The Dusty Universe: From ISO and Spitzer to Herschel, SOFIA, and JWST

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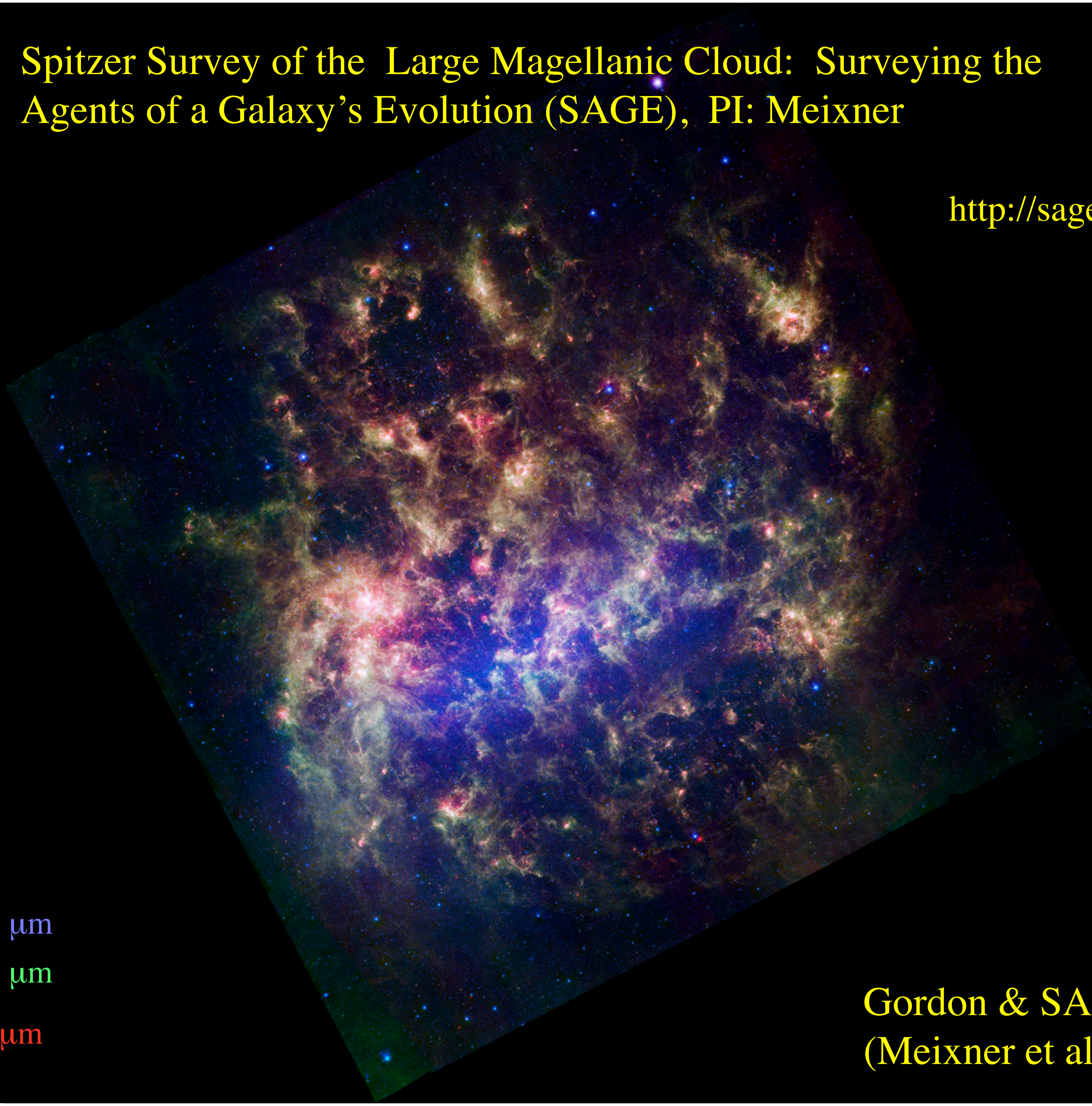
Key Questions

- Where: Origin of Interstellar dust
- What: Inventory of interstellar dust
- How: key processes in its formation and evolution
- When: interstellar dust over the ages
- Why: do we care

Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy's Evolution (SAGE), PI: Meixner

http://sage.stsci.edu/



IRAC 3.6 µm

IRAC 8.0 µm

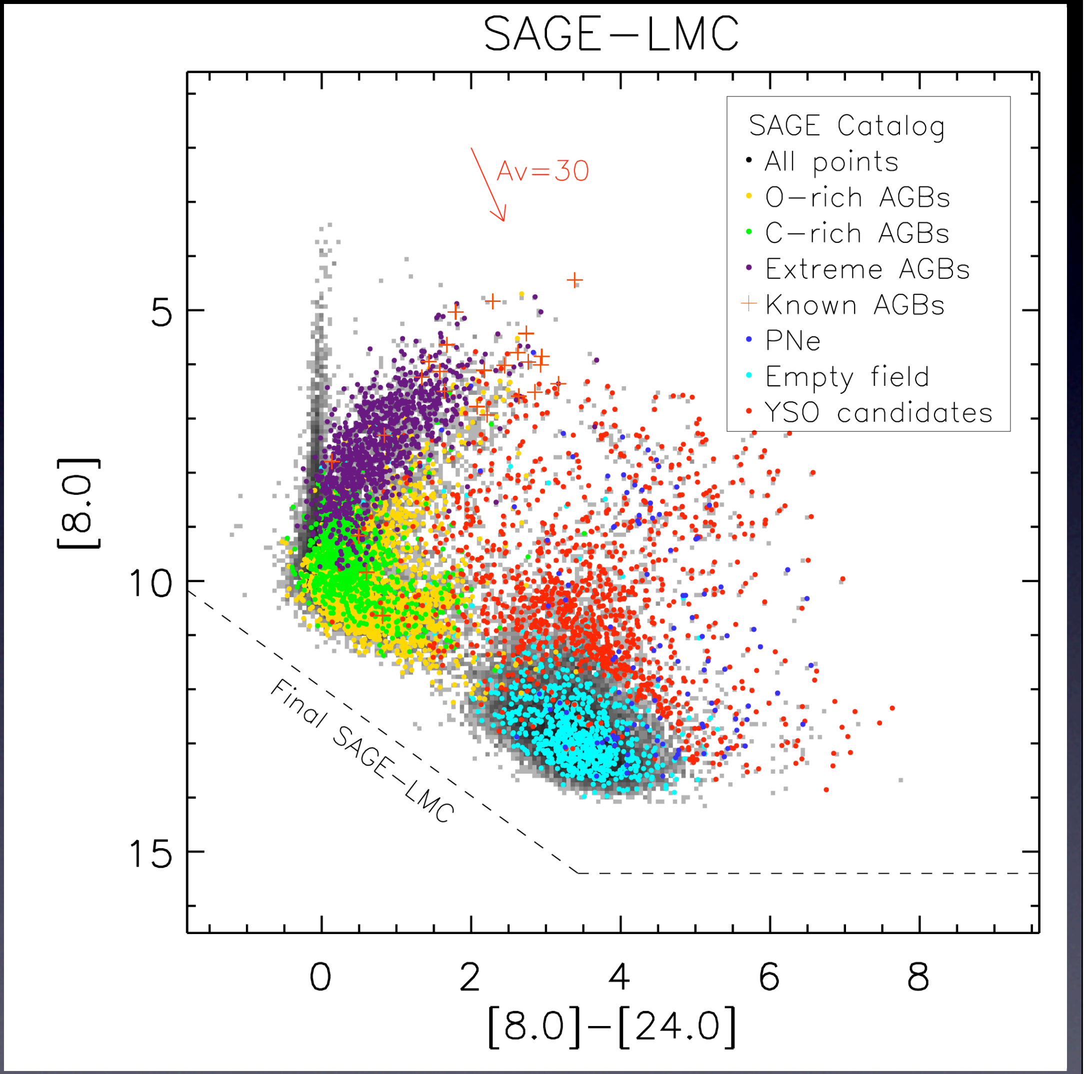
MIPS 24 µm

Gordon & SAGE team
(Meixner et al. 2006)

Inventory of the LMC

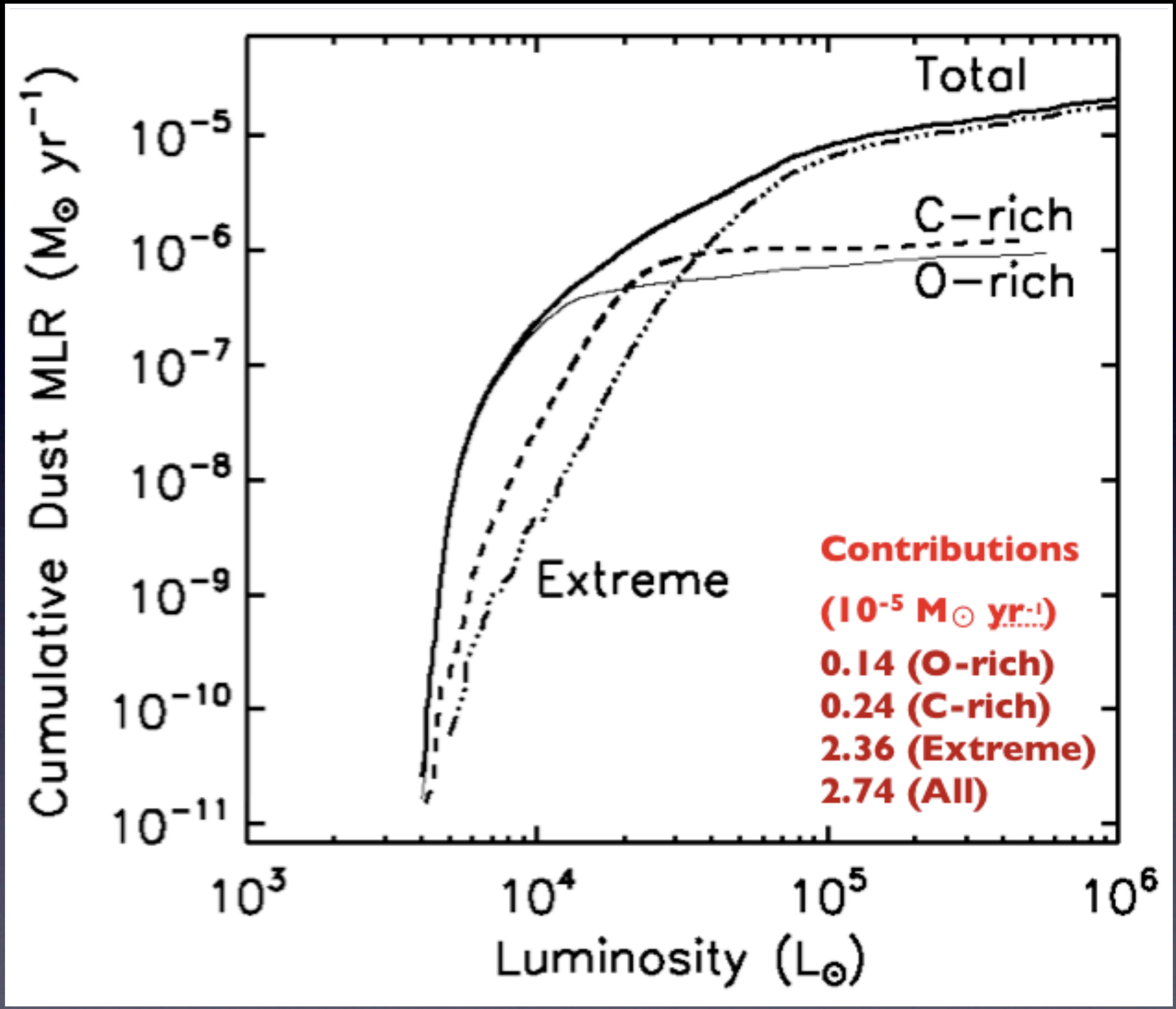
AGB stars: Blum et al. (2006)
YSO candidates: Whitney et al. (2008)
PNe: Hora et al. (2008)
Empty field = background galaxies: Whitney, Sewilo et al. (2008)

Final Source Counts:
~6.3 million point sources
>650,000 red giant stars
>45,000 dusty evolved stars
>1200 Young Stellar Objects



Sewilo & SAGE Team (2006)

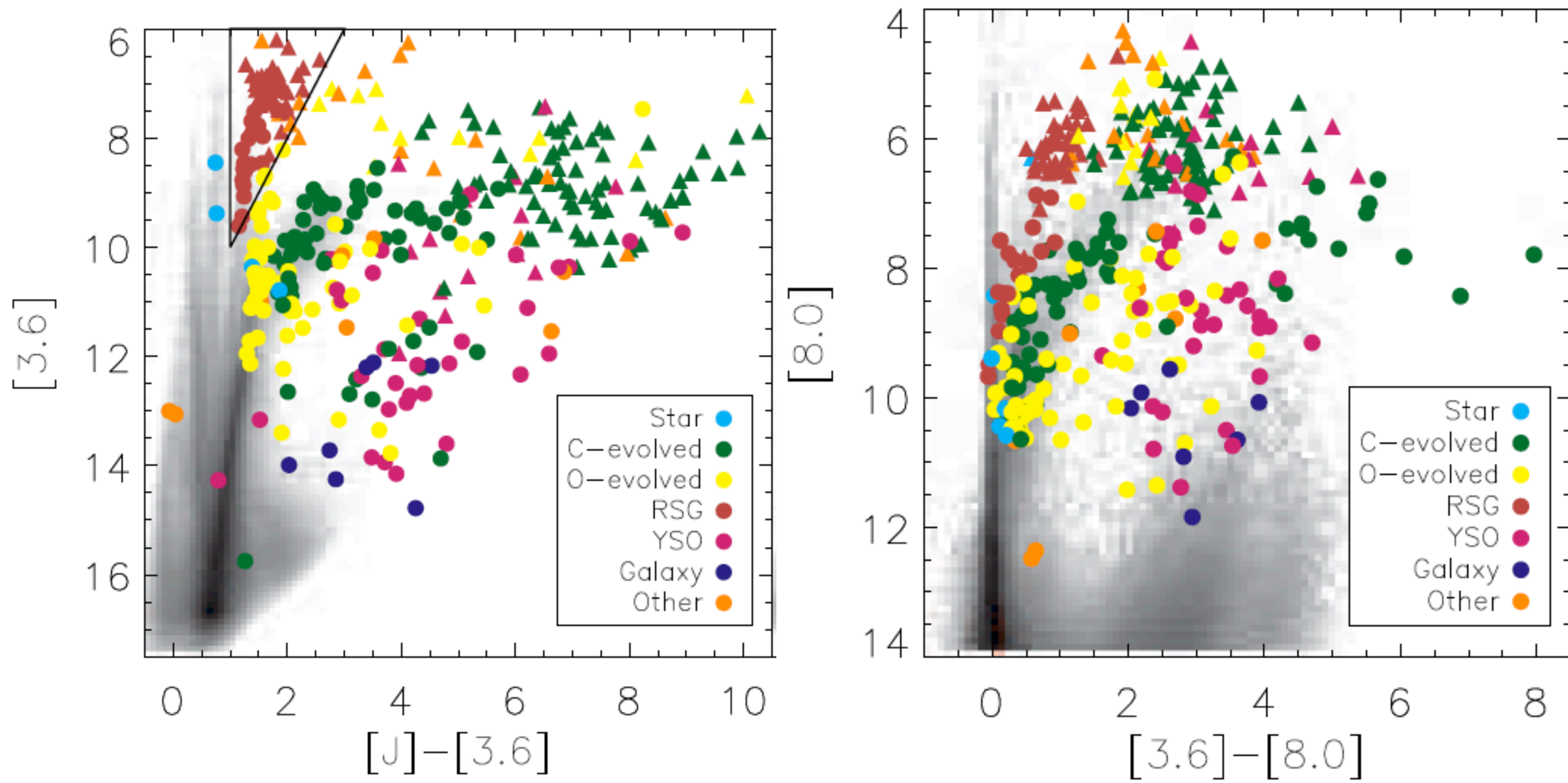
AGB Dust Mass Loss Return



First cut based on colors

Srinivasan et al. 2009

SAGE-Spec: LMC
PI: F. Kemper



First analysis based on spectroscopy: to be completed

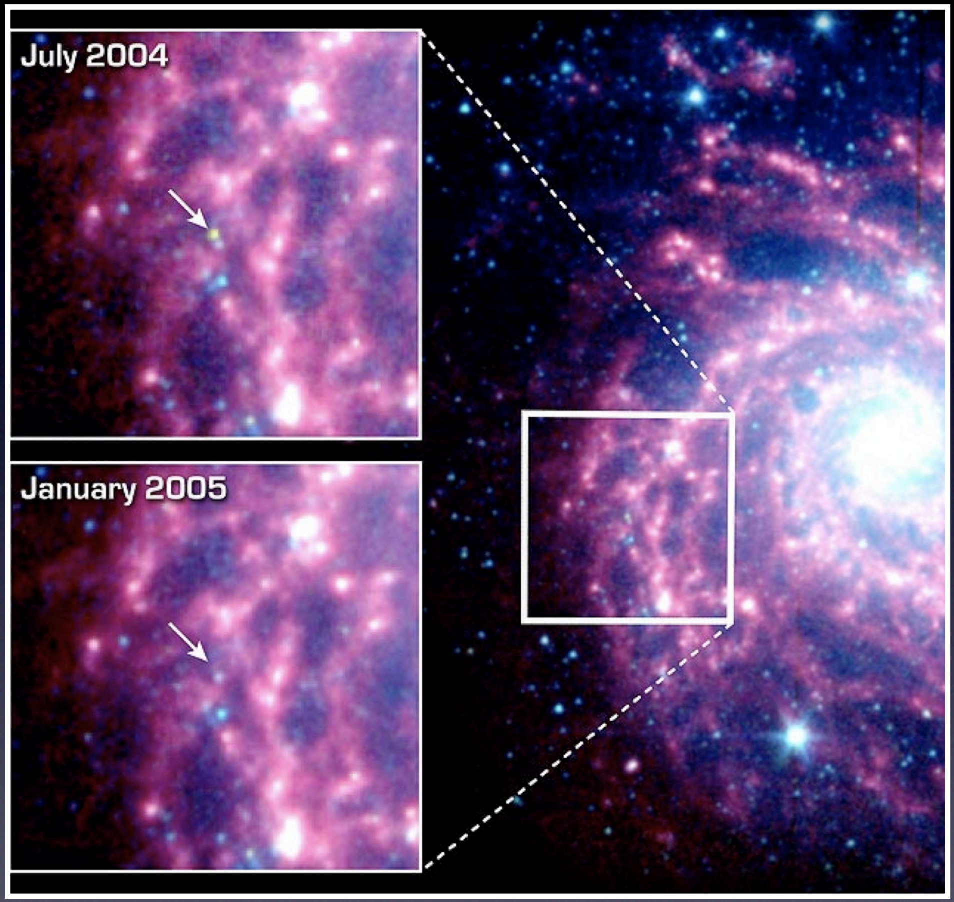
Woods et al. submitted: source ID

SAGE-LMC Inventory

Component	Mass or rate
Total mass of dark halo	~1 - 3 x 10^{10} $M_\odot$
Stellar Mass	3 x 10^9 $M_\odot$
ISM mass, 160 μm	**10^9 $M_\odot$**
Star formation rate	**~0.1 $M_\odot$ yr^{-1}**
AGB Mass Loss return	**6-13 x 10^{-3} $M_\odot$ yr^{-1}**
Planetary nebulae Massive stars: Red supergiants, LBV, SNs	**~3 x 10^{-2} $M_\odot$ yr^{-1}**

Spitzer & Supernova

- SN ejecta
  - limited to the near universe (~10Mpc)
  - inefficient dust formation
- Young SNRs
  - biased to warm (shocked) dust
  - Silicates, oxides & PAH (clusters)

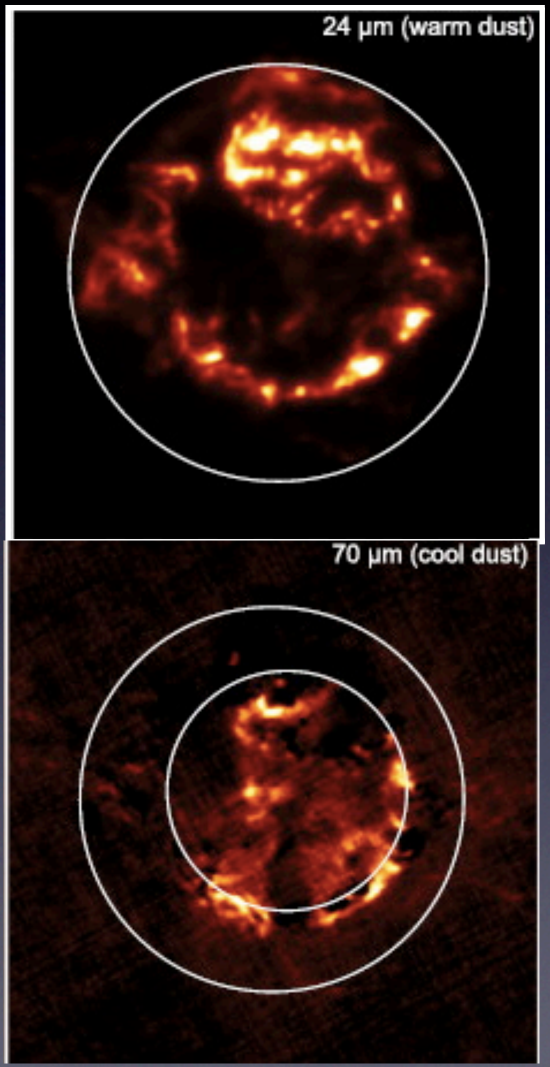


Also Akari, see Seok p43

Rho & Reach et al
Barlow et al

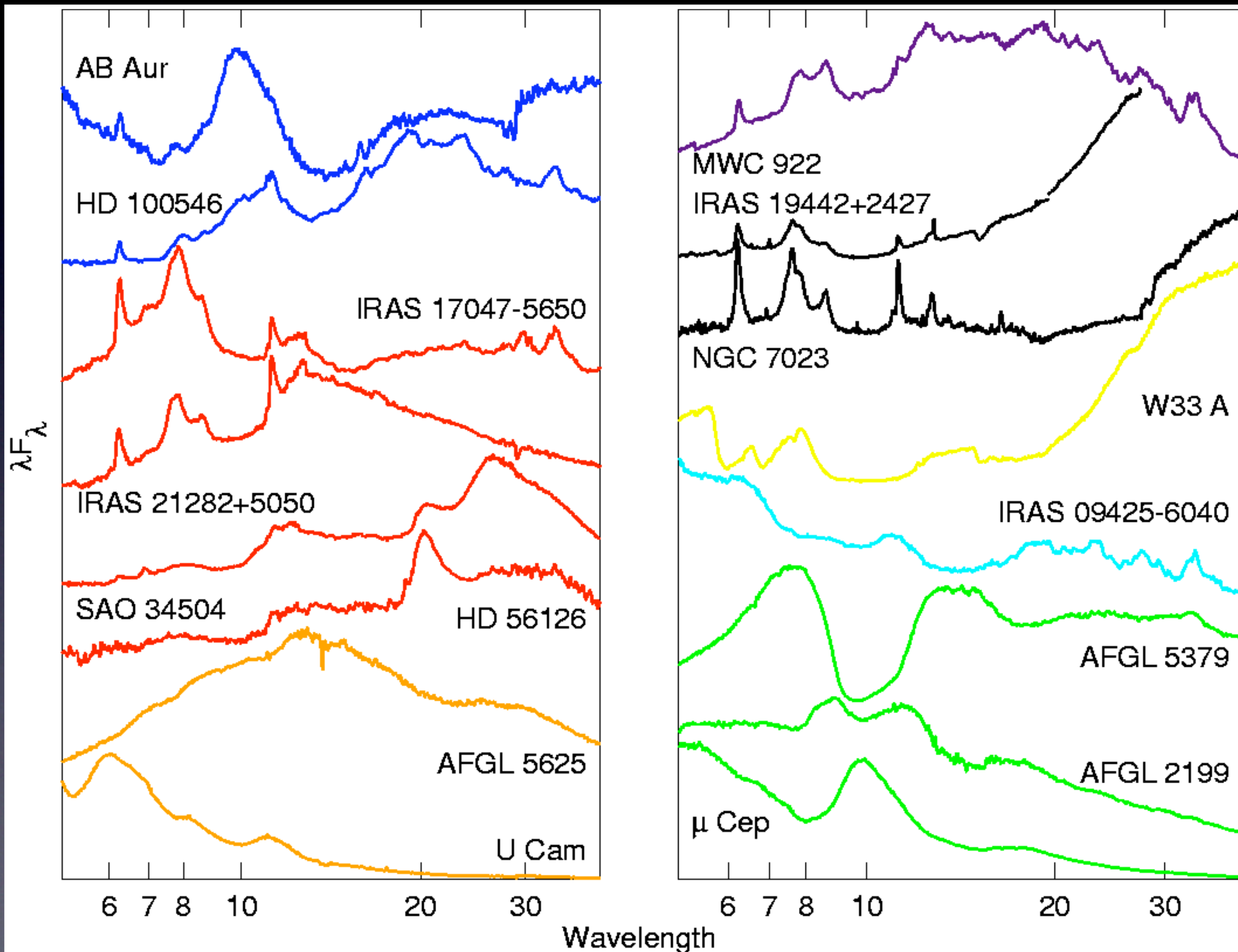
Herschel & Supernova

- Young SNRs
  - warm dust in reverse shock region
  - cool dust interior to reverse shock region
  - M_{dust}~0.075 M_{sun}



Barlow et al, 2010, A&A, 518, L138

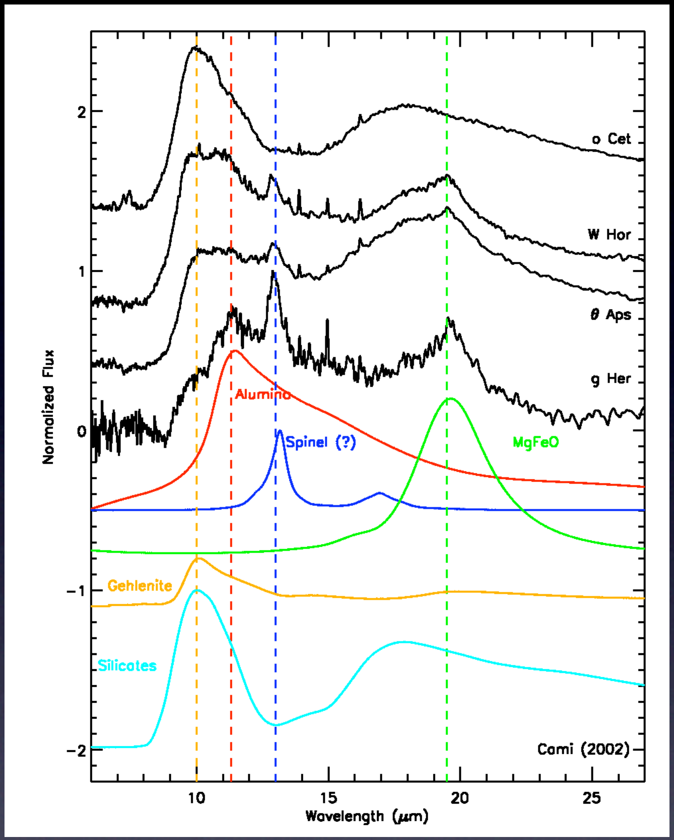
The Spectral Richness of Dust

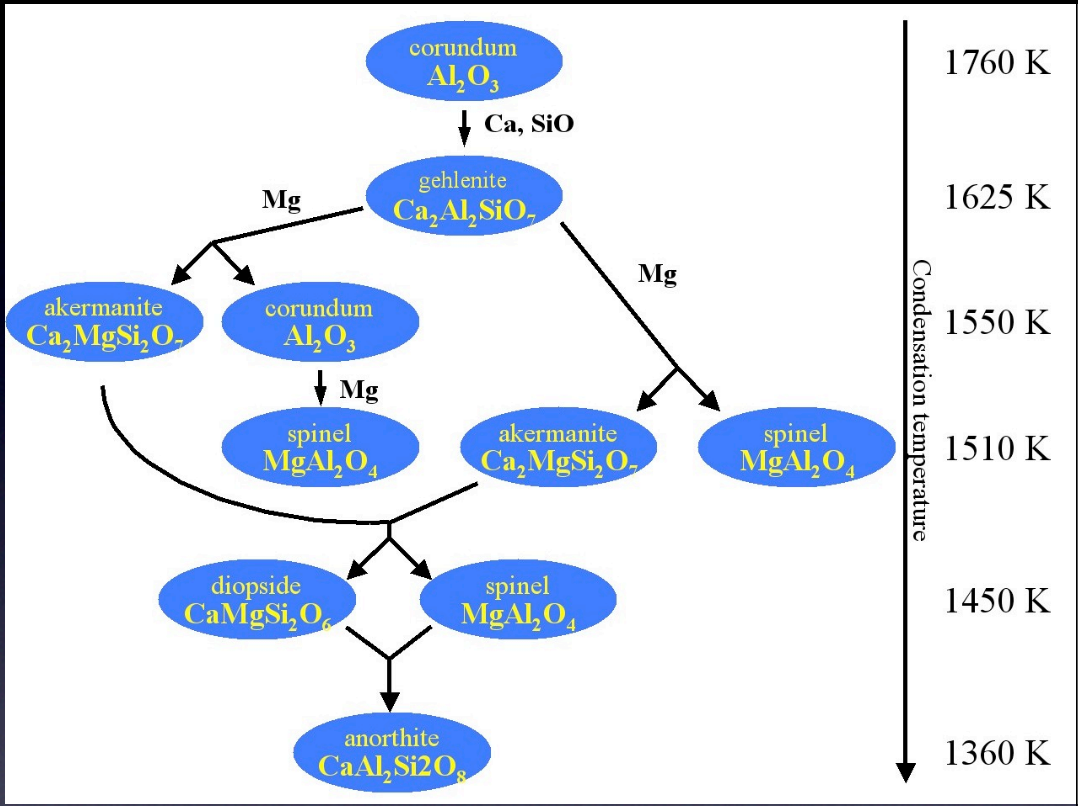


Dust Inventory of the ISM

- Silicates:
  - Amorphous FeMg-silicates
  - Forsterite
  - Enstatite
  - Montmorillonite ?
- Oxides:
  - Corundum
  - Spinel
  - Wuestite
  - Hibonite
  - Rutile
- Sulfides:
  - Magnesium sulfide
  - Iron sulfide ?
- Ices
  - Simple molecules such as H_2O, CH_3OH, CO, CO_2
- Carbides:
  - Silicon carbide
  - Titanium carbide
  - And others
- "Pure" Carbonaceous compounds:
  - Graphite
  - Diamonds
  - Hydrogenated Amorphous Carbon
  - Polycyclic Aromatic Hydrocarbons
  - Fullerenes
- Others:
  - Silicon nitride
  - Metalic iron ??
  - Carbonates ?
  - Silicon/silicon dioxide ??

Oxides Condensation Sequence





- Oxides at low mass loss rates
- Silicates at high mass loss rates
- Freeze out

- Cami, 2001, PhD thesis
- Posch et al., 2002, A&A, 393, L7
- DePew et al., 2006, ApJ, 640, 97
- Sloan & Price, 1998, ApJS, 119, 1411

Spitzer's Contribution

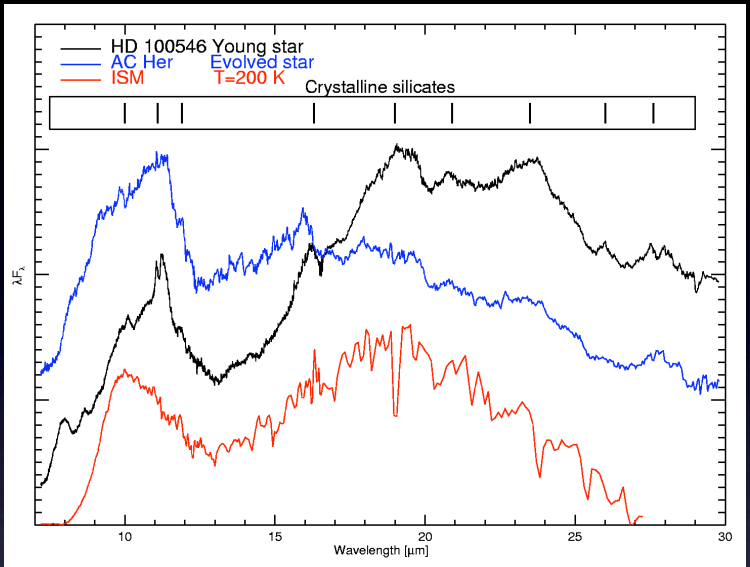
- Systematic studies
- Metallicity dependence with LMC, globular cluster & bulge samples
  - more metals = more dust
  - diversity is everywhere
  - composition not dependent on metallicity
- Larger samples are needed

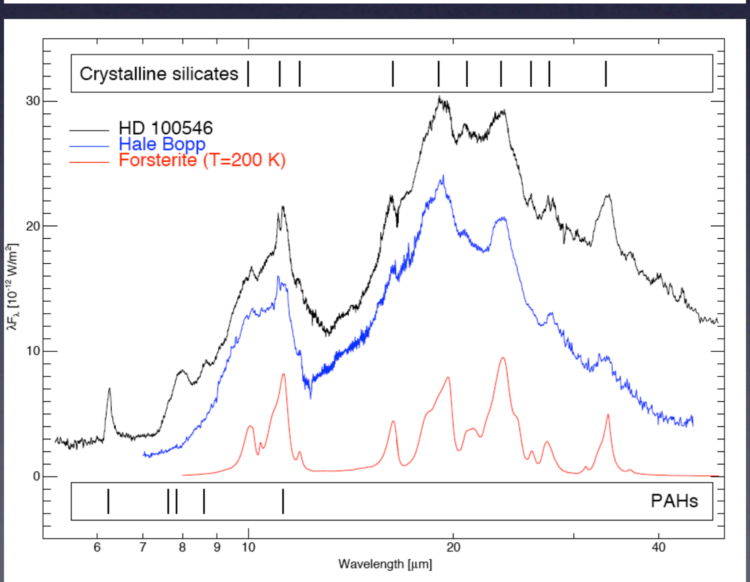
Sloan et al, 2010, ApJ, 719, 1274
Sage-spec
Blommaert et al, in prep

Crystalline Silicates Galore

ISO

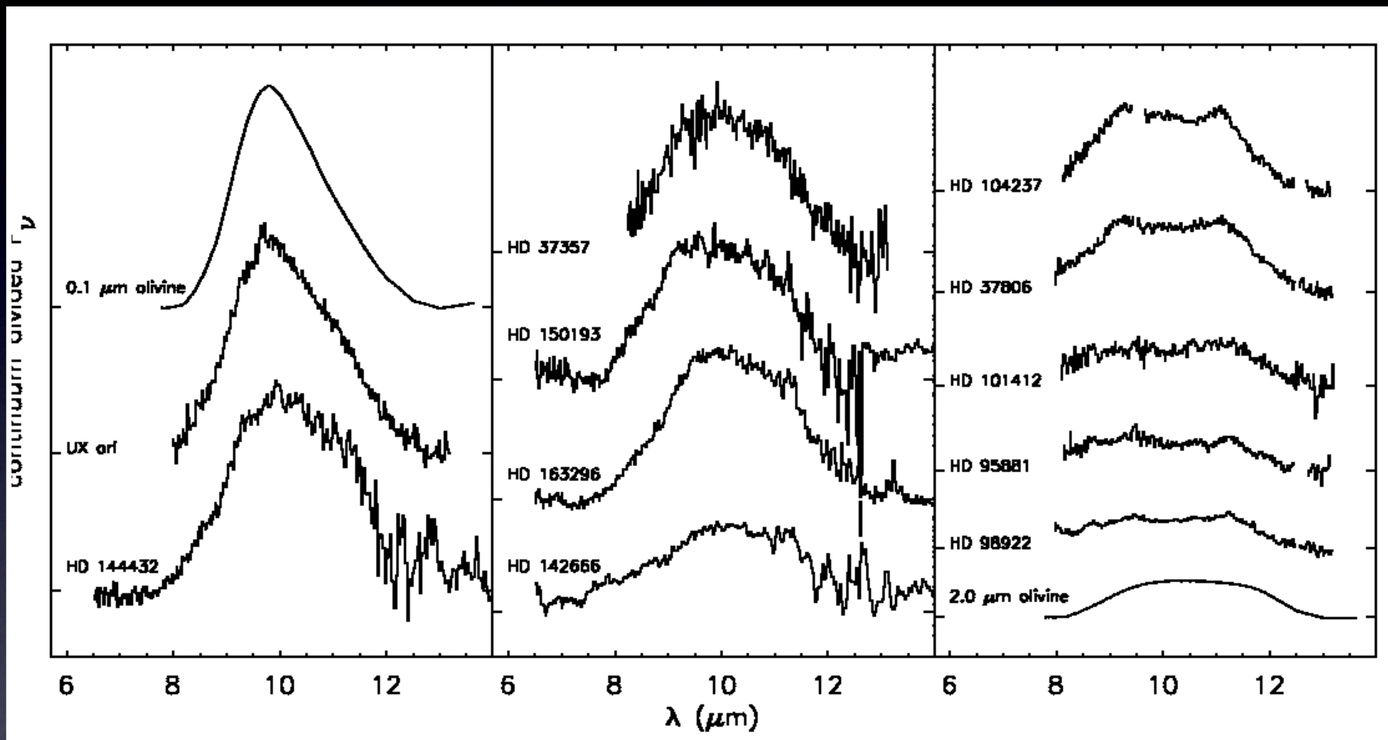
- Crystalline silicates
  - Forsterite/enstatite
  - Magnesium-rich
  - Cold
  - Disk sources
- Amorphous silicates
  - Role of iron
- High mass loss rates





Malfait et al. 1998, A&A 332, L25
Molster et al., 2000, A&A 382, 184
Kemper et al, 2004, ApJ 609, 826
Crovisier et al, 1997, Science, 275, 1904

Crystallinity and Grain Growth



Van Boekel et al., 2005, AA, 437, 189
Kessler-Silacci et al., 2006, ApJ, 639, 275

Spitzer's Contribution

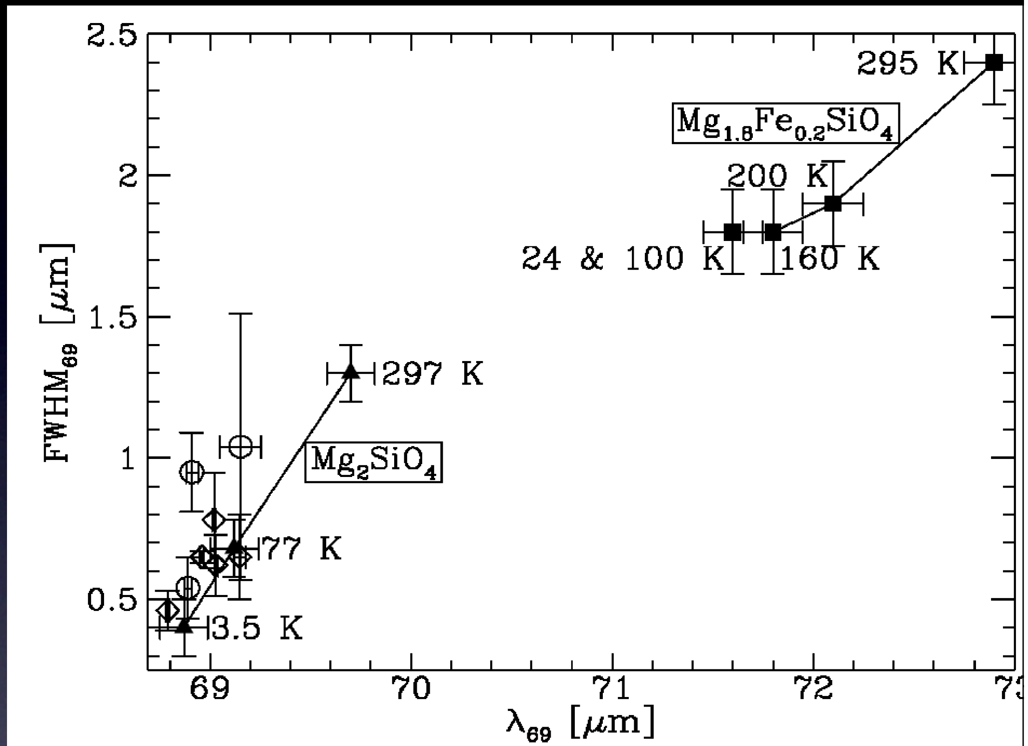
- Large systematic samples
- Disks are everywhere: differences & similarities
  - Herbig Ae & Be stars (ISO)
  - T Tauri stars
  - Brown Dwarf disks
- Better characterization of dust composition
  - eg., silica

Sargent et al, 2009, ApJ, 690, 1193; 2009; ApJS, 182, 477
Pascucci et al, 2009, ApJ, 696, 143

The 69 µm Forsterite Band

ISO

Width and peak position are sensitive to composition & temperature



Laboratory-Observations

- Composition: Mg_2SiO_4
- Temperature: <200 K

Koike et al, 2000, A&A 363, 1115

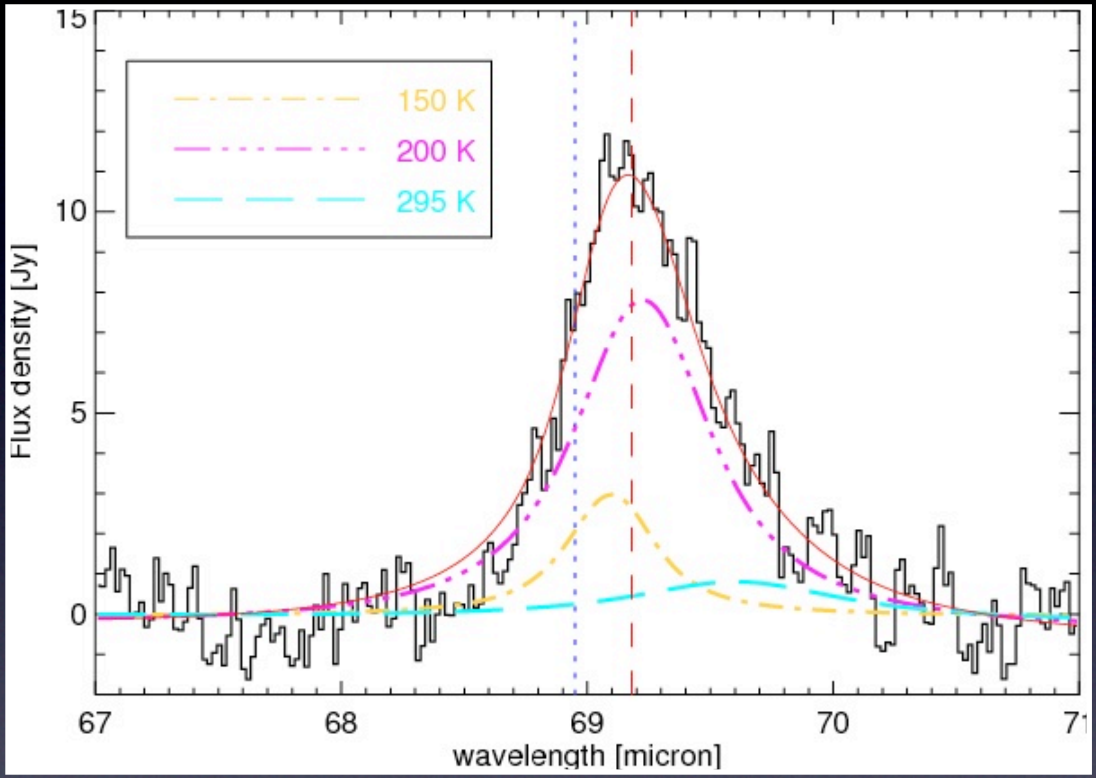
Molster et al, 2002, A&A 382, 184

See also Brusentsova, P1

Herschel's Contribution

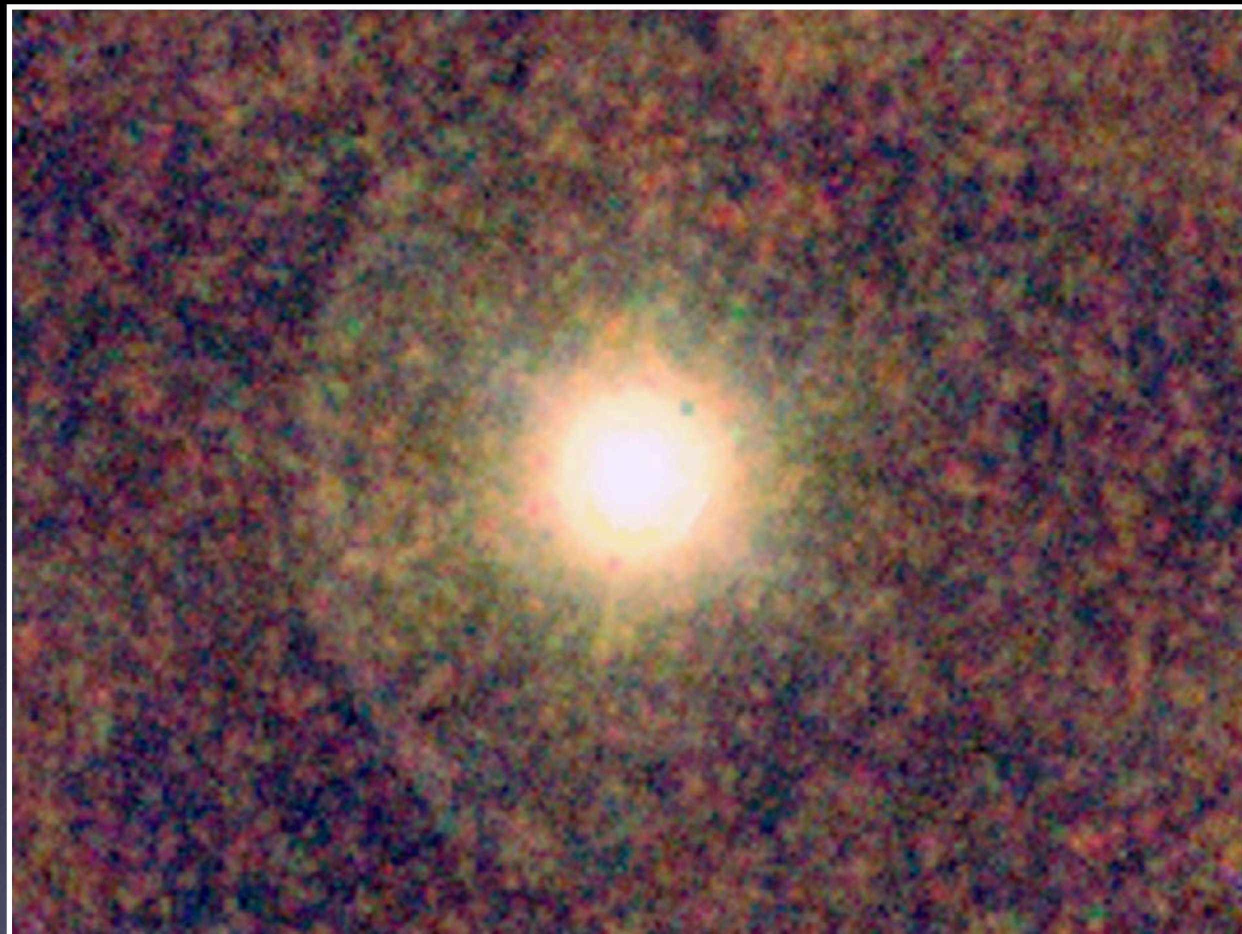
Accurate profiles & detailed models

- 'perfect' crystals
- 'pure' forsterite (<few % Fe)
- temperature gradient



Sturm et al, 2010, A&A,

Dust Formation in IRC+10216



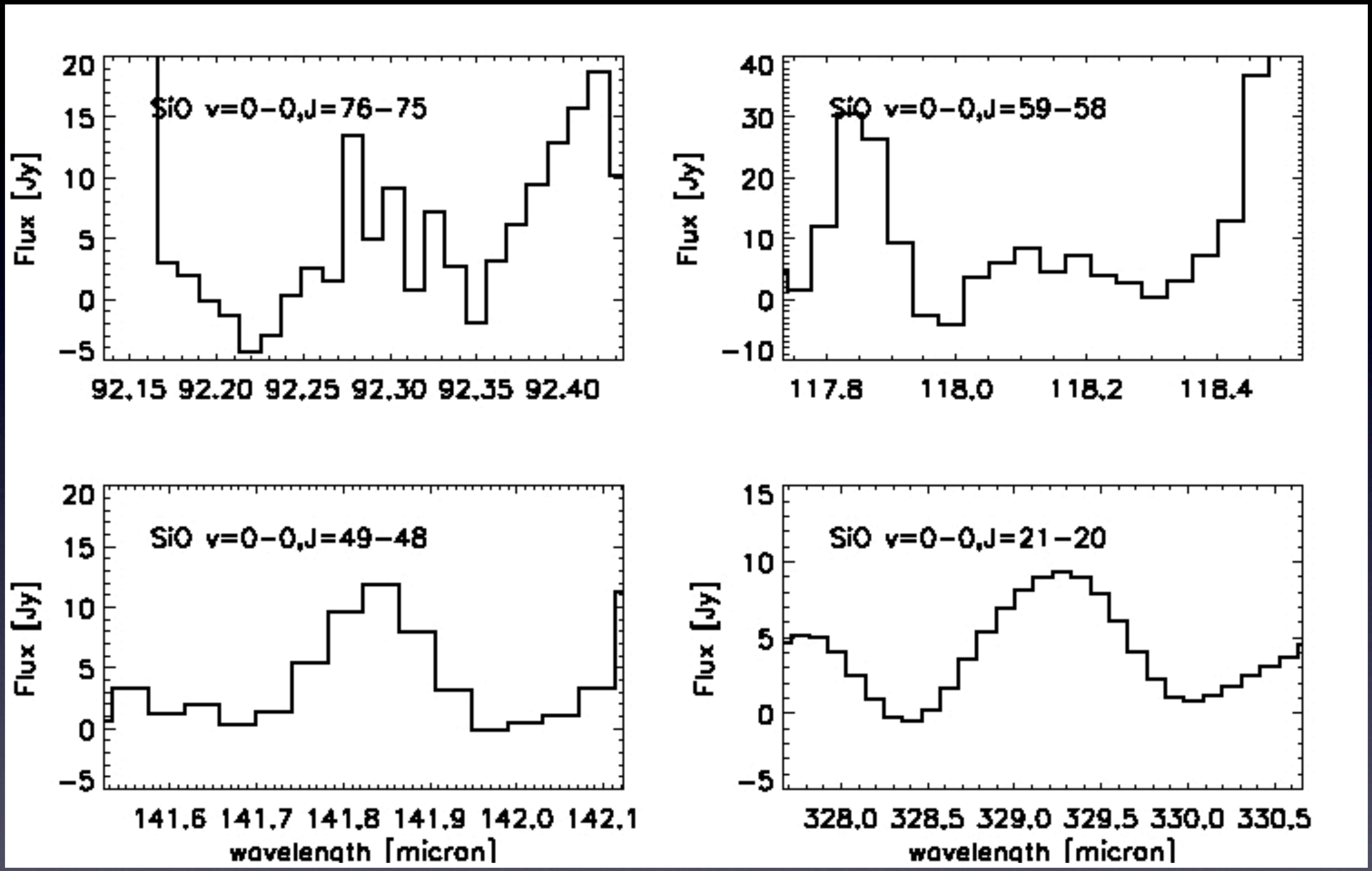
Herschel & the power of spectroscopy

First PACS +SPIRE Spectroscopic Results

Molecular inventory

VY CMa	IRC+10216
o-H_2O } 2/3 of all lines	$H^{12}CN$ } 1/2 of all lines
p-H_2O	$H^{13}CN$
^{12}CO, ^{13}CO, $C^{17}O$, $C^{18}O$	^{12}CO, ^{13}CO, $C^{18}O$
NH_3	o-H_2O
OH	p-H_2O
SiO	NH_3
HCN	SiS
CN	SiO
CS	CS
SO	C_3
SiS	C_2H
H_3O^+?	HCl
[C II]	
[O I]	
+ unidentified lines	+ unidentified lines
TOTAL: ~500 unblended	TOTAL: ~500 unblended

Silicon in the Dust Formation Zone

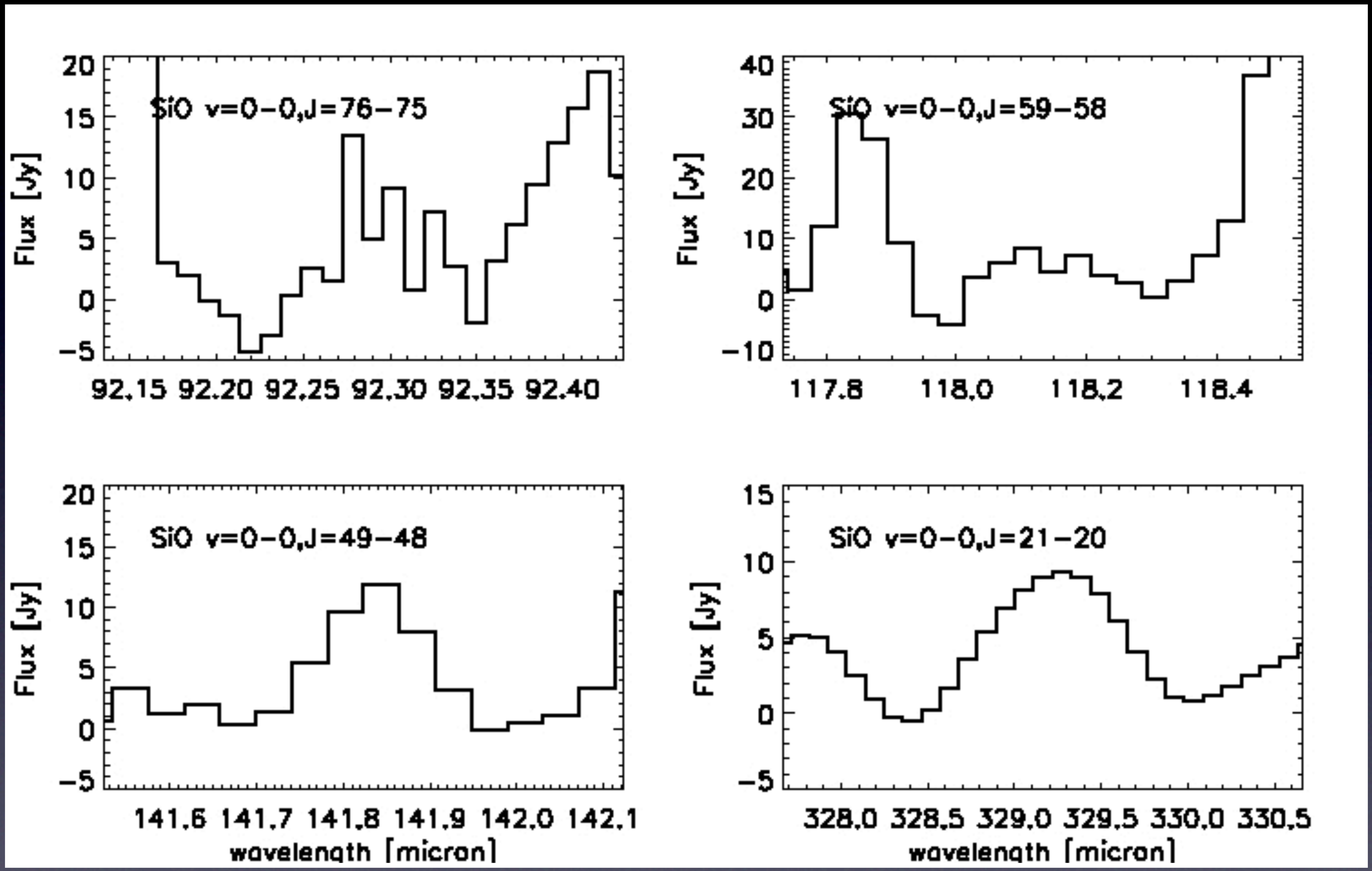


High J lines of SiO and SiS: Trace dust formation zone

SiO : J=11-10 to J=90-89 (E_{up} = 8432 K)

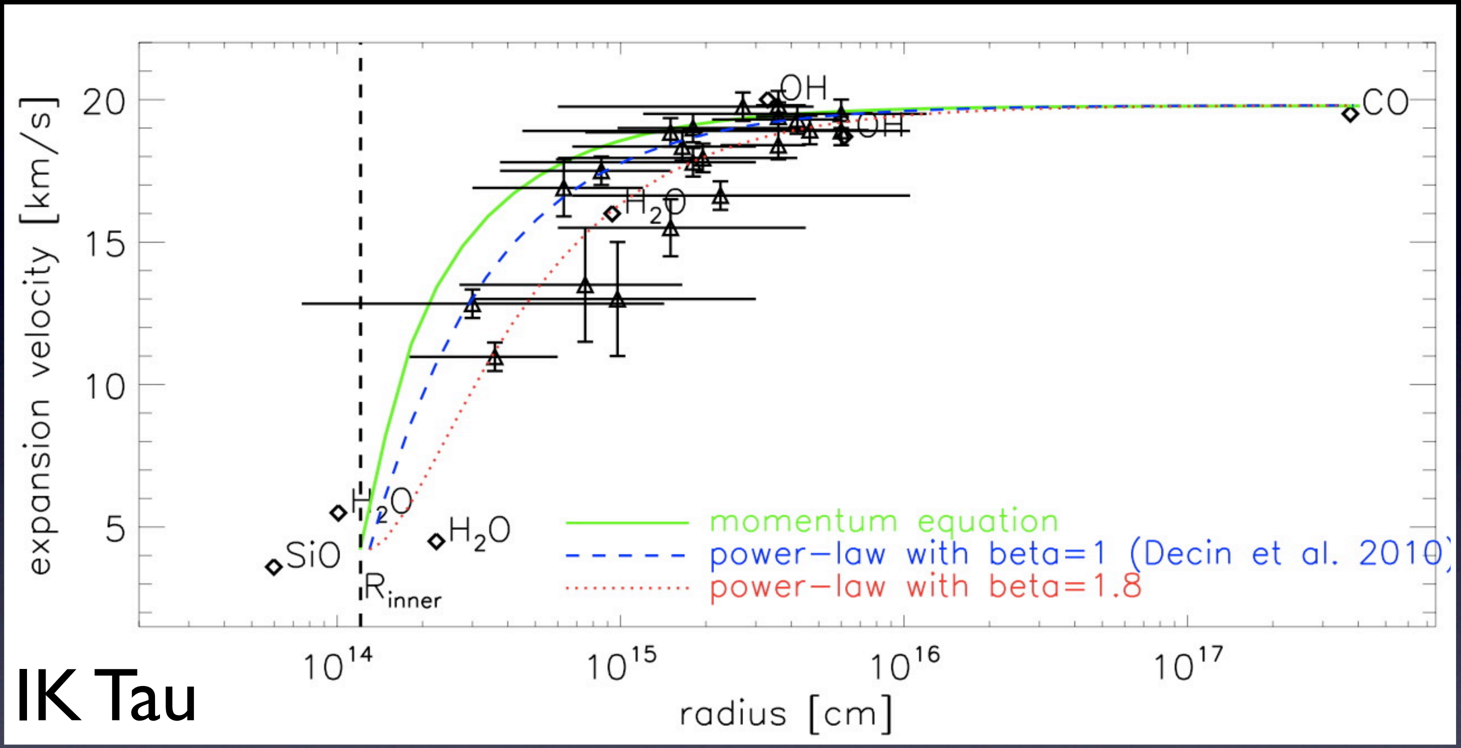
SiS: J=26-25 to J = 124-123 (E_{up} = 6678 K)

Silicon in the Dust Formation Zone



Less than 30% of the silicon seems involved

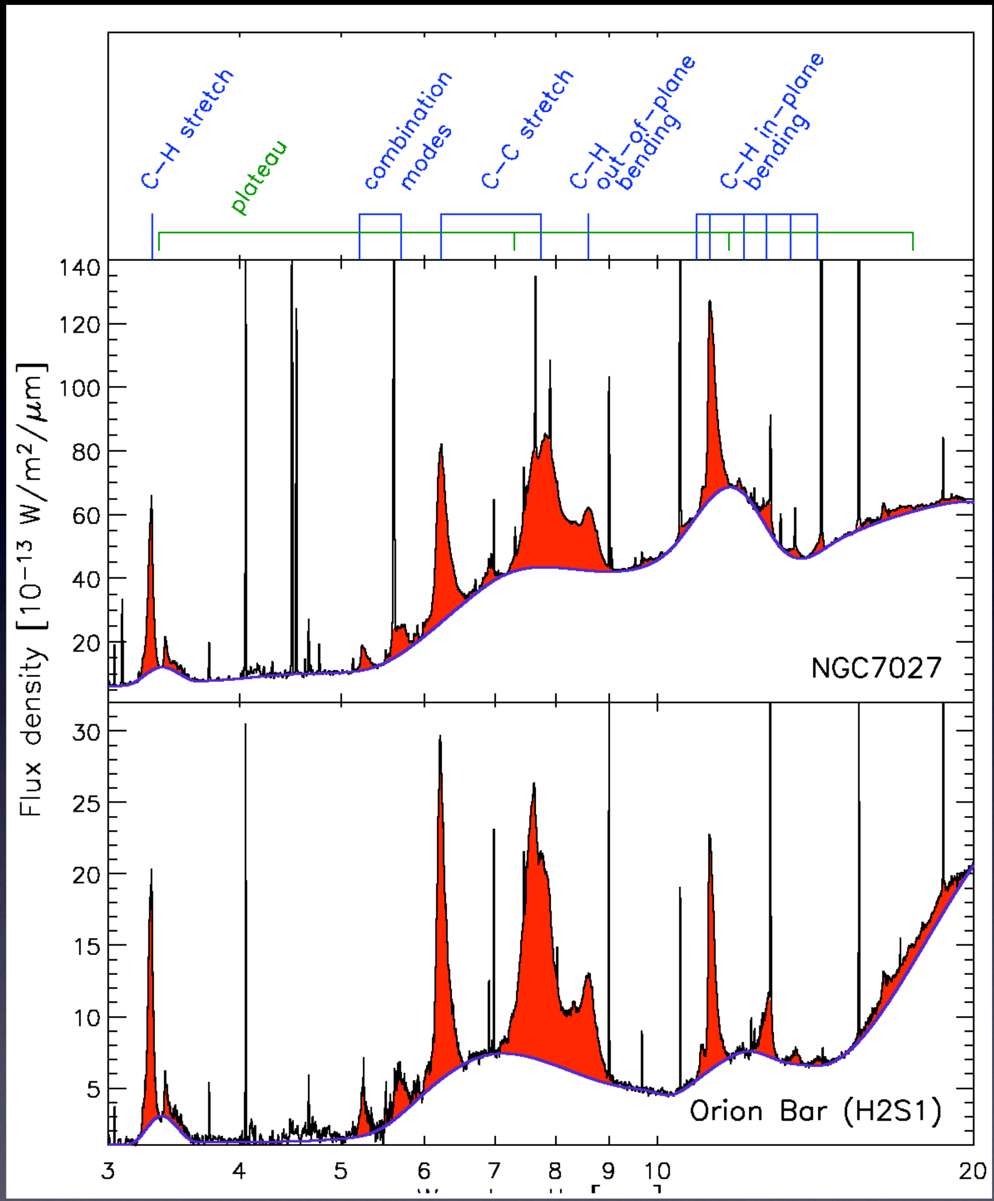
HIFI & Dust Acceleration



Herschel will probe the gas-to-grain process

Decin et al, 2010, A&A, in press

The incredibly rich spectrum of interstellar PAHs

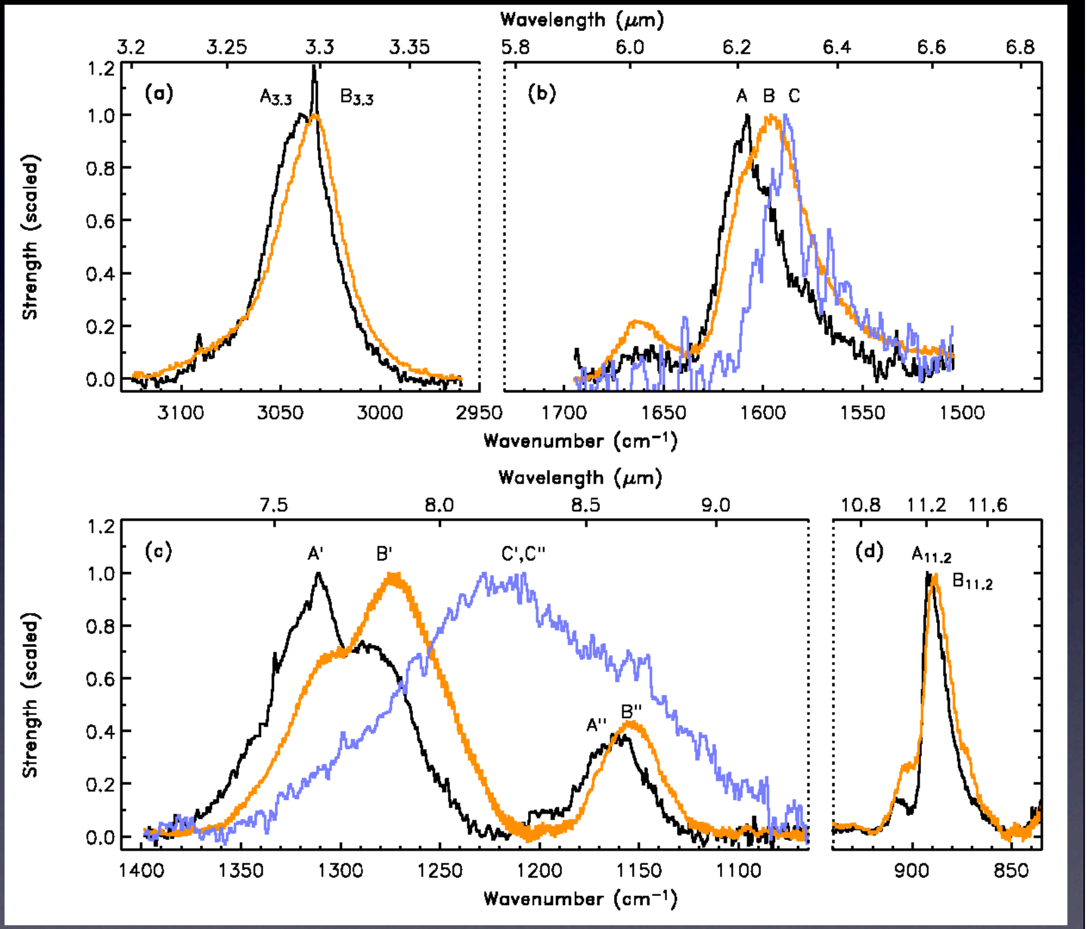


Peeters et al, 2002, A&A, 390, 1089

PAH Spectral Variations

ISO

- Profile variations
- Strongest for CC modes
- Classes A, B, C
- Classes correlate well for CC modes
- Correspond to object type

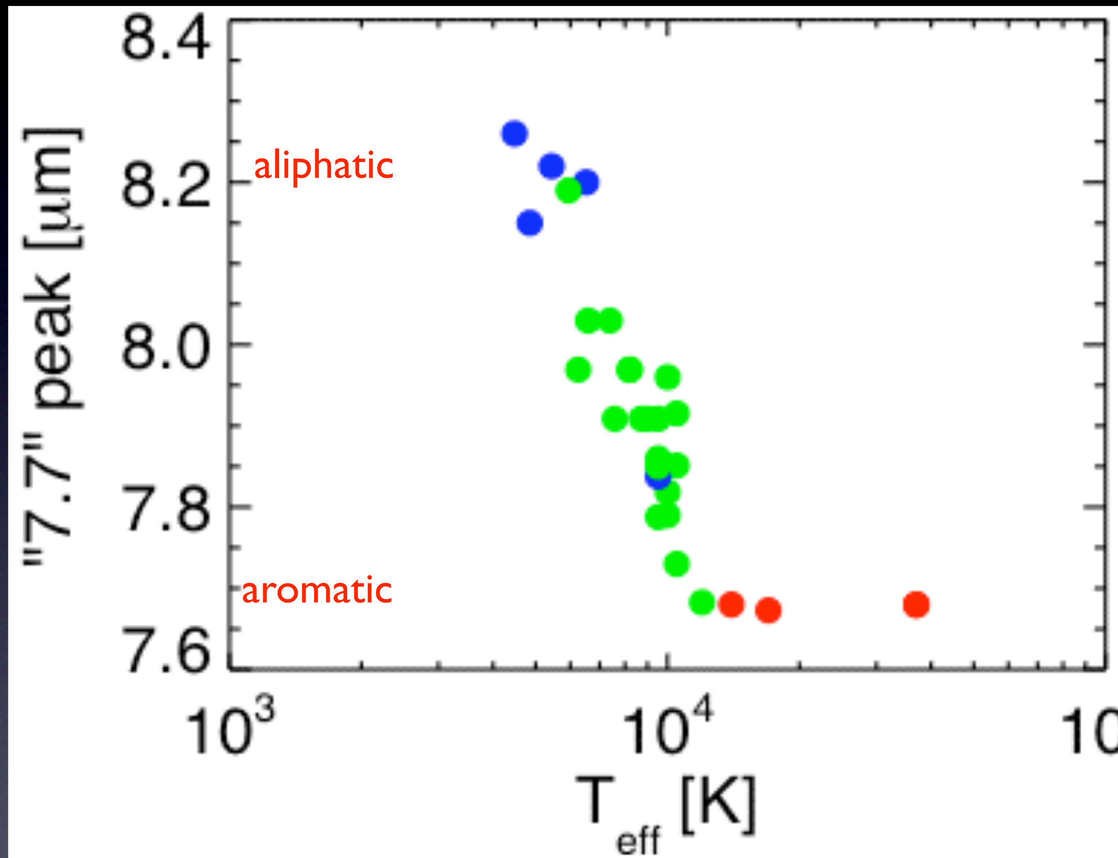


Peeters et al, 2002, A&A,390, 1089

PAHs in Regions of Star Formation

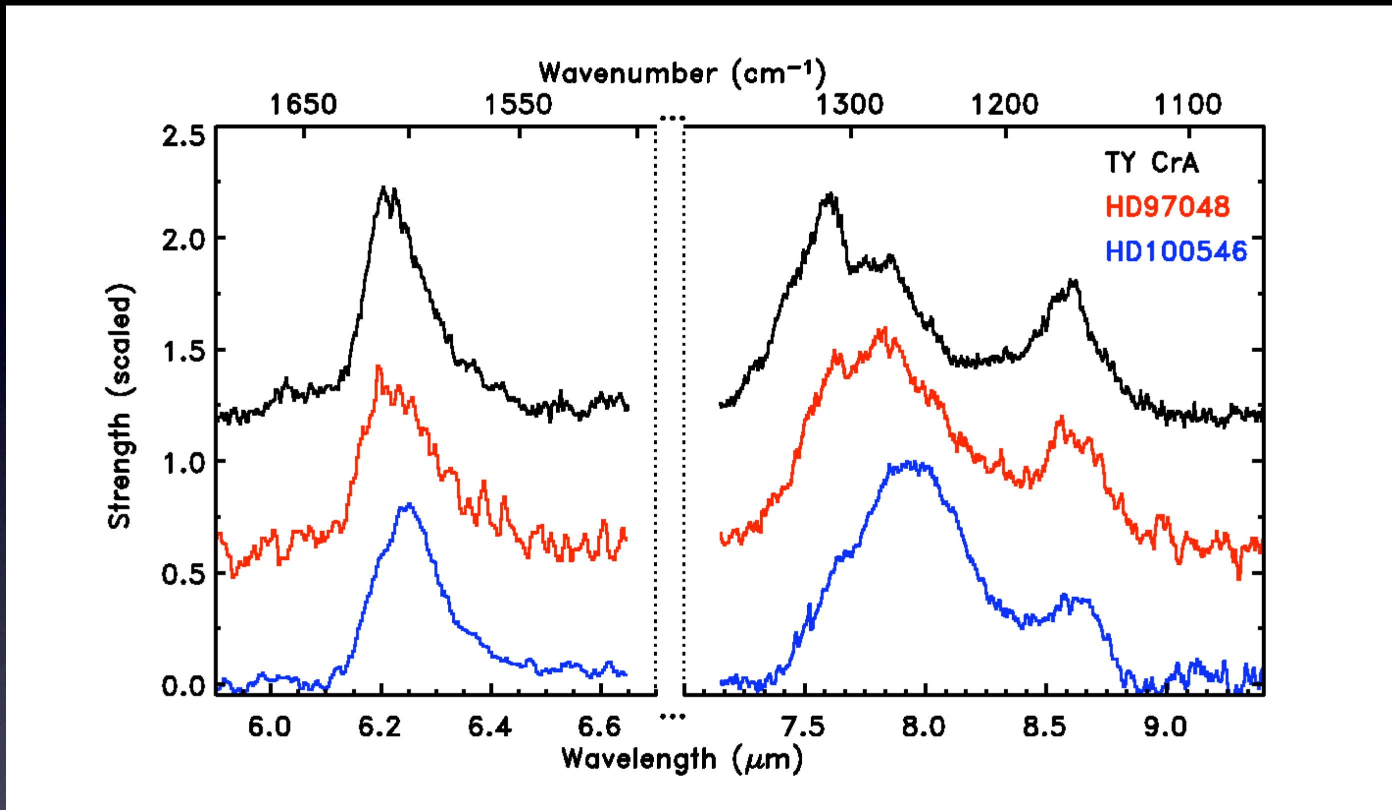
Spitzer

- Variations in the peak position of the 7.7 μm band
  - Aromatic versus aliphatic hydrocarbons
  - N incorporation into rings or clusters
- Active chemistry



Sloan et al 2007, ApJ, 664, 1144
Keller et al, 2008, ApJ, 684, 411
Boersma et al 2009, A&A, 502, 175

PAHs and Herbig Stars



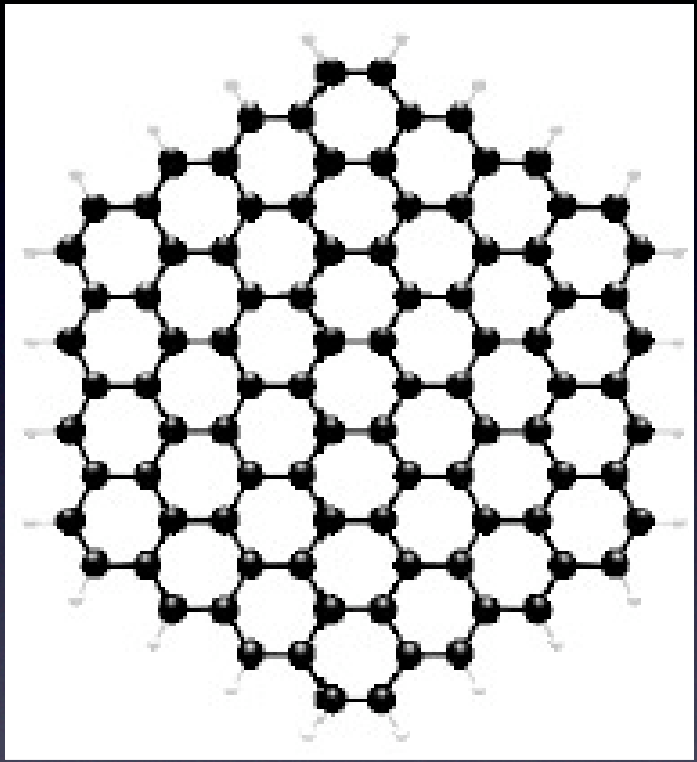
Source	Sp T	Size	Location
TY Cra	B7-B9	~2000 AU	HAeBe in cloud
HD 97048	B9-A0	~100-1000 AU	HAeBe cloud edge
HD 100546	B9	~150 AU	isolated HAeBe star

Boersma et al 2009, A&A, 502, 175

‘GrandPAHs’

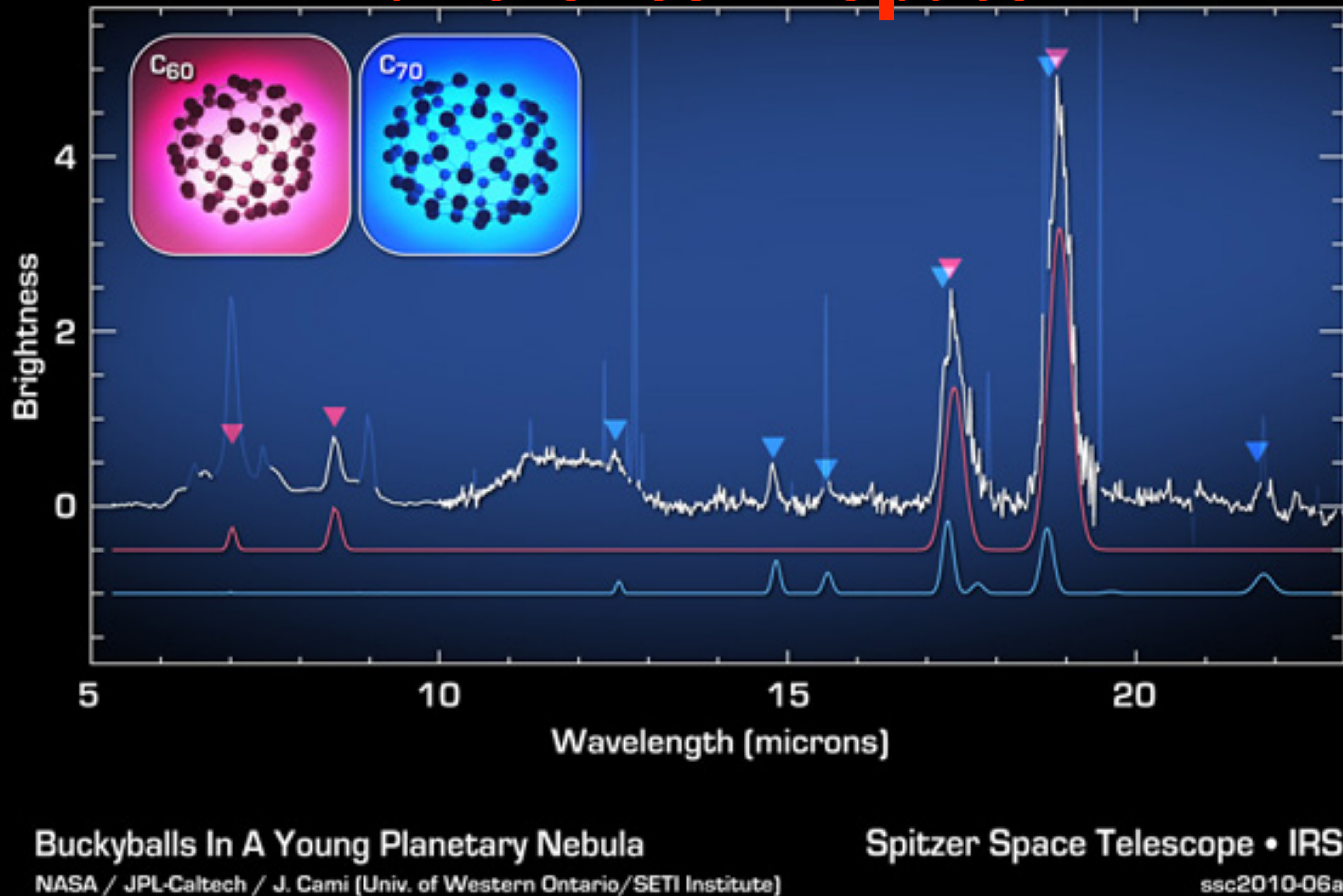
Spitzer

- IR emission spectra are very similar, particular in the “extreme” regions of the ISM
- 15-20 micron region dominated by a few bands (16.4/17.4/17.0 micron)
- Typical PAH will absorb some 10^8 UV photons over its lifetime. What can break, will break
- Interstellar PAH family dominated by a few, extremely stable species



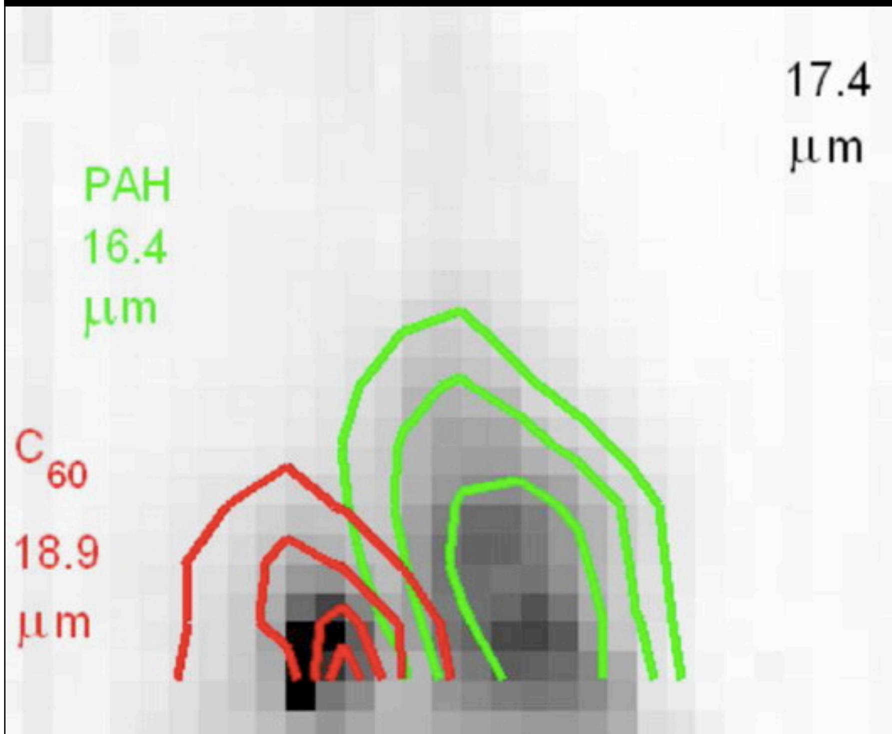
$C_{96}H_{24}$

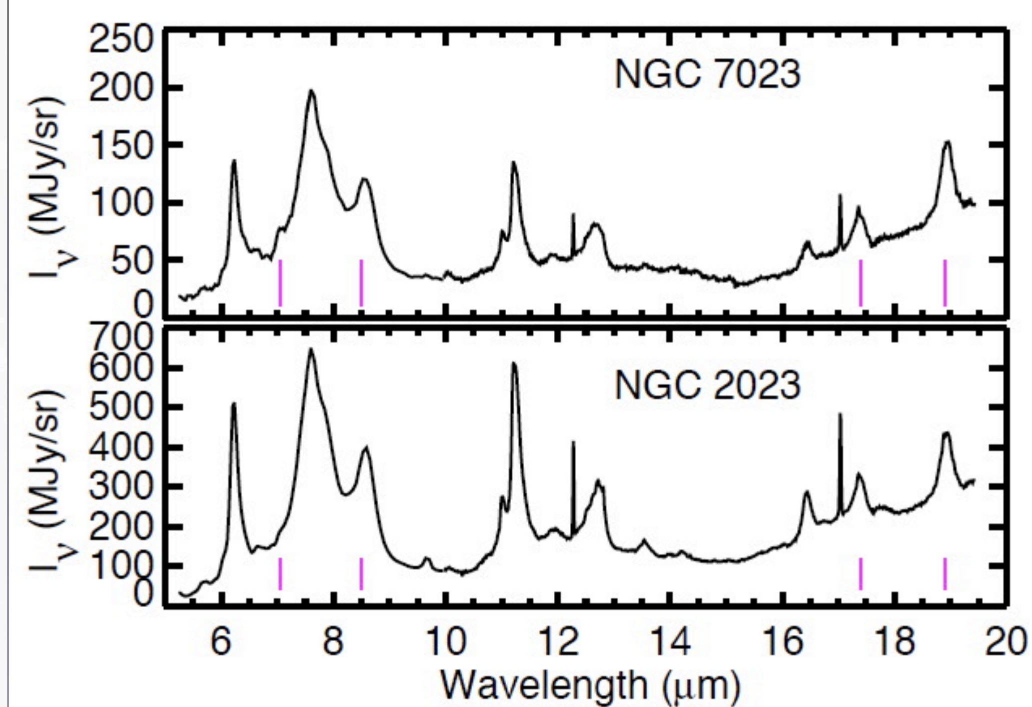
Fullerenes in Space



See Cami et al, P2

C_{60} in the ISM



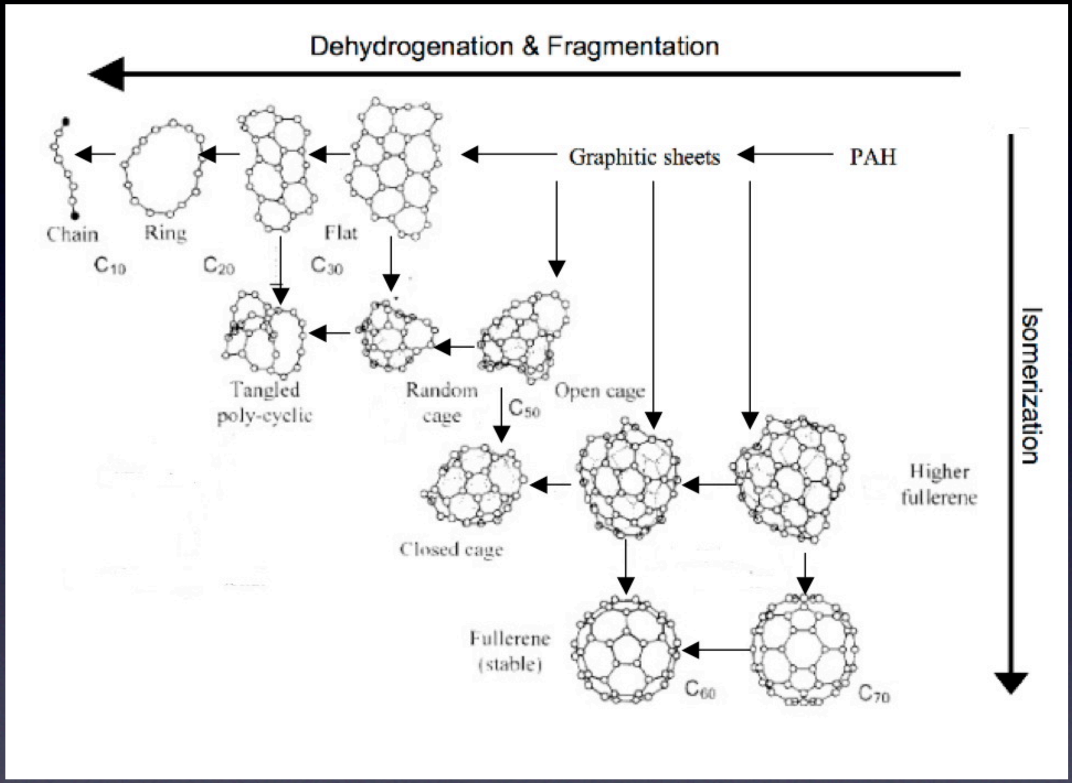


PAHs dominate the spectra
but C60 is present as well at 0.3% of the C

Sellgren et al, 2010, ApJ, 722, L54

PAH & Fullerene Chemistry

- Stellar ejecta
  - Fullerenes at ~3500 K
  - PAHs at ~1000 K
- H-poor environments
  - RCrB stars, WC stars
  - vaporizing grain-grain collisions
- UV photochemistry
  - H-loss
  - isomerization



Herschel may probe the 'grandPAH' evolution

Key Questions

- Where: Origin of Interstellar dust
- What: Inventory of interstellar dust
- How: key processes in its formation and evolution
- When: interstellar dust over the ages
- Why: do we care

Key Questions: ISO & Spitzer Answers

- What: The rich inventory of interstellar dust
- Where: AGB stars (and elsewhere including ISM)
- How: Dust condensation sequence
- When: To be done
- Why: planetary formation & molecular complexity

Key Questions: Herschel's promise

- What: Cold dust in the ISM
- Where: will add supernova remnants
- How: Gas-Grain interaction in AGB ejecta
- When: To be done
- Why: planetary formation & molecular complexity

Dust Inventory: what & where

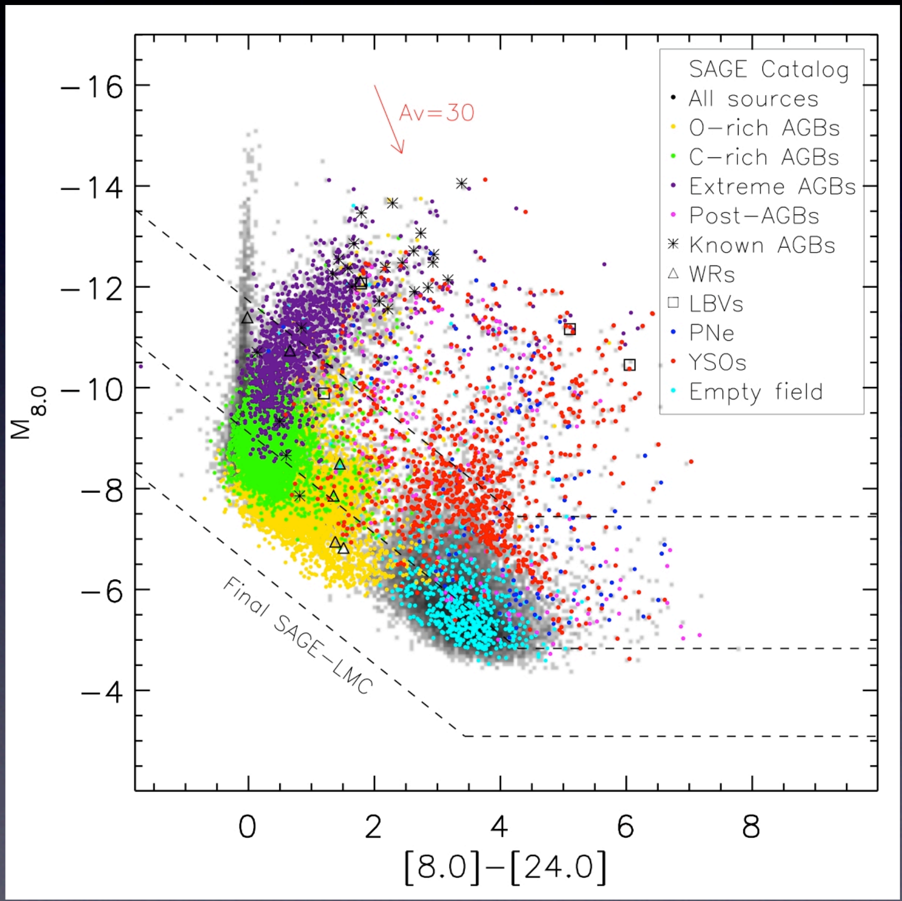
SOFIA:

- census of stardust injected into the Milky Way
- compare to interstellar dust characteristics
- Volume limited sample of stardust sources in the Milky Way based on GAIA distances

JWST/MIRI:

- census of stardust injected into the Andromeda Galaxy
- Contribution from cannibalized dwarf galaxies
- Dust formation in supernova ejecta

LMC: SAGE & SAGE-Spec



Dust & Gas: How

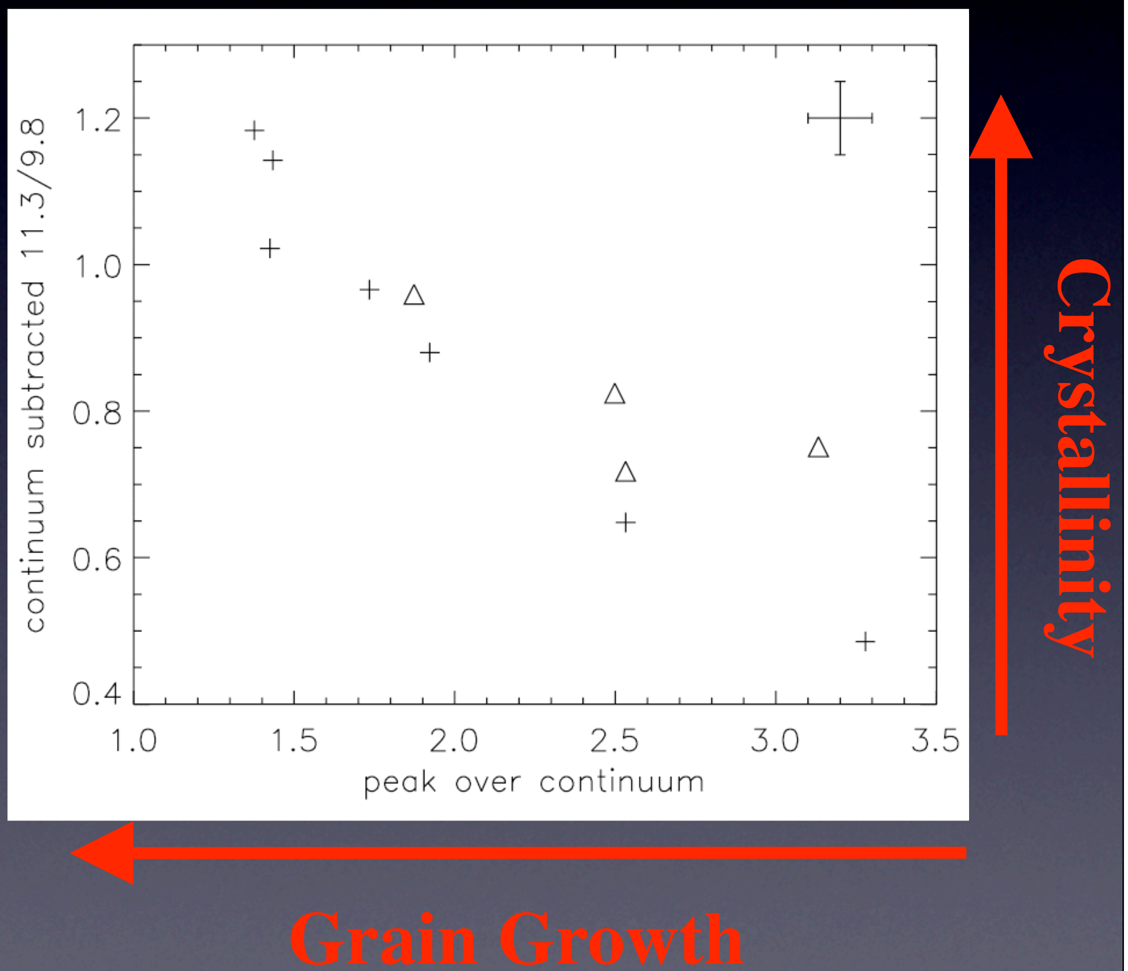
SOFIA

- Wide spectral coverage & high spectral resolution
- Dust formation & destruction
- Molecular complexity
- Continue where Herschel will leave off

PAHs & Dust Evolution in Protoplanetary Environments

JWST

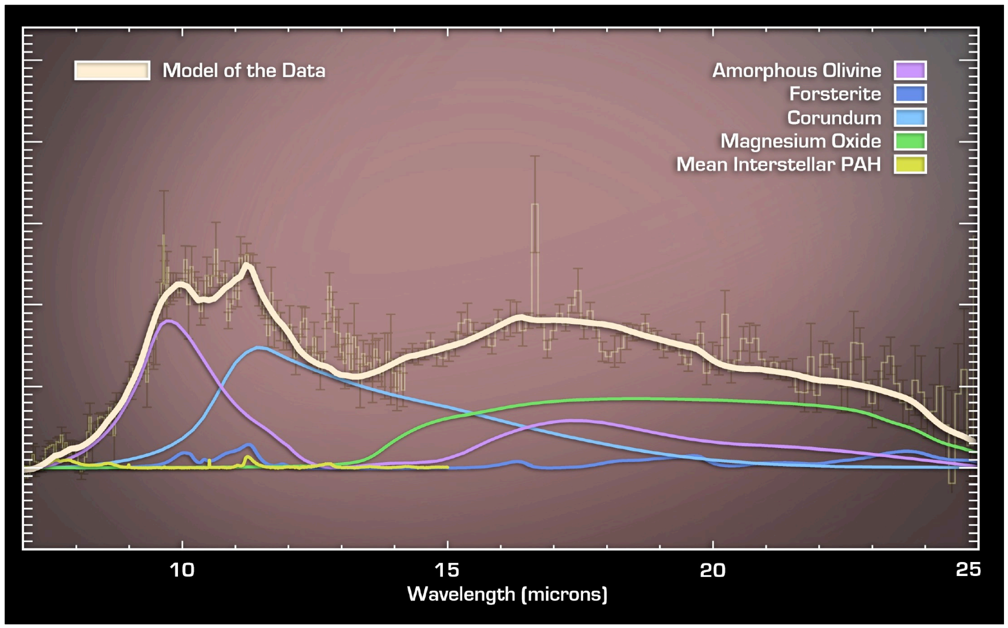
- Silicates: composition, crystalization and grain growth in the terrestrial zone
- PAHs: Organic inventory & tracing the geometry of the disk



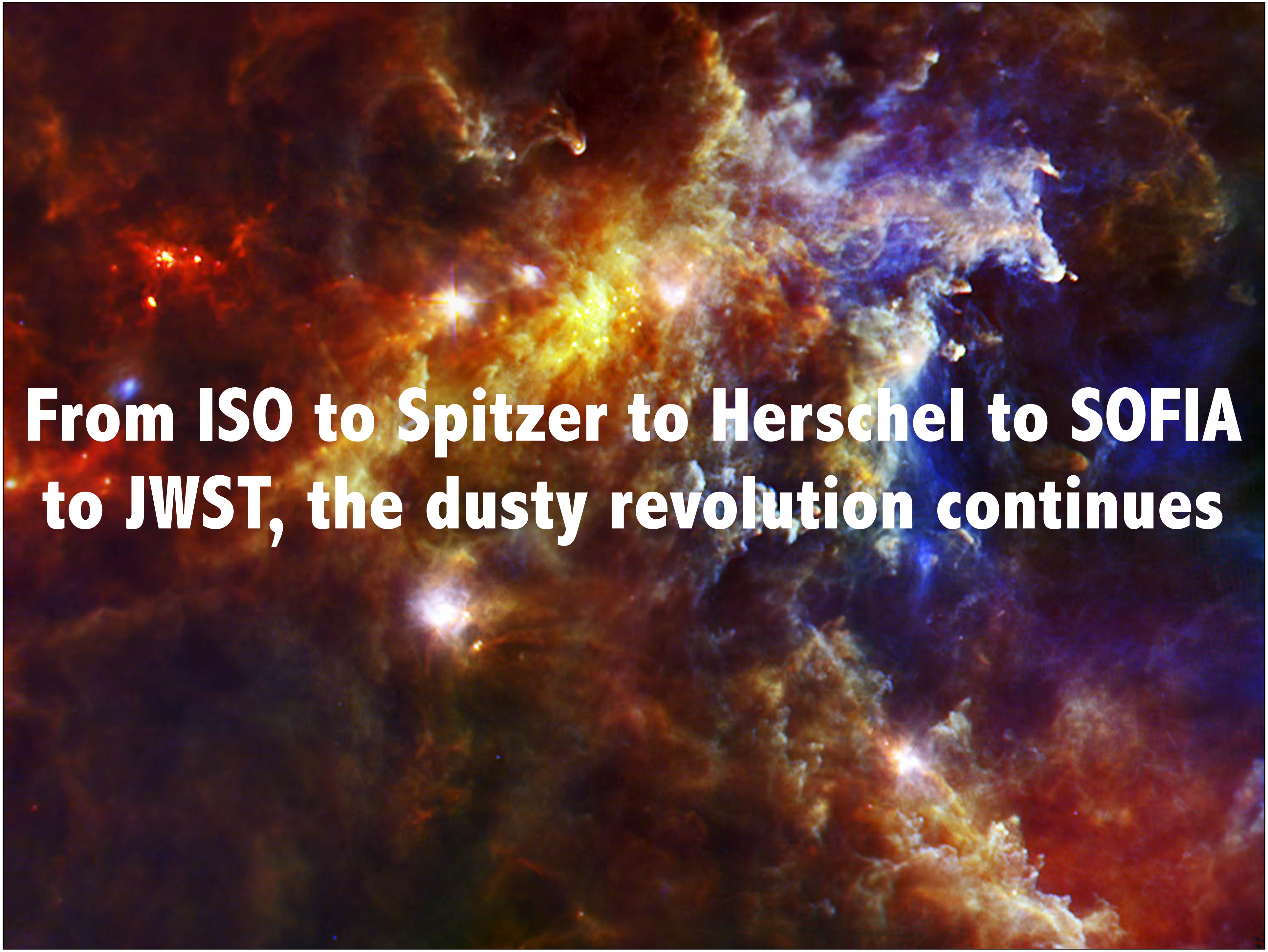
Dust through the Ages

JWST

Dust composition in extreme environments: quasar (winds), ULIRGS, super star clusters, SNe, high-z



Kemper et al, ApJ, 668, L107


From ISO to Spitzer to Herschel to SOFIA
to JWST, the dusty revolution continues