Star Formation in the Cosmological Context

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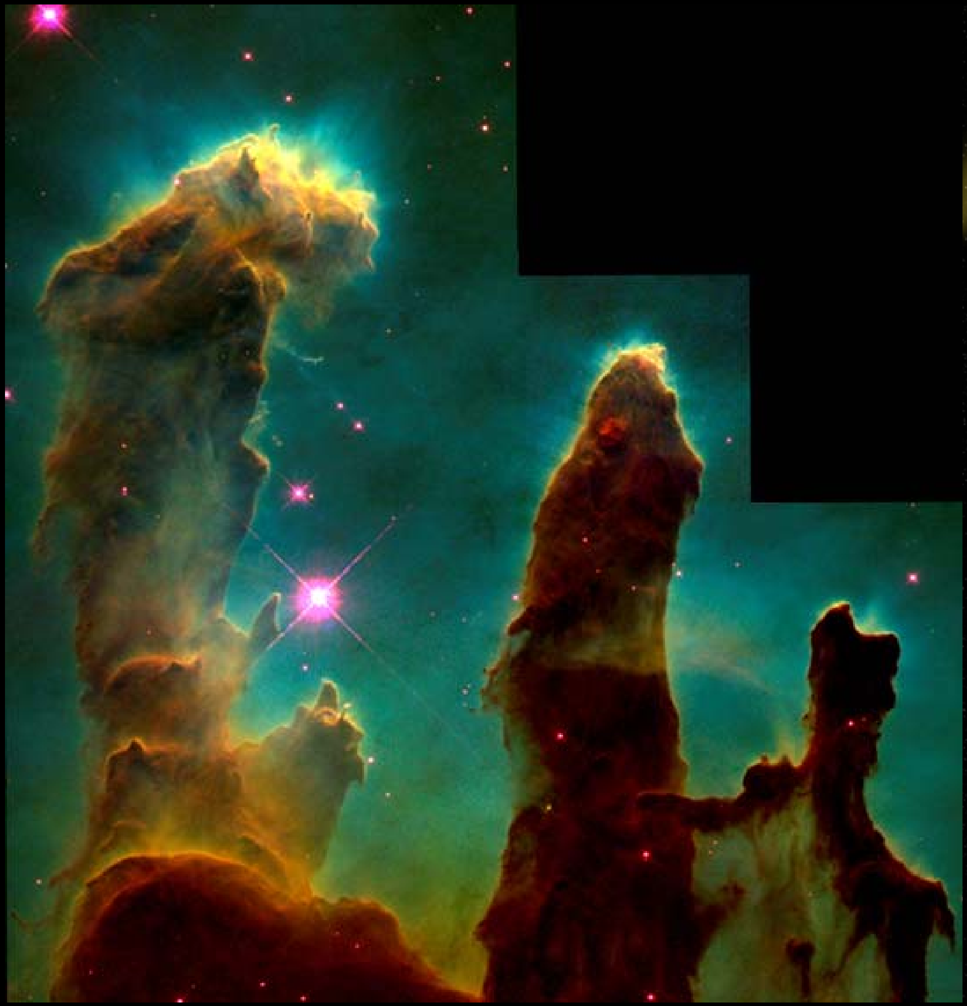
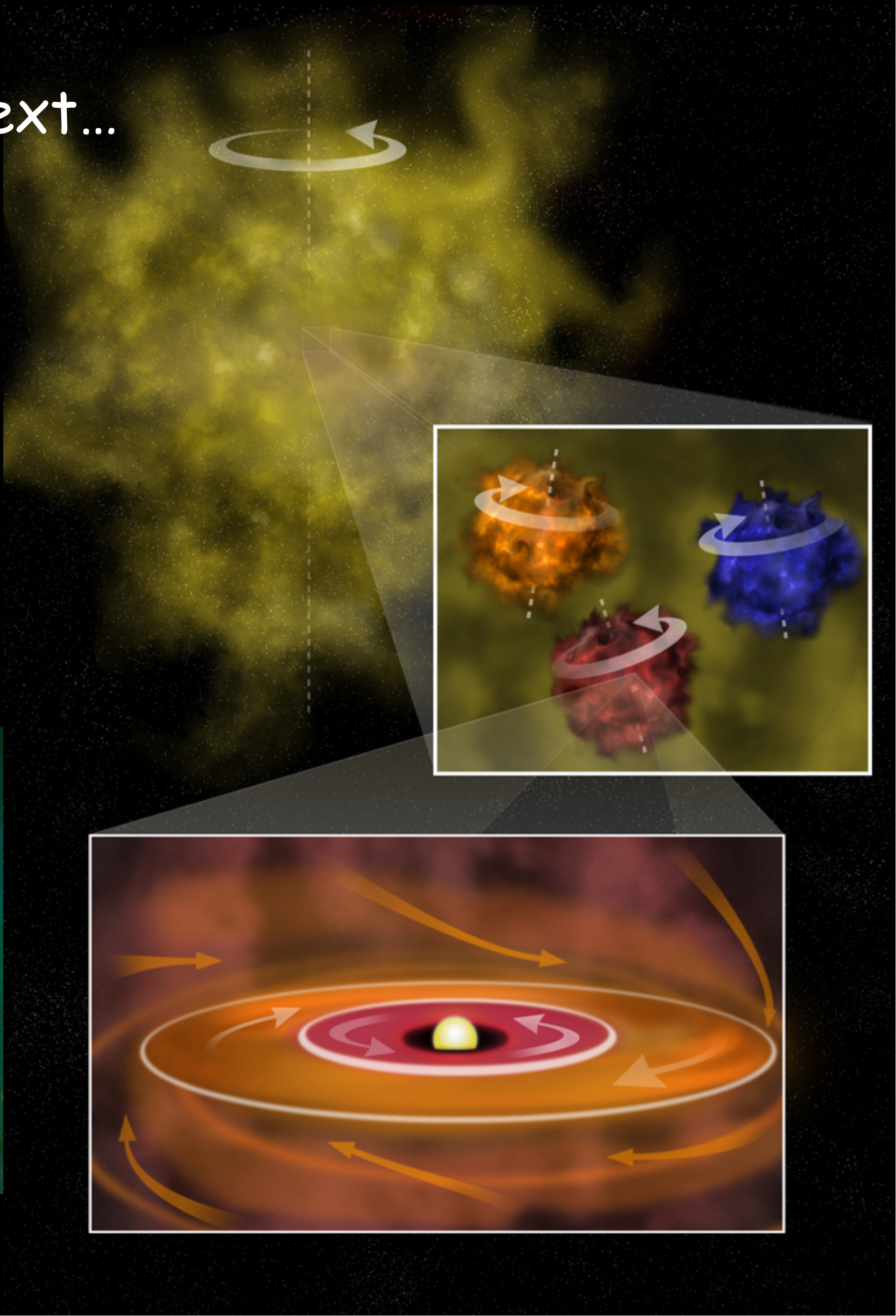
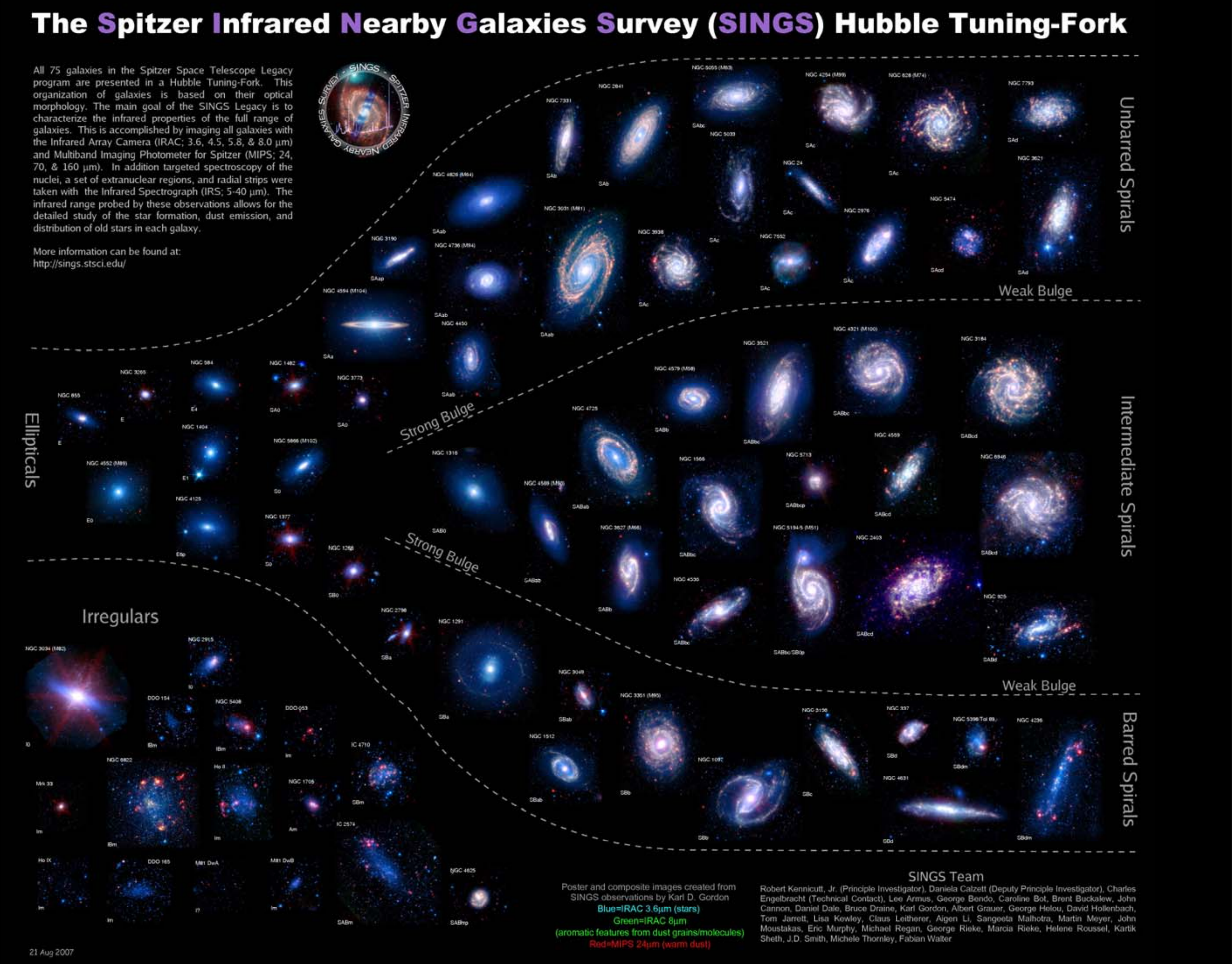
In Contrast to…

Star Formation in a Local Context…



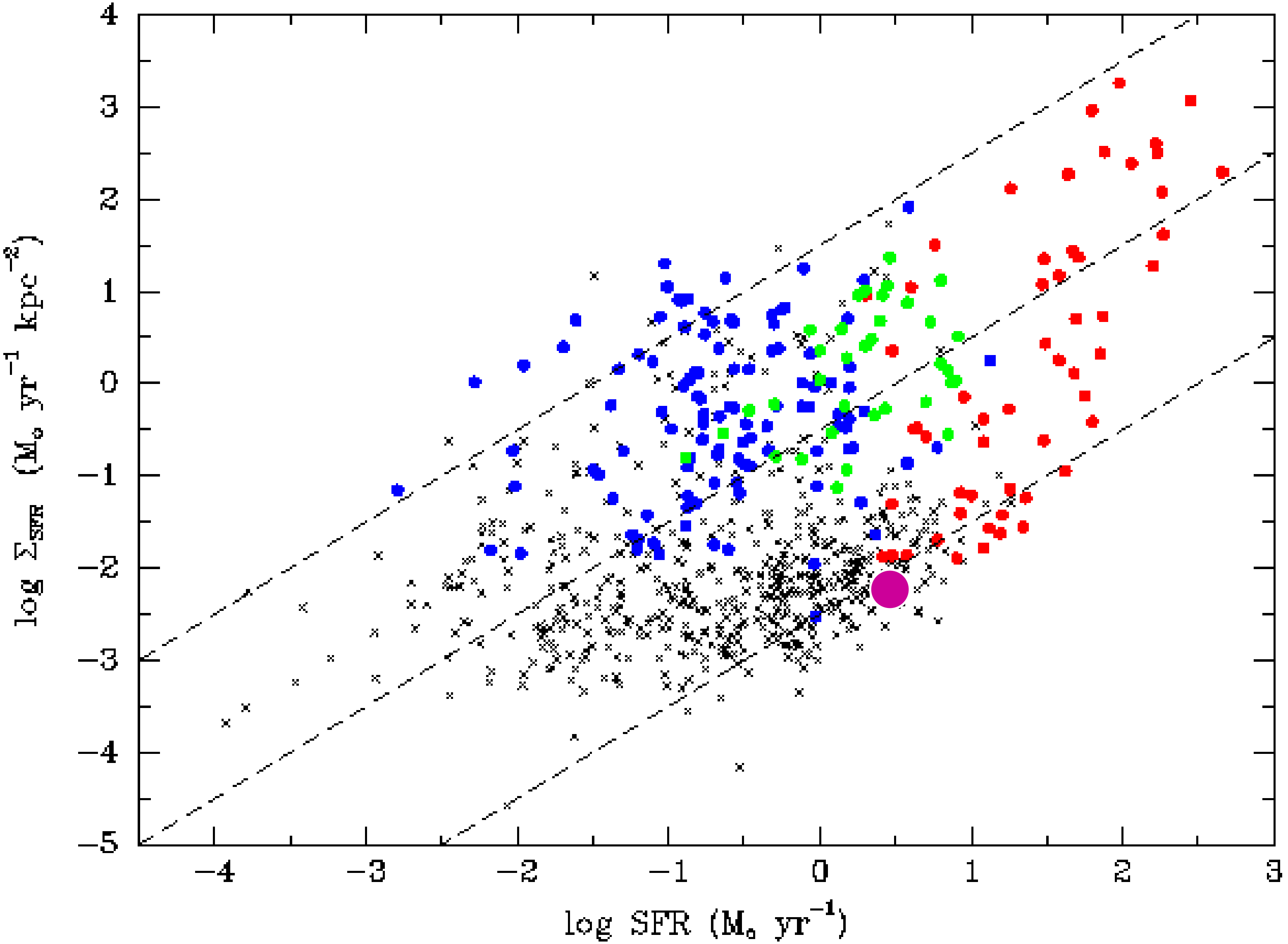



The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
All 75 galaxies in the Spitzer Space Telescope Legacy program are presented in a Hubble Tuning-Fork. This organization of galaxies is based on their optical morphology. The main goal of the SINGS Legacy is to characterize the infrared properties of the full range of galaxies. This is accomplished by imaging all galaxies with the Infrared Array Camera (IRAC; 3.6, 4.5, 5.8, & 8.0 μm) and Multiband Imaging Photometer for Spitzer (MIPS; 24, 70, & 160 μm). In addition targeted spectroscopy of the nuclei, a set of extranuclear regions, and radial strips were taken with the Infrared Spectrograph (IRS; 5-40 μm). The infrared range probed by these observations allows for the detailed study of the star formation, dust emission, and distribution of old stars in each galaxy.
More information can be found at:
http://sings.stsci.edu/
SINGS - SPITZER INFRARED NEARBY GALAXIES SURVEY
Unbarred Spirals
Weak Bulge
Intermediate Spirals
Strong Bulge
Strong Bulge
Weak Bulge
Barred Spirals
Ellipticals
Irregulars
Poster and composite images created from SINGS observations by Karl D. Gordon
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, George Helou, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter
21 Aug 2007

Motivations

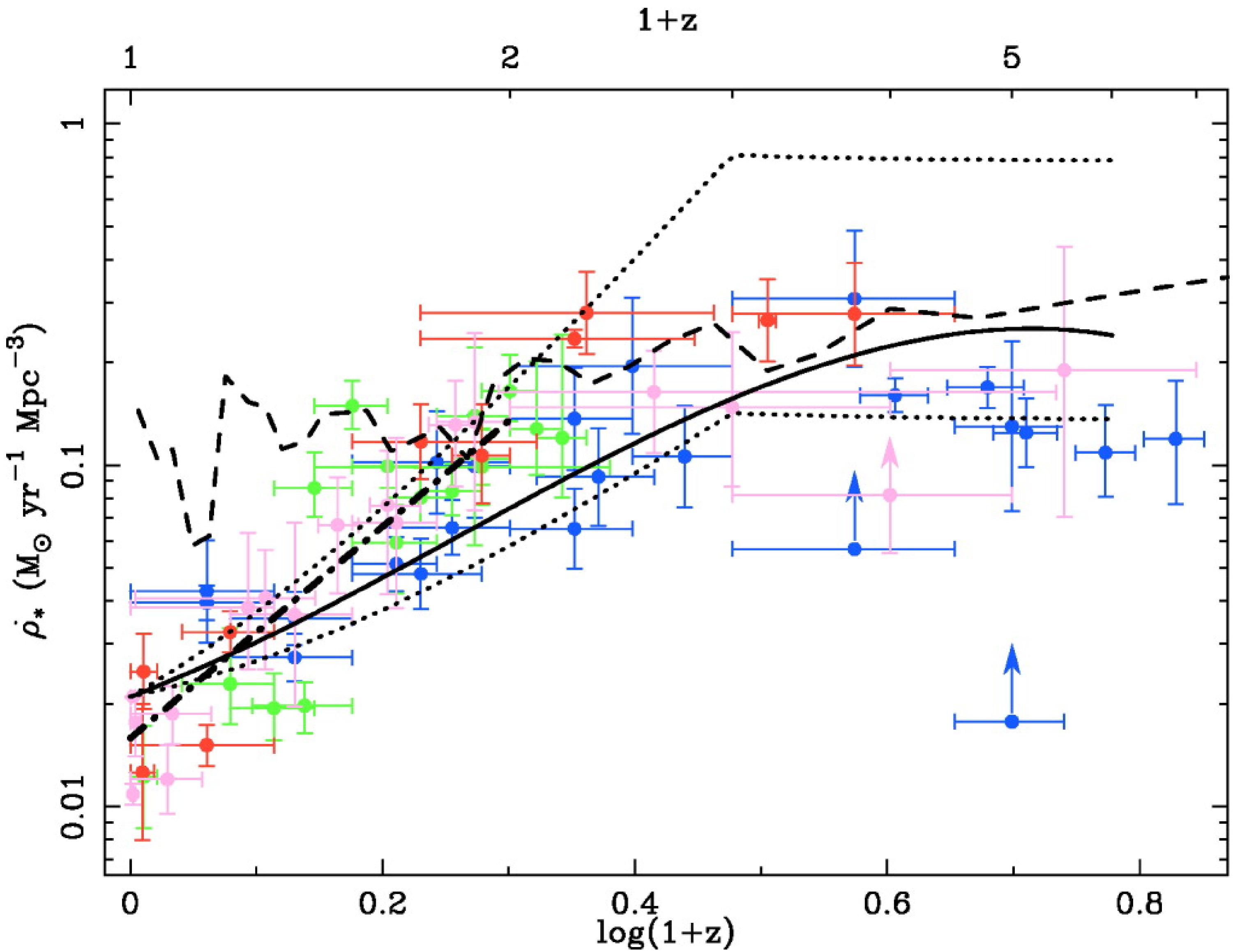
- Observations of external galaxies reveal star formation events ranging over >10^7x in absolute scale--- in a diverse range of physical environments
- Star formation is a primary component of galaxy evolution and cosmic evolution
- Despite its central role, galactic-scale SF is barely understood, and disconnected from our understanding of local star formation

Understanding star formation in extreme environments



star formation rate per unit area

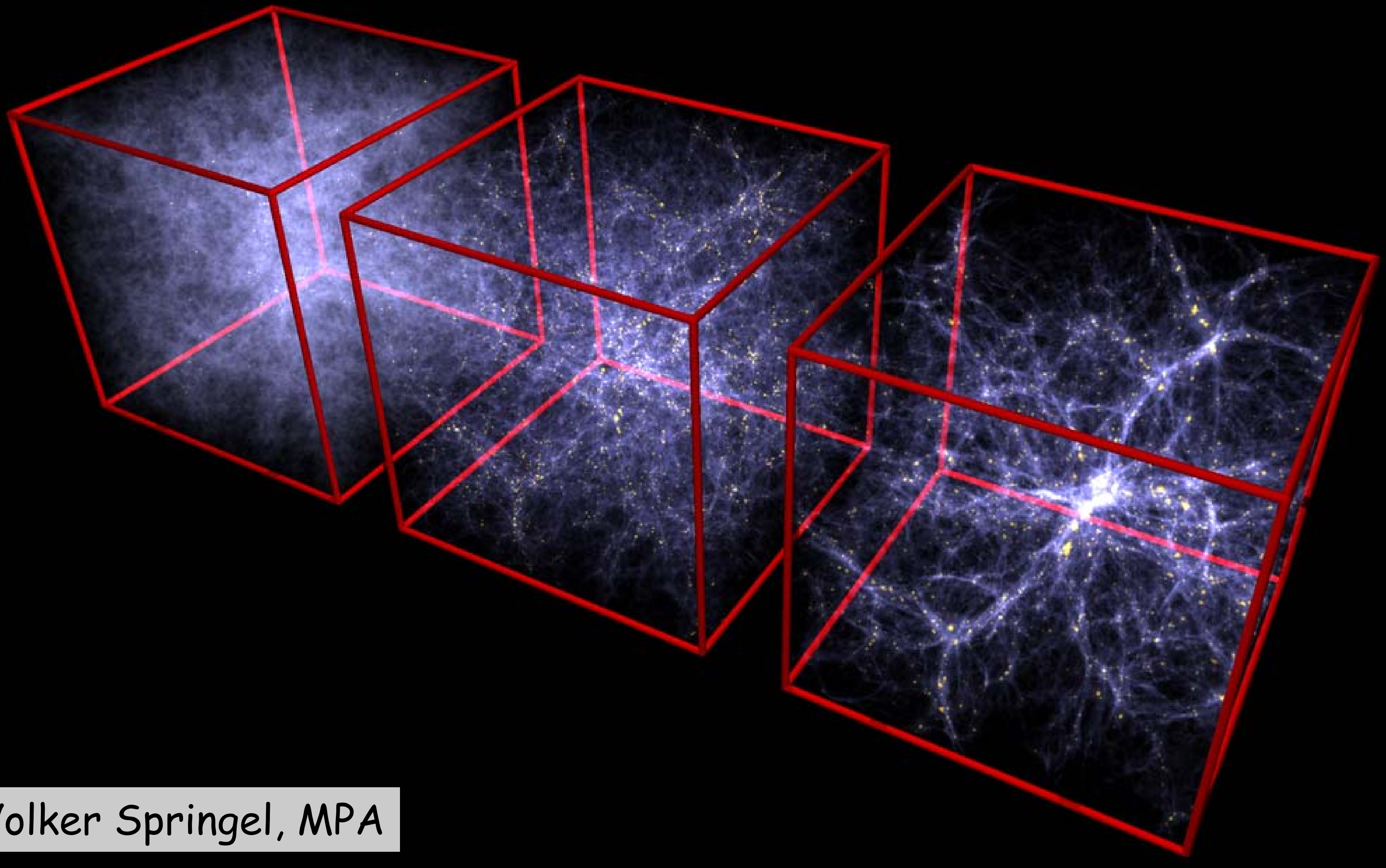
star formation rate



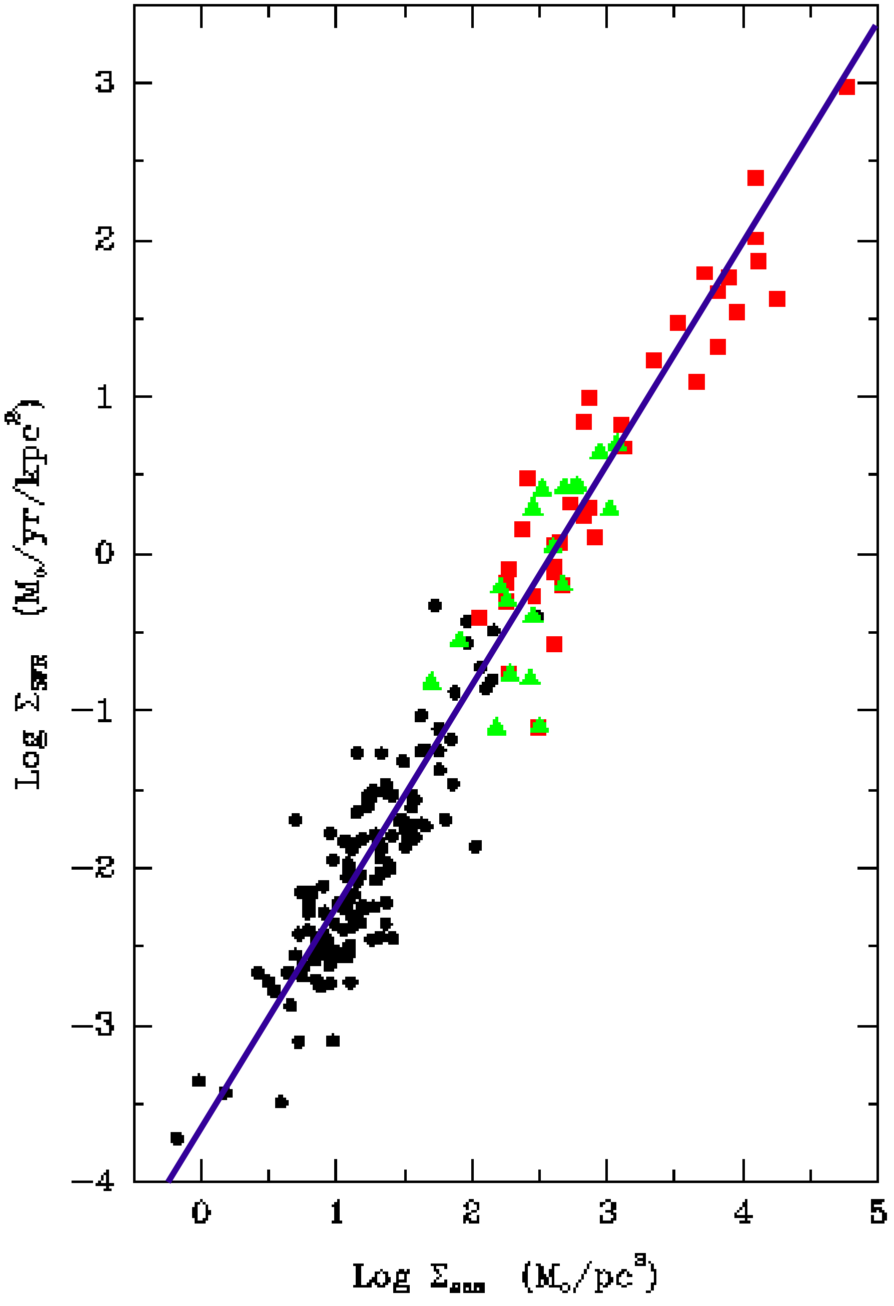
Hopkins 2004, ApJ, 615, 209

Unraveling the baryonic physics of galaxy formation/evolution

- gas cooling, disk formation, cloud/star formation, feedback



Volker Springel, MPA



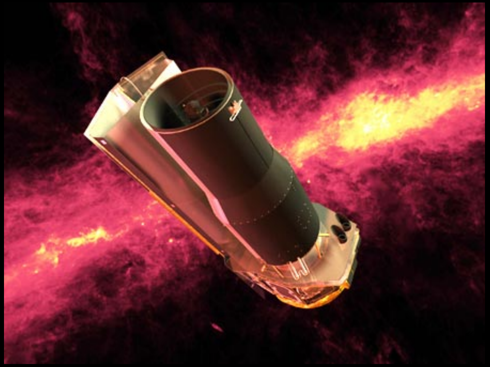
Log Σ_{SFR} ($M_{\odot}$/yr/kpc^2)
3
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5
Log Σ_{gas} ($M_{\odot}$/pc^2)

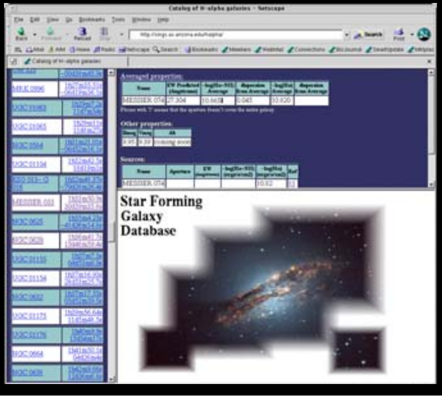
Lectures

1. The Multiwavelength Toolbox for Measuring Star Formation in Galaxies
2. Demographics of Star-Forming Galaxies and Starbursts
3. The Star Formation Law: Connecting to the Physics of Star Formation

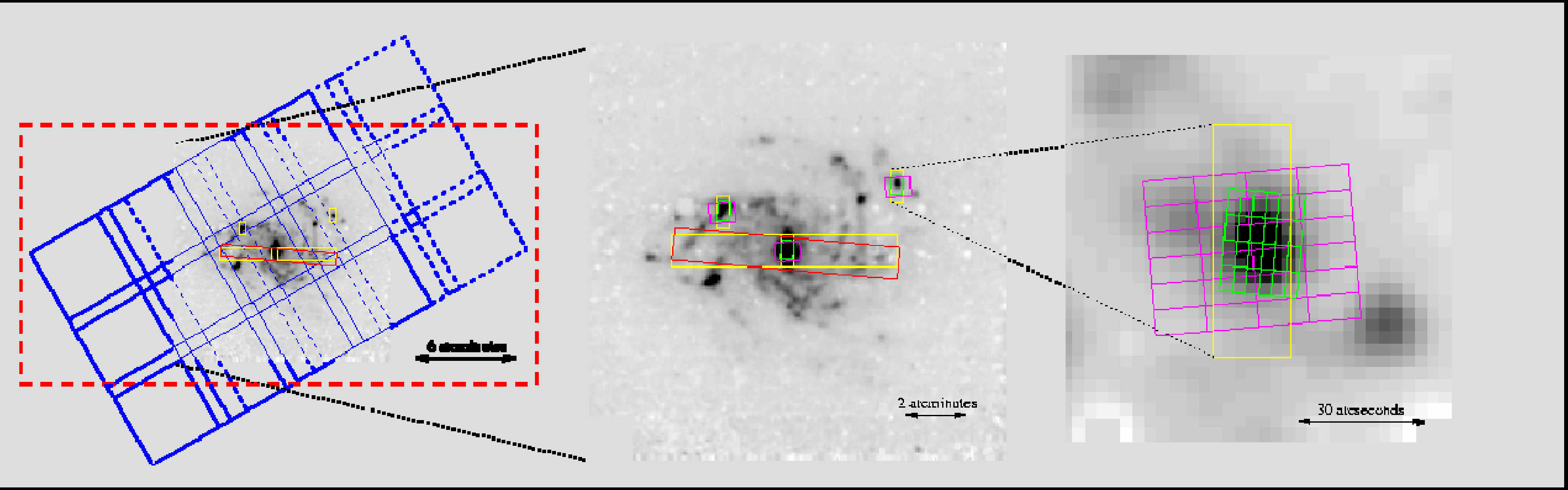
An Information Explosion

- advent of the mega-survey
  - SDSS, 2DF --> imaging, spectra for $\gg 10^6$ galaxies to z=0.5
- GALEX
  - SFRs for 10^7 galaxies to z>1
  - ~10000 galaxies within 70 Mpc
- Spitzer
  - 3 Legacy surveys + MIPS/IRS GTO starburst survey
- large Hα surveys
  - SFR maps for >4000 galaxies
- ISM surveys
  - e.g., WHISP, THINGS, BIMA SONG --> ALMA, Herschel





Spitzer Infrared Nearby Galaxies Survey (SINGS)

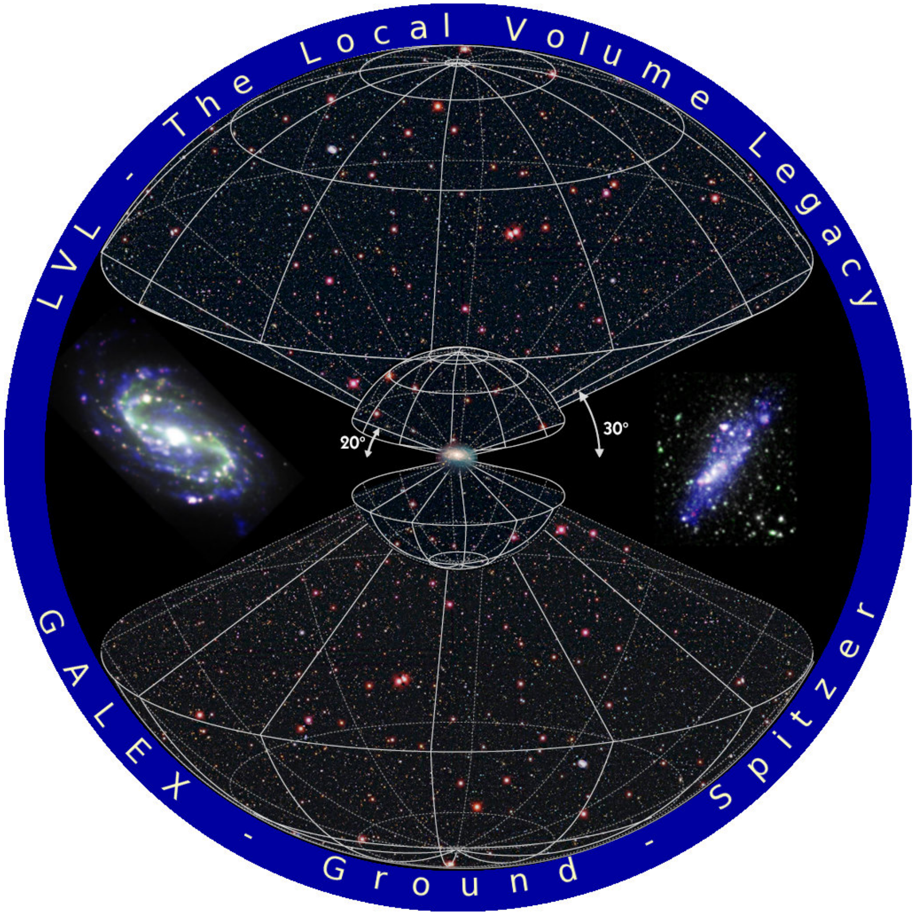


- complete IRAC, MIPS imaging of 75 nearby galaxies (3.5 – 160 μm)
- IRS, MIPS radial strip maps (10 – 100 μm)
- IRS maps of centers, 75 extranuclear sources (5–37 μm)
- ancillary imaging campaign covering UV to radio

Kennicutt et al. 2003, PASP, 115, 928

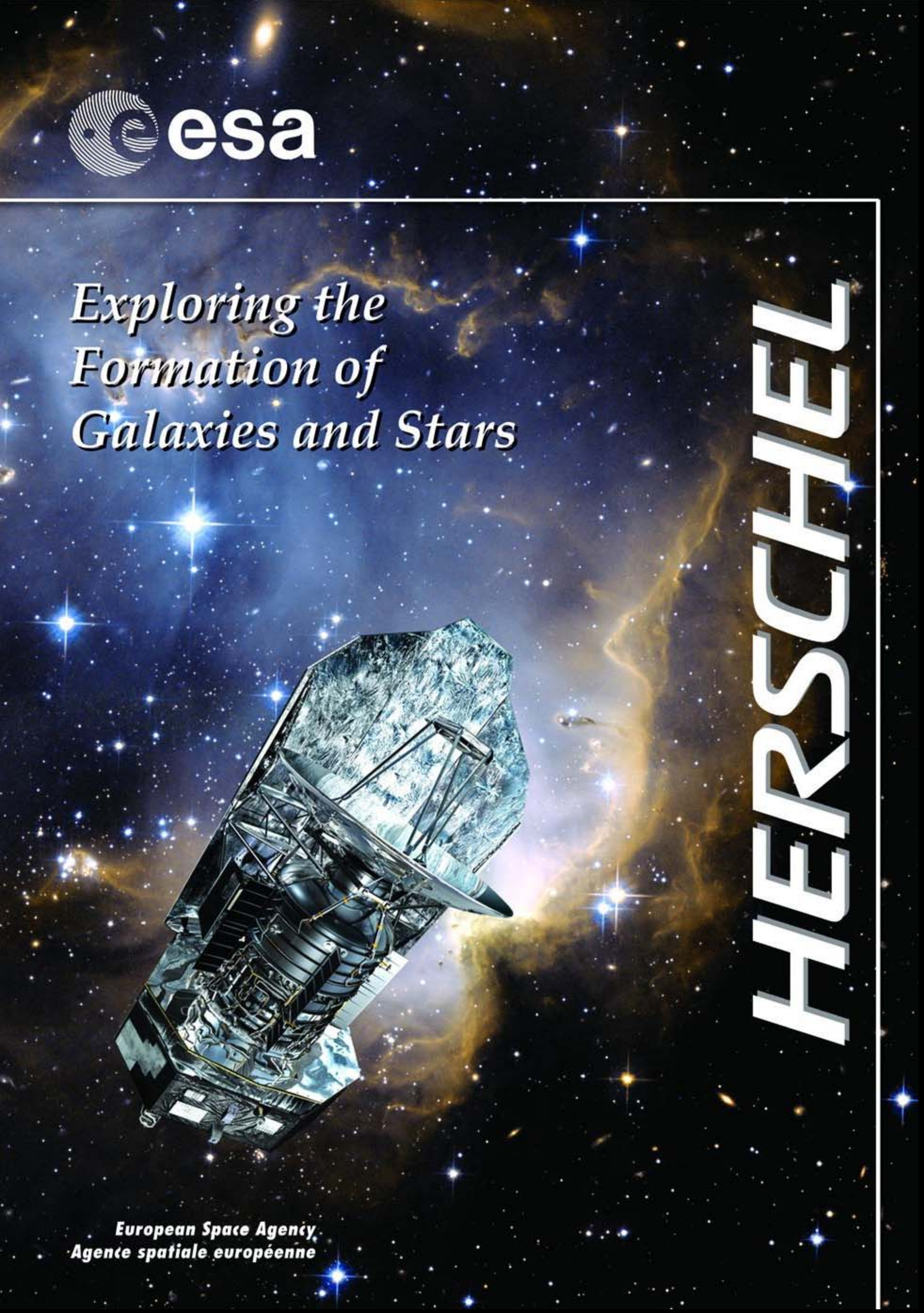
Spitzer Local Volume Legacy

- Cycle 4 Spitzer Legacy project
- UV/Hα/IR Census of Local Volume
  - HST ANGST sample to 3.5 Mpc
    - all galaxies outside LG |b|>20
  - GALEX 11HUGS sample to 11 Mpc
    - all S0/a–Irr with |b|>30, B<15
- IRAC + MIPS imaging for 258 galaxies

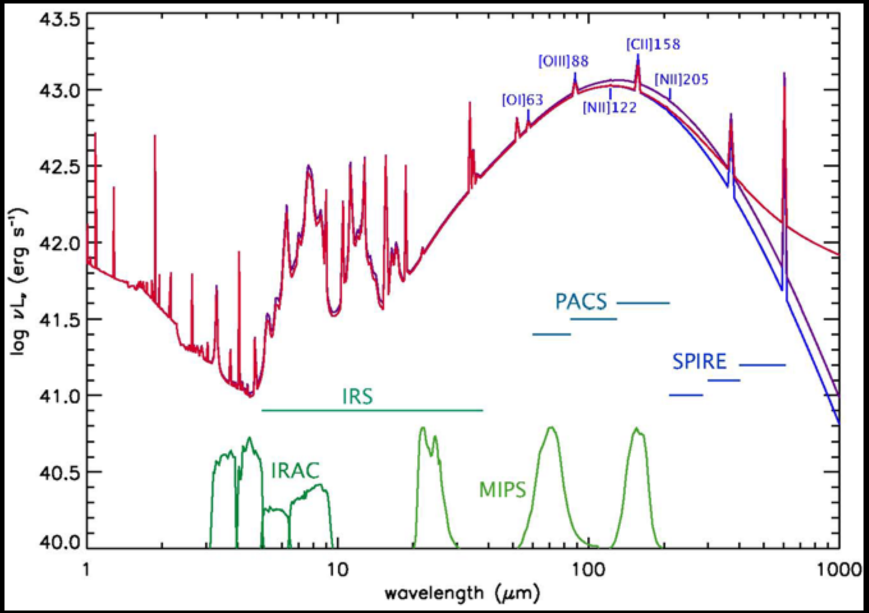


SINGS Team
10/2006

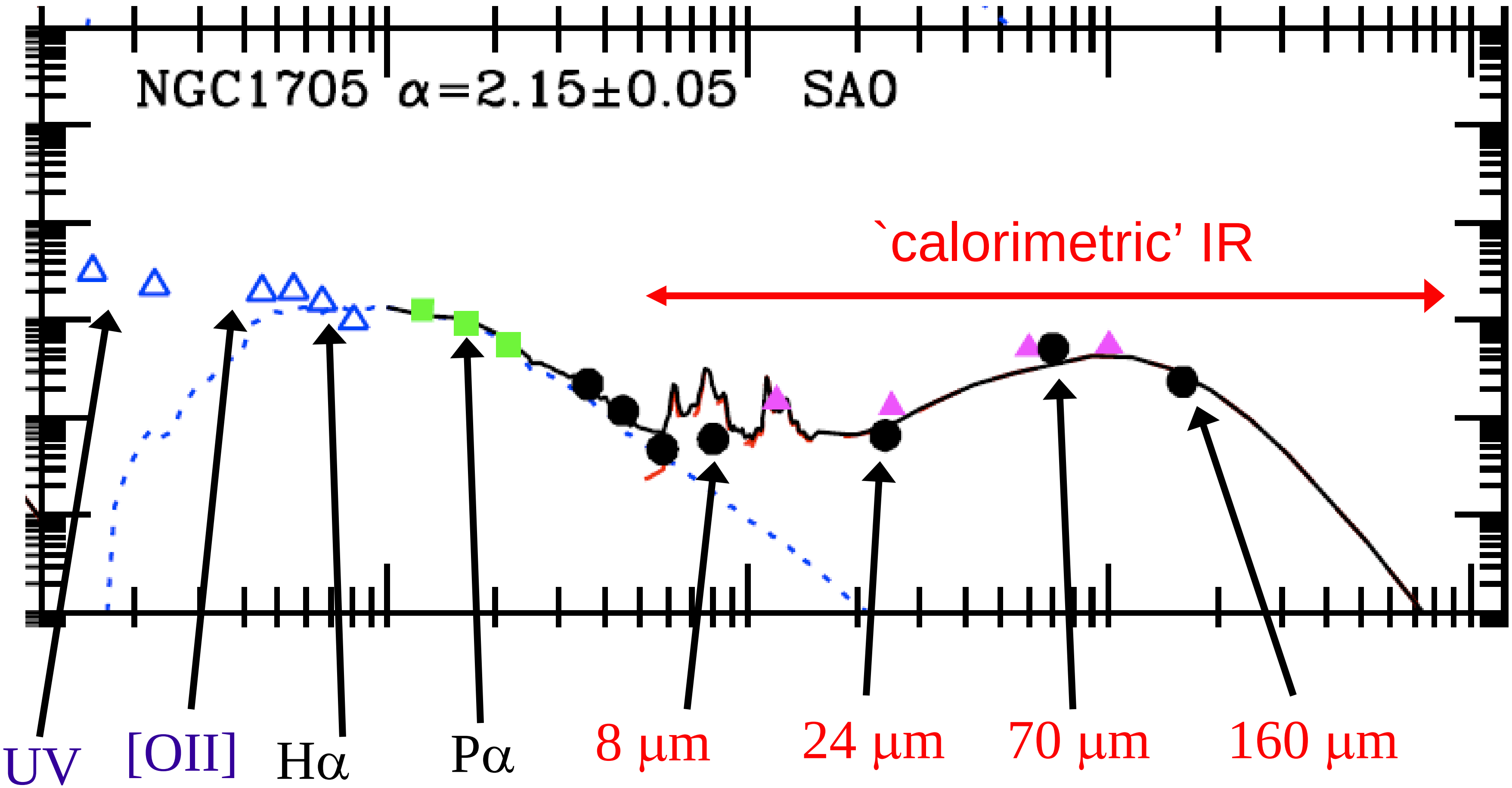
LVL Team
08/2008



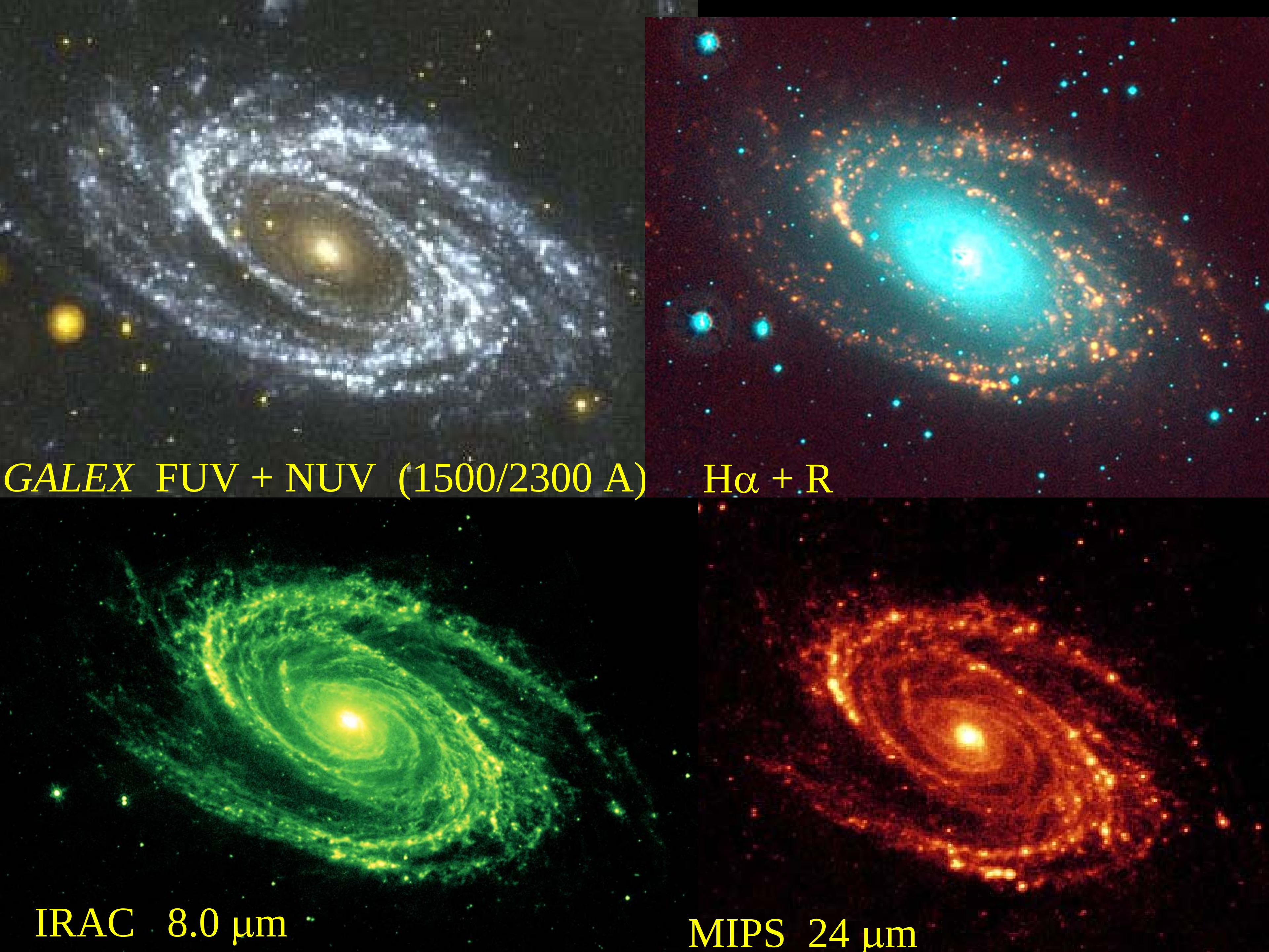
Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel (KINGFISH)



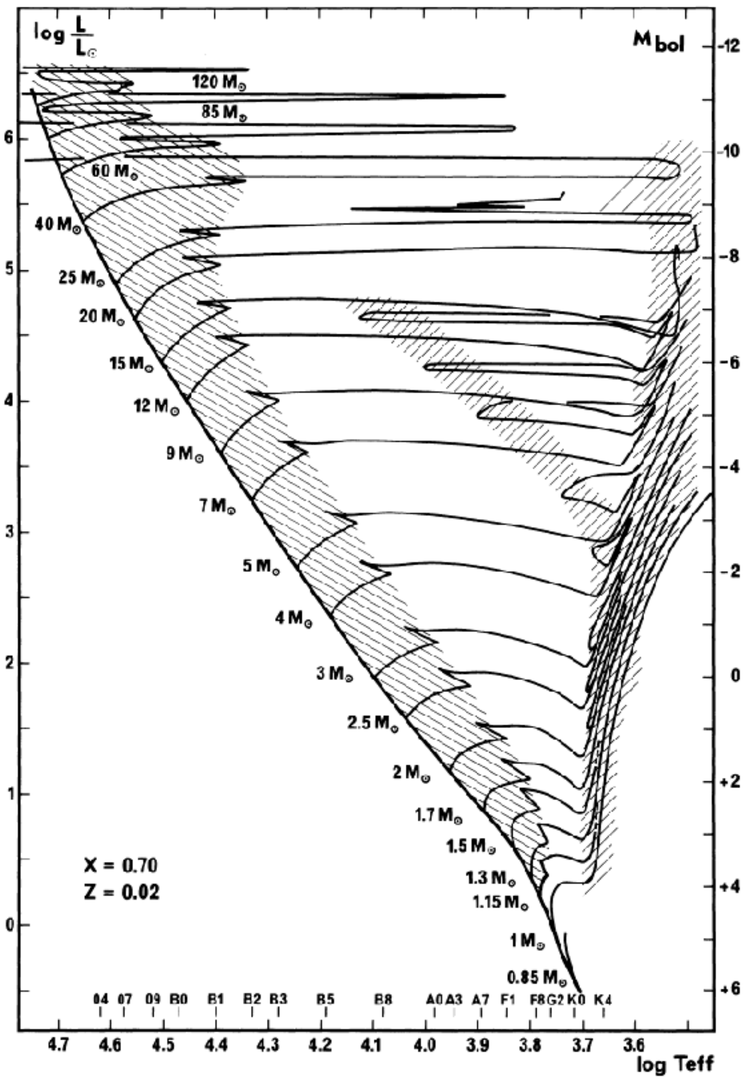
Multi-Wavelength SFR Diagnostics



Dale et al. 2007, ApJ, 655, 863

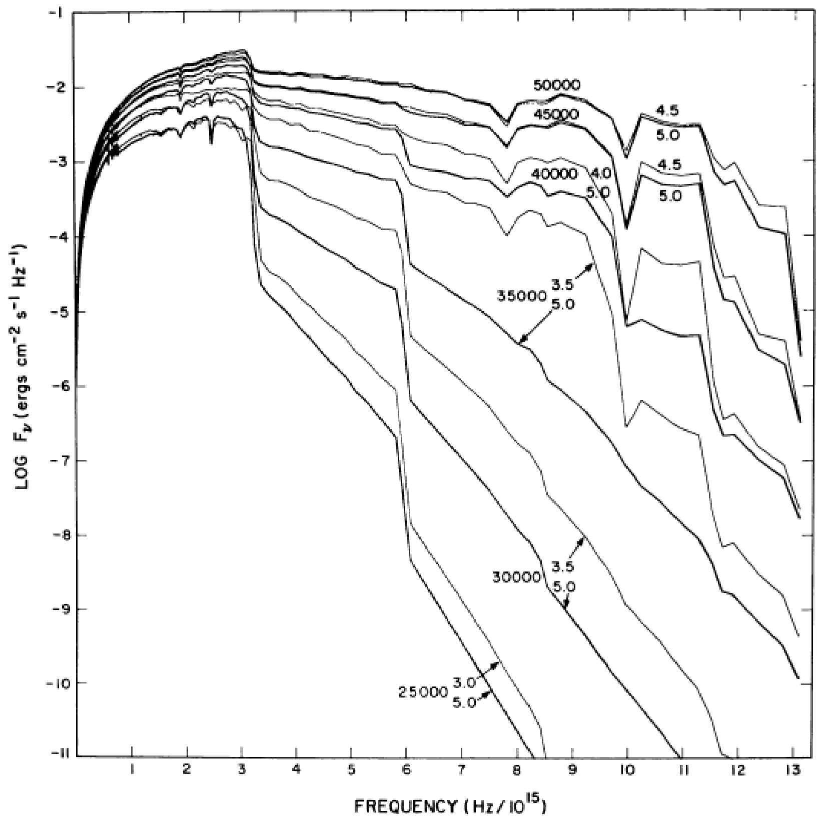

GALEX FUV + NUV (1500/2300 A)
Hα + R
IRAC 8.0 μm
MIPS 24 μm

Building an Evolutionary Synthesis Model



Maeder, Meynet 1988, A&AS, 76, 411

+

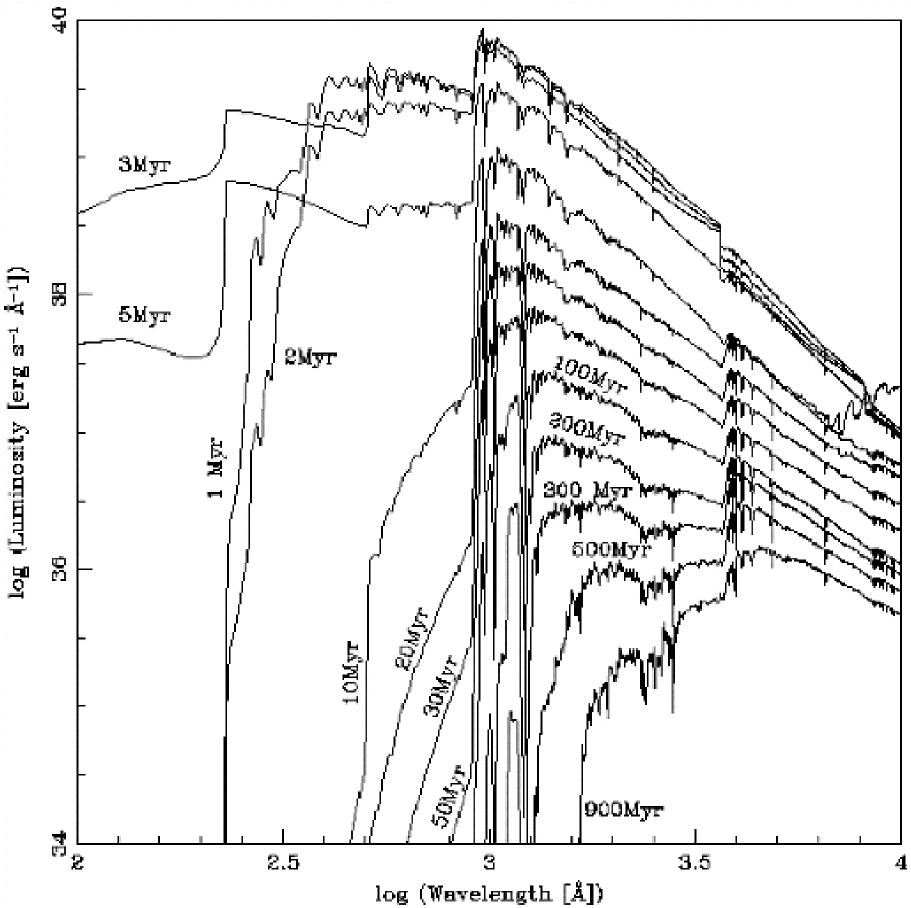


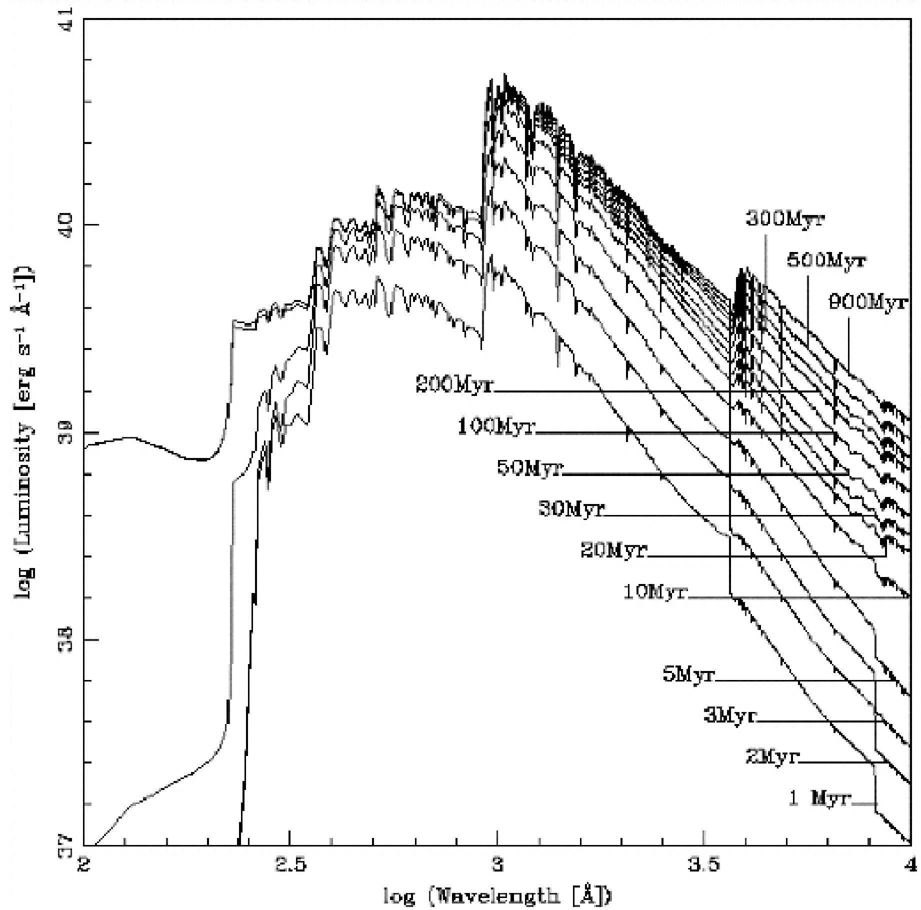
Kurucz 1979, ApJS, 40, 1

single star SED evolution model

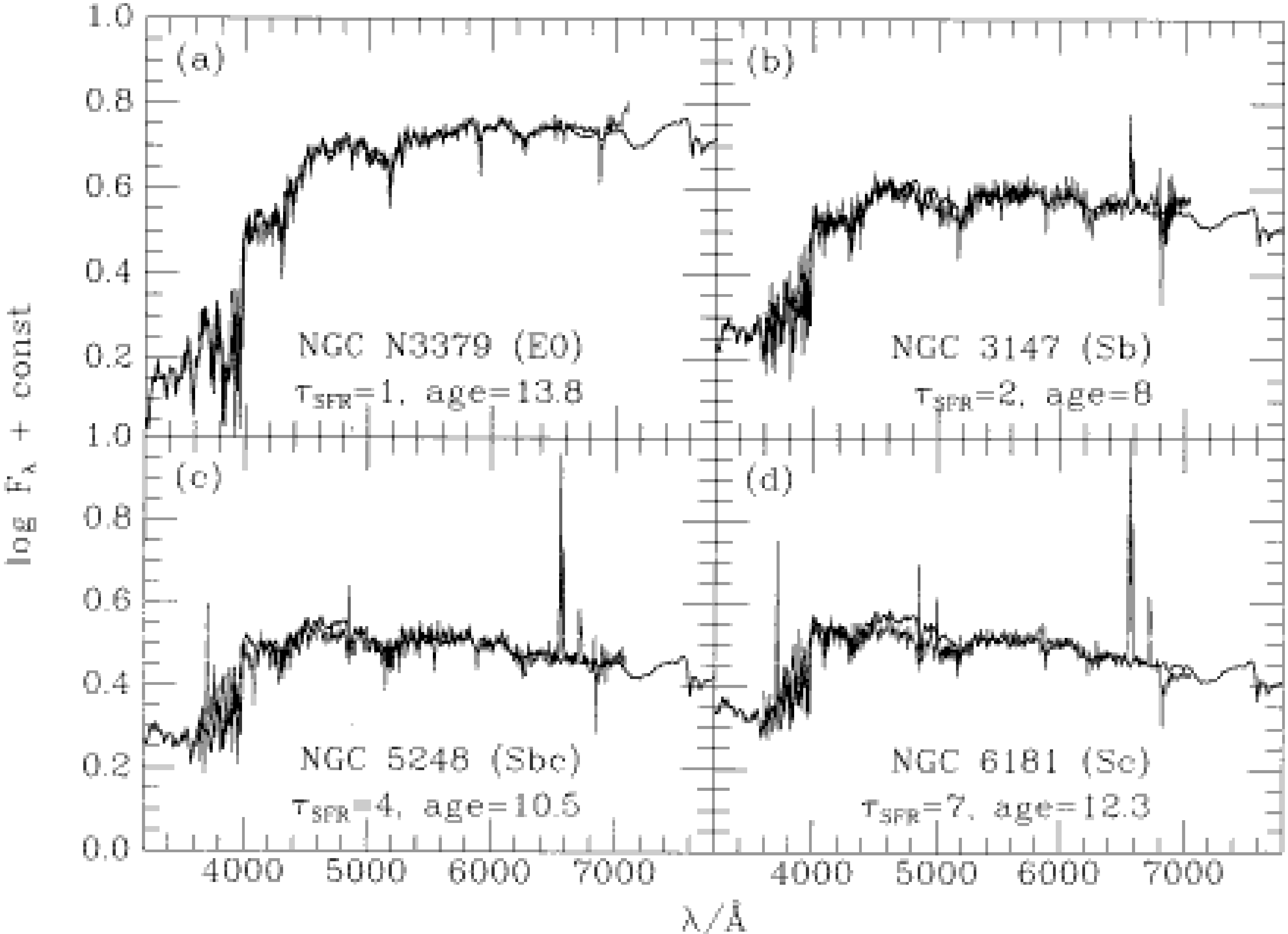
“single burst models”
(single age star clusters)

“continuous star formation” models



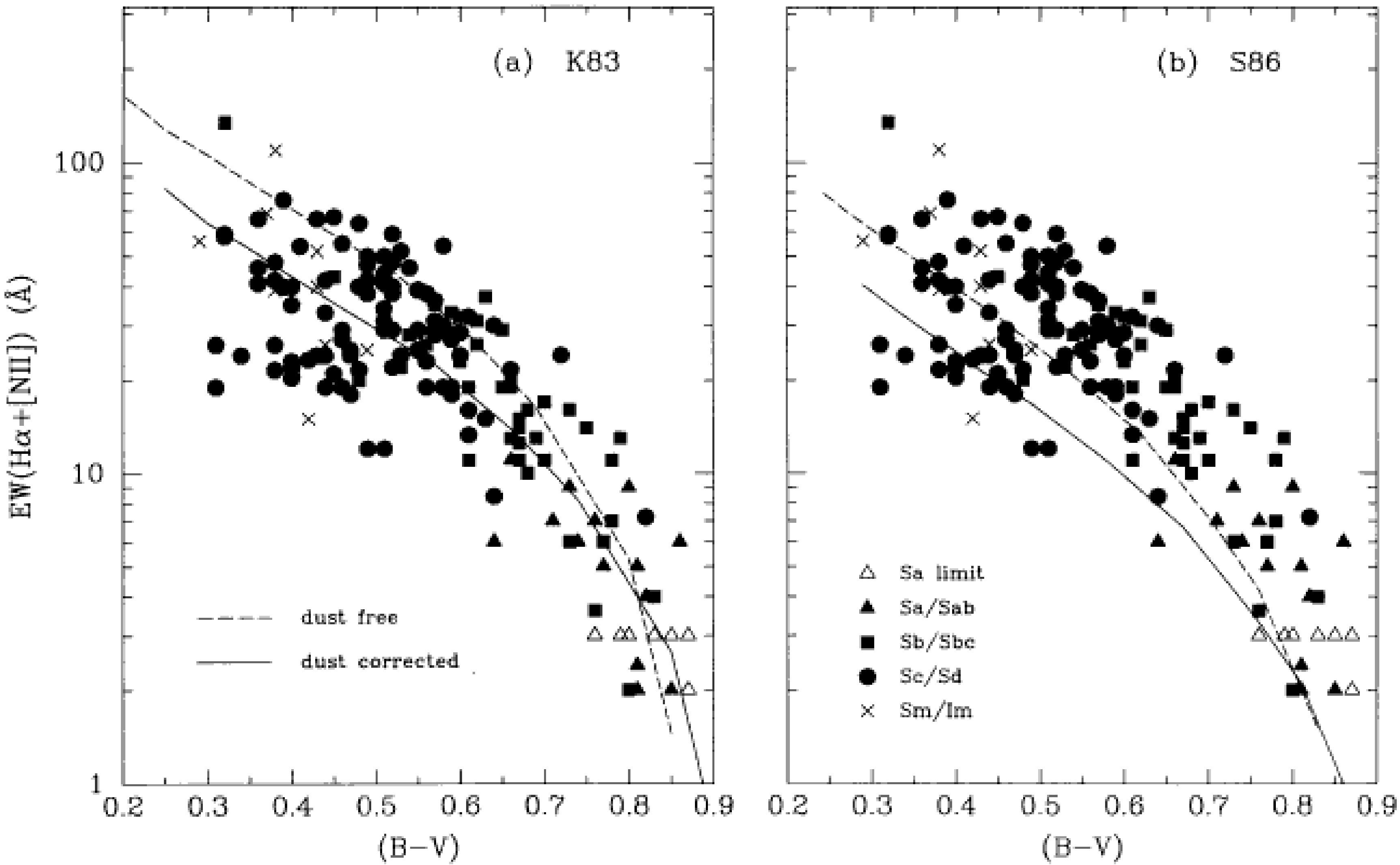


Leitherer et al. 1999, ApJS, 123, 3 “Starburst99”



Bruzual, Charlot 1993, ApJ, 405, 538

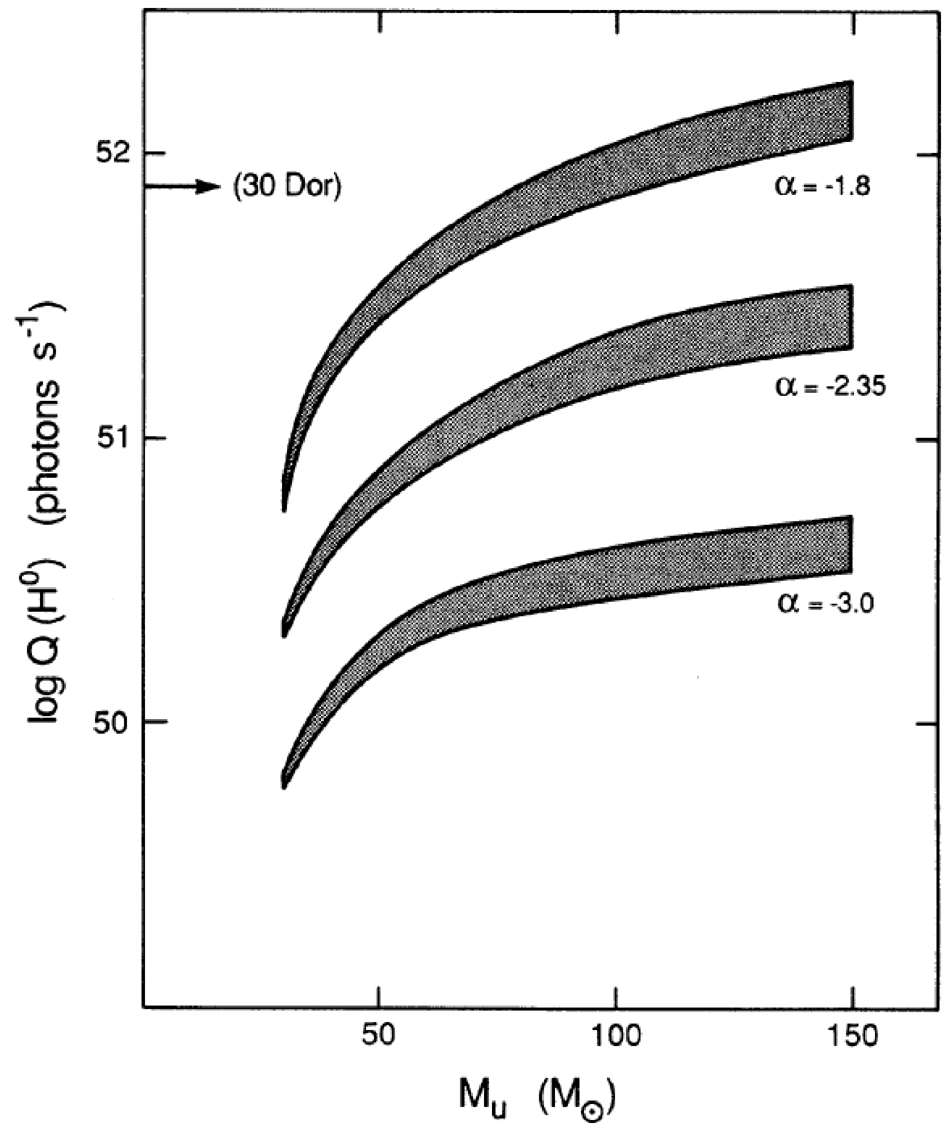
apply evolutionary synthesis models to constrain IMF



Kennicutt, Tamblyn, Congdon 1994, ApJ, 435, 22

Systematic Uncertainties in All Integrated SFR Scales

- IMF (slope and M_{max})
- dependence of stellar evolution, radiation on Z, Y
- quasi-bolometric measures (e.g., UV, TIR, Hα) mainly tied to total hydrogen consumption, and are insensitive to many details of models. But some effects (e.g., stellar rotation) can be very important

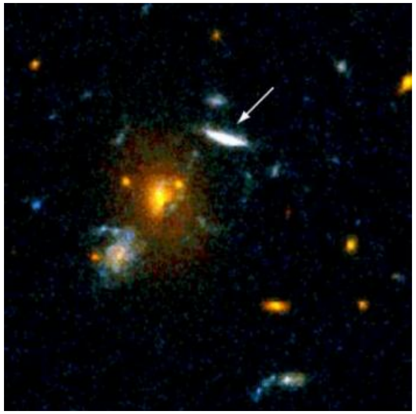


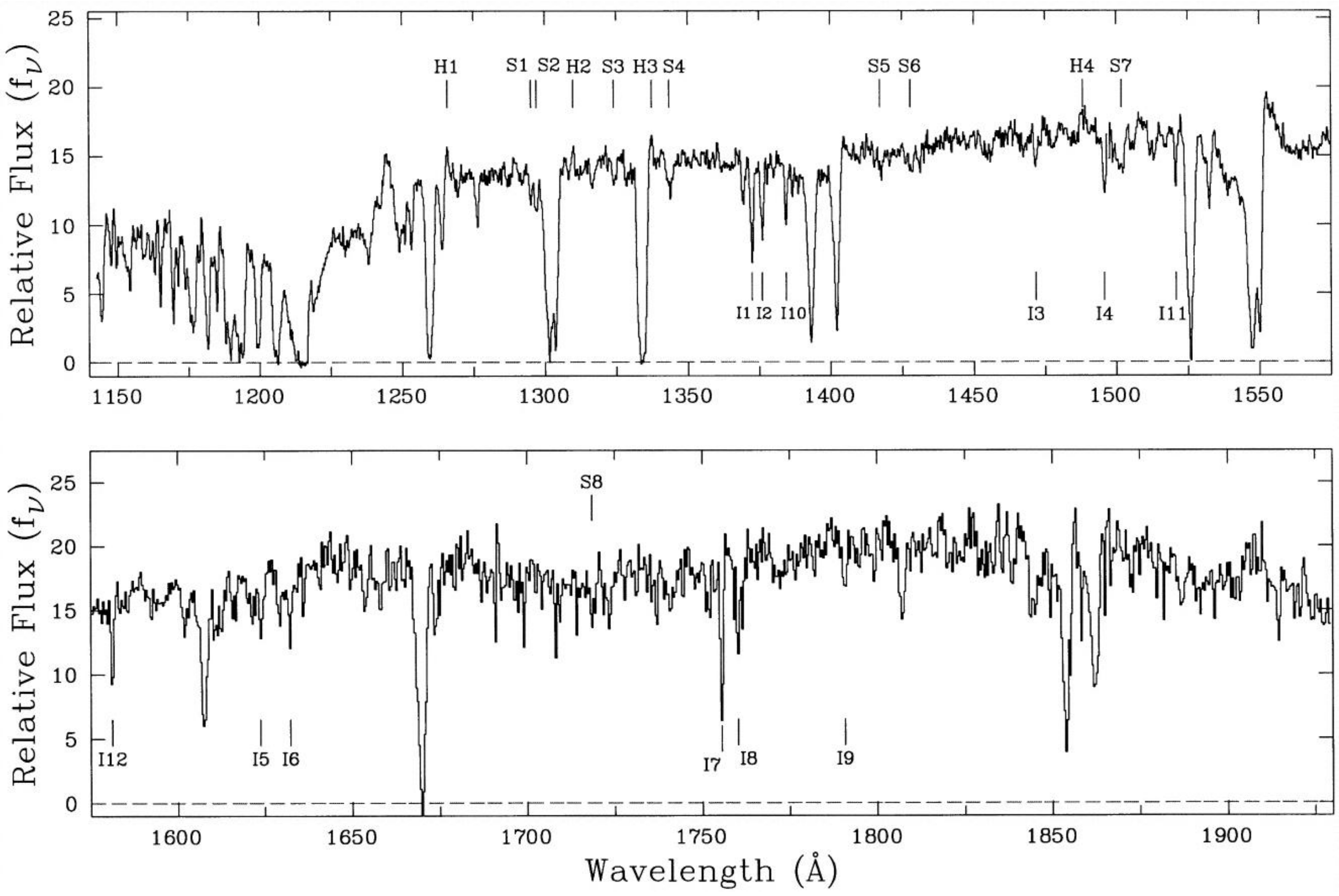
UV Continuum Emission

Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)

MS 1512-cB58   z=2.76

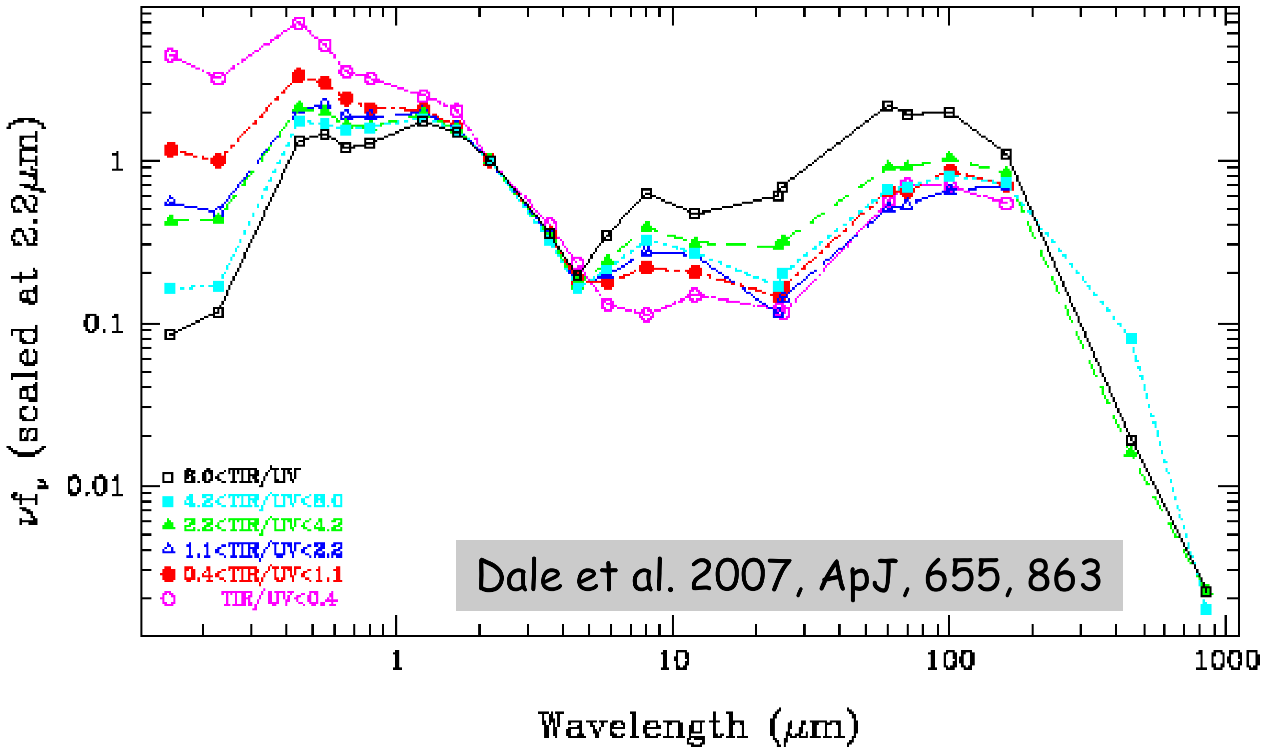




Pettini et al. 2000, ApJ, 528, 96

Ultraviolet stellar continuum: key advantages

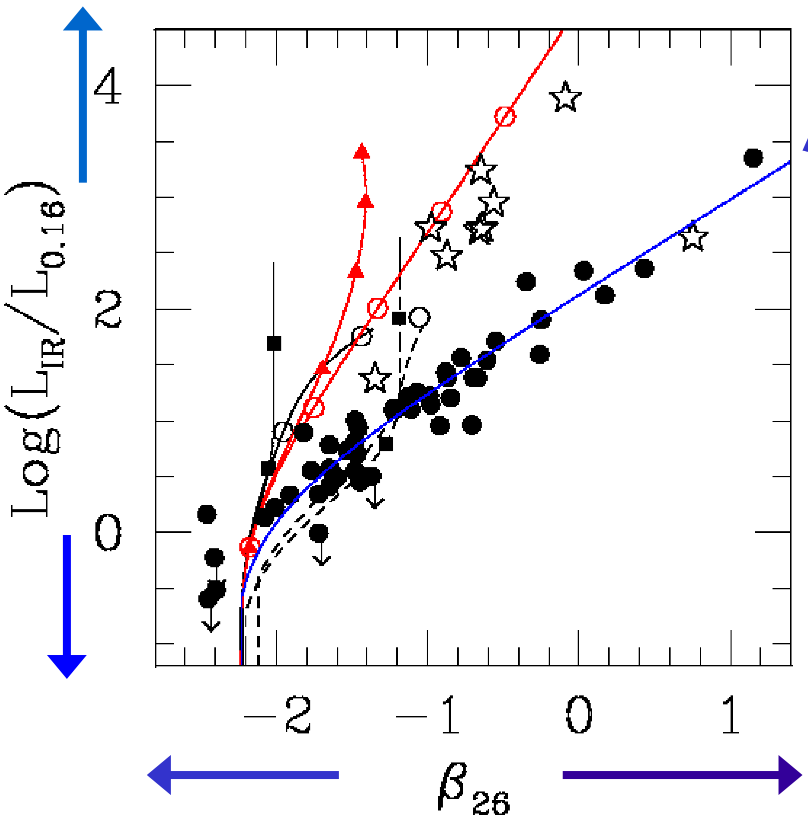
- direct photospheric measure of young massive stars
- primary groundbased SFR tracer for galaxies at z>2

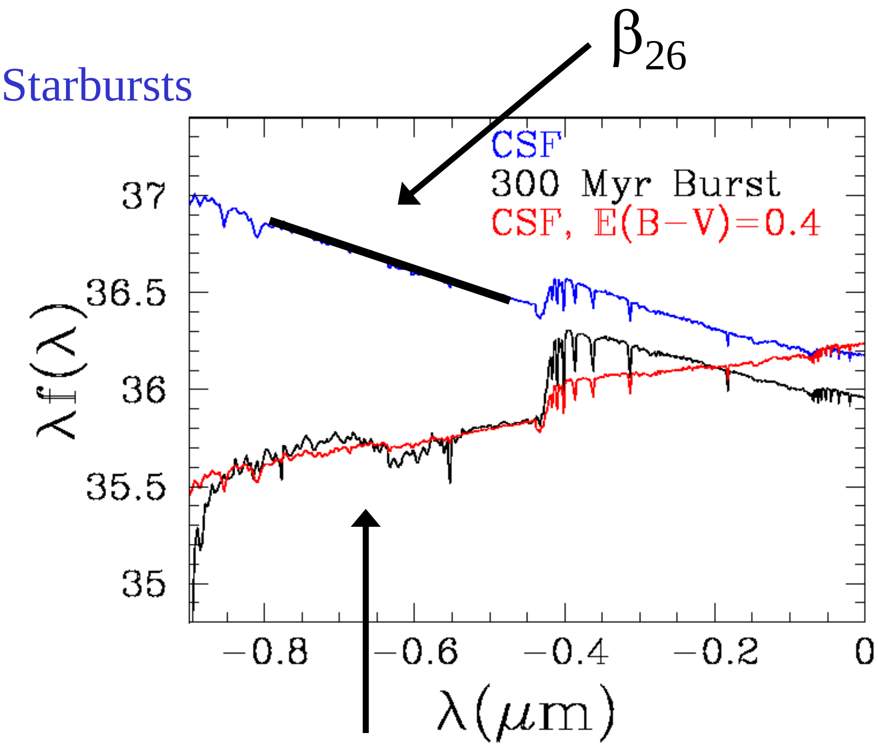


However:

- heavily attenuated by dust. Dust `correction' methods have limits (age-dust degeneracy).
- dependent on the stellar population mix, usually measures timescales of ~100 Myr.

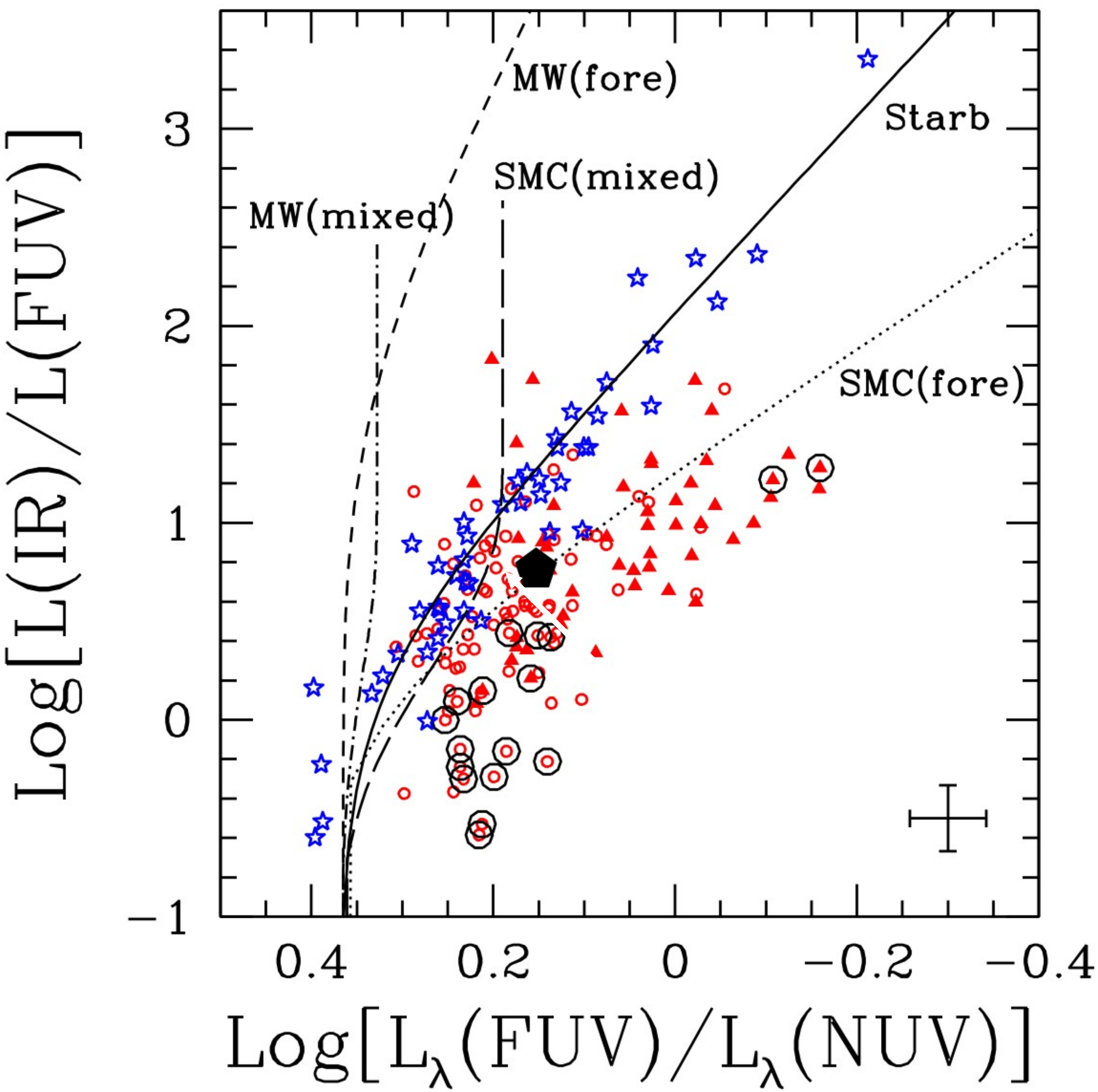
UV, Dust, and Age





A dusty stellar population may have similar UV characteristics of an old population

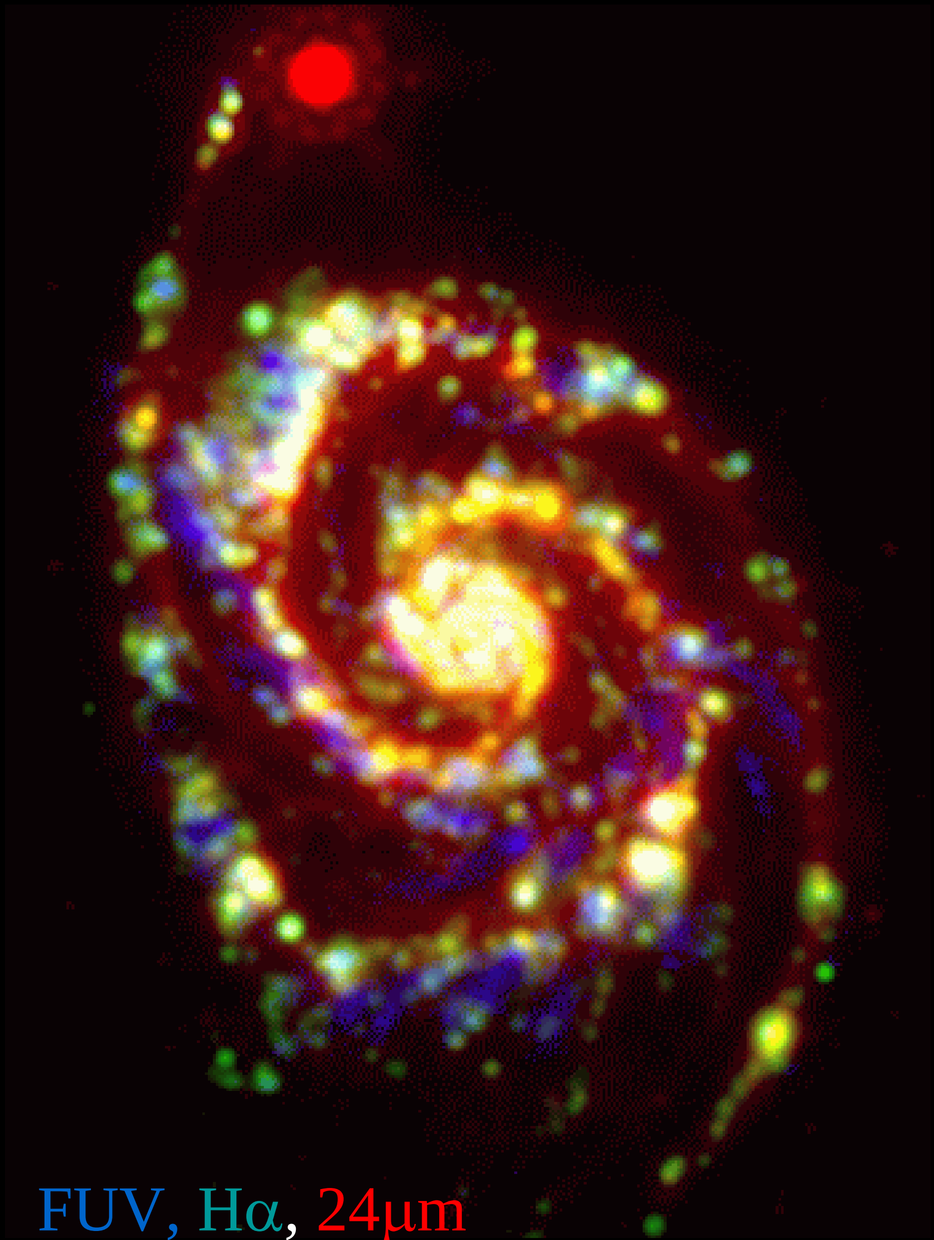
(Calzetti et al. 1994,1995,1996,1997,2000, Meurer et al. 1999, Goldader et al. 2002)



β_{26}

Blue= starbursts
Red= normal SF

M51 Calzetti et al. 2005, ApJ, 633, 871



Photoionization Methods: Emission Lines

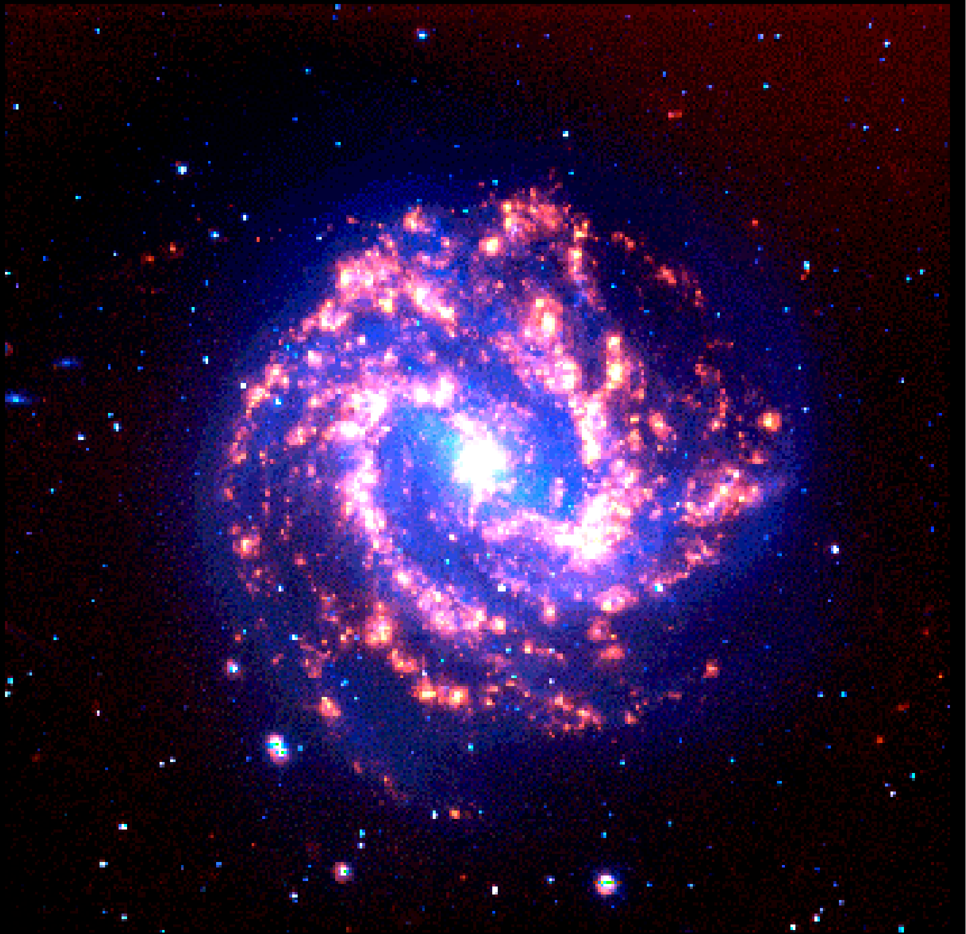
• for ionization-bounded region observed recombination line flux scales with ionization rate

• ionization dominated by massive stars ($M > 10\ M_{o}$), so nebular emission traces SFR in last 3-5 Myr

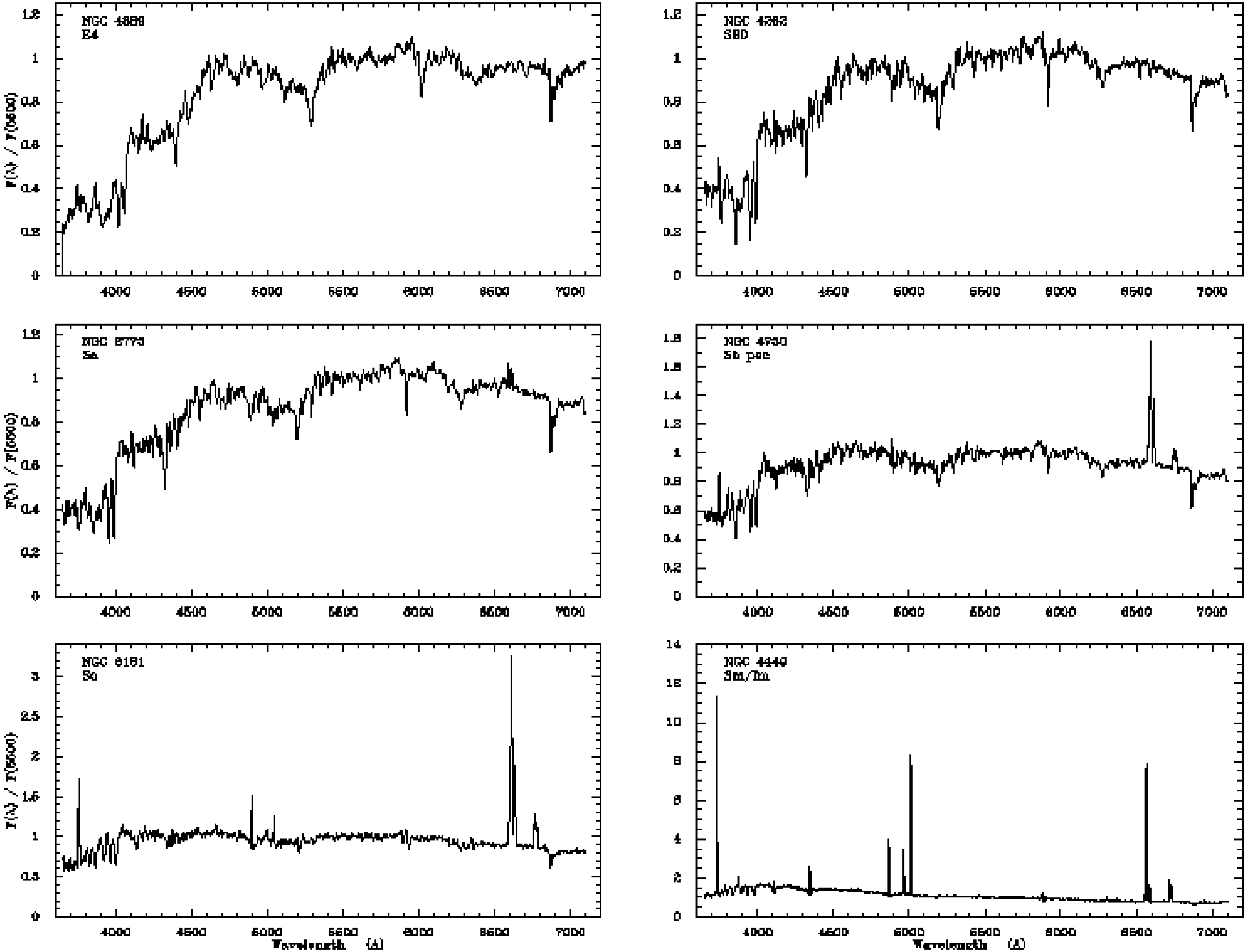
• ionizing UV reprocessed through few nebular lines, detectable to large distances

• only traces massive SFR, total rates sensitive to IMF extrapolation, small number statistics at lowest SFRs

• SFRs subject to systematic errors from extinction, escape of ionizing radiation from galaxy



SINGG survey, G. Meurer et al. (NOAO)



Kennicutt 1992, ApJS, 79, 255

Local Hα Surveys

Survey	N_{gal}	Selection		PI
GOLDMine	277	magnitude	Coma/Virgo	G. Gavazzi
MOSAIC	~1000	Hα	Abell clusters	R. Kennicutt
HαGS	450	mag/volume	field (<40 Mpc)	P. James
SINGG/SUNGG*	468	HIPASS	field (<40 Mpc)	G. Meurer
STARFORM	150	volume	field (<25 Mpc)	S. Hameed
11HUGS/LVL **	470	volume	field (<11 Mpc)	R. Kennicutt
AMIGA	~270	magnitude	isolated field	L. Montenegro
SINGS **	75	multi-param	<30 Mpc	R. Kennicutt
SMUDGES	~1000	mag	field dwarfs	L. van Zee
UCM	376	obj prism	field	J. Gallego
KISS	~2200	obj prism	field	J. Salzer

* paired GALEX survey ** paired GALEX+Spitzer survey

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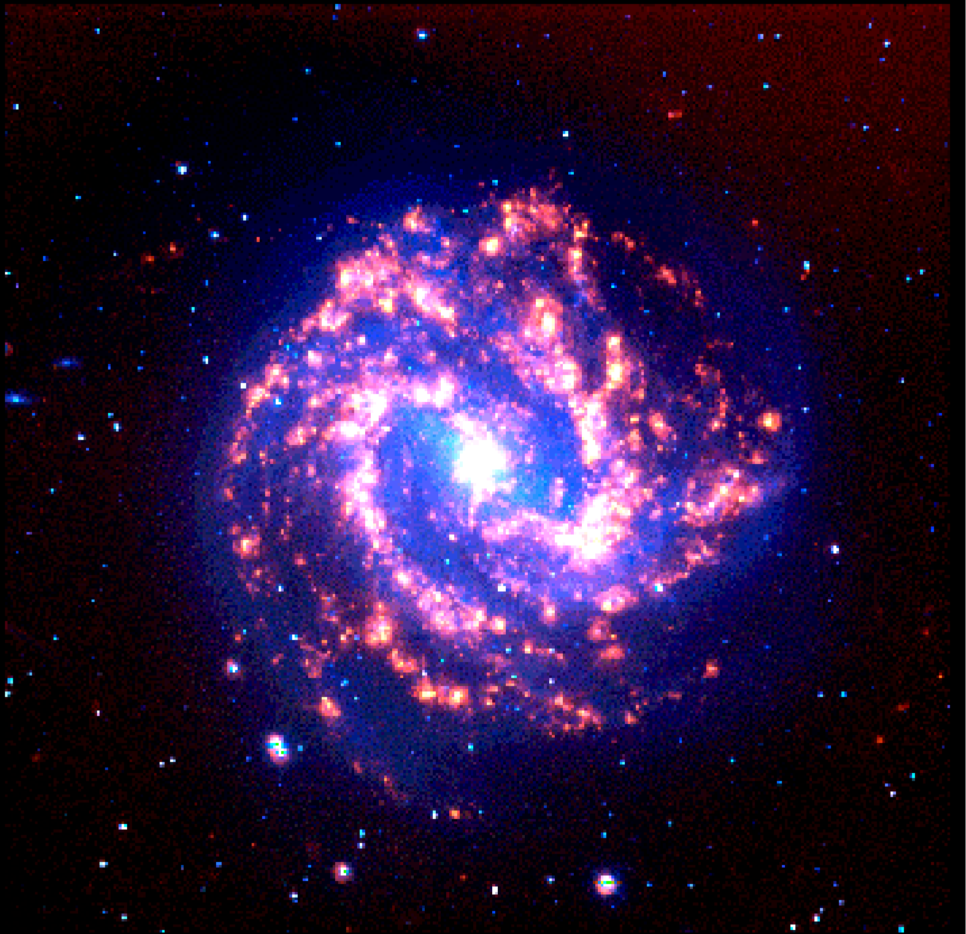
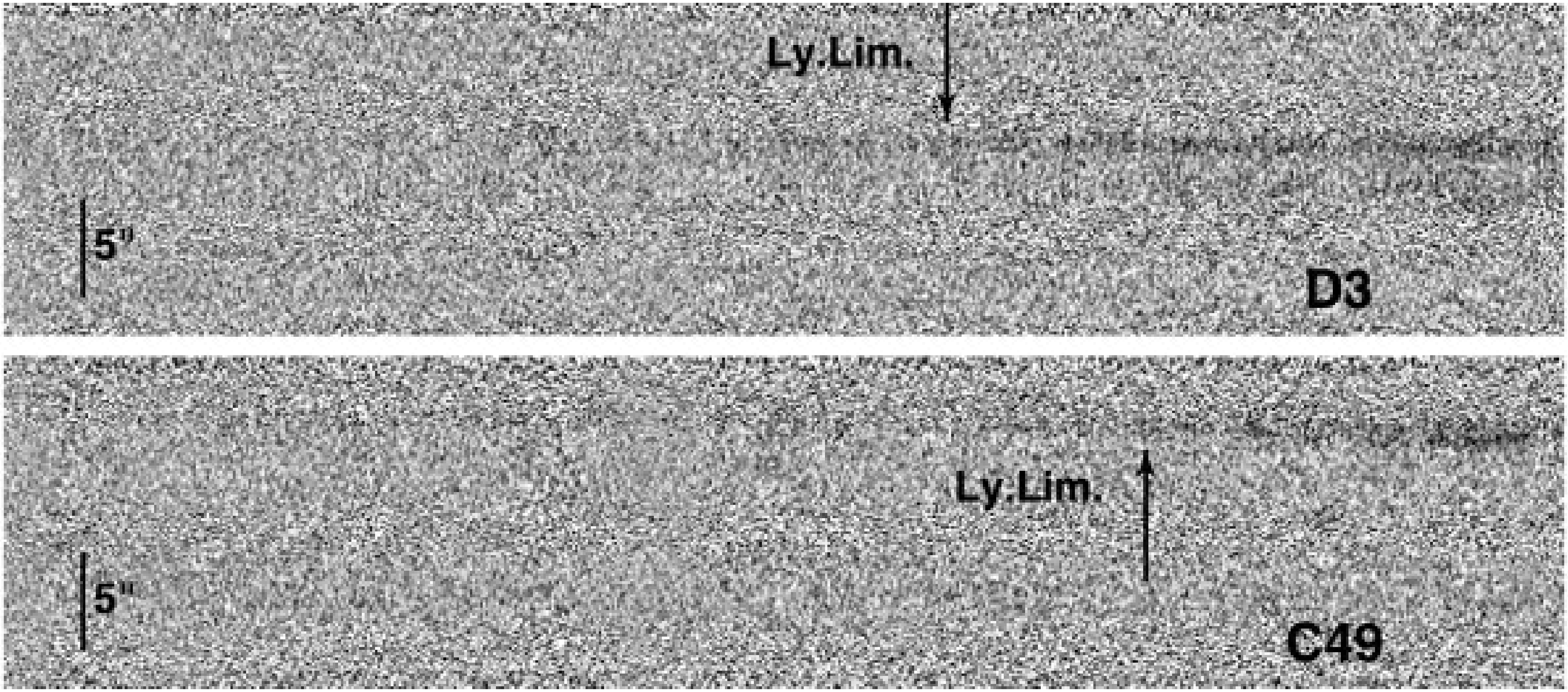


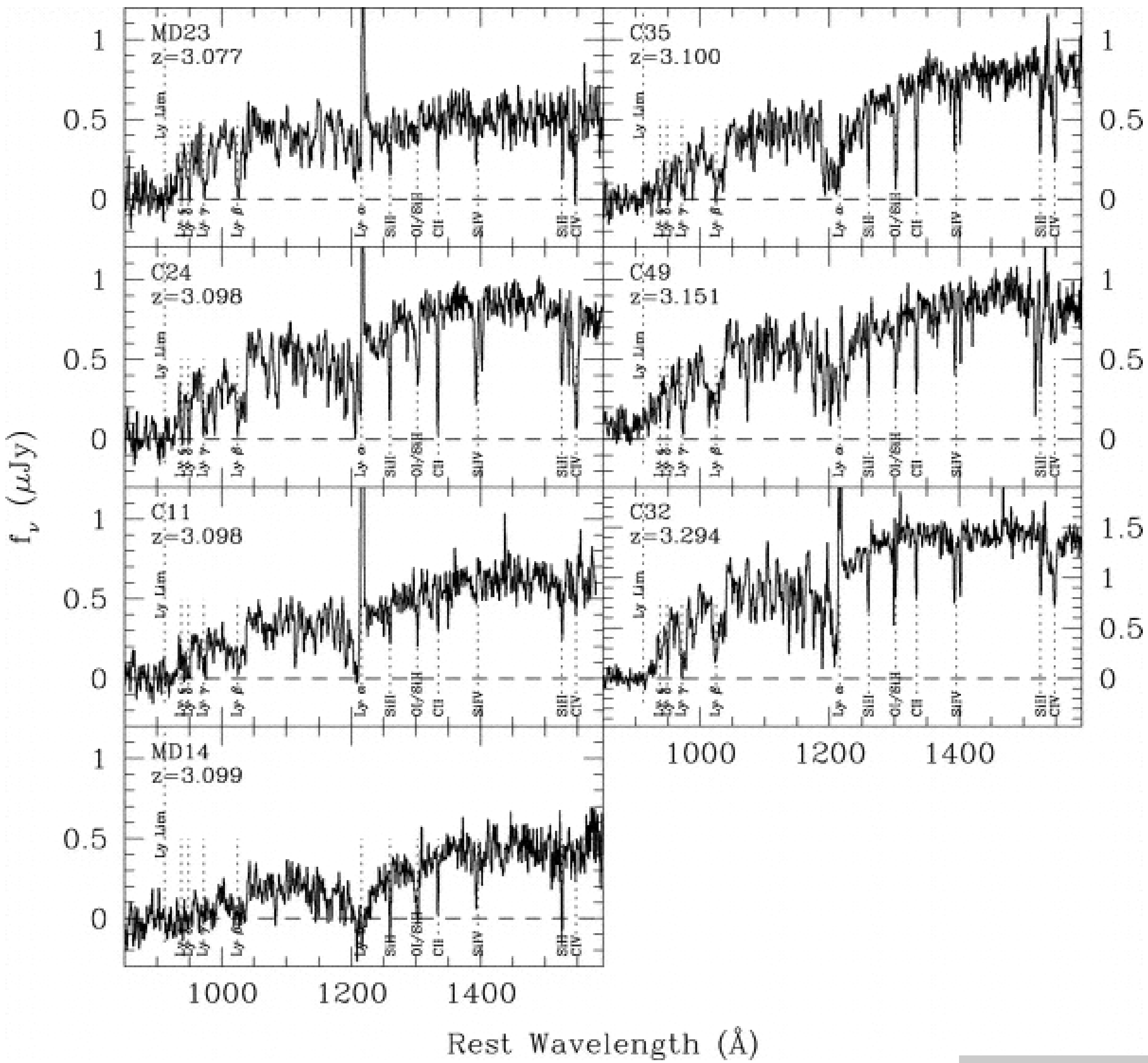
SINGG survey, G. Meurer et al. (NOAO)

Leakage of Ionizing Flux at z ~ 3

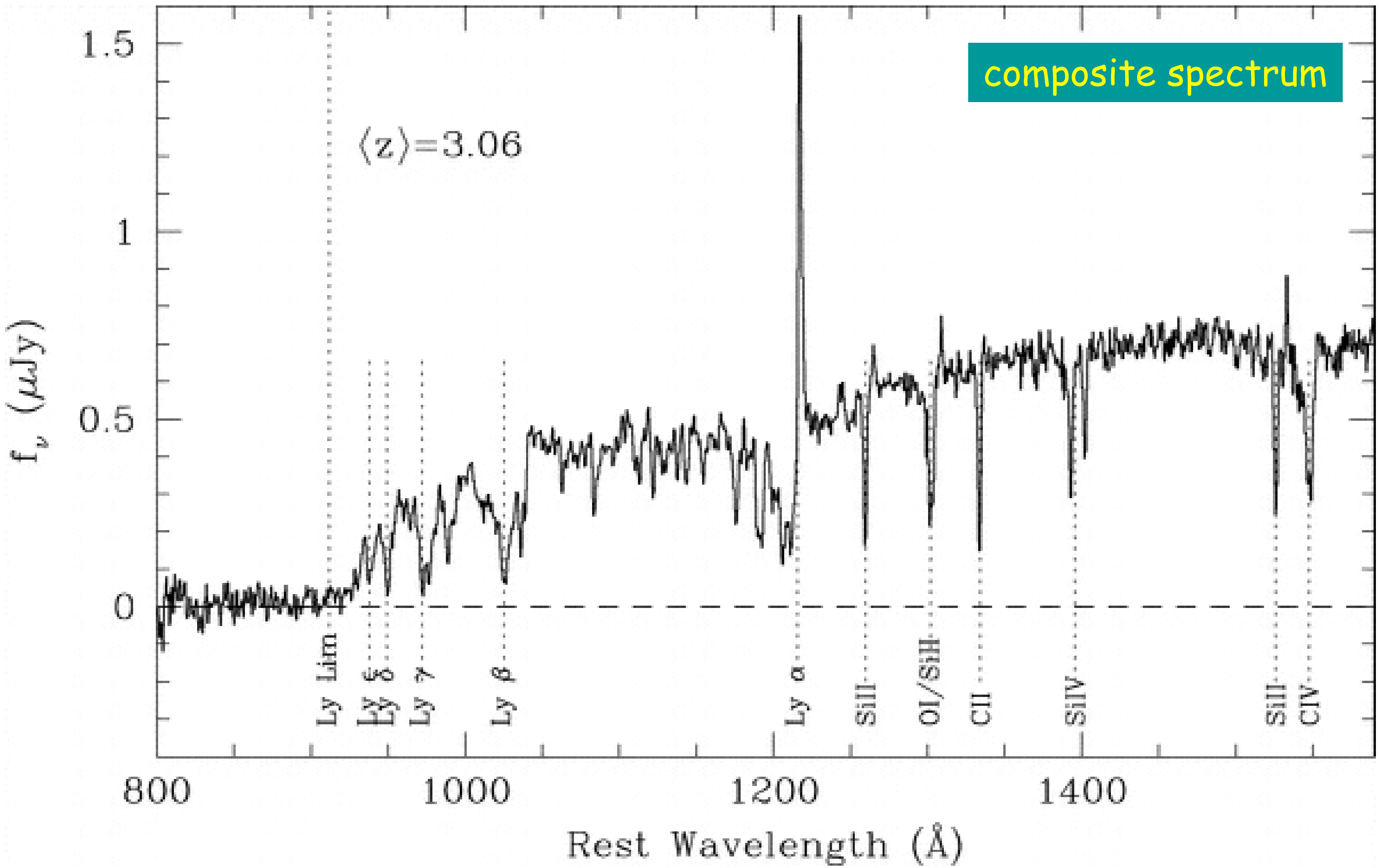


Shapley et al. 2006, ApJ, 651, 688

Leakage of Ionizing Flux at z ~ 3



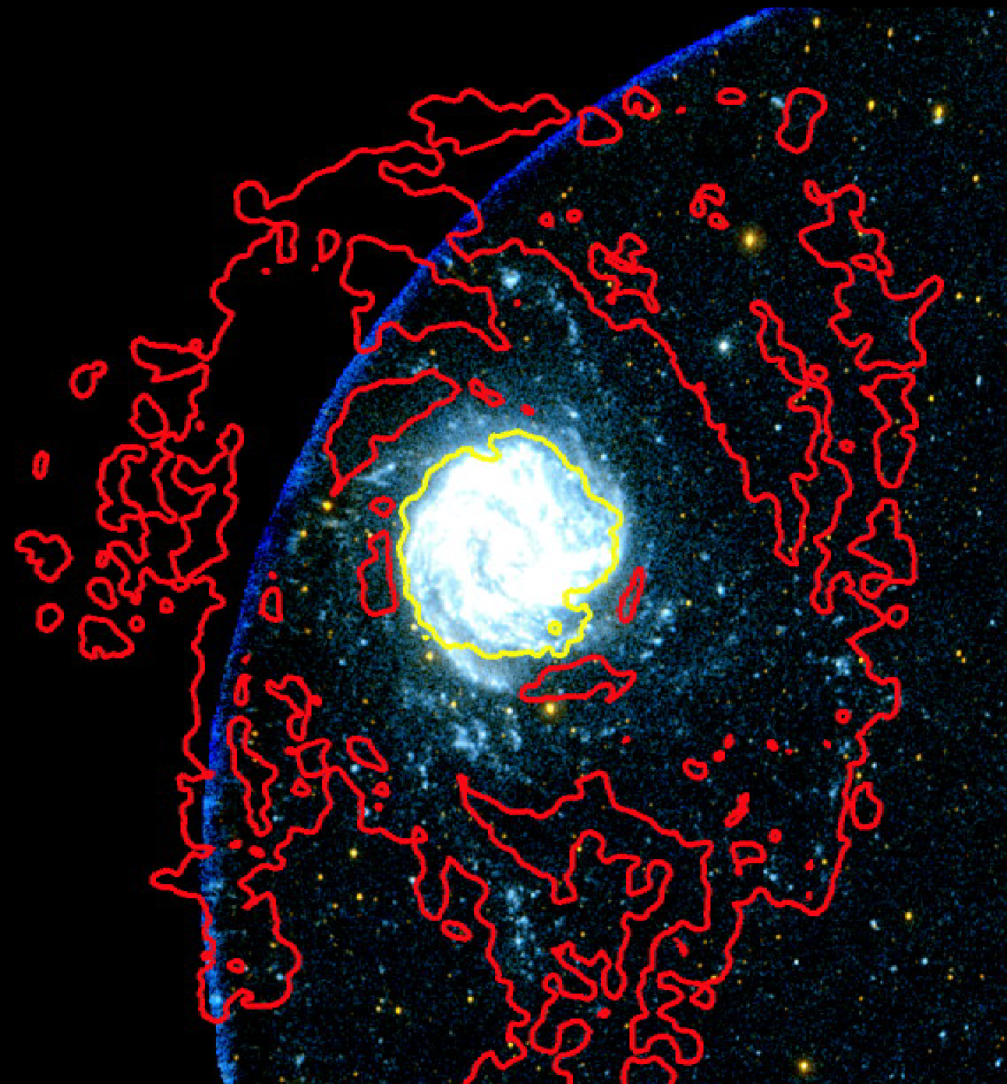
Shapley et al. 2006, ApJ, 651, 688



Shapley et al. 2006, ApJ, 651, 688

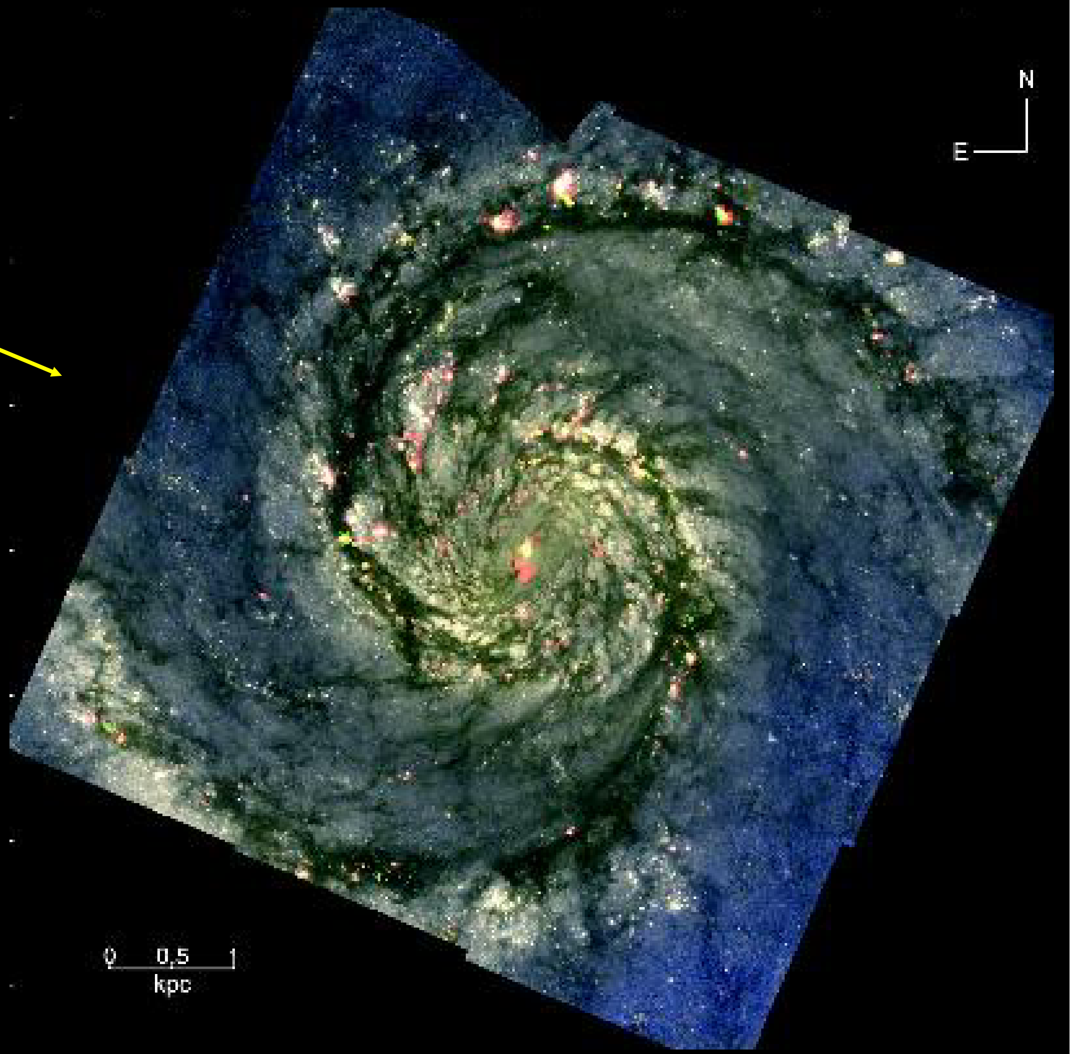
11 Mpc Ha/Ultraviolet Survey (11HUGS)

SINGG: Survey for Ionization in Neutral-Gas Galaxies

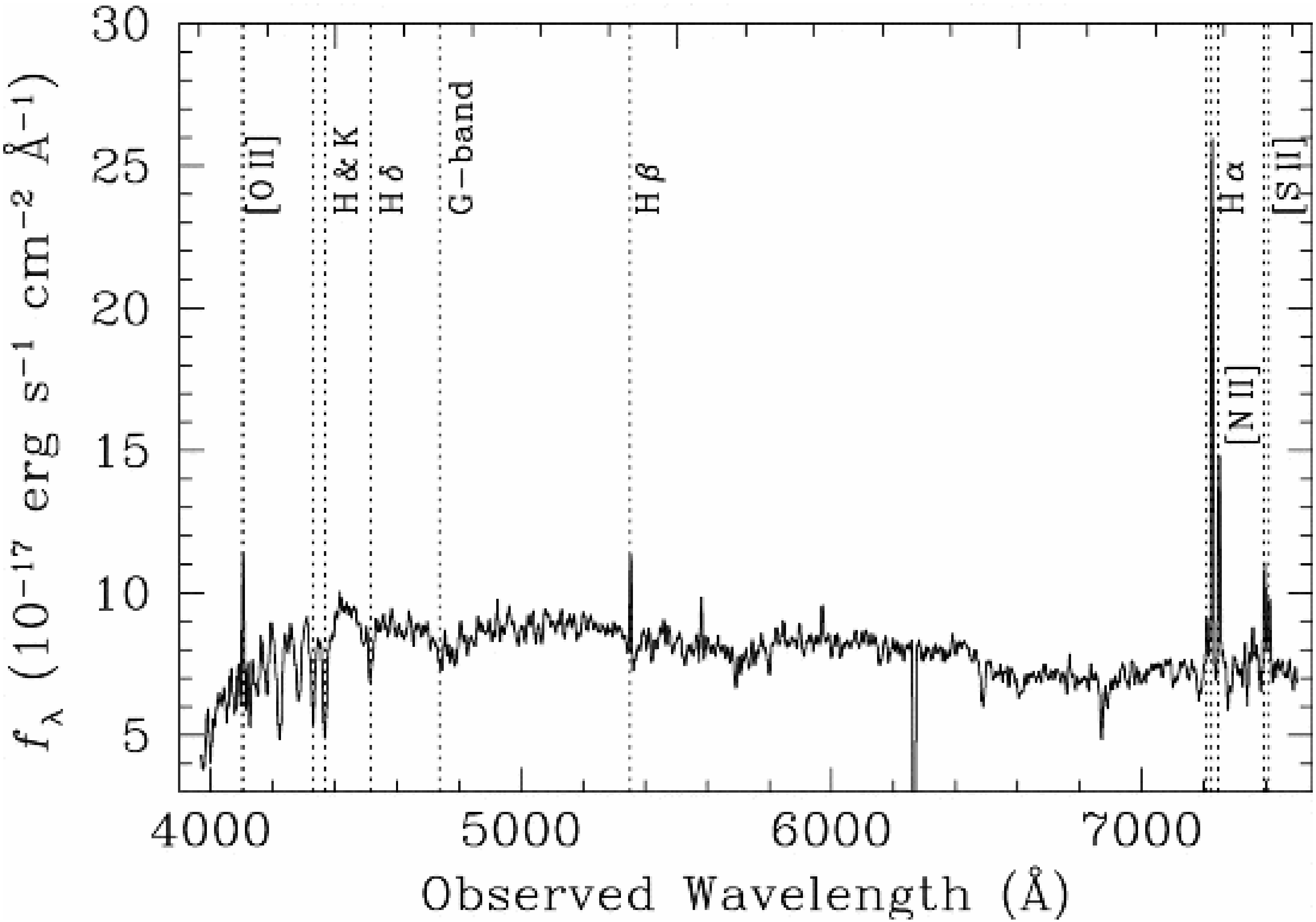


Other Emission Lines

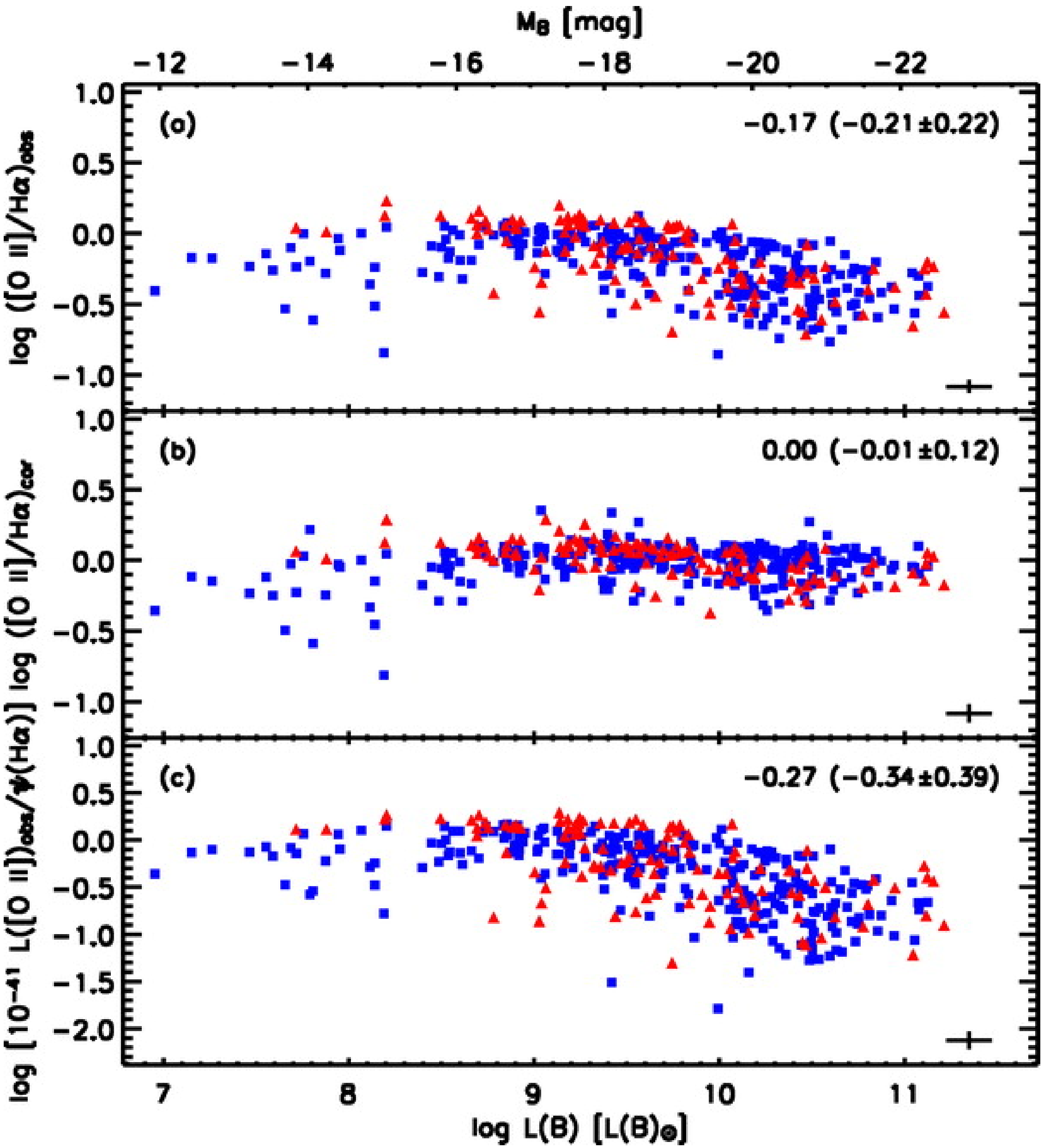
- Hβ (0.48 μm)
- Paschen-α (1.9 μm)
- Brackett-γ (2.2 μm)
- [OII] (0.37 μm)
- Lyman-α (0.12 μm)



Scoville et al. 2000, AJ, 122, 3017



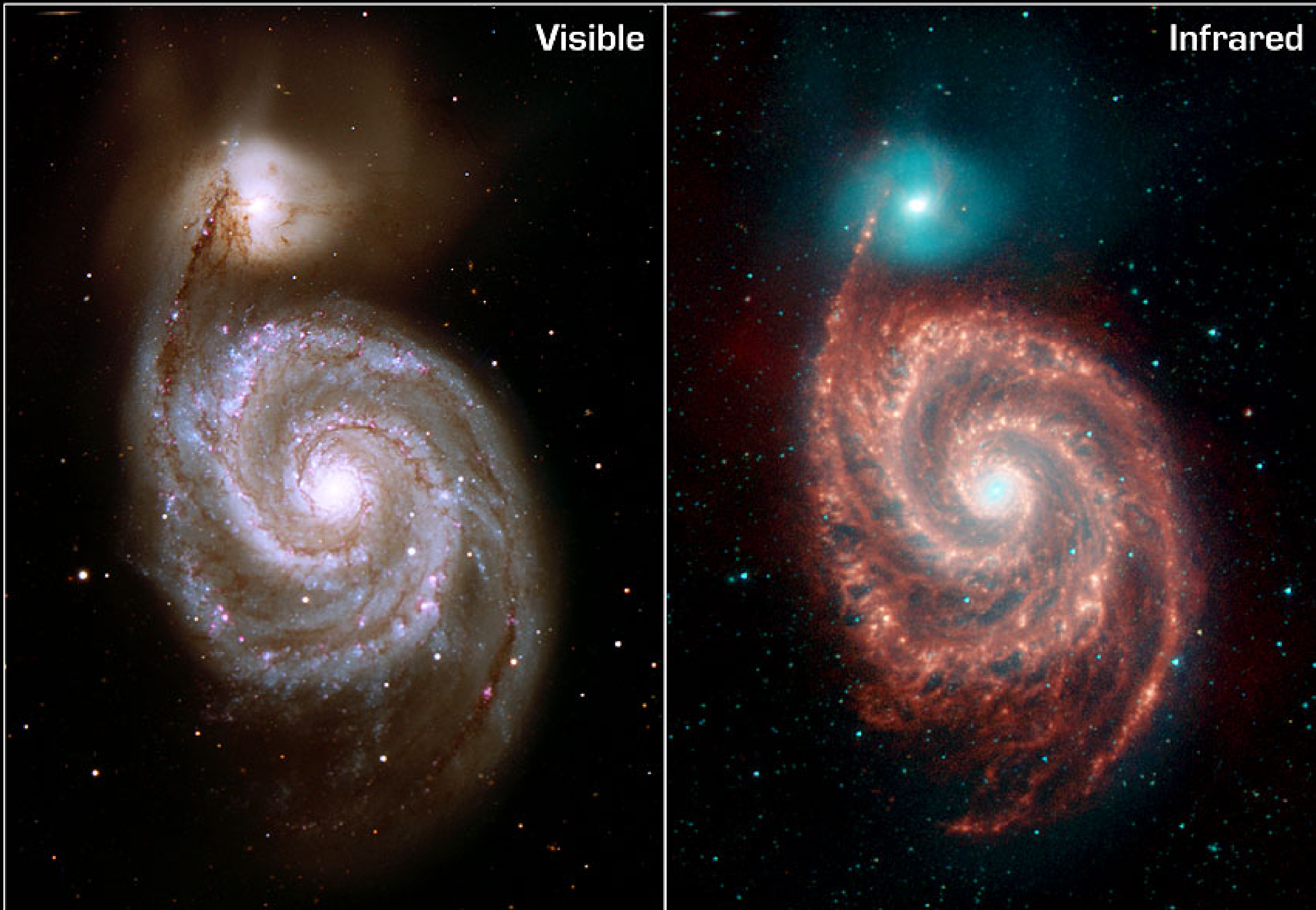
30
25
20
15
10
5
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
[O II]
H & K
H δ
G–band
H β
H α
[N II]
[S II]
4000
5000
6000
7000
Observed Wavelength (Å)



Moustakas, Kennicutt, Tremonti 2006, ApJ, 642, 775

Dust Emission

- Interstellar dust absorbs ~50% of starlight in galaxies, re-radiates in thermal infrared (3–1000 μm)
- Provides near-bolometric measure of SFR in dusty starbursts, where absorbed fraction ~100%
- Largest systematic errors from non-absorbed star formation and dust heated by older stars
- Different components of IR trace distinct dust species and stellar sub-populations

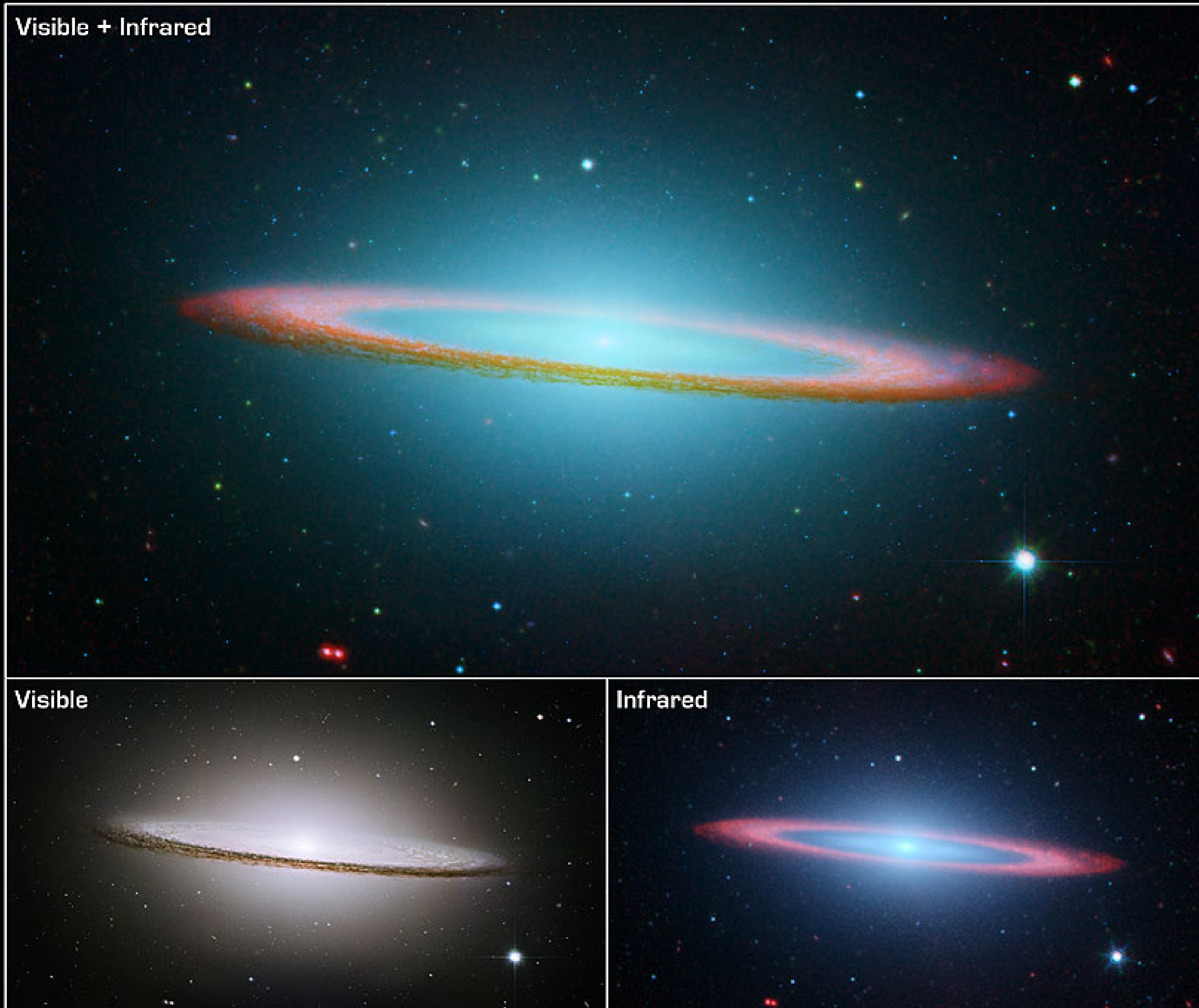


Spiral Galaxy M51 (“Whirlpool Galaxy”)

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

ssc2004-19a



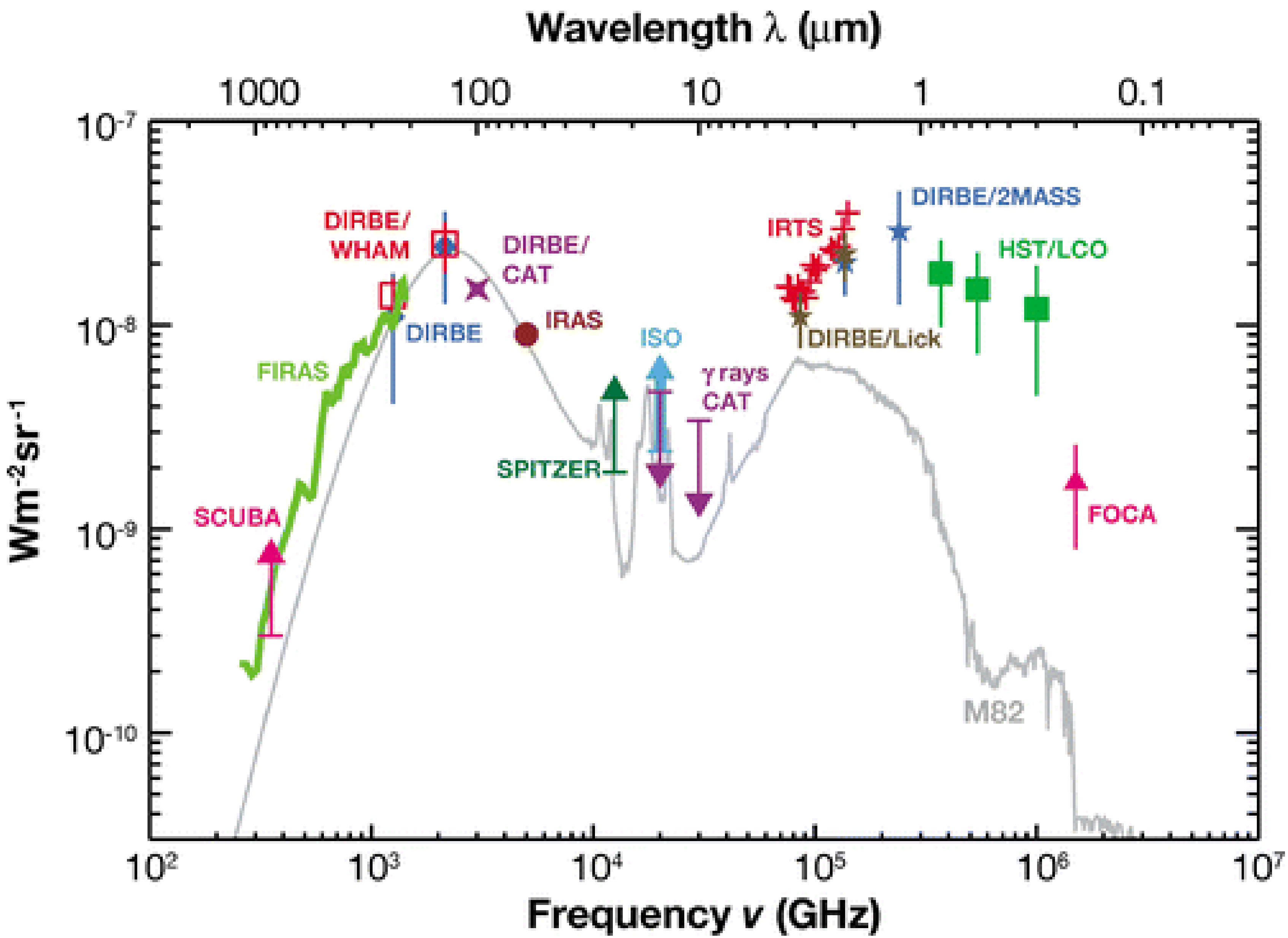
Sombrero Galaxy/Messier 104

Spitzer Space Telescope • IRAC

Visible: Hubble Space Telescope/Hubble Heritage Team

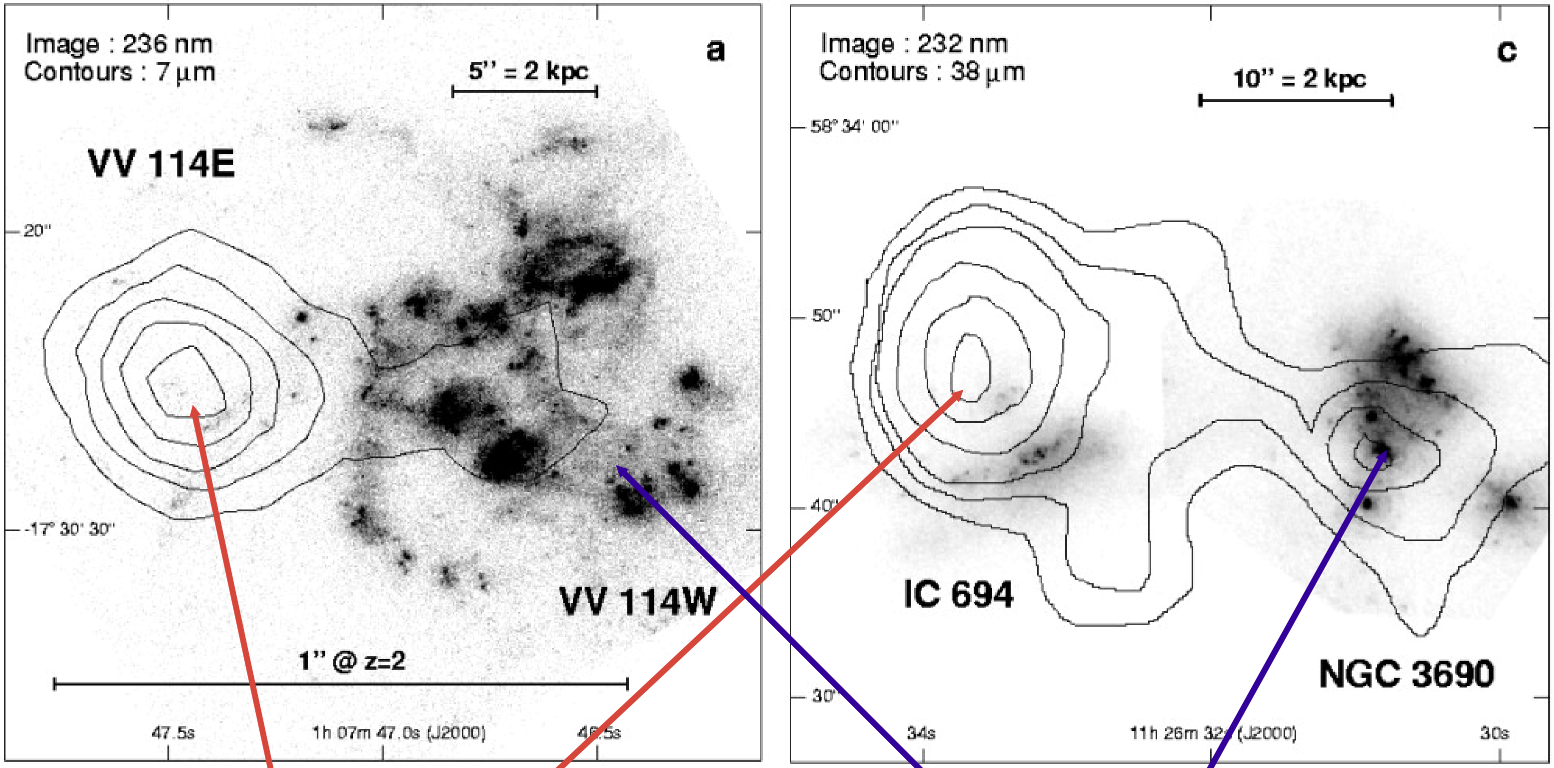
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team

ssc2005-11a



Lagache, G et al. 2005
Annu. Rev. Astron. Astrophys. 43: 727–68

Luminous Infrared Galaxies (interacting pairs)

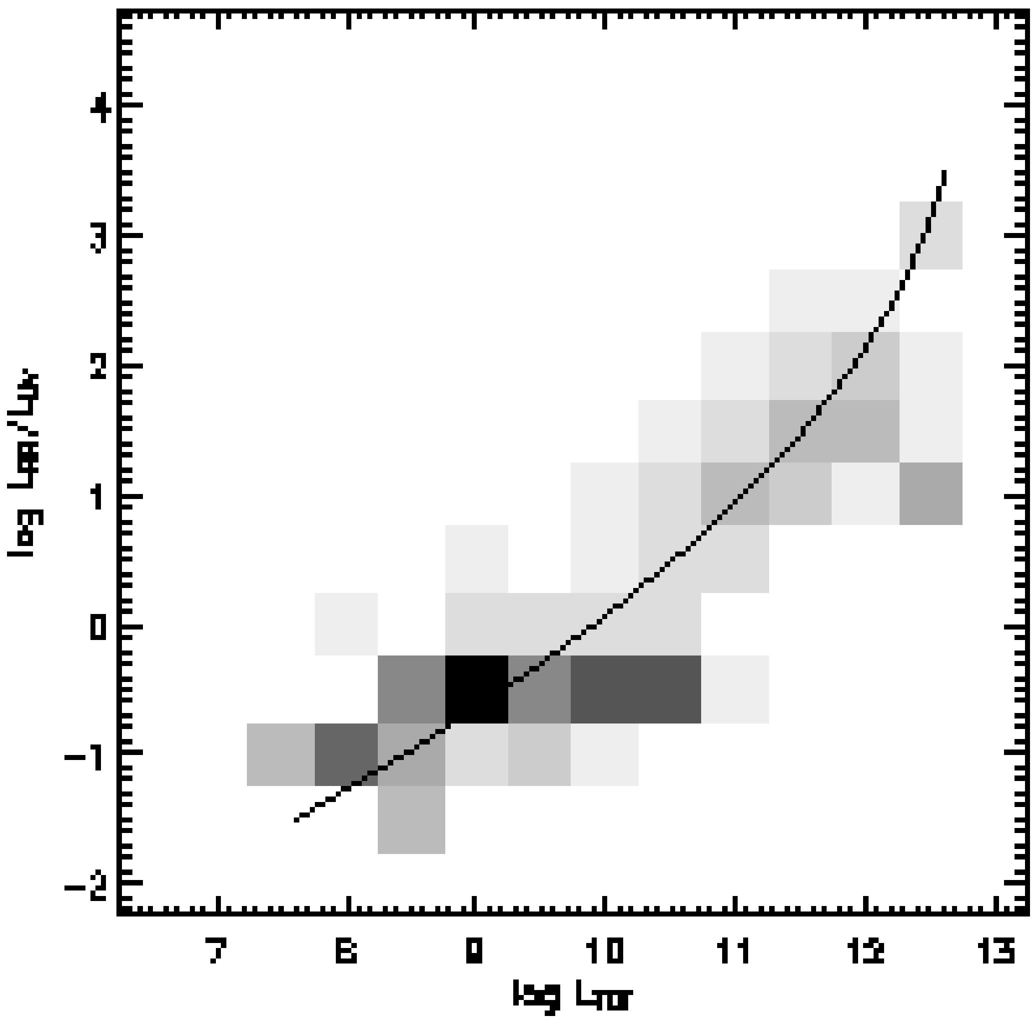


infrared contours

UV images

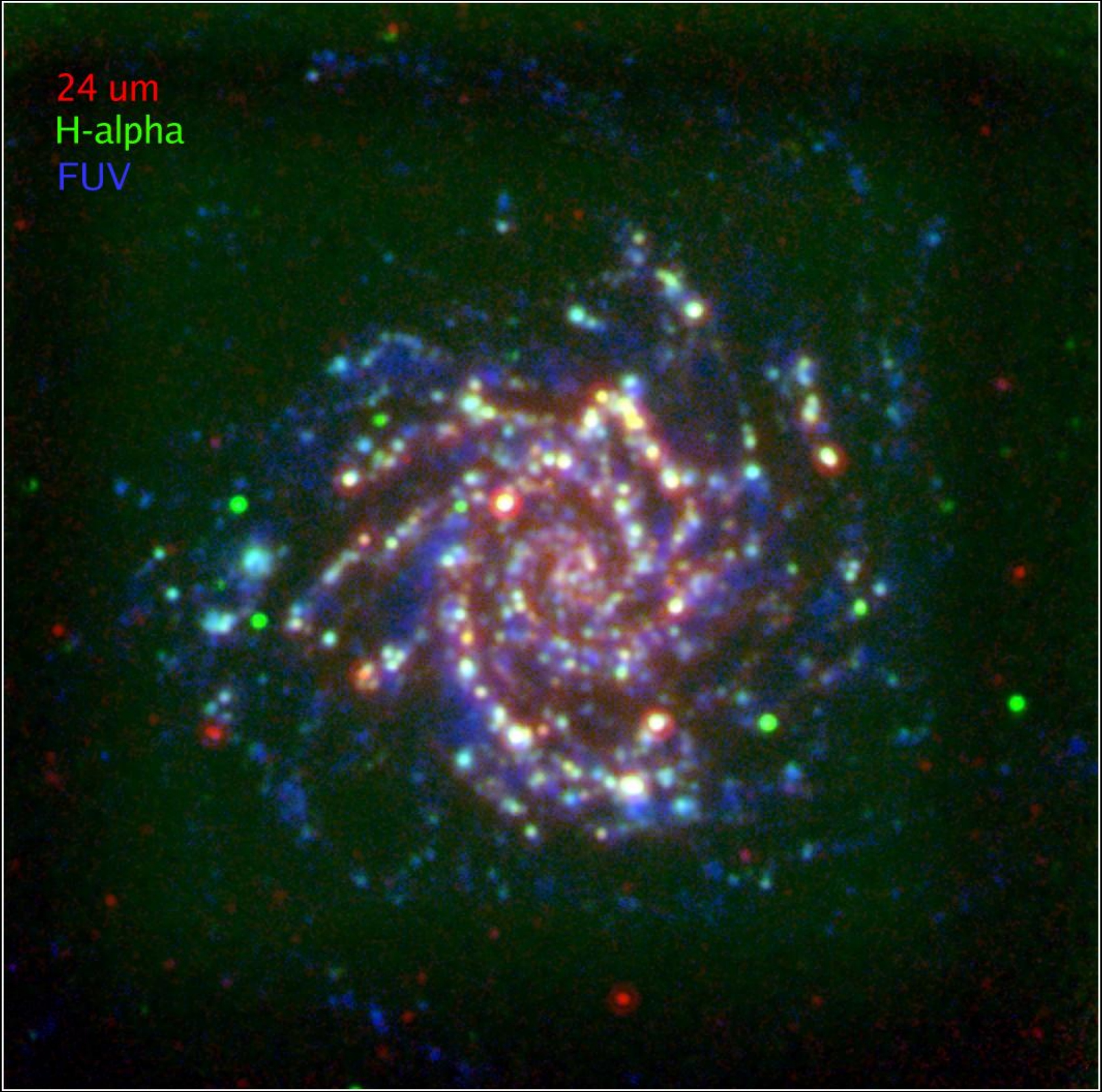
Charmandaris et al. 2004, ApJ, L15

FIR observations probe the most luminous star-forming galaxies, with SFR >> SFR* (>>10 M_o/yr at present epoch).



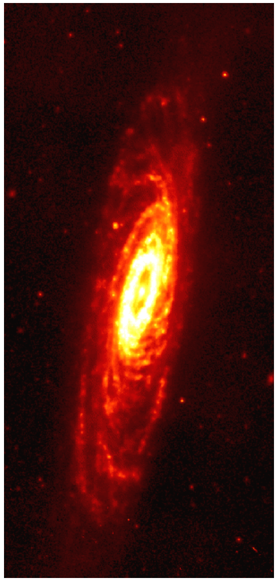
Martin et al. 2005, ApJ, 619, L59

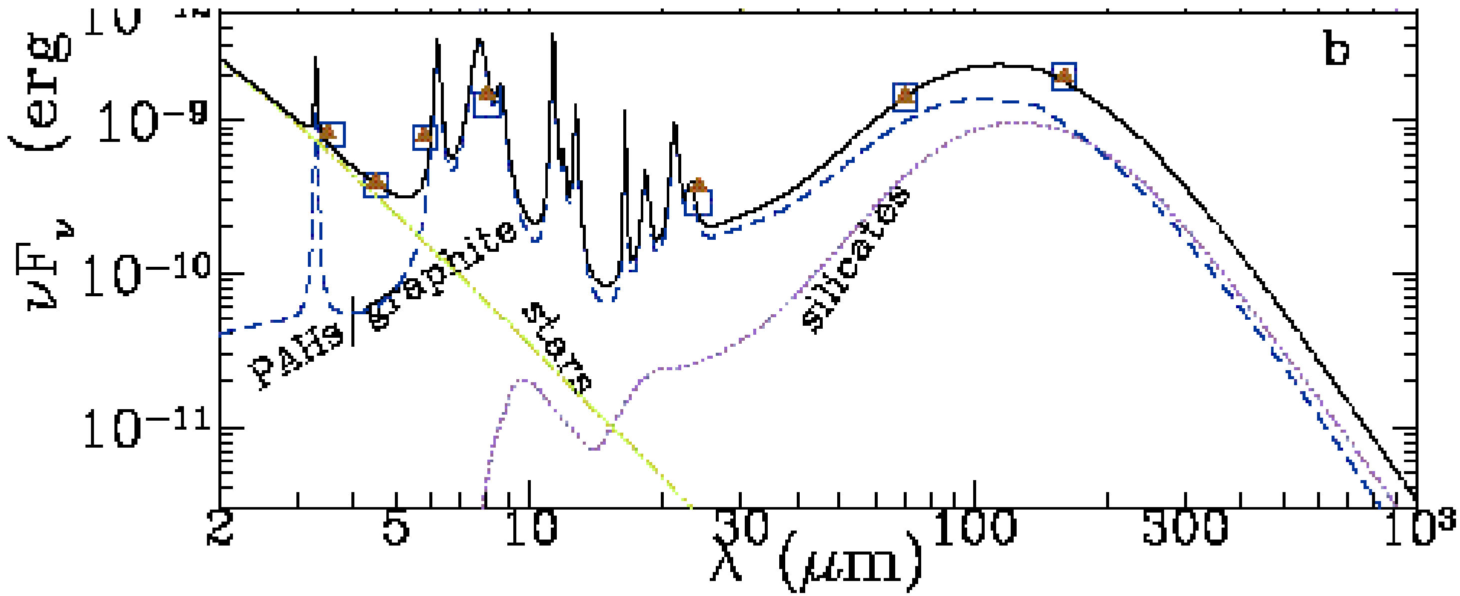
NGC 628 (M74)

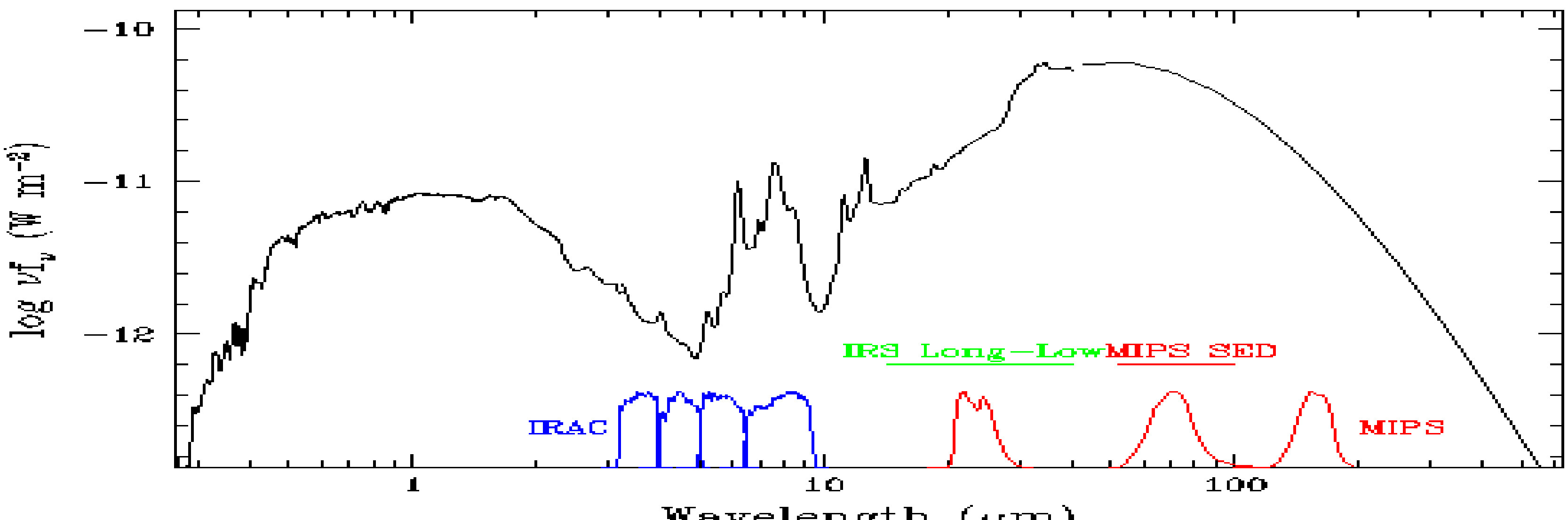


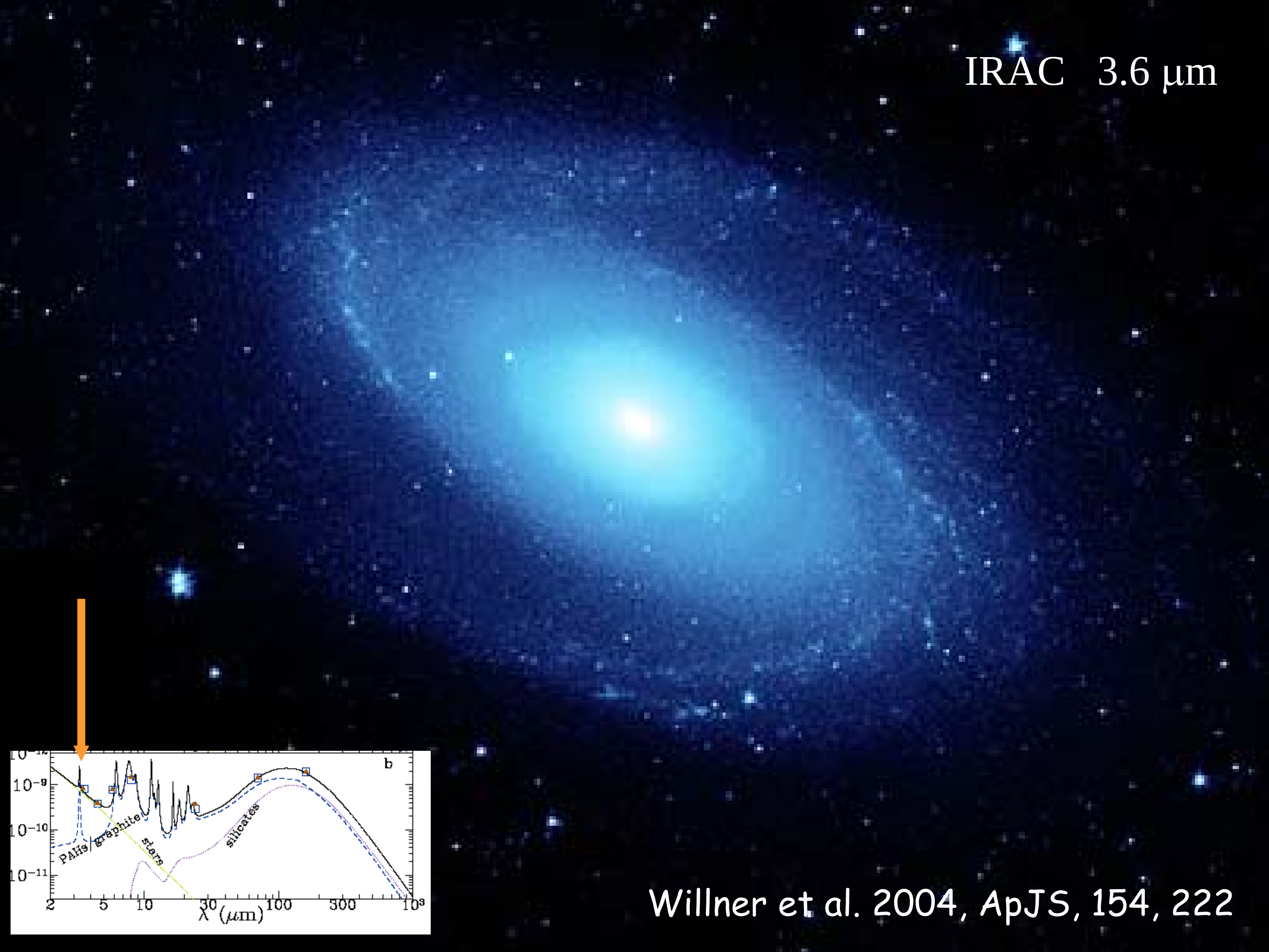
C. Tremonti

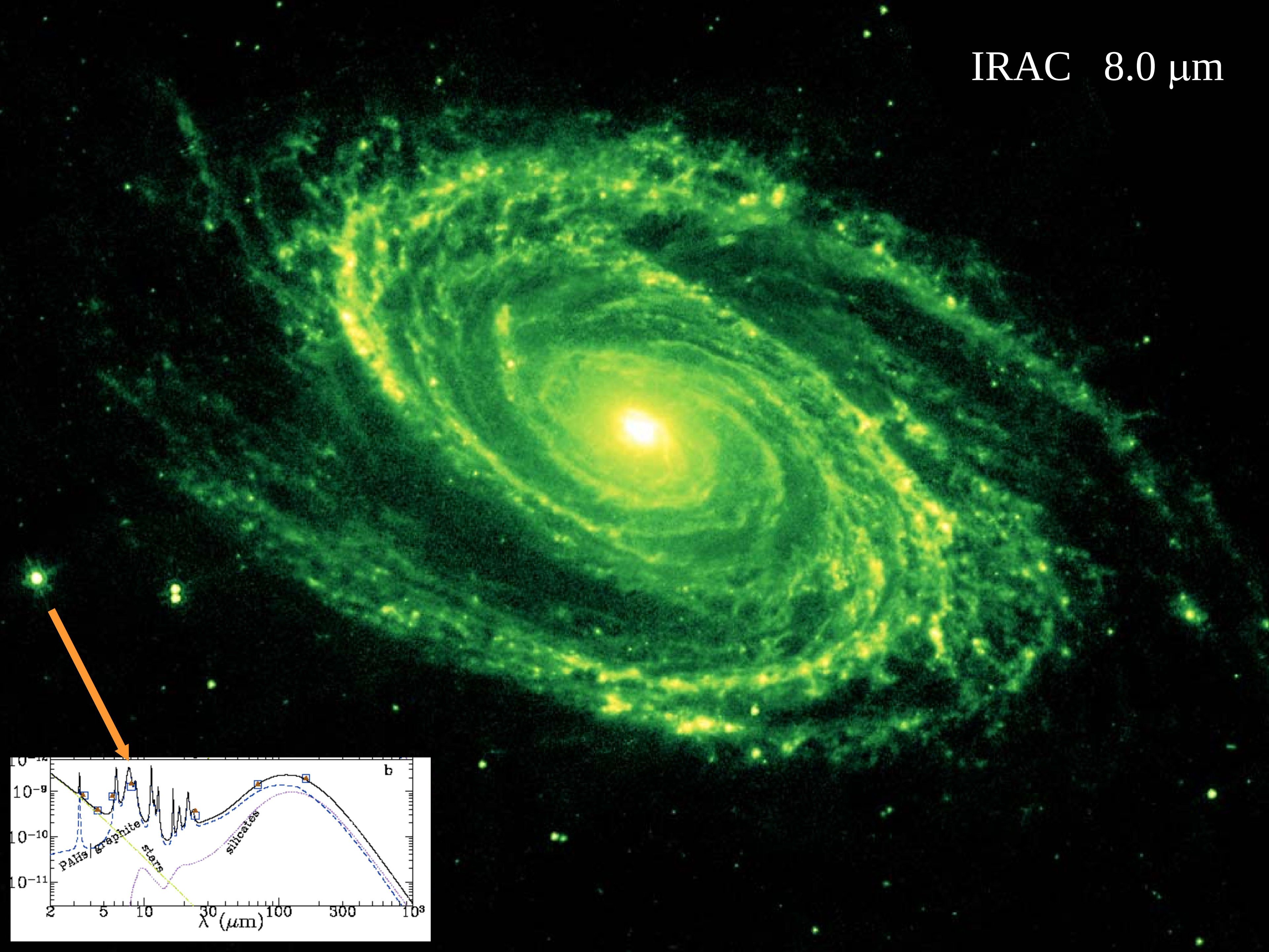
NGC 7331: Regan et al. 2004, ApJS, 154, 204





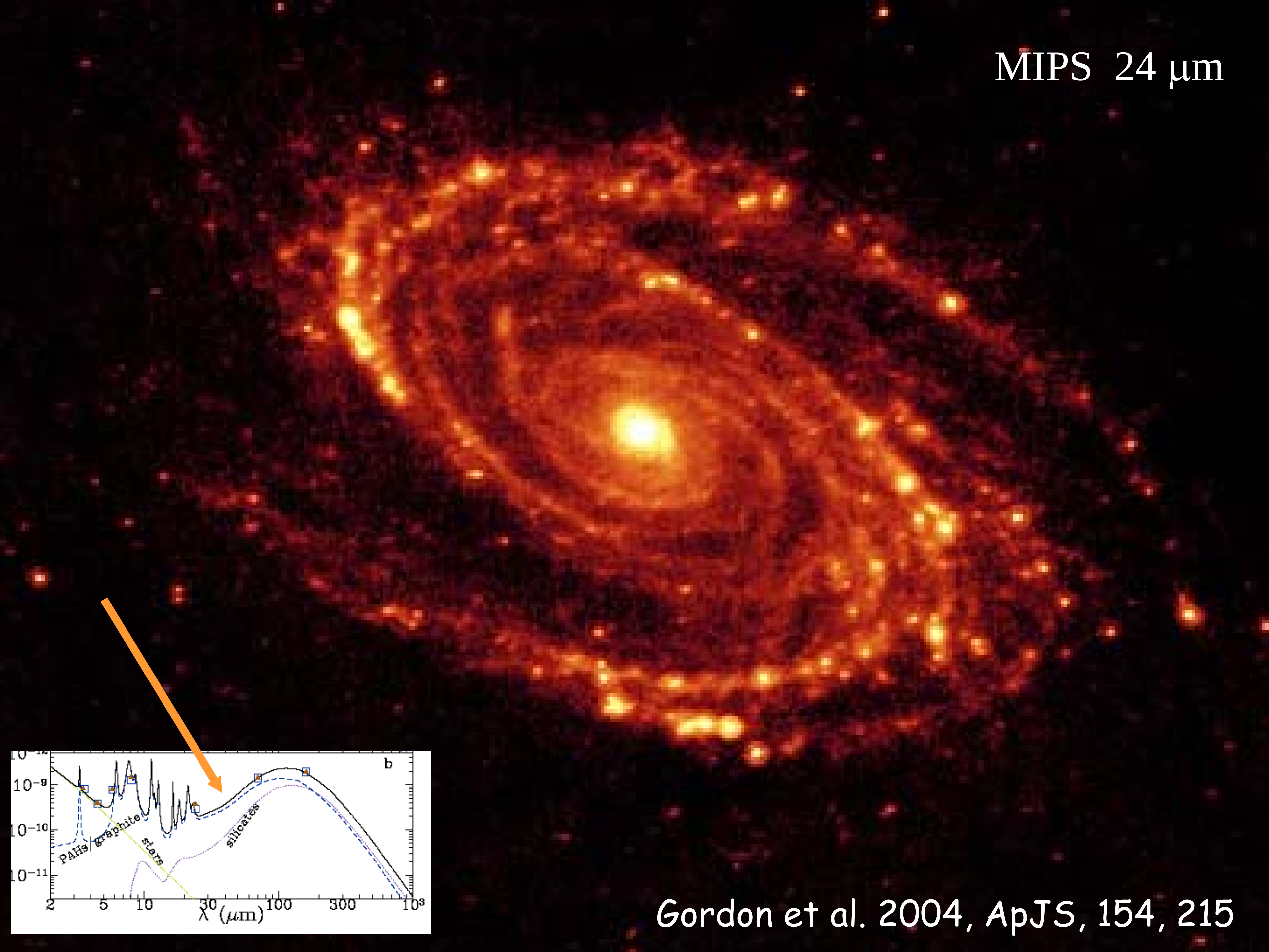



IRAC 3.6 μm
b
10^-9
10^-10
10^-11
PAHs/graphite
stars
silicates
2
5
10
30
100
300
10^3
λ (μm)
Willner et al. 2004, ApJS, 154, 222

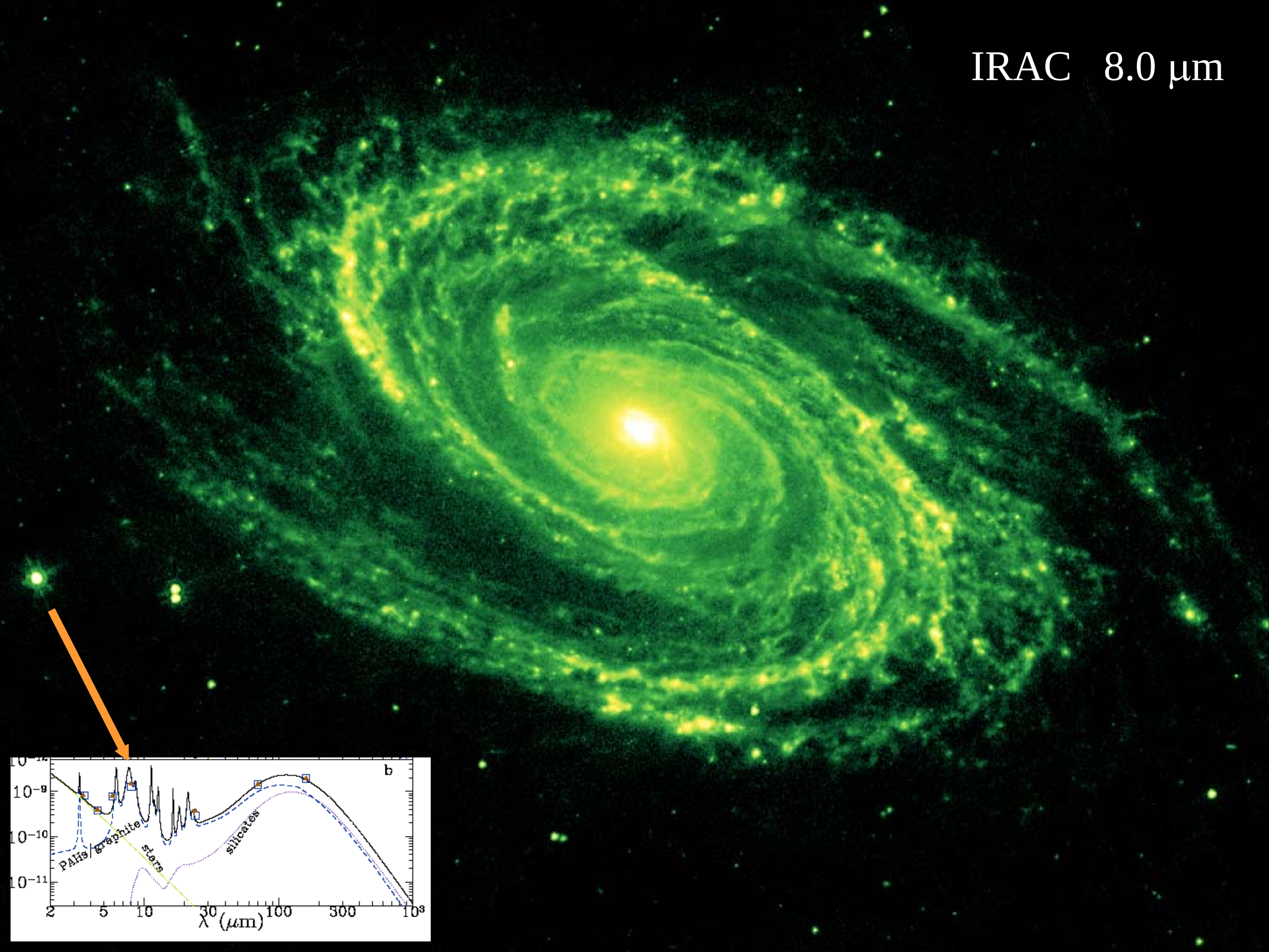

IRAC 8.0 μm
b
PAHs/graphite
stars
silicates
10^{-9}
10^{-10}
10^{-11}
2
5
10
30
100
300
10^3
λ (μm)


Visible (NOAO)


Infrared IRAC + MIPS

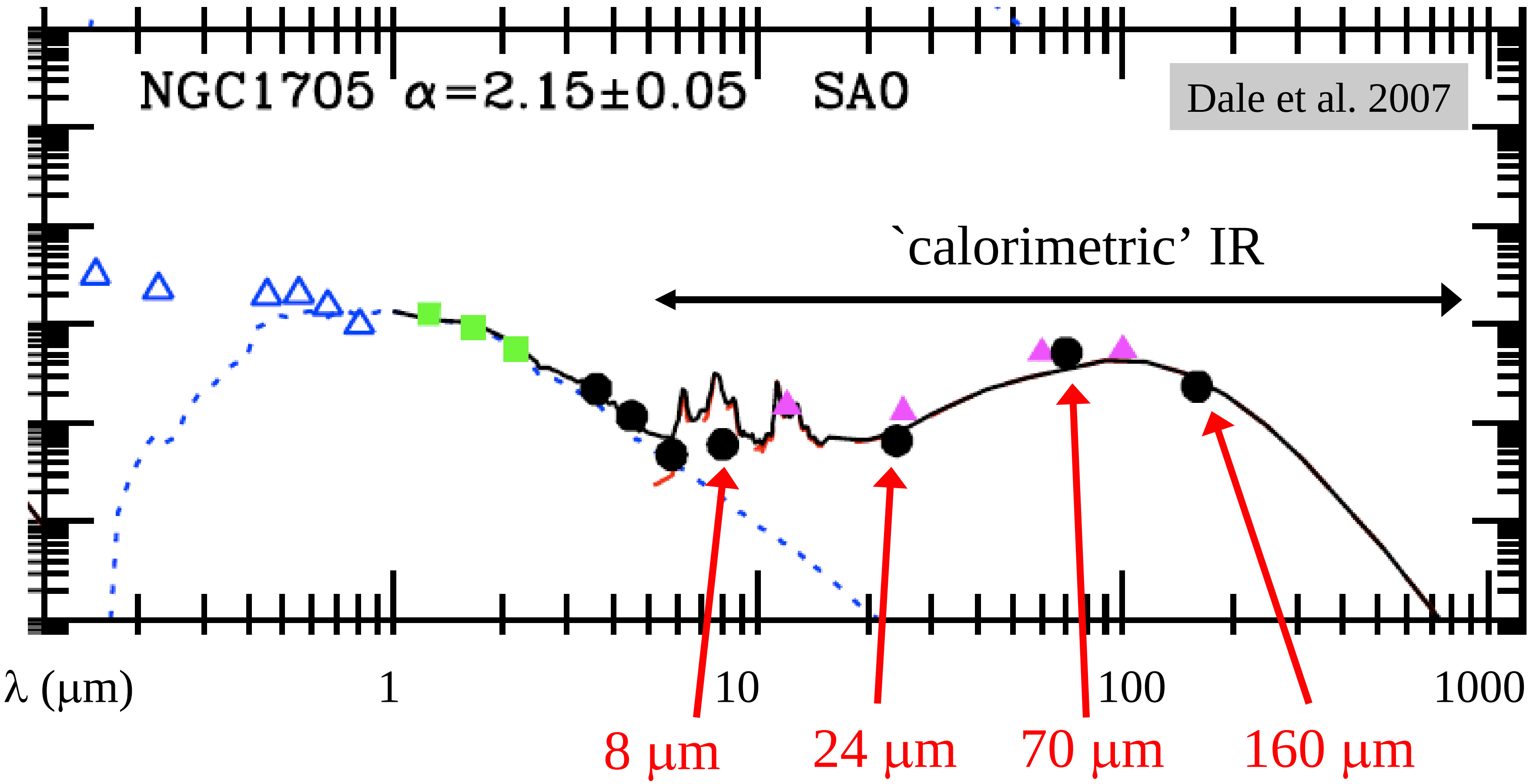


Gordon et al. 2004, ApJS, 154, 215



IRAC 8.0 μm
b
PAHs/graphite
stars
silicates
λ (μm)

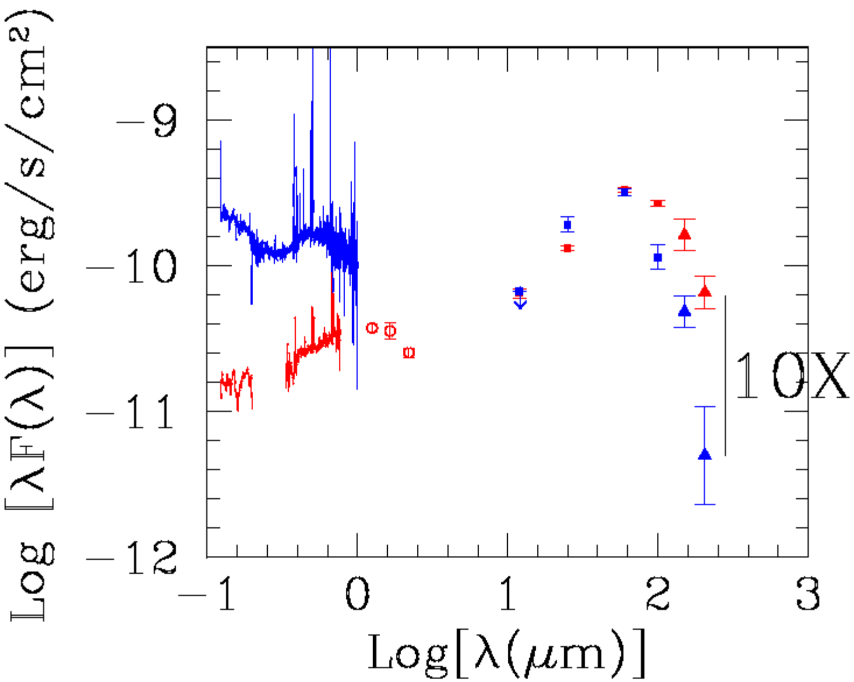
FIR to SFR?



FIR - sensitive to heating from old stellar populations
8 μm - mostly single photon heating (PAH emission)
24 μm - both thermal and single photon heating
70 μm and 160 μm - mostly thermal, also from old stars

SFR (FIR)

- Idea around since IRAS times (e.g., Lonsdale & Helou 1987): SFRs from bolometric IR emission
- Depending on luminosity, bolometric IR may be measuring star formation or old stars' heating
- FIR SEDs depend on dust temperature (stellar field intensity; Helou 1986); problematic if wavelength coverage is not complete.

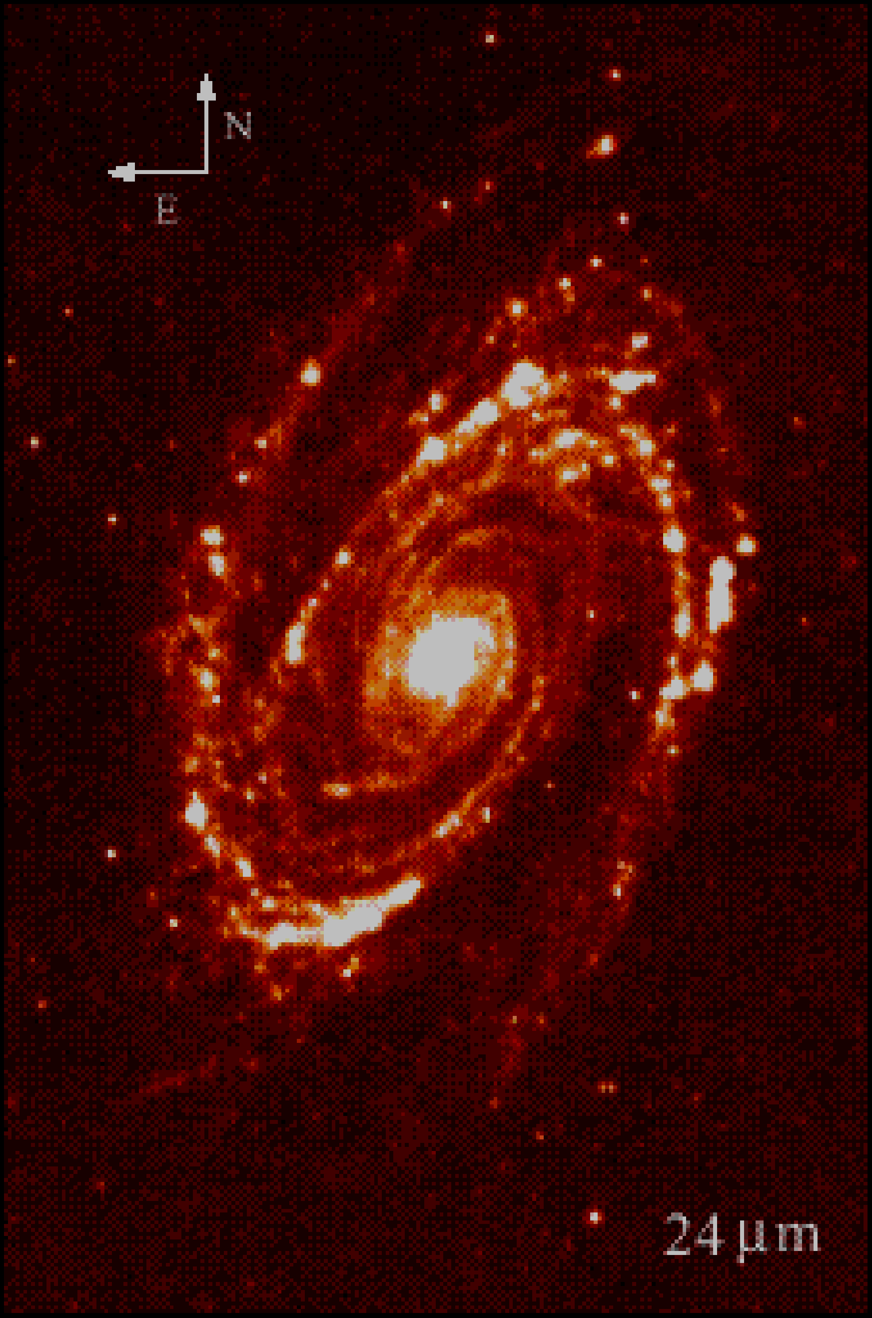


Higher SFR (stellar radiation field intensity) ~ higher dust `temperature'

SFR(8 μm, 24 μm)

- ISO provided ground for investigating monochromatic IR emission as SFR tracers, esp. UIB=AFE=(?)PAH (e.g., Madden 2000, Roussel et al. 2001, Boselli et al. 2004, Forster-Schreiber et al. 2004, Peeters et al. 2004, Tacconi-Garman et al. 2005).

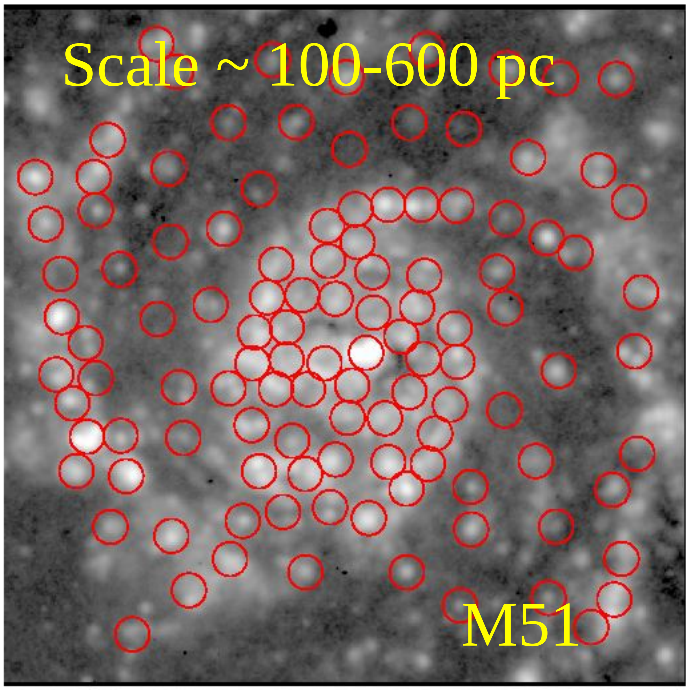
- Spitzer has opened a `more sensitive' window to the distant Universe:
  - A number of studies with Spitzer has already looked at the viability of monochromatic IR emission (mainly 8 and 24 μm) as SFR indicator (Wu et al, 2005, Chary et al., Alonso-Herrero et al. 2006, etc.)
  - Appeal of PAH emission (restframe 7.7 μm emission for z~2) for investigating star formation in high-z galaxy populations (e.g., First Look, GOODS, MIPS GTO, etc.; Daddi et al. 2005)
  - Monochromatic 24 μm (restframe) emission also potentially useful for measuring high-z SFRs (see Dickinsons' Spitzer Cy3 Legacy)

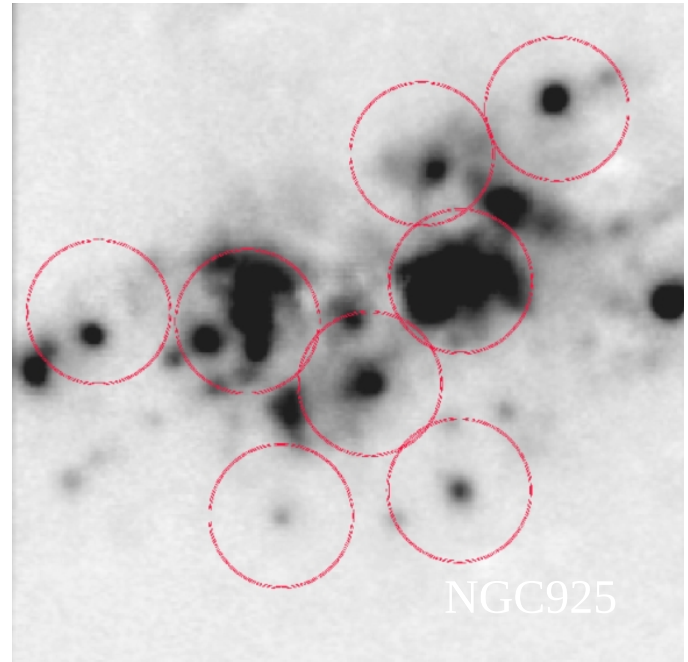

N
E
24 µm


M81
Hα + R


MIPS 24 μm

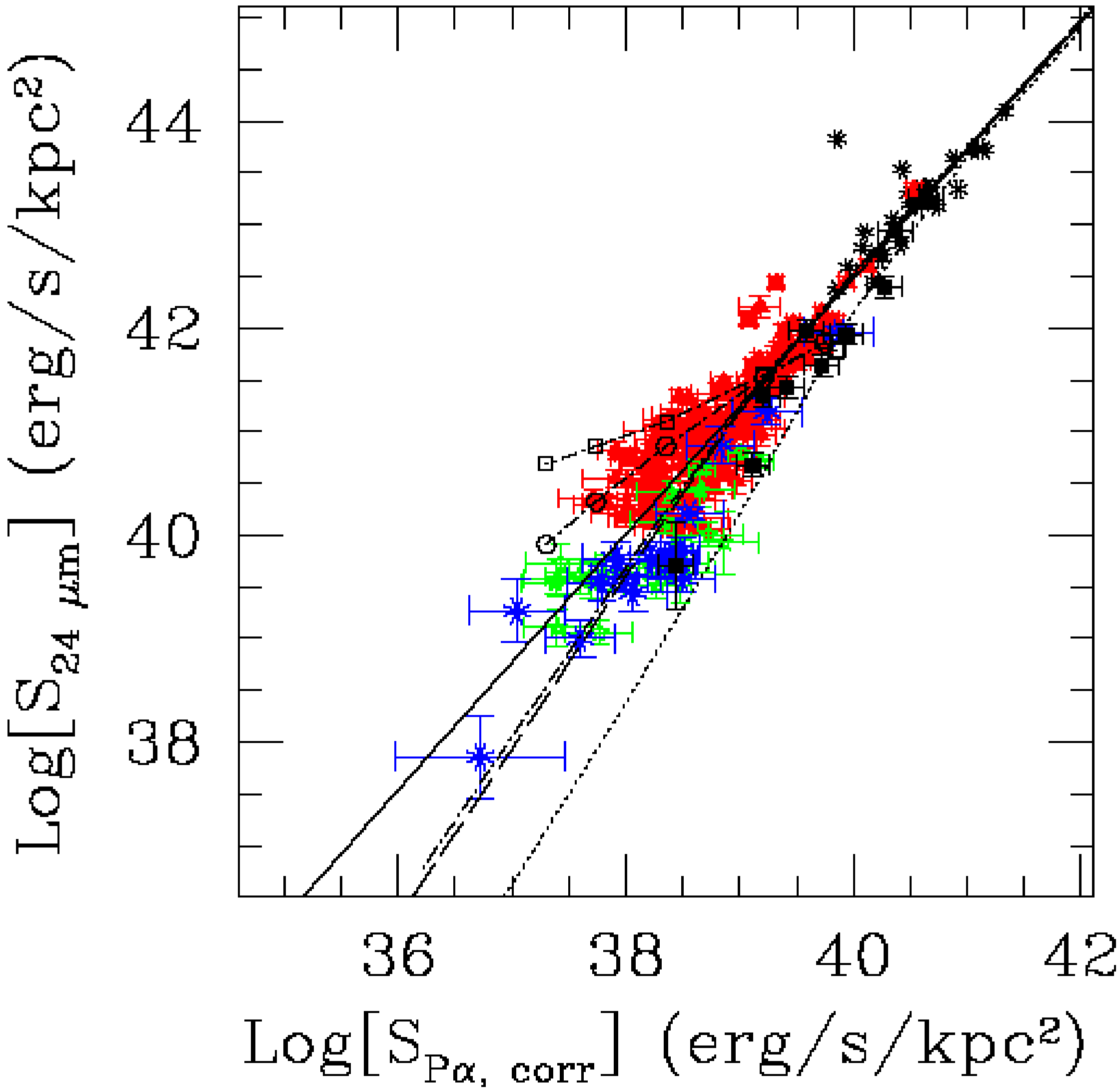
Hα + R





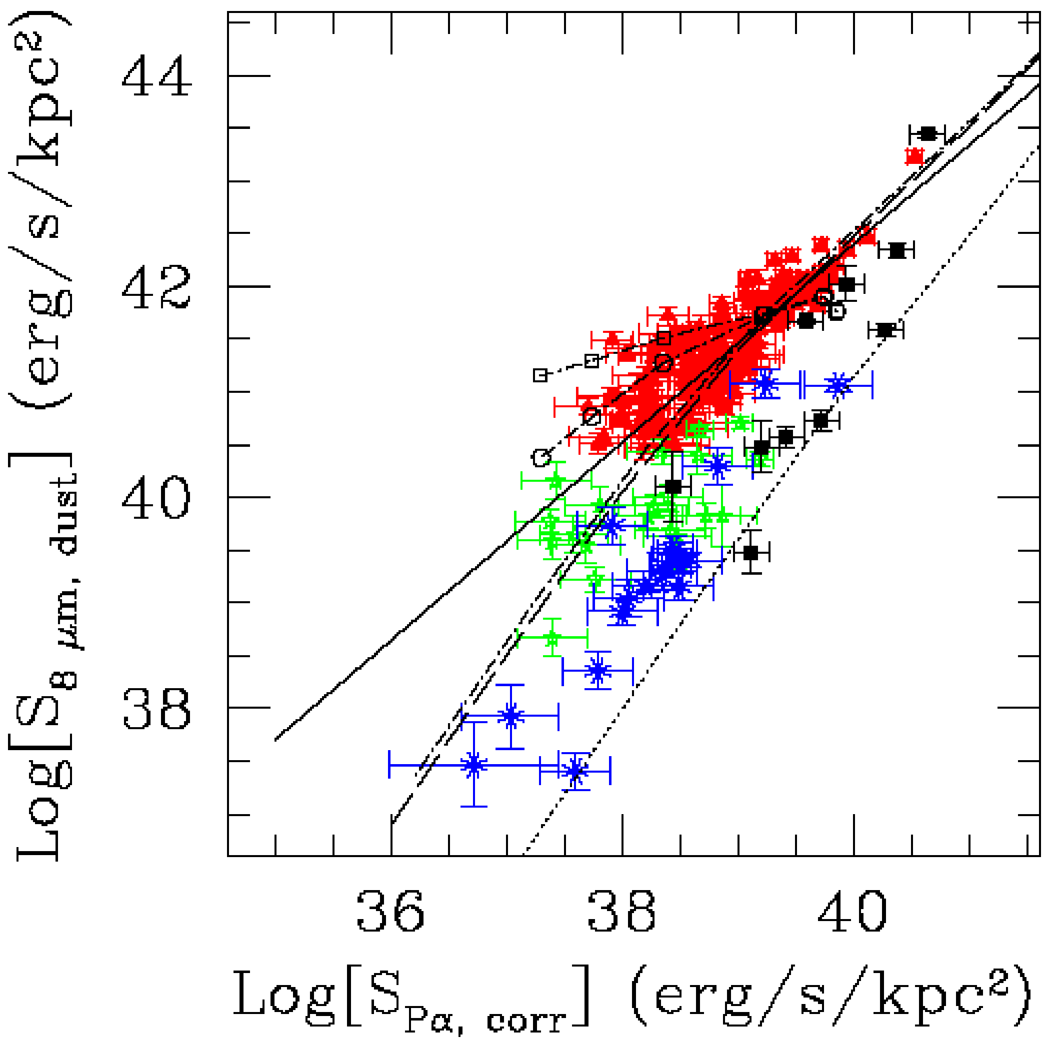
33 normal galaxies (220 regions)
34 starbursts

- Use starbursts or SF regions in galaxies (SINGS).
- Use Pα as `ground truth' measure of instantaneous SFR (Boeker et al. 1999; Quillen & Yukita 2001)
- Measure 8 μm, 24 μm, Hα, and Pα.



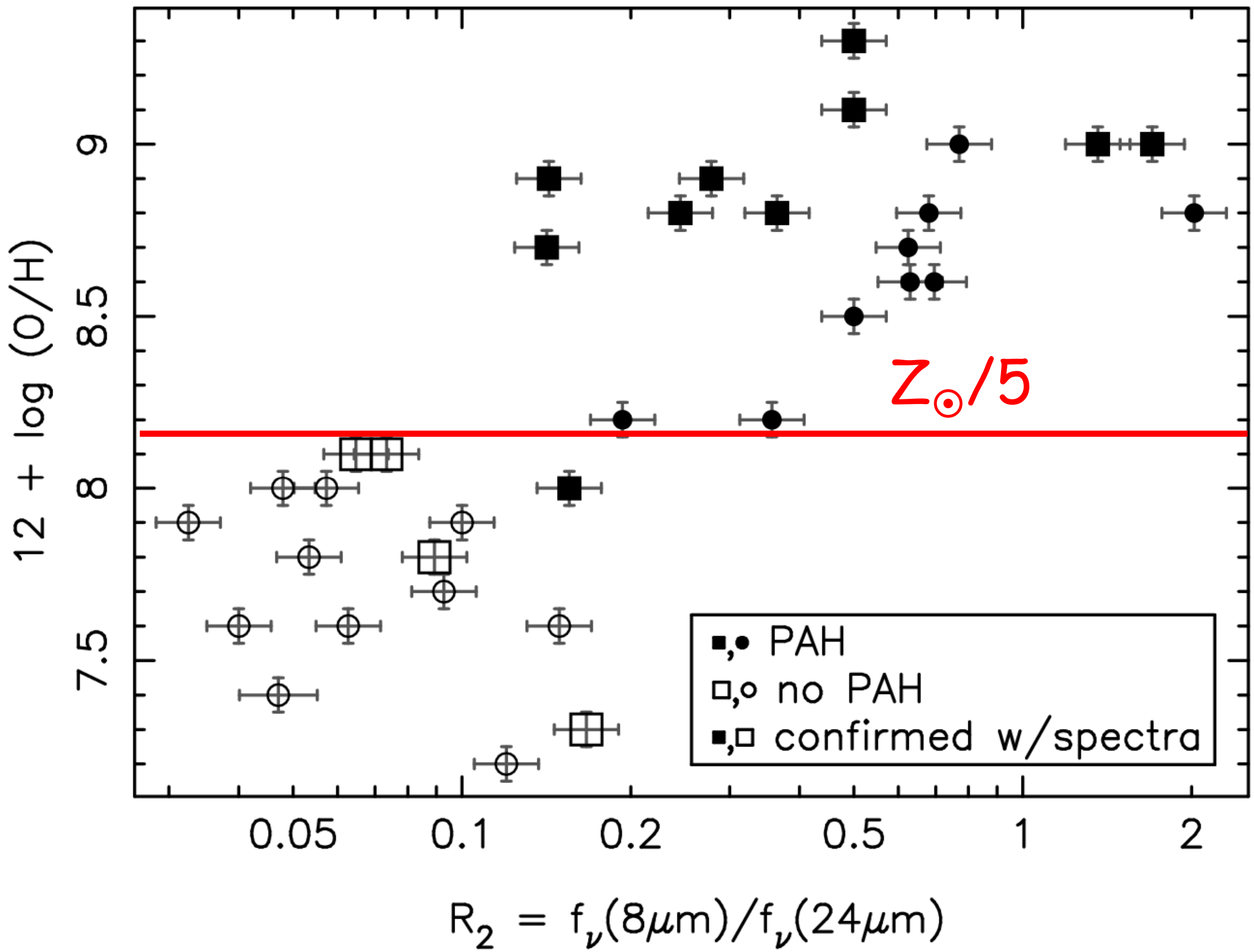
Calzetti et al. 2007, ApJ, 666, 870

- 8 μm emission is less reliable as a local SFR tracer, at least for young (HII) regions

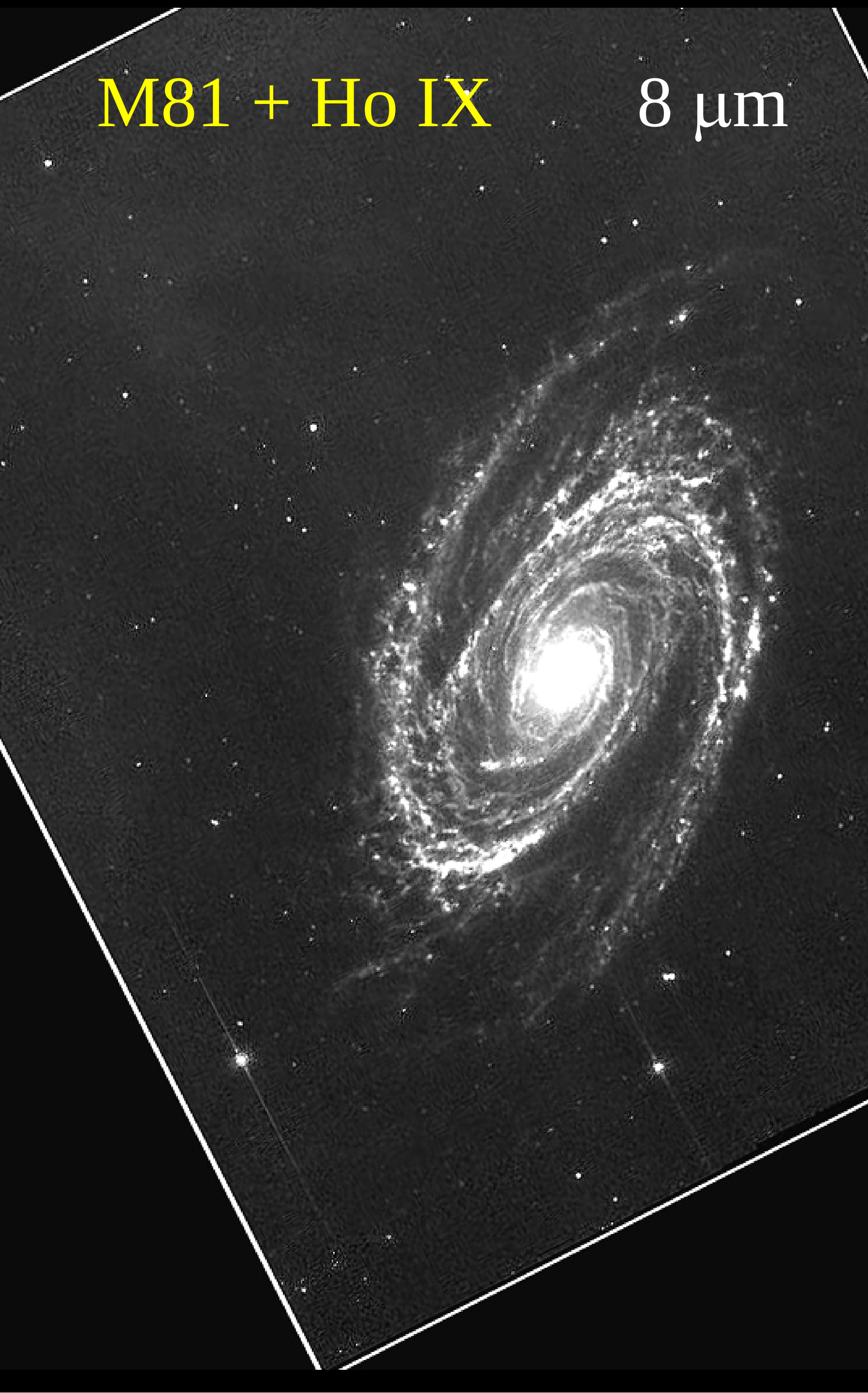


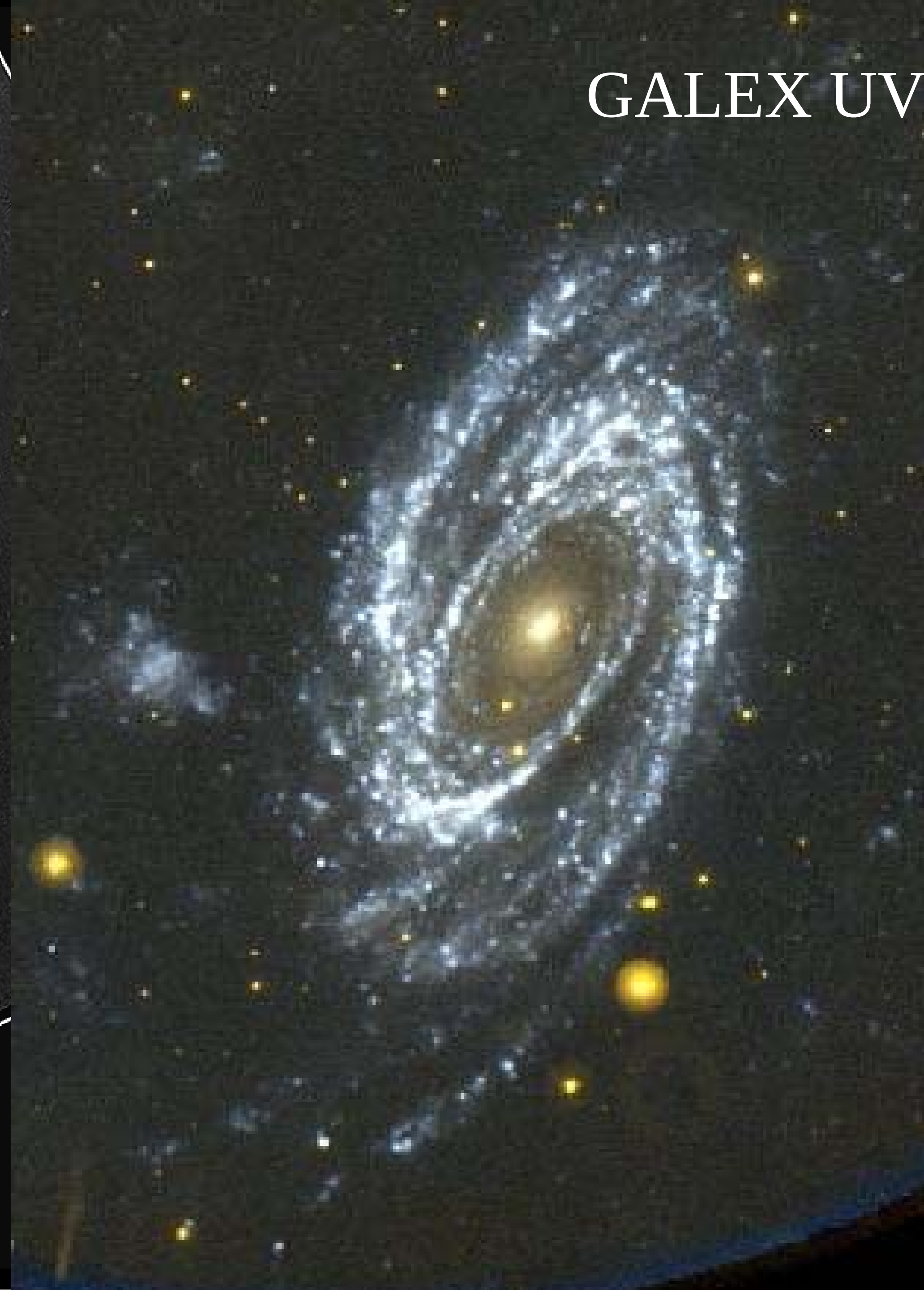
Calzetti et al. 2007, ApJ, 666, 870

PAH Emission vs Metallicity



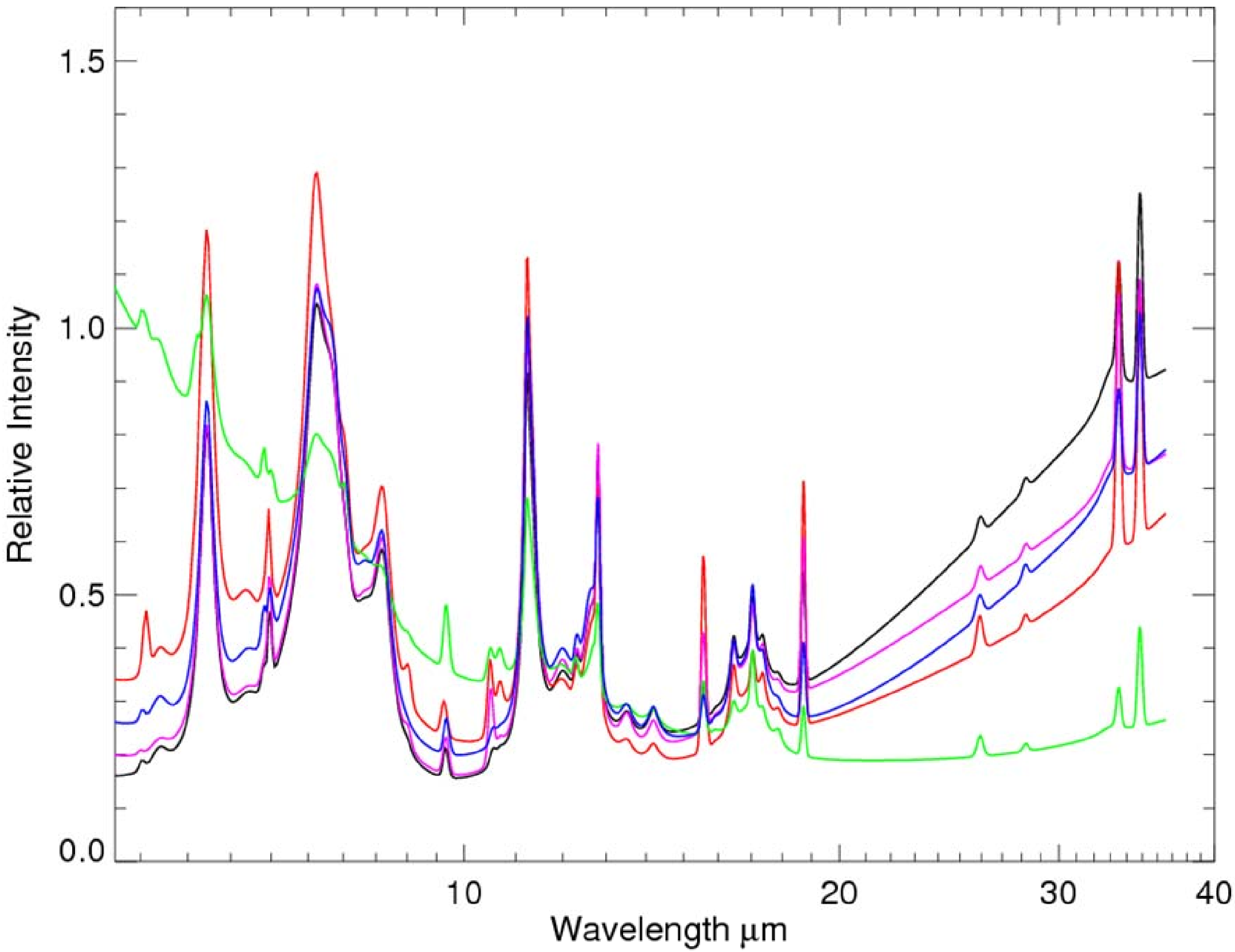
Low-Z starbursts: Engelbracht 2005, ApJ, 628, L29


M81 + Ho IX
8 μm

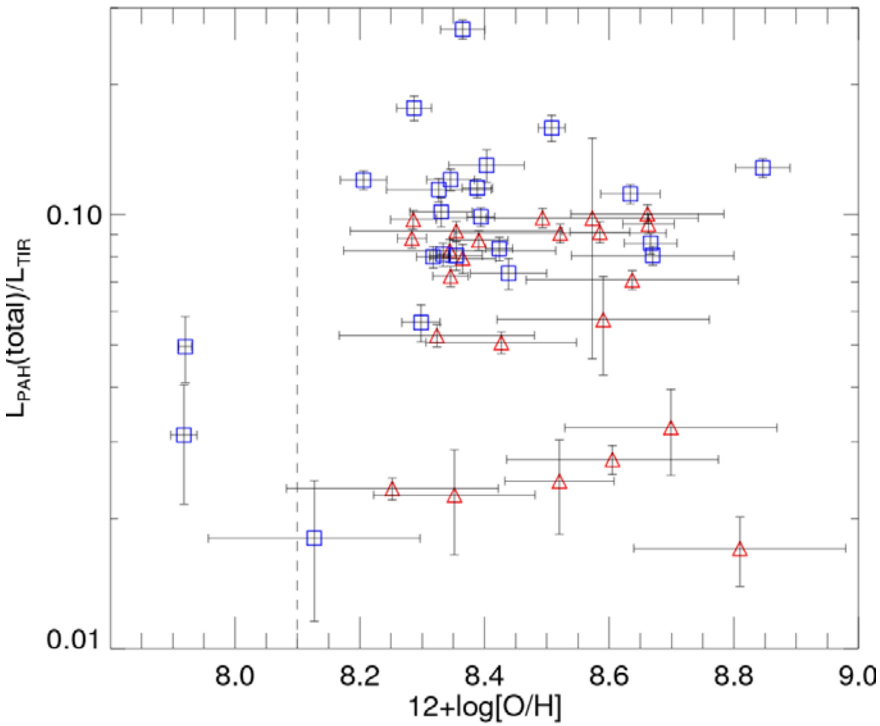

GALEX UV

Spectral Variations in SINGS Galaxies (centers)

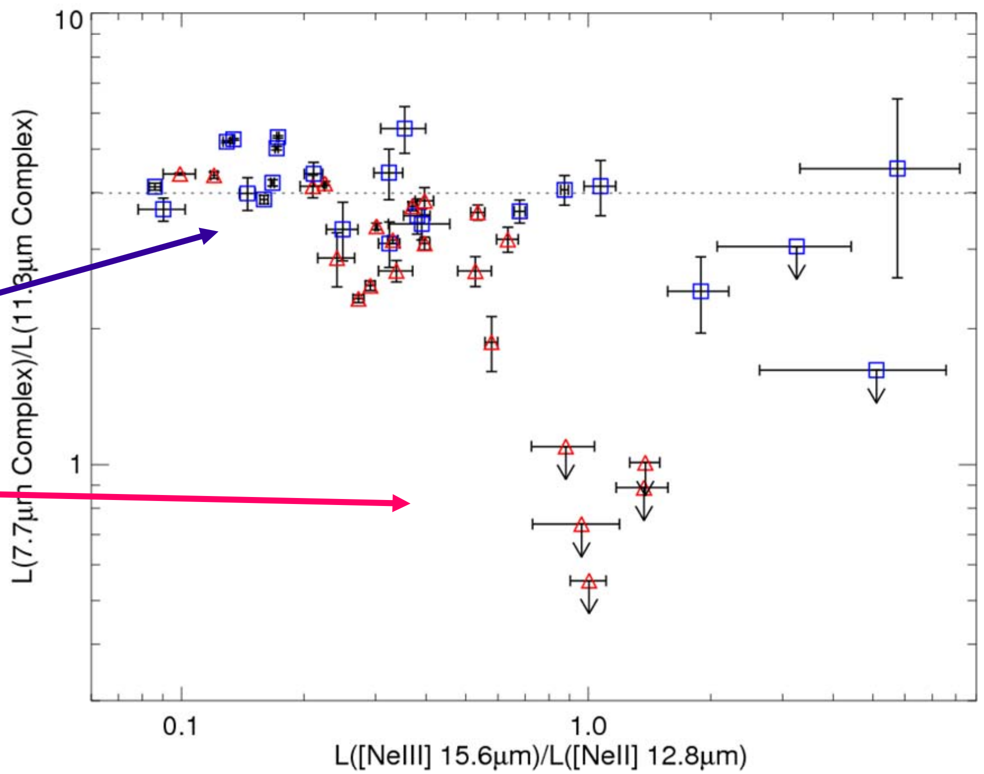
Smith et al. 2007, ApJ, 656, 770



- significant variations in absolute <u>and</u> relative PAH band strengths



- variations driven by metallicity and ambient radiation field



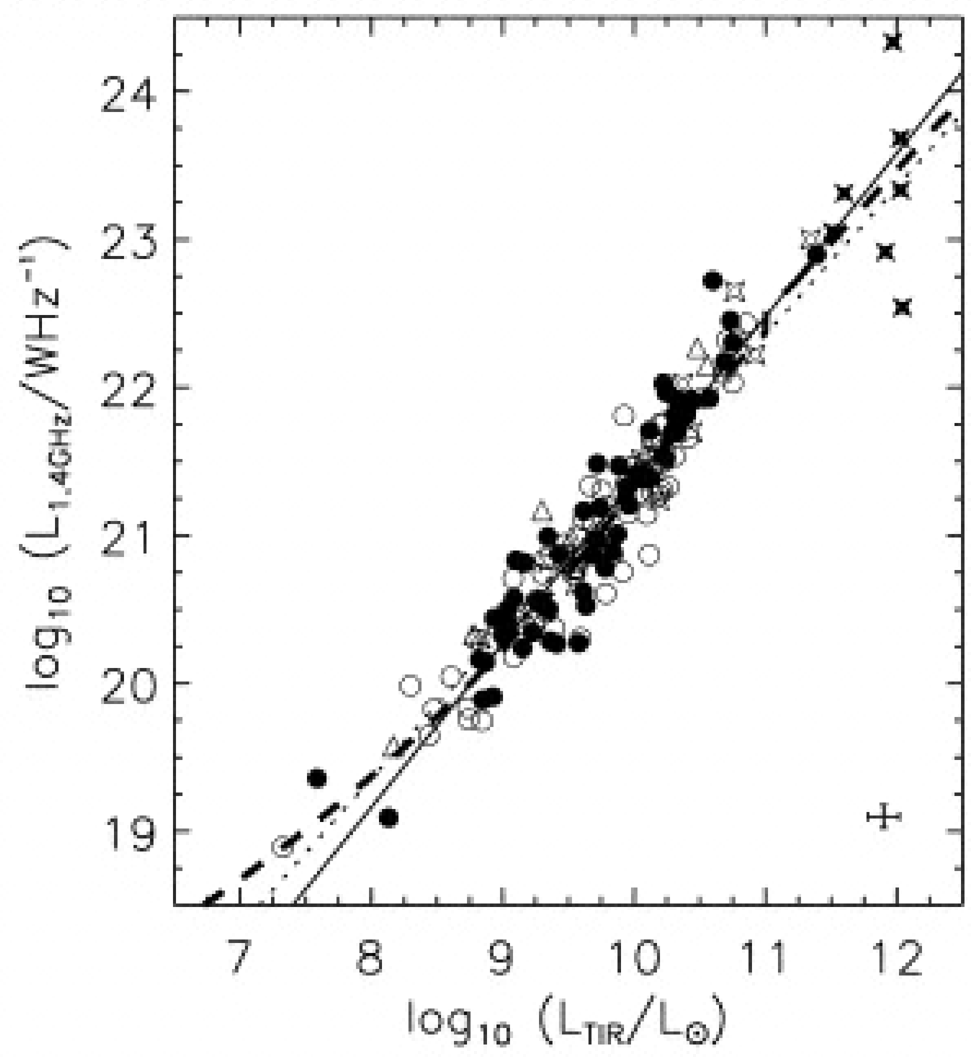
HII region dominated

AGN dominated

Smith et al. 2007

Radio Continuum Emission

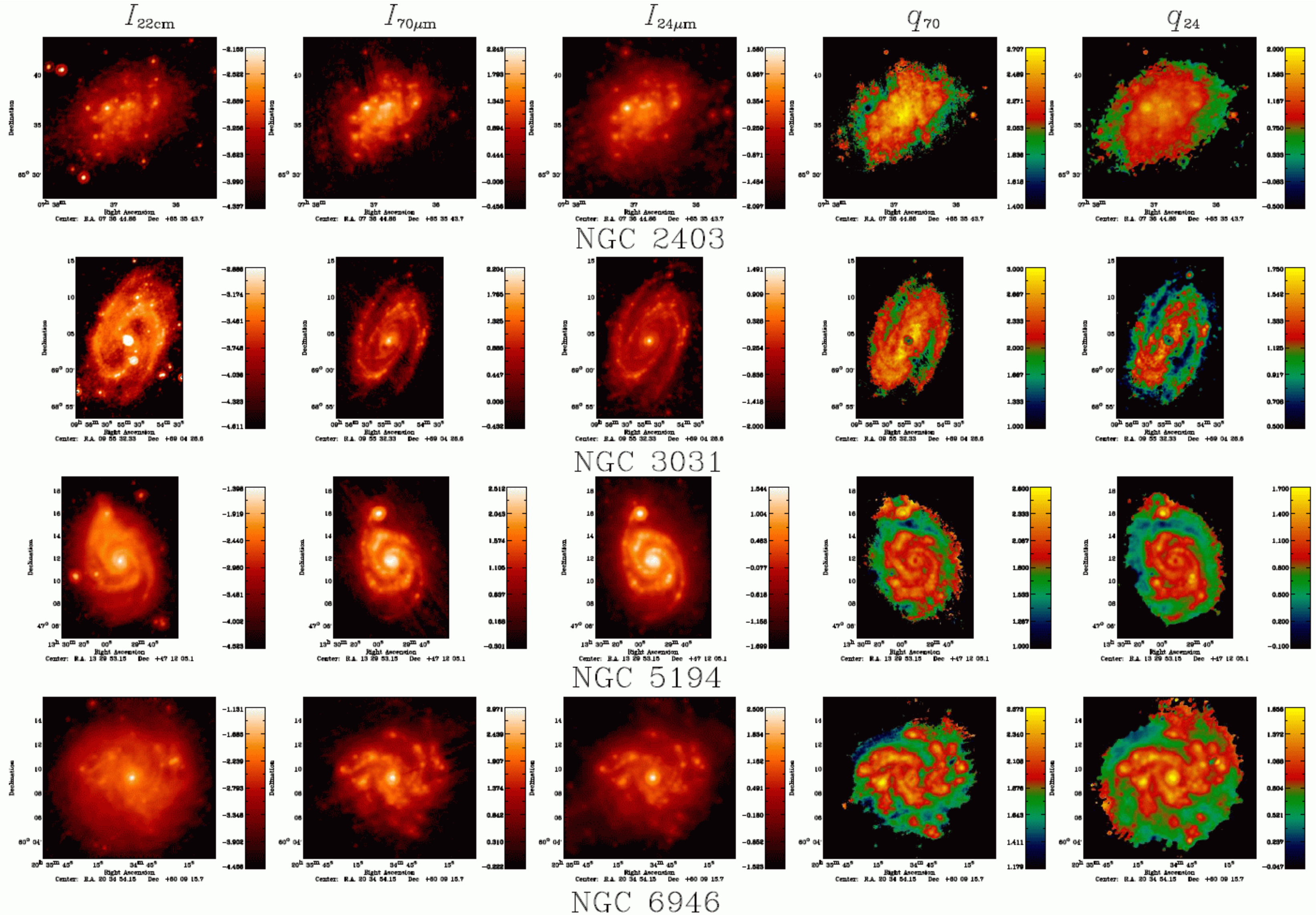
- exploits tight observed relation between 1.4 GHz radio continuum (synchrotron) and FIR luminosity
- correlation may reflect CR particle injection/acceleration by supernova remnants, and thus scale with SFR
- no *ab initio* SFR calibration, bootstrapped from FIR calibration
- valuable method when no other tracer is available

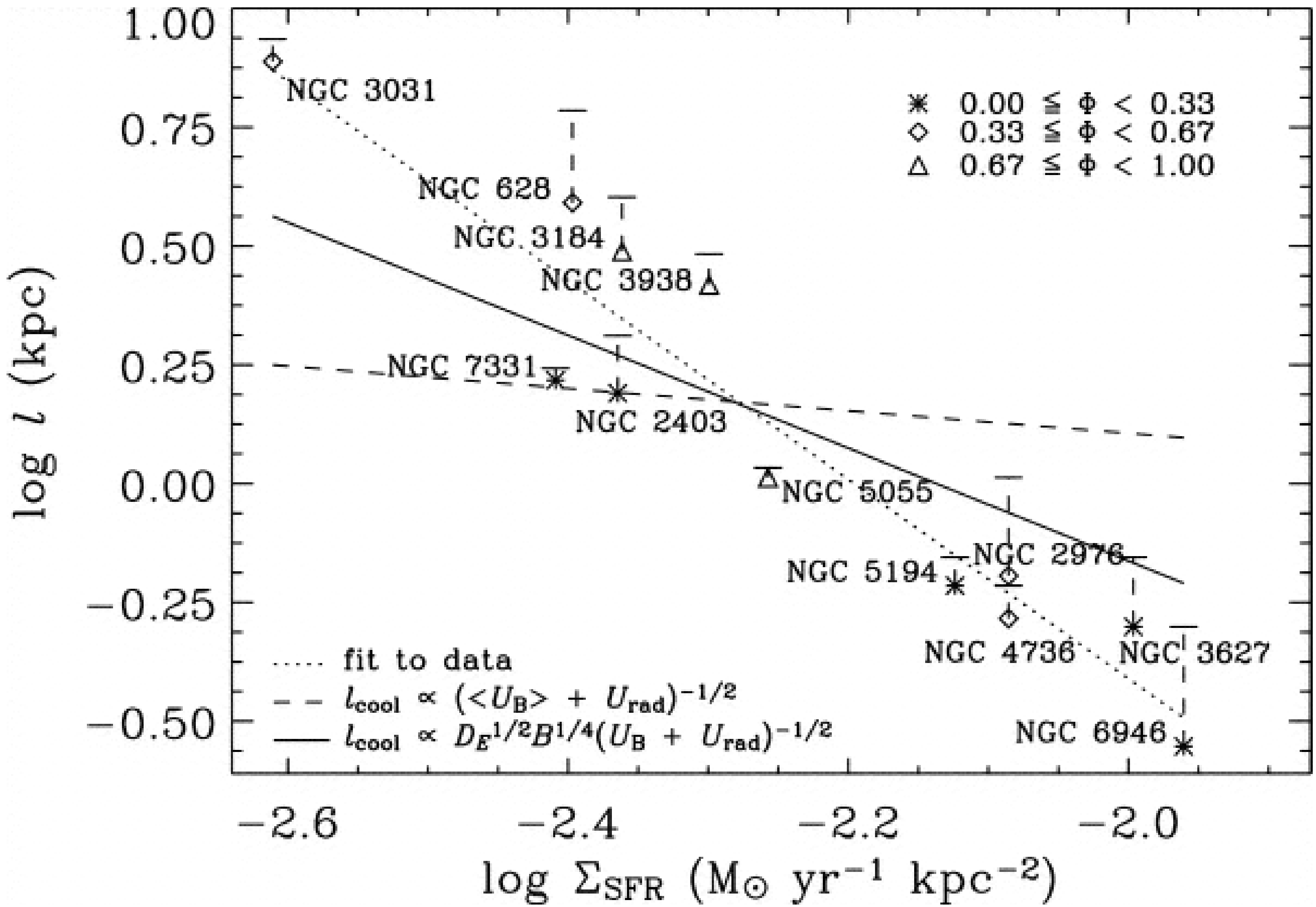


Bell 2003, ApJ, 586, 794

The Radio-FIR Correlation

Murphy et al. 2006, ApJ, 638, 157; ApJ, 651, L111





NGC 3031
NGC 628
NGC 3184
NGC 3938
NGC 7331
NGC 2403
NGC 5055
NGC 2976
NGC 5194
NGC 4736
NGC 3627
NGC 6946
$0.00 \leqq \Phi < 0.33$
$0.33 \leqq \Phi < 0.67$
$0.67 \leqq \Phi < 1.00$
fit to data
$l_{cool} \propto (<U_B> + U_{rad})^{-1/2}$
$l_{cool} \propto D_E^{1/2} B^{1/4} (U_B + U_{rad})^{-1/2}$
log l (kpc)
log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−2.6
−2.4
−2.2
−2.0

Cookbook

Extinction-Free Limit (Salpeter IMF, $Z=Z_{Sun}$)

$$SFR\ (M_o\ yr^{-1}) = 1.4 \times 10^{-28}\ L_\nu\ (1500)\ \text{ergs/s/Hz}$$

$$SFR\ (M_o\ yr^{-1}) = 7.9 \times 10^{-42}\ L\ (H\alpha)\ (\text{ergs/s})$$

Extinction-Dominated Limit; SF Dominated

$$SFR\ (M_o\ yr^{-1}) = 4.5 \times 10^{-44}\ L\ (\text{FIR})\ (\text{ergs/s})$$

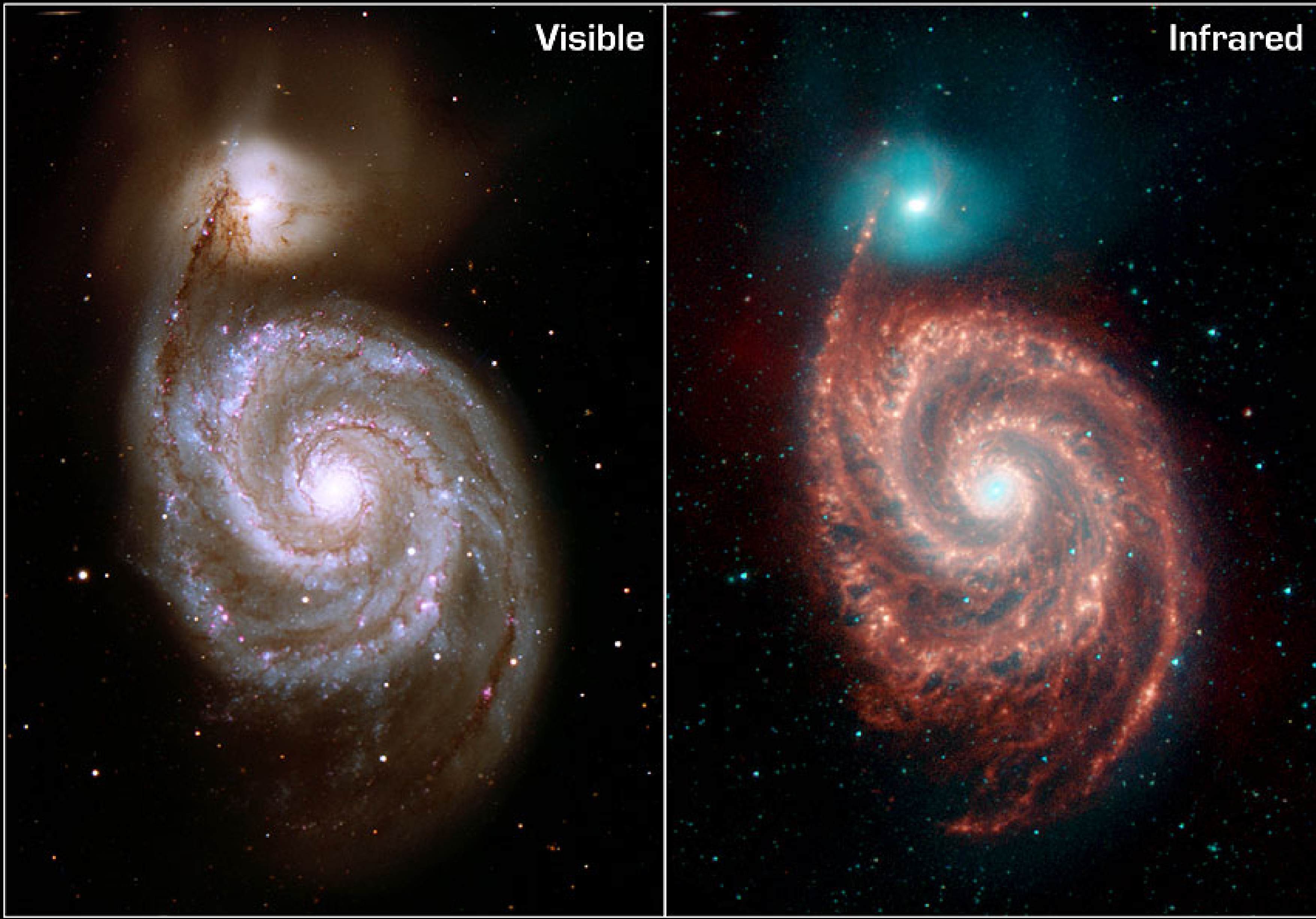
$$SFR\ (M_o\ yr^{-1}) = 5.5 \times 10^{-29}\ L\ (1.4\ \text{GHz})\ (\text{ergs/Hz})$$

Composite: SF Dominated Limit

$$SFR\ (M_o\ yr^{-1}) = 7.9 \times 10^{-42}\ [L_{H\alpha,\ obs} + a\ L_{24\mu m}]\ (\text{erg s}^{-1})$$

$[a = 0.15 – 0.31]$

$$SFR\ (M_o\ yr^{-1}) = 4.5 \times 10^{-44}\ [L(UV) + L\ (\text{FIR})]\ (\text{ergs/s})$$



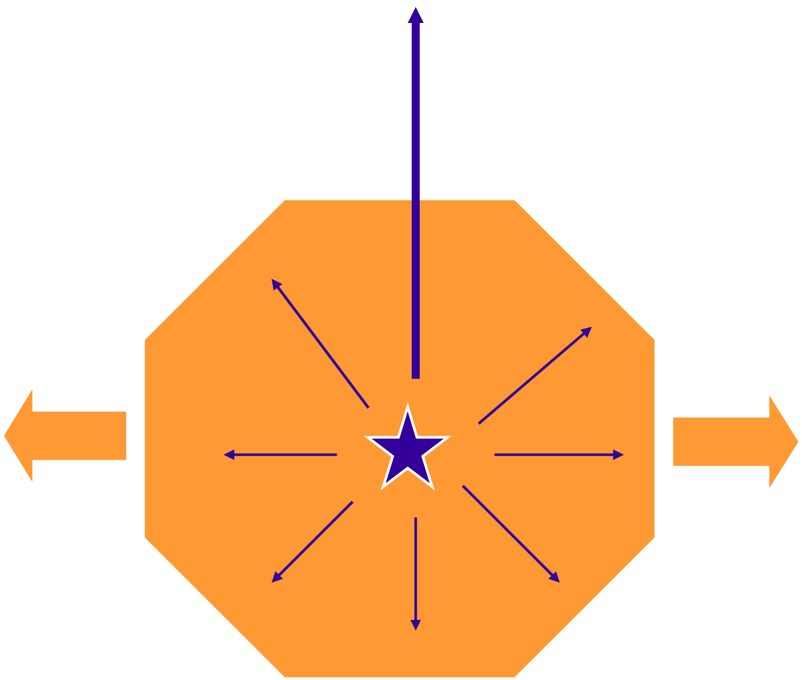
Spiral Galaxy M51 ("Whirlpool Galaxy") Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona) ssc2004-19a

Method: Simple Energy Balance

Transmitted luminosity

$$L(H\alpha)_{obs} = L(H\alpha)_{corr} \; e^{-\tau\,(H\alpha)}$$
$$L(H\alpha)_{obs} = \eta L(bol) \; e^{-\tau\,(H\alpha)}$$



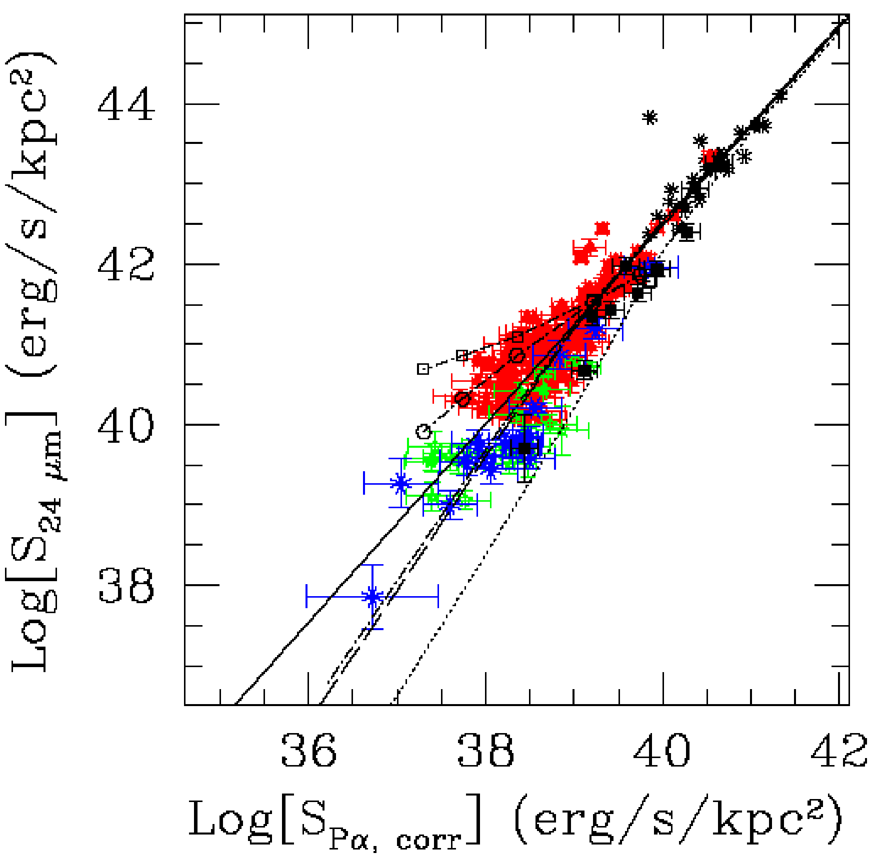
Dust re-emitted luminosity:

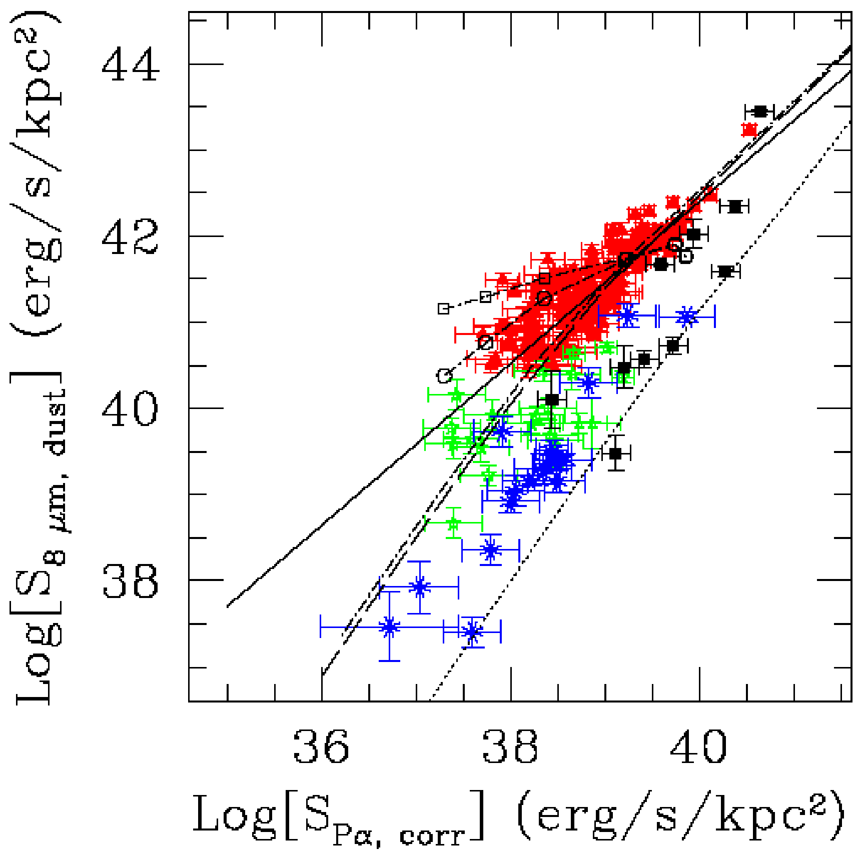
$$L(TIR) = L(bol) \; (1 - e^{-\tau(eff)})$$

if $\tau(Ha) \sim \tau(eff)$

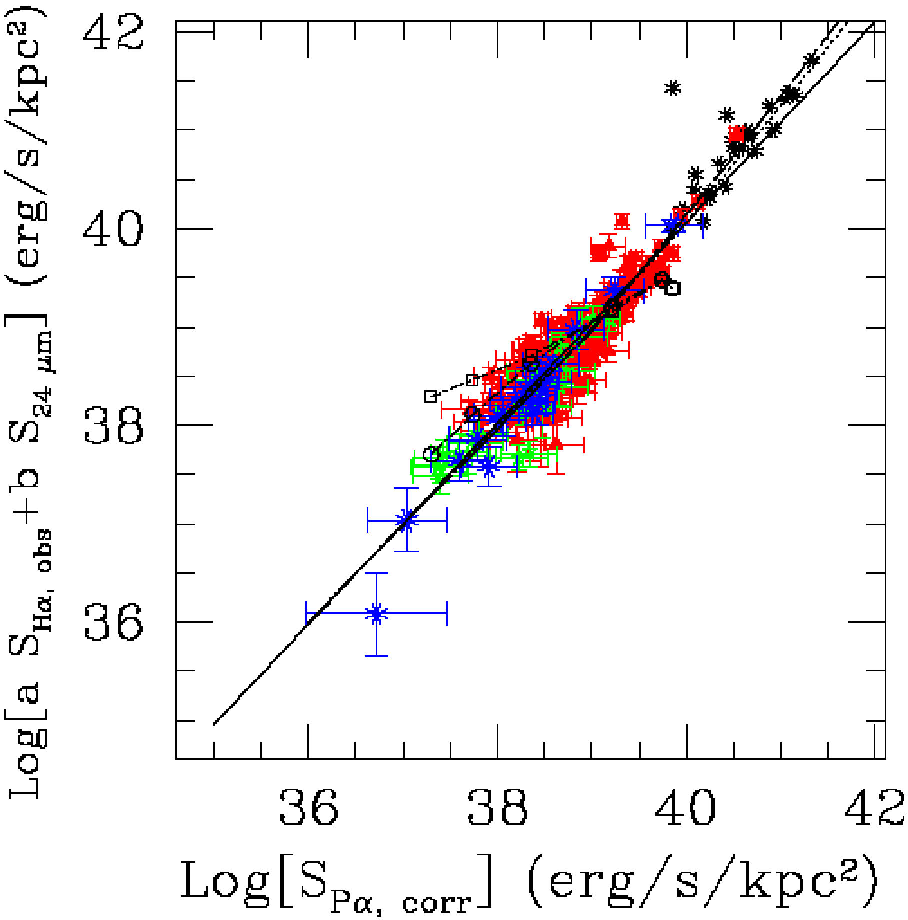
$$L(H\alpha)_{corr} = L(H\alpha)_{obs} + \eta L(TIR)$$

First application: 220 HII regions in 33 SINGS galaxies





Calzetti et al. 2007, ApJ, 666, 870
Prescott et al. 2007, ApJ, 668, 182



$$L(H\alpha)_{corr} = L(H\alpha)_{corr} + aL(24)$$
$$a = 0.031 \text{ +- } 0.006$$

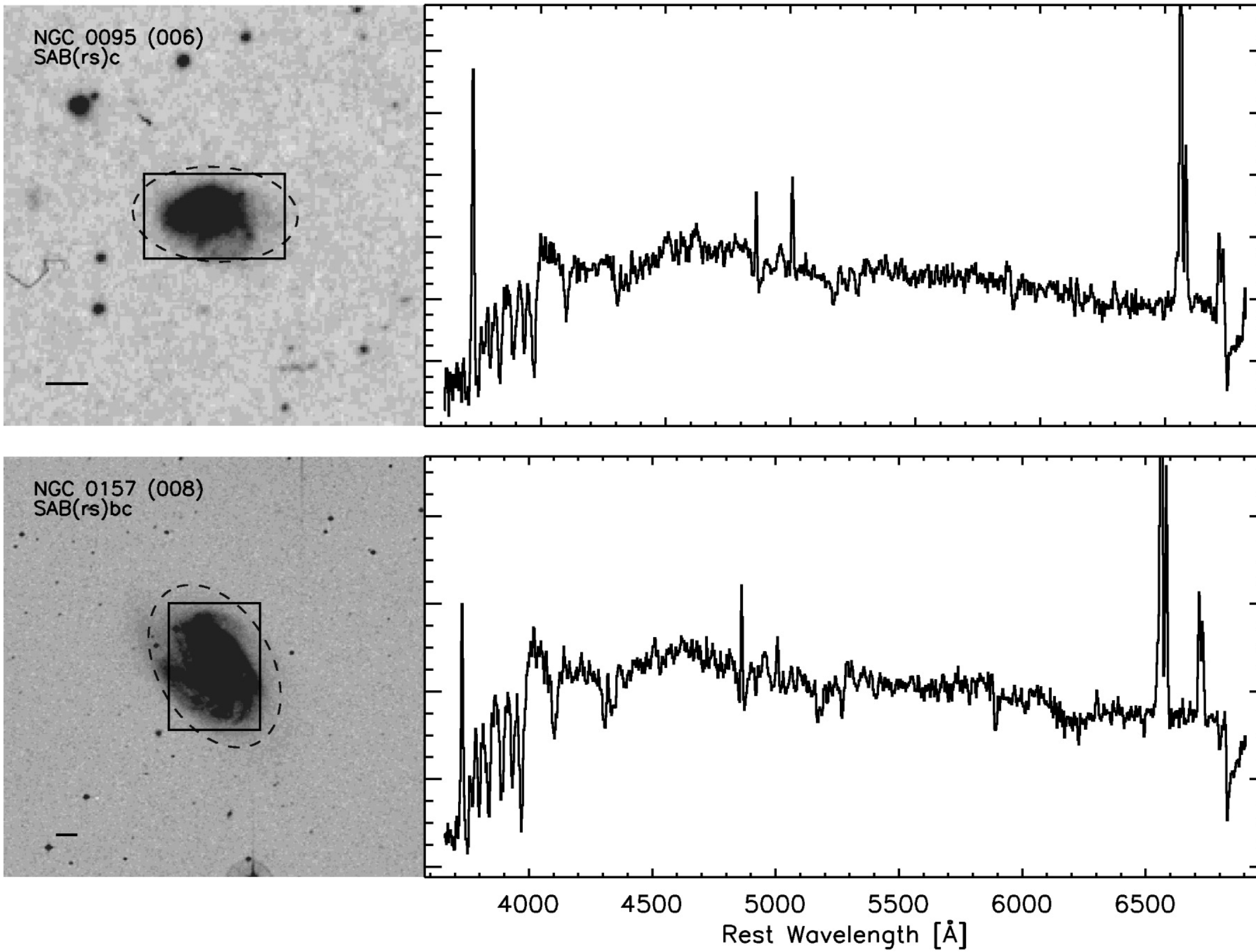
- combination of 24μm and Hα fluxes provides robust measure of extinction-corrected ionizing flux

- dispersion for individual HII regions is significant (+-0.3-0.4 dex)

- scatter mainly from variations in geometry and cluster age, IMF

- applicability limited by sufficient population of upper IMF (low limit) and extinction (A(Hα) ~ 4-5 mag)

Calzetti et al. 2007, ApJ, 666, 870



RCK, Hao, Calzetti et al. 2008, in prep

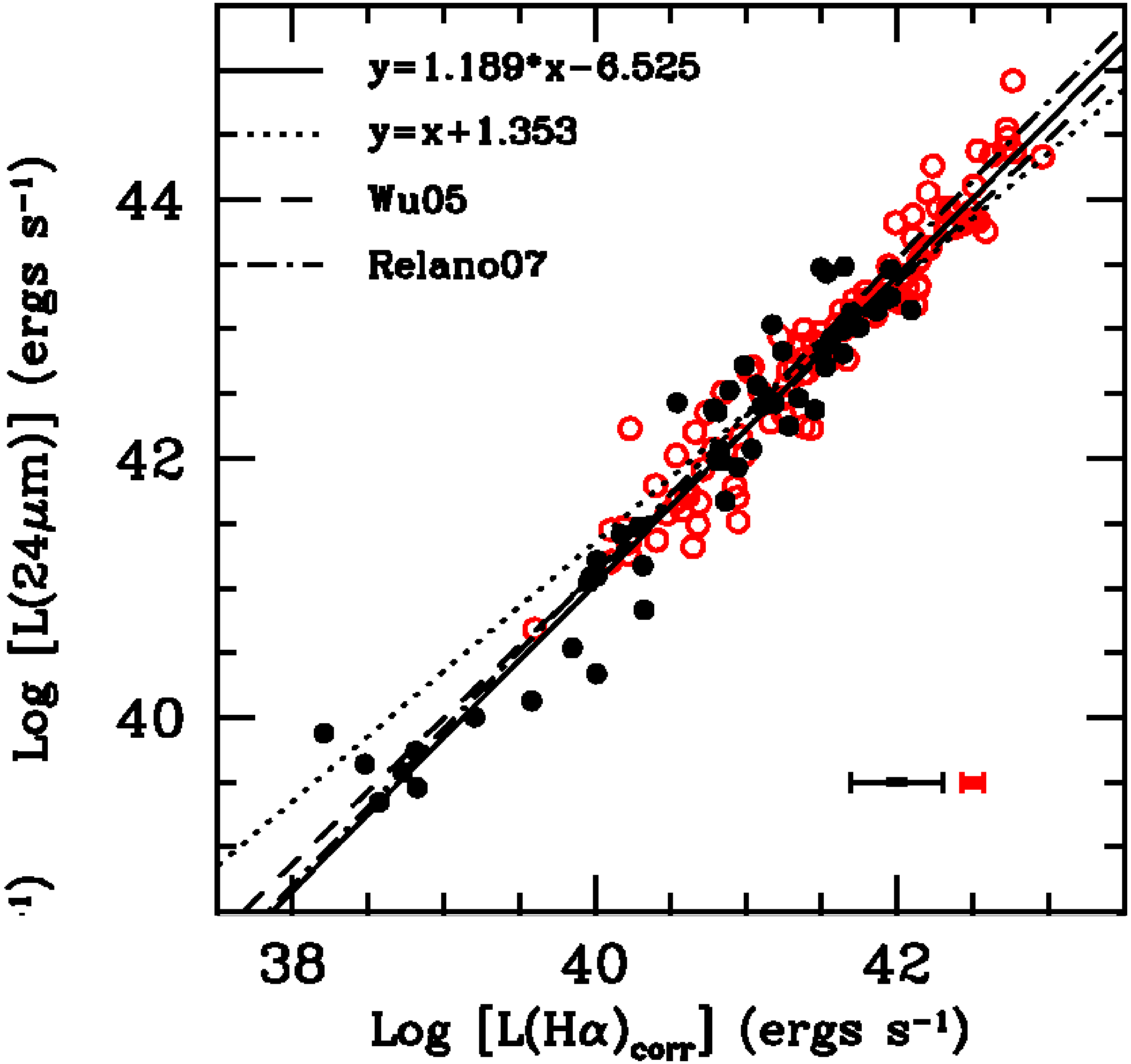
Datasets

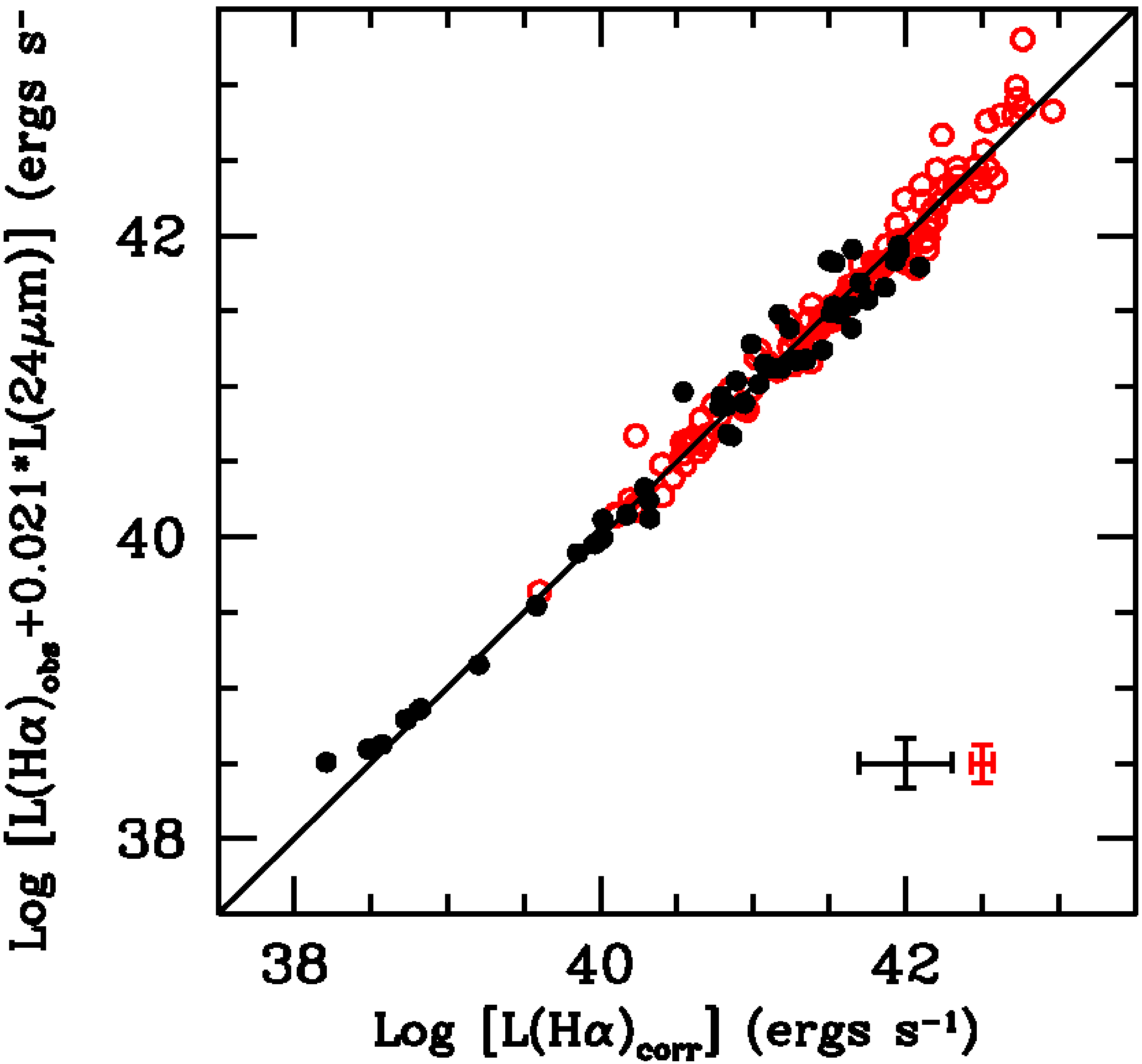
- Spitzer Infrared Nearby Galaxies Survey (SINGS)
    - 75 galaxies
    - UV, Hα, IR, radio maps + optical spectra
    - Paα maps for central 55"x55" regions

- Integrated Spectral Atlas

    (Moustakas, Kennicutt 2006, ApJS, 164, 81)

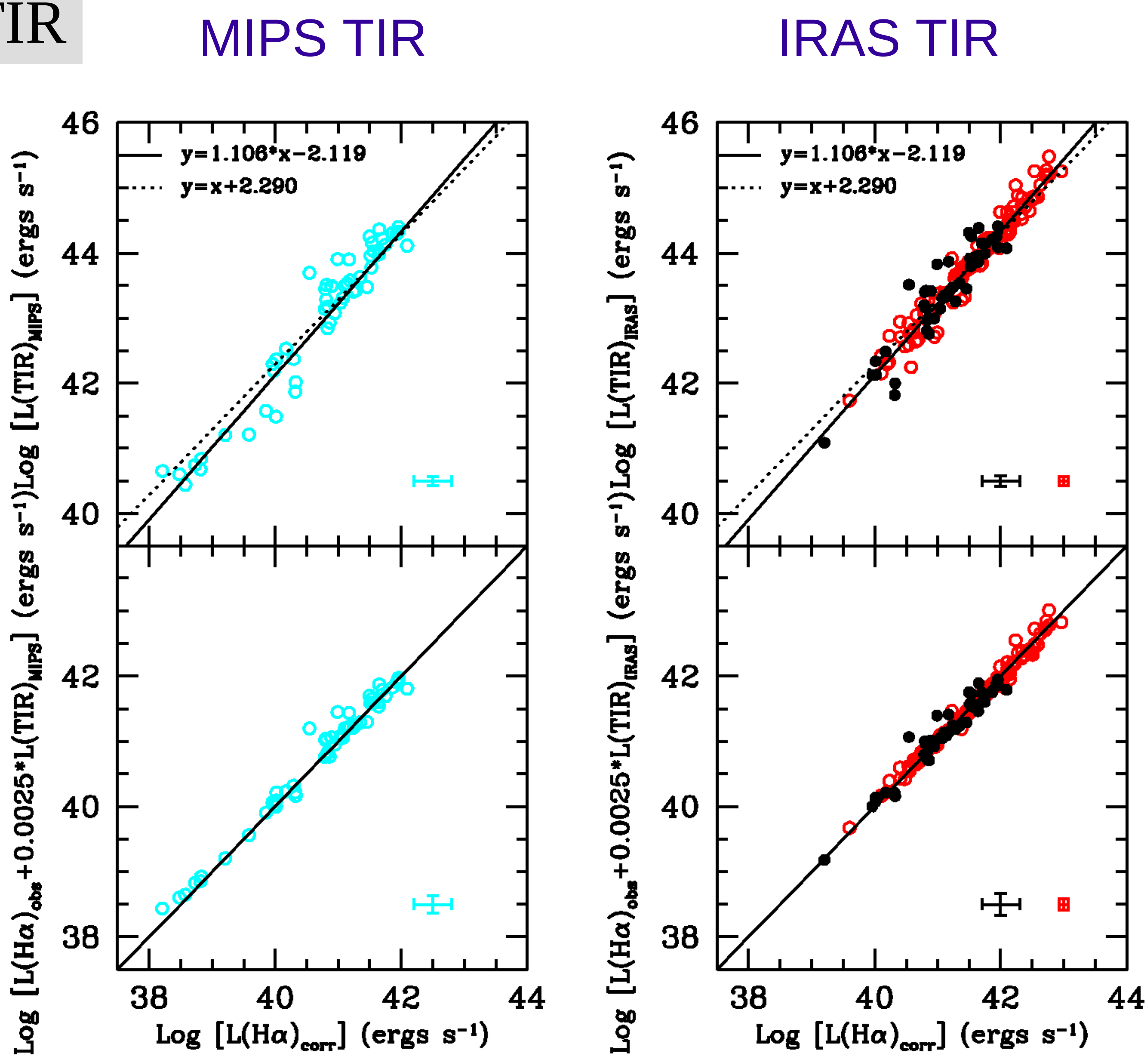
    - 417 galaxies: normal, starburst, LIRG
    - optical spectra + IR, radio fluxes (IRAS, NVSS)


y=1.189*x-6.525
y=x+1.353
Wu05
Relano07
Log [L(24μm)] (ergs s⁻¹)
Log [L(Hα)corr] (ergs s⁻¹)
38
40
42
40
42
44



Log [L(Hα)$_{obs}$+0.021*L(24μm)] (ergs s^{-1})
Log [L(Hα)$_{corr}$] (ergs s^{-1})
38
40
42

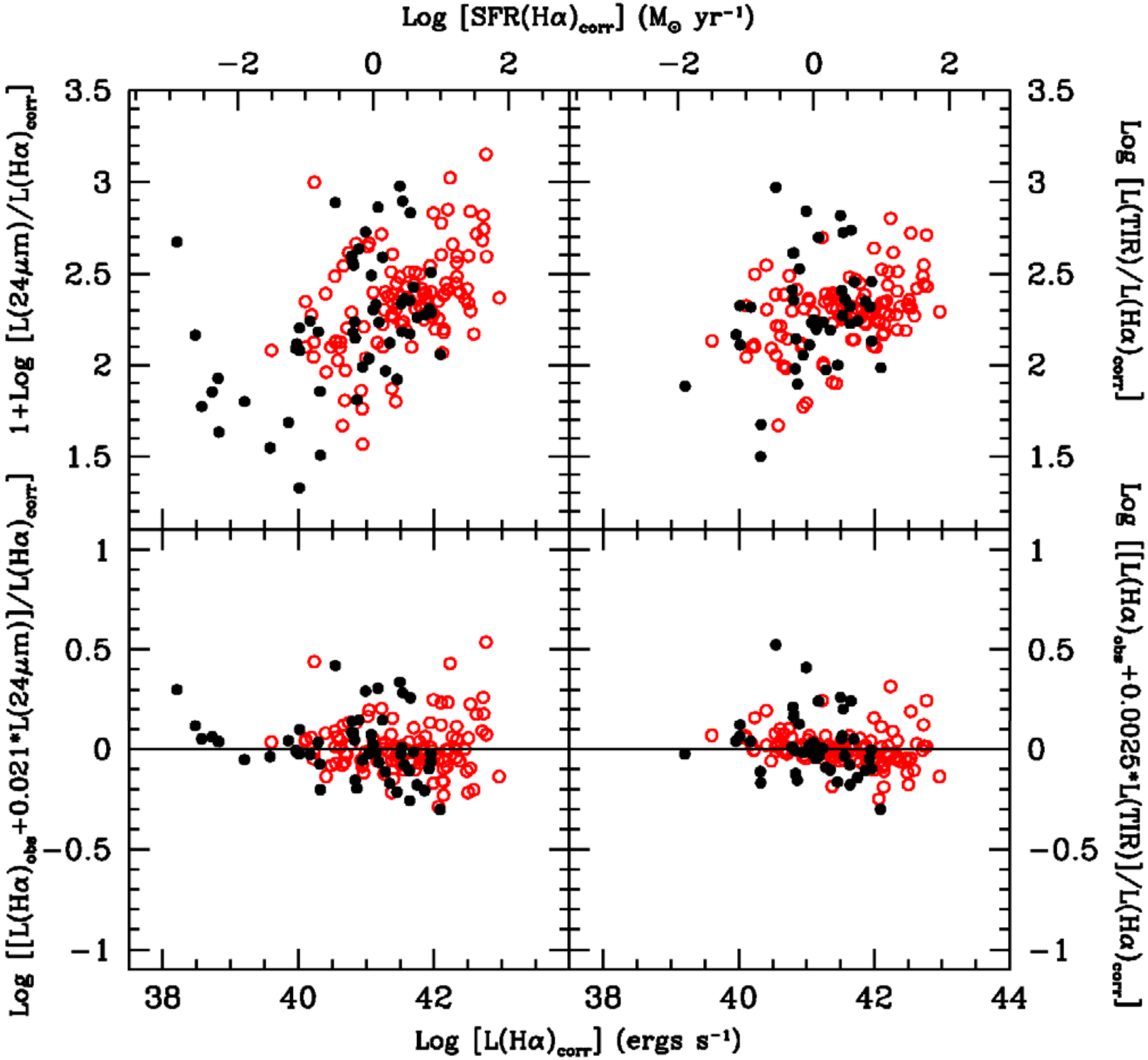
Hα + TIR



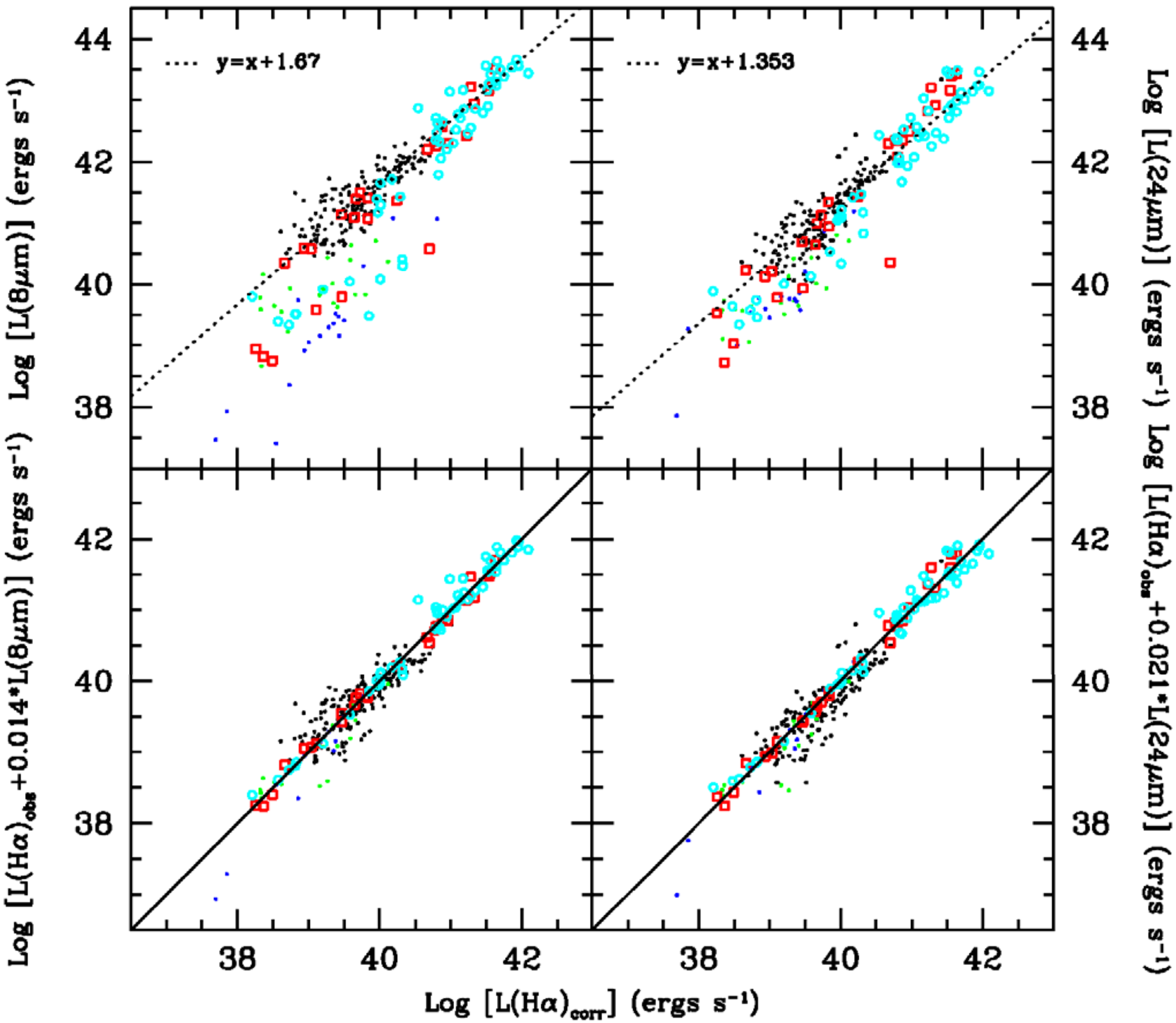
MIPS TIR
IRAS TIR
y=1.106*x−2.119
y=x+2.290
Log [L(TIR)MIPS] (ergs s−1)
Log [L(TIR)IRAS] (ergs s−1)
Log [L(Hα)obs+0.0025*L(TIR)MIPS] (ergs s−1)
Log [L(Hα)obs+0.0025*L(TIR)IRAS] (ergs s−1)
Log [L(Hα)corr] (ergs s−1)
38
40
42
44
46

Residuals vs SFR

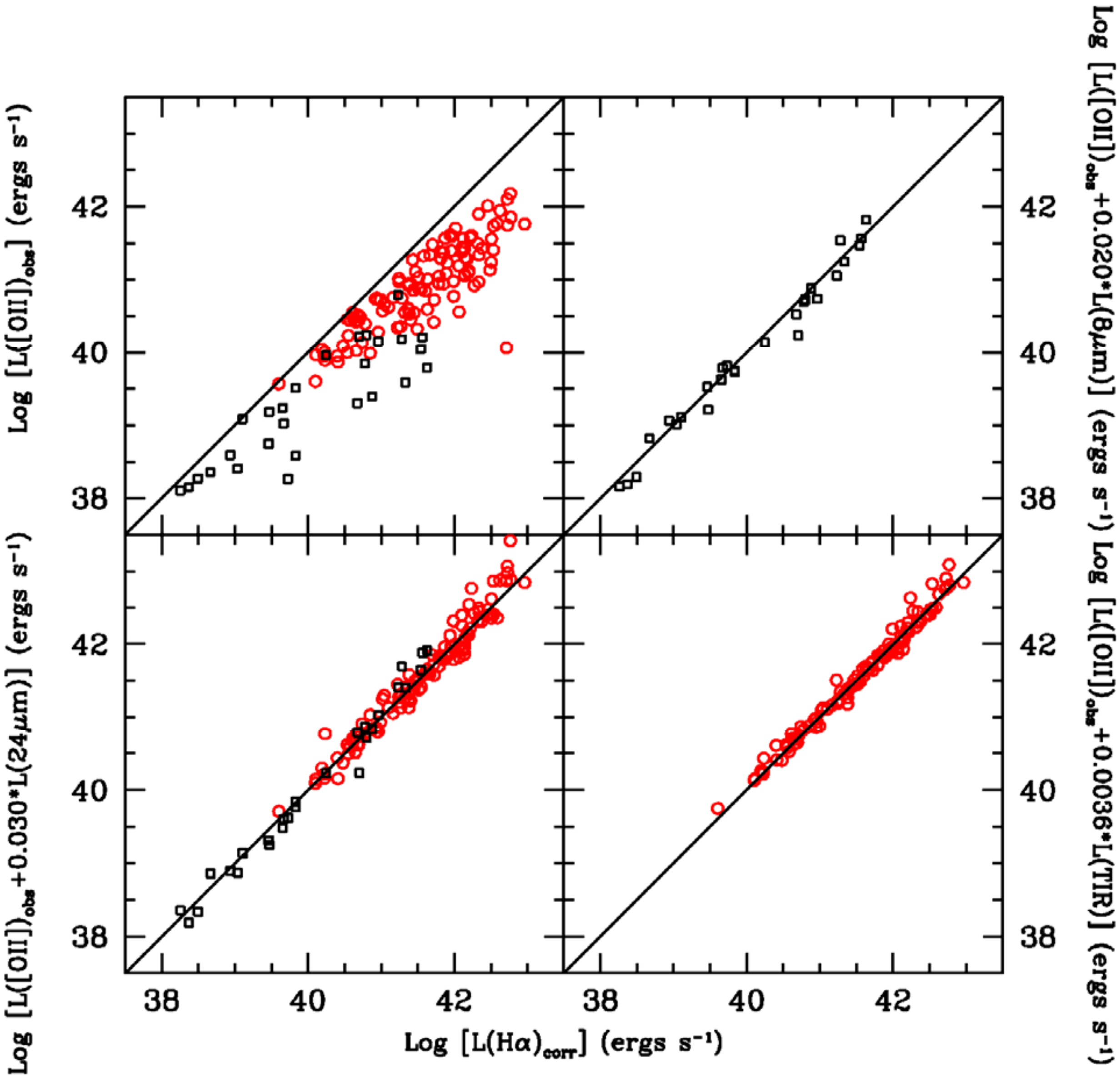
24 μm TIR



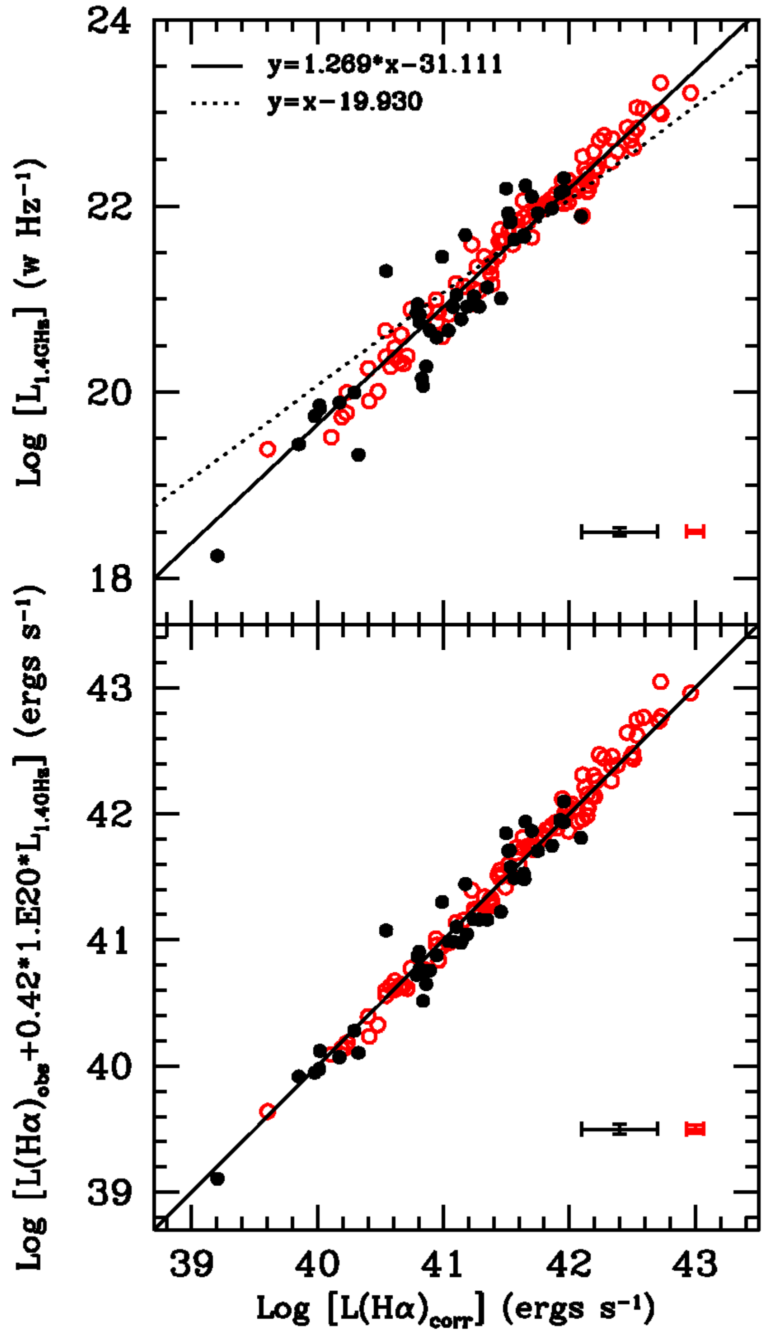
SINGS Sample: 8 μm and 24 μm



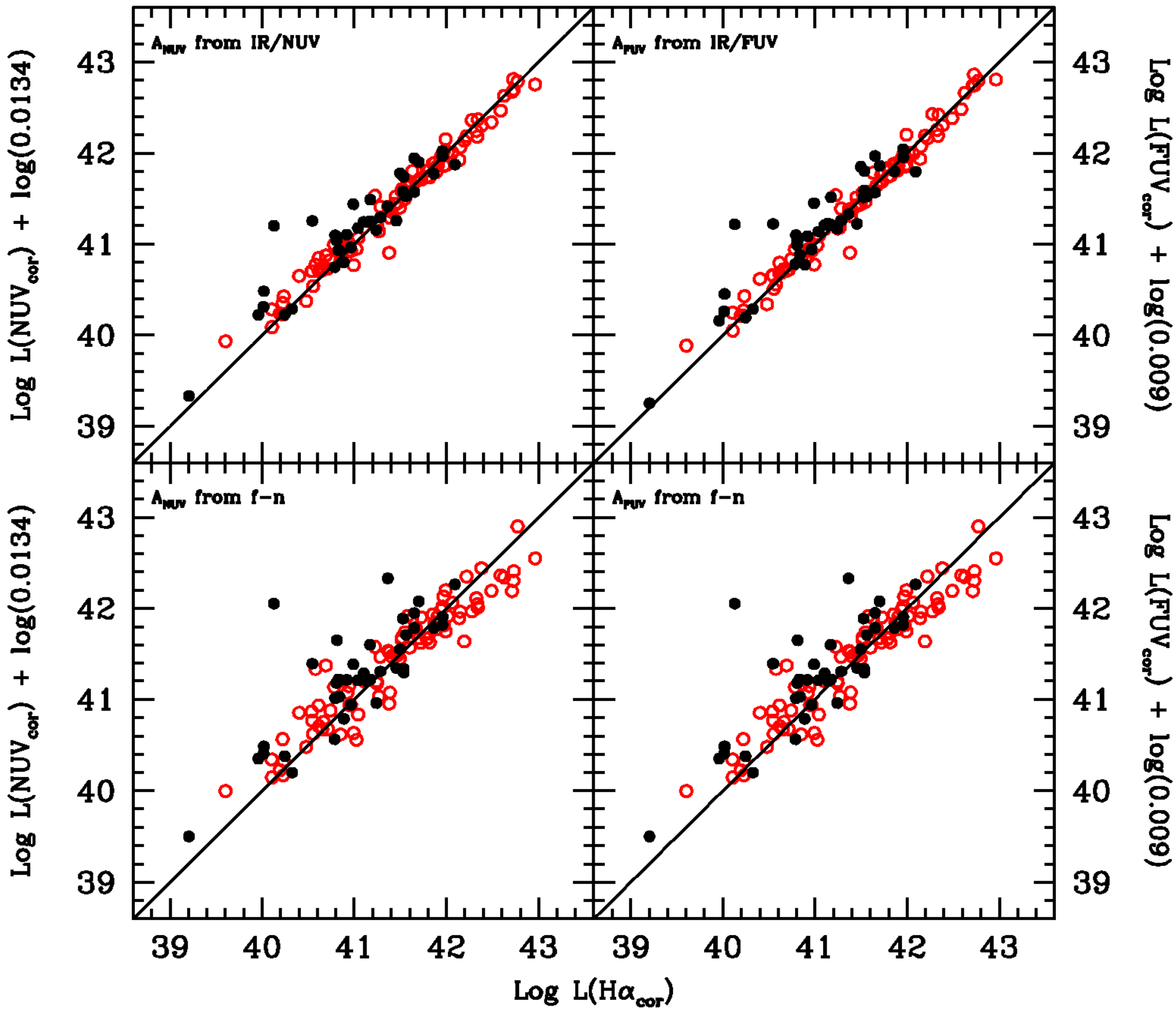
[OII] + 8μm, 24μm, TIR



Hα + 1.4 GHz Radio



this work



A_{NUV} from IR/NUV
A_{FUV} from IR/FUV
A_{NUV} from f−n
A_{FUV} from f−n
Log L(NUV$_{cor}$) + log(0.0134)
Log L(FUV$_{cor}$) + log(0.009)
Log L(Hα_{cor})
39
40
41
42
43

Cookbook

Extinction-Free Limit (Salpeter IMF, $Z=Z_{Sun}$)

SFR (M_o yr^{-1}) = 1.4×10^{-28} L_ν (1500) ergs/s/Hz

SFR (M_o yr^{-1}) = 7.9×10^{-42} L ($H\alpha$) (ergs/s)

Extinction-Dominated Limit; SF Dominated

SFR (M_o yr^{-1}) = 4.5×10^{-44} L (FIR) (ergs/s)

SFR (M_o yr^{-1}) = 5.5×10^{-29} L (1.4 GHz) (ergs/Hz)

Composite: SF Dominated Limit

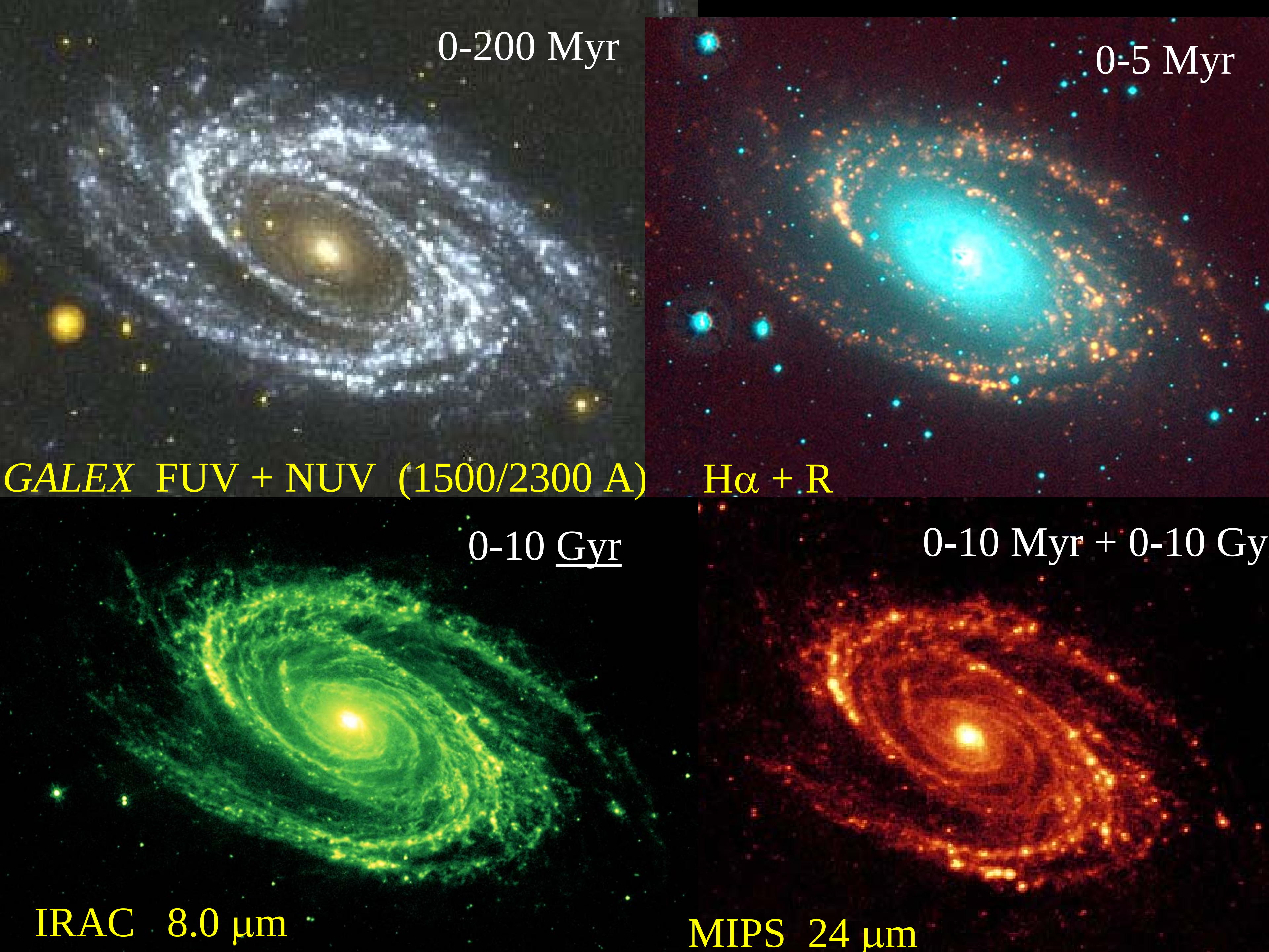
SFR (M_o yr^{-1}) = 7.9×10^{-42} [$L_{H\alpha, obs}$ + a $L_{24\mu m}$] (erg s^{-1})

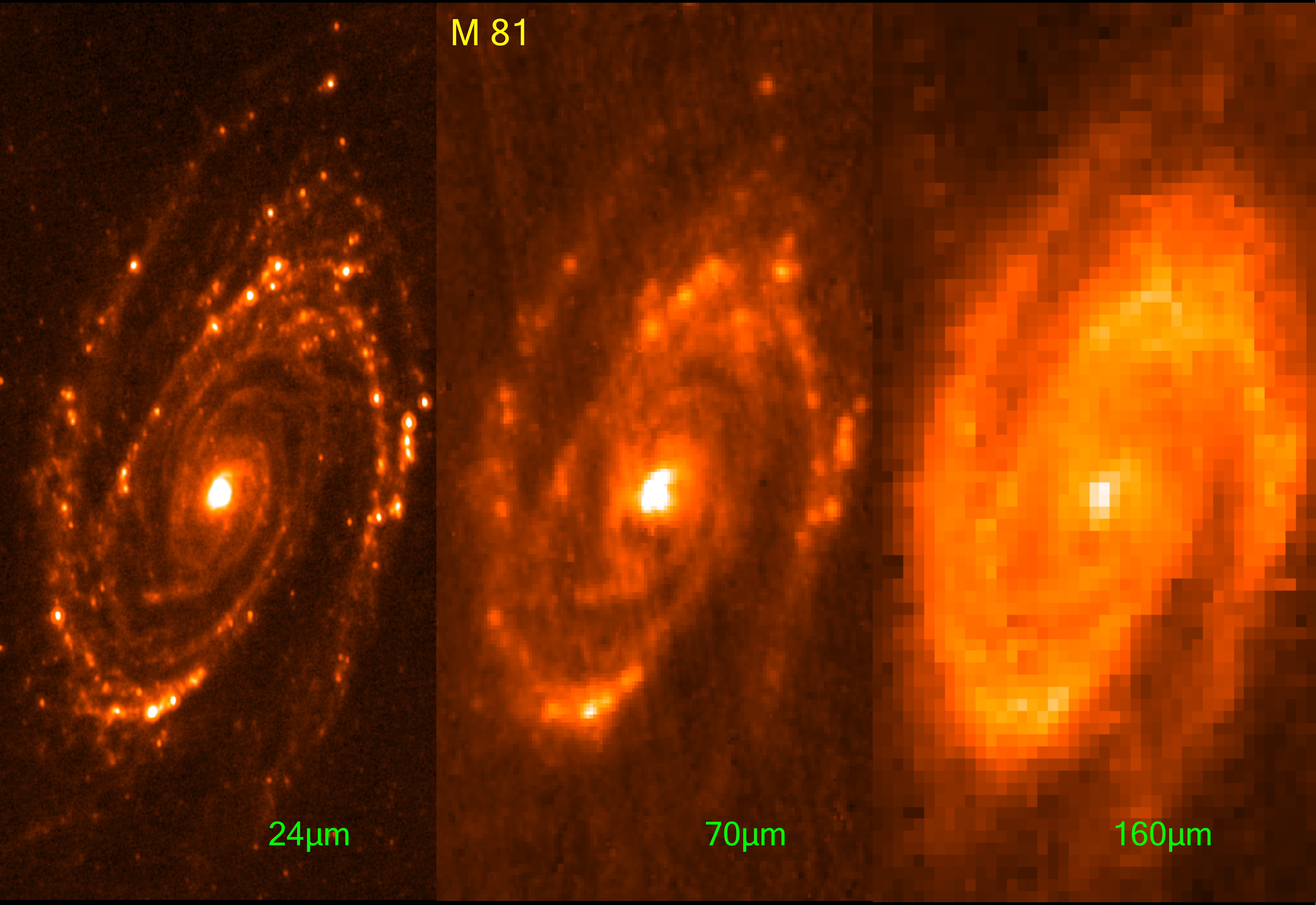
[a = 0.15 – 0.31]

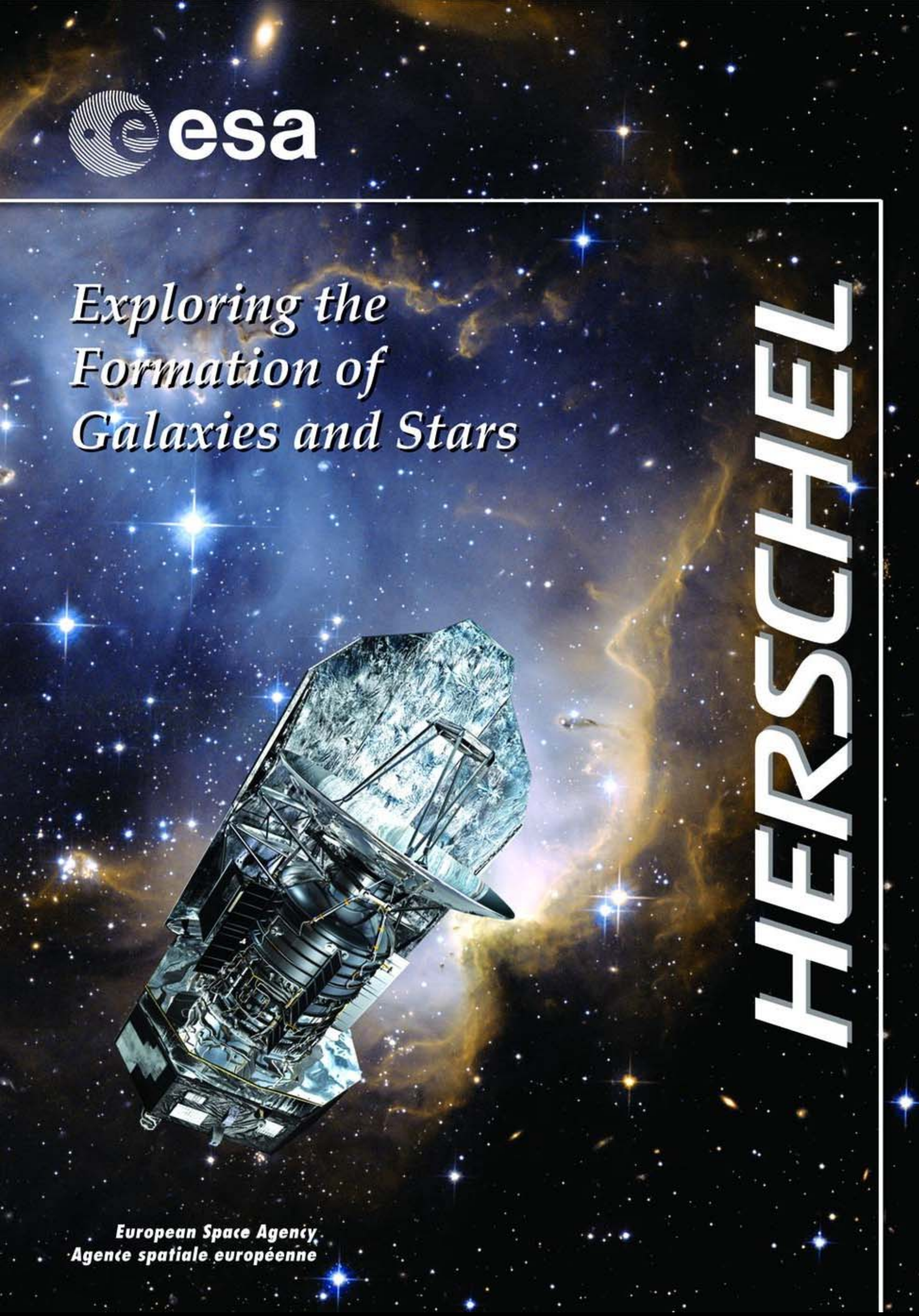
SFR (M_o yr^{-1}) = 4.5×10^{-44} [L(UV) + L (FIR)] (ergs/s)

General Points and Cautions

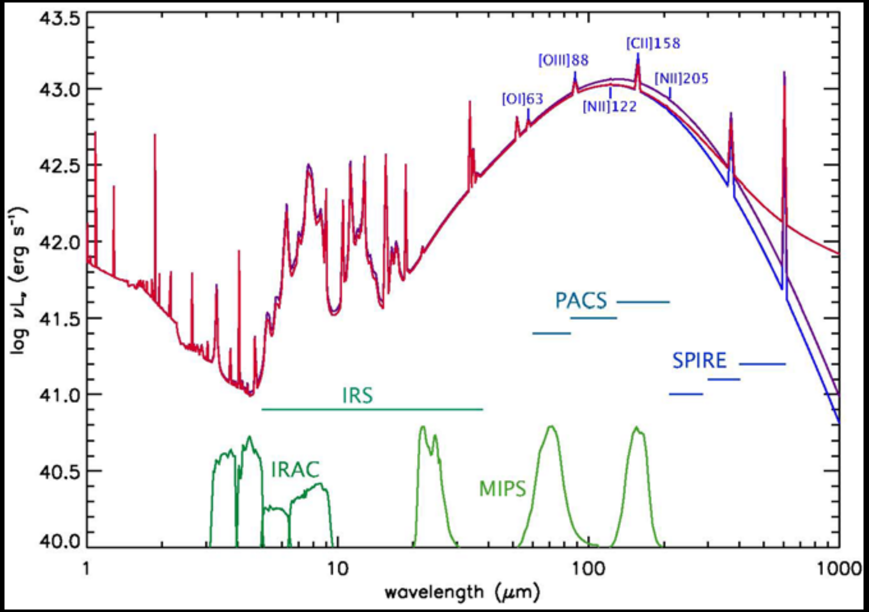
- Different emission components trace distinct stellar populations and ages
  - nebular emission lines and resolved 24 μm dust sources trace ionizing stellar population, with ages <5-10 Myr
  - UV starlight mainly traces "intermediate" age population, ages 10-200 Myr
  - diffuse dust emission and PAH emission trace same "intermediate" age and older stars– 10 Myr to 10 Gyr(!)
- Consequence: it is important to match the SFR tracer to the application of interest
  - emission lines – Schmidt law, early SF phases
  - UV – time-averaged SFR and SFR in low surface brightness systems
  - dust emission – high optical depth regions
- Multiple tracers can constrain SF history, properties of starbursts, IMF, etc.

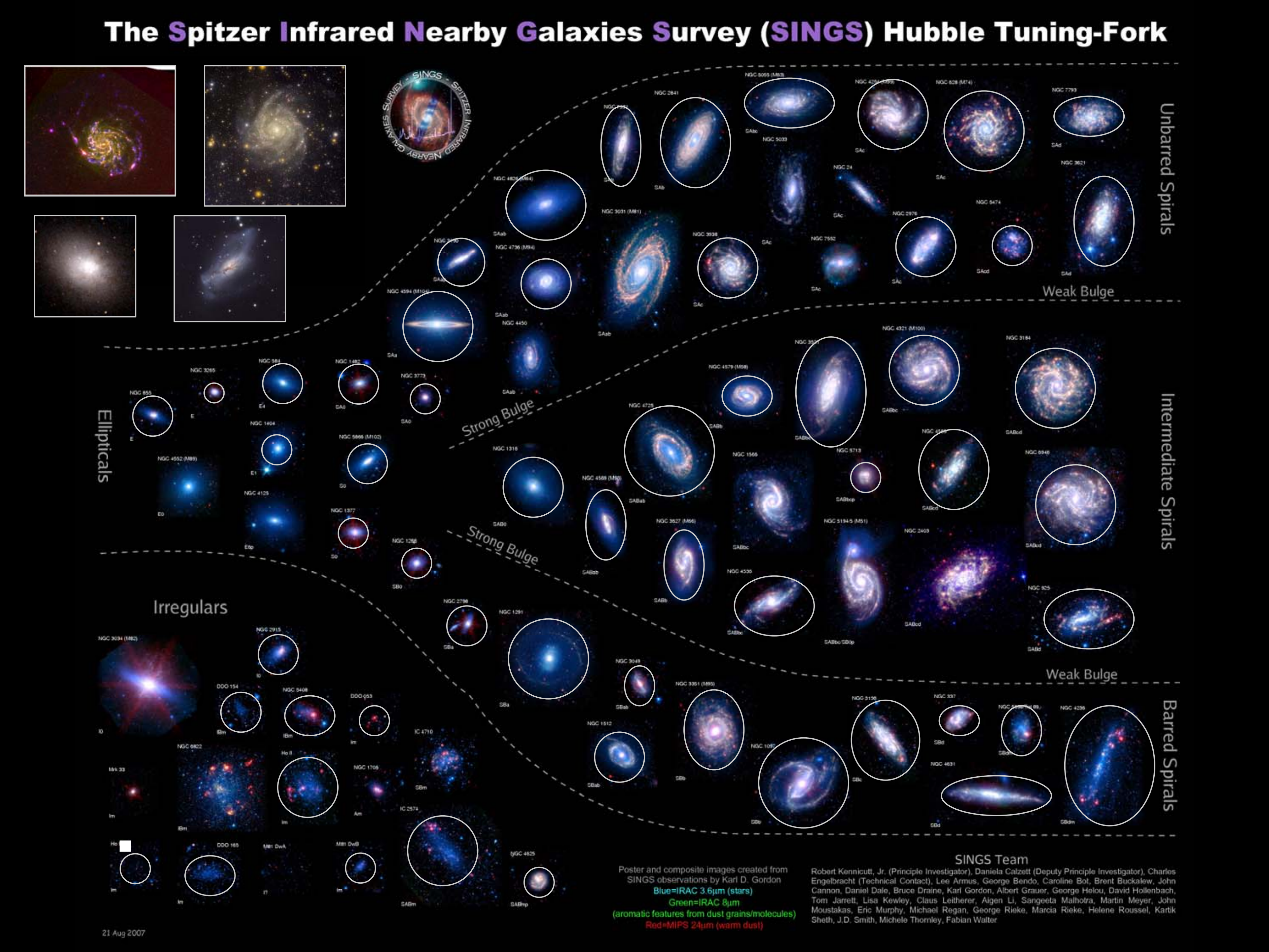

0-200 Myr
GALEX FUV + NUV (1500/2300 A)
0-5 Myr
Hα + R
0-10 Gyr
IRAC 8.0 μm
0-10 Myr + 0-10 Gy
MIPS 24 μm


M 81
24µm
70µm
160µm



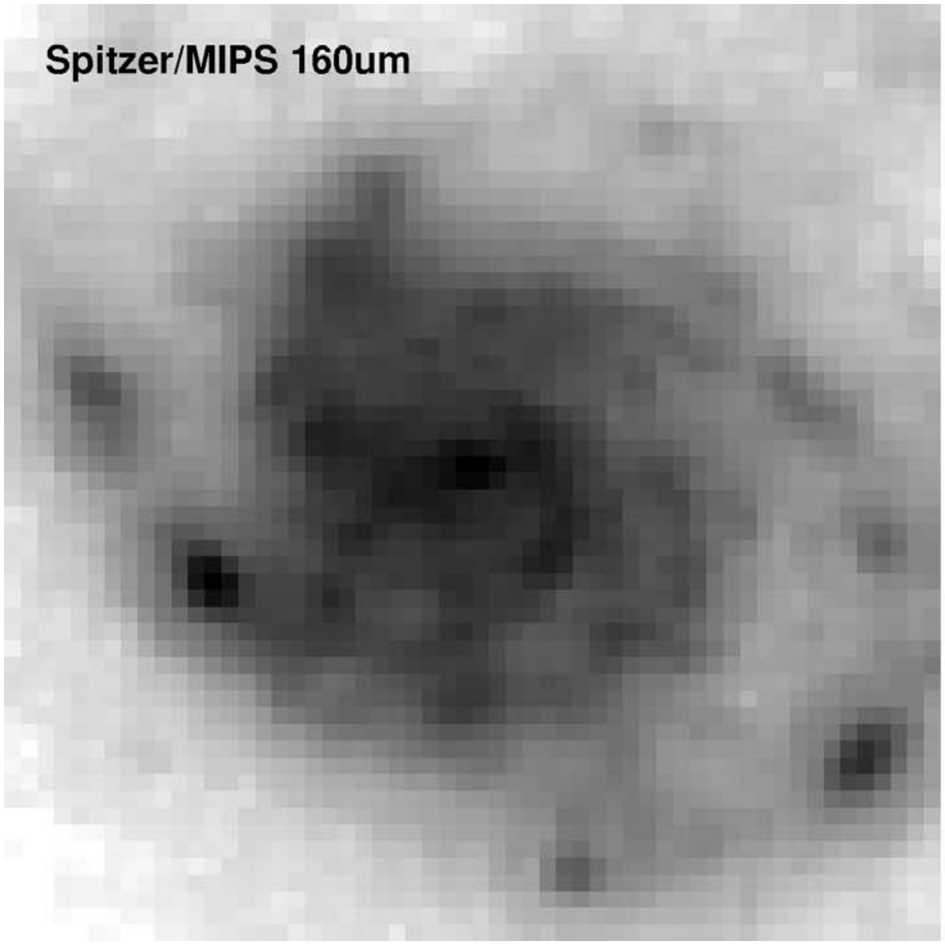
Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel (KINGFISH)

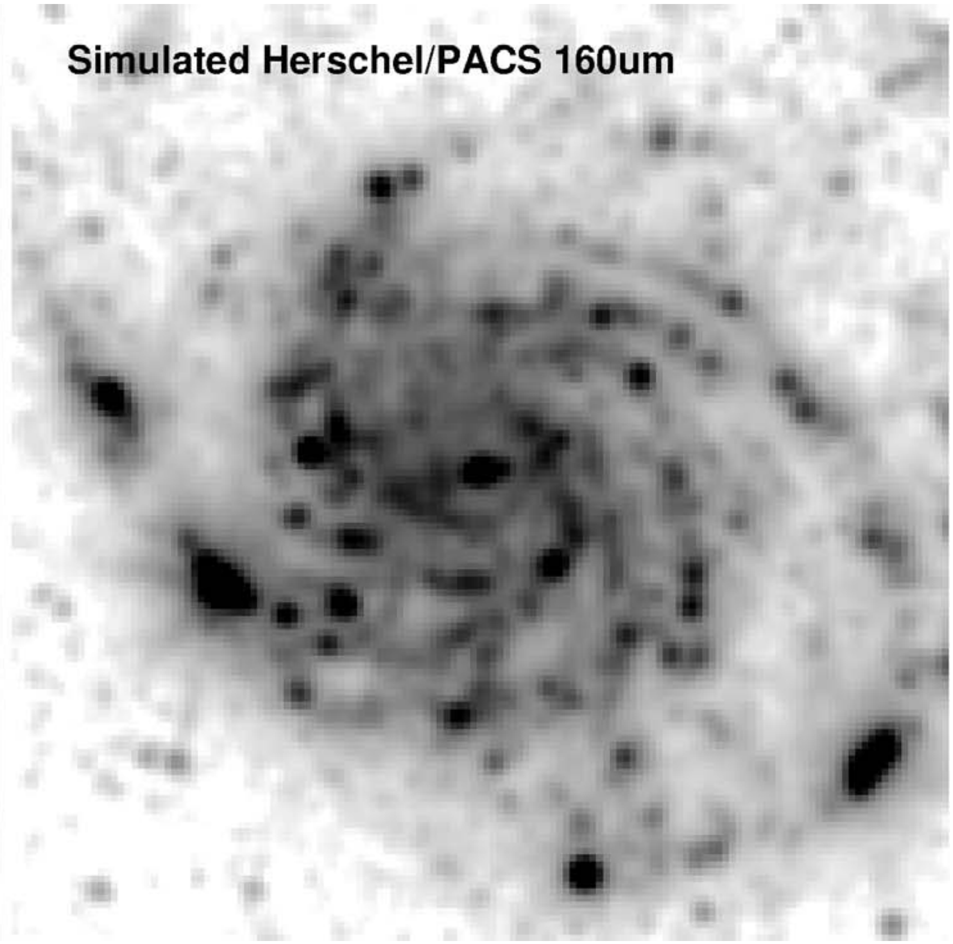


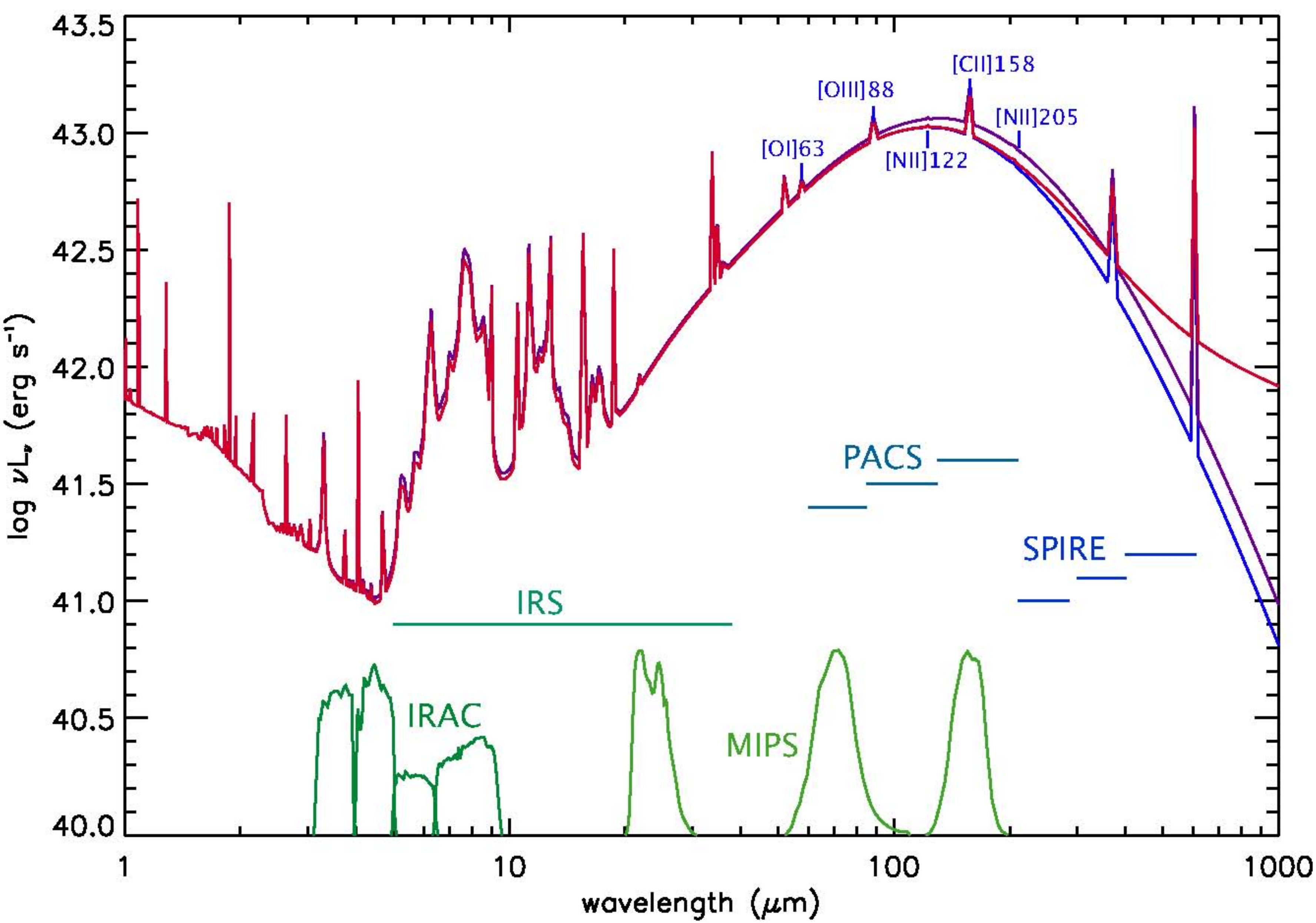


The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
SINGS - SPITZER INFRARED NEARBY GALAXIES SURVEY
Unbarred Spirals
Weak Bulge
Strong Bulge
Intermediate Spirals
Strong Bulge
Weak Bulge
Barred Spirals
Ellipticals
Irregulars
Poster and composite images created from SINGS observations by Karl D. Gordon
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, George Helou, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter
21 Aug 2007

M101: Spitzer vs Herschel Resolution Comparison







43.5
43.0
42.5
42.0
41.5
41.0
40.5
40.0
log νL_ν (erg s^{-1})
1
10
100
1000
wavelength (μm)
[OIII]88
[CII]158
[NII]205
[OI]63
[NII]122
PACS
SPIRE
IRS
IRAC
MIPS