Nearby Galaxies

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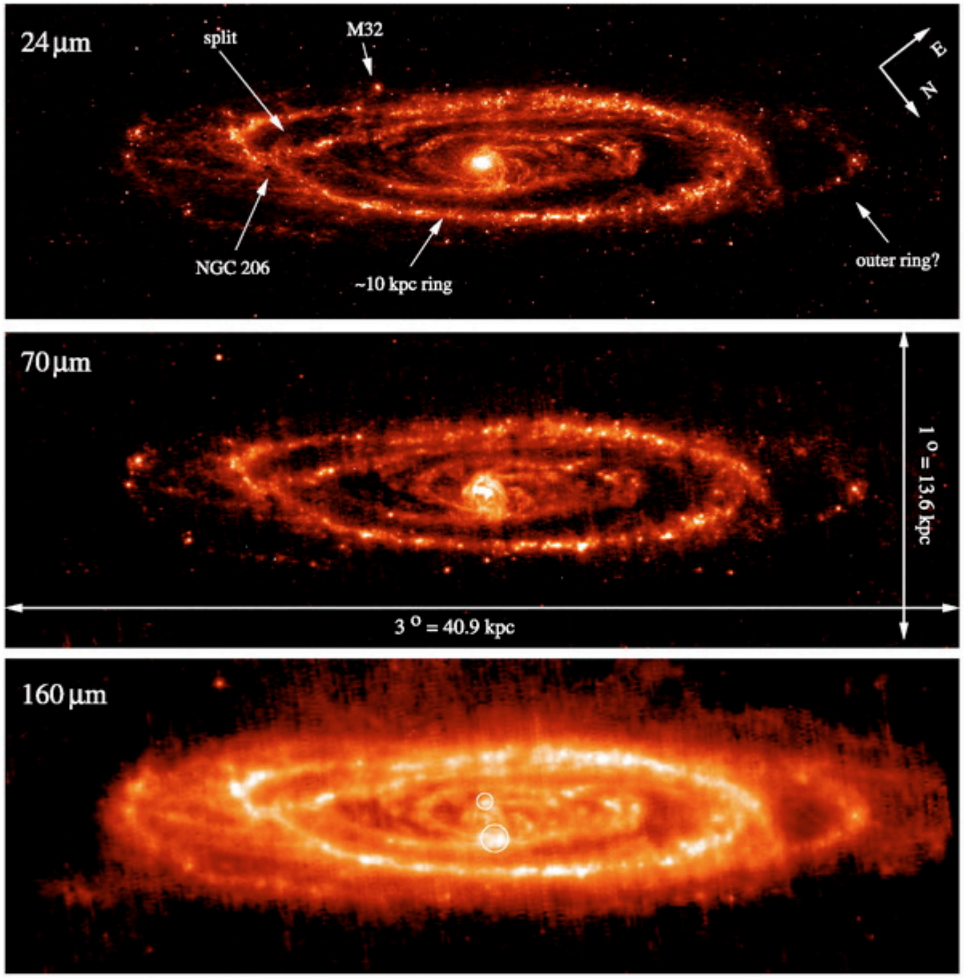
DISCLAIMER

It is a nearly-impossible, and obviously daunting, task to try to summarize the fertile and thriving field of nearby galaxies investigations with the Spitzer Space Telescope.

For this field, Spitzer `warm' is likely as important as the `cryogenic' Spitzer, with fundamental contributions to be made in the investigation of the formation and evolution of structures (bars, arms, etc.) within galaxies and of the evolution of the extended disks, as traced by the long-lived, low-mass stars.

BTW: This presentation reflects the biases of the presenter.

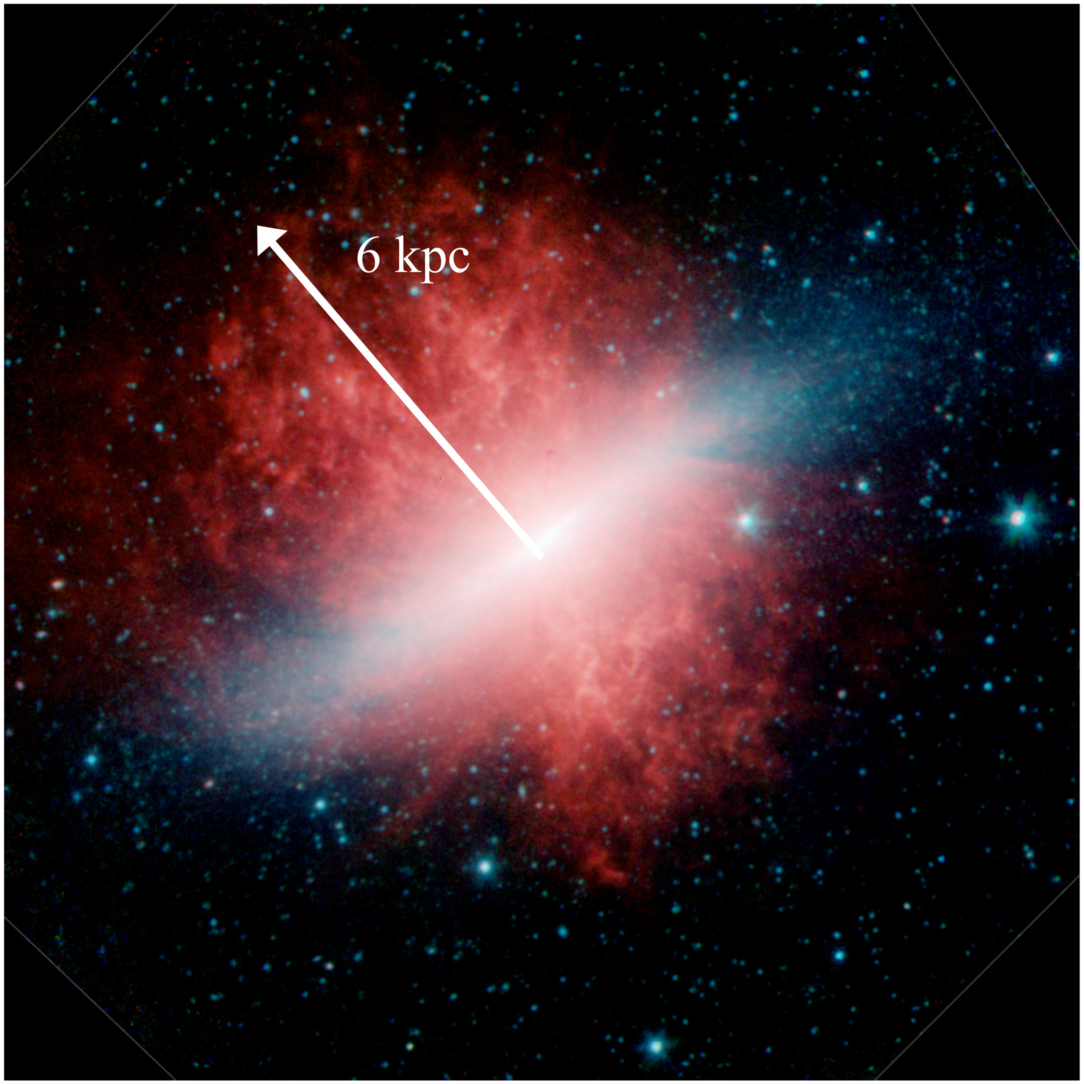
M31: Our closest Spiral



The morphology of this spiral is affected by the interaction with the M32 dwarf

(Gordon et al. 2006)

M82: Our Closest Starburst



M82: 3.5 Mpc
3.6 and 8 µm
(Spitzer) composite

Ejecta from starbursts (or at least a few starbursts!) contain significant amounts of dust: PAHs as traced at 8 µm

Engelbracht et al. 2006

The Broader Picture

How do stars, gas, dust cycle and evolve in galaxies?

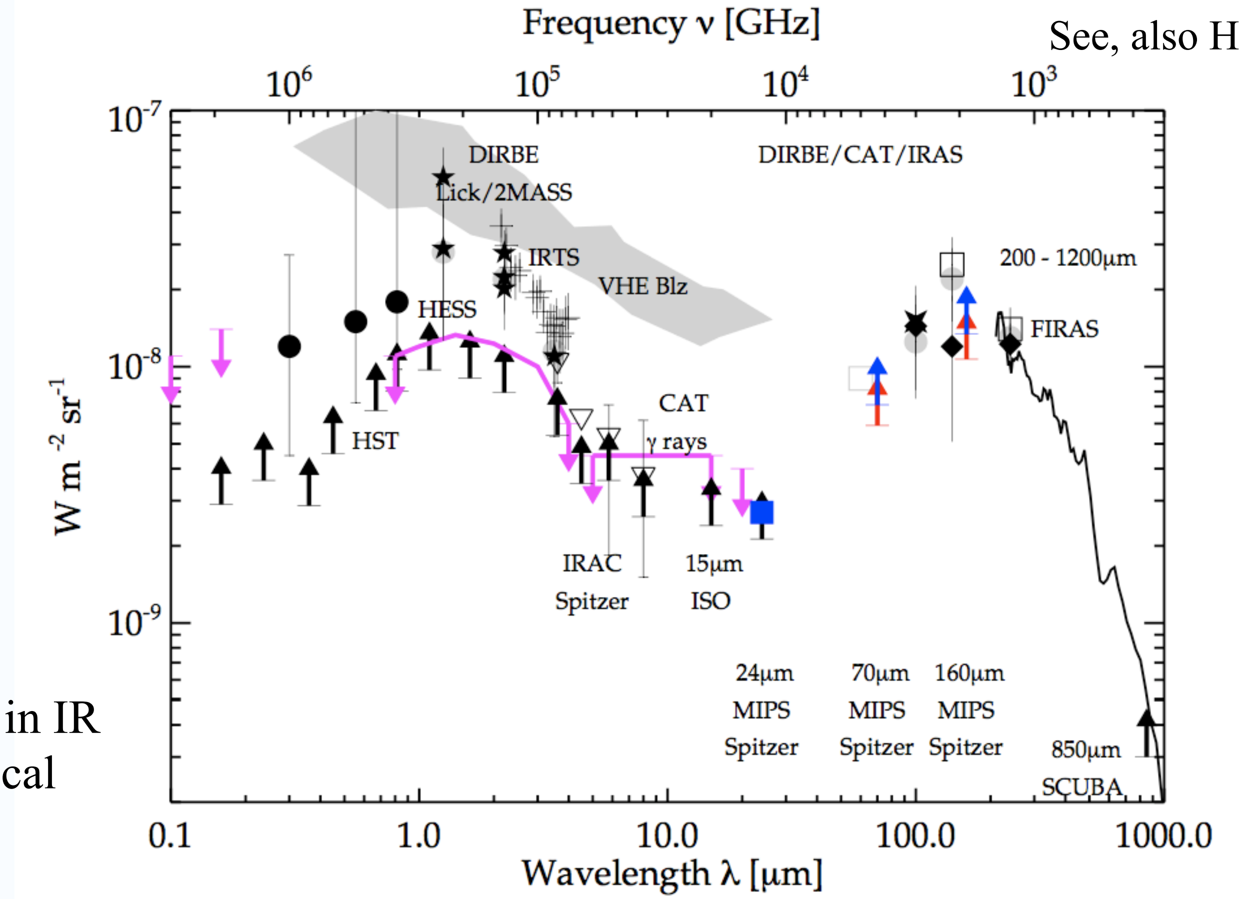
- star formation; measurement, phases, relation to gas/dust
- gas phases, evolution, metal enrichment
- heating of dust; physics of dust
- galaxy transformations; morphology, bars, interactions, etc.
- AGN role(s) [BH-bulge mass relation]

How does the cycling occur at the interface of galaxies and IGM?

- mechanical, luminous, chemical feedback (stellar and AGN)
- gas accretion

Interest in FIR from Galaxies

Dole et al. 2006
See, also Hauser & Dwek 2001



Roughly 1/2
energy each in IR
and UV/optical

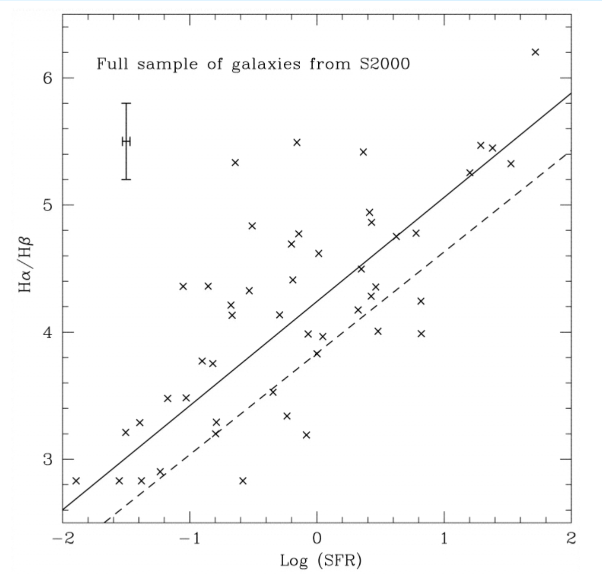
About 80% of UV light (tracer of SF) is absorbed and re-emitted by dust.

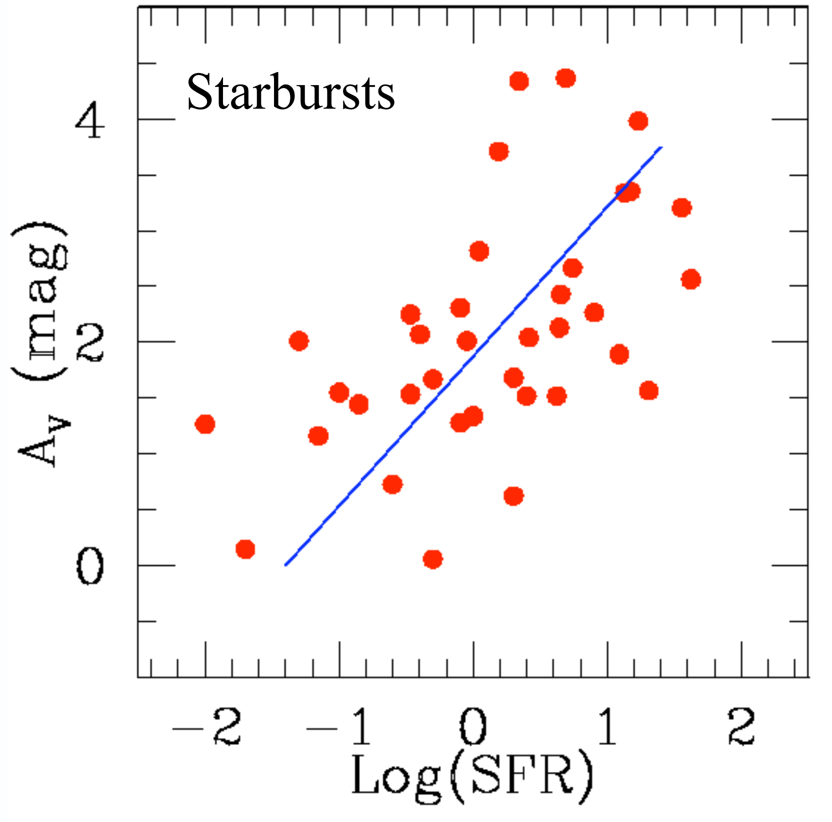
AGNs are also heavily dust-absorbed.

SFR-Extinction

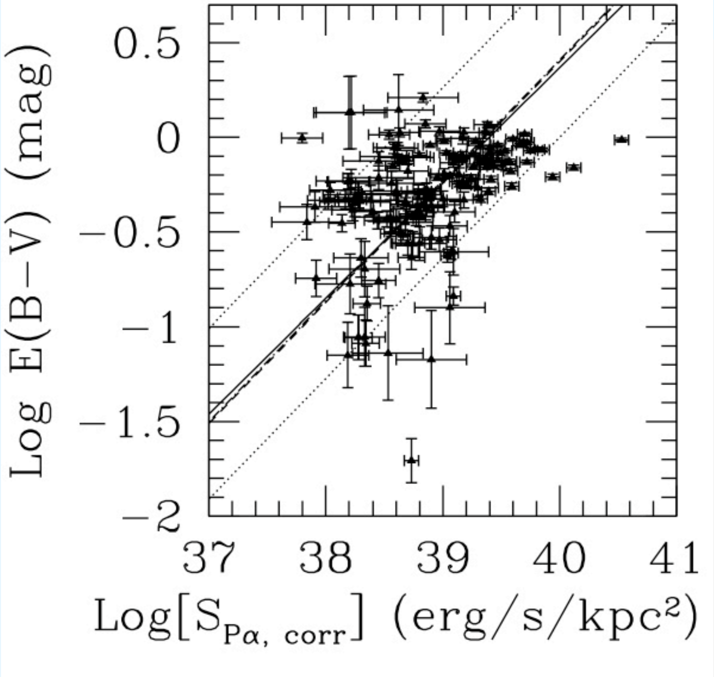
(Wang & Heckman, 1996; Heckman et al. 1998; Calzetti 2001
Hopkins et al. 2001, Sullivan et al. 2001, C. et al. 2007)

Strongest SF systems tend to be the most dust obscured; need for IR at higher L's.

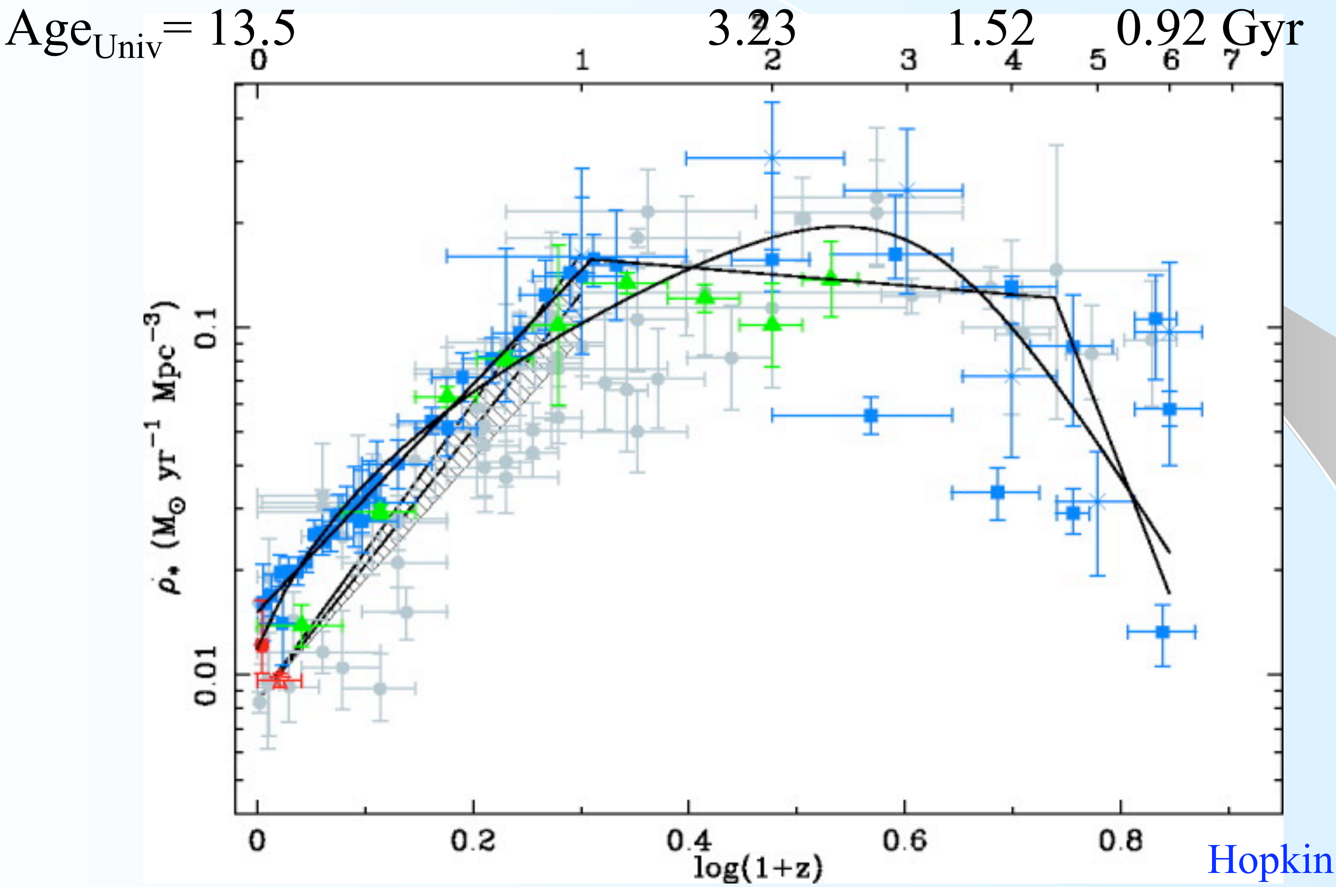




SF regions in normal galaxies



Dust and Cosmic Star Formation



Hopkins & Beacom 2006

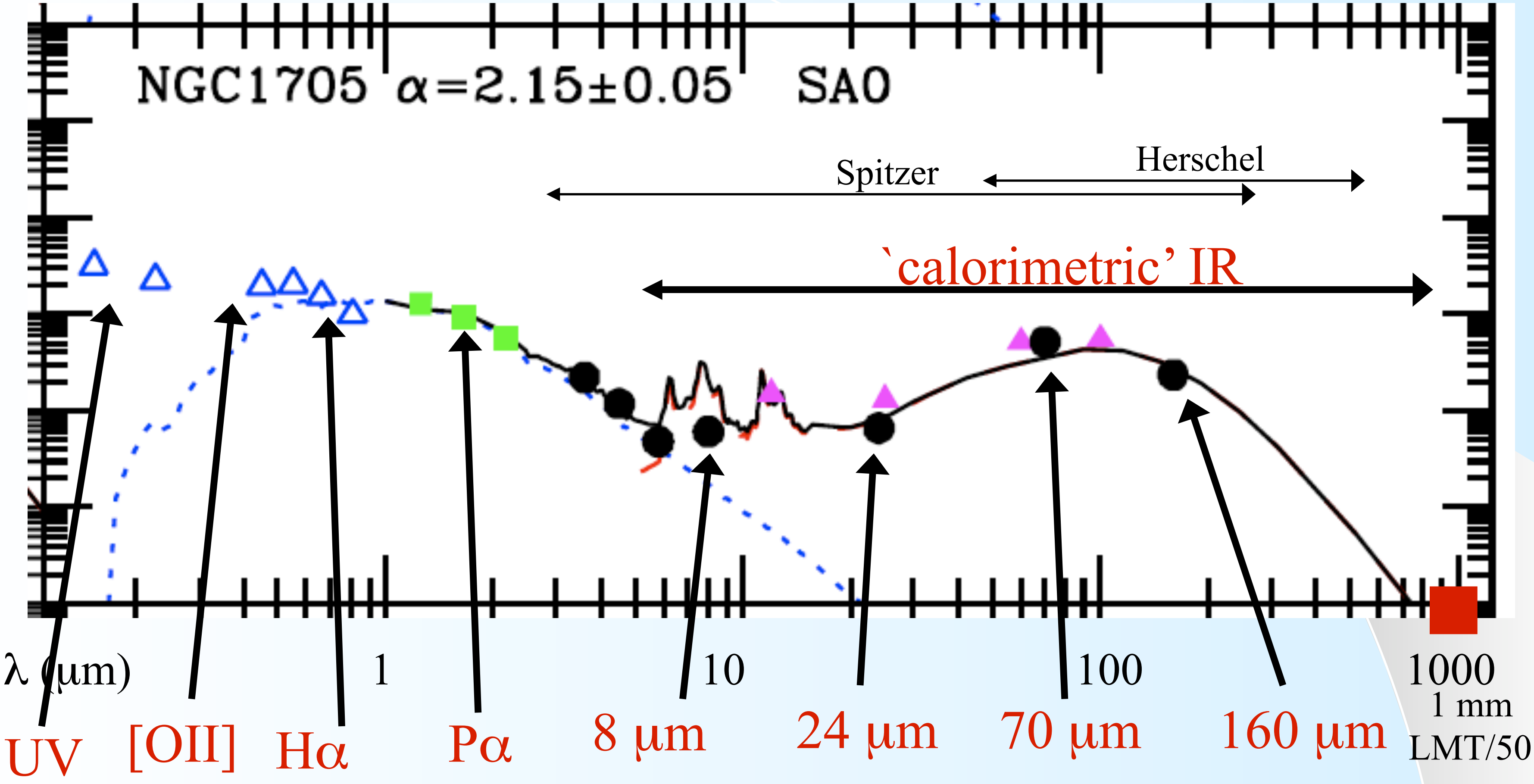
Dust:

1. Helps accounting for all the SF
2. Informs the star formation/feedback prescriptions (in models)

Talking about SFRs….

Galaxies SED's

Dale et al. 2007



← Direct stellar light → ← Dust-processed light →

- Look first at IR as `global', then at `monochromatic' IR.

`Monochromatic' SFRs

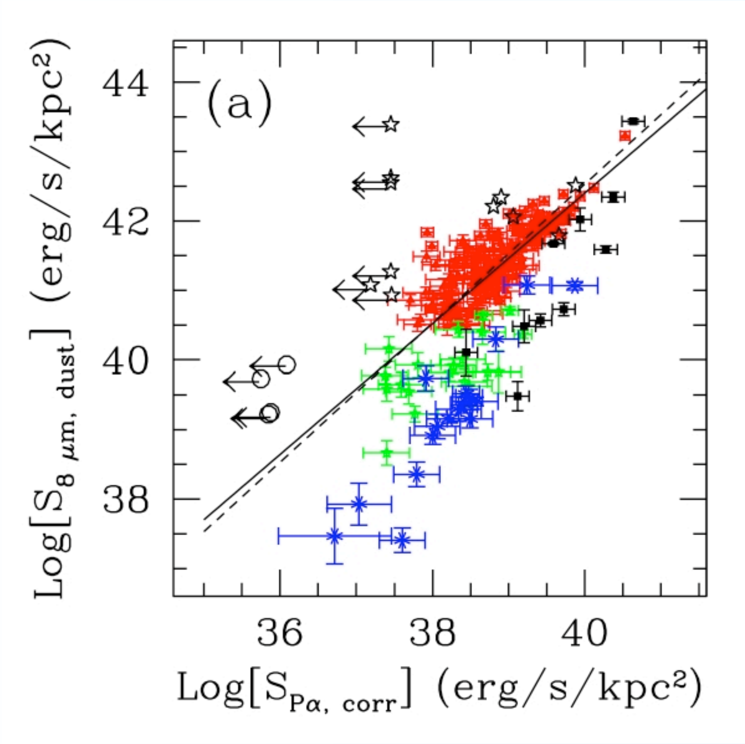
- ISO provided the first opportunity for investigating monochromatic IR emission as SFR tracers, esp. in the mid-IR: UIB=AFE=PAH (e.g., Madden 2000, Roussel et al. 2001, Boselli et al. 2004, Forster-Schreiber et al. 2004, Peeters et al. 2004, Tacconi-Garman et al. 2005).

- Spitzer has opened a `more sensitive' window to the near and distant Universe, with unprecedented angular resolution:

  - At high redshift, `monochromatic' (i.e., single-band) measures avoid uncertain extrapolations to unknown FIR SEDs

  - Appeal of nearby galaxies studies: provide sufficient resolution to separate galaxies in elemental constituents (e.g., HII regions/complexes, stellar clusters, sub-structures). Investigate contributors (dust heaters) to different IR bands.

SFR(8) - Fair



C. et al.2007

Red: High Metallicity SF regions
Green: Medium Metallicity SF regions
Blue: Low Metallicity SF regions
Black symbols: Low Met Starbursts and LIRGs

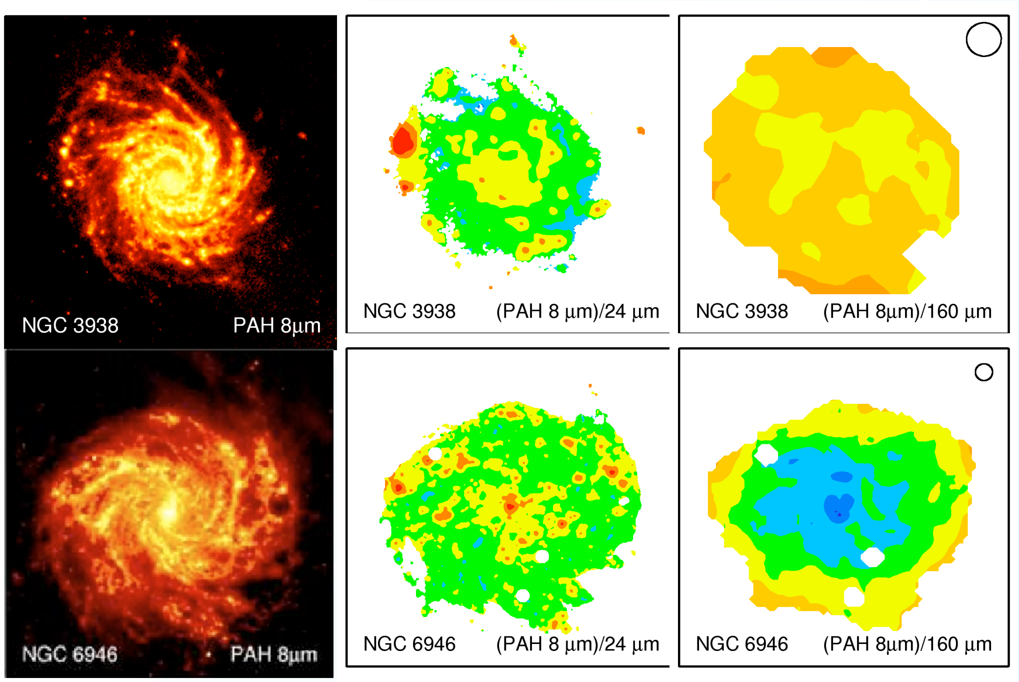
1. Slope is `sub-linear'
2. Strong dependence on metallicity (Engelbracht et al. 2005, 2008; Rosenberg et al. 2006, Wu et al. 2006, Draine et al. 2007)
3. Dependence on region sampled

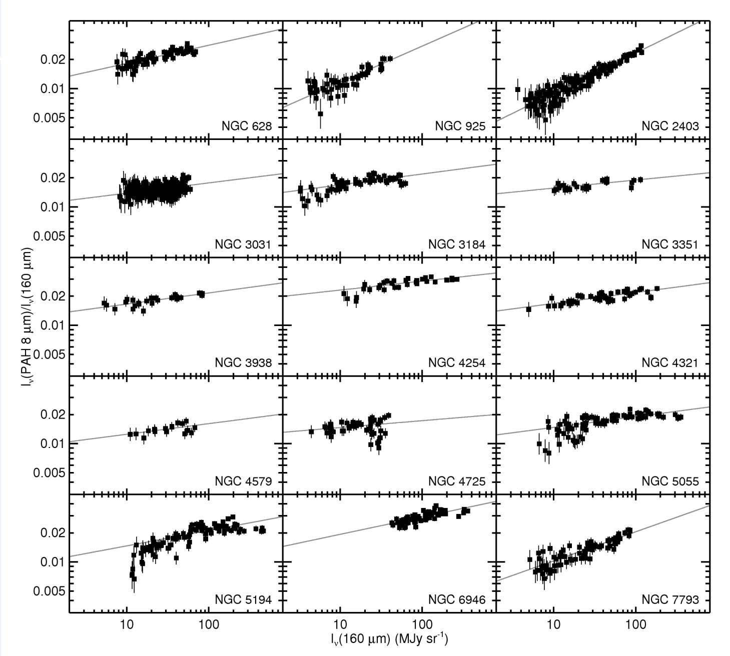
HII Regions & Starbursts

o Lower-than-unity slope and region-size dependence unaccounted for by models; measured L(8) may be `contaminated' by diffuse emission heated by underlying (non-star-forming) populations; or may be destroyed/fragmented by high intensity radiation.

o L(8 μm) is strongly dependent on metallicity; lower metallicity may lower number of low-mass PAH (Draine & Li 2007)

Dust versus Stars

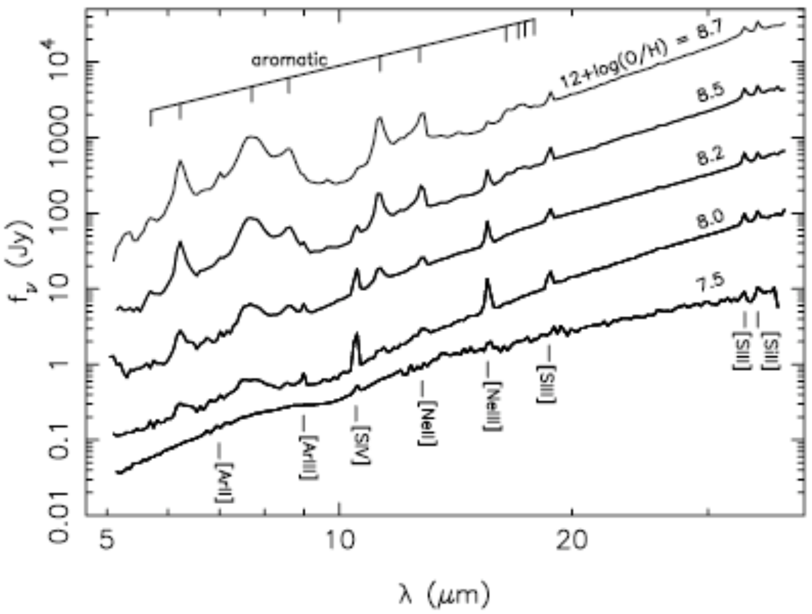




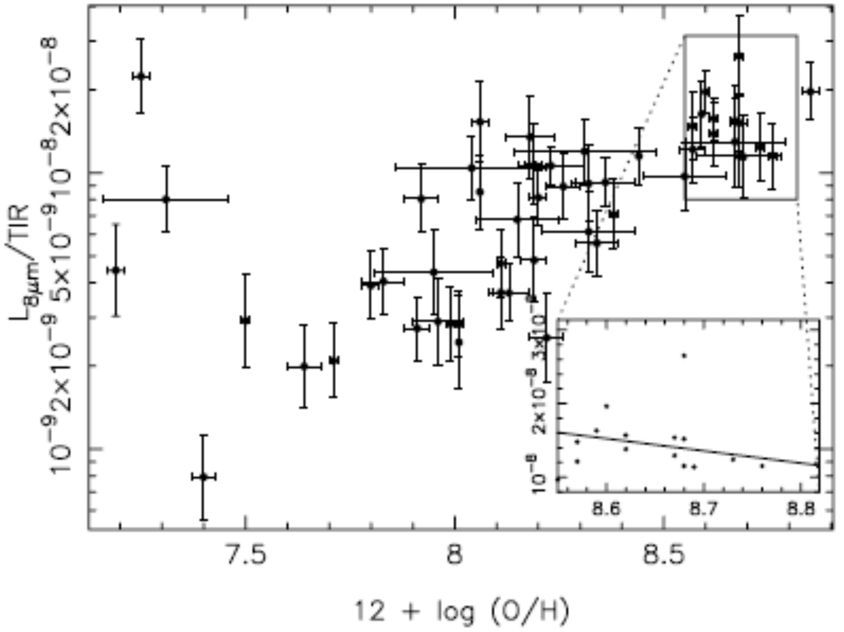
(Bendo et al. 2007)

- L(PAH) shows large scatter relative to L(24), but well correlated with L(160) (on ~ 2 kpc scales); PAHs associated with cool dust in galaxies;
- L(PAH)/L(160) increases with L(160), but L(PAH)/L(IR) constant with L(IR), suggesting that L(PAH) has additional dependence on the intensity/spectrum of the heating field (Bendo et al. 2008)

8 μm-band and metallicity

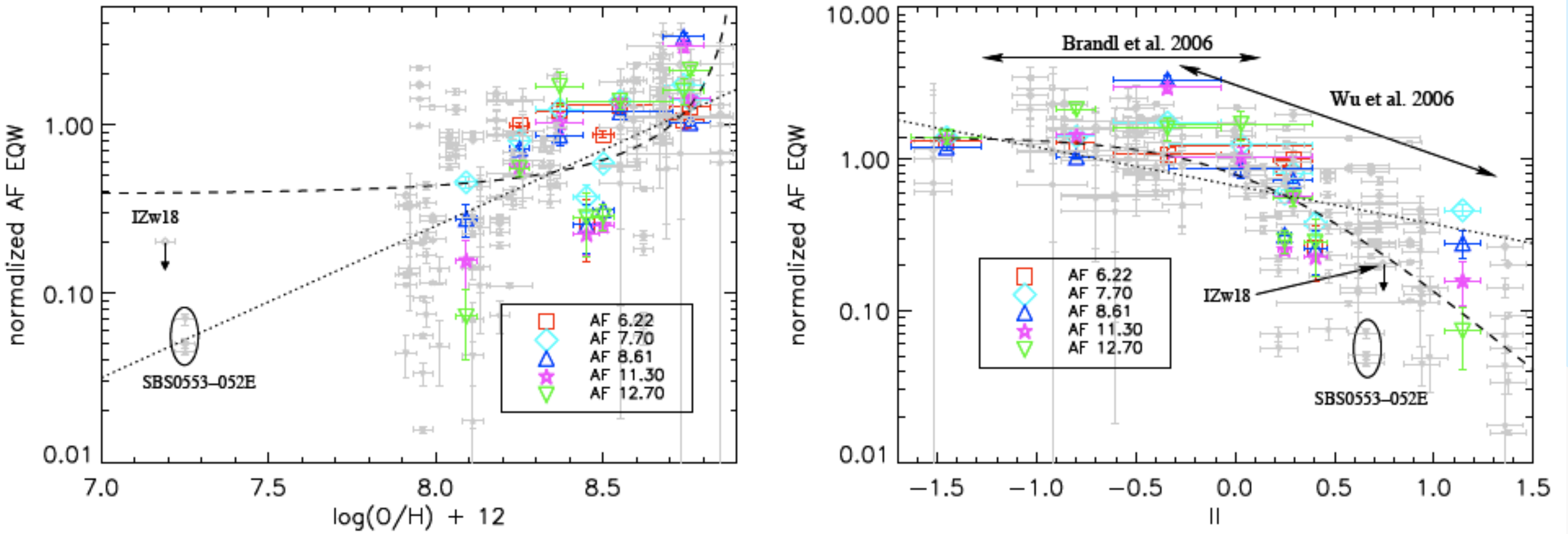


Engelbracht et al. 2008



(Engelbracht et al. 2005;
Rosenberg et al. 2006, Wu et al.
2006, Draine et al. 2007)

Processing of AF Carrier(s)?



Better correlation with ionization index (a combination of [NeIII]/[NeII] and [SIV]/[SIII] ratios], than with metallicity, from M101 and a sample of starbursts. (Gordon et al. 2008)

(Cesarsky et al. 2000; Berne' et al. 2007)

Dust physical properties: Radial profiles

q_{PAH} vs. oxygen abundance

- q_{PAH} increases with the oxygen abundance up to log(O/H)~8.9 and flattens out and even reverses at higher abundances.

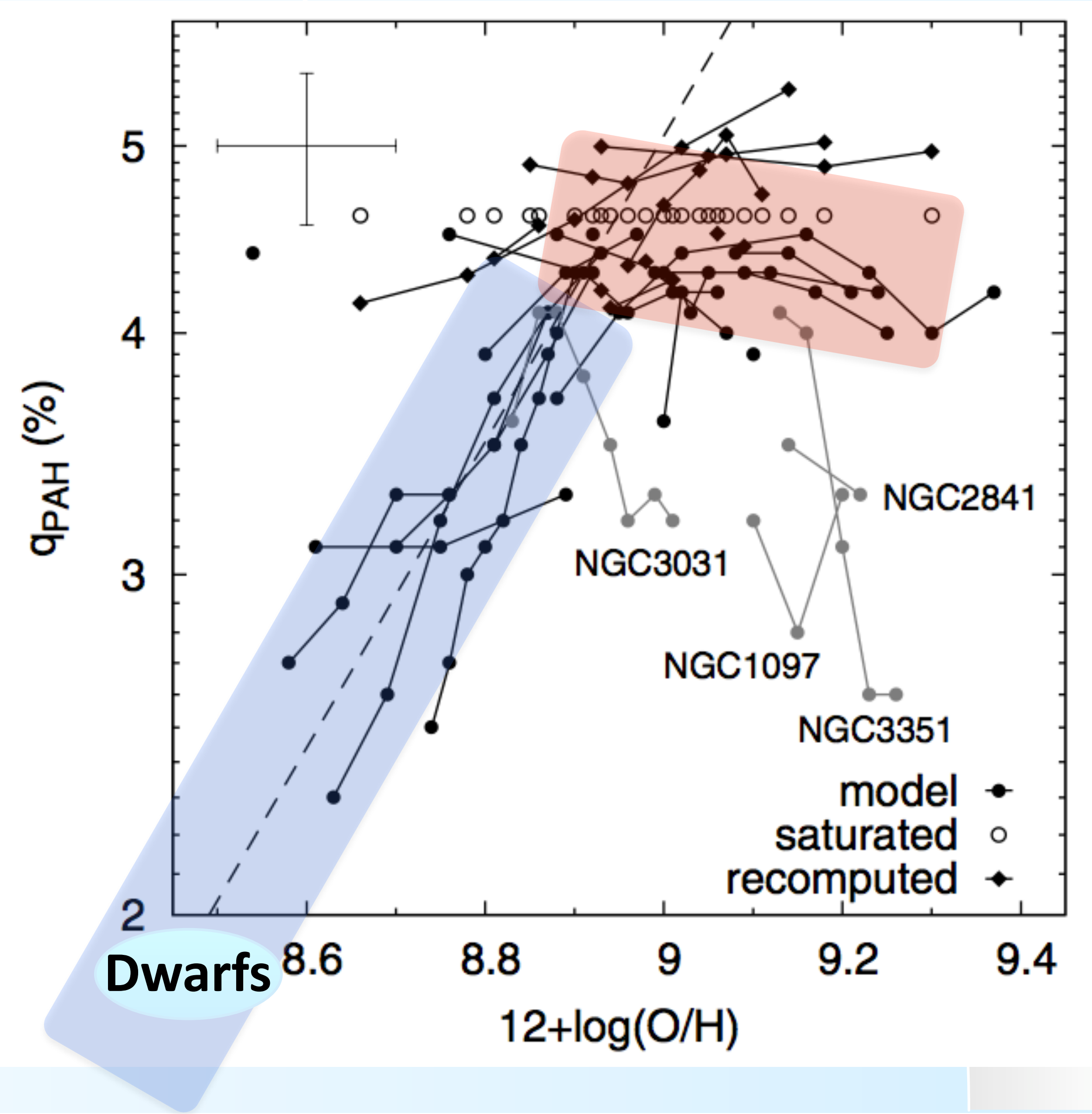
- **Possible explanation**:

Initial increase due to the progressively larger contribution of AGB stars (compared to SN II) to the C/O yield ratio.

Flattening due to increased contribution of oxygen rich (high-Z and/or very low-mass) AGBs.

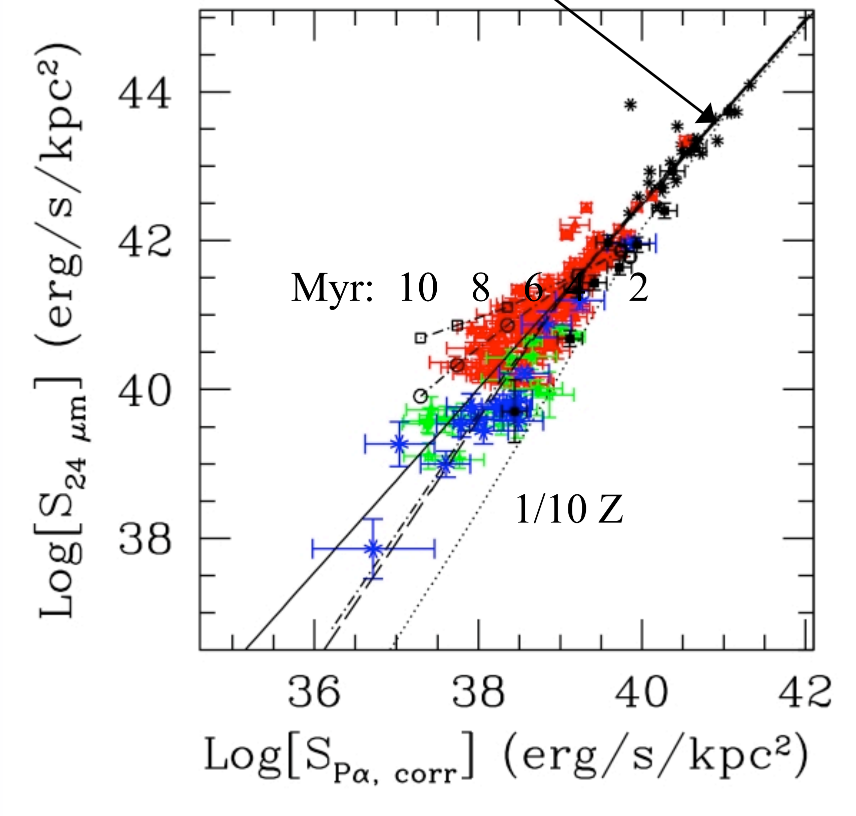
In agreement with the predictions by Galliano et al. (2008).

(Munoz-Mateos et al. 2009)



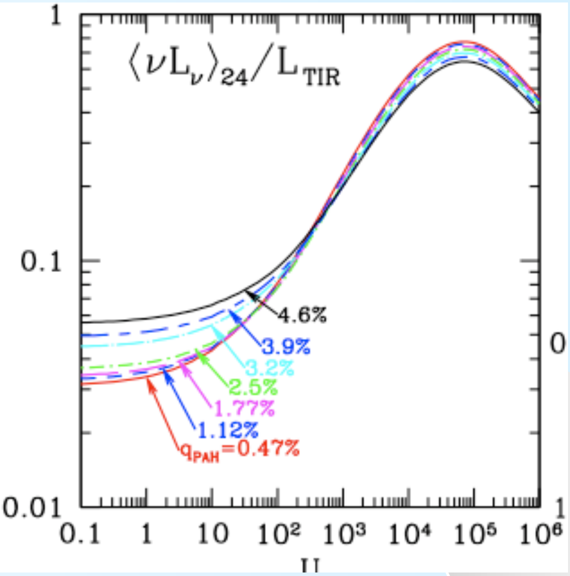
SFR(24)

4 Myr burst (or 100 Myr constant) SF, solar metallicity



L(IR) ~ L(Pα) for E(B-V) > 1 mag

How do we get a super-linear slope?



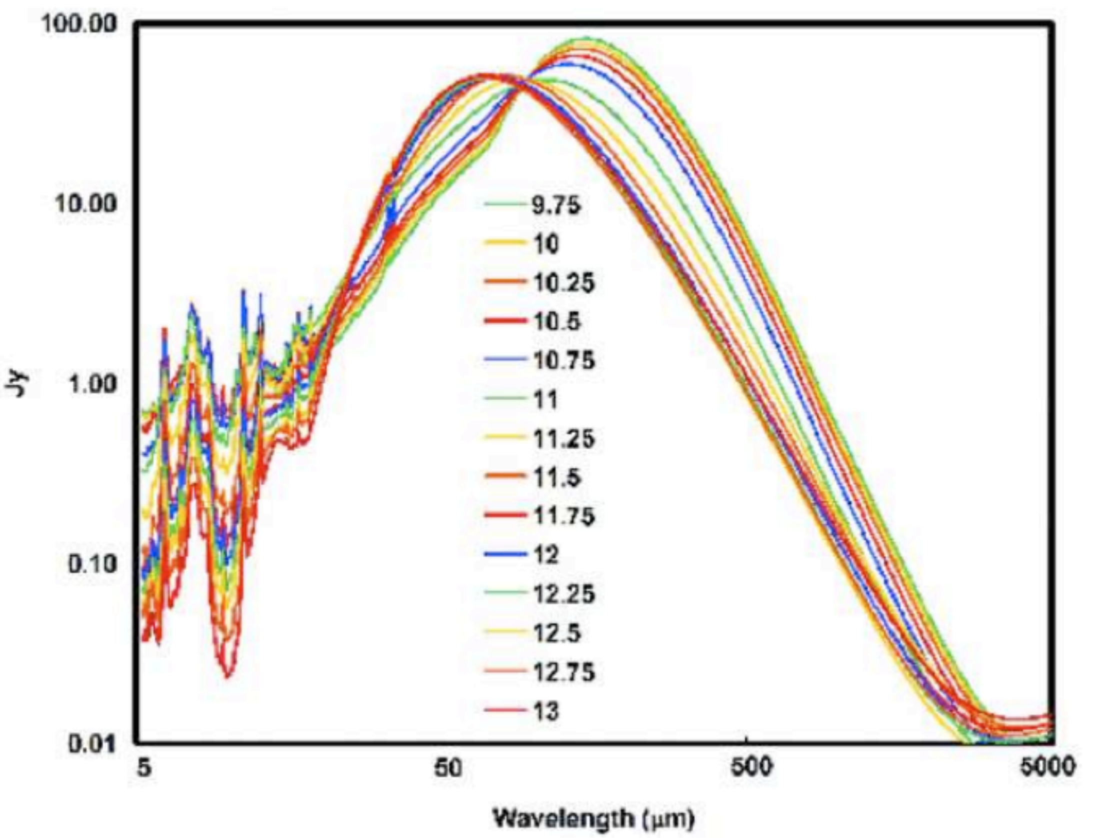
Draine & Li 2007

$$SFR(M_o\ yr^{-1}) = 1.27 \times 10^{-38}\ [L_{24}(erg\ s^{-1})]^{0.885}$$

(C. et al. 2007)

- Larger-than-unity slope (in log-log scale) is effect of increasing `dust temperature'
- Non-linear behavior at decreasing luminosities is due to increasing transparency of the ISM (see Walter et al. 2007, Cannon et al. 2005, 2006)
- Spread due to range of HII regions ages (~2-8 Myr)

SFR(24) - cont'd



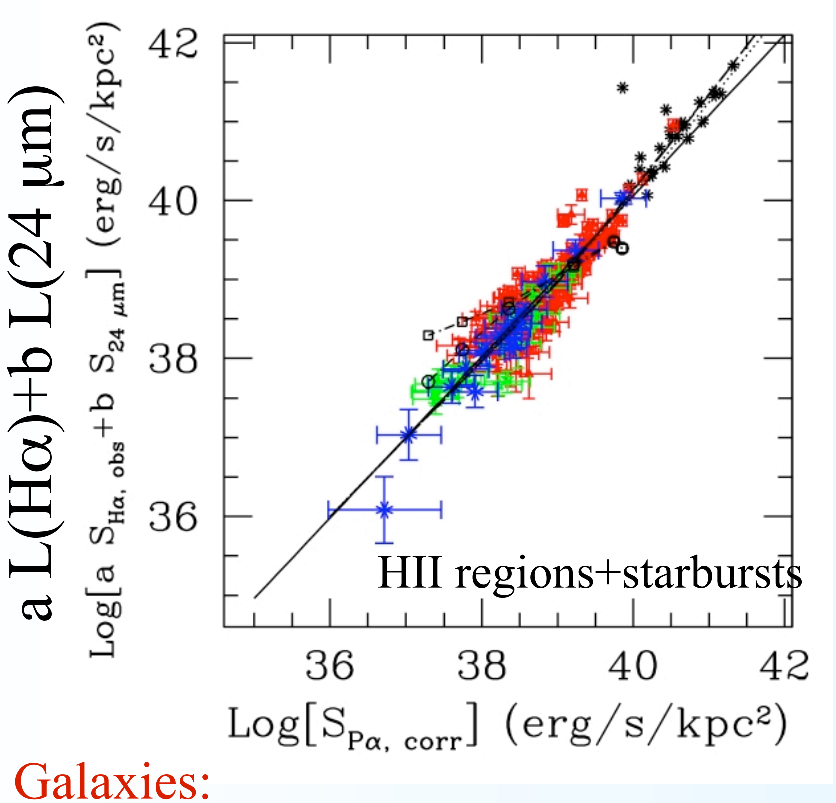
LIRGs and ULIRGs templates
(Rieke et al. 2009)

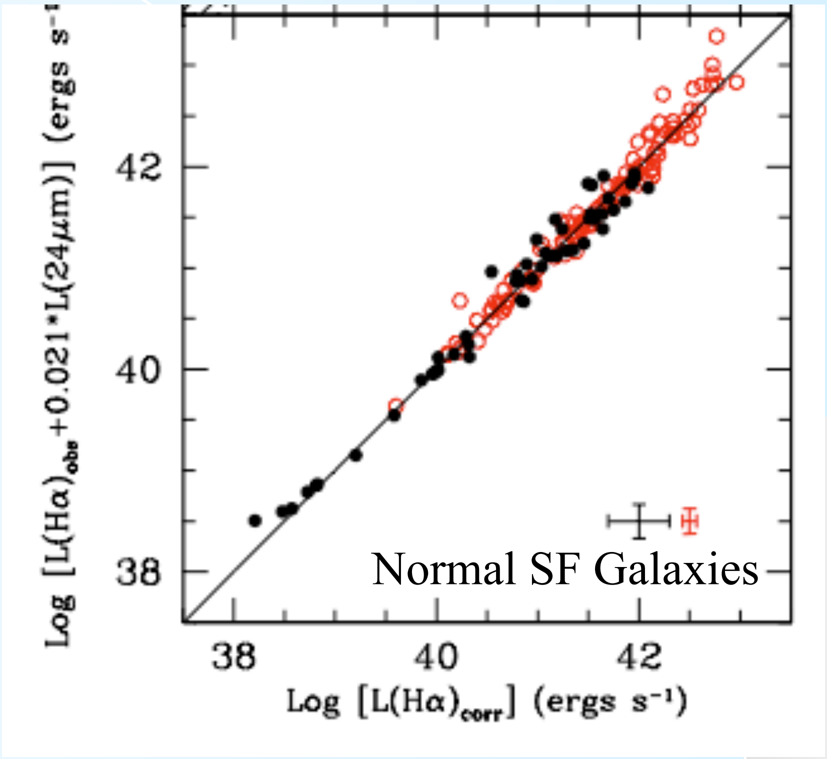
High luminosity ~ high dust attenutation ~ high opacity at NIR and MIR wavelengths

SFR ~ L(24) for L(24)< 5 X 10^{43} erg/s
SFR ~ L(24) $[2.03\text{x}10^{-44}\ \text{L}(24)]^{0.048}$ for L(24)> 5 X 10^{43} erg/s

A Robust Measure of SFR

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





Galaxies:

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

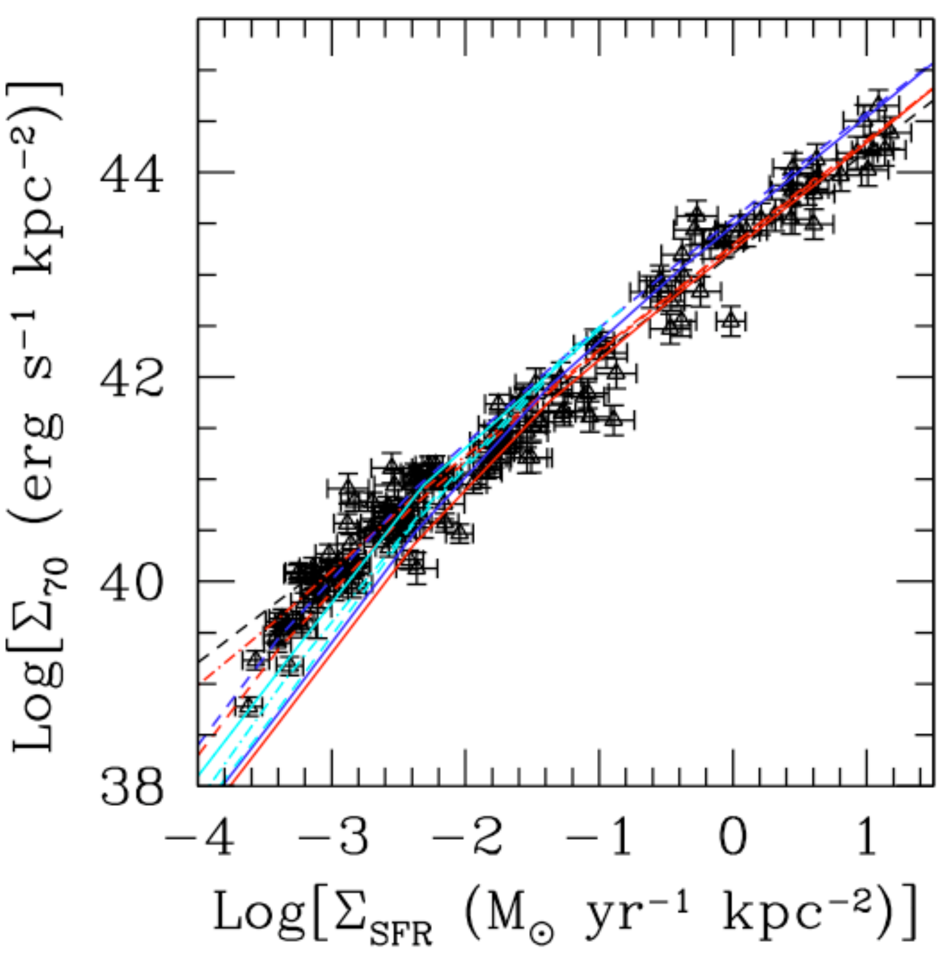
= $5.45 \times 10^{-42}\ [L_{H\alpha,\ obs} + 0.031\ L_{24\mu m}$ (erg s^{-1})]

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

C. et al. 2007, Kennicutt et al. 2007, 2008, Rieke et al. 2009; C et al. 2009 subm.

SFR(70)

Whole galaxies



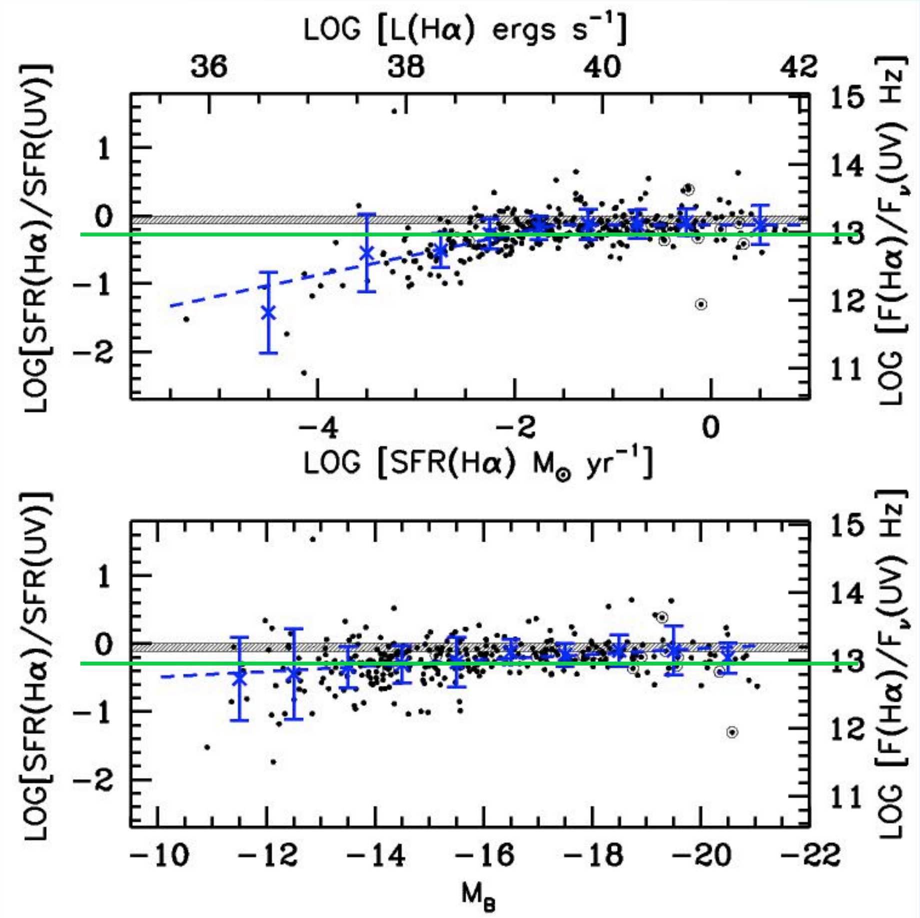
Advantage: close to peak of IR emission

However, scatter increases relative to 24 μm (by ~30%): increasing contribution from evolved stars.

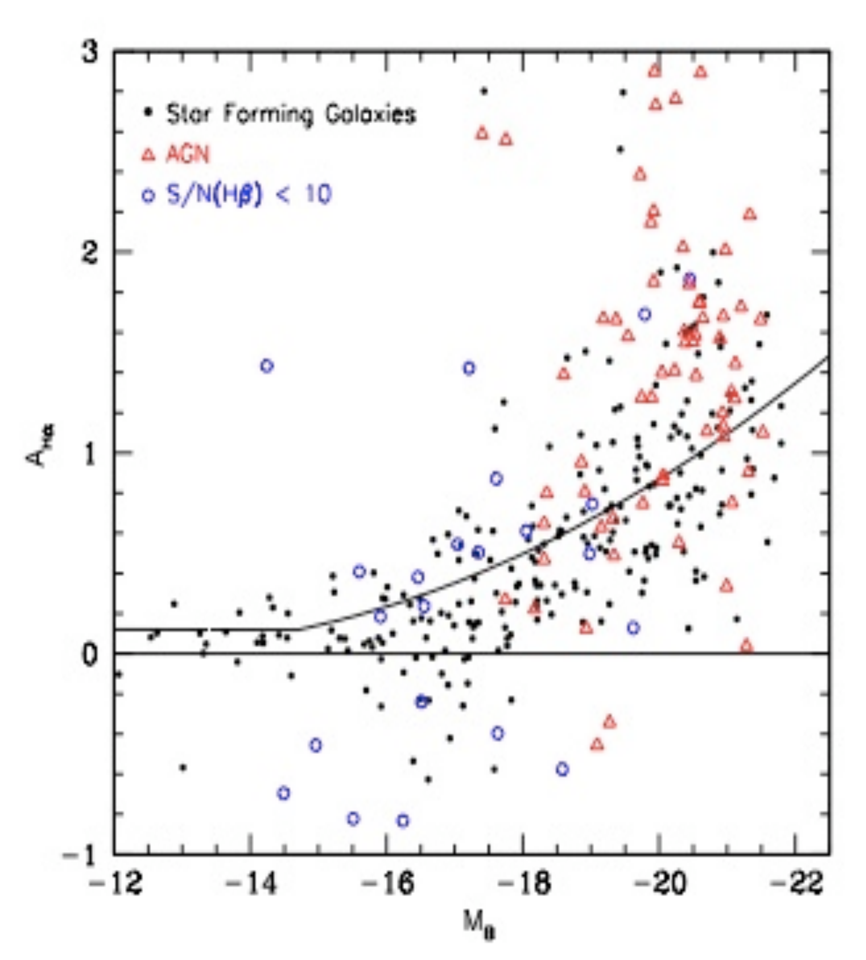
Similar analysis for 160 μm leads to ~2x increase in scatter.

C. et al. 2009, subm.

Hα and UV SFR Comparisons from 11HUGS/LVL



*observed relation, **after** corrections for internal dust attenuation (from Spitzer images)*

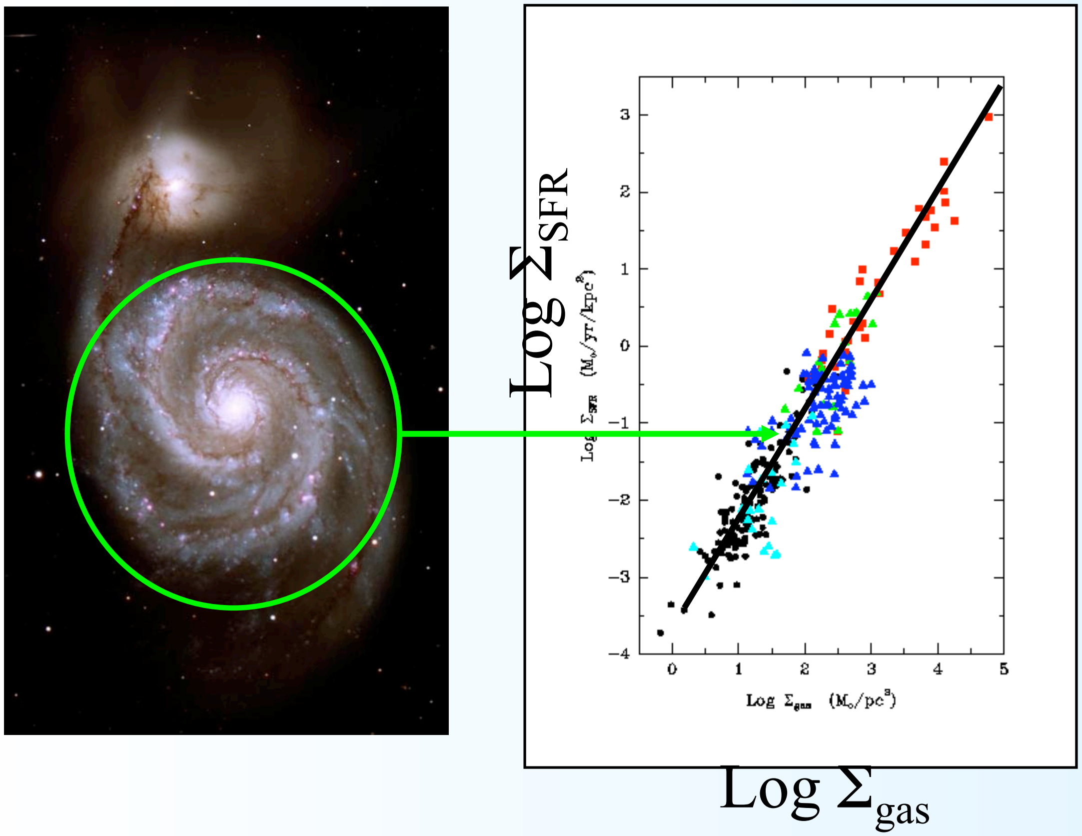


(J. Lee et al. 2009)

The Scaling Law(s) of SF

In galaxies considered as a whole, the SFR scales with the gas surface density **(Kennicutt 1989, Kennicutt 1998, Kennicutt 2006)**:

$$\Sigma_{SFR} \sim \Sigma_{gas}^{1.4}$$

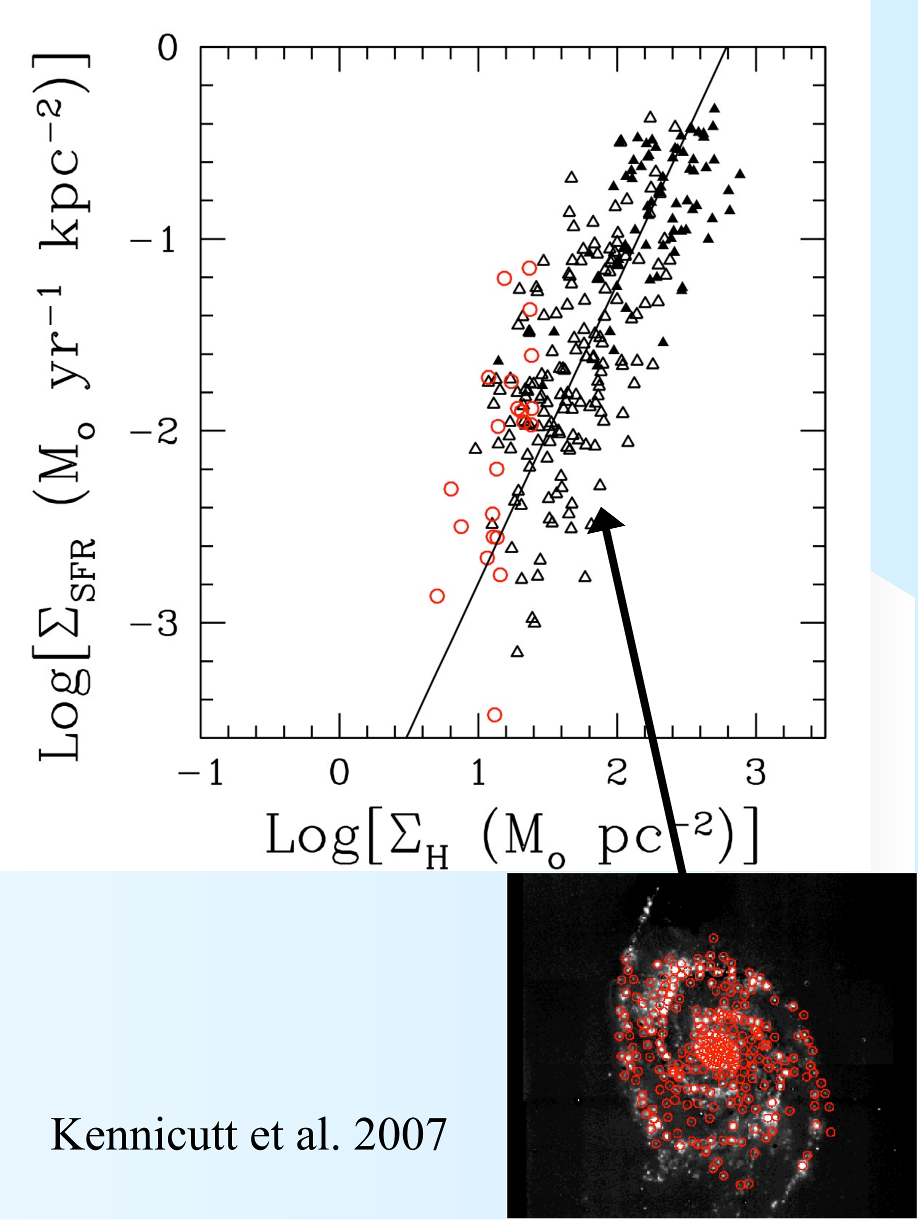


Underlying Mechanism(s)?

- large scale gravitational instabilities: $\rho_{SFR} \sim \rho_{gas}^{1.5}$
- global resonances (frequency of the spiral waves): $\rho_{SFR} \sim \rho_{gas}\Omega_r f(Q)$ (Wyse & Silk 1989)
- galactic shear (irregular galaxies; Hunter et al. 1998)
- cloud-cloud collisions (Tasker & Tan 2008)
- threshold-driven thermal instabilities (Schaye 2004)
- turbulence (Krunholz et al. 2008)
- dust shielding (Gnedin et al. 2008)
- etc. etc.

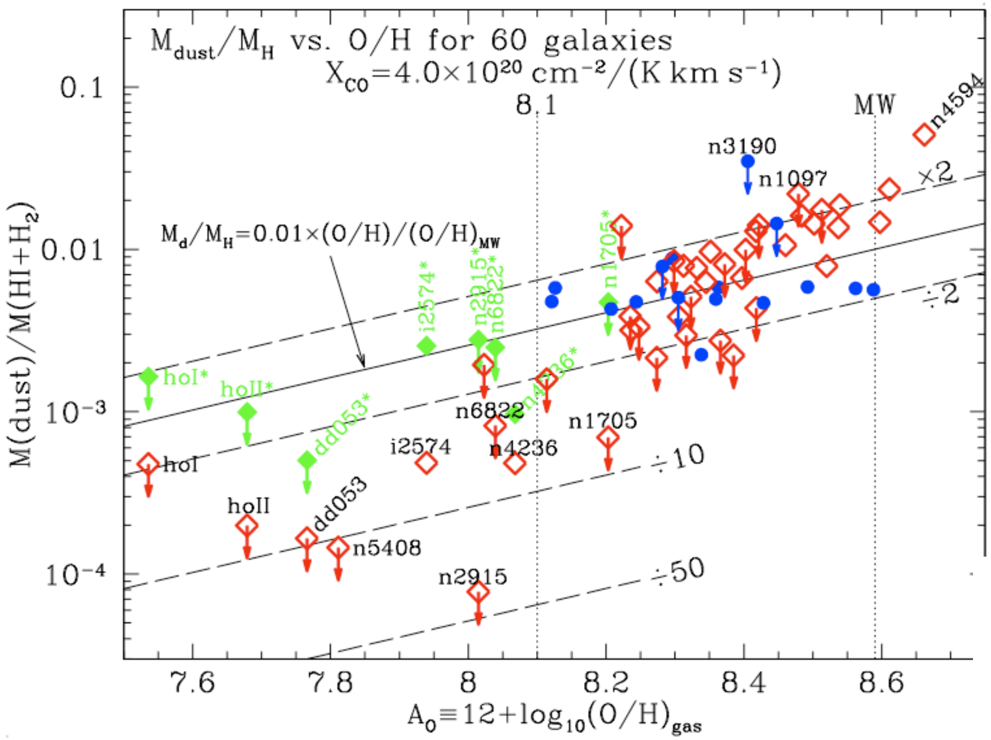
What is the Next Step?

- Galaxies, taken as whole units, are too complex to enable discrimination among the different possible mechanisms
- Next step: `dissect' the galaxies into their sub-components.
    - Need unbiased SFR tracers
    - Need reliable measures of cold gas content.
- Then: Extend the analysis to cover the full parameter space of densities, SFRs, surface brightness, metallicity, etc.

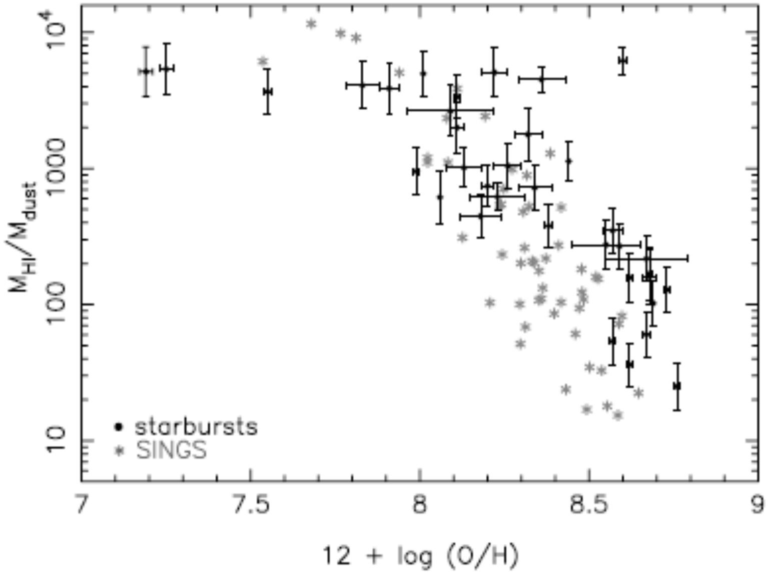


Kennicutt et al. 2007

Dust Traces Metals



(Engelbracht et al. 2008)

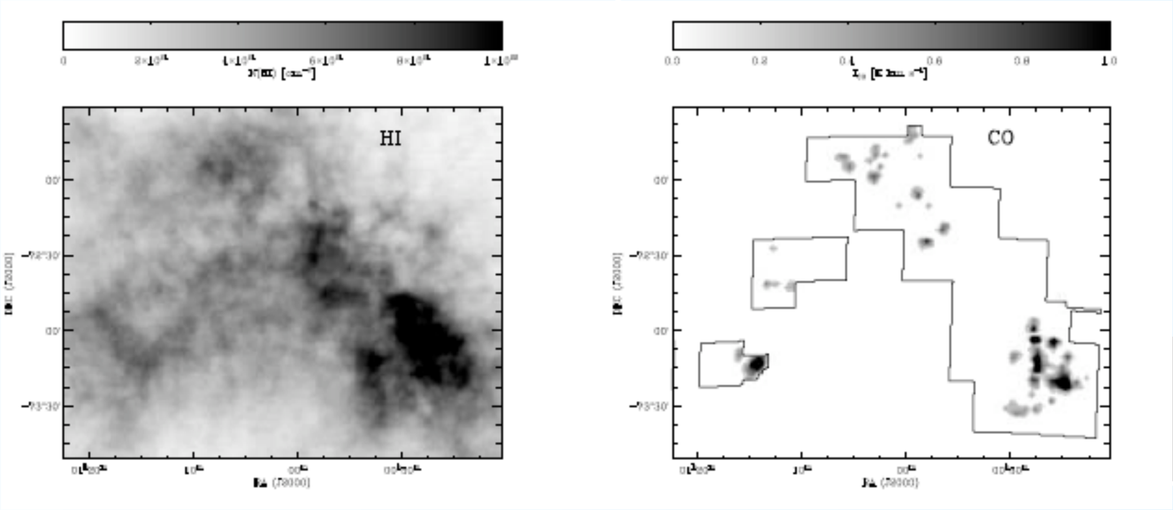


Draine et al. 2007:

$M_d/M_g \sim 0.01$ x metallicity

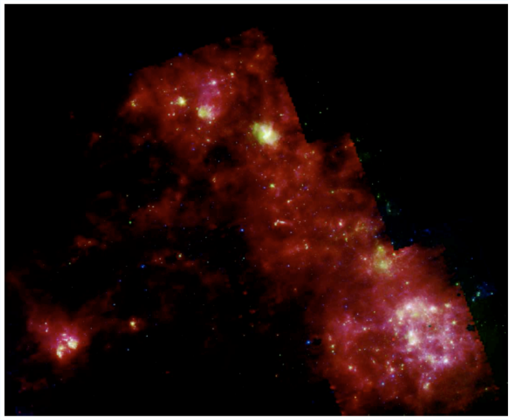
Can Cold Dust `Stand in' for CO?

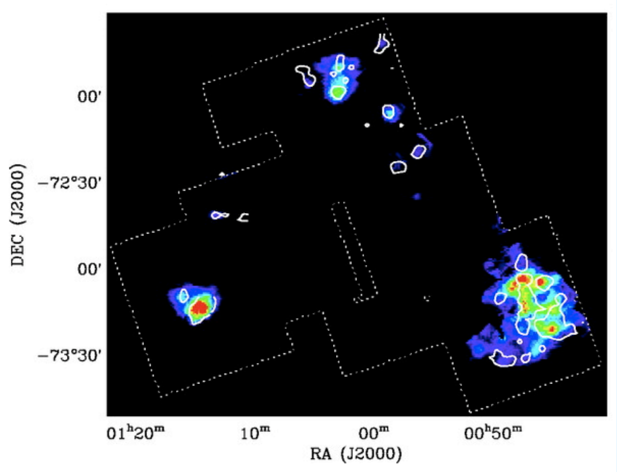
HI



CO

3-color IRAC/MIPS map (8, 24, 160 μm)





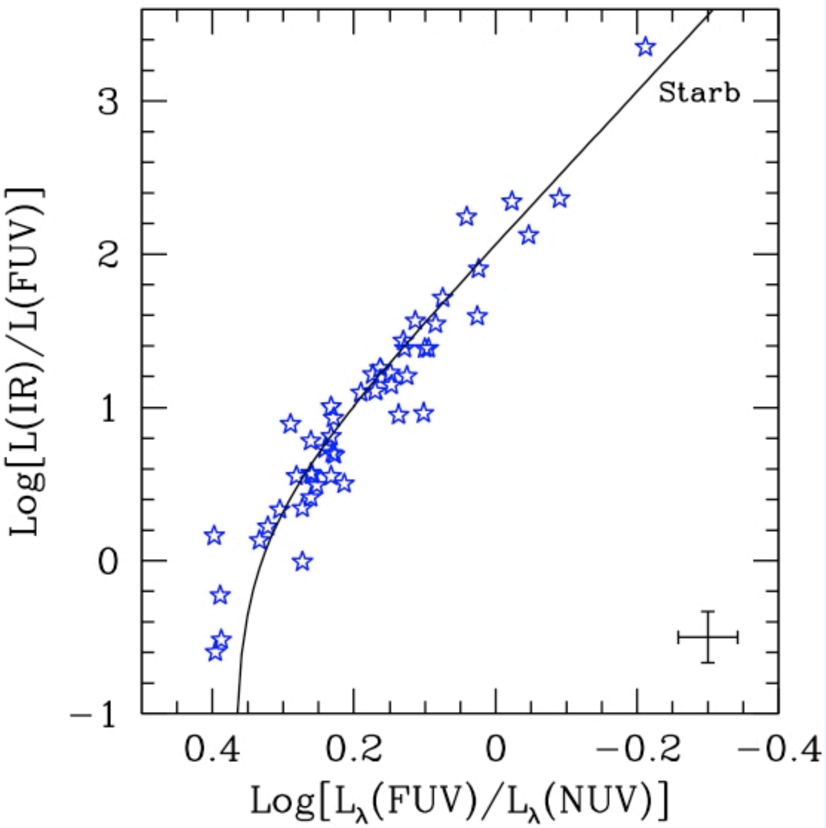
Dust-derived `CO'

An experiment on the SMC

(Leroy et al. 2007)

Dust emission from galaxies dependent not only on dust properties, but also on **geometry**

Dust Geometry

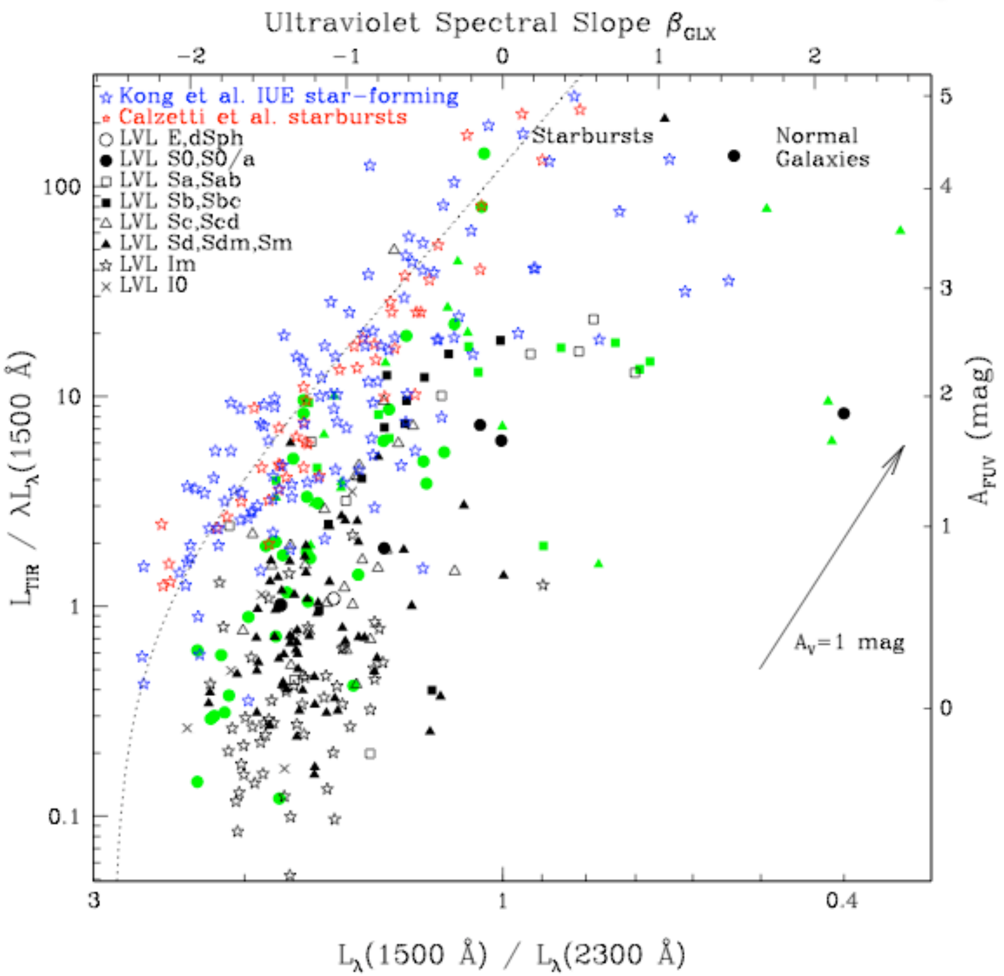


(Meurer et al. 1999, C. et al. 2000, C. 2001)

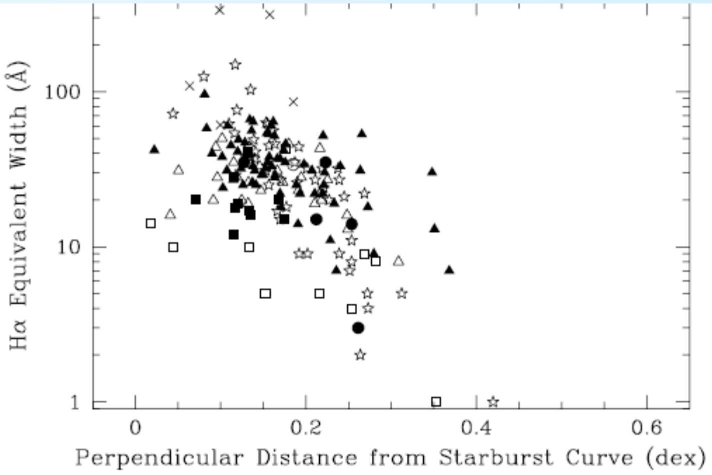
IR offers the necessary information for recovering the full UV emission (SFR) at high z.

However….

Dust/Stellar Pop. Geometry



(Dale et al. 2009)



An effect of mean stellar population ageing…. but we can't forget galaxy-to-galaxy dust geometry variations

(Boquien et al. 2009)

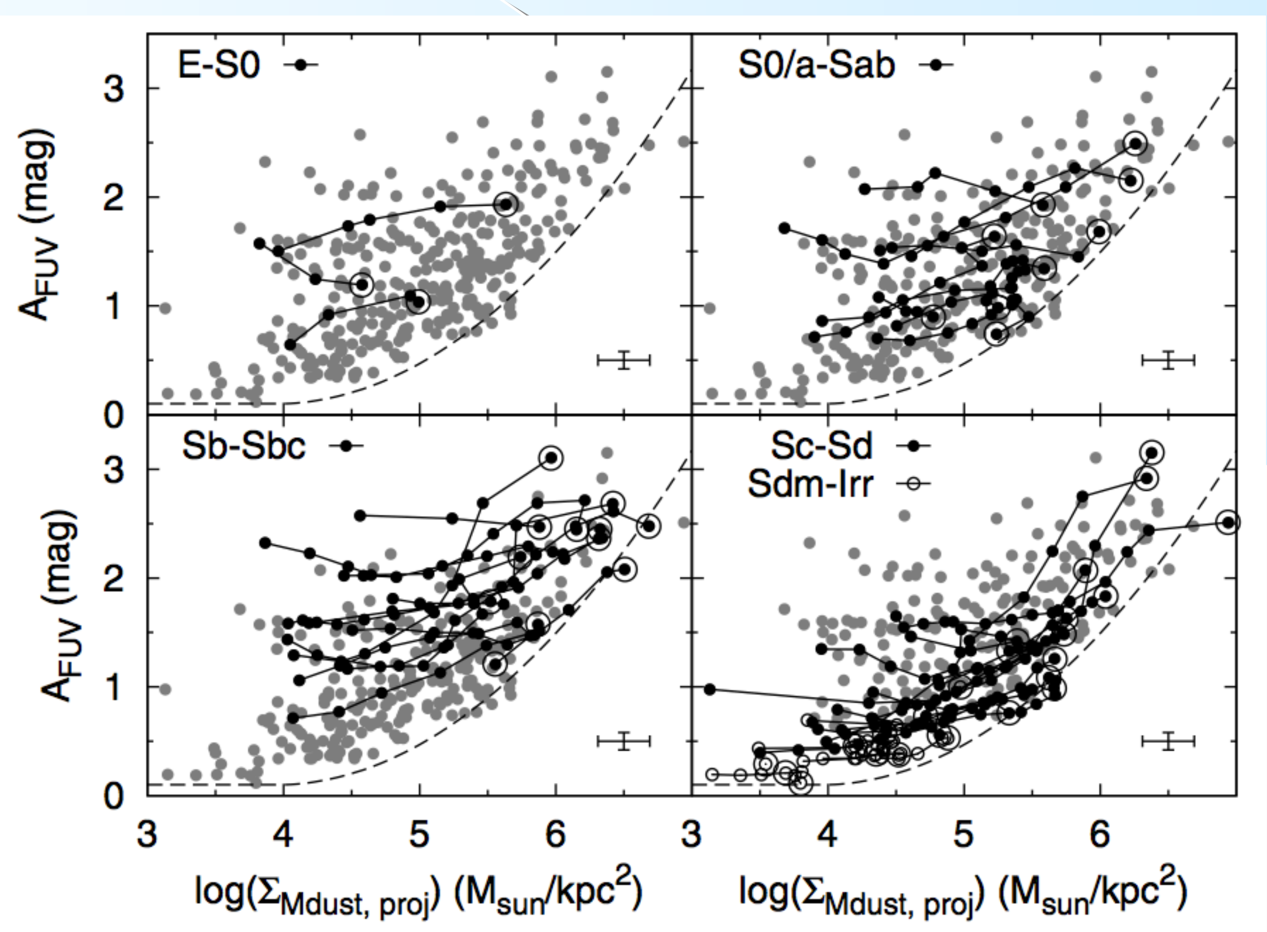
(Buat et al. 2002, 2005, Bell 2002, Gordon et al. 2004, Xu et al. 2004, C. et al. 2005, Seibert et al. 2005, Cortese et al. 2006, Dale et al. 2007, Munoz-Mateos et al. 2009)

Dust physical properties: Radial profiles

A_{FUV} (TIR/FUV) vs. dust-mass surface density

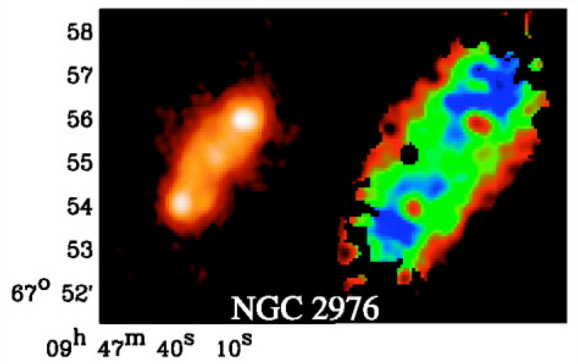
- Minimum A_{FUV} for any given projected dust column density.

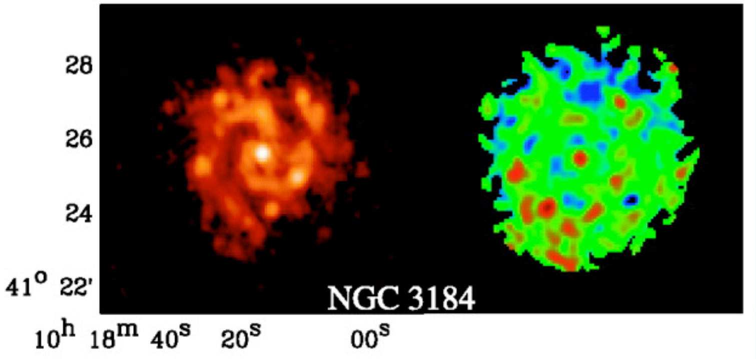
- **Possible explanation**: Dust is more porous in Sc-Irr galaxies than in earlier types, yielding lower attenuation for the same dust column density.

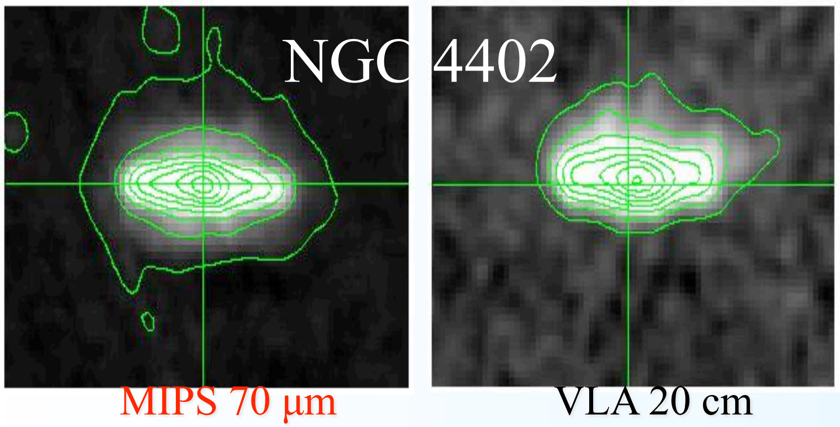


(Munoz-Mateos et al. 2009)

The FIR-Radio Correlation







MIPS 70 μm VLA 20 cm

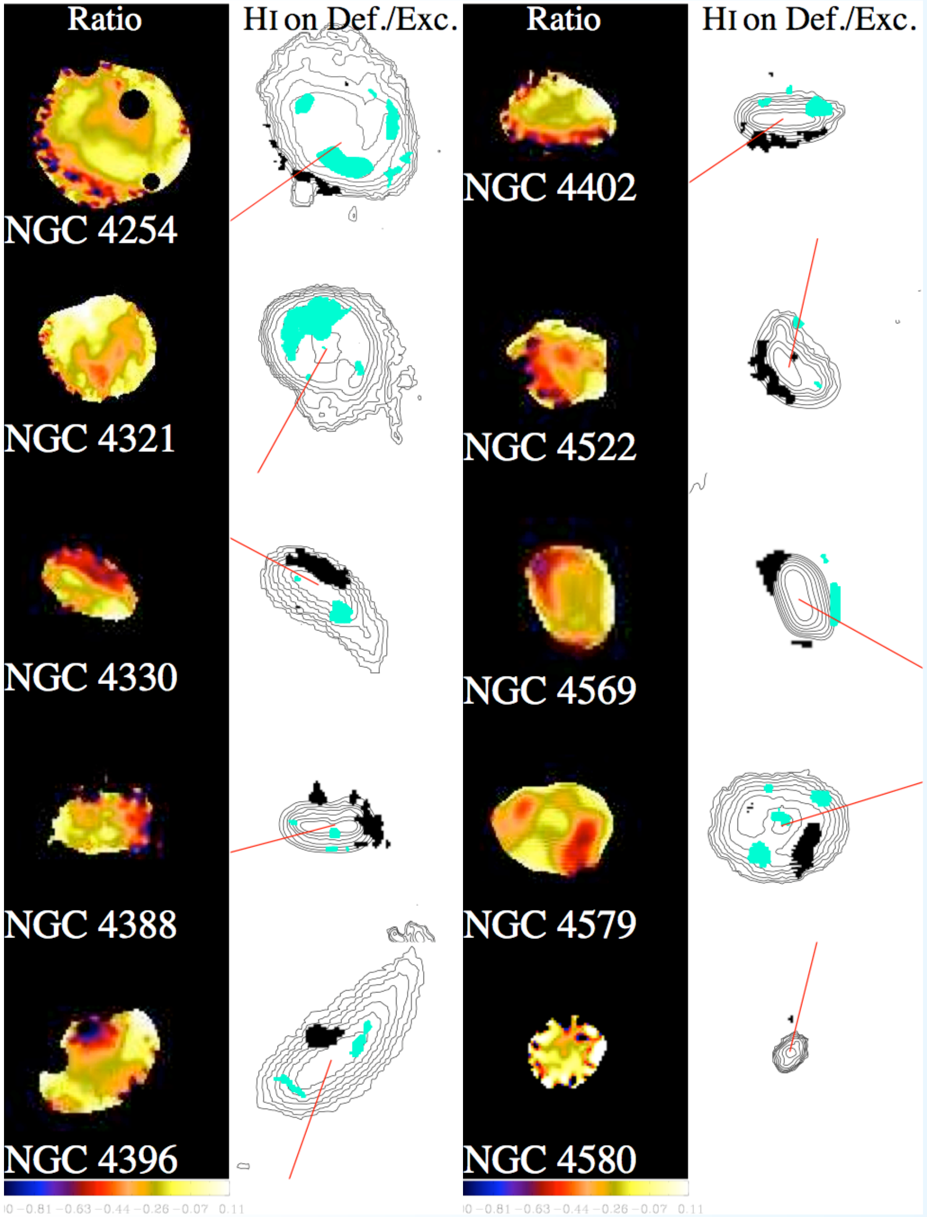
What is the underlying physics of the FIR-radio correlation over 5 orders of magnitude?
Clearly, SF involved. However, how are differentprocesses, heating of dust and propagation of CRs, related over 4-5 orders of magnitude?
(Cannon et al. 2006, Roussel et al. 2006)

From Spitzer data (Murphy et al. 2006, 2008), radio images are smoother versions of FIR images.

Kernel lengths prop to SFR/area.
`Age effect': CR electrons in more recent SF events have not diffused significantly.

Use FIR to predict `undisturned' radio distribution; and search for deviations between observed and predicted radio morphology

Radio Continuum Deficit/Excess Regions



HI contours overlaid

– 6/10 galaxies: we detect deficit regions (pix < 0.50)

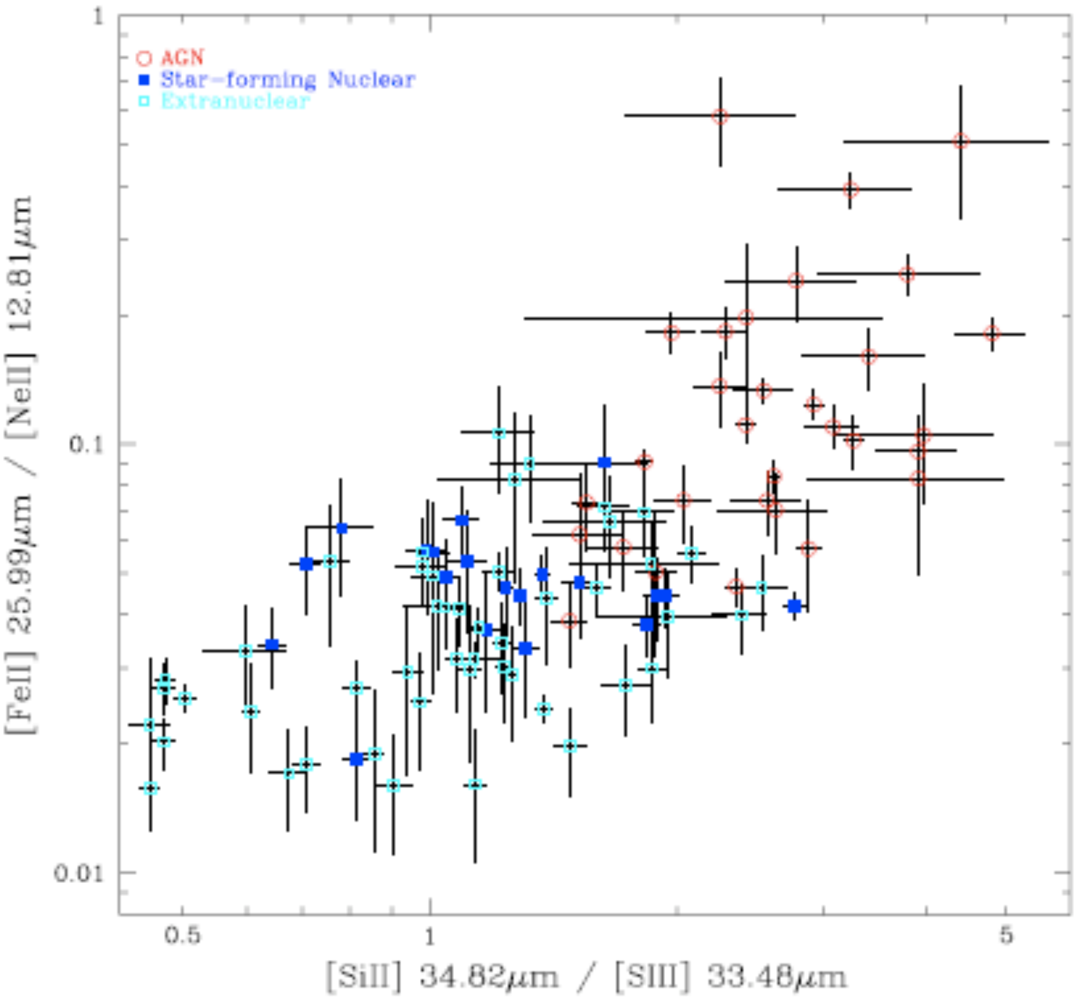
→ Each shows additional evidence of ram pressure effect

Radio Deficits located opposite synchrotron tails & excess regions:

- associated with ICM wind

(Murphy et al. 2009)

What about Spectroscopy?



(this would require a full, separate talk)

A clear separation between AGNs and star-foming regions.

Reasons?

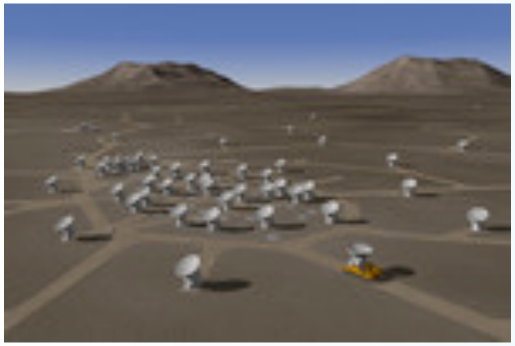
1. Destruction of dust grains (photodesorp., shuttering, fragmentation, etc.) by hard AGN radiation;
2. X-ray dissociation regions.

(Dale et al. 2009)

A Look to the (Immediate) Future

Herschel Space Telescope is going to complement the IR wavelength coverage down to 0.5 mm. Many programs (guaranteed and open time).

1. ISM physical and chemical characteristics
2. Cold dust emission; modeling of dust abs/emission



ALMA and other facilities (e.g., LMT) will extend that coverage all the way to mm wavelengths. Beyond the `obvious' (CO, HCN, and other molecular emission lines):

1. the R-J tail of the cold dust emission, the ultimate test of how closely cold dust can trace molecular hydrogen.

Summary

The Spitzer Space Telescope has enabled unprecedented investigations of nearby galaxies, thanks to a combination of high angular resolution and sensitivity. A few highlights:

- SFRs: Robust recipes for star formation rates from monochromatic IR light are now available, but many caveats are still present: AGNs, range of applicability of various combinations of different bands, …
- Dwarf galaxies: extinction corrections from IR data have enabled an unambiguous determination of an Hα deficiency in dwarf galaxies (environment-dependent IMF?)
- The 8 μm emission is better correlated with tracers of cold dust (160 μm emission), rather than tracers of warmer dust (and SFR). Heavily deficient in low metallicity galaxies, possibly related to a destruction process.
- Dust/gas appears well correlated with galaxy metallicity. This is promising for probing H_2 in low-metallicity galaxies (where CO likely fails).
- The FIR-radio correlation is definitely linked to star formation; larger CR diffusion lengths are associated with older SF events. This is being exploited to investigate the impact of the ICM in cluster galaxies.