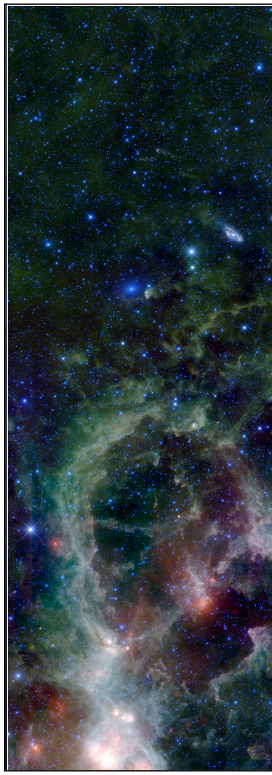


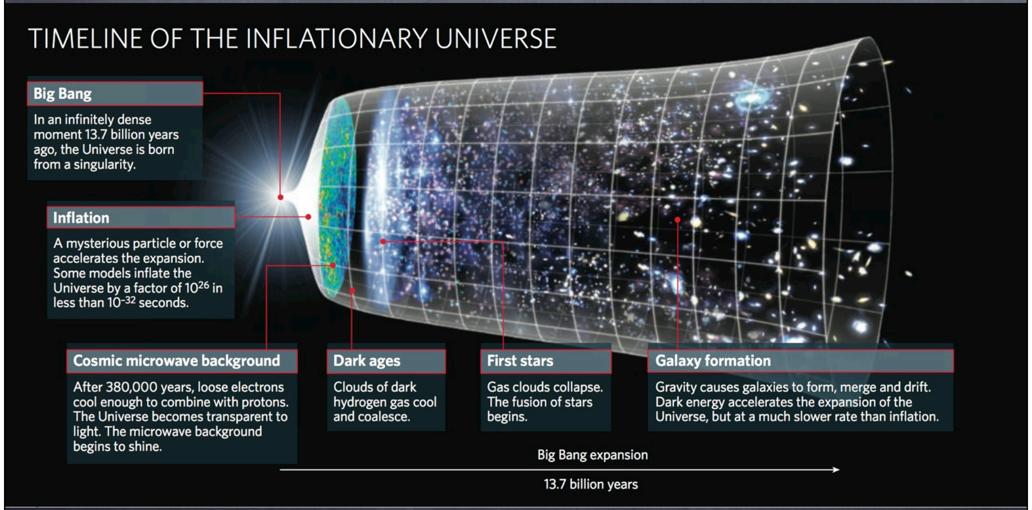
Line Diagnostics of the Intermediate redshift Universe:

SOFIA Science Prospects

George Helou
Caltech

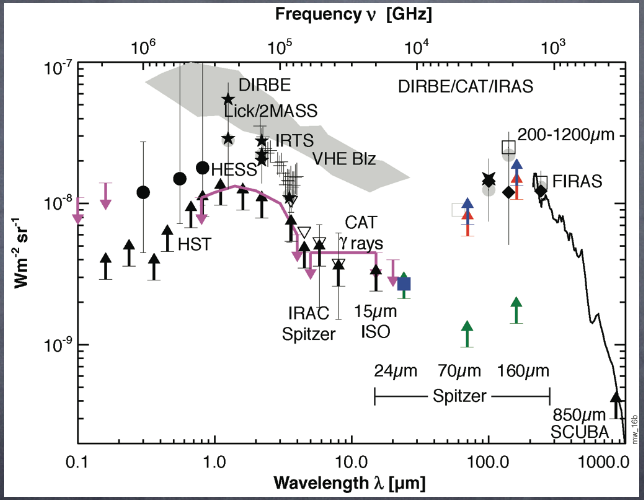
Science Opportunities for
New Instrumentation
Asilomar, June 2010

Cosmic History in a Nutshell



Integrated Light (Galaxies + QSO)

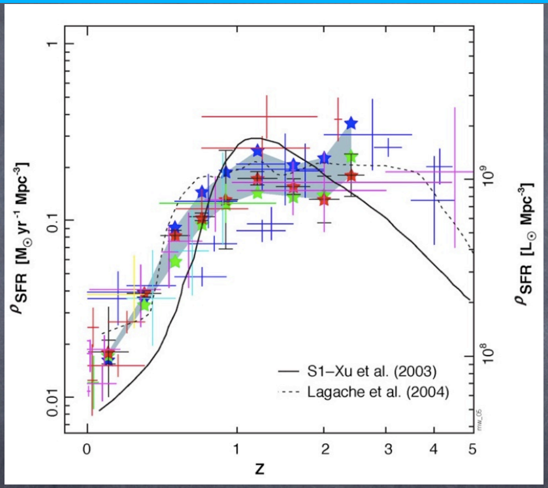
Soifer, Helou & Werner AARA 2008



- UV/Vis and IR bumps do not arise at same time nor in same objects

Star Formation Intensity History

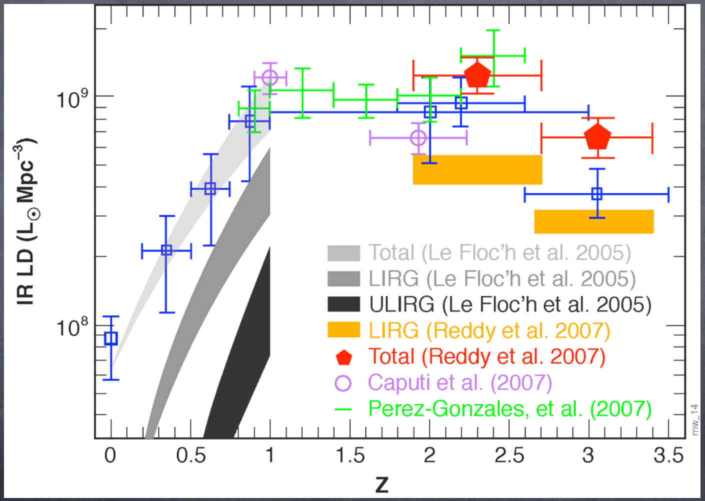
Soifer, Helou & Werner AARA 2008



- No model today can reproduce all the data on IR galaxy populations

More Luminous Galaxies at Higher z

Soifer, Helou & Werner AARA 2008



More Luminous Galaxies at Higher z

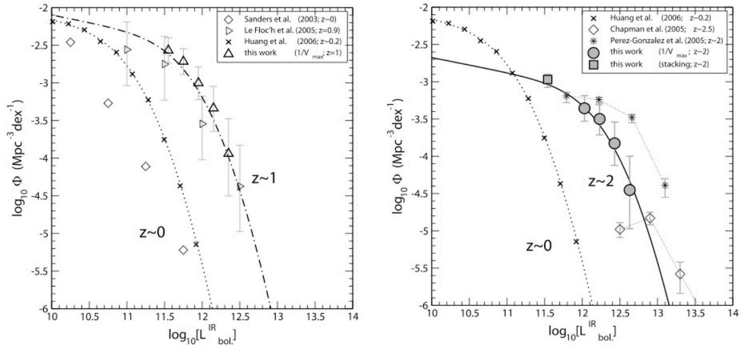
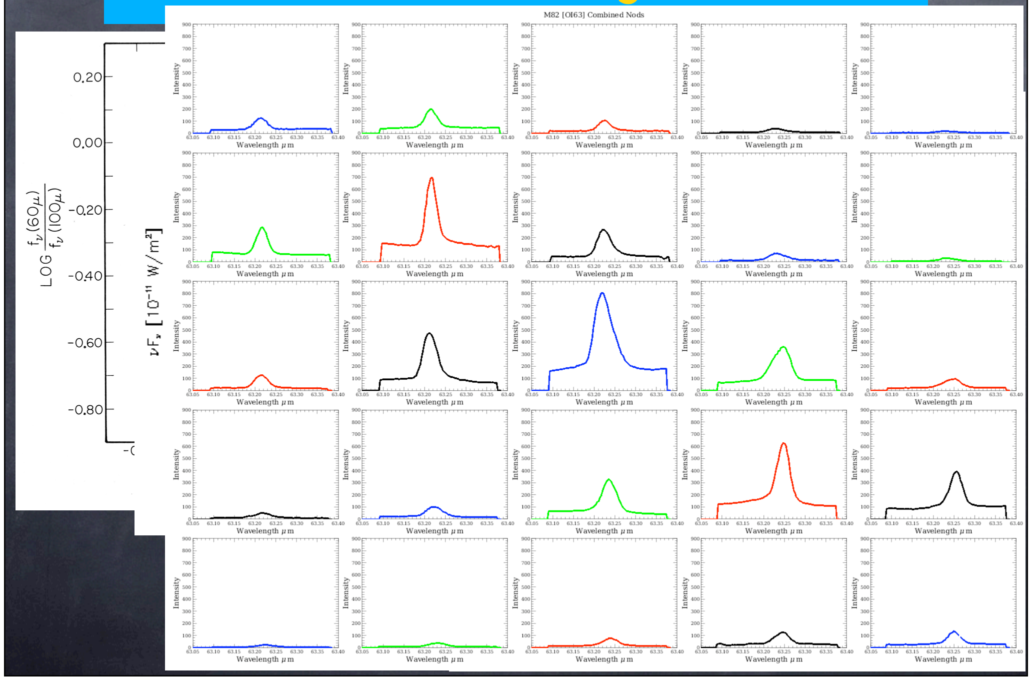


FIG. 14.—Bolometric IR LF obtained in this work compared to the determinations of other authors at similar redshifts: $z \sim 1$ (*left*) and $z \sim 2$ (*right*).

Caputi et al, 2009

Tremendous Progress...



… And Many Open Questions

- How, where and when first collapse to stars?
- How are the various wavelength-defined coeval galaxy populations related?
- How do galaxy populations evolve?
- What controls “evolution” in individual galaxies?

  Gas accretion, interaction, mergers, internal dynamics?
  Entanglement of accretion and astration

Themes

- Population studies (surveys) in the continuum are well in hand, especially from Spitzer and Herschel, augmented with ground facilities
- SOFIA can help decipher ISM diagnostics, and illuminate galaxy scaling laws, perhaps mechanics
- SOFIA can help understand physics relevant to first collapse
- Key is high resolution spectroscopy in the mid to far-IR

Definitions and Disclaimers

- “Intermediate redshifts” are roughly $0<z<1$
  - Galaxies are at the tail-end of the “golden age” of SF
  - Mechanics of galaxy evolution are likely same as $z\sim1$, so the intermediate z is key to earlier times
- Sensitivity assumptions are quite liberal
  - SOFIA’s goal is to facilitate breakthrough technology

Three Chapters

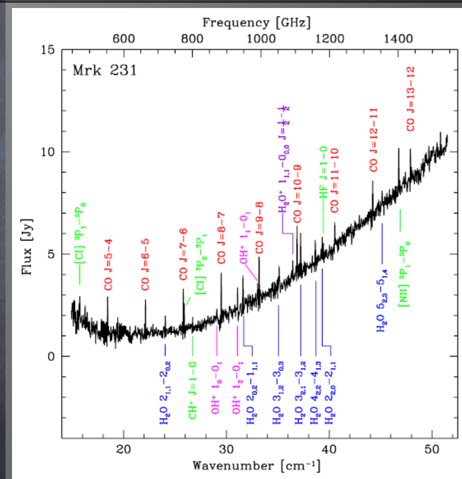
- FIR Fine-Structure Lines: OI, CII, OIII
- Making Sense of Galaxies
- Molecular Hydrogen

FIR Fine-Structure Lines

- ISO themes:
  - OI, OIII, CII as key indicators of ISM gas conditions
  - CII deficiency in high-intensity SF systems
  - CII-Aromatic connection
- Herschel is rewriting the book on FIR FSL

Herschel SPIRE spectrum of Mk 231

Markarian 231

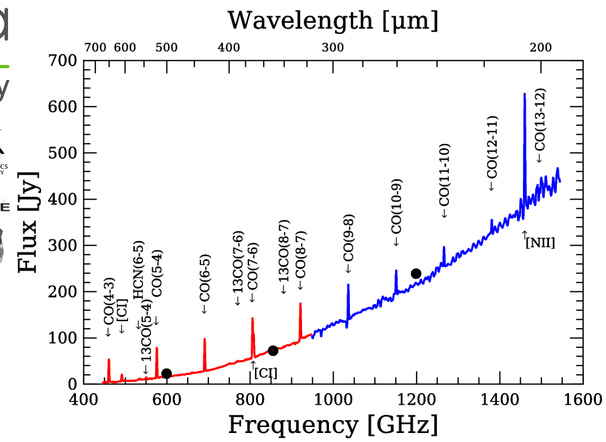


- 25 lines:
  - 9x CO (5-4 to 13-12)
  - 7x H_2O
  - 3x OH^+
  - H_2O^+
  - CH^+
  - HF
  - 2x [CI]
  - [NII]
- More coming?

Loenen, van der Werf et al, A&A Herschel Special Issue

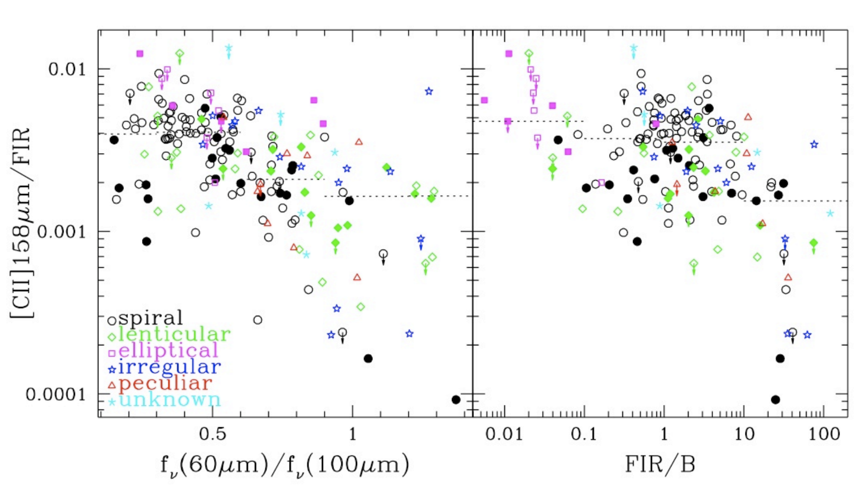
Herschel SPIRE Spectrum of M82

M82 reconstructed apodized spectrum



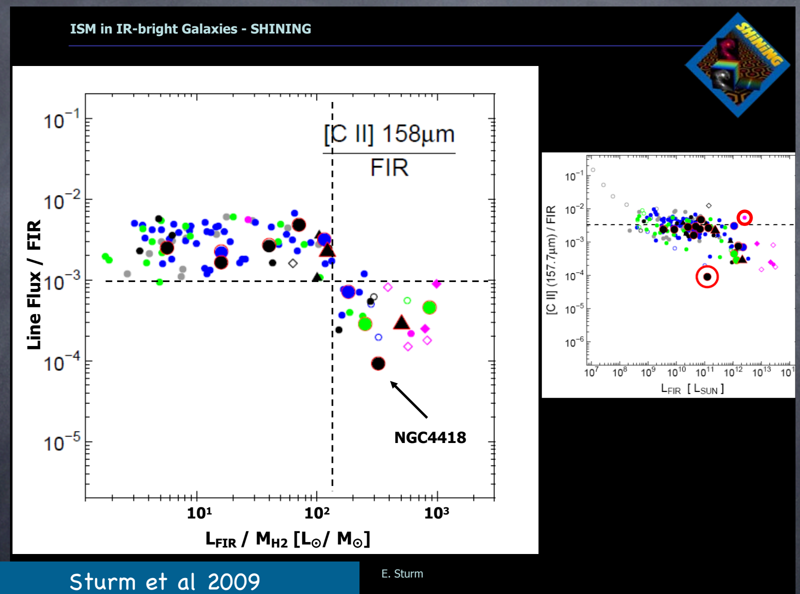
5/12/10 - P. Panuzzo et al. - Herschel/SPIRE FTS View of M82 6

Pre-Herschel Example



Brauher et al 2009

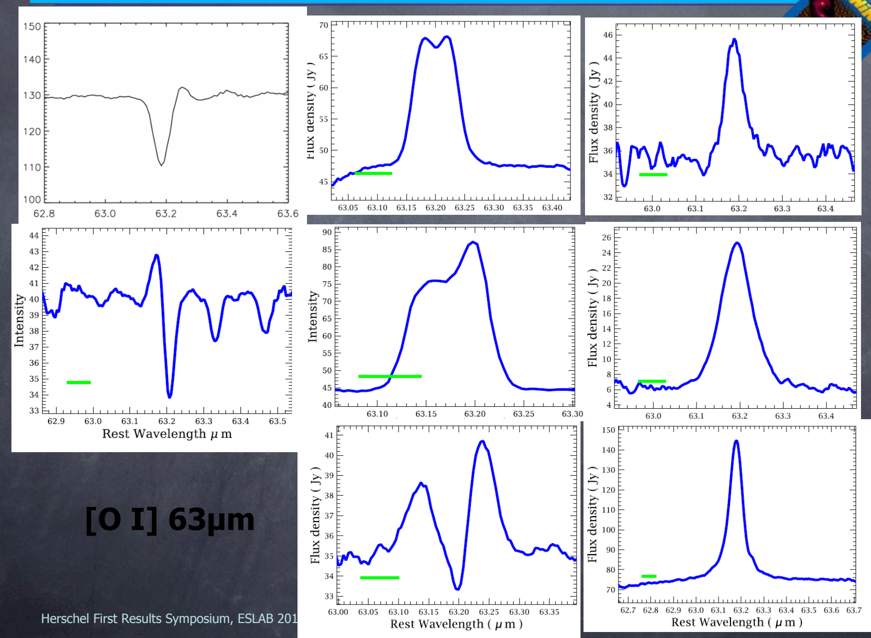
Pre-Herschel Example (better plot)



Sturm et al 2009

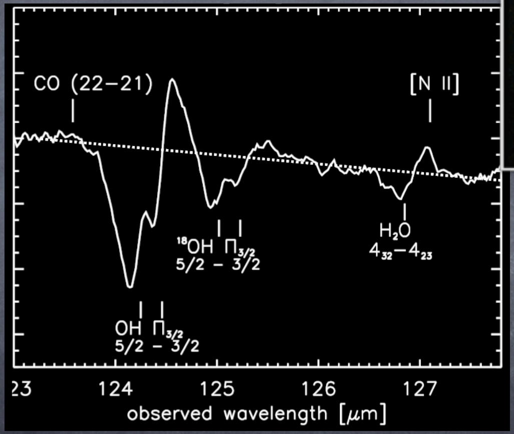
PACS Spectroscopy (Sturm et al)

ISM in IR-bright Galaxies - SHINING



[O I] 63μm

Herschel-PACS Spectrum of Mk231



Gonzalez-Alfonso et al. 2010, A&A *Herschel* issue

FIR Fine Structure Lines Summary

- Complex structure of lines calls for well resolved spectroscopy
  - "CII deficiency" may include self-absorption as well as intrinsic factors
- Interpreting these lines in simple terms of single-zone emitting regions will be clearly inadequate
- SOFIA can contribute with high-resolution spectroscopy of critical lines

Three Chapters

- FIR Fine-Structure Lines: OI, CII, OIII
- Making Sense of Galaxies
  - Continuum and Mid-IR FSL from Spitzer
- Molecular Hydrogen

Conceptual Infrared Galaxies (1)

- $\overrightarrow{IR(\lambda)} = [T_{ISM}] \cdot \overrightarrow{Heating(\lambda)}$
- Heating(λ) is the input heating spectrum from all stars (neglecting AGN)
- IR(λ) is the Infrared SED, i.e. Cooling
    + escaping radiation from stars (ignore gas cooling)
- T is a matrix with all the coupling terms between Heating and Cooling
    - Cross-sections, opacities, etc
    - Geometry(local, initial), geometry(age), geometry(d/g), geometry(morphology), etc

Conceptual Infrared Galaxies (2)

- $\overrightarrow{IR(\lambda)} = [T_{ISM}] \cdot \overrightarrow{Heating(\lambda)}$ simplifications:
- Most drastic approximation is "L(IR) $\doteq$ k$\cdot$SFR"
- More useful for extracting information:

  Heating = Σ IUV(>13.6eV)+FUV(>6eV)+NUV+Vis+NIR

  - Σ is taken over stars in various age groups

  IR(λ) = Σ SED(dust species, U range, λ)

  - Dust {VSG, Aromatics, LG} at $U \doteq 0.1$--$10^6 G_0$

  $[T_{ISM}]$ connects star populations to dust emission via ISM phases

  Biggest challenge is geometry, but galaxy size helps!

Estimating [T_{ISM}]

- It should be possible to derive [T_{ISM}] today, using dust models, radiative transfer codes & IR(λ) maps. For instance:

  FUV(>6eV) originates in **B stars** mostly, heats dust in HII regions, **PDR**, with some escape into diffuse ISM

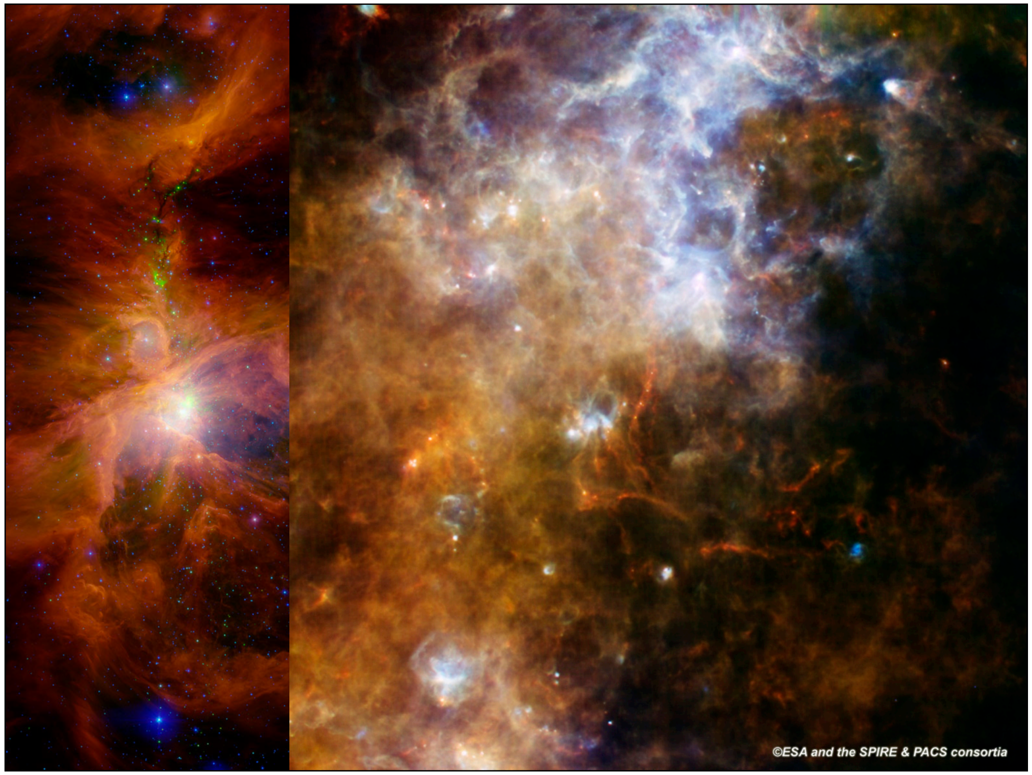
  IR emissions from **PDR** is typical of U≈100-1000, Aromatics-rich dust, n≈100-1000

- Use IR SED and resolved IR(λ) maps in MW and nearby galaxies to validate estimates

  Take out geometry by averaging over many cases

  [T_{ISM}] elements not universal, but it should be possible to index them on basic galaxy parameters

  Estimate [T_{ISM}]$^{-1}$ and a sequence of SFR indicators


©ESA and the SPIRE & PACS consortia

Conceptual Galaxies: Gas Phase

- [T_{ISM}] can be applied to gas phase diagnostics, though additional terms are needed to connect radiation to gas
  - Ionization coupling
  - Photo-electric coupling
- SOFIA opportunity is here: spectrally well resolved line diagnostics will add this dimension
- However, mechanical excitation terms appear, not directly traceable to Heating(λ)
  - Shocks, turbulence

Conceptual Galaxies: Radio, X-Ray, ...

- These components are further removed from Heating(λ)
  - Mostly derived from SN, possibly stellar winds
- Coupling terms are much further removed from [T_{ISM}]
  - New parameters enter, e.g. magnetic field
  - Time-dependent terms, e.g. cooling CR, plasma

Empirical Galaxies

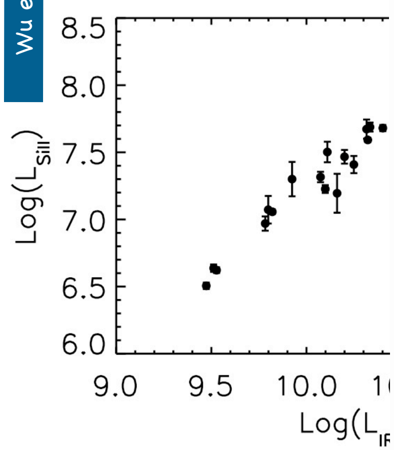
- Galaxies are complex systems, with deceptively simple properties as a population
  - Many diverse processes: astration to dynamics
  - Many episodic influences: starbursts to mergers
  - Many physical couplings: radiation, density, CR, B
- Most galaxy parameters will inter-correlate, mostly with trivial physical content, ie L or U
  - This is helped by averaging within each galaxy
- The few useful correlations are simple and unexpected, e.g. Tully-Fisher or IR-Radio
  - Their physical interpretation is NOT simple

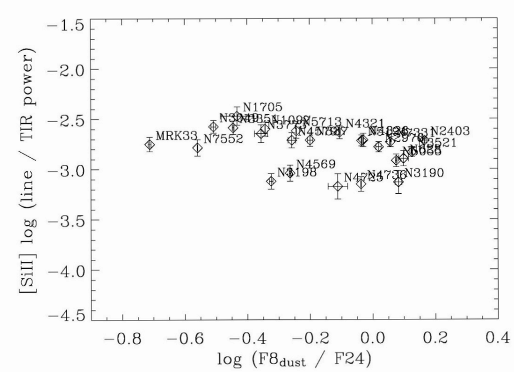
All truths are easy to understand once they are discovered; the point is to discover them (Galileo)

Yet Another Correlation: SiII vs L(IR)

Wu et al subm; Helou et al

- 5MUSES sample: fnu(24)>5mJy, median z~0.1, mix of SF and AGN
- SiII inhabits, like CII, inhabits neutral and HII regions, shifted down in ionization potential

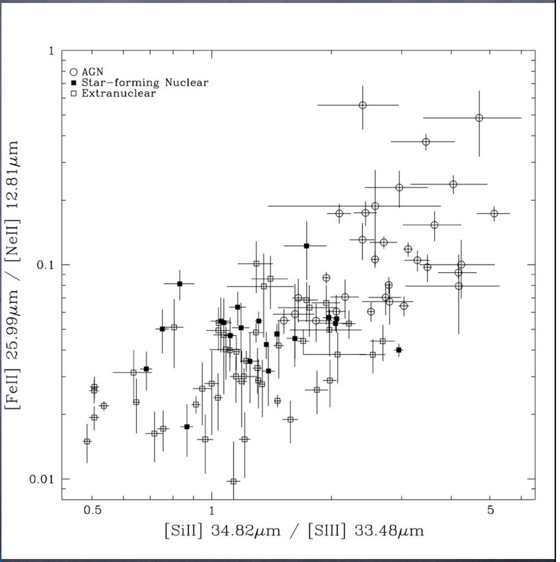




SINGS (Nearby Galaxies)

And an AGN/SF Index

- Importance of XDR
- Similar to OI/CII



Dale et al 2009

Making Sense of Correlations

- In the case of line correlations, spectrally well-resolved data are critical, and good maps of local sources are important

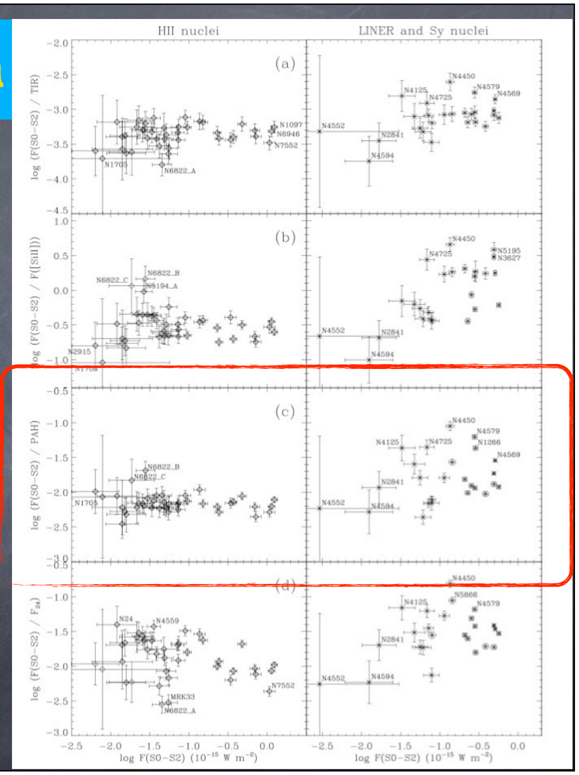
- Again pointing to high-resolution spectroscopy

Three Chapters

- FIR Fine-Structure Lines: OI, CII, OIII
- Making Sense of Galaxies
- **Molecular Hydrogen**

H_2: Spitzer Data

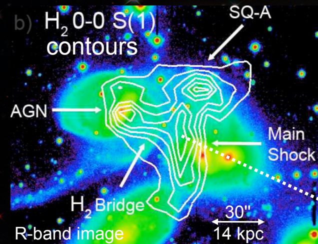
- SINGS sample
- H_2/Aromatics ratio
- LINERS & Sy tend to high values of H2/AFE

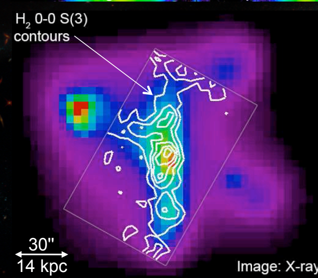


Roussel et al 2007

H_2: IGM Shock in Stephan's Quintet

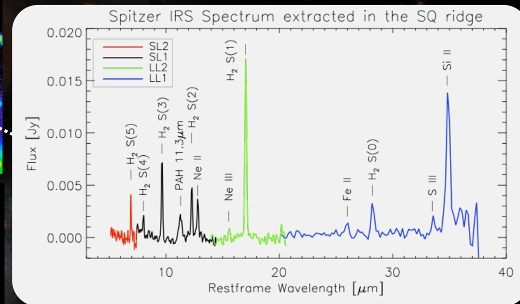
Discovery of the first galaxy-scale H_2-dominated MIR source





Cluver et al. 2010

Strong molecular Hydrogen and little else! (Appleton et al. 06, Cluver et al. 2010).



- $L(H_2) \sim 10^{42}$ erg/s
- $\sim 10^9\ M_\odot$ of warm (>50 K) H_2
- **$L(H_2)/L(X\text{-ray}) > 3$**
- **$L(H_2)/L(IR) \sim 0.3$** (1000 x PDR values!)
- 17μm S(1) line resolved! FWHM=860±40 km/s
- G_{UV}~1, so low dust emission (Guillard+, '10a)

H_2: Spitzer Data

Soifer, Helou & Werner AARA 2008

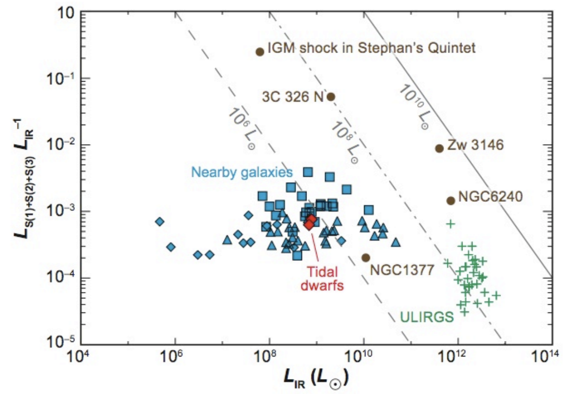
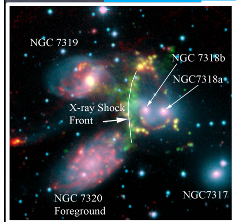
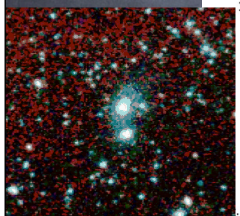


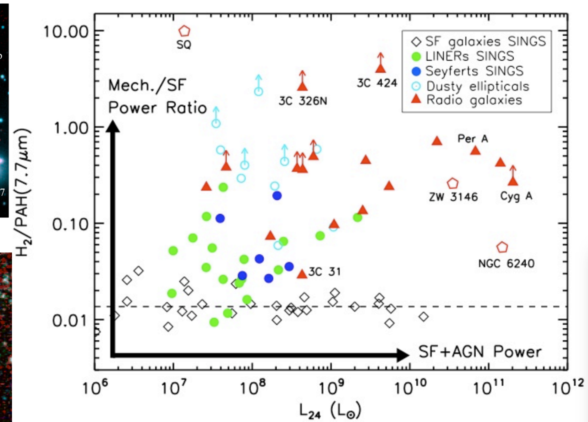
Figure 13

Compilation of H_2 measurements for normal galaxies (Roussel et al. 2007), ULIRGs (Higdon et al. 2006), and a variety of other objects. The ratio of the luminosity in the sum of the S(1), S(2) and S(3) lines (of the ground vibration state) of H_2 to the IR luminosity of the system is plotted versus the IR luminosity. Nearby galaxies are shown as open symbols, diamonds represent dwarf galaxies, triangles represent star-forming galaxies with no other type of activity, and squares represent galaxies with Seyfert or LINER nuclei. ULIRGs are shown as crosses. Gray lines of constant H_2 luminosity (10^6, 10^8, and 10^{10} $L_{\odot}$) show that, in spite of the variations in L_{H_2}/L_{ir}, ULIRGs are still more luminous in H_2 rotational lines, whereas intergalactic shocks can easily outshine whole galaxies in these lines.

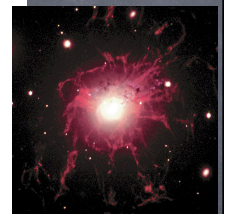
H_2: Radio Galaxies and Dusty E's

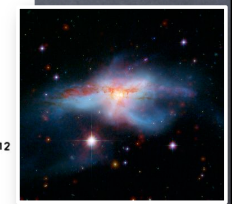






14.— Ratio of H_2 luminosity summed over the 0-0 S(0)-S(3) lines to 7.7 μm PAH luminosity vs. νL_ν(24 μm,rest) continuum luminosity. This ratio indicates the relative importance of mechanical heating (via shocks) and star formation power. All but one (3C 31) of the H_2 detected radio galaxies from our sample (red triangles) stand out above normal star forming galaxies from the SINGS survey (diamonds). Lower limits are shown for sources with undetected 7.7 μm PAH emission. All sources in this plot with $L(H_2)/L(PAH7.7) > 0.04$ are considered to be MOHEGs. Many of the LINERs and Seyferts from the SINGS sample and several of the Kaneda et al. (2008) dusty ellipticals are MOHEGs. Other MOHEGs in the literature (NGC 6240 and Zw 3146, open red pentagons) and the Stephan's Quintet intergalactic shock ... re plotted for comparison.

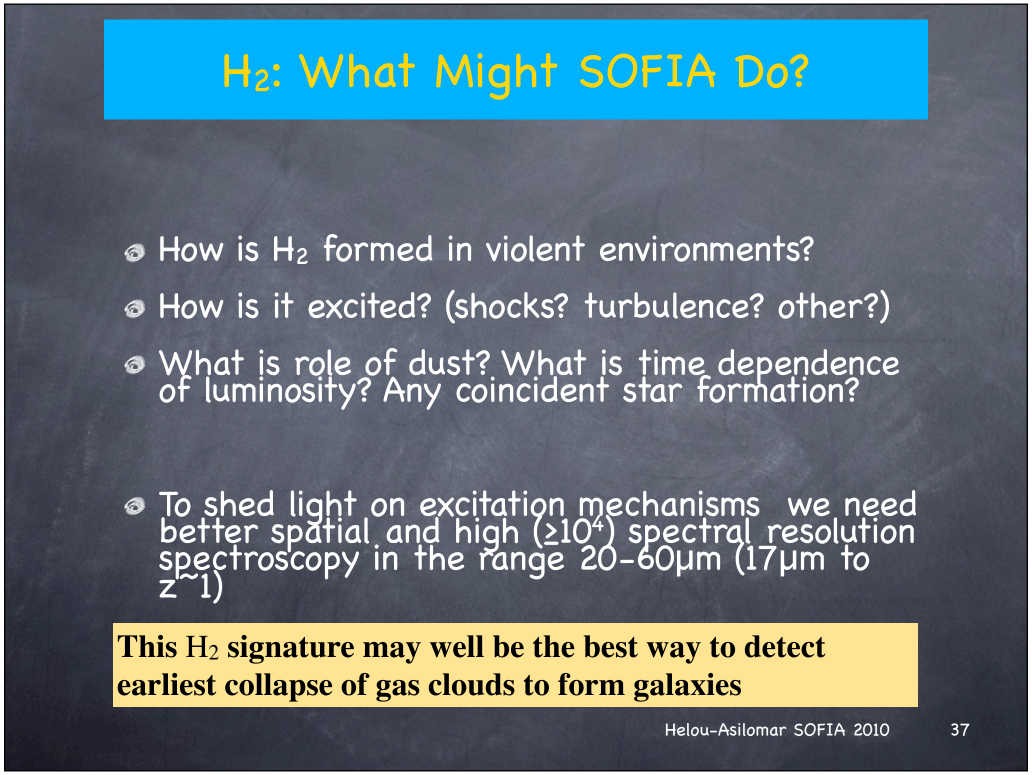




Ogle et al 2010; Guillard et al

Molecular Hydrogen Excess Emission

- Excess emission in the pure rotational transitions of H_2 has been observed with Spitzer in many environments
- Most likely common thread is shock excitement, but many questions remain
    - Main puzzle is how molecular material can be the main coolant for a violent injection of mechanical power


H2: What Might SOFIA Do?
How is H2 formed in violent environments?
How is it excited? (shocks? turbulence? other?)
What is role of dust? What is time dependence of luminosity? Any coincident star formation?
To shed light on excitation mechanisms we need better spatial and high (≥10^4) spectral resolution spectroscopy in the range 20-60μm (17μm to z~1)
This H2 signature may well be the best way to detect earliest collapse of gas clouds to form galaxies
Helou-Asilomar SOFIA 2010
37

Summary

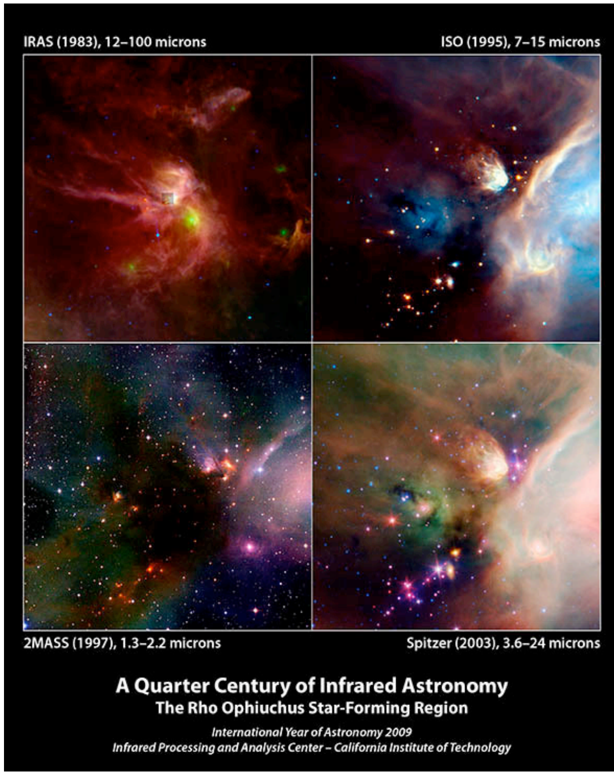
- SOFIA high (≥10^4) spectral resolution spectroscopy in the range 20-100μm will address several important questions

- Challenges within reach:

  solve for the star/dust heating/cooling matrix

  advance on physical underpinning of correlations and decorrelations

  construct higher-fidelity ISM physical representations (as basis for population models)


IRAS (1983), 12–100 microns
ISO (1995), 7–15 microns
2MASS (1997), 1.3–2.2 microns
Spitzer (2003), 3.6–24 microns
A Quarter Century of Infrared Astronomy
The Rho Ophiuchus Star-Forming Region
International Year of Astronomy 2009
Infrared Processing and Analysis Center – California Institute of Technology