The Kuiper Belt:

Shedding light on Planet Formation & Collisional Evolution in Debris Disks

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The Future of Astronomy

Northwestern University

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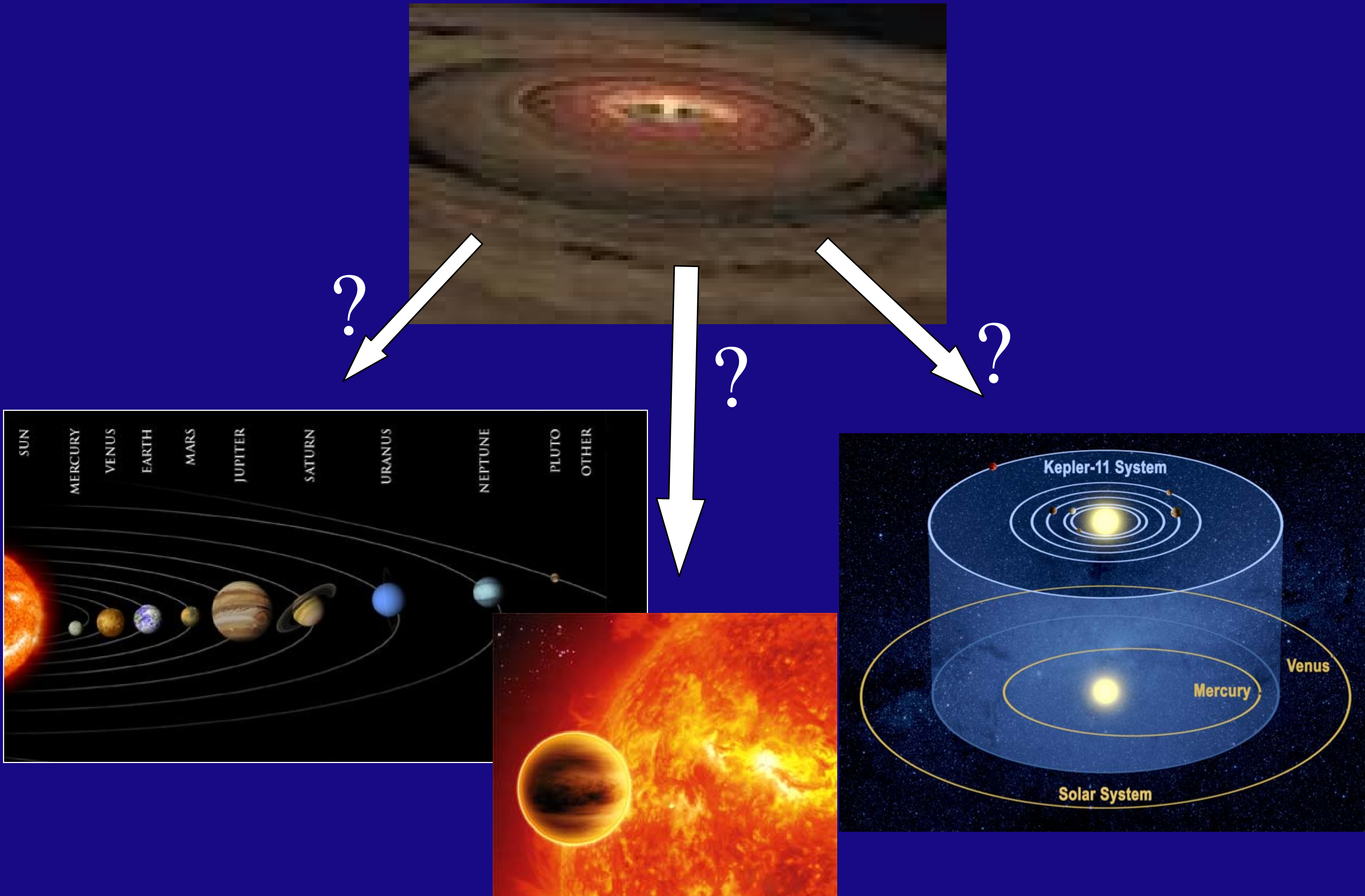
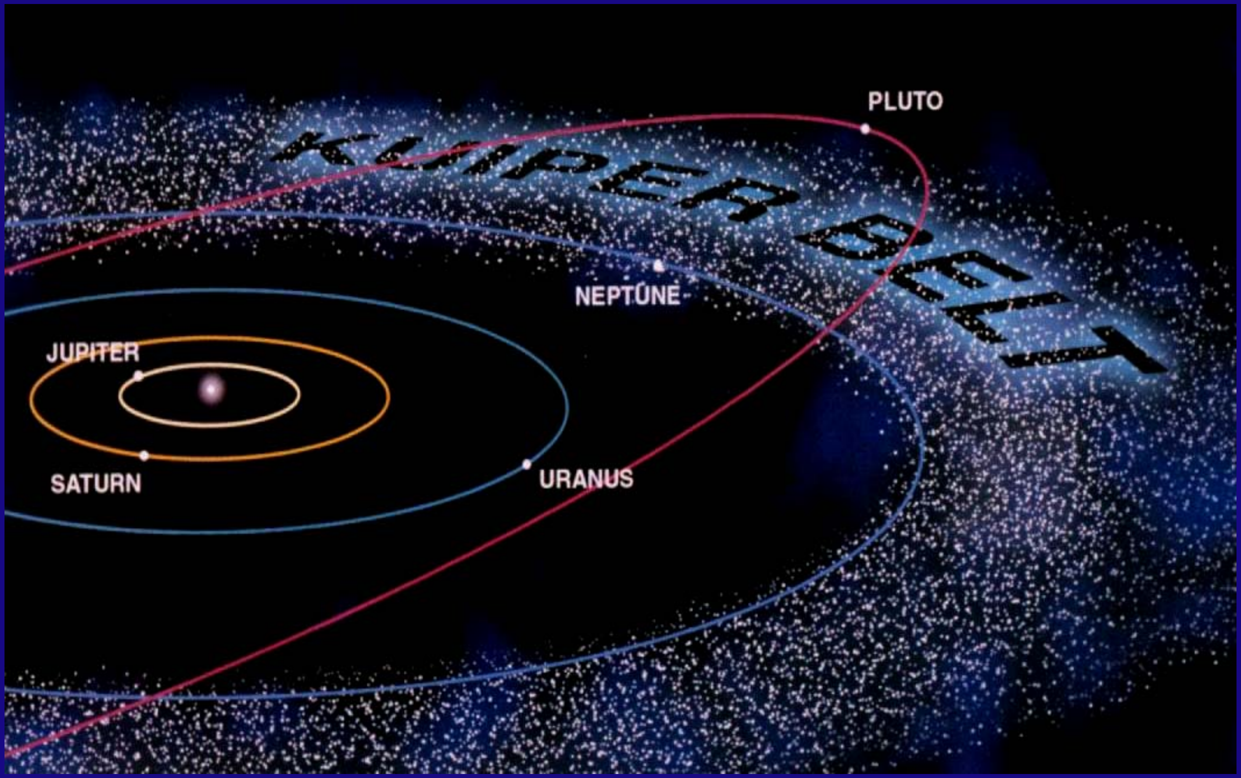
From Gas & Dust to Planets

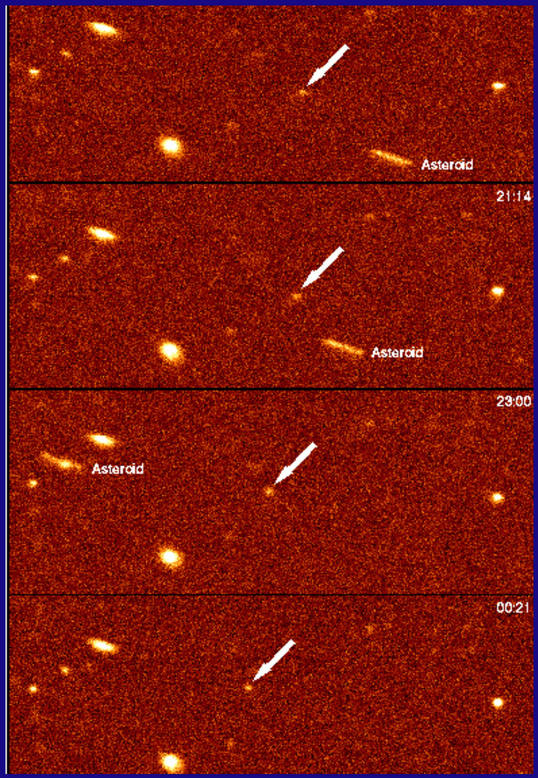


Kuiper Belt

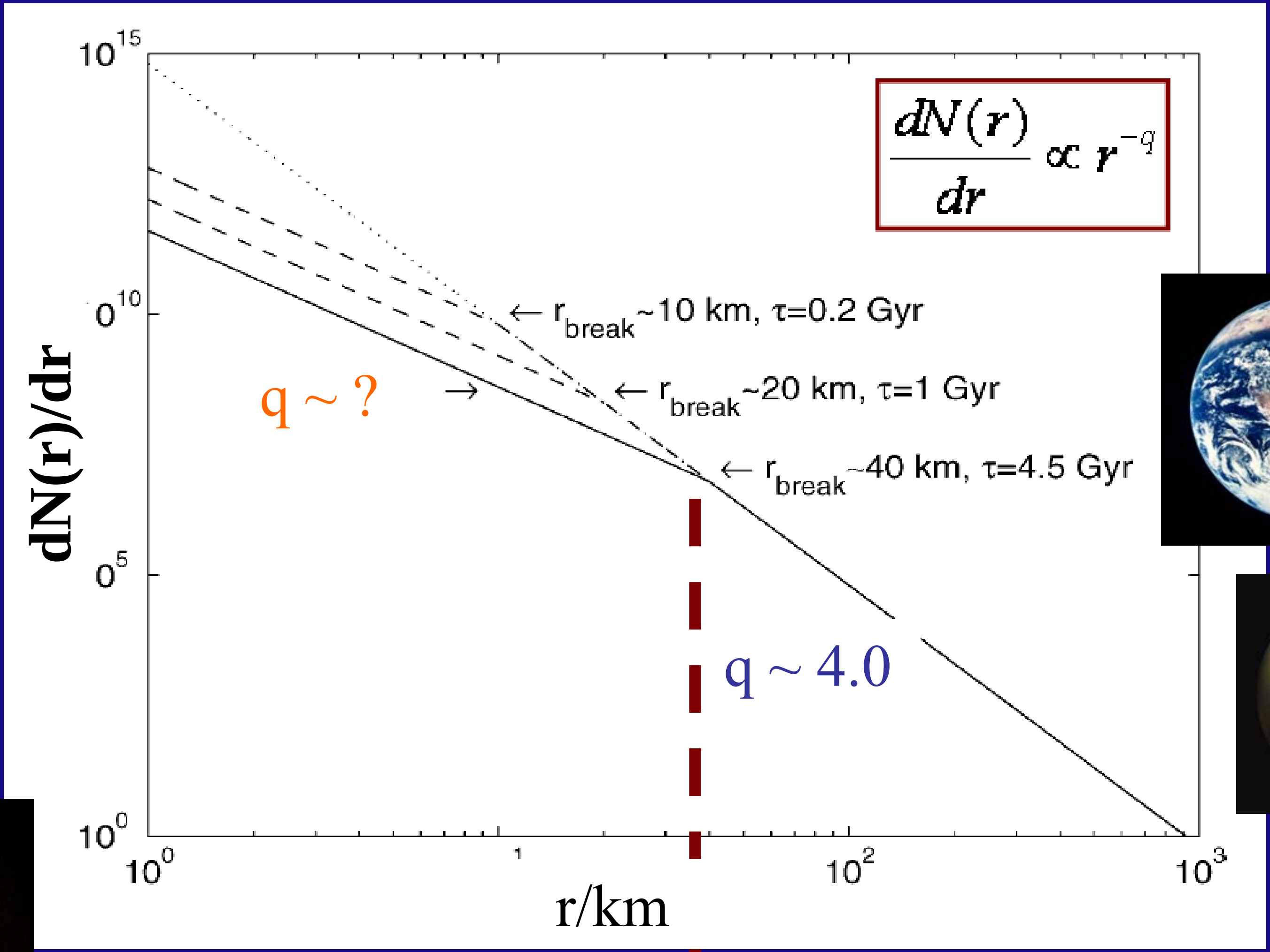
- ~40 AU from the Sun
- Source of the short period comets
- ~1000 detected objects

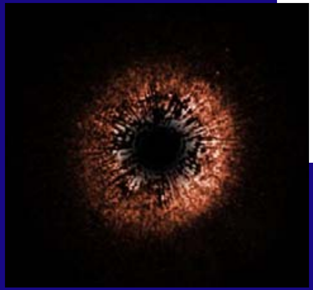
- Solar System Debris Disk
- Size estimates based on brightness
  - Typical radius R=100km

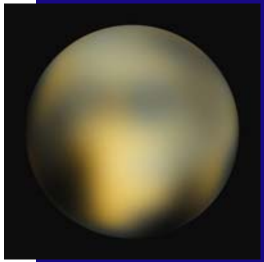




The Kuiper Belt Size Distribution

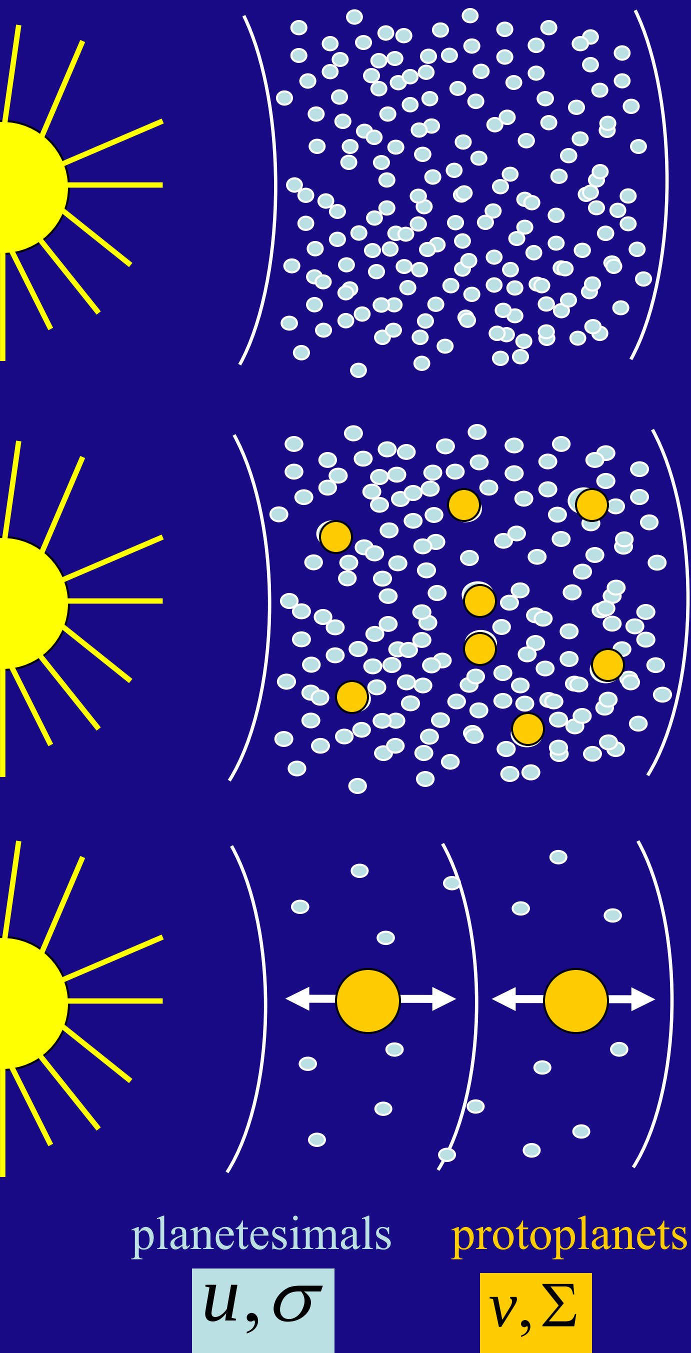






Evolved

Primordial



1. Planetesimal formation:

2. Runaway growth:

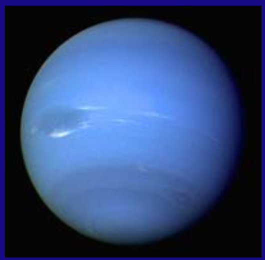
$$\frac{1}{R_1}\frac{dR_1}{dt} \propto R_1$$

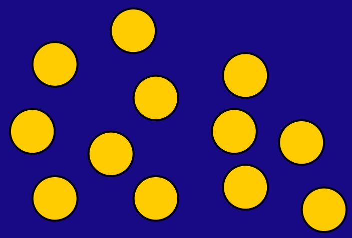
For $v_{esc} > u$ gravitational focusing enhances the accretion rate

$$\frac{1}{R}\frac{dR}{dt} \sim \frac{\sigma\Omega}{\rho R}\left(\frac{v_{esc}}{u}\right)^2 \longrightarrow t_{grow} \sim 10^7 \text{ years}$$

3. Oligarchic growth & Isolation:

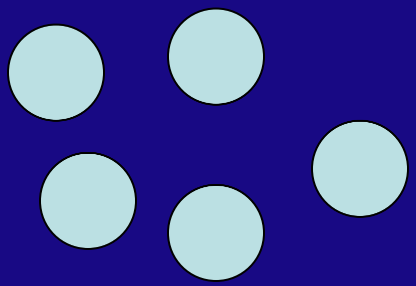
$$M_{iso} \approx 2\pi a(\Delta a_{zone})\Sigma \sim M_{Neptune}$$





Small bodies

Runaway Growth



Big Bodies

$$\frac{1}{R}\frac{dR}{dt} \sim \frac{\sigma\Omega}{\rho R}\left(\frac{u}{v_{esc}}\right)^{-2} + \frac{\Sigma\Omega}{\rho R}\alpha^{-3/2}$$

Accretion of small bodies

Accretion of big bodies

$$\alpha \sim R_{Sun}/a$$
$$\sim 10^{-4} \text{ at } 40 \text{ AU}$$

When accretion of small and big bodies contribute equally to the growth:

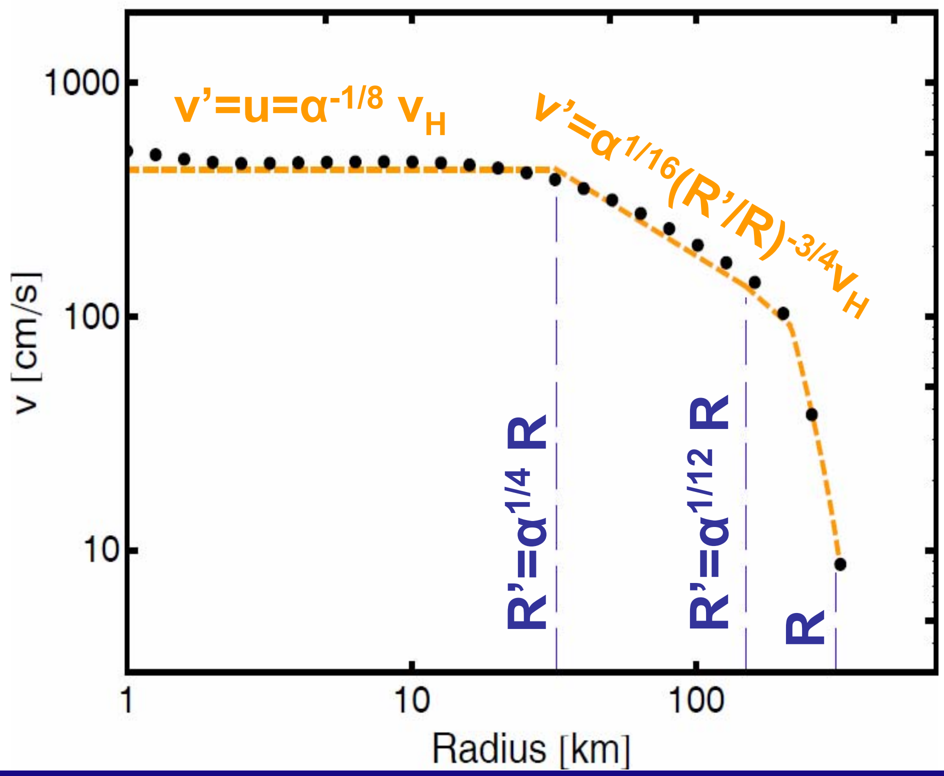
$$\Sigma \sim \alpha^{3/4}\sigma \sim 10^{-3}\sigma \sim 3\times10^{-4} \text{ g/cm}^2$$

$$\sigma \sim \sigma_{\text{MMSN}}$$
$$\sim 0.3 \text{ g/cm}^2$$

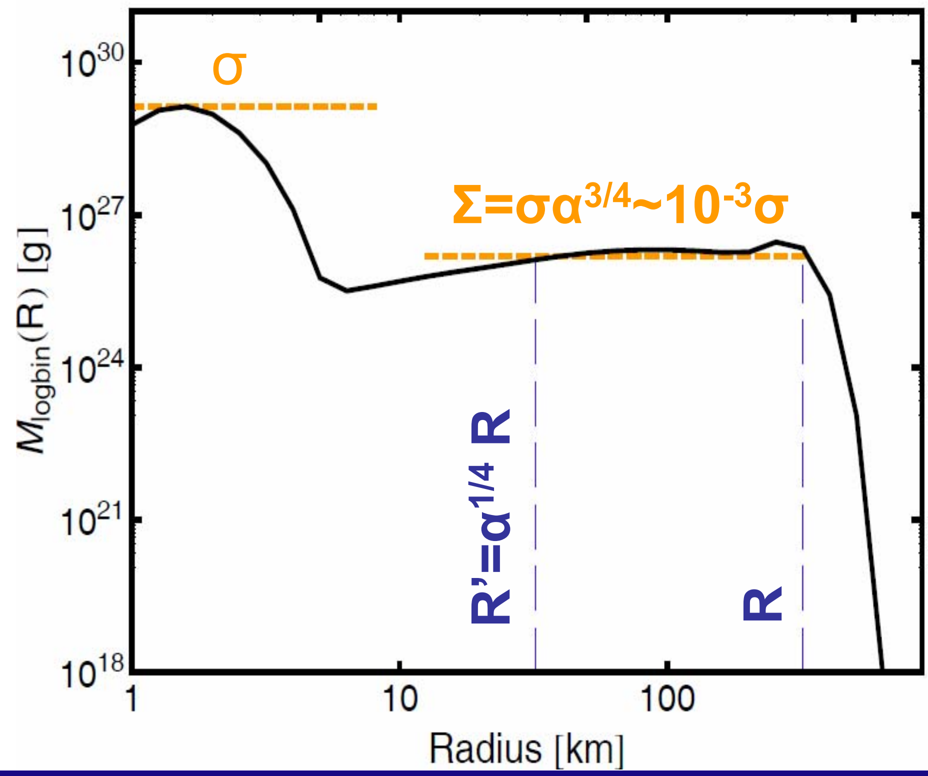
$$\Sigma \propto N(>R)R^3 \sim \text{const} \;\rightarrow\; \text{N}(>\text{R}) \propto \text{R}^{-3} \;\rightarrow\; \text{q} = 4$$

i.e. Equal mass per logarithmic mass bin

Velocity

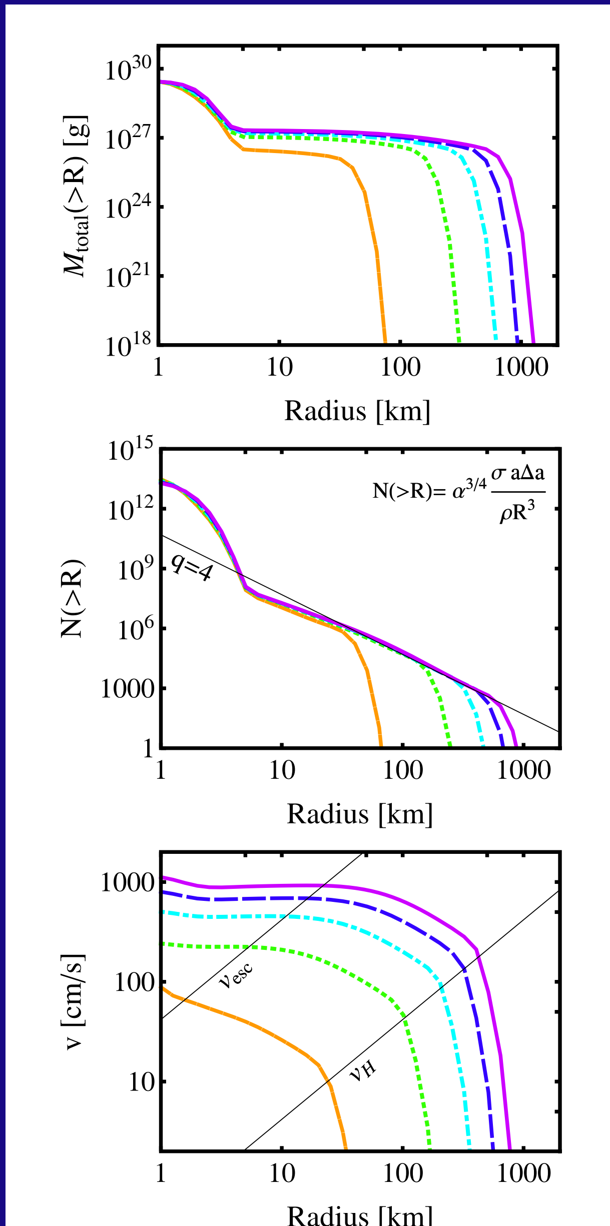


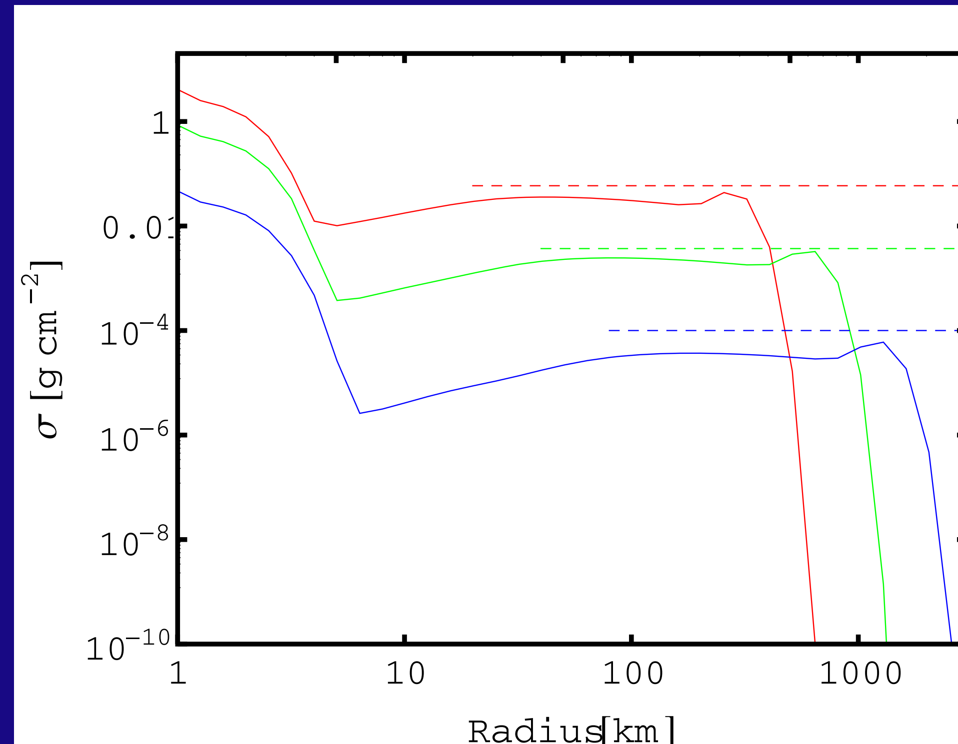
Mass



(Schlichting & Sari, 2011)

Time = 10^7 years





$$\frac{dN(R)}{dR} \propto R^{-q}$$

(Schlichting & Sari, 2011)

t = 10^6 years, t= 10^7 years, t = 2 x 10^7 years, t = 3 x 10^7 years, t = 5 x 10^7years

Results

Runaway growth:

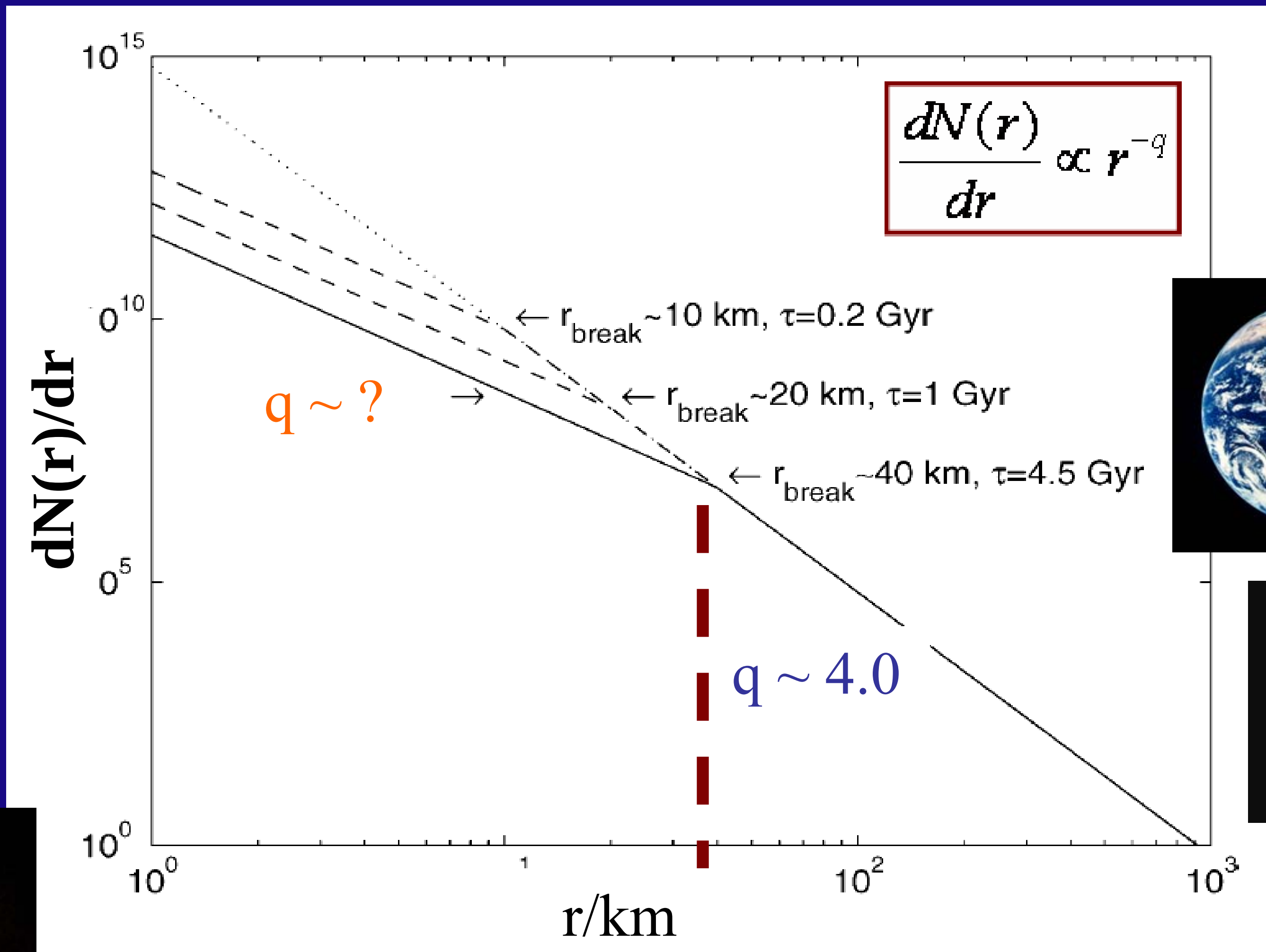
1) Only a small fraction of initial mass in converted into protoplanets during runaway growth: $\Sigma \sim \sigma \alpha^{3/4} \sim 10^{-3} \sigma_{MMSN}$
2) Size distribution of runaway tail: q ~ 4, equal mass per logarithmic mass bin
3) Results also apply to debris disks

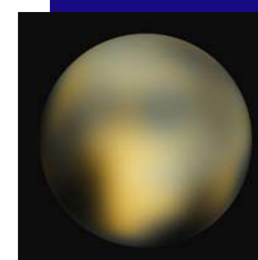
For the Kuiper Belt we can successfully explain:

1) The total mass in large KBOs ($\Sigma \sim \sigma \alpha^{3/4} \sim 10^{-3} \sigma_{MMSN}$)
2) The slope of KBO size distribution (q ~ 4)

This argues strongly against that there was significantly more mass in large Kuiper Belt objects in the past.

The Kuiper Belt Size Distribution





Evolved

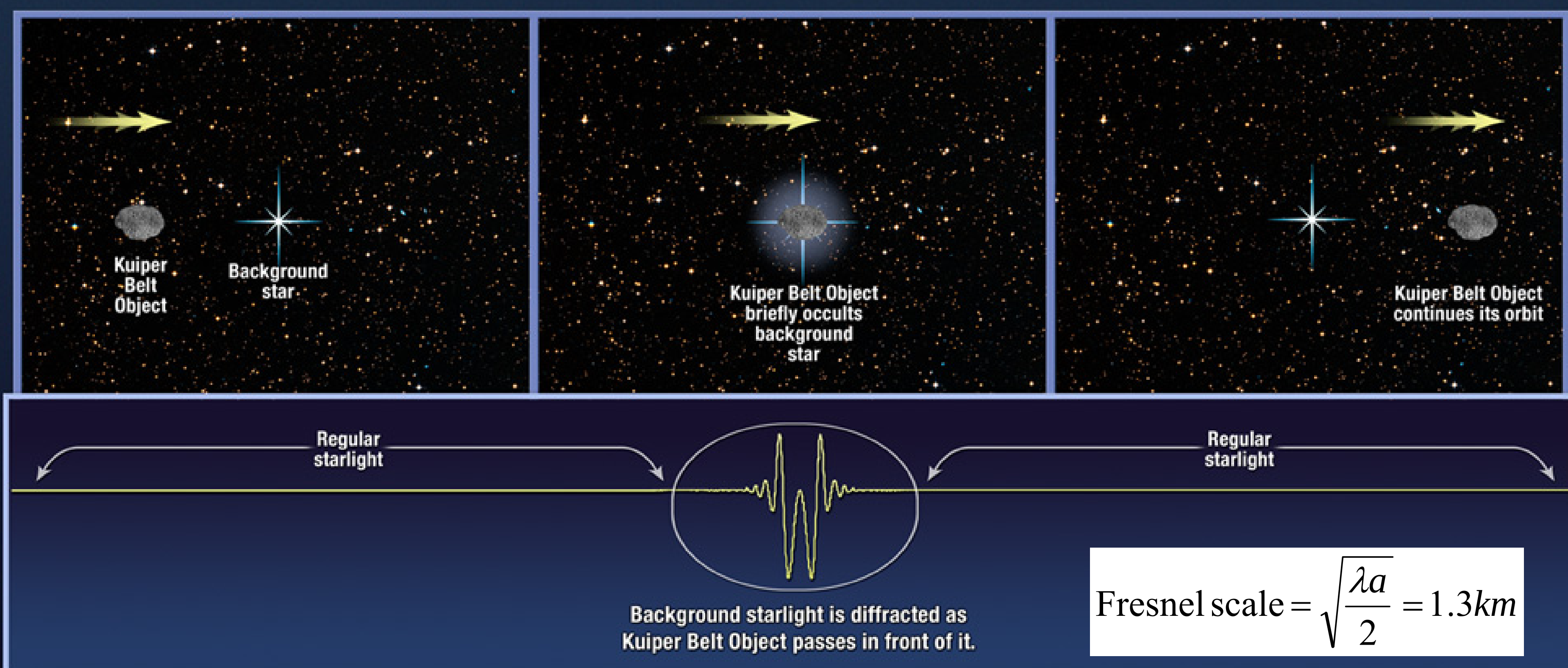
Primordial

Transiting Kuiper Belt Objects

KBOs < 10km too small to be detected directly

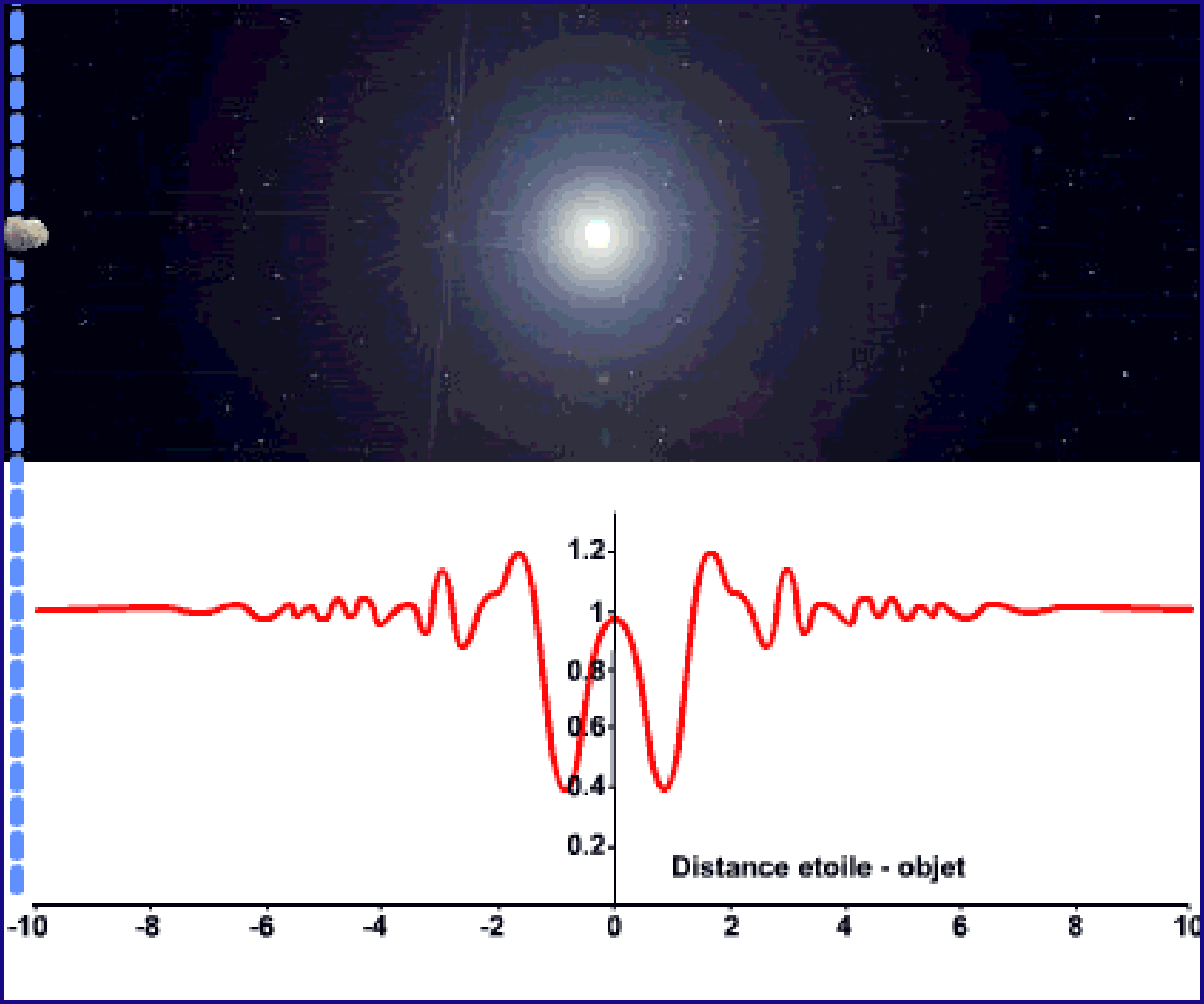
→ Observe indirectly using stellar occultations

(Dyson 1992, Axelrod et al. 1992)



$$\text{Fresnel scale} = \sqrt{\frac{\lambda a}{2}} = 1.3km$$

Transiting Kuiper Belt Objects



(Roques)

Event Duration ~ 3km/v_{earth} ~3km/30km/s ~ 0.1 s!

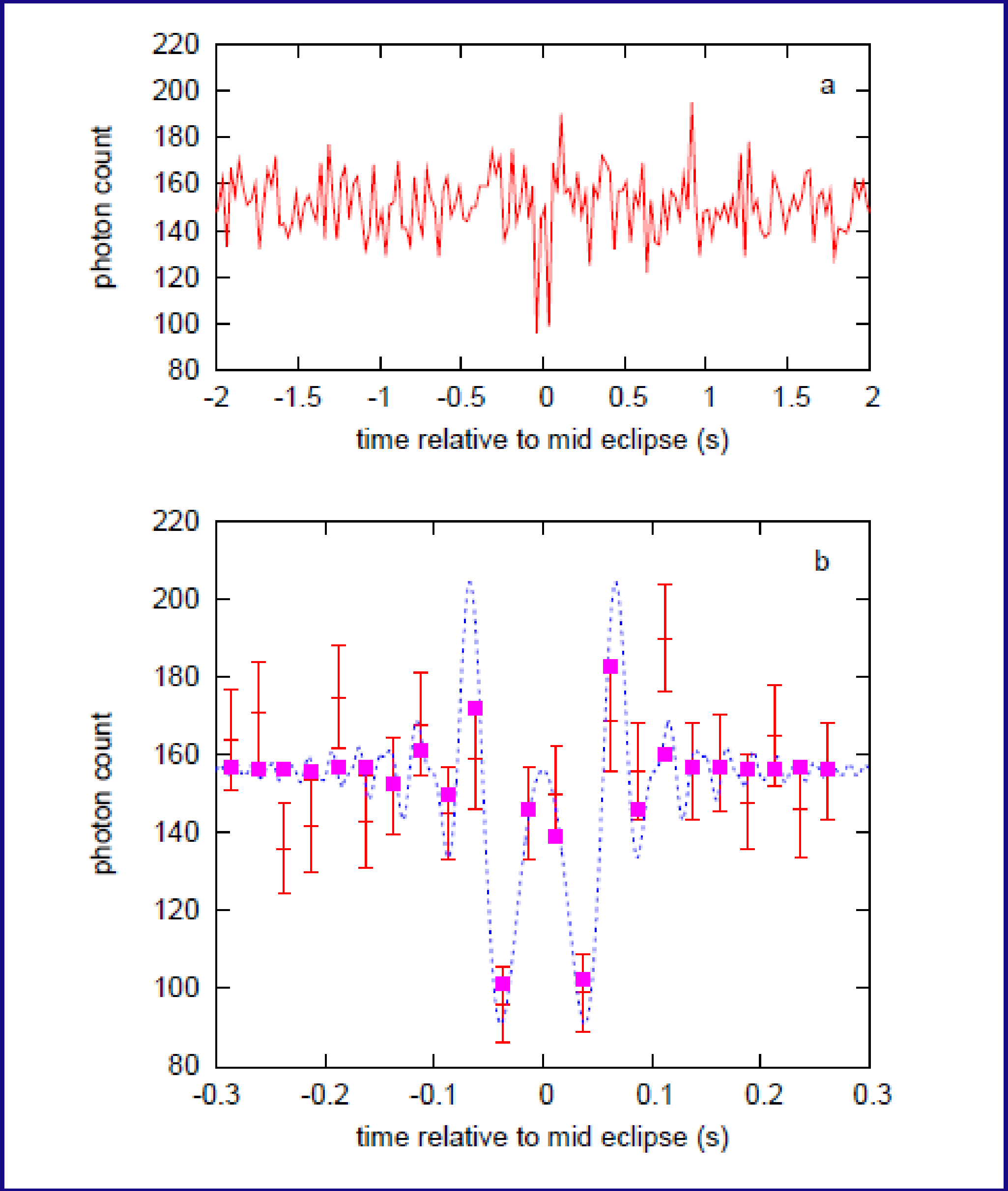
Occultation events produced by KBOs are rare & of short duration → Large number of star hours & high frequency

HST Fine Guidance Sensors

- FGS observations are ideal because
  1) 40 Hz sampling frequency
  2) long baseline: 16 years
  3) space based
  4) good control sample

q_2~4.5	~180 events	no break
q_2~3.5	~1 event	break

- ~ 40,000 Star hours of observations with i < 20 deg
- Typical size that can be detected r ~ 250m



Schlichting et al. 2009, Nature

Best fit values:

r ~ 520 m

a ~ 45 AU

$r \propto \sqrt{amplitude}$

Chi-squared fit:

χ^2 /dof=20.1/21

From the observations we know:

- $\theta_{Star} / \theta_{Fresnel} \sim 0.3$
- Ecliptic latitude +14 deg

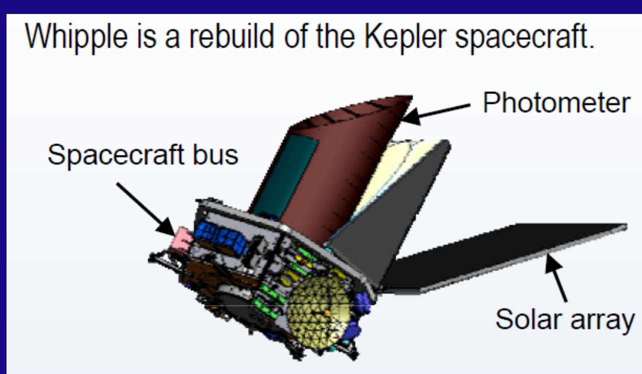
- Compared PMT readings
- Checked second FGS
- No correlated noise
- Examined the engineering telemetry for HST
- Less than 2% chance to be false-positive

Implications

- Break in KBO Size Distribution → Collisional evolution
- Small KBO size distribution similar to Centaurs (q ~ 4, Sheppard et al. 2000) → Kuiper Belt source region of Centaurs
- Inferred KBO abundance consistent with required supply rate for Jupiter Family Comets (Volk & Malhotra 2008, Chiang & Pan 2010)

Future

- Analyze the remaining 66% to the data
- Whipple Mission



$$q = 3.9 \pm 0.3$$

$$N(r > 250m) = 2.1^{+4.8}_{-1.7} \times 10^{7}\ \deg^{-2}$$