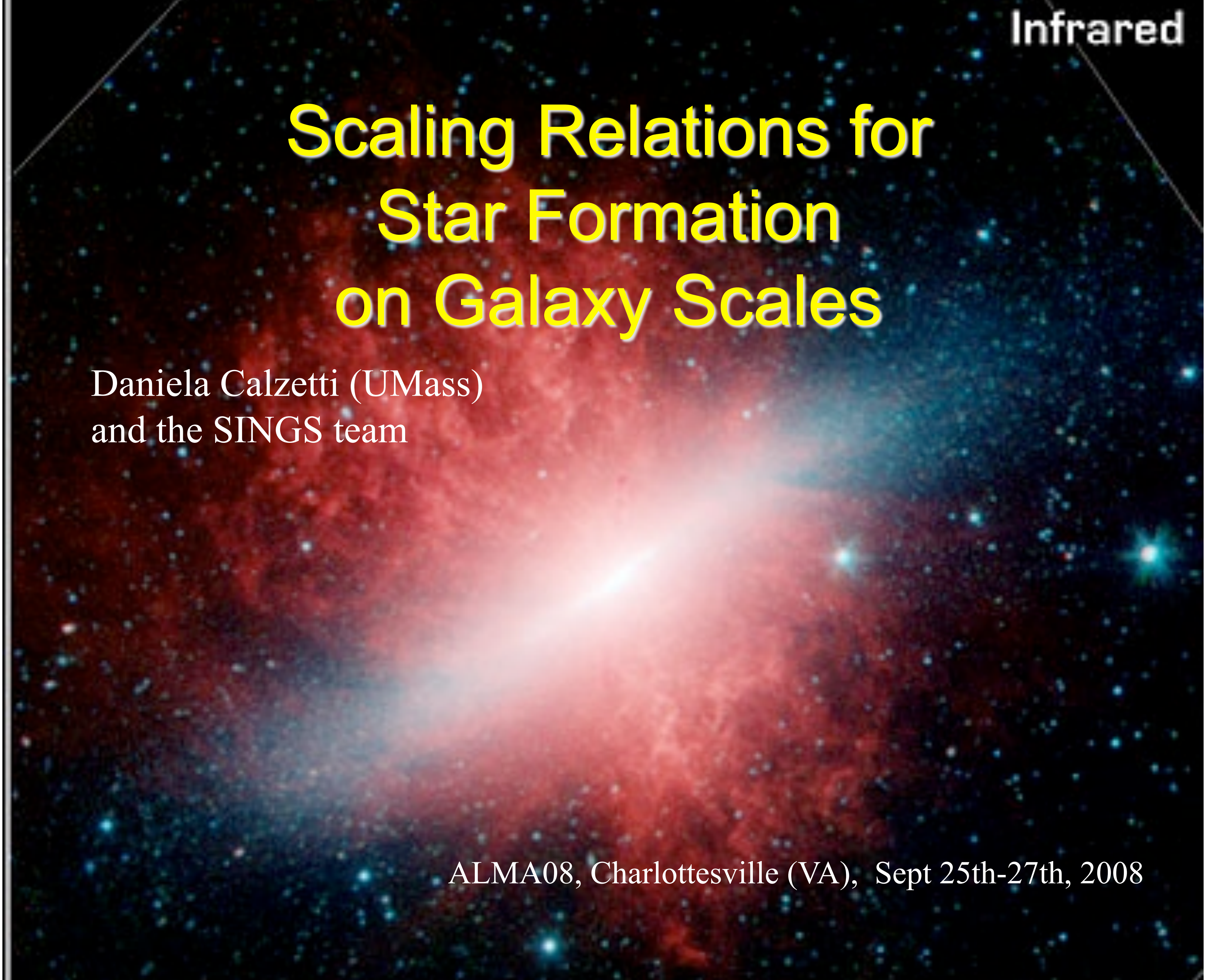
Scaling Relations for Star Formation on Galaxy Scales

Daniela Calzetti (UMass)
and the SINGS team

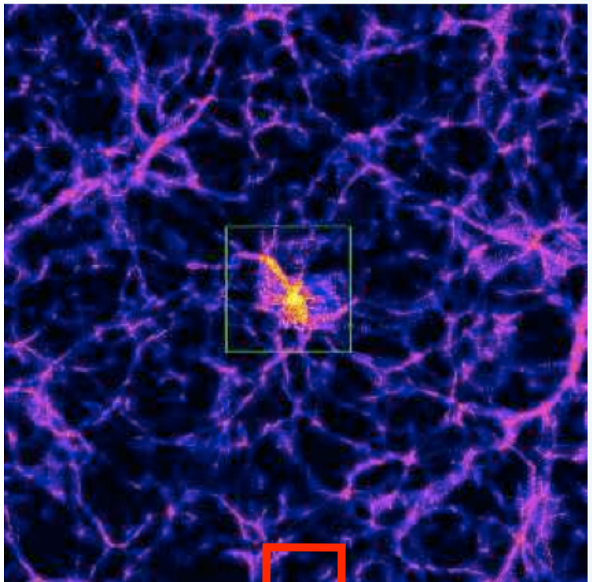


ALMA08, Charlottesville (VA), Sept 25th-27th, 2008

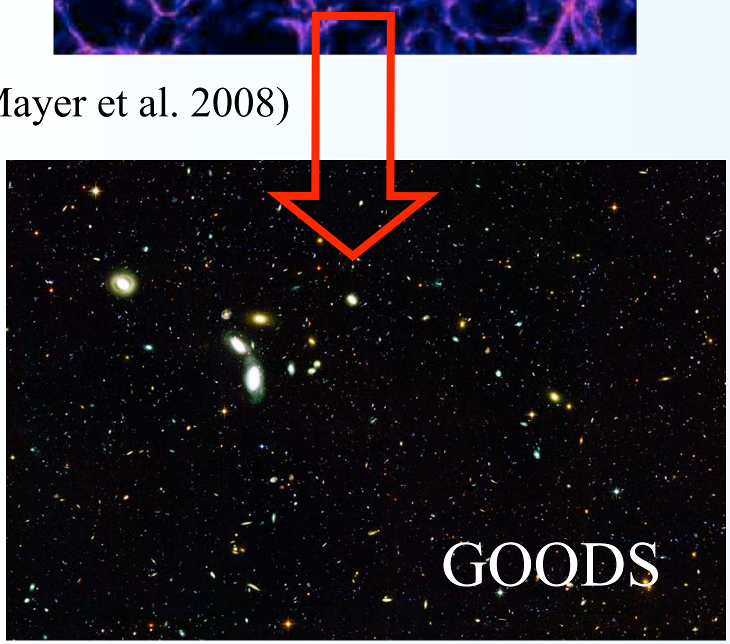
Outline

- The `burning' questions for galaxy formation and evolution
- How do we measure star formation?
- How well is star formation related to its `fuel'?
- What are we still missing?

Structure Formation

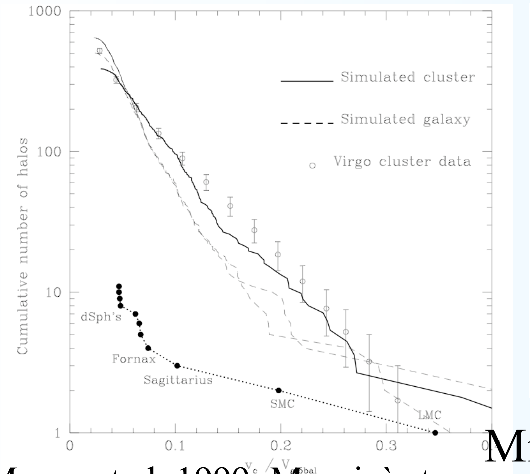


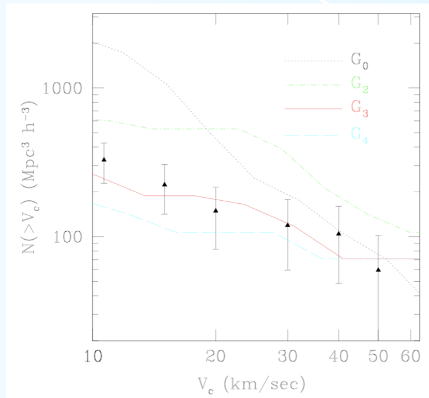
(L. Mayer et al. 2008)



- Many of the open issues in ΛCDM models of structure formation have moved from the realm of the DM structures evolution to the interplay between the DM structures and baryonic matter.
- Open questions include:
  - how the two interact;
  - how well the baryonic (stars and gas) matter traces the DM haloes.

Problems? Solutions?

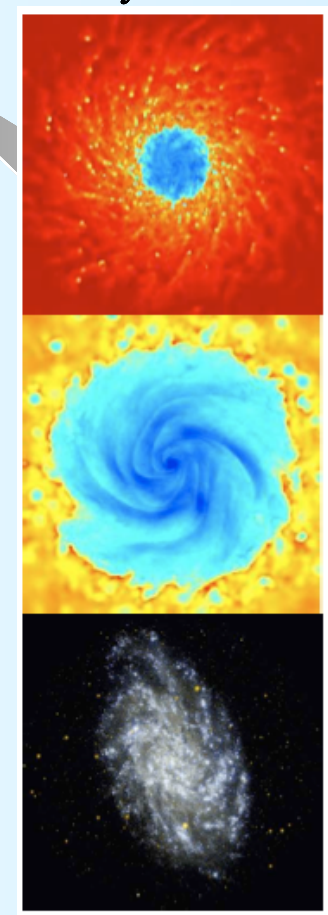


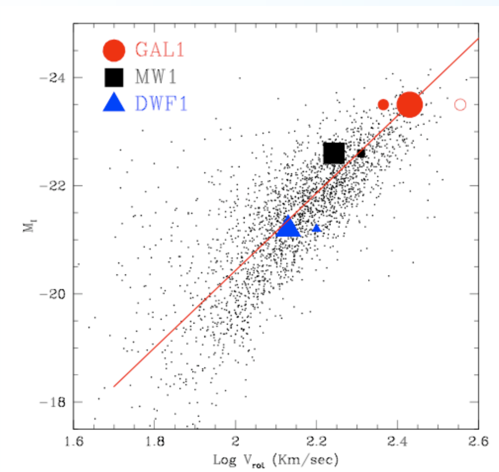


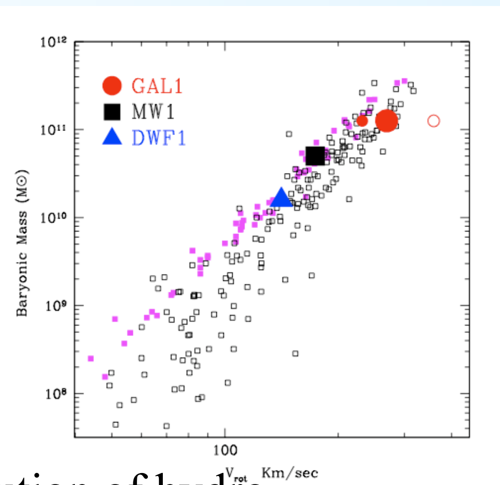
(Moore et al. 1999; Maccio` et al. 2006; Mayer et al. 2007)

Missing satellites: reionization, UV heating, ram-pressure stripping?

NFW cusps: fragility? tracing of baryonic matter?



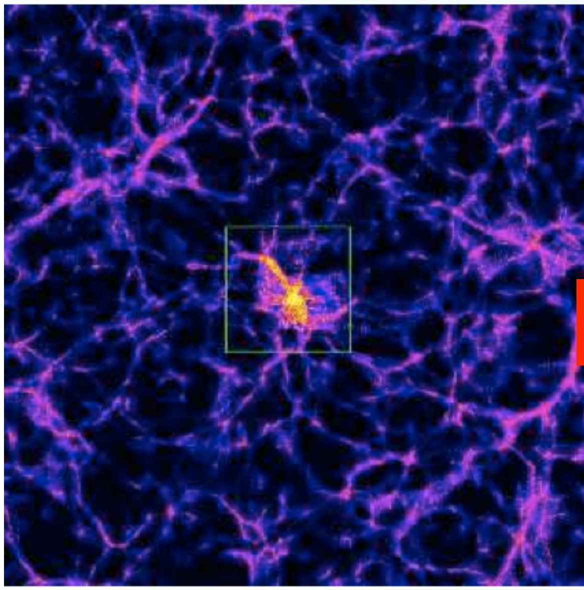


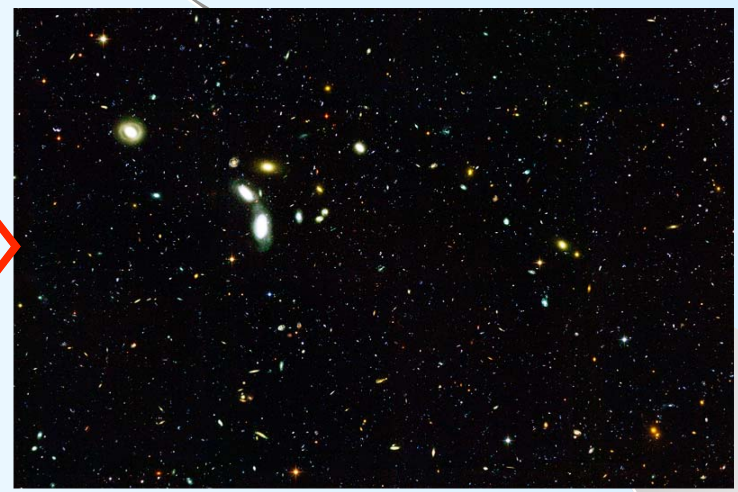


Angular momentum: resolution of hydro codes? Feedback?; Governato et al. 2006

Bulge-less galaxies: SF recipes? Mayer et al. 2008

DM - BM Connection



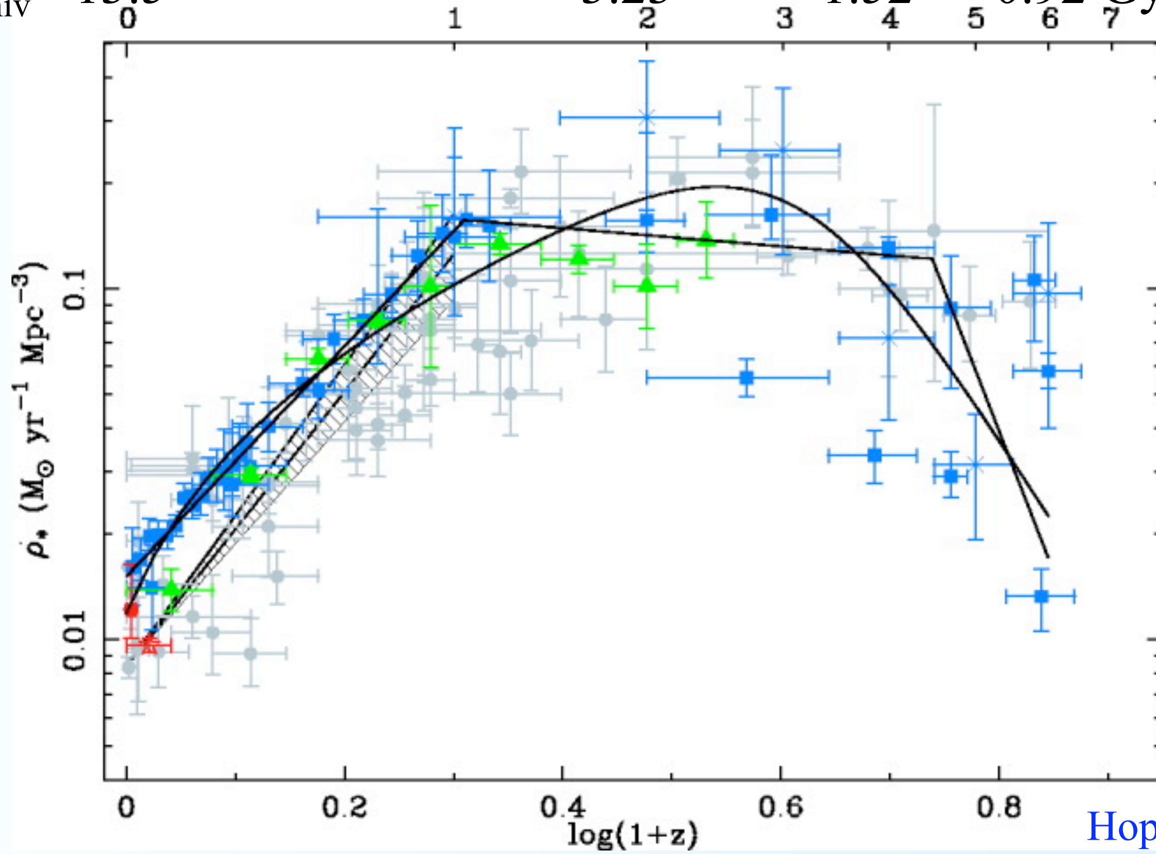


Assumptions/recipes are required in models for:

1. ISM physics
2. Star Formation (SFR?)
3. Stellar/AGN feedback
4. Connections among the 3 above (e.g., `laws of SF'; thresholds of SF).

Cosmic Star Formation

Age_{Univ}= 13.5 3.23 1.52 0.92 Gyr



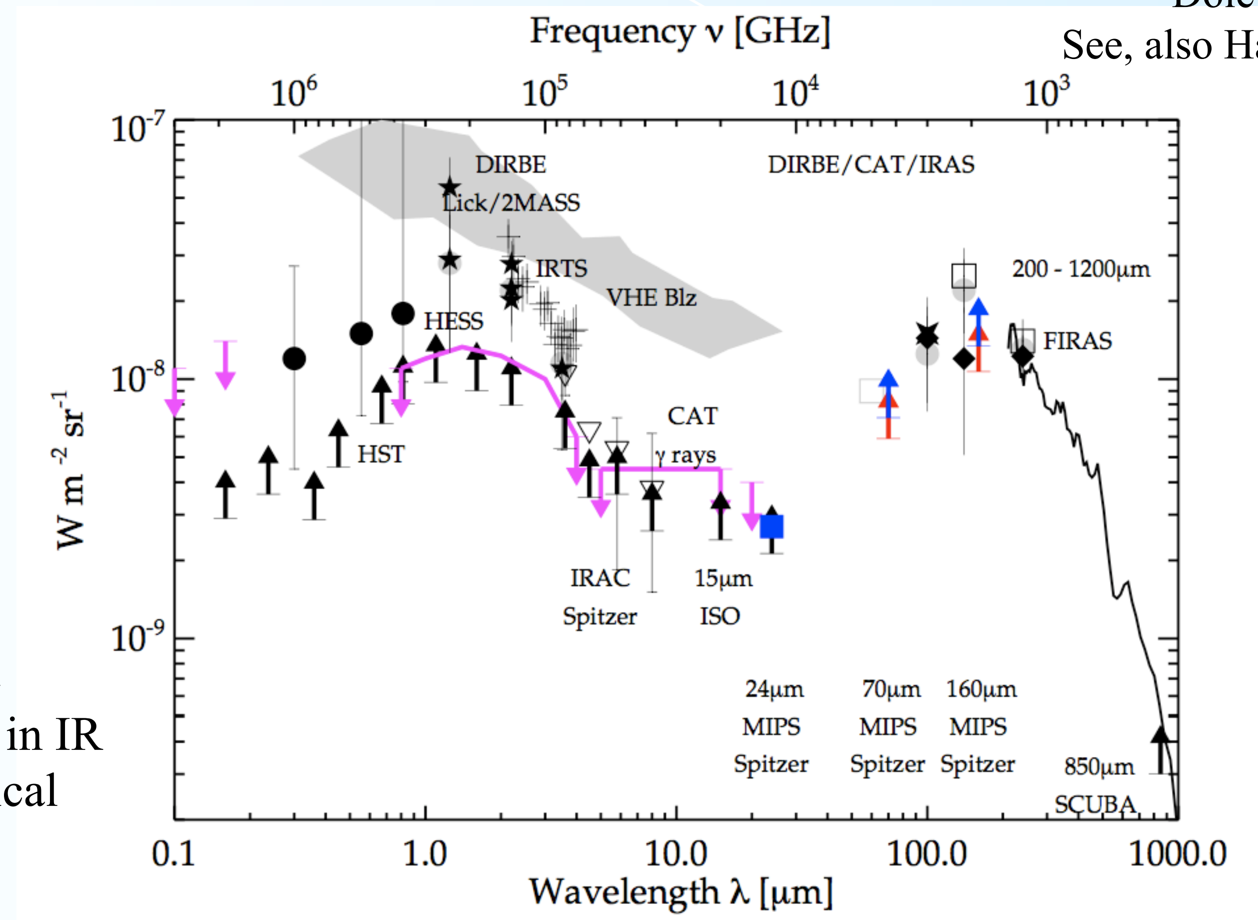
Hopkins & Beacom 2006

Two ingredients:

1. Accurate measurements of SFRs (in the observations)
2. `Knowledge' of the star formation/feedback laws (in models)

Star Formation and Dust in Galaxies

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



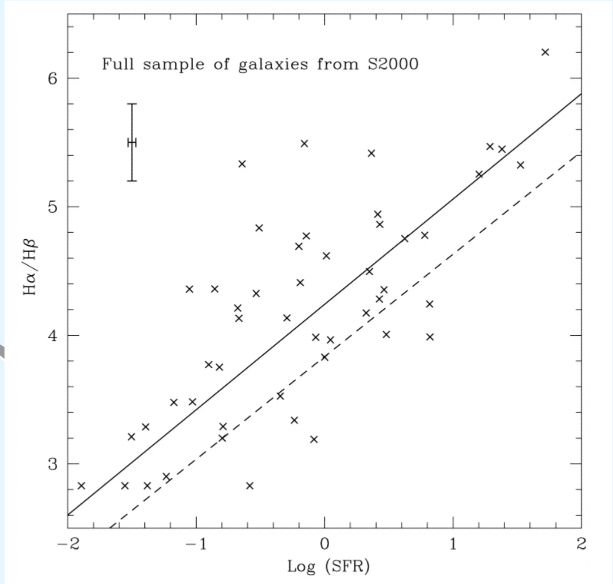
Roughly 1/2 energy each in IR and UV/optical

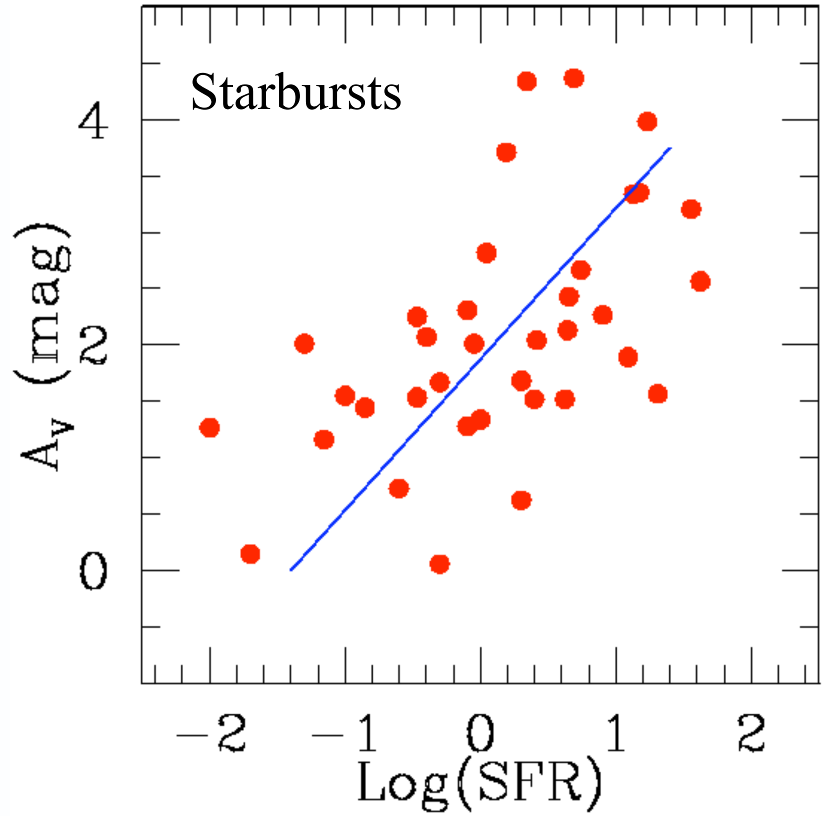
About 80% of UV light (tracer of SF) is absorbed by dust; AGNs are also heavily dust-absorbed.

SFR-Extinction

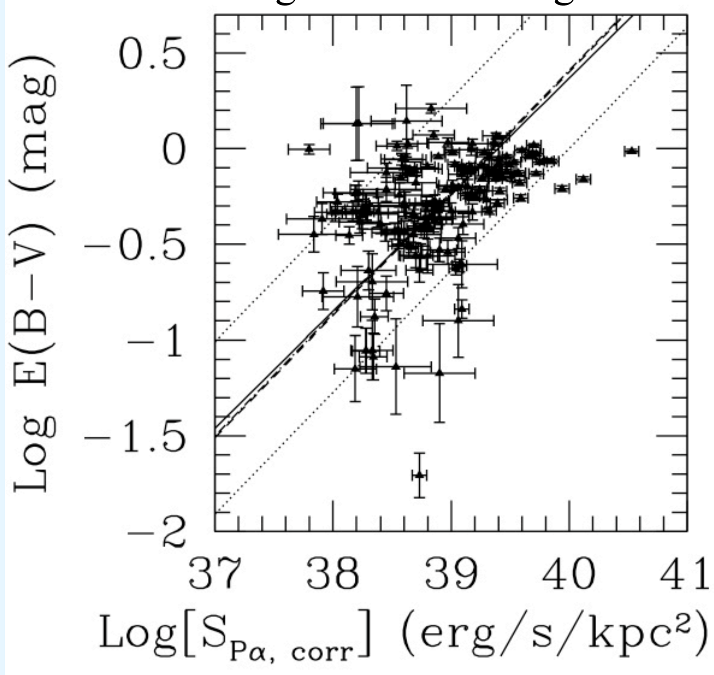
(Wang & Heckman, 1996; Heckman et al. 1998; Calzetti 2001 Hopkins et al. 2001, Sullivan et al. 2001, C. et al. 2007)

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





SF regions in normal galaxies



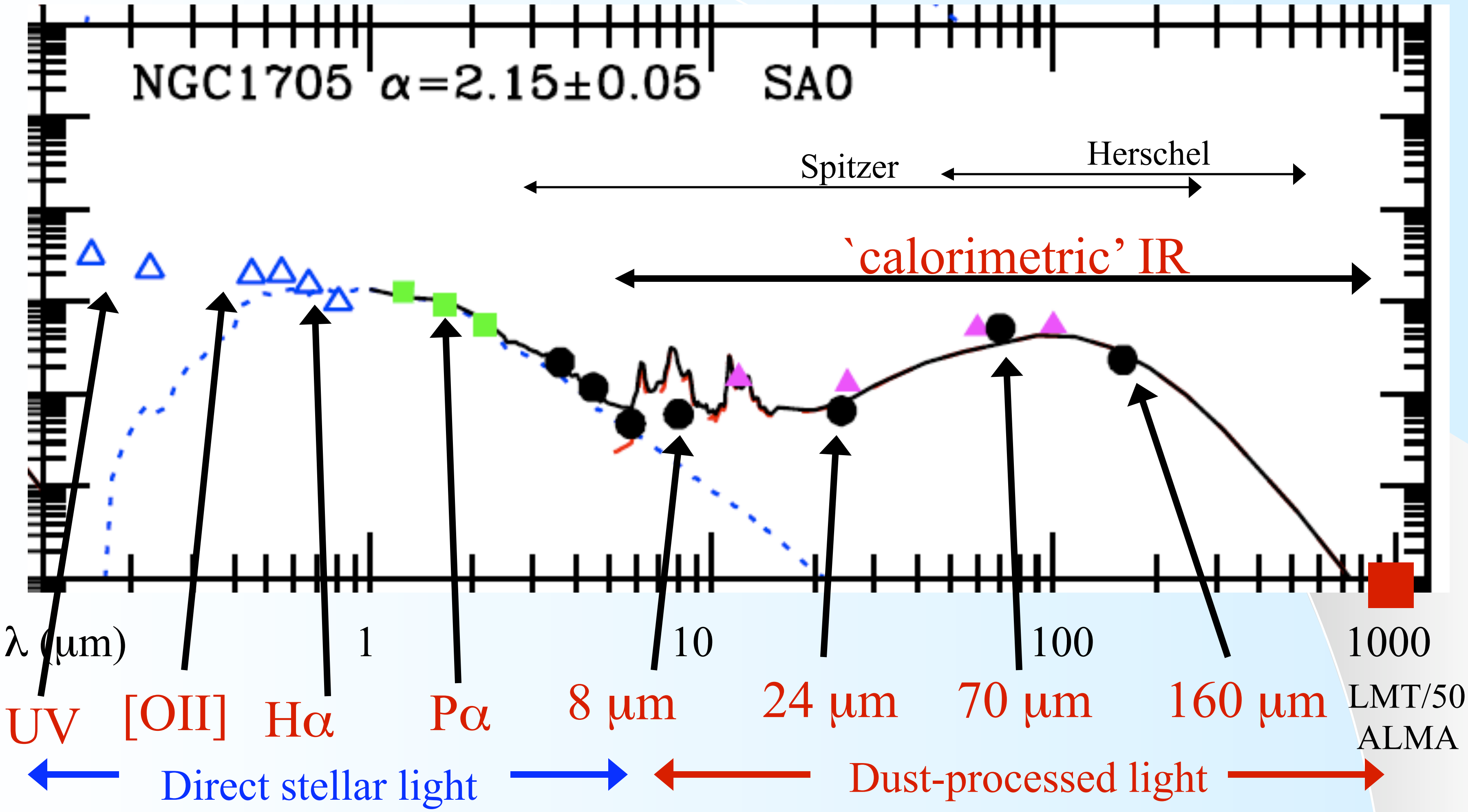

M51


Sombrero


M81

Galaxies SED's

Dale et al. 2007

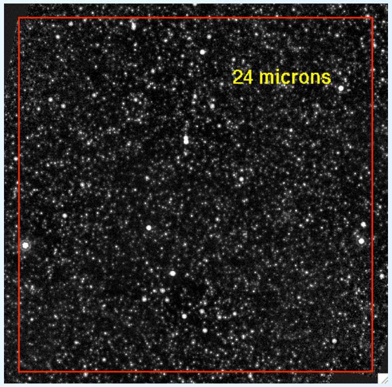


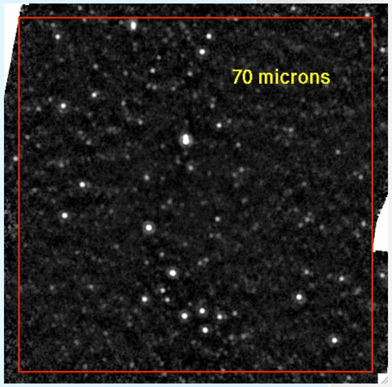
SFR(mid-IR)

- 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).

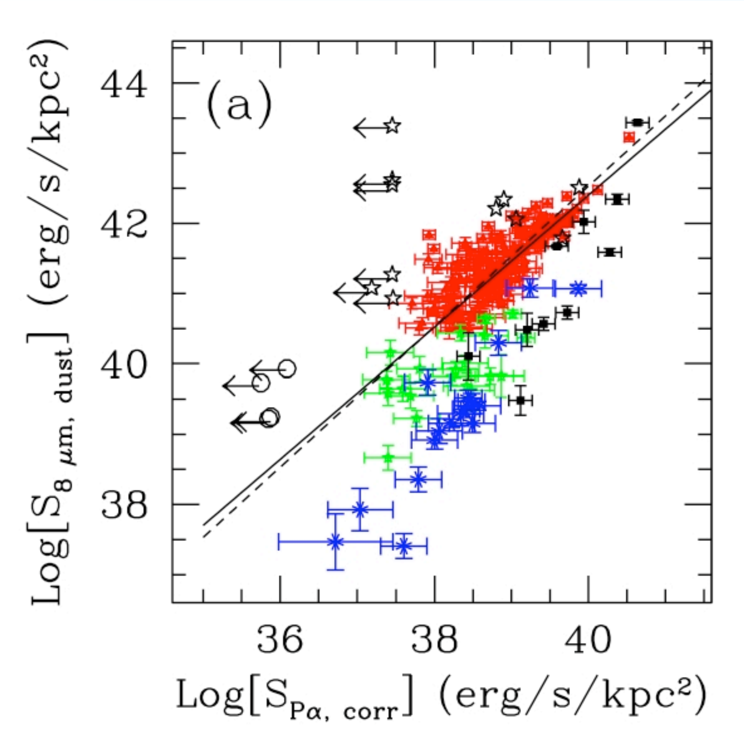
- Spitzer has opened a `more sensitive' window to the distant Universe:
  - viability of monochromatic IR emission (mainly 8 and 24 μm) as SFR indicator (Wu et al, 2005, Chary et al., Alonso-Herrero et al. 2006, etc.)
  - Appeal of PAH emission (restframe 7.7 μm emission for z~2) for investigating star 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 FIDEL)

Advantage: they are monochromatic measures!





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

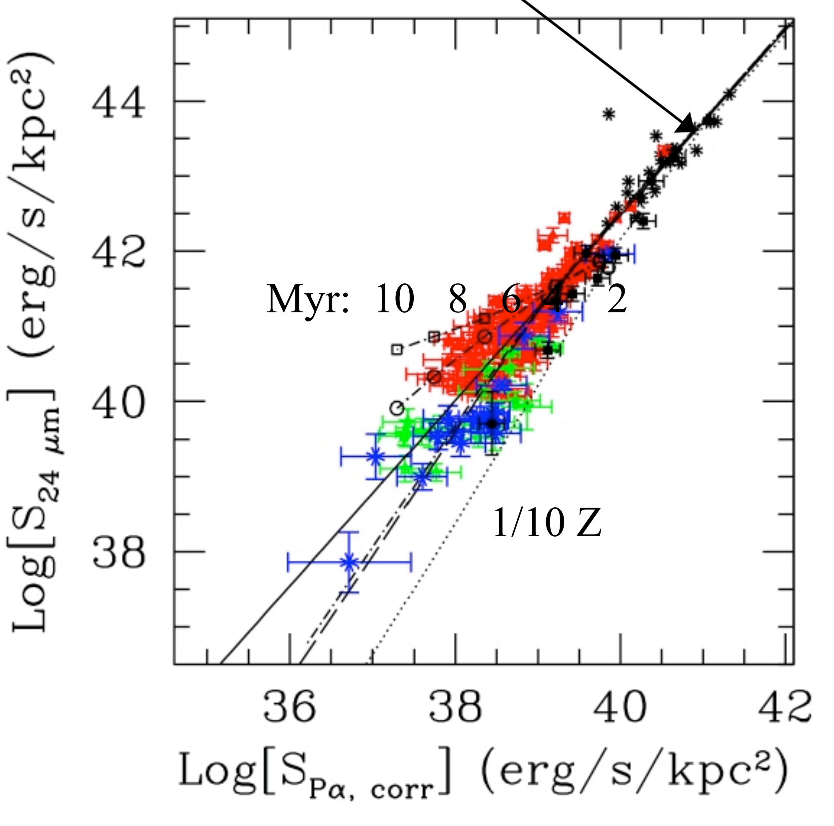
1. Slope is `sub-linear'
2. Strong dependence on metallicity (Engelbracht et al. 2005, 2008; Rosenberg et al. 2006, Wu et al. 2006, Draine et al. 2007)
3. Dependence on region sampled

HII Regions & Starbursts

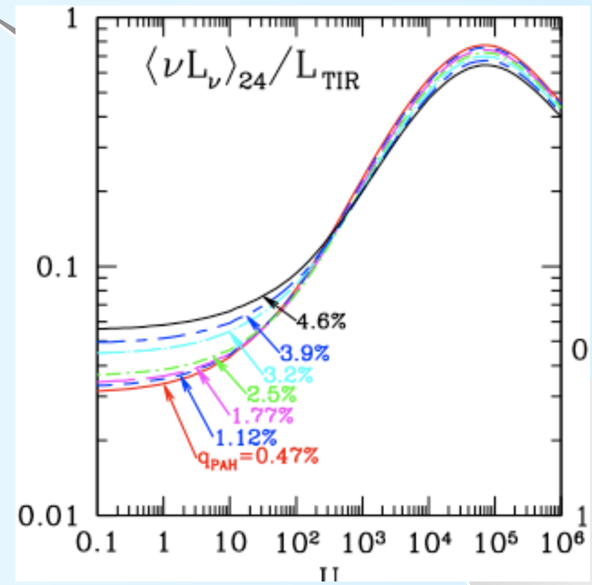
- Lower-than-unity slope and region-size dependence unaccounted for by models; measured L(8) may be `contaminated' by diffuse emission heated by underlying (non-star-forming) populations; or may be destroyed/fragmented by high intensity radiation.
- L(8 μm) is strongly dependent on metallicity; lower metallicity may lower number of low-mass PAH (Draine & Li 2007)

SFR(24) - Good

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

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

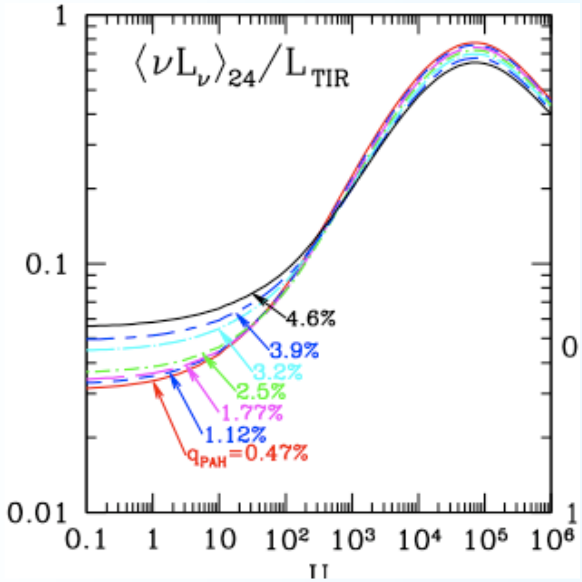
o Larger-than-unity slope (in log-log scale) is effect of increasing `dust temperature'

o Non-linear behavior at decreasing luminosities is due to increasing transparency of the ISM (see Walter et al. 2007, Cannon et al. 2005, 2006)

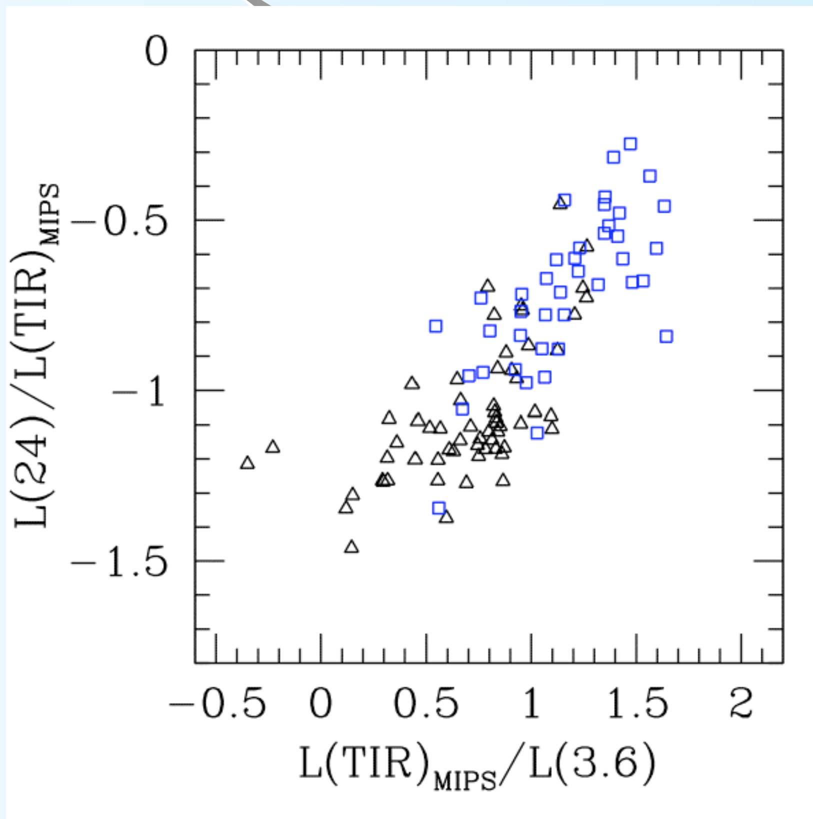
o Spread due to range of HII regions ages (~2-8 Myr)

C. et al.2007

Does L(24) vs T work?

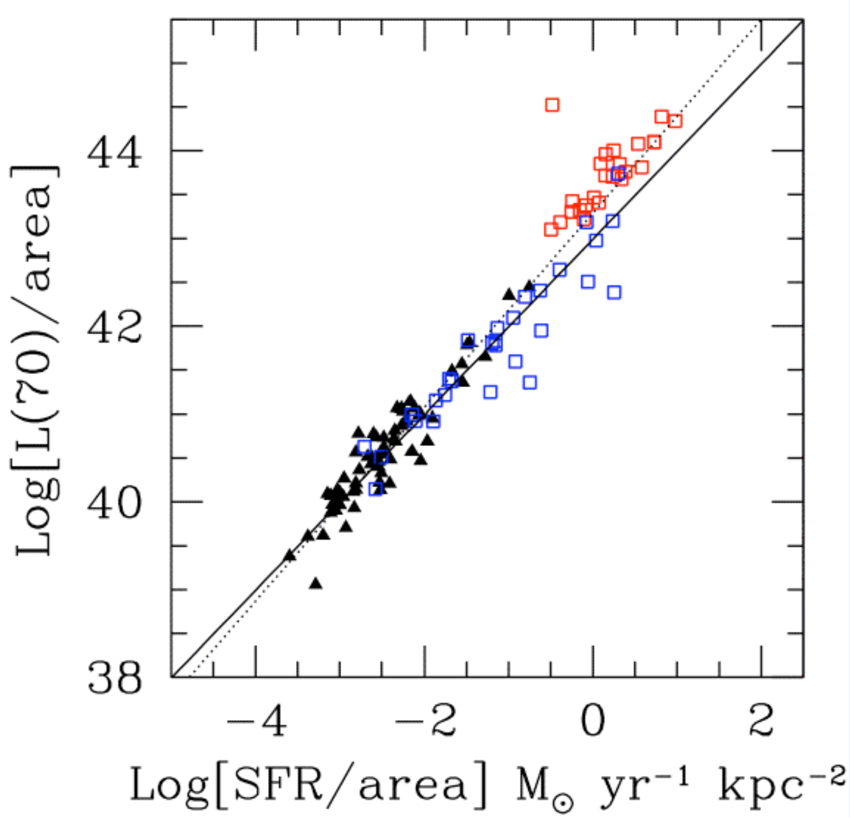


Draine & Li 2007



Whole galaxies!

SFR(70) - ??



Advantage: close to peak of IR emission

Disadvantage: potential large contribution from evolved stars

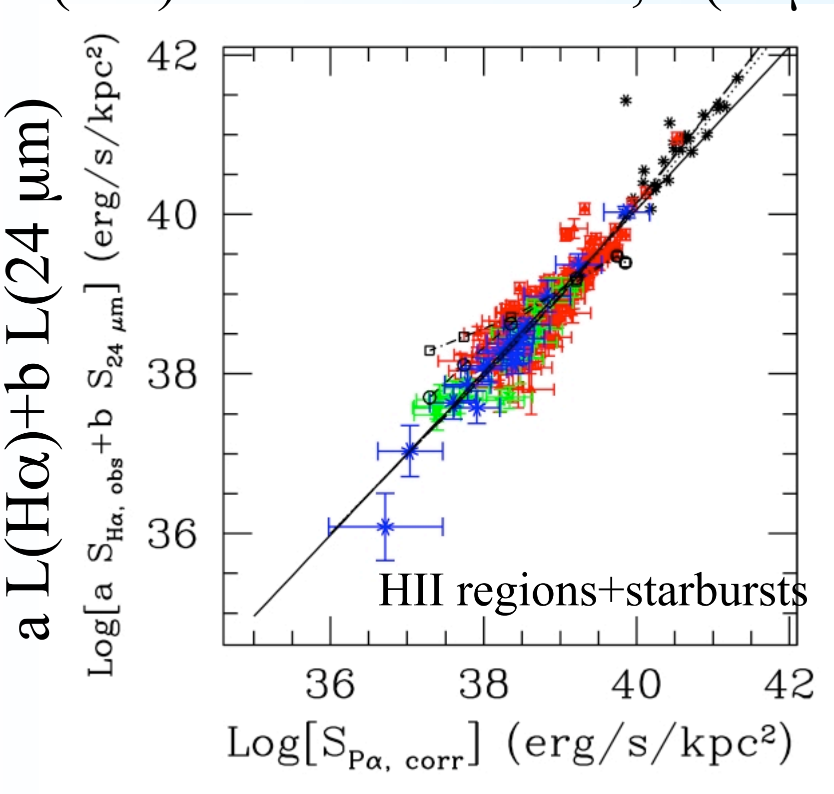
Data: indicative of over-luminosity of LIRGs.

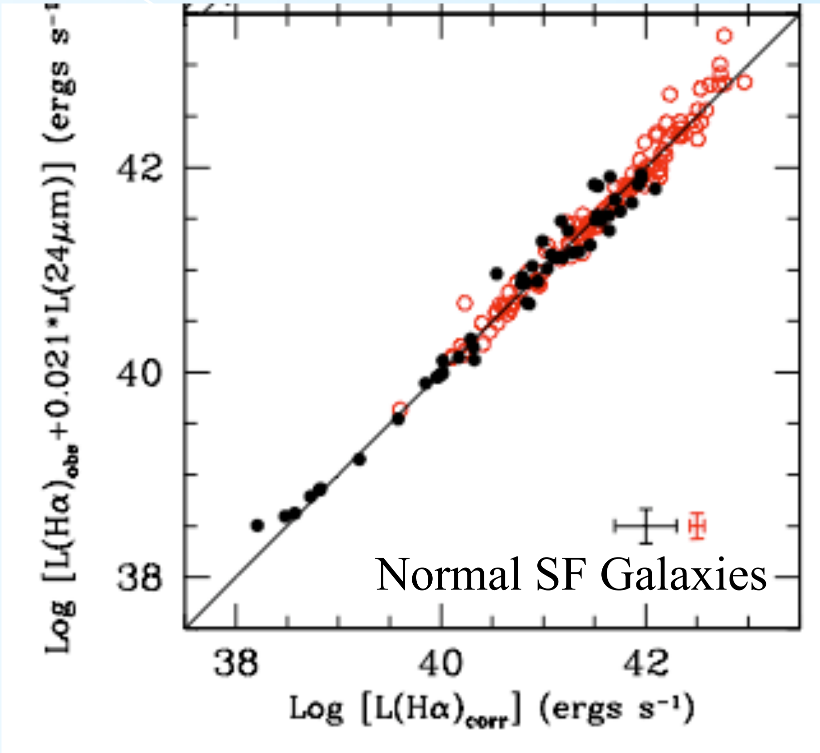
Black = normal SF galaxies
Blue = starbursts
Red = LIRGs

C. et al. 2008, in prep.

A Robust Measure of SFR

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





$$\text{SFR } (M_o \text{ yr}^{-1}) = 5.3 \times 10^{-42} [L_{H\alpha,\,obs} + 0.031\ (0.021)\ L_{24\mu m} (\text{erg s}^{-1})]$$

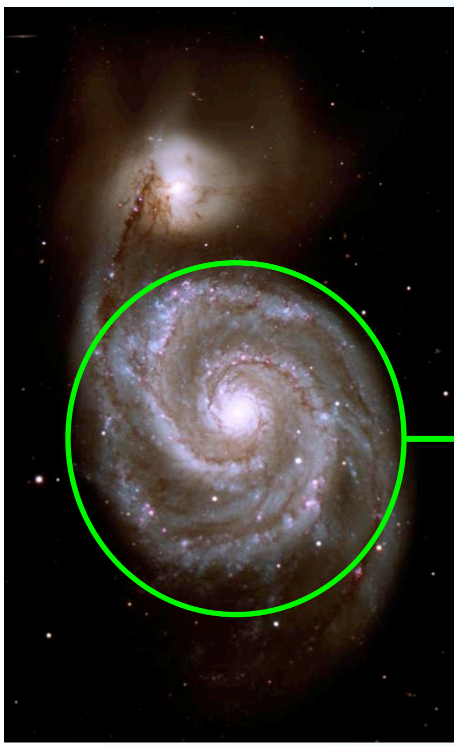
C. et al. 2007, Kennicutt et al. 2007, 2008)

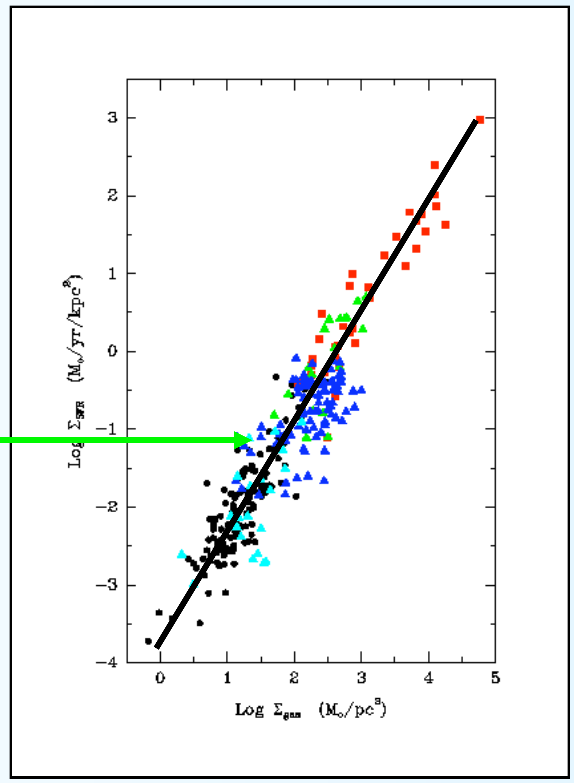
Not necessarily `practical' for high-z studies

The Scaling Law of SF

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

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





Questions:

Down to which scales?

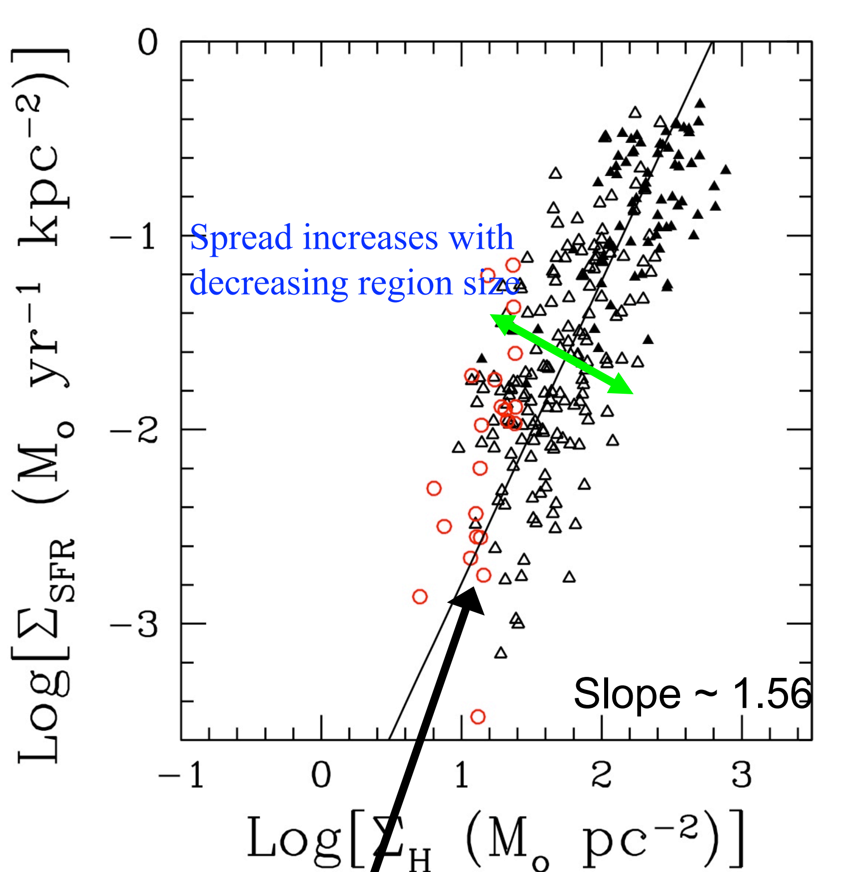
Physical model?

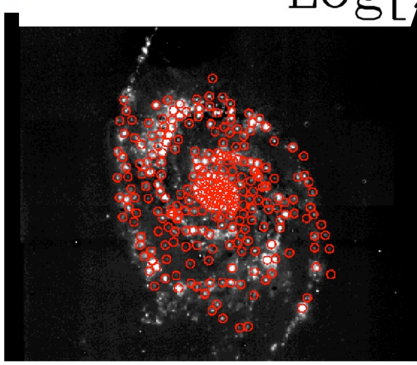
- local: $\rho_{SFR} \sim \rho_{gas}^{1.5}$
- global: $\rho_{SFR} \sim \rho_{gas} \Omega_r f(Q)$

Primary correlation?

Gas, H_2, HCN, …

Local (~0.5 kpc) Scaling Law





Kennicutt et al. 2007

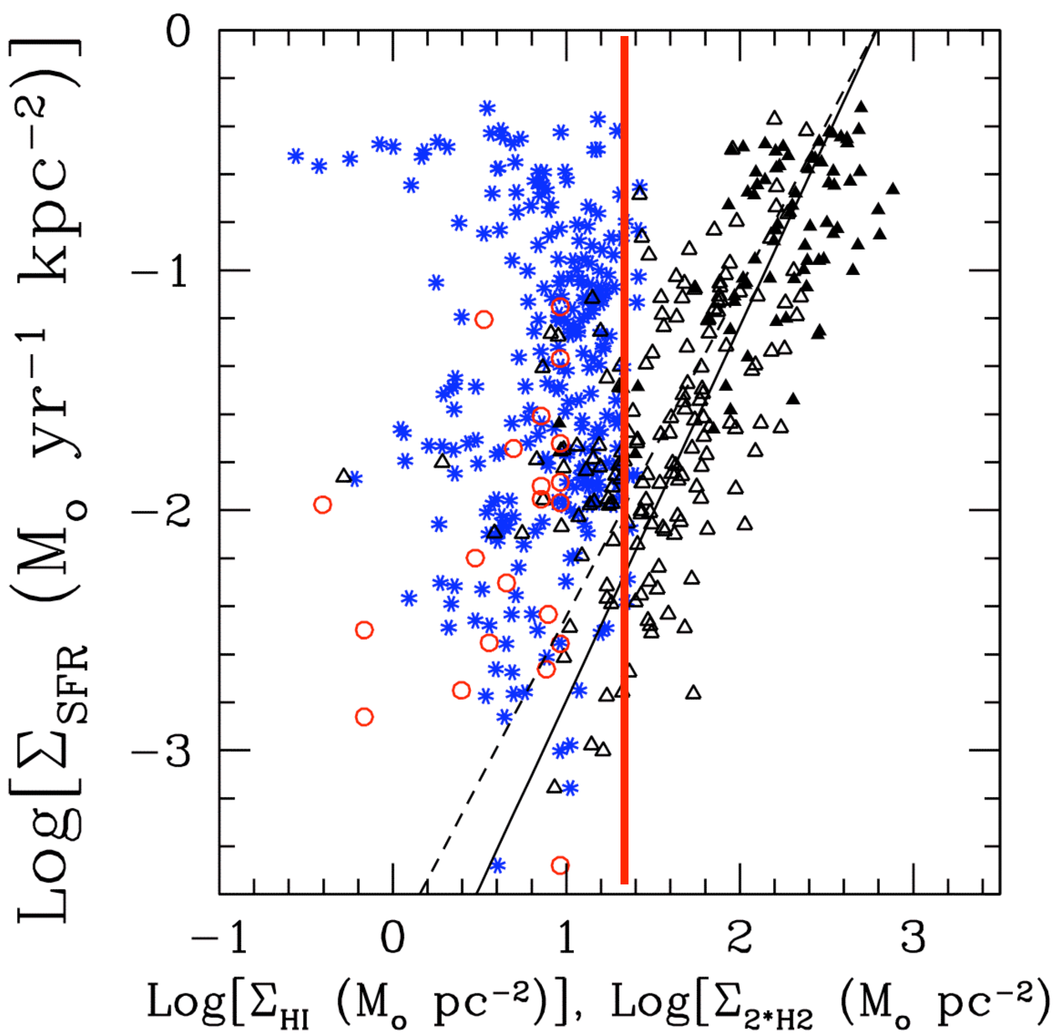
Spitzer, ground

For many of the outstanding questions, lack of adequate H_2 images is the main limitation:

- Dominant dependence?
  - ALMA, CARMA, LMT
- Environmental dependence? (interarm regions, etc.)
  - LMT, ALMA
- Thresholds? (low SB galaxies; dwarf galaxies)
  - LMT
- H_2/CO conversion?
  - ALMA
- Break-down scale(s)? Dependence? Physical model?
  - ALMA

Exhaustive analysis of 24 SINGS galaxies, by A. Leroy et al. (2008)

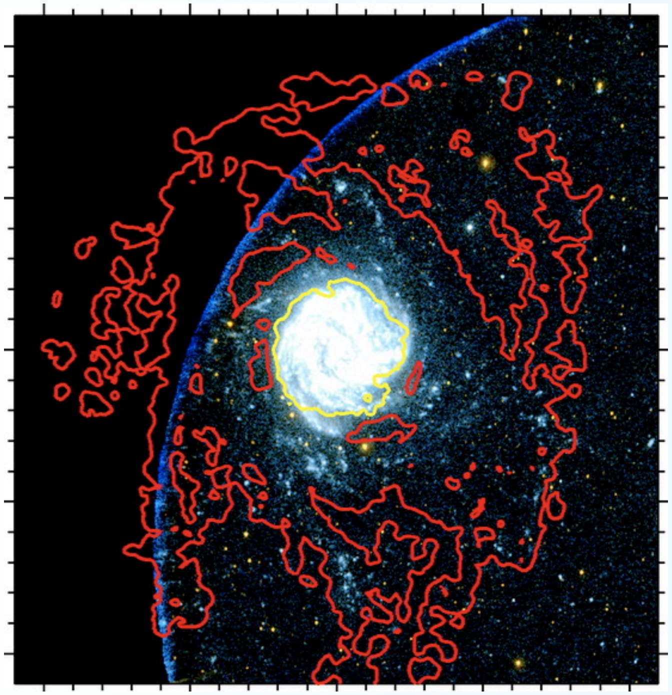
HI versus H_2



SFR correlates with H_2, but not with HI in M51

`Upper limit' to HI density

SF in Extreme Environments



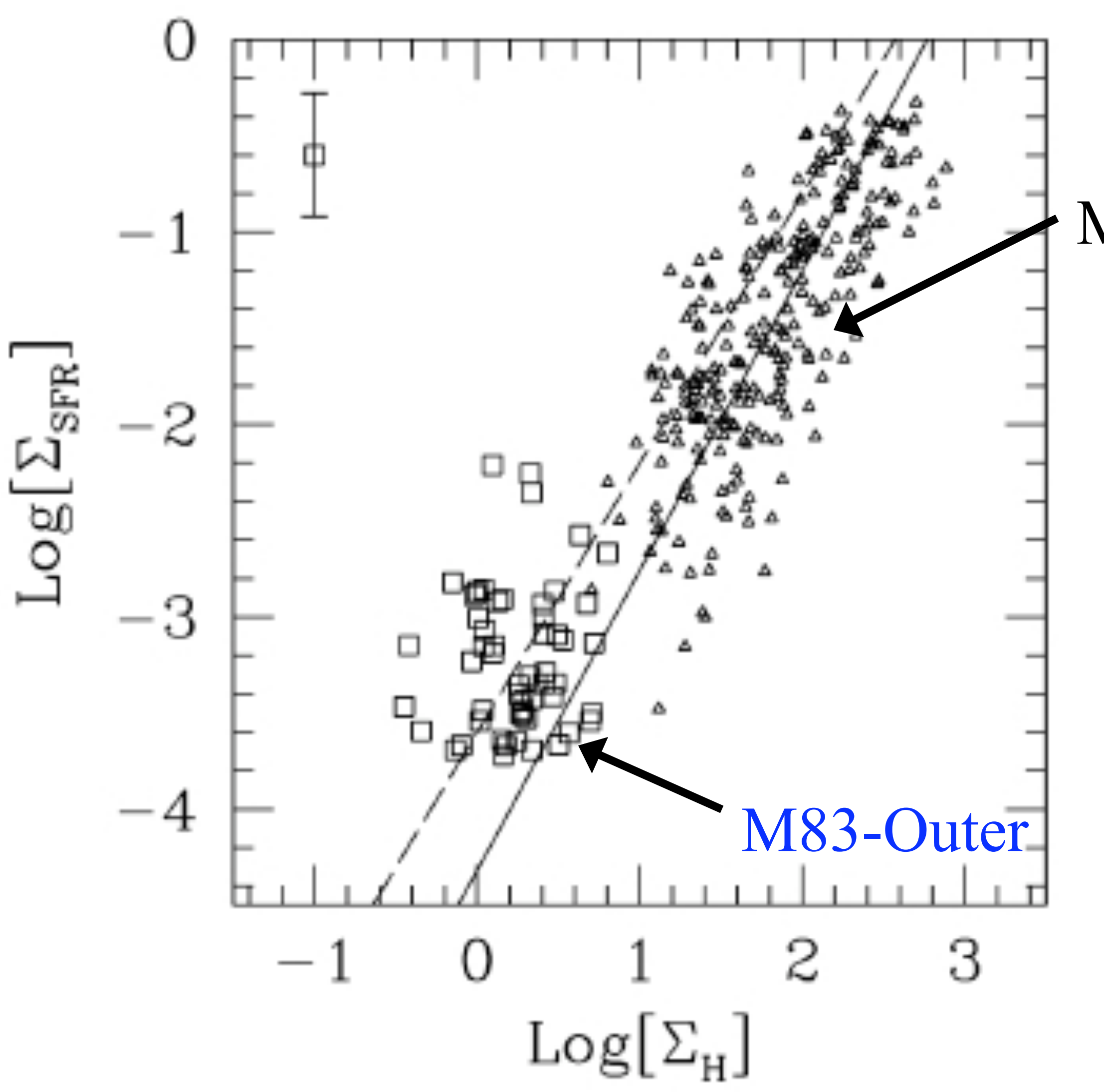
GALEX has found that about 30% of all local disk galaxies have extended UV disks, much beyond the optical disk (up to ~ 3-4 R_{opt}). (Zaritsky & Christlein 2007, Thilker et al. 2007)

UV clumps generally associated with extended HI structures, and metal poor (~1/5-1/10 Z_{sun}) (Thilker et al. 2005)

HII regions are faint, small, isolated.

- Implications:
  - Chemical enrichment of outer disk: metal and dust formation in the extended HI envelopes?
  - Energy & metal injection: easier from the shallow potential well at large radii: heating and enrichment of haloes and pristine IGM?
  - Star formation threshold (Martin & Kennicutt 2001): does it still hold? Or are we in the presence of a different `mode' of star formation?
  - What about the scaling SF law?

SK Law in the Outer M83

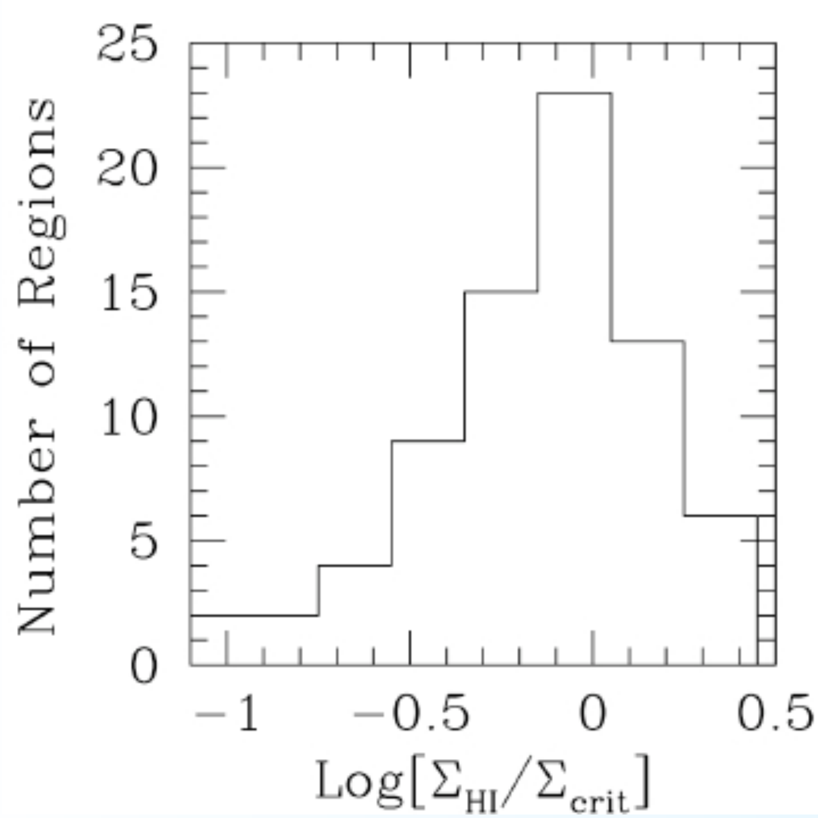


SFR = SFR(UV)+SFR(8)

Recall: approximate; and very sensitive to metallicity

Important: no H_2 obs in M83-Outer

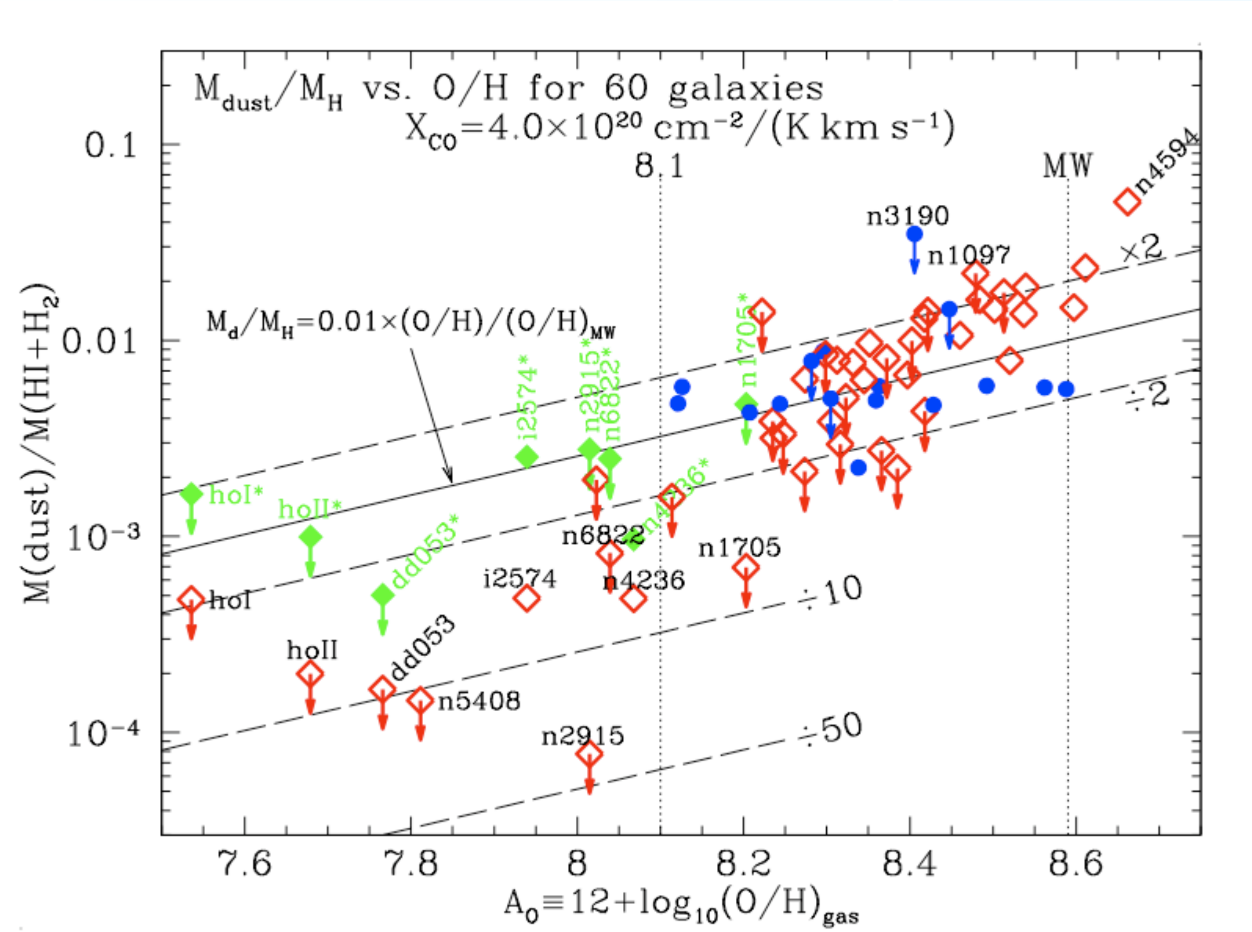
The Threshold of SF



In M83-Outer, the ratio $\Sigma/\Sigma_{crit} \sim 1$, thus SF still obeys a basic `threshold' requirement (Martin & Kennicutt 2001)

This is, however, a `local' threshold, not a global one!

Dust Traces Metals



Draine et al. 2007:

$M_d/M_g \sim 0.01$ x metallicity

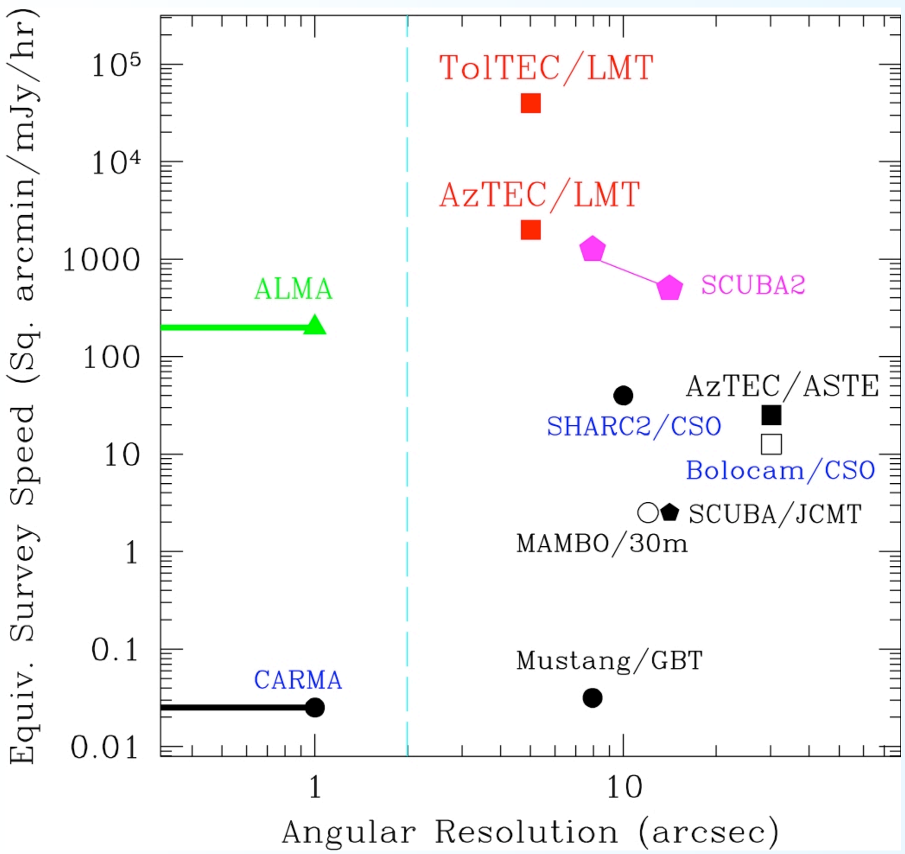
Cold dust from ALMA? LMT?

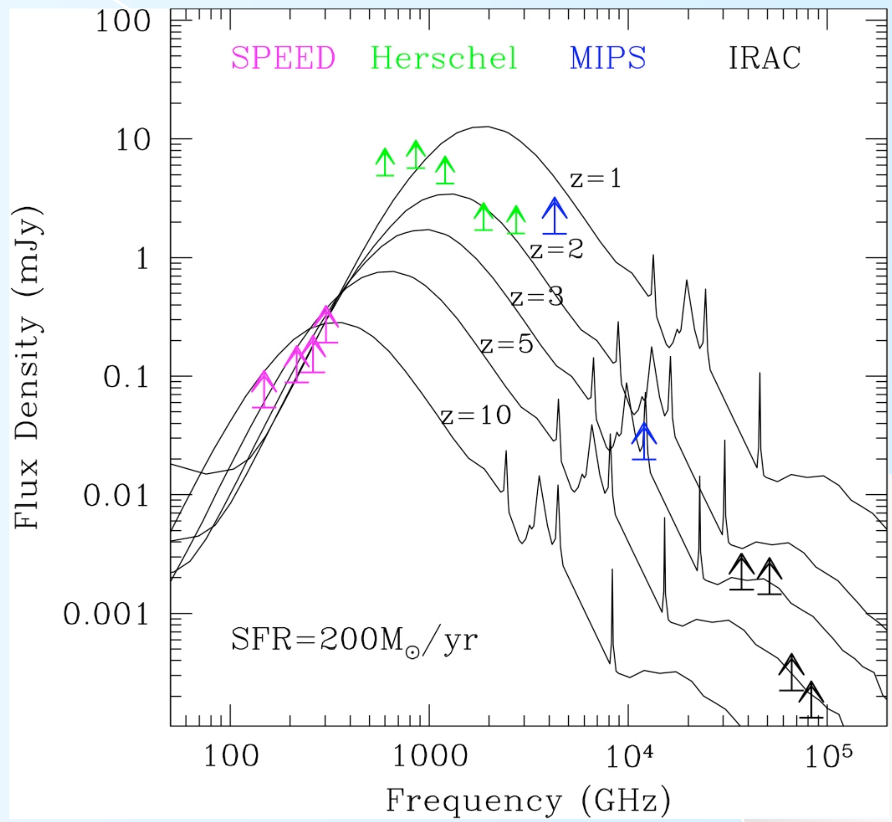
A Look to the Future

The Large Millimeter Telescope

- UMass-Mexico (INAOE) collaboration
- Single-dish 30/50 m antenna; 2.5 m secondary
- 4'-8' non-aberrated FOV; 5" resolution at 1 mm
- ~1-4 mm science: cold dust emission, CO, HCN, etc.
- Expected first *science* light ~ winter 2009
- Accessible to broad astronomical community

LMT `Discovery Space'





Yun et al. 2008 (priv. comm.)

KINGFISH:

Key Insights on Nearby Galaxies: a Far Infrared Survey with **Herschel**

R. Kennicutt (PI), D. Calzetti (Deputy-PI, US-PI), Phil Appleton, Lee Armus, Alberto Bolatto, Bernard Brandl, Daniel Dale, Bruce Draine, Charles Engelbracht, Karl Gordon, Brent Groves, Joannah Hinz, Leslie Hunt, Jin Koda, Oliver Krause, Adam Leroy, Eric Murphy, John Richer, Hans-Walter Rix, Helene Roussel, Marc Sauvage, Eva Schinnerer, JDT Smith, Laurent Vigroux, Fabian Walter, Brad Warren, Christine Wilson, Mark Wolfire

Approach:

- Over 500 hours of approved Herschel time, to image 61 nearby galaxies at 75, 110, 170, 250, 350, and 500 μm, and obtain low-res spectroscopy in [OI]63μm, [OIII]88μm, [NII]122,205μm, and [CII]158μm.
- The sample, representative of morphologies, luminosities, and IR/optical ratios of local Universe galaxies, is mainly drawn from SINGS

Core Science Objectives:

- Derive robust SFR tracers in the long wavelength regime (~near the IR peak)
- Model dust heating and emission in galaxies
- Probe the nature/origin of extended cold dust envelopes; link warm-cold dust emission
- Understand the physical underpinning of the IR-radio correlation
- Probe the ISM physical properties, and understand the metal abundance scale.

Summary

- A number of issues related to the scaling of star formation in galaxies still need to be clarified.
- H_2 content of low-metallicity and low-SB galaxies, and in the outskirts of galaxies
- dependence of scaling laws on environment.
- dependence on gas density
- H_2/CO ? Other tracers of H_2?
- ALMA and other mm facilities will be pivotal for these issues

- ALMA/LMT will also measure cold dust content of galaxies; together with other missions (Spitzer, Herschel, JWST) we will obtain a full picture of fundamental quantities like dust/gas.

- Robust recipes for star formation rates from bolometric and monochromatic IR fluxes are available, but many caveats are required. Without AGNs (!!!), L(24) and L(24)+L(Hα) [or L(IR)+L(Hα)]provide more robust SFR indicators than L(8).
- The 8 μm emission correlates with tracers of cold dust (160 μm emission), rather than tracers of warmer dust (and SFR).