# Overview of Extragalactic Dust Observations

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"Have Dust – Will Study"

Current Problems in
Extragalactic Dust
Copenhagen
29 Jun 2009

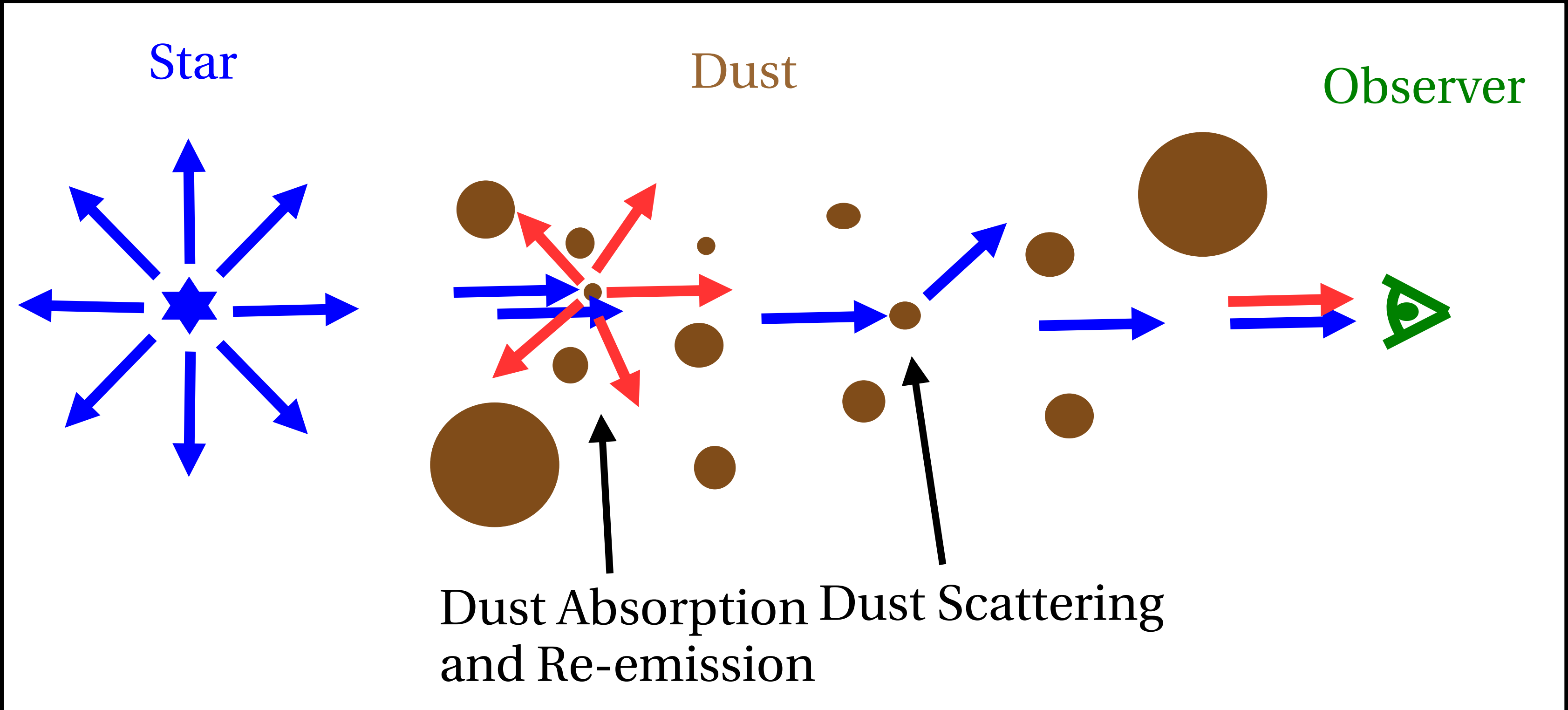
R=MIPS 24 µm, G=IRAC 8 µm, B=IRAC 3.6 µm

M101

# Outline

- UV/optical extinction curves in the Local Group
- UV/optical attenuation curves in galaxies
- IR/submm emission
- Briefly mention ancillary observations
  - Metals, HI, CO, etc.
- Major understanding of dust in galaxies comes from Local Group/Universe work

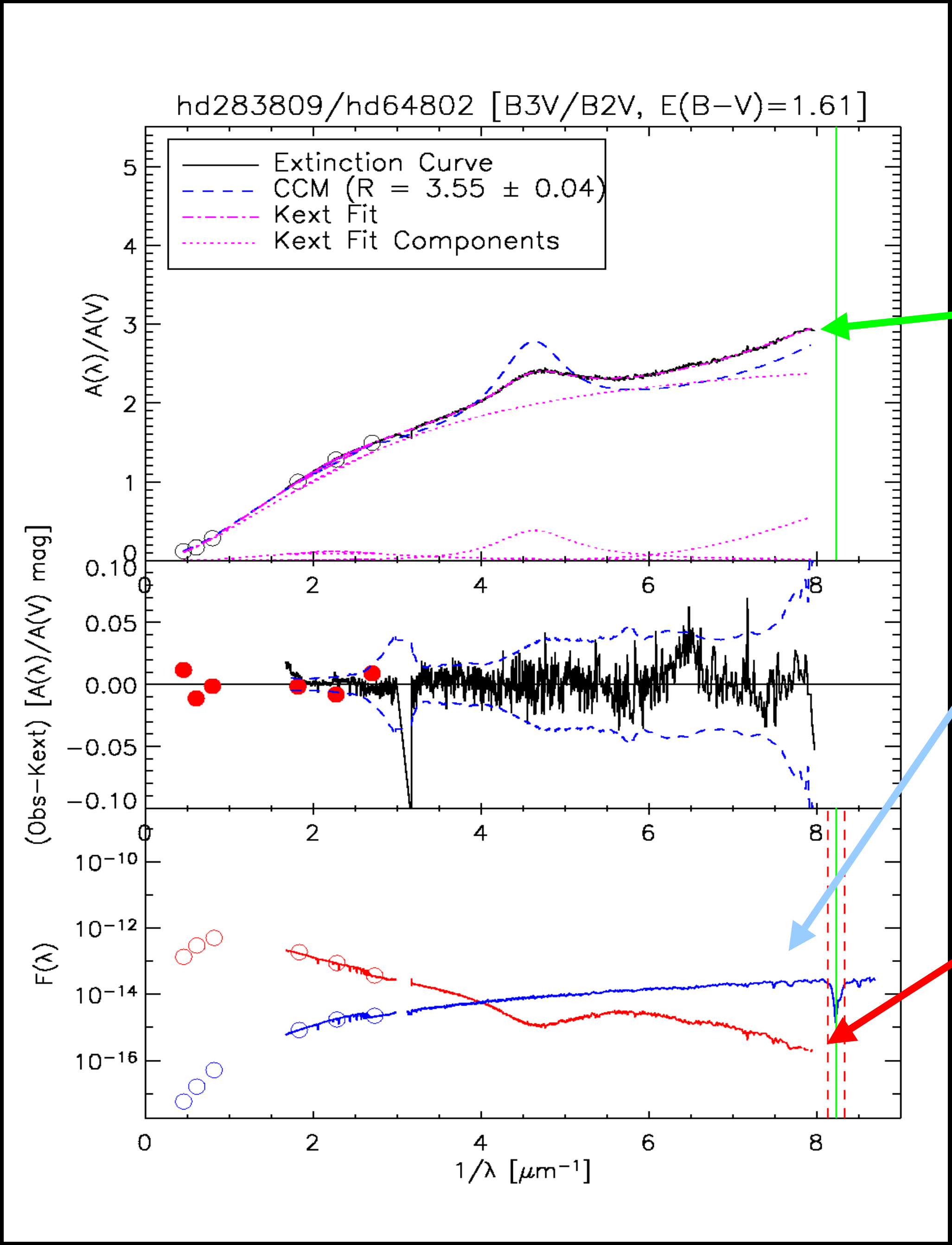
# Screen Geometry




$$F(\lambda) = F_o(\lambda)e^{-\tau(\lambda)} \qquad \tau(\lambda) = \text{optical depth}$$

- Wavelength dependence of dust attenuation is determined only by the physical parameters of the dust grains

# How to make an Extinction Curve




3) Take the ratio = extinction curve (good when the spectral lines cancel)

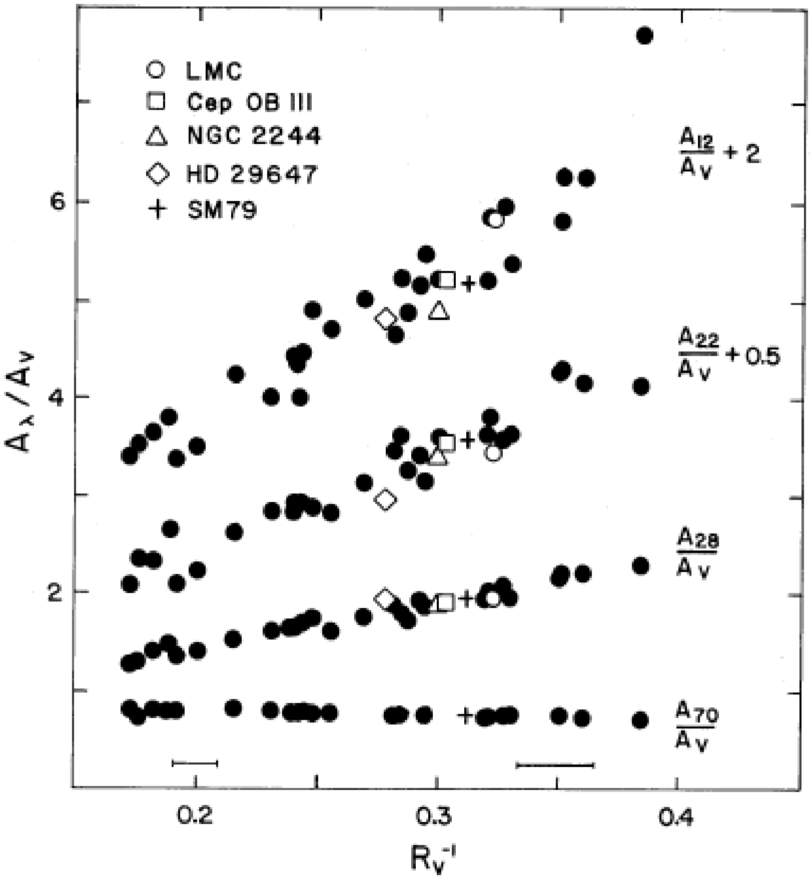
2) Find another star with the same spectral type = same physics (temperture and gravity) but is not affected by dust.

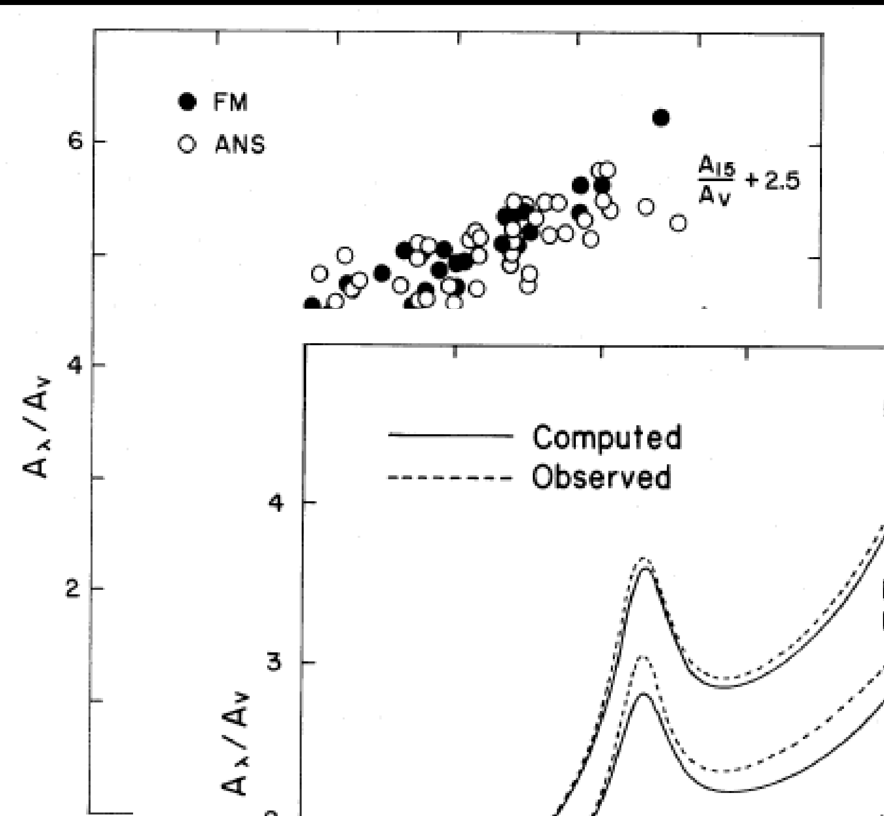
1) Start with a star which is affected by dust (fainter and redder than expected)

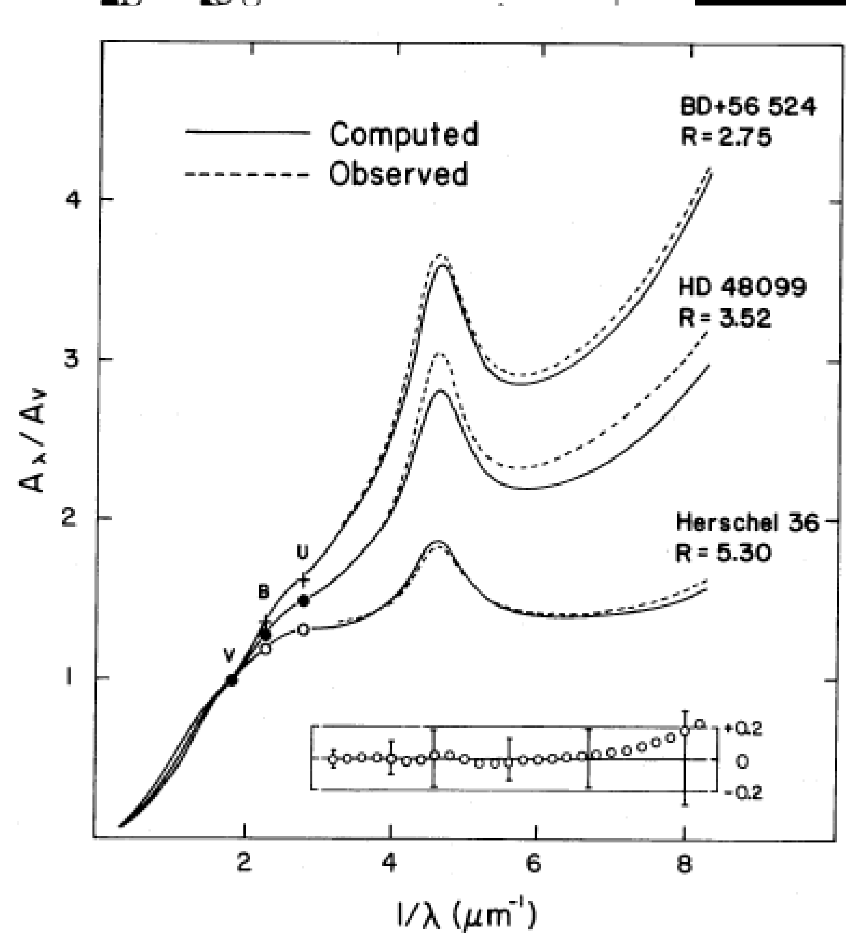
The Astrophysical Journal, 345:245–256, 1989 October 1


# THE RELATIONSHIP BETWEEN INFRARED, OPTICAL, AND ULTRAVIOLET EXTINCTION

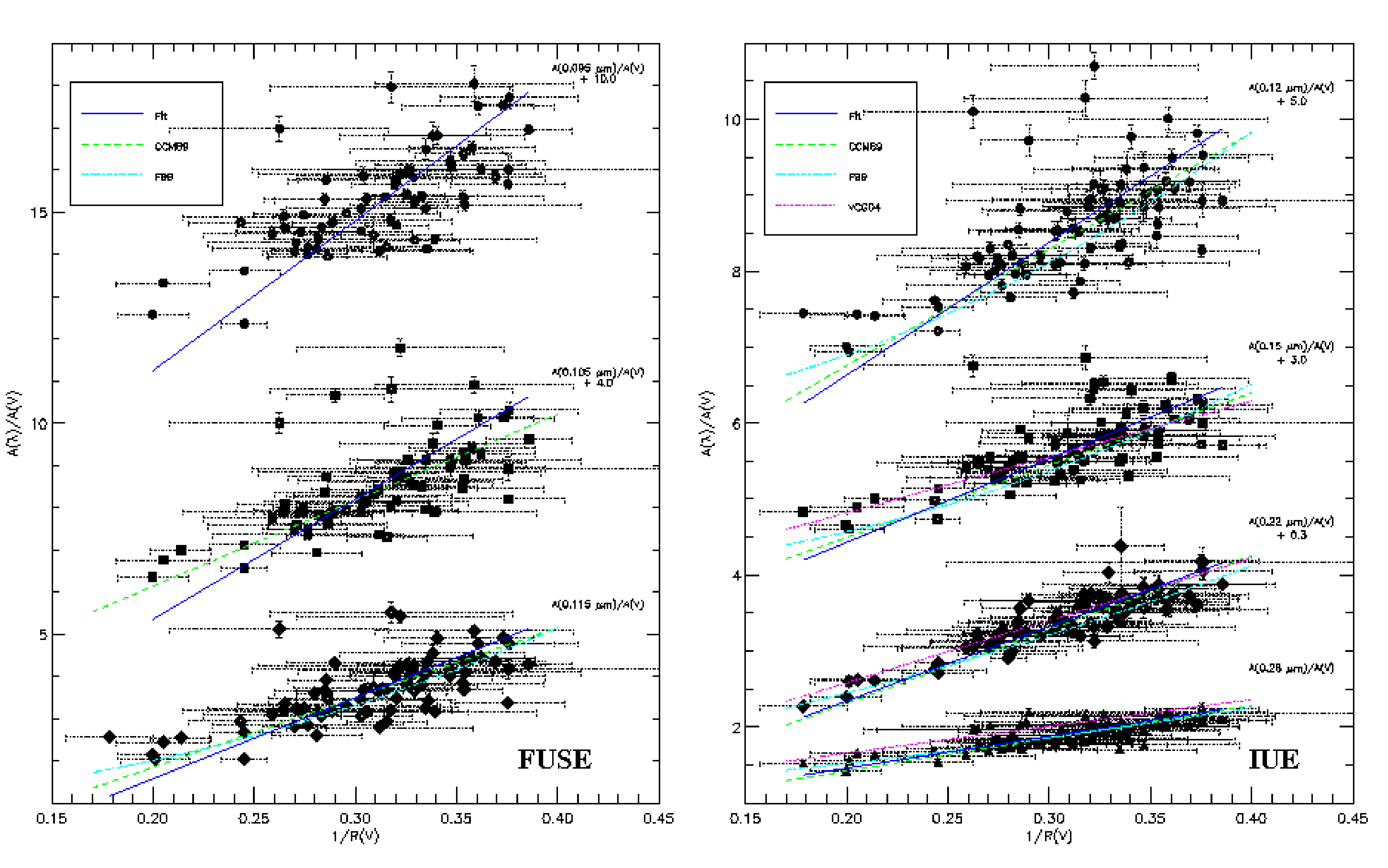
Jason A. Cardelli, Geoffrey C. Clayton, and John S. Mathis
Wasburn Observatory, University of Wisconsin-Madison
*Received 1989 January 12; accepted 1989 March 24*



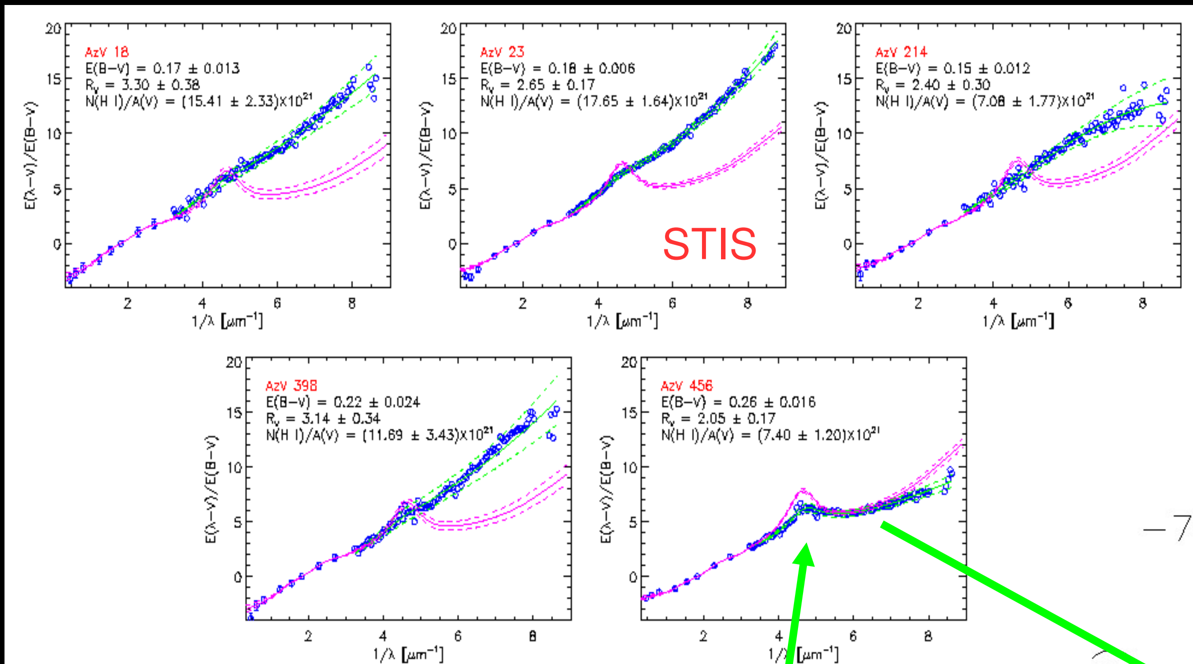



# Far-UV R(V) Dependent Relationship with FUSE



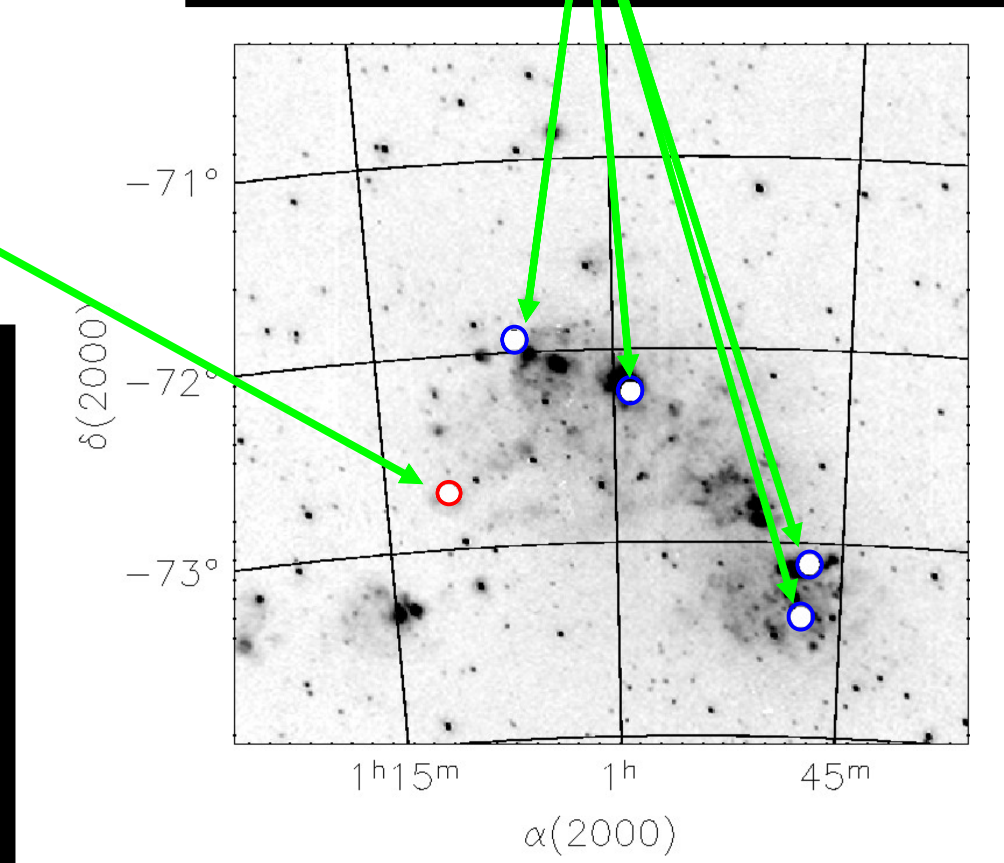

Gordon, Cartledge, & Clayton (2009, ApJ, submitted)

# Small Magellanic Cloud Extinction Curves




4 similar curves are found in the star forming bar of the SMC!

**Milky Way-like!**
**(2175 Å bump)**

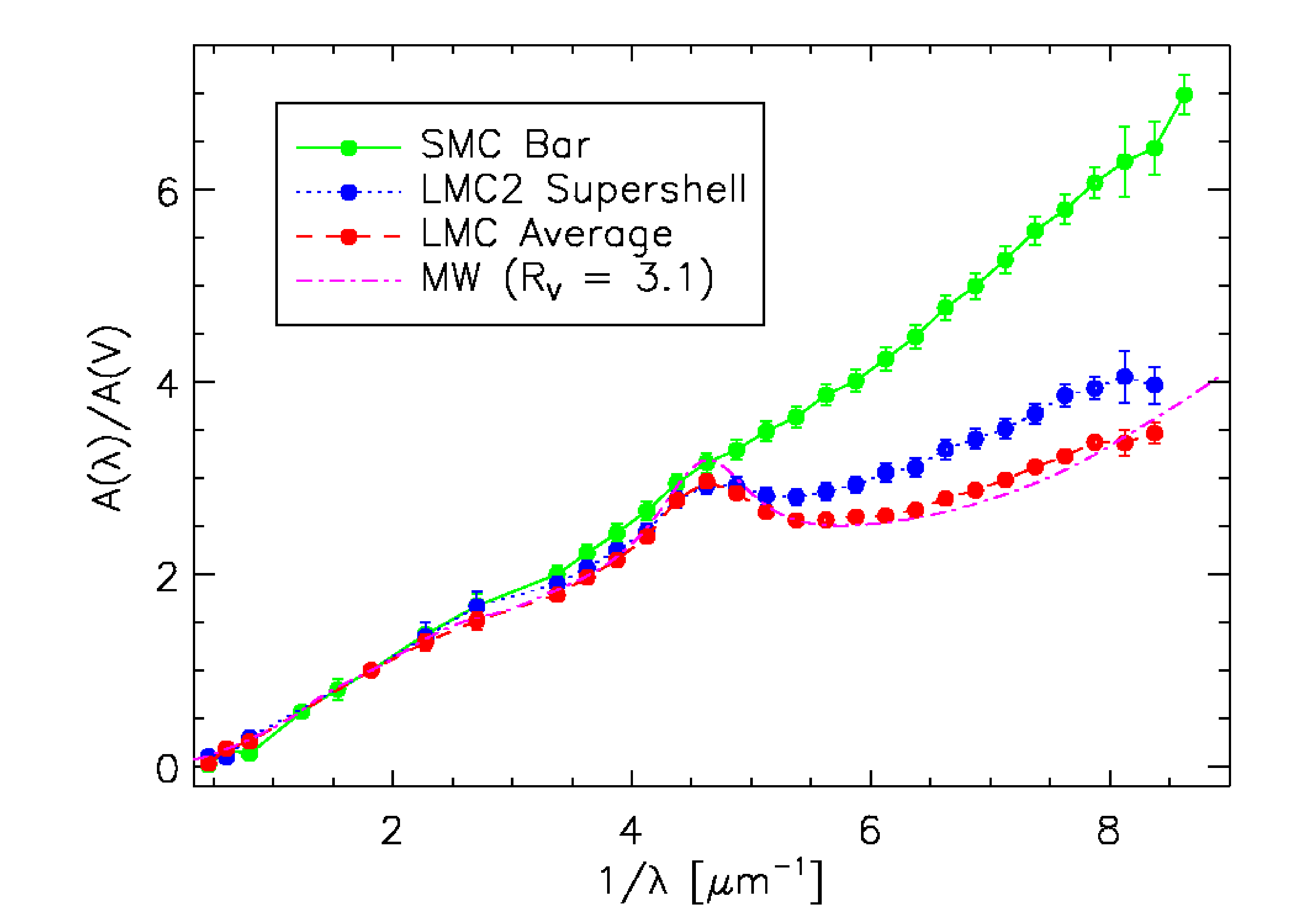



Hα image of the SMC

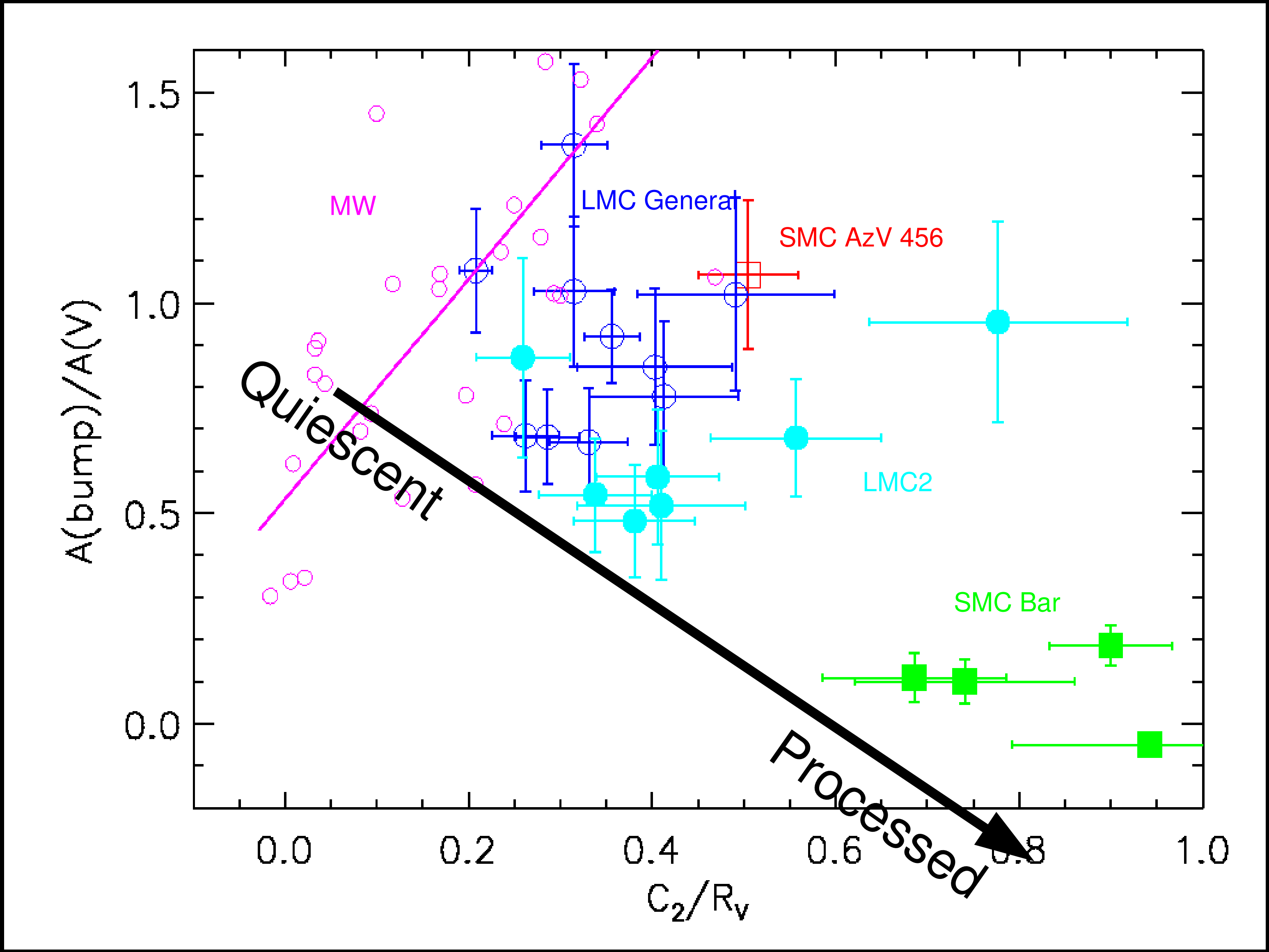
Gordon & Clayton (1998, ApJ, 500, 816)
Gordon et al. (2003, ApJ, 594, 279)

# Local Group Extinction Curves

- Does the known extinction curves in the Milky Way, Large Magelllanic Cloud, and Small Magellanic Cloud support nearby star formation suppressing 2175 Å bump?
- SMC? Yes.
  - absent 2175 Å bump in star forming Bar, strong 2175 Å in Wing
    - Gordon & Clayton, 1998, ApJ, 500, 816
- LMC? Yes.
  - weaker 2175 Å bump near LMC-2 supershell (in 30 Dor region)
    - Misselt, Clayton, & Gordon 1999, ApJ, 515, 128
- MW? Yes.
  - weak 2175 Å along low density sightlines with evidence for processing
    - Clayton, Gordon, & Wolff 2000, ApJS, 129, 147
  - absent 2175 Å bump once foreground subtracted from HD 204827
    - Valencic, Clayton, & Gordon 2003, ApJ, 598, 369

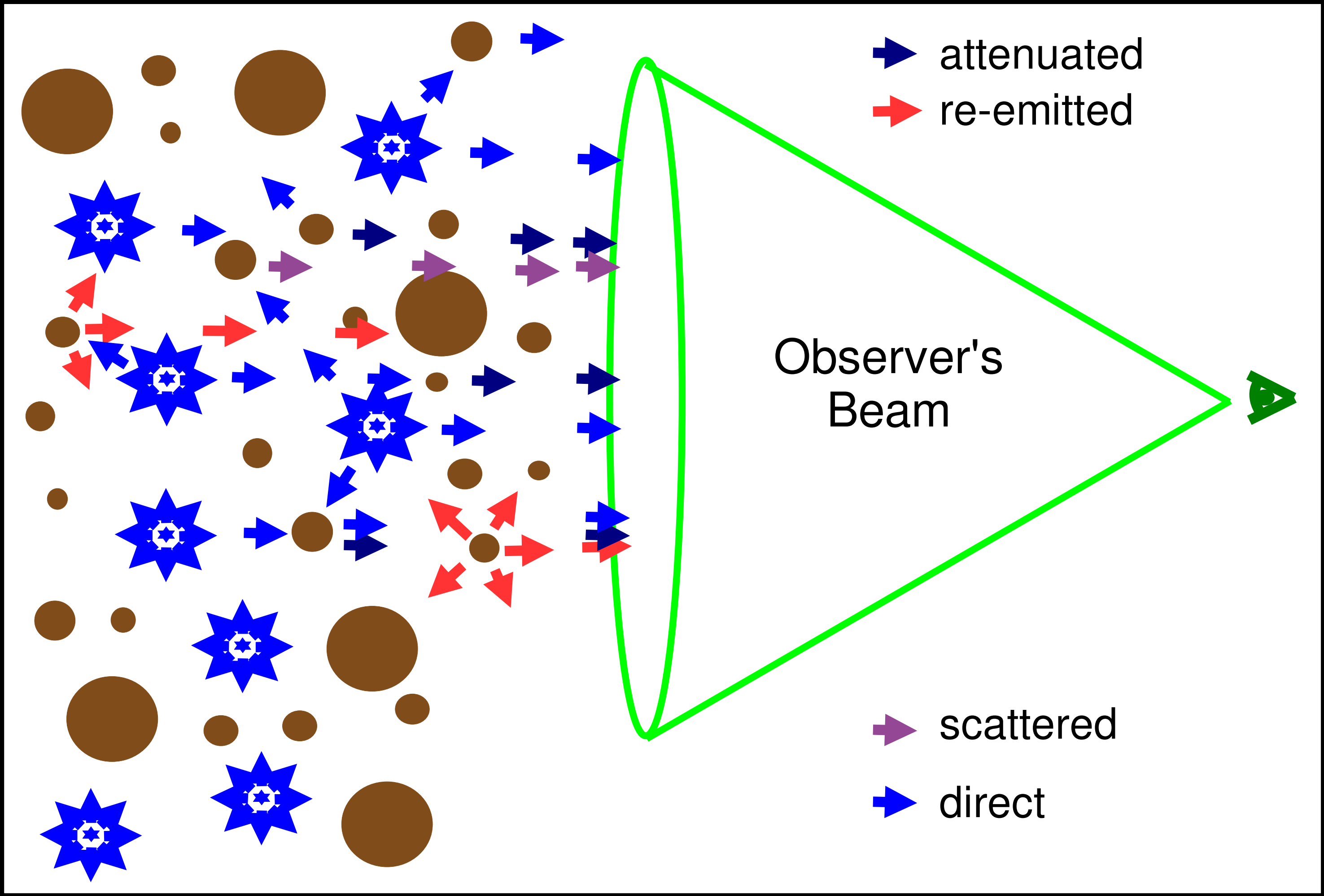

SMC Bar
LMC2 Supershell
LMC Average
MW ($R_V$ = 3.1)
A(λ)/A(V)
1/λ [μm$^{-1}$]
0
2
4
6
8

# Known UV Extinction Curves:
## Continuum of Properties




Gordon et al. (2003, ApJ, 594, 279)

# Mixed Stars & Dust




- Observations in beam includes multiple stars attenuated by differing amounts of dust and dust scattered starlight
- Least attenuated stars contribute the most light
- Scattered light included in the beam (reduces attenuation)
- Attenuation is now dependent on both the dust grain properties and the geometry of the stars/dust

# Empirical Starburst Attenuation Curve

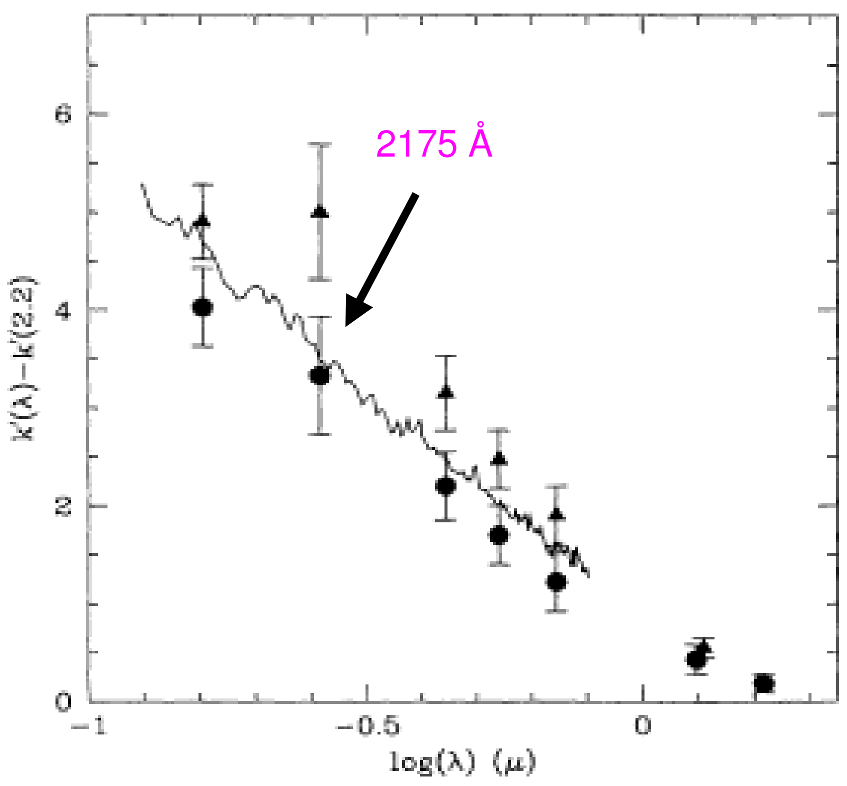
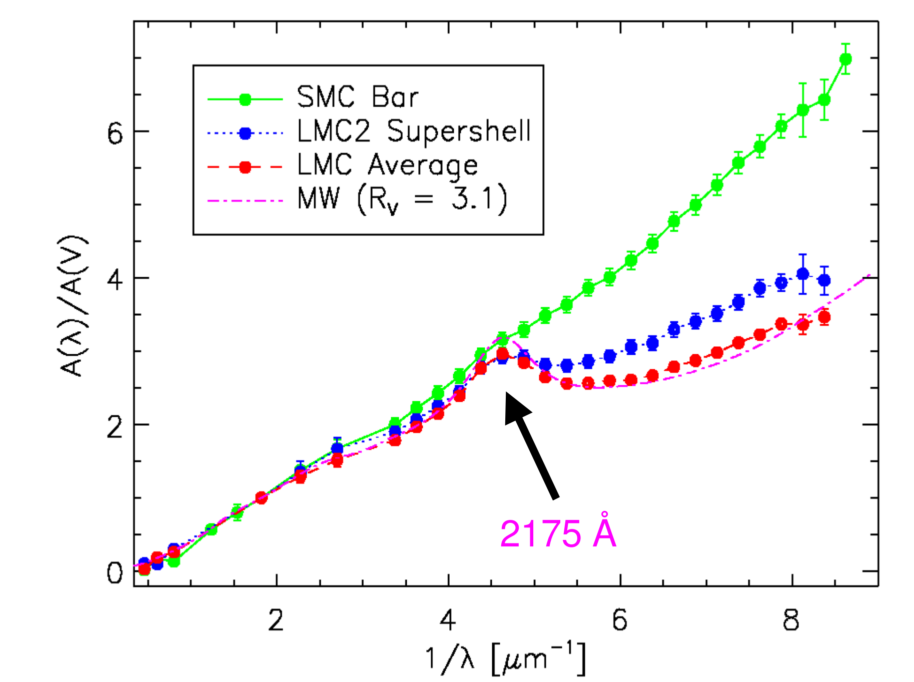



FIG. 6. The obscuration curve derived from the stellar continuum flux densities of the starburst galaxies in the sample. The vertical axis shows the difference $k'(\lambda)-k'(2.2)$, where the $K$-band (2.2 $\mu$m) flux densities are the selected reference values. The horizontal axis is $\log\lambda(\mu m)$. The filled circles are from the $E(B-V)_{H\alpha/H\beta}$ fits; the filled triangles are from the $E(B-V)_{H\beta/Br\gamma}$ fits. The $1\sigma$ uncertainties are reported. The obscuration curve derived by CKS94 is overlapped, with the $V$-band value arbitrarily chosen to be $k'(0.55)-k'(2.2)=2$ (continuous line).

Starbursts = no 2175 Å bump

Almost all known extinction curves show a 2175 Å bump.

Only SMC does not - but this is usually attributed to metallicity




Calzetti et al. 1994, ApJ, 429, 582 and Calzetti 1997, AJ, 113, 162

# The DIRTY Model

DIRTY = DustI Radiative Transfer, Yeah!

Monte Carlo Techniques for the Radiative Transfer

II

Arbitray Geometries of
photon emitters (stars & gas)
and
photon scatterers and absorbers (dust)

and

Analytic Techniques for the Dust Emission

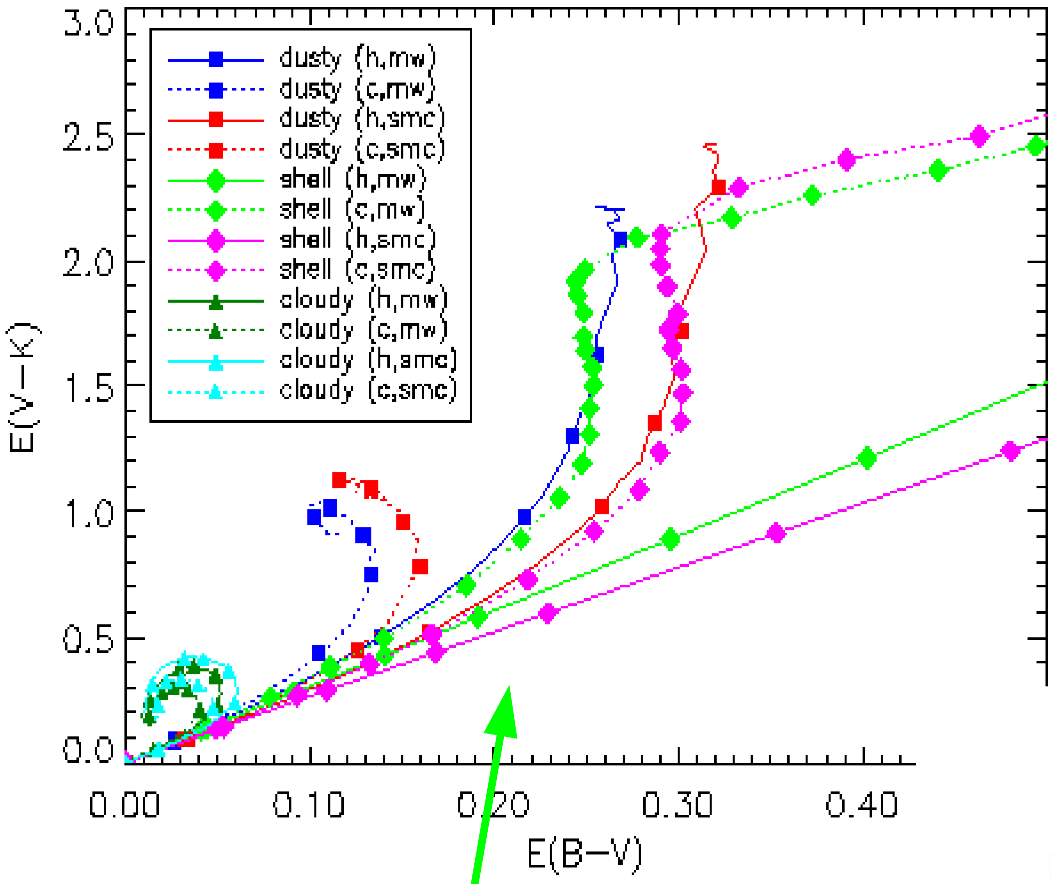
II

Equilibrium heating (large grains)
Non-equilibrium (transient) heating (small grains)
Aromatic features (molecules - large PAHs?)

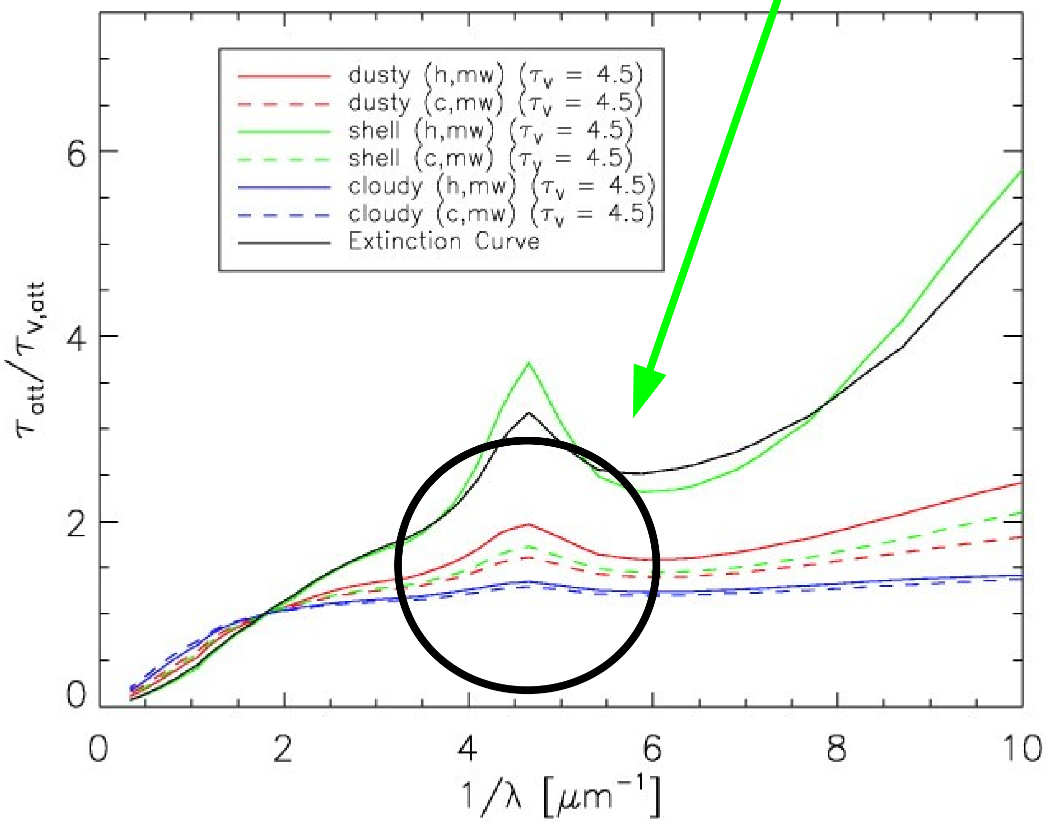
Gordon, Misselt, Witt, & Clayton (2001, ApJ, 551, 269)
Misselt, Gordon, Clayton, & Wolff (2001, ApJ, 551, 277)

# Radiative Transfer Effects

Witt & Gordon (1996; 2000)

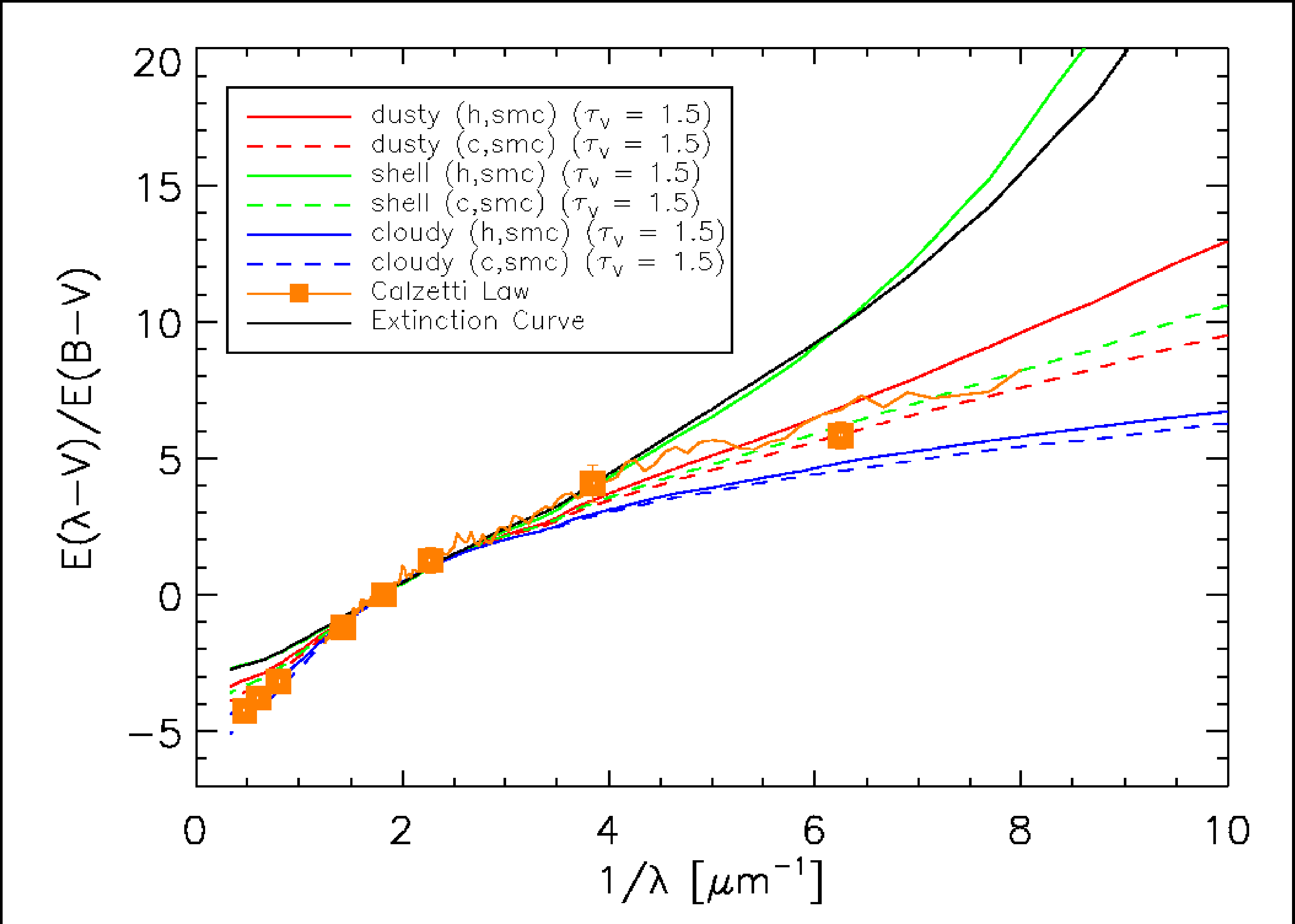



Shape of attenuation curves not constant, but depends on the geometry as well as the dust type. 2175 Å bump can be suppressed, but with the result of gray UV extinction



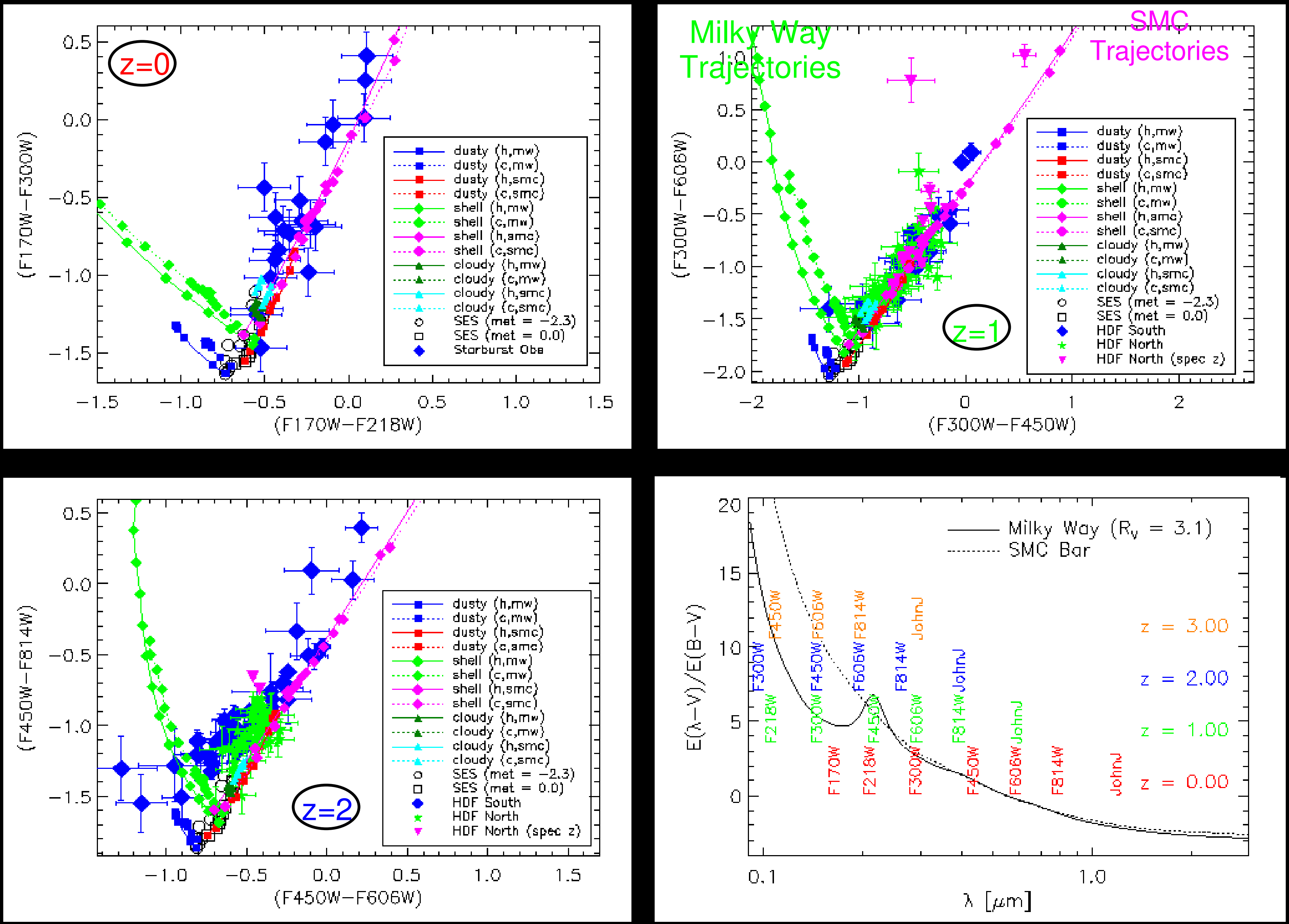

Affects of dust now reddening trajectories instead of reddening arrows. Dependent on star/dust geometry, amount of dust, and clumpiness of dust, instead of just type of dust

# Calzetting Law is clumpy SHELL with τ(V) = 1.5 SMC Dust




Witt & Gordon ( 2000)

# Dust in Starburst Galaxies
# z=0-2




Gordon, Smith, & Clayton (1997, ASP Conf. Proc. v. 193, 517)

# “High” redshift galaxies

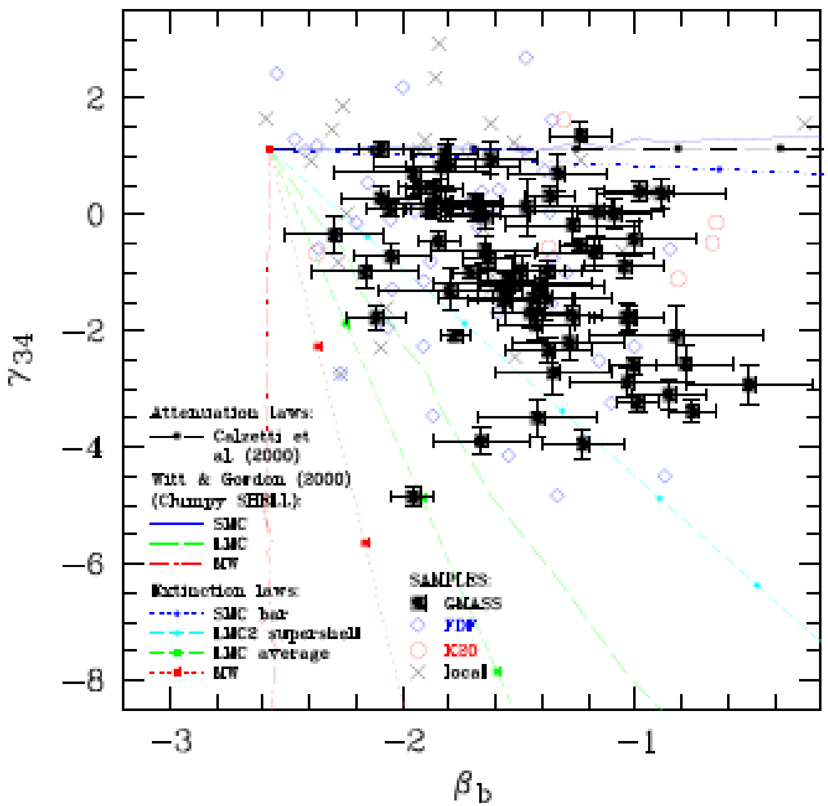



**Fig. 3.** The UV-bump indicator $\gamma_{34}$ versus the UV reddening measure $\beta_{\rm b}$ for the GMASS (filled squares), FDF (open lozenges), and K20 galaxies (open circles) at $1.5 < z < 2.5$, and a comparison sample of 24 local starburst galaxies (crosses; see NP05). The diagram also shows different dust attenuation models (see legend) for a Maraston (2005) model with Salpeter IMF, continuous SF, an age of 100 Myr, and solar metallicity. The symbols are plotted in intervals of $\Delta E_{B-V} = 0.1$. A Maraston model with a SF $e$-folding time of 3 Gyr and an age of 3 Gyr would produce intrinsically redder continua and, thus, would slightly shift the plotted model curves by 0.20 to the right and by 0.08 to the top.

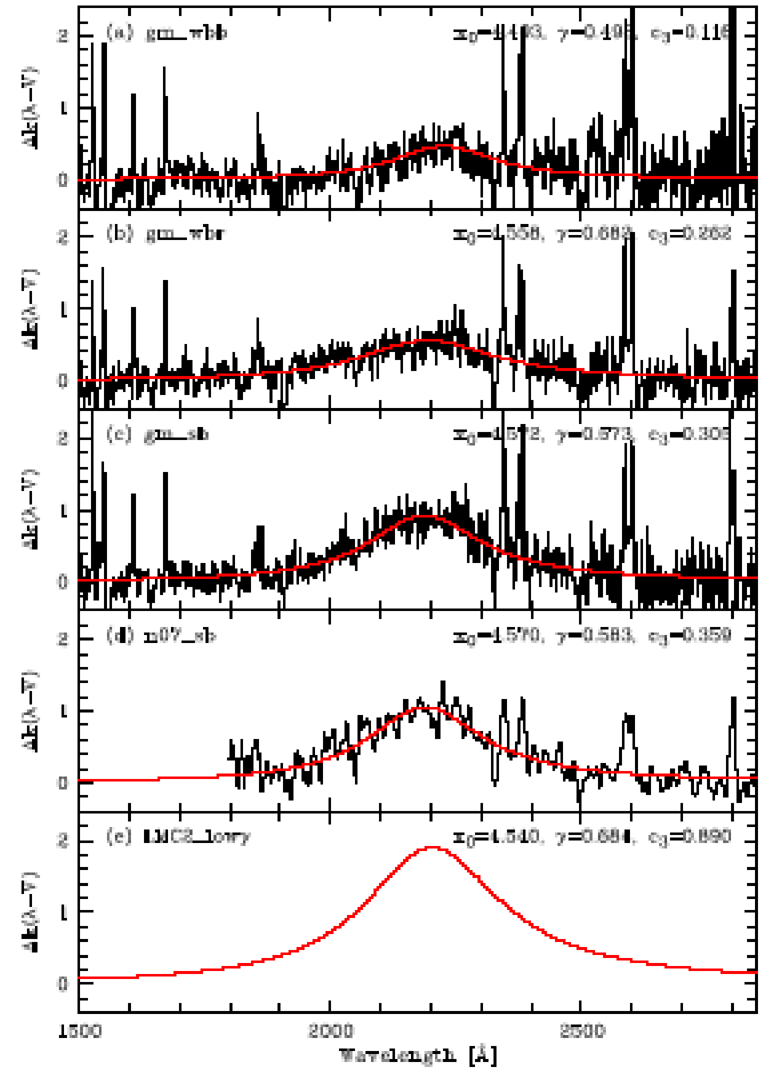



**Fig. 7.** Best Lorentzian fits of the bump component of the average extinction curves of the three GMASS subsamples at $1.5 < z < 2.5$ (a - c) and a subsample of FDF and K20 galaxies at $1.0 < z < 1.5$ with $\gamma_{34} < -2$ (d). Moreover, the average 2175 Å bump of a sample of measurements in the LMC 2 supershell region close to 30 Dor showing low $\gamma$ is presented (e). More details about the samples and the fits can be found in Table 2.

Noll, Pierini, et al. 2009, A&A, 499, 69

# Gravitational Lensed QSOs

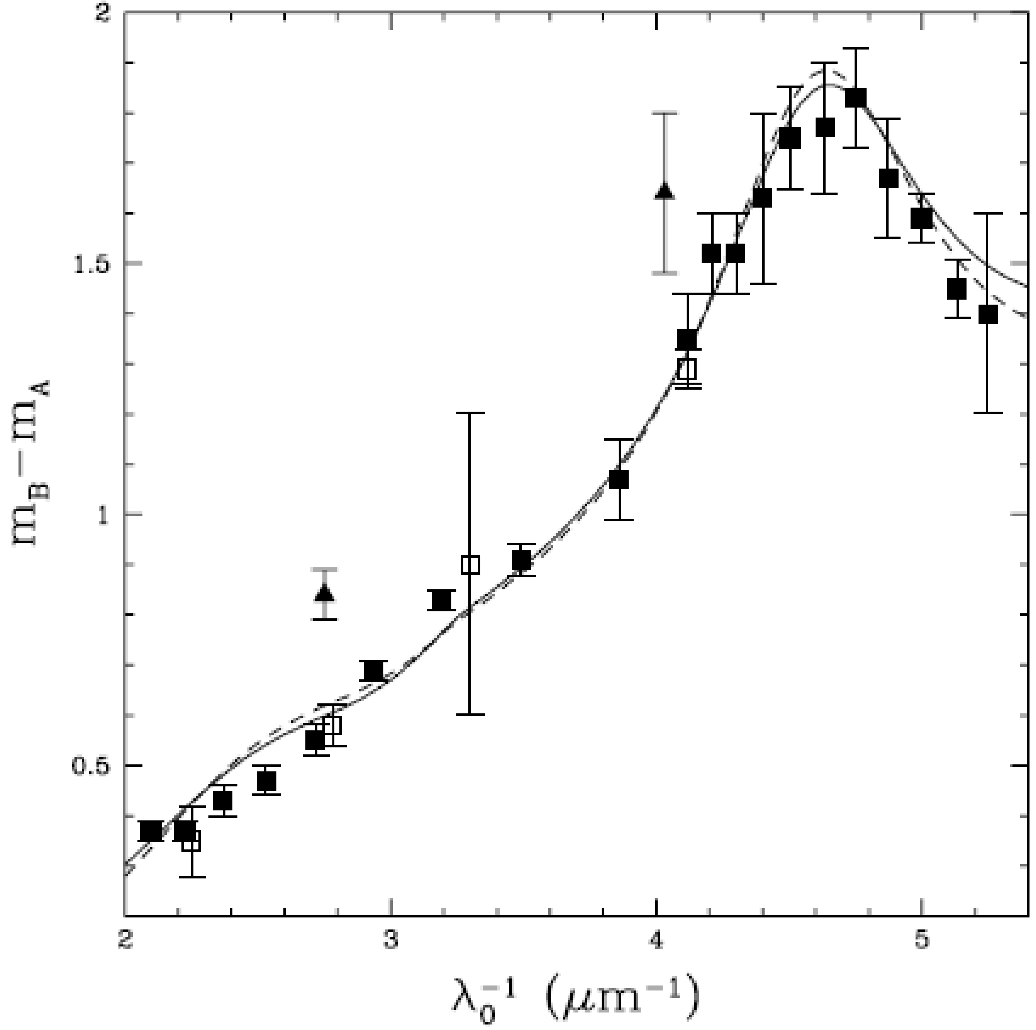



FIG. 4.—*Filled squares*: Magnitude differences ($m_B - m_A$) obtained from continuum images as a function of inverse wavelength in the lens galaxy rest frame. *Open squares*: *B*, *V*, *R*, and *I* broadband observations (Kochanek et al. 1997; Lehár et al. 2000). *Solid line*: Best fit of the analytical average MW extinction law to the observed extinction curve (*filled squares*) for a fixed $z = 0.83$. The values $R_V = 2.1 \pm 0.9$ and differential extinction $E(B-V) = 0.21 \pm 0.02$ were obtained in the fit. *Filled triangles*: $m_B - m_A$ differences computed from the emission in the Mg II and C III lines. *Dashed line*: Best fit for $R_V = 3.1$.

Motta et al. 2002, ApJ, 574, 719

Gravitational lens
SBS 0909+532 z = 0.83
QSO at z= 1.38

(Difference between two extinction curves,
McGough et al. 2005, ApJ, 624, 118)

# Gamma Ray Bursts

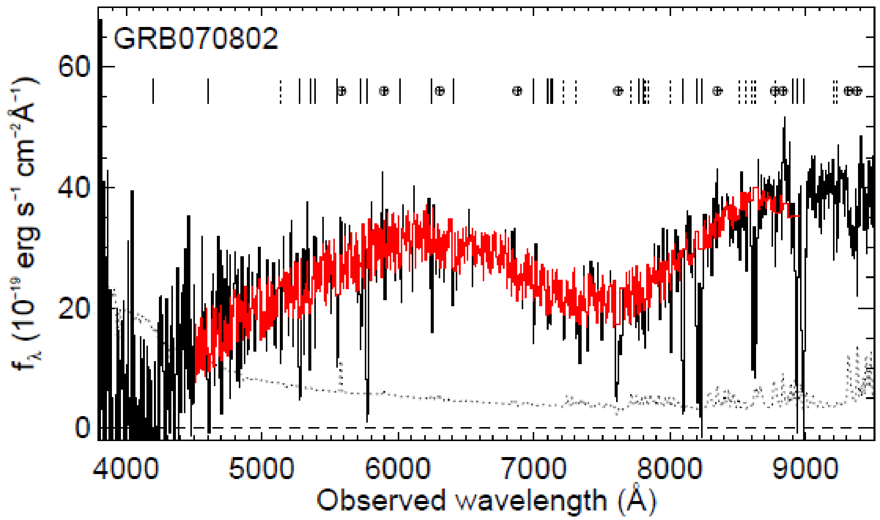
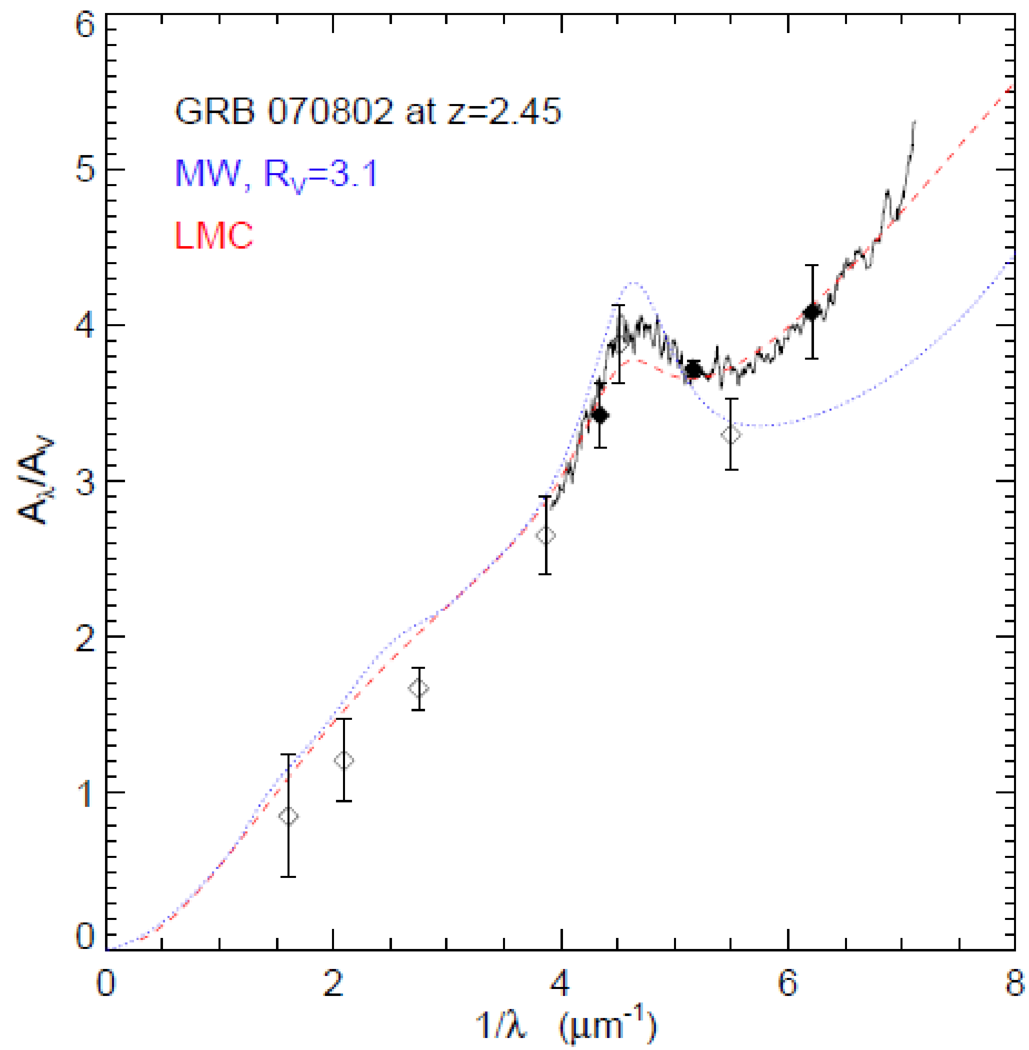


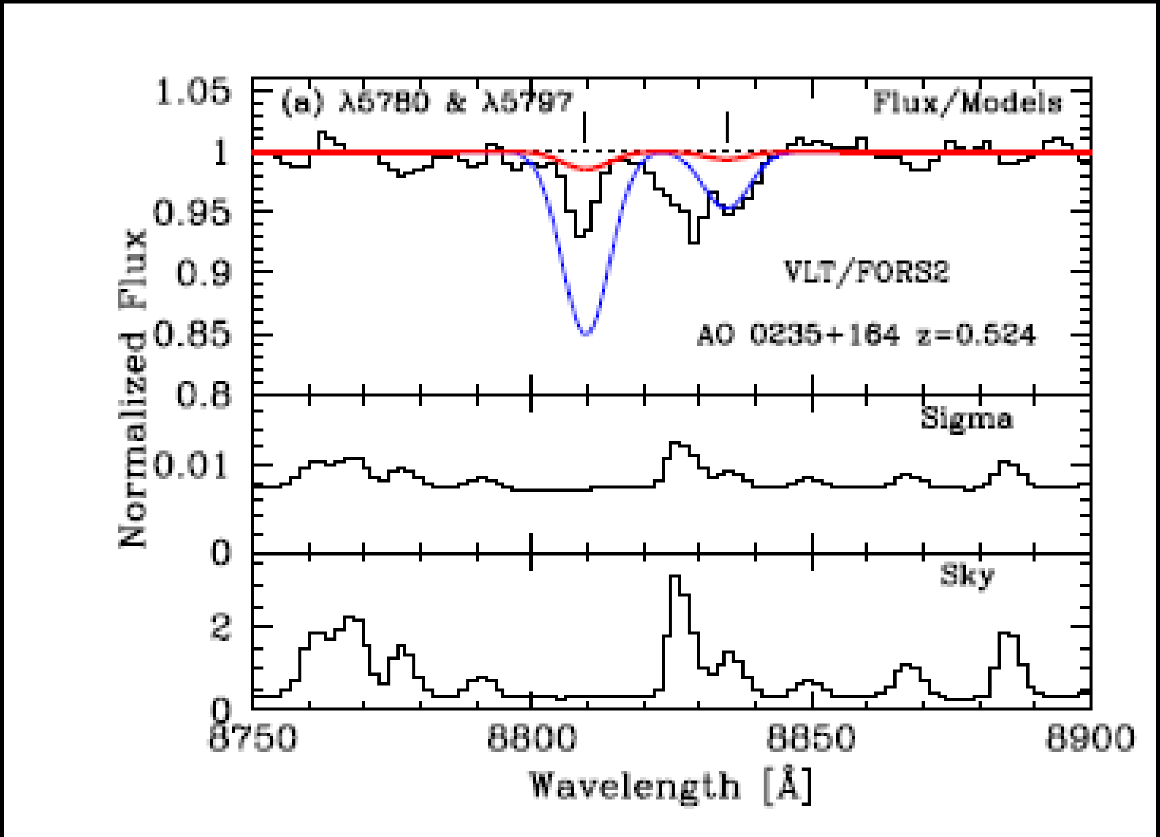

FIG. 1.— The flux-calibrated spectrum of the GRB 070802 afterglow vs. observed wavelength. Metal lines at the host redshift are marked with solid lines whereas the lines from the two intervening systems are marked with dotted lines. The broad depression centered around 7500 Å is caused by the 2175 Å extinction bump in the host system at $z_{\rm abs} = 2.4549$. The cleaned spectrum used for the extinction curve analysis in § 3 is overplotted in red. Telluric features are indicated with ⊕.




Eliasdottir et al. 2009, ApJ, 697, 1725

# Extragalactic DIBs

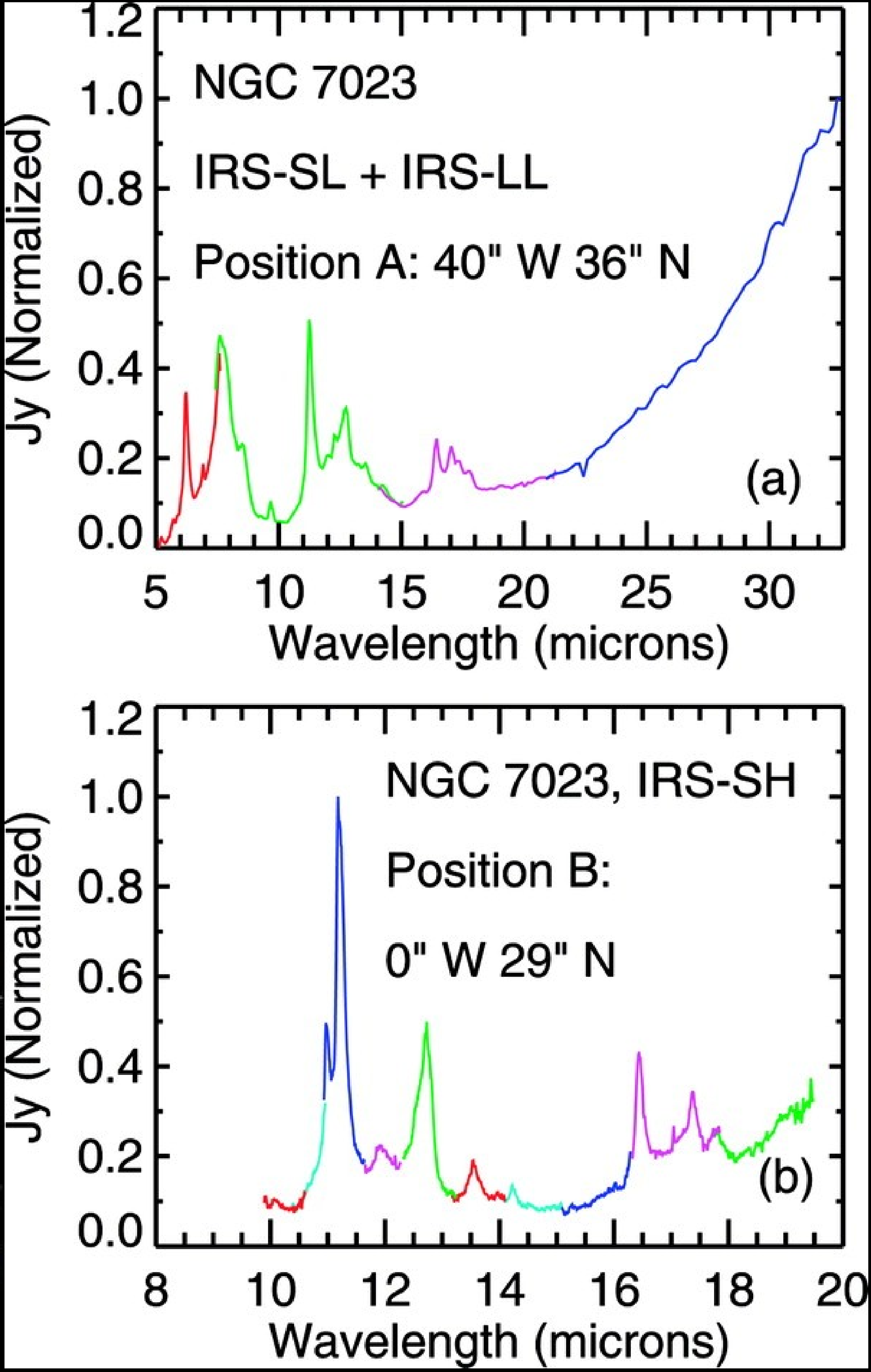
LMC/SMC DIBs
show variations similar
and correlated with
UV properties
(Cox et al. 2006, 2007)




Lawton et al. 2008, AJ, 136, 994

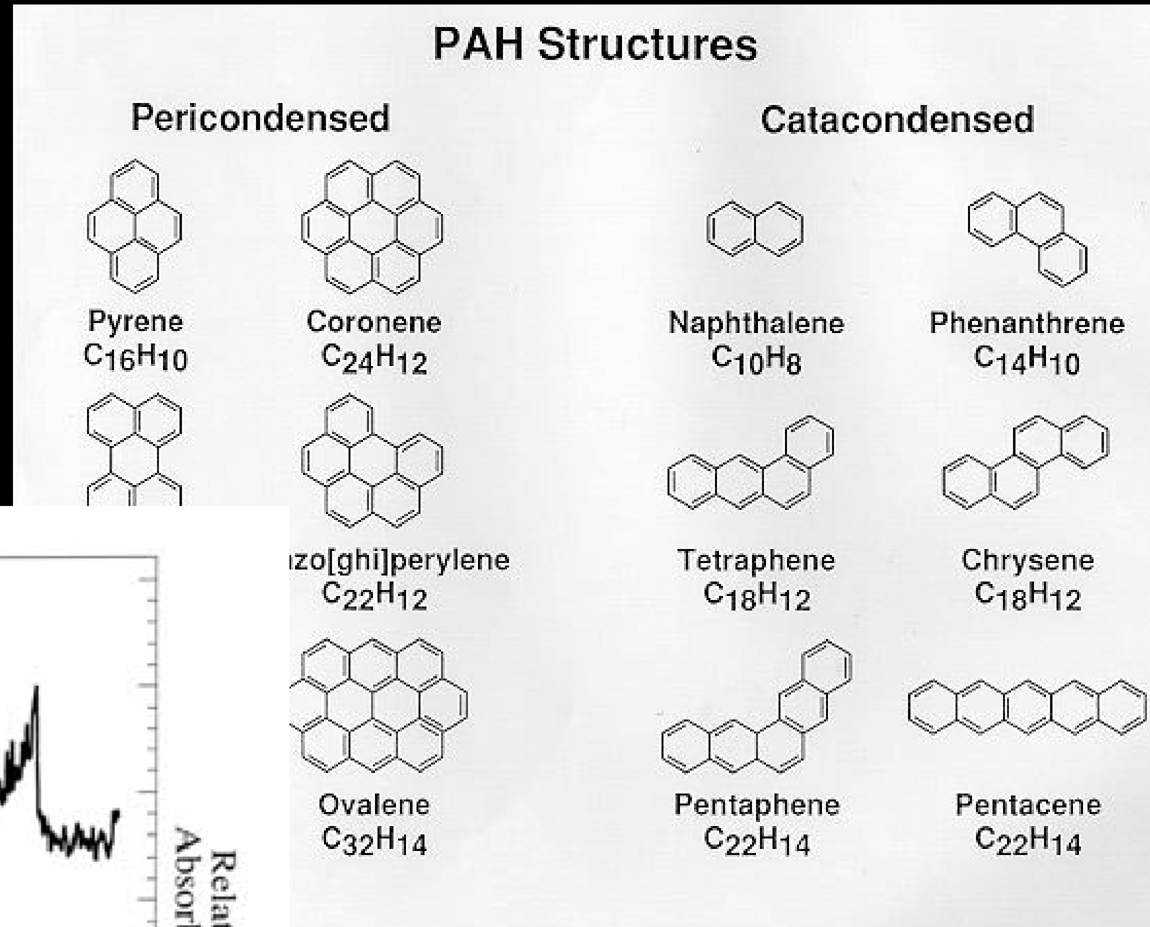
# What are the Aromatic Features?

- Emission features seen in many dusty astrophysical objects
- Main features at 3.3, 6.2, 7.7, 8.6, 11.3, 17.0 μm
- Spectrum of NGC 7023 – bright reflection nebula often observed for dust emission




Werner, M. et al. 2004, ApJS, 154, 309

# Polycyclic Aromatic Hydrocarbons



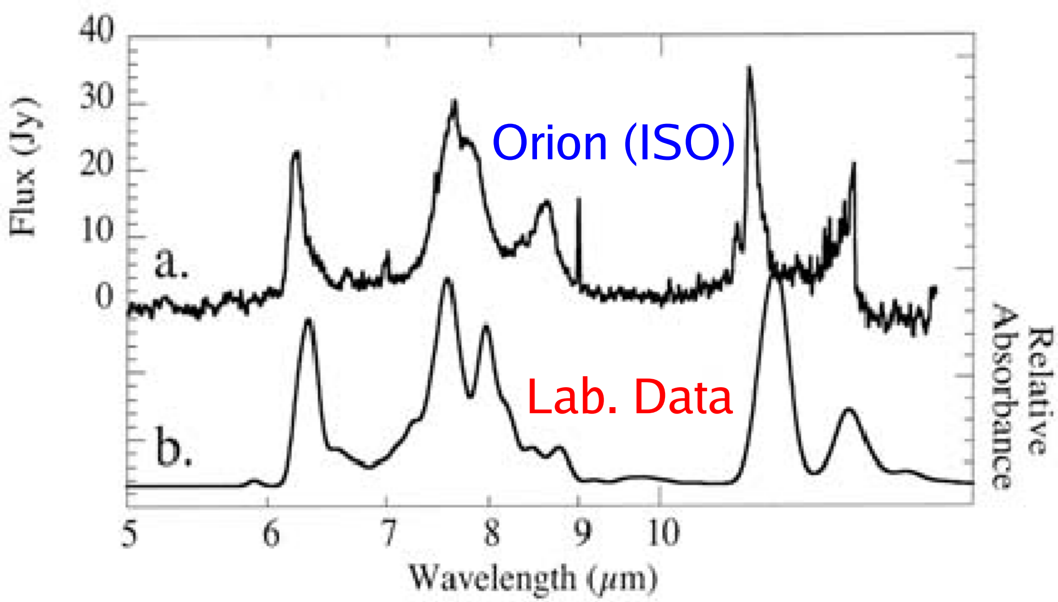
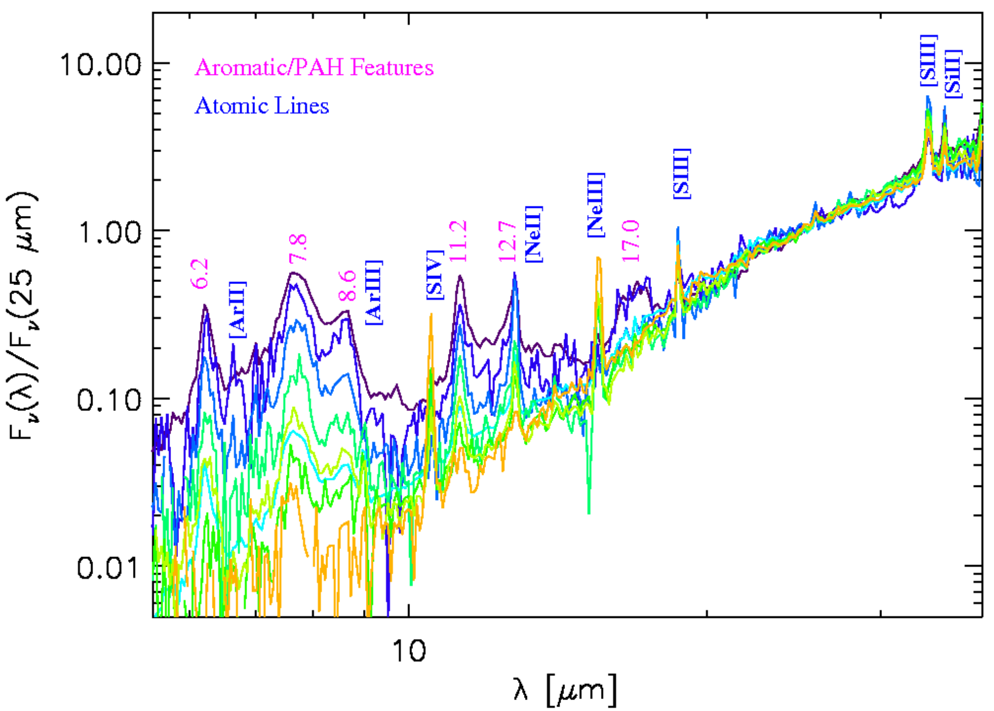



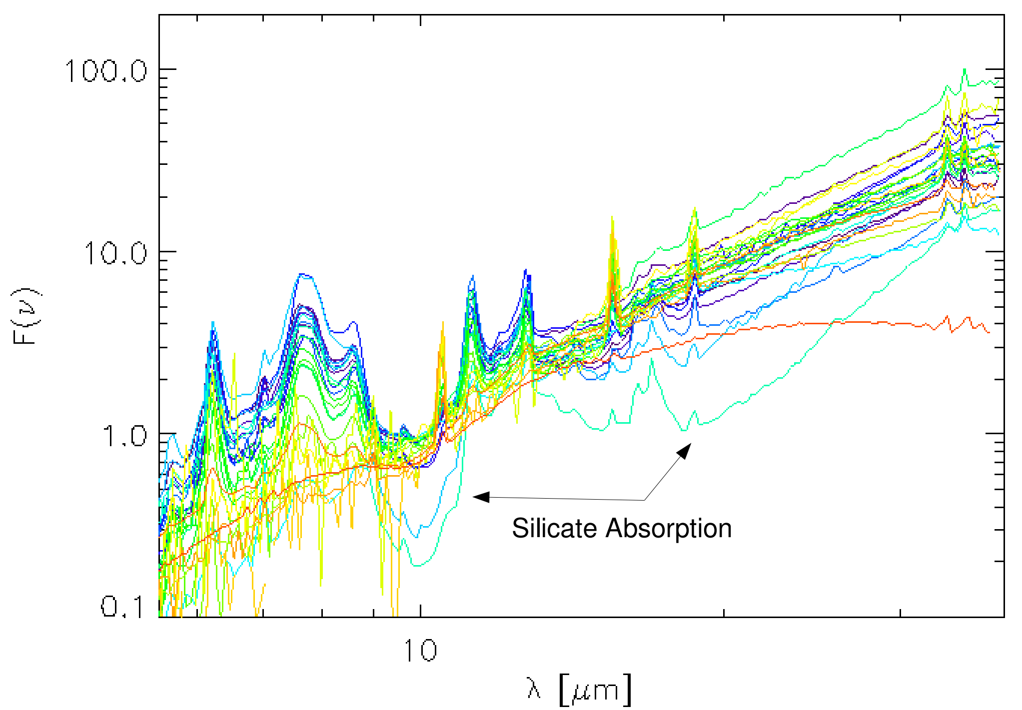

Figure 5. A comparison of a simple visual fit consisting of the coadded spectra of 11 neutral and ionized PAHs to the IR emission spectrum of the Orion ionization ridge (trace a). The model illustrates that the concerted emission of mixtures of neutral and ionized PAH species can accommodate all the salient features of the interstellar spectrum. The composition of the model spectrum and the details of the modeling procedure can be found elsewhere (Allamandola, Hudgins, & Sandford 1999; Peeters et al. 2002). The Orion spectrum was measured by the ISO SWS instrument and is adapted from Peeters et al. (2002).

Hudgins, D. M. & Allamandola, L. J.
Astrophysics of Dust,
ASP Conference Series, Vol. 309,
Eds. Adolf N. Witt, Geoffrey C.
Clayton and Bruce T. Draine., 665

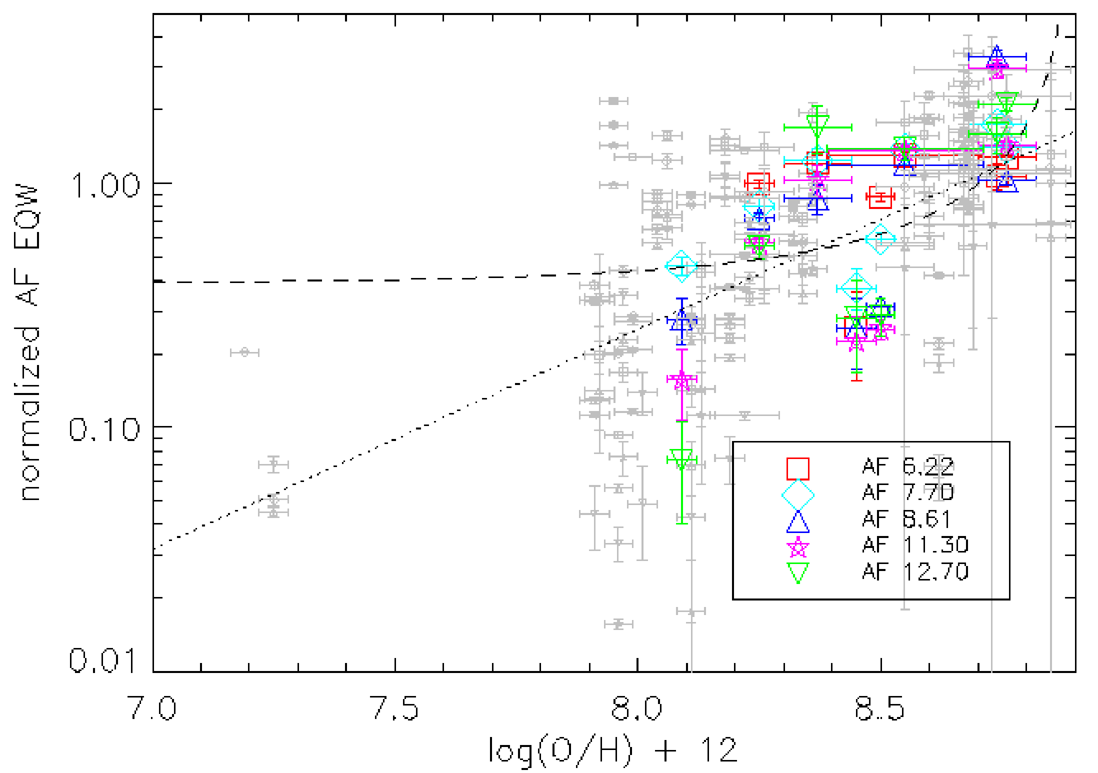
# M101 & Starburst Galaxies with Spitzer/IRS

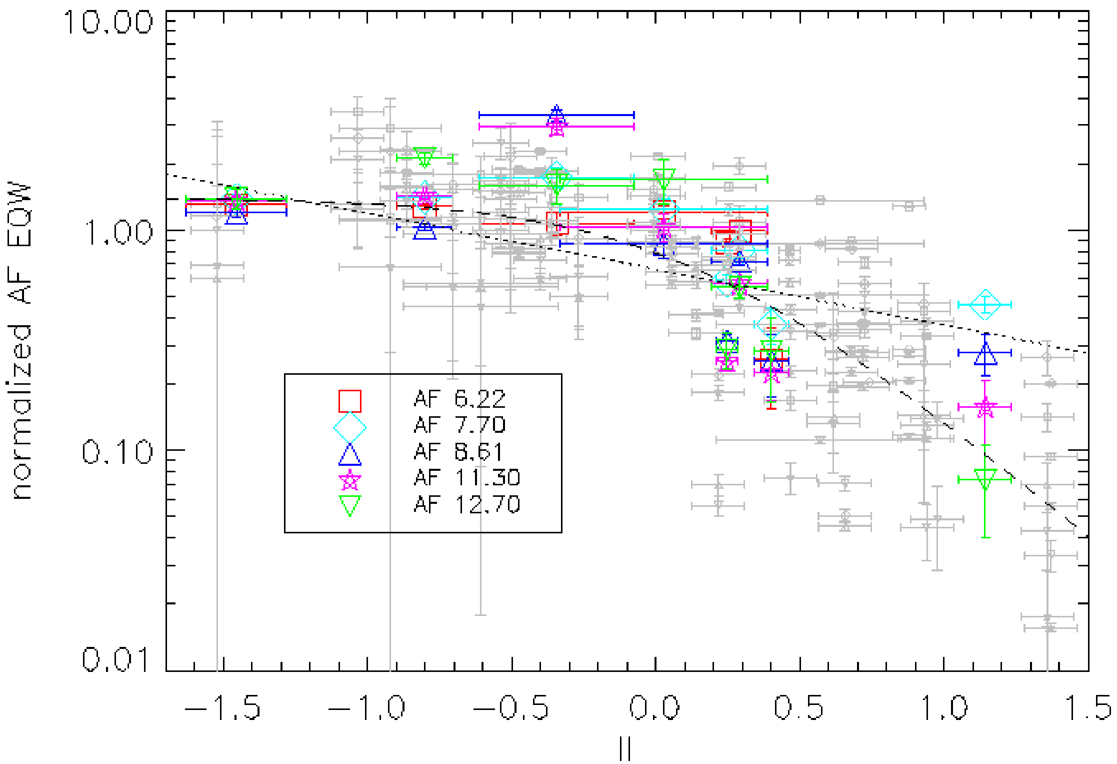
- M101
  - Observed in cluster mode with small spectral maps
  - Reduced using CUBISM (JD Smith)
  - All 6 IRS low-res orders merged
  - Expanding aperture used for extraction
- Starbursts
  - Observed with simple staring observations
  - Reduced using SPICE and IRAF
  - All 4 main IRS low-res orders merged
  - Full slit extraction



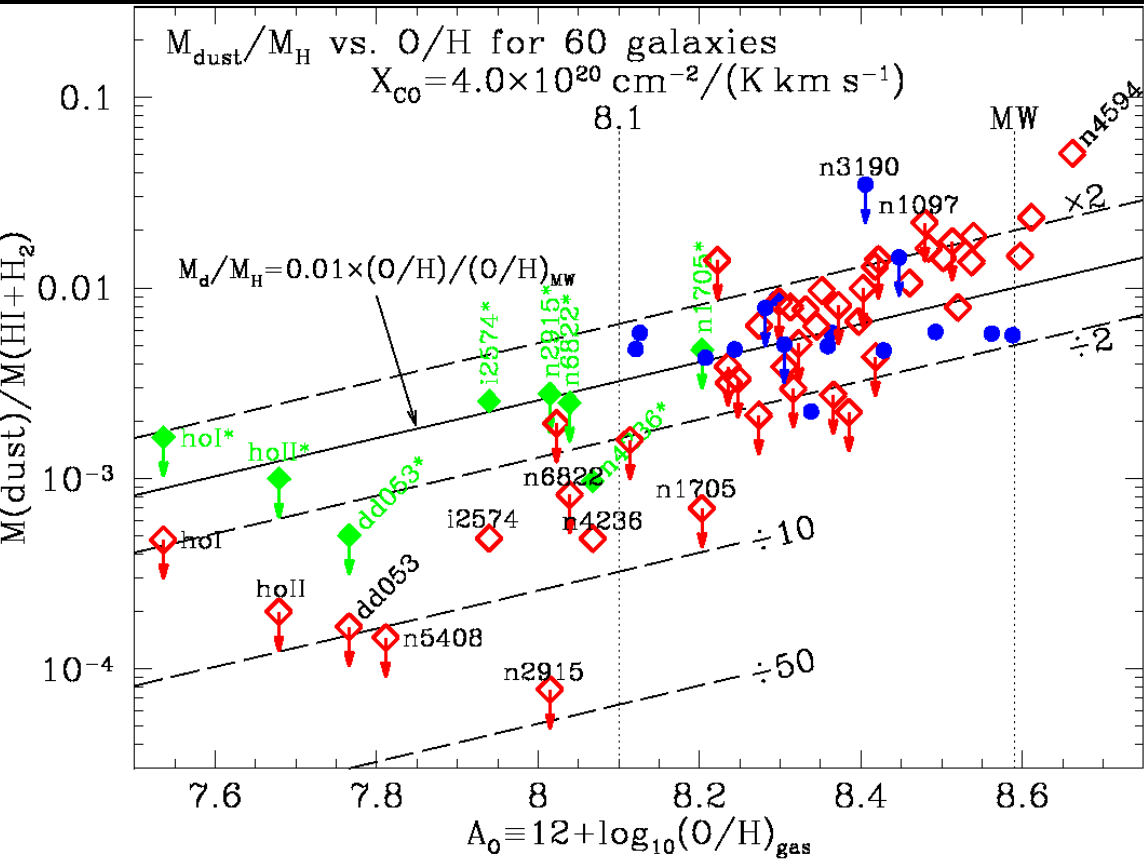
# M101 HII Region and Starburst Nuclei Normalized Equivalent Widths of Aromatics



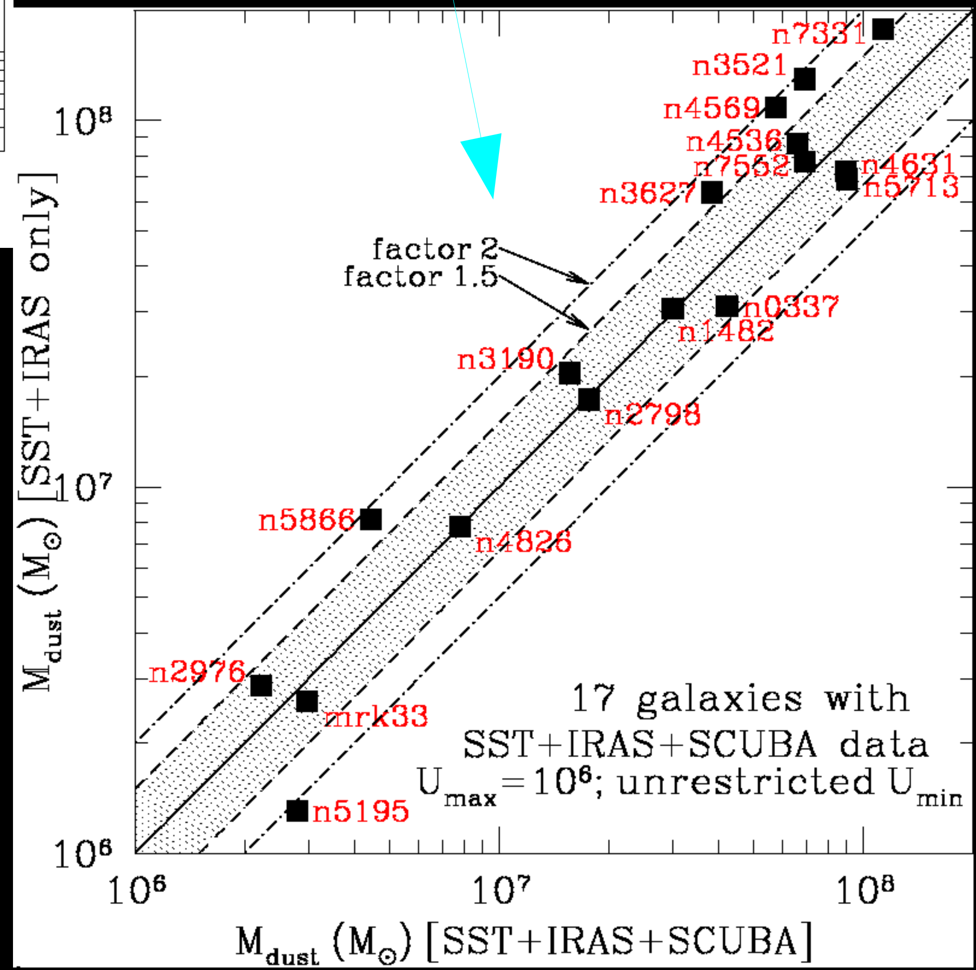

Starbursts also show better correlation with II, but with more scatter.

M101 measurements and plot from:
Gordon, K. D. et al. 2008, ApJ, 682, 336
Starburst mesurements from:
Engelbracht, C. E. et al. 2008, ApJ, 678, 804




# Modeling of Global SEDs

No need for large amounts of submm cold dust (within factor of 1.5-2)



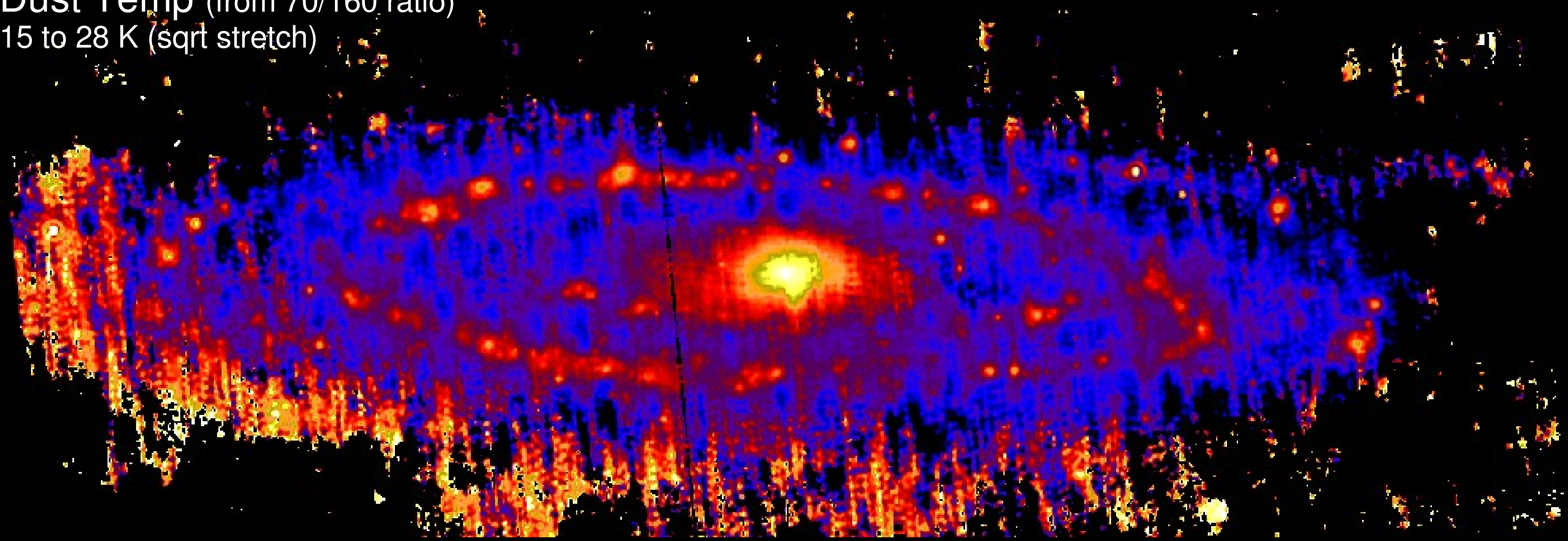

Draine et al. 2007, ApJ, 663, 866

# Magellanic Clouds

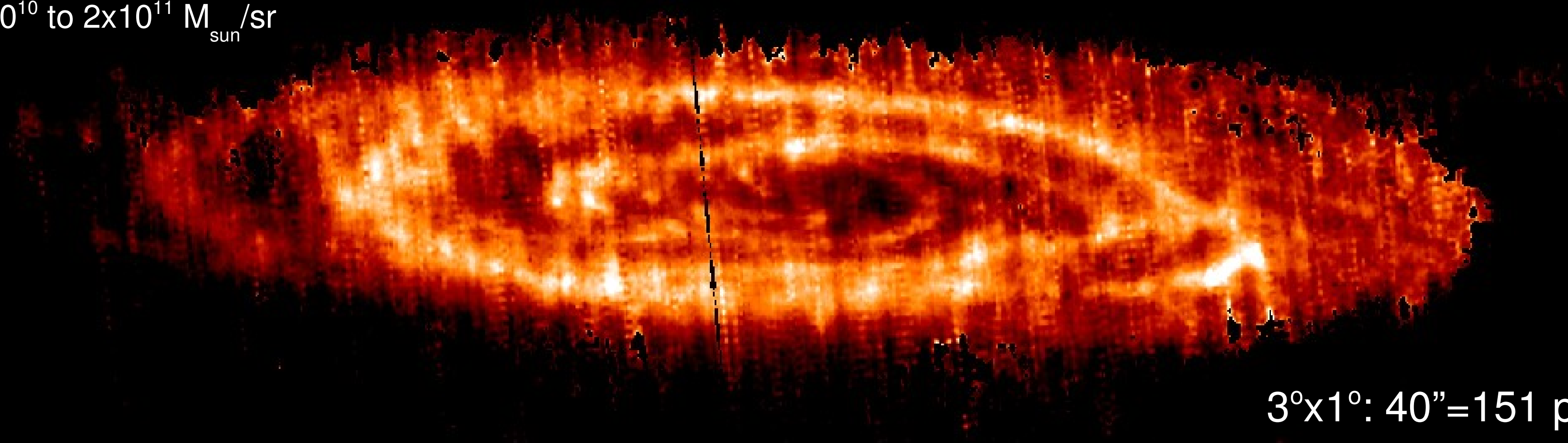
- Internal varations in gas-to-dust ratio by approx. a factor of 2
  - From the UV, N(HI)/A(V), Gordon et al. 2003
  - From the IR/radio in the LMC, Bernard et al. 2008
- Is lower than expected in the SMC based on metallicty
  - Metallicity 5x lower, IR/radio dust-to-gas ratio 12x lower (Body and Tail)
  - Bot et al. 2004, Gordon et al. 2009
- Local variations in gas-to-dust ratio tracking processing?
  - Tentative evidence from UV, Gordon et al. 2003

# M31

Dust Temp (from 70/160 ratio)
15 to 28 K (sqrt stretch)



Dust Mass
$1x10^{10}$ to $2x10^{11}$ $M_{sun}$/sr



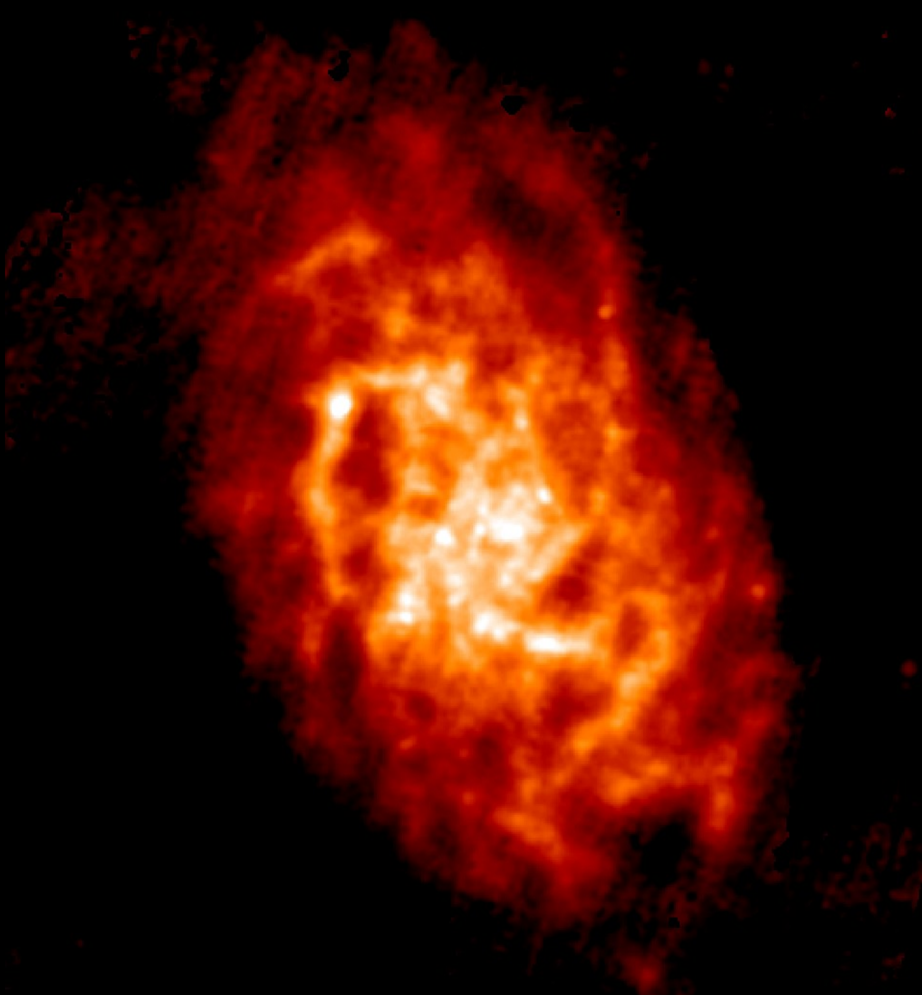
3°x1°: 40"=151 pc

MIPS/GTO observations (1 scan map); Gordon et al. 2006, ApJ, 638, L87 [later extended to 5°x1°]

# M33

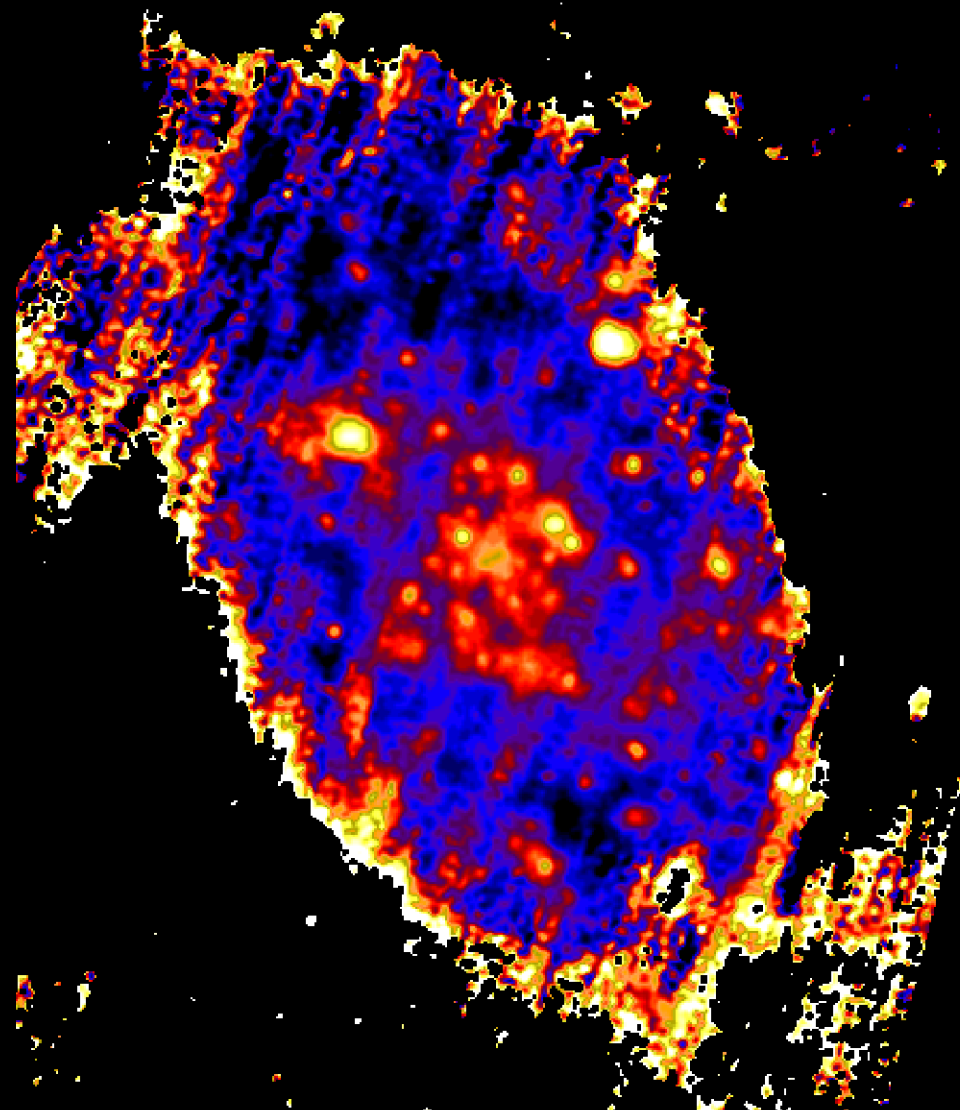
Dust Mass

$1x10^9$ to $1.5x10^{11}$ $M_{sun}$/sr



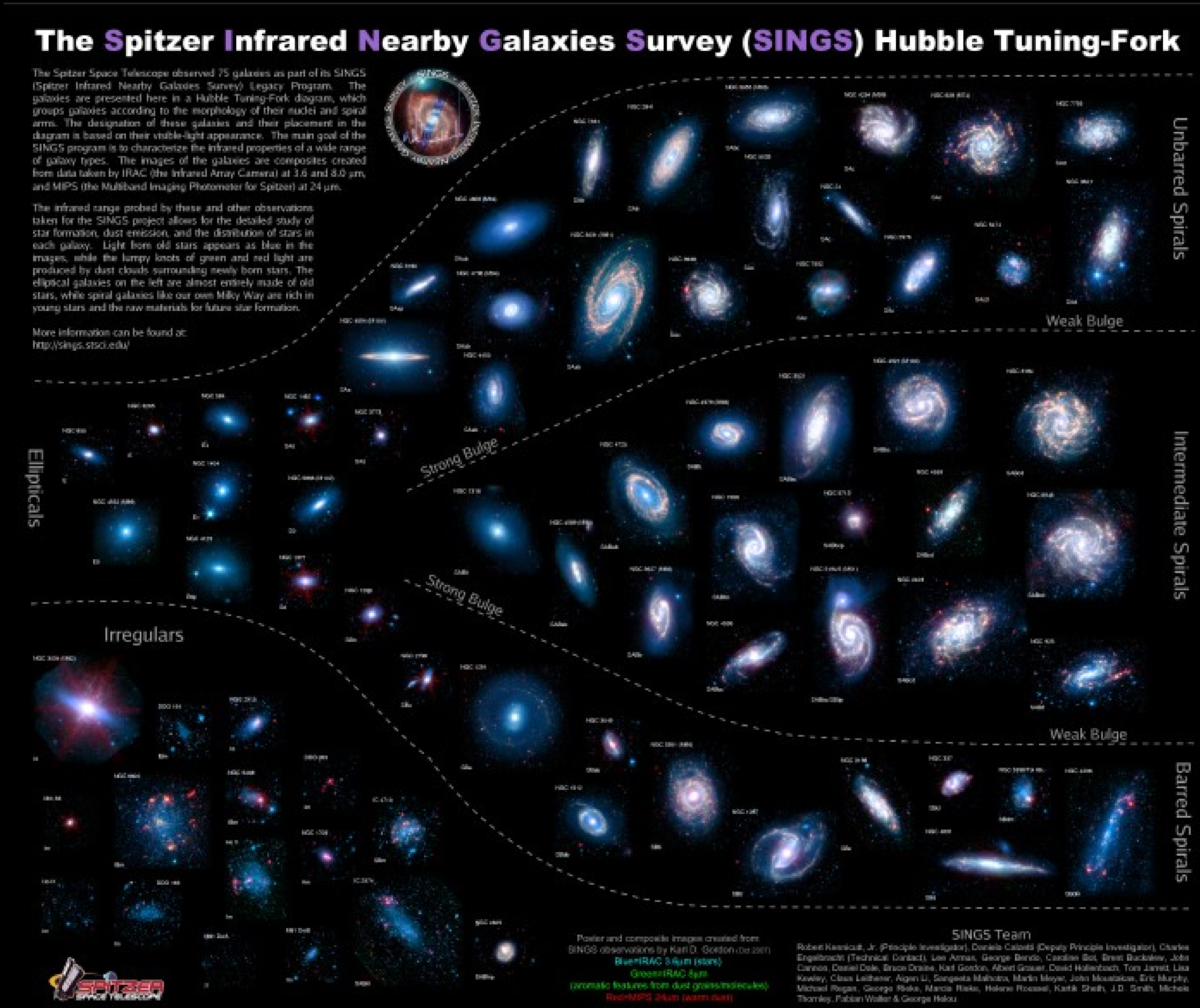
Dust Temp (from 70/160 ratio)

15 to 28 K (sqrt stretch)



1°x1.2°: 40" = 163 pc

GTO observations (4 scan maps); Tabatabaei et al. 2007, A&A, 466, 509


The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 µm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 µm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Unbarred Spirals
Weak Bulge
Intermediate Spirals
Strong Bulge
Ellipticals
Strong Bulge
Weak Bulge
Irregulars
Barred Spirals
Poster and composite images created from
SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6µm (stars)
Green=IRAC 8µm
(aromatic features from dust grains/molecules)
Red=MIPS 24µm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE


THINGS
The HI Nearby Galaxy Survey
NGC 2841
NGC 3621
NGC 7331
NGC 4826 (M64)
NGC 3198
NGC 6946
NGC 3184
NGC 925
NGC 3351 (M95)
NGC 5194 (M51)
NGC 5236 (M83)
NGC 3521
NGC 4214
NGC 2976
DDO 53
NGC 1569
M81dwB
NGC 2366
Our Galaxy
HI
stars
M81dwA
IC 2574
NGC 4449
NGC 3627 (M66)
Holmberg II
NGC 7793
DDO 154
NGC 4736 (M94)
NGC 3077
Holmberg I
NGC 5055
NGC 2903
NGC 628 (M74)
NGC 5457 (M101)
NGC 3031 (M81)
NGC 2403
10 kpc
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

# Summary

- From UV and IR, a small grain/molecule component of dust is processed by massive star formation
  - Quiesent → processed dust
- Metallicity is important for the **amount** of dust, but not the **type**
- Dust found in the Local Group is consistent with dust found in all other galaxies
- Implication is that dust formation/processing is a **local** phenomenon
- Observations that probe active star formation regions will see a weak/absent 2175 A bump and weak/absent aromatic features
- Observations that probe quiesent regions will see a strong 2175 A bump and aromatic features

# Questions?

- What about molecular cloud dust?
  - UV extinction hard to measure (Whittet et al. → no 2175 A bump)
  - IR extinction different than diffuse
- Why doesn't metallicity play a role in the type of dust found?
  - Different types of AGB stars are known to produce varying types of dust
  - The ratio of these typse of AGB stars changes with metalicity
- Is there any evidence for dust beyond that found in the Local Group (e.g., MW, LMC, & SMC)?
  - What about AGN? Just processed?


The End