Star Formation Rates from Dust

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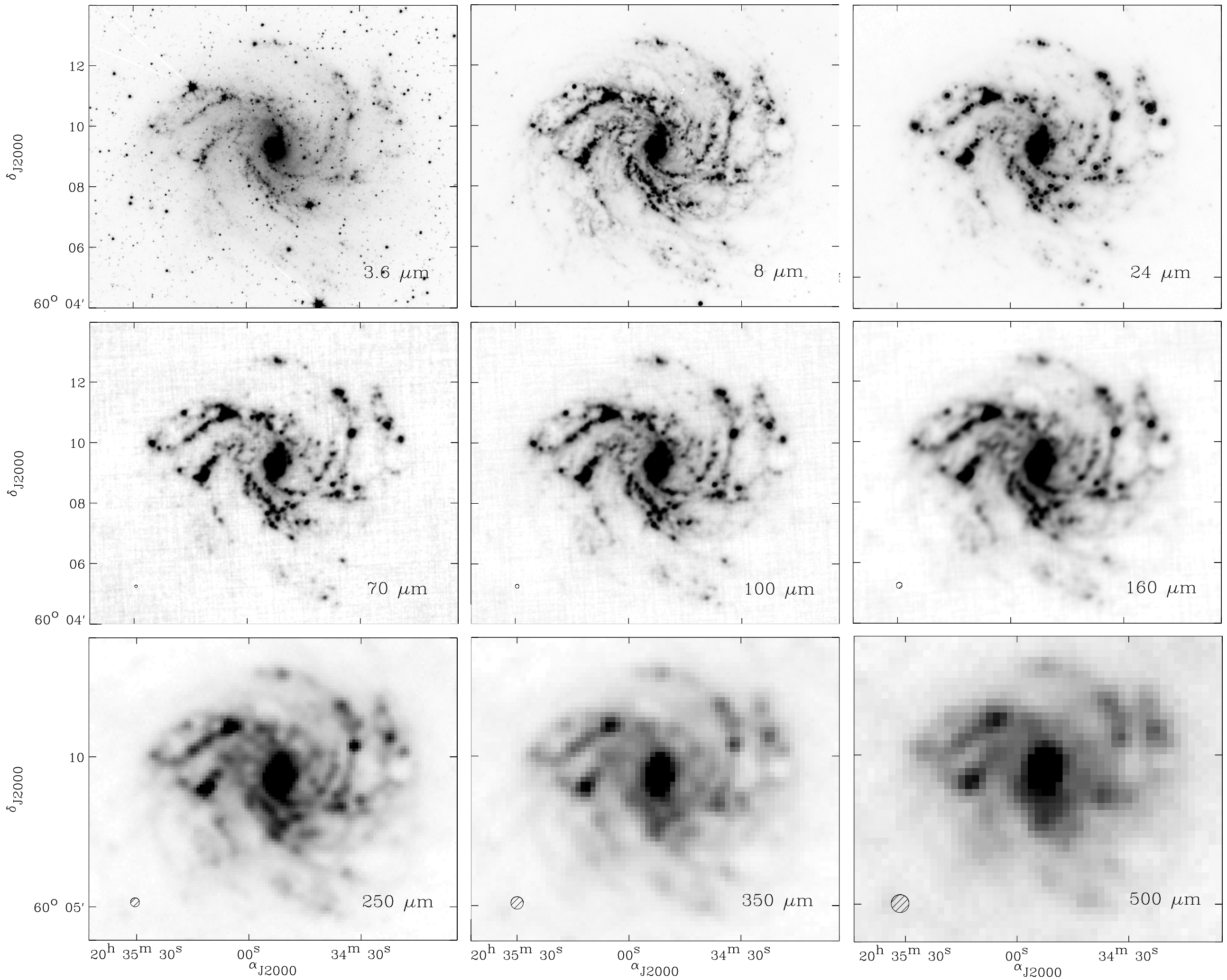

KINGFISH TEAM

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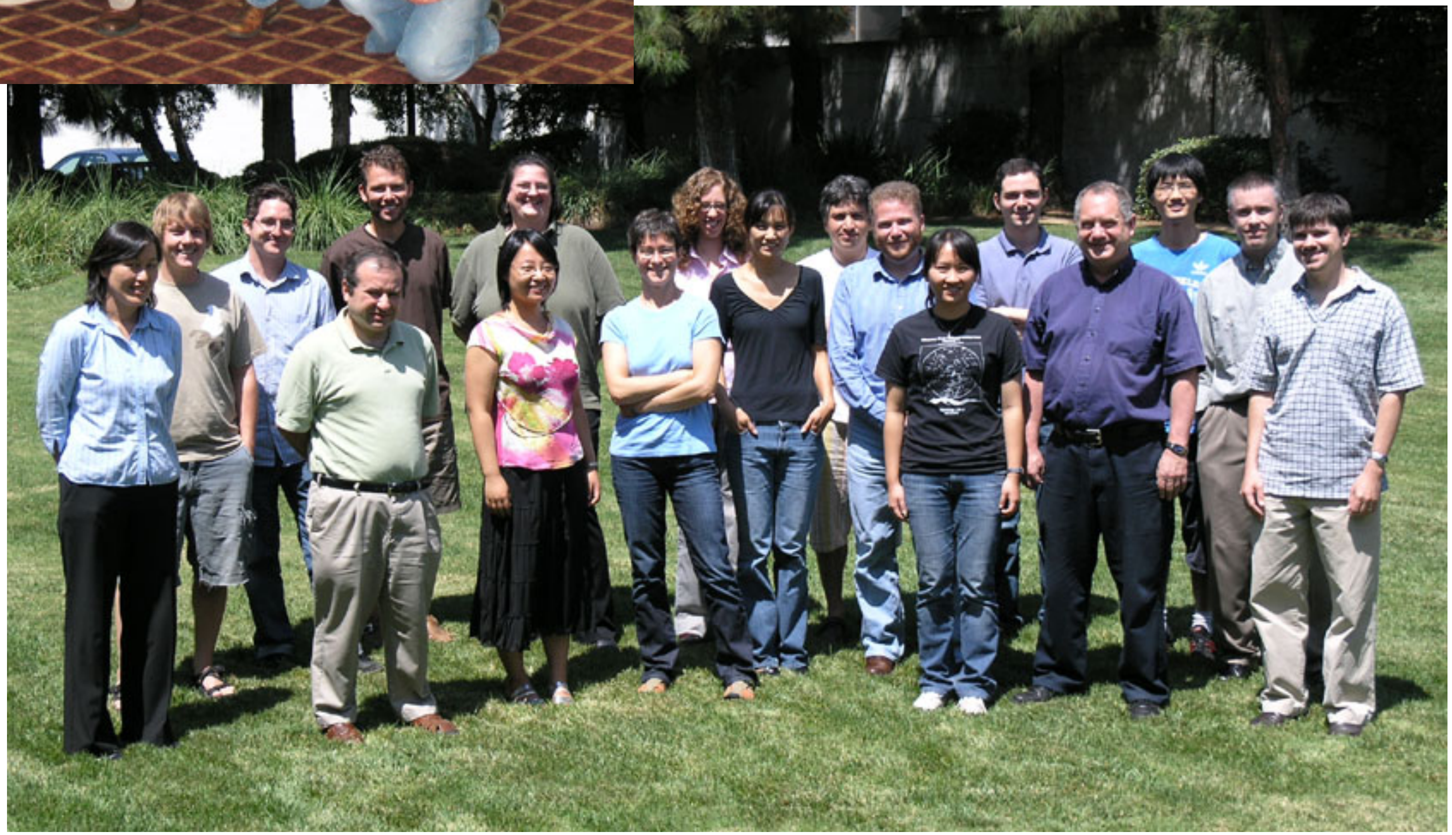
SINGS Team



LVL Team

Outline

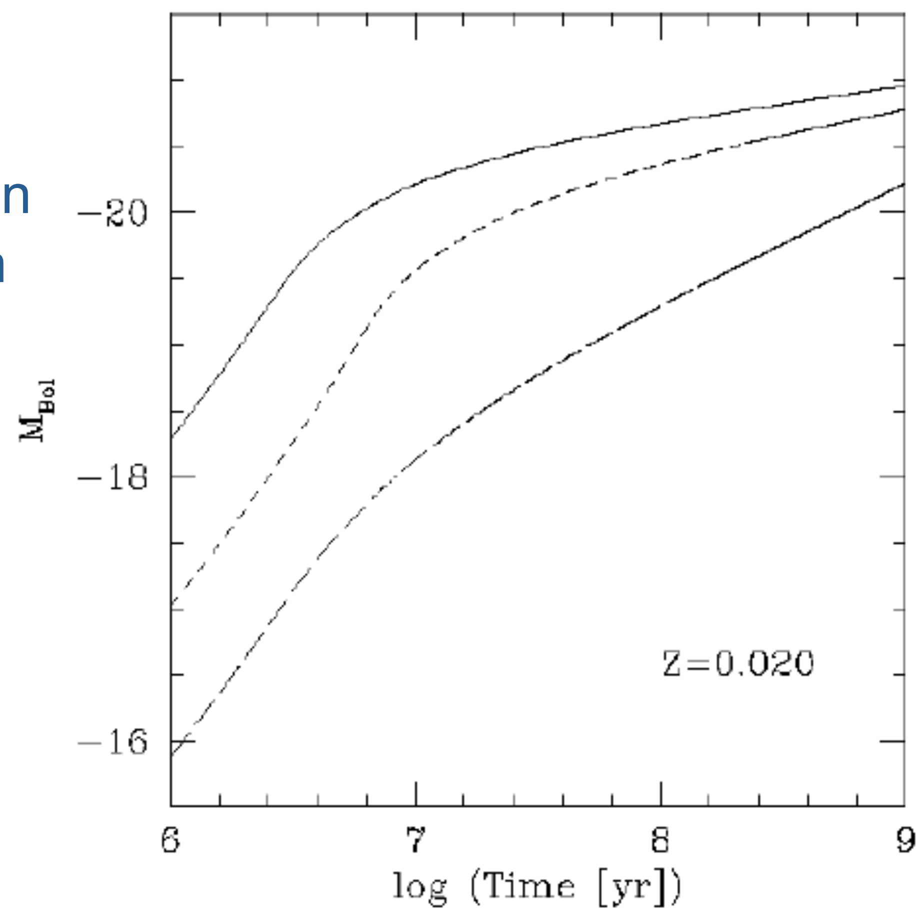
- integrated star formation rates
  - bolometric dust tracers
  - monochromatic dust tracers
  - multi-wavelength tracers
- the new challenge: spatially-resolved SFRs
- the future

Basic Idea : Energy Balance

- For a completely embedded SF region the dust reprocesses the bolometric luminosity of a [galaxy, starburst…]
- This provides a rock-solid conversion of integrated IR luminosity to SFR in the limit of:
  - complete dust absorption
  - young stars dominate the starlight
  - a fully populated IMF
  - stellar age is constrained

- K98: SFR = 4.5e-44 L_{TIR}
  (Salpeter IMF, <t> ~ 30 Myr)

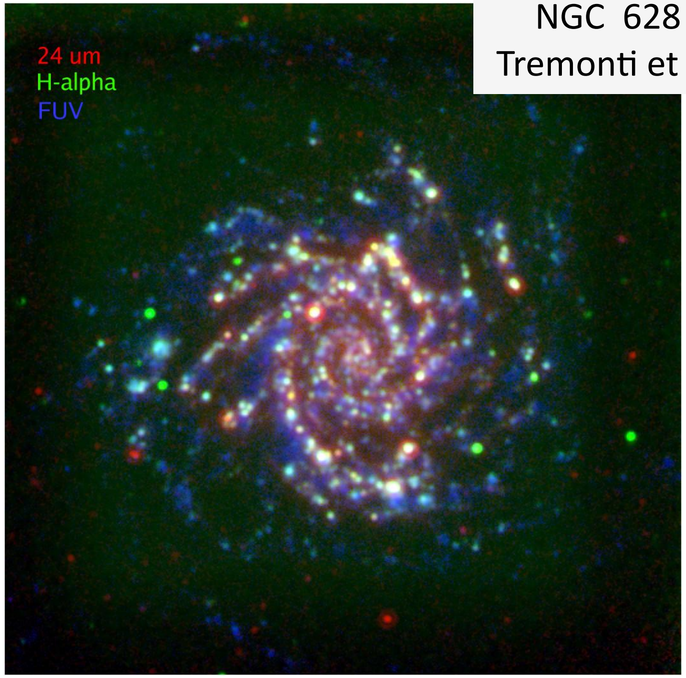
- This limit approximately applies in most LIRGs and ULIRGs



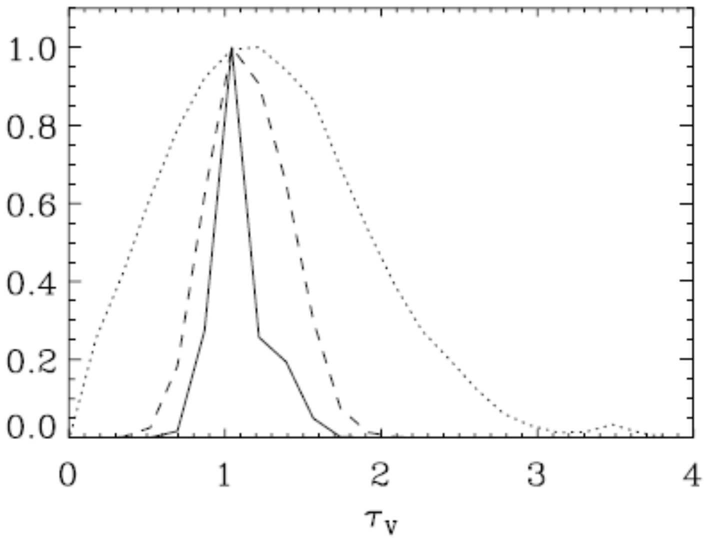
Starburst99
Leitherer et al. 1999

Real Galaxies

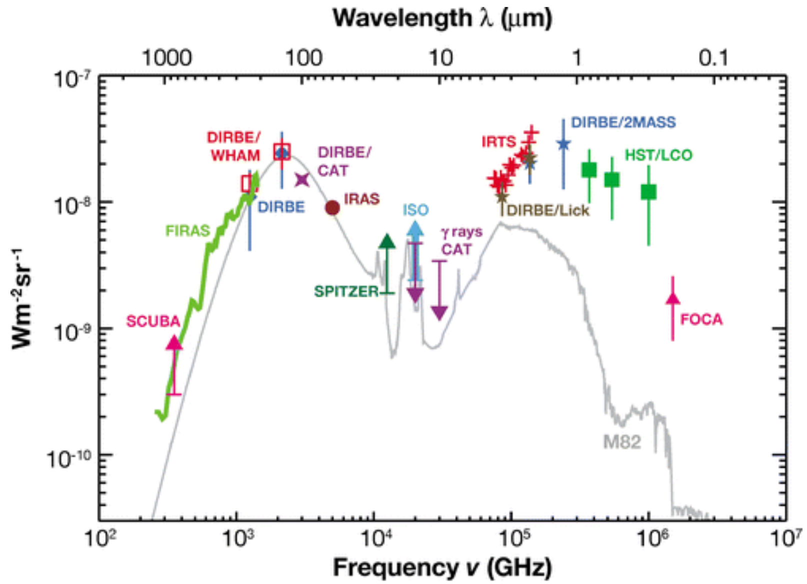
- dust opacity is finite
  - for normal spirals (and the Universe!) attenuated fraction is ~50%
  - consequently dust emission only accounts for approximately half of the SFR
  - attenuated fraction varies dramatically, from nearly 0% to nearly 100%
  - attenuation varies locally and systematically with radius, gas density



NGC 628
Tremonti et al.

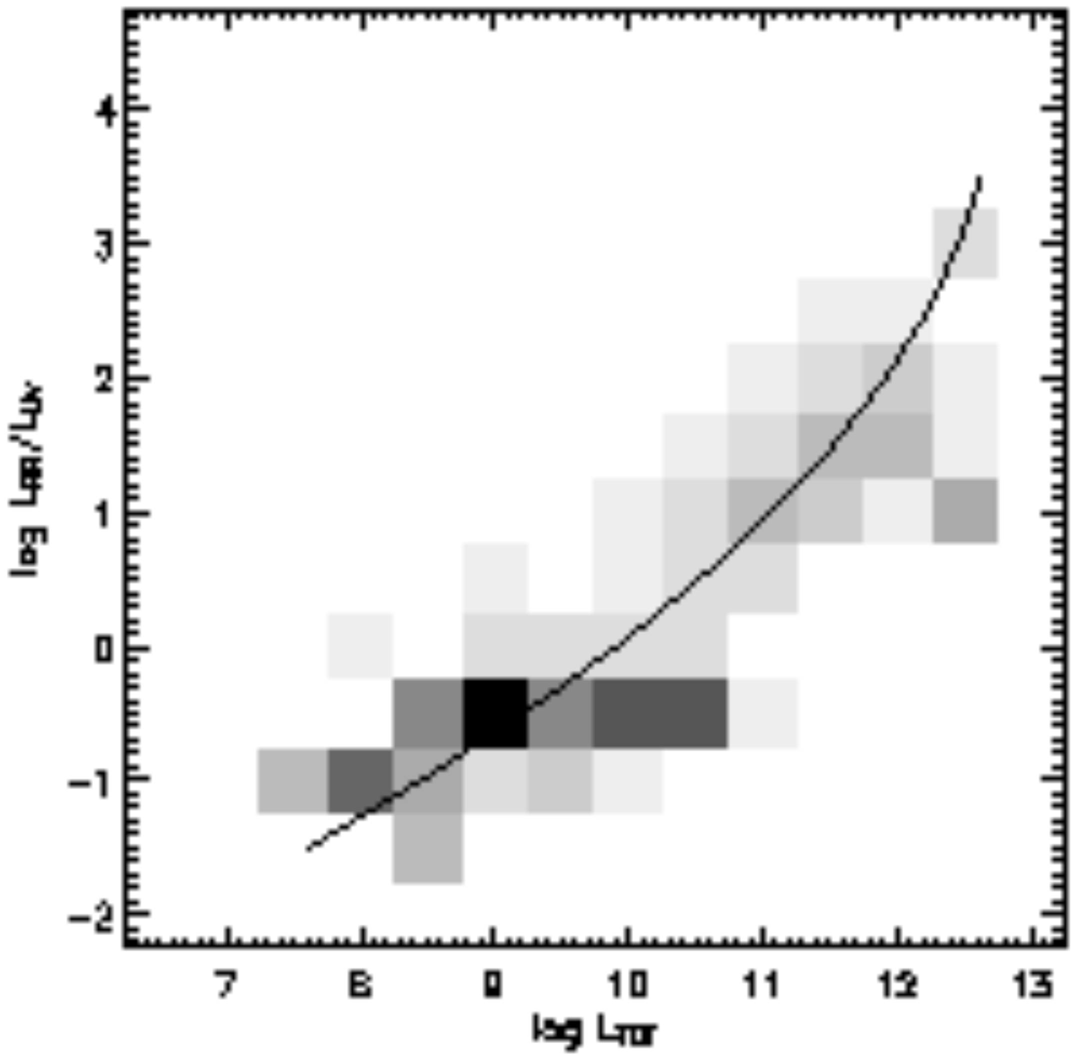


Brinchmann et al. 2004 (SDSS galaxies)



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

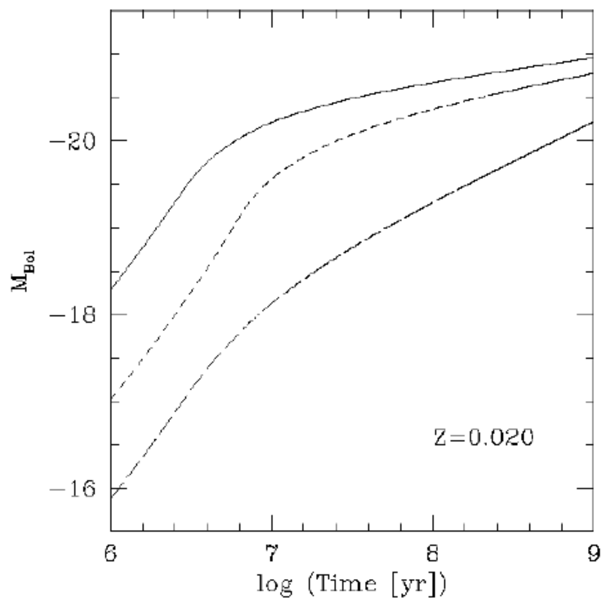
Characteristic dust opacity increases with the SFR itself

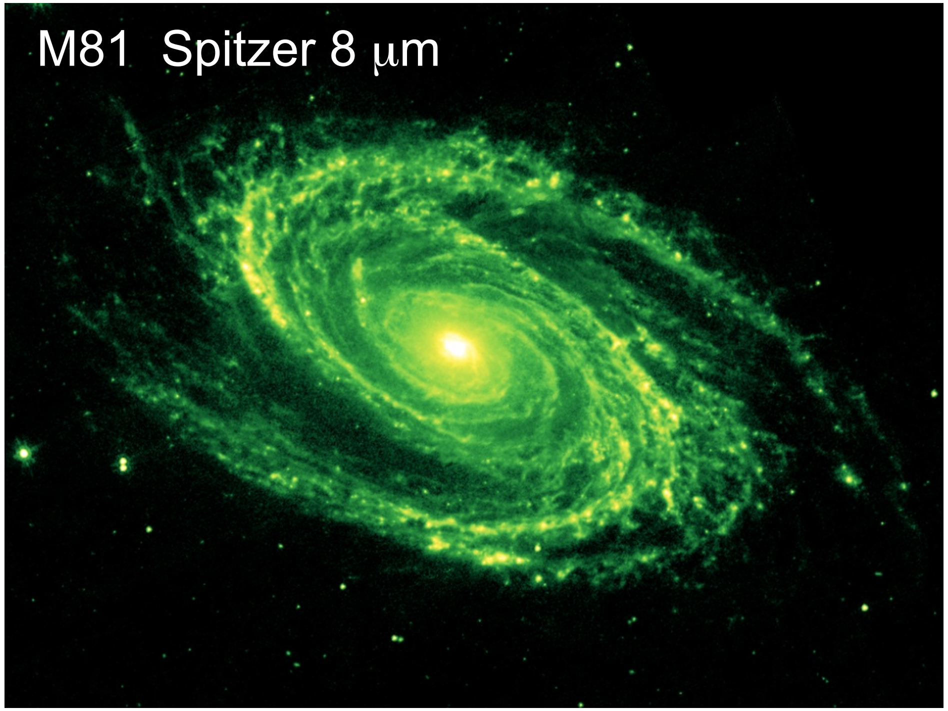


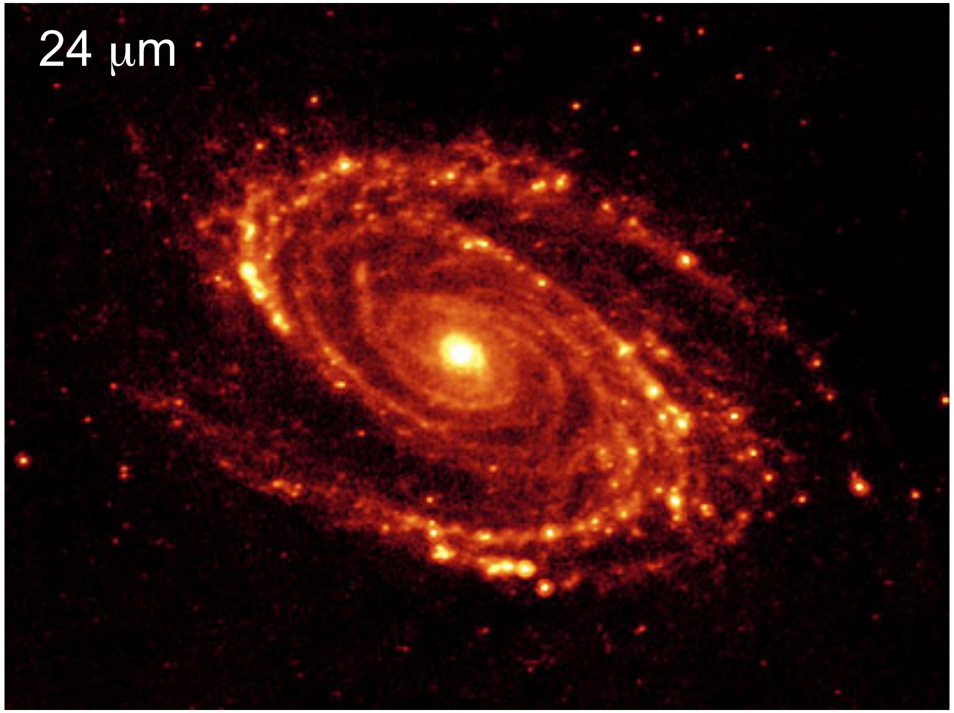
Martin et al. 2005, ApJ, 619, L59

Real Galaxies

- some dust is heated by “evolved” stars (>100 Myr) -- the infamous IR cirrus problem
  - cirrus contribution dependent on SF history of region and age-opacity profile
  - so the starburst SFR calibration should not work
- emission of dust correlated with illuminating intensity and optical depth

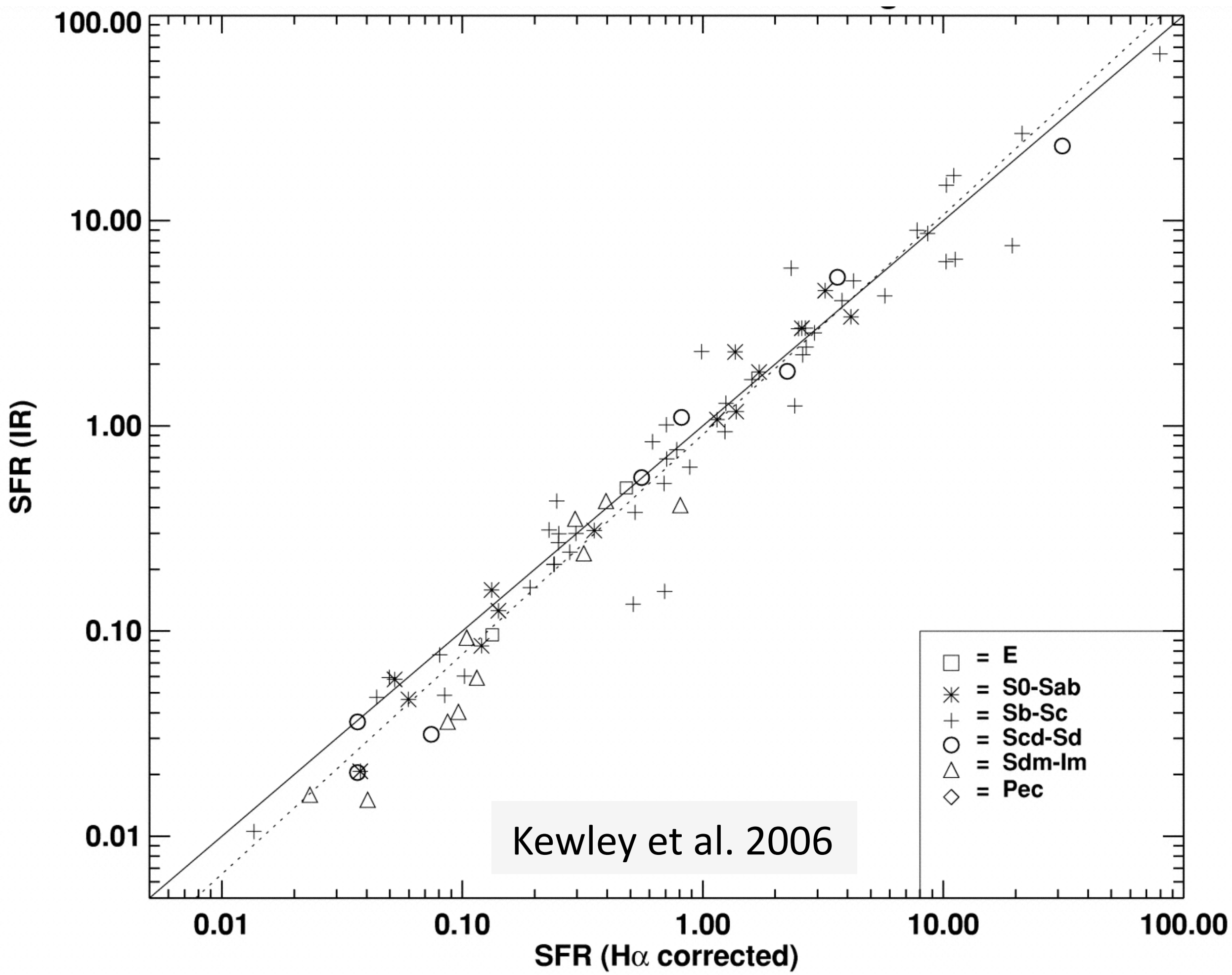






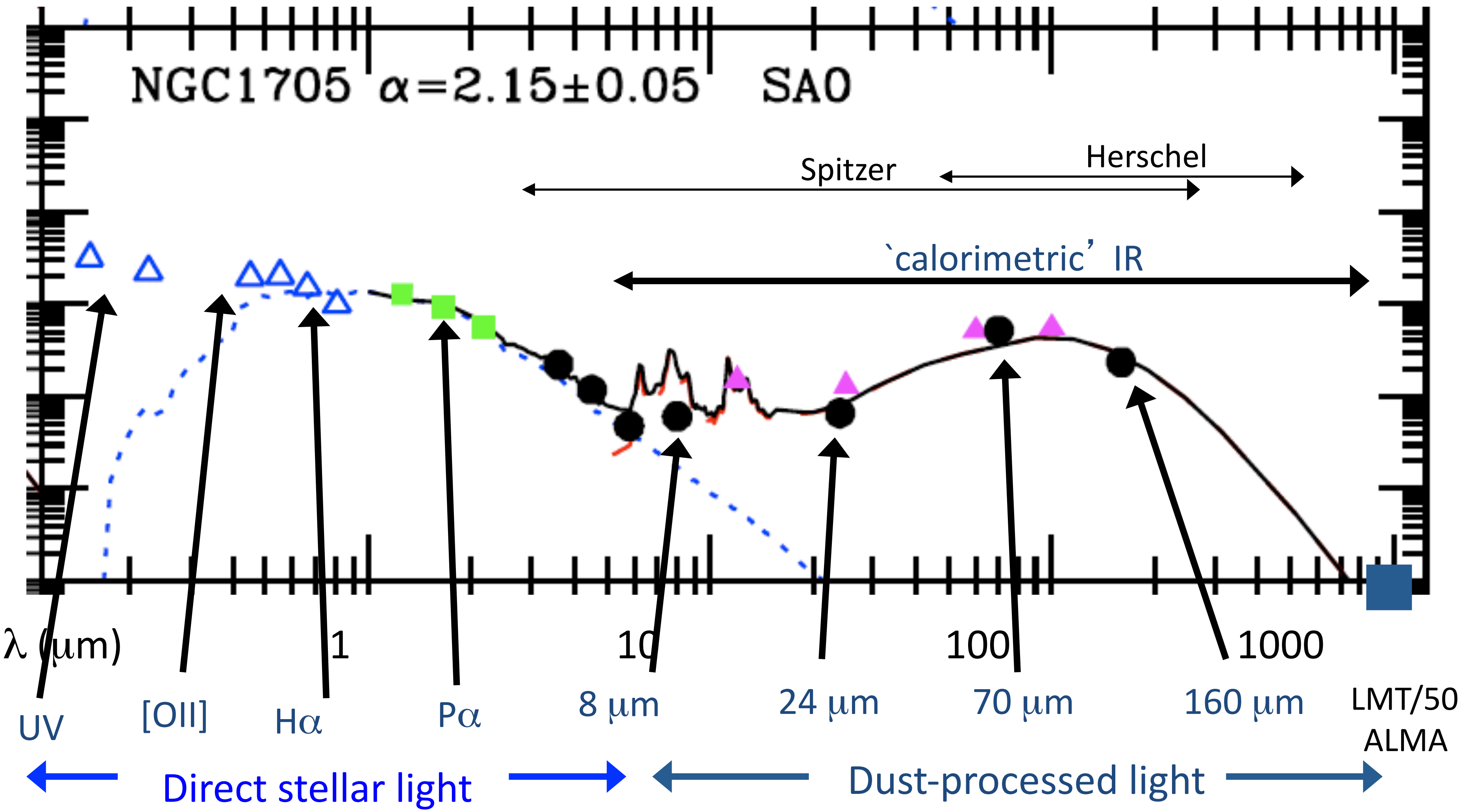
Comparison: NFGS

Kennicutt (1998) starburst recipe(!)



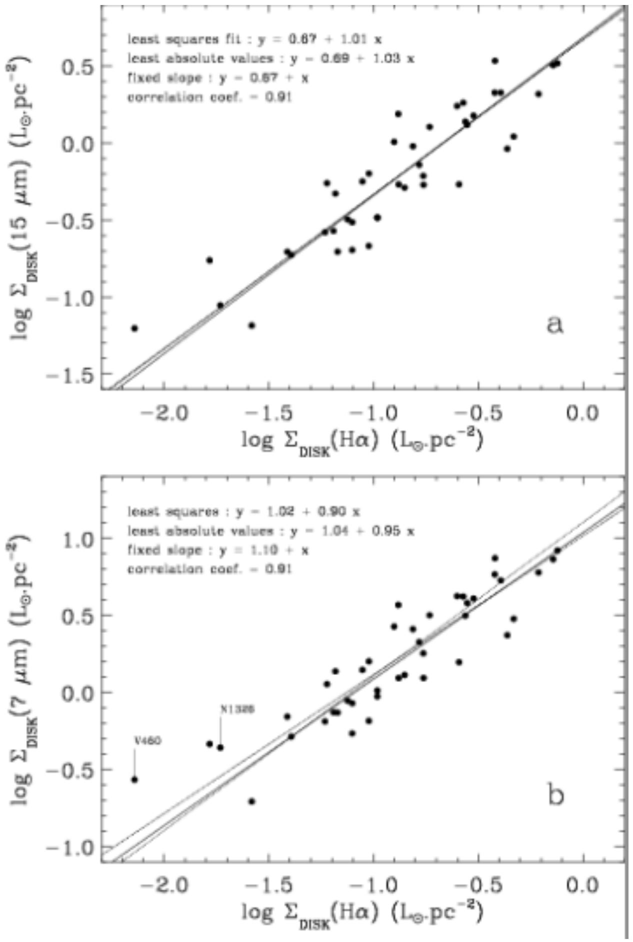
Despite these biases the dust-based SFRs (w/SB recipe) are consistent!
Explanation: The opacity and cirrus effects roughly cancel in this sample.
Errors can be much larger in more diverse samples of galaxies.

“Monochromatic” SFR Tracers

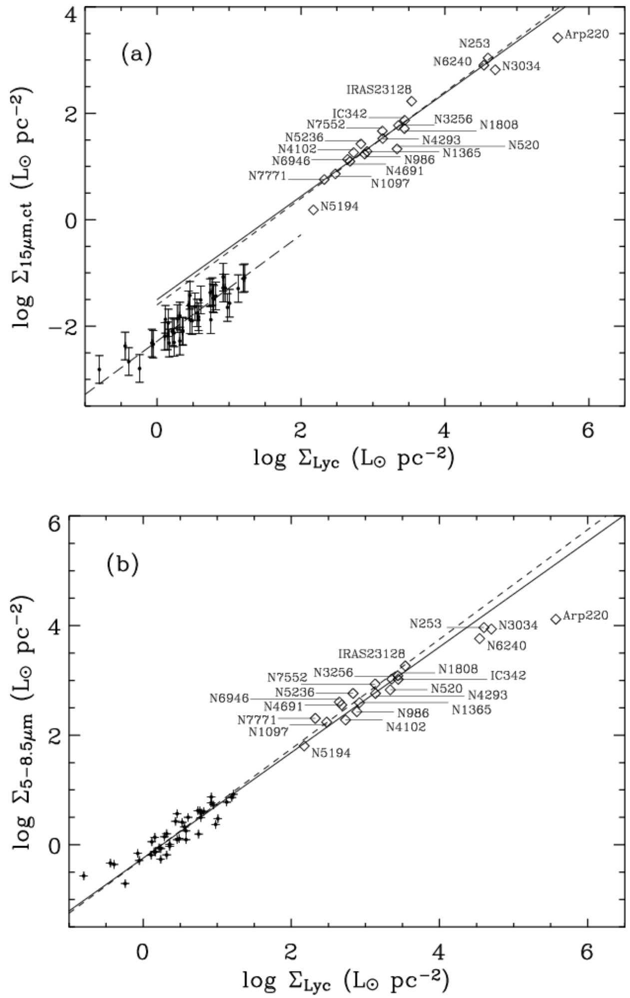


SFR(mid-IR)$_{PAH}$

ISO enabled the first studies of monochromatic IR emission as SFR tracers, specifically in the UIB=AFE=PAH bands

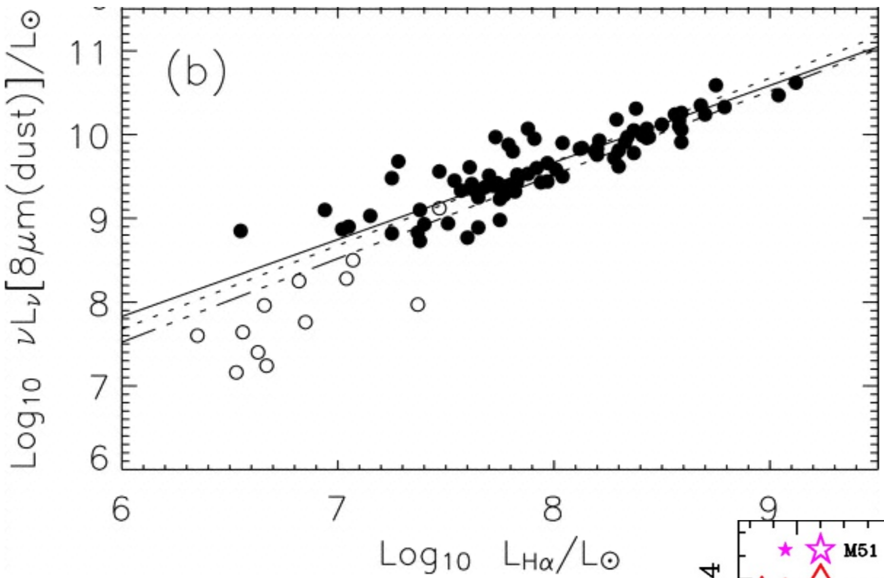


Roussel et al. 2001

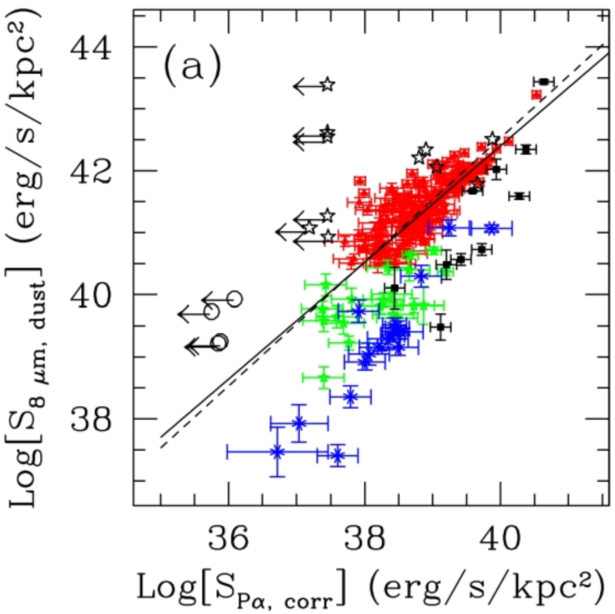


Forster-Schreiber et al. 2004

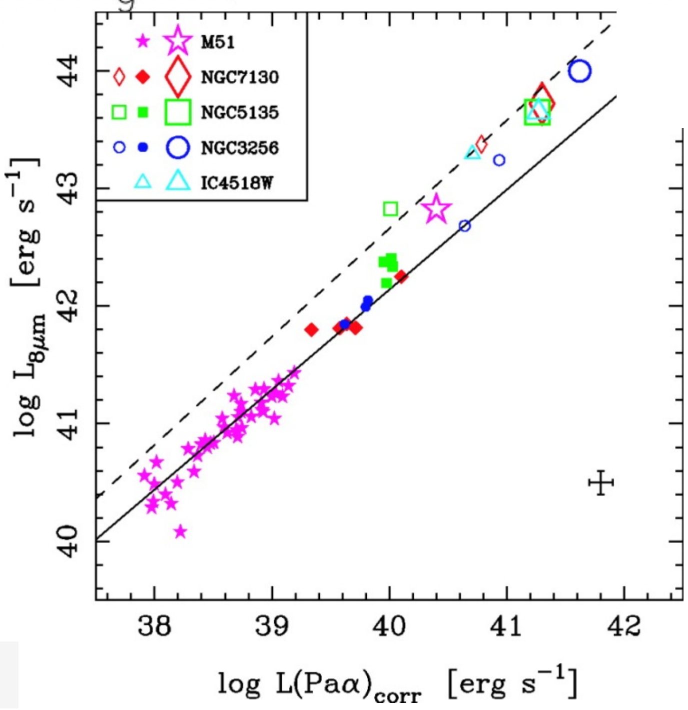
Spitzer extended this work… SFR(8)



Wu et al. 2005



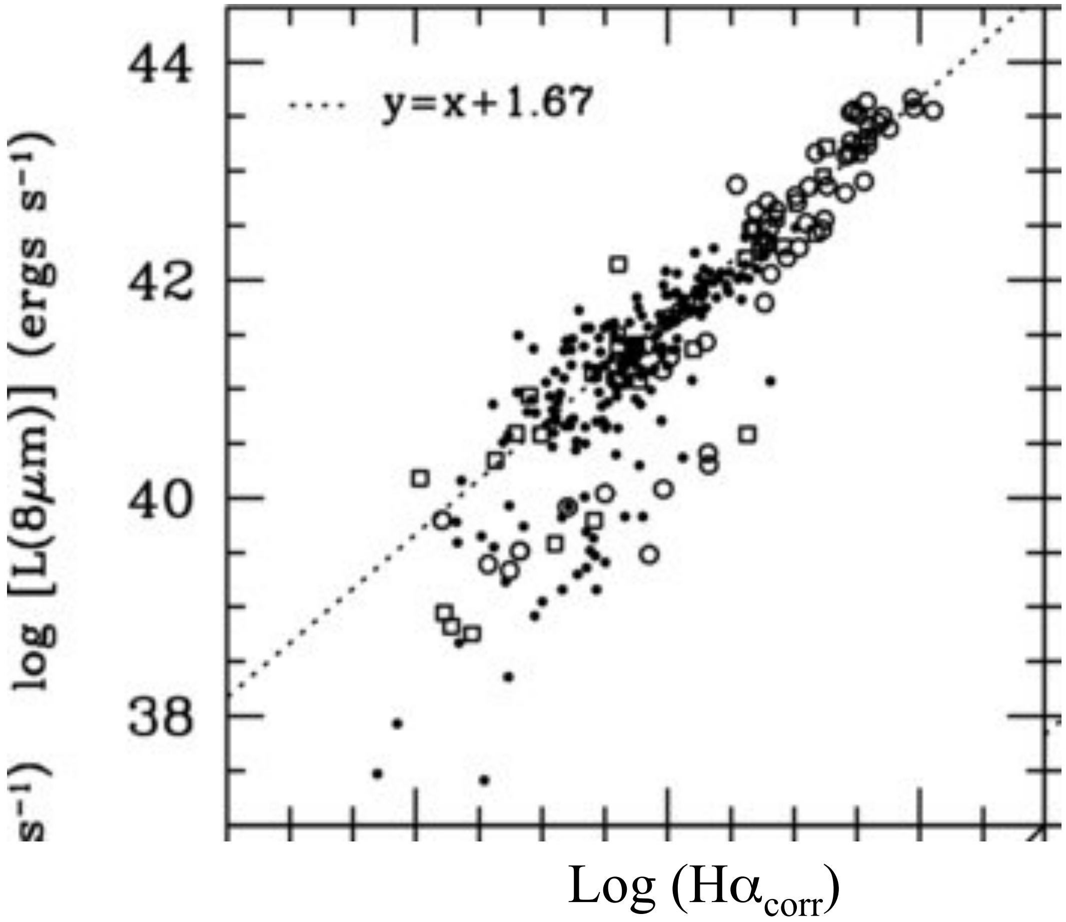
Calzetti et al. 2007



Alonso-Herrero et al. 2006

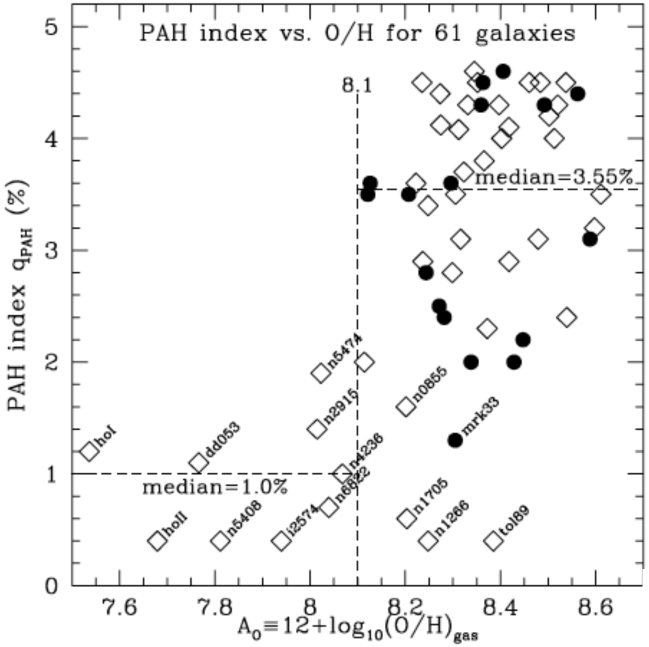
Common Features

1. A linear or slightly sub-linear correlation between L(PAH) and SFR
2. A strong dependence on metallicity;
3. Possibly offset between HII regions and galaxies calibrations: ~< 0.1 dex

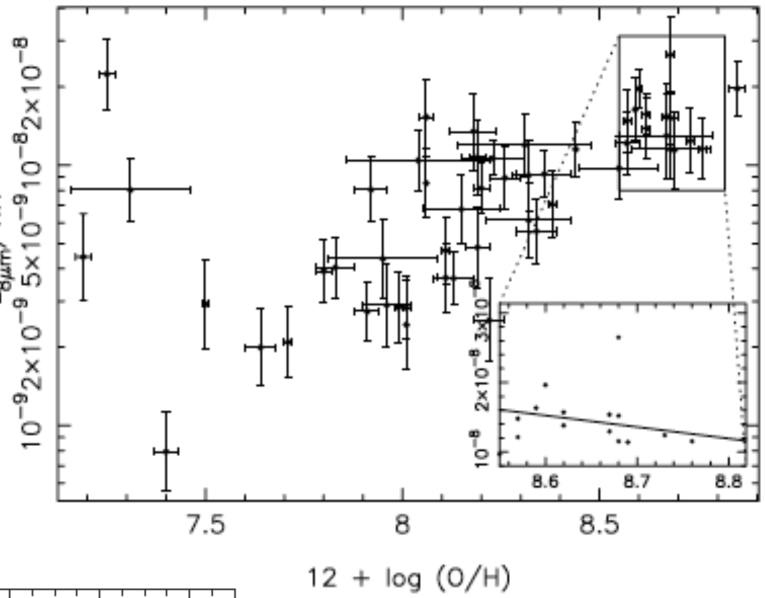


Kennicutt et al. 2009

Dependence on Metallicity

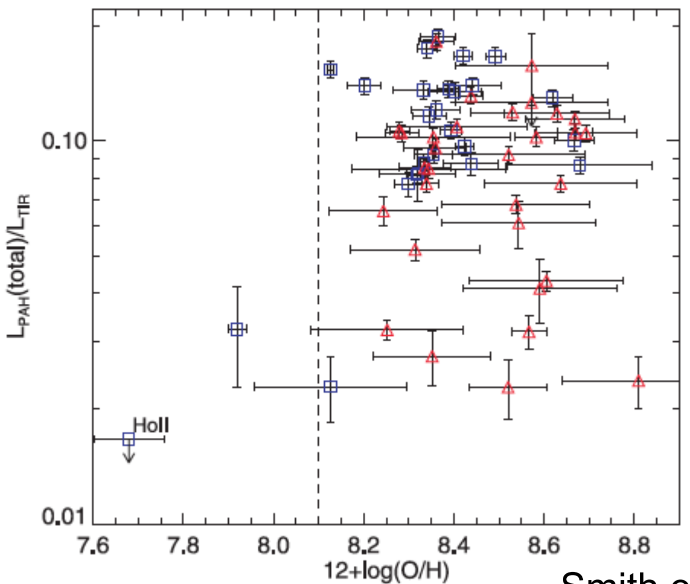


Draine et al 2007



Engelbracht et al. 2008

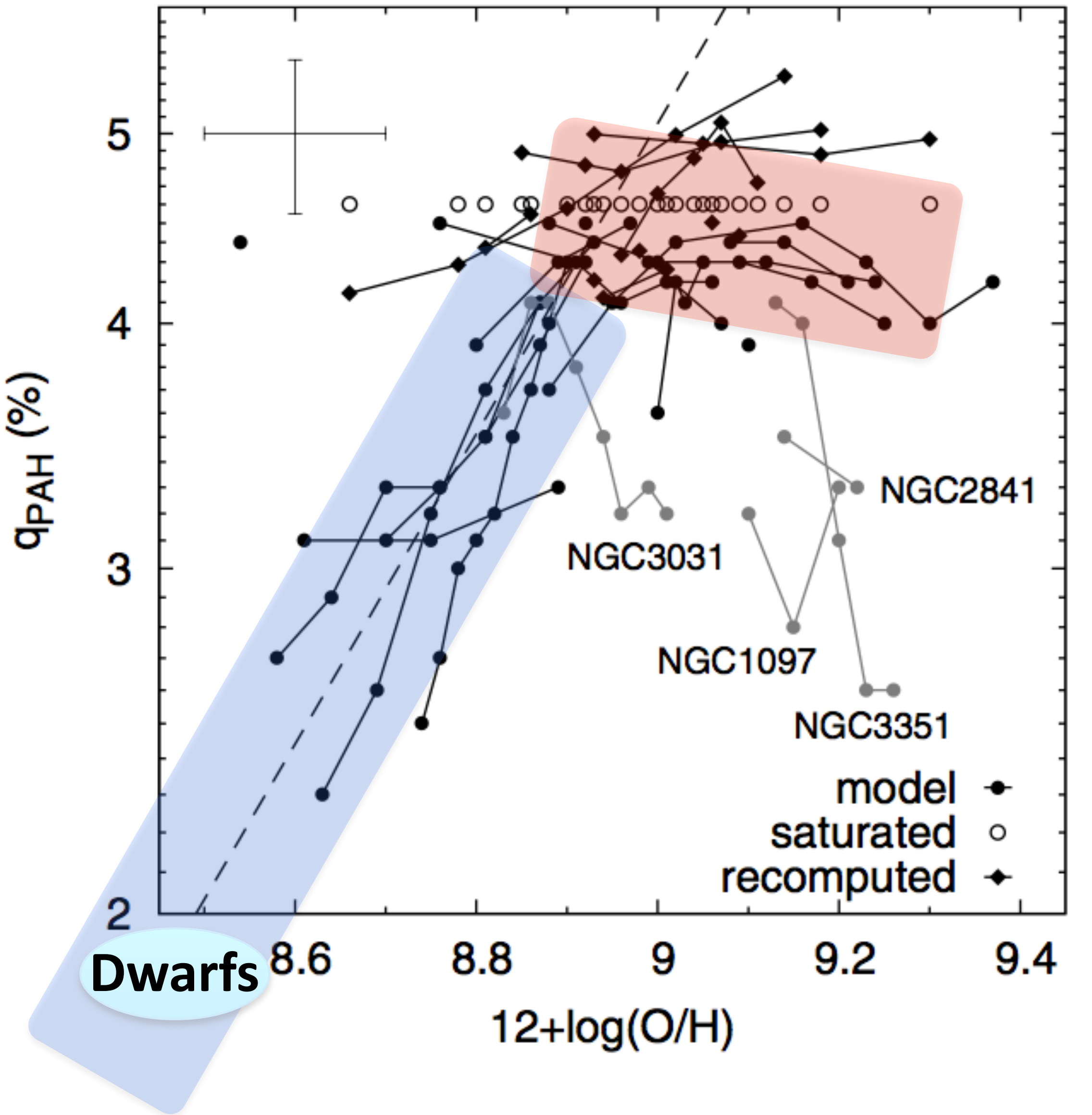
Boselli et al. 2004, Madden et al. 2006, Engelbracht et al. 2005, Hogg et al. 2005,Galliano et al. 2005,2008, Rosenberg et al. 2006, Wu et al. 2006, Munoz-Mateos et al. 2009, Marble et al. 2010



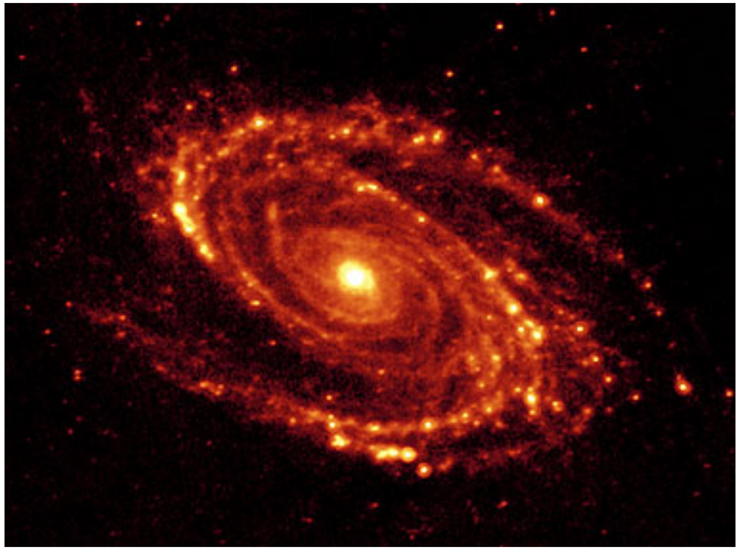
Smith et al. 2007

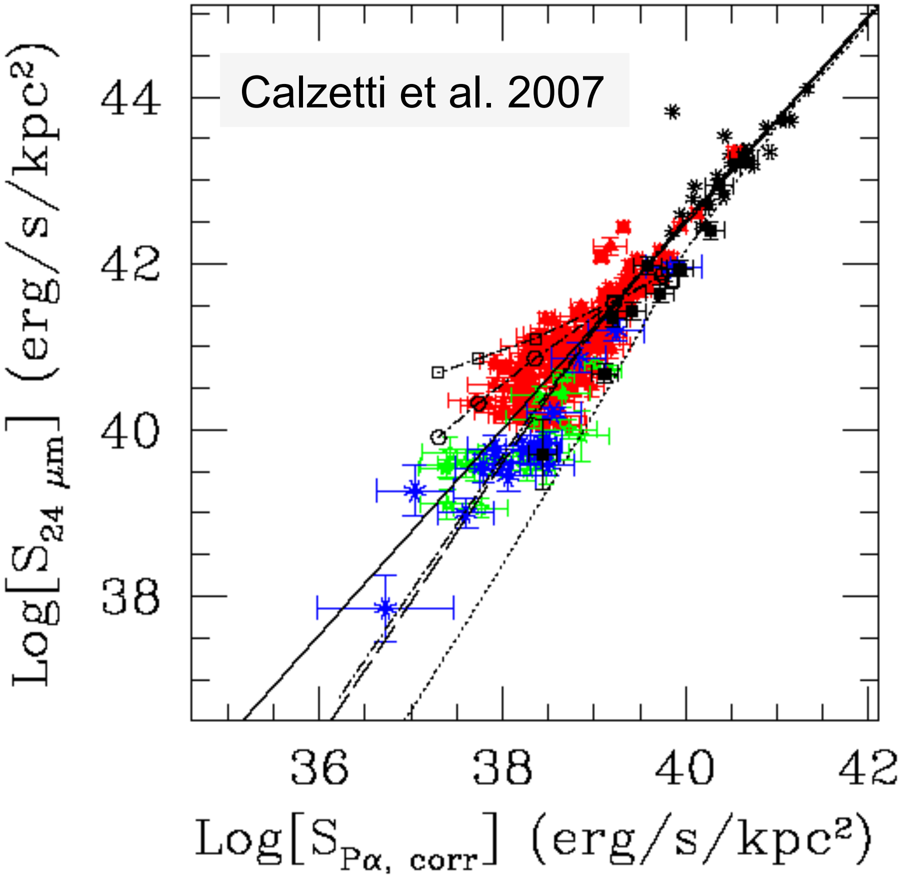
Trend observed also in radial profiles (Gordon et al. 2008; Munoz-Mateos et al. 2009)

Munoz-Mateos et al. 2009

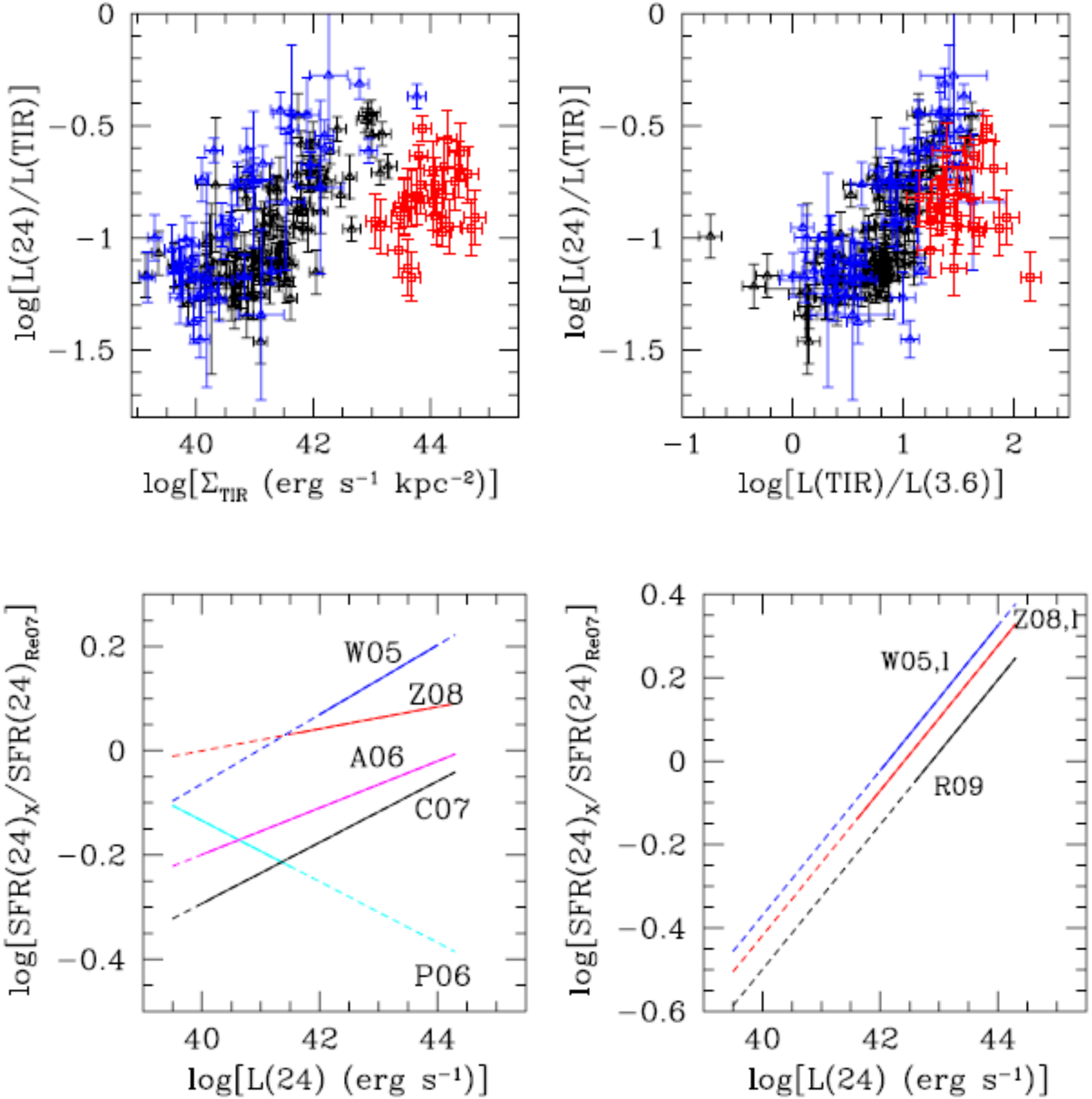


24 μm Emission – SFR(24)





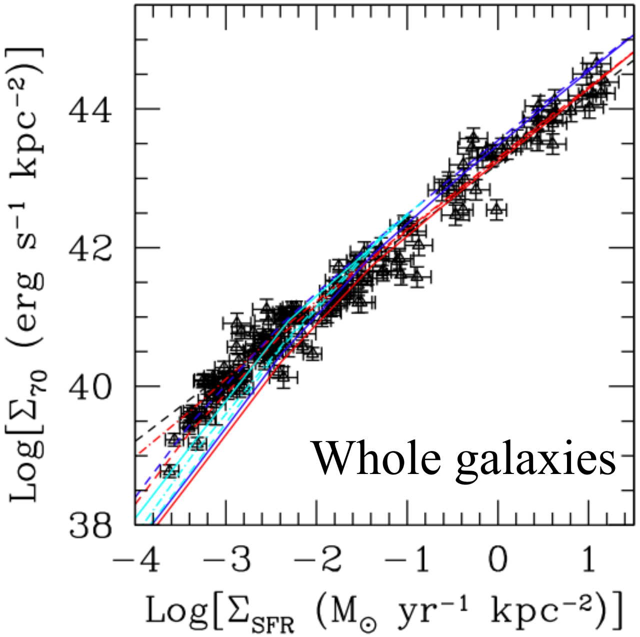
Wu et al. 2005; Alonso-Herrero et al 2006; Perez-Gonzalez et al. 2006; Calzetti et al. 2007; Prescott et al. 2007; Relano et al. 2007; Zhu et al. 2008; Rieke et al. 2009; Calzetti et al. 2010



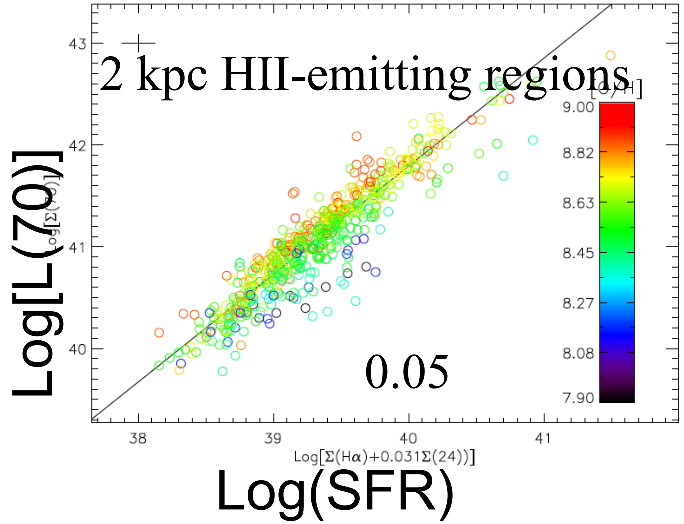
Calzetti et al. 2010

SFR(70)

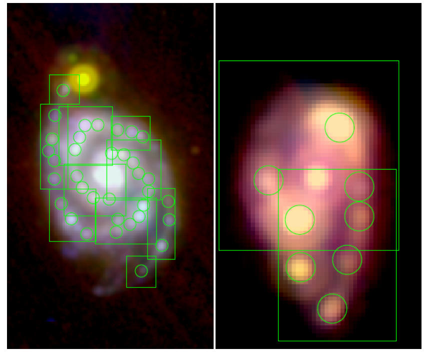
Mostly linear….



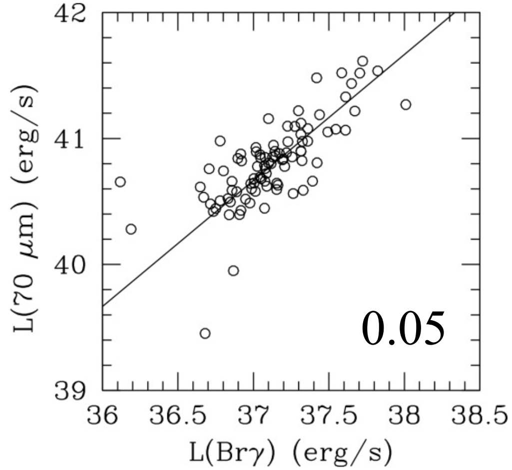
Calzetti et al. 2010; 190 galaxies



Y. Li et al. 2010; 550 regions



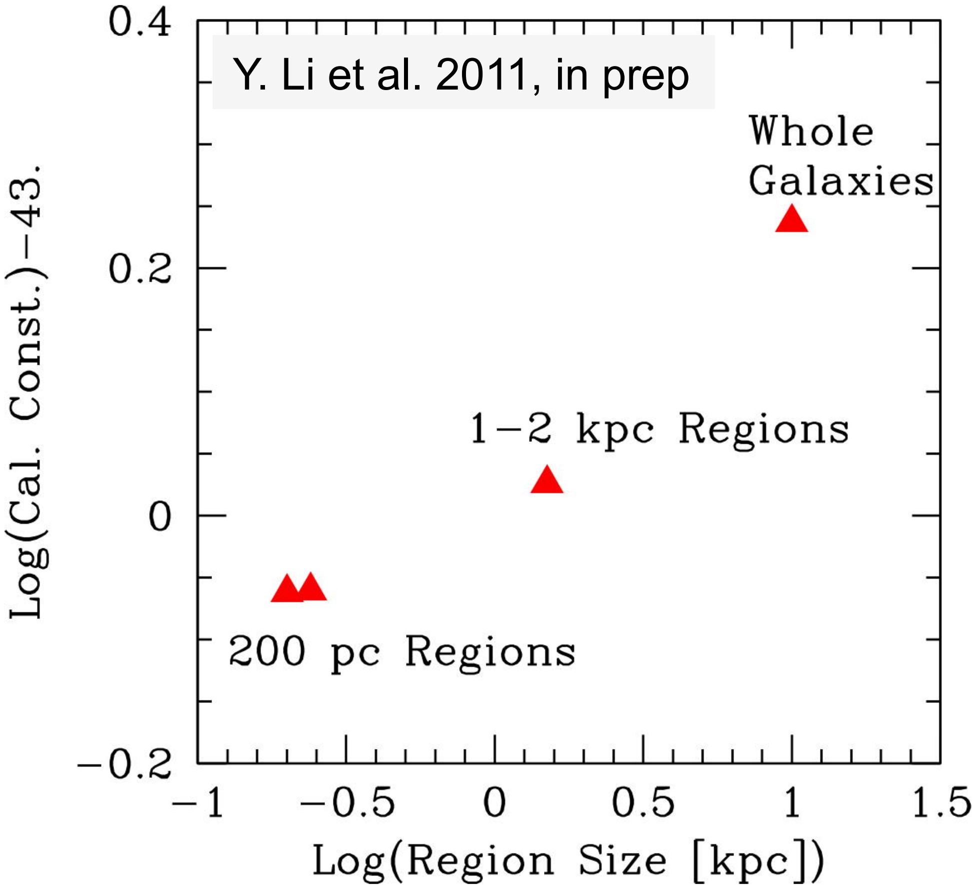
HII regions (200 pc)



Y. Li et al. 2011, Herschel PACS/70 +ground-based Brg; 200 regions

The relation between 70 μm and SFR is generally linear, in whole galaxies, in ~2 kpc-size HII-emitting regions, and in ~200 pc regions. However, …

SFR(70) Normalization Changes

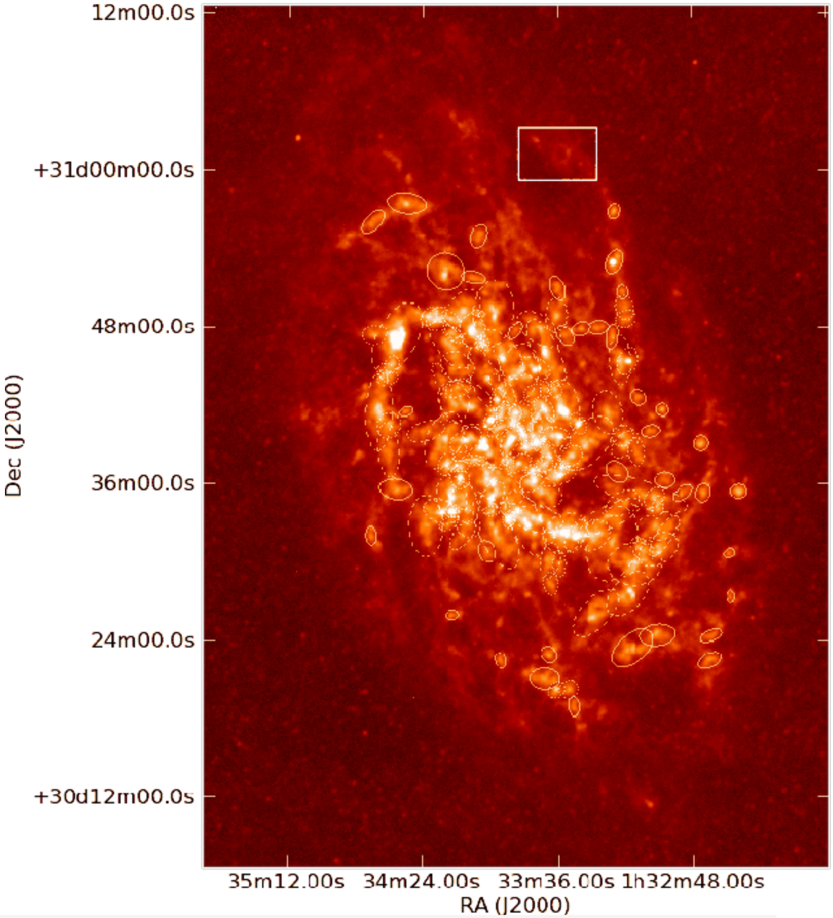


SFR(70) = L(70)/(Cal. Const.)

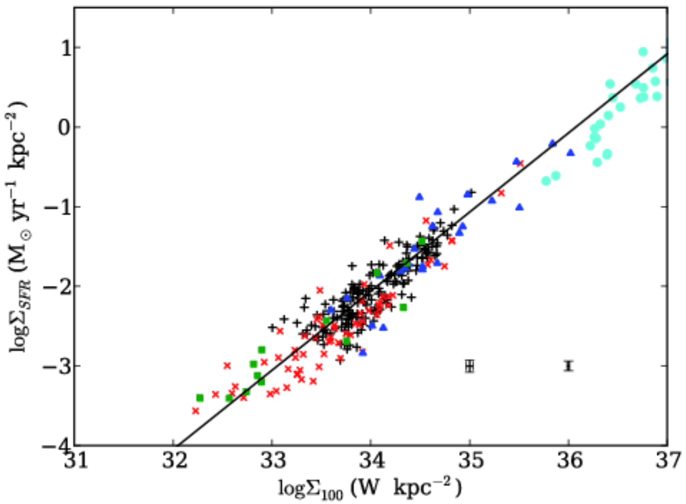
- Calibration constant at 70 μm is lower in sub-galactic regions than whole galaxies. Non-star-forming populations (diffuse emission) contamination at ~50% level? [PRELIMINARY]

Diffuse emission fractions ~50% at 24 μm and ~40% at 8 μm (Crocker et al. 2011, in prep.)

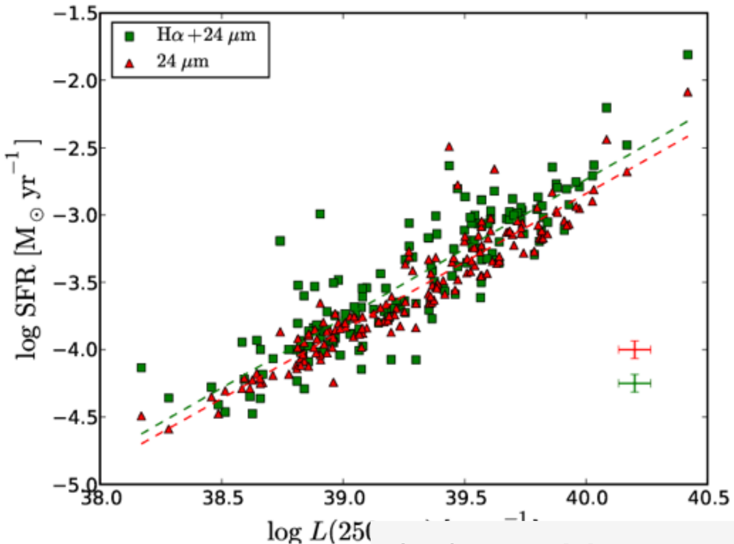
SFR(100), SFR(250),...



M33, 840 kpc; SPIRE 250 μm; HerM33es (P.I.: C. Kramer)



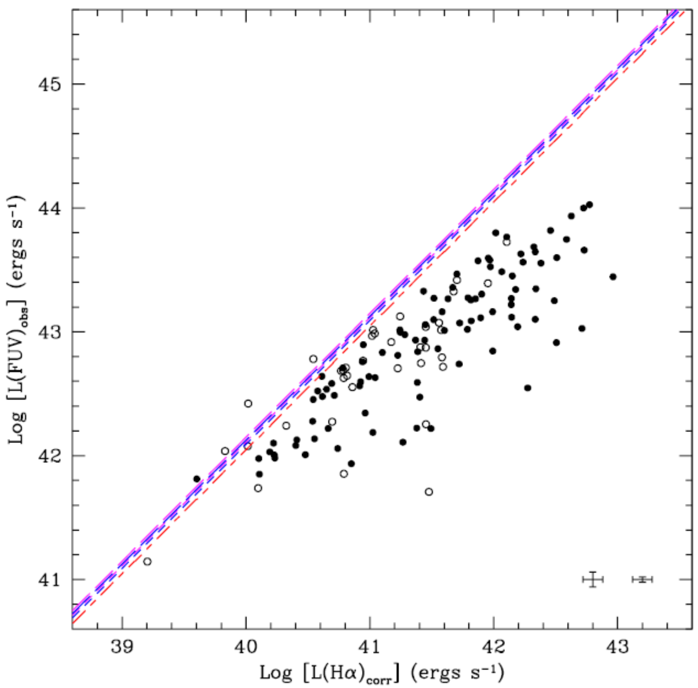
100 μm; Boquien et al. 2010

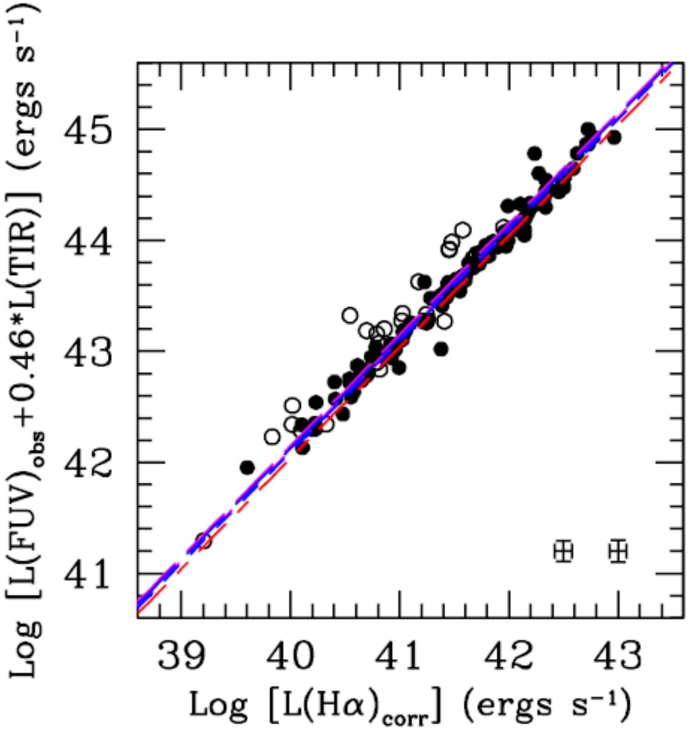


250 μm; Verley et al. 2010

Multi-Wavelength Methods

- Combine IR flux with observed flux in UV or Hα, etc.
- First applied to UV + TIR to correct UV-based SFRs for dust attenuation, but can be seen as correcting IR-based SFR for unabsorbed starlight
  - combinations of Hα and IR indices also work
  - main limitation is variable contribution to dust heating from evolved stars (up to factor of two uncertainty in calibration)

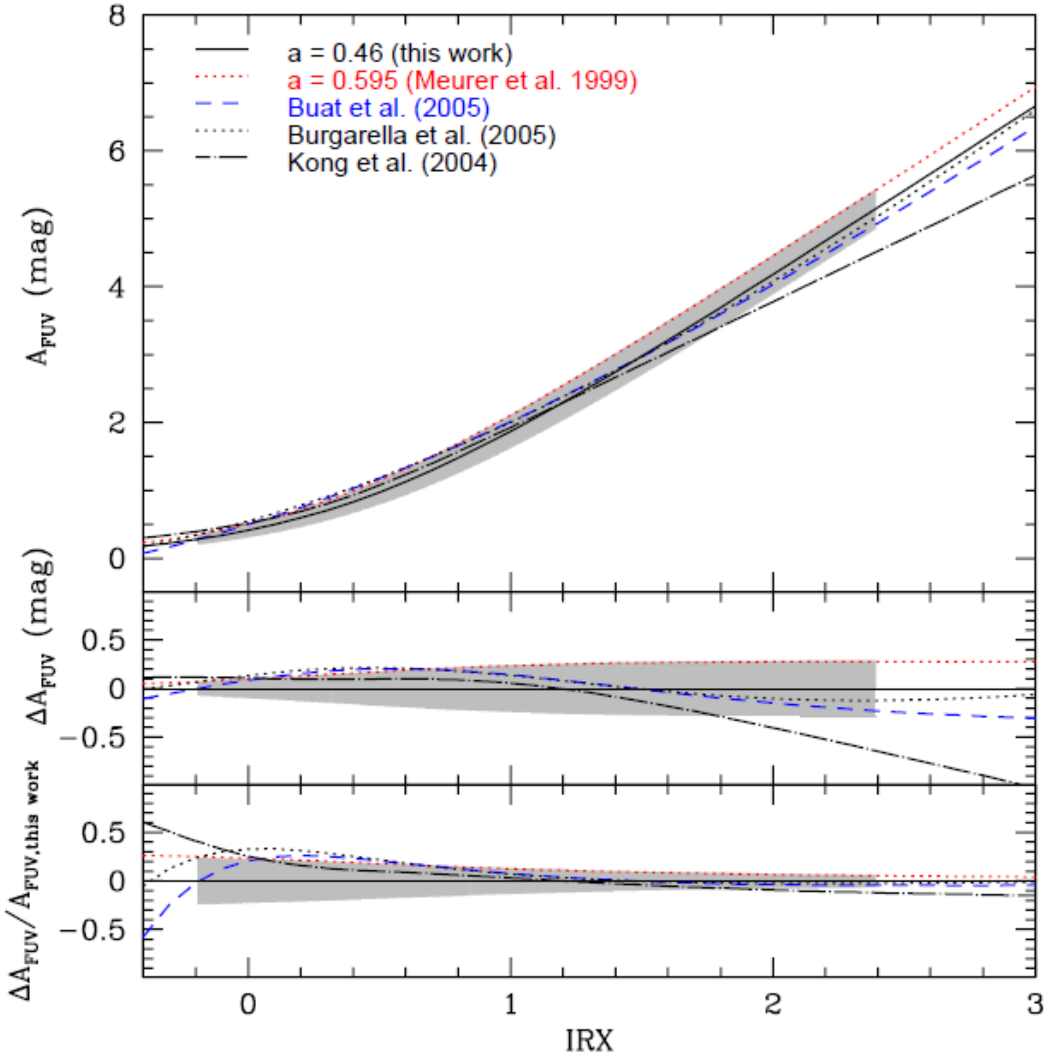




Hao et al. 2011, ApJ, submitted

UV+TIR

Buat et al. 1999; Meurer et al. 1999; Gordon et al. 2000; Bell 2002; Hirashita et al. 2003; Kong et al. 2004, Calzetti et al. 2005; Seibert et al. 2005; Cortese et al. 2007; Boissier et al. 2007; Gil de Paz et al. 2007; Johnson et al. 2007; Panuzzo et al. 2007; Salim et al. 2007, 2009; Treyer et al. 2007; Boquien et al. 2009; Buat et al. 2010; Takeuchi et al. 2010 (and many more…)

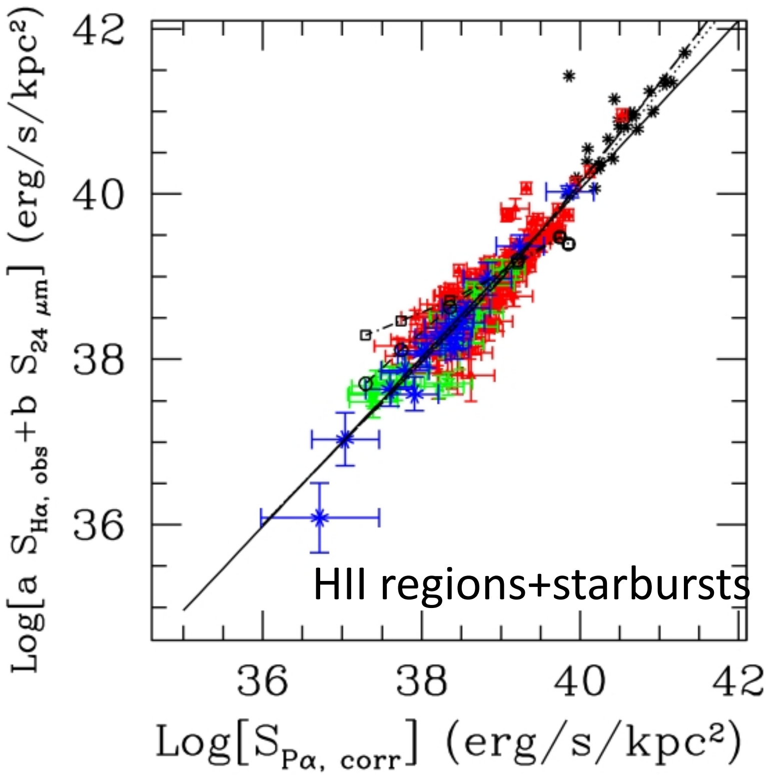


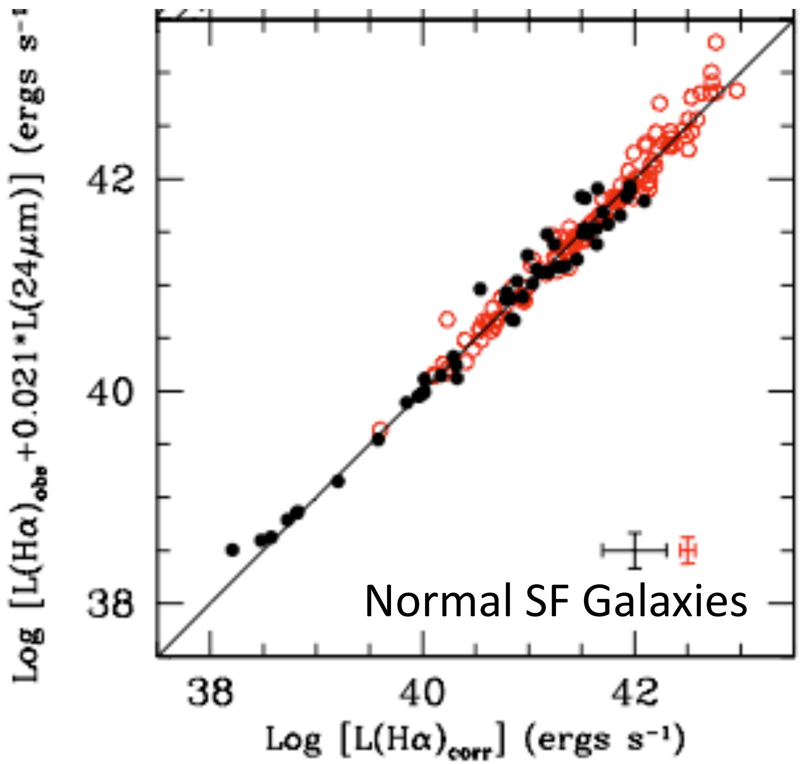
Hao et al. 2011, ApJ, submitted

The same works for Hα

L(Hα) = unobscured SF; L(24μm) = dust-obscured SF

a L(Hα)+b L(24 μm)





SFR (M_o yr^{-1}) = 5.45 x 10^{-42} [L $_{H\alpha,\ obs}$ + 0.020 L$_{24\mu m}$ (erg s^{-1})] L(24)<4 X 10^{42}

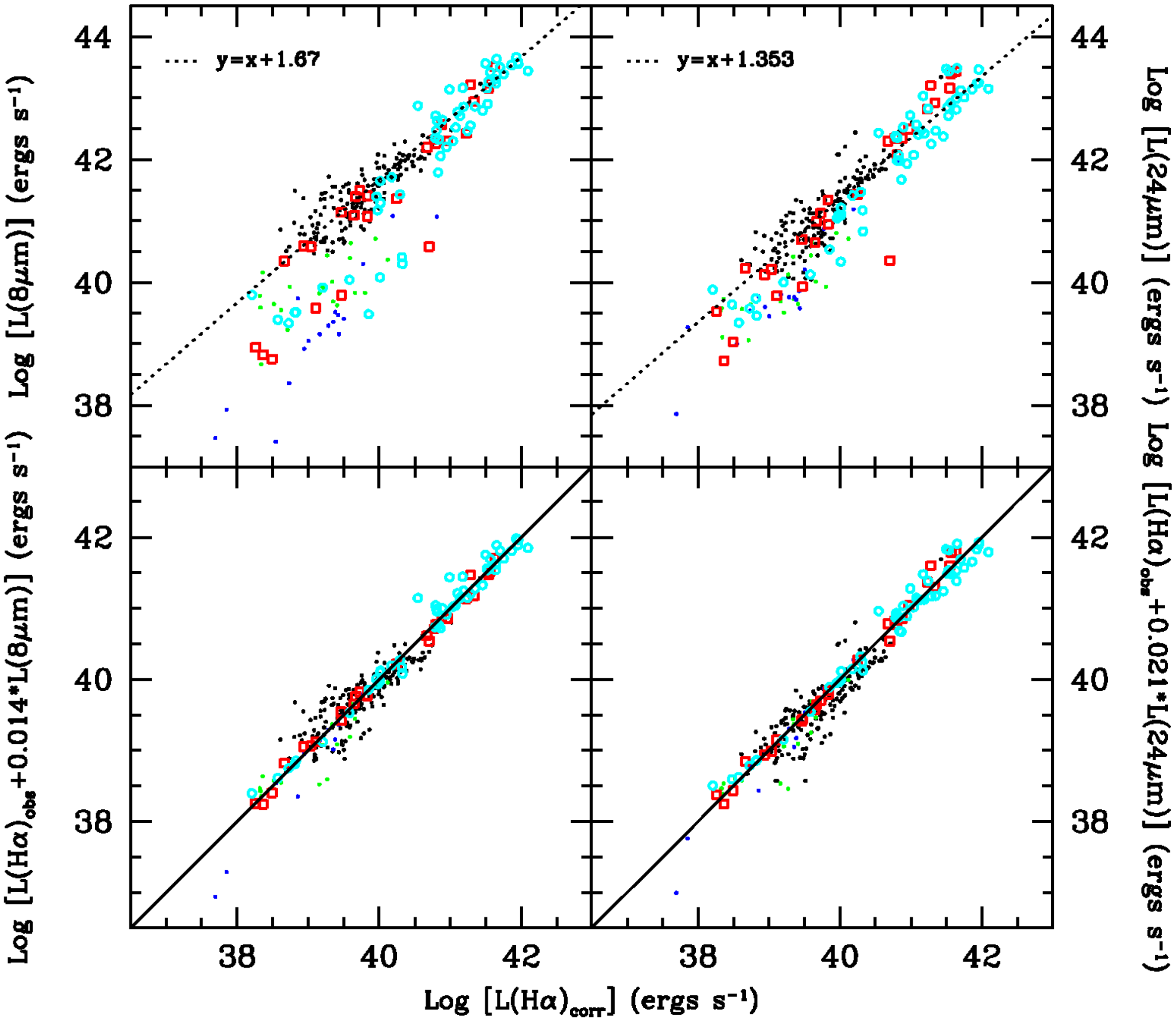
= 5.45 x 10^{-42} [L $_{H\alpha,\ obs}$ + 0.031 L$_{24\mu m}$ (erg s^{-1})]

= 1.70 x 10^{-43} L$_{24\mu m}$ [2.03 x 10^{-44} L$_{24\mu m}$]$^{0.048}$ L(24)>5 X 10^{43}

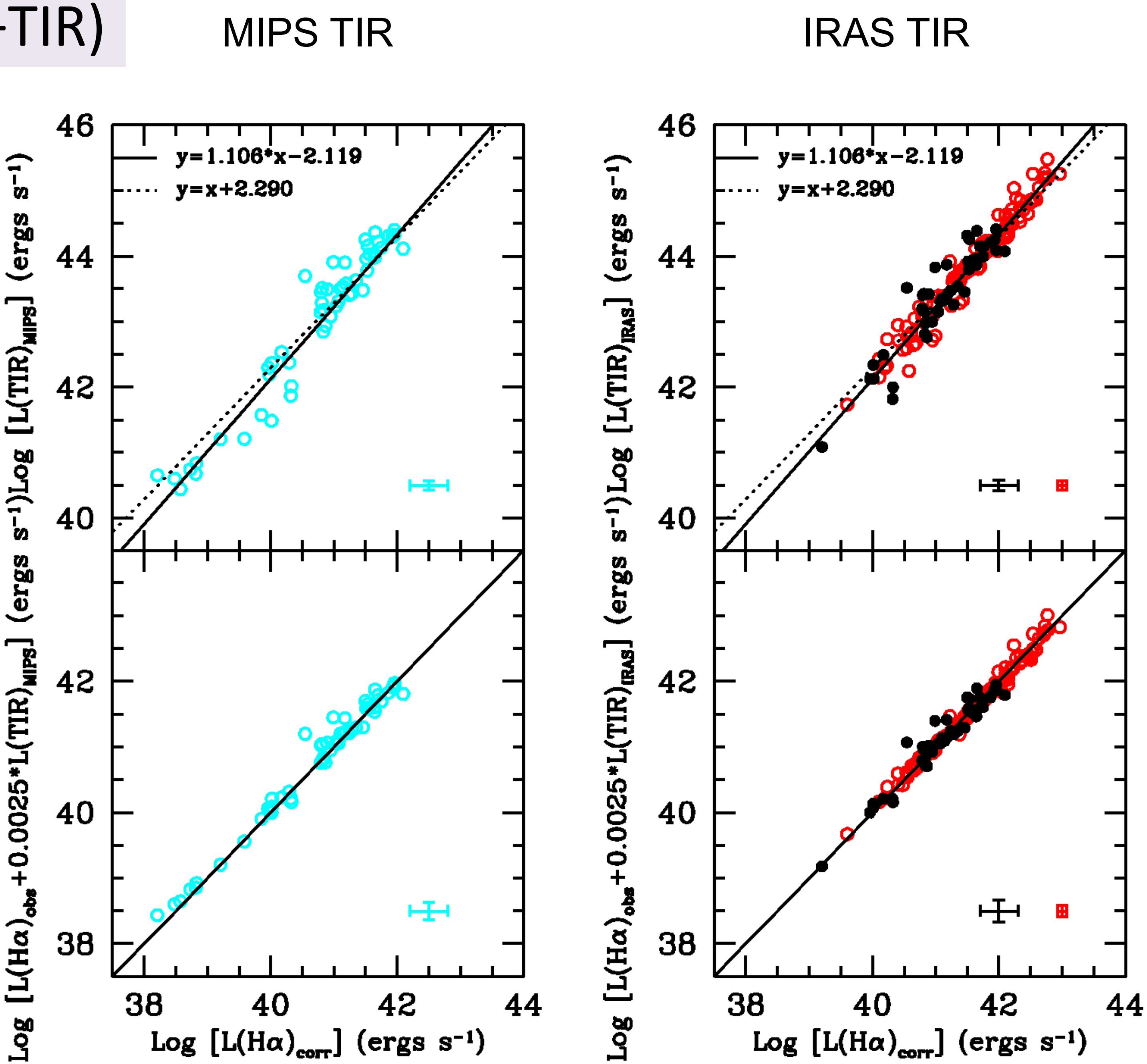
~30% diffuse fraction

Hirashita et al. 2003; Kennicutt et al. 2007, 2009; Calzetti et al. 2007, 2010

SFR(Hα+IR): 8 μm and 24 μm



SFR(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)
46
44
42
40
38
38
40
42
44

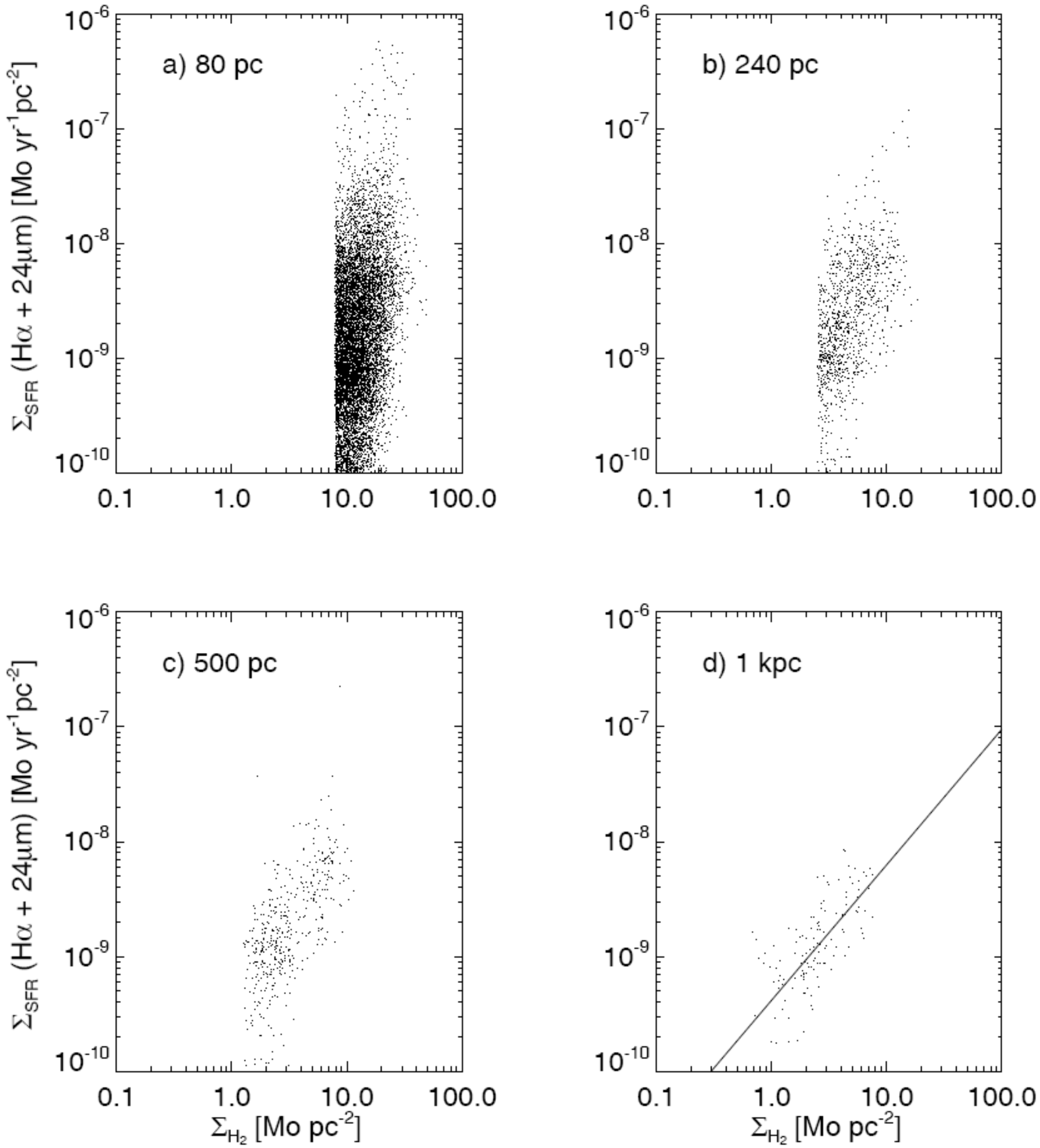
The Next Challenge: Spatially-Resolved SFRs

- the robustness of galaxy-wide SFRs rests several approximations:
  - averaged over full range of region ages
  - IMF is fully populated, well represented
  - dust geometry effects average out
  - SFR averaged over a galaxy roughly steady with time, so age sensitivity of tracers (Hα, UV, IR) can be ignored
- extending this approach to a "SFR map" uncovers several systematic effects:
  - local emission dependent on small number statistics of individual stars, "cosmic variance" (especially for Hα, other ionised gas tracers)
  - variations in dust geometry add scatter to "SFRs"
  - age of stellar population varies locally, altering Hα/UV/IR emission per unit SFR
  - Hα and dust emission trace gas, not stars
  - diffuse emission produces false "star formation" signal far away from any young stars
  - meaning of "SFR" itself ill defined on local scales

M33

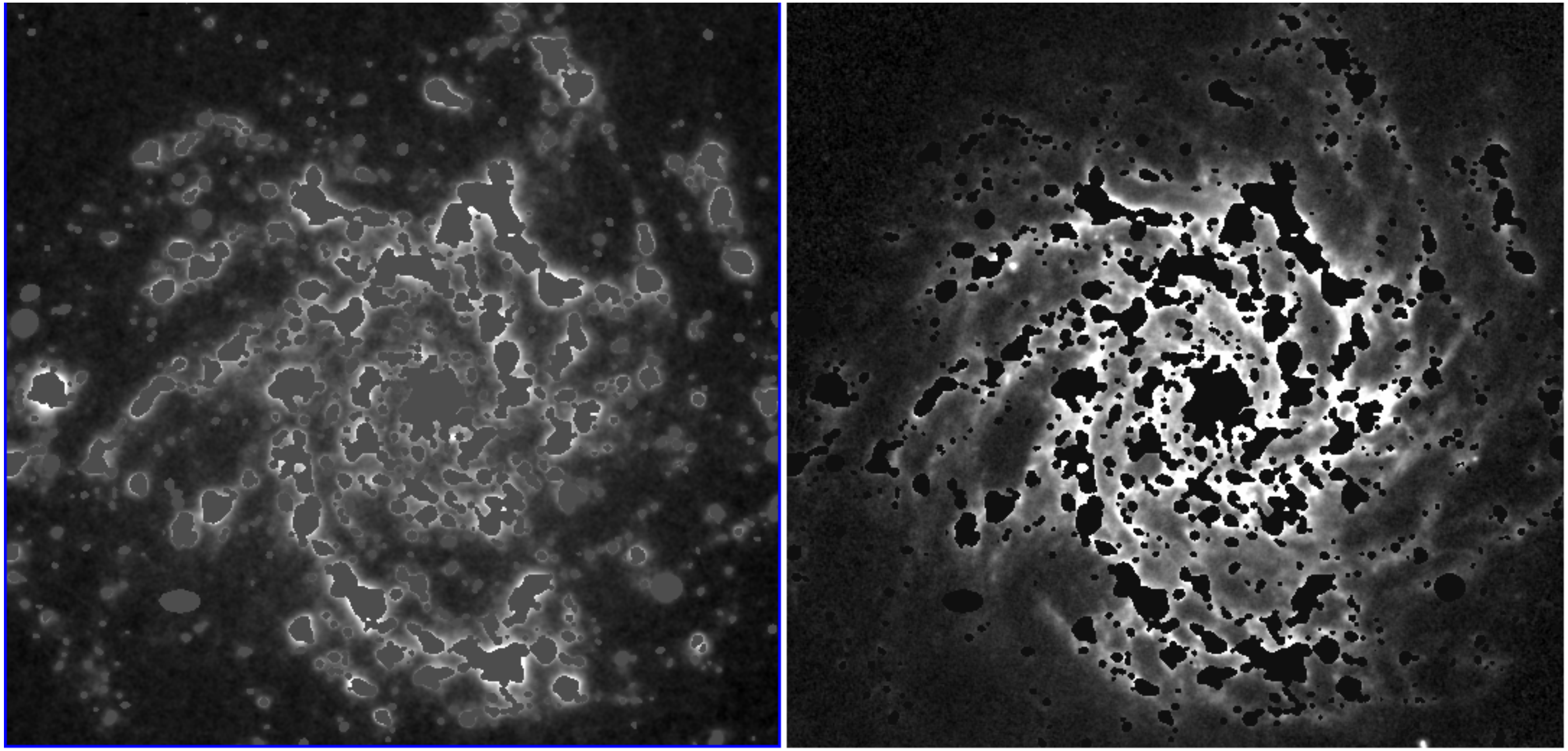
- SFR-gas correlations break down completely on scales <200 pc

- result reflects breakdown in SFR (and possibly gas) diagnostics on small scales, not necessarily from a breakdown in the SF scaling laws



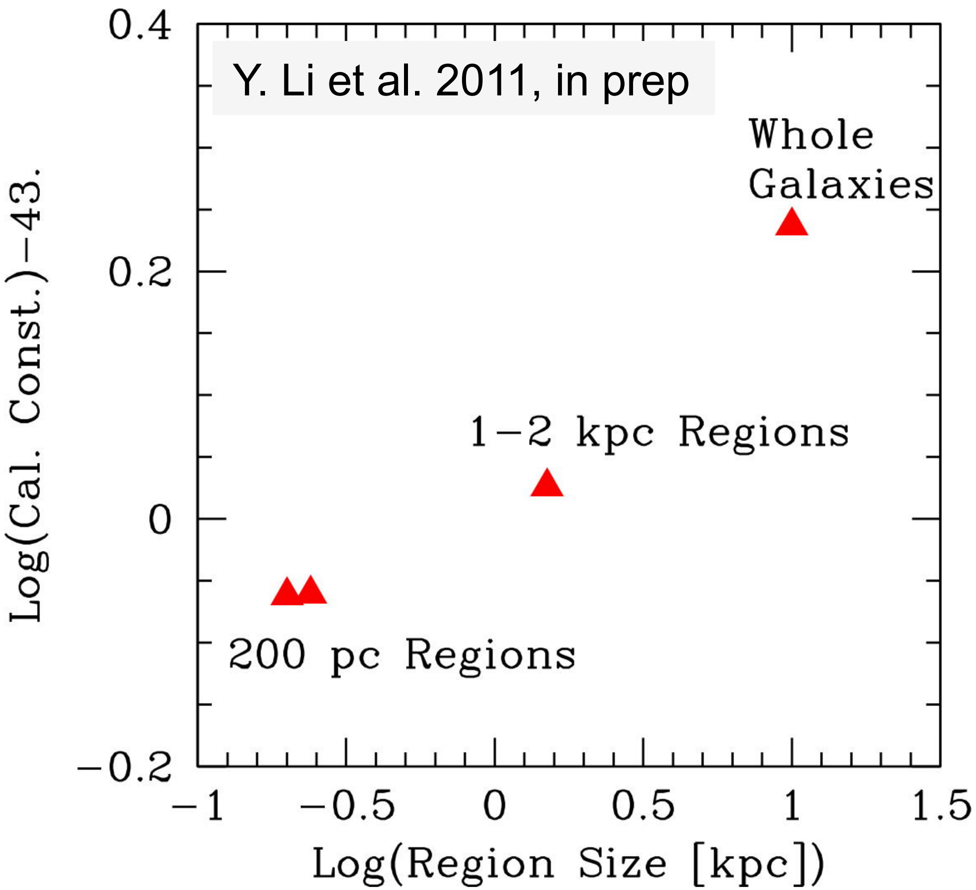
Onodera et al. 2010

Contamination by diffuse emission



❖ Difficult problem that requires masking out of clustered regions of star formation (HII regions/clusters) and separate diffuse SF-associated PAH emission associated from non-SF diffuse PAH emission (Crocker et al., in prep.)

SFR(70) Normalization Changes

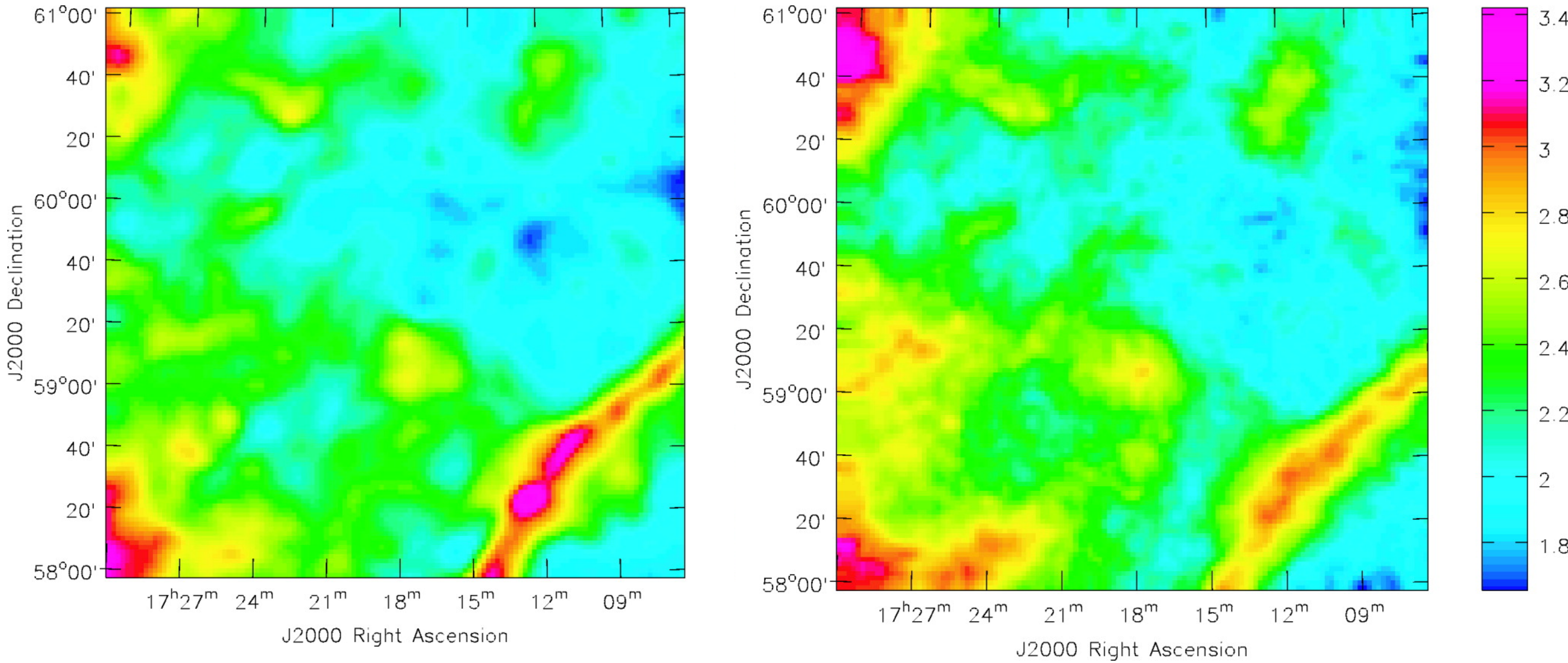


SFR(70) = L(70)/(Cal. Const.)

- Calibration constant at 70 μm is lower in sub-galactic regions than whole galaxies. Non-star-forming populations (diffuse emission) contamination at ~50% level? [PRELIMINARY]

Diffuse emission fractions ~50% at 24 μm and ~40% at 8 μm (Crocker et al. 2011, in prep.)

Diffuse dust emission also tends to trace gas column density, not the SFR…



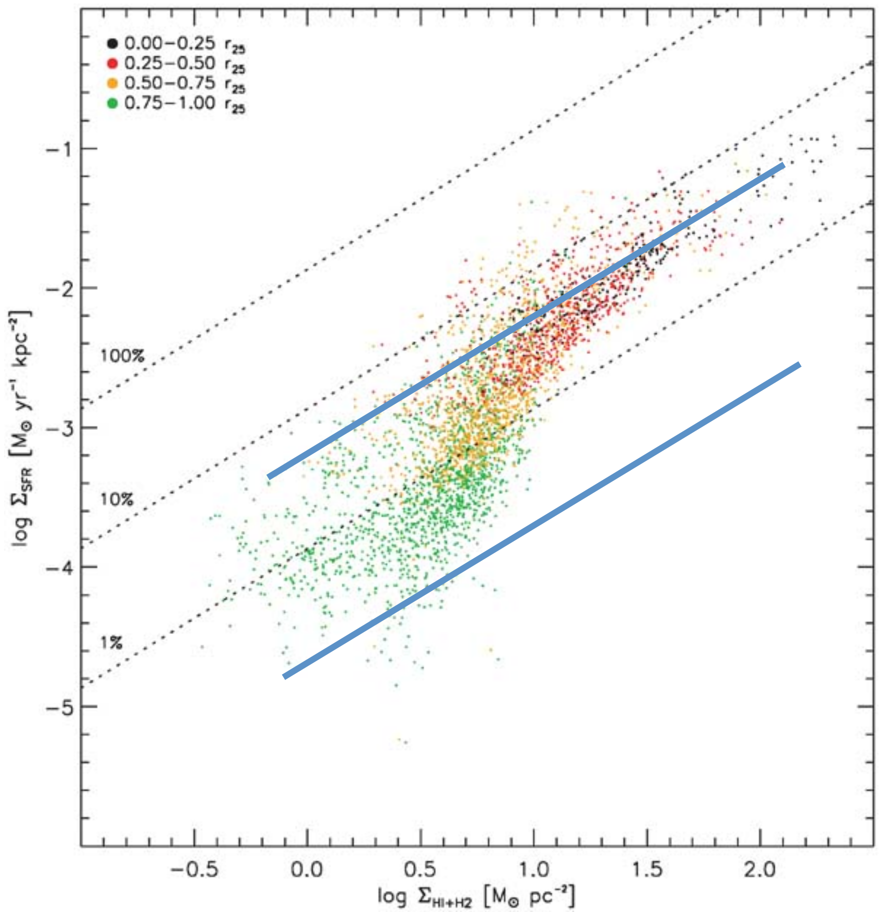
Spitzer FLS field:

Which is COBE/IRAS dust emission and which is HI column density?

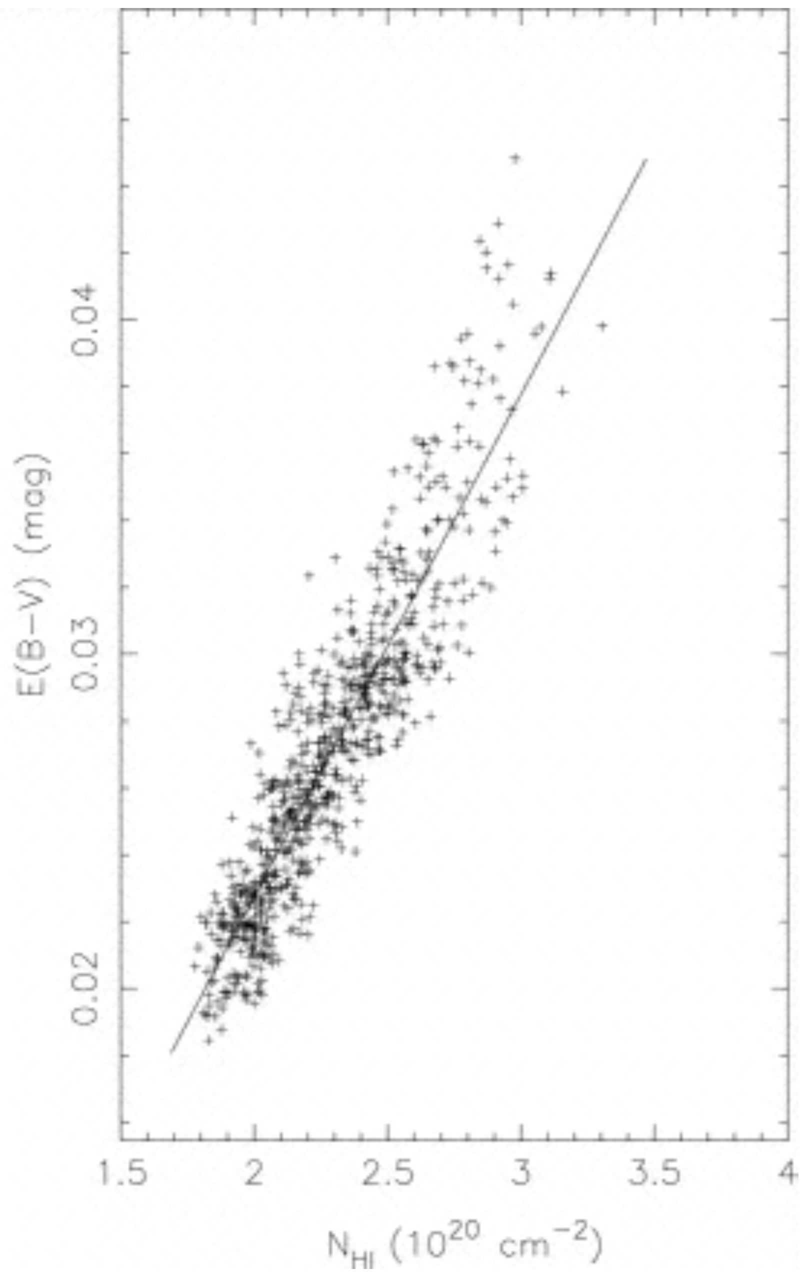
Lockman & Condon (2005)

Implications for SF Laws

Diffuse emission follows a “Schmidt law” with slope N=1, without star formation!



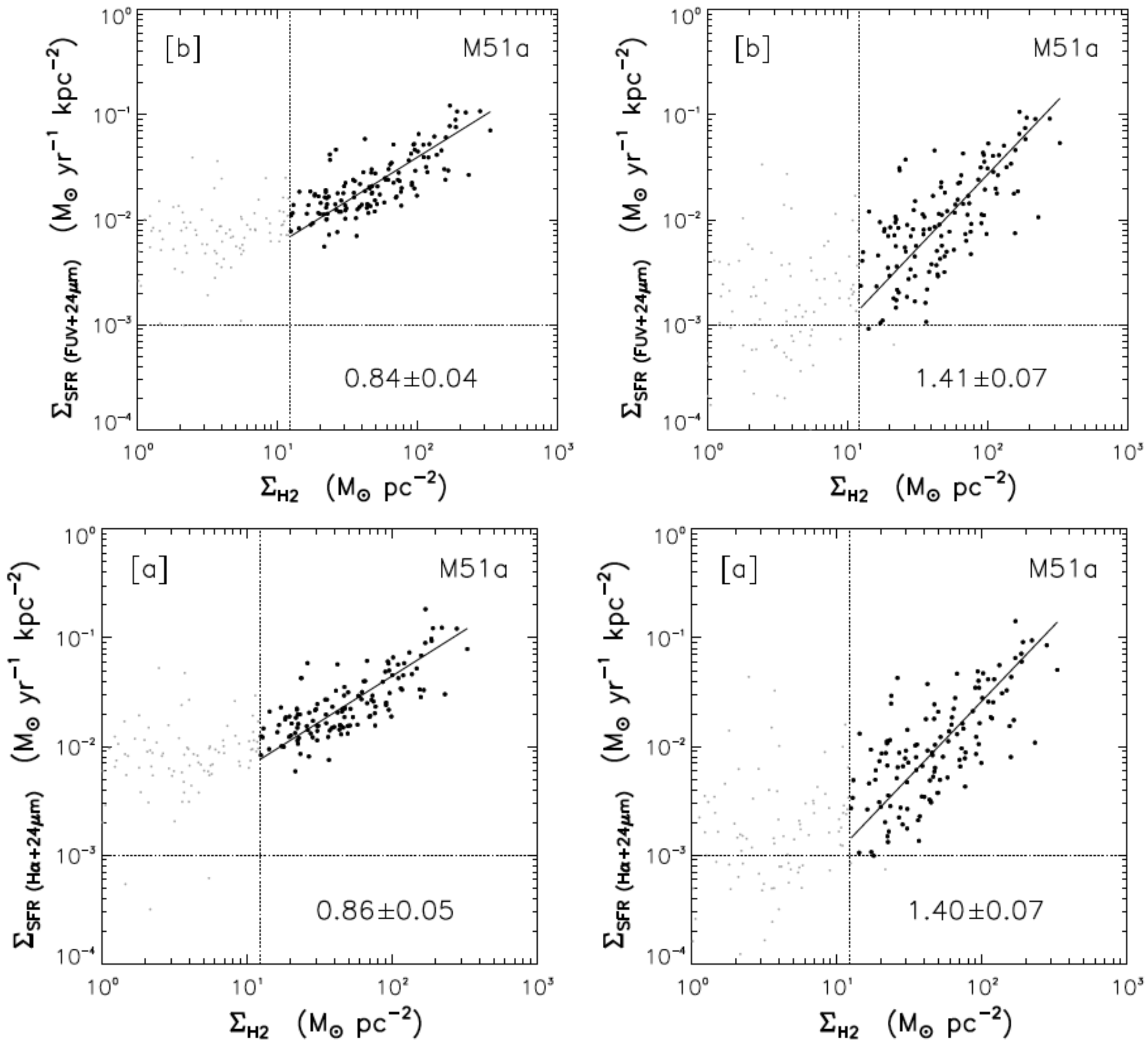
Bigiel et al 2008



Lockman, Condon 2006

Impact of Background Light

$\Sigma_{SFR} \sim \Sigma_{H2}^{\gamma_{H2}}$

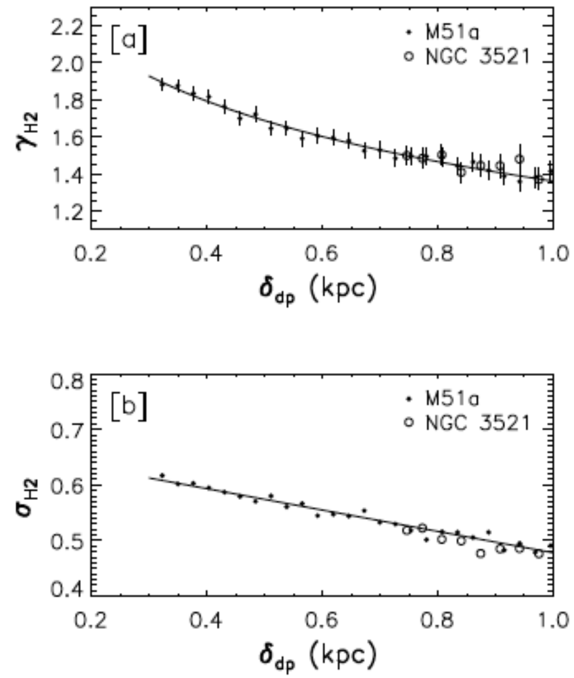


Non-bck sub

Bck-sub

Observed, both with SFR(UV +24μm) and with SFR(Ha+24μm) in two galaxies: M51 (depicted) and NGC3521.

Local bck subtraction on the stellar pops can have a major impact on the SFR measurements



Liu et al. 2011, ApJ, in press

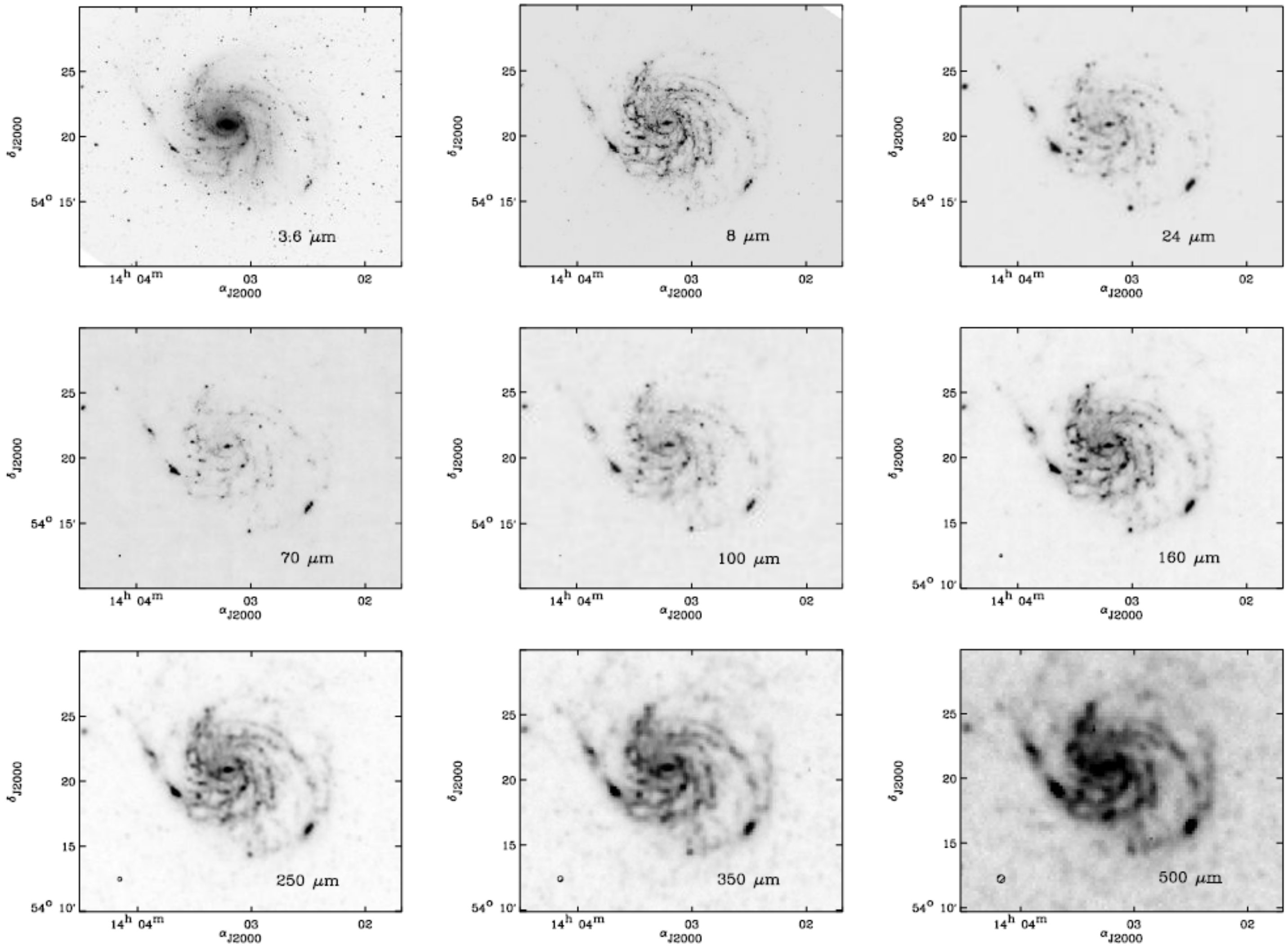
Summary: On small scales the precise definition of a “star formation rate” changes (size matters).

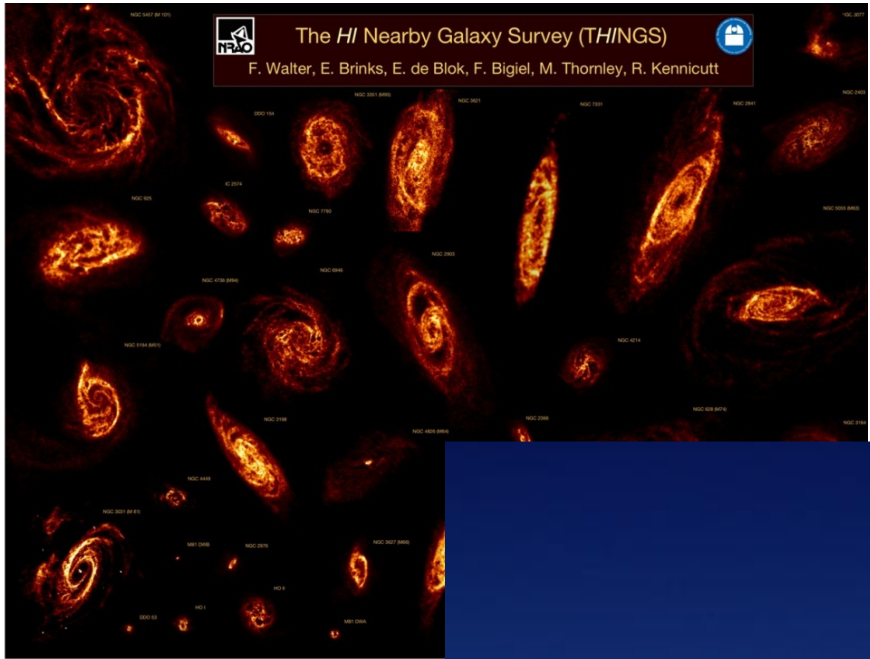
- entire galaxies, luminous starbursts (1-10 kpc+)
  - definition (and measurements) are unambiguous
- radial profiles, annular averages (~1 kpc+)
  - integrated diagnostics probably OK, so long as IMF fully populated
- young massive clusters, active SF regions (~500 pc+)
  - statistics should be reliable, but large scatter from geometry, age variations
  - zeropoints of SFR scales offset from galaxy-scale calibrations
- cloud scale (<100-200 pc)
  - forget it! (unless you measure stars or YSOs directly)
- fully-sampled images of galaxies
  - OK in bright SF regions, but enormous (orders-of-magnitude) systematic errors in low-SFR regions

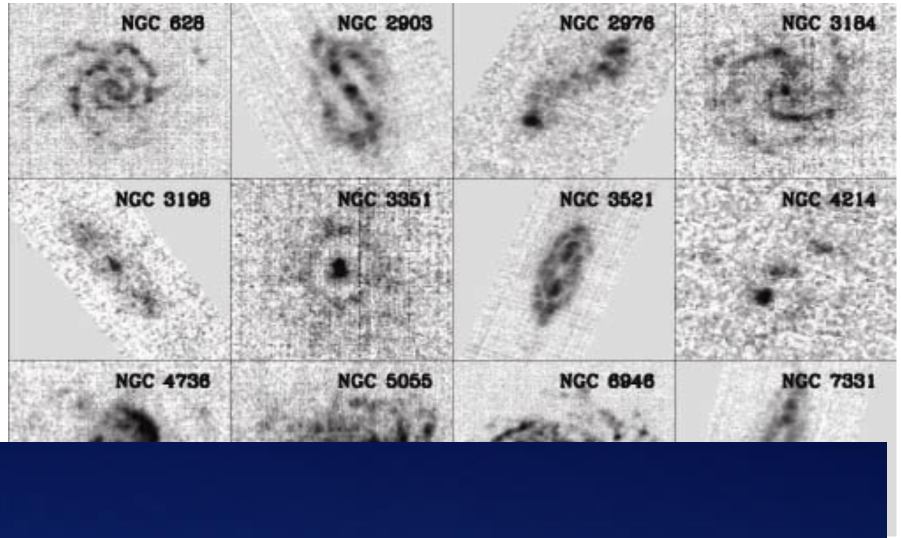
The Future…

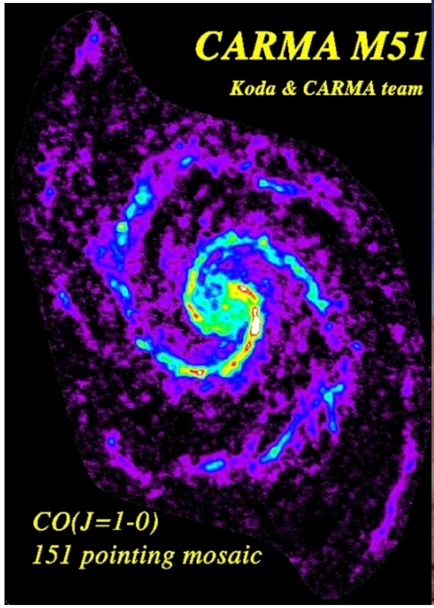
- Spitzer + Herschel imaging enables full separation of young and diffuse dust components
- ancillary multi-wavelength imaging (Hα, Paα, Brγ, UV) provides independent mapping of SFR

NGC 5457:









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