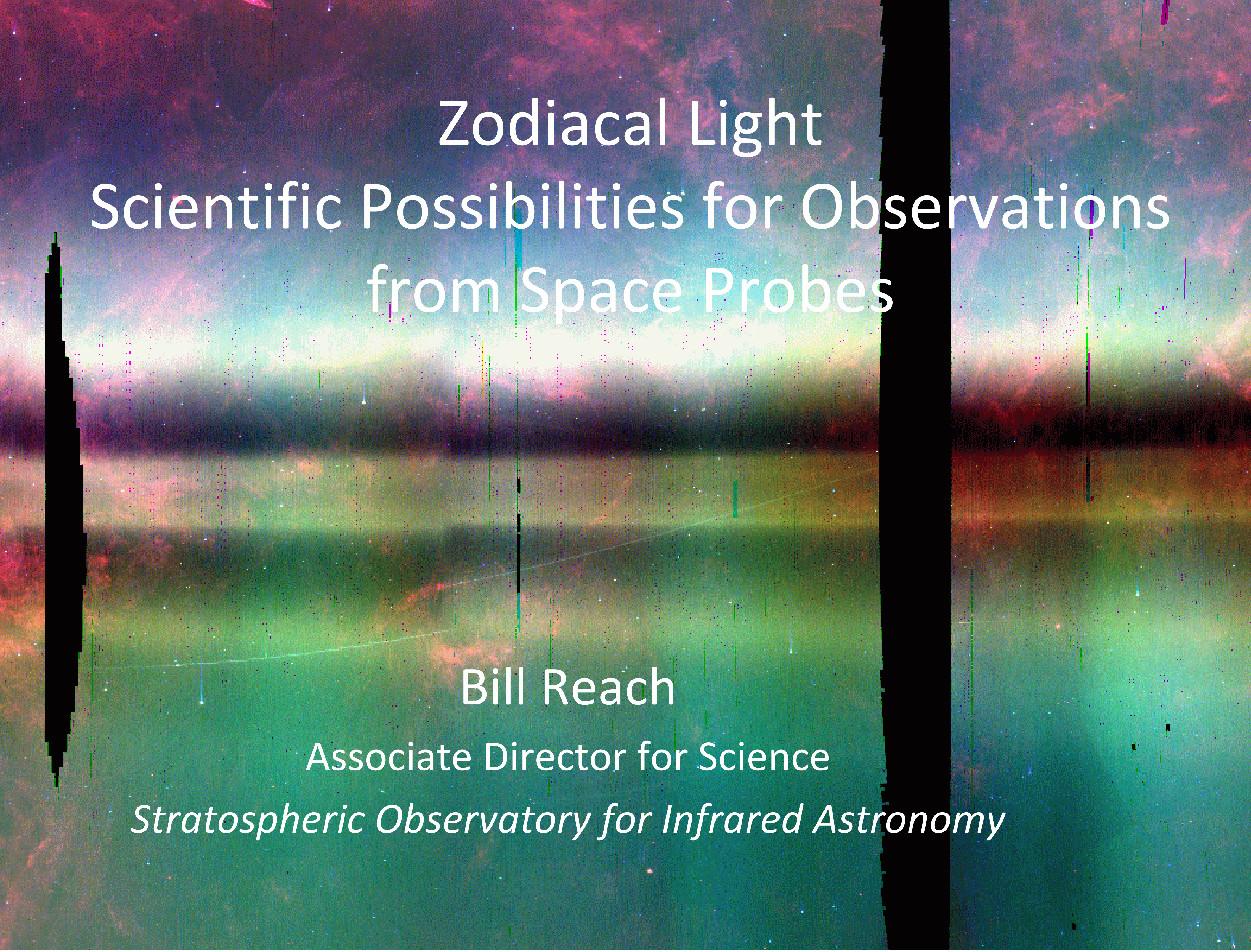


Zodiacal Light
Scientific Possibilities for Observations from Space Probes

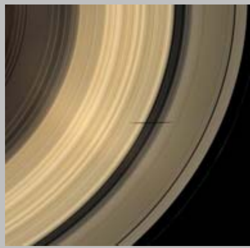
Bill Reach

Associate Director for Science

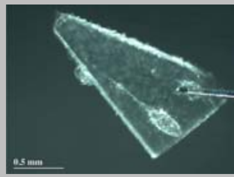
Stratospheric Observatory for Infrared Astronomy

Why Study the Smaller Bodies?

① Tracer of gravitational potential

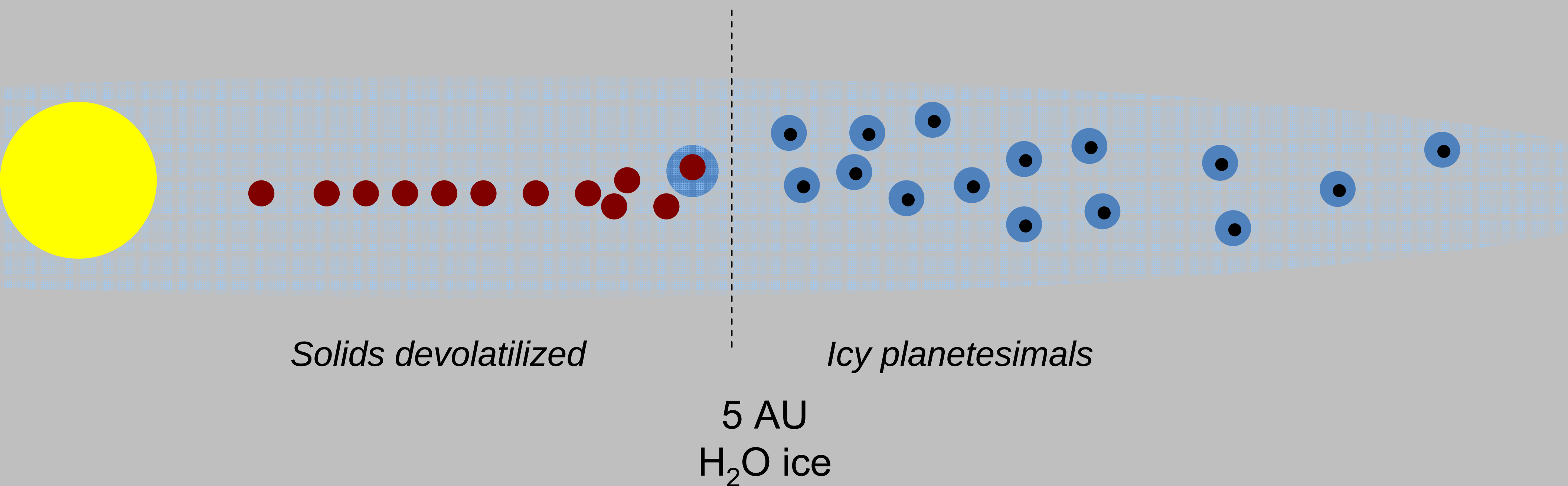


② Sample of material from solar nebula and major bodies

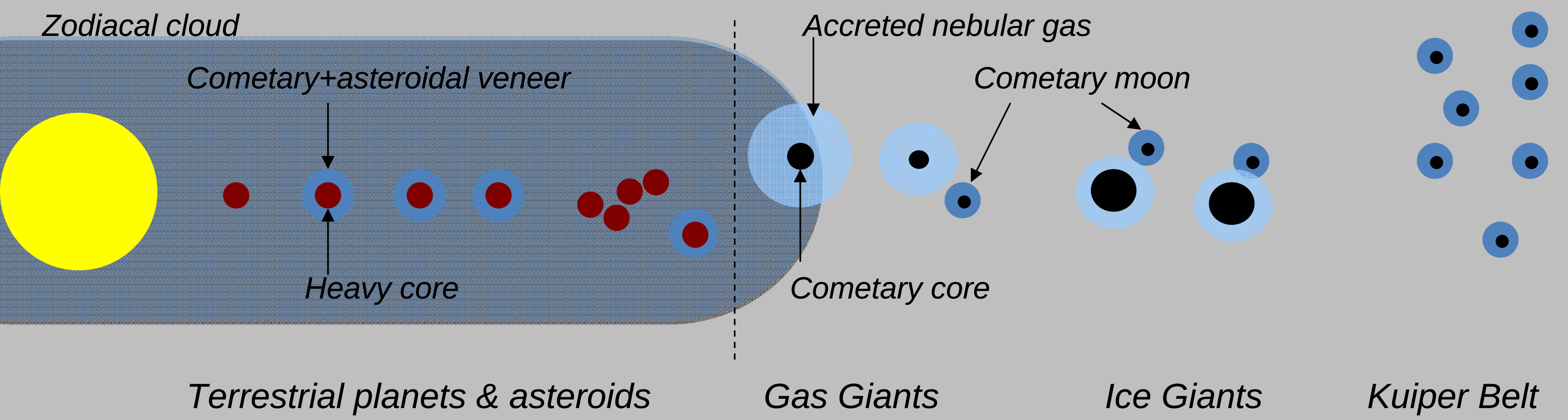


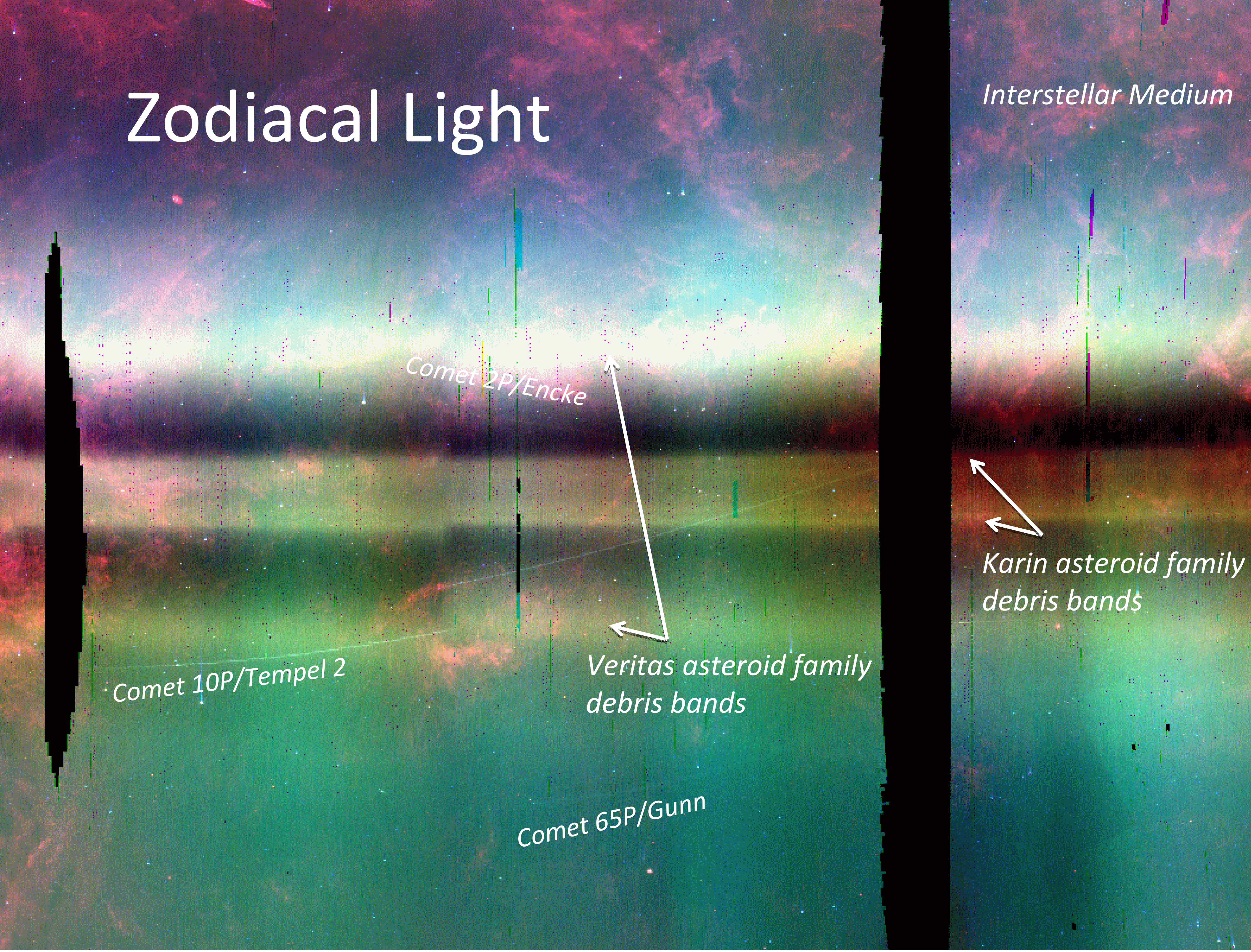
③ Transport of material and construction of major bodies

Asteroidal and Cometary Planetsesimals in the Solar Nebula



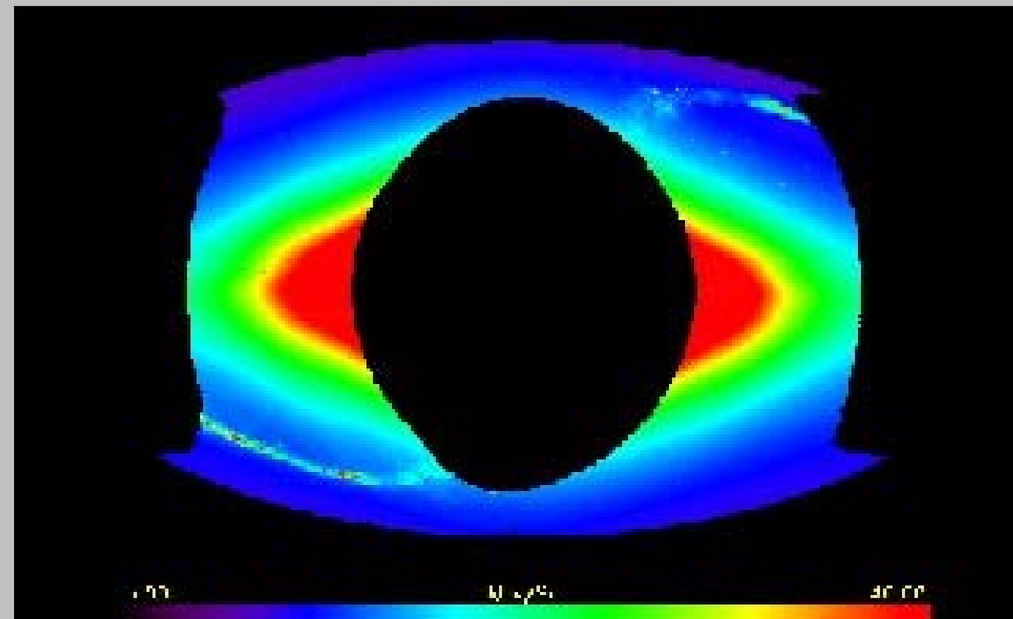
Cometary Material in Present Solar System

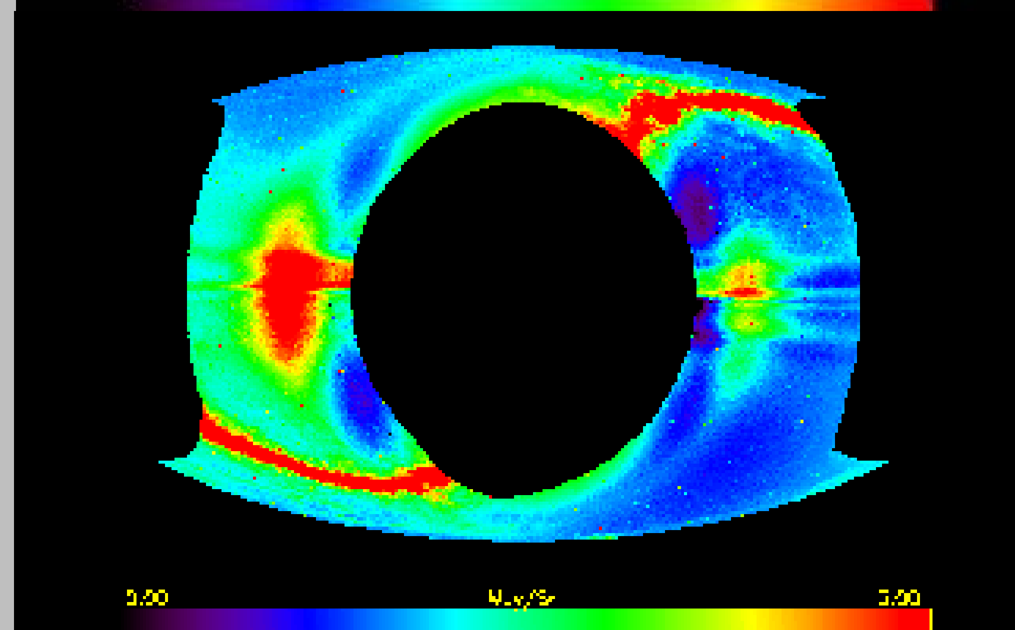


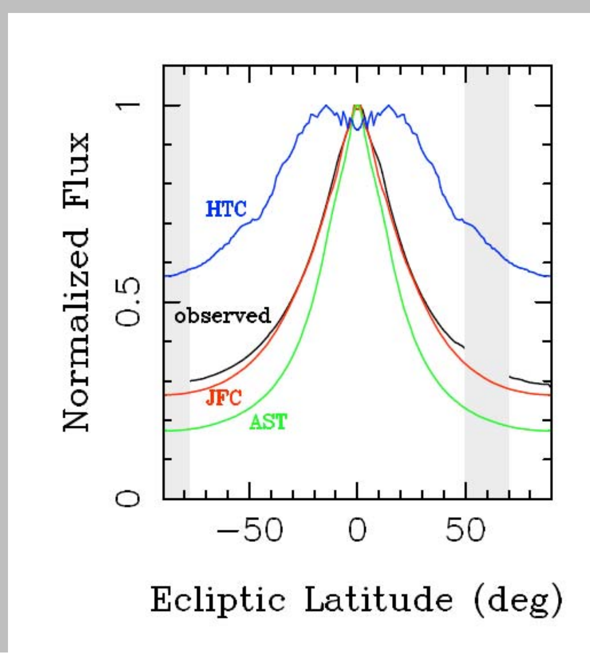

Zodiacal Light
Interstellar Medium
Comet 2P/Encke
Karin asteroid family
debris bands
Veritas asteroid family
debris bands
Comet 10P/Tempel 2
Comet 65P/Gunn

Infrared Zodiacal Light (view from 1 AU)

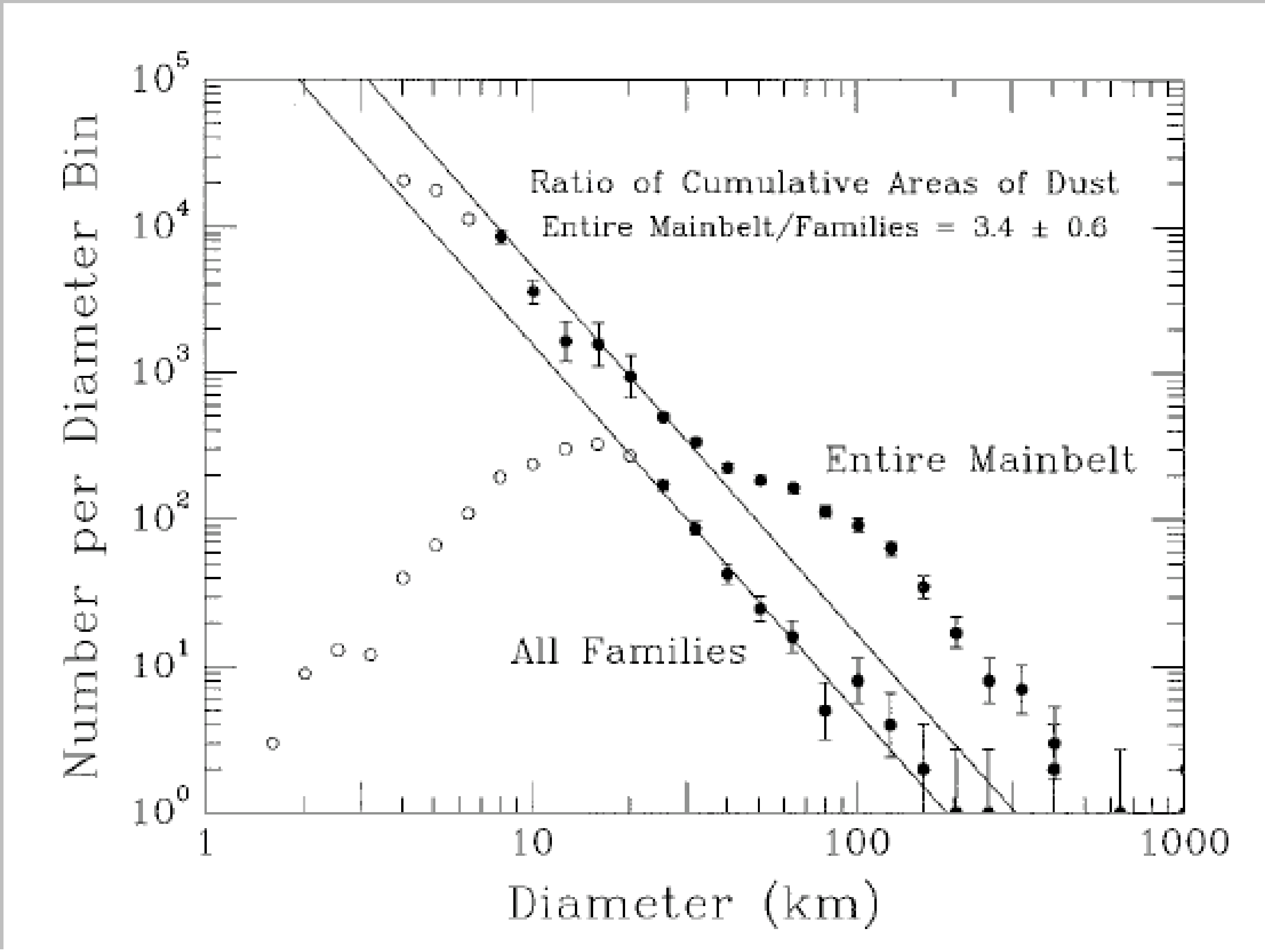
- dominates sky brightness from 1 to 100 microns
- Structures include bands, warp, terrestrial anisotropy
- From width of the zodiacal cloud, >90% Jupiter family comets (Nesvorny et al 2009)



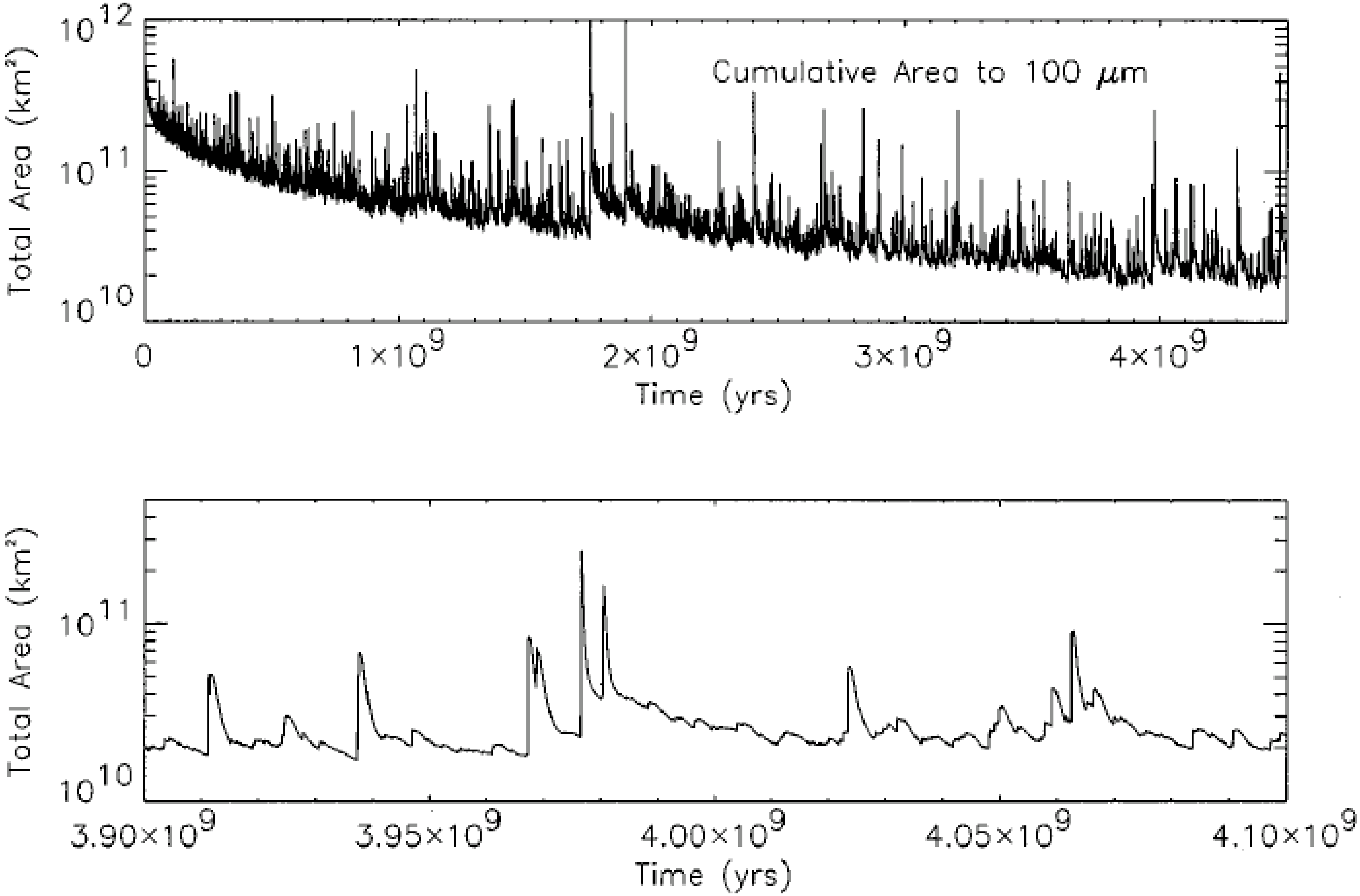




Asteroids: family VS entire



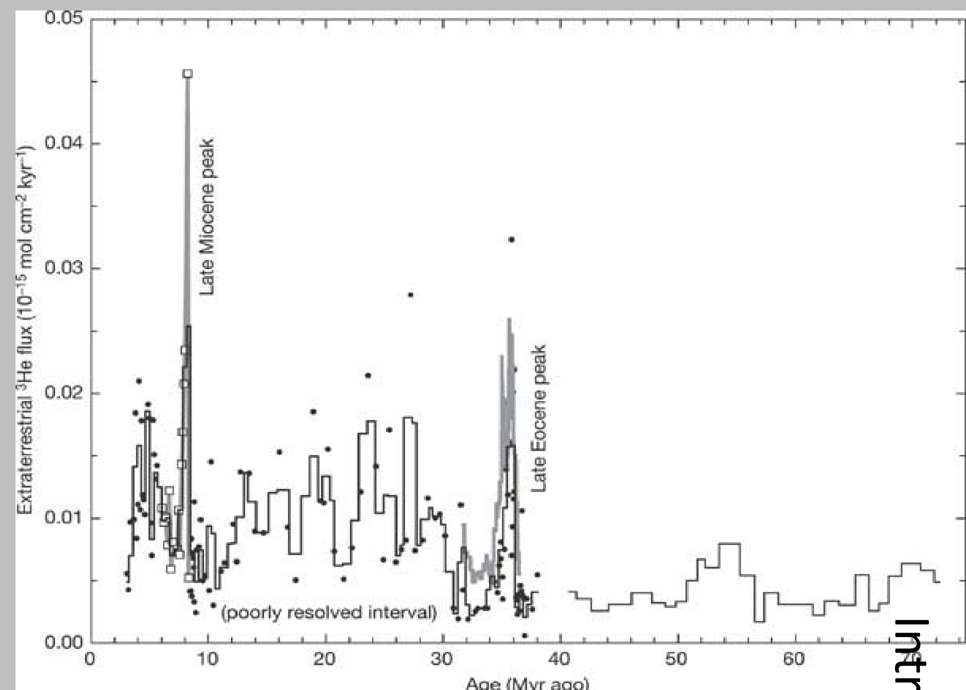
Asteroidal Dust History



Influx to Earth

- Considered to be asteroidal (low velocity)

- Seafloor sediment contains ^{3}He from IDPs, enhancement in Miocene tied to asteroid disruption that formed Veritas family *(Farley+ 2006, Science)*



- Cometary contribution to meteorites considered elusive, but ***possibly most IDPs and some carbonaceous chondrites are cometary*** *(cf. Nesvorny et al 2010)*

Recent Asteroid Collisions

Age	Source	Feature	Reference
50-250 kyr	1999 YC2		Nesvorny (2006 AJ 132, 1950)
220±2 kyr	Emilkowalski		
300-800 kyr	Lucasavin		
450 kyr	Datura	trail?	Nesvorny (2006 Sci 312, 1490)
<5 Myr	Beagle	1.4°band	Nesvorny (2008 ApJ 679, L143)
5.0±0.2 Myr	Karin	2.1°band	Nesvorny (2006Icarus 183, 296)
8.3±0.5Myr	Veritas	9.3°band	Nesvorny (2003 ApJ 591, 486) Farley (2006 Nature 432, 295)
~10Myr	Semajoki	17°band	Nesvorny (2003 ApJ 591, 486)
35 Myr (Eocene)	Comet shower	Chesapeake Bay, Popigai crater	Farley (1998 Sci 280, 1250)

Observations from Spaceprobe

- From fixed platform, only measure integrals along line of sight, not readily inverted
- Inner zodiacal light best measured by Helios spaceprobes, 0.3-1 AU eccentric orbit photopolarimeter (Leinert et al.) in 1970’s
- Azimuthal asymmetries near 1 AU probed by Spitzer (new; next slides)
- Zodiacal light only measured out to 3.5 AU by Pioneer 10
- Prime real estate still available outside 3.5 AU, to measure “outer zodiacal light”

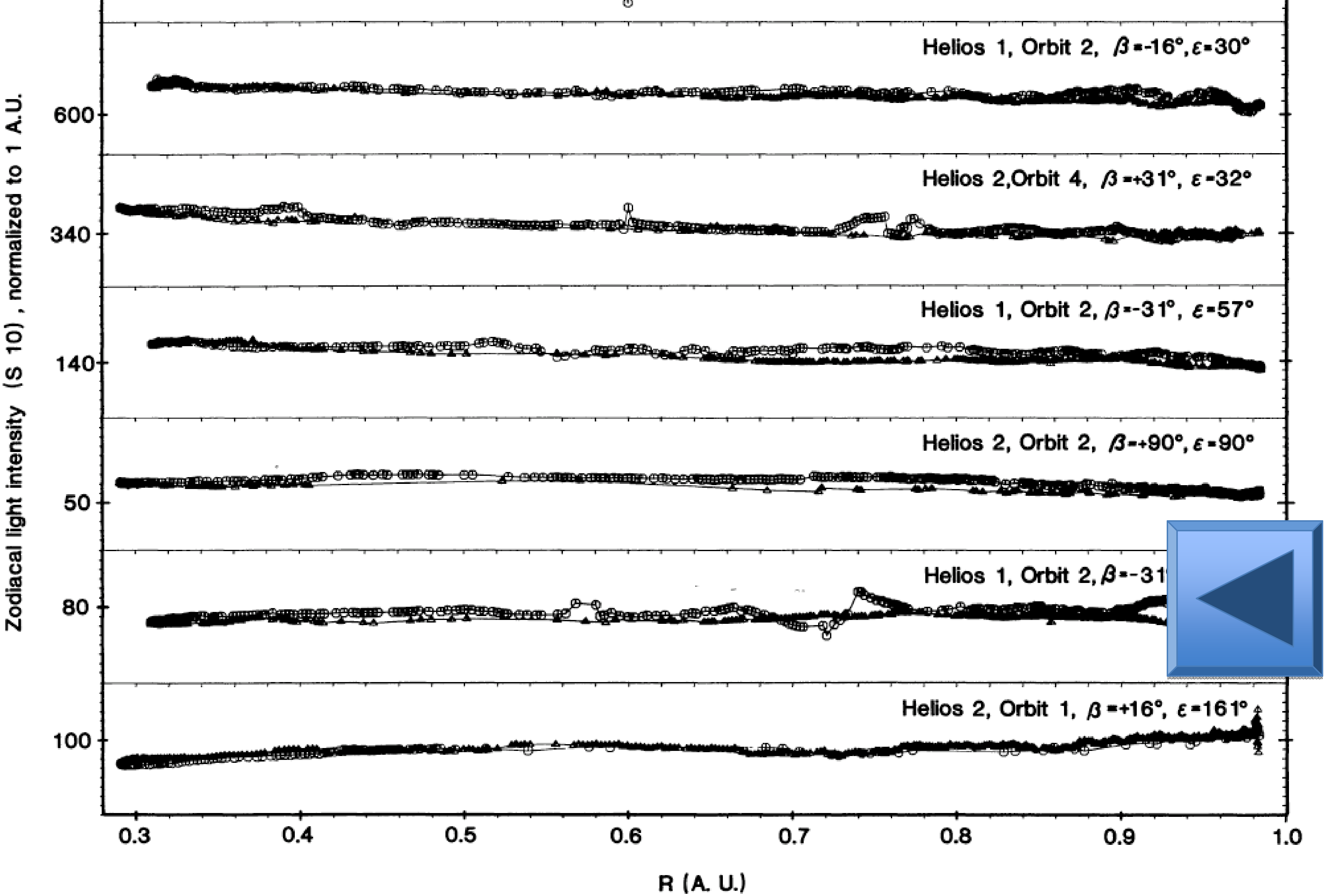
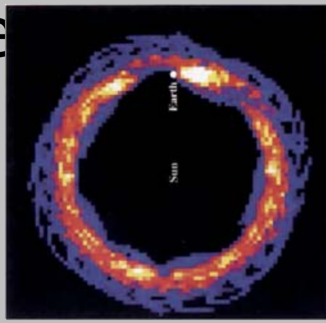


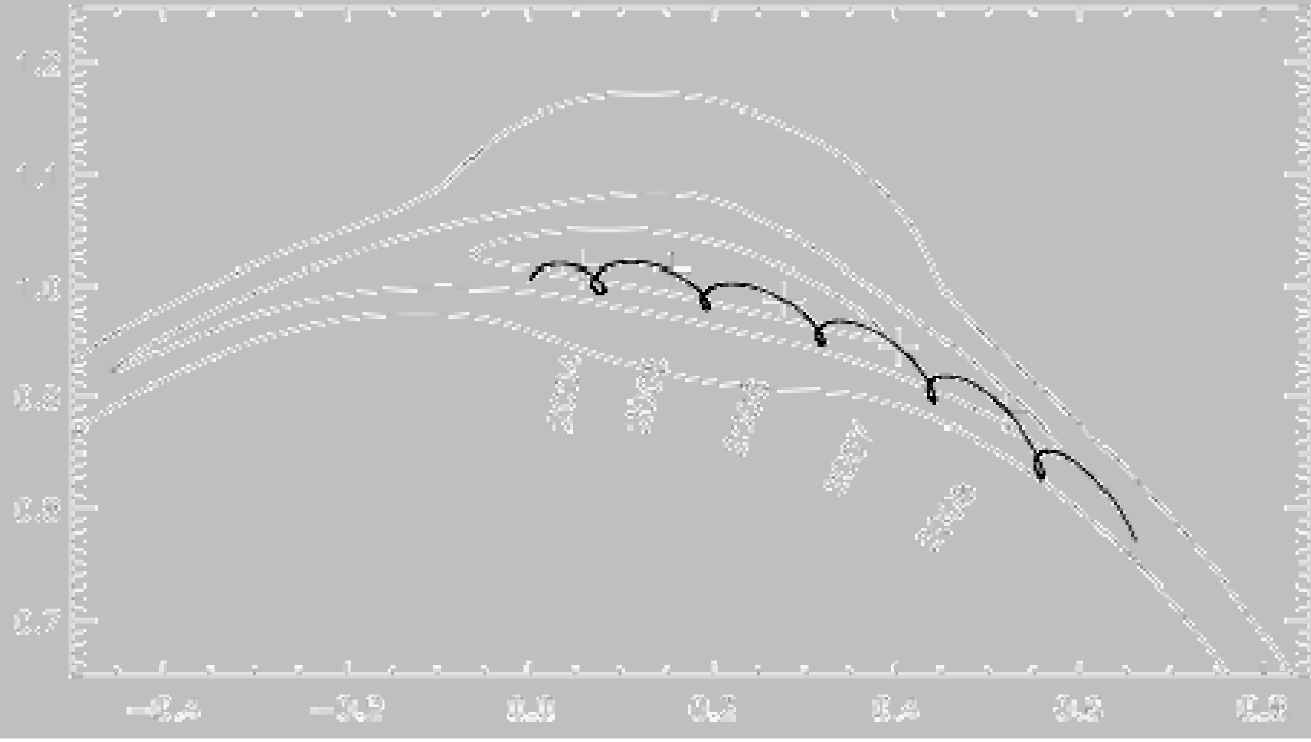
Fig. 5. Brightness increase of zodiacal light in *B* towards sun for different viewing directions relative to a power law $I(R) \sim R^{-2.3}$. Δ refers to inbound, ○ to outbound part of orbit. λ_{eff} of observations is 425 nm, 1 S10 corresponding to $1.02\ 10^{-12}$ W cm^{-2} sterad^{-1} μm^{-1}. For each viewing direction the step size of ordinate division is 5% of the given intensity value

Resonant structures in Zodiacal Cloud

- Smooth cloud traces mean orbital elements
  - Node randomized by Jupiter in 10^6 yr so only secular long-time-averaged perturbations survive

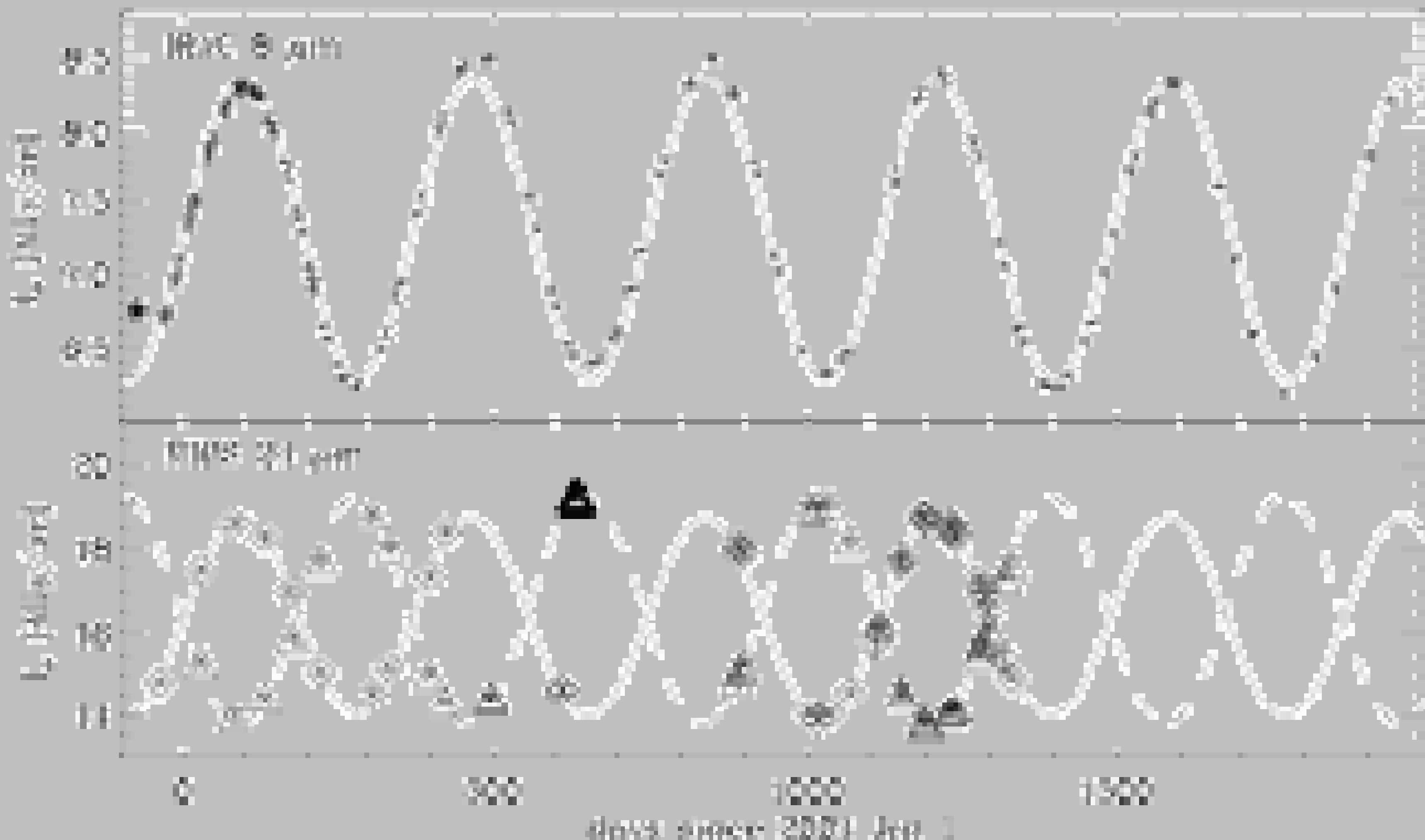


- Resonant effects in comoving frame with planet



- *Spitzer Earth Ring experiment*
- Frame comoving with Earth
- Contours of the COBE/DIRBE zodiacal cloud model
- Trajectory of Spitzer (thick) with crosses every year
- Able to probe azimuthal structure of zoiacal cloud

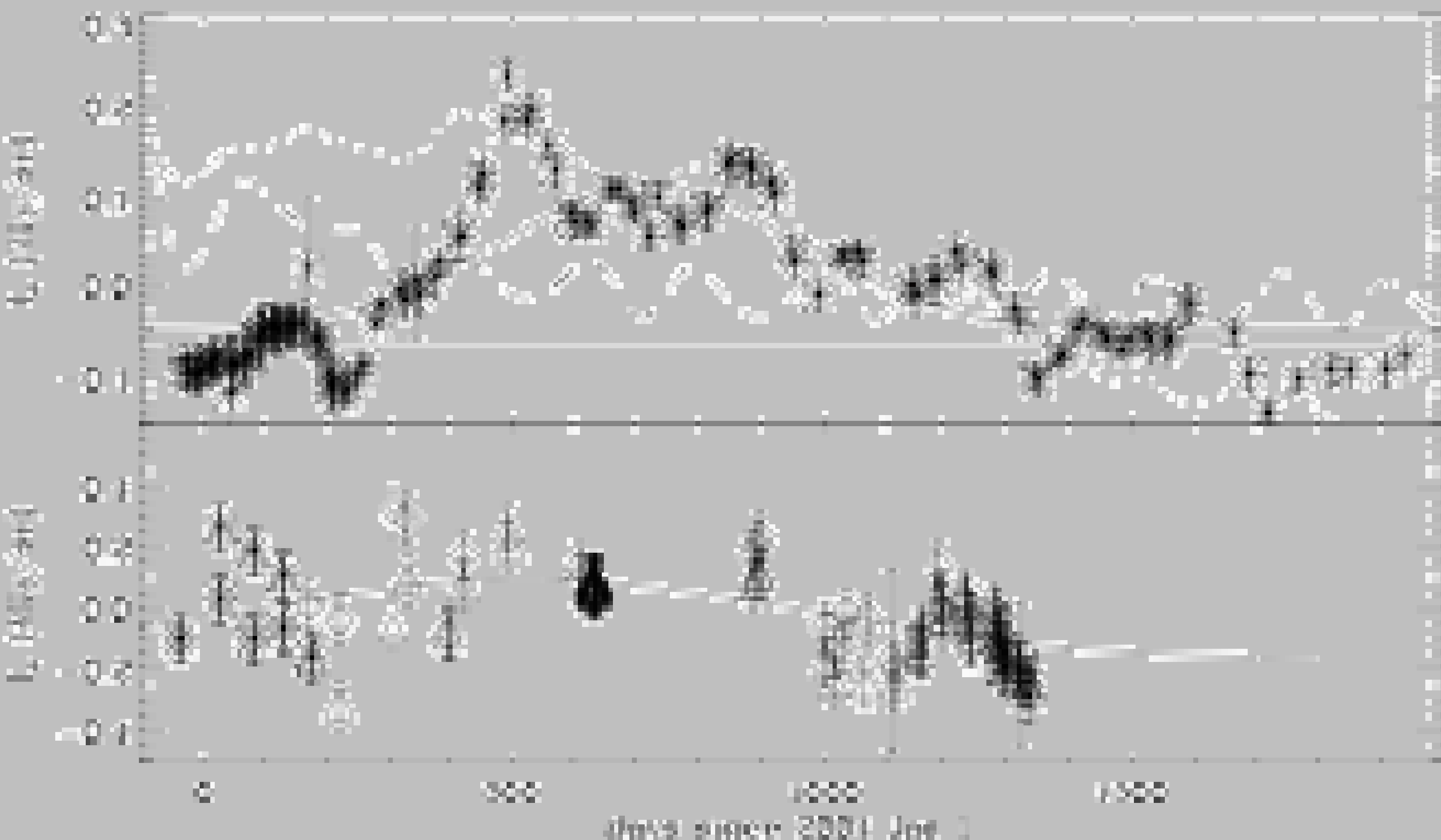
Observed brightness of North Pole



Sinusoidal variation due to inclination of zodiacal plane, and eccentricity of orbits

Infrared/Zodiacal Light

observed MINUS sinusoid



Residual variation due to longitudinal asymmetry of zodiacal cloud

Observations from Spaceprobe

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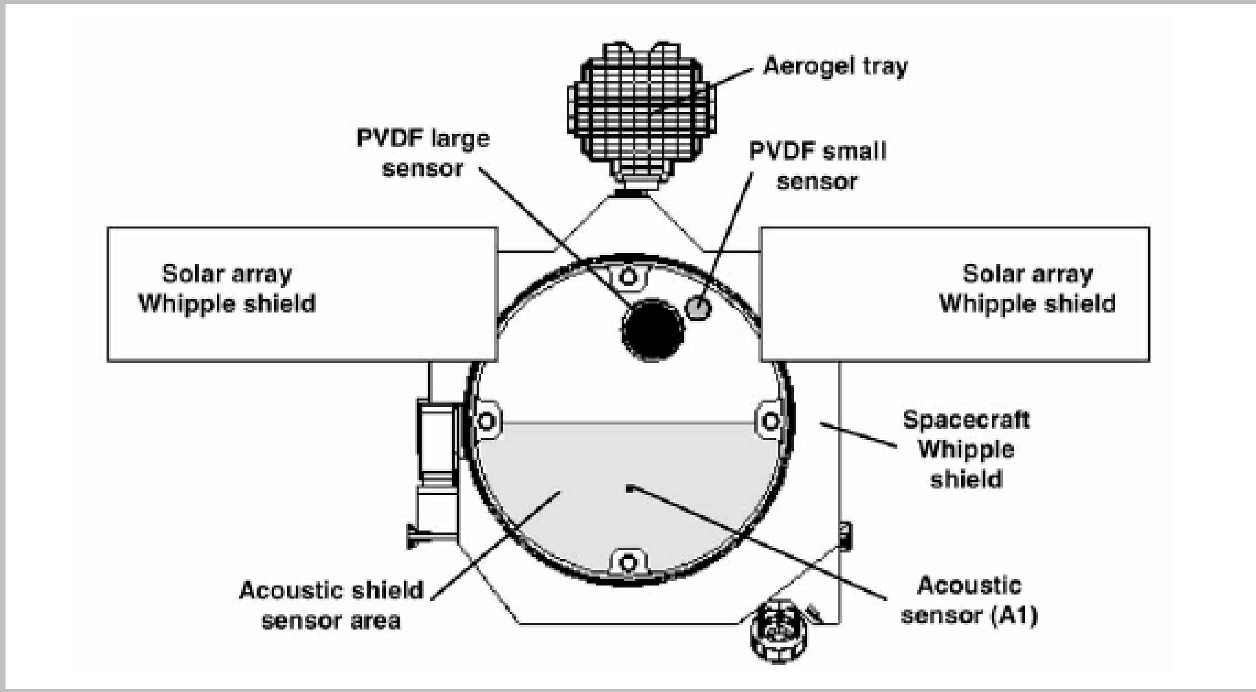
STARDUST *in situ* particle detection

- Dust Flux Monitor Instrument
  - Impacts onto polarized film generate current pulse
- Acoustic sensor
  - piezoelectric crystals respond to impacts onto shield



- Radio Doppler and attitude control
  - Responded to large particle ~30 mg, 15 s before close approach
  - Similar large particles jogged *Giotto* and destroyed its camera

Particle Size Distribution

For power-law $n(<m) \sim m^{-\alpha}$

- Most mass in largest particles if $\alpha<1$
- Surface area in large particles if $\alpha<2/3$

Halley & Wild2 → $\alpha=0.75\text{-}0.88$

- Applies to m<1 μg
- Mass in large, area in small

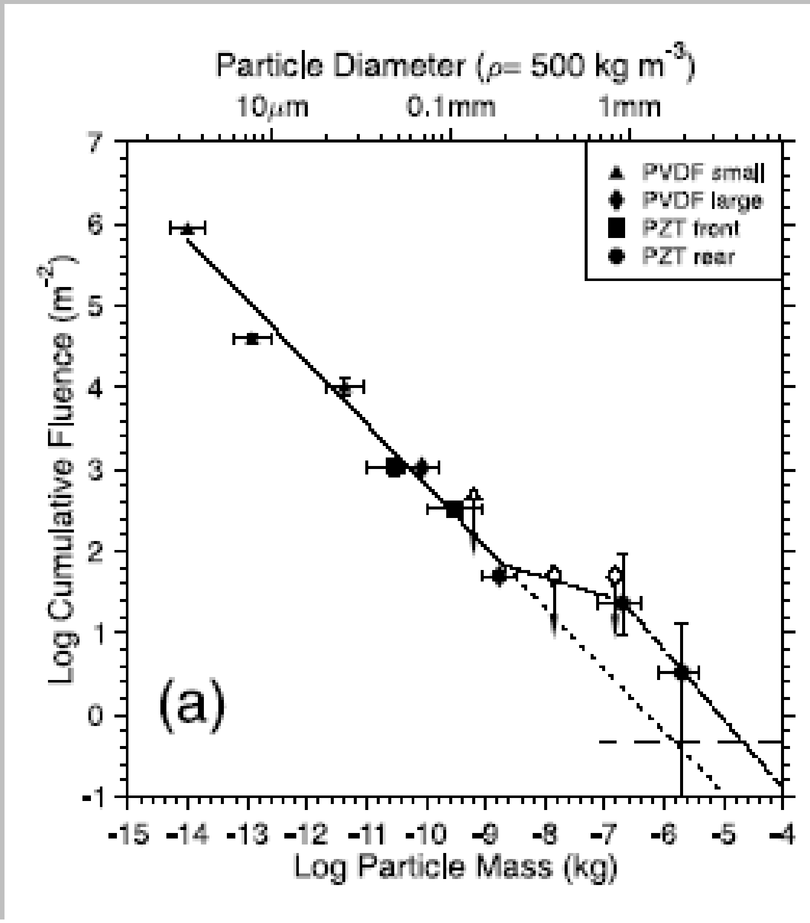
Large particle excess

- Double power-law fit

Radio Doppler

- 20-40 mg particle shifted attitude

(Anderson et al 2004 JGRE 109) a~2 mm



Green et al 2004 JGRE 109

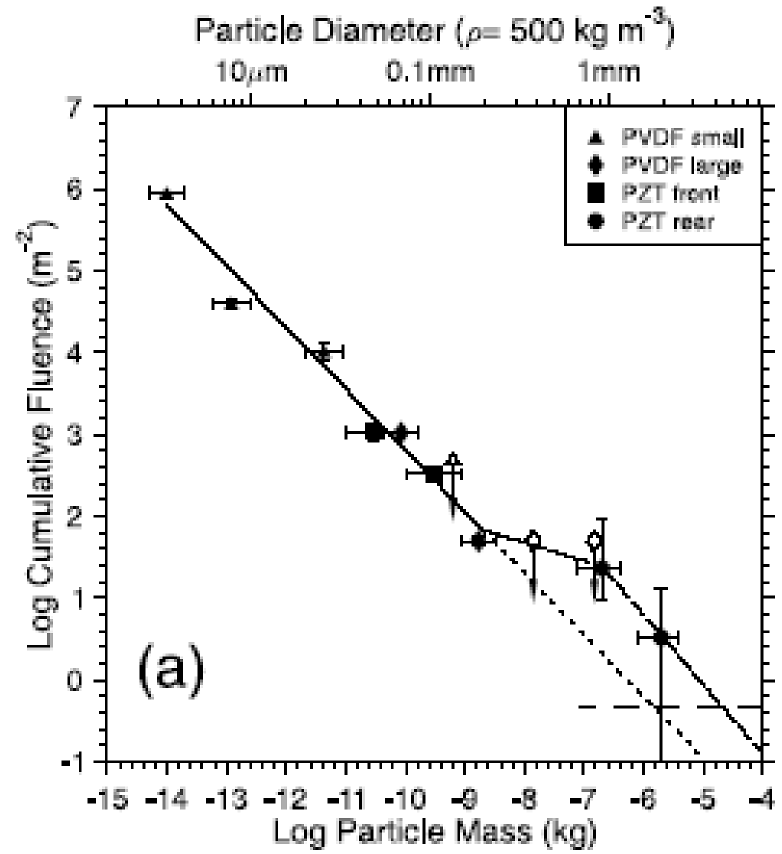
Application to Stardust data

Mass ratio

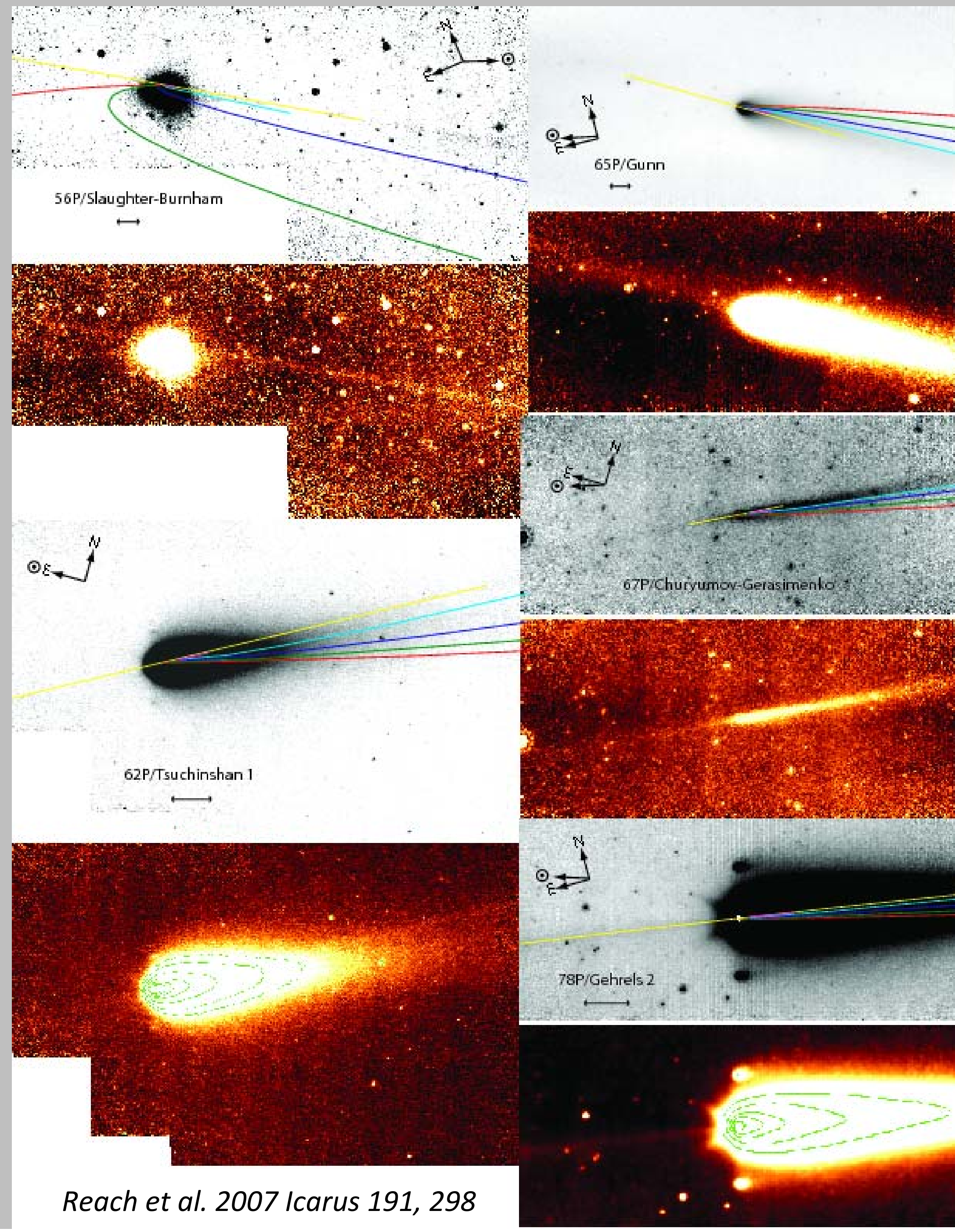
- Observe: $m_{max}/m_1>100$, $m_2/m_1 \sim 300$
- → $M_2/M_1 \sim 600$
- Bulk of mass in "bump"

Area ratio:

- Observe: $m_1/m_{min}>10^6$
- → $A_2/A_1<7$
- Significant area in "bump"
- Coma due to large+small particles

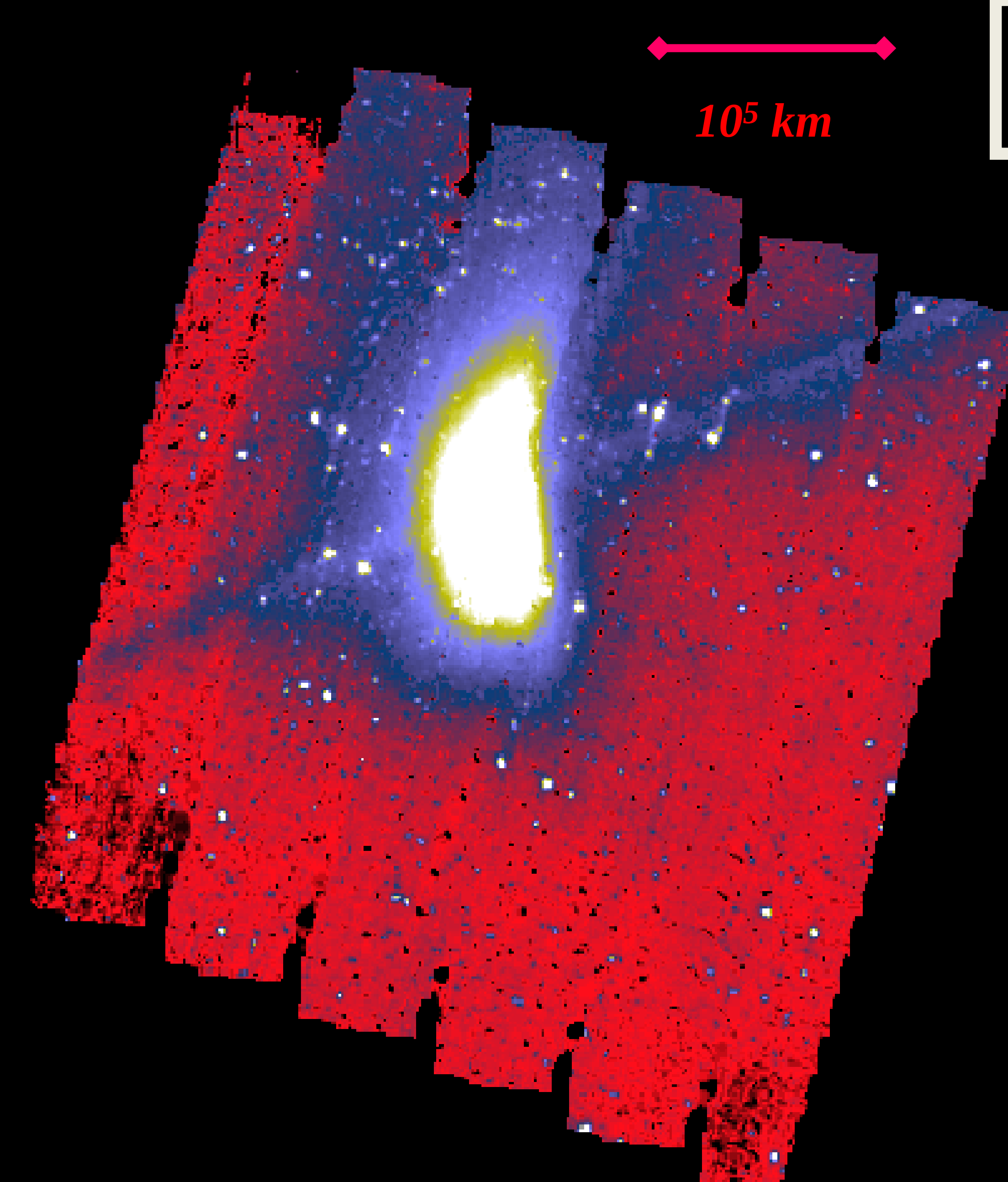


Cometary dust production



Reach et al. 2007 Icarus 191, 298

2P/Encke: ISOCAM



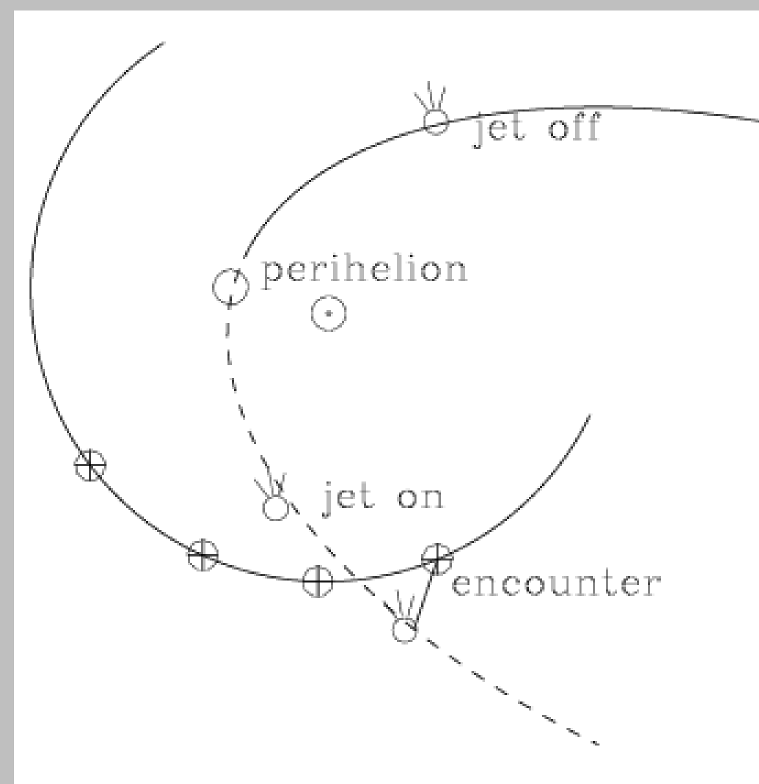
July 14, 1997

close approach to Earth

(Δ=0.25, R=1.15 AU)

Post-perihelion

wavelength: 12μm

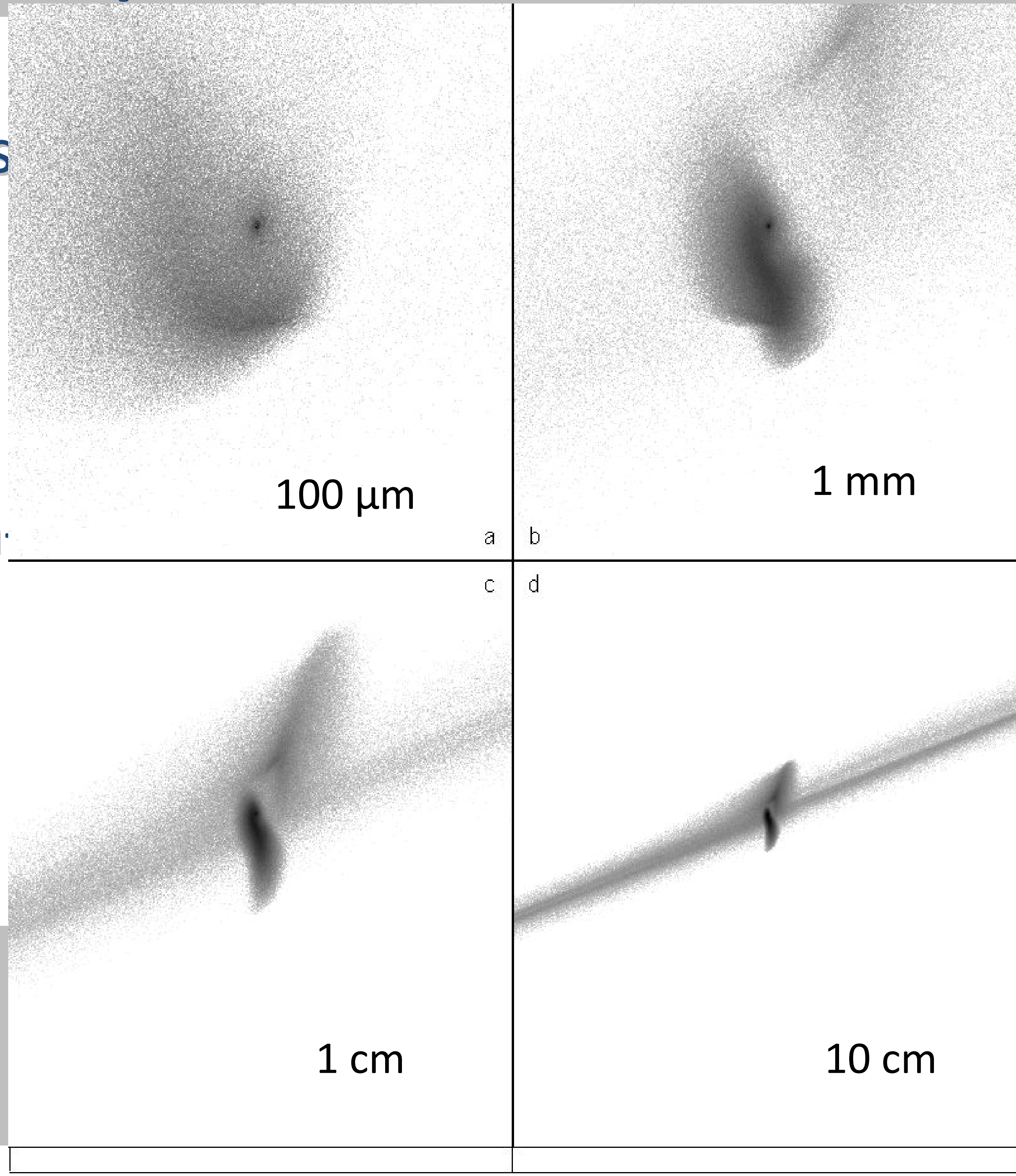


Trail and coma versus particle size

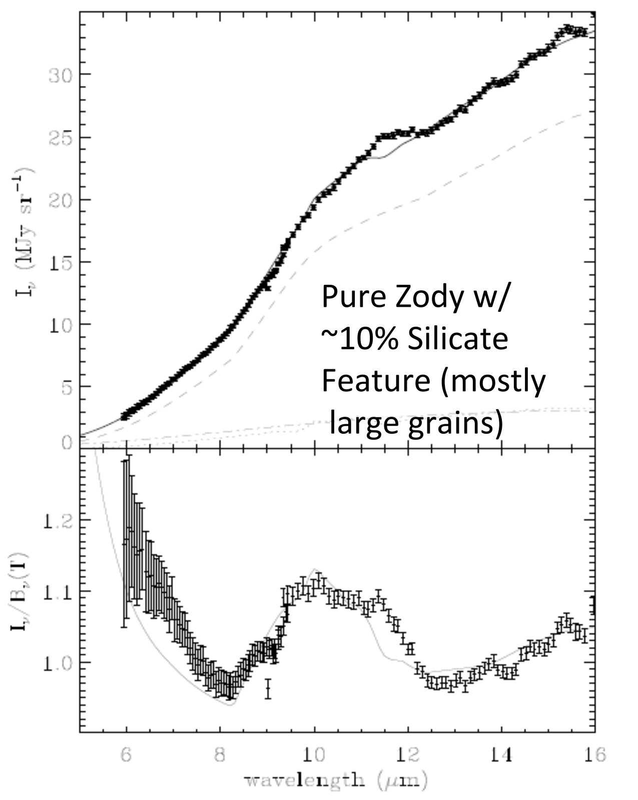
- Model: particles ejected since previous aphelion
- ISOCAM geometry

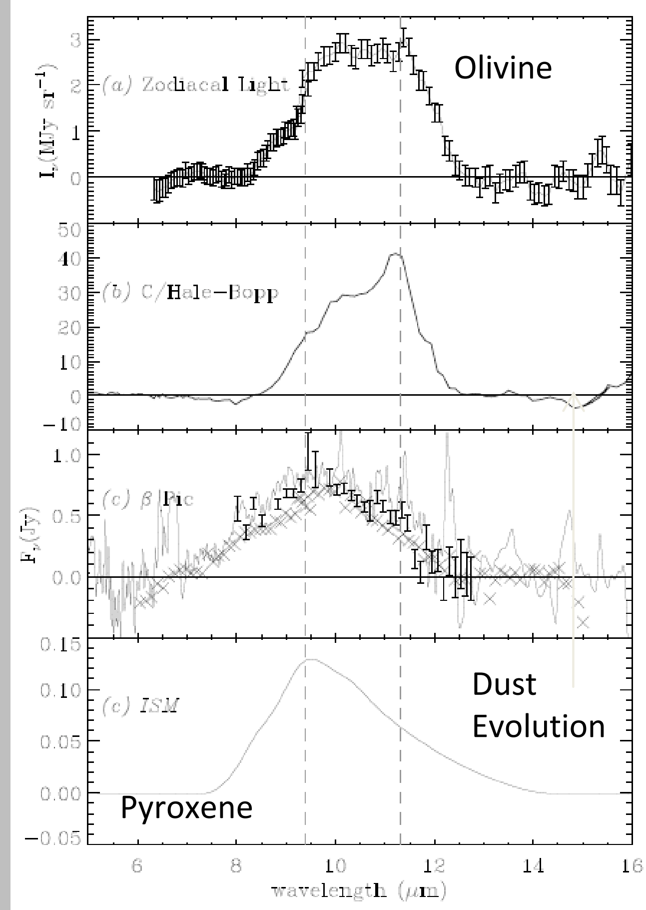
→

- The trail is due to cm-sized particles
- Even the "coma" is due to mm sized particles

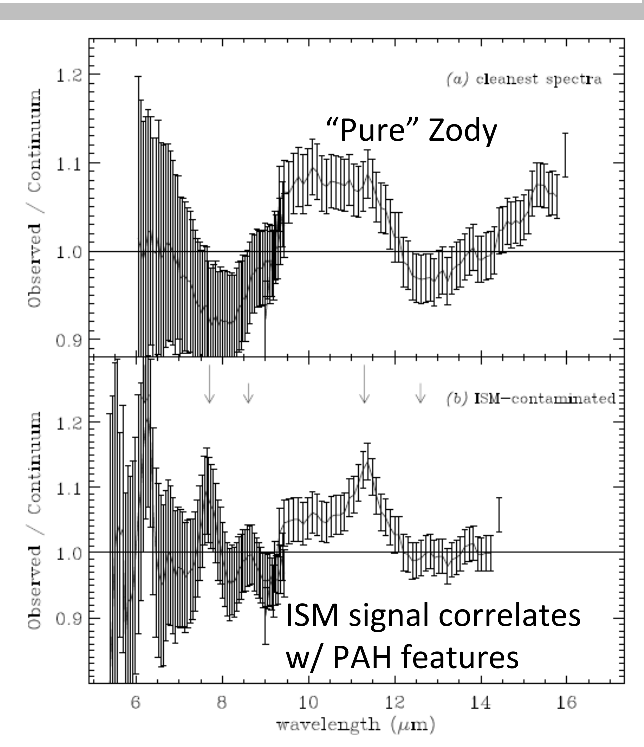


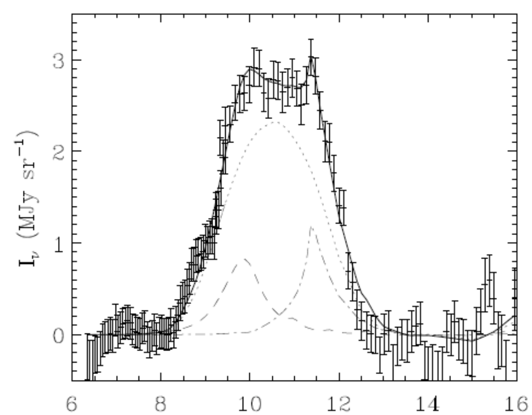
Zody Light Spectra from ISO – Small But Finite Silicate Emission Feature. (Reach *et al.* 2003)





But: Need to update spectral analysis for Deep Impact, STARDUST, dynamical, & Spitzer lessons learned re: cometary & asteroidal dust.





Best Decomposition = ~20% Asteroid +80% Comet

Fig. 13.— Comparison of a mixture of silicates with all possible ellipsoidal shapes to the observed, continuum-subtracted, spectrum of the zodiacal light. The solid line is the mixture fit, the dotted line is the amorphous olivine contribution, the dashed line is the montmorillonite contribution, and the dash-dotted line is the crystalline olivine contribution.

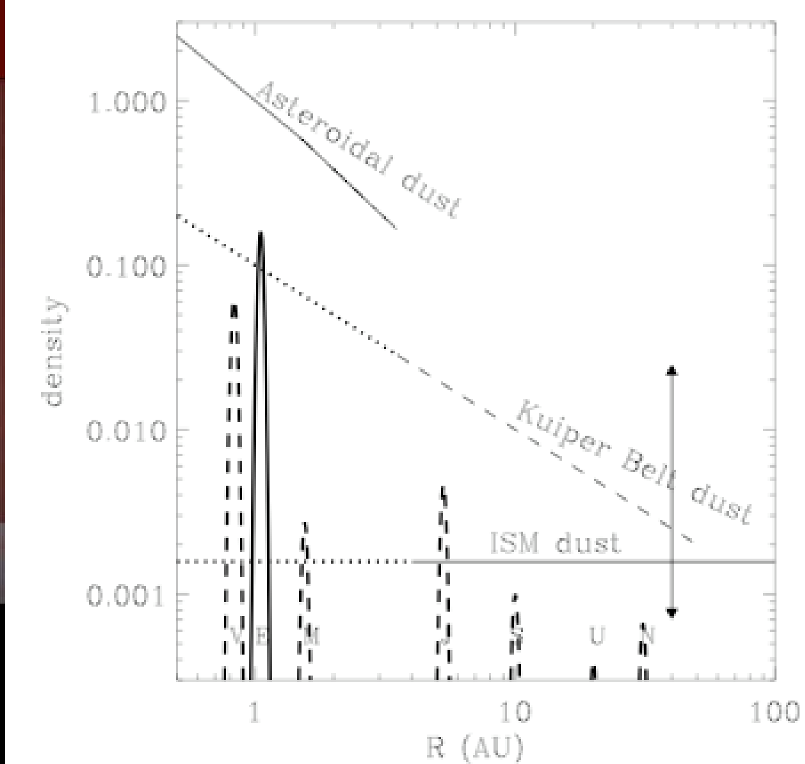
See also:
Messenger & Keller - (IPD like Hale-Bopp)

New CIBER Results- Zody Refl. Like S-Type Asteroids

Nesvorny IRAS Fitting - >90% of IPD input is from JFCs

Outer Zodiacal Light

Next frontier
Collisional evolution of Kuiper Belt



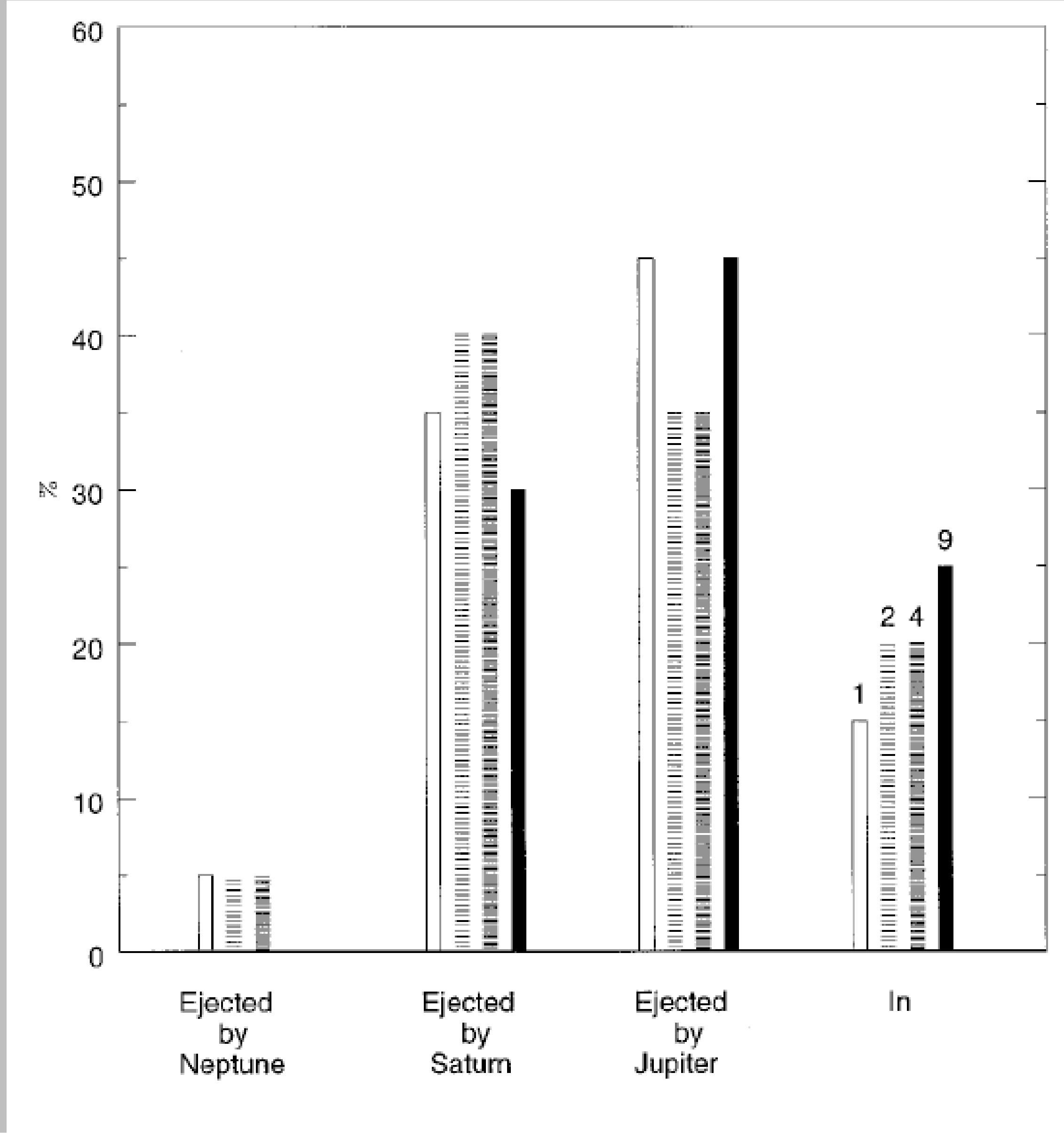
Kuiper Belt origin of Interplanetary Dust

Liou, Zook, & Dermott (1996)

Modeling dynamical evolution of grains from KBOs, including resonances and perturbations

Interstellar grain collisions are more rapid than mutual KB grain collisions

ISD may shatter KB particles >10 um before they reach the inner solar system



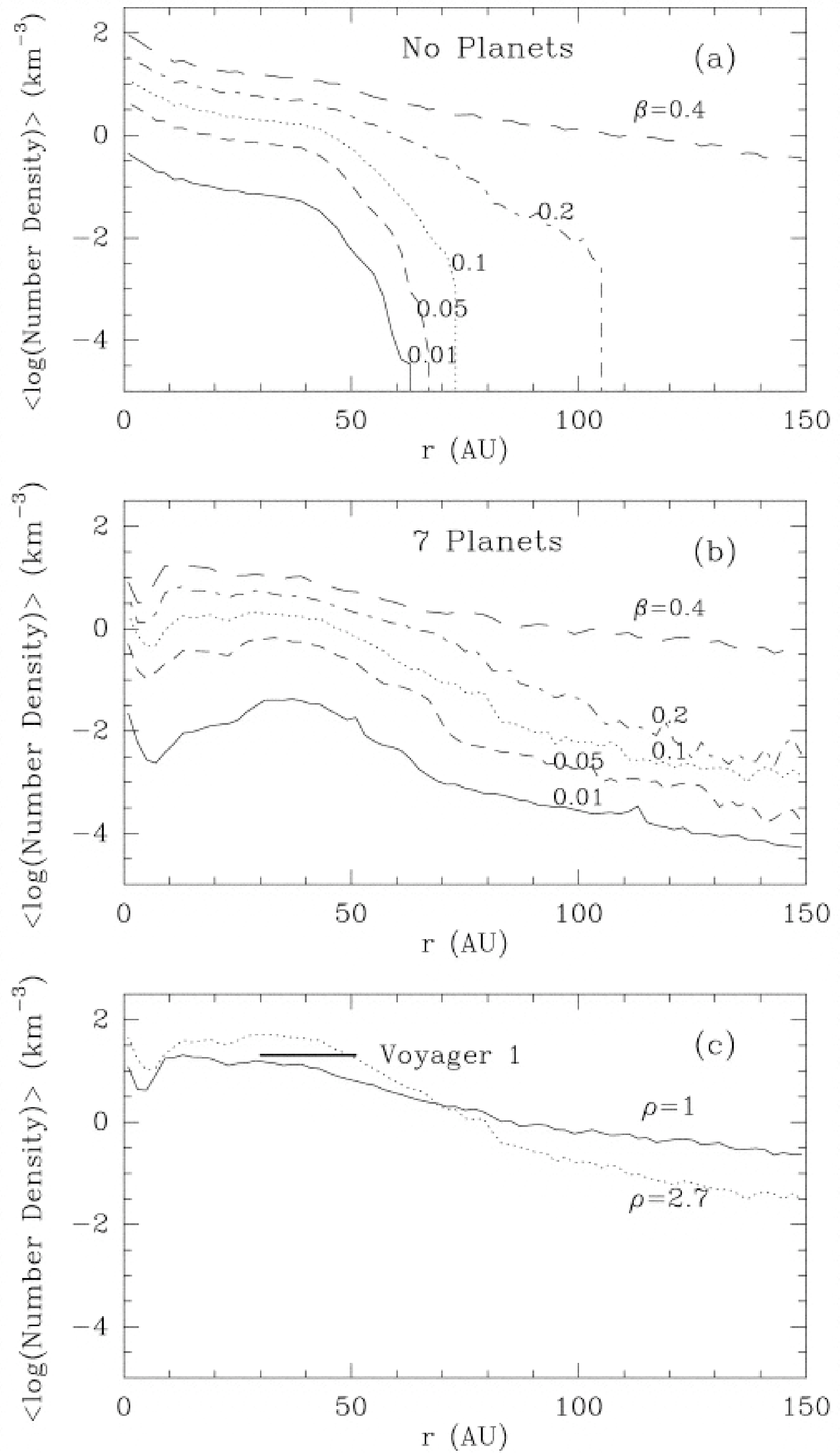
Dust Density predictions for Outer Solar System

Moro-Martin and Malhotra (2003)

Collisional production rate 10^6-10^8g/s (Stern 1996, Landgraf 2002)

KB dust cloud mass ~ 10^{22}g

Relatively high eccentricities when passing Earth, like comets

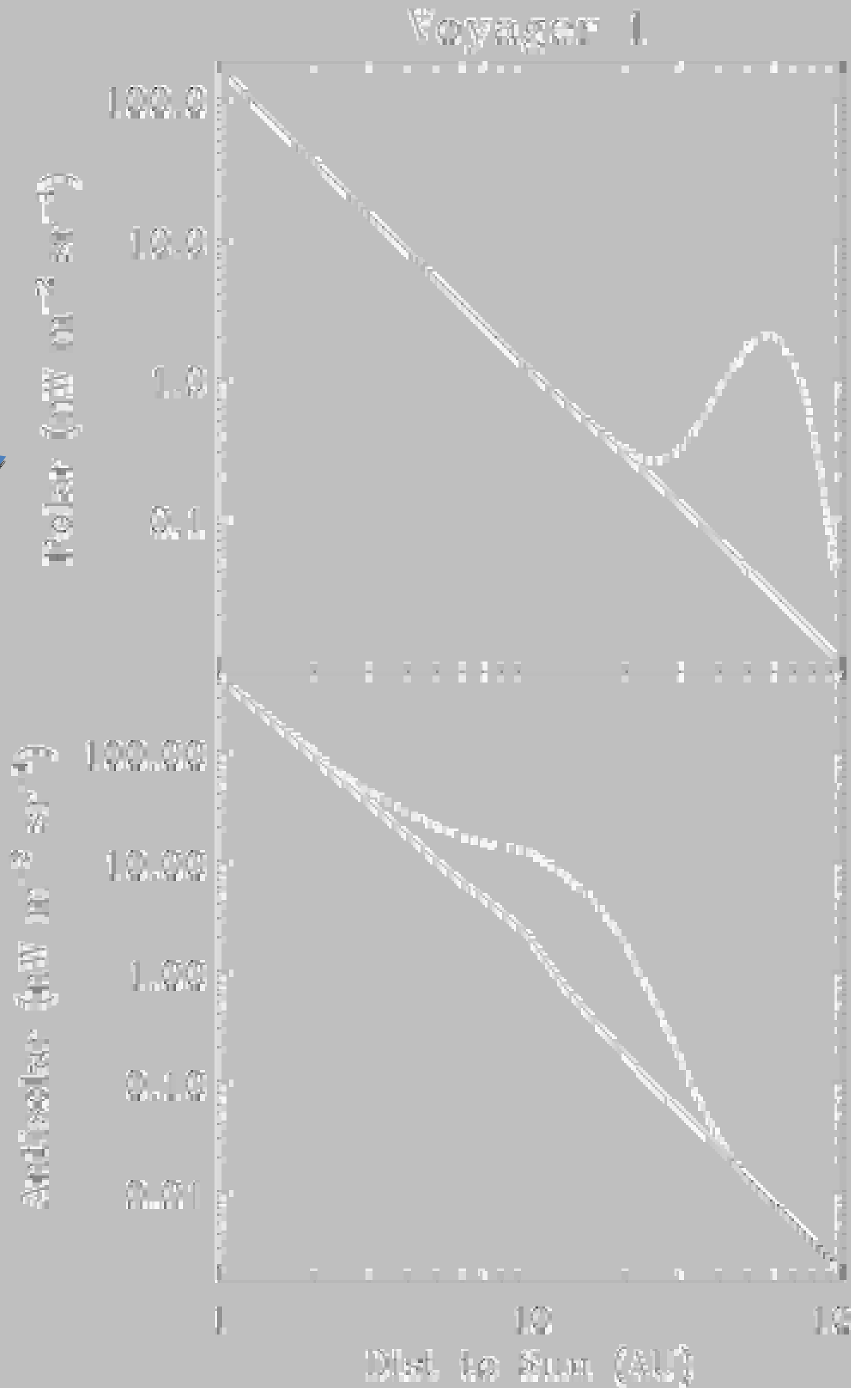


Zodiacal Light Predictions for spaceprobe

Use the Voyager 1 spacecraft trajectory (as an example)

- ecliptic pole
- antisolar direction

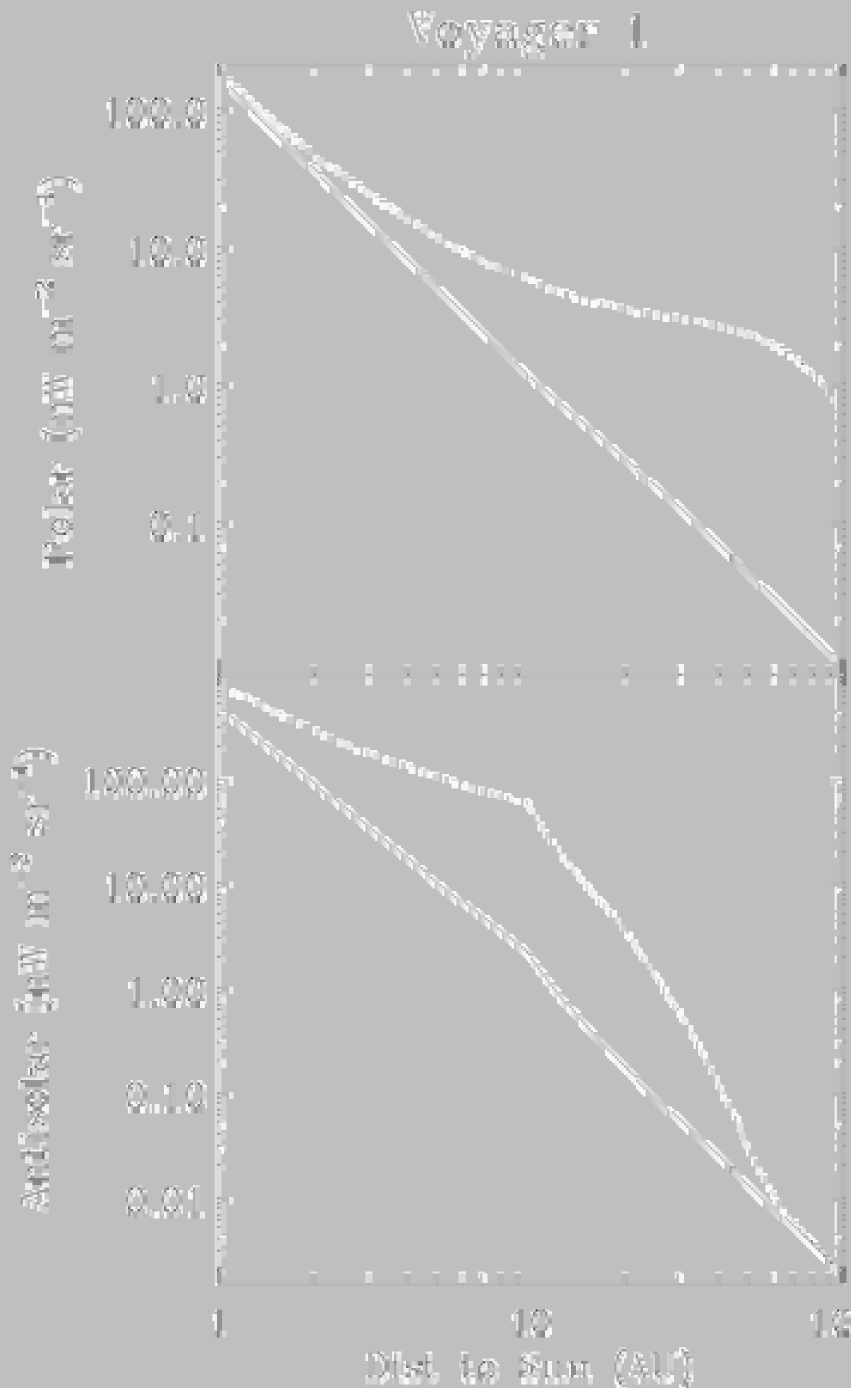
Illustrative calculation: power-law zodiacal cloud extrapolation, plus gaussian torus at Kuiper Belt



Outer Zodiacal Light: radial profile

Same as previous slide, but:

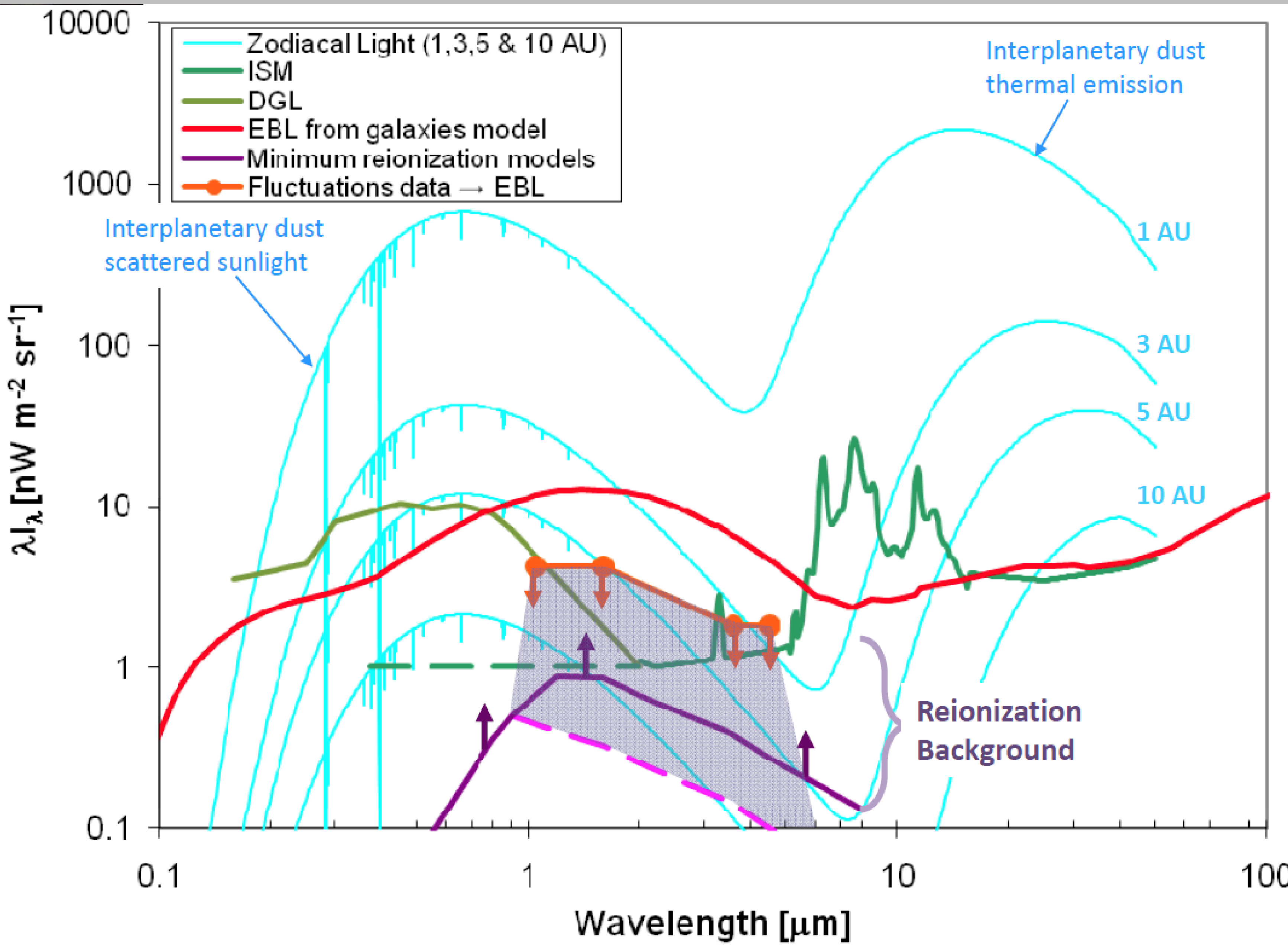
- Density estimate from Jewitt&Luu and Moro-Martin &Malhotra.
- Much wider distribution of KB dust (spiraling inward due to PR drag)



Planetary System Architecture

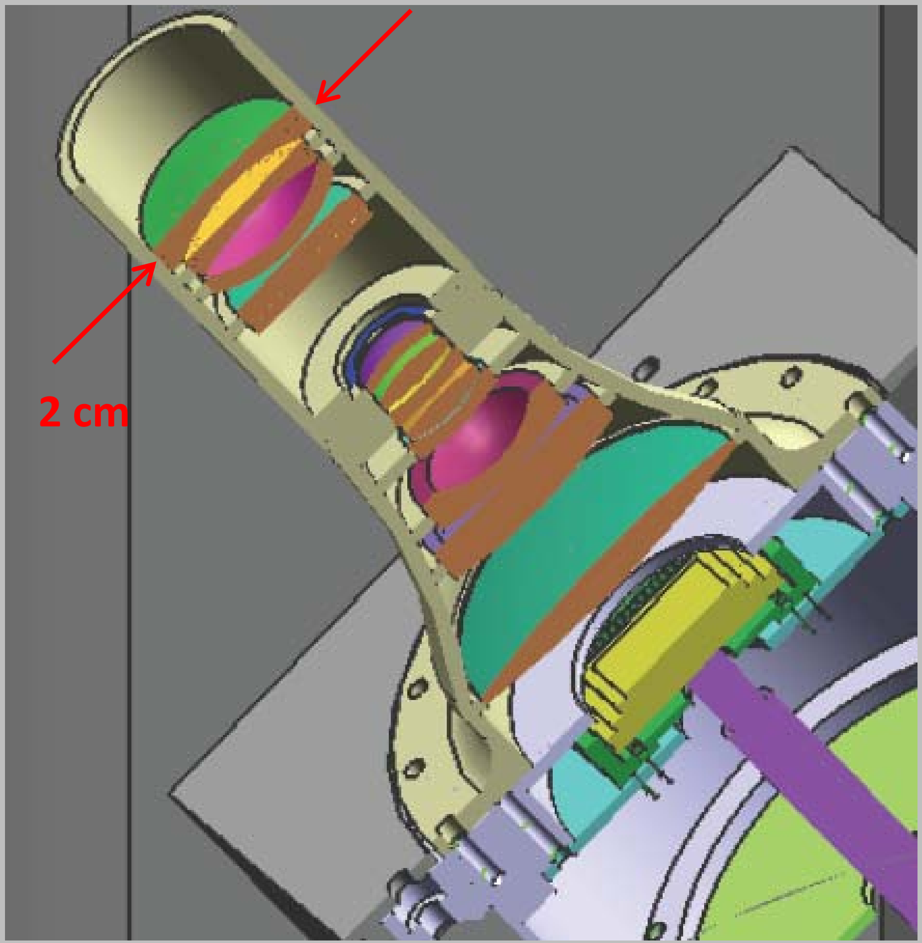
- Under the Nice Model, giant planet mutual gravitational interactions violently perturbed shape of the outer solar system
- Shape of Kuiper Belt and scattered disk population relate to past history of perturbations
- KB dust relates to collision rate in the KB, as do asteroidal dust bands in the inner zodiacal light

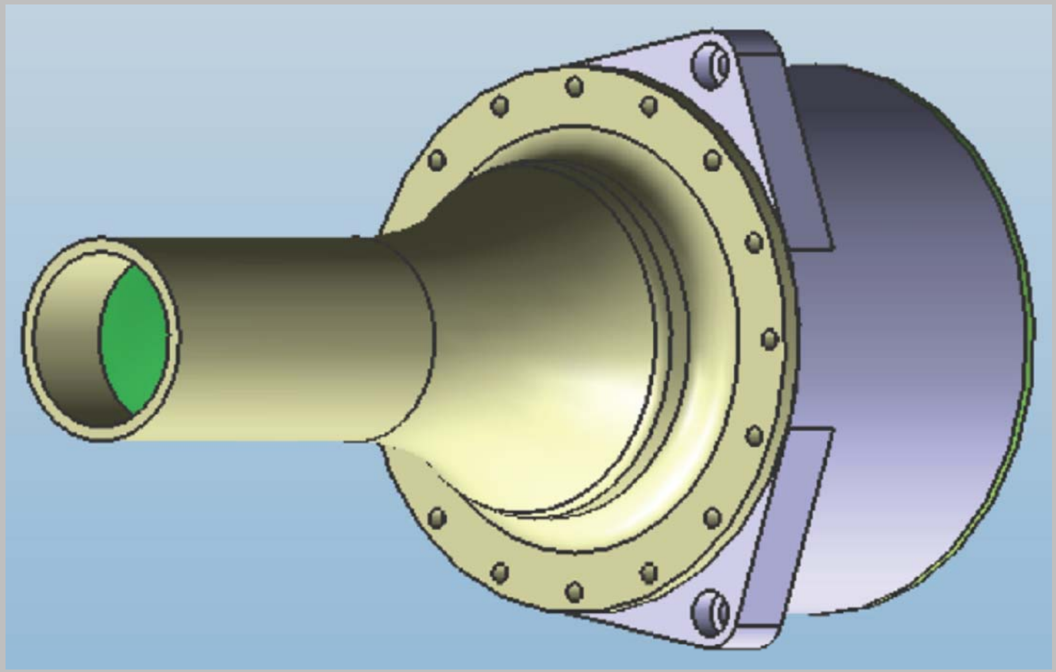
Tagalong science



Wide-Field Camera

Refracting Optics





Specifications

Spatial resolution: 5' x 5' pixels

Wavelength band: 800 nm

Field of view: 85º x 85⁰

Sensitivity: < 0.1 nW/m^2 sr per pixel

Focal plane: 1024^2 HAWAII 1.7 um HgCdTe or HiViSi

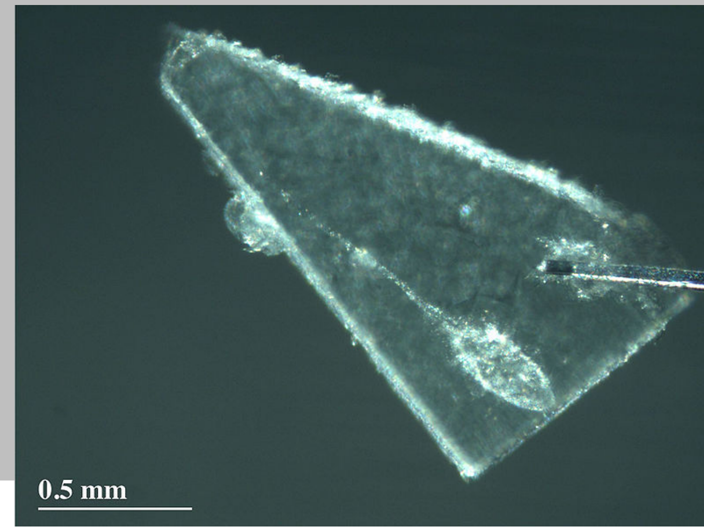
Science

- Kuiper belt cloud structure
- Interplanetary dust cloud structure

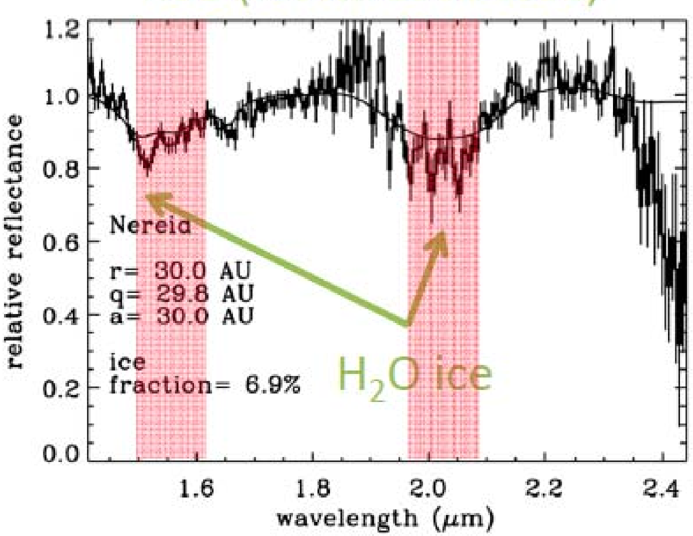
Composition of IDPs

Infrared spectra measure mineralogy of parent bodies

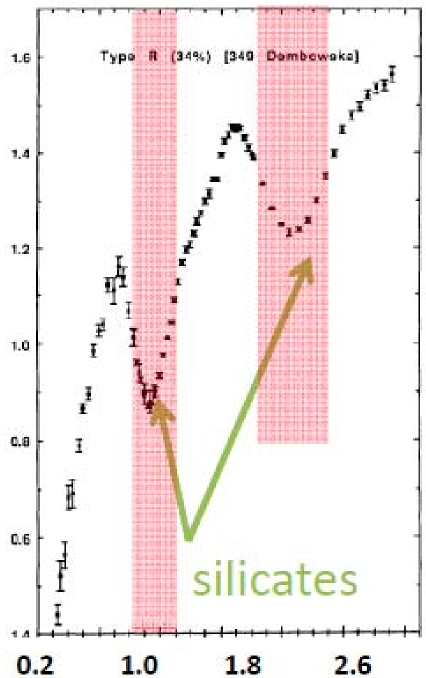
Comeplement laboratory work on IDPs and STARDUST



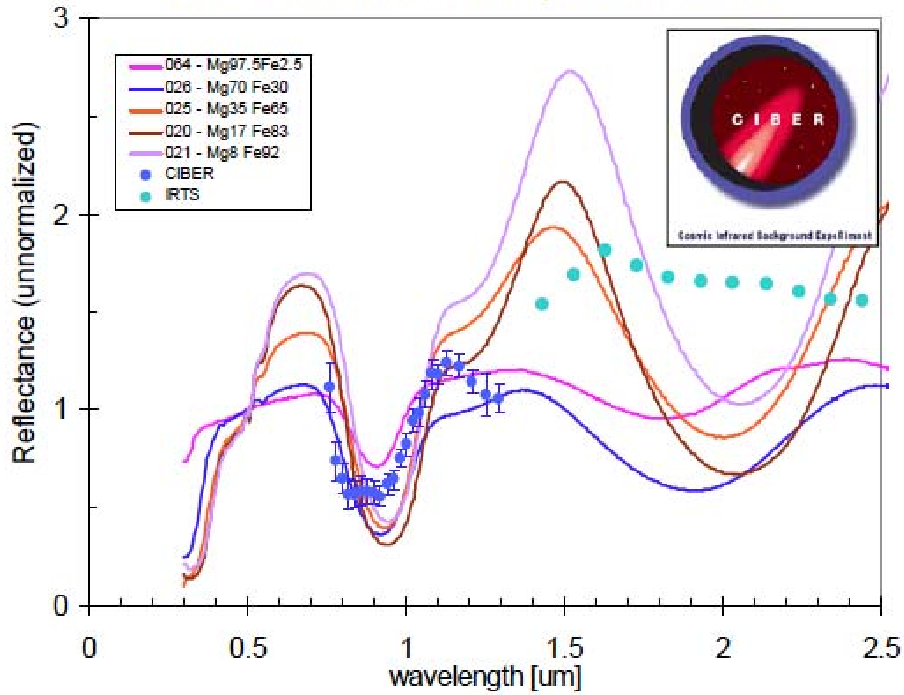
KBO (Brown et al. 1998)

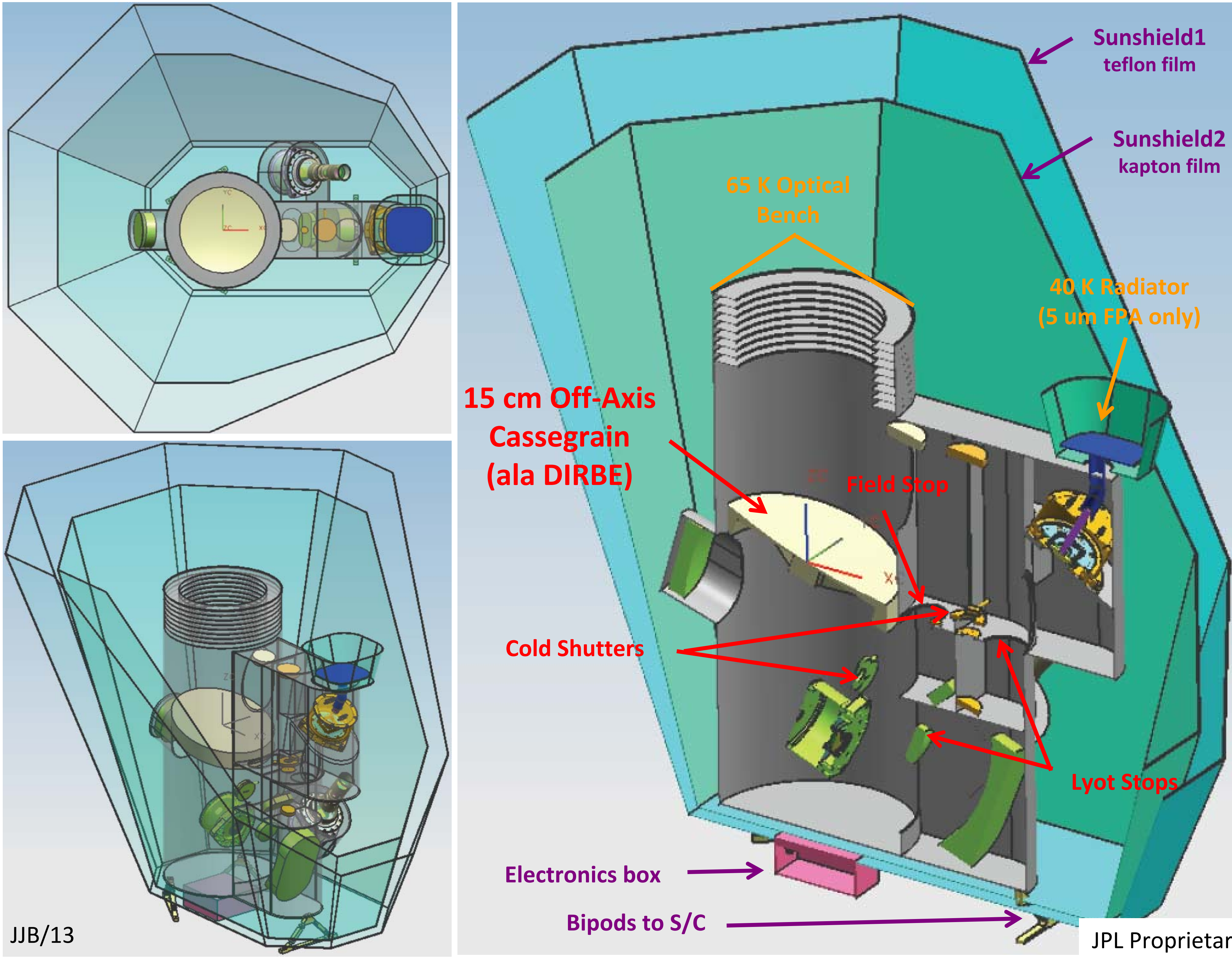


Asteroids (Gaffey et al. 1996)



New Detection of Pyroxene in ZL





JPL Proprietary