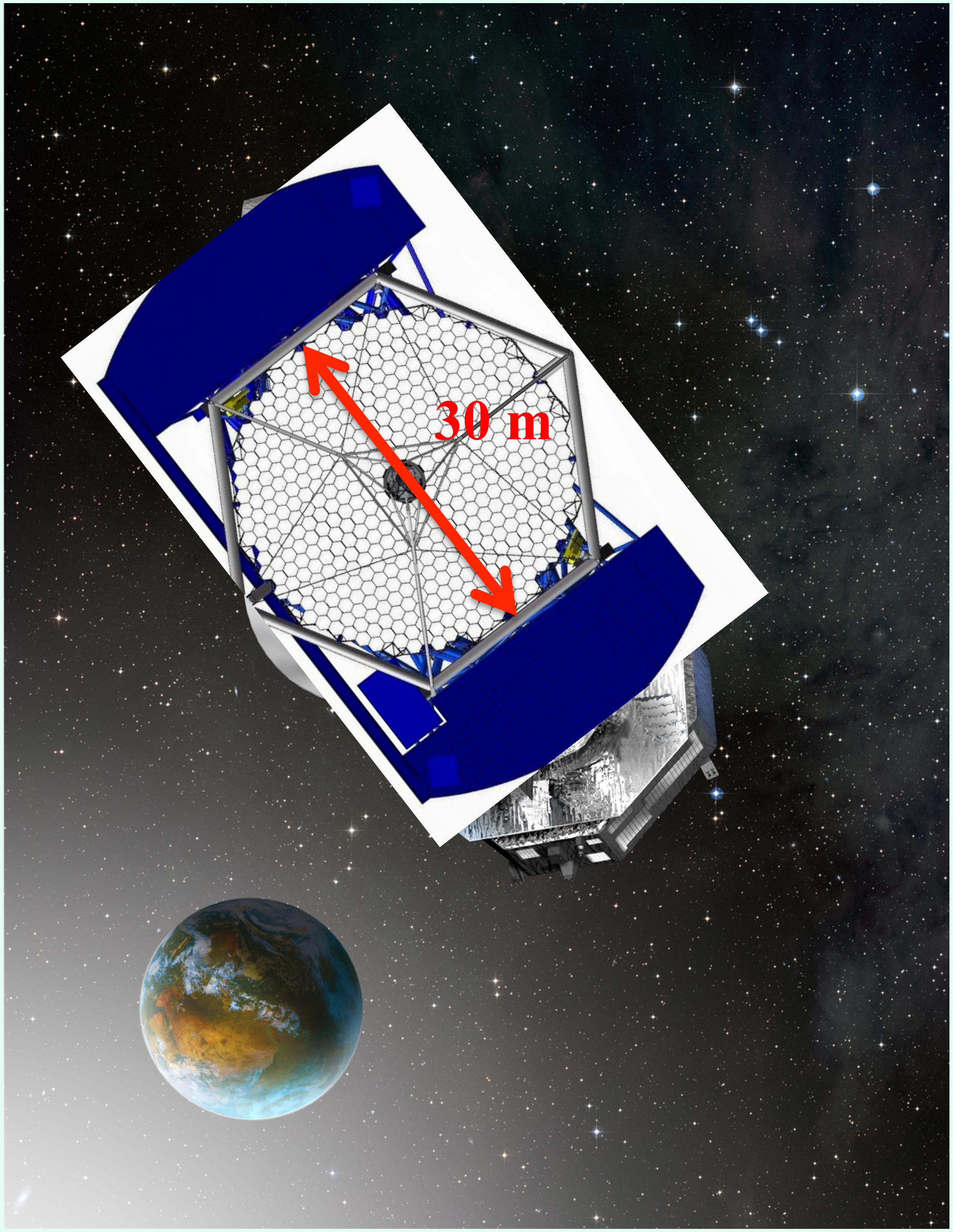
Star Formation in Nearby Galaxies: Evolution in Your Neighborhood

Daniela Calzetti (UMass)
+ Many Others + ….

Legacy ExtraGalactic LEGUS Ultraviolet Survey

Star Formation Across Space and Time,
ESA-ESTEC, Noordwijk, The Netherlands, 11-14 Nov. 2014

Göran's Introduction yesterday reminded me of something…

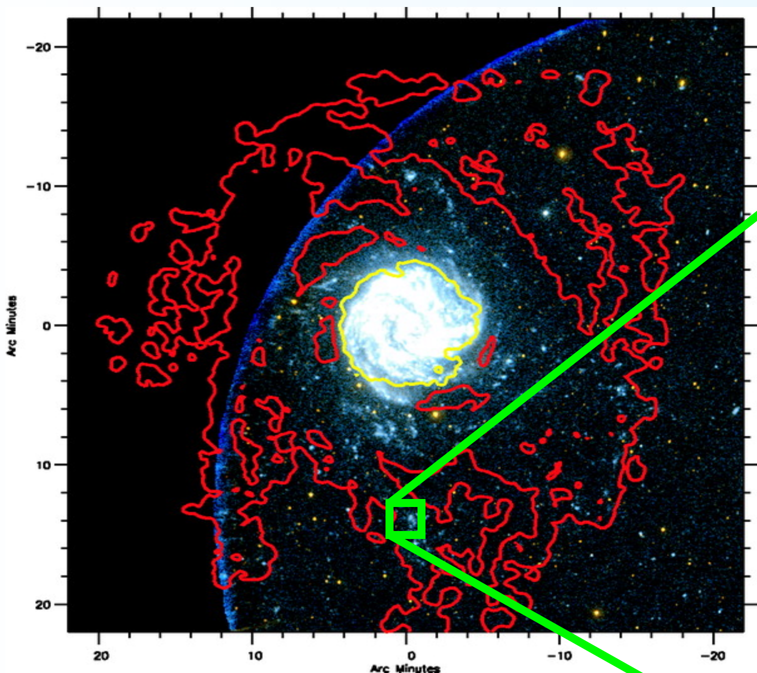


What about a 30 meter far-infrared (40-400 μm) telescope in space?

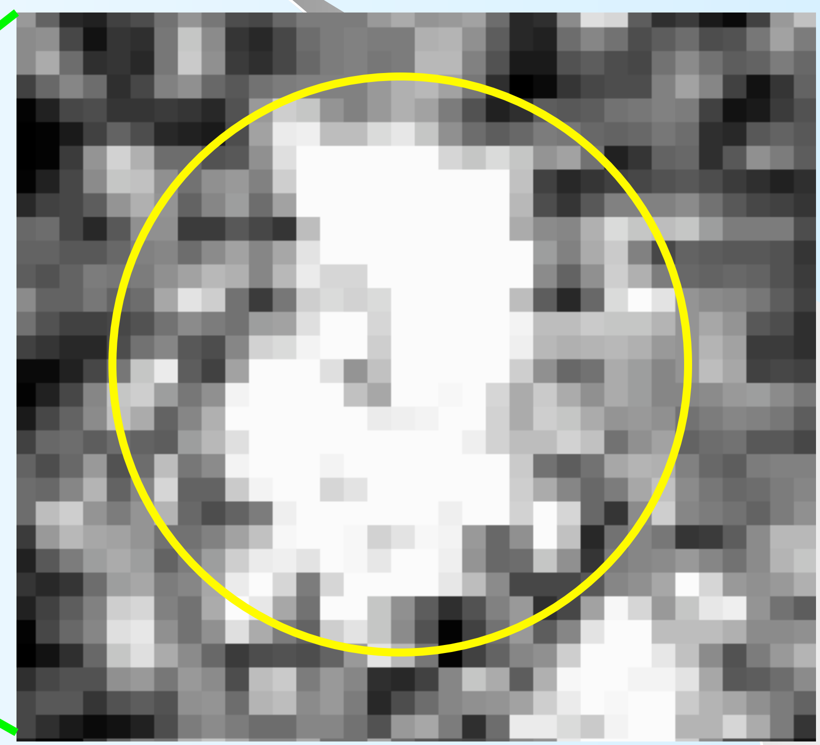
~1” at 150 μm

Angular Resolution - 1

M83 - GALEX



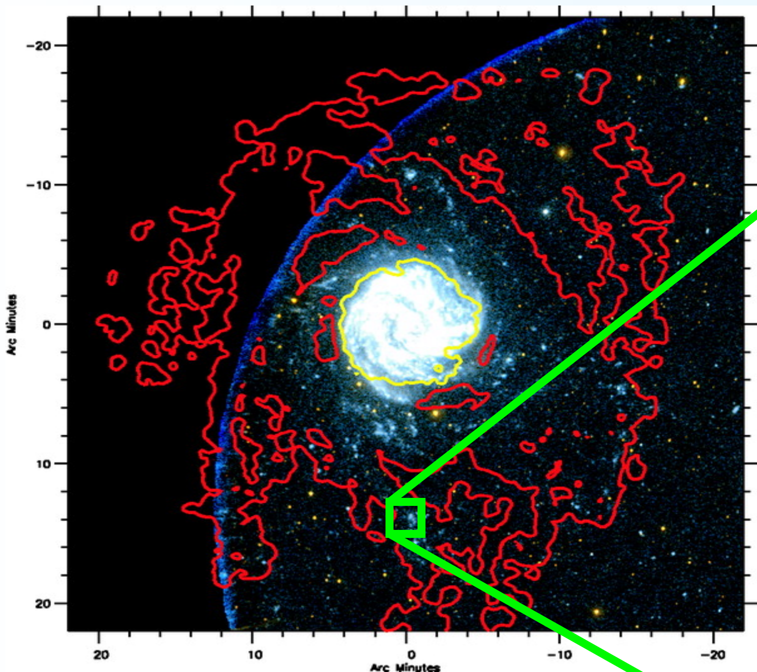
Thilker et al, 2005



GALEX resolution ~ 5”, similar to Herschel/70

How do I infer that these are stellar clusters, how many, their stellar population content? (degeneracies: dust, metallicity, age, etc.)

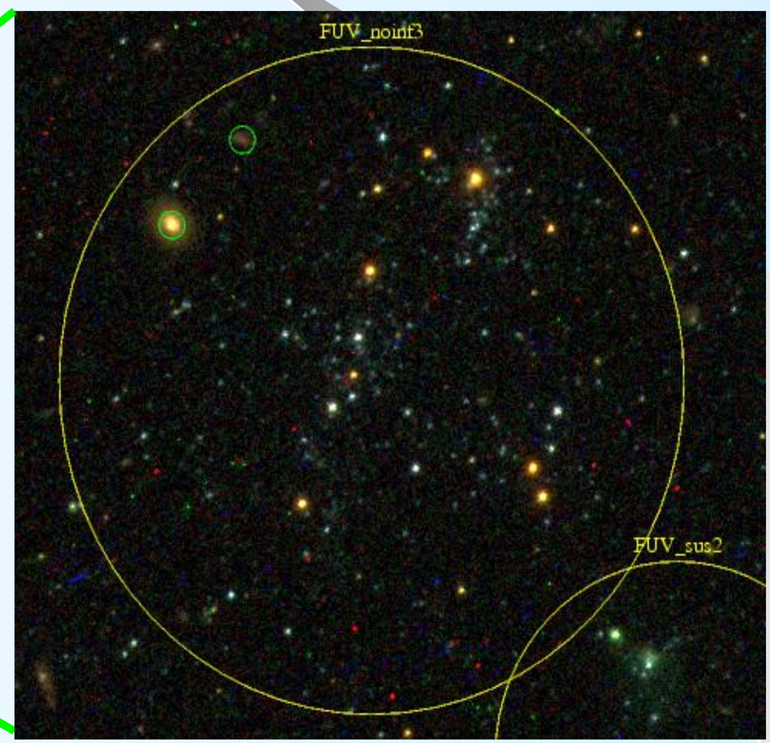
Angular Resolution - 2



Thilker et al, 2005

M83 - HST/ACS

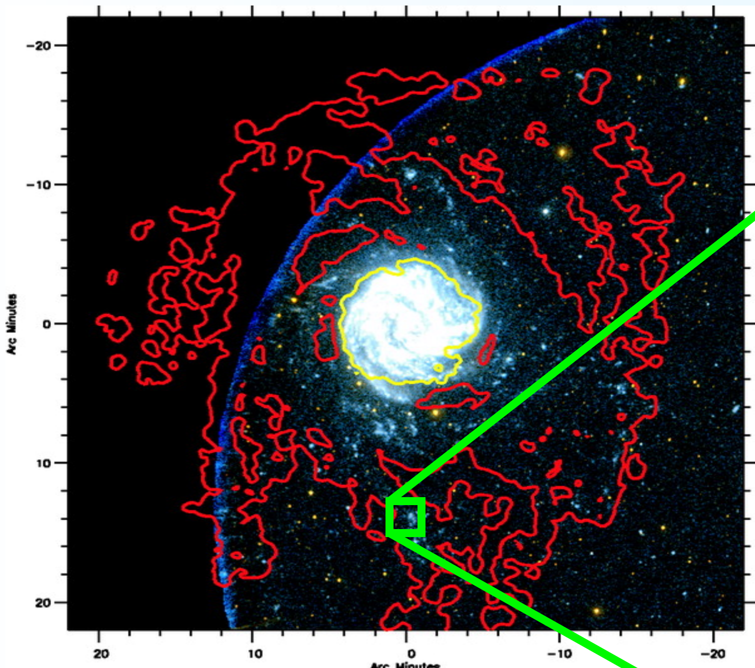
Thilker et al.



Resolution ~ 0.1”

I rest my case.

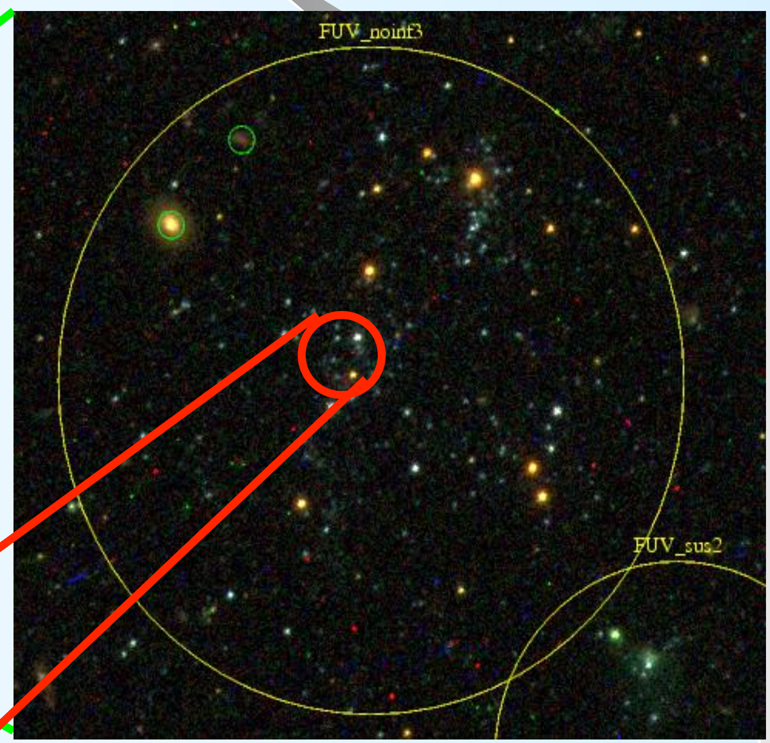
Angular Resolution - 2



Thilker et al, 2005

M83 - HST/ACS

Thilker et al.



Resolution ~ 0.1"

Truth in advertising: THIS is 1"

I rest my case.

Legacy ExtraGalactic

LEGUS

Ultraviolet Survey

The LEGUS Team

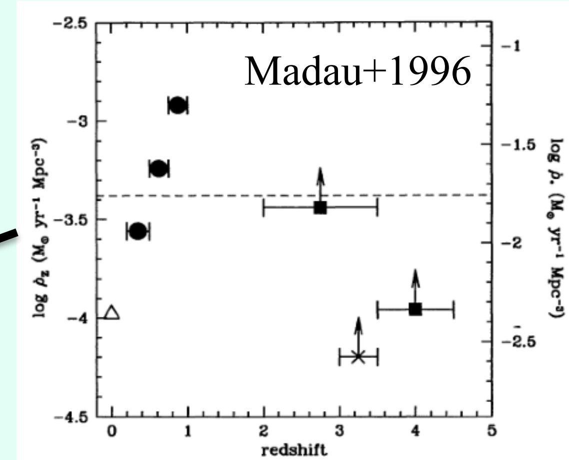
Red for Senior Advisory Group

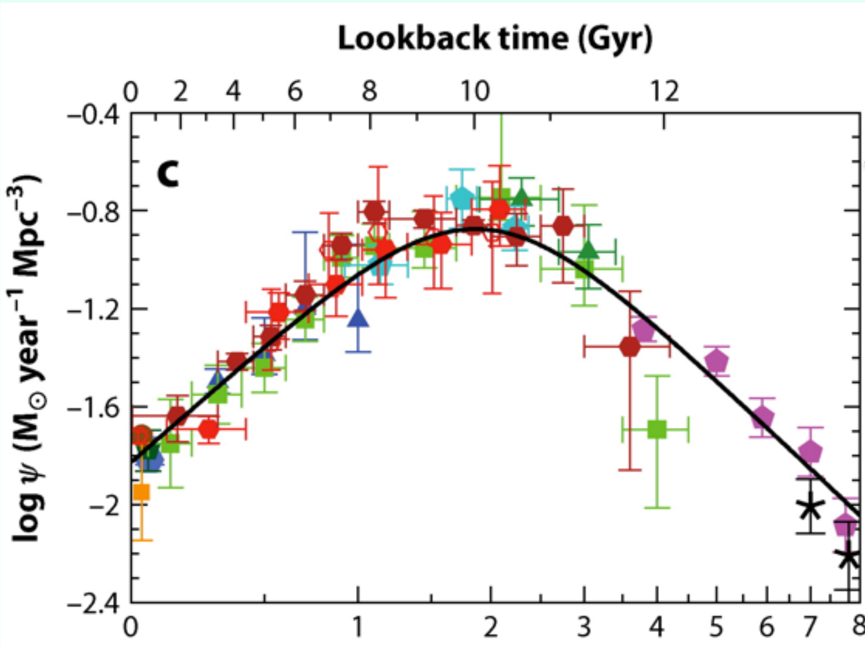
Blue for Science, Data Processing, EPO Leads

54 investigators (so far) at 30+ Institutions (US+EU):

D. Calzetti (PI, Umass), J. Lee (Deputy PI, STScI), J. Andrews (U Arizona), A. Aloisi, S.N. Bright, T. Brown, C. Christian, M. Cignoni, K. Levay, M. Regan, E. Sabbi, L. Ubeda, B. Whitmore (STScI), A. Adamo, M. Messa, G. Östlin (Stockholm U), R. Chandar (Utoledo), G. Clayton (LSU), D. Cook, D. Dale (U Wyoming), R. da Silva, M. Krumholz (UCSC), S. de Mink (Carnegie Obs., Amsterdam U), C. Dobbs (UExeter), B. Elmegreen (IBM), D. Elmegreen (Vassar), A. Evans, K. Johnson (UVa), M. Fumagalli (U Durham), J. Gallagher, J. Ryon (UWisc), D. Gouliermis, E. Grebel (Heidelberg U), K. Grasha, (UMass), A. Herrero, S. Taibi (IAC, Canarias), D. Hunter (Lowell Obs), L. Kahre, R. Walterbos (NMSU), R. Kennicutt (IoA, Cambridge), H. Kim (ASU), D. Lennon (ESA), C. Martin, S. van Dyk (Caltech), P. Nair (U Alabama), A. Nota, L. Smith (STScI/ESA), A. Pellerin (SUNY-Geneseo), J. Prieto (UC de Chile), D. Schaerer (Geneva Obs), D. Schiminovich (Columbia U), D. Thilker (JHU), M. Tosi, E. Sacchi (INAF-Ubologna), A. Wofford (IAP)

Across Time…

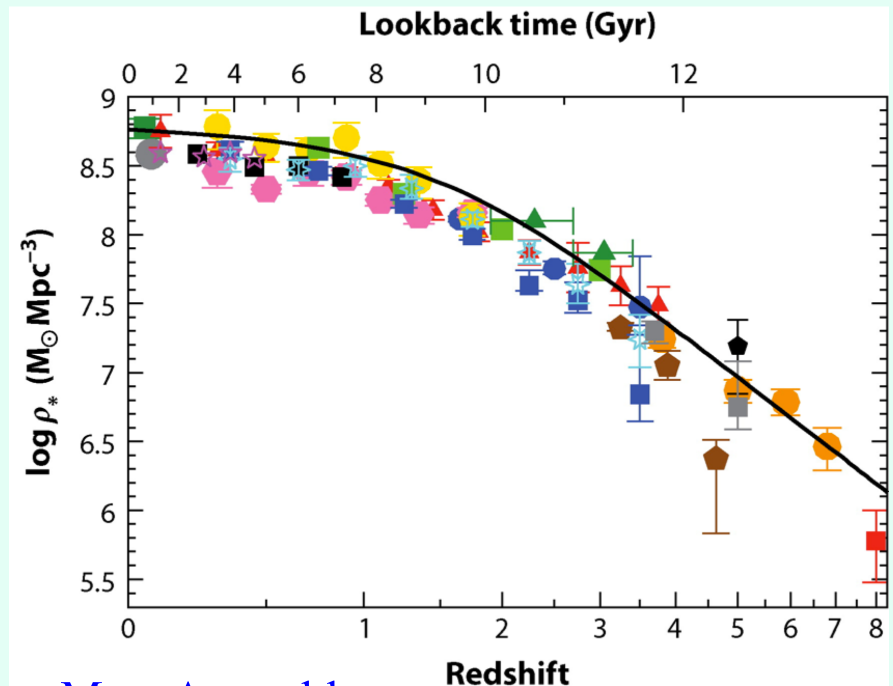




Cosmic SFR

Madau & Dickinson 2014, ARAA

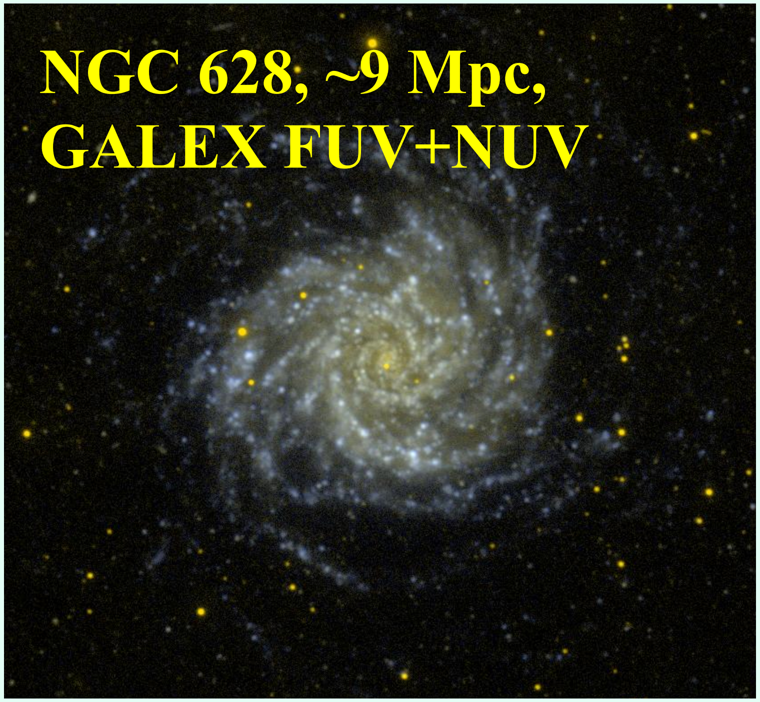
We are currently in a position to describe to some accuracy the evolution of SFR and mass assembly across cosmic times…



Mass Assembly

Across `Space'?

Image kindly provided by D. Thilker



The über-questions:

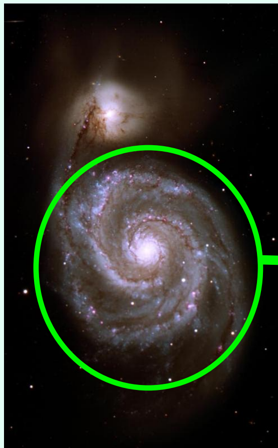
1. How does the Hubble sequence form?
2. How is SF linked to the gas supply (Kennicutt-Schmidt Law)?
3. What is the role of feedback in shaping galaxies and regulating SF?

We can't yet connect the two scales of `global' galaxies and stars/star clusters:

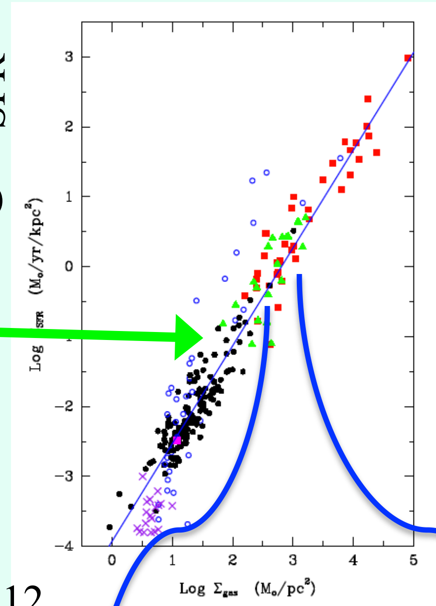
- How do stars form? Always clustered? In a scale—free hierarchy? (Elmegreen et al. 2006)
- Do we have one or two modes of star formation (clustered and diffuse)? (Meurer et al. 1995, Crocker et al. 2014)
- How has the mode of SF evolved with time? (10^9 M_o clump at z~1)

- On what timescale do stars disperse?
- What are the bound structures (star clusters) tracing? How do they evolve?
- How does SF power the ISM?
- Do we have a universal stellar IMF?
- How are `local' SFRs affected?

The KS Law: One or Many?



Log Σ_{SFR}



Kennicutt+Evans2012

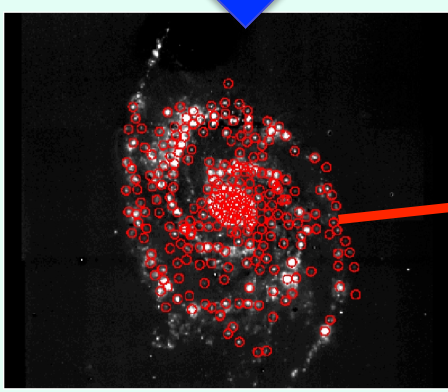
Log Σ_{gas}

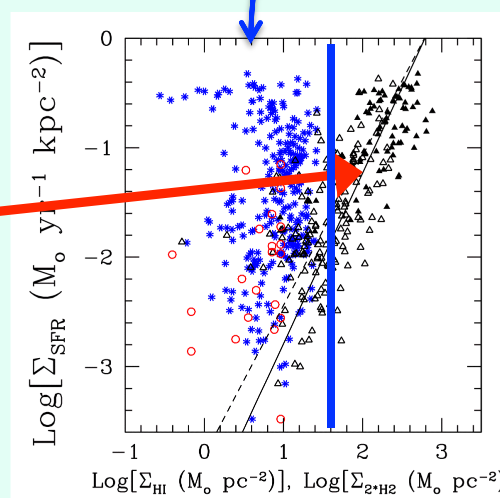
$\Sigma_{SFR} \sim \Sigma_{gas}^{gas}$

$\gamma_{gas} = 1.4$

Connected to physics

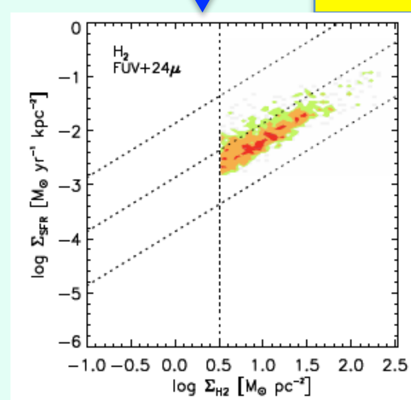
$\gamma_{H2,local,obs} =$
0.7, 1, 1.4,
…
??????





Kennicutt+2007

Log Σ_{H2}

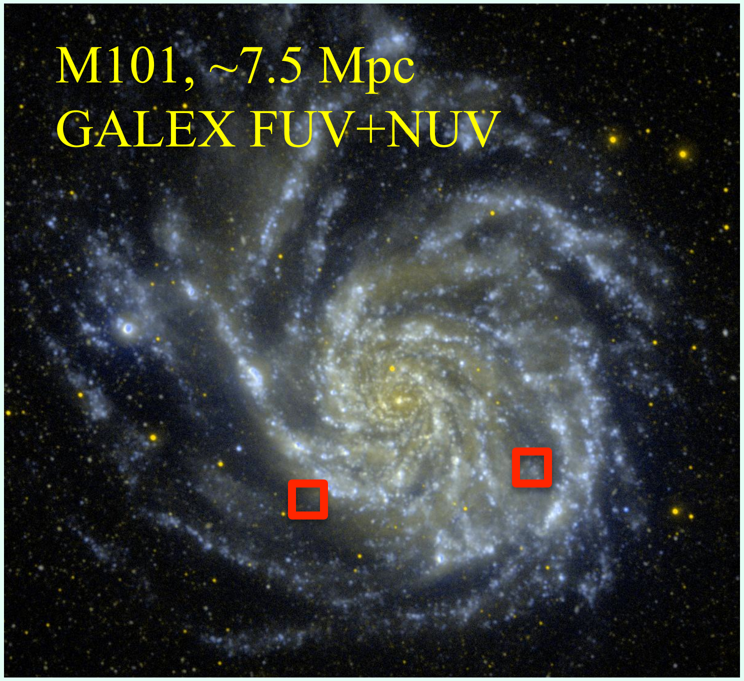


Bigiel+2008

See, also,
Blanc+2009,
Shetty+2014

Cloud-counting
C+2012

Stellar Pops Diffusion, SF Modes?



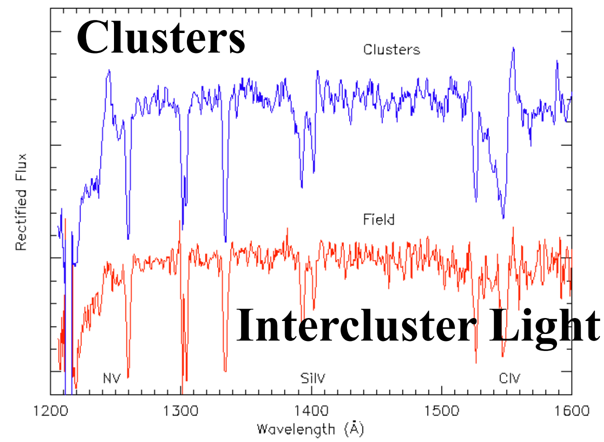
A common characteristic of local spirals: GALEX FUV-NUV color maps show that interarm regions have redder UV colors than arm regions

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 et al. 2014, HST UV)

In starburst galaxies, the intercluster light only shows evidence for B stars (no O stars, like clusters). IC light = 80% of all UV light.

Dispersion of clusters (Tremonti et al. 2001, Chandar et al. 2005) or two modes of SF (Meurer et al. 1995)?



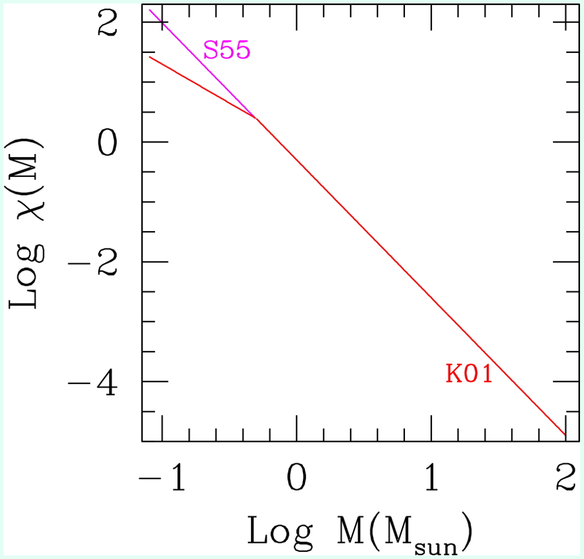
The Stellar IMF

Kroupa (2001) and Chabrier (2003) formulations are roughly equivalent to each other. For Kroupa:

$$\chi(M) = dN/dM = A\ M^{-1.3} \qquad 0.1 \leq M(M_\odot) \leq 0.5,$$
$$= 0.5\ A\ M^{-2.3} \qquad 0.5 \leq M(M_\odot) \leq 120$$

Variations in the IMF can crucially affect SFRs:

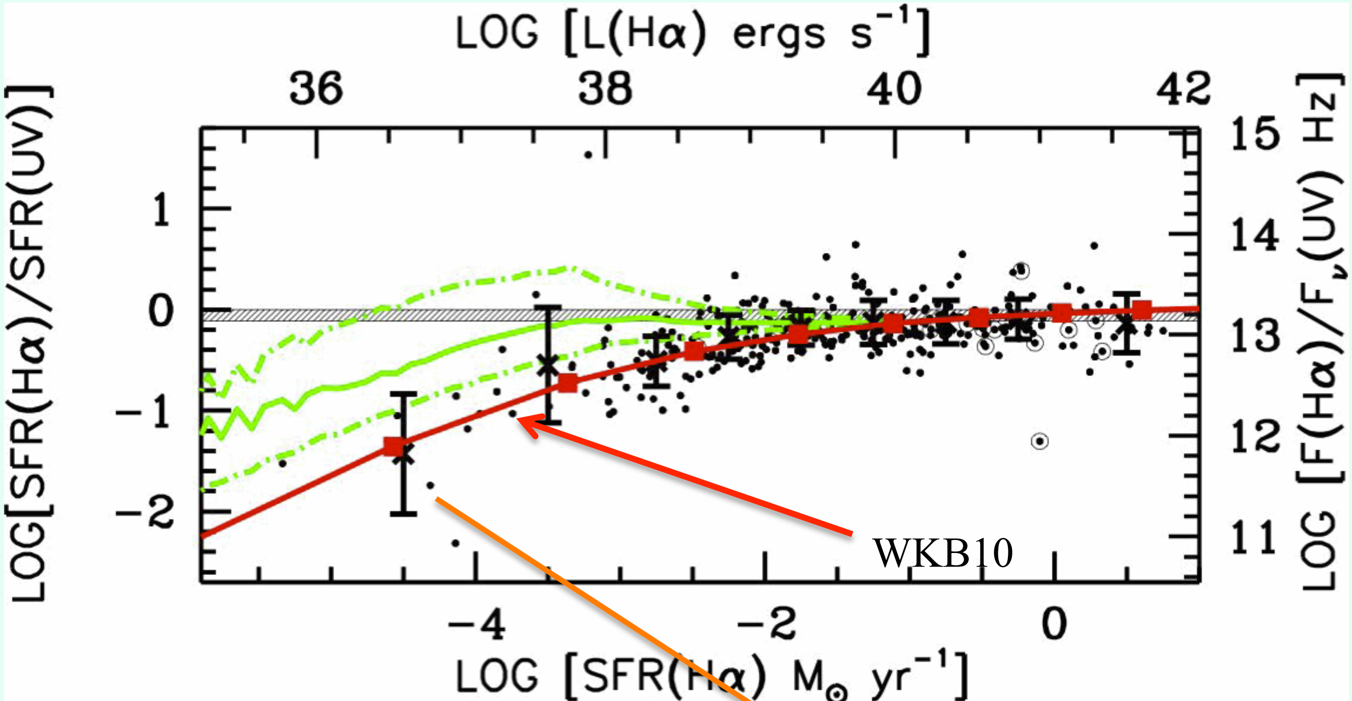
$$SFR(\lambda) = C(\text{IMF,SFH}) \times L(\lambda)$$



Stochasticity in IMF sampling:

- In order to fully sample the Kroupa IMF, at least $2.7\ 10^5\ M_o$ in stellar mass need to be formed ($4.2\ 10^5$ stars!).

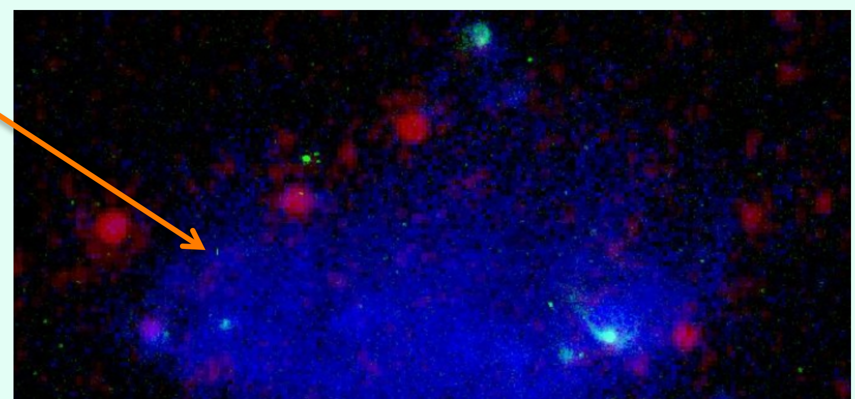
IMF Variations in/between Galaxies?



Lee+2009

See, also, Hoversten +2008, Meurer+2009, Gunawardhana+2011

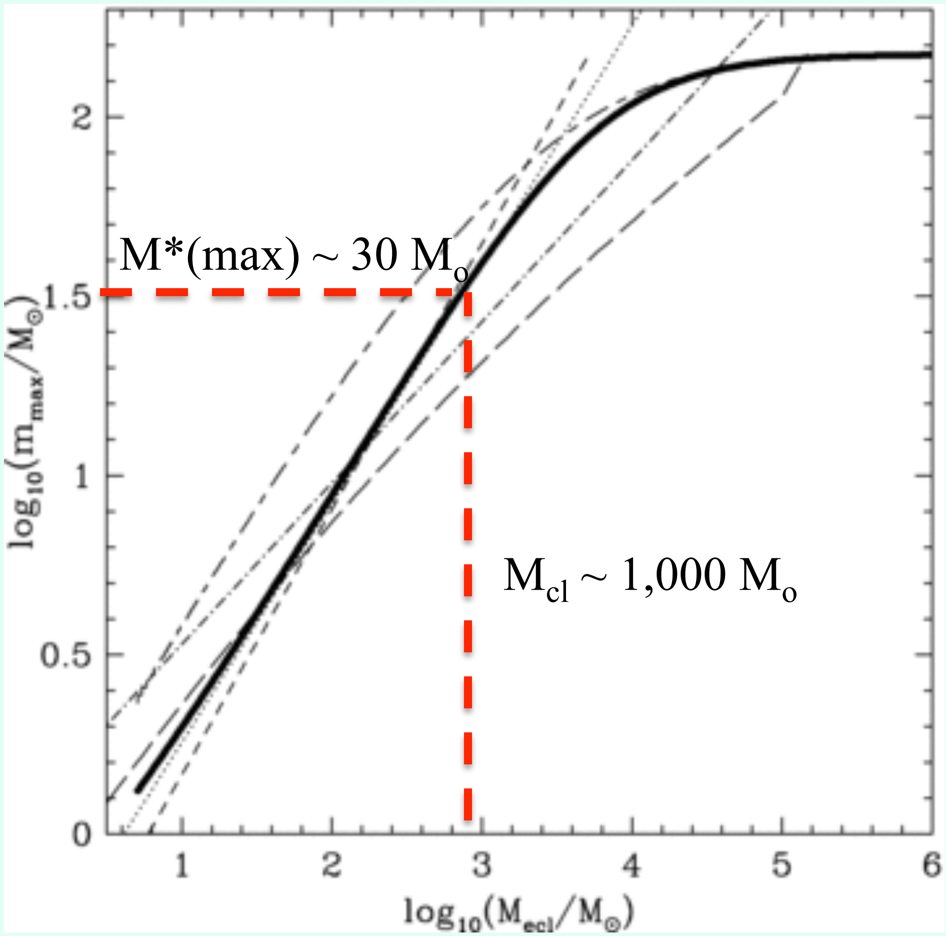
SFR(λ) = C(IMF,SFH) x L(λ)


UGC8201, UV(GALEX)+Hα+24(Spitzer)

The effect can result if:

1. Small galaxies only form small clusters (Larsen 2006)
2. Small clusters only form low-mass stars (sorted IMF sampling, Weidner+2006)

The `Sorted-Sampling' IMF

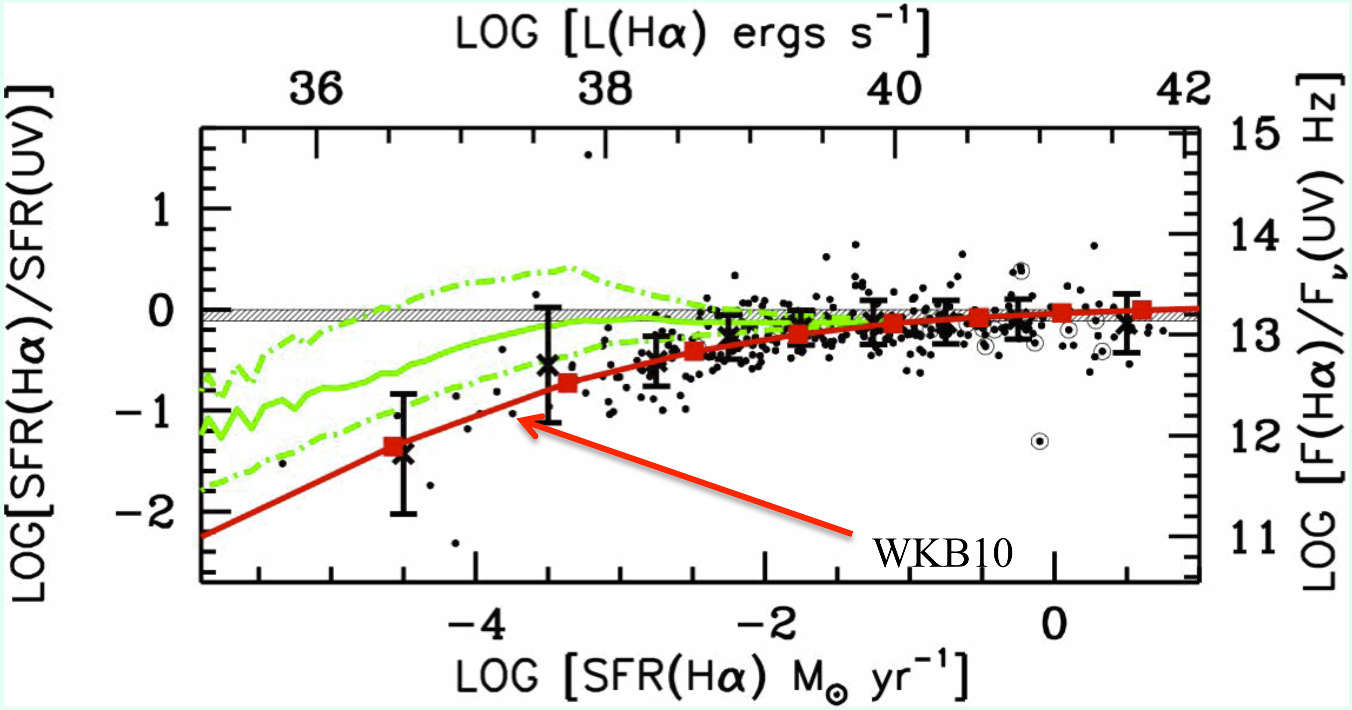


One of the most subtle ways to `vary' the IMF is to make the stellar population of a system (e.g., a star cluster) dependent on some parameter of the system itself (e.g., its mass). This is the principle of the IGIMF theory of Weidner et al. (Weidner & Kroupa 2005, Pflamm-Altenburg+2009, Weidner+2010).

In the IGIMF theory, the maximum stellar mass formed in a cluster is a (stochastic) function of the cluster mass. I.e., stars form from the `bottom up'.

Weidner, Kroupa & Bonnell 2010

IMF Variations in Galaxies?



Lee+2009

The WKB10 IGIMF theory is degenerate with:

1. Stochastic IMF sampling + SFH (Weisz+2012, Fumagalli+2011)
2. Loss of ionizing photons in low-mass galaxies (Hunter+2010, Pellegrini+2012)

Compare with evidence for low-end IMF variations (Geha+2013). See Cappellari et al 2012 and van Dokkum & Conroy 2012 for ellipticals, but also Russell Smith 2014 for a critical look.

Do NOT Assume…

… that all these issues are uncorrelated. For instance, cannot assume that there are two modes of SF without also assuming that the high-end of the IMF changes.

UV-red interarm SF regions = truncated IMF (or sorted-sampled IMF)

How to Make Progress…

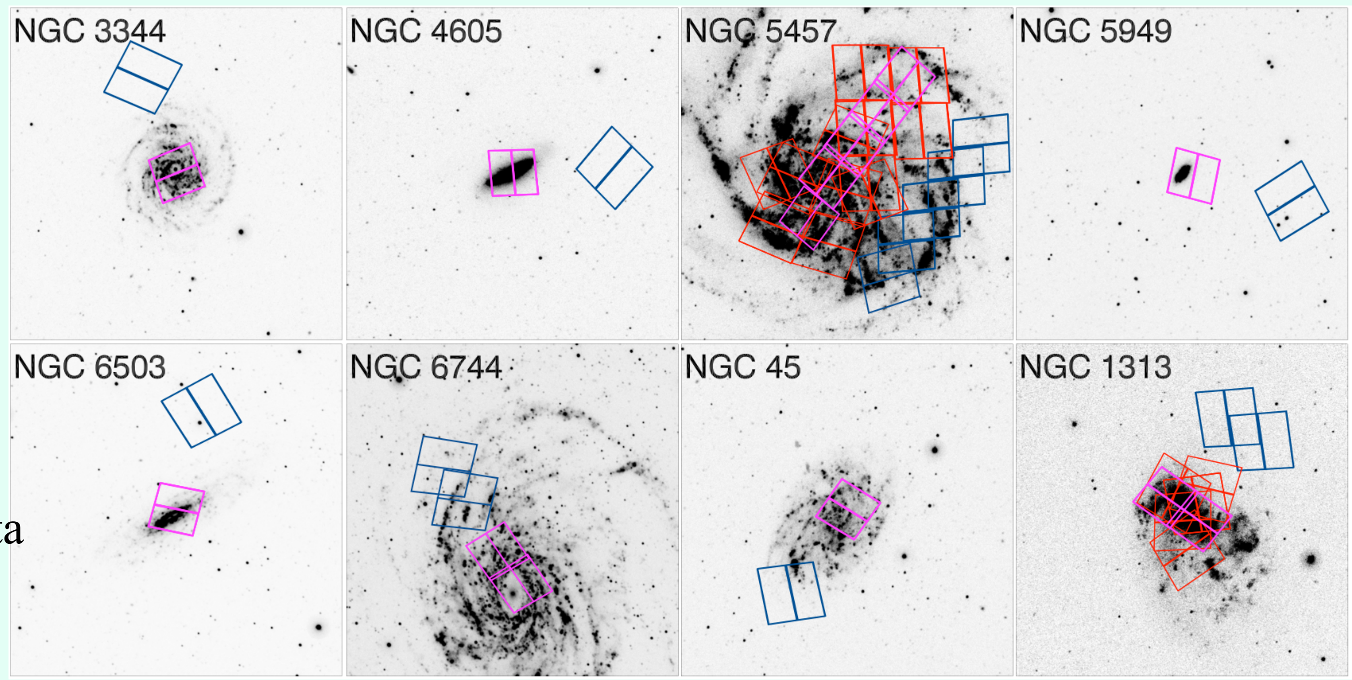
(hint: need exquisite resolution on a statistically significant number of galaxies)

- Recent SFHs (< 100 Myr) as a function of location
  - Catalogs of UV stars (location, luminosity, etc)
    - HST 5-band photometry (Cycle 21 LEGUS)
- Cluster populations evolution, formation history
  - Catalogs of young clusters (ID, location, mass, age)
    - HST 5-band photometry (Cycle 21 LEGUS)
- Ionized gas, HII regions distributions
  - Hα images
    - HST (Cycle 22 Halpha-LEGUS)
- Ionized gas conditions, gas extinction maps
  - Spectral maps
    - Ground-based IFU, narrow-band imaging, long slit spectroscopy

The Project

legus.stsci.edu, C+2014

- Cycle 21 HST Treasury Program (154 primary + 154 parallel Orbits)
- 50 galaxies, in the range 3.5-12 Mpc, in 126 pointings (63 primary); 100% complete as of Sept 2014.
- Primary: WFC3/NUV,U,B,V,I (5 bands) – leverage the HST Archive as much as possible
- Parallel: ACS/B,V,I



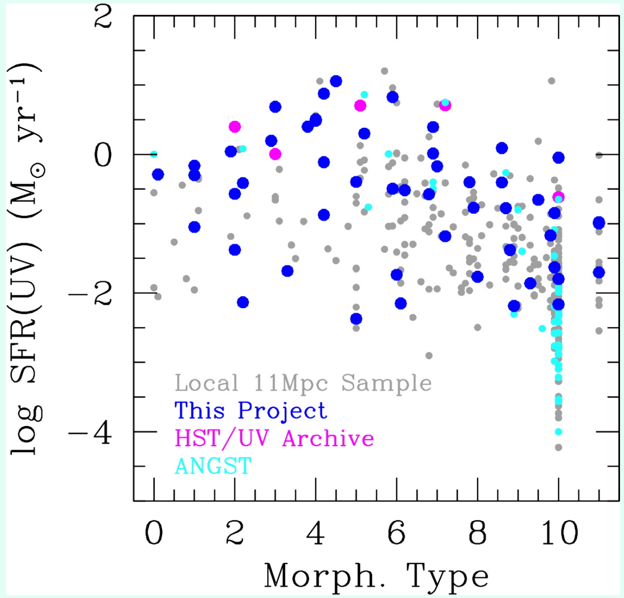
LEGUS footprint=magenta
LEGUS parallels=blue
Archival data=red

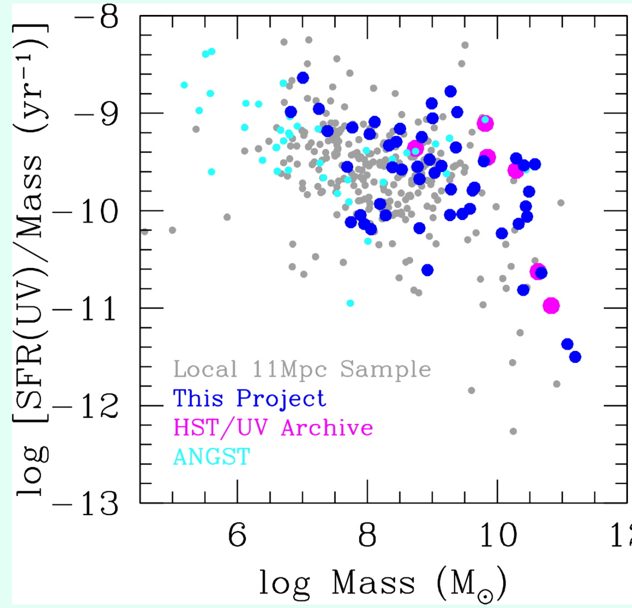
Legacy ExtraGalactic

LEGUS

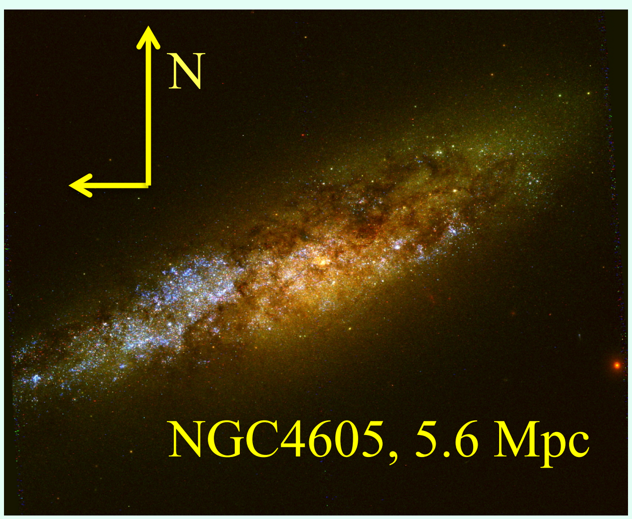
Ultraviolet Survey

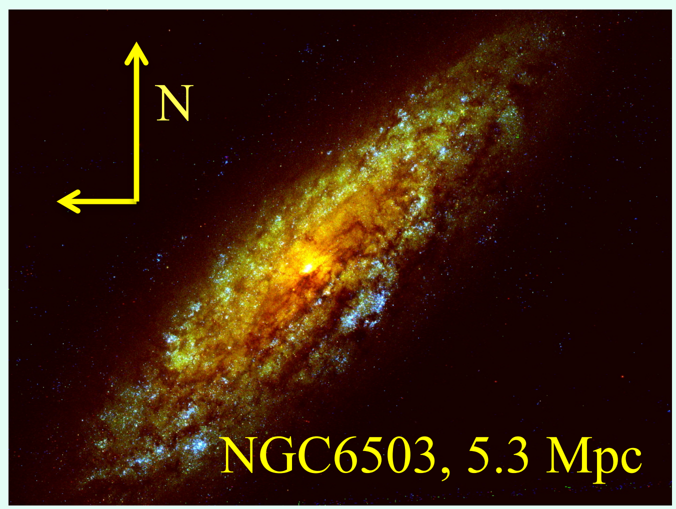
The Sample





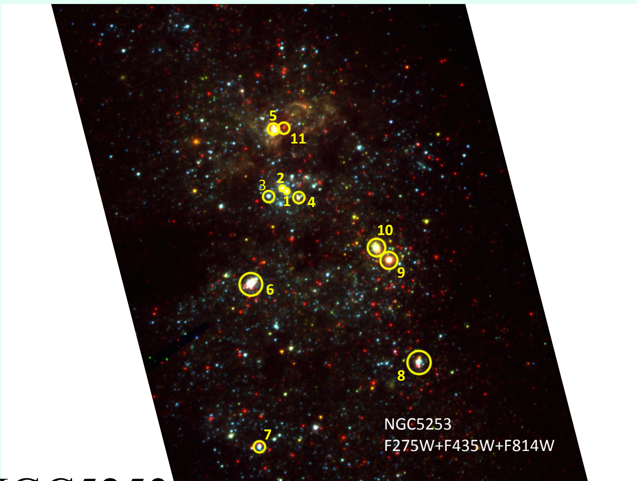
Full range of basic properties (morphology, sSFR, SFR, mass, interaction type, presence/absence of bars, etc.) found in the local Universe, < 12 Mpc.





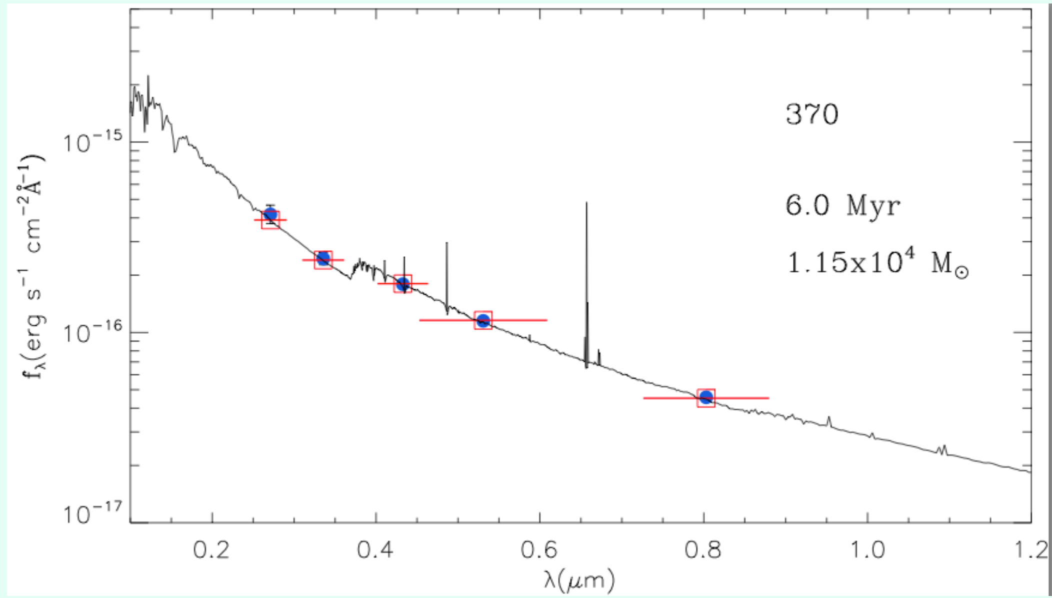
Color-composites: NUV (blue), B (green), and I (red)

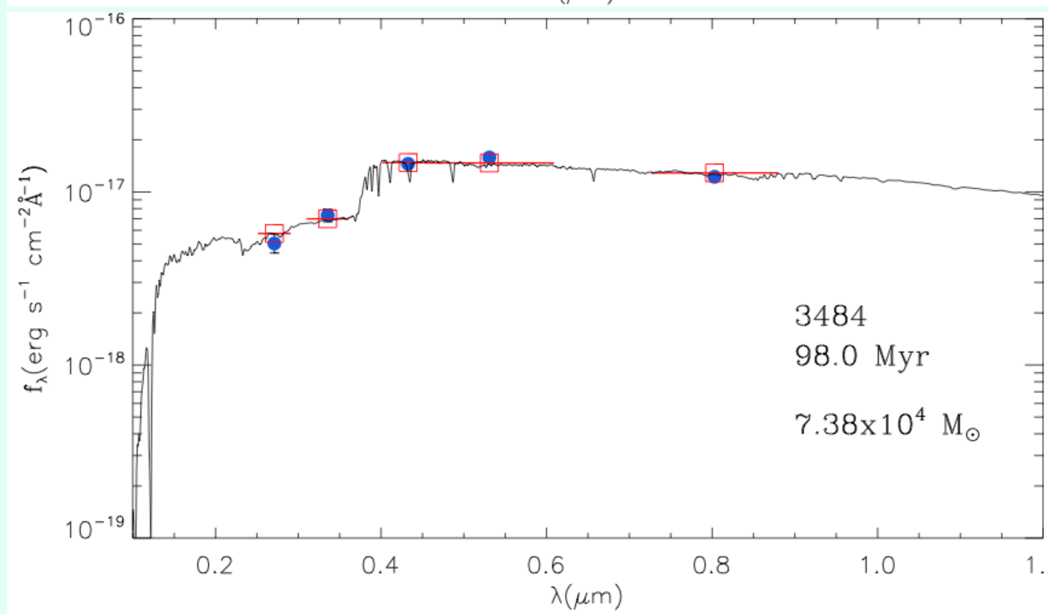
Star-Clusters:
Age+Masses via BB Photometry



NGC5253
3.7 Mpc

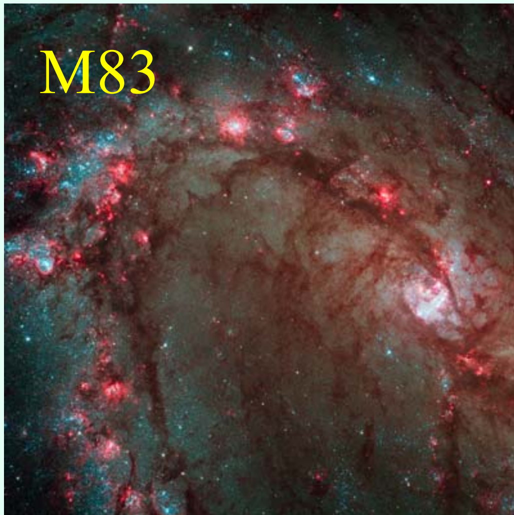
5th band breaks degeneracy in SED fitting.
UV more stable (~4X) than Hα for separating young, Q°-deficient from aging clusters, esp. at **low cluster masses** (da Silva+2014)



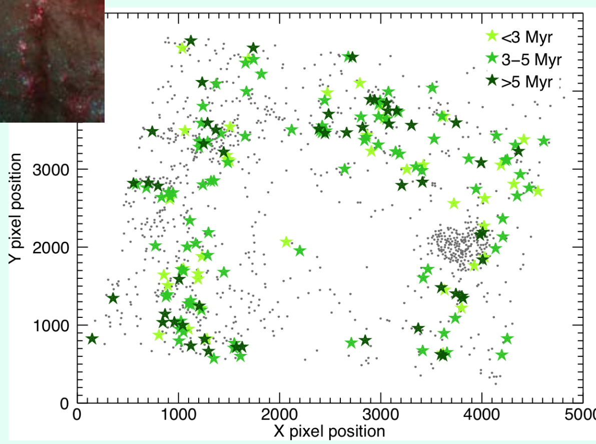


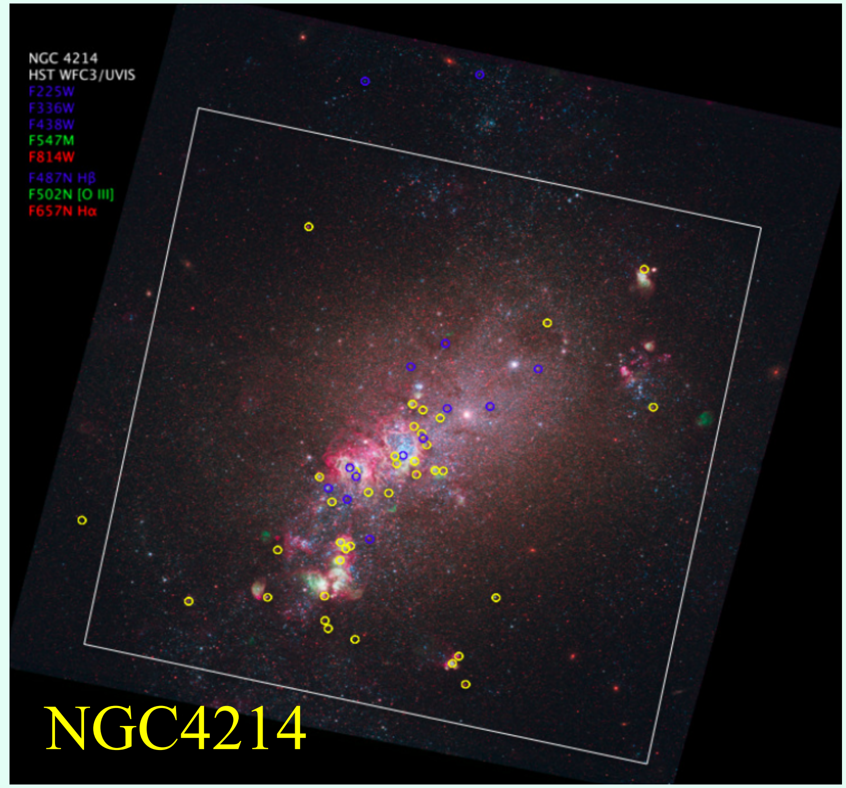
Test the High-End of the IMF

Andrews et al. 2013, 2014



WFC3-ERS:
BB+NB HST imaging





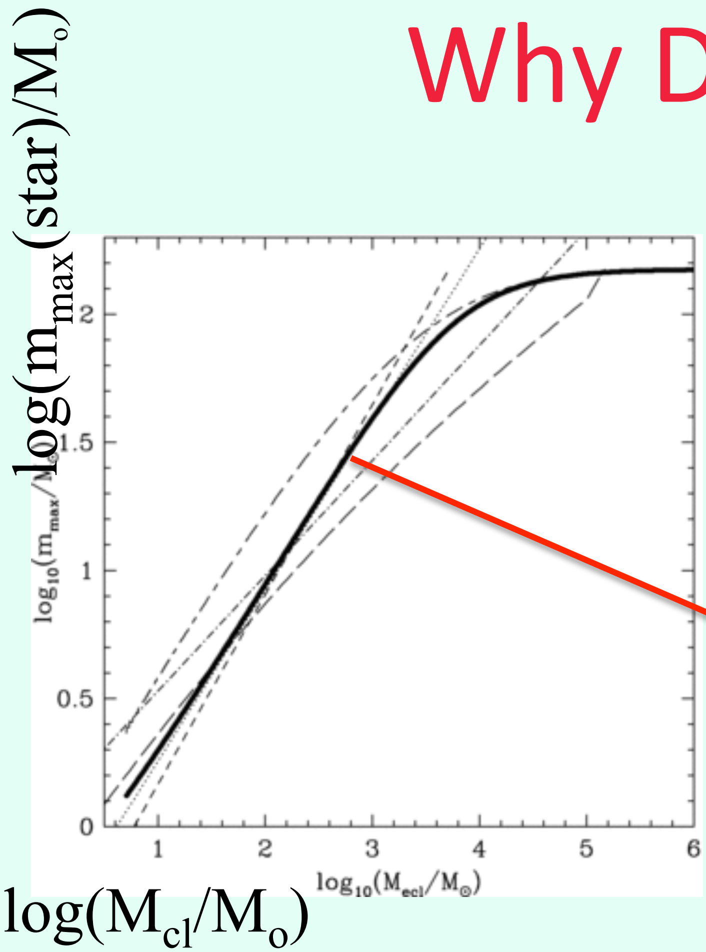
5 bands (UV-to-I) to derive ages, masses, extinctions of star clusters ***at all masses***, with stochastically sampled models (LEGUS-like).

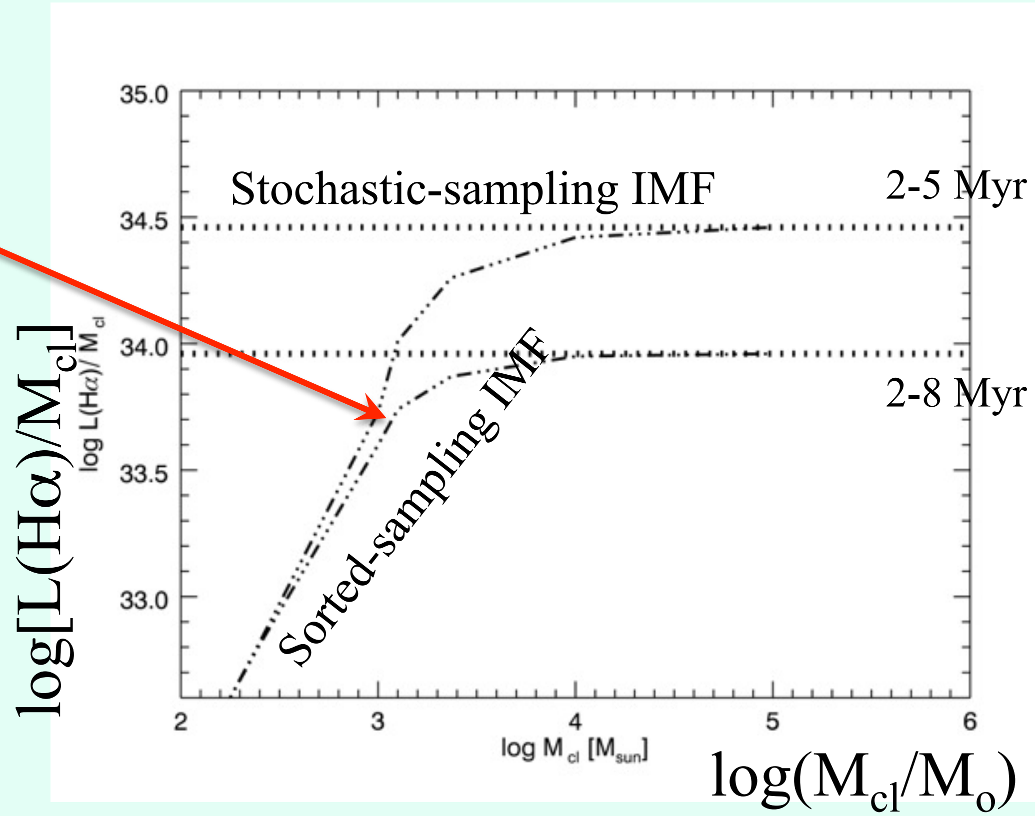
Additional information required: extinction-corrected ionizing photon flux: Hα (e.g., Halpha-LEGUS) + one other recombination line (e.g., ground)

Why Do We Need Hα?

Andrews+2013,2014

(also, C.+2010, Hermanowicz+2012)

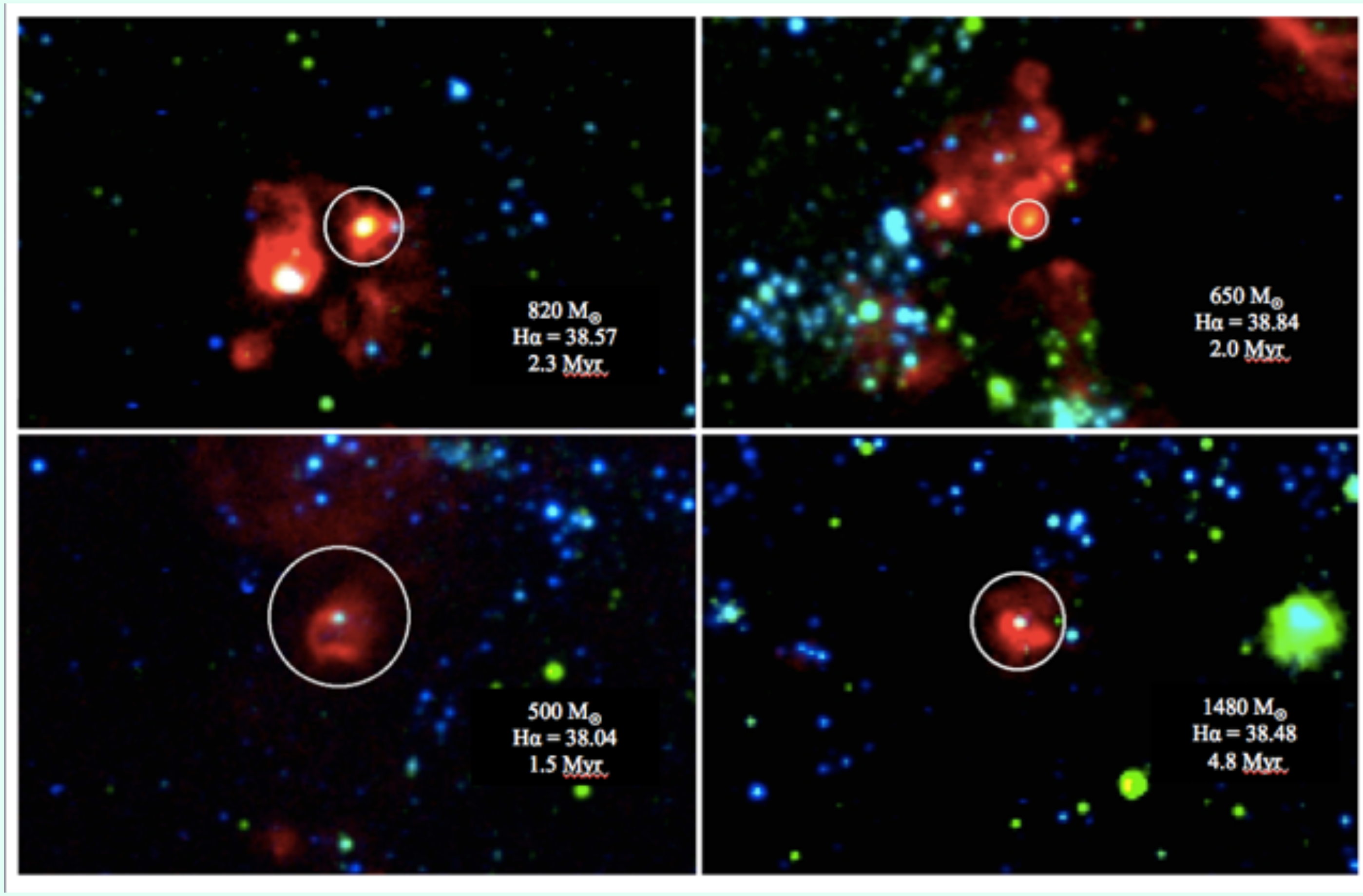




L(Hα) probes the ionizing photon rate (presence of massive stars) in unresolved, young star clusters

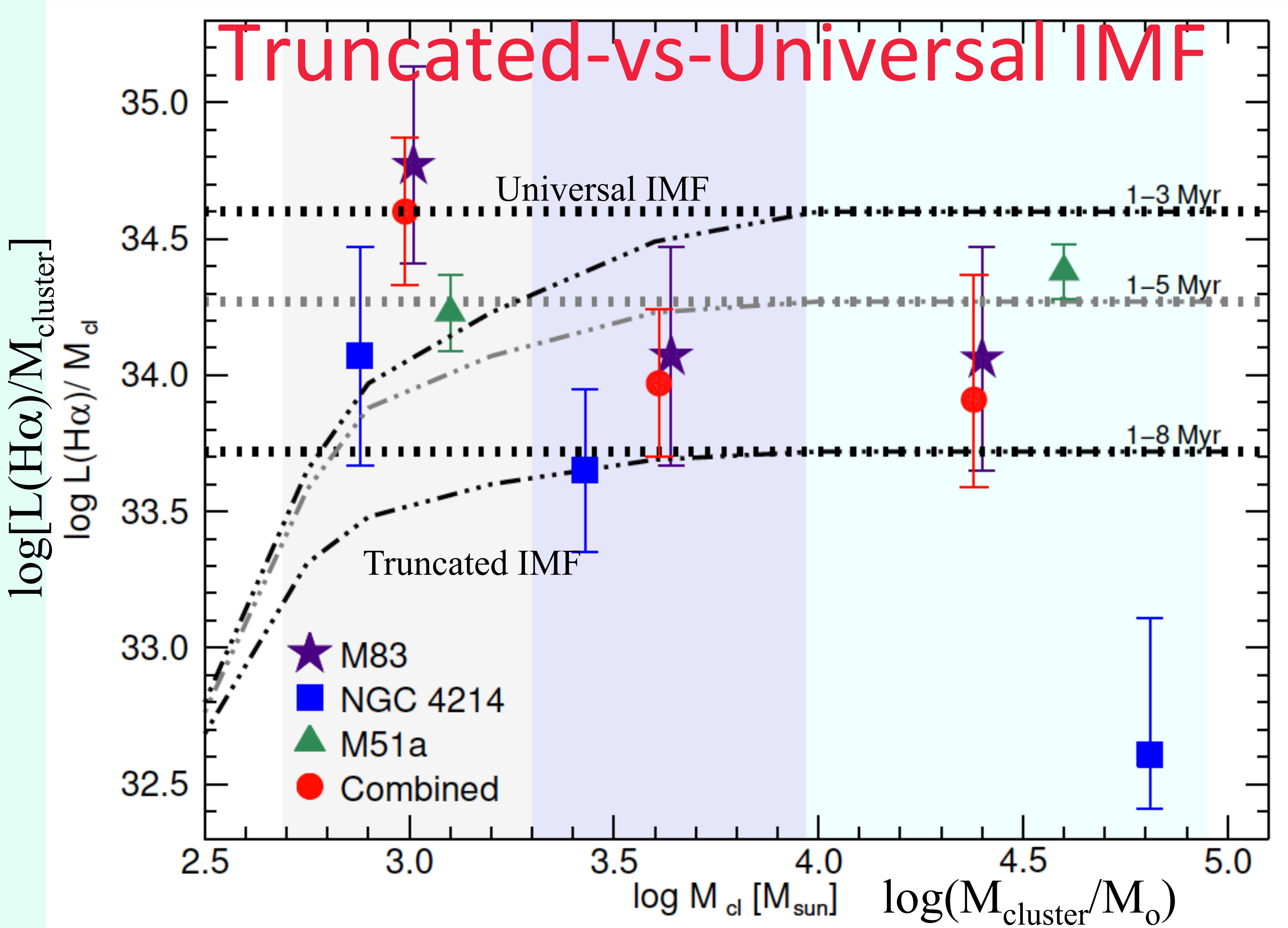
A luminosity-independent extension of Corbelli et al. 2009

What the high Hα/M_{cl} Look like…



Andrews et al. 2014

M83 clusters: high Hα, with cluster mass < 1500 M_o



Similar results hold for integrated galaxy photometry
(Fumagalli et al. 2011)

(Andrews, C. et al. 2013, 2014)

Conclusions

1. The spatial (and not only temporal) evolution of stellar populations has major impact on our understanding of:
   1. Presence of multiple modes of SF
   2. Variations of the high-end of the IMF
   3. Calibration of local SFR(UV); (e.g., resolved KS Law)
   4. Dynamical evolution of galaxies
   5. Models of formation of massive stars (competitive accretion vs. core collapse)

2. To the extent that we have been able to test, variations of the stellar IMF at the high end are unlikely to occur in the star cluster populations of nearby galaxies. More tests will be necessary, to bring this result to a statistically significant level and to capture the full range of galactic environments.

3. And….
   1. We NEED a 30-meter far-infrared telescope in space.