

#### Talk overview

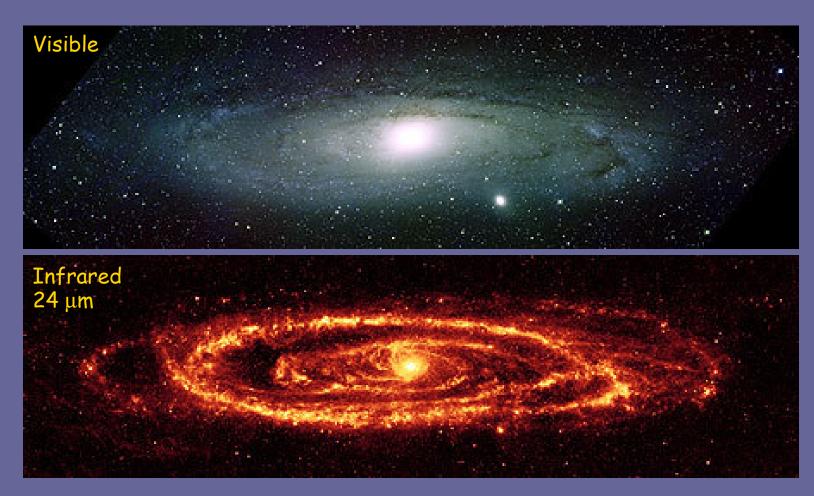


- · Spitzer history, hardware, & status
- · Science results: Our solar system
- · Science results: Other solar systems
- Science results: Our galaxy
- Science results: External galaxies & cosmology
- · Spitzer's legacy for the future



#### Latest Spitzer results: Andromeda Galaxy

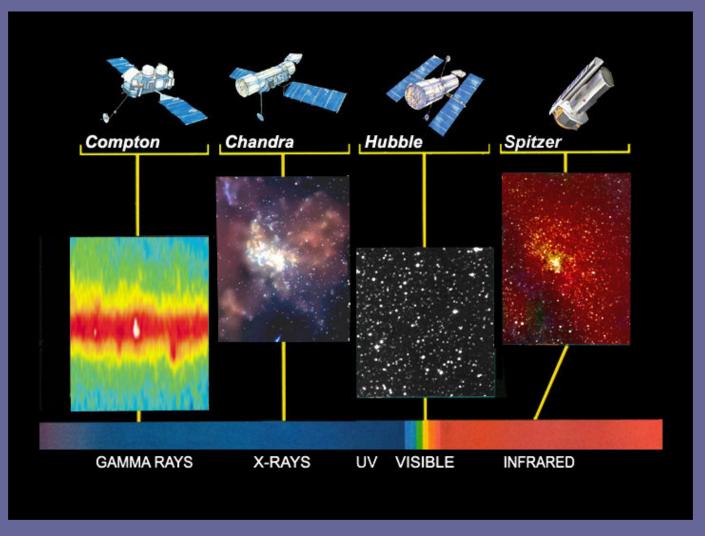






#### NASA's Great Observatories







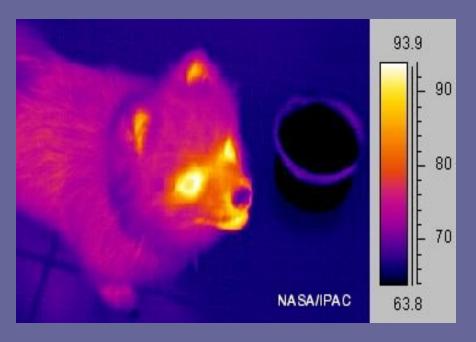
#### Rusty the Dog



#### Visible Light







#### Visit the Infrared Zoo at:

http://coolcosmos.ipac.caltech.edu/image\_galleries/ir\_zoo/index.html



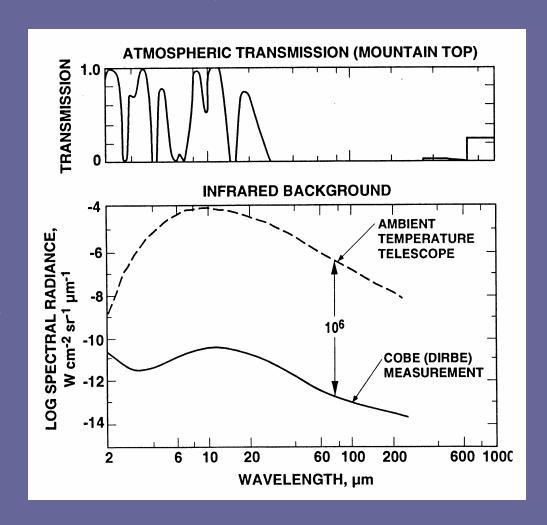
#### Advantages of a Space Infrared Telescope



100% transmission

Millionfold decrease in sky brightness

In the infrared, a 1 meter cold telescope in space is vastly more sensitive than the largest ground telescope





#### Infrared Astronomy Goals:



- The Old: The Expansion of the Universe redshifts the light of oldest, most distant objects into infrared wavelengths
- The Cold: Blackbody radiation from stars peaks at visible wavelengths; for cold objects (T < 1000 K) the emission peaks in infrared</li>
- The Dirty: Interstellar dust strongly absorbs visible light, but not infrared light.
   IR is a window into dusty star-forming regions

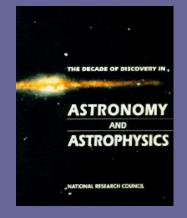


#### Spitzer Project Chronology



- Space InfraRed Telescope Facility (SIRTF) mission studies began in the late 1970s
- IRAS all-sky infrared survey (1983) made clear that a pointed observatory was needed to conduct followup observations
- · Three science instruments selected in 1984
- Project nearly cancelled several times; major descope in early 1990s; Phase B began 1997.

"The highest priority for a major new program in space-based astronomy is SIRTF." National Research Council, Astronomy and Astrophysics Survey Committee, 1991



"SIRTF remains unparalleled in its potential for addressing the major questions of modern astrophysics."

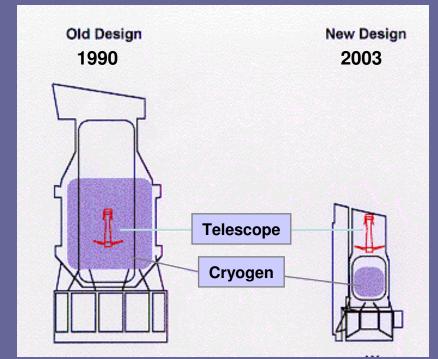
> National Research Council, Committee on Astronomy and Astrophysics, 1994



#### Spitzer Design Changes



- Spitzer was launched warm and cooled down in orbit.
- A cool-down in orbit is possible because it is a solar orbit.
- This novel approach yields significant cost and weight savings over cold launch designs with no reduction in telescope size for a given desired lifetime.
- Future NASA missions, e.g. TPF & JWST, will use this same approach.



# Cold launch Earth Orbit 5700 kg 3800 liters 5 yrs ~\$2.2 B De Titan IV ~\$0.4 B

Architecture
Type of Orbit
Launch Mass
Cryogen Volume
Lifetime
Development Cost
Launch Vehicle
Launch Cost

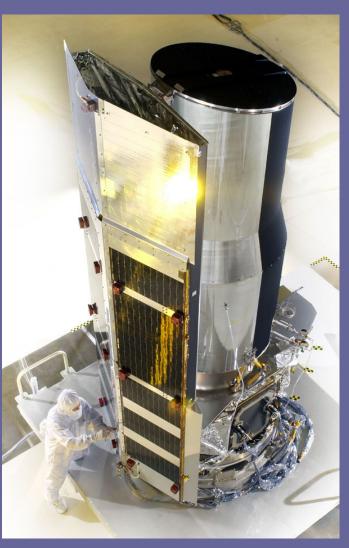
# Warm launch Solar Orbit 870 kg 360 liters 5 yrs \$0.74 B Delta \$0.07 B



#### Spitzer: A General-Purpose Space Observatory for Infrared Astronomy



- 85 cm f/12 Beryllium Telescope, T ~ 5.5K
- 6.5 μm Diffraction Limit
- Two science cameras, plus a low/moderate resolution spectrograph; 3< λ< 180 μm</li>
- · Earth-trailing Solar Orbit
- 10-100x more sensitive than 1983 IRAS mission







#### Cutaway View of the Spitzer Space Telescope

**Dust Cover** 

Solar Panel

Solar Panel Shield -

**Outer Shell** 

Cryostat-

Helium Tank —

Spacecraft Shield

Spacecraft Bus -

Cutaway provided by Ball Aerospace

Secondary Mirror
Primary Mirror
Instrument Chamber
Startrackers & Gyros

High Gain Antenna

#### Spitzer Science Instruments



IRS
[InfraRed
Spectrograph]
J.Houck
Cornell Univ.

MIPS
[Multiband
Imaging
Photometer]
G.Rieke
Univ. of Arizona

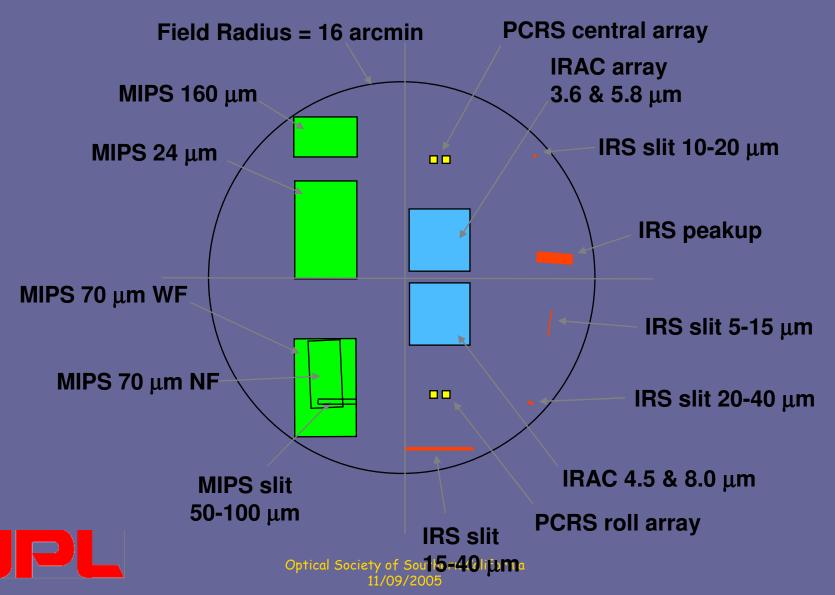


IRAC [InfraRed Array Camera] G.Fazio Harvard/ SAO



#### Spitzer Focal Plane Apertures





#### Spitzer Telescope





at Ball Aerospace (August 2000)



#### Mating Telescope to Cryostat



Telescope Primary . Mirror



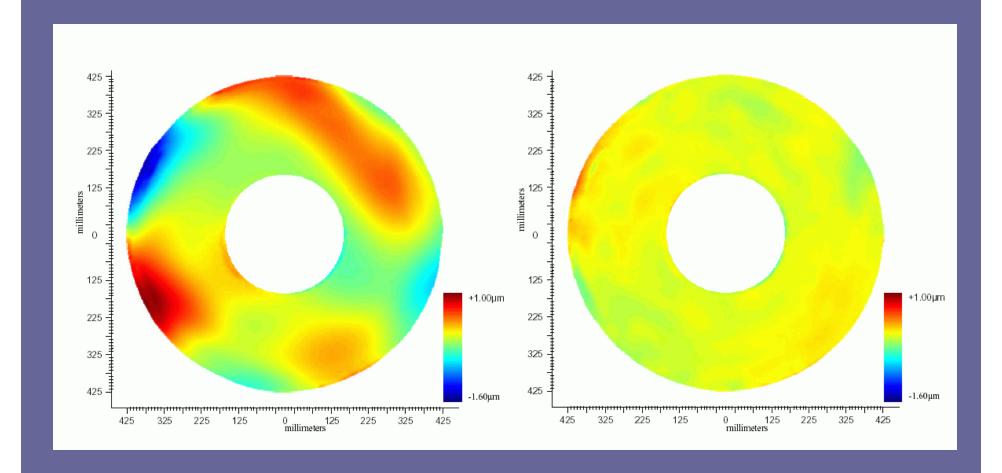
Cryostat Dome

Lower Portion of Outer Shell



## Primary mirror surface: Warm vs. Cold







#### Spitzer launch: August 2003











- Launched August 25, 2003;
   science ops since Dec. 2003
- Observatory in good health
- Excellent cryogenic system performance will allow full science operations into late 2008, + extended mission
- Small, efficient ops team (Lockheed/JPL/Caltech)
- Observing time is strongly in demand
- 200+ refereed publications to date



#### Spitzer on-orbit focus

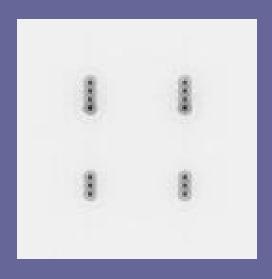


- 8 week waiting period for telescope cooldown
- Assessed focus by model fitting to static images; no "focus sweep". 3 moves of secondary mirror:
  - Small exploratory move
  - "most of the way" move
  - Final tweak
- Telescope focus unchanged since Nov. 2003

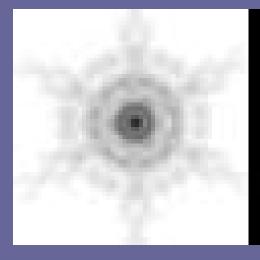


## MIPS 24 µm Focus Check Results:

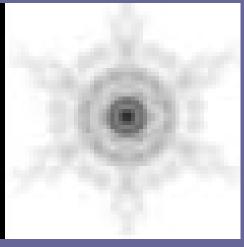




Input image data from 14 dither positions



Single observed image



In-focus model PSF

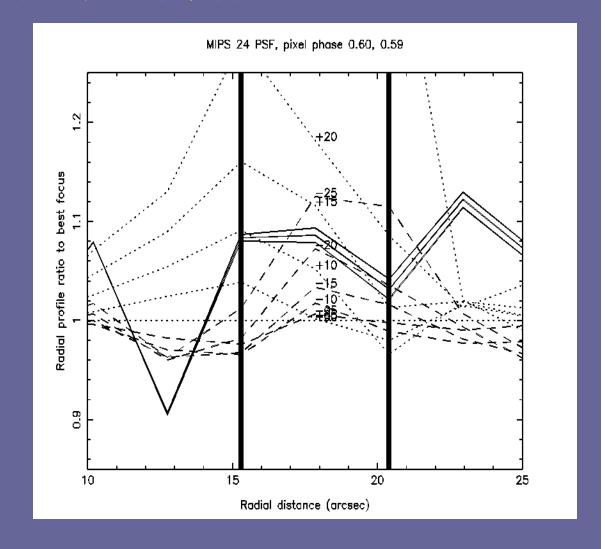
• Observed image core diameter is 2.11 pixels at half maximum, indicating that MIPS is within +/-  $50~\mu m$  of nominal focus



## MIPS 24 µm Focus Determination Results:



- We compare radial profile of star image (solid lines) to that of model defocused images (dotted, dashed lines; labels in µm units)
- 15-20 arcsec radial region provides best results
- Focus results are:
  - +10 to + 15 μm OR
  - -20 to -25  $\mu$ m





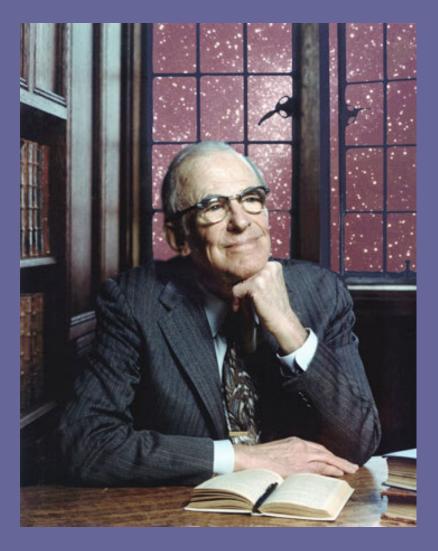


## AND NOW ... THE SCIENCE RESULTS



#### SIRTF renamed Spitzer



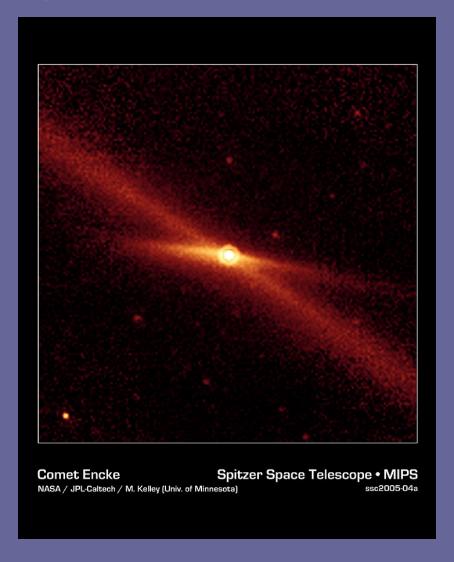


- Name was chosen from >7000 entries.
- It was named for Princeton astronomy professor Lyman Spitzer (1914-1997)
- In 1946, Dr. Spitzer proposed putting a telescope in space, and was a primary force behind Hubble.
- Key researcher of the interstellar medium



#### Comet jets & dust trails

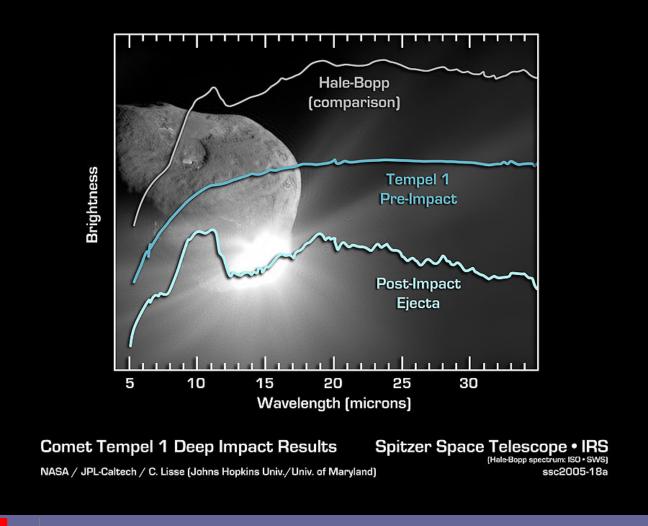






## Spectra of Comet Tempel 1, Before and After Deep Impact Impact

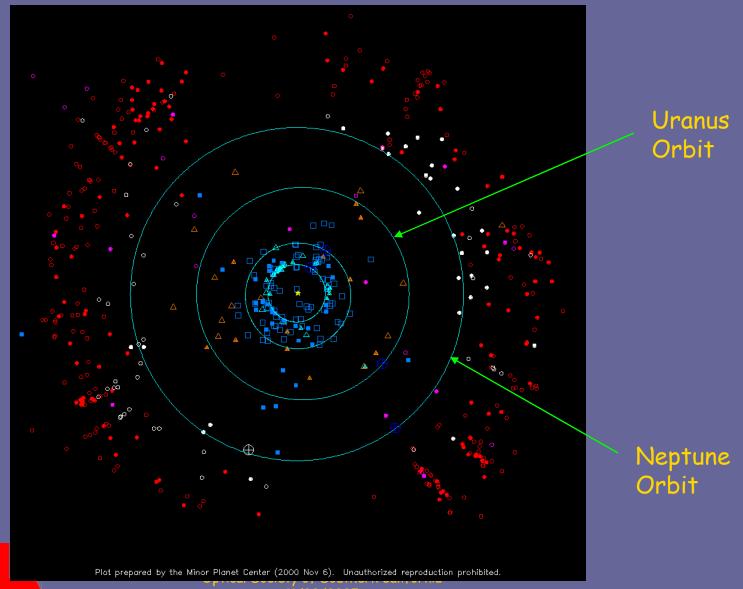






#### Kuiper Belt Objects: Our Solar System's 2<sup>nd</sup> Asteroid Belt



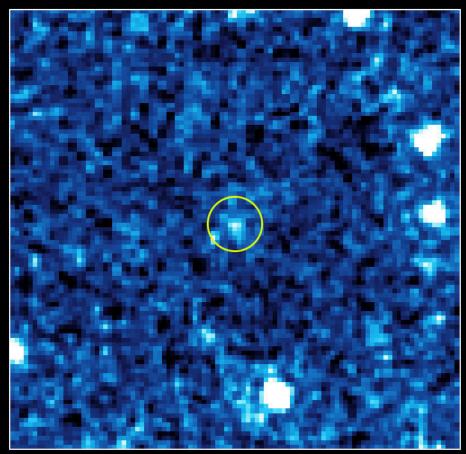


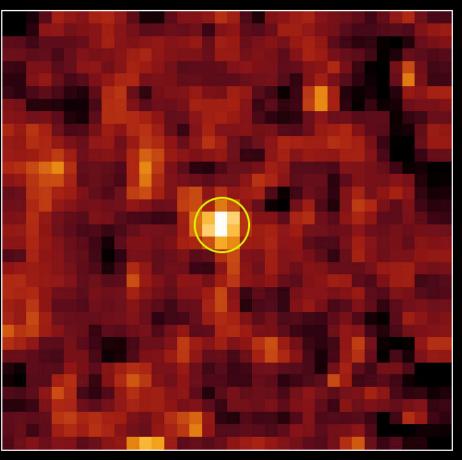
#### Spitzer detects Kuiper Belt objects



24 microns

70 microns





Kuiper Belt Object 2002 AW<sub>197</sub>

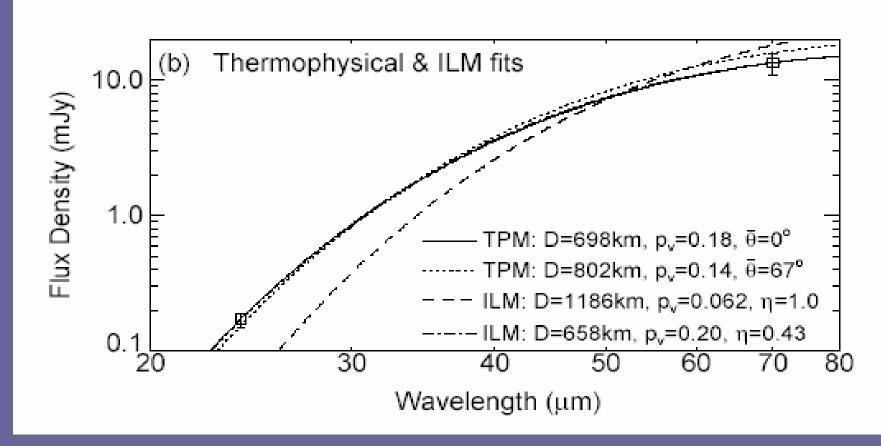
Spitzer Space Telescope • MIPS

NASA / JPL-Caltech / J. Stansberry (Univ. of Arizona)











#### Other KBO Results



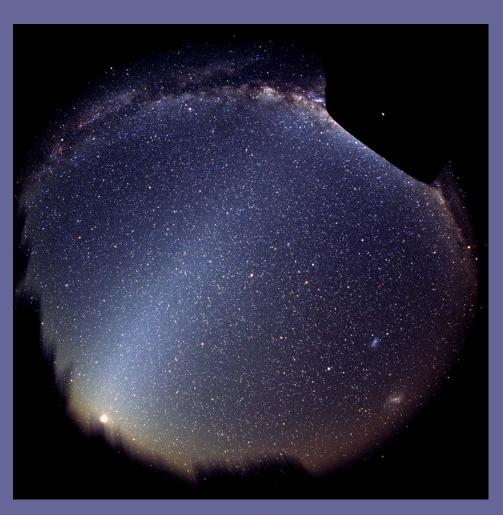
- Binary KBO (1999 TC36) primary object albedo ~0.08, primary object density 0.5-to-0.8 gm/cm³, primary diameter ~400 km
- Jumbo KBO's [inclined, elliptical orbits]:
  - 2003 UB313 [a.k.a Tenth Planet] Diameter ~1.25 Pluto's if albedos are similar [Spitzer data in work]
  - 2003 EL61[binary] and 2005 FY9 Diameter ~ 0.75 Pluto's based on Spitzer detections
- Diameters, albedos now available for >15 large
   [diameter > 50km] KBOs; albedos 3-35 %



#### We live inside a dust disk



- Interplanetary dust particles are released by asteroid collisions & cometary passages
- These particles concentrate in the ecliptic plane, causing the zodiacal light
- Even though its fractional luminosity is just 10<sup>-7</sup> of the Sun, the zodiacal light is the most luminous component of our planetary system



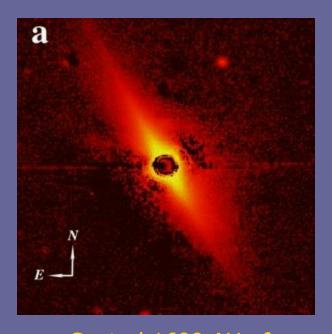
Fish-eye view of zodiacal light



### Extrasolar dust disks were discovered in 1984 by IRAS

- Vega, Fomalhaut, and  $\beta$  Pictoris: nearby A-type stars with large far-IR excess, were spatially resolved by IRAS
- Dozens more detected in IRAS catalogs
- They contain 30 to 20,000 times as much material as our Sun's zodiacal cloud
- Disk masses very small < few lunar masses of solid particle.
- Theory says this dust should be cleared out quickly by stellar radiation; so it can't be left over from the star's formation. New particles created continuously by comets & asteroids.





Central 1600 AU of edge-on  $\beta$  Pictoris disk; Kalas & Jewitt 1995

Best evidence of extrasolar planetary systems prior to 1995

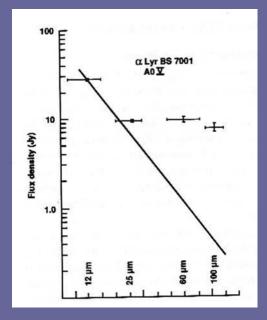


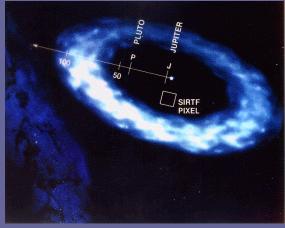
#### Background on Vega disk

- A0 V star,  $50 L_{\odot}$ , 8 pc distant
- Prototype main sequence star with IR excess
  - Large particle population, T≈ 80 K, IRAS measured disk radius of 80 AU central hole (IRAS; Aumann et al. 1984)
  - about 200 times the dust content of our Sun's zodiacal cloud
- Disk undetectable in scattered light with Hubble

1990's artist rendering of the Vega disk



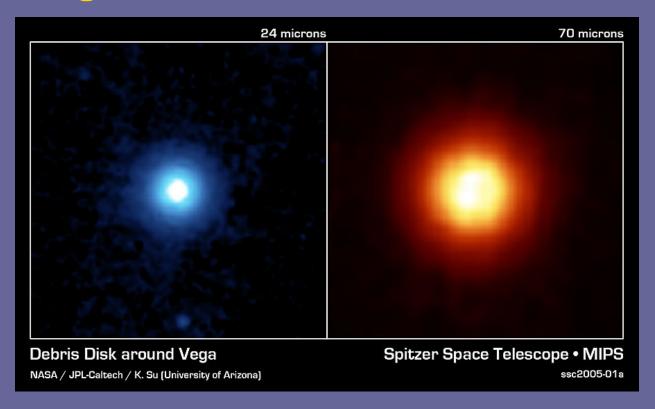






## Spitzer images of the Vega dust disk:





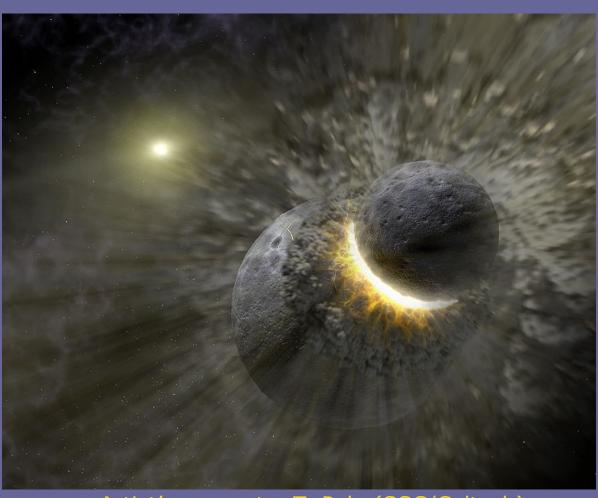
- · Disk is viewed face-on
- · Outer radius > 500 AU
- Outer disk warmer than expected - explained if dust particles very small



## Explaining the Vega disk: a recent smash-up?



- The small dust particles needed would blow out very quickly - in just 1000 yrs!
- Recent major asteroid collision may be particle source

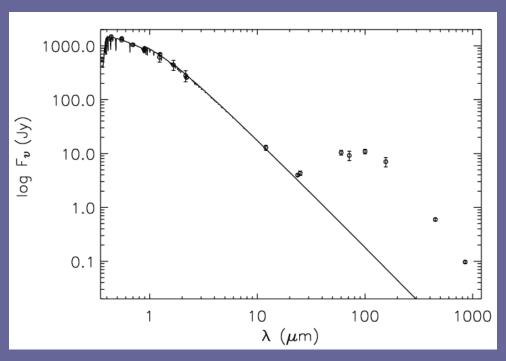




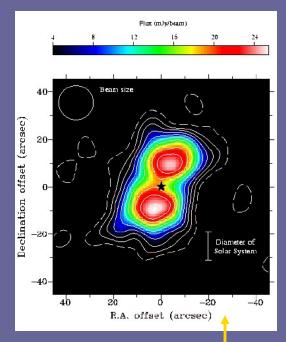


Optical Society of Southern California 11/09/2005

#### Background on Fomalhaut disk







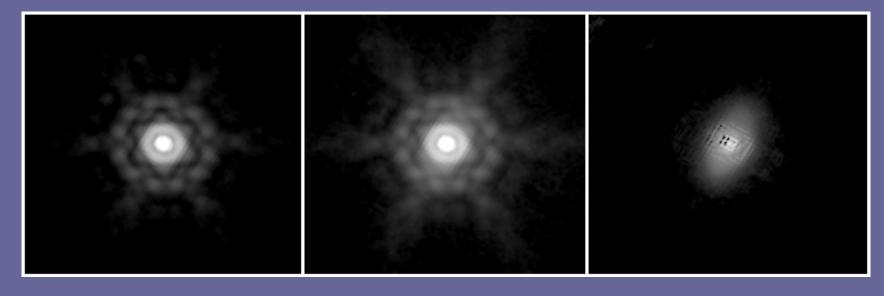
- A3 V star, distance= 8 parsecs = 26 light years
- Disk resolved with IRAS & KAO (Gillett et al. 1986; Harvey et al. 1996)
- Very nice submm detection of edge-on ring by Holland et al. 1998-
  - 110 AU ring radius
  - First debris disk science target for Spitzer, November 2003



#### Fomalhaut MIPS 24 µm

(Stapelfeldt et al. 2004)





• Left: Reference star image

160" FOV

• Center: Fomalhaut direct image

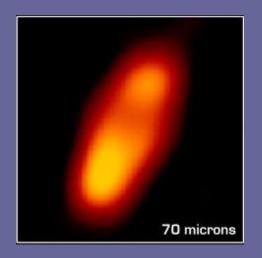
Right: Dust disk revealed by PSF subtraction



## Spitzer view of the Fomalhaut dust ring

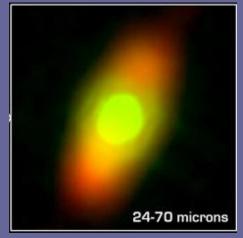


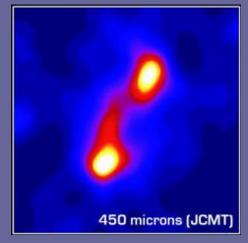






Eccentric ring model



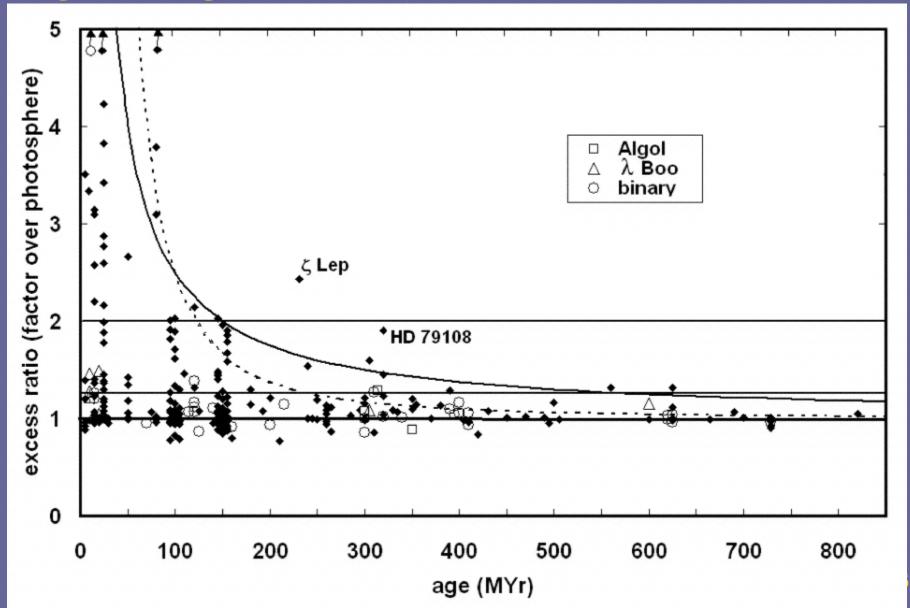


Planet interior to the ring is needed to maintain its eccentricity



#### Temporal decay of Planetary Debris Disks Around A Stars

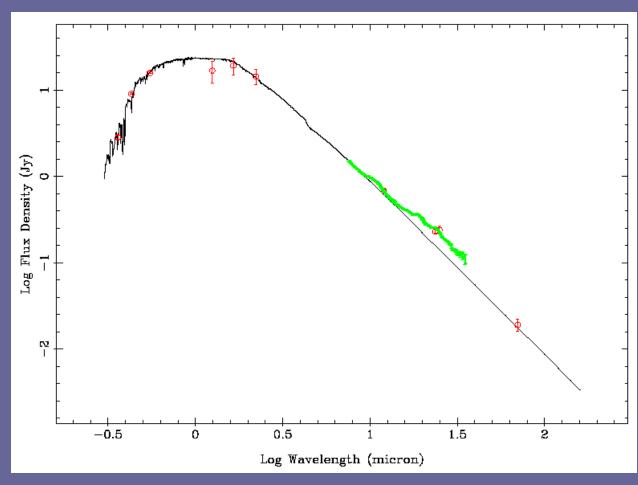




### Infrared Excess in the KO Star HD 69830



- V= 6
- dis= 12.3 pc
- · age ~ 2 Gyrs
- · No RV planet
- Spitzer/MIPS detects excess at 24  $\mu$ m, but not at 70  $\mu$ m
- → Warm dust

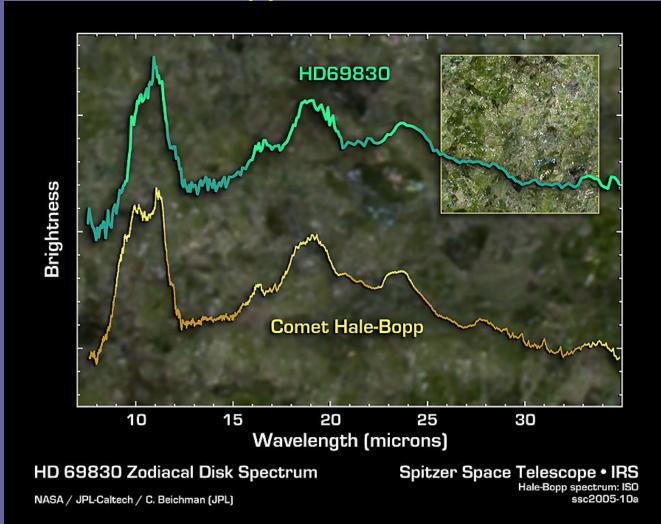


(Beichman, Bryden et al. 2005b)



## Cometary dust grains circling the "Hale-Bopp star" HD 69830





Even smaller than
the dust grains
seen around
Vega, and would
likewise blow
out easily

Recent asteroid collision, or major comet passage?

These features seen in only 1/36 stars surveyed - a rare object.



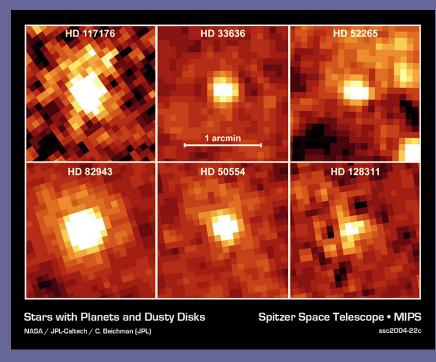
## Survey for infrared excess in stars with radial velocity planets



(Beichman, Bryden et al. 2005a)

- 25 sunlike stars known to have Jovian planets were measured at 24 & 70 µm with MIPS
- 24 µm: No excesses detected
- 70 µm: Excesses of 0.7-14 x the stellar photosphere were detected in six stars





→ First unambiguous association of dust disks & extrasolar planets



## Spitzer & Direct detection of light from extrasolar planets

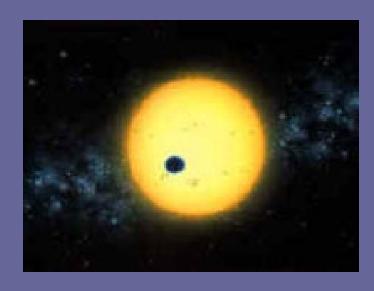


- Spitzer is sensitive enough to detect a few Jupiter mass planet at the distance of nearby stars they strongly emit at 4.5  $\mu$ m wavelength
- Spitzer does not carry any high contrast instruments (coronagraphs, nullers). Planet imaging searches are thus limited to radii > 50-100 AU from their star.
   Dozens of stars have been surveyed, but no candidate planets yet; data still being analyzed
- In the unique circumstances of <u>transiting planets</u>, Spitzer has recently made a major contribution



### Transiting planets pass



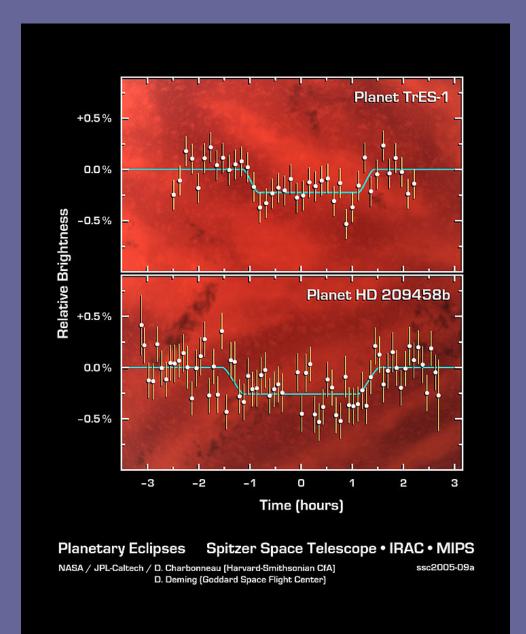


In front of the star

#### And behind the star









#### Transiting planets:

Planet's orbit passes alternately in front of and behind its parent star

Half-dozen examples discovered by ground telescopes to date

At time when planet is passing behind the star, Spitzer measures 0.2% drop in total light. This is a differential detection of the planet's light!

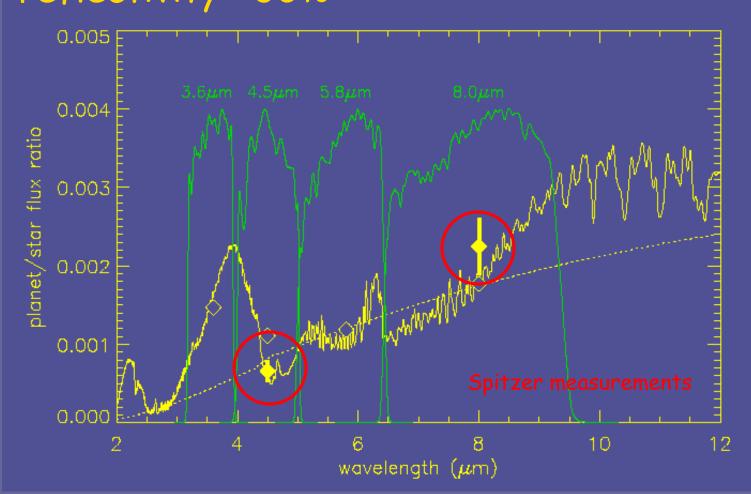


# Planet brightness measurements allow estimates of T= 1100 K, reflectivity ~30%



Spitzer camera bands

Model spectrum





Charbonneau et al. 2005

Optical Society of Southern California 11/09/2005



Embedded Outflow in HH 46/47

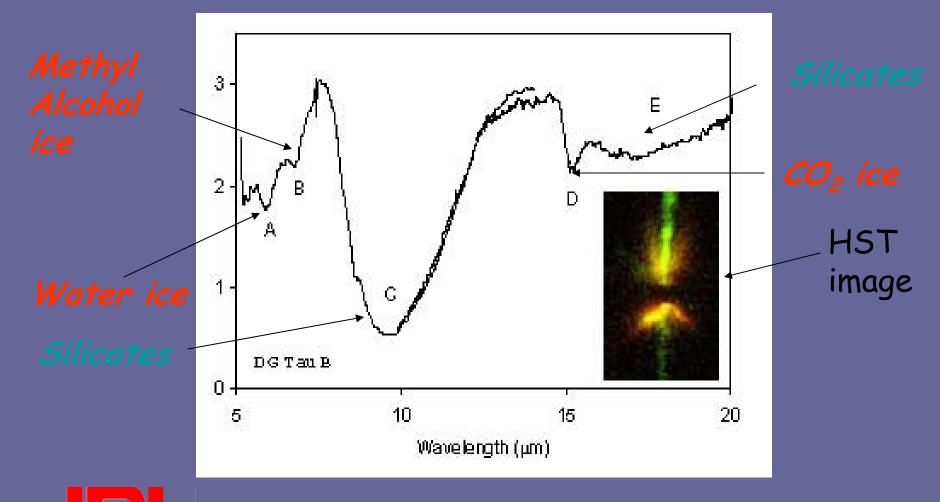
Spitzer Space Telescope • IRAC
Inset: visible light (DSS)

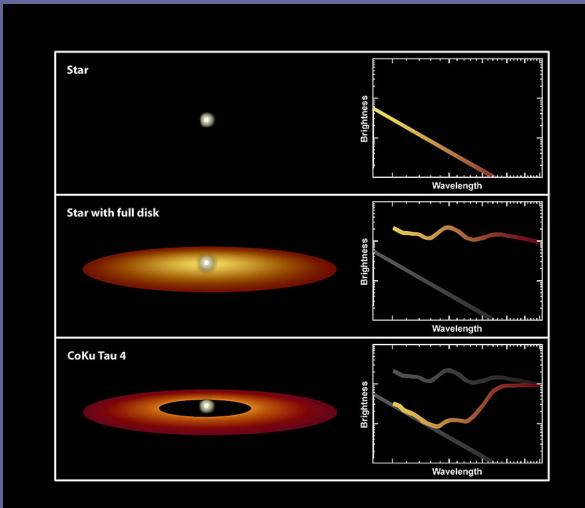
ssc2003-06f

NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)

# Spitzer Sees Organic Materials in Protoplanetary Disks

Spitzer Spectrum of Solar-type Young Star/Disk System in Taurus:







NASA / JPL-Caltech / D. Watson (University of Rochester)

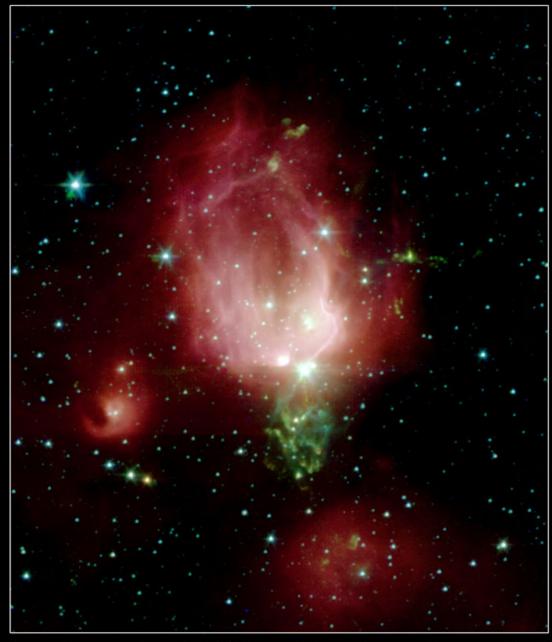
ssc2004-08c





- Very young

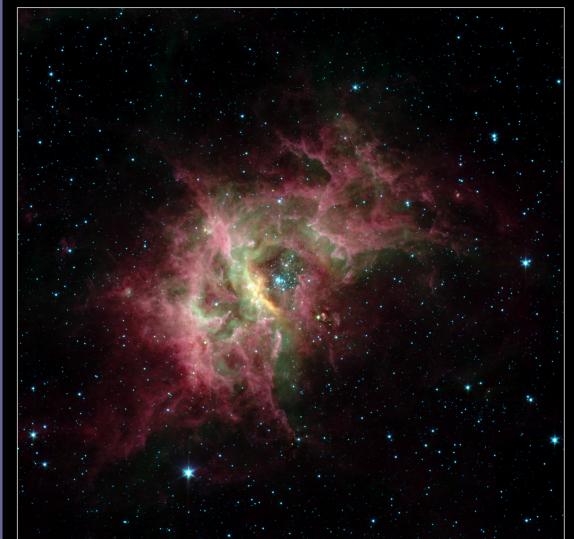
   (1 Myr old) star
   has a central
   hole in its disk
- "Transition disk"
- What process has cleared dust from this inner region?
  - Companion star ?
  - Agglomeration of dust into larger particles ?
  - Newborn Planet ?







Reflection Nebula NGC 7129 Spitzer Space Telescope • IRAC



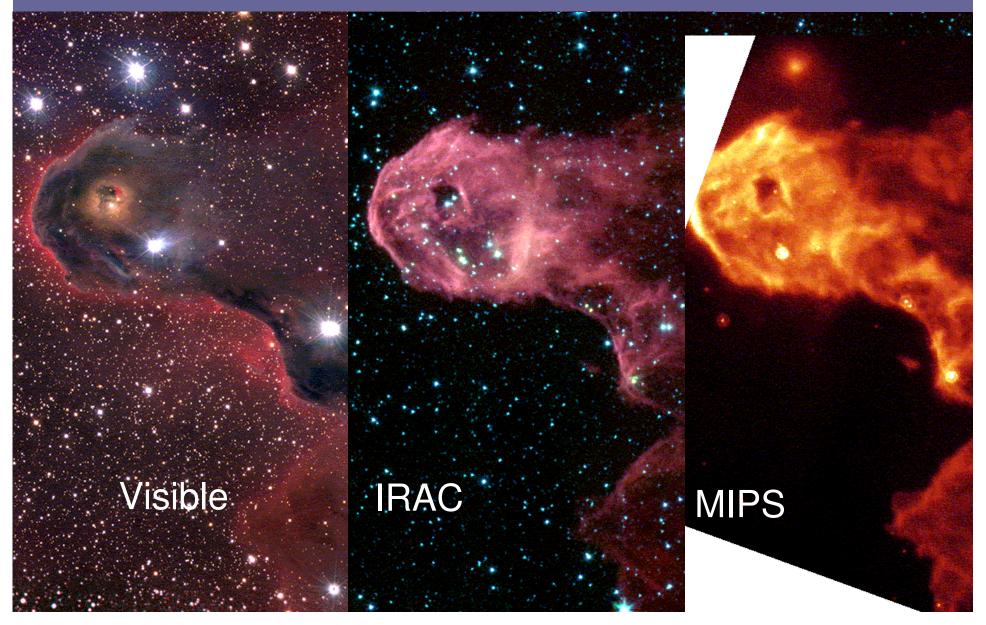






### Star Forming Region IC 1396





#### An Embedded Young Star Cluster in NGC 2264



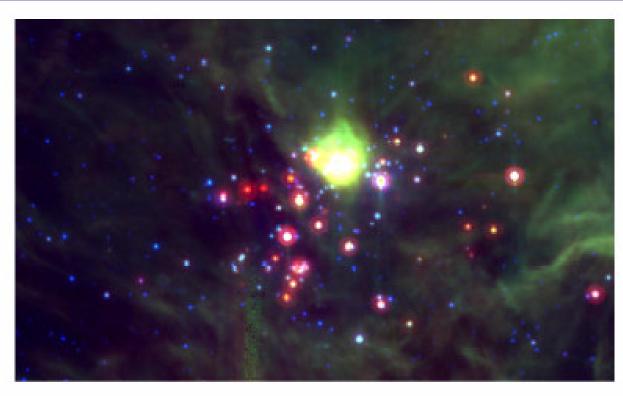


FIG. 1.— False color image of the Spokes region constructed from MIPS  $24\,\mu\mathrm{m}$  (red), IRAC  $8.0\,\mu\mathrm{m}$  (green), and IRAC  $3.6\,\mu\mathrm{m}$  (blue) data. The image shows unusual linear spatial alignments of the brightest  $24\,\mu\mathrm{m}$  sources. The central saturated source is IRAS 06382+0930 (IRAS 12).

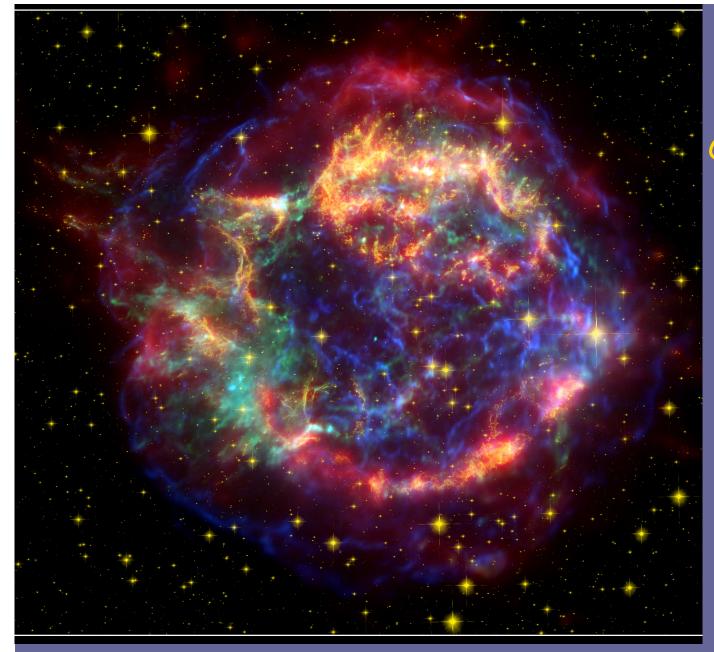


#### Ring Nebula (=M57)





2000 LtYrs away, in Lyra. Dying star like our Sun. (image is 11x9 arcmin, taken with IRAC) **53** 





Cas-A Supernova Remnant (SNR), studied by all three Great Observatories! (blue=Chandra, yellow=Hubble, red=Spitzer) The star exploded 325 years ago. (11,000 light years away, in Cassiopeia.)



Krause et al., 2005, Nature

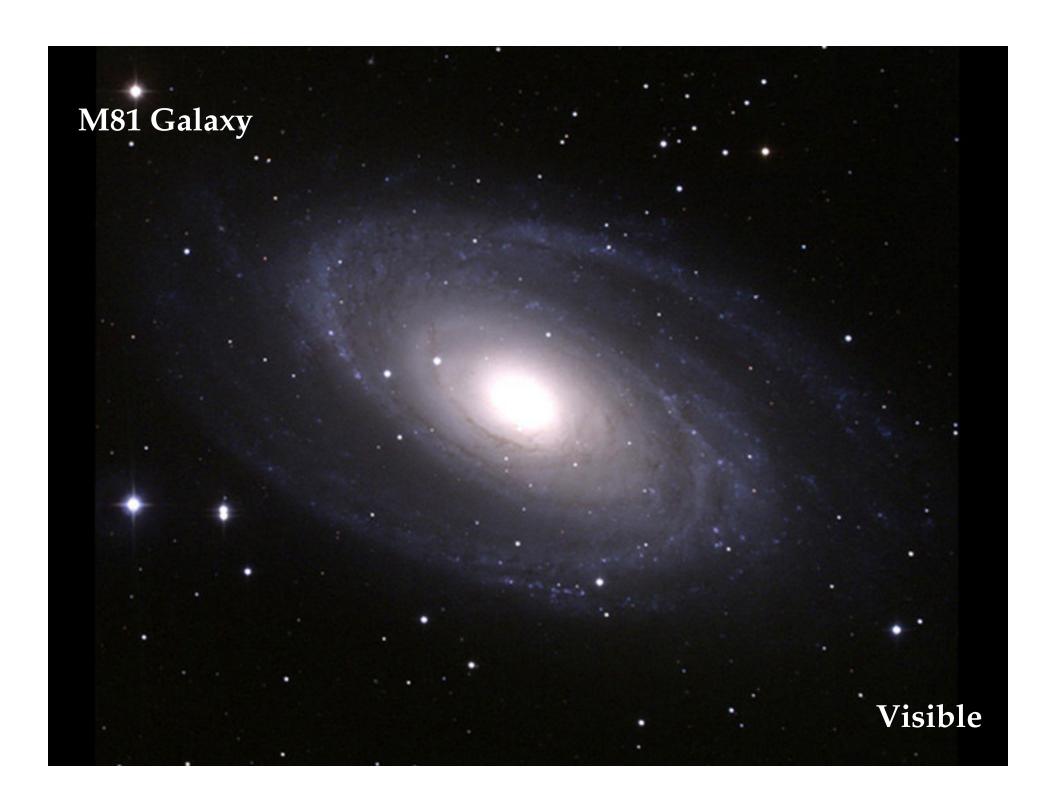
Optical Society of Southern California 11/09/2005

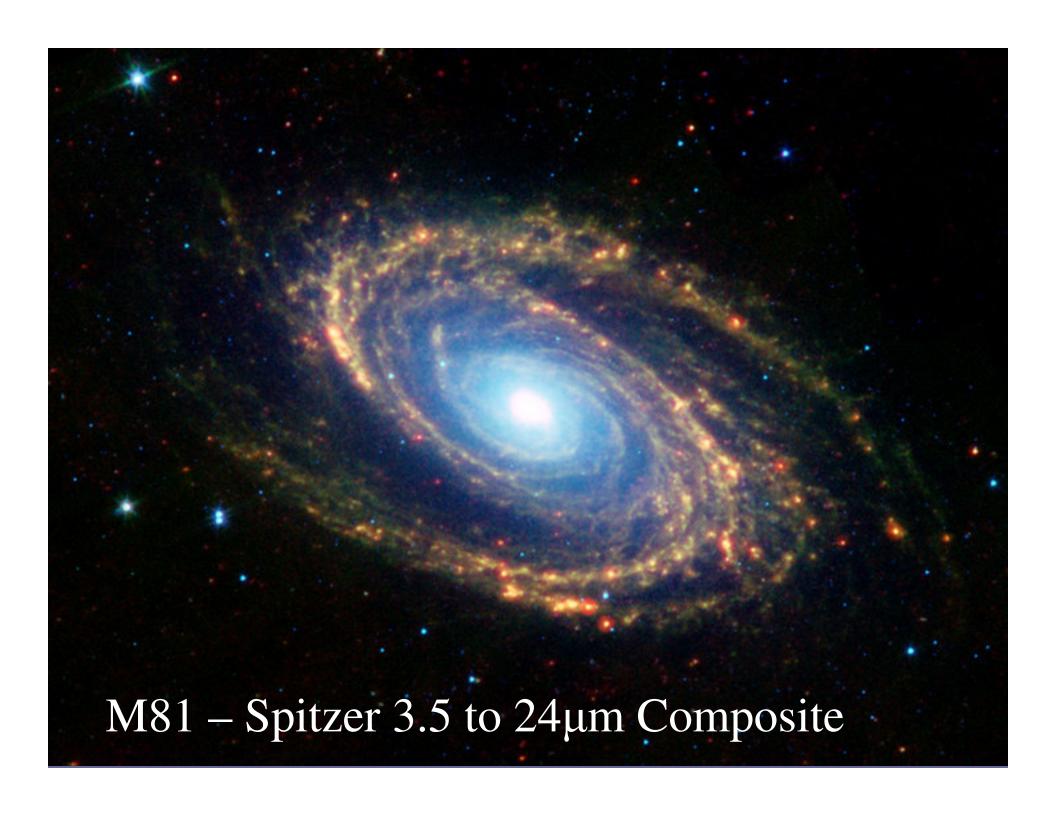
### Casseopeia-A Infrared Light Echo

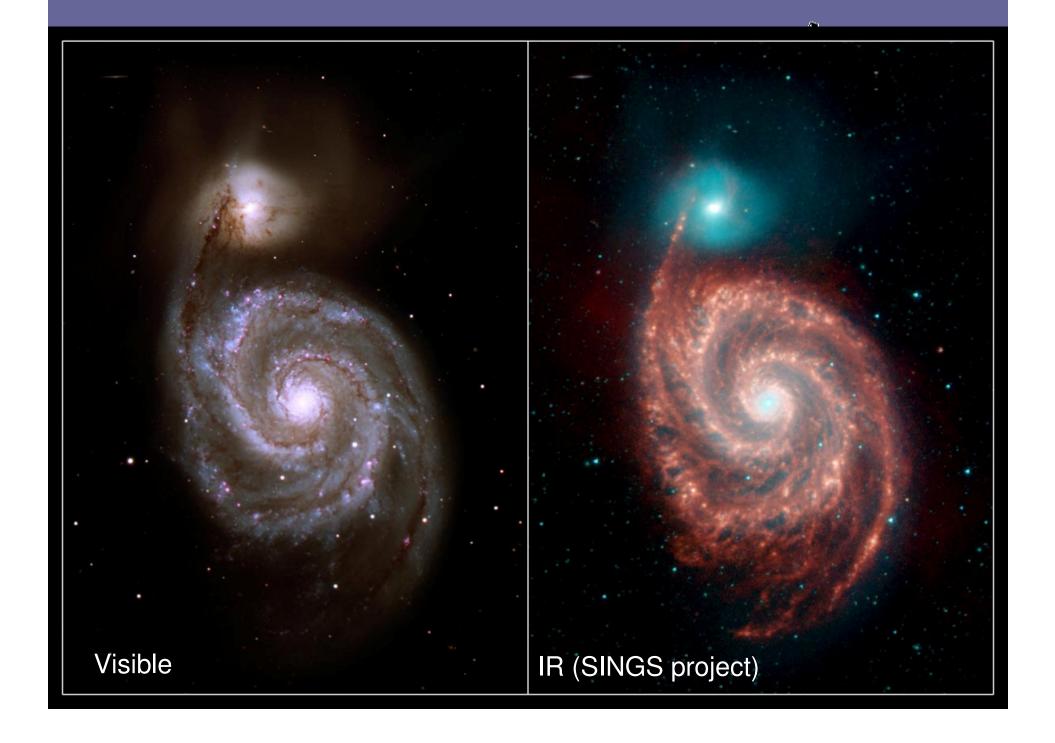










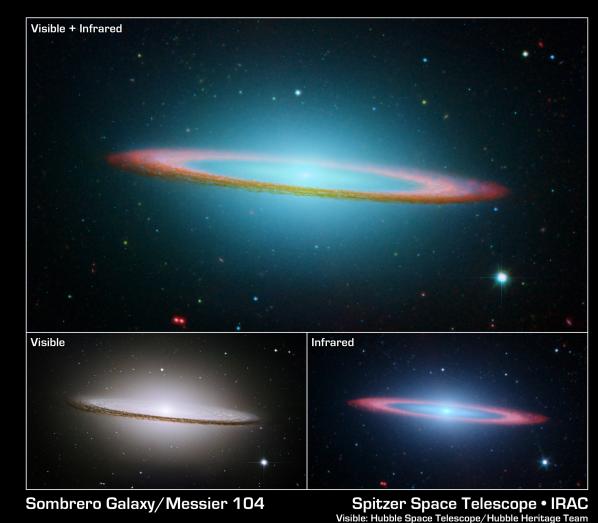


#### Sombrero Galaxy



Sombrero Galaxy (M104) 28 million lightyears, in Virgo

IRAC 4-color image, plus HST ACS image in the optical

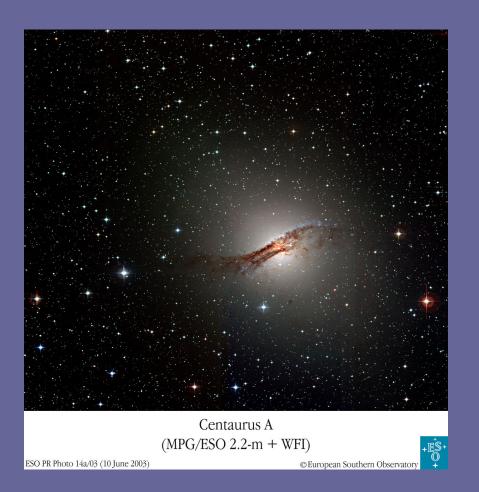


VISIDIE: Hubble Space Telescope/ Hubble Heritage Team
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team
ssc2005-11a



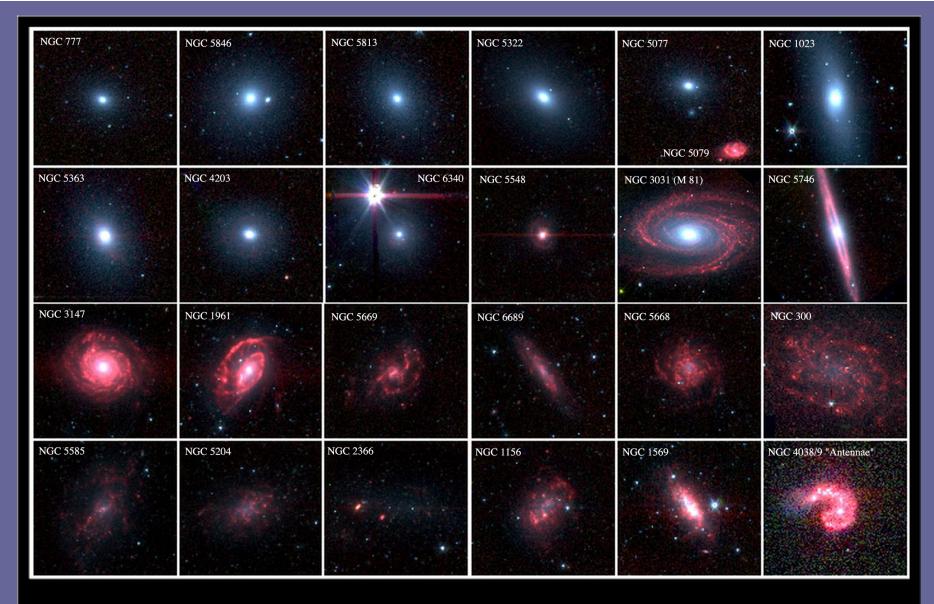
# Dusty galaxy in visible, infrared light









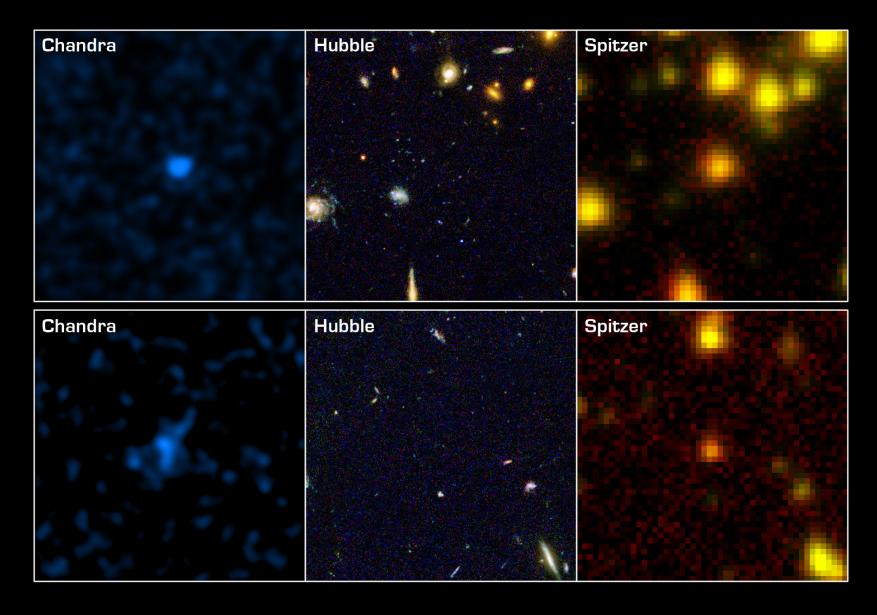


Infrared Mosaic of Nearby Galaxies

Spitzer Space Telescope • IRAC

M. A. Pahre & G. G. Fazio (SAO) / NASA / JPL-Cattech

sao-2004 -19



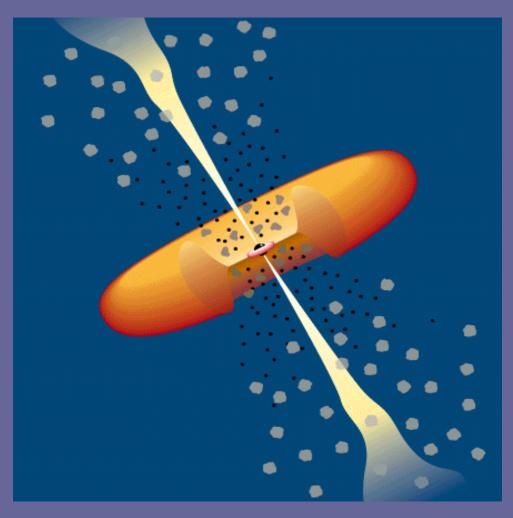
Hidden Black Holes Revealed in GOODS Field

NASA / JPL-Caltech / A.M. Koekemoer (STScI), M. Dickinson (NOAO) ssc2004-10a

Spitzer Space Telescope • IRAC Hubble Space Telescope Chandra X-Ray Observatory

#### Active Galactic Nuclei -The Standard Model

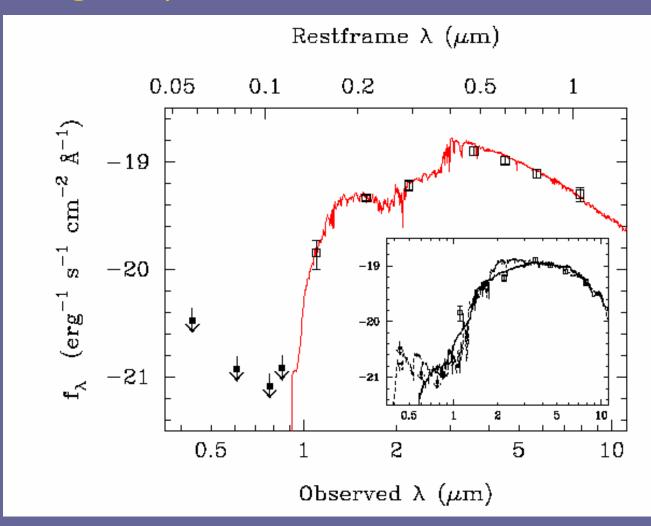




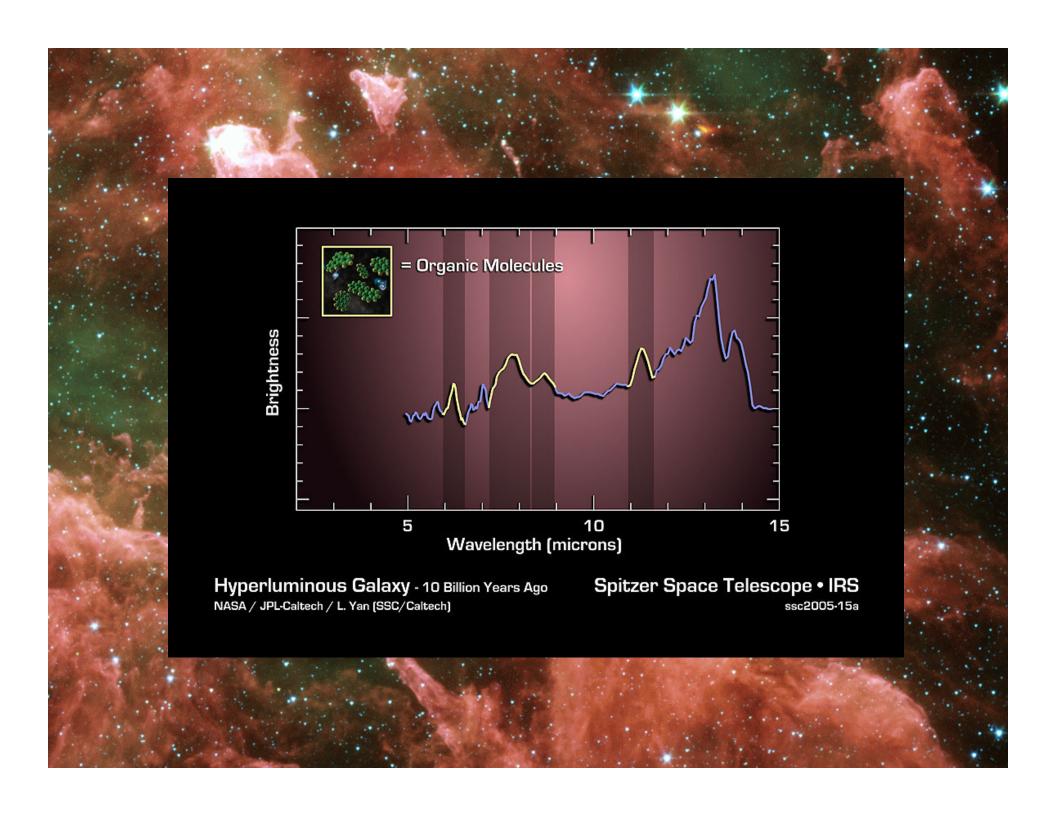


## Spectral Energy Distribution of galaxy at redshift 6.5









#### Spitzer has:

- Resized Kuiper Belt objects
- Detected dusty debris in 15% of nearby sunlike stars, including those with extrasolar planets
- Made first detection of light from an extrasolar planet
- Seen inner holes in protoplanetary disks
- Discovered a bizarre infrared light echo
- Outlined star-forming regions in other galaxies
- Detected carbon molecules in the early universe
- 3 more years of groundbreaking science to go
- Spitzer is well on its way to surveying the dust around nearby stars where future terrestrial planet searches will be made; a key precursor investigation.
  - High dust levels will preclude planet-finding for some stars

## Terrestrial Planet Finder Coronagraph - 2018 ??



