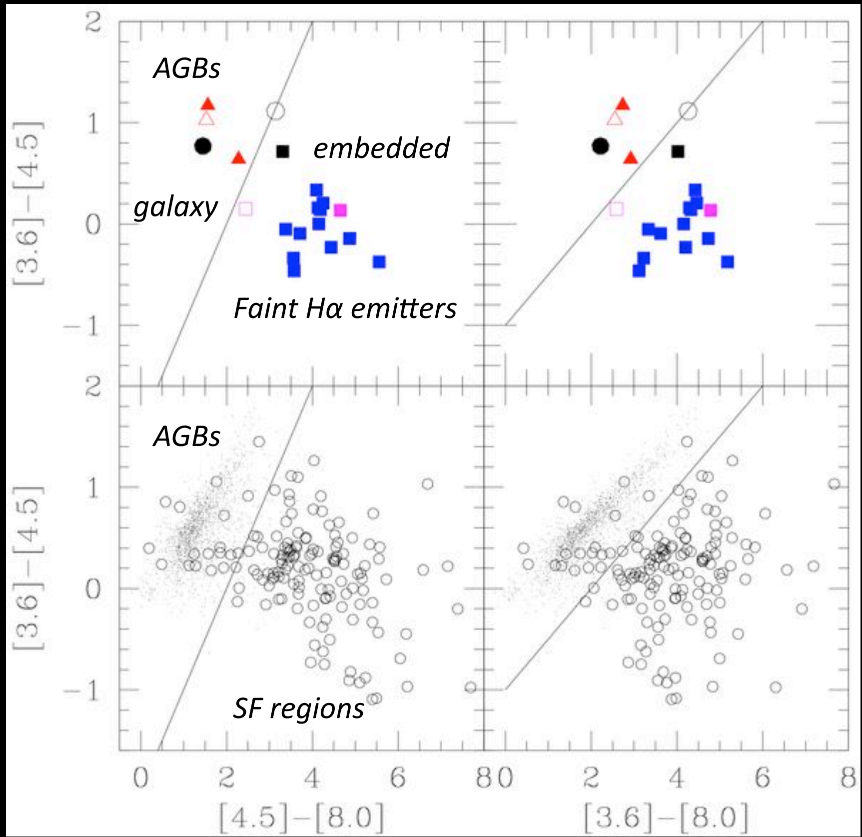


Fully embedded and less embedded sources



The IRAM CO map of M33 and the cloud catalogue. Panels for Hα, FUV, 8 and 24 μm (Gratier, Braine et al. 2011) show that the MIR selected sample has SF sources at different stages of evolution





Are young sources outside Gratier's map, surrounded by molecular hydrogen? and is this detectable through CO emission ?

Yes !

Corbelli, Giovanardi, Palla, Verley 2011

Sources observed up to now are within 8 kpc. The weakness of the CO lines around all of our MIR sources is indicative of the existence of a large population of faint CO clouds in M 33. IRAC color-color diagrams, as well as CO searches, help identifying young SF regions from AGBs , nearby stars and background galaxies.

Hidden molecules, higher SFE or non equilibrium chemistry in the far outer disk?

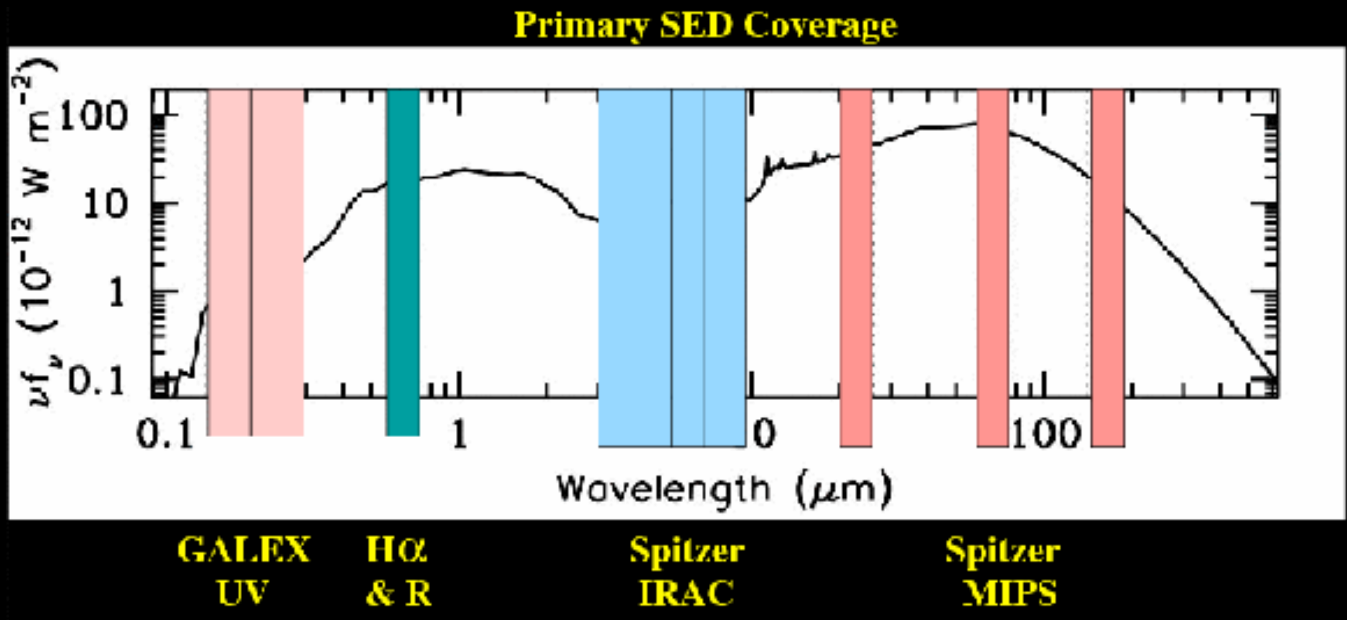
Observations/chemical evolution models indicate that SF efficiency with respect to molecular hydrogen must increase with radius (Magrini et al. 2011), but…..

$t_{chem}/t_{ff} = 2/(Z\ n^{0.5}\ c)$ is large in low metallicity, low density, unperturbed outer disks

It might then be that molecular hydrogen content is low because we are out of chemical equilibrium or that we don't see it because CO is absent

SED fitting procedures to young clusters

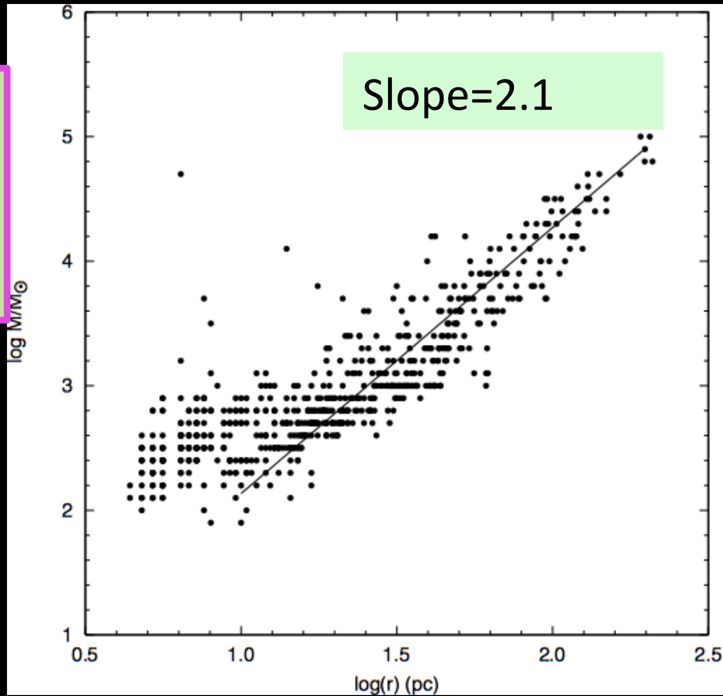
SED fits to 650 MIR sources (Sharma et al. 2011)

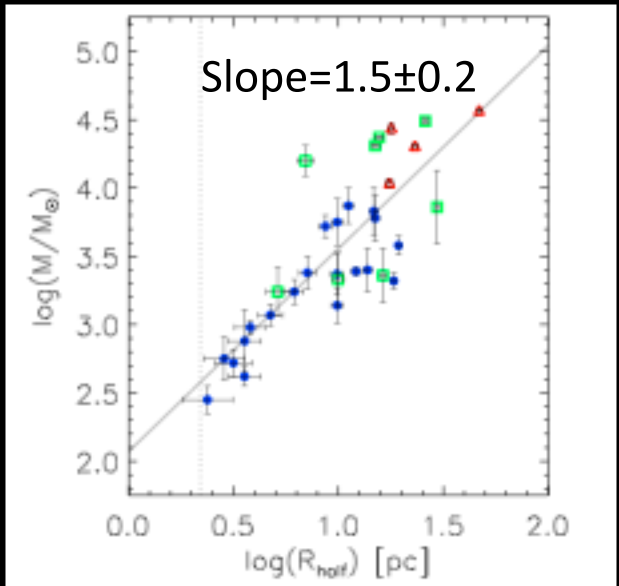


To a subsample do accurate fits using FUV,NUV and additional optical images (UBVRI) *(Grossi, Corbelli et al. 2010)* + metallicity measurements. Determine ages and masses. Results are in reasonable agreement but we recover:

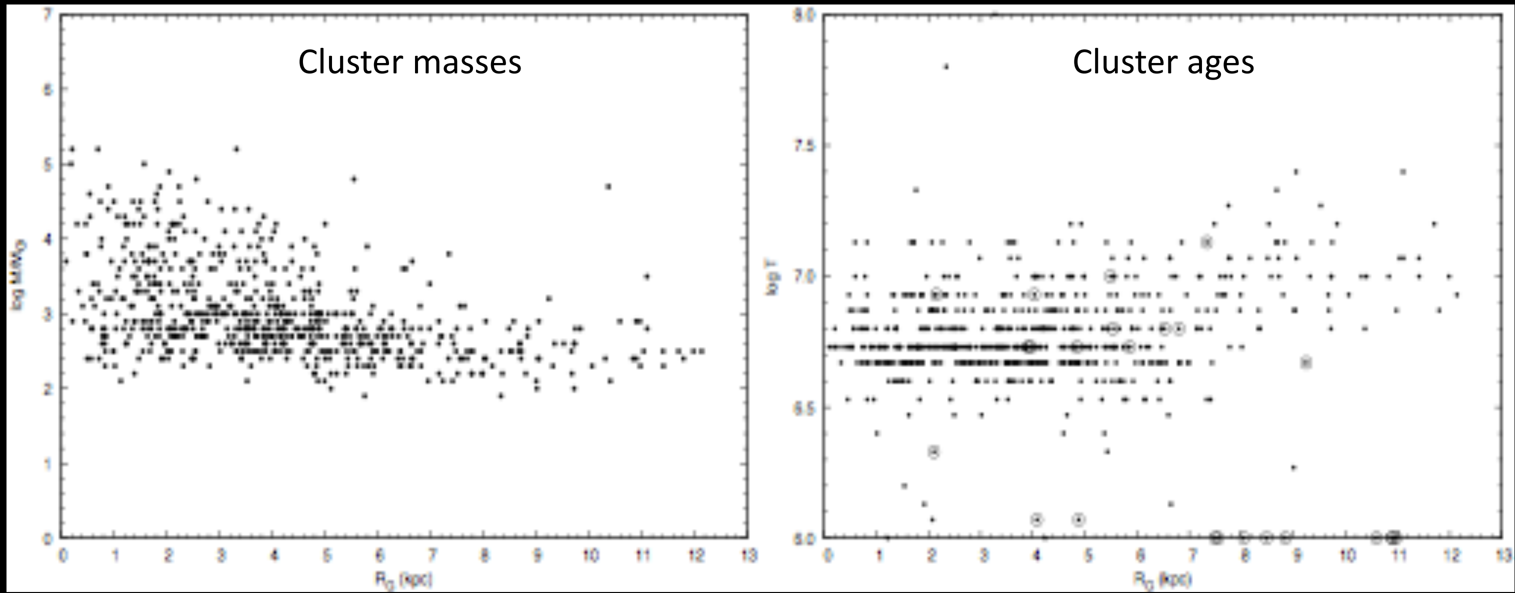
- A somewhat (0.2-0.3) younger ages for intermediate and low mass clusters
- Larger stellar masses for the smallest clusters (aperture recentering)

The mass-radius relation is consistent with the Larsen relation found for compact clusters <1 Gyrs old and with the GMC mass-radius relation. The population is young!





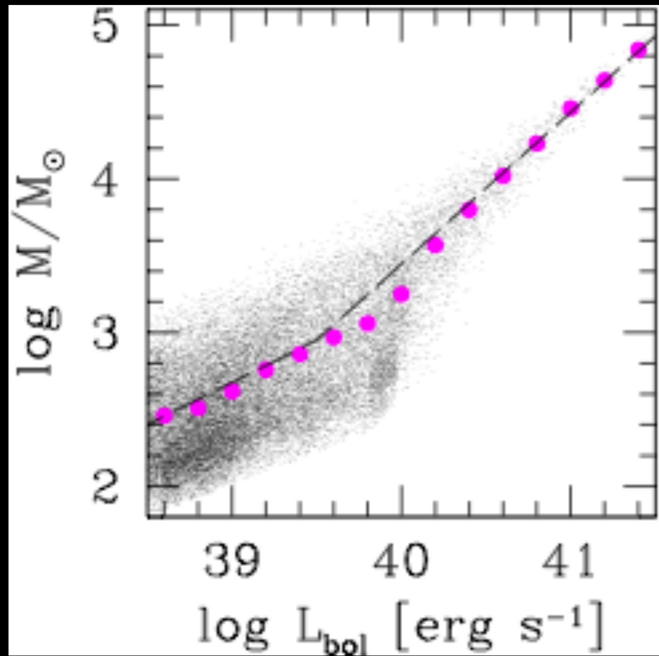
A similar relation is found also on smaller radii for the sample with the more accurate optical photometry. R are measured from optical images.

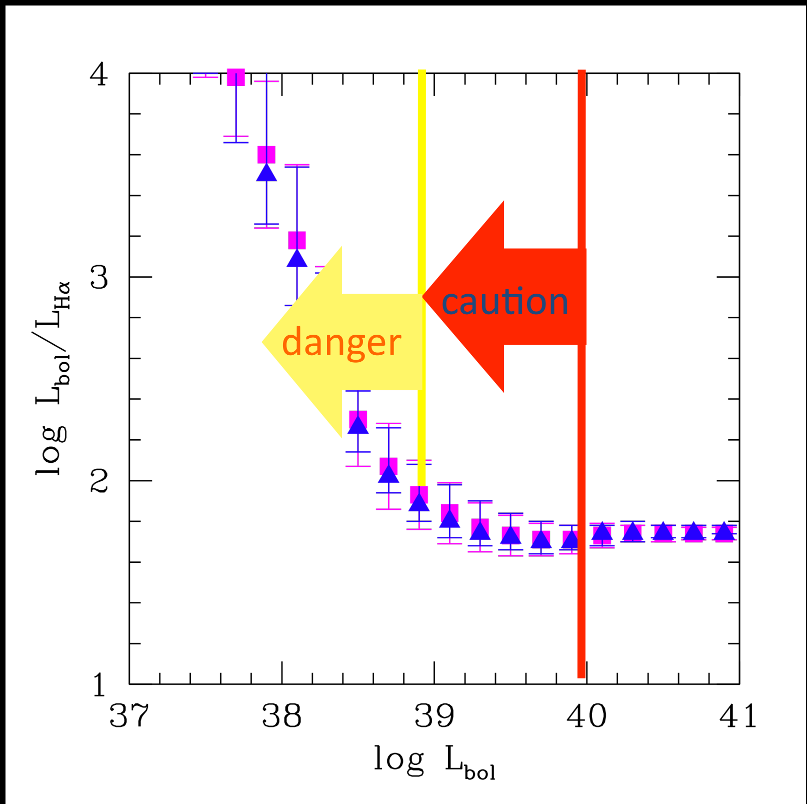


- GMCs and massive clusters are very rare beyond 5 kpc
- Outer disks form only clusters less massive than 1000 Msun
- Extinction (Av) mostly between 0 and 1, decreases with cluster age
- Outer disks might host somewhat older clusters: 10 Myrs (singificant?)

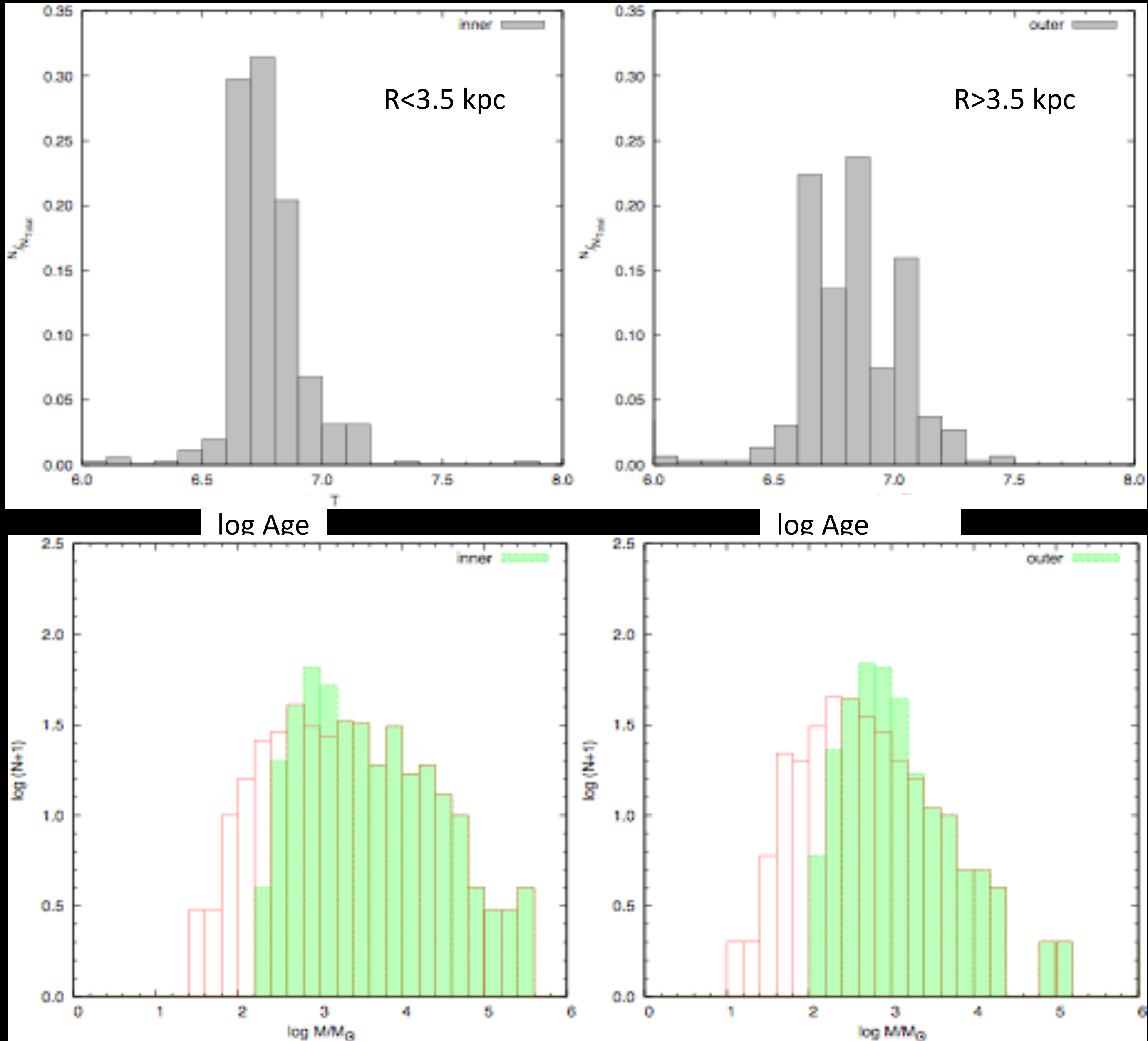
The incompleteness of the IMF

Simulated distribution of cluster mass as a function of the cluster luminosities at birth (Corbelli, Verley, Elmegreen, Giovanardi 2009).



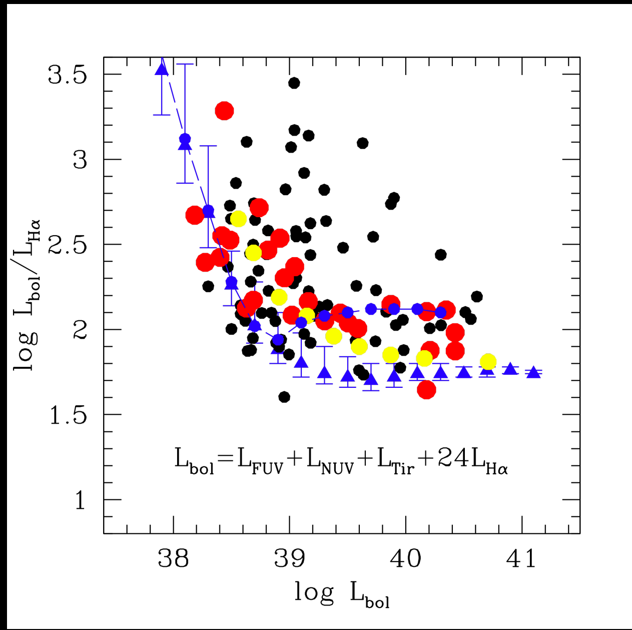


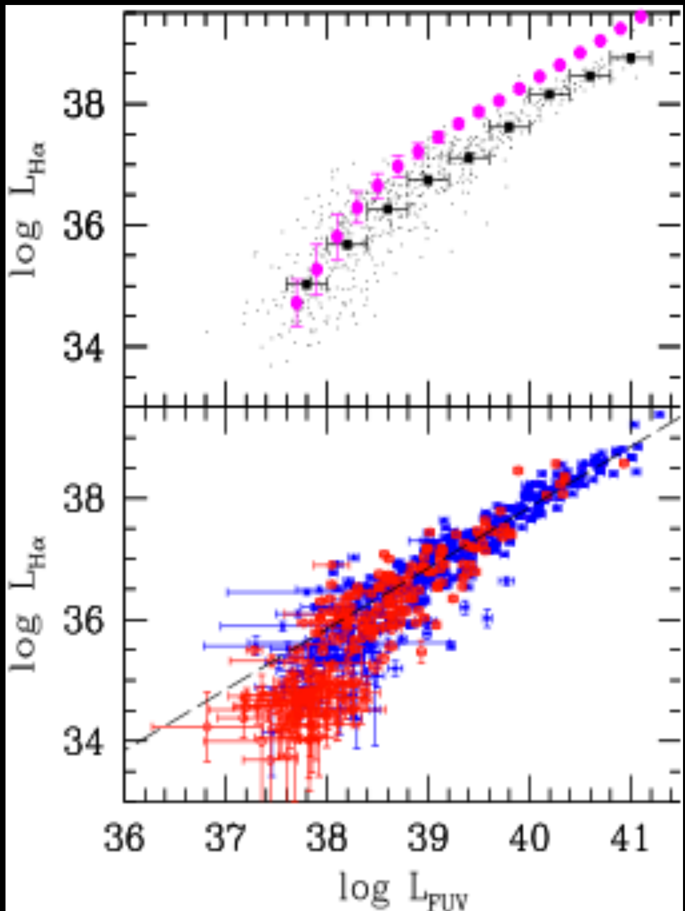
SED fits to clusters to determine masses and ages need corrections to account for IMF incompleteness (green areas show the mass distribution corerct for incompleteness)



1.The IMF is not a function of cluster mass

2.cHα is not a good SFR tracer as fragmentation decreases the cluster mass

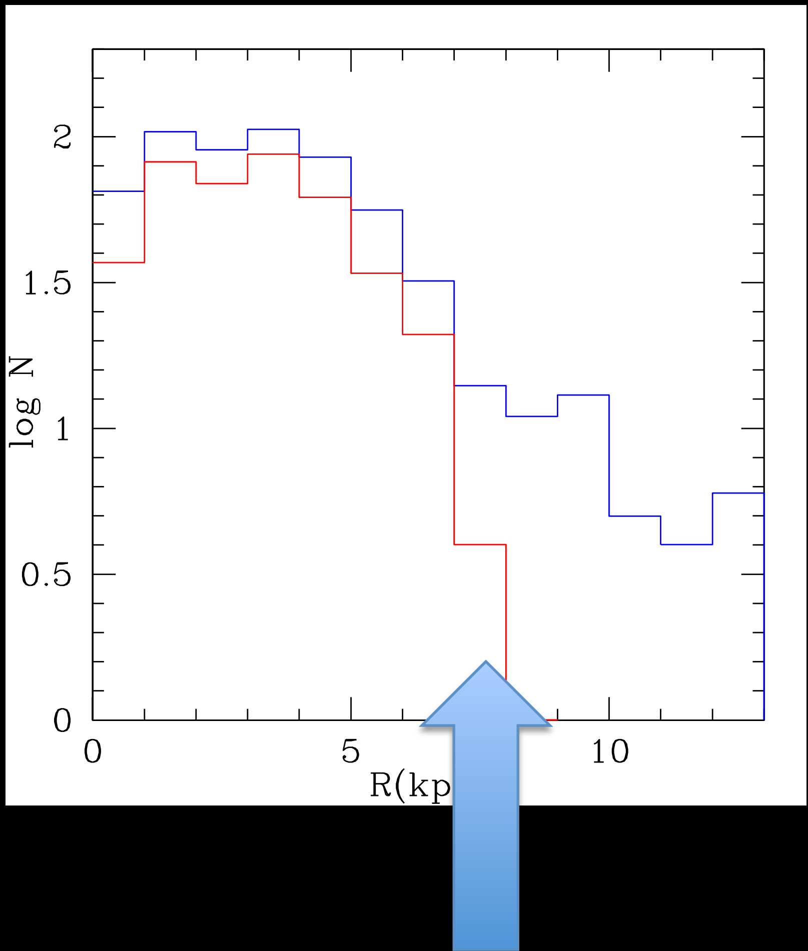


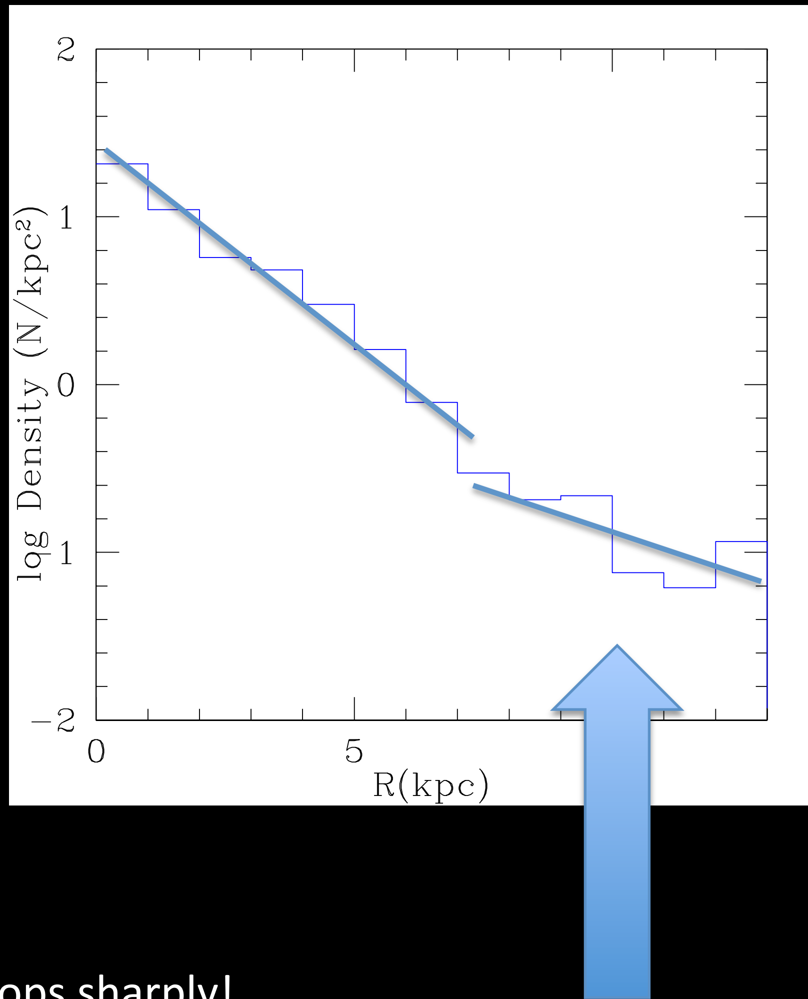


A fraction of UV ionizing photons escape from the HII regions because of the porous ISM, as supported by the large diffuse fractions in this galaxy.

24μm sources in outer disk of M33 after cleaning:

The distribution flattens beyond the Hα drop



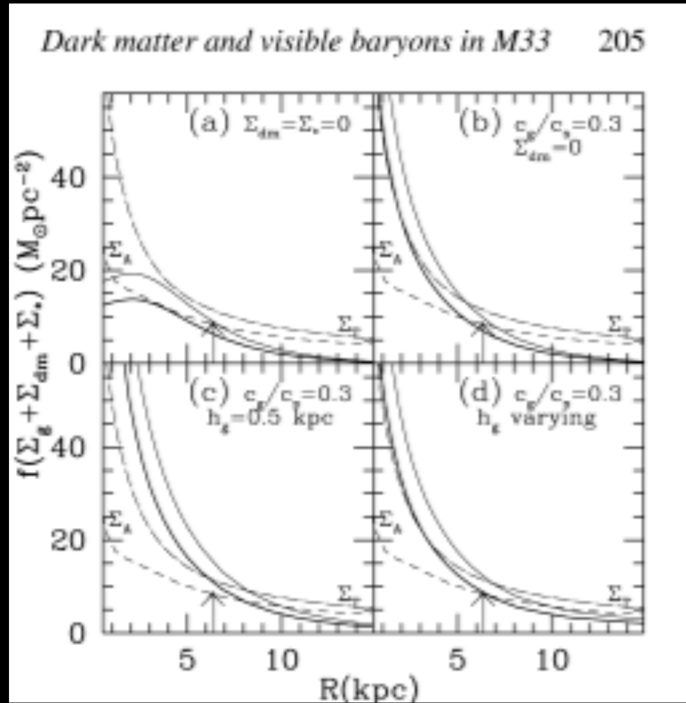


Detection rate of sources with associated Hα drops sharply!

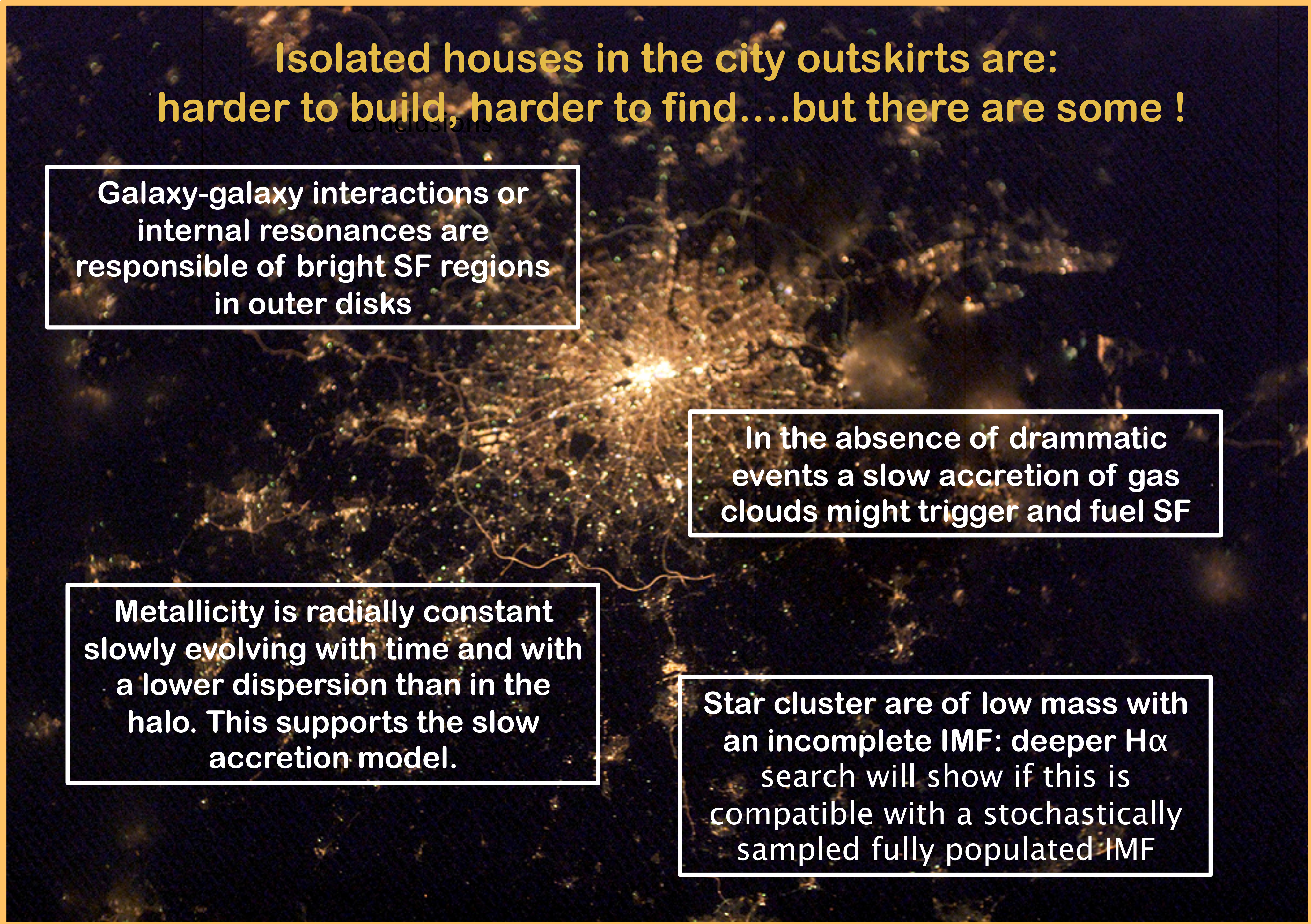
(*Survey is sensitive to Hα luminosities of 15 Msun stars*)

Flattening

Major mechanism that regulate SF is Toomre instability (stars + gas +...)
(Corbelli 2003)



How can we check that the IMF of low mass cluster candidates in the far outer disk ?
Hα deep searches if IMF stochastically populates the upper mass end.


Isolated houses in the city outskirts are:
harder to build, harder to find….but there are some !
Conclusions
Galaxy-galaxy interactions or internal resonances are responsible of bright SF regions in outer disks
In the absence of drammatic events a slow accretion of gas clouds might trigger and fuel SF
Metallicity is radially constant slowly evolving with time and with a lower dispersion than in the halo. This supports the slow accretion model.
Star cluster are of low mass with an incomplete IMF: deeper Hα search will show if this is compatible with a stochastically sampled fully populated IMF