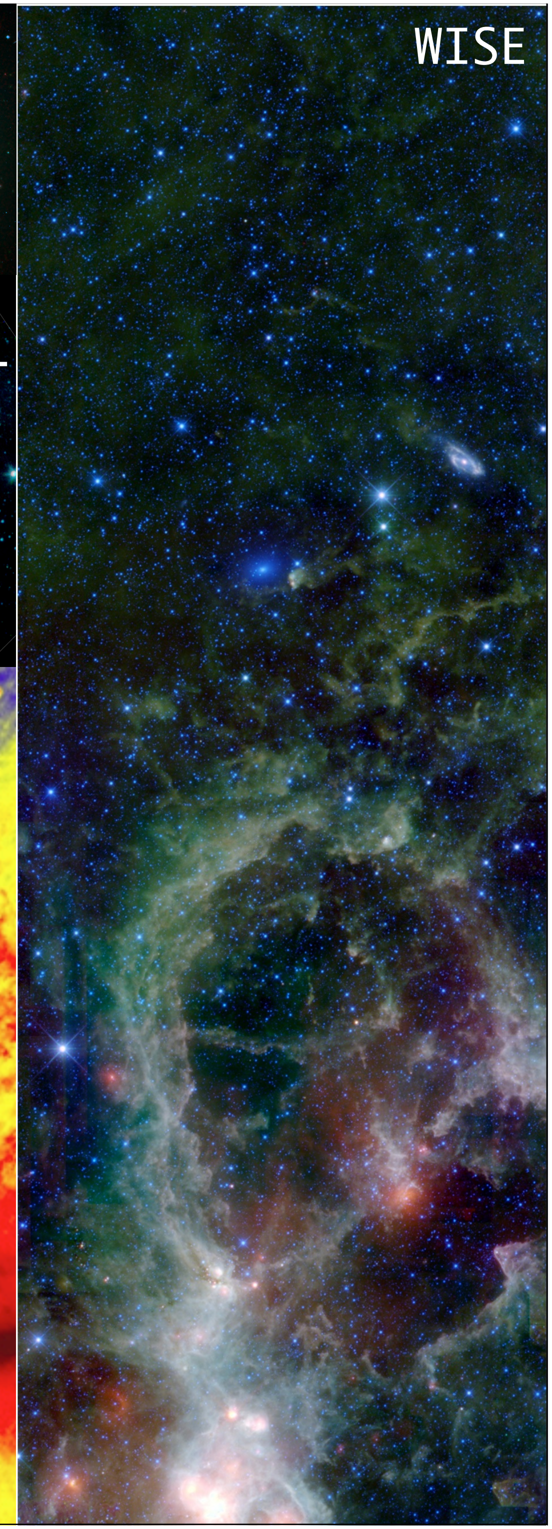
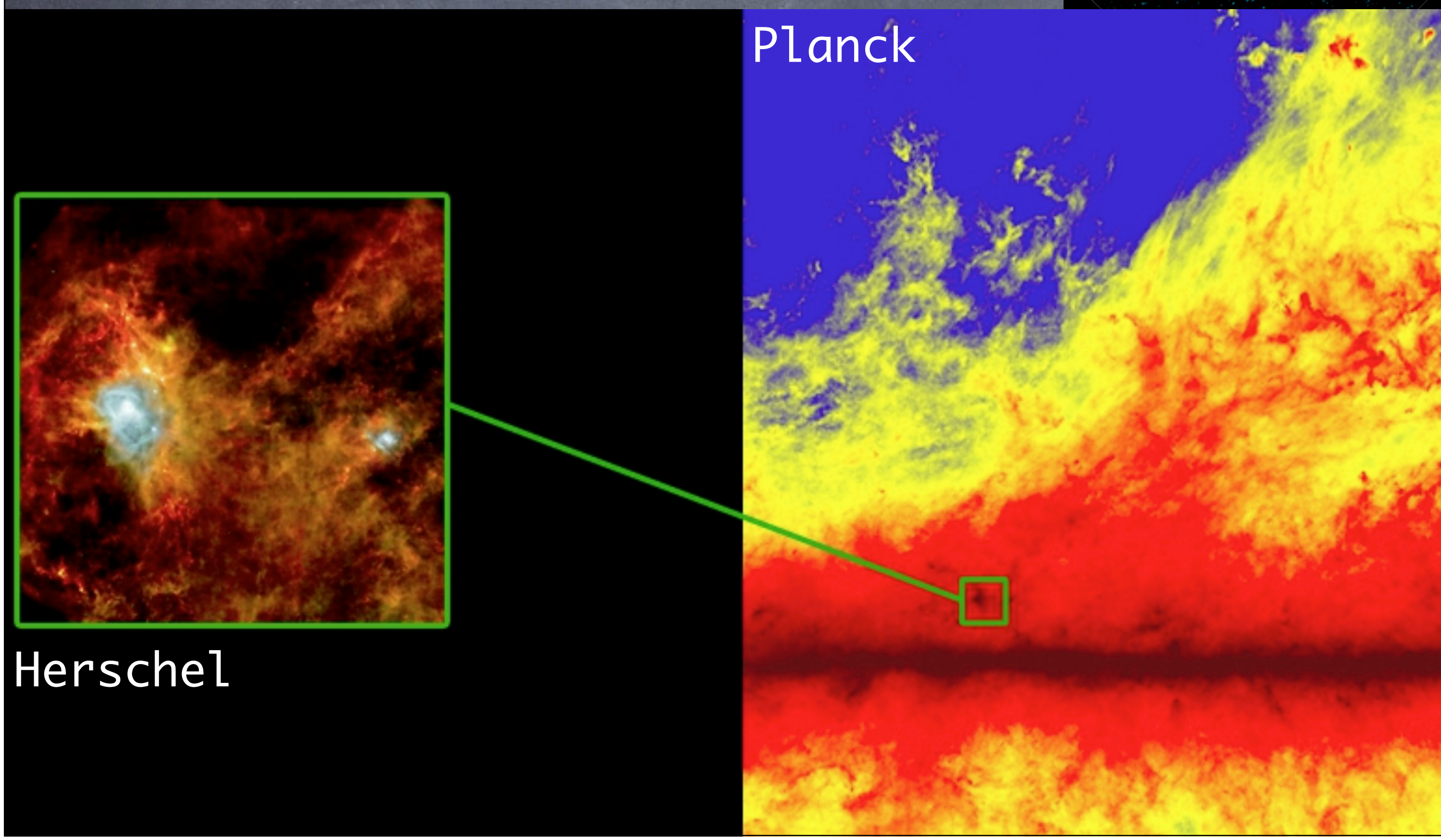
On Dust and Galaxies

A Preface

George Helou
Caltech

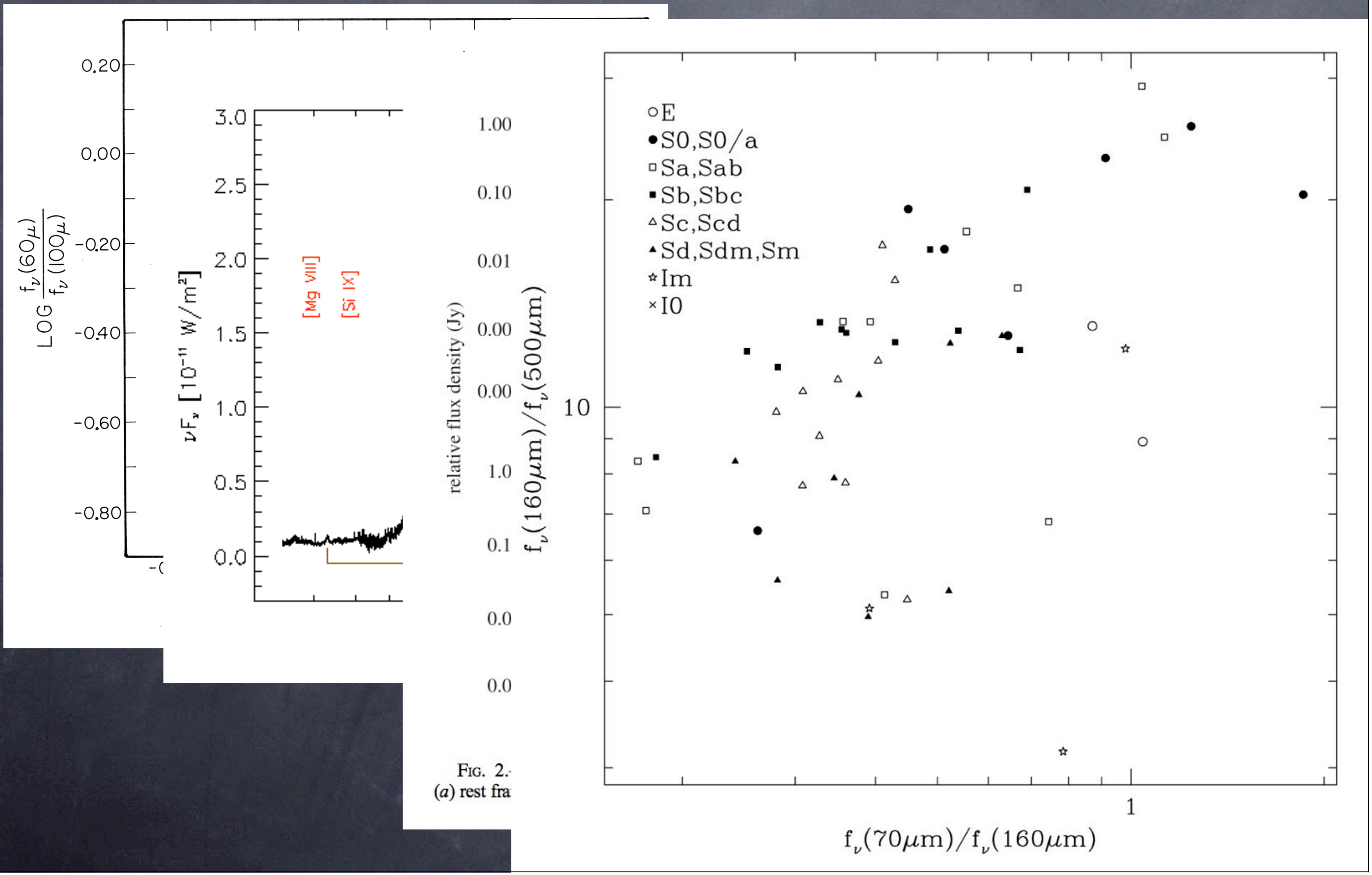
From Dust to Galaxies
Paris, June-July 2011





Tremendous Progress

Tremendous Progress



2010: Red-Letter Year

- Herschel, Planck, WISE all working beautifully
  - Spitzer (& AKARI) still going, at shorter λ bands
  - Cryogenic relay
- Continuing opportunities:
  - Herschel has OT2 Call open now!
  - Spitzer should issue at least one more call: GO9, 2013
- Most important:
  - Get the most out of the data already in hand!

Not Covered Here

- A systematic review of knowns and unknowns
- Astrophysical importance of dust to star/galaxy formation and evolution
- Diagnostic value of dust in understanding galaxies
- The many species of dust and their formation, destruction, transformation processes
- The effects on dust of AGN, low metallicity, heating spectrum, interstellar conditions

A Preface to the Colloquium

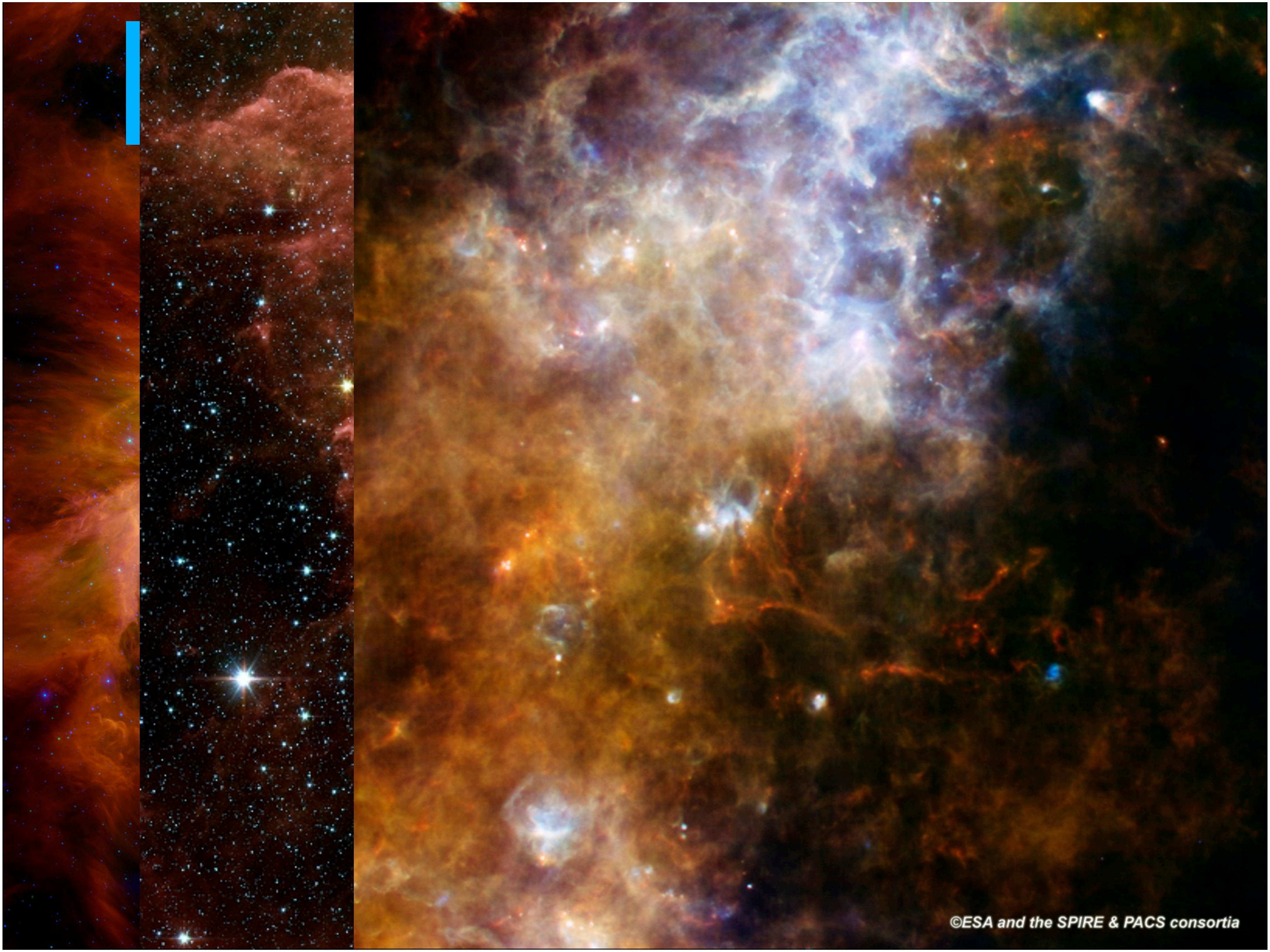
- A random walk (stochastic emission?)
- Special perspective of dust emission integrated over galaxies

Challenges: Rest Frame

- Physical: complexity of galaxies
- Physical: dust inhabits the whole EM spectrum in significant ways, and all λ are needed
- Technical: limited, variable spatial resolution

Large-Scale Color Gradients

Structure on All Scales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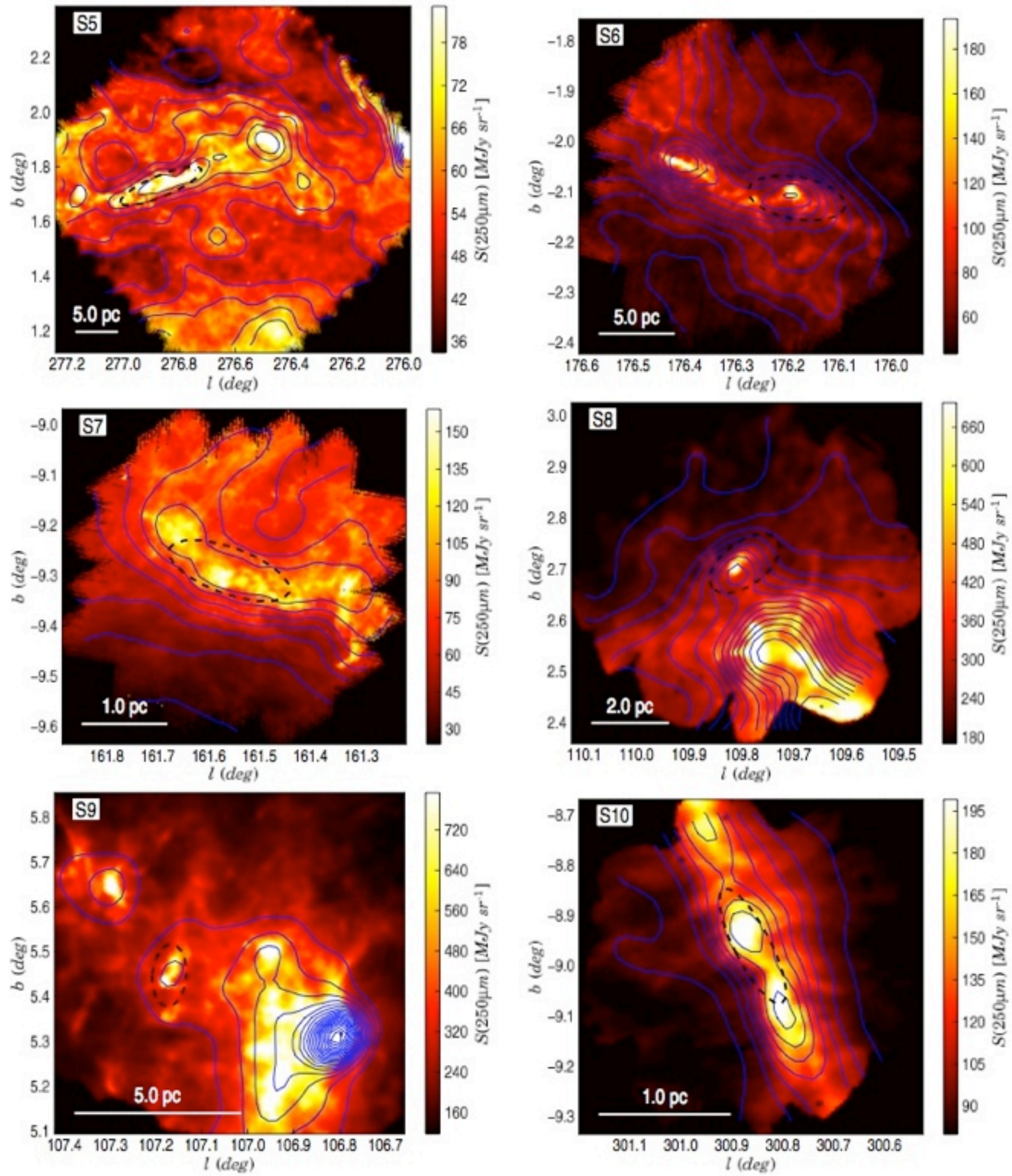
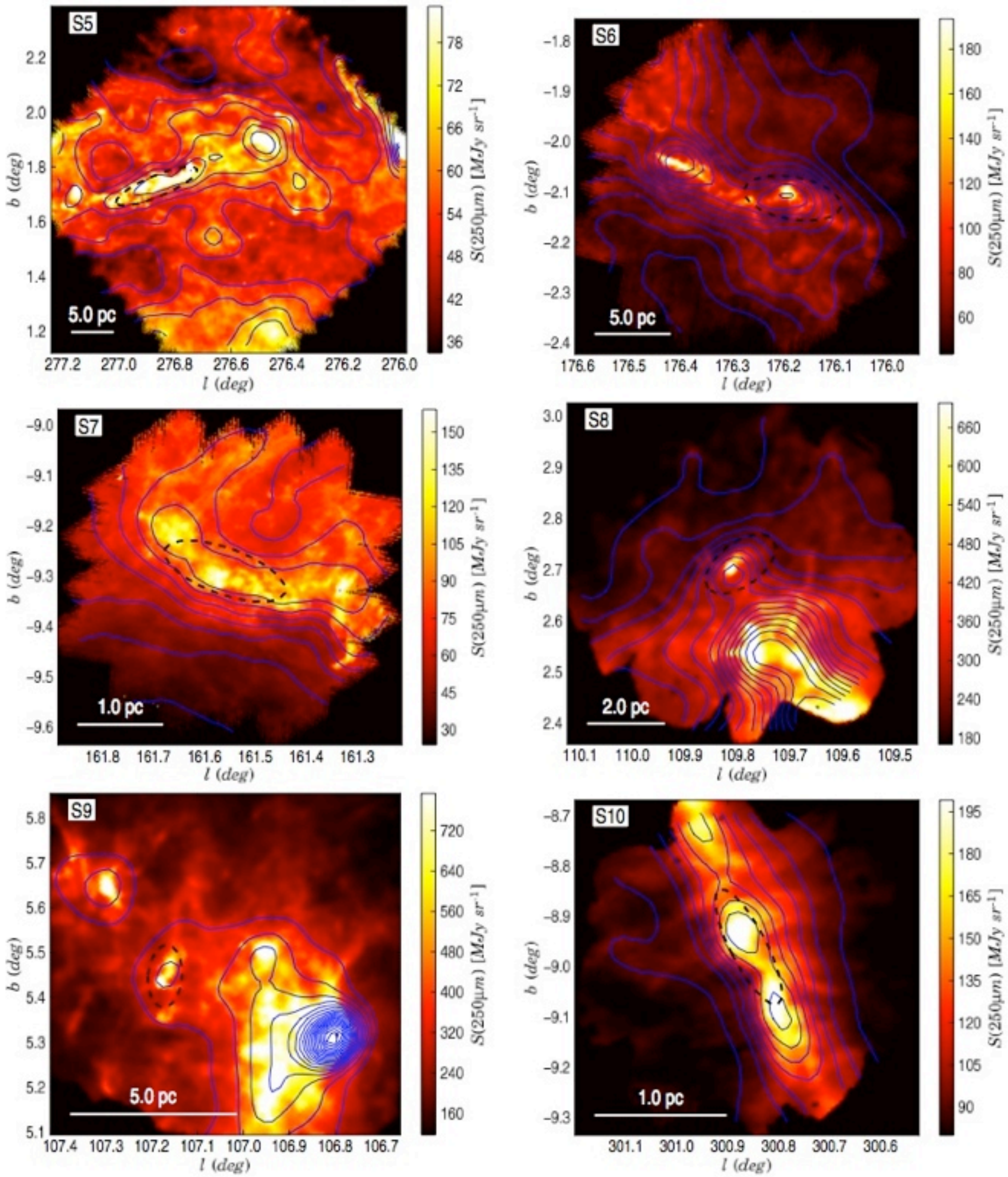


Fig. 4. *Planck* 857 GHz surface brightness contours on *Herschel* SPIRE maps at 250 μm. The source S2 has not been observed with *Herschel* and the displayed image corresponds to the *AKARI* 90 μm wide filter. **As in Fig. 3, the dashed ellipses are tracing the estimated size of the *Planck* cold clump.**

emissivity variations?



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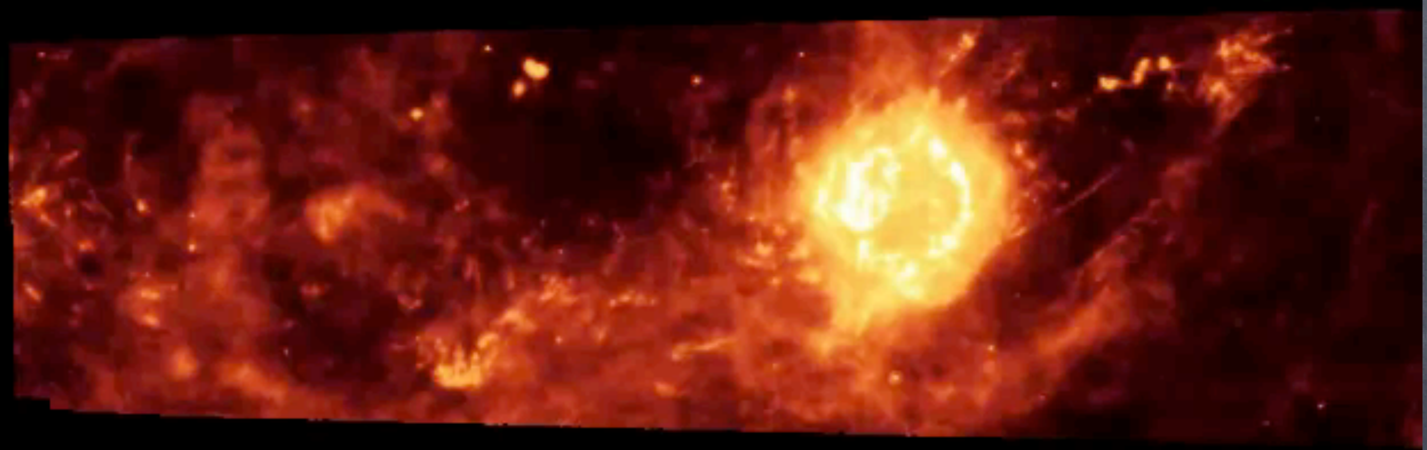
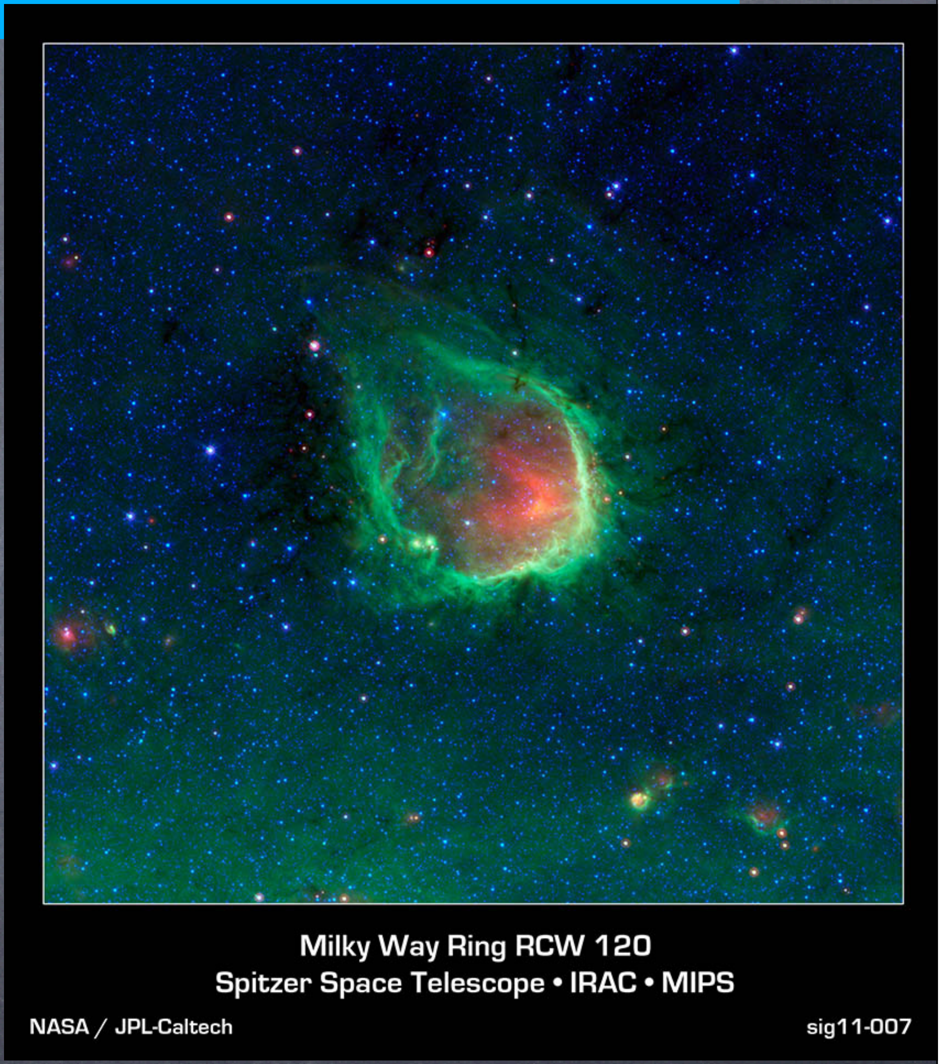
IR Echoes at 24μm in SNR Cas A

- IR echo observed at a few to 20 pc
- IR echo ~1% of burst at ~60 $L_\odot$ for ~4 months



Krause et al 2005

Inside galaxies: scale-up to RCW120



- Ring ~3.5 pc across
- O8 star ~1.3 10^5 $L_\odot$
- A few % fluctuation in L is 100x the Cas A burst

Anderson et al 2010

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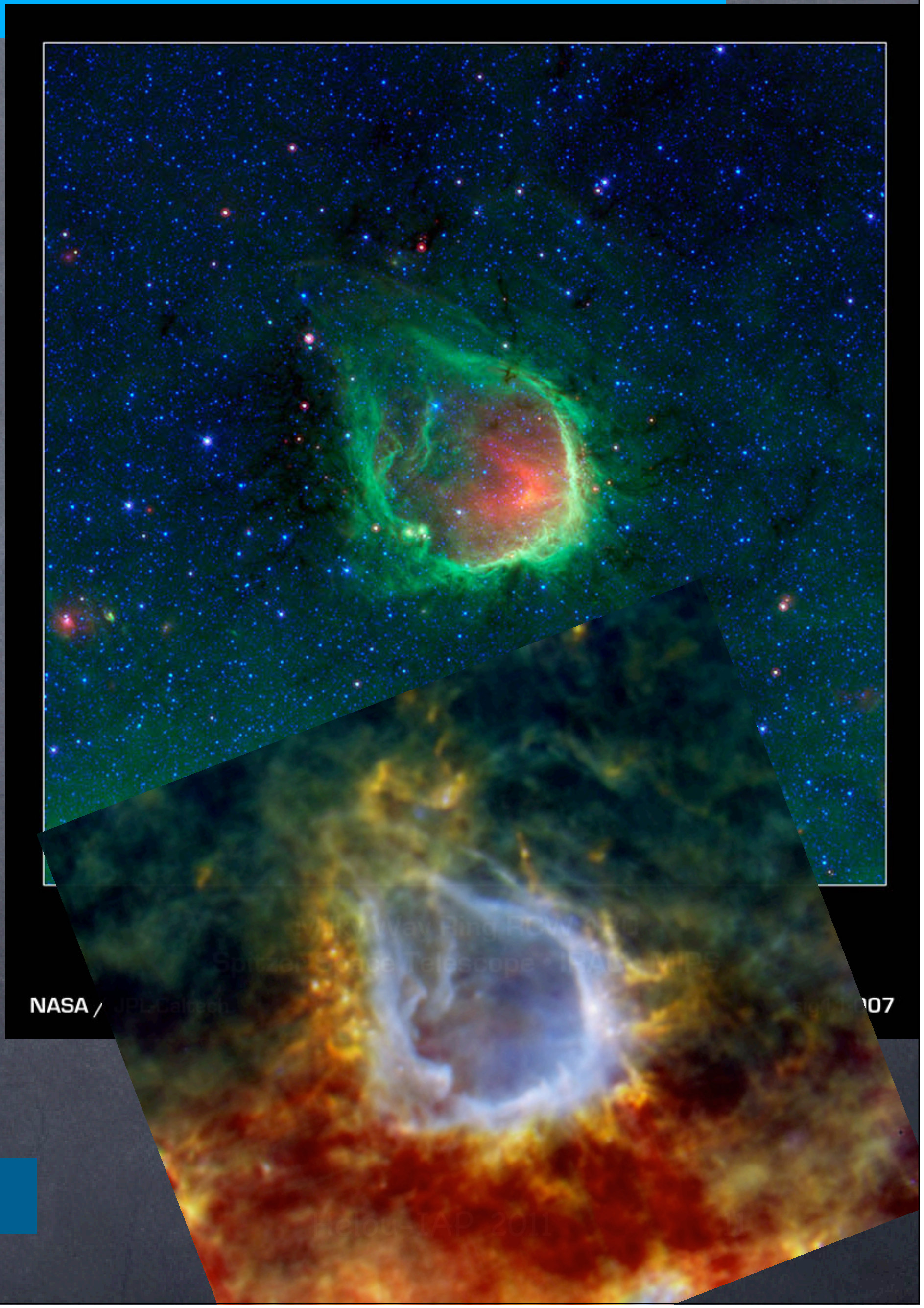


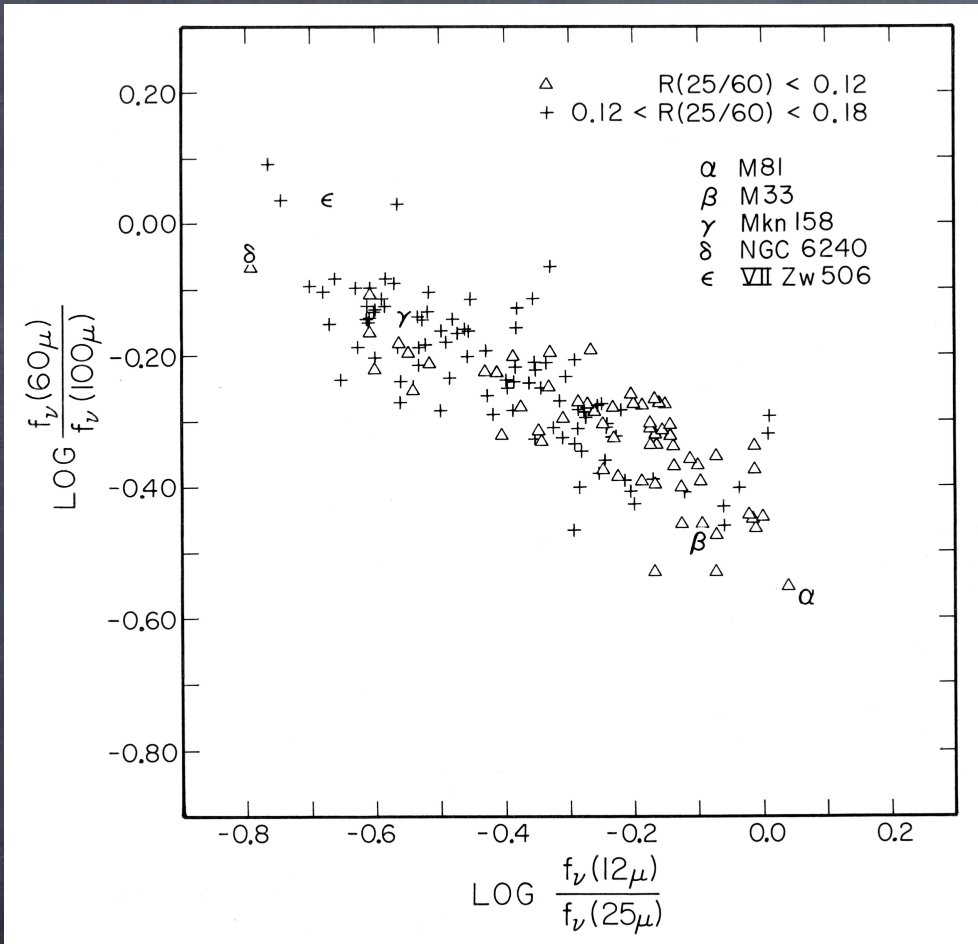
Anderson et al 2010

Many Origins of Diversity

- Varied architecture in galaxies
  - Different mix of phases
  - Different geometries
- Dust itself is a rich construct
  - Multiple species, evolving in connected ways
  - Multiple emission modes and mechanisms

- Result is great variety in IR SED of galaxies

Diversity in Galaxy/Dust SED



- IRAS galaxies
- NOTE: Blackbody??
- 5MUSES: $f_\nu(24\mu m)$ limited sample

Helou 1986; Wu et al 2010 (5MUSES)

Diversity in Galaxy/Dust SED

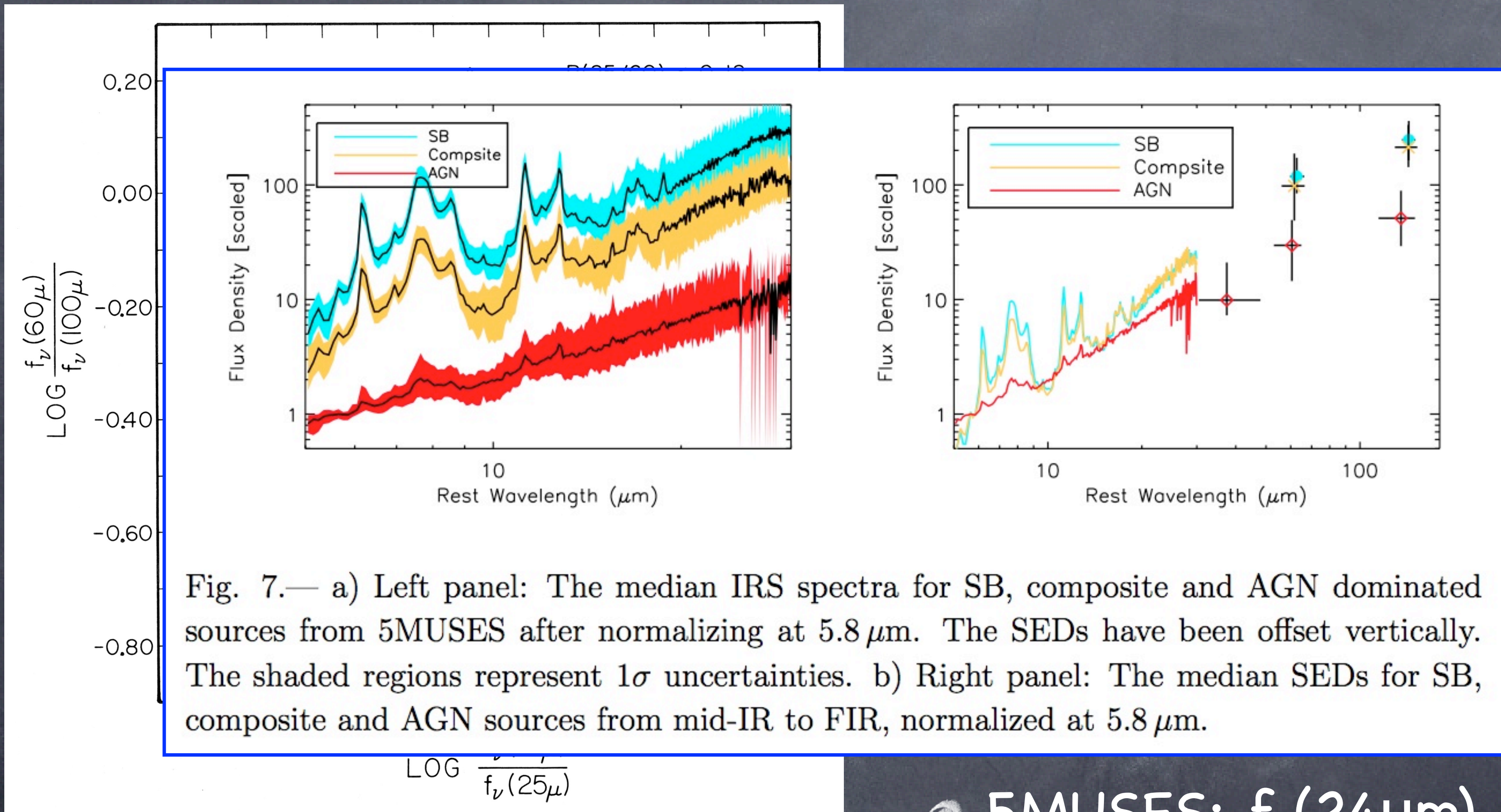


Fig. 7.— a) Left panel: The median IRS spectra for SB, composite and AGN dominated sources from 5MUSES after normalizing at 5.8 μm. The SEDs have been offset vertically. The shaded regions represent 1σ uncertainties. b) Right panel: The median SEDs for SB, composite and AGN sources from mid-IR to FIR, normalized at 5.8 μm.

- 5MUSES: $f_\nu(24\mu m)$ limited sample

Helou 1986; Wu et al 2010 (5MUSES)

Diversity in Galaxy/Dust SED

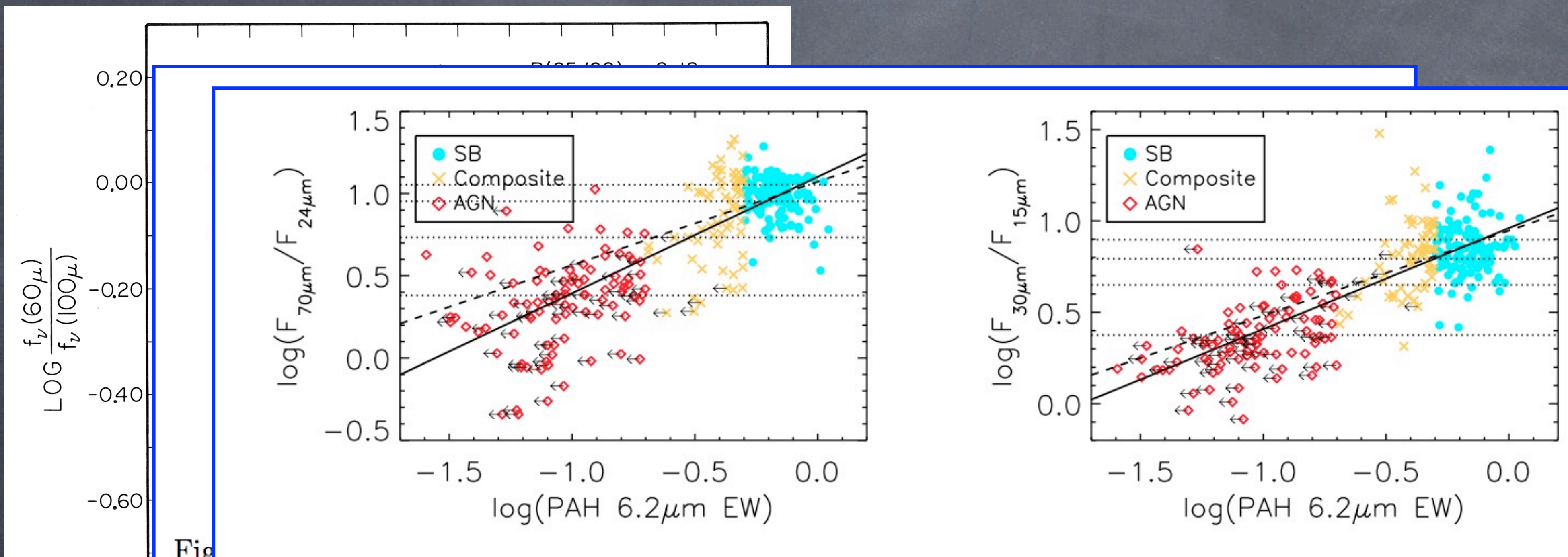
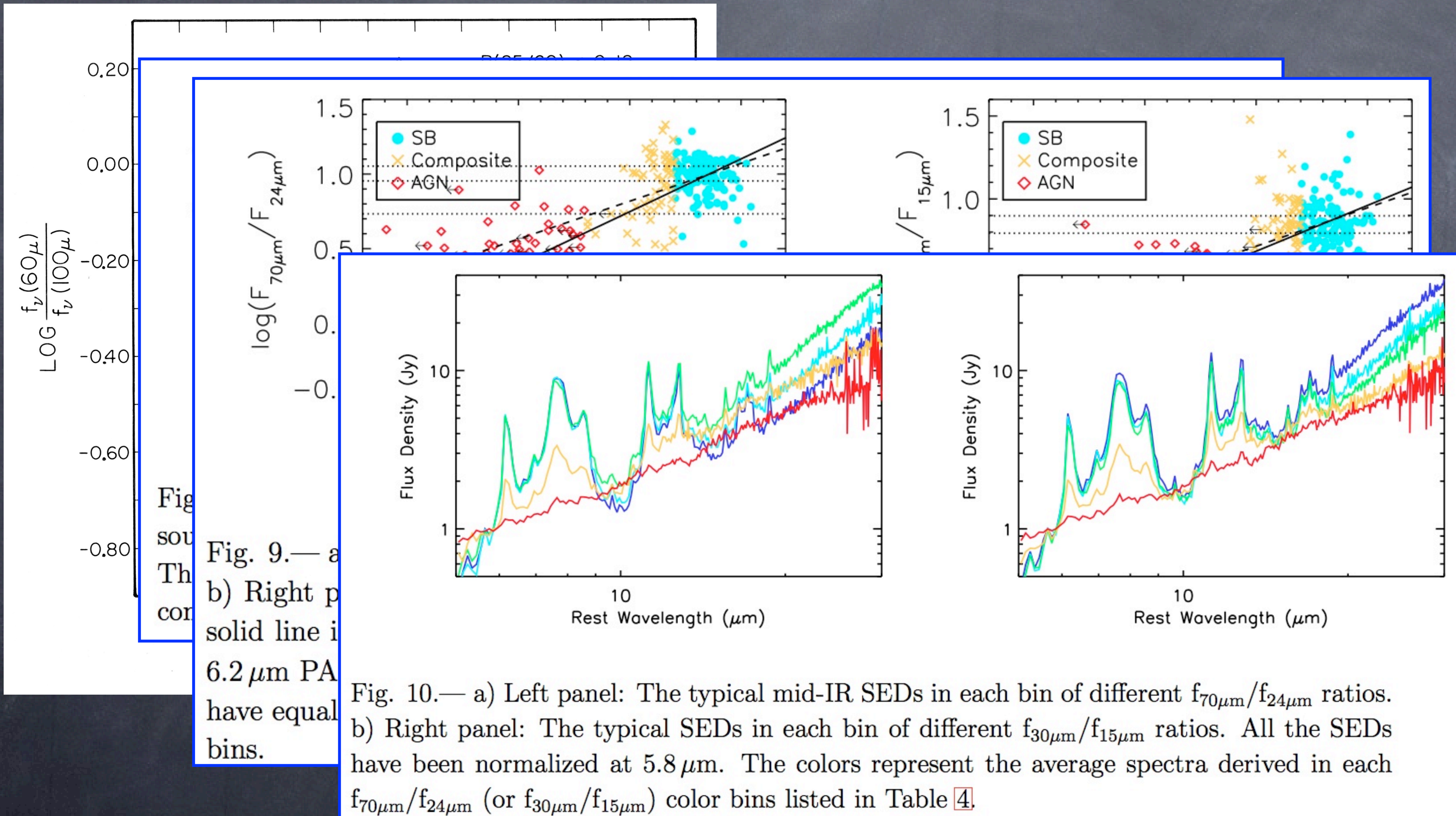


Fig. 9.— a) Left panel: The continuum flux ratio of $f_{70\mu m}/f_{24\mu m}$ versus the 6.2 μm PAH EW. b) Right panel: The continuum flux ratio of $f_{30\mu m}/f_{15\mu m}$ versus the 6.2 μm PAH EWs. The solid line is a fit to all the data points while the dashed line is a fit excluding sources with 6.2 μm PAH EW upper limits. We bin the objects according to their continuum slopes and have equal numbers of objects in each bin. The dotted lines indicate the boundaries of those bins.

Helou 1986; Wu et al 2010 (5MUSES)

Diversity in Galaxy/Dust SED



Helou 1986; Wu et al 2010 (5MUSES)

Diversity in Galaxy/Dust SED

- Ultra-Luminous IR Galaxies (ULIRG)
- NOTE:

  Arp220 is unusual

Armus et al 2006

Diversity in Galaxy/Dust SED

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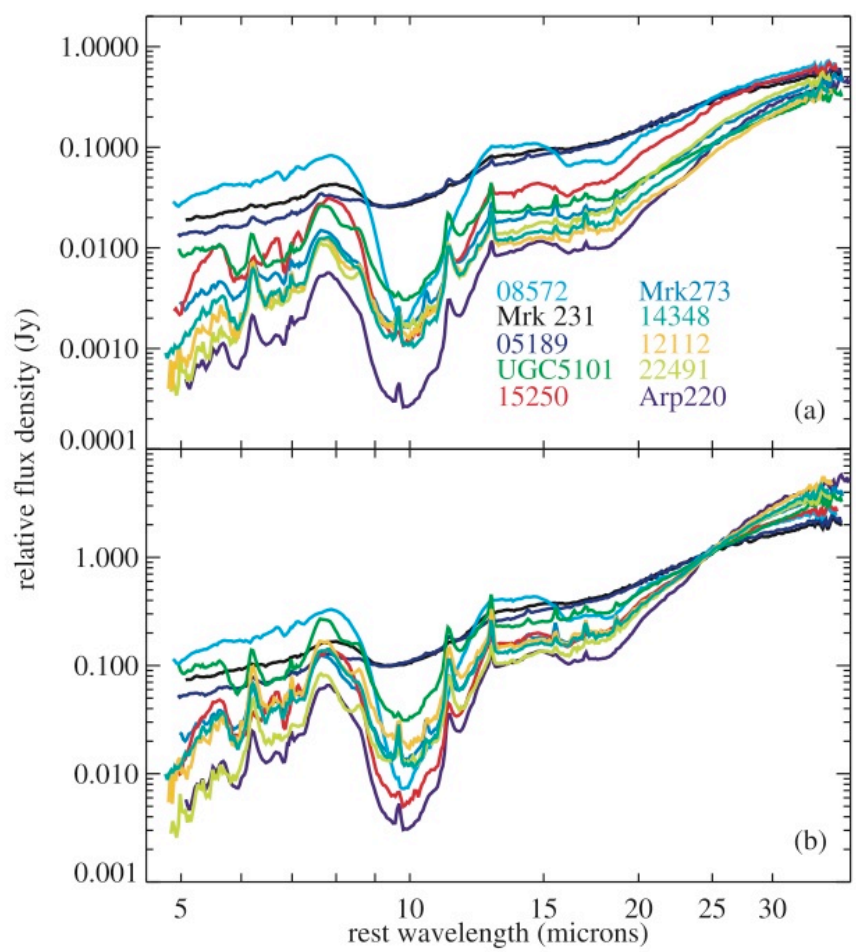


FIG. 2.—Normalized low-resolution IRS spectra. Spectra are normalized at (*a*) rest frame 60 μm, and (*b*) rest frame 25 μm.

Armus et al 2006

Diversity in Galaxy/Dust SED

- Spitzer +Herschel data
- NOTE:
  - Decorrelation Δλ

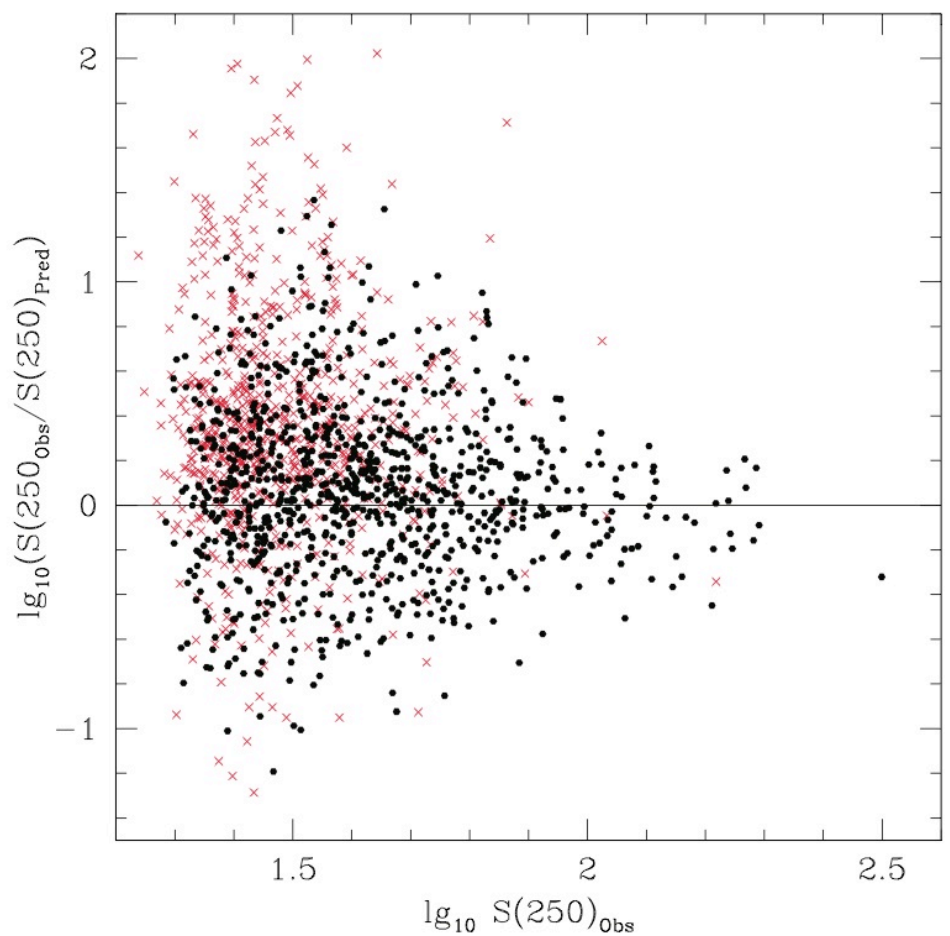


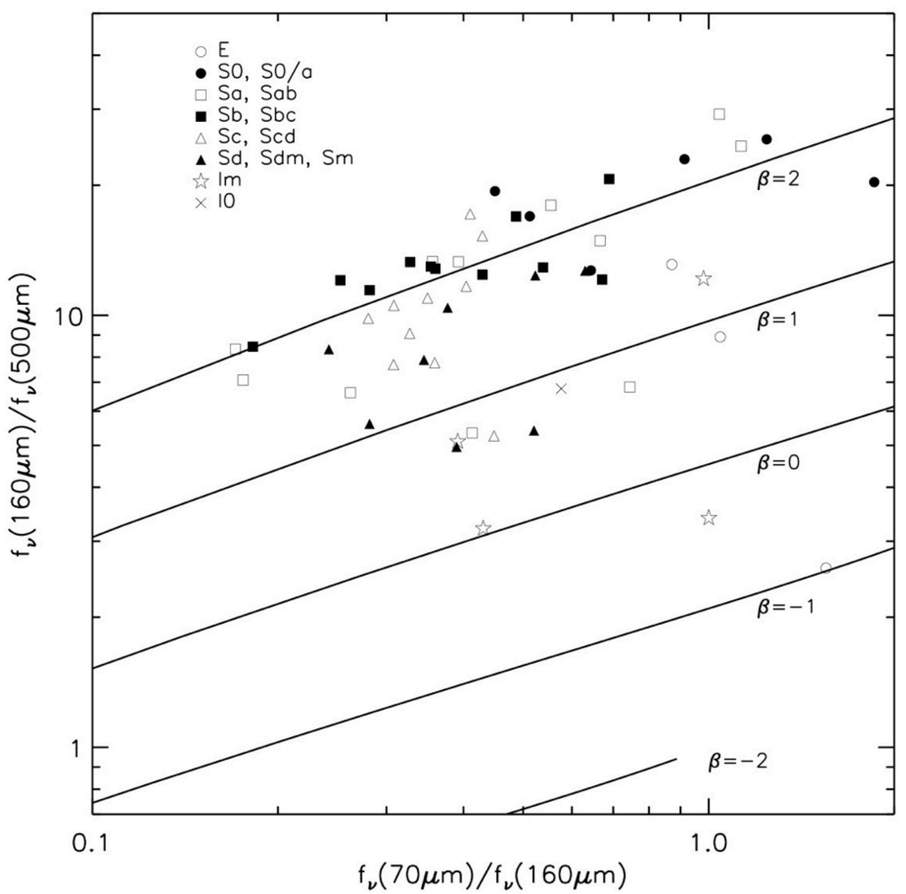
Figure 12. Ratio of observed flux at 250 μm to predicted flux, based on 4.5–24 μm data, versus observed 250-μm flux (red crosses). Filled black circles are predictions based on 4.5–70 μm data.

Rowan-Robinson et al 2010

Diversity in Galaxy/Dust SED

- KINGFISH (Herschel KP Nearby Galaxies, Kennicutt PI)
- NOTE:

  log-normal distribution



Dale et al in prep

Challenges: Rest Frame

- Main rest-frame challenge is inherent complexity of dust and galaxies
- In the face of great diversity
  - Detailed physical modeling too unwieldy; parametric approach can be effective
  - Natural empirical approach is correlative analysis, targeted trend analysis, and statistical inference
- Need to keep that inherent complexity in mind, even when we have 2 data points per source

Challenges: Observer Frame

- Response to nature's diversity
  - The Blackbody fit
  - The Arp 220 presumption
  - The stacking mania

The Blackbody Fit

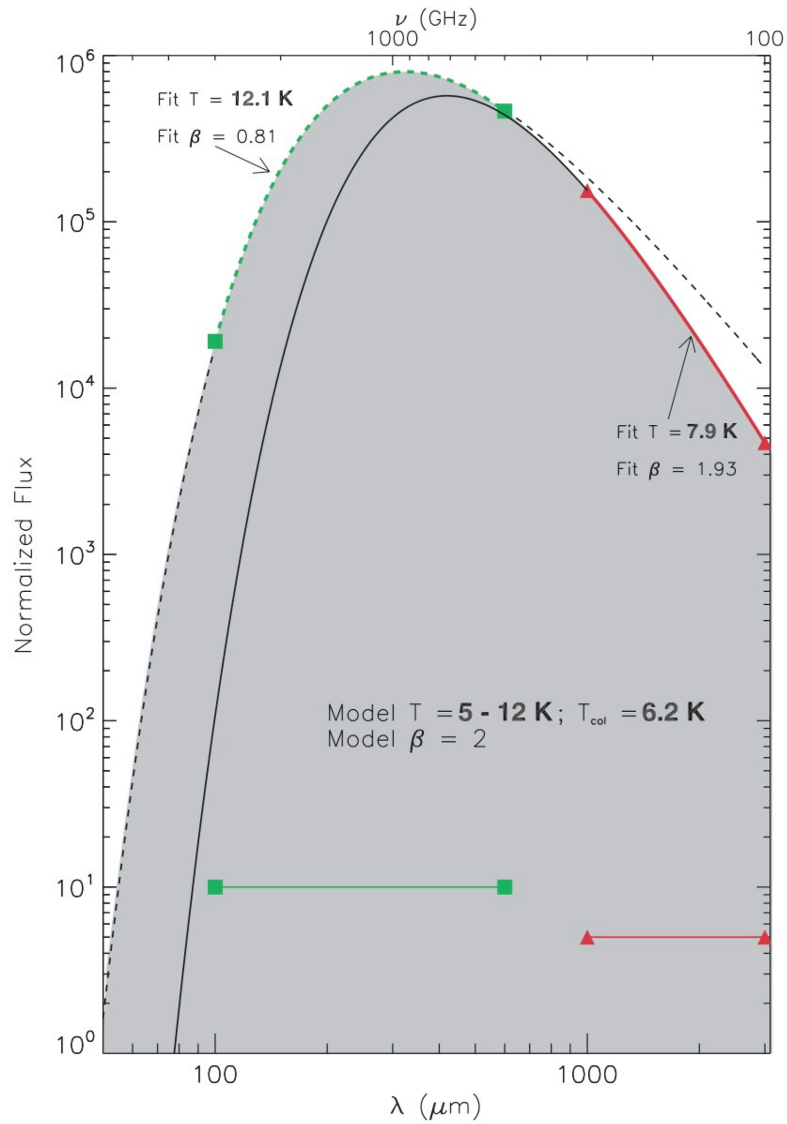


Figure 5. Actual and fit SEDs from model Core 2 (see text). The boundary of the shaded region is the emergent SED of the core. The dashed SED shows the best fit to fluxes between 100 and 600 μm (marked by squares). The solid line shows the best fit to fluxes between 1000 and 3000 μm (marked by triangles). The green and red lines mark the extent of the wavelength ranges used in the two fits.

Shetty et al 2009b

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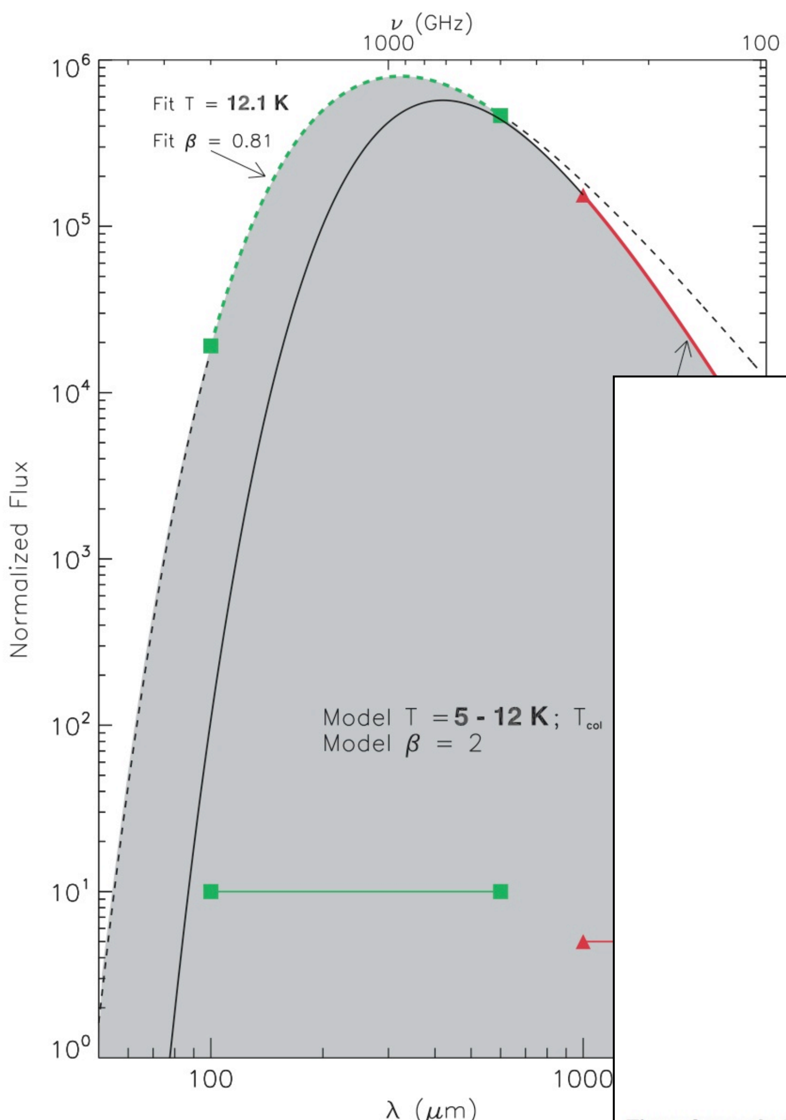
The Blackbody Fit



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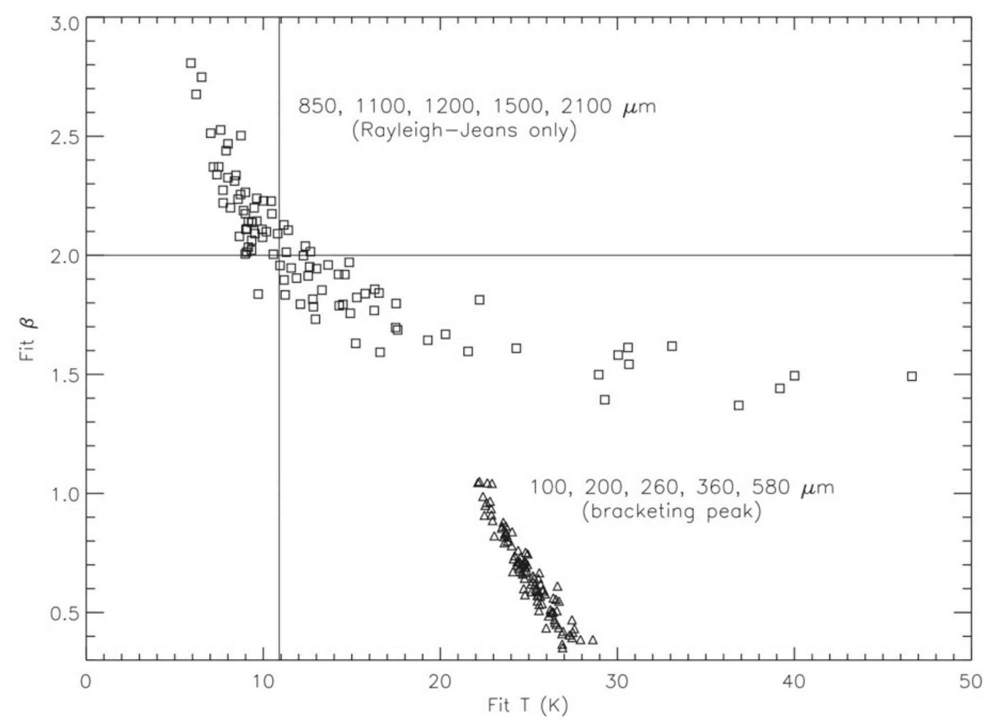


Figure 8. Best-fit β and T to observed fluxes from the two-component source "2COMPd" (with $T_1 = 10$ K, $T_2 = 20$ K, and $N_2/N_1 = 0.1$; see Figure 3). Five fluxes are used in each fit: 850, 1100, 1200, 1500, and 2100 μm (squares), or 100, 200, 260, 360, and 580 μm (triangles). Each flux includes a small (Gaussian distributed) random component, with $\sigma = 5\%$. The lines indicate the model parameters $\beta = 2$ and column temperature = 10.9 K.

Shetty et al 2009b

The Blackbody Fit

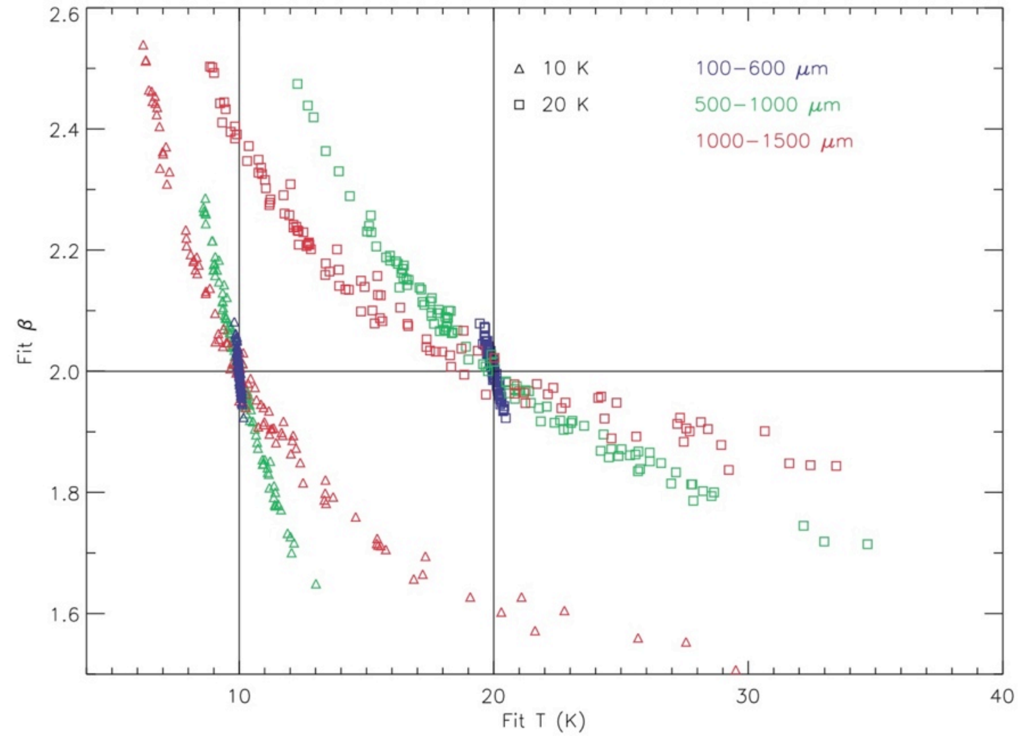


Figure 6. Best-fit T and β from Monte Carlo simulations of noisy fluxes from 10 K (triangles) and 20 K (squares) isothermal sources. The vertical lines indicate the true source temperatures, and the horizontal line marks the true spectral index. Fluxes with different wavelengths were considered in each fit: 100–600 μm (blue), 500–1000 μm (green), and 1000–1500 μm (red). Gaussian distributed noise is added to each flux, with $\sigma = 5\%$.

Shetty et al 2009a

The Blackbody Fit

- An indicative T(BB) may be "useful", but dust mass estimates will be seriously off using BB

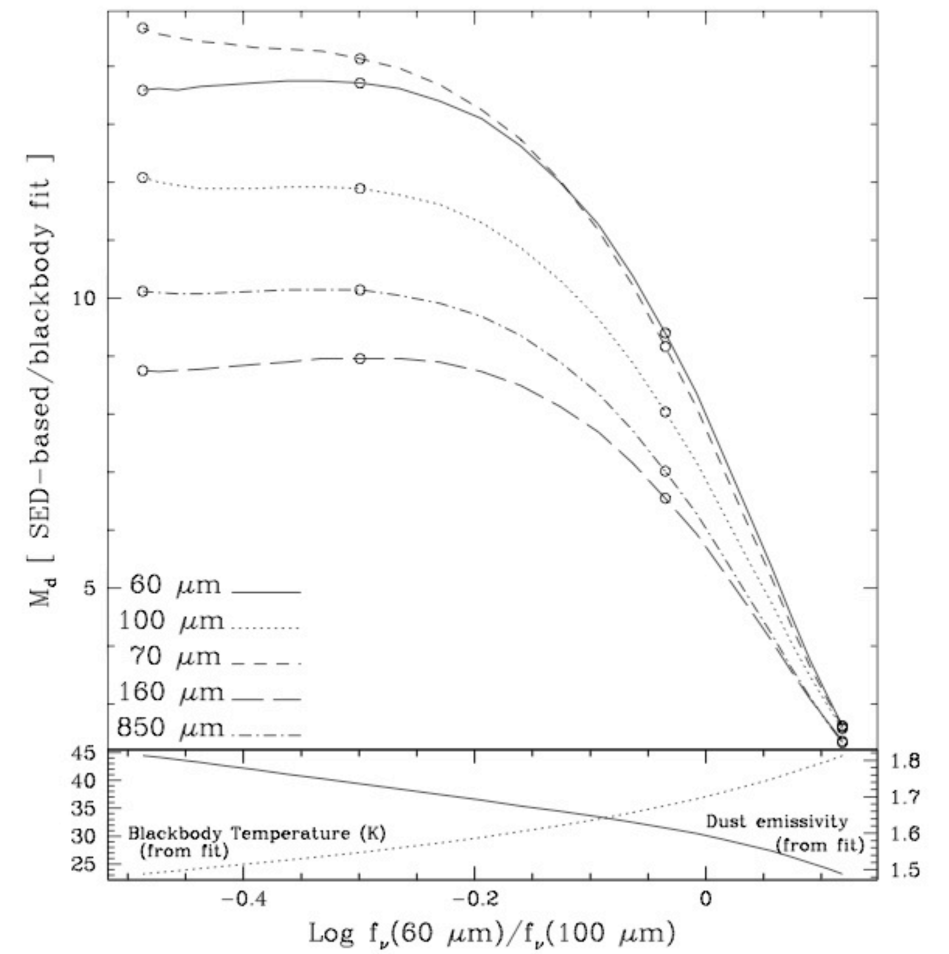
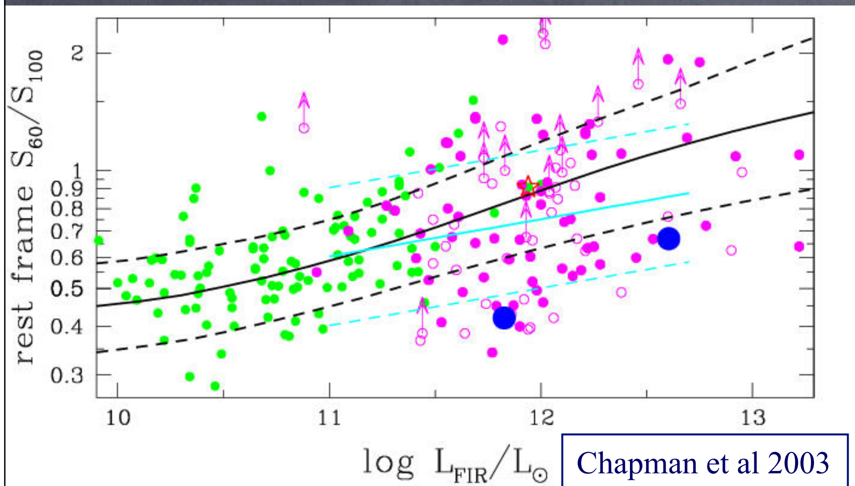
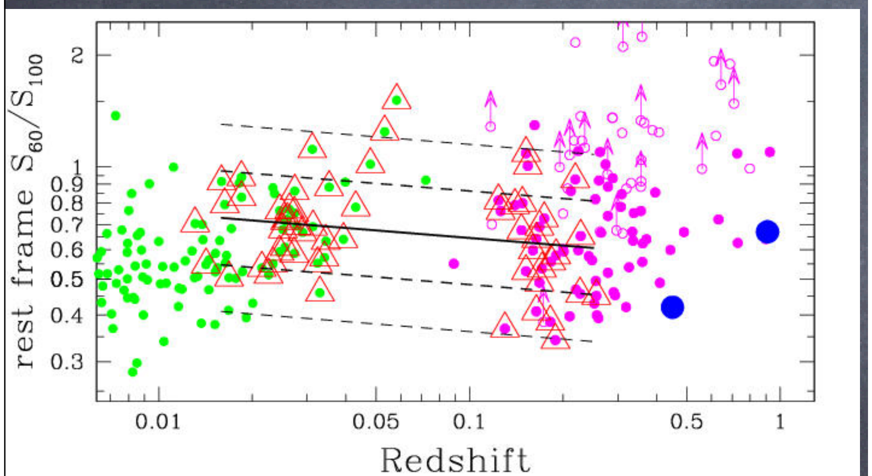


FIG. 6.—*Top*: Comparison of dust masses computed from single blackbody fits to the infrared SEDs with the actual dust masses. The various curves correspond to using broadband flux densities at different wavelengths. *Bottom*: Best-fit blackbody temperature for each SED (*dotted* ...*ve*) and best-fit dust emissivity index (*solid curve*). The sequence of open ...cles indicates models that correspond to power-law exponent values of ...= 2.5, 2.0, 1.5, and 1.0 [in order of increasing $f_\nu(60\ \mu m)/f_\nu(100\ \mu m)$]. [*See the electronic edition of the Journal for a color version of this figure.*]

Dale & Helou 2002

The Arp220 Presumption





- Arp 220 is rare in L and SED in the local universe
- It is also a rare SED in general
- Galaxies of any L span wide SED range

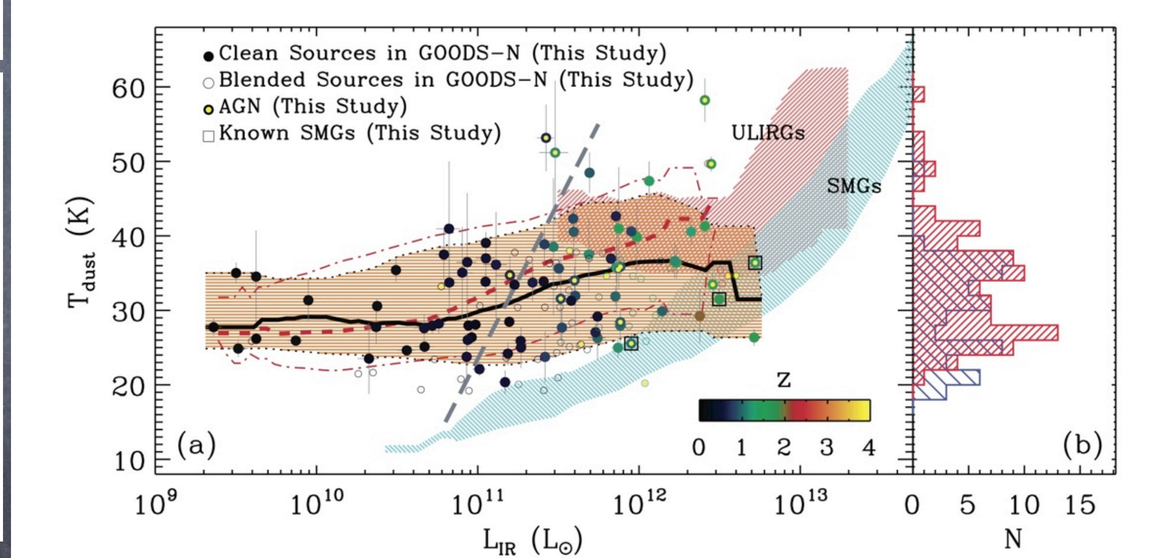


Figure 4. (a) T_{dust} versus L_{IR} for galaxies in GOODS-N. Galaxies hosting AGN are indicated by yellow symbols. The thick dashed line is a smoothed median trend of T_{dust} for local galaxies adopted in Fig. 3, and the dot–dashed lines are its 90 per cent envelope. The loci of known SMGs and ULIRGs in Fig. 3 are plotted as regions filled by cyan and coral colour, respectively. Clean and blended galaxies are denoted by filled and open circles, respectively. The thick solid line is a median trend of T_{dust} for galaxies in the GOODS-N field and the dotted lines are its 90 per cent envelope (filled with orange colour). Inclined, grey long-dashed lines indicate the *AKARI* selection function at the maximum redshift of local galaxies ($z = 0.119$). (b) Distribution of T_{dust} for high-z galaxies. Clean and blended galaxies including AGN are denoted by hatched histograms with orientation of 45° (// with red colour) and of 315° (\\ with blue colour) relative to horizontal, respectively.

Chapman et al 2003

Hwang et al 2010

“Stacking”

- Stacking is a linear operation, equivalent to taking simple mean
- Colors are not linearly distributed, so stacking will distort colors
- For some applications (e.g. deriving CIB), it might be safe to “stack”
  - Best to “stack” very homogeneous populations

Interlude

Journal of Glaciology, Vol. 55, No. 192, 2009

Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland)

J. OERLEMANS, R.H. GIESEN, M.R. VAN DEN BROEKE

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LETTERS

PUBLISHED ONLINE: 23 JANUARY 2011 | DOI: 10.1038/NGEO1068

nature geoscience

Spatially variable response of Himalayan glaciers to climate change affected by debris cover

Dirk Scherler[1]*, Bodo Bookhagen[2] and Manfred R. Strecker[1]

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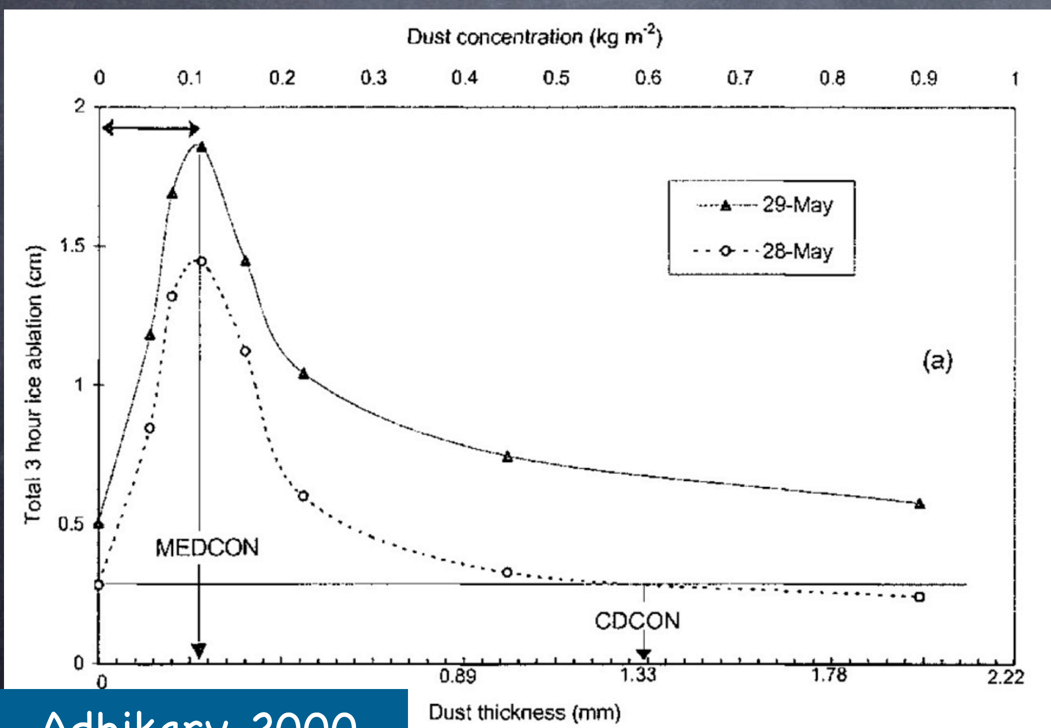

Adhikary 2000

nature geoscience

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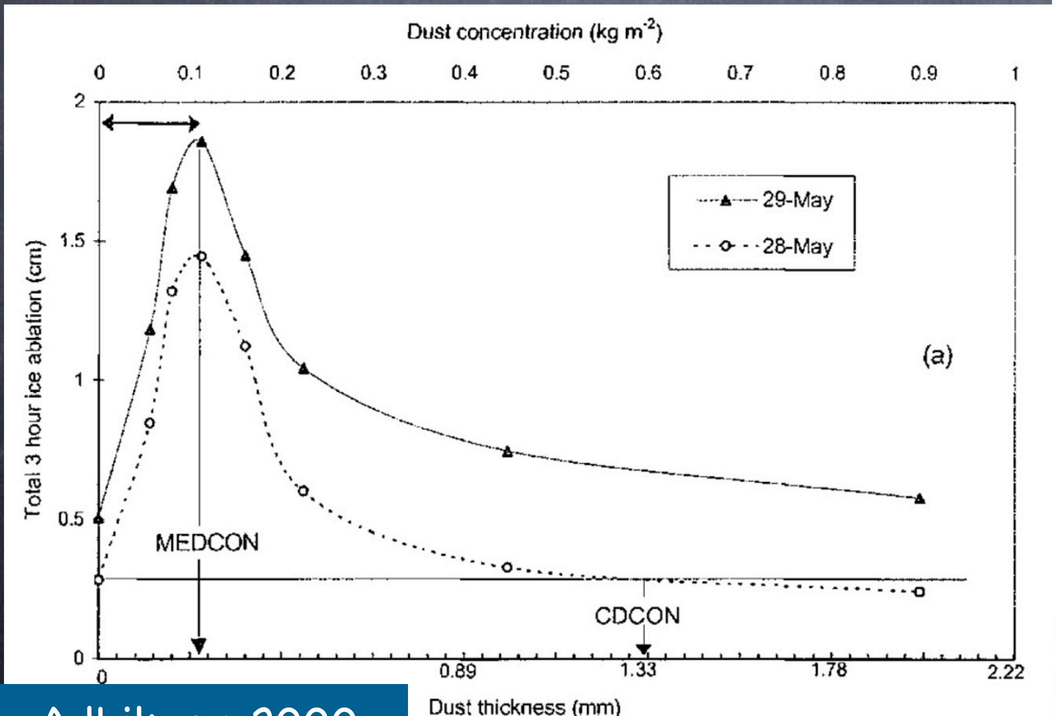

Adhikary 2000

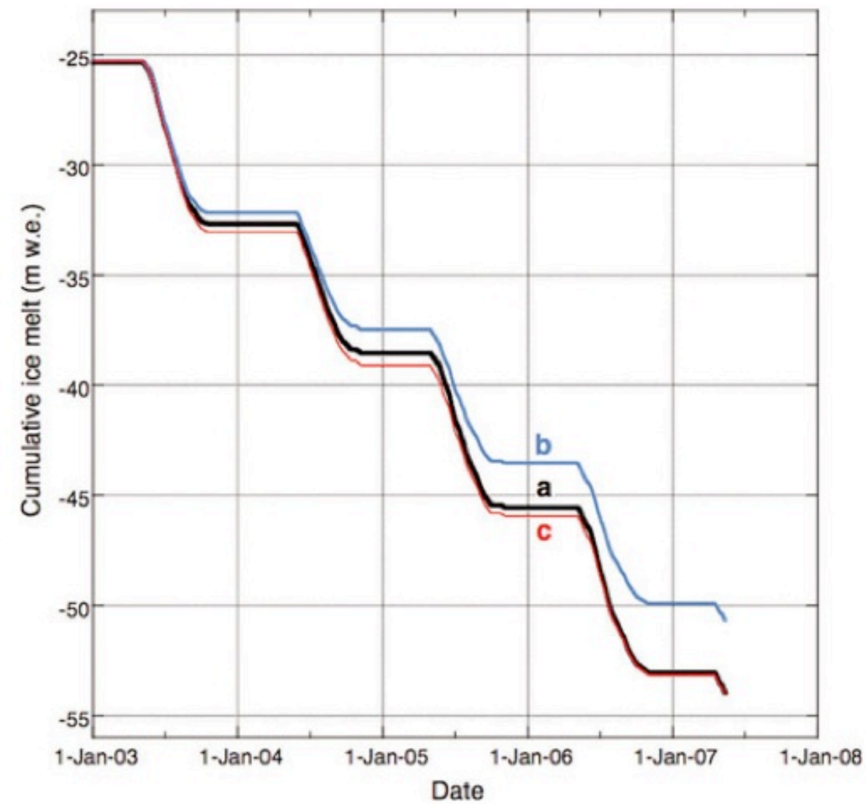

Fig. 8. Calculated ice melt for (a) the standard input data, (b) a run with constant ice albedo and (c) a run with constant ice albedo and a 1.7 K temperature increase since 2003.

Some Early-Universe questions

- Is early Universe dust different? Or does galaxy architecture dominate SED shapes?
  - How late does dust remain "different"? Are there signatures in the Cosmic Infrared Background?
- Which came first, silicates, Aromatics/Aliphatics/etc or large amorphous grains?
  - When did they appear? Where?
  - Do same sources apply today?

Some Local-Universe questions

- How much variation in dust properties inside and among galaxies at low z?
- How much of a galaxy's dust is observable today?
- How much dust in IGM? How much near T(CMB)?
- What do we not know? Unrecognized species? Other roles in ISM, SF?
- How narrowly correlated are physical states of dust and gas? Are there truly co-spatial tracers?
- Polarization!

Some Answers?

- QSO reddening as evidence of extended dust haloes around galaxies
- Note extent over x10^3 in distance, up to 10 Mpc

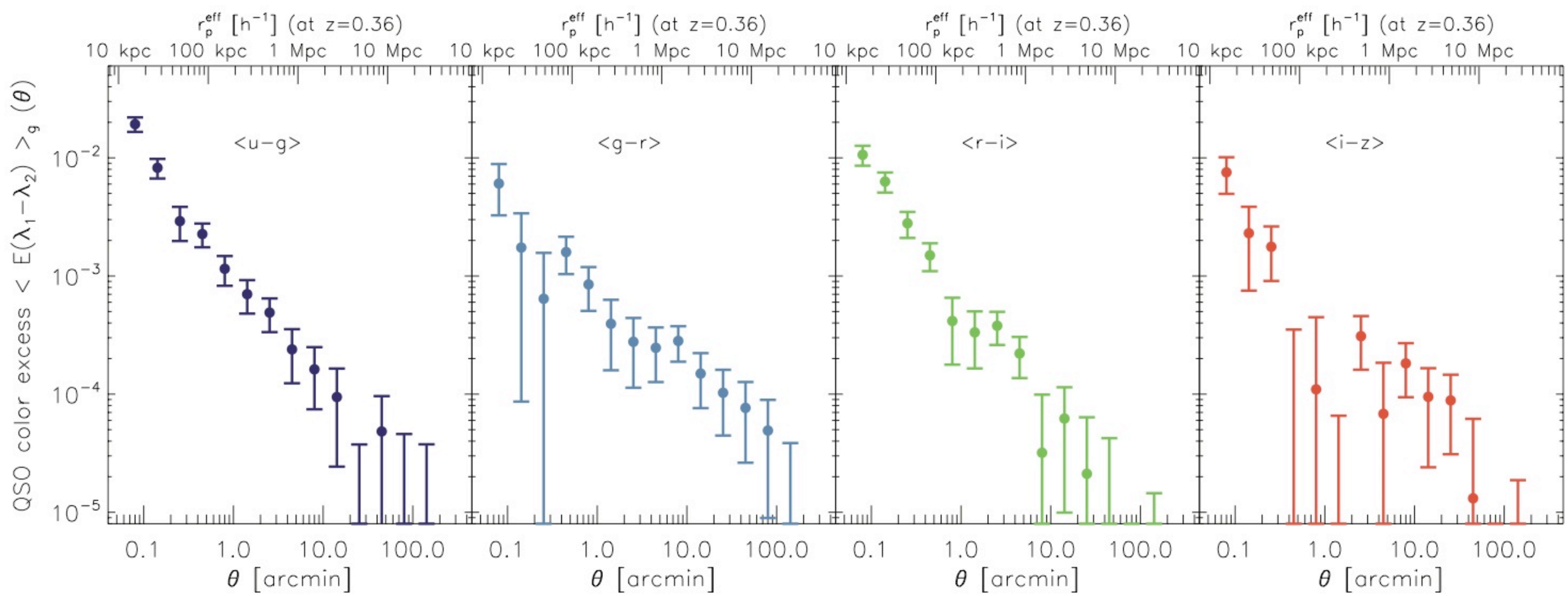

Figure 4. Correlation between QSO reddening and galaxy overdensity as a function of angular scale. Note that the four independent colours are taken from adjacent pass bands and do not maximize the signal-to-noise ratio (see Fig. 6 for such a quantity).

Menard et al 2010

Some Answers?

- M(dust)/M(total) constant?
- Result based on QSO-galaxy correlation statistics

Menard et al 2010

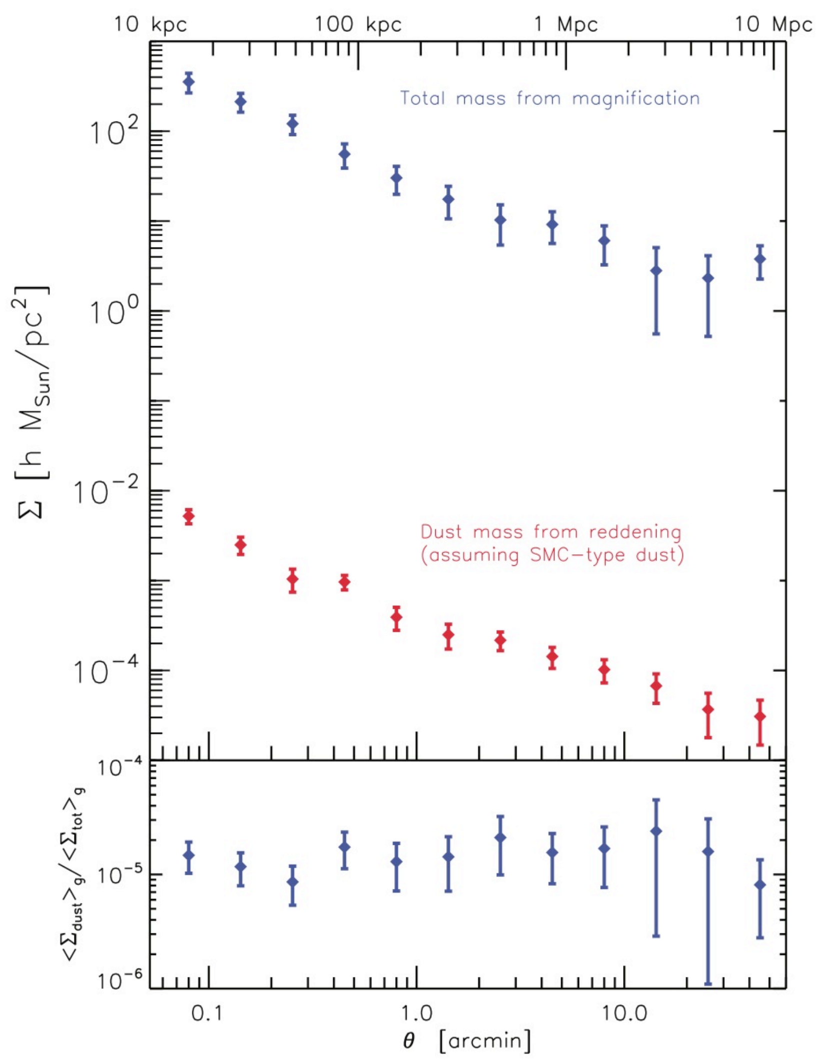

Figure 8. Mean surface mass density profile around galaxies selected with $i < 21$. The total mass density is obtained from magnification measurements. The dust mass density is inferred from reddening measurements, assuming SMC-type dust. The lower panel shows the dust-mass to total-mass ratio.

Opportunities

- This is the golden era of ISM astrophysics, and dust plays a leading role
- Still untapped potential in telescopes & archives:
  - ISO, Spitzer, AKARI, Herschel, WISE, and Planck
  - ALMA will be a great tool for high z, and for high spatial resolution in Local Universe
  - EVLA, SKA and its precursors, especially for q(z)
  - JWST will also be great for high z, high resolution
- Data flood is stimulating theoretical work
  - Need to bring to interpretation the benefits of theory progress, or at least update the methods and tools

Opportunities: Low Redshift

- Integrating across radio-IR-visible-UV

  How to invert IR(λ) for heating spectrum given galaxy parameters (Z, effective age, gas contents, etc)

- Integrating across dust and gas diagnostics

  Building an understanding that can be applied to deciphering the high-redshift galaxies

- Next Step: A large, cold, filled aperture with adequate detectors to measure the details of SED beyond 50μm

  SPICA would be an excellent start!

Opportunities: High Redshift

- Build better population models out to z~3 using Local Universe data, and deep survey constraints
- Aromatics at high redshifts
  - JWST will cover out to z~3
  - Need large, cold telescope to see the rise of Aromatics at z~5 and earlier
- FIR at high redshifts
  - CCAT (and ALMA) will explore that frontier

Parting Thoughts

- Challenges within reach:

  solve for the star/dust heating/cooling matrix

  construct higher-fidelity population models

  get the statistical methods right!

- A simple prediction:

  dispersion(SED), other properties rises with z, especially at z>1

  No single "primordial galaxy" template: Understand the locals and look with an open mind!


IRAS (1983), 12–100 microns
ISO (1995), 7–15 microns
2MASS (1997), 1.3–2.2 microns
Spitzer (2003), 3.6–24 microns


QUESTA EFFIGIE DEL DIVINO GALILEO
FECE PORRE NEL MDCCCXLIII
ANTONFILIPPO MARCHIONNI
ΣΥΝ ΘΕΩ
AEDES QVAS VIATOR INTVERIS LICET EXIGVAS
DIVINVS GALILAEVS
COELI MAXIMVS SPECTATOR
ET NATVRALIS PHILOSOPHIAE RESTITVTOR
SEV POTIVS PARENS
PSEVDOSOPHORVM MALIS ARTIBVS COACTVS
INCOLVIT AB ANNO MDCXXXI KAL NOVEMBRIS
AD ANNVM MDCXLII VI IDVS IANVARI
HEIC NATVRAE CONCESSIT
LOCI GENIVM SANCTVM VENERARE ET TITVLVM
AB IO BAPTISTA CLEMENTE NELLIO
STEPHANIANI ORDINIS EQVITE
SENATORE AC PATRICIO FLORENTINO
AETERNITATI DICATVM SVSPICE
ANTONIO BONAIVTI IC FVNDI DOMINO ANNVENTE
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Merci!