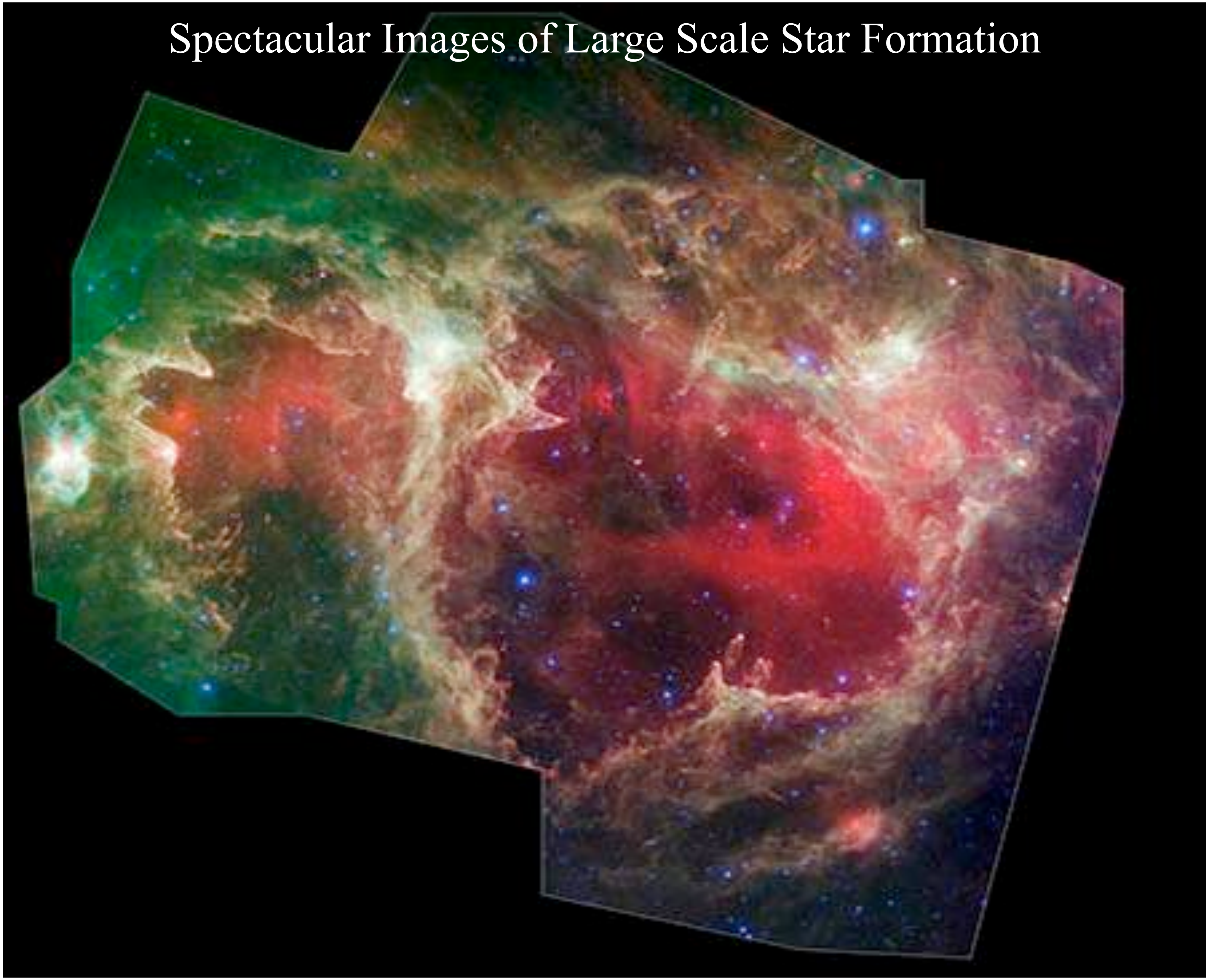
Things I Never Imagined Spitzer Would Do

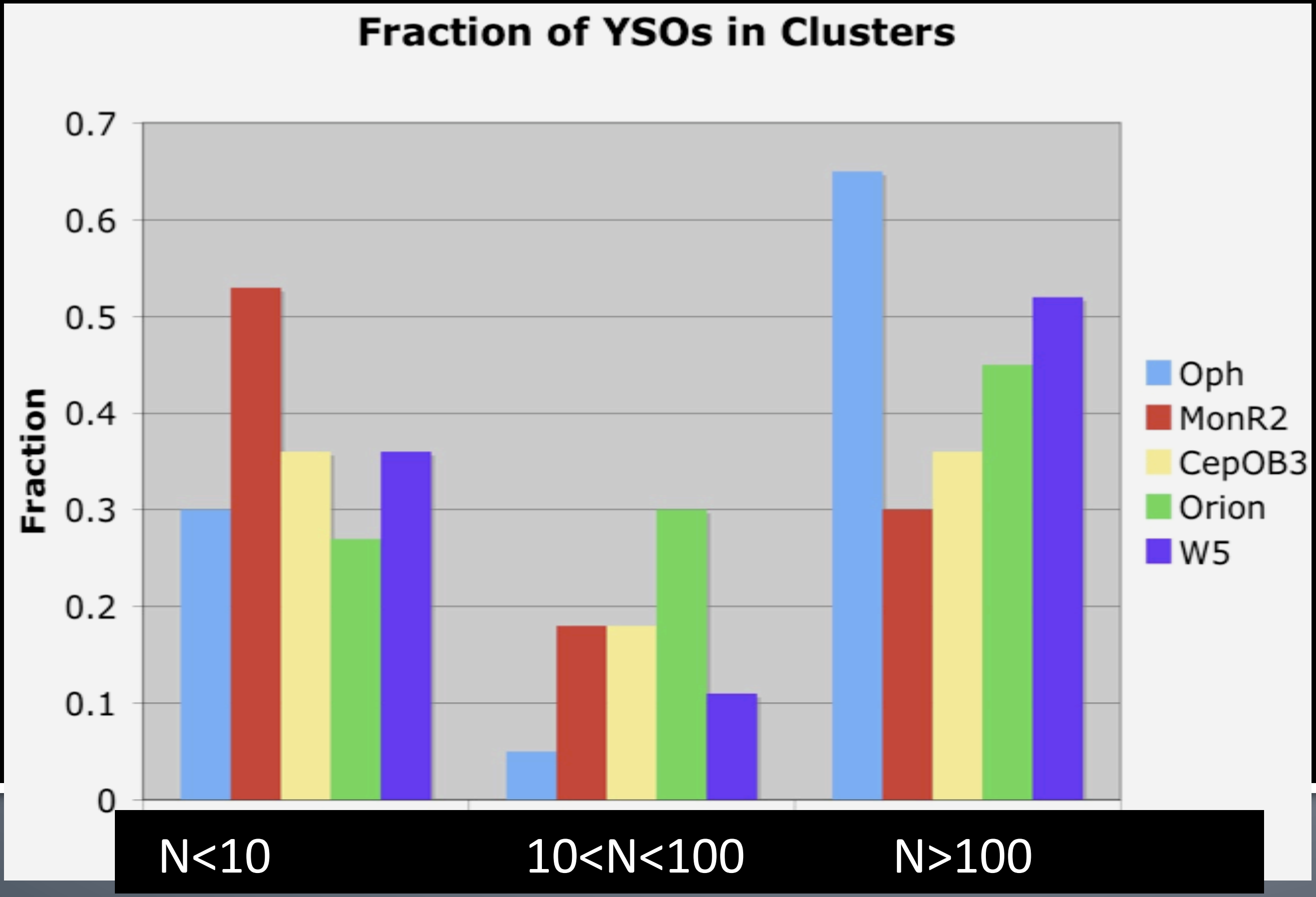
A Summary Talk at the Spitzer Science Conference
Michael Werner
28 October 2009

c2d image of Serpens Cloud

Spectacular Images of Large Scale Star Formation



Thousands of Young Stellar Objects, permitting powerful statistical conclusions [Neal Evans, c2d]

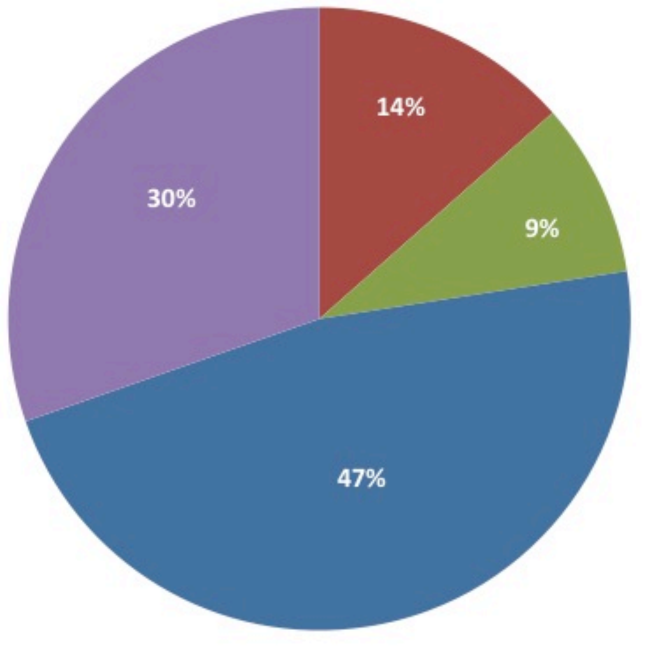


33% 19% 48%

L. Allen

Another Example…….

19 clouds, 3158 YSO



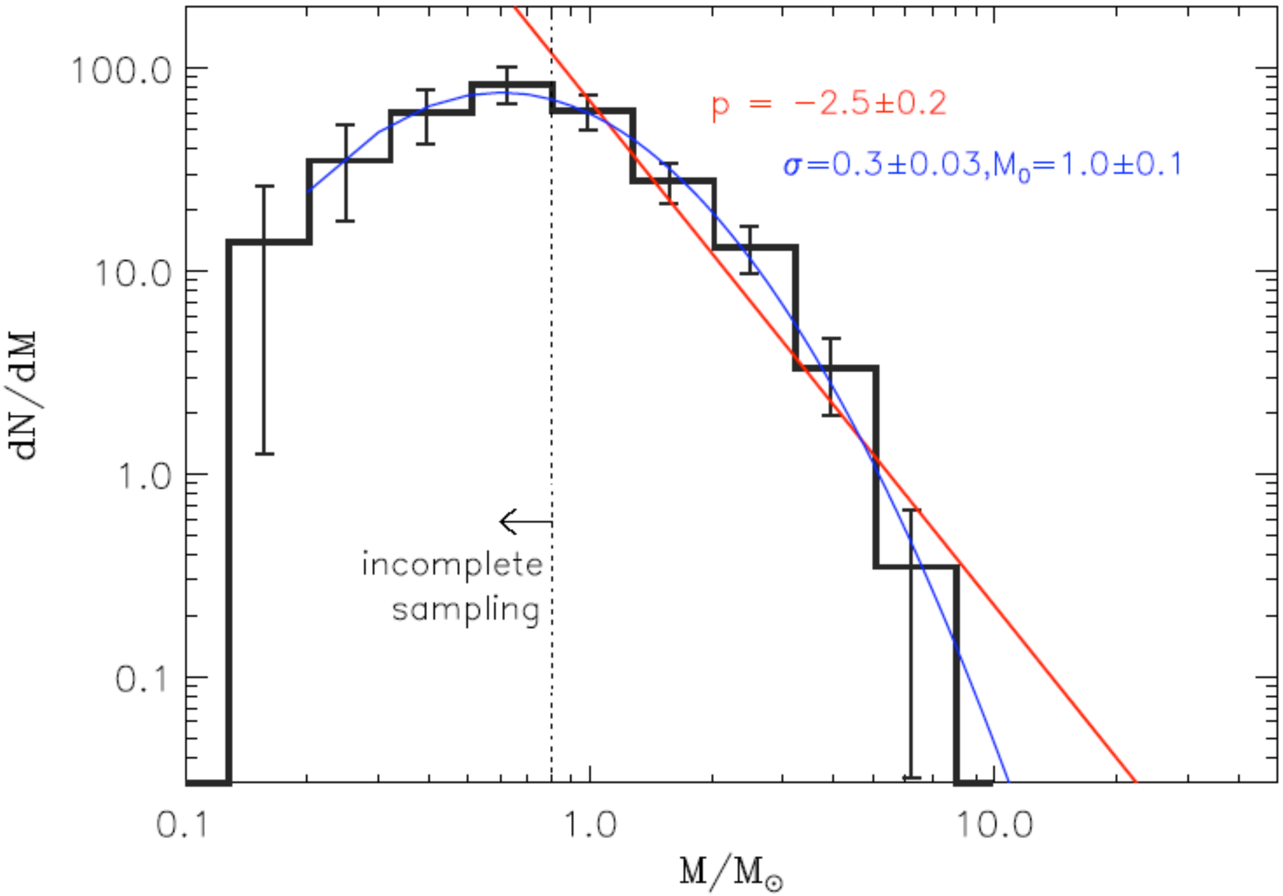
I:	$\alpha \geq 0.3$	14%
Flat:	$-0.3 \leq \alpha < 0.3$	9%
II:	$-1.6 \leq \alpha < -0.3$	47%
III:	$\alpha < -1.6$	30%

IF Time is the only variable
AND
IF star formation continuous
for t > t(II)
AND
IF Class II lasts 2 Myr,
THEN

Class I lasts 0.57 Myr
Flat lasts 0.38 Myr
(longer than most previous
estimates)

Caveats:
GB clouds extincted
(decrease by ~0.1 Myr)
Class III census incomplete
Class III not included in timescale
Depends on *how* α is calculated
Class 0 mixed with Class I

Combined starless core mass distribution leads to well-constrained estimate of the IMF

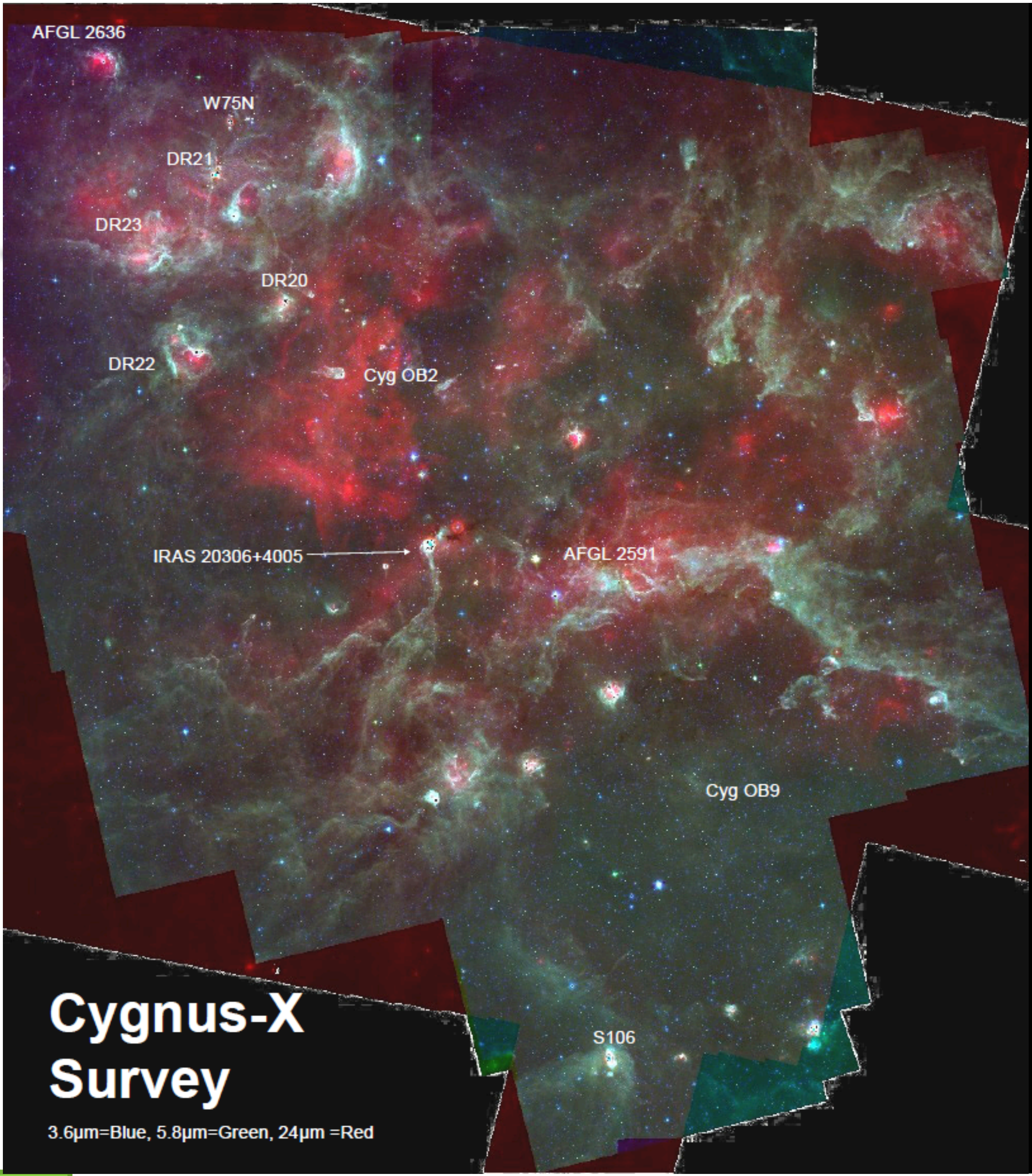


⇒

determined during core formation. If so, >25% goes into star.

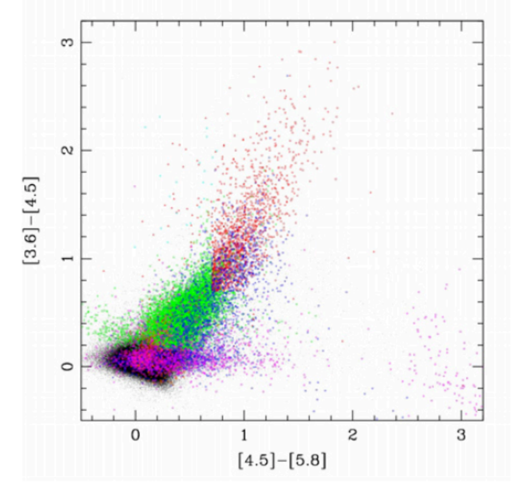
Enoch et al. 2008

10, 000 YSOs in Cygnus X – Joe Hora et al

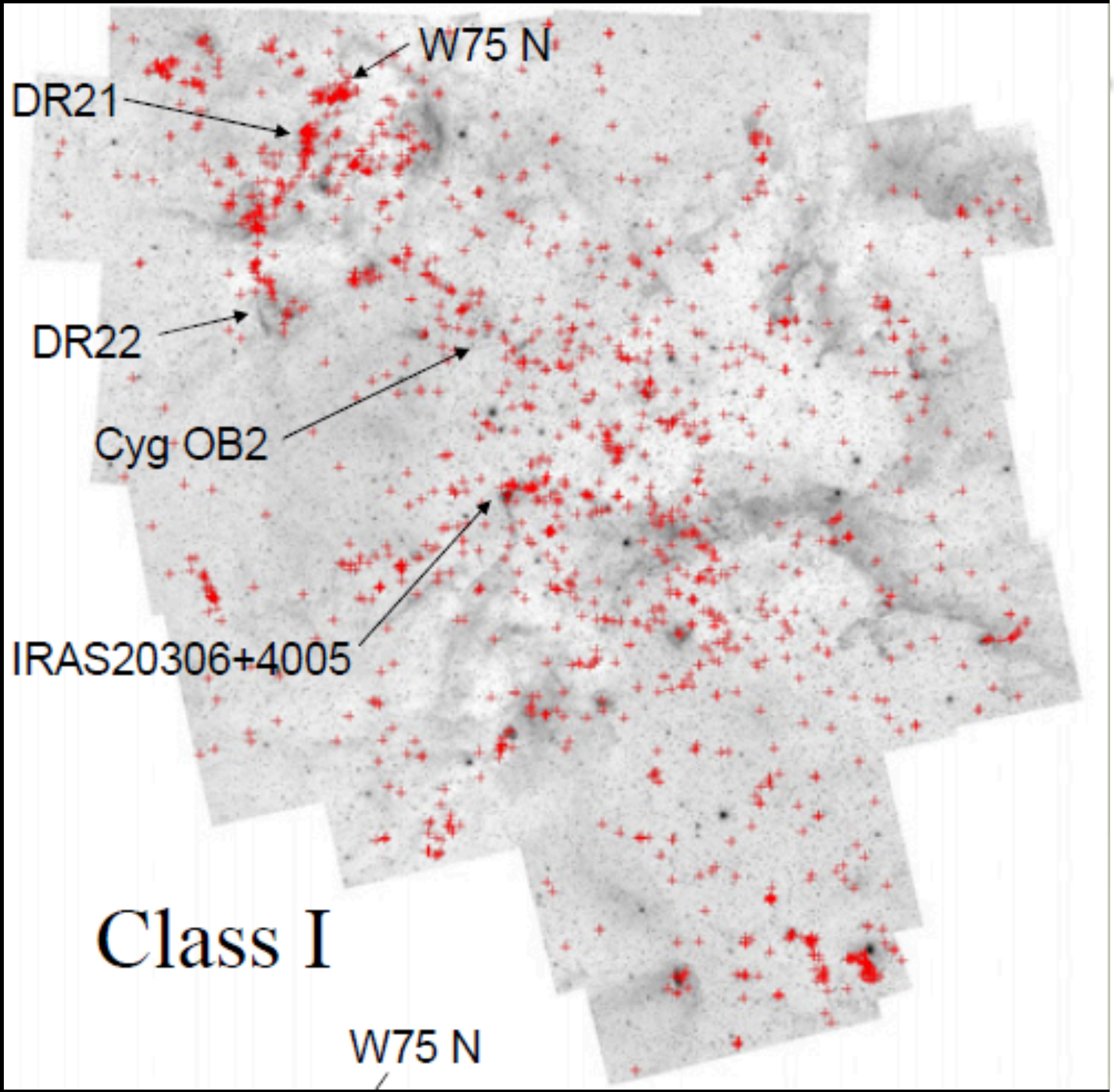


Cygnus-X Survey

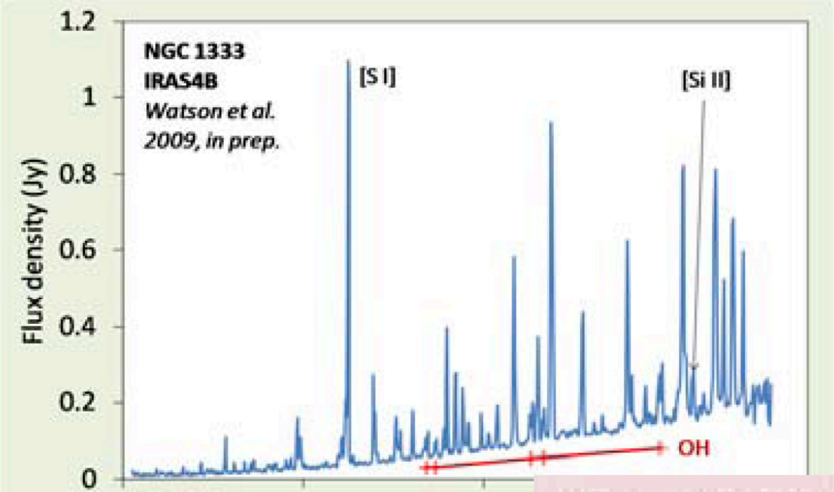
3.6µm=Blue, 5.8µm=Green, 24µm =Red

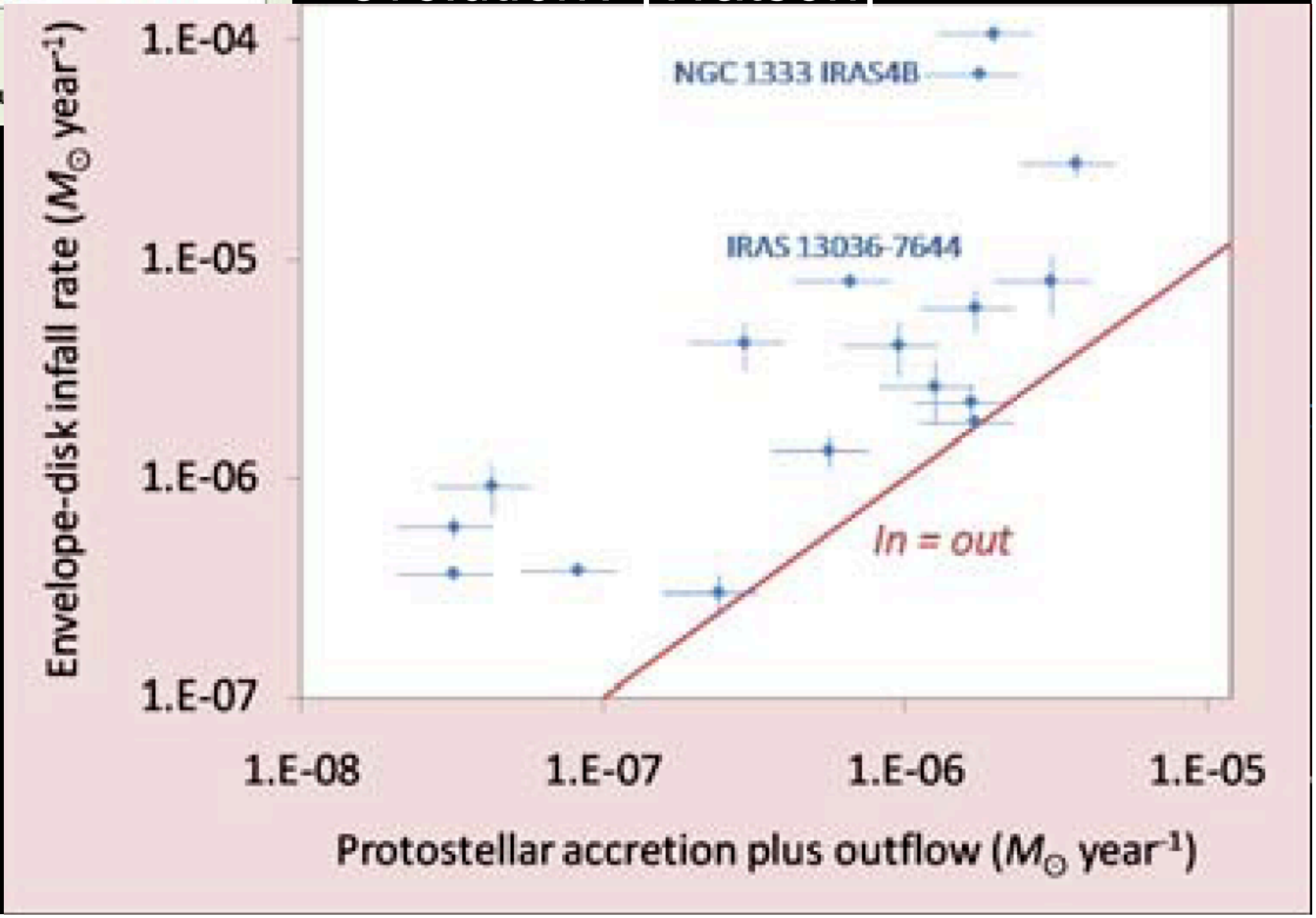


In Cygnus X, the Youngest Objects are found in filamentary structures. A similar result is found by Tereby for Taurus

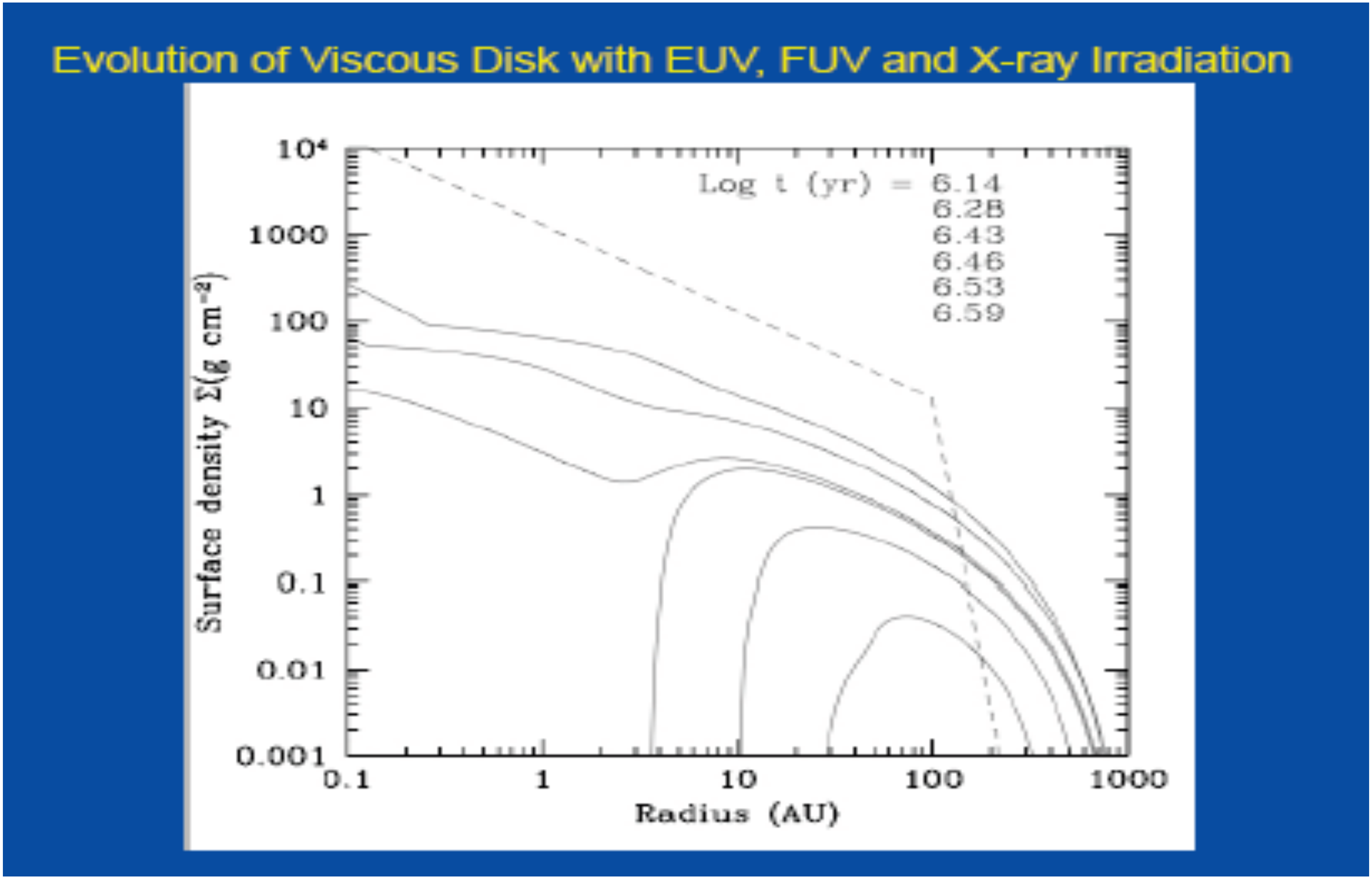


Further evidence for episodic accretion – how might this affect disk appearance and evolution? [Watson]



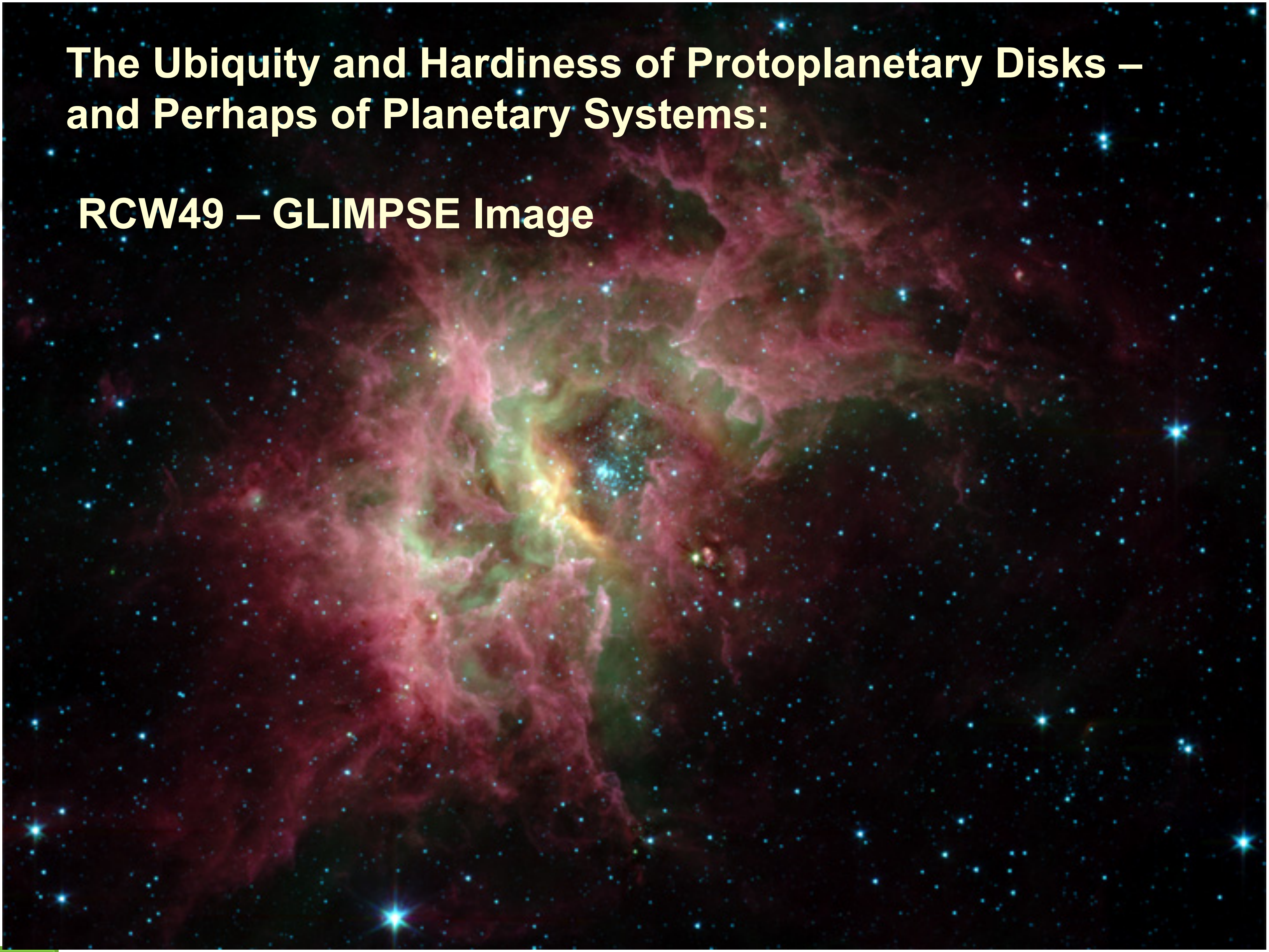


It seems that many fundamental issues about disk evolution and dissipation are still poorly understood….perhaps consideration of theoretical dissipation mechanisms, as shown in the calculation below by Hollenbach, could be helpful.



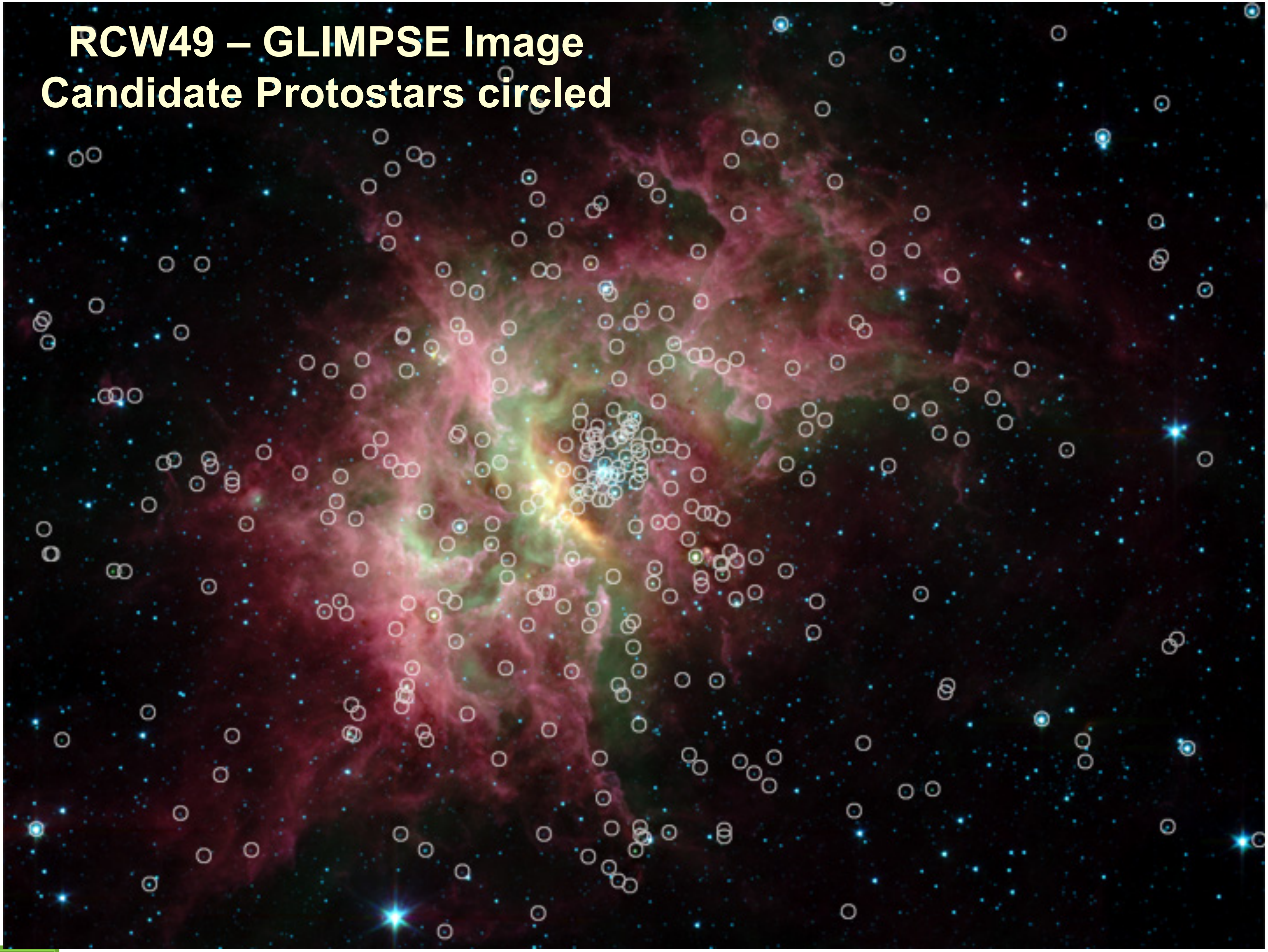
Evolution of Viscous Disk with EUV, FUV and X-ray Irradiation

The Ubiquity and Hardiness of Protoplanetary Disks – and Perhaps of Planetary Systems:



RCW49 – GLIMPSE Image

RCW49 – GLIMPSE Image
Candidate Protostars circled



Solar Systems Everywhere

The central star of the Helix Nebula, a hot, luminous White Dwarf, shows an infrared excess attributable to a planetary debris disk around the white dwarf central star

(Su et al)

Asteroidal debris around white dwarfs implies survival of solar system throughout the evolution of the original star [Jura et al]

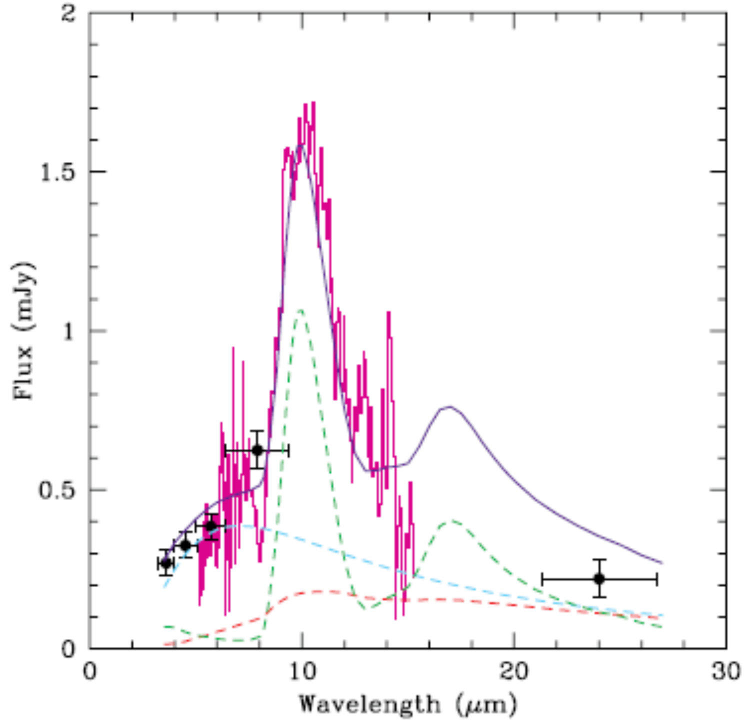


FIG. 3.—Comparison between photospheric-subtracted observations and predicted fluxes for the model disk described in the text. The points represent the IRAC and MIPS data listed in Table 1, while the IRS data from Fig. 1 are shown as the magenta line. The solid blue curve shows the total flux from the model, while the fluxes from regions I, II, and III are shown as dashed lines of cyan, red, and green, respectively.

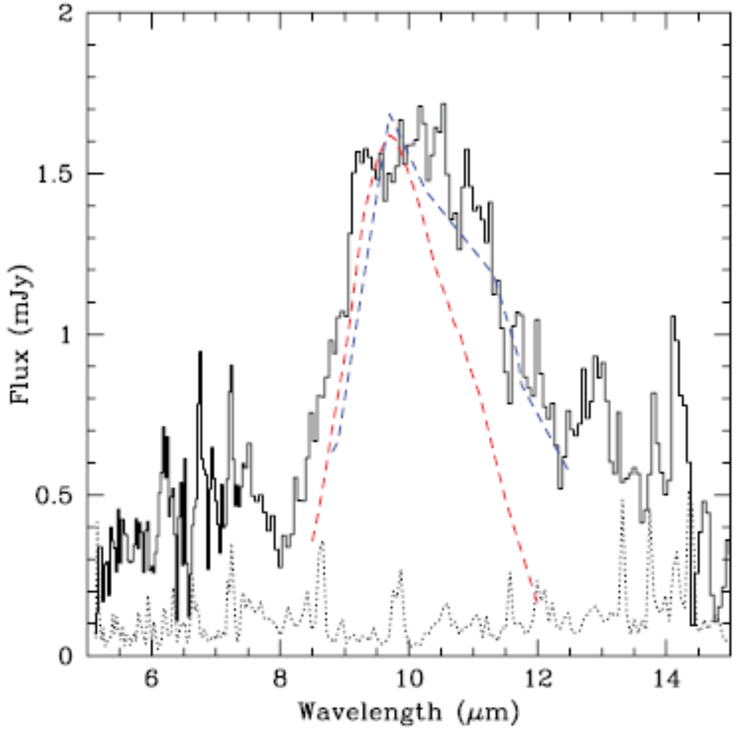


FIG. 1.—IRS spectrum of GD 362. The errors are shown as the dotted black line; the feature near 14 μm is a detector/instrument artifact. For comparison, we display the scaled profiles of interstellar silicates (Kemper et al. 2004) as a dashed red line and the emission from BD +20 307 (Song et al. 2005) as a dashed blue line.

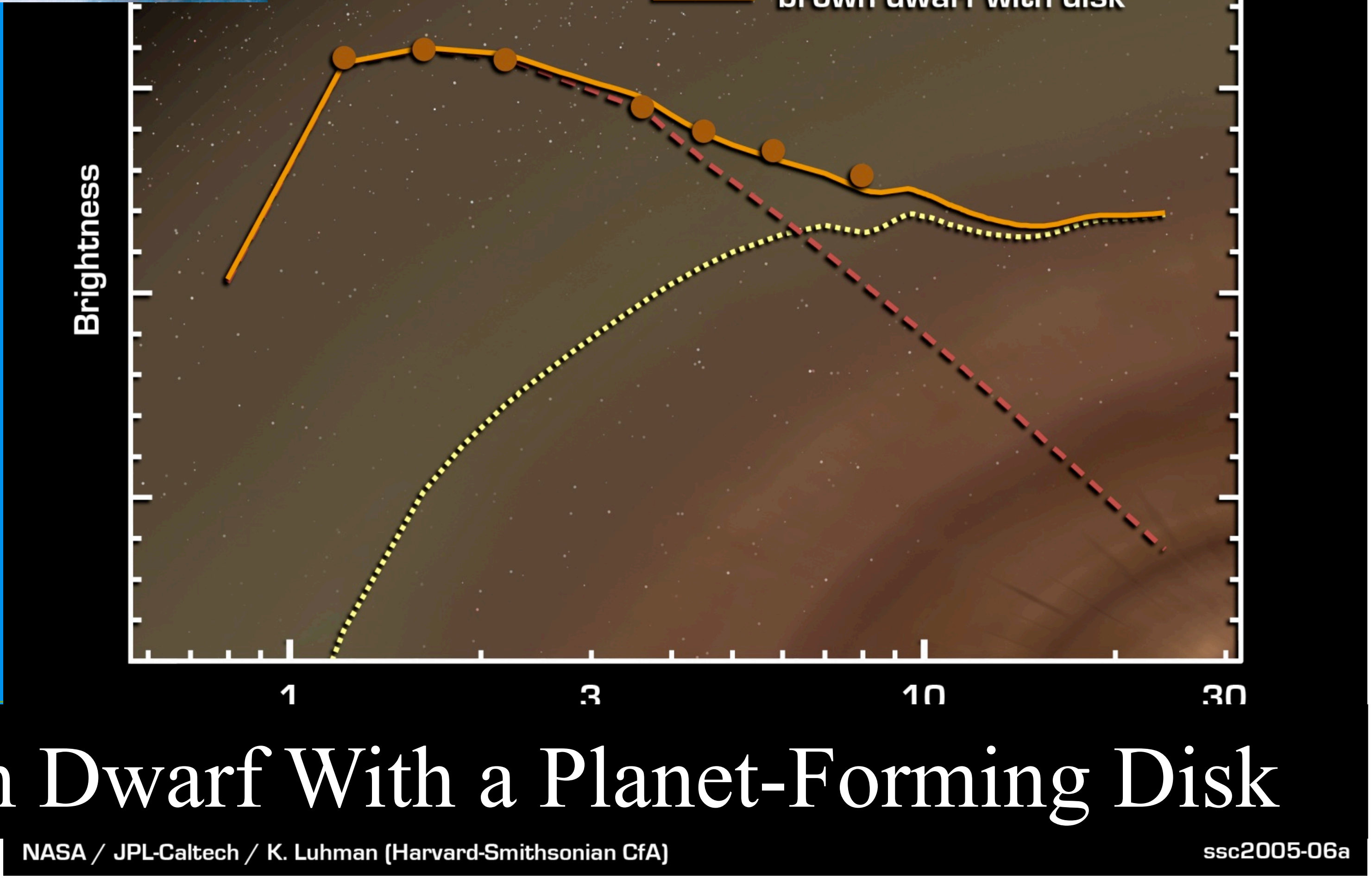
Planetary systems around white dwarfs

Prior to Spitzer, there was some evidence for infrared excesses around white dwarfs GD 362 and G29-38.

Spitzer has dramatically confirmed and extended these results:

- Crystalline silicate emission seen around 362 and 29-38
- Similar results for several other white dwarfs
- All such objects amongst small fraction of WD which show atmospheric metals
  - Metals should sink gravitationally in WD atmosphere
  - Presence of metals implies external pollution
  - Suggest common origin for circumdwarf dust and atmospheric pollution in tidal break up of asteroidal object
- Comparison of abundance pattern in white dwarf atmospheres allows study of asteroidal composition – comparative exoplanetology

Brown Dwarfs Form Like Stars: Can “Planets” have Planets?

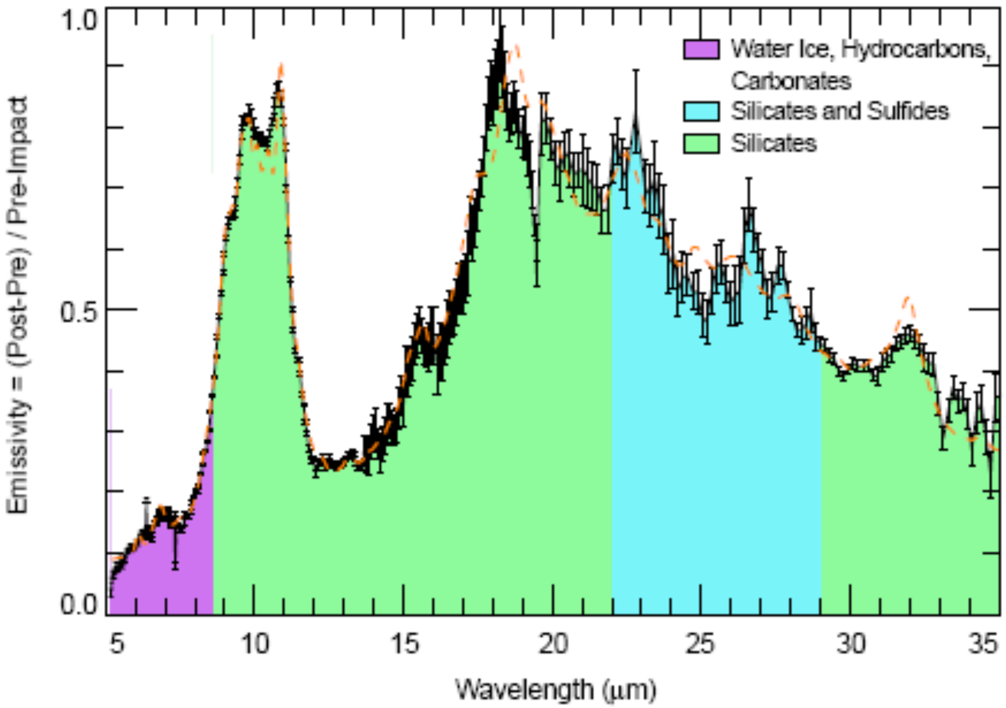


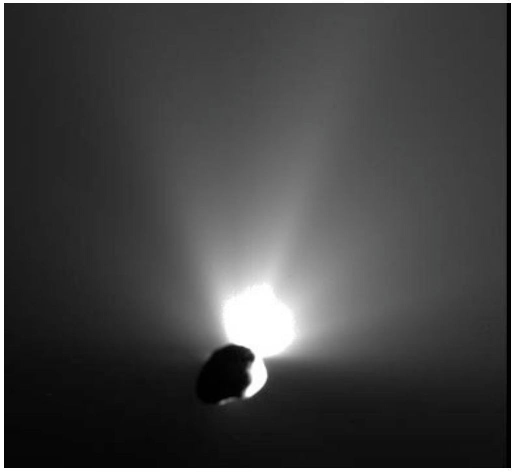
A Brown Dwarf With a Planet-Forming Disk

NASA / JPL-Caltech / K. Luhman (Harvard-Smithsonian CfA)

ssc2005-06a

Fate brought Deep Impact, Comet Tempel 1, Spitzer, and Casey Lisse together……





Spitzer spectrum of ejecta from Deep Impact event in which a refrigerator-sized projectile collided with a small cometary nucleus

COMPARATIVE (EXO)PLANETOLOGY

Crystalline silicates - from the green sand beaches of Hawaii to the outer solar system to nearby stars and beyond…..

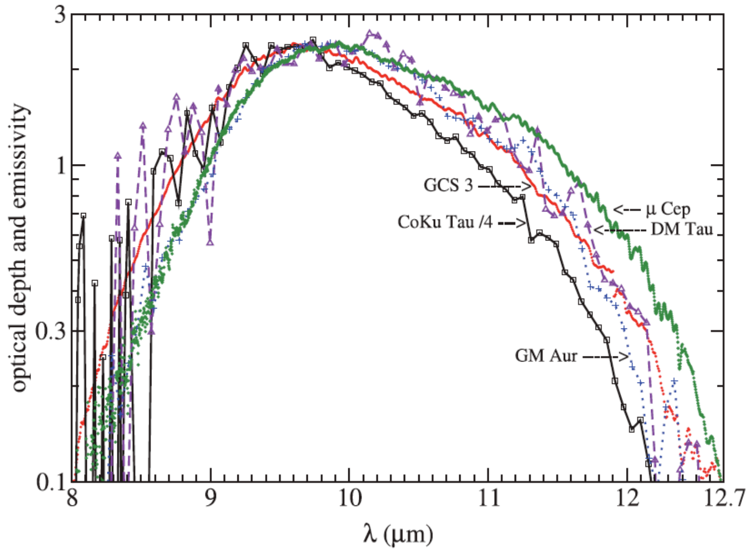
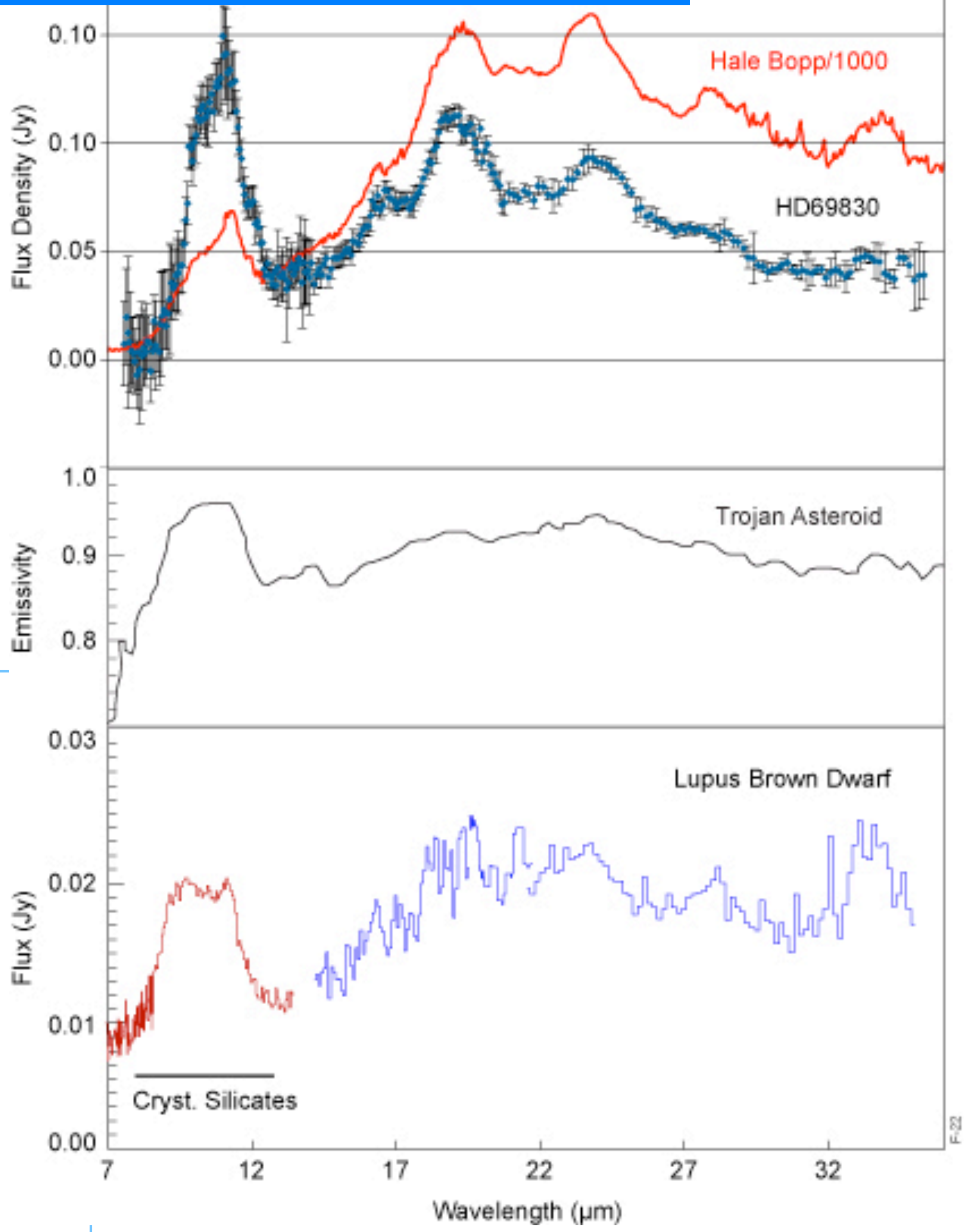


FIG. 3.—The 10 μm silicate profiles of GCS 3, CoKu Tau/4, DM Tau, GM Aur, and μ Cep. The GCS 3 profile of Kemper et al. (2004) is the interstellar silicate absorption toward the Galactic center and the other four profiles are scaled emissivities with baselines subtracted (see Table 3).



Solving the amorphous-crystalline conversion question?

Spectral Studies By Abraham *et al.* (2009) & Van Boekel *et al.* (2004) have suggesed flares as the source of crytallization and radial gradients in crytallization towards the primary

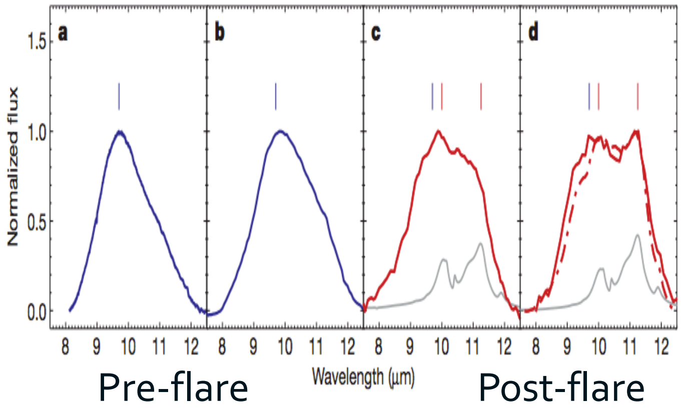
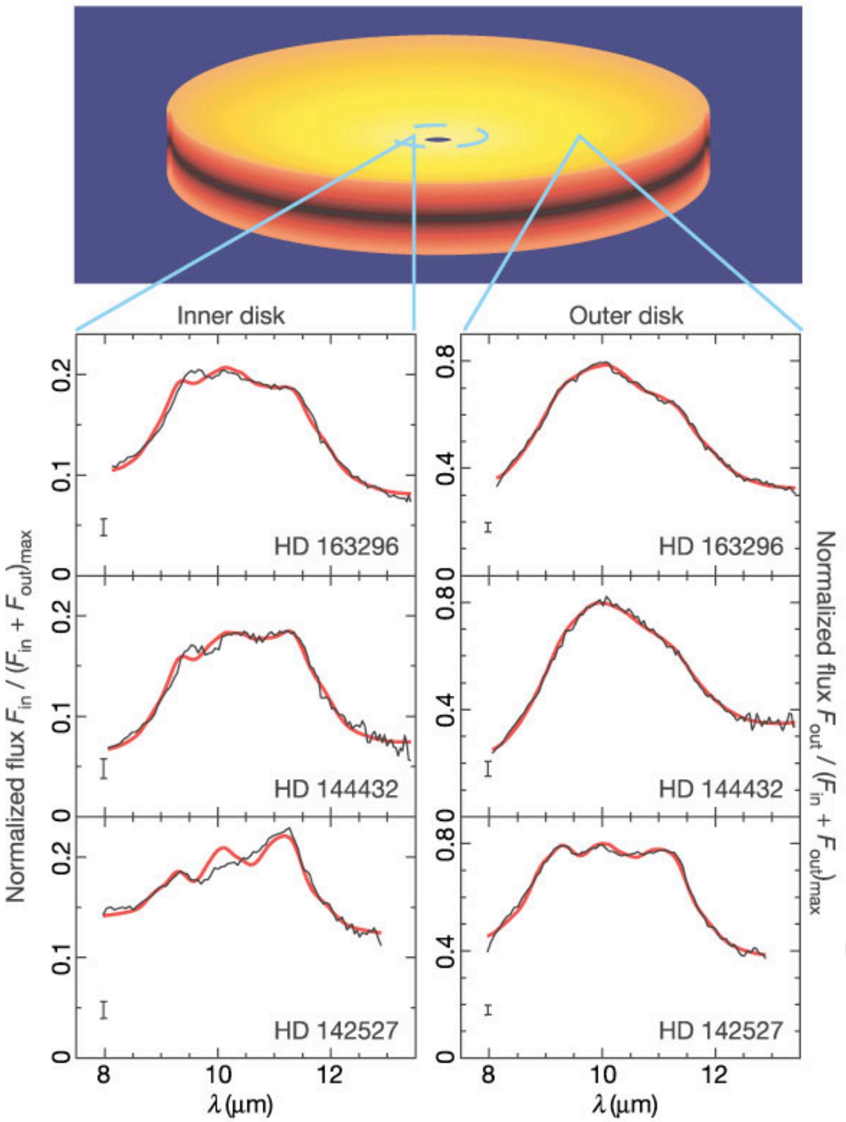


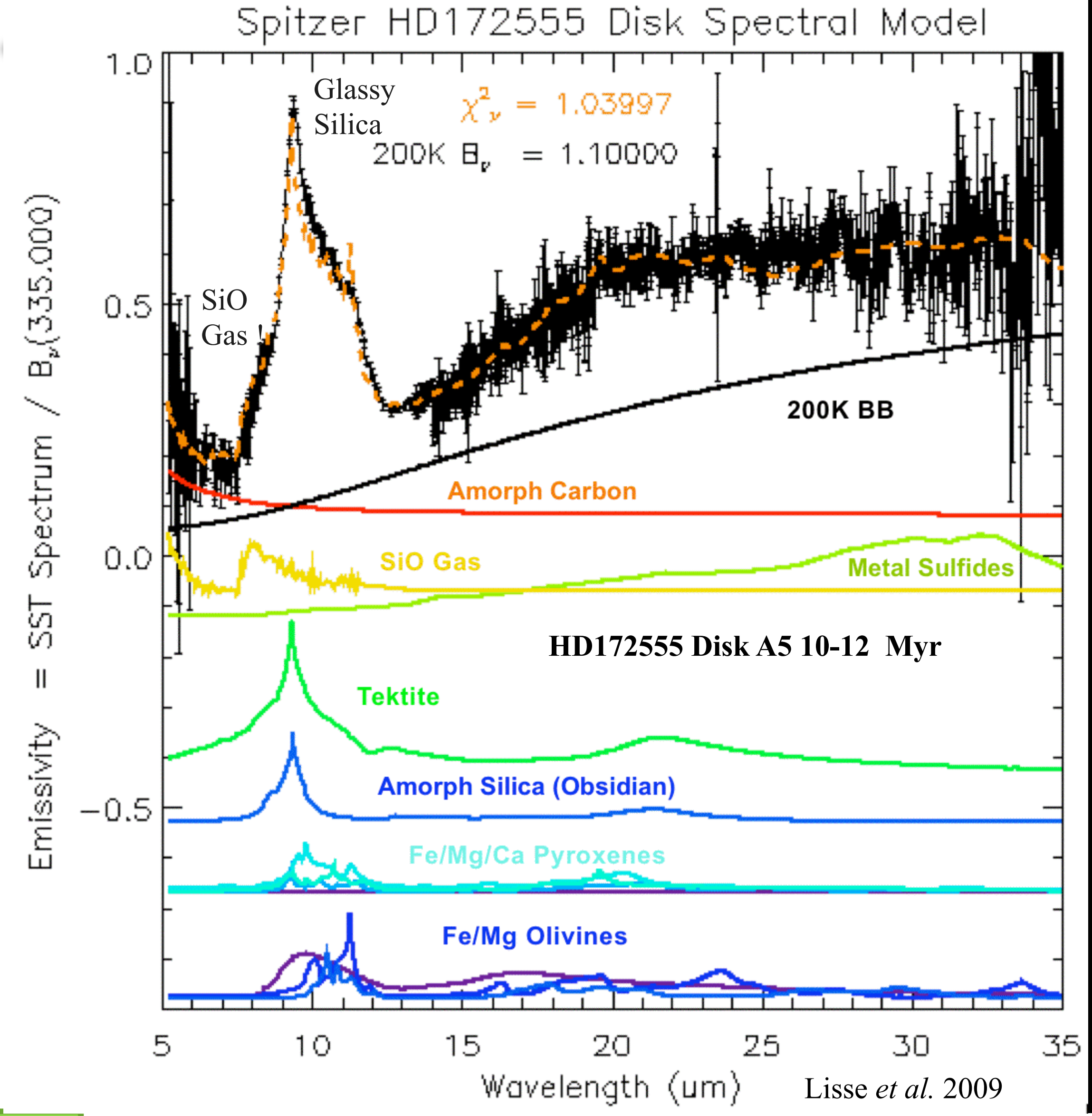
Figure 1 | Silicate emission in the 8–12-μm range. **a**, Spectrum of interstellar grains measured in the direction of the Galactic Centre[1]. **b**, Spitzer Infrared Spectrograph spectrum of EX Lupi, obtained on 2005 March 18, in quiescent phase. **c**, Our Spitzer spectrum of EX Lupi, obtained on 2008 April 21, in the middle of the present outburst. **d**, Red line, ground-based spectrum of Comet 1P/Halley[3]; dash–dot line, Spitzer spectrum of the ejecta from Comet 9P/Tempel 1 during the Deep Impact experiment[14] (available in the Spitzer archive). After a linear continuum removal, the spectra were normalized to their peak values. In **a**, we see the characteristic triangular shape profile attributed to amorphous silicate grains[1]; the vertical blue dash at 9.7 μm (repeated in all panels) corresponds to the peak wavelength of the amorphous silicate profile as measured in the laboratory[11]. In **b**, the EX Lupi spectrum closely resembles the amorphous profile, with some slight excess on the long-wavelength side. In **c**, peaks and shoulders due to crystalline silicates can be identified. Peak wavelengths of forsterite at 10.0 and 11.2 μm, as measured in laboratory experiments[12,13], are marked by red dashes. The grey curves in **c** and **d** display the emissivity curve of pure forsterite[13], assuming representative silicate grain temperatures of 1,250 K and 300 K, respectively. Panel **d** shows that the same crystalline features can be observed in cometary spectra.



EX Lupi, Abraham *et al.* (2009)

HD 142527, Van Boekel *et al.* (2004)

HD172555, like β Pic, is an A5V star in the BPMG (~12 My old), with a highly unusual circumstellar dust spectrum rich in emission from amorphous *silica* and *SiO* gas. Unlike any other system modeled to date, tektite & obsidian thermal emission spectra are required to fit the data. A combination of olivines and pyroxenes cannot make a good fit. In fact, there are almost no pyroxenes present, suggesting these have been destroyed to make silica.



Spitzer HD172555 Disk Spectral Model

Lisse *et al.* 2009

Tektite and Obsidian Dust : products of quick quenching of molten rock at high T, low P.

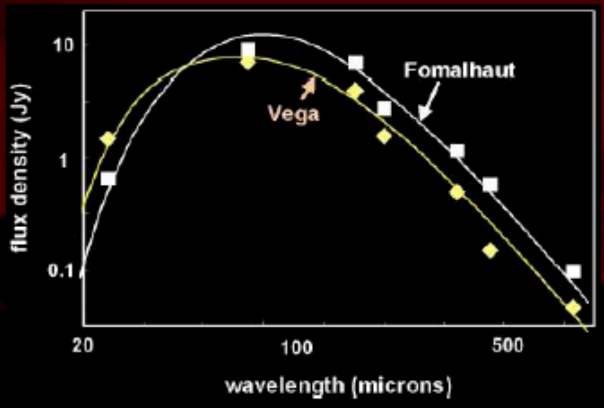
SiO gas : produced by vaporizing rock.

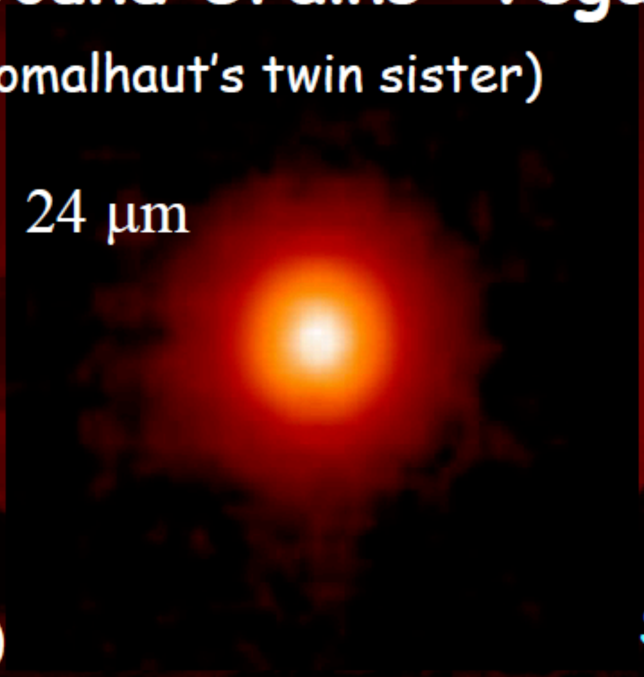
$M_{Dust} > M_{Pluto}$: 150 - 200 km radius asteroid's worth (4×10^{19} – 2×10^{20} kg) of fine silica rich material; ~500 km radius worth (10^{21} – 10^{22} kg) of large rubble; and ~10^{22} kg of SiO gas at ~5.6 AU.

Mineralogy: Parent object does not seem like any known taxonomy, asteroid or comet. If one has to be selected, the parent appears to be closest to an A-type igneous asteroid : there is copious metal sulfide and olivine-type rock. **However, it is not easy to show where the sizeable silica content originates - A-types are not known for this.**

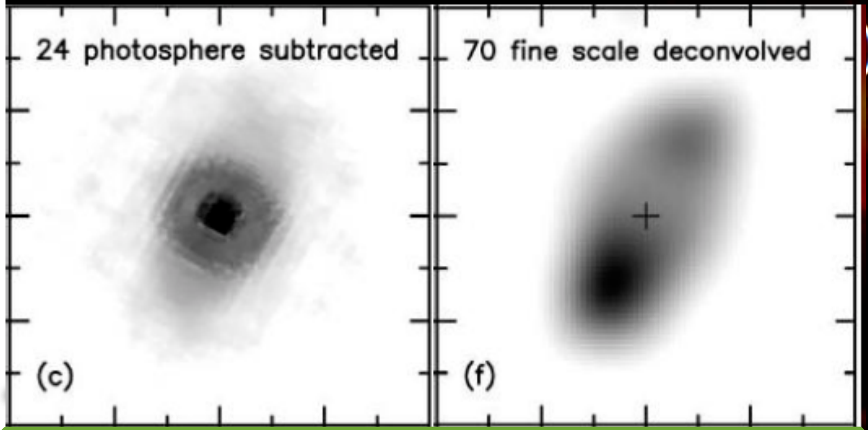
Outflows and Weakly Bound Grains: Vega

Vega, A0V, 7.7 pc, ~200 Myr (Fomalhaut's twin sister)

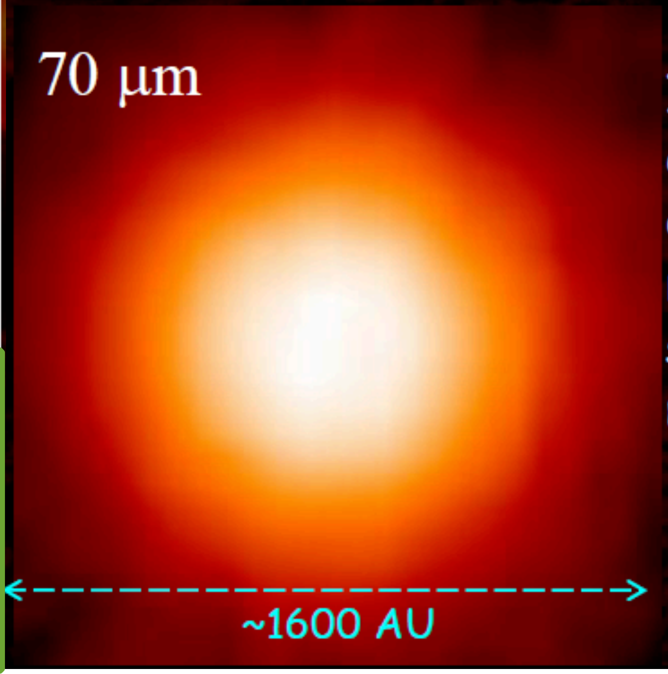




Su et al. 2005

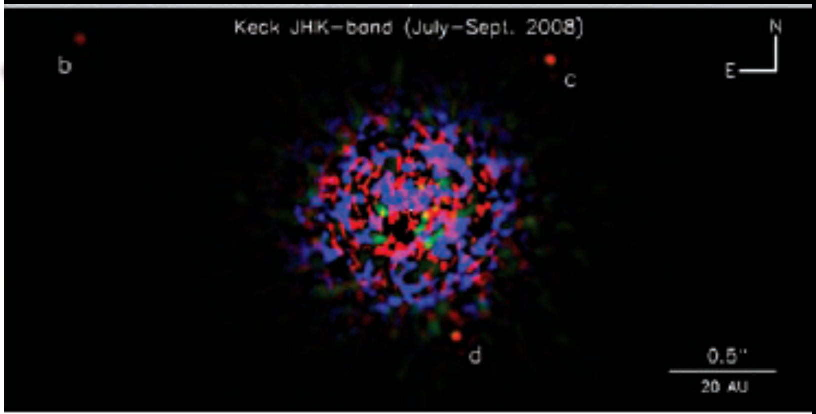


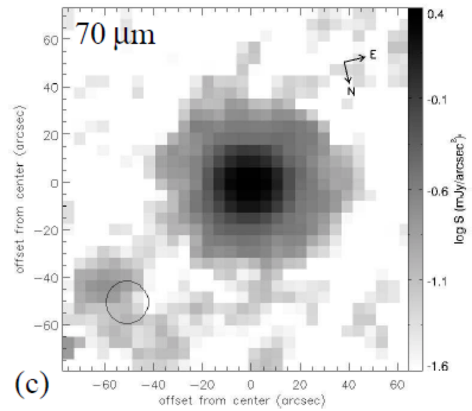
Fomalhaut Images [above] look nothing like Vega, although their SEDs are virtually identical

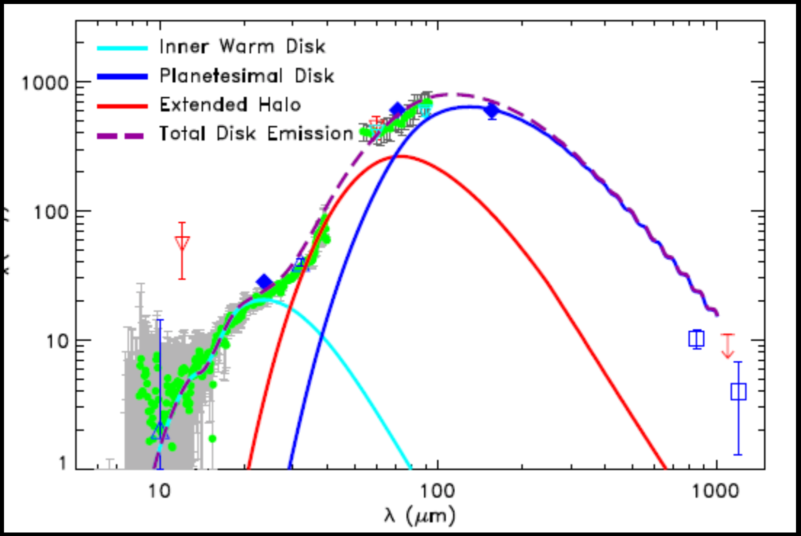


IR emission extends far outside the ring-like disk seen at sub-millimeters

The Anatomy of an Exoplanet System







HR8799 and its planets: A5V star: M~1.5 Msun 40 pc from Earth Estimated age 20-160MY

Marois et al imaged three planets:

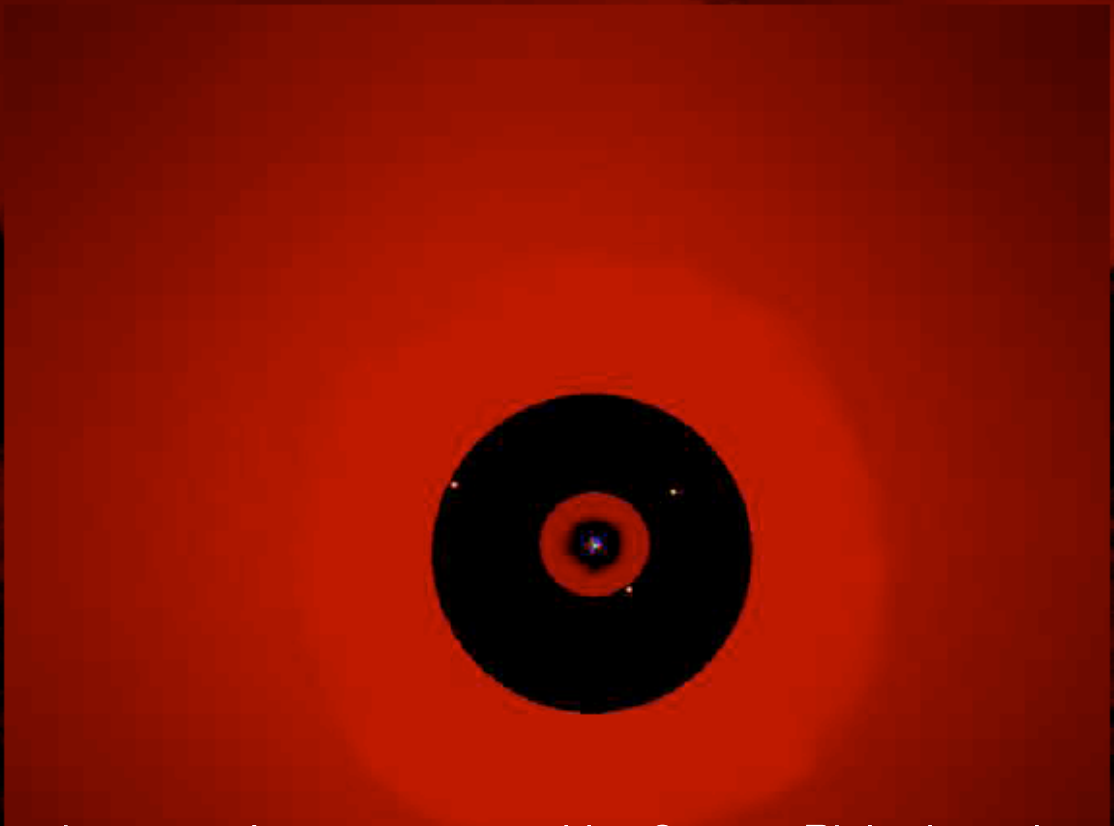
8799b, r=68au, M~7Mjup

8799c, r=38au, M~11Mjup

8799d, r=24au. M~10Mjup

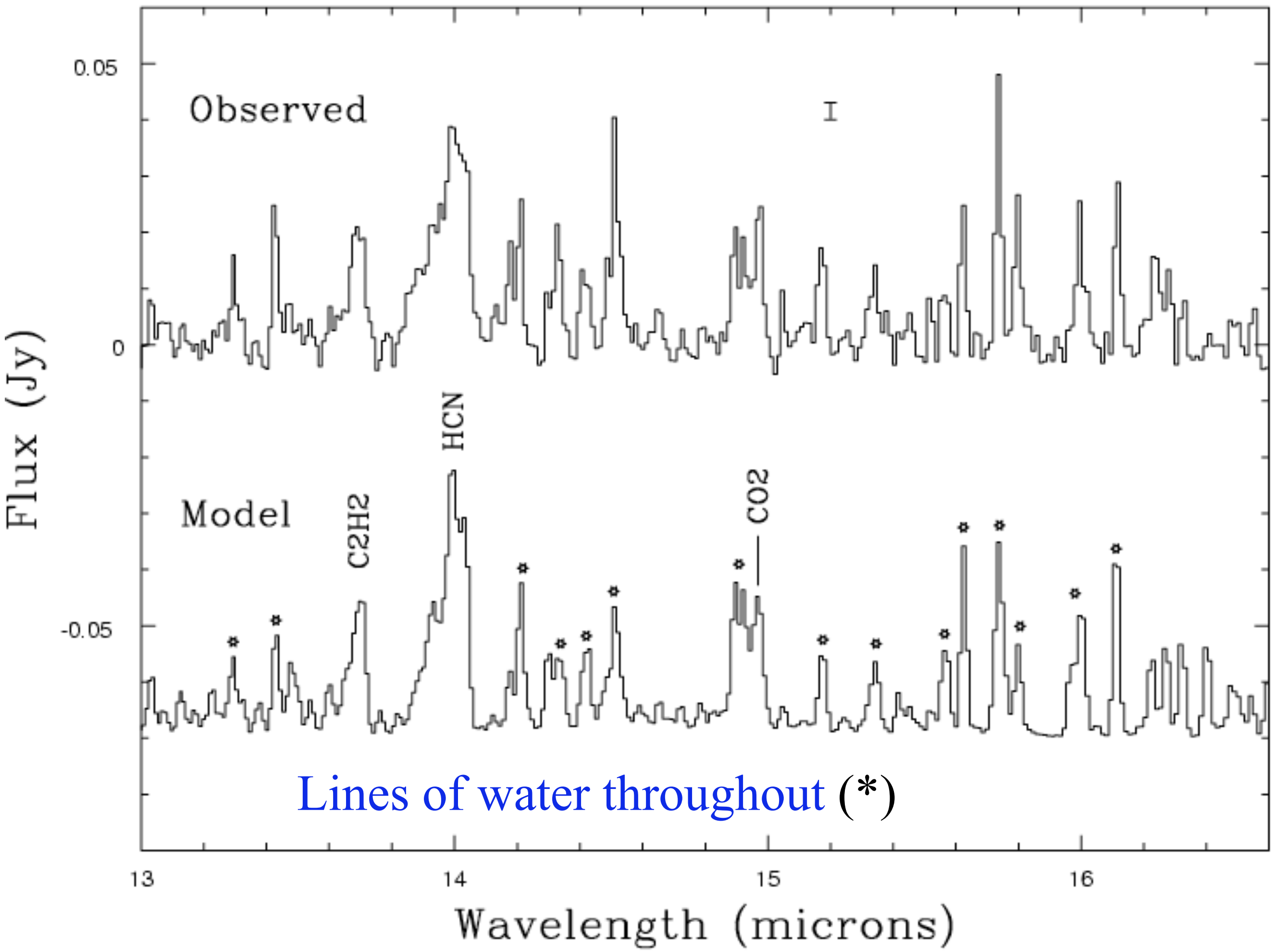
“a scaled up version of our solar system”

A Full View of the HR8799 System



This image, not quite to scale, was prepared by George Rieke based on Spitzer data combined with direct imaging of the three planets. It shows the star HR8799, its three known planets, and the complex dust disk surrounding it. It is totally amazing. Like the Vega images and some of Lisse’s results, it is suggestive of dynamical episodes which mirror similar processes in our Solar System

Continuum-subtracted T Tauri Star Spectrum – Prevalence of planets heightens interest in these and other spectra



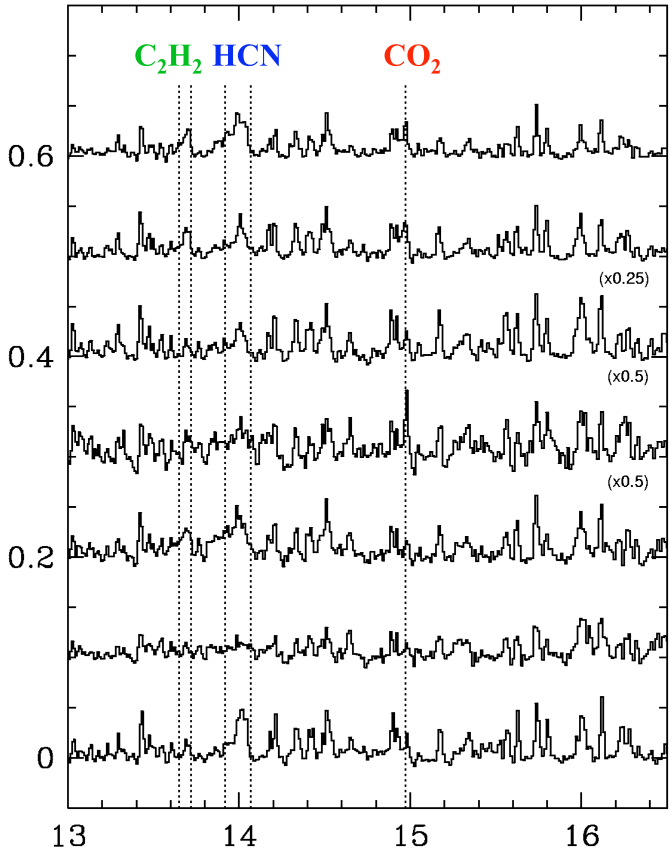
Lines of water throughout (*)

Molecular Emission Properties

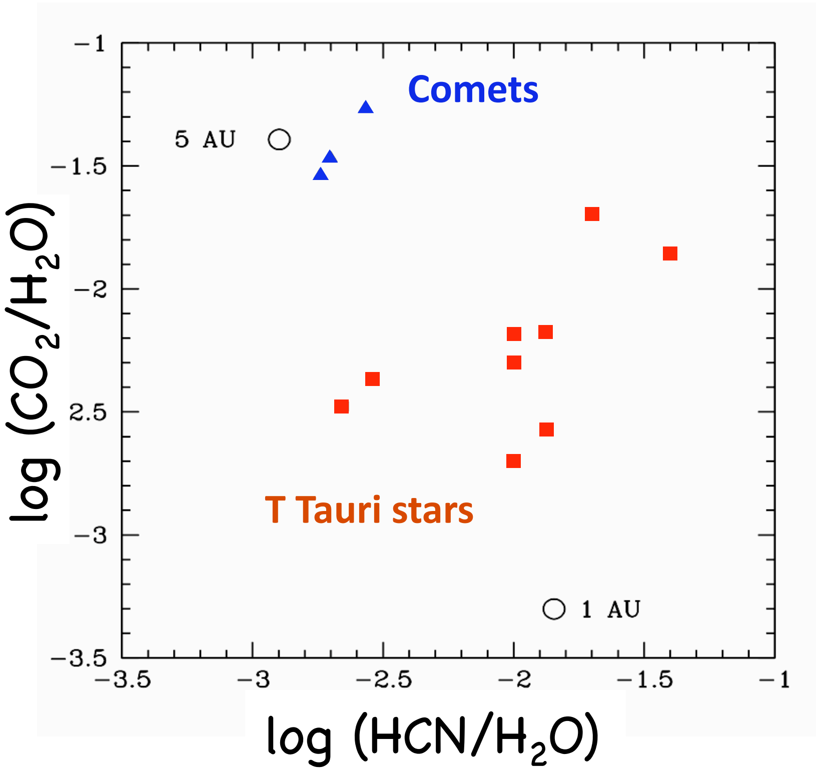
Molecule	T (K)	N (10^{16}cm^{-2})	R (AU)
H_2O	575	65	2.1
OH	525	8.1	2.2
HCN	650	6.5	0.6
C_2H_2	650	0.81	0.6
CO_2	350	0.2–13	1.2
CO	900	49	0.7

Temperatures and emitting areas consistent with an origin in the terrestrial planet region of the disk

Molecular Emission is Common, Diverse

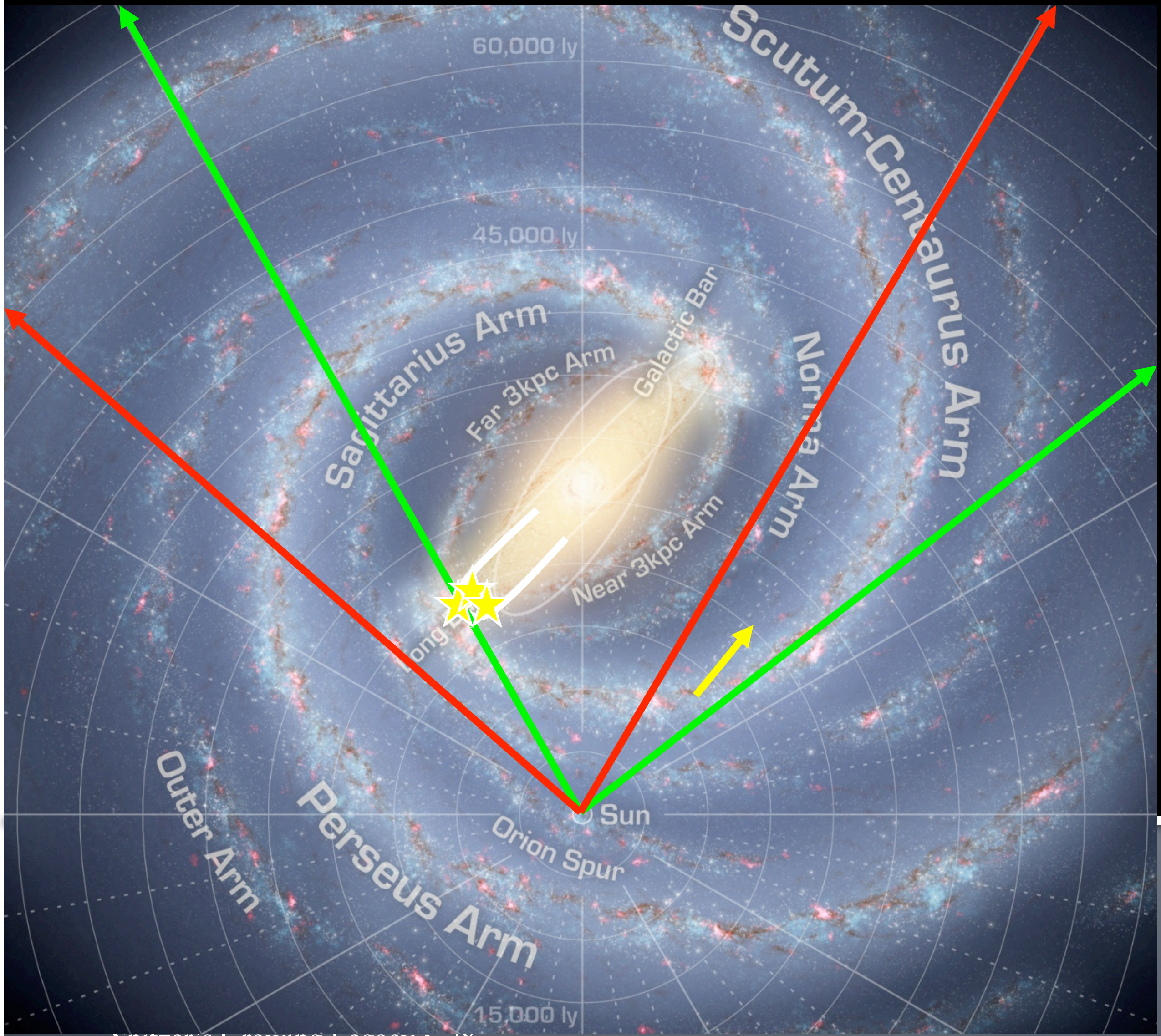


See also Salyk et al. (2008)



Spectra of YSOs provide evidence for grain growth and disk settling (Furlan)

4. Galactic Structure: Summary



Artist's conception by Robert Hurt (SSC/IPAC/JPL)

1. Long Bar confirmed and (partially) mapped.

2. Tangencies confirm Drimmel (2000) and Drimmel & Spergel (2001) based on K band light from COBE, but provide more precise information.

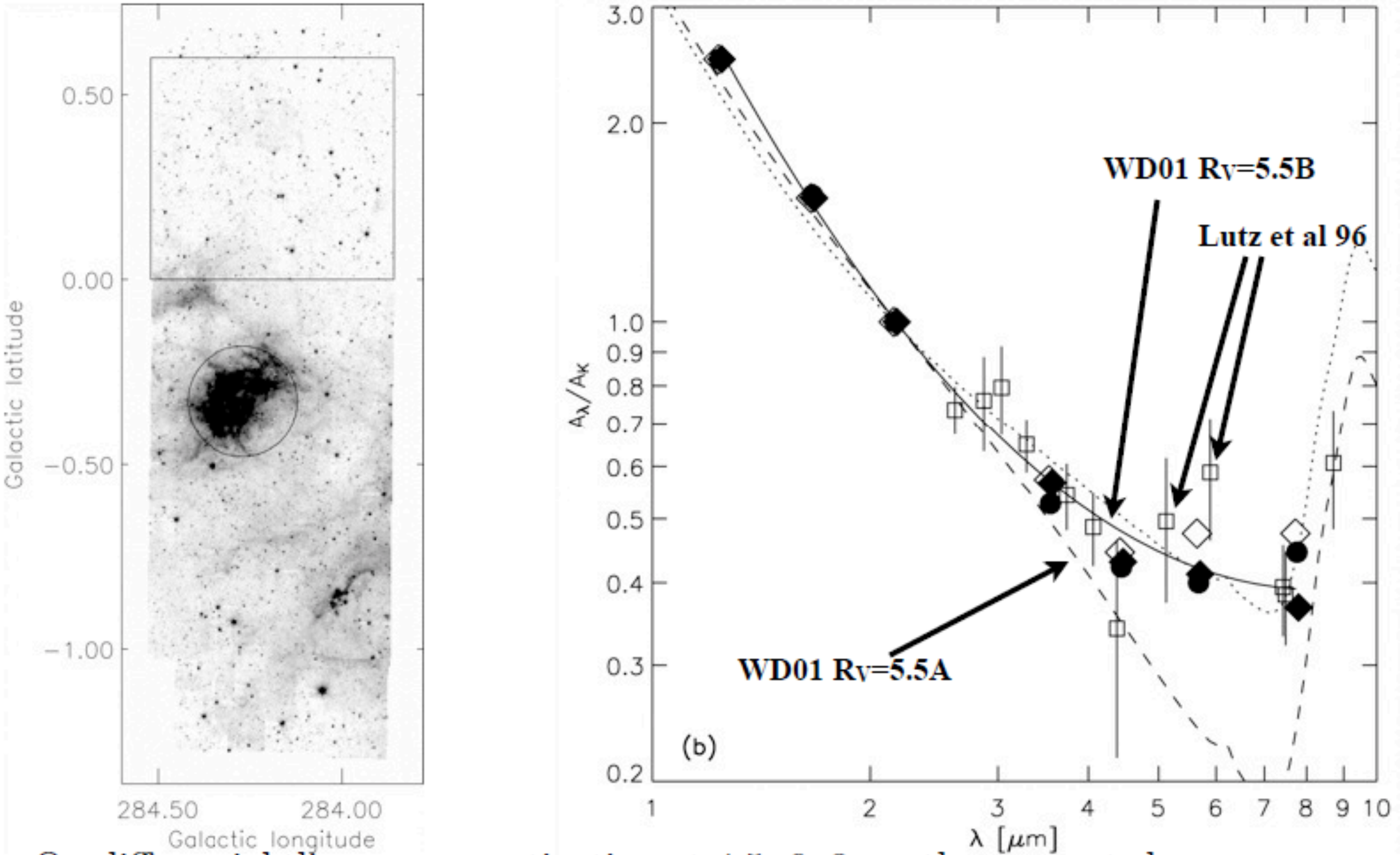
3. Lack of stellar tangencies for other arms indicates qualitative difference between spiral arms.

4. Vigorours star formation detected at near end of Long Bar.

5. Part of Scutum Centaurus arm mapped!

Extinction in the Infrared

Indebetouw et al 2005



On diffuse sightlines, more extinction at 4.5, 6, 8 μm than expected:

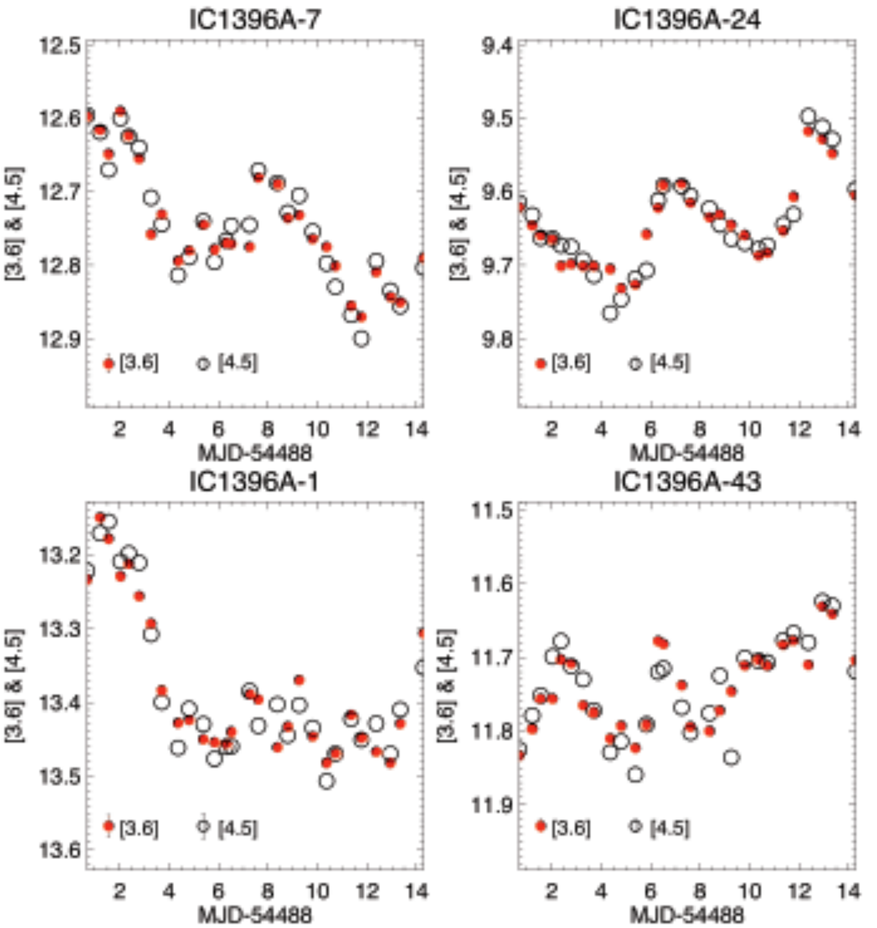
- WD01 $R_V = 3.1$ model (not shown, but was *expected* to be appropriate for diffuse regions) falls short from 3.6 – 8 μm
- WD01 $R_V = 5.5B$ model seems OK – but this model does <u>not</u> reproduce the optical-UV extinction in diffuse ISM.

Some Coming Attractions….

Table 1: Performance summary

Band	S9W	L18W
Wavelength	9 μm	18 μm
Detection limit (5σ)	~50 mJy	~120 mJy
Spatial resolution	~5″	~5″
Source number	~851,000	~195,000

Akari [above] and WISE all sky surveys



Warm Spitzer – YSO Variability Program
[cf. Muzerolle et al, 2009]

Finally, words of thanks

Patrick Ogle

Pat Patterson
Geoff Bryden
Mari Castillo
Jim Colbert
Andrea Dean
Sergio Fajardo-Acosta
Justin Howell
Eloise Kennedy
Seppo Laine
Helga Mycroft
Rosanne Scholey
Elena Scire
Helene Seibly
Kartik Sheth

Bob Benjamin
Ted Bergin
Roger Blandford
Daniella Calzetti
Dave Charbonneau
Richard Ellis
Casey Lisse
Ewine van Dishoeck