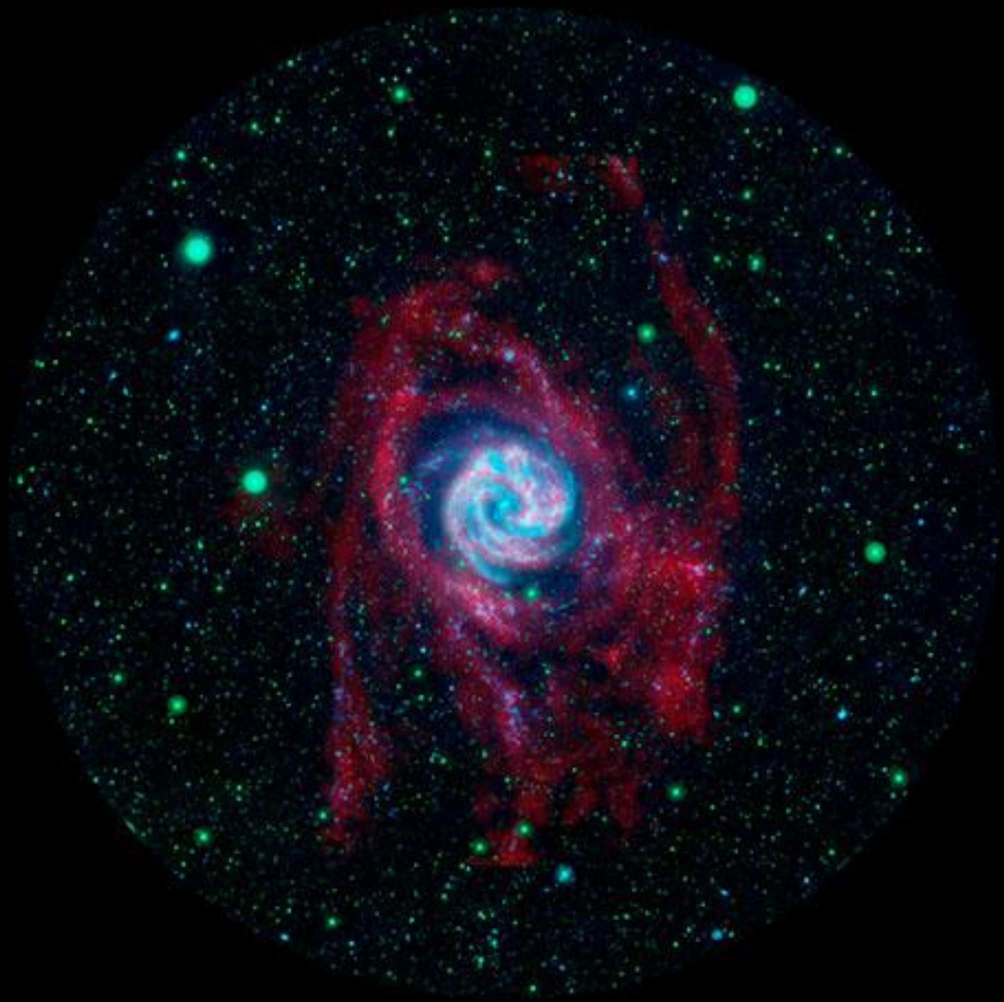
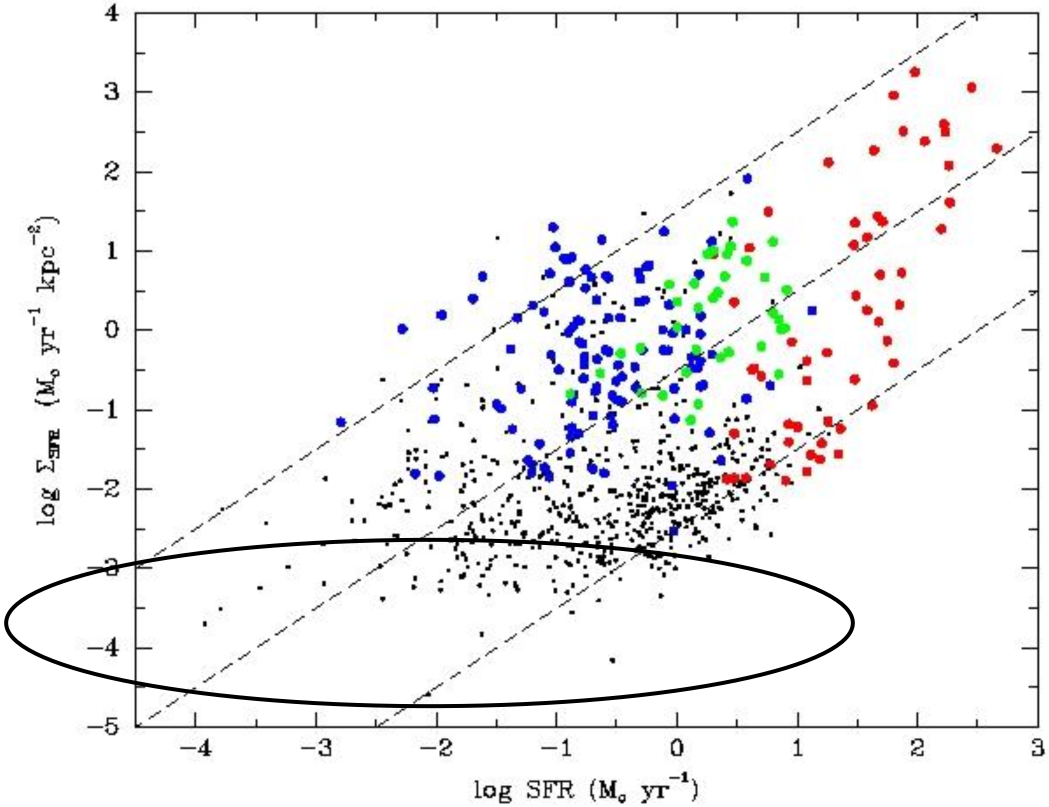
Star Formation in the Desert: Probing the Low Density Extremes

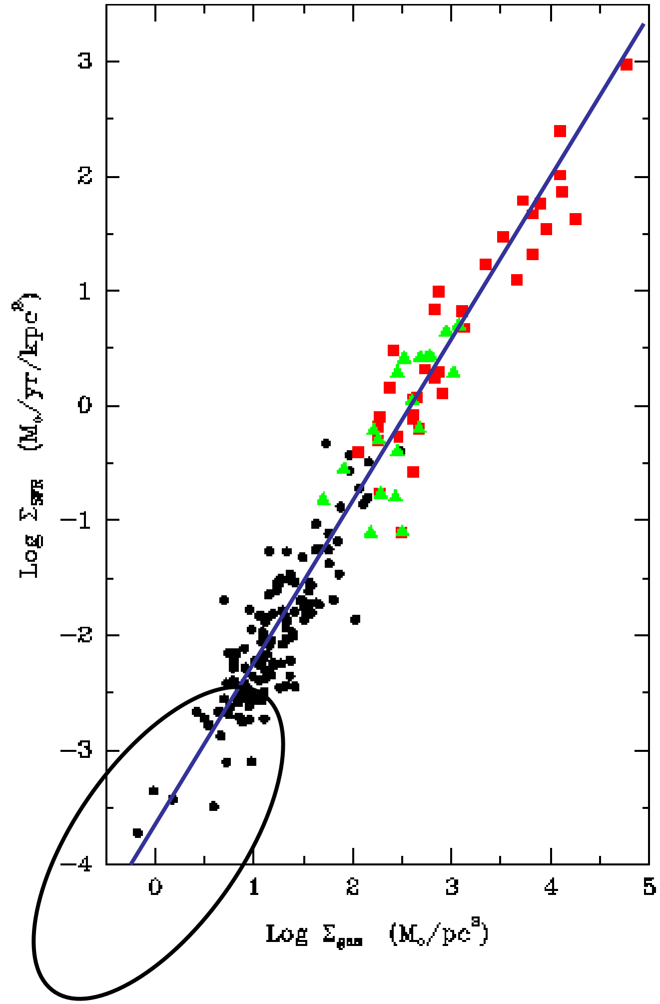
Robert Kennicutt

Institute of Astronomy
University of Cambridge

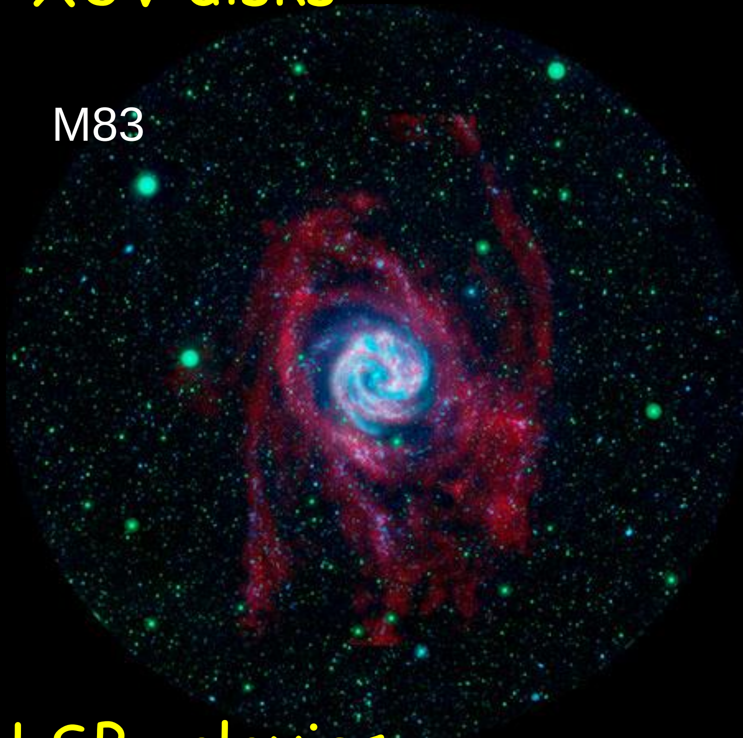


Collaborators:
- Fabio Bresolin
- Jose Funes
- Quinton Goddard
- Ben Johnson
- Janice Lee
- Fabian Rosales-Ortega
- Emma Ryan-Weber

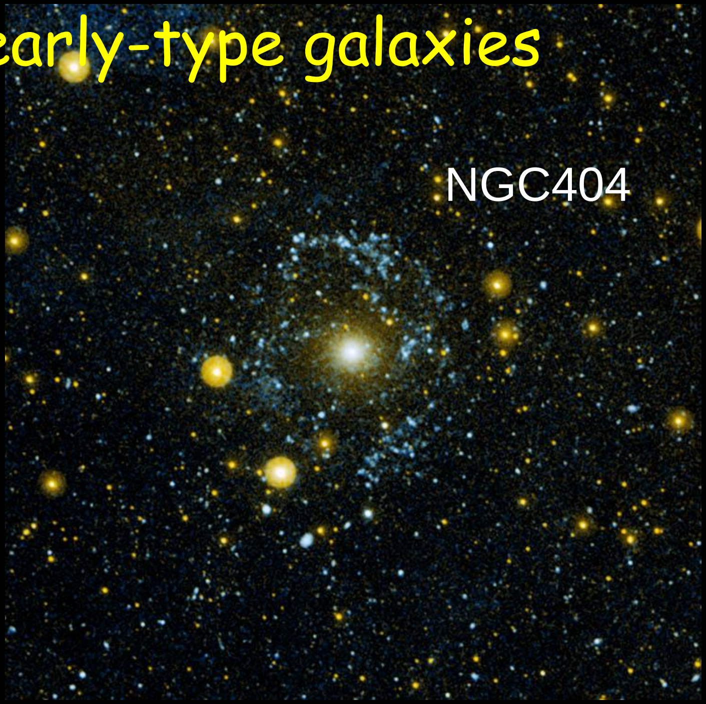

log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
log SFR ($M_\odot$ yr^{-1})


Log Σ_{SFR} ($M_\odot$/yr/kpc^2)
Log Σ_{gas} ($M_\odot$/pc^2)

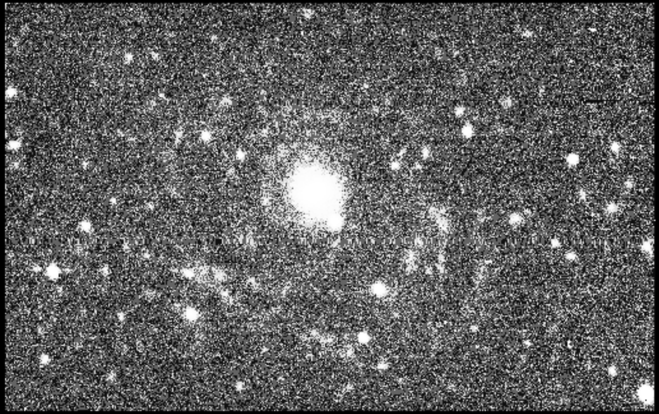
"XUV disks"



early-type galaxies



LSB galaxies



Malin 1

dwarf galaxies

NGC 6822

Questions

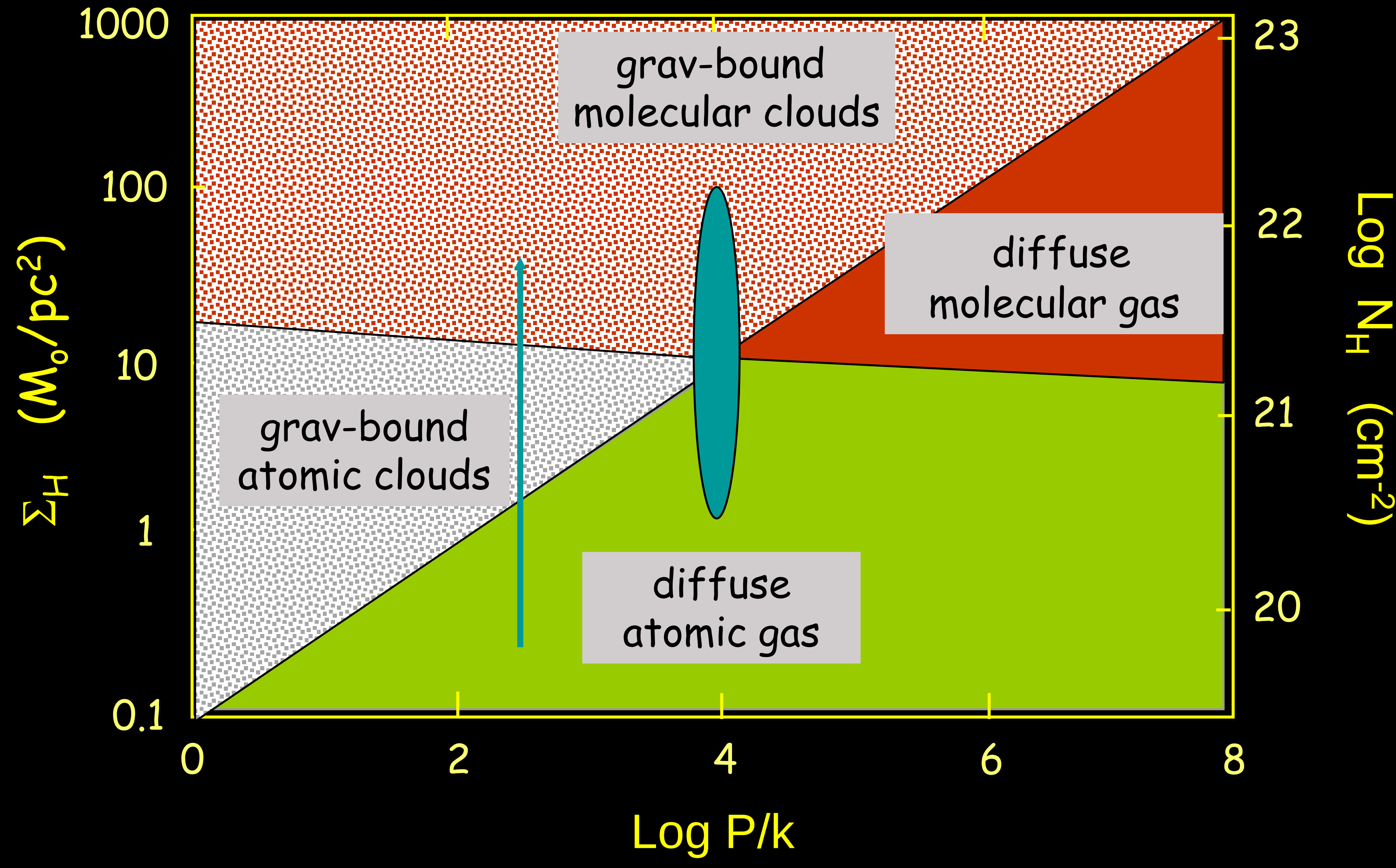
- Is low density SF the same as local SF (but more dispersed), or does it represent a distinct SF mode? (e.g., SF law, SF efficiency, IMF, controlling physics)?

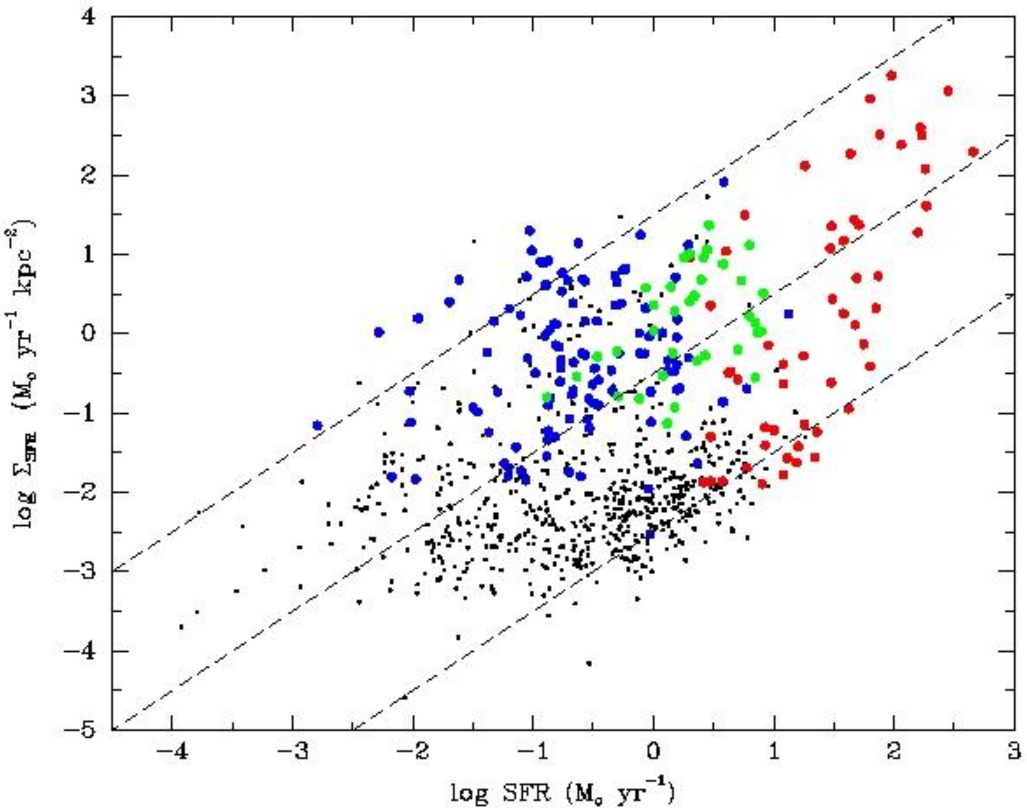
- What do these regions reveal about the physics of star formation?

- What do these regions reveal about the evolution of their parent galaxies?

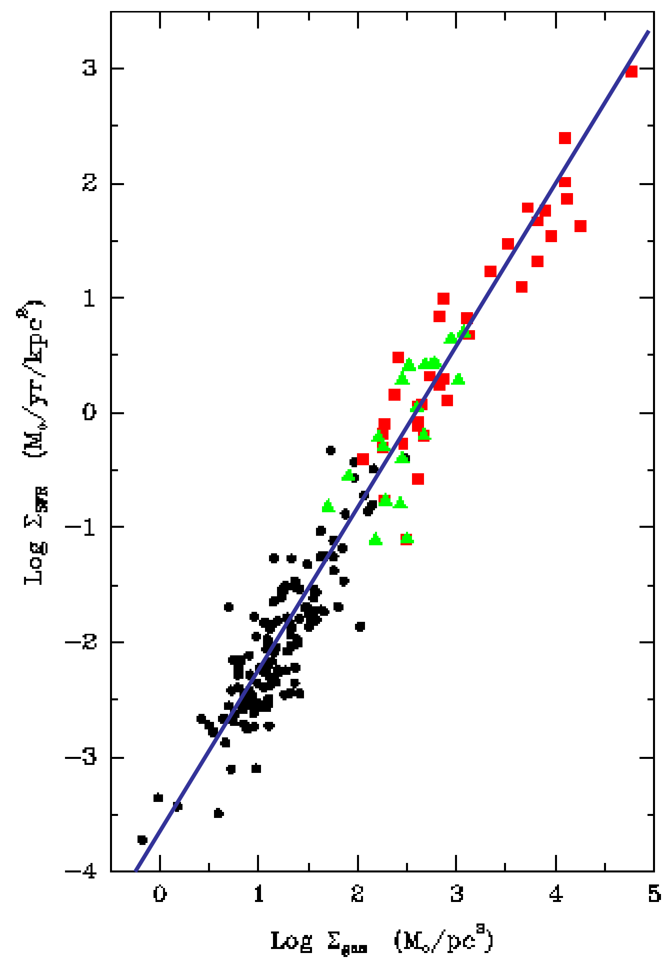
- The path from accretion to star formation involves several steps, with "critical path" dictated by the most difficult physical hurdle.
  - accretion from the cosmic web – incidental or fundamental??
  - formation of a neutral ISM (cooling, thermal instabilities)
    - easy for disks, difficult for massive spheroids
    - dictated by gas density and ambient UV radiation field (internal and external)
  - formation of bound interstellar clouds (Jeans/gravitational instabilities)
    - dictated by gas density and galactic shear, tidal field
  - formation of a cool neutral phase (thermal/pressure instabilities)
    - dictated by ISM pressure and temperature
  - formation of molecular gas (phase instability)
    - dictated by cloud opacity (photodissociating UV) and ambient UV field
  - formation of bound molecular cloud cores
    - dictated by Jeans, fragmentation, turbulence, competitive accretion…
  - formation of stars, planets
- Only the latter of these processes appear to be deterministic in galaxies today. Which processes are "critical" is a subject of debate, and may change in different environments, cosmic epochs.

ISM Phase vs Gravitational Instabilities



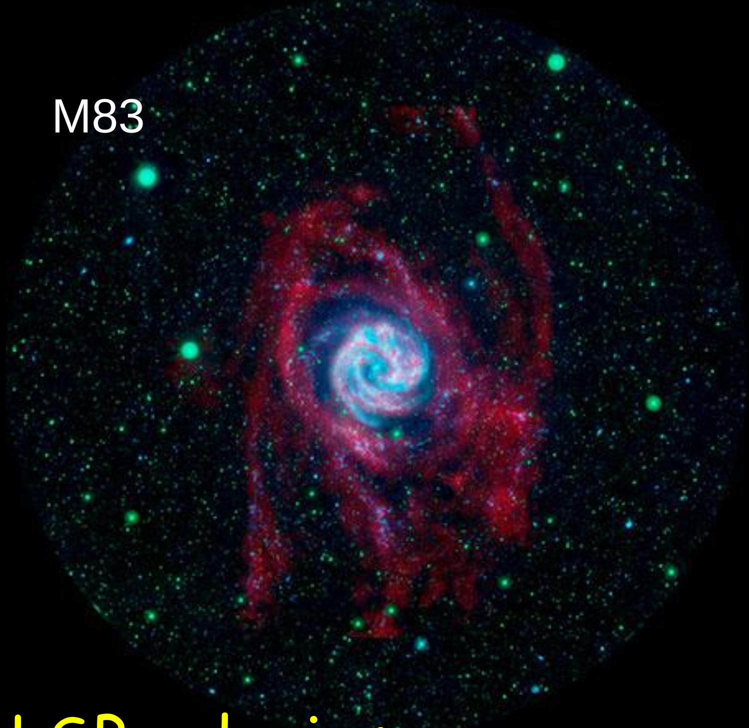


log SFR (M☉ yr^{-1})
log Σ_{SFR} (M☉ yr^{-1} kpc^{-2})

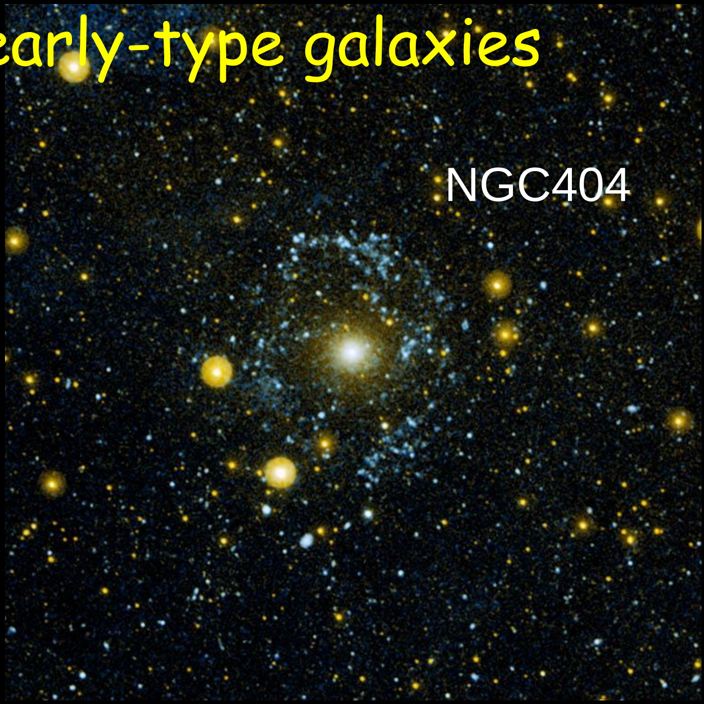


Log Σ_{gas} (M☉/pc^2)
Log Σ_{SFR} (M☉/yr/kpc^2)

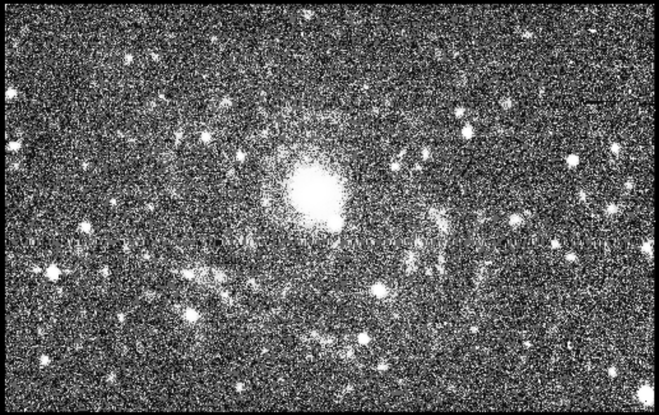
“XUV disks”



early-type galaxies



LSB galaxies

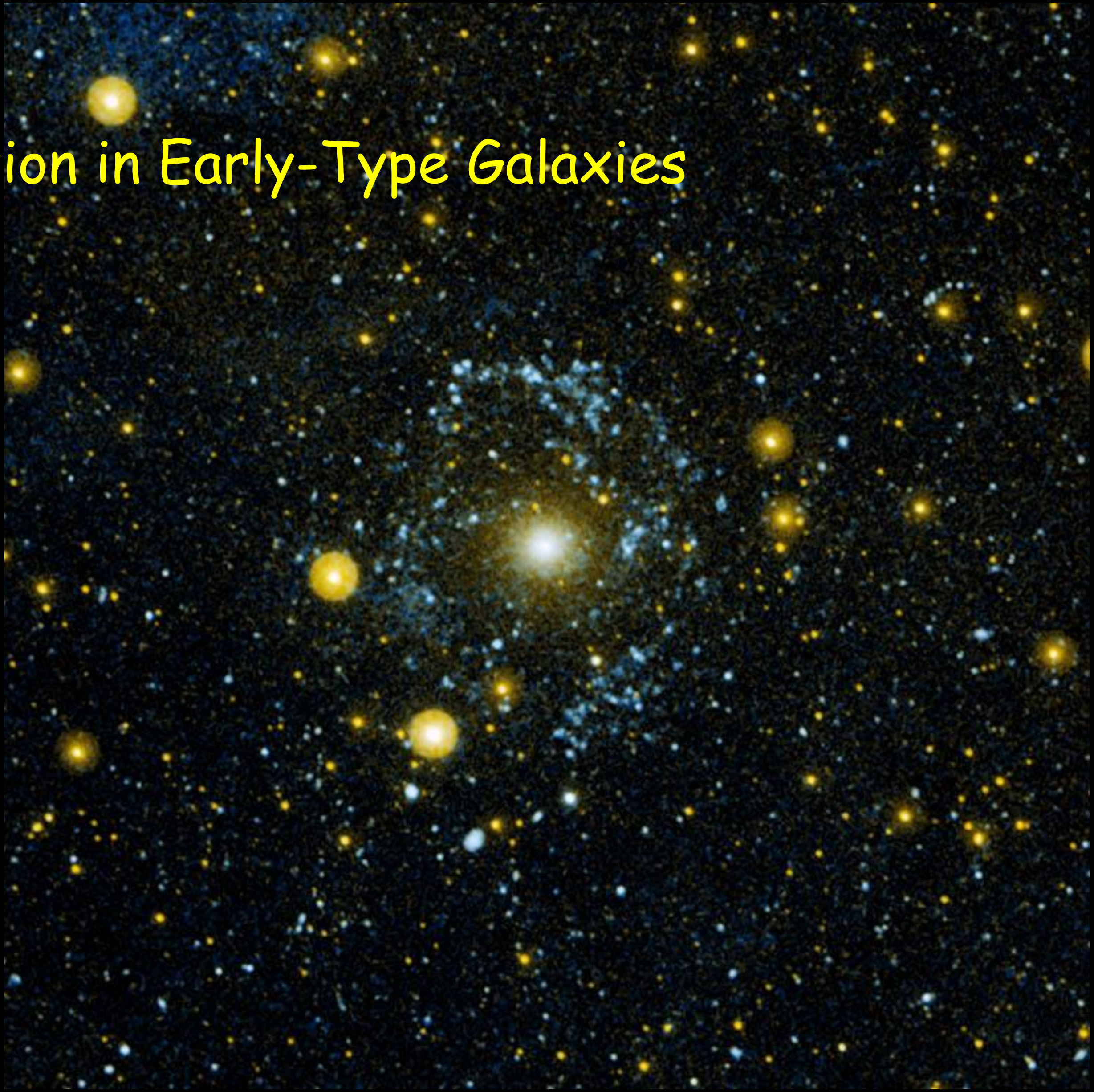


Malin 1

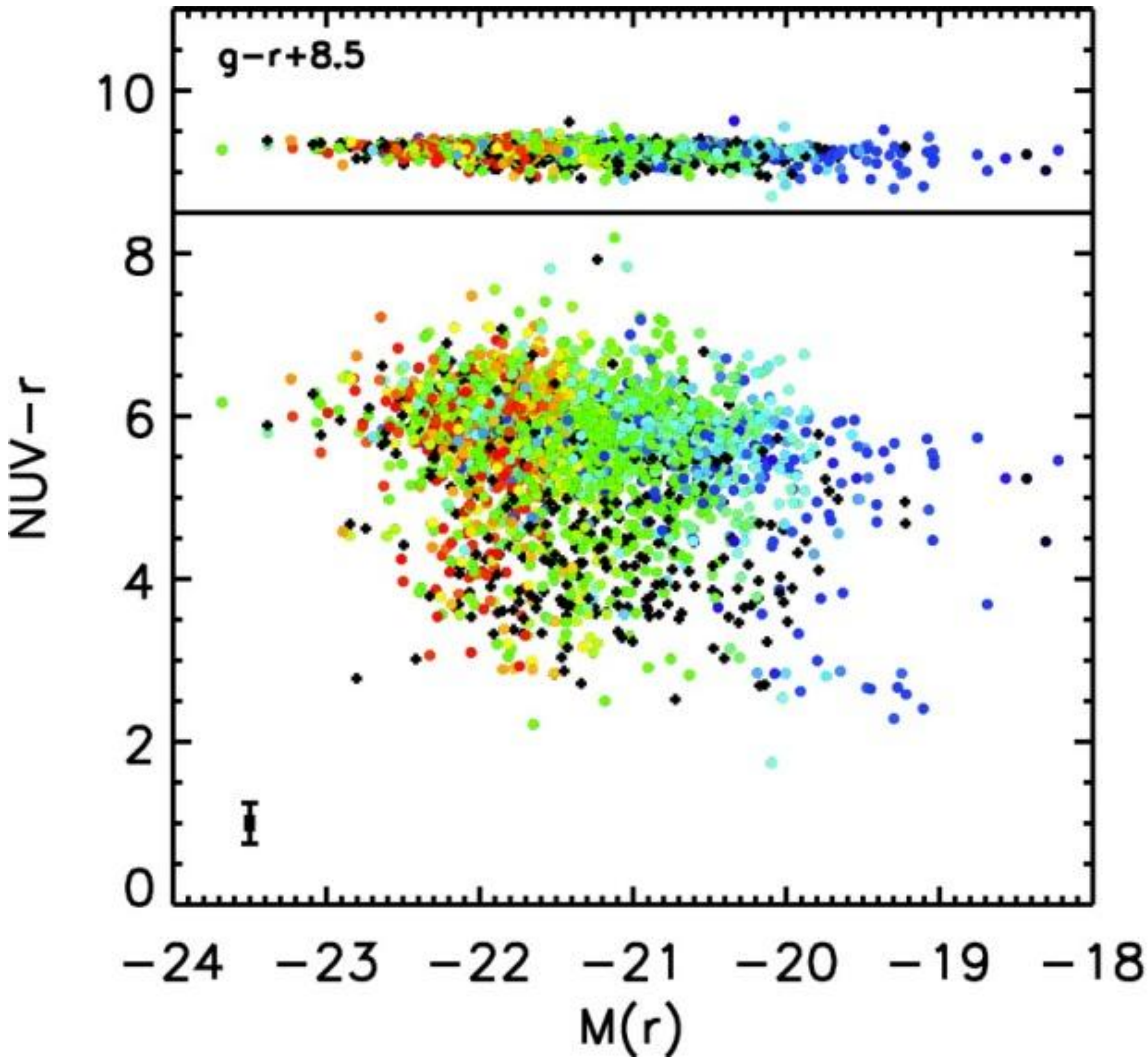
dwarf galaxies

NGC 6822

Star Formation in Early-Type Galaxies



Thilker et al. 2010, ApJ, 714, L171

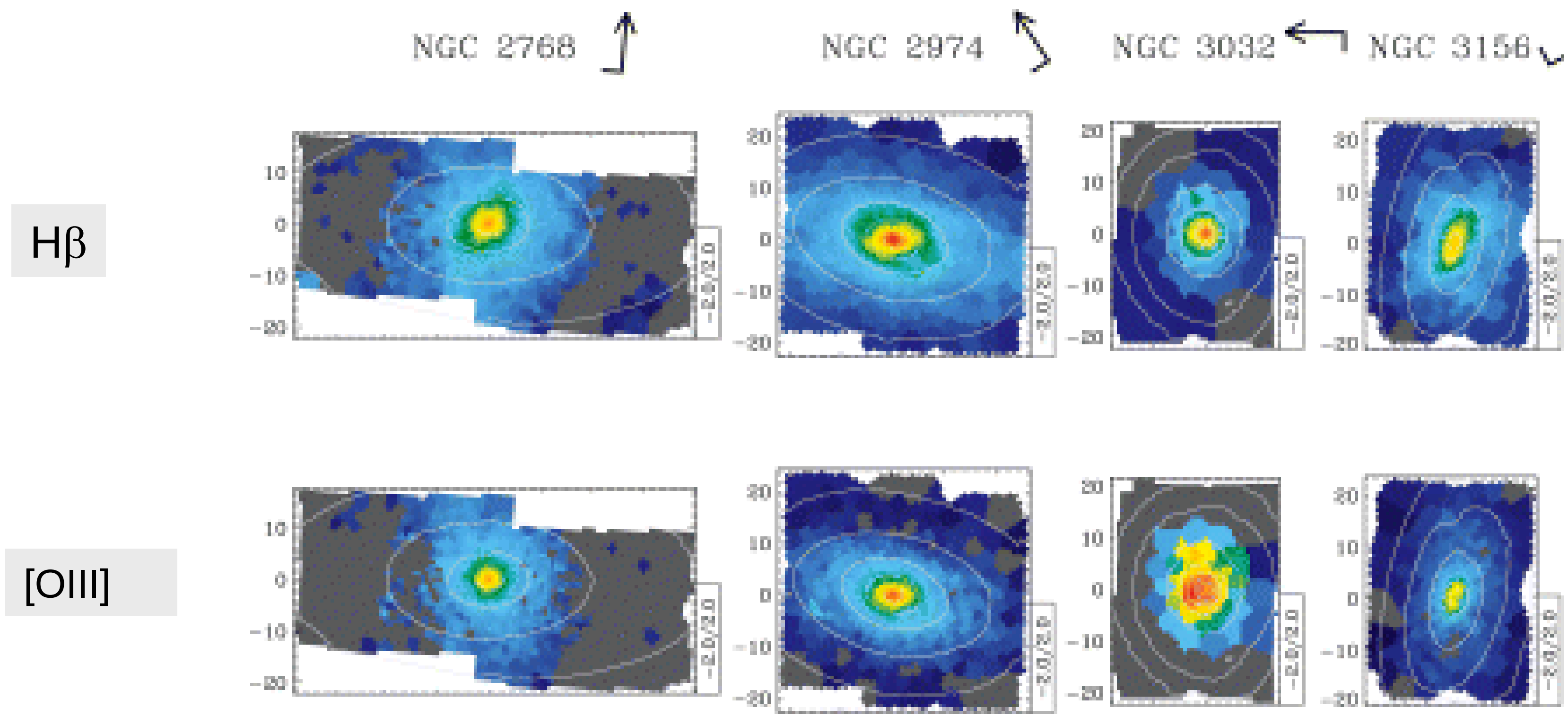


30% of 2100 E and S0 galaxies formed stars in last 300-500 Myr

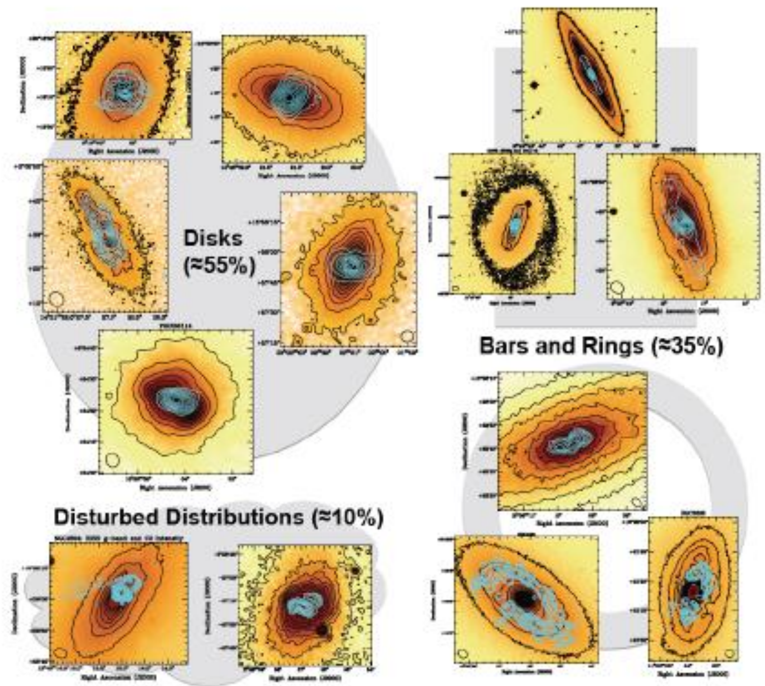
Kaviraj et al. 2007, ApJS, 173, 619

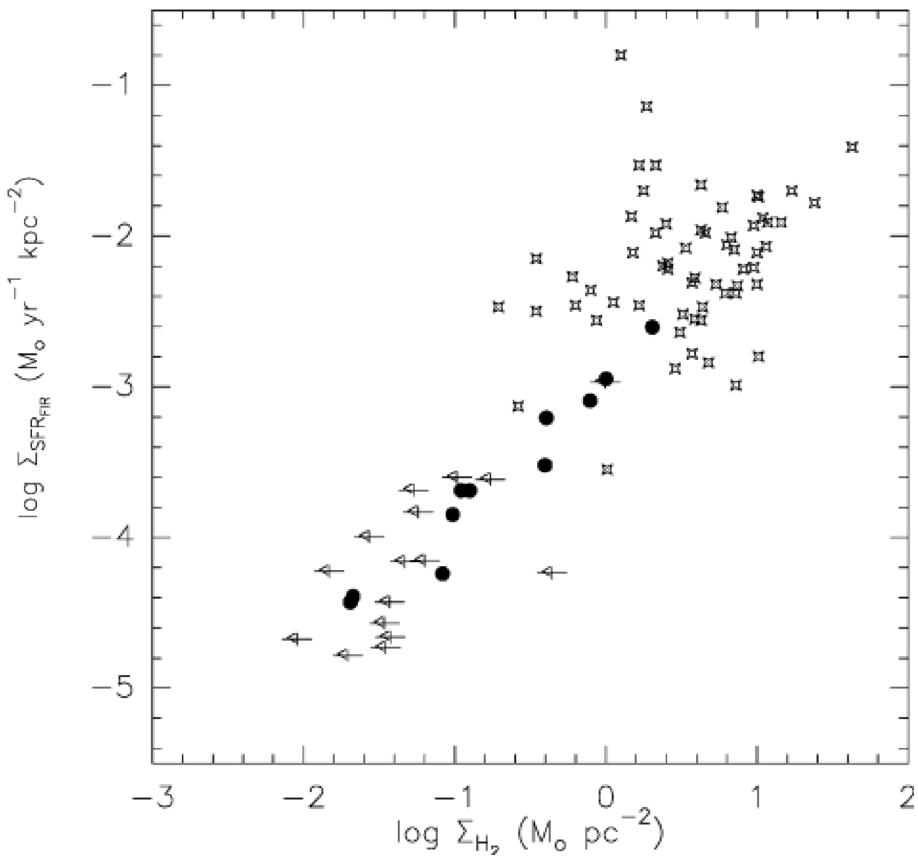
SAURON Sample (now Atlas3D survey - 320 galaxies)

- 48 E/S0 galaxies observed (43 in CO)
- 75% detected in Hβ (16/24 E, 20/24 S0), 28% detected in CO
- typical SFRs of order 0.01-1 M_{o}/yr
- disk-averaged SF properties extend Schmidt law for spirals



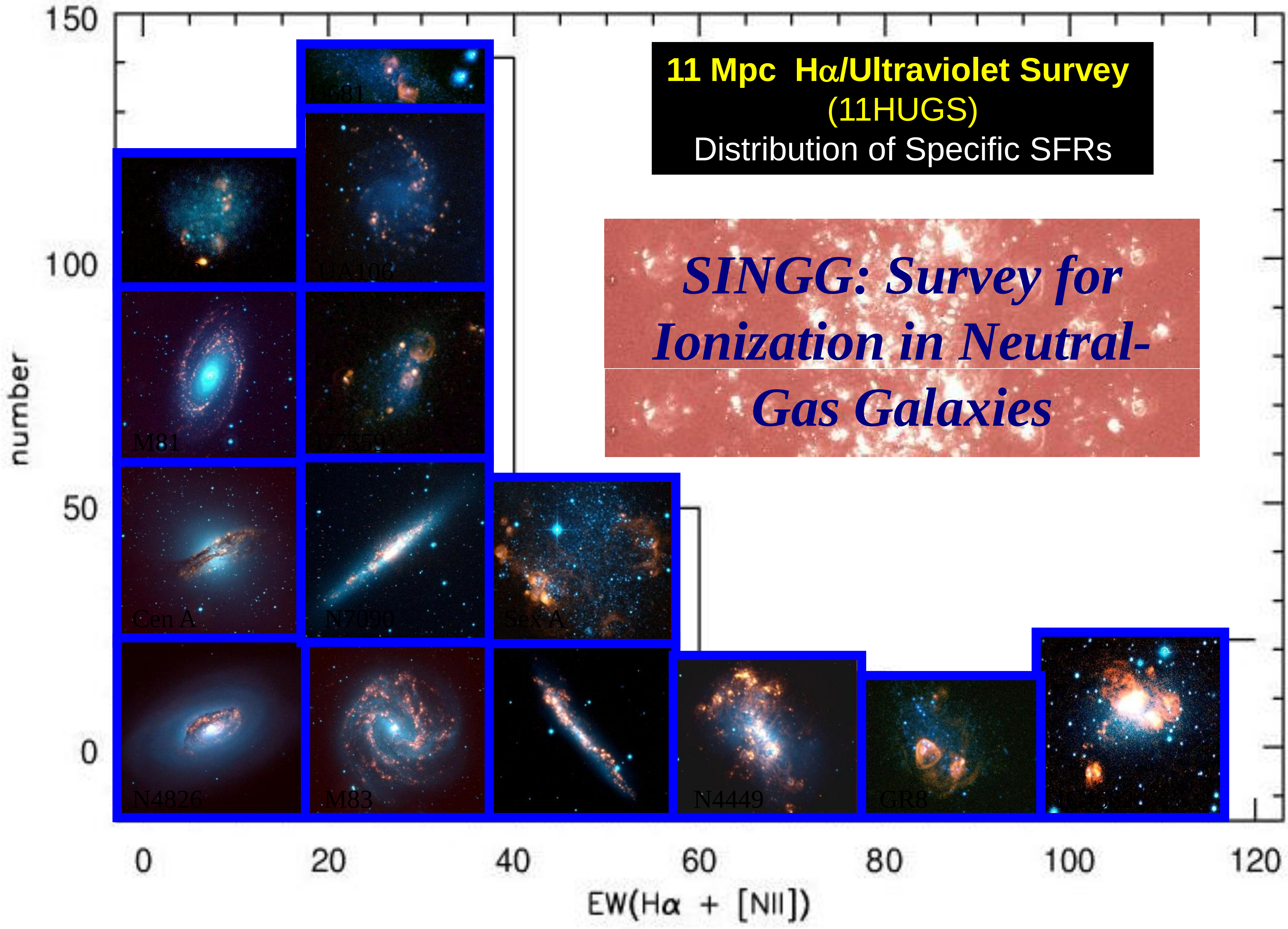
Sarzi et al. 2006, MNRAS, 366, 1151





Bureau et al. 2011, arXiv:1102:1922
Young et al. 2011, arXiv:1102.4633

Combes et al. 2007, MNRAS, 377, 1795



11 Mpc Hα/Ultraviolet Survey
(11HUGS)
Distribution of Specific SFRs
SINGG: Survey for Ionization in Neutral-Gas Galaxies
UA106
M81
U7559
Cen A
N7090
Sex A
N4826
M83
N4449
GR8
number
EW(Hα + [NII])
150
100
50
0
0
20
40
60
80
100
120

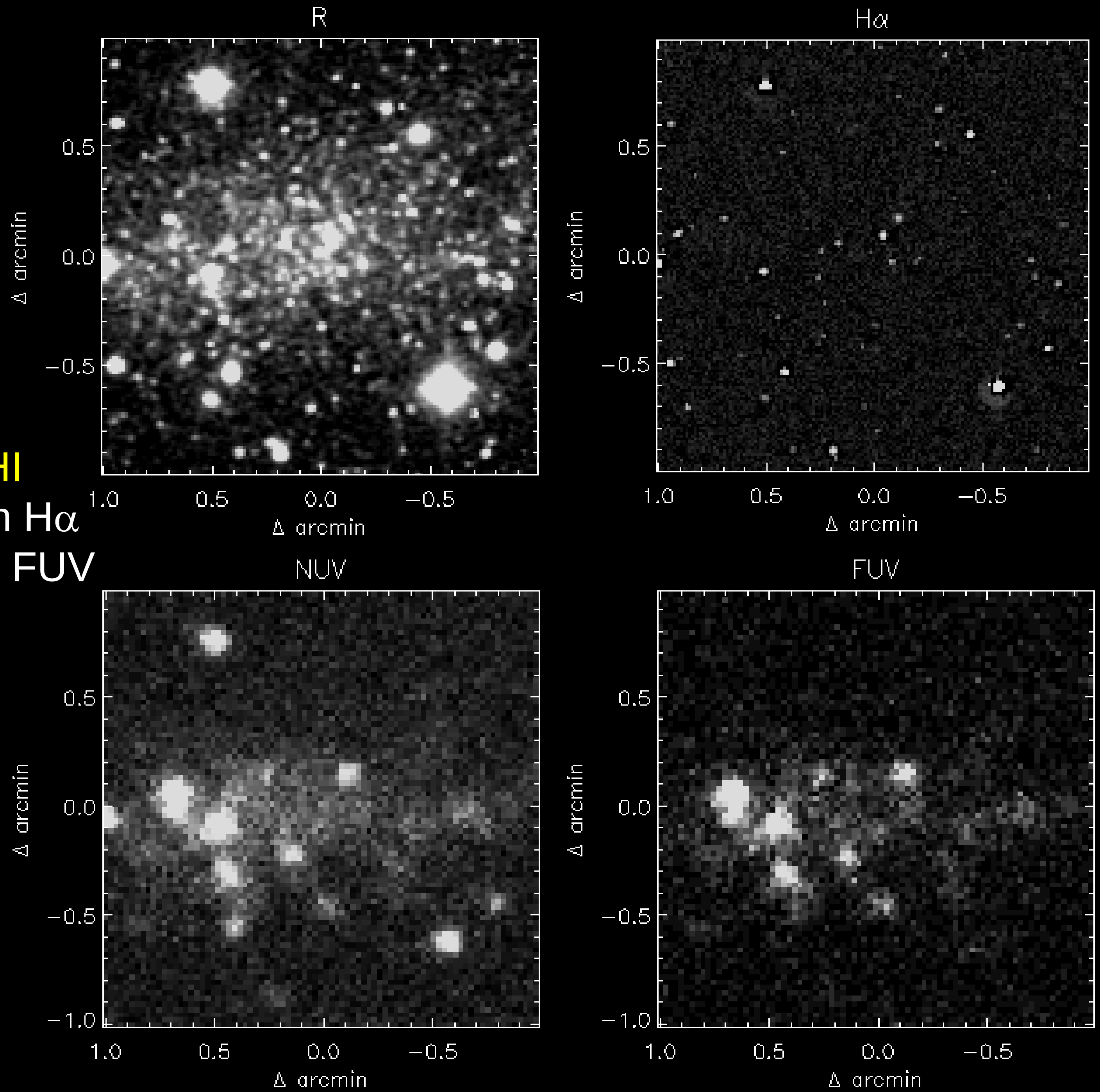
DDO 210

IB(s)m

M_B = -12:

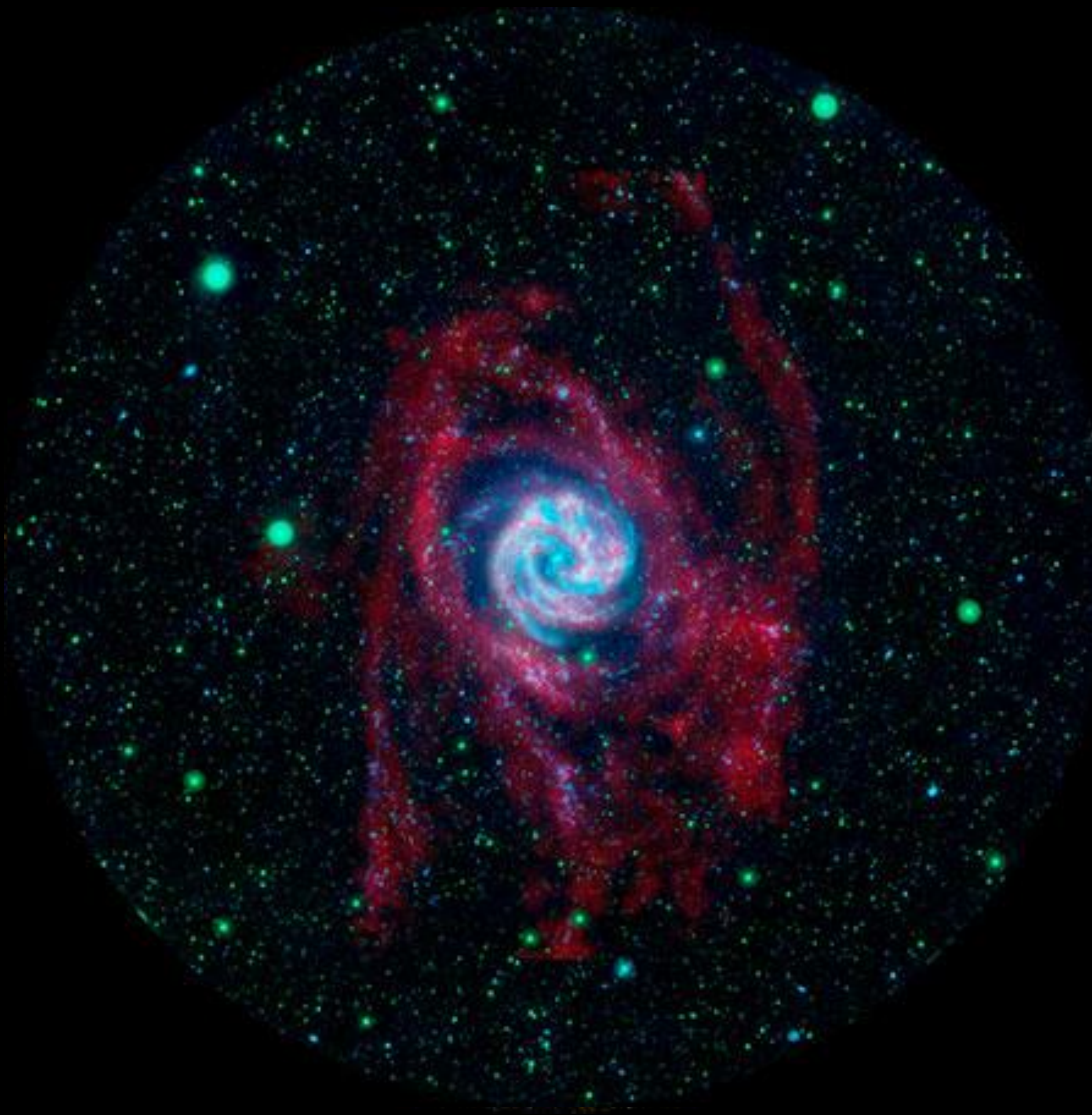
~300 dwarfs with HI

- -10 non-detects in Hα
- - 2 non-detects in FUV

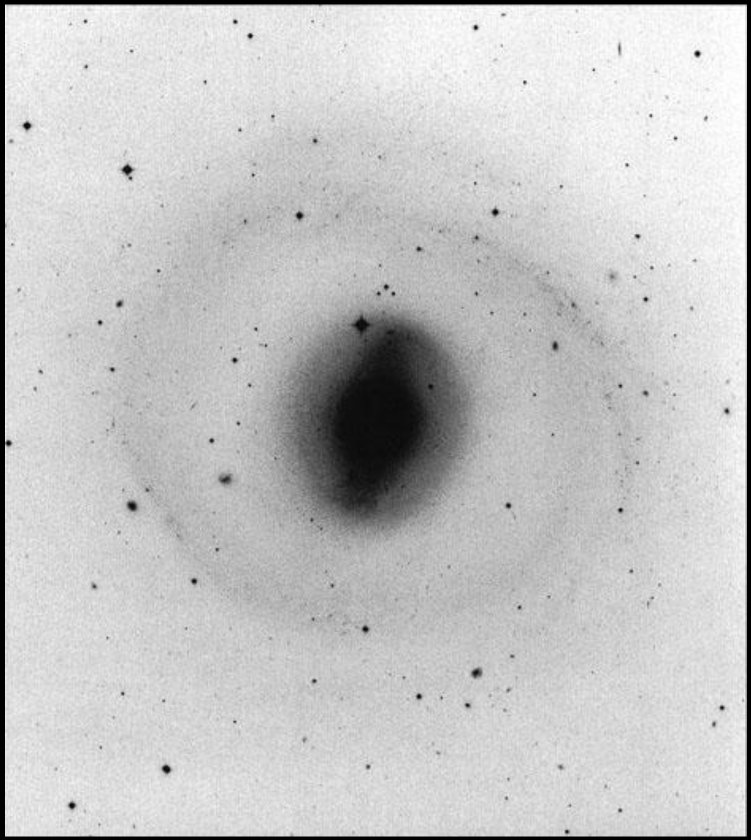


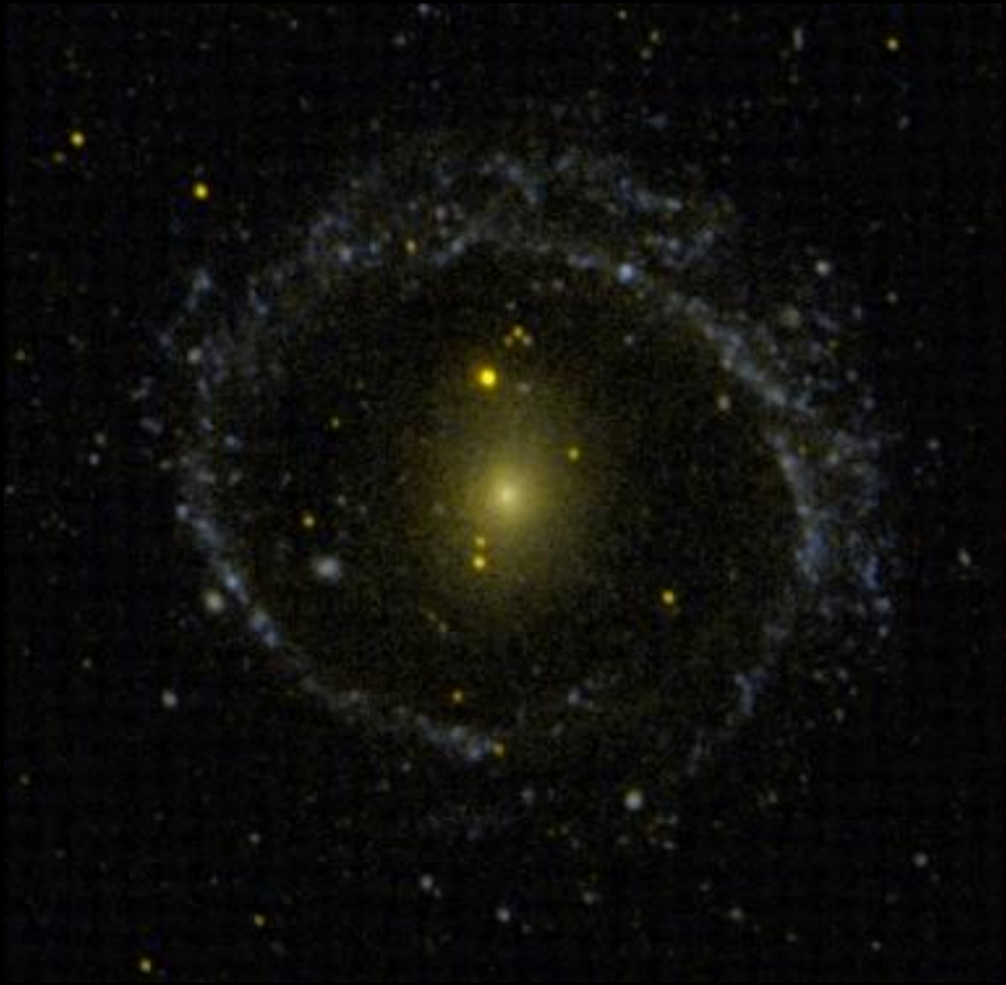
"XUV Discs"

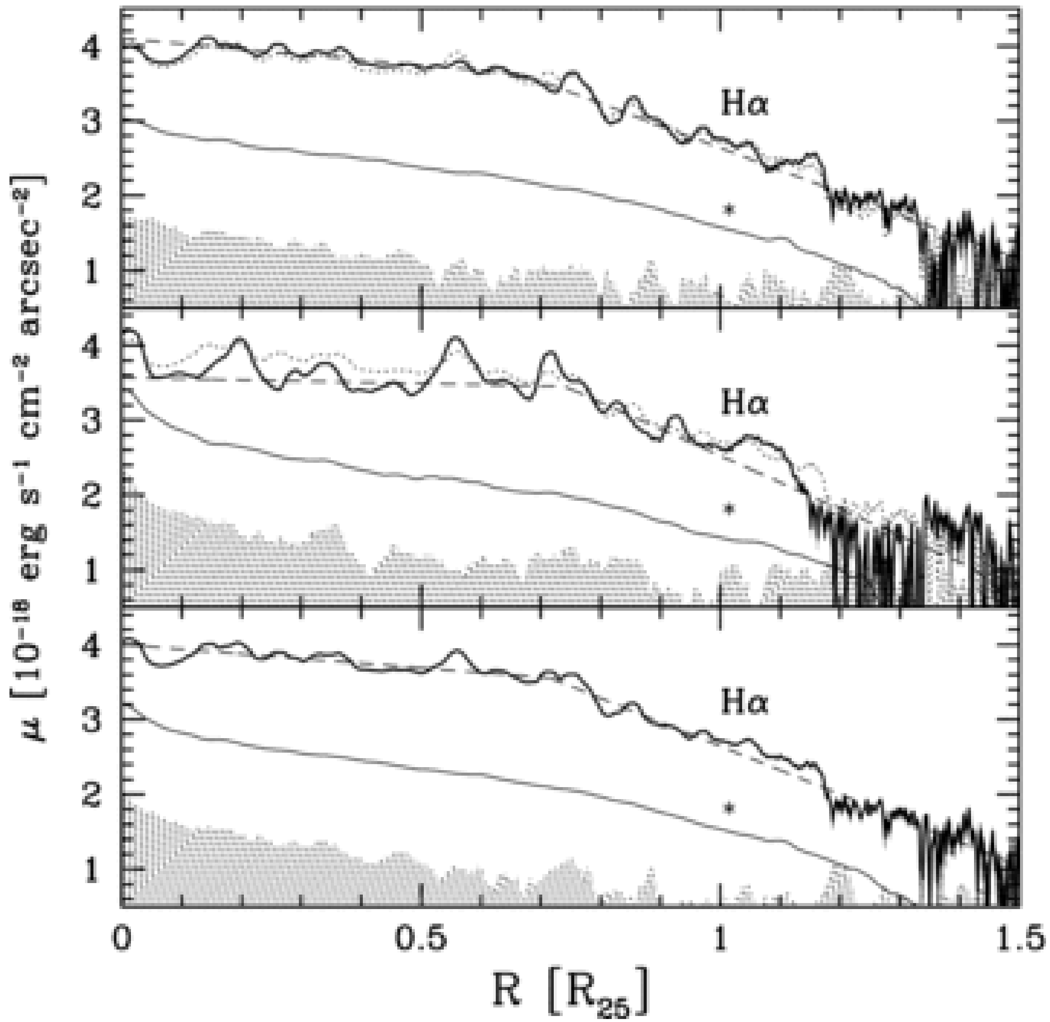
M83 = NGC 5236



NGC 1291

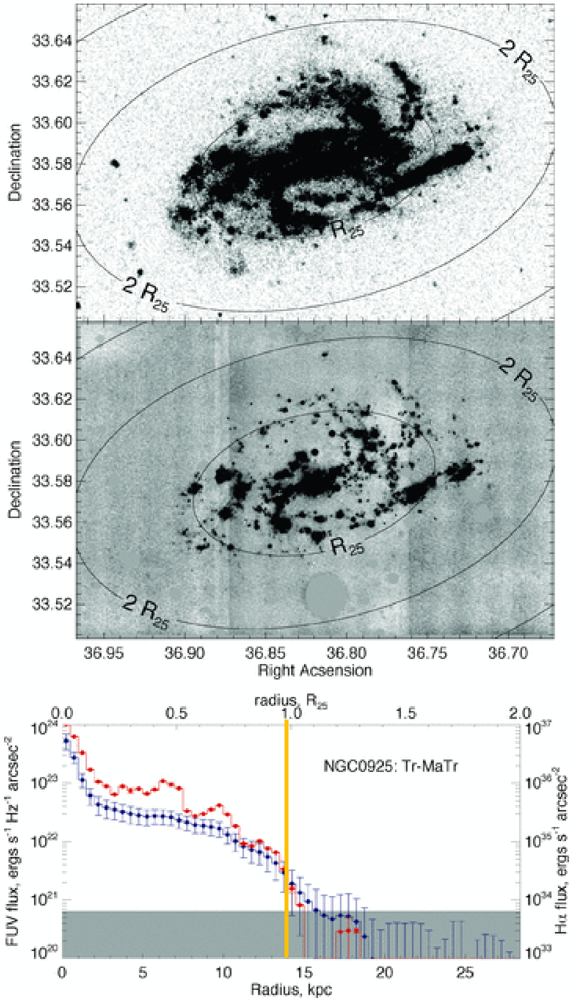






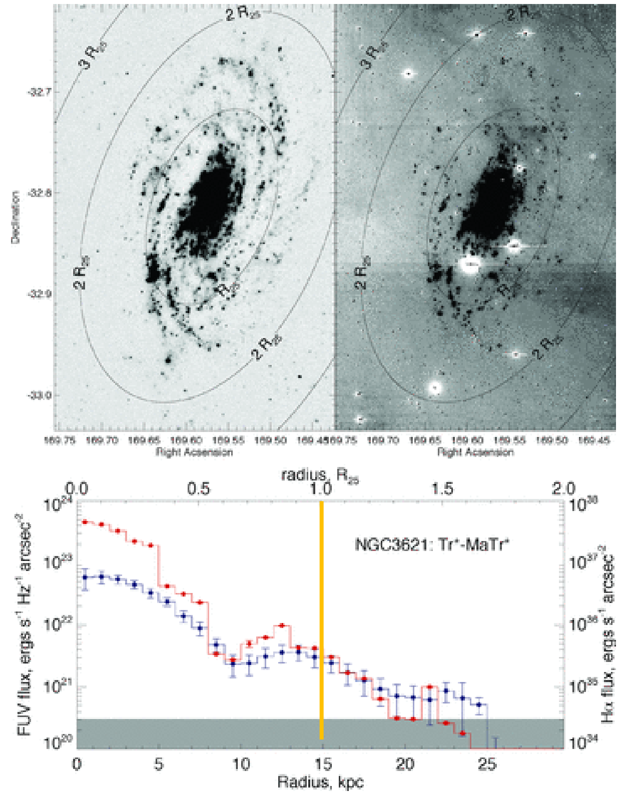
Christlein et al. 2010, MNRAS, 405, 2549

NGC 925



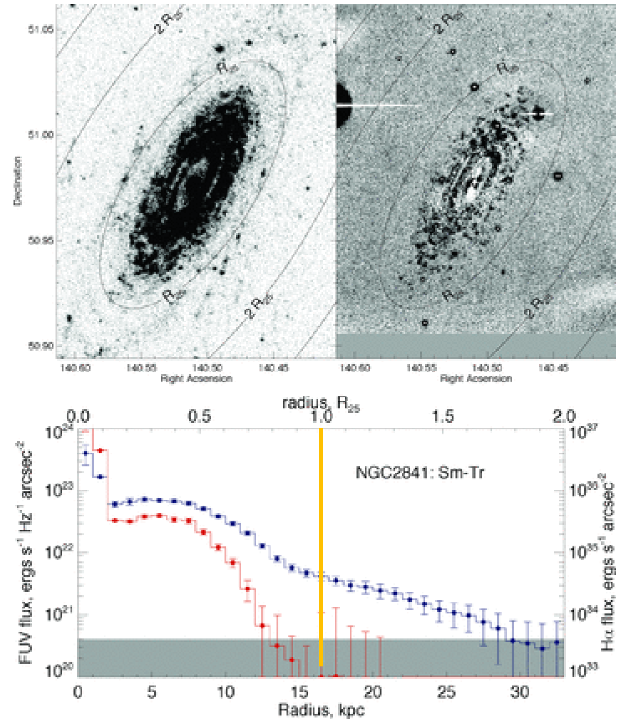
Hα and UV truncated

NGC 3621



Hα and UV extended

NGC 2841

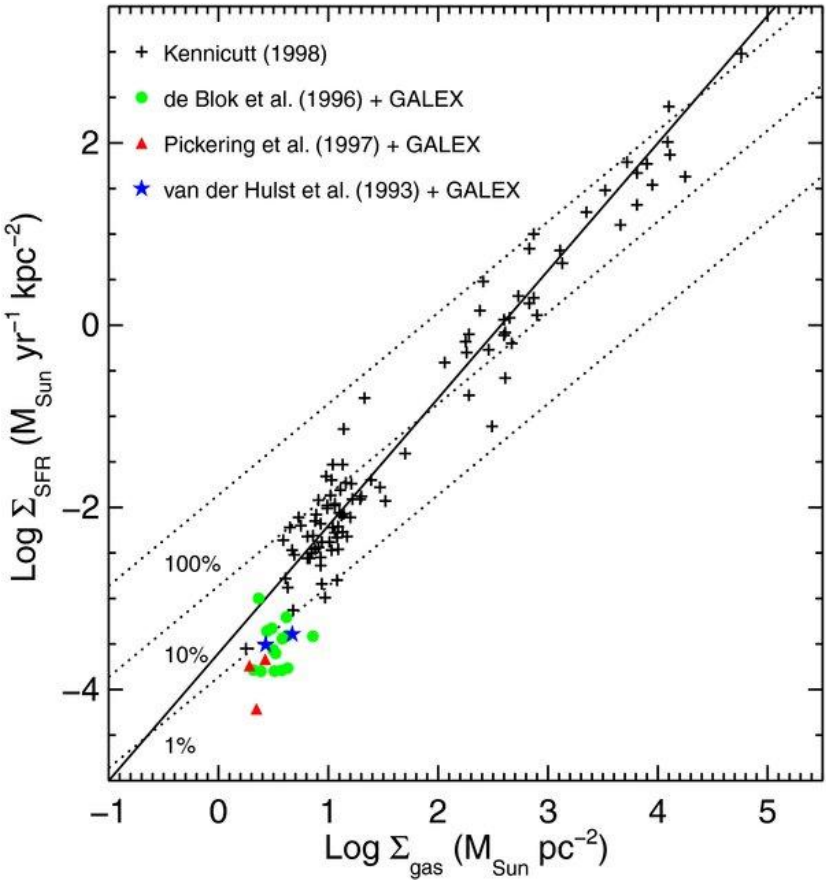


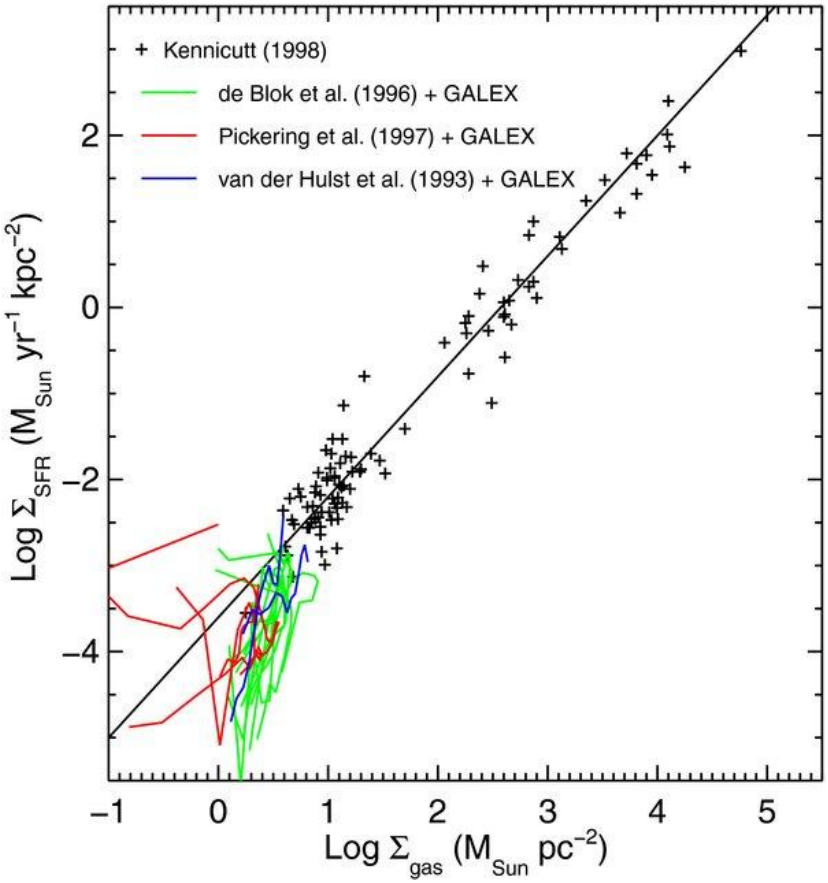
Hα truncated
UV extended

Goddard et al. 2010, MNRAS, 405, 2791

Application 1: The SF Law at Low Surface Densities

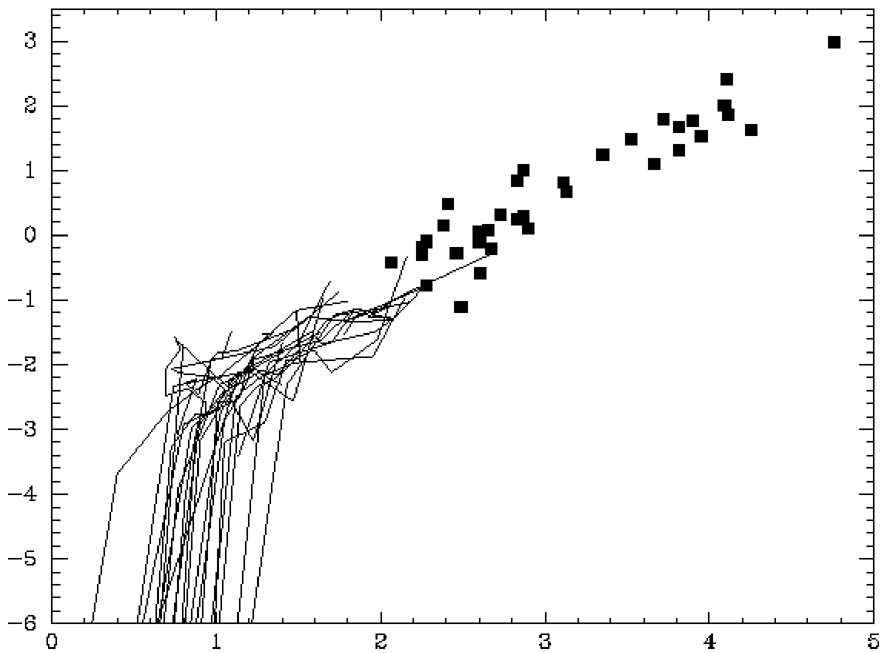
Low Surface Brightness Spirals



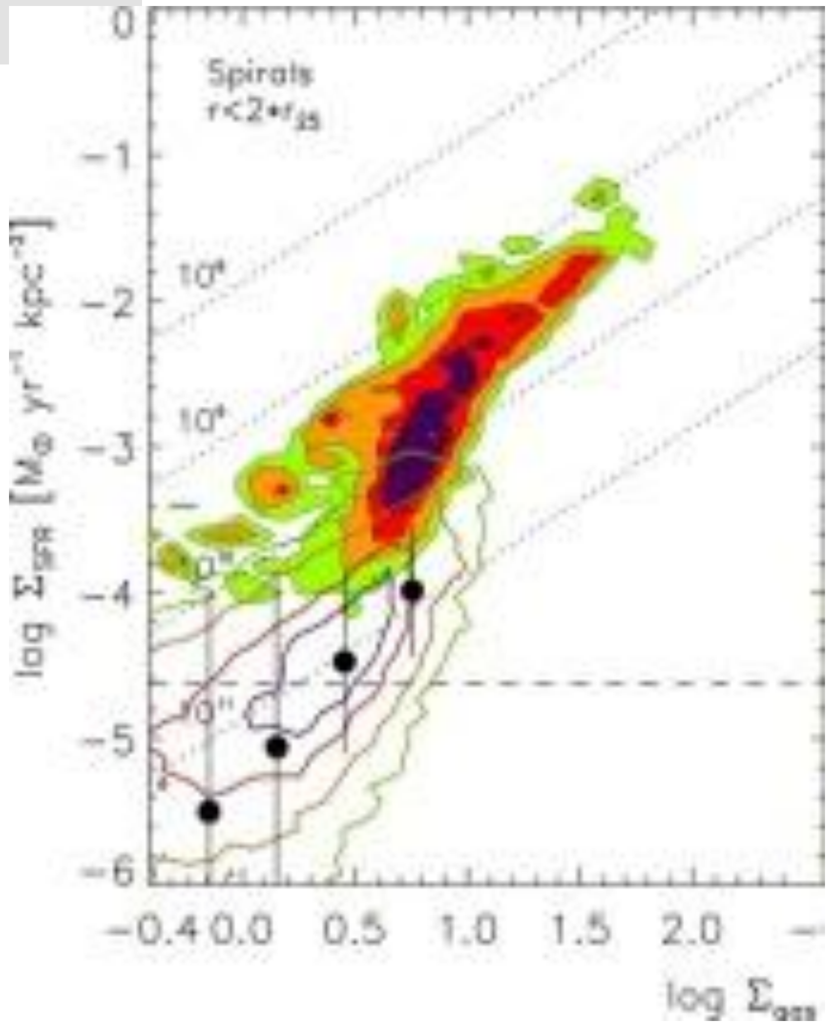


Wyder et al. 2009, ApJ, 696, 1834

Confirming Evidence for Thresholds: Radial Profiles of Spirals



Martin, Kennicutt 2001, ApJ, 555, 301



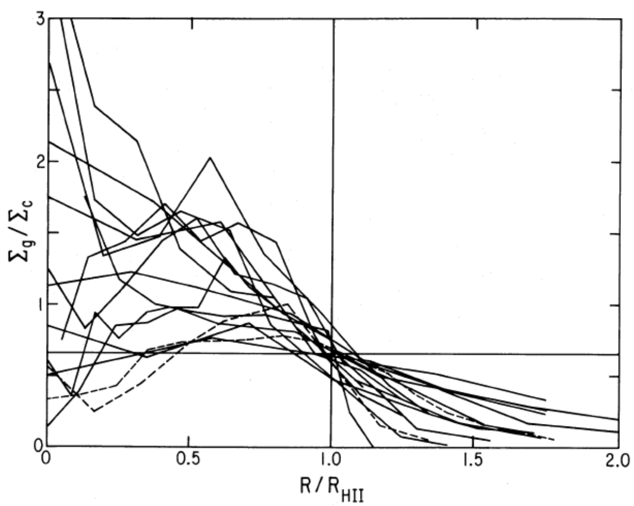
Bigiel et al. 2010, AJ, 140, 1194
Bigiel et al. 2008, AJ, 136, 2846

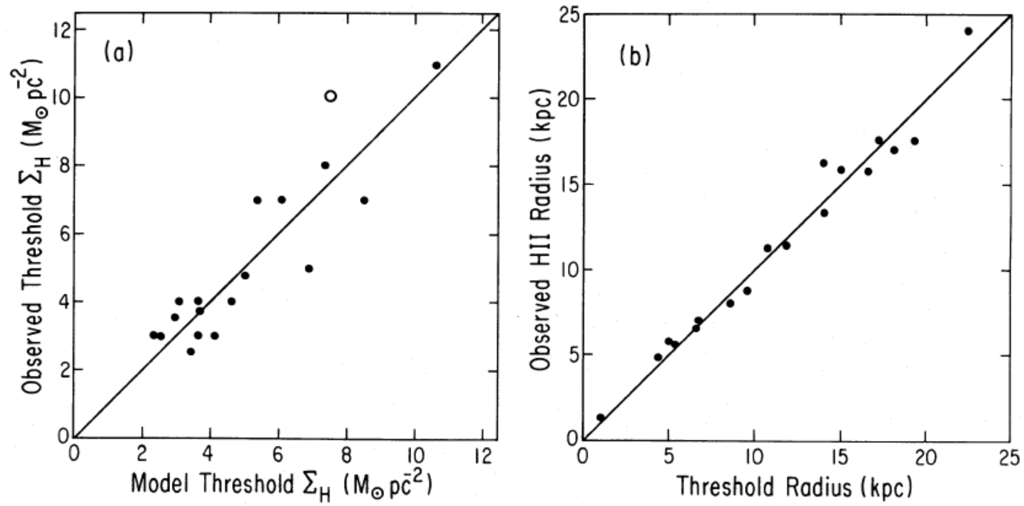
the case for gravity…

- the radial transitions in SFR coincide with a large range of gas surface densities, but a much narrower range in Q_{gas}

  where $Q = \Sigma_{Toomre}/\Sigma_{gas} = const \cdot \kappa c/\pi G\Sigma_{gas}$

- Q ~ 1 also discriminates between gas-rich galaxies with low SFRs everywhere (e.g., LSBs) and those with active SF in their disks
- The radial surface density profiles of gas disks roughly follow Q ~1

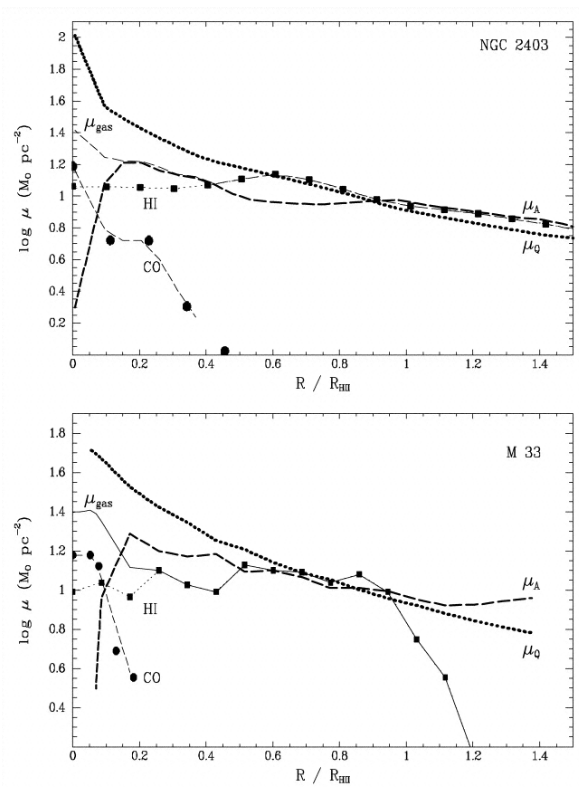


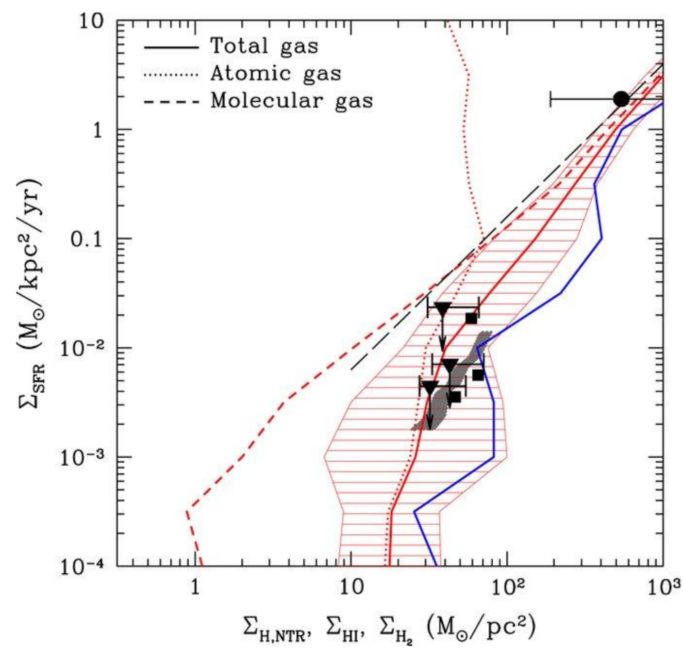


Kennicutt 1989, ApJ, 344, 685

the trouble with gravity…

- the Q criterion breaks down in low-mass spiral and dwarf irregular galaxies (Q>1, but lots of star formation)
- damped Lyman-alpha absorber galaxies show much less UV emission than expected from extrapolation of K-S law (Wolfe & Chen 2006)



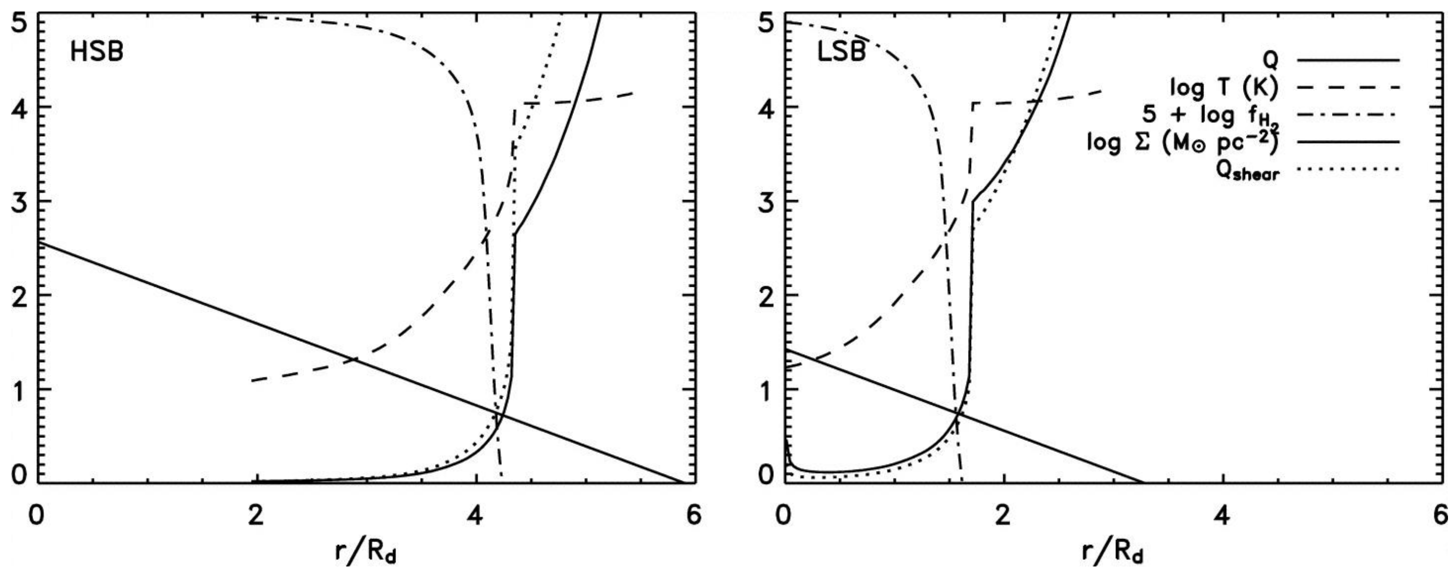


Martin, Kennicutt 2001, ApJ, 555, 301

Gnedin, Kravtsov 2010, ApJ, 714, 287

alternatives: cold phase instabilities

- ISM phase transition from atomic-dominated to molecular-dominated may occur over small range in density, radius, mimicing and triggering a transition from a pressure-supported medium to gravitationally bound clouds
- Observationally it is difficult to separate the chicken from the egg. In some environments formation of bound clouds may lead to subsequent formation of molecular cores

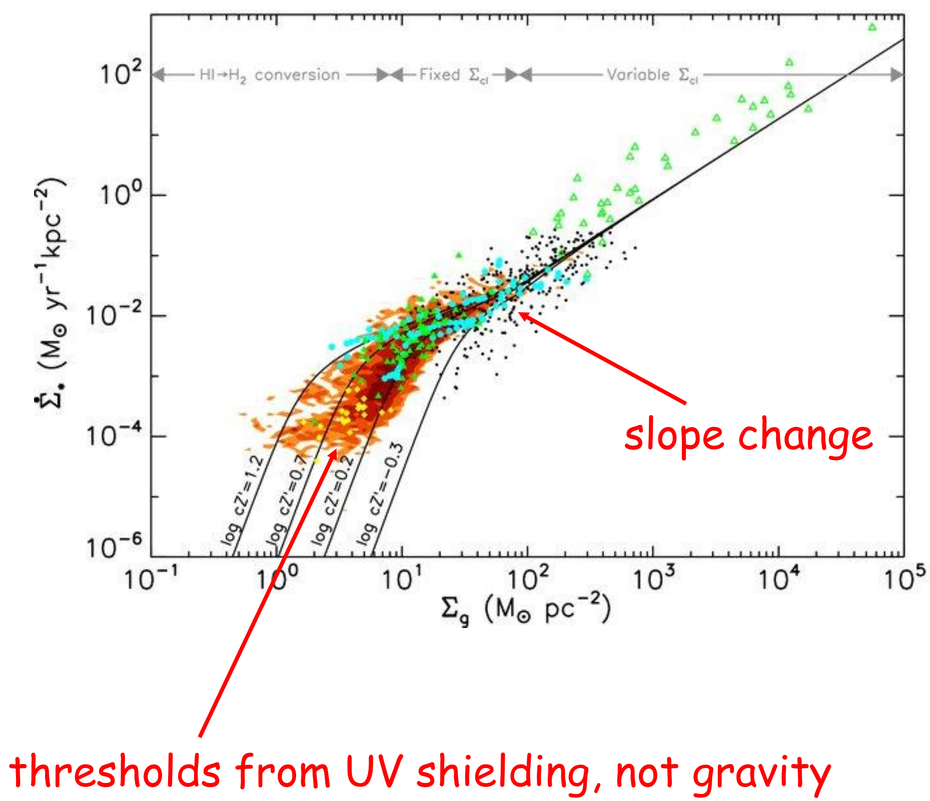


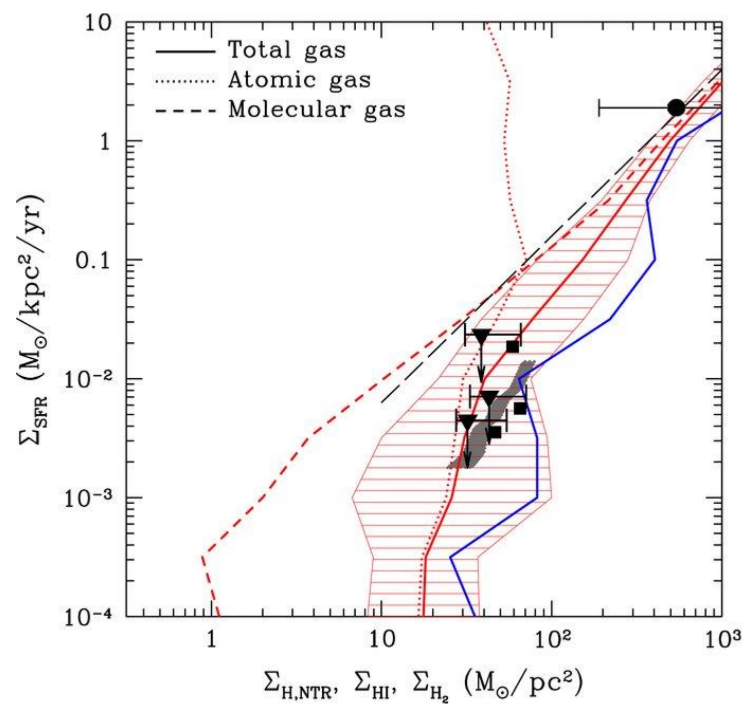
Schaye et al. 2004, ApJ, 609, 667

alternatives: turbulence-regulated SF

- SFR fixed by density of molecular gas and local free-fall time

$$\Sigma_{sfr} = \Sigma_g f_{H2} \varepsilon_{ff} / t_{ff}$$



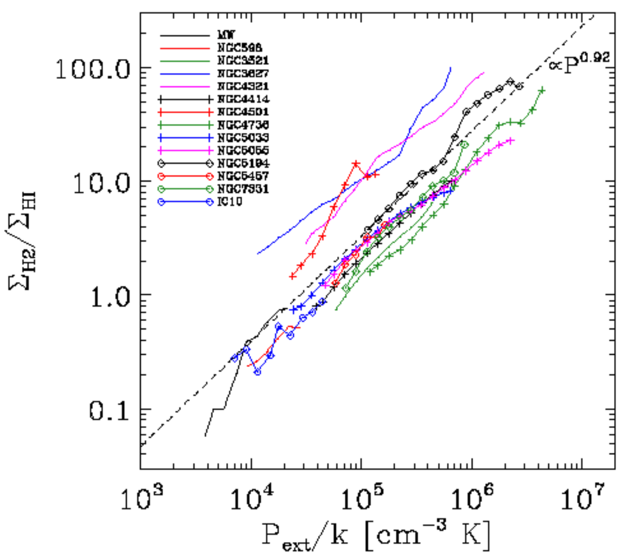


Krumholz et al. 2009, ApJ, 699, 850

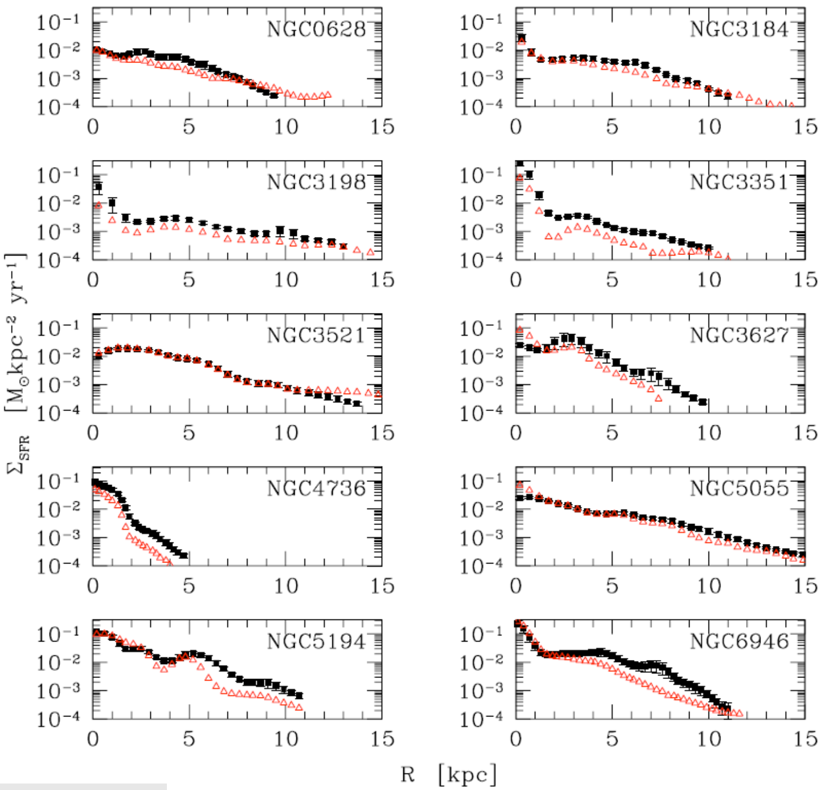
Gnedin, Kravtsov 2010, ApJ, 714, 287

alternatives: pressure-regulated SF

- Blitz & Rosolowsky (2006) and Leroy et al. (2009) argue that molecular gas fraction in disks is tightly coupled to local hydrostatic pressure
- Ostriker et al. (2010) present model where SFR itself is driven by the requirement that UV heating (i.e., SFR) adjusts so thermal pressure matches midplane hydrostatic pressure of ISM (also see Dopita 1985)



Blitz, Rosolowsky 2006, ApJ, 650, 933



Ostriker et al. 2010, ApJ, 721, 975

Alternatives

Self-gravity timescales (Larson 1991, Elmegreen 2002, 2003)

Cloud-cloud collision rates (Tan 2000)

Gravitational instabilities + linear SFE
(Friedli et al. 1994, Li et al. 2005, 2006)

GMC PDF + turbulence (Kravtsov 2003; Tasker & Bryan 2006)

Self-regulation via GMC turbulence
(Krumholz & McKee 2005, Krumholz et al 2009)

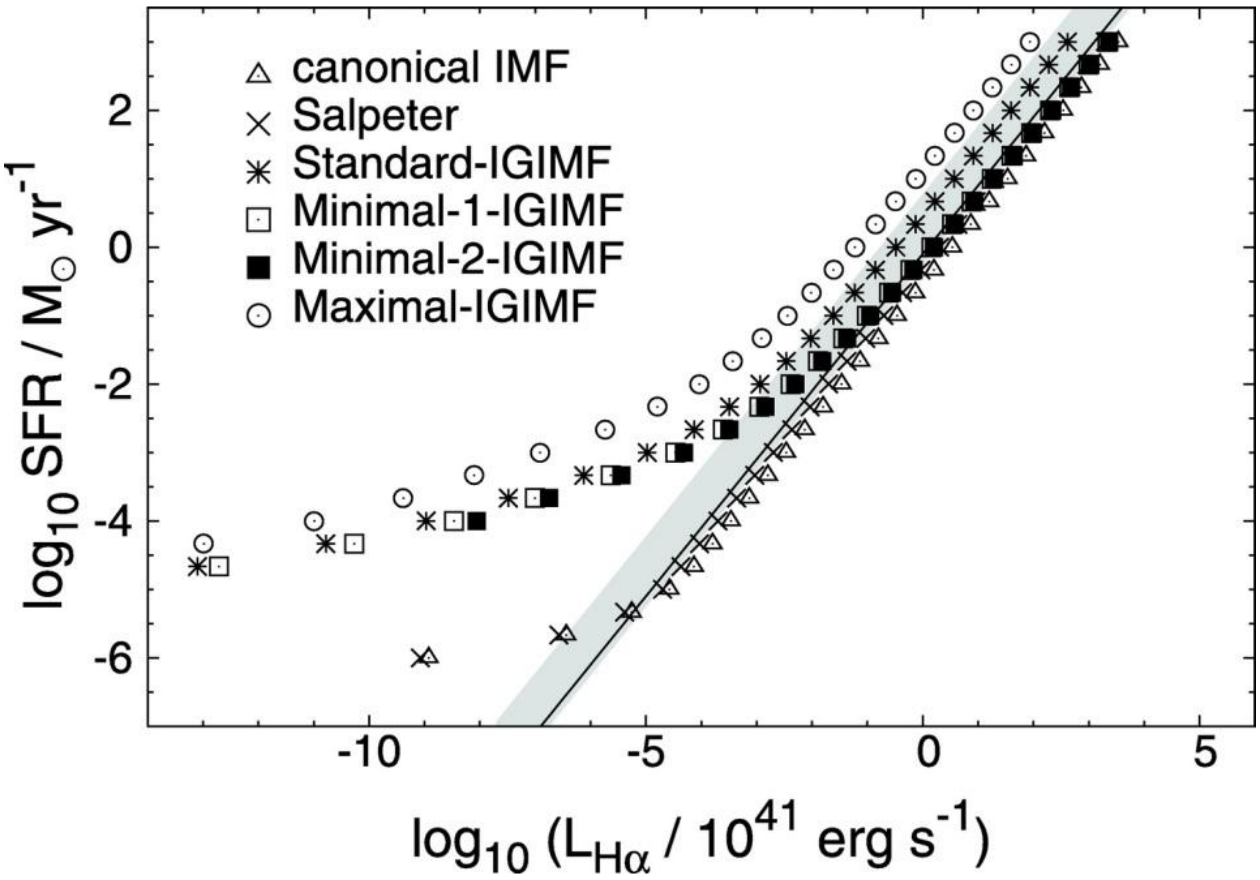
Self-regulation via ISM pressure
(Dopita 1985; Ostriker et al. 2010)

Self-regulation via ISM porosity (Silk 1997)

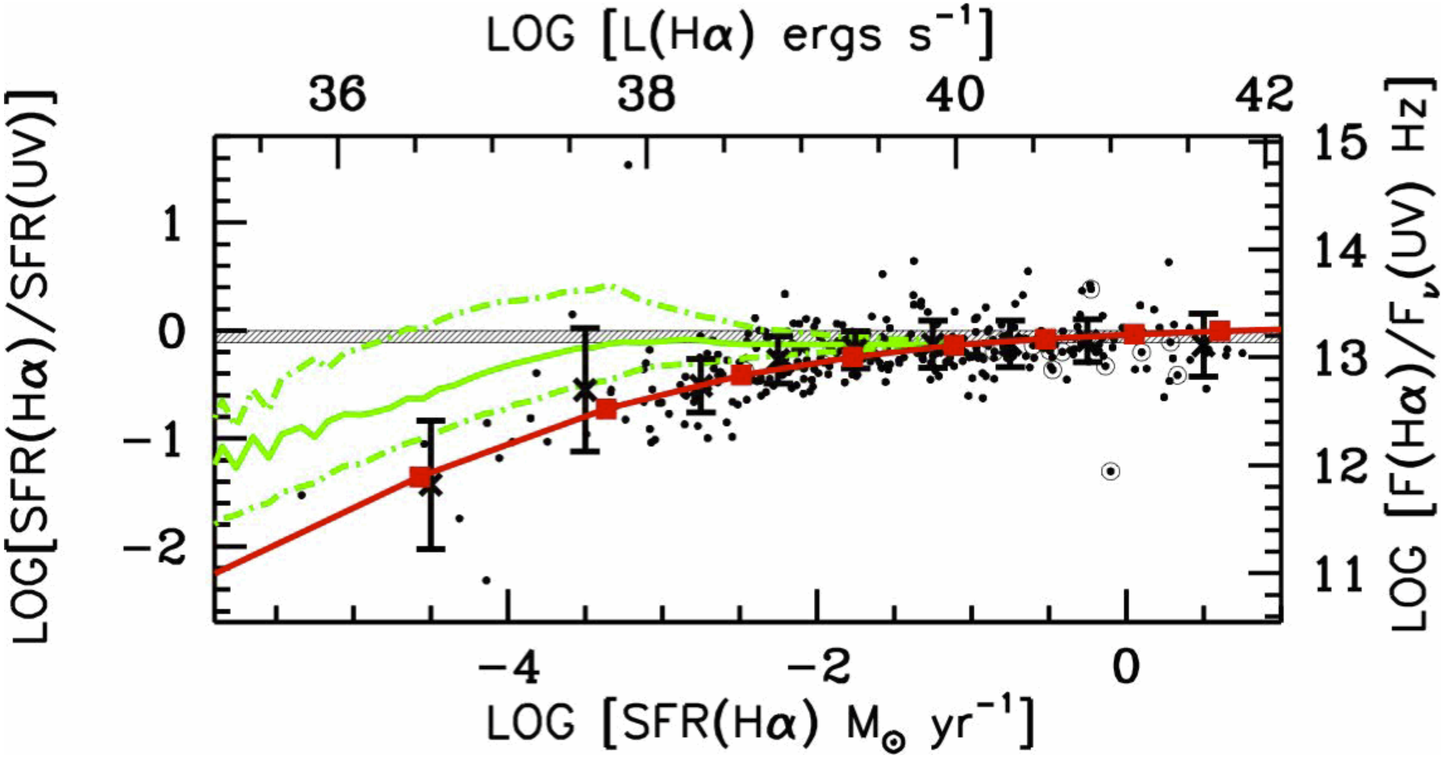
http://conference.astro.ufl.edu/STARSTOGALAXIES/science_final/talks/

Application 2: The Initial Mass Function

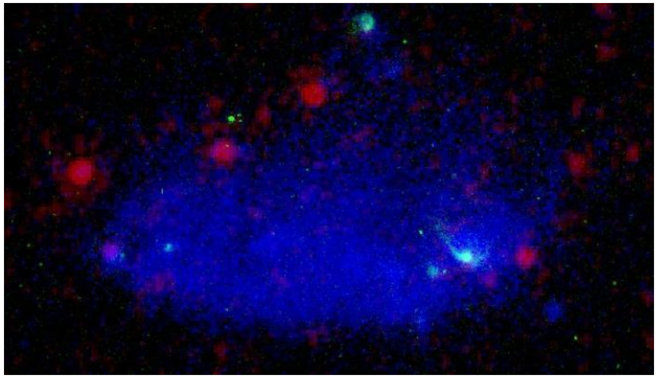
Evidence for a Truncated IMF?



Pflamm-Altenburg & Kroupa (2007)

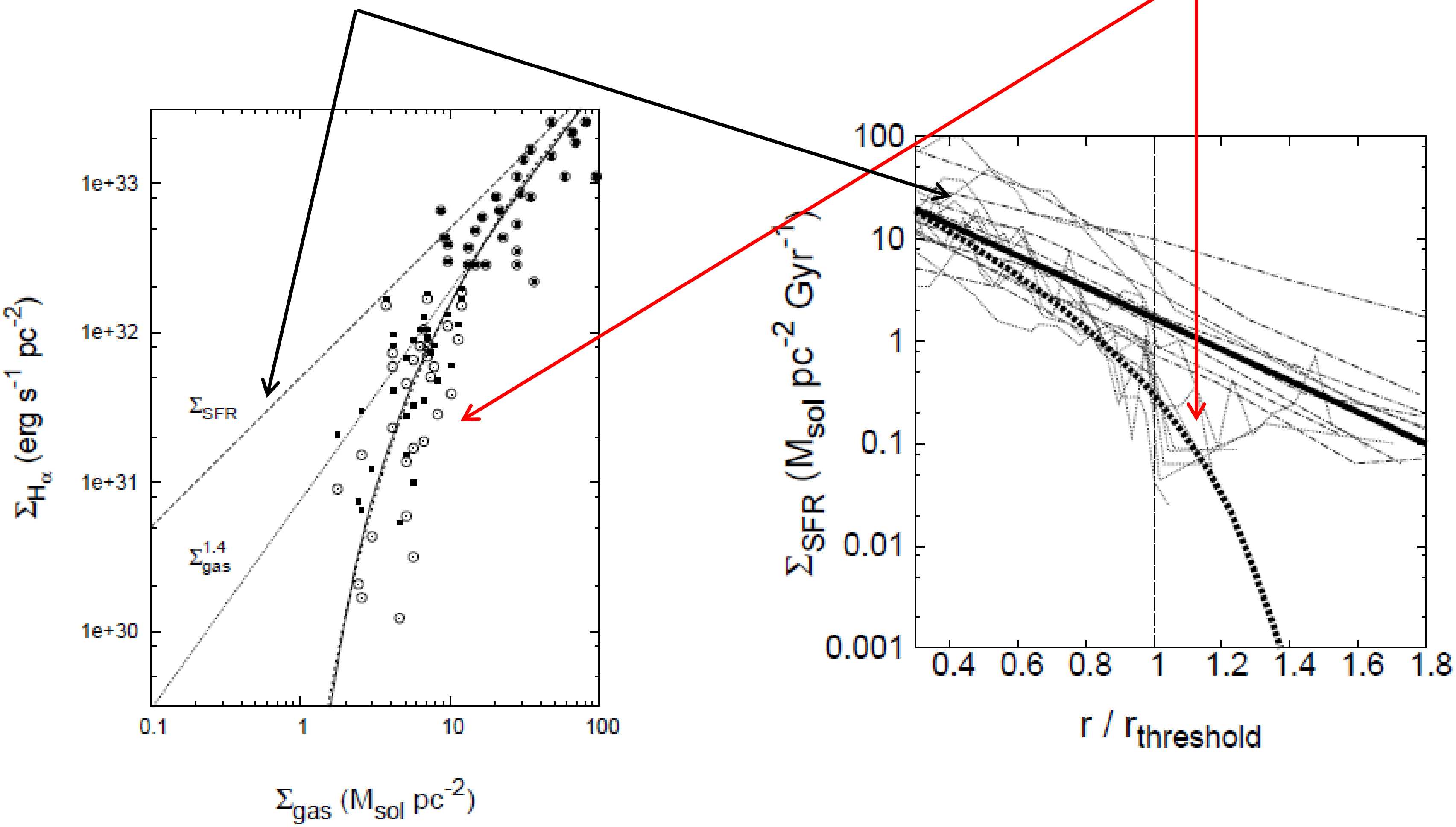


Lee et al. 2009, ApJ, 706, 599
Meurer et al. 2009, ApJ, 695, 765



UGC8201, UV(GALEX)+Hα+24(Spitzer)

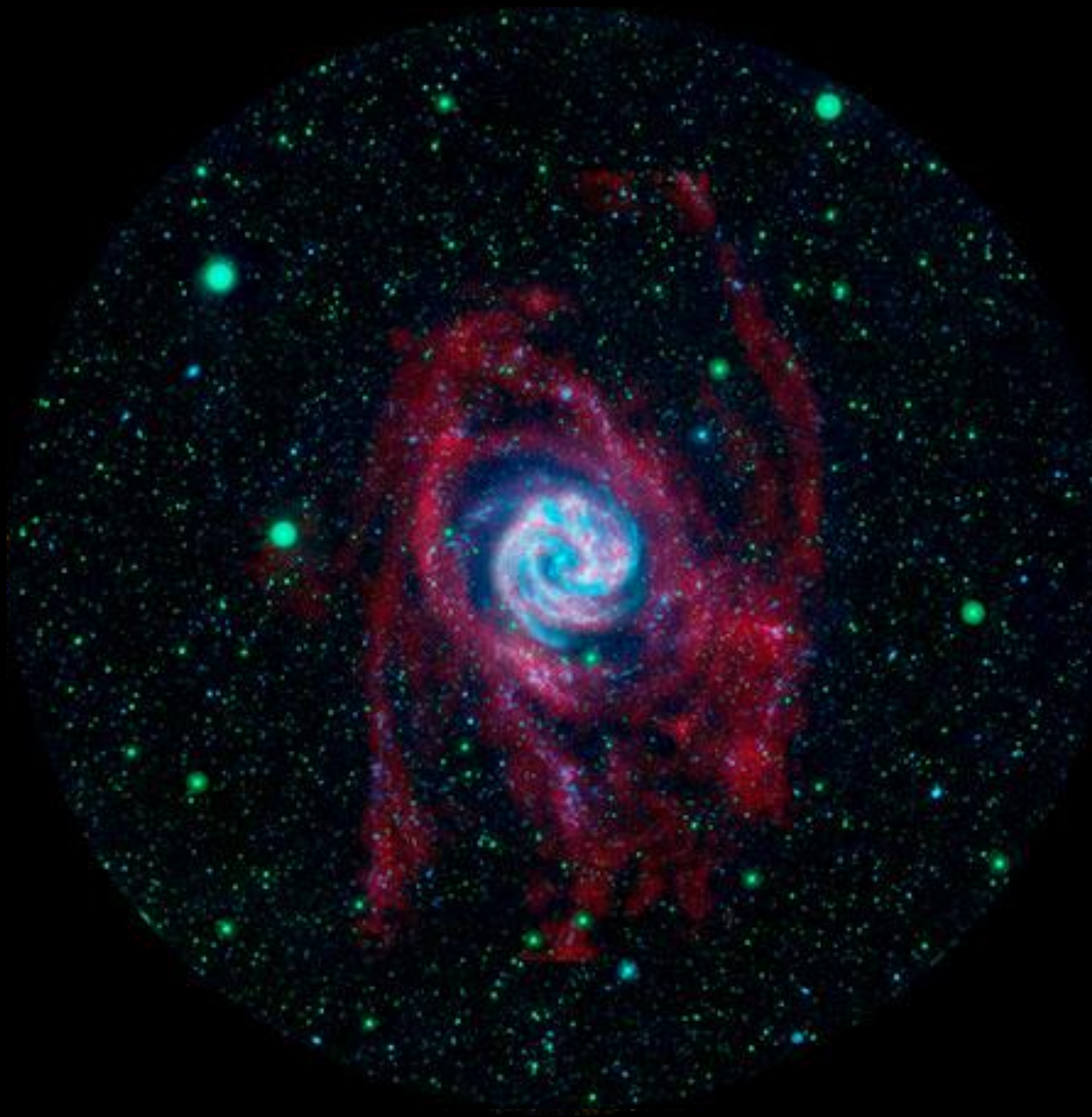
theory predicts that the total SFR follows gas, but measured (massive stars) SFR is suppressed due to de-populated upper IMF



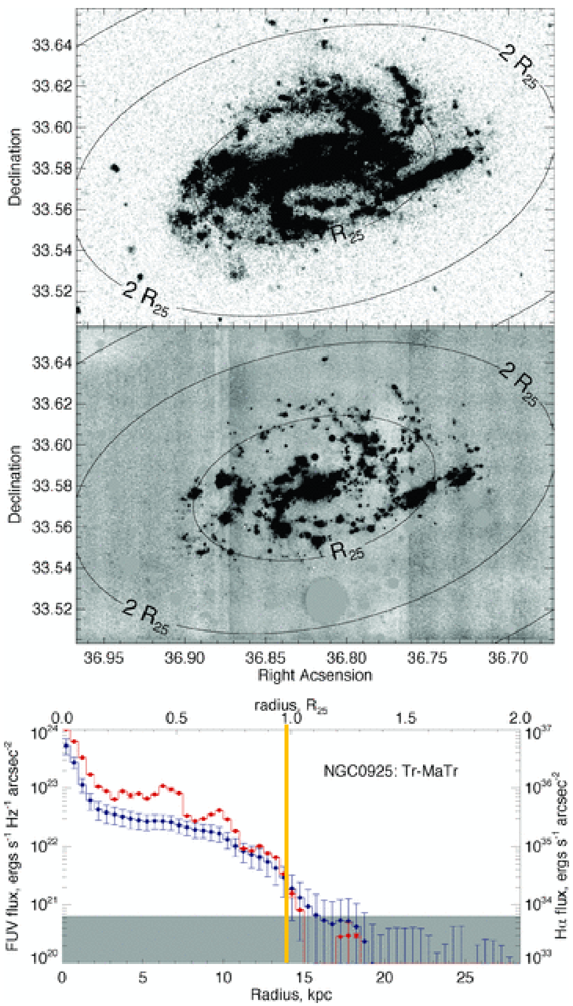
Pflamm-Alternberg, Kroupa 2008, Nature, 455, 641

"XUV Discs"

M83 = NGC 5236

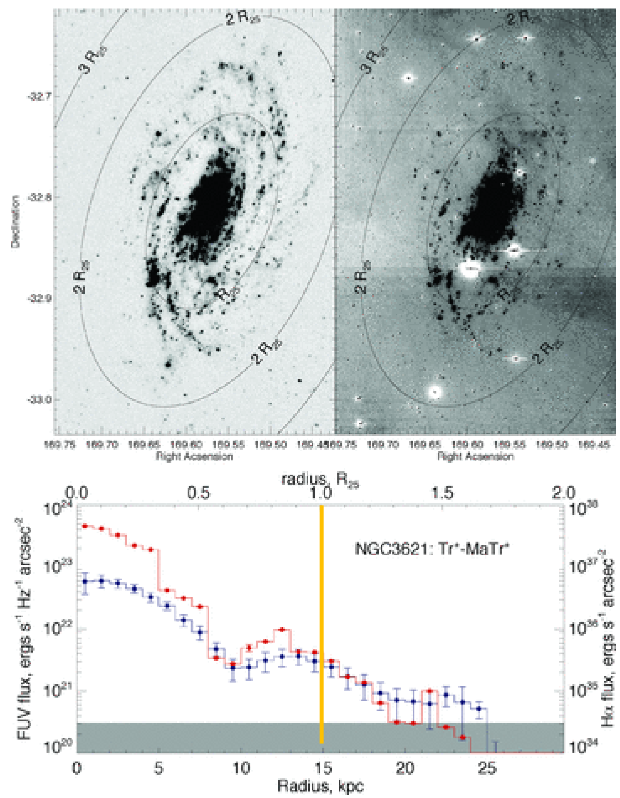


NGC 925



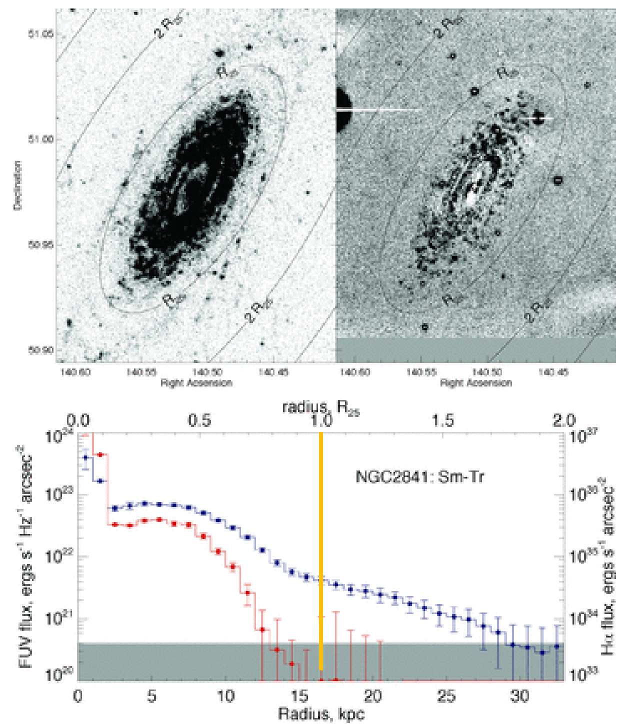
Hα and UV truncated

NGC 3621



Hα and UV extended

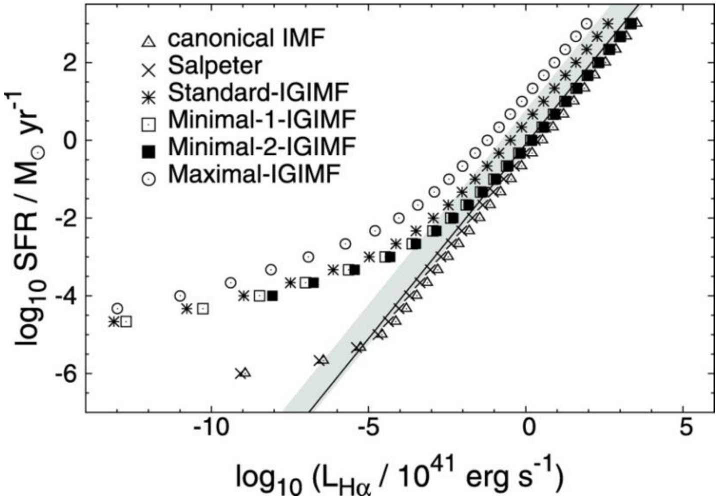
NGC 2841

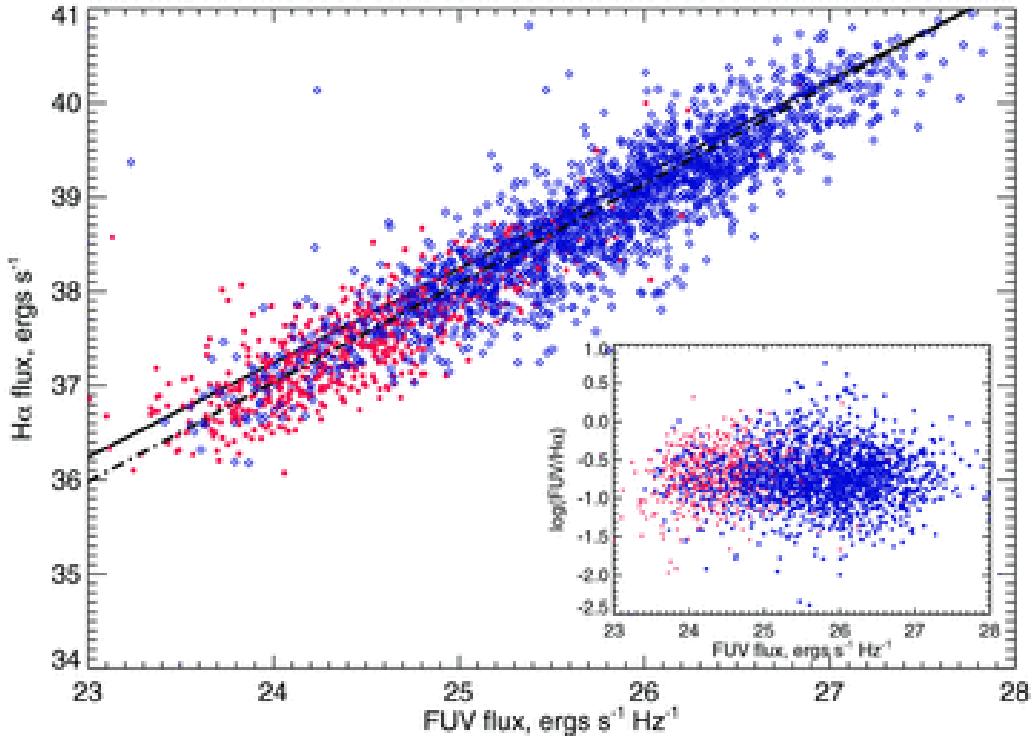


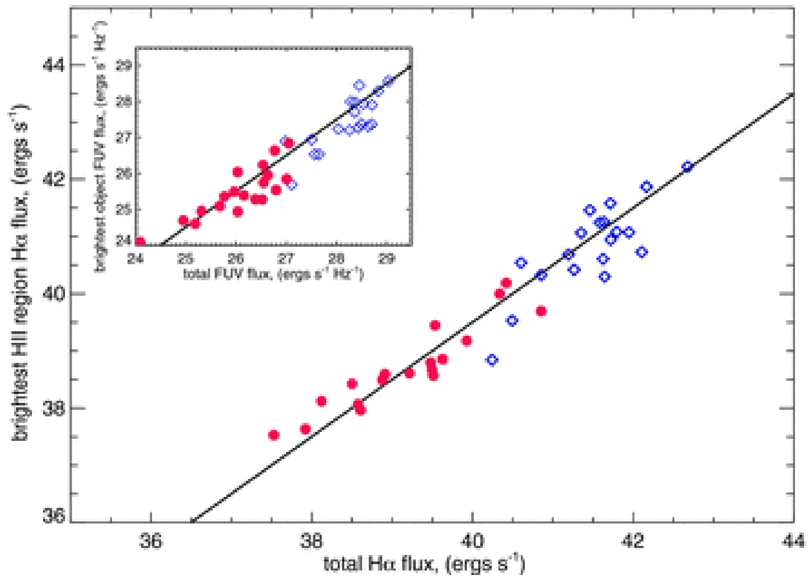
Hα truncated
UV extended

Goddard et al. 2010, MNRAS, 405, 2791

Properties of Individual SF Regions

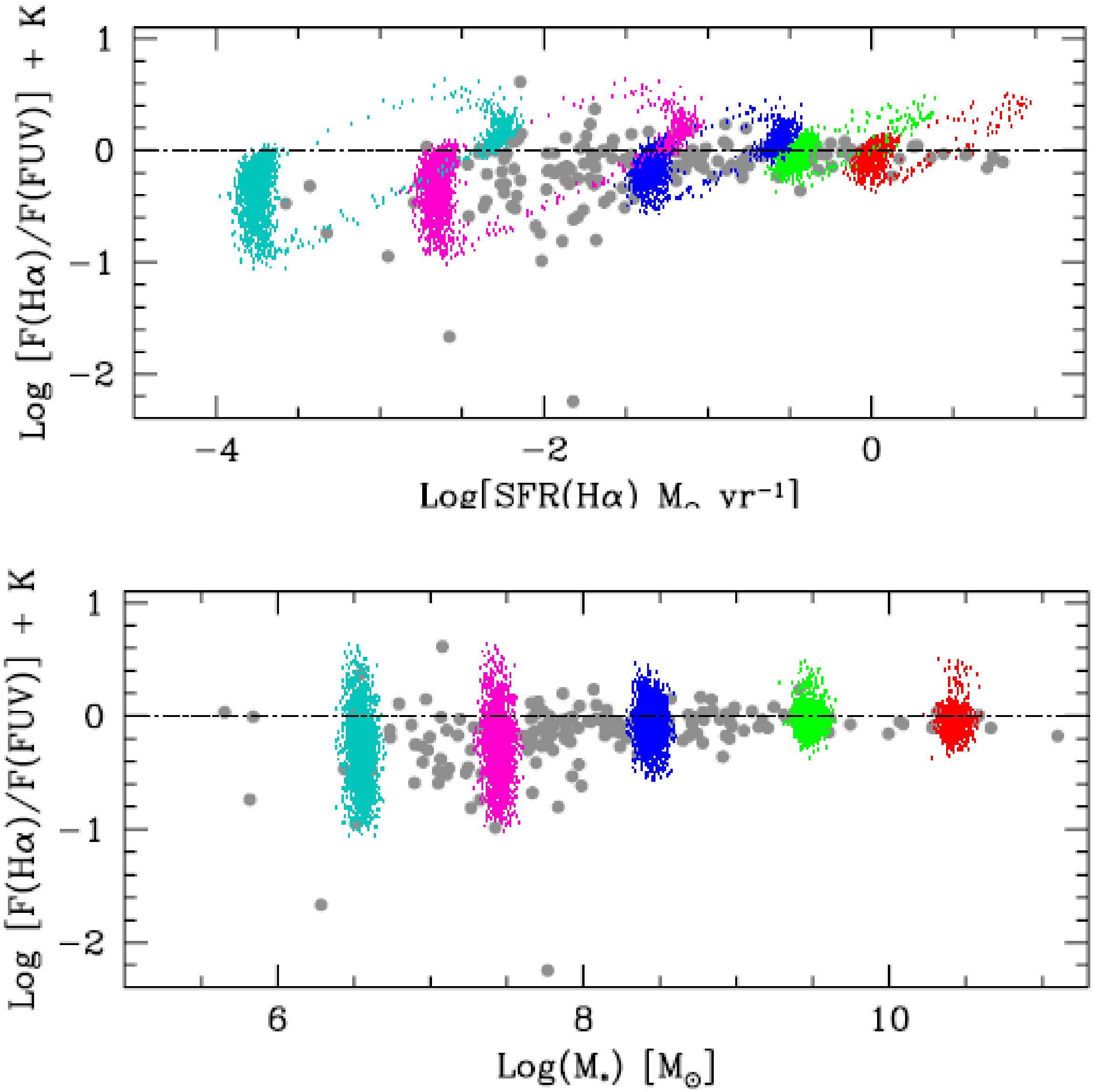




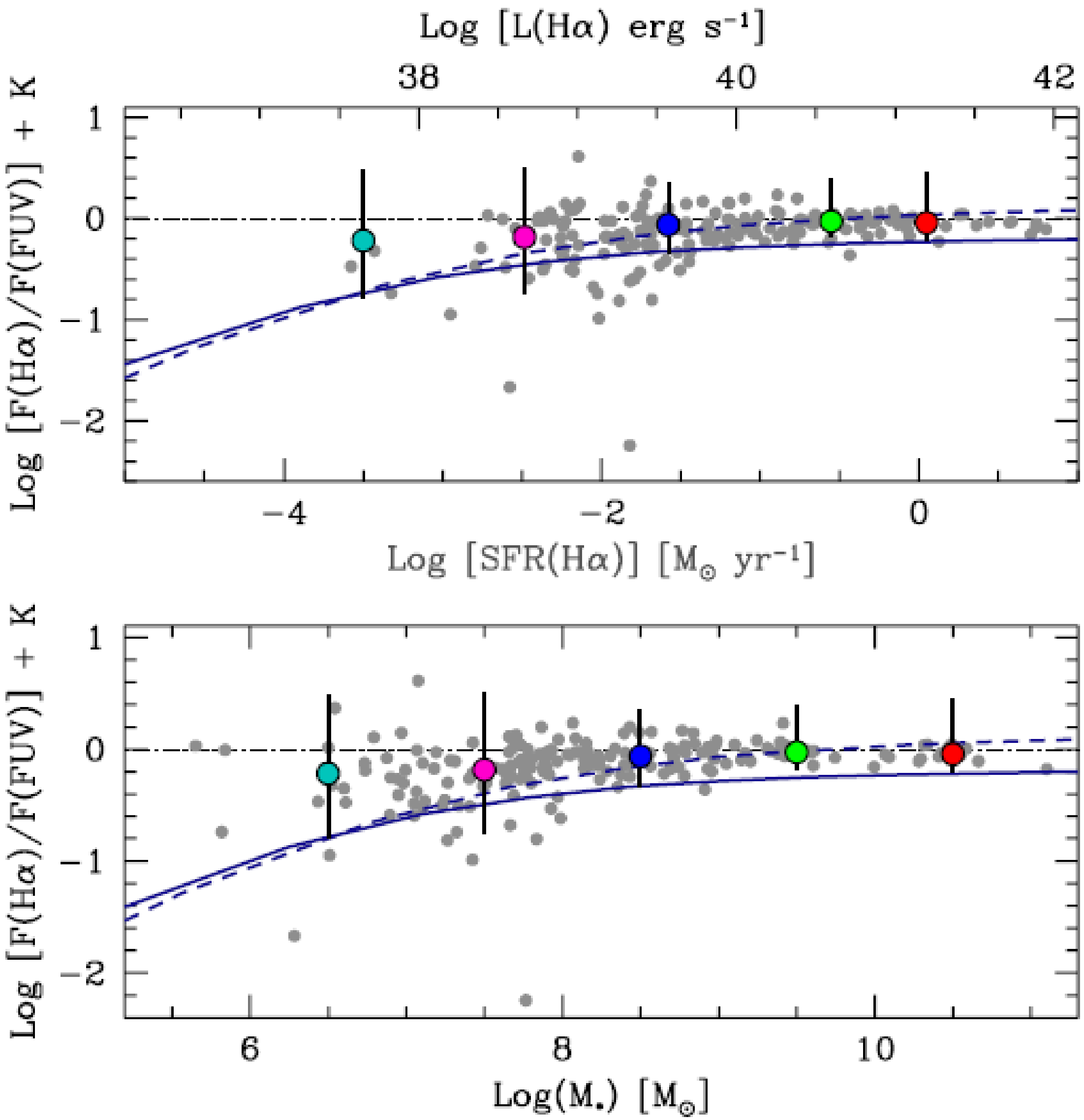


Weisz et al. 2011

- behaviour of Hα/UV can be explained with bursty SF histories



Whereas a truncated IMF does not fit the mass dependance of Hα/UV



Application 3:
Abundances, Physical Properties

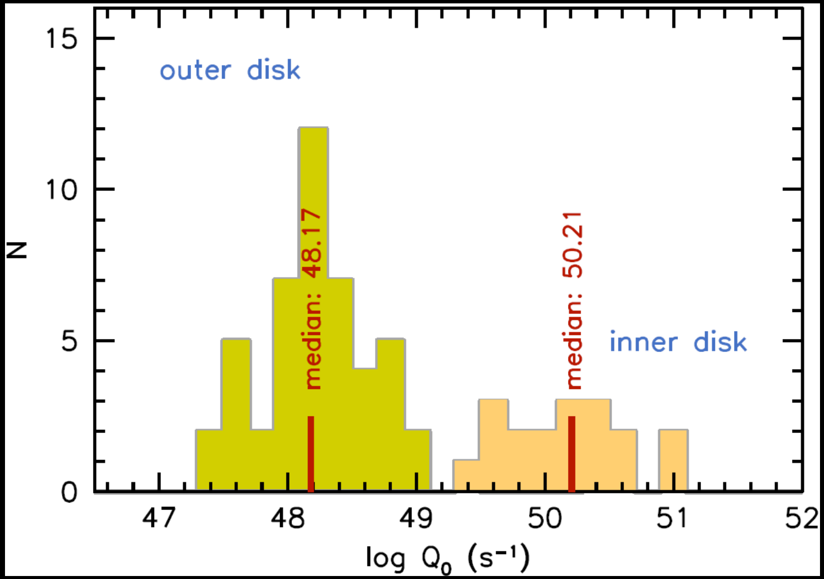
Case Study 1:

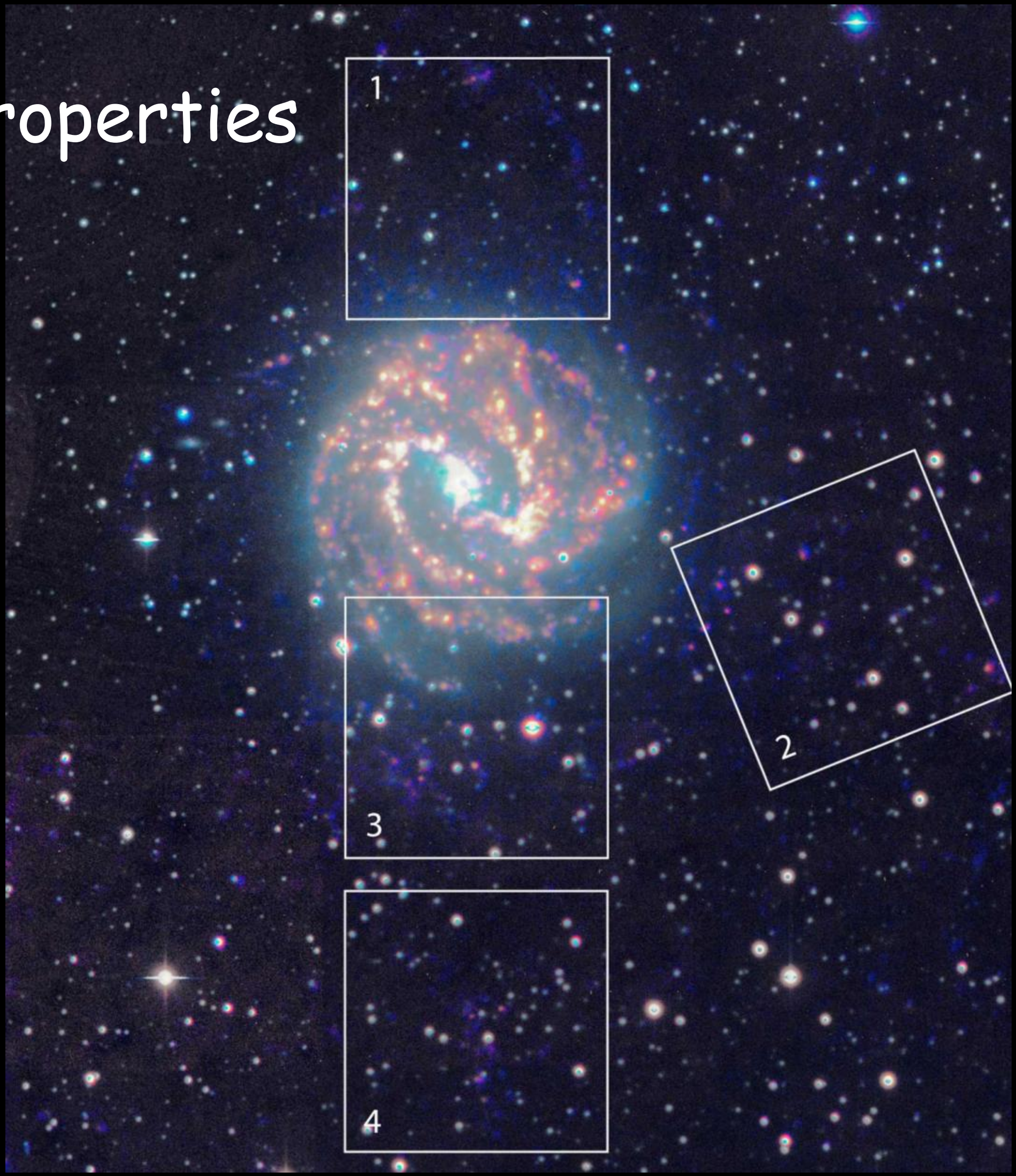
M83 = NGC 5236

Hα + R

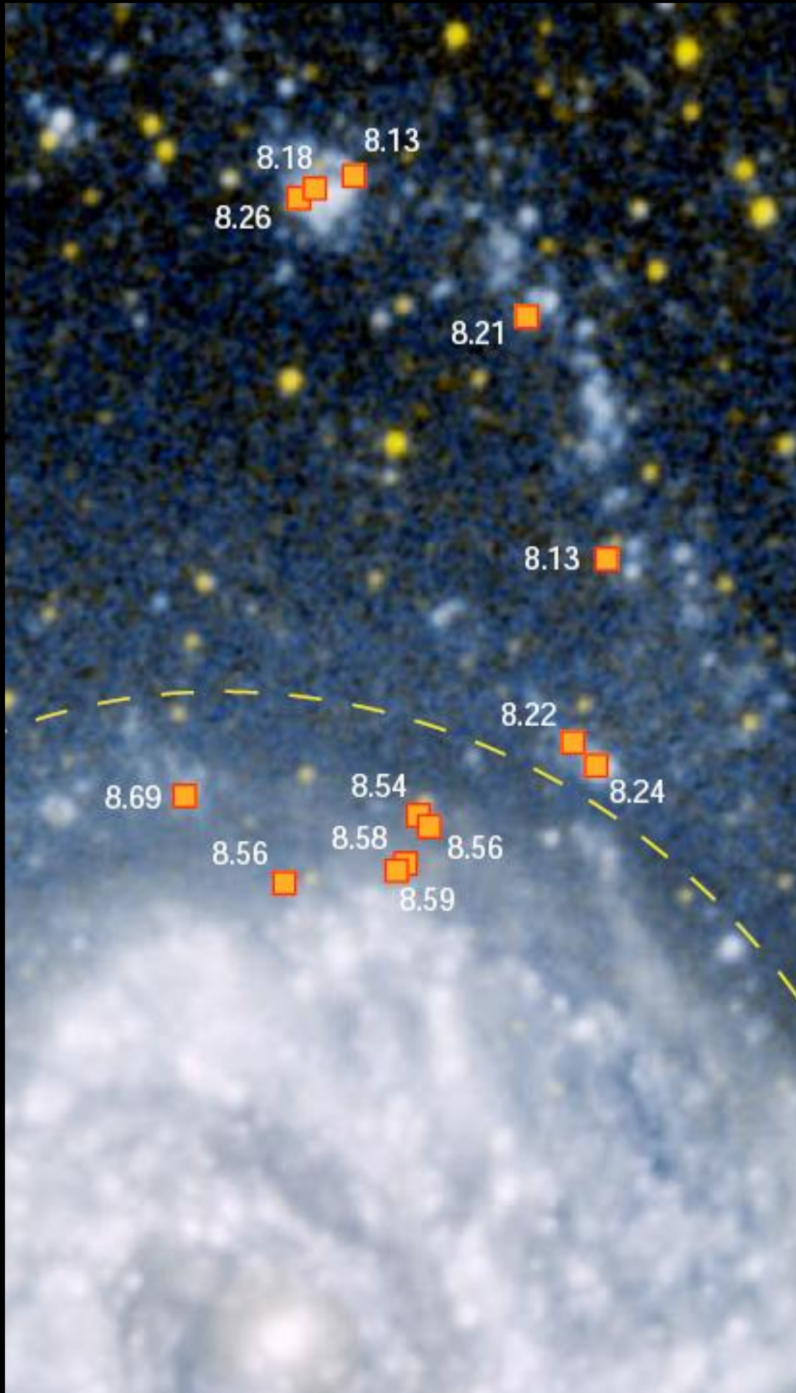
Bok 90Prime Camera

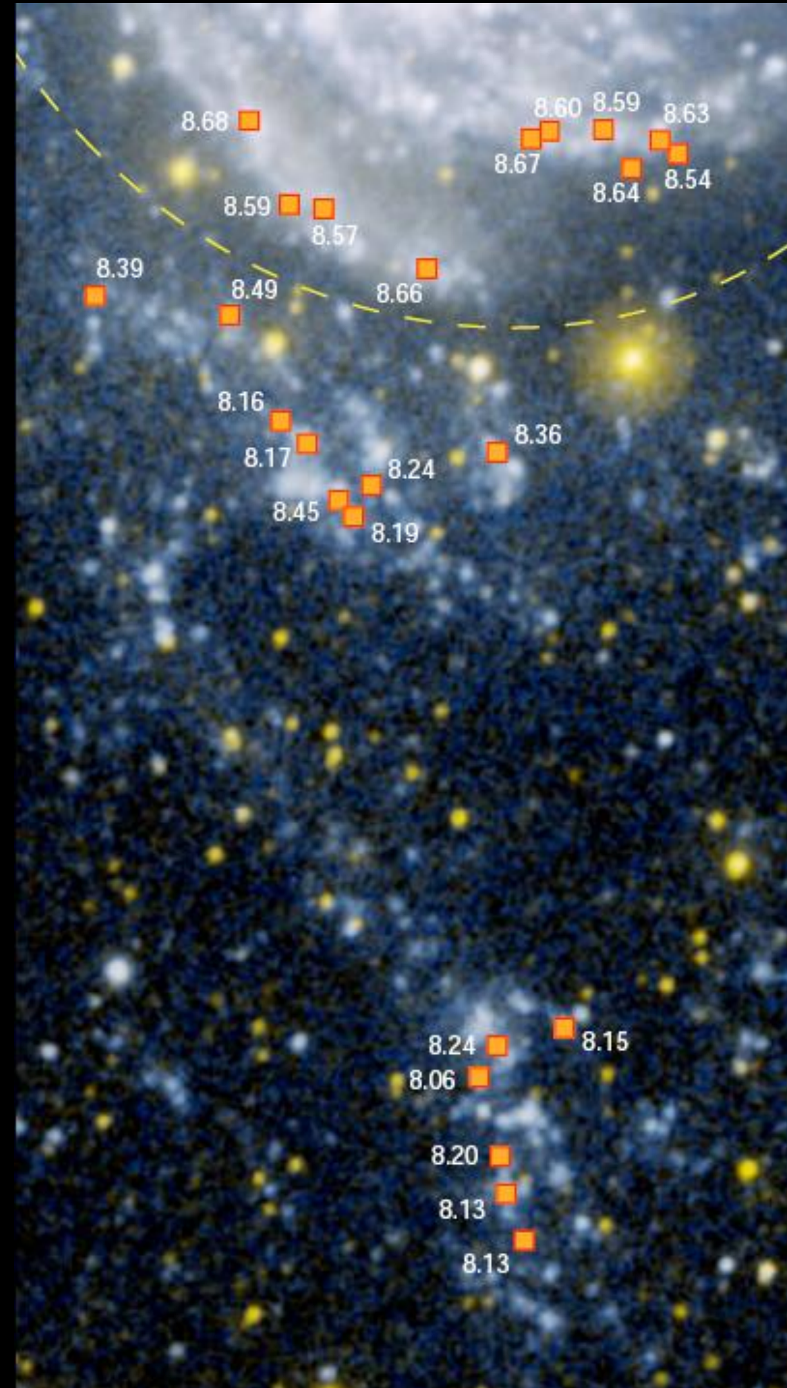
+ VLT FORS2 Fields

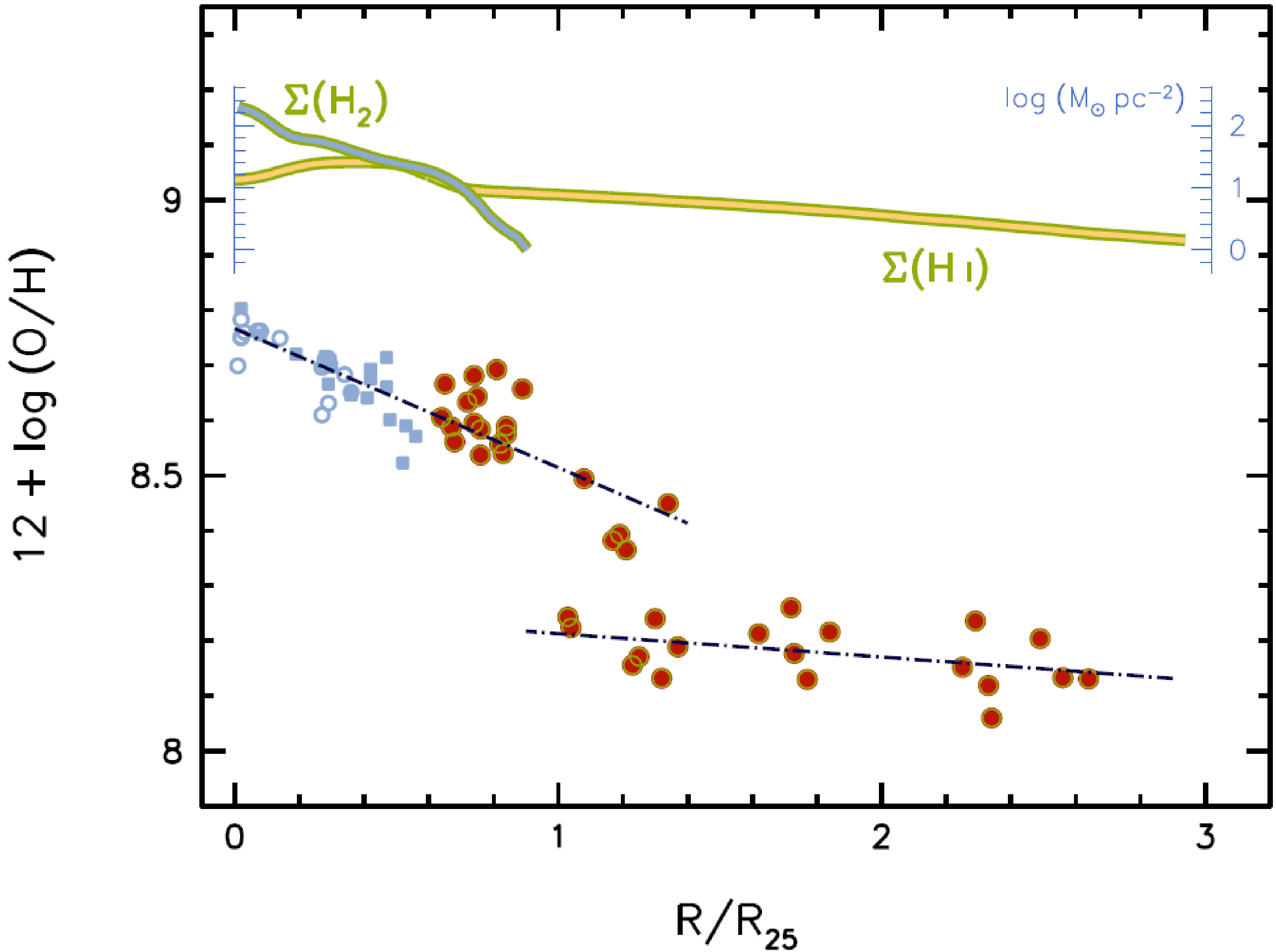




Bresolin et al. 2009, ApJ, 695, 580

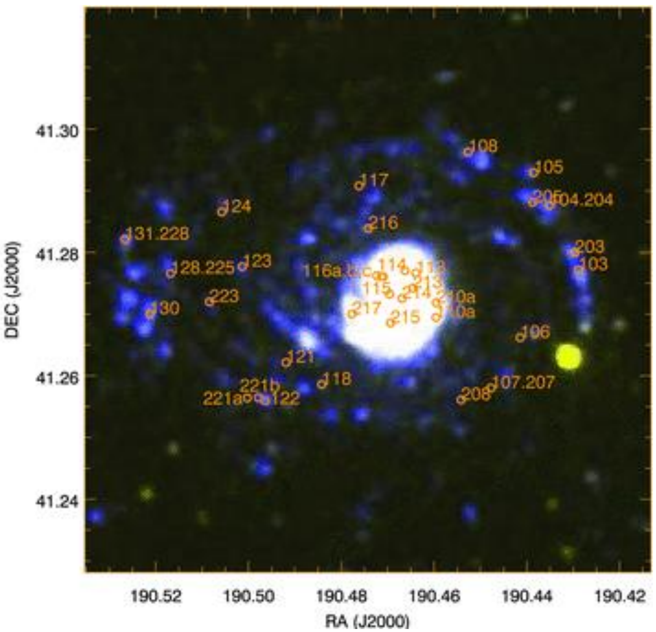

8.18
8.13
8.26
8.21
8.13
8.22
8.24
8.69
8.54
8.58
8.56
8.56
8.59

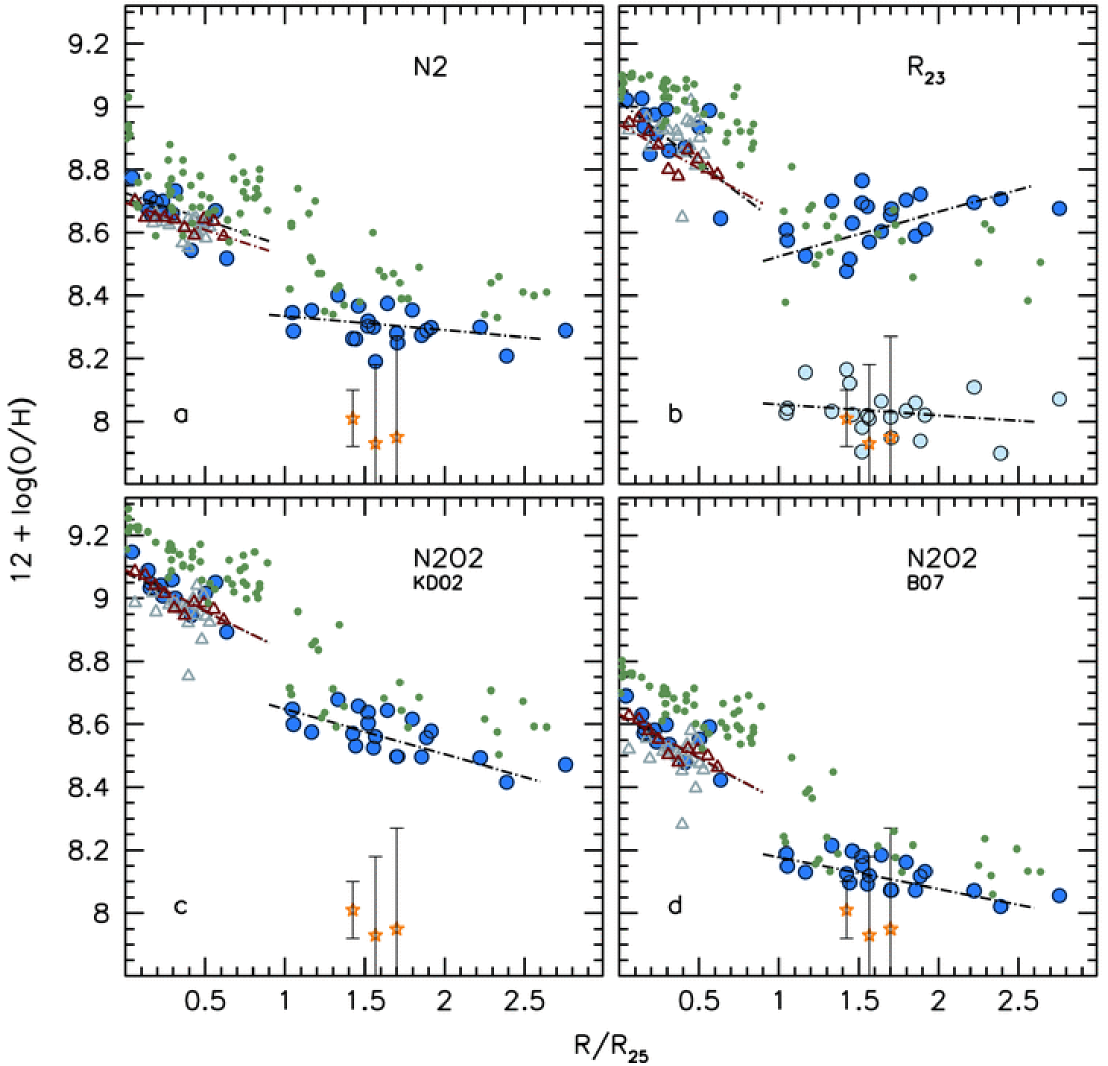

8.68
8.60
8.59
8.63
8.67
8.64
8.54
8.59
8.57
8.39
8.49
8.66
8.16
8.36
8.17
8.24
8.45
8.19
8.24
8.15
8.06
8.20
8.13
8.13



Bresolin et al. 2009, ApJ, 695, 580

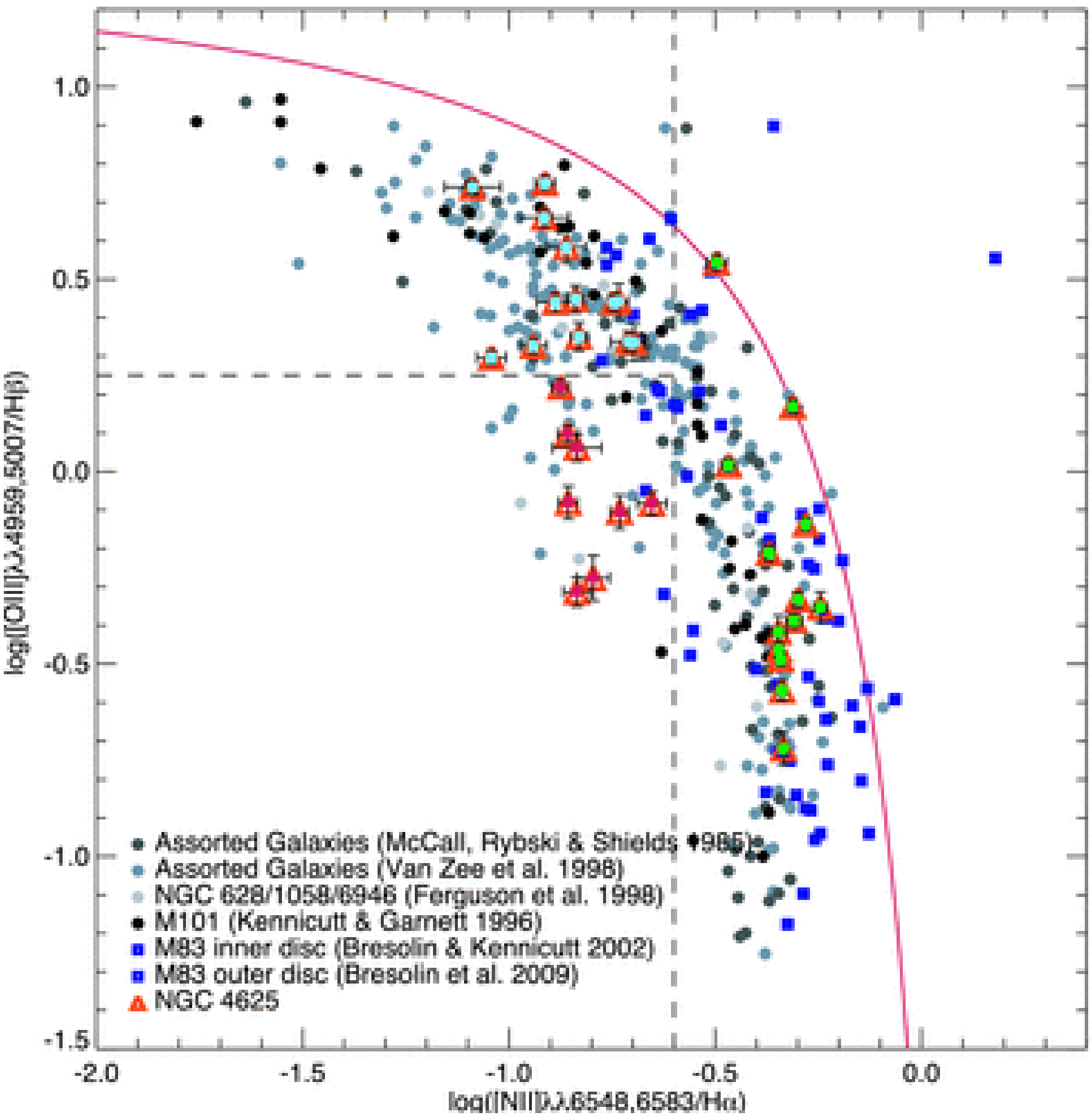
Case Study 2: NGC 4625 (Subaru)





Goddard et al. 2011, MNRAS, 412, 1246

Some HII regions in XUV disc show anomalously low ionisation.
May reflect absense of very massive (hot) O-stars, cf. Kroupa et al.



Questions

- Is low density SF the same as local SF (but more dispersed), or does it represent a distinct SF mode? (e.g., SF law, SF efficiency, IMF, controlling physics)?
- What do these regions reveal about the physics of star formation?
- What do these regions reveal about the evolution of their parent galaxies?