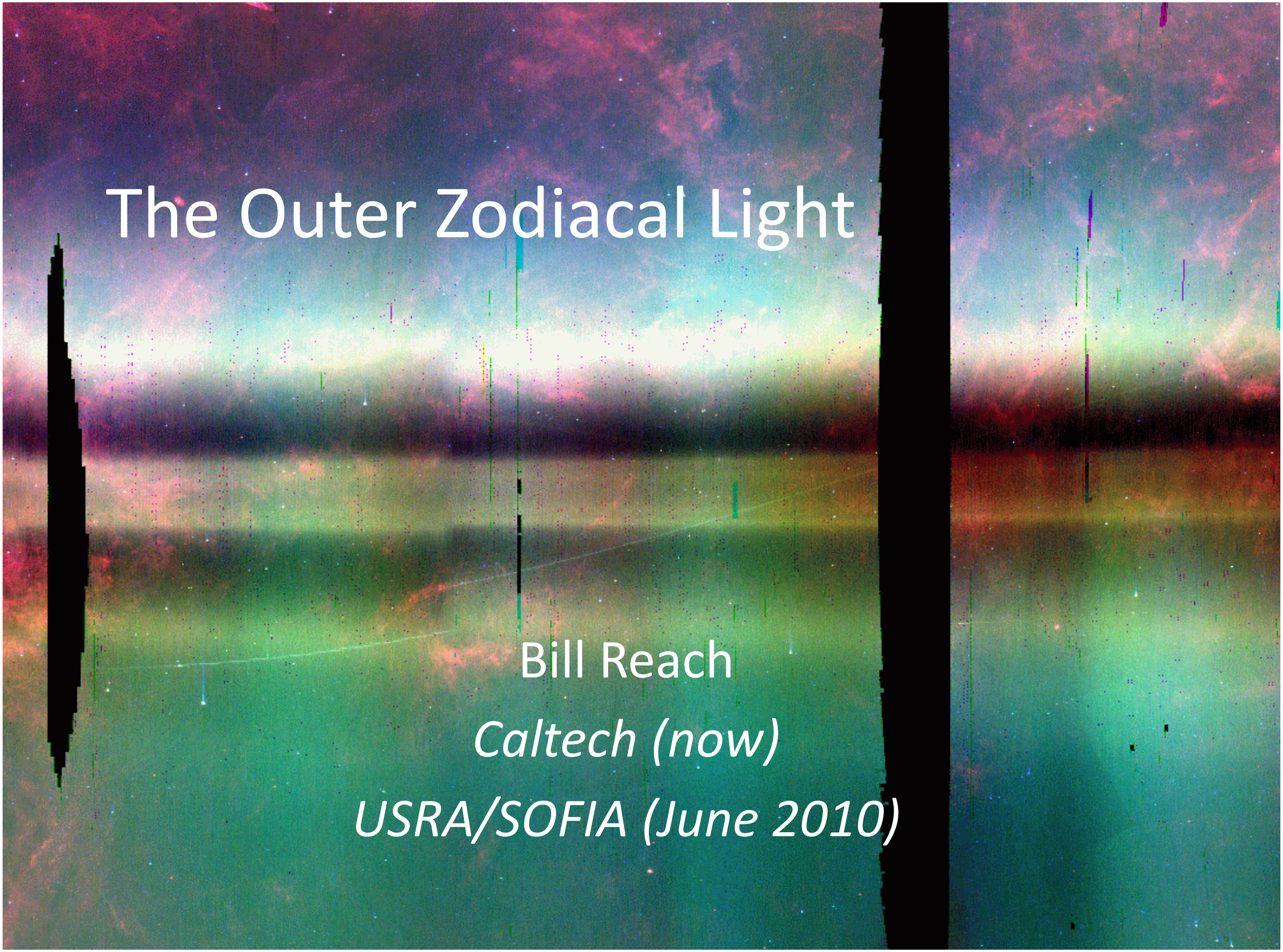
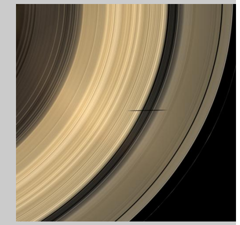


The Outer Zodiacal Light

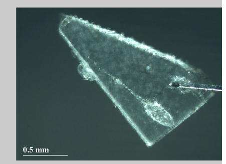
Bill Reach
Caltech (now)
USRA/SOFIA (June 2010)

Why Study the Smaller Bodies?

① Tracer of gravitational potential

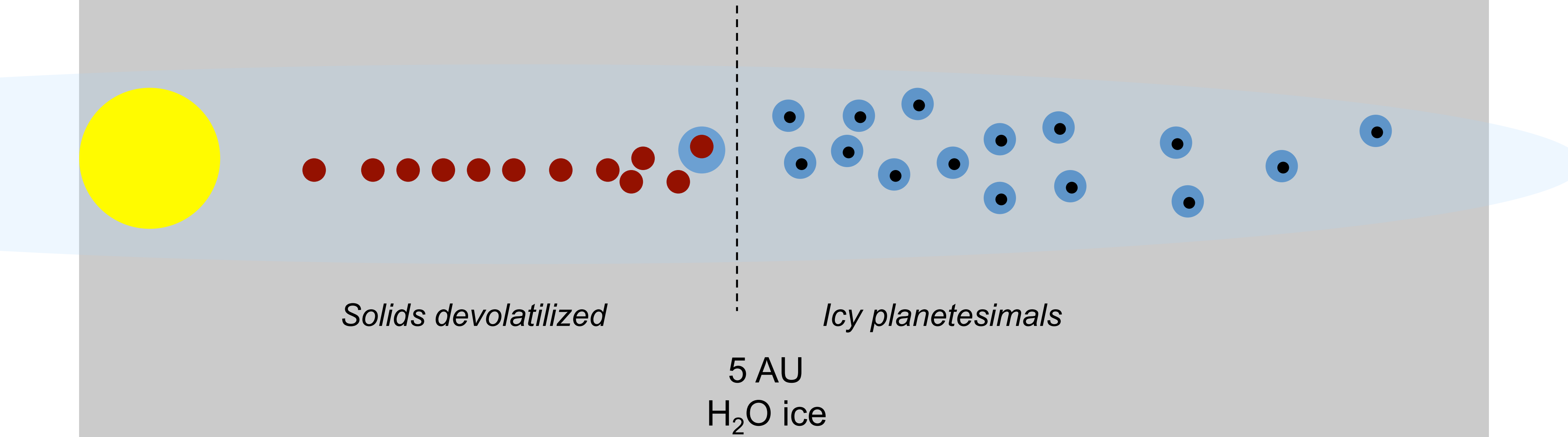


② Sample of material from solar nebula and major bodies

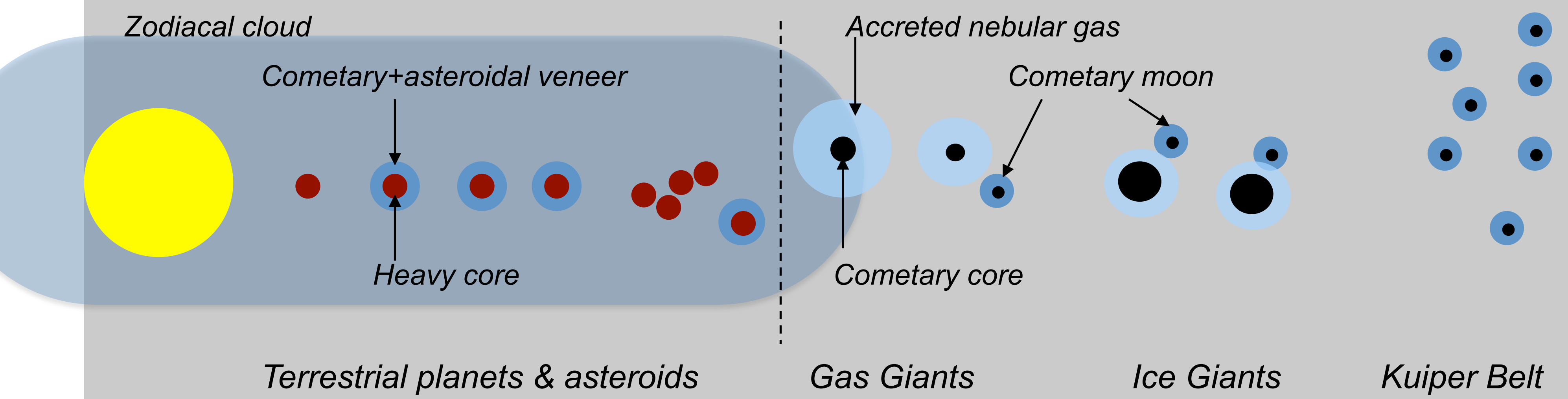


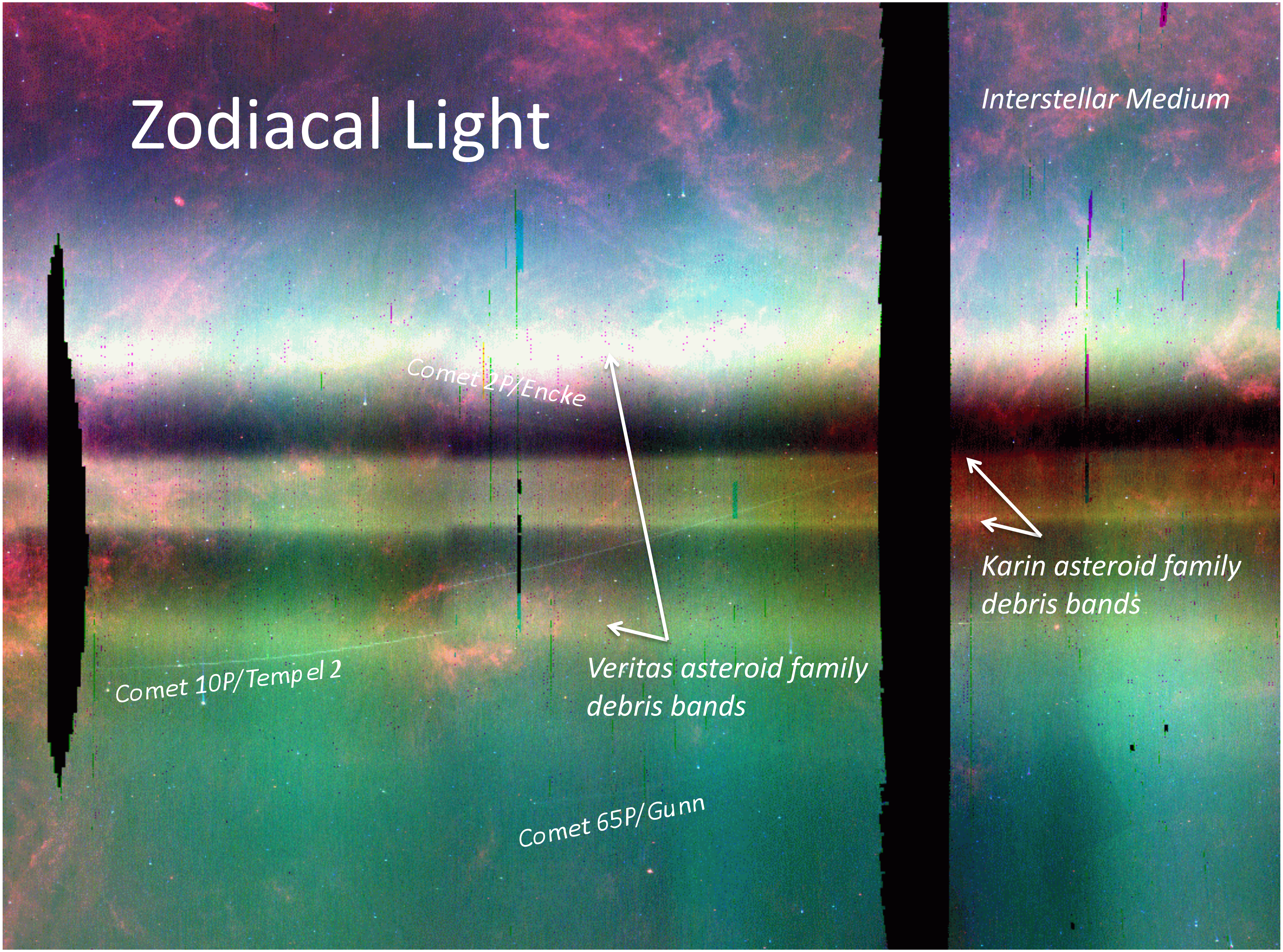
③ Transport of material and construction of major bodies

Asteroidal and Cometary Planetsesimals in the Solar Nebula



Cometary Material in Present Solar System

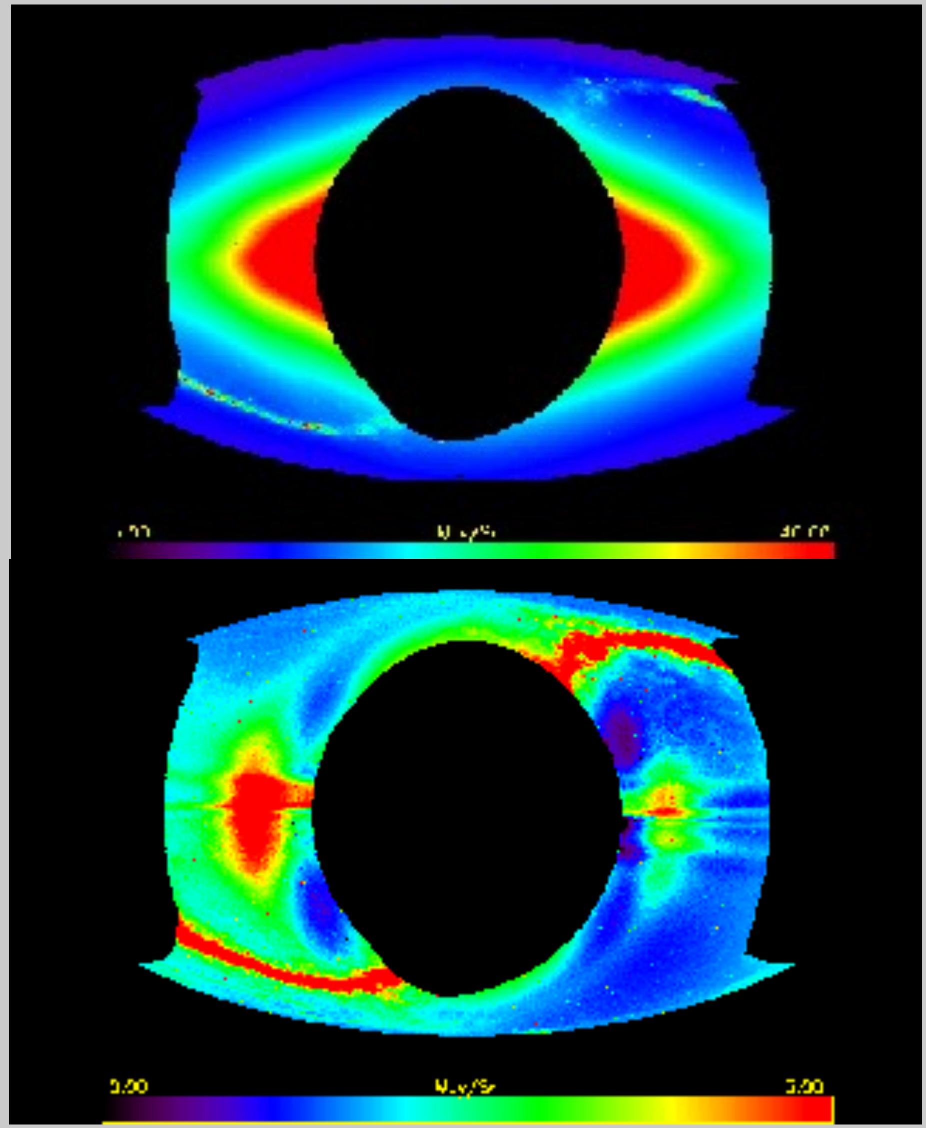


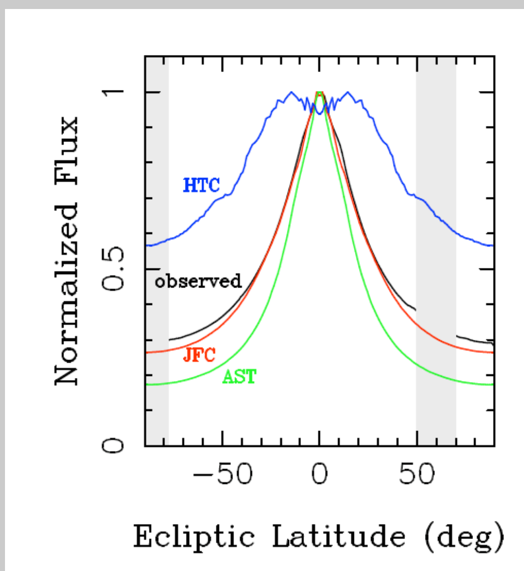


Zodiacal Light
Interstellar Medium
Comet 2P/Encke
Karin asteroid family
debris bands
Veritas asteroid family
debris bands
Comet 10P/Tempel 2
Comet 65P/Gunn

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)





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"

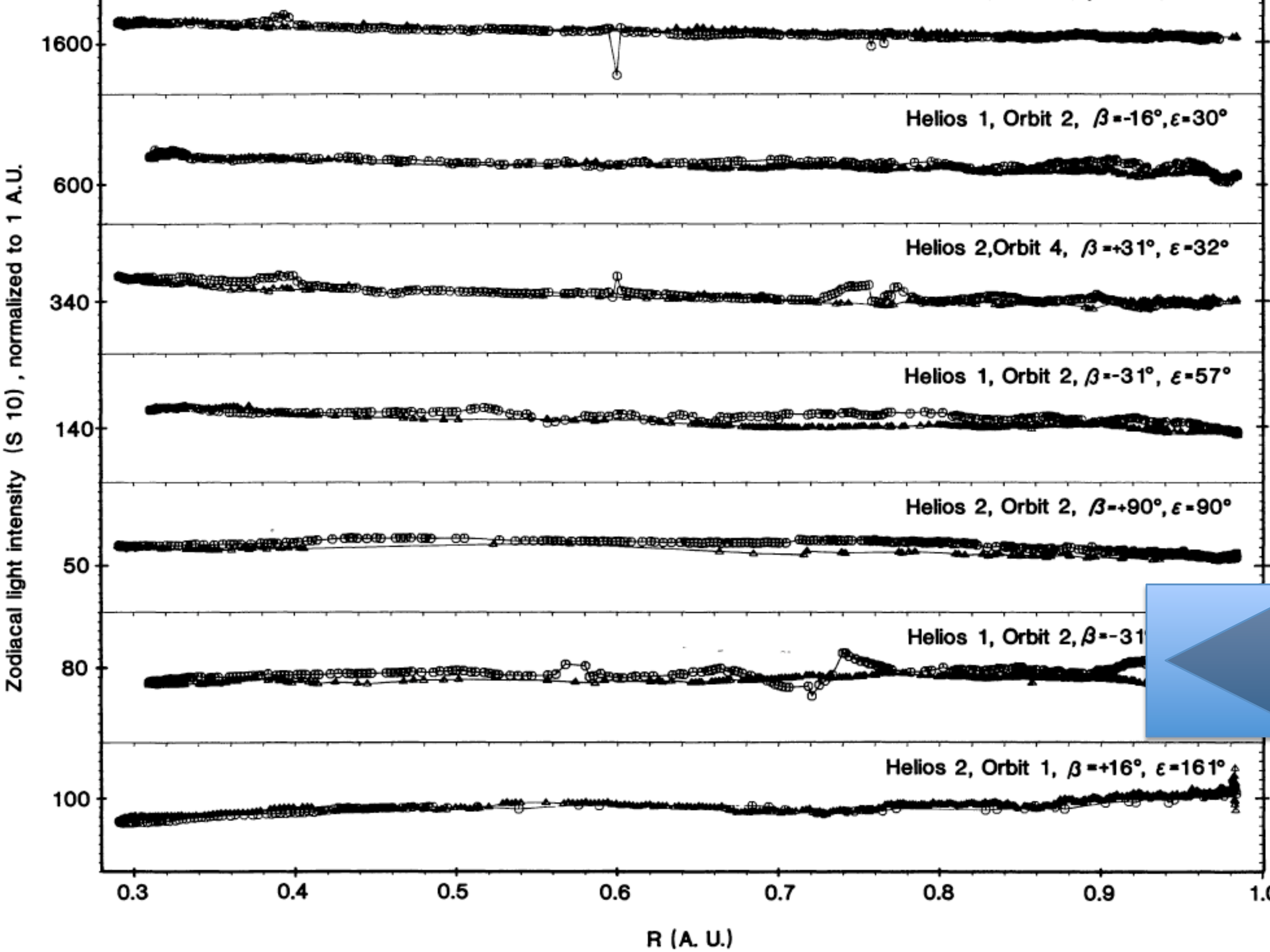
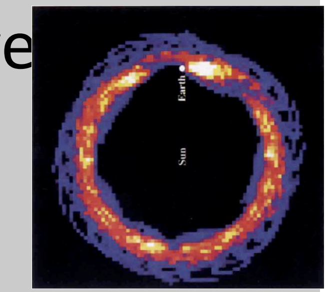


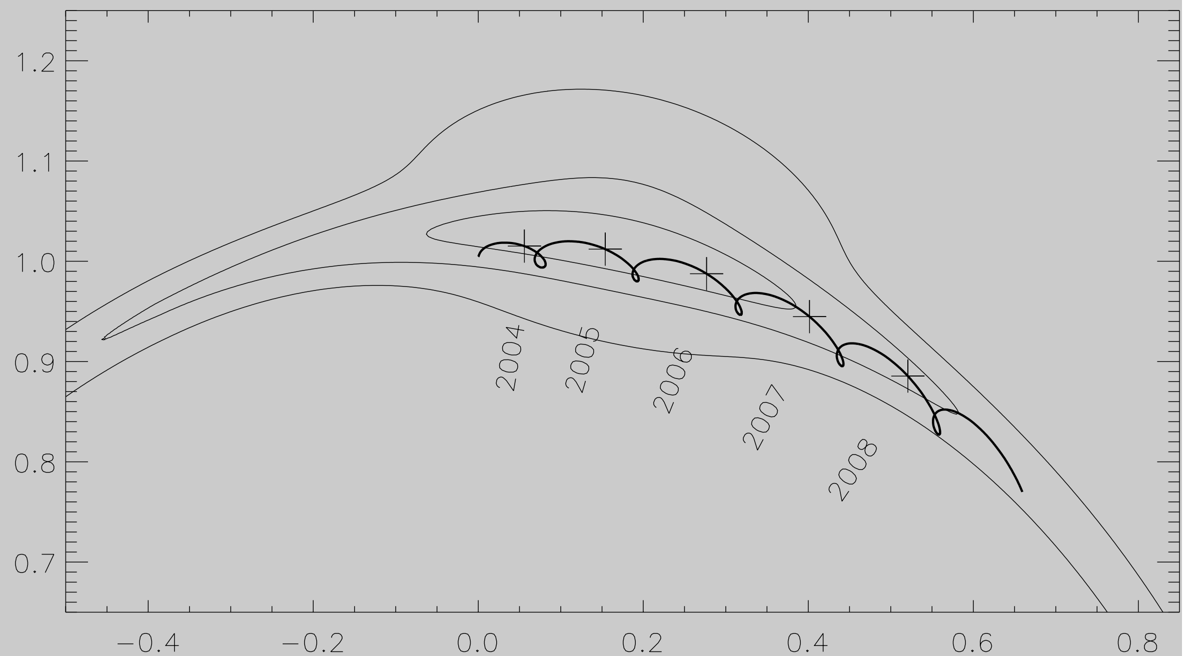
Fig. 5. Brightness increase of zodiacal light in B towards sun for different viewing directions relative to a power law $I(R) \sim R^{-2.3}$. Δ refers to inbound, ○ to outbound part of orbit. λ_{eff} of observations is 425 nm, 1 S10 corresponding to $1.02\ 10^{-12}\ \mathrm{W\ cm^{-2}\ sterad^{-1}\ \mu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

Resonant structures in Zodiacal Cloud

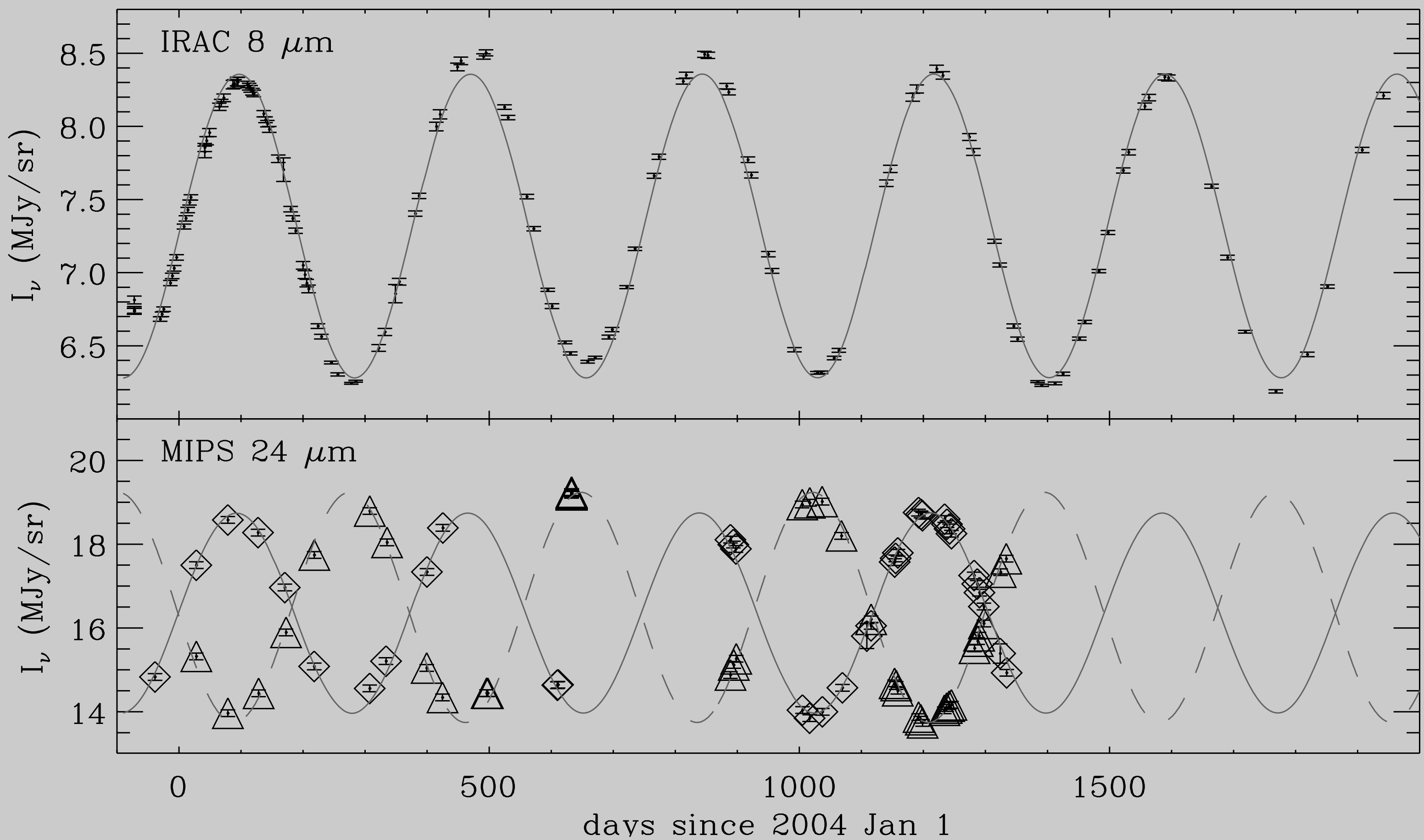
- Smooth cloud traces mean orbital elements
  - Node randomized by Jupiter in 10^6 yr so only secular long-time-averaged perturbations survive
- Resonant effects in comoving frame with planet



- *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



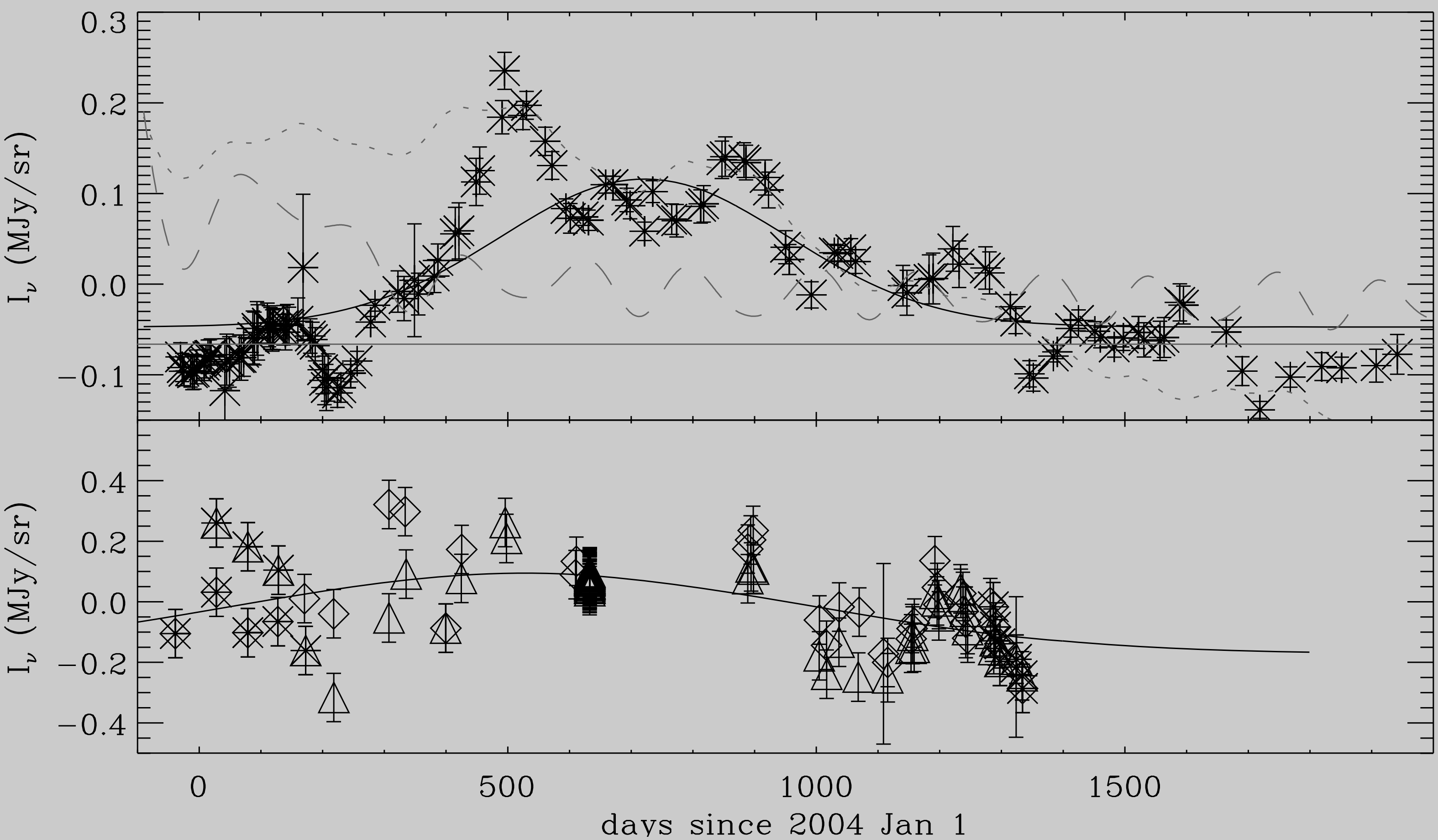
Observed brightness of North Pole



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

- From fixed platform, only measure integrals along line of sight, not readily inverted
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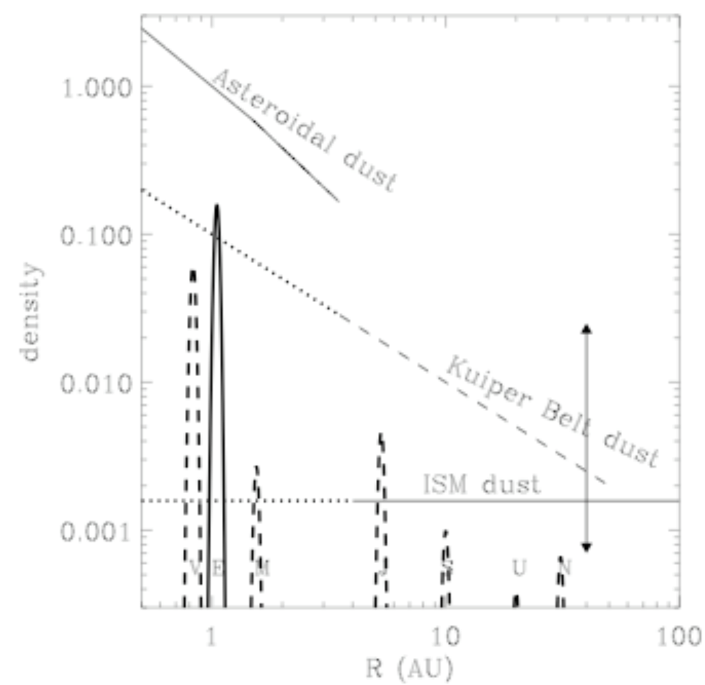
Outer Zodiacal Light

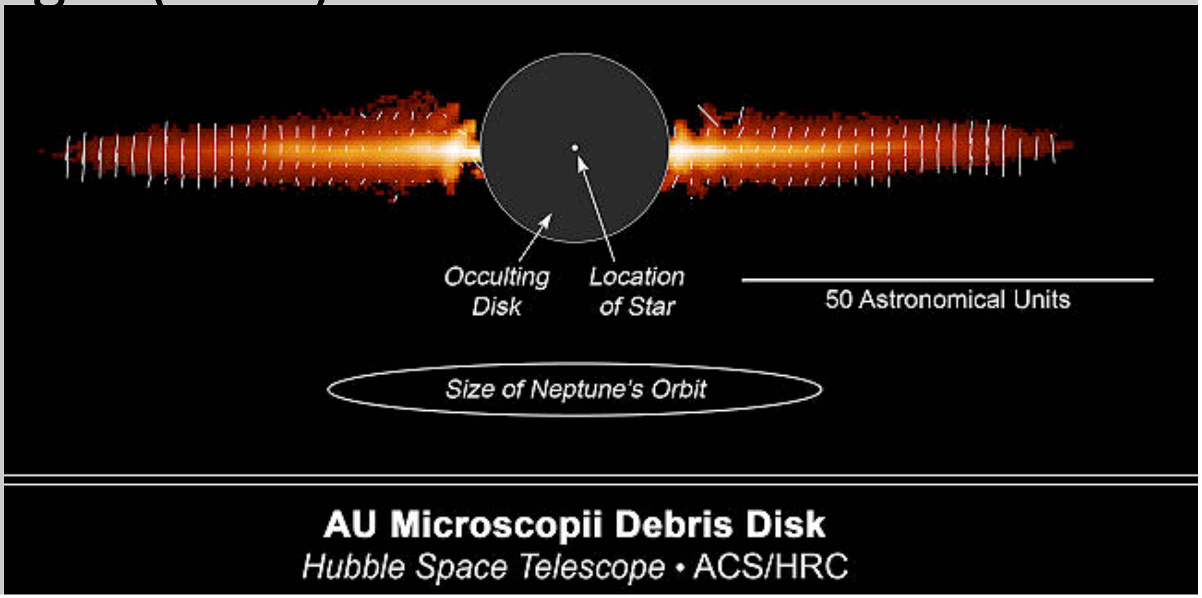
Next frontier

Collisional evolution of Kuiper Belt



Exozodiacal Light

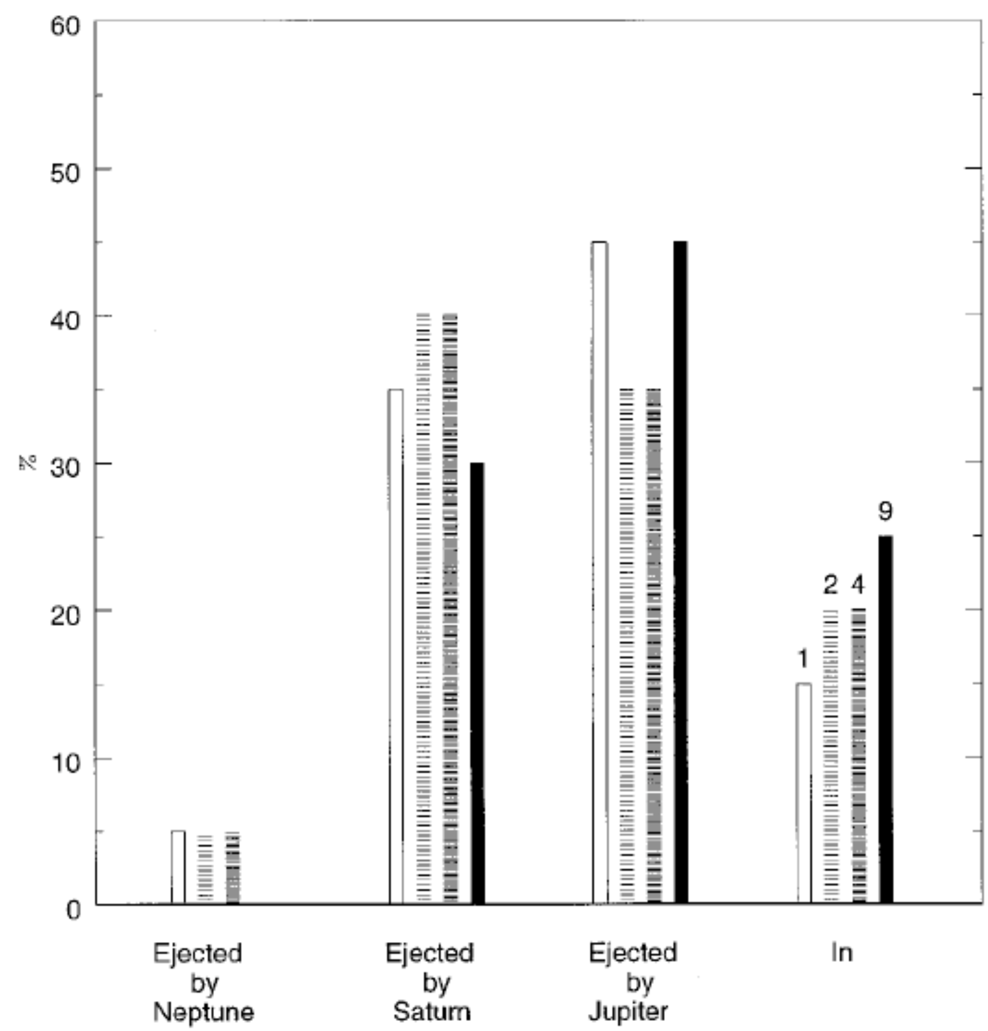
- Debris disks around other stars are dynamically analogous to Solar System Kuiper belt
  - Studying extrasolar debris can reveal what the solar system might (have) looked like



Zodiacal and exozodiacal light
Observations allow a link between
The solar system and exoplanetary
Systems.

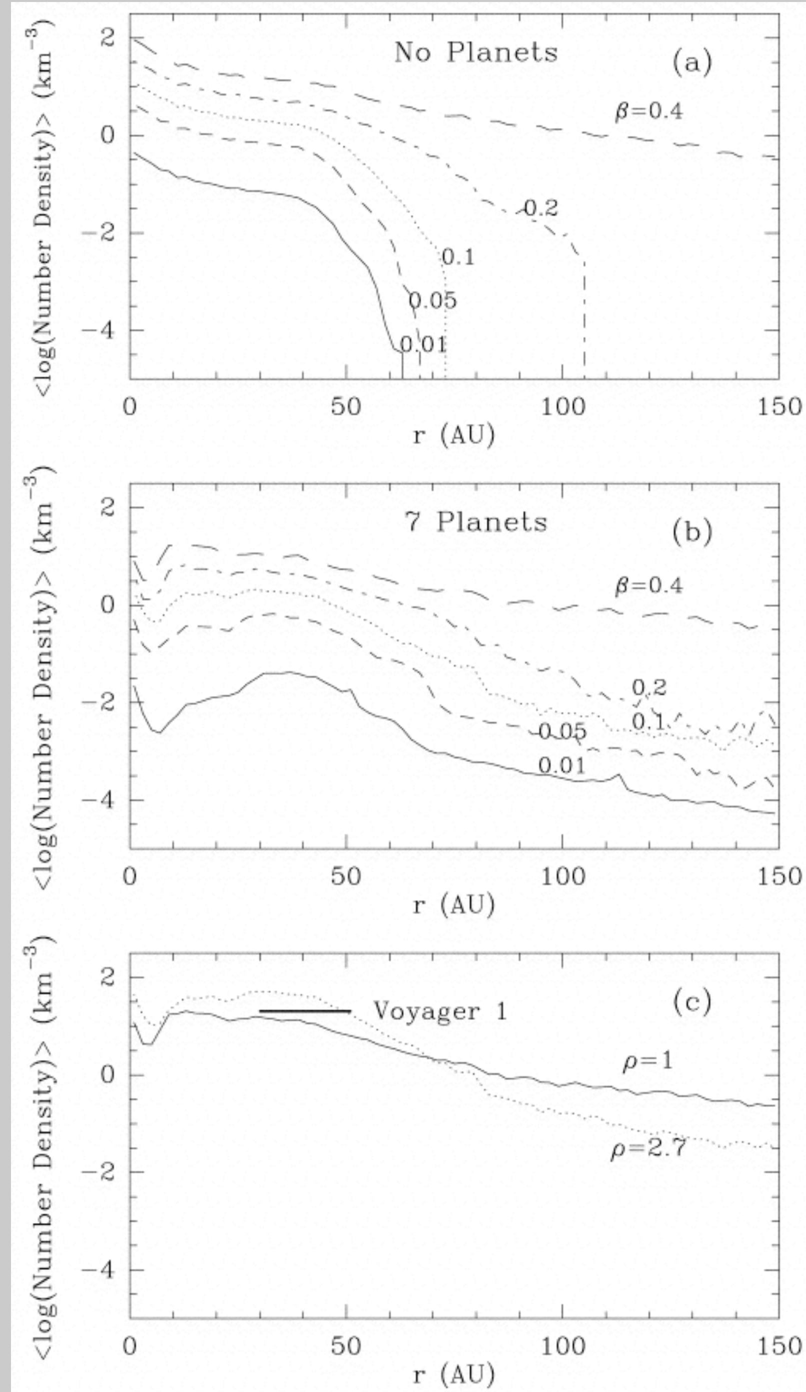
Kuiper Belt origin of Interplanetary Dust

- 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

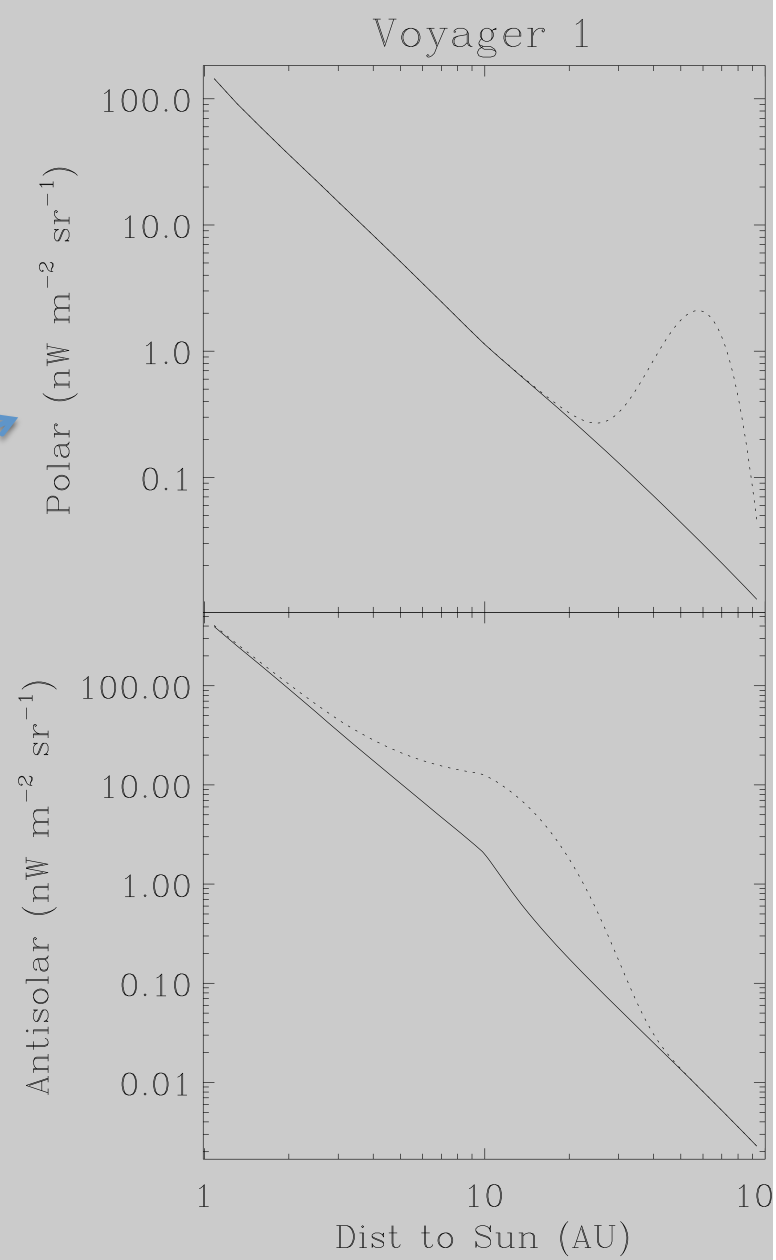
- Moro-Martin and Malhotra (2003)
- Collisional production rate 10^6-10^8 g/s (Stern 1996, Landgraf 2002)
- KB dust cloud mass ~ 10^{22}g
- Relatively high eccentricities when passing Earth, like comets



Zodiacal Light Predictions for spaceprobe

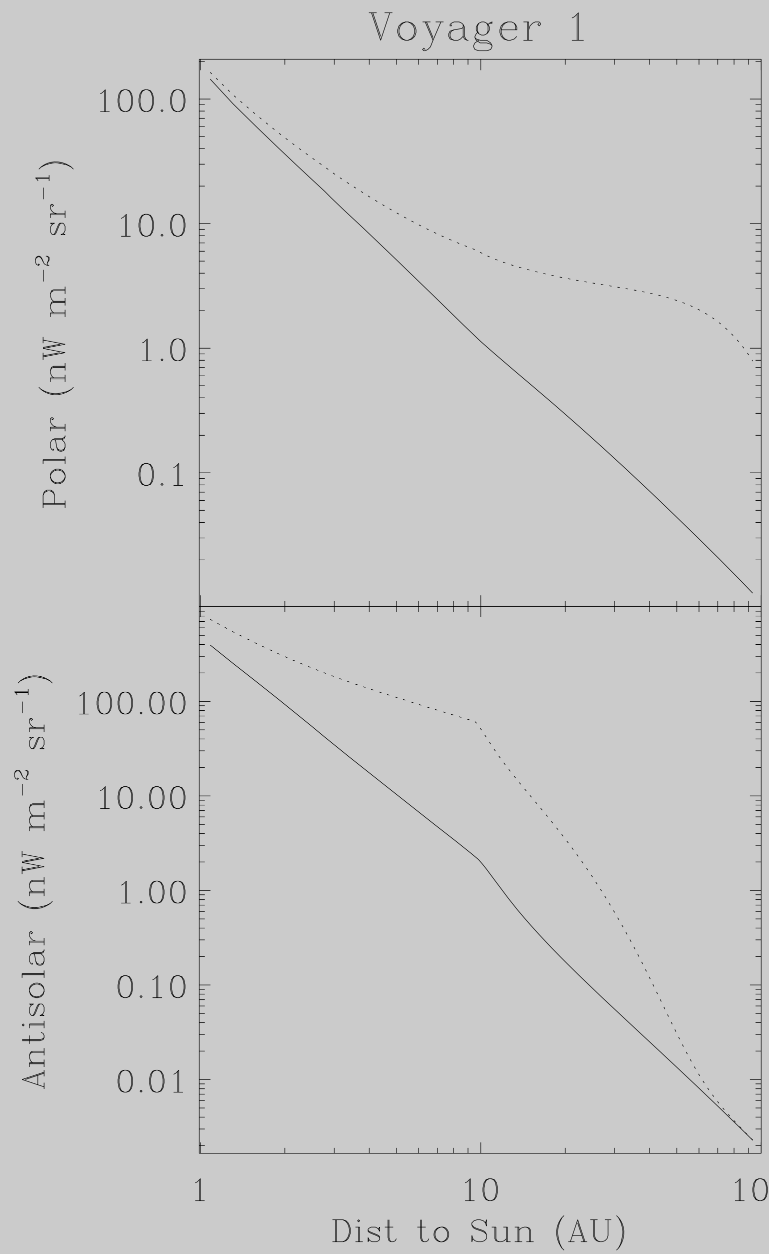
- Use the Voyager 1 spacecraft trajectory (as an example)
    - ecliptic pole
    - antisolar direction

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

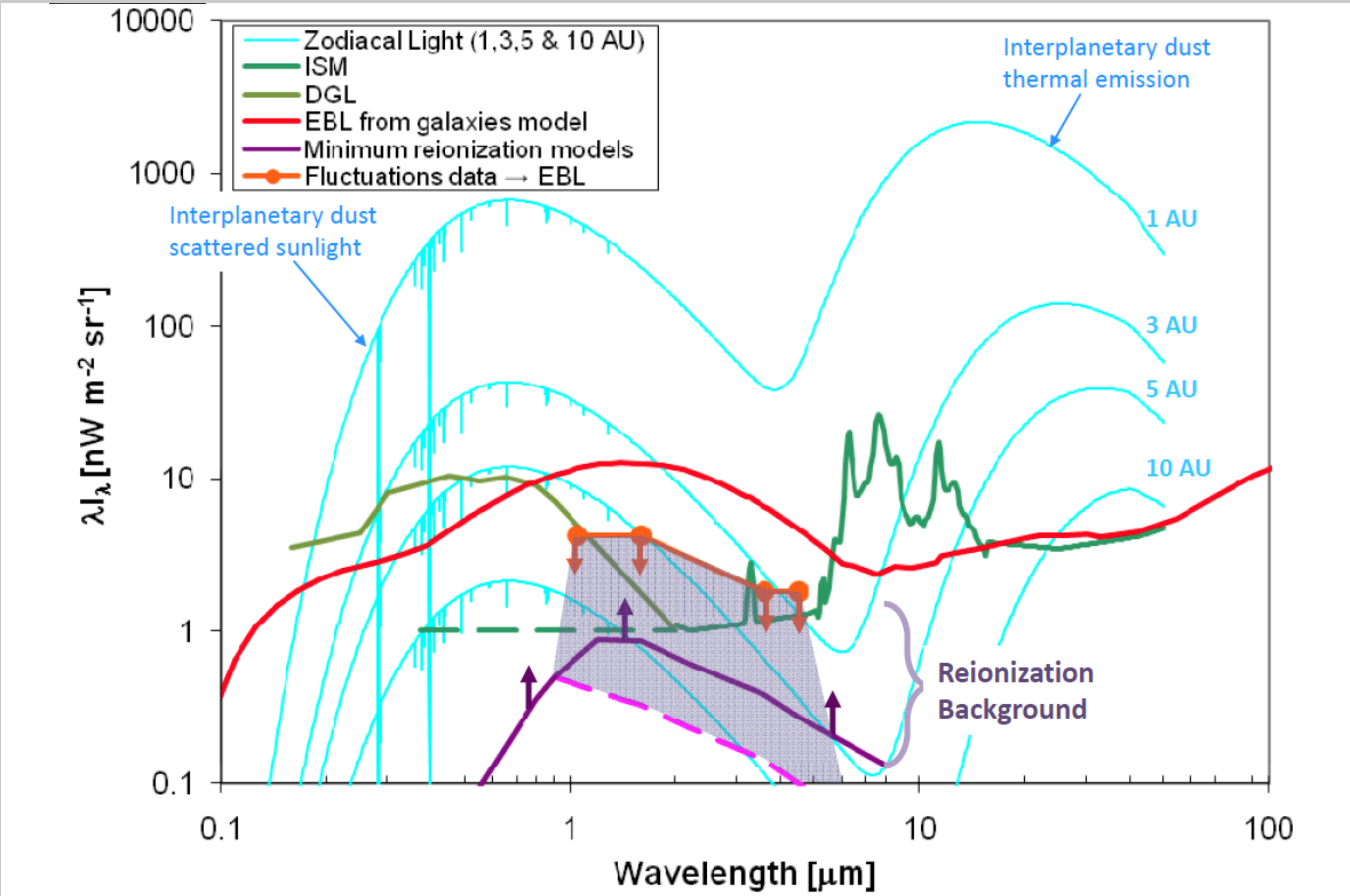


Outer Zodiacal Light: radial profile

- 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)

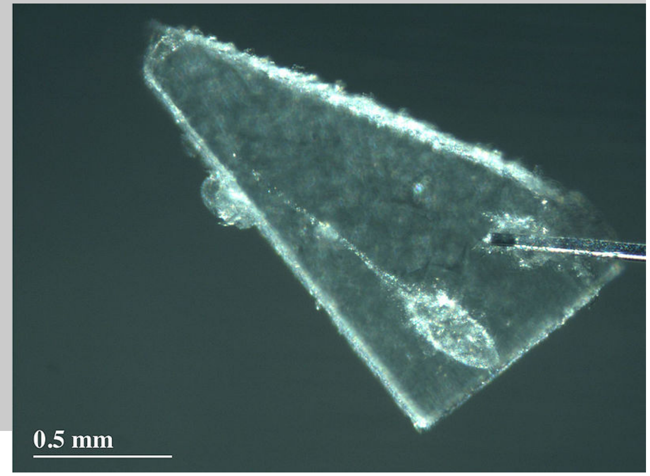


Tagalong science

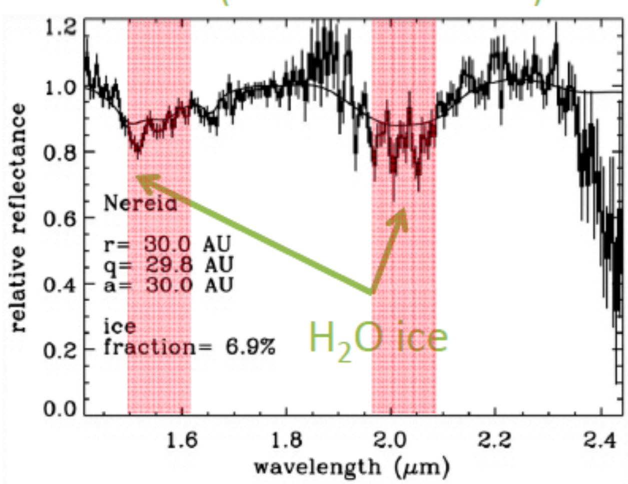


Composition of IDPs

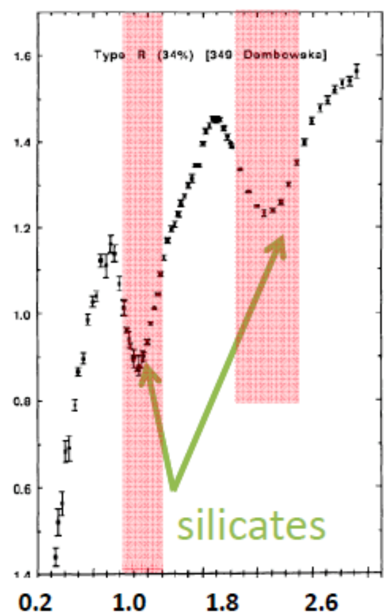
- Infrared spectra measure mineralogy of parent bodies
- Comeplement laboratory work on IDPs and STARDUST



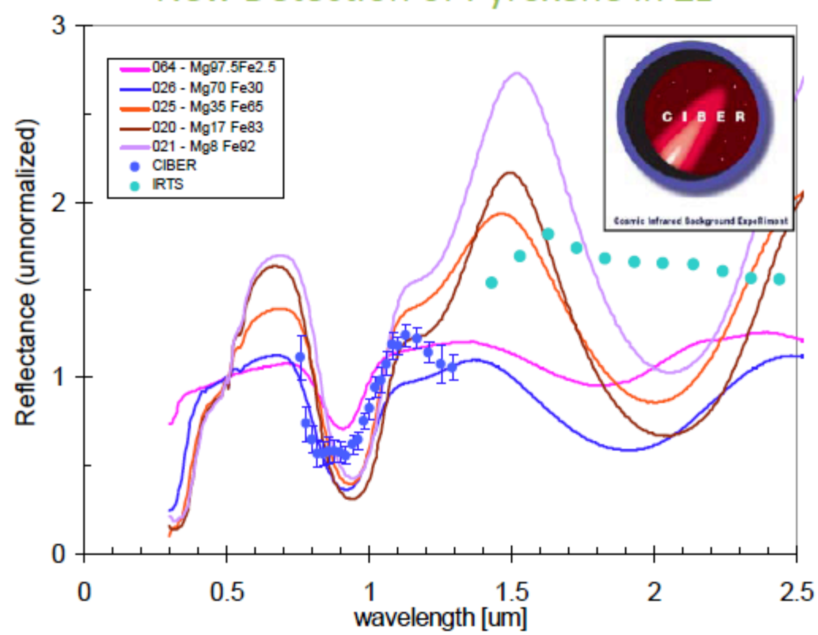
KBO (Brown et al. 1998)



Asteroids (Gaffey et al. 1996)



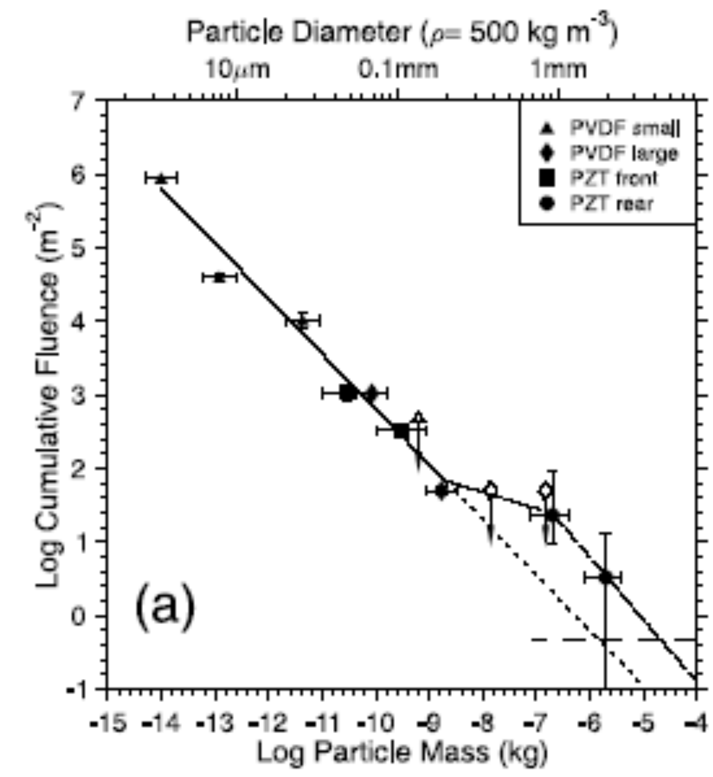
New Detection of Pyroxene in ZL



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 → $\alpha=0.75-0.88$
  - 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

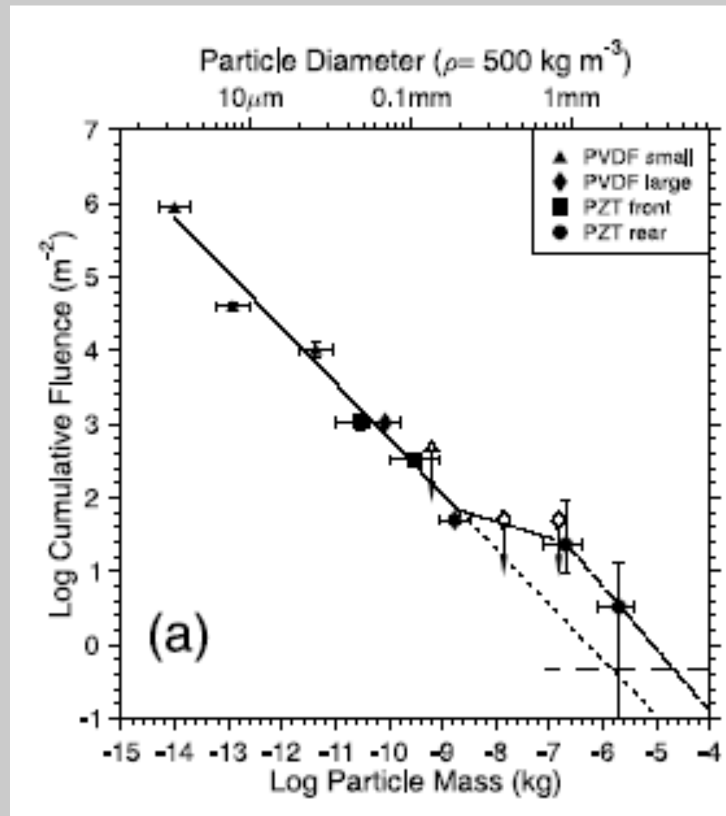
Application to Stardust data

- 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:

$$\frac{A_2}{A_1} \approx \left(\frac{m_2}{m_1}\right)^{2/3} \left(\frac{m_1}{m_{\min}}\right)^{\alpha - 2/3}$$

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



Planetary Science Questions

1. What is the origin of interplanetary dust in the inner and outer solar system?
2. How does the interplanetary dust interact with the outer planets?
3. What is the composition of inner and outer solar system material?
4. How does the solar system dust cloud relate to exoplanetary systems?