Occultation Studies of the Outer Solar System

B. Scott Gaudi
(Harvard-Smithsonian Center for Astrophysics)

Collaborators

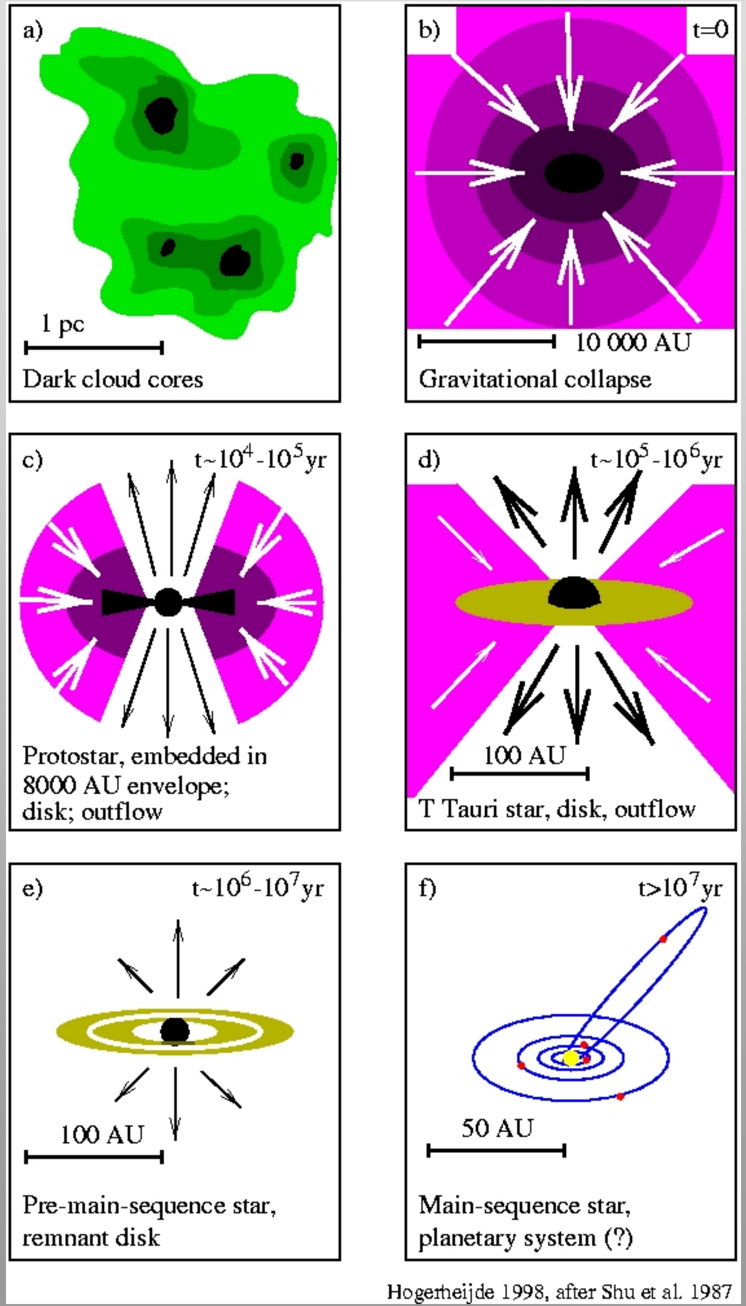
- Cheongho Han (Chungbuk National University)
- Charles Alcock (CfA)
- Matt Lehner (University of Pennsylvania)

Publications

- Gaudi 2004, ApJ, 610, 1199
- Han & Gaudi 2005, in preparation
- Gaudi & Han 2005, in preparation

Star Formation 101

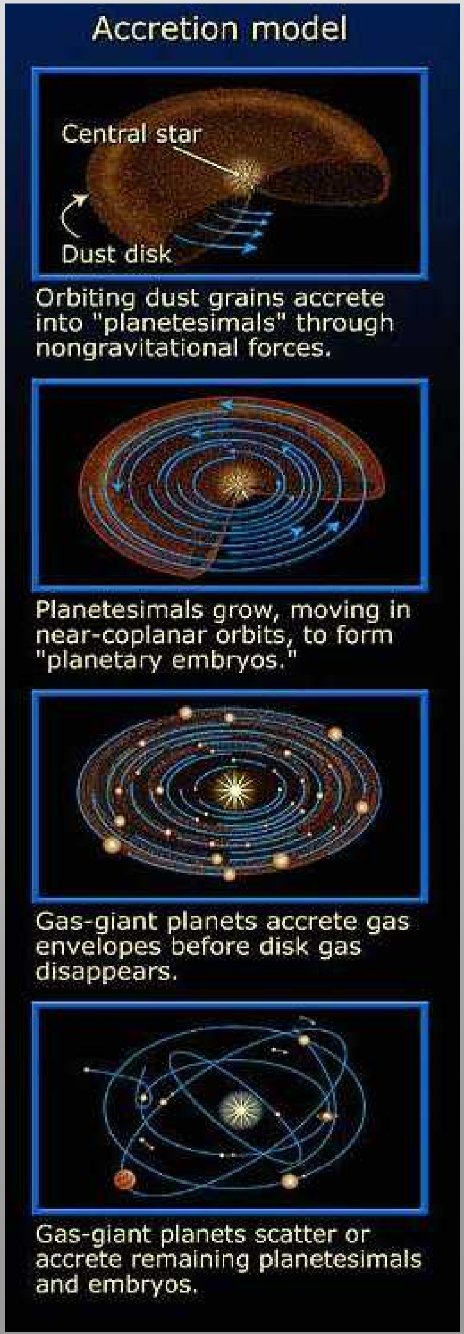
- Molecular Cloud
- Cores
- Collapse
- Ignition/Outflow
- Protoplanetary Disk
- Planetary System



Hogerheijde 1998

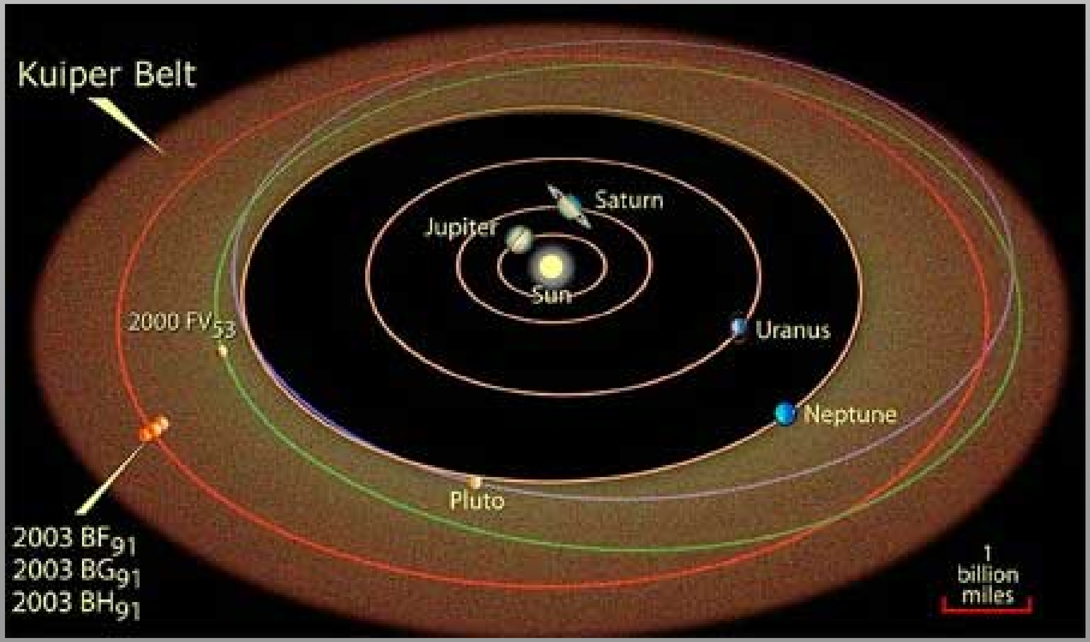
Planet Formation 101

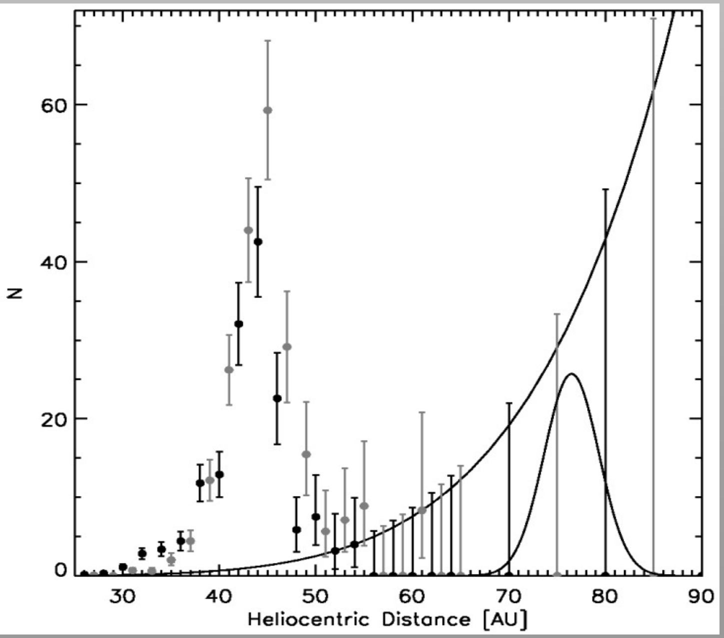
- Core-accretion Model
- Dust → Planetesimals (non G)
- Planetesimals → Protoplanets
- Protoplanets → Terrestrial Planets
  Inner Solar System (<3AU)
- Protoplanets → Gas Giants
  Outer Solar System (3AU-40AU)
- Protoplanets → Planetoids
  Distant Solar System (> 40AU)



The Kuiper Belt – General Properties

- 1st member discovered in 1992
  (1992 QB1; Jewitt & Luu 1993)
- ~850 known. Total mass ~1% Earth
- Radial Extent (30-50)AU, peak near 45 AU.

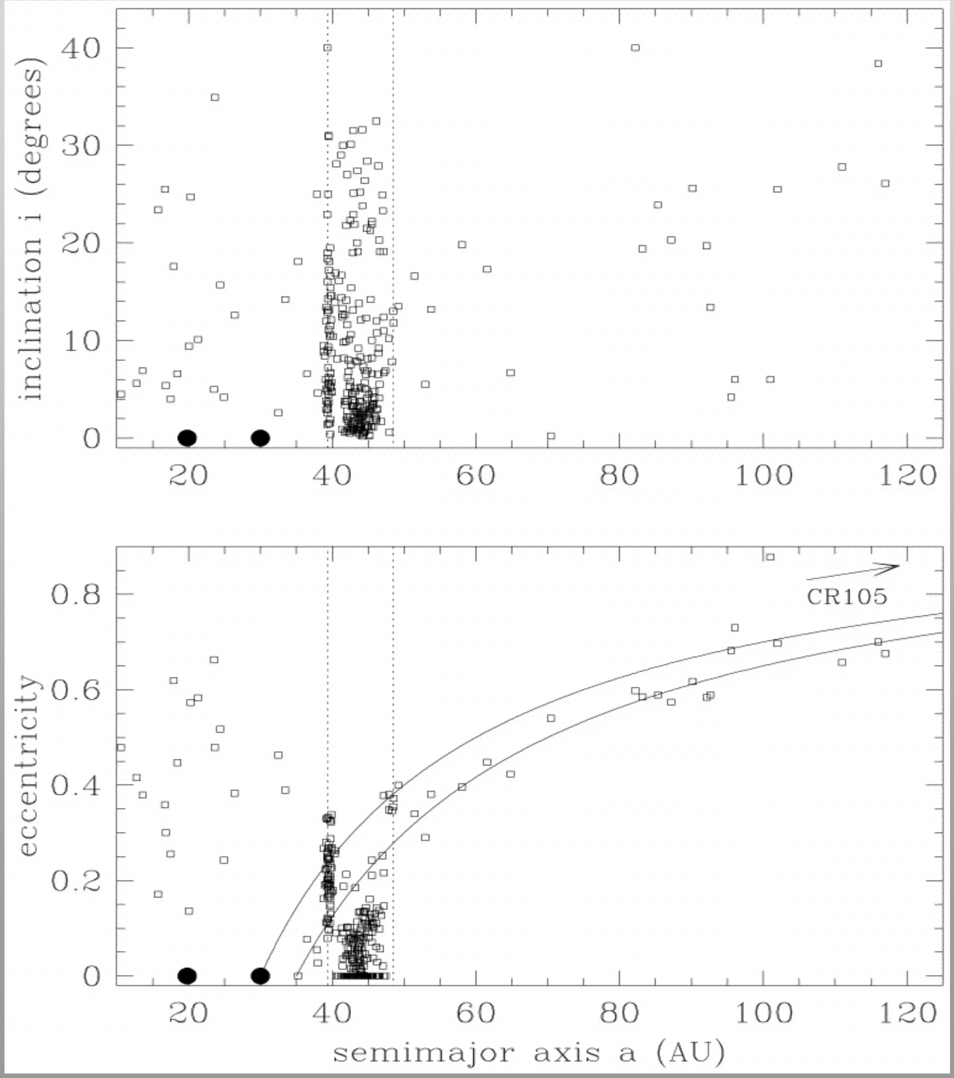




(Trujillo & Brown 2001)

The Kuiper Belt – Dynamical Classes

- Classical
- Resonant
- Scattered
- Extended Scattered??



(Gladman et al. 2001)

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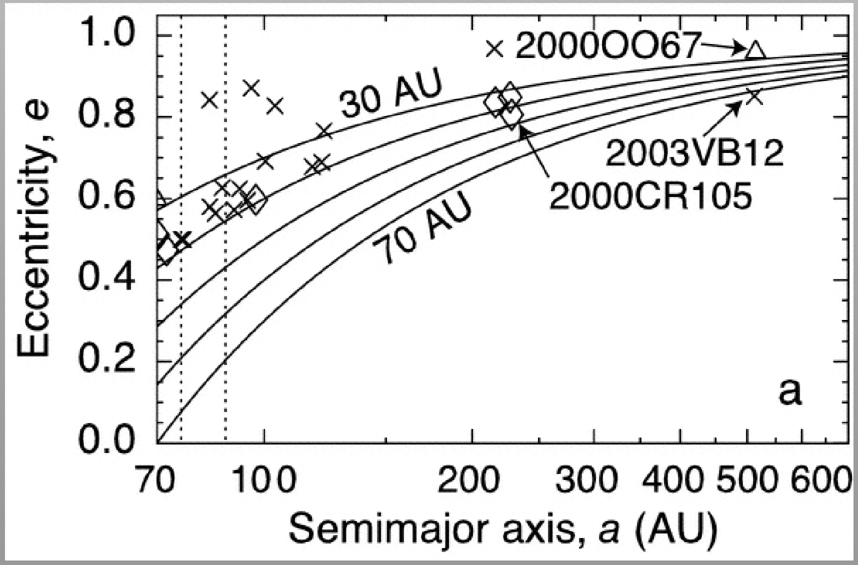
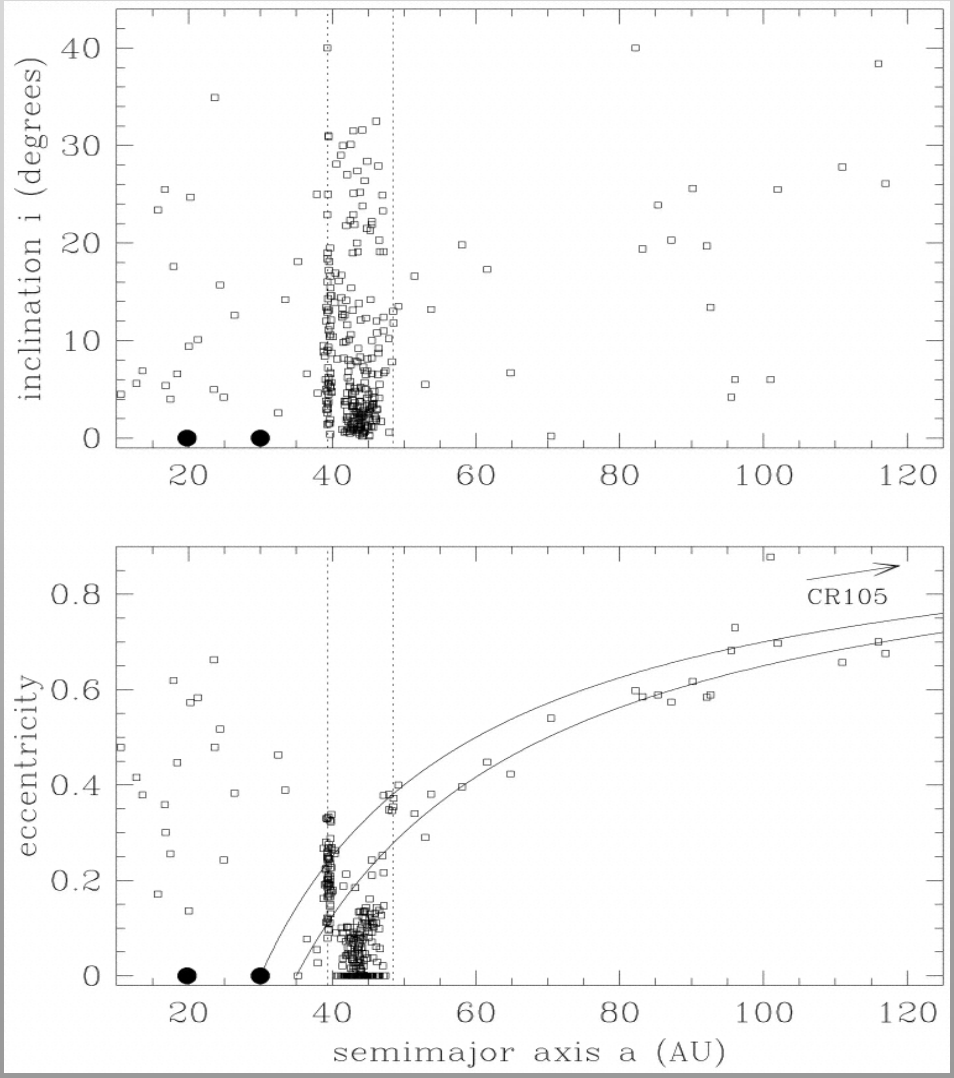


(Elliot et al. 2005)



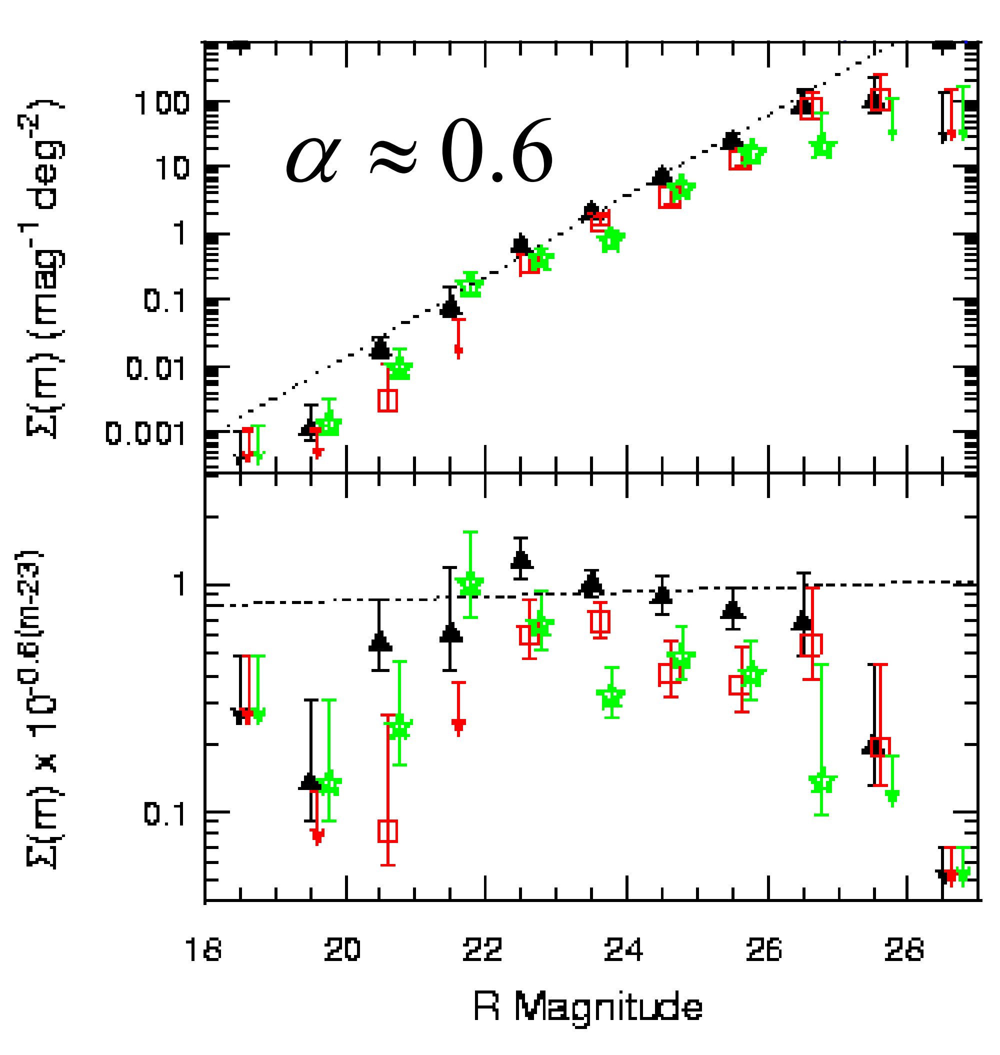
(Gladman et al. 2001)

The Kuiper Belt – Size Distribution

- Power Law

$$\Sigma \propto 10^{\alpha m}$$
$$\propto r^{-q}$$
$$(q = 5\alpha + 1)$$

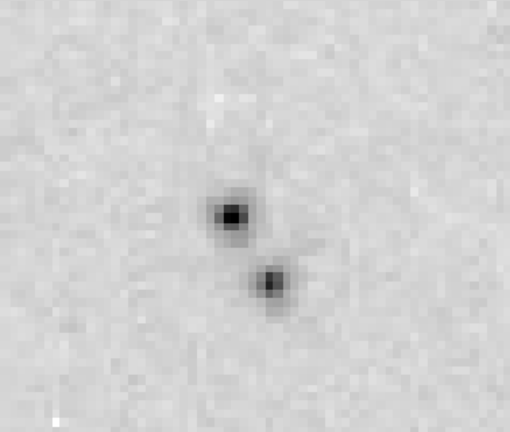
  - Assumes albedo
- Break
  - age ~ collision time
  - HST/ACS
  - r ~ 100 km



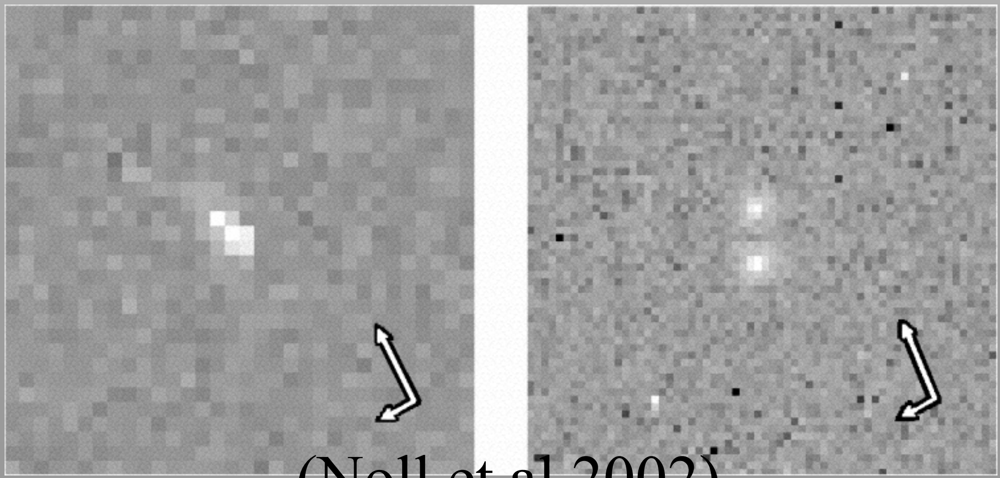
(Bernstein et al. 2004)

The Kuiper Belt – Binaries

- At least 5%-10% of KBOs in binaries
- Size ratios ~ unity
- Separations ~ 100 x radius
- Formation mechanisms
  - Weidenschilling (2002)
  - Goldreich et al. (2002)
  - Funato et al. (2003)
  - Astakhov et al. (2005)



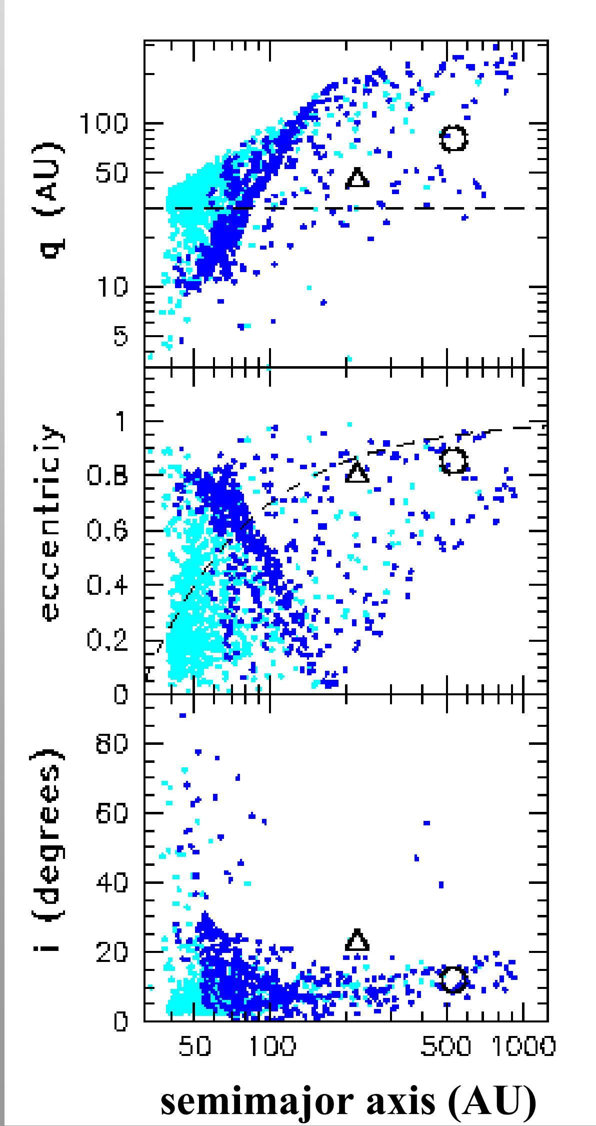
(Noll et al 2004)



(Noll et al 2002)

The Kuiper Belt – Open Questions

- Extended Scattered Disk?
- Faint-end distribution?
  - Slope?
  - Number?
  - Dynamical classes?
- Albedos/Sizes?
- Close binaries?
- The rest of the solar system?
  - Three orders of magnitude in distance
  - Nine orders of magnitude in volume!



(Kenyon & Bromley 2005)

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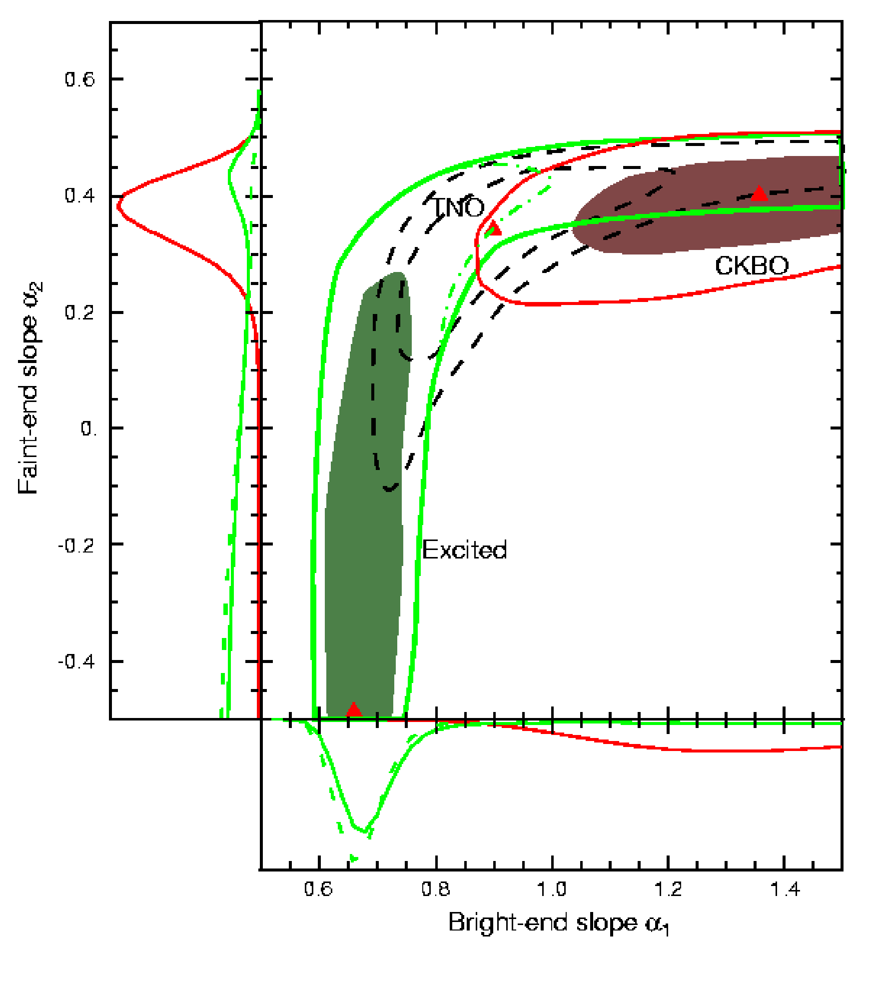

(Bernstein et al. 2004)

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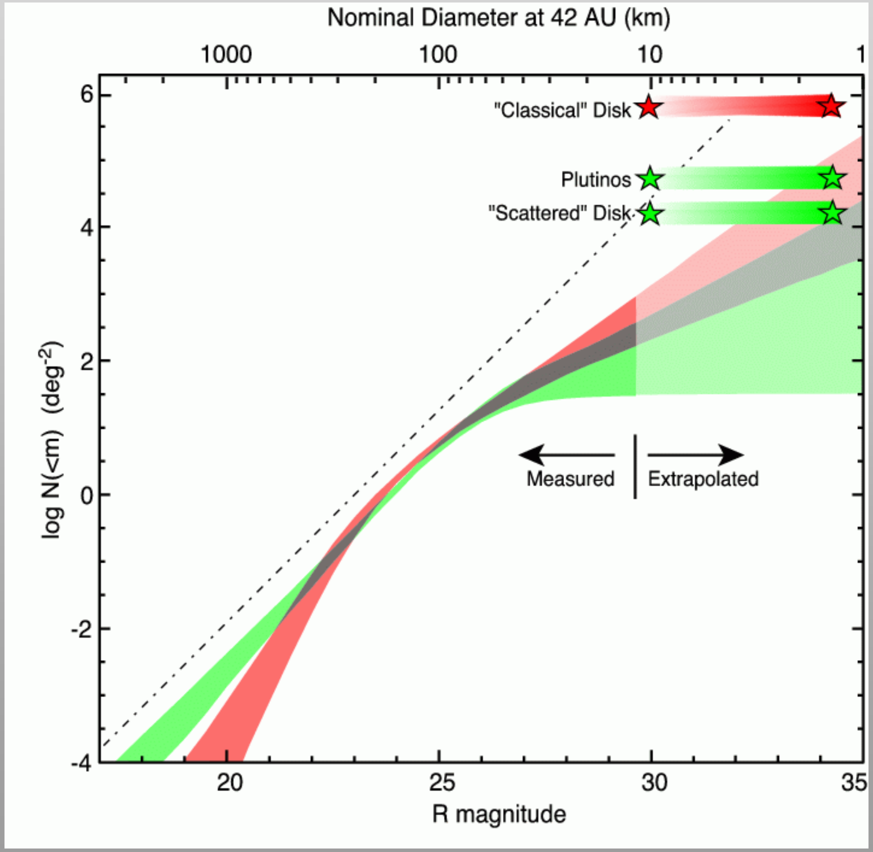

(Bernstein et al. 2004)

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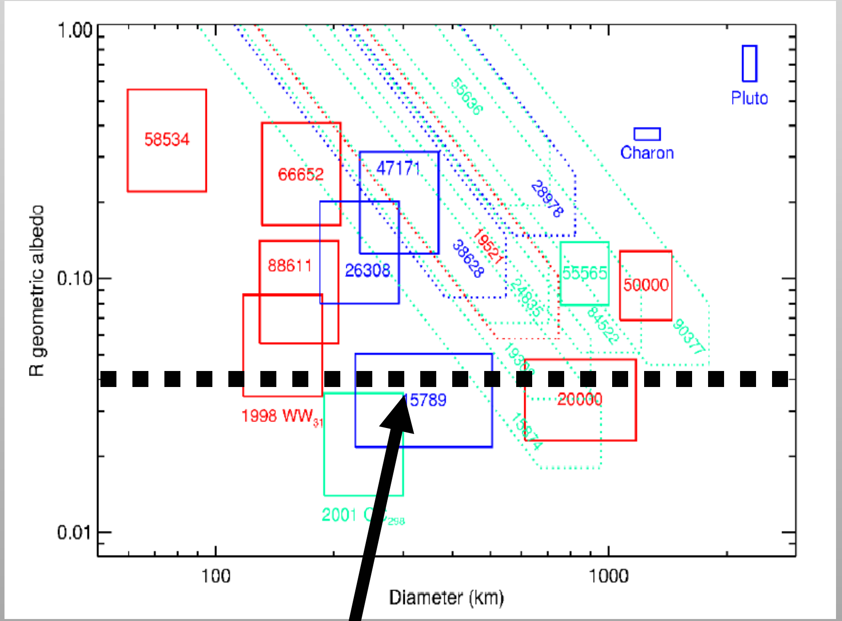

(Grundy et al. 2005)

canonical ~ 4%

The Kuiper Belt – Open Questions

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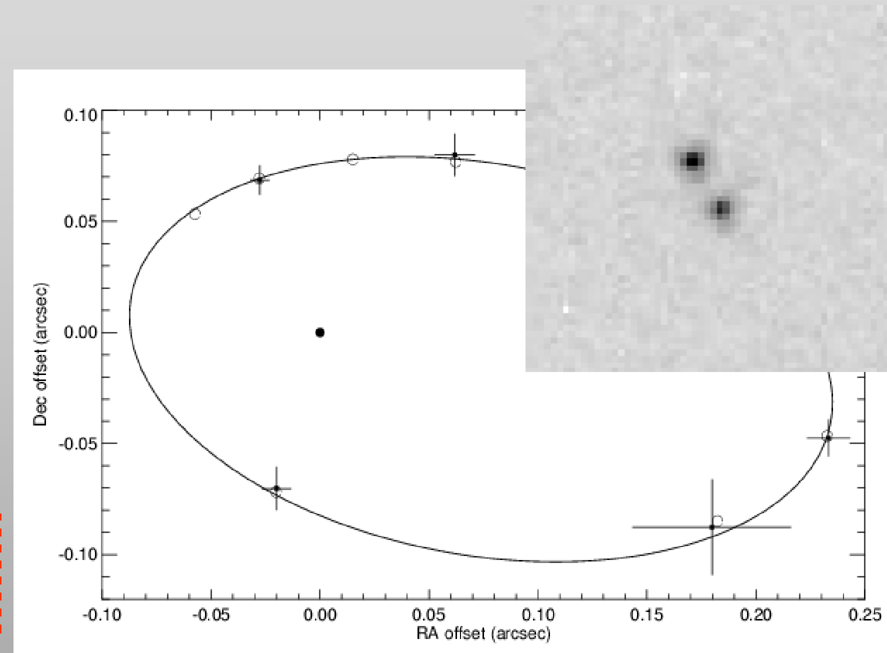

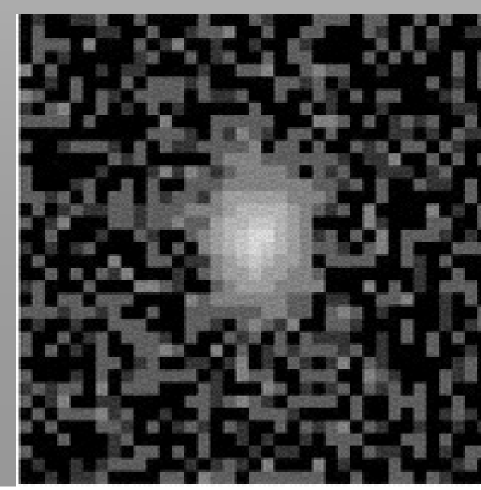

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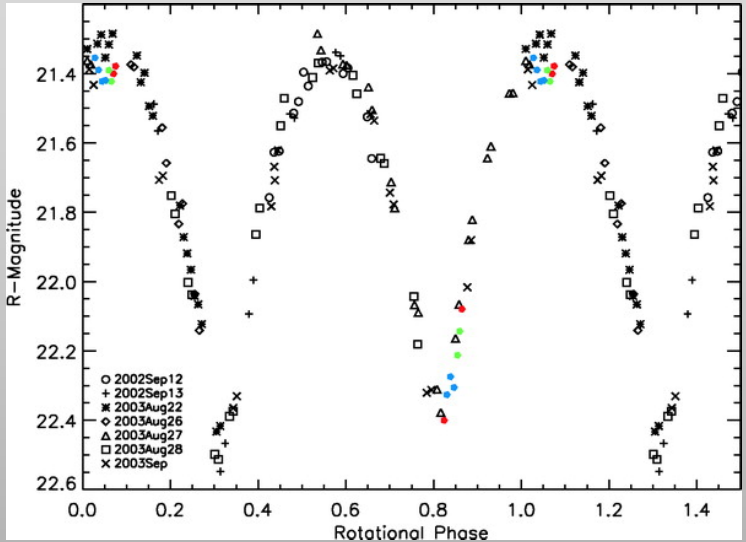

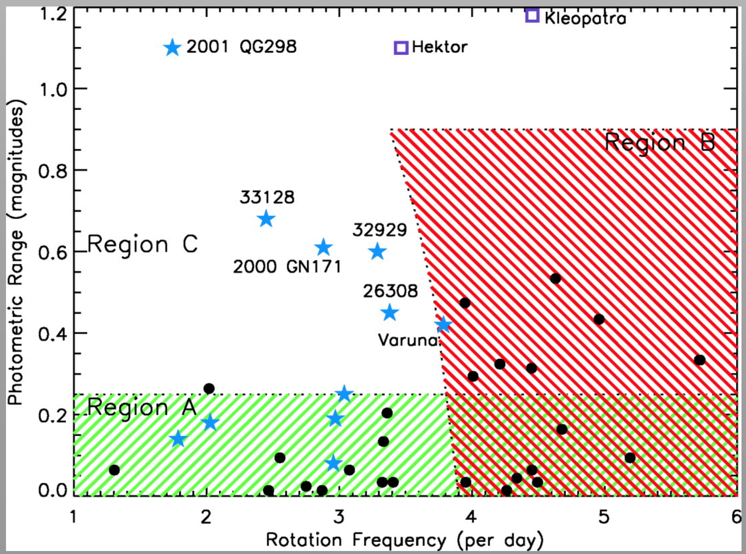

(Sheppard & Jewitt 2004)

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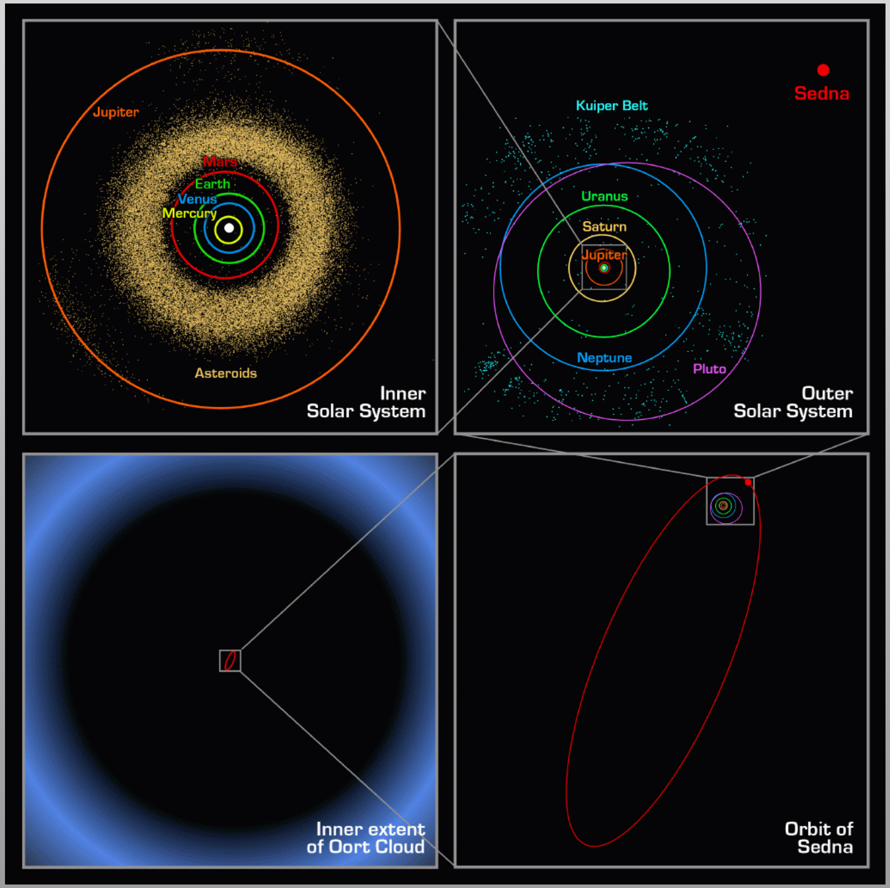
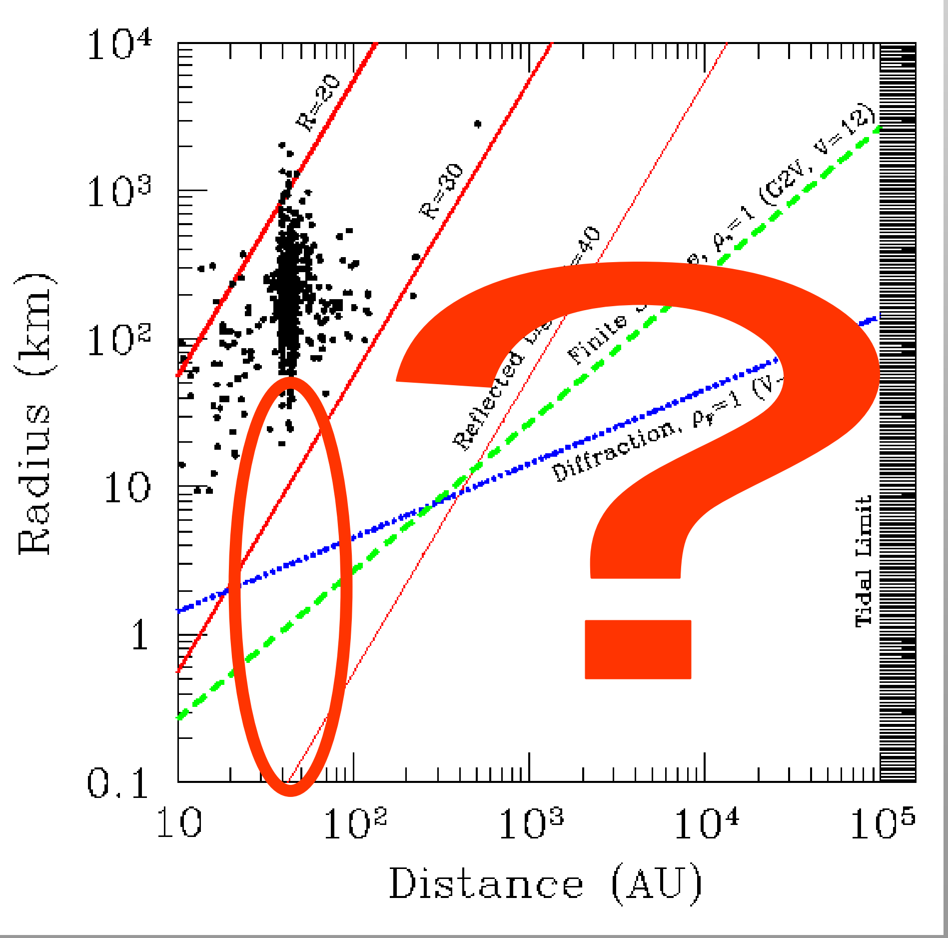


Limitations of Direct Measurements

- Strong scaling with size and distance

$$\text{Flux} \propto R^2 d^{-4}$$



- Occultations
  - Bailey (1976)
  - Dyson (1992)
  - Brown & Webster (1997)
  - Roques & Moncuqeut (2000)

Principles of Occultations

- Physical Parameters

$$R, d, v$$

- Scales
  - angular size $\theta = \frac{R}{d} \approx 140\mu\text{as}\left(\frac{R}{10\text{km}}\right)\left(\frac{d}{100\text{AU}}\right)^{-1}$
  - velocity $v = v_{\oplus}\left(\cos\varphi - \sqrt{\frac{\text{AU}}{d}}\right) \approx 27\text{km s}^{-1}$ at opp.
  - proper motion $\mu = \frac{v}{d} \approx 1''\text{hr}^{-1}\left(\frac{d}{100\text{AU}}\right)^{-1}\left(\frac{v}{30\text{ km}}\right)$

Principles of Occultations

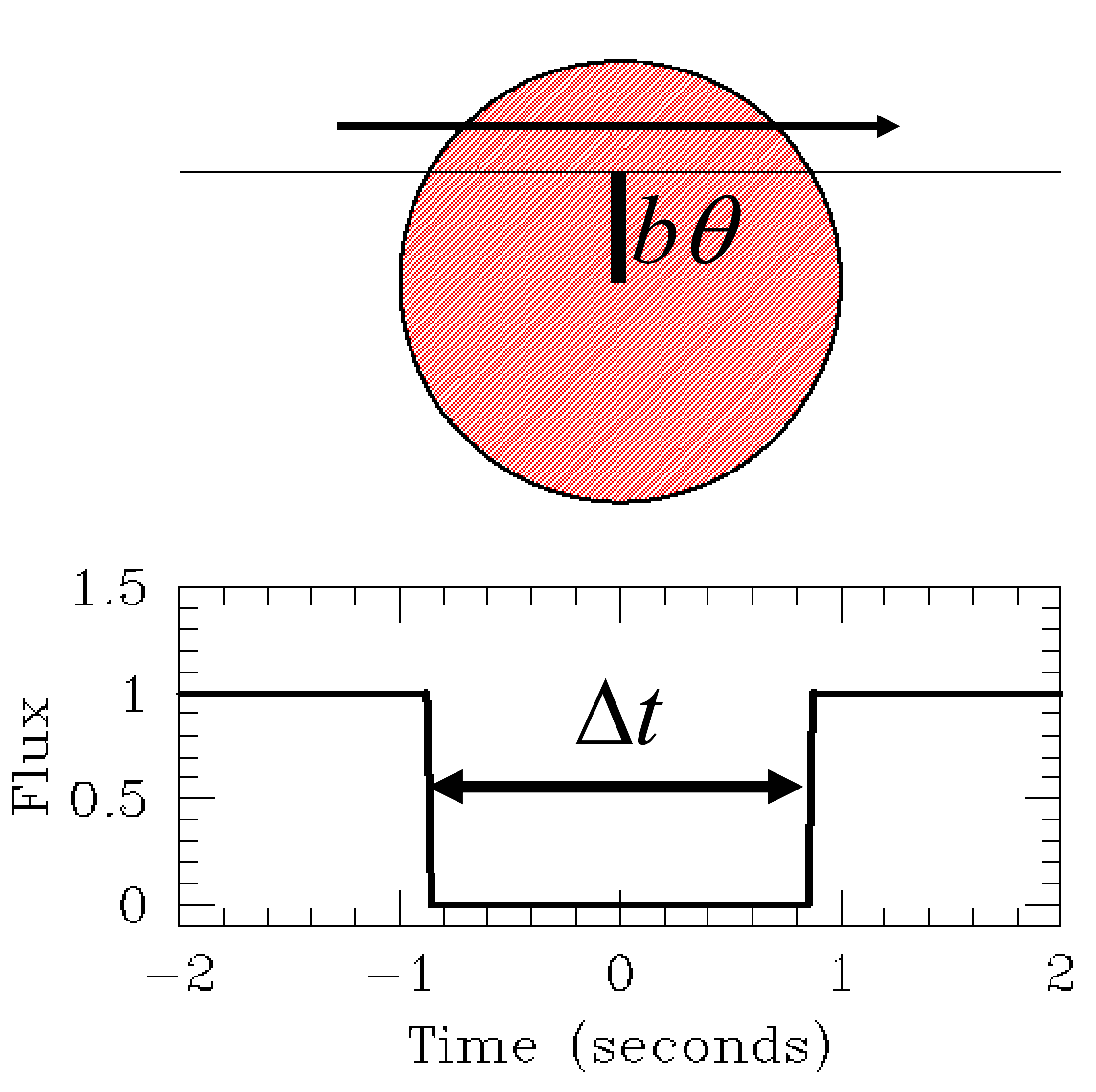
- Observables
  - Duration Δt

$$\Delta t = 2t_K\sqrt{1-b^2}$$

  - Crossing Time

$$t_K = \frac{\theta}{\mu}$$
$$\approx 0.3\mathrm{s}\left(\frac{R}{10\mathrm{km}}\right)\left(\frac{v}{30\ \mathrm{km\ s^{-1}}}\right)^{-1}$$

Statistical information only



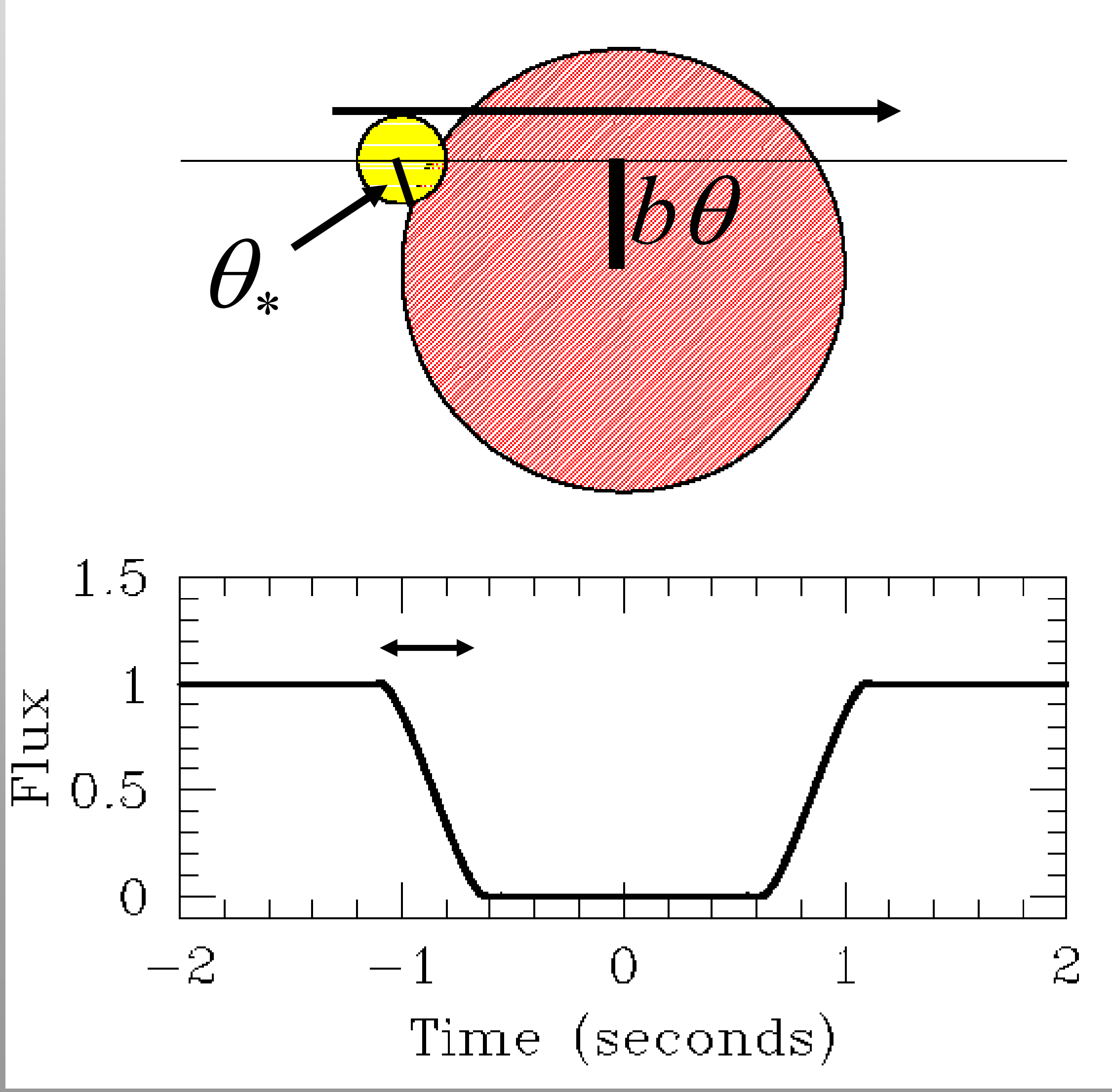
Principles of Occultations

- Observables
  - Ingress/Egress time
  - Impact parameter b
  - Dimensionless source size

$$\theta_* \approx 20\mu\text{as}\left(\frac{R_*}{\mathrm{R_{Sun}}}\right)\left(\frac{d_*}{250\text{pc}}\right)^{-1}$$

$$\rho_* = \frac{\theta_*}{\theta}$$

$$\approx 0.1\left(\frac{R}{10\text{km}}\right)^{-1}\left(\frac{d}{100\text{AU}}\right)\left(\frac{R_*}{\mathrm{R_{Sun}}}\right)\left(\frac{d_*}{250\text{pc}}\right)^{-1}$$



Principles of Occultations

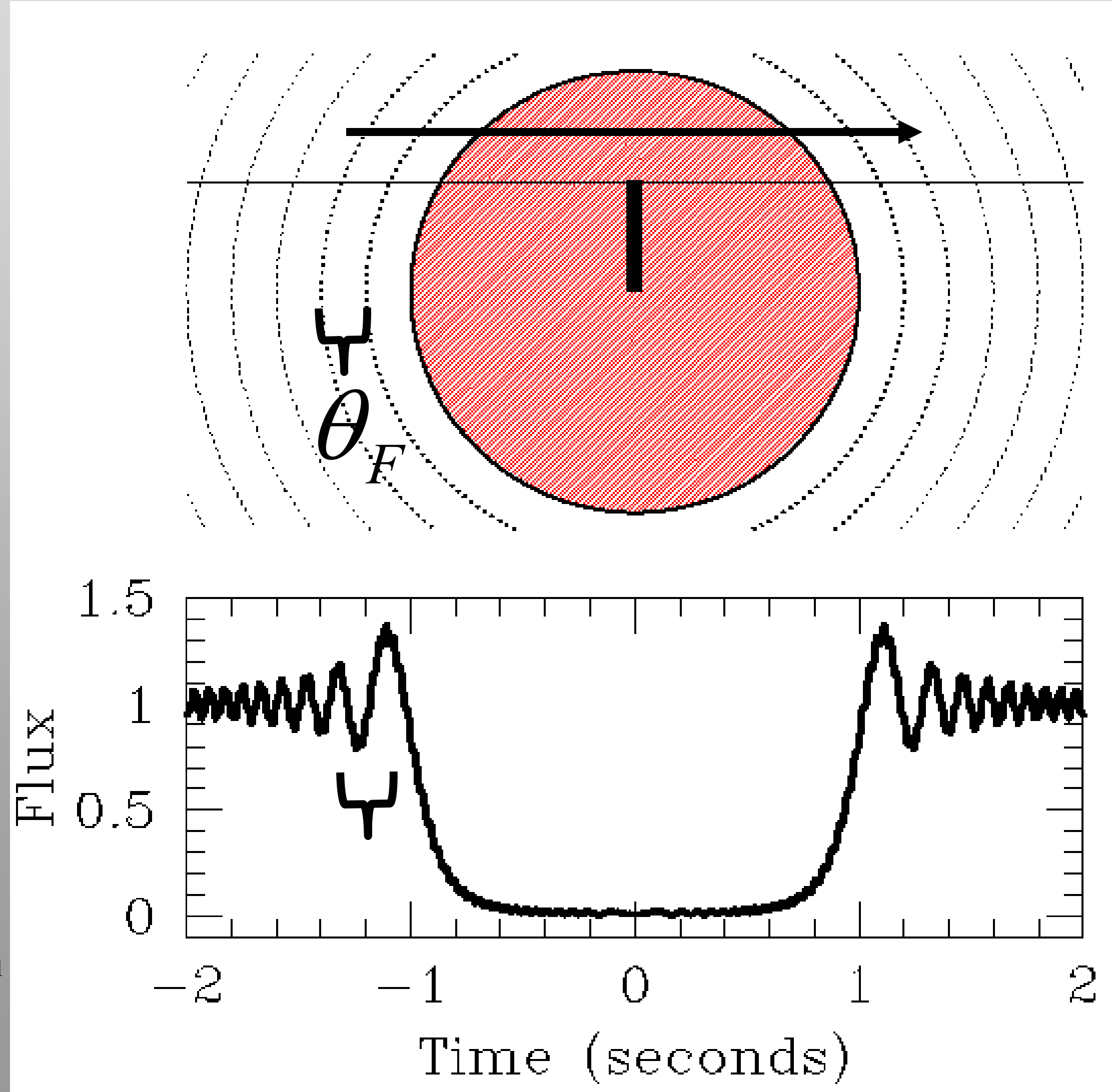
- Observables
  - Fringe Spacing
  - Dimensionless Fresnel angle

$$\theta_F = \sqrt{\frac{\lambda}{d}}$$

$$\approx 4\mu\mathrm{as}\left(\frac{\lambda}{545\mathrm{nm}}\right)^{1/2}\left(\frac{d}{100\mathrm{AU}}\right)^{-1/2}$$

$$\rho_F = \frac{\theta_F}{\theta}$$

$$\approx 0.03\left(\frac{\lambda}{545\mathrm{nm}}\right)^{1/2}\left(\frac{d}{100\mathrm{AU}}\right)^{1/2}\left(\frac{R}{10\mathrm{km}}\right)^{-1}$$



Principles of Occultations

- Observables

$$\Delta t, \rho_*, \rho_F$$

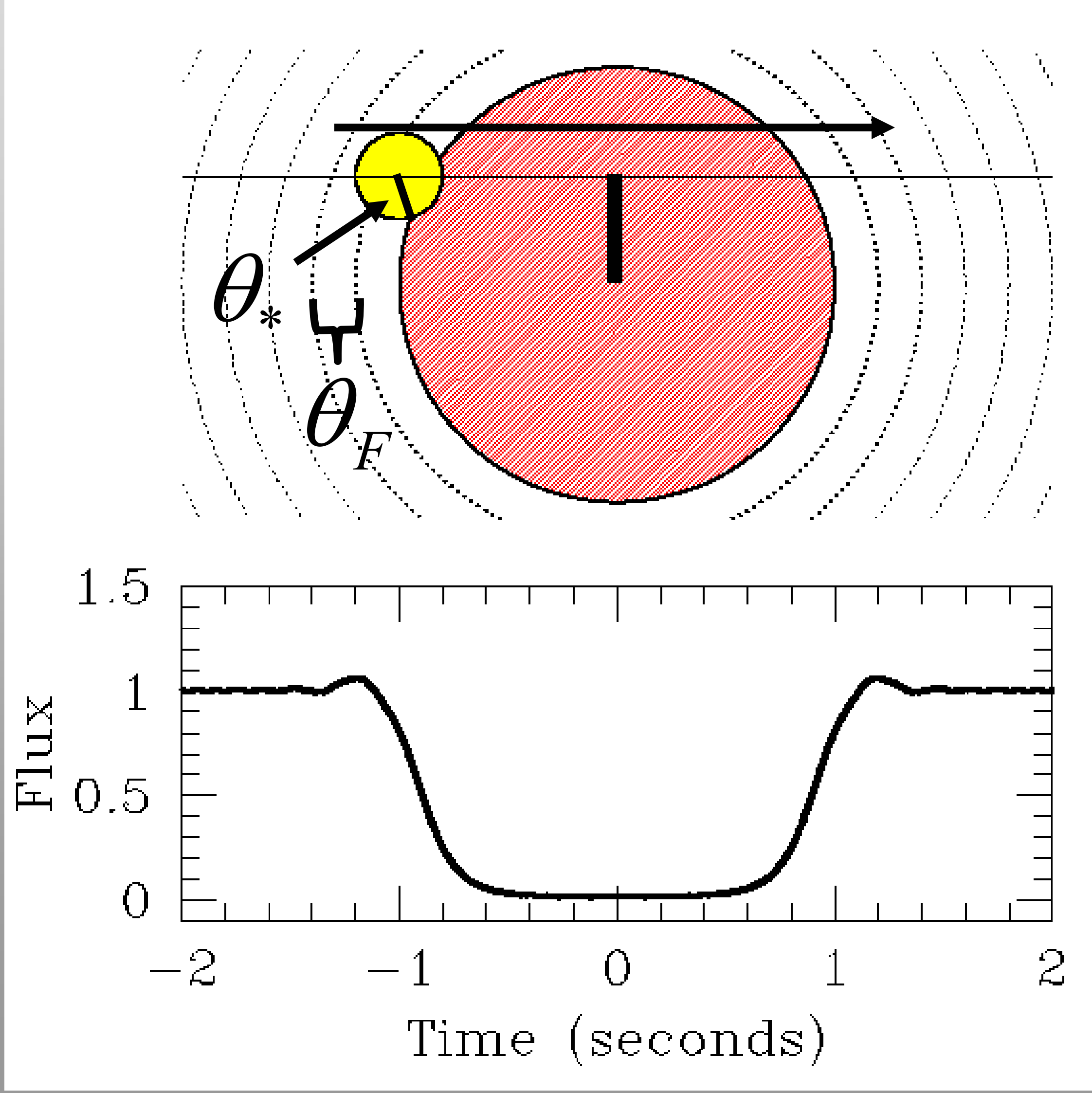
- Parameters

$$d = \frac{\lambda}{2\theta_*^2}\left(\frac{\rho_*}{\rho_F}\right)^2$$

$$R = \frac{\lambda}{2\theta_*}\frac{\rho_*}{\rho_F^2}$$

$$v = \frac{\lambda}{2\theta_*}\frac{\rho_*}{\rho_F^2}\frac{1}{t_K}$$

$$\longrightarrow R, d, v$$



Parameter Uncertainties

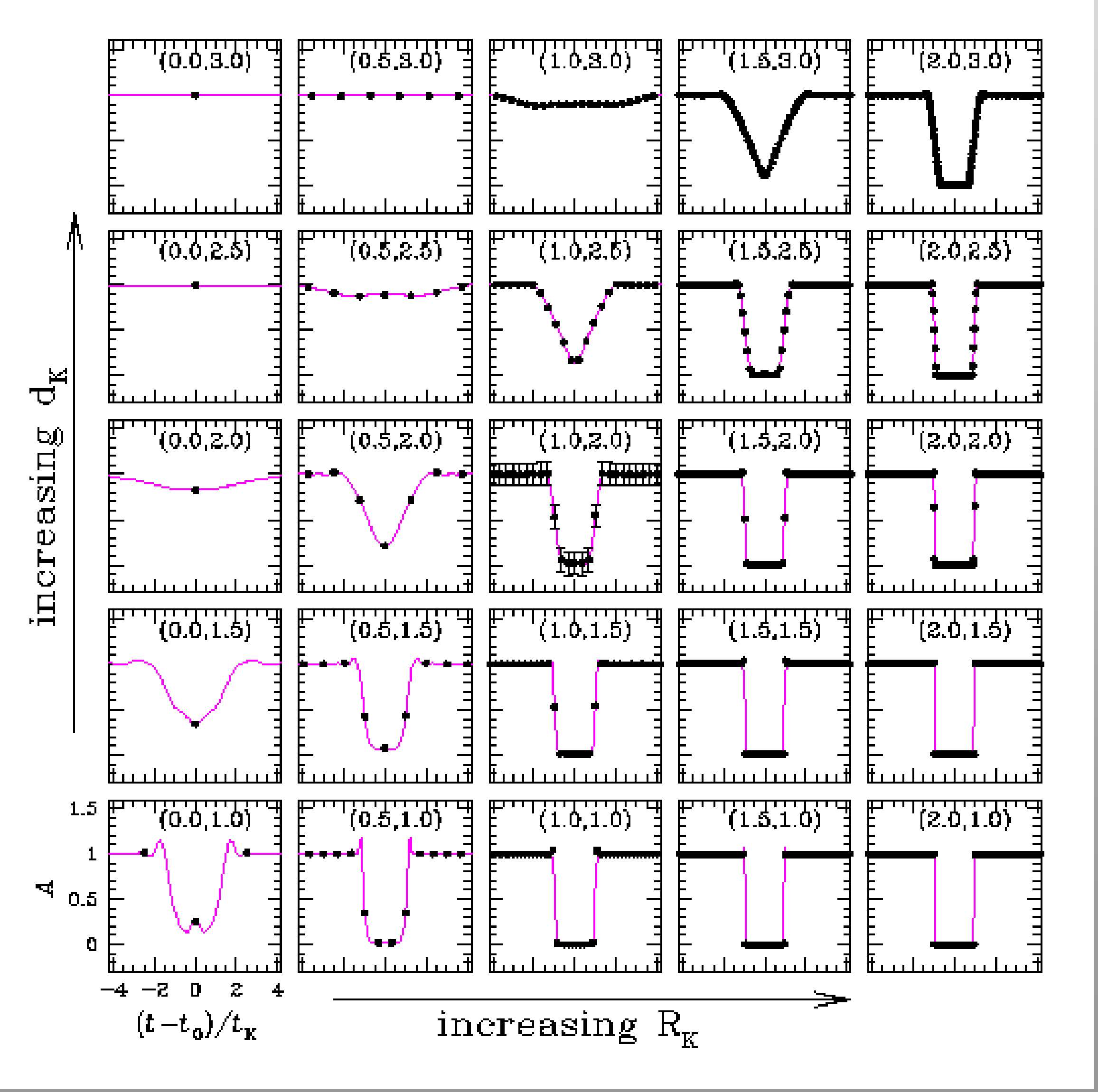
- Light curves
  - 10% errors (V=14)
  - 5 Hz sampling
- Parameters p_i
  - N measurements F_k

$$c = b^{-1}$$

$$b_{ij} = \sum_{k=1}^{N} \frac{\partial F_k}{\partial p_i} \frac{\partial F_k}{\partial p_j} \frac{1}{\sigma_k^2}$$

- Uncertainties

$$\sigma_i = \sqrt{c_{ii}}$$



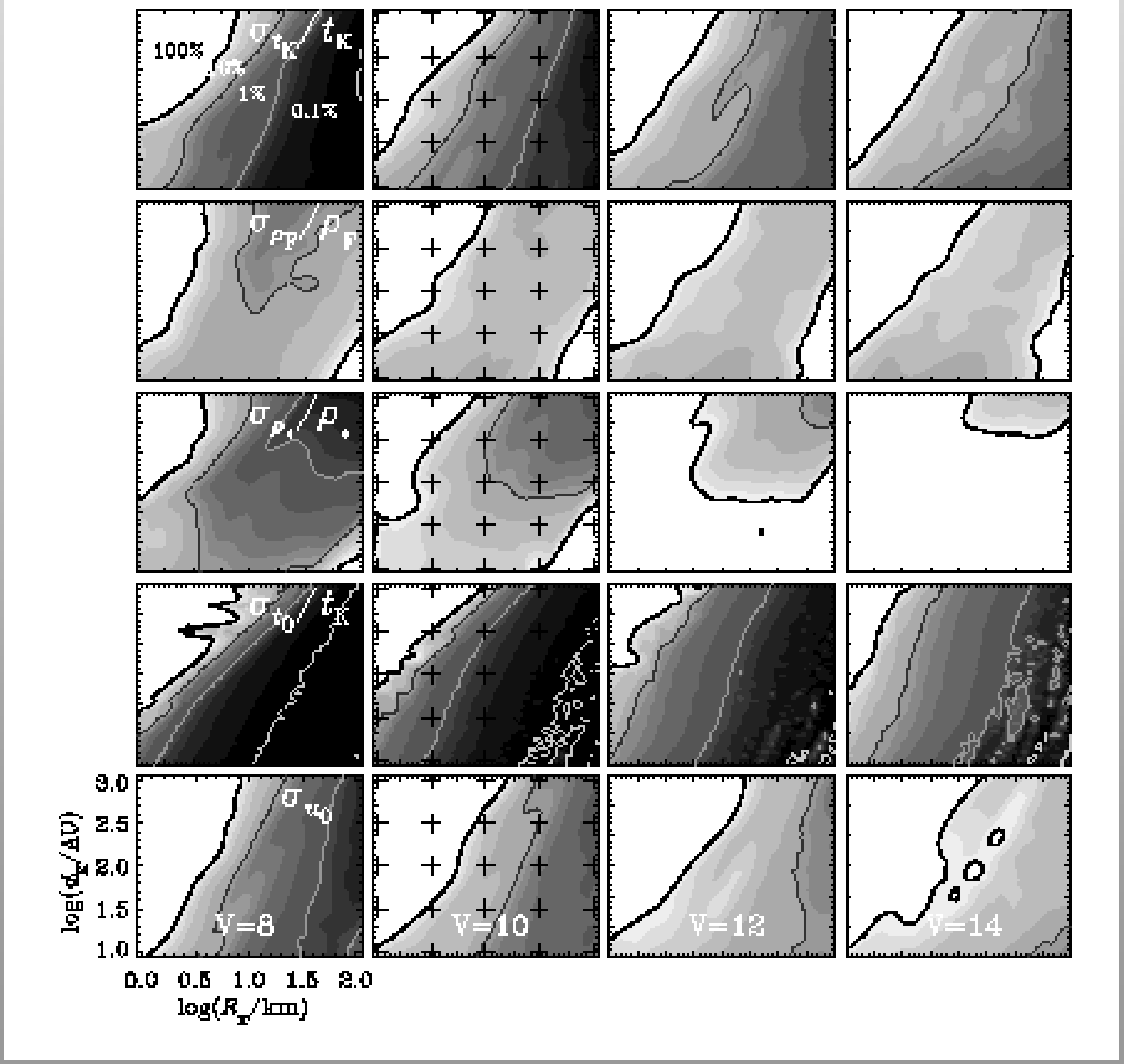
Parameter Uncertainties

- Uncertainties
  - Well-constrained

$$t_K, t_0, b$$

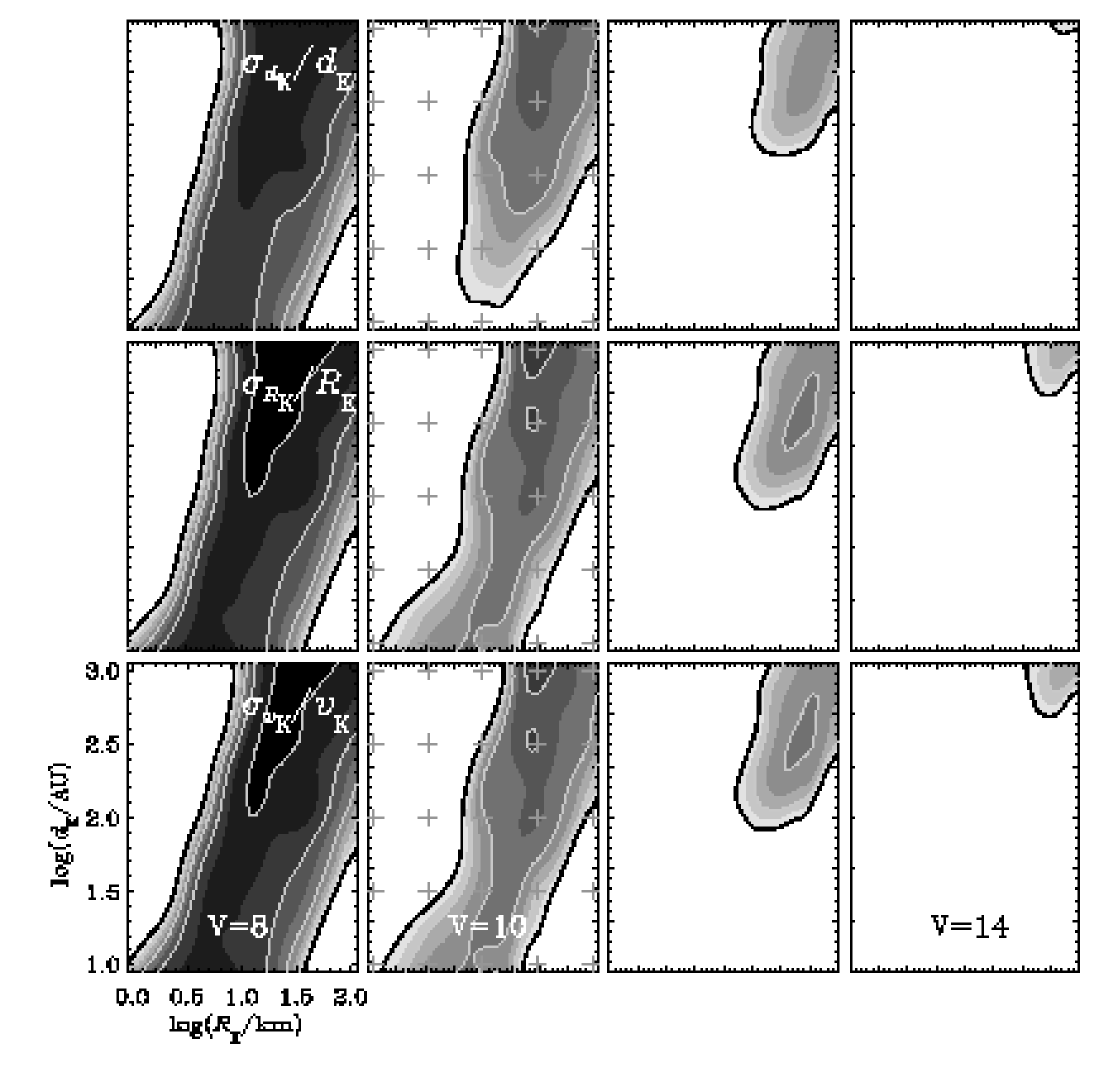
  - Poorly constrained

$$\rho_*, \rho_K$$



Parameter Uncertainties

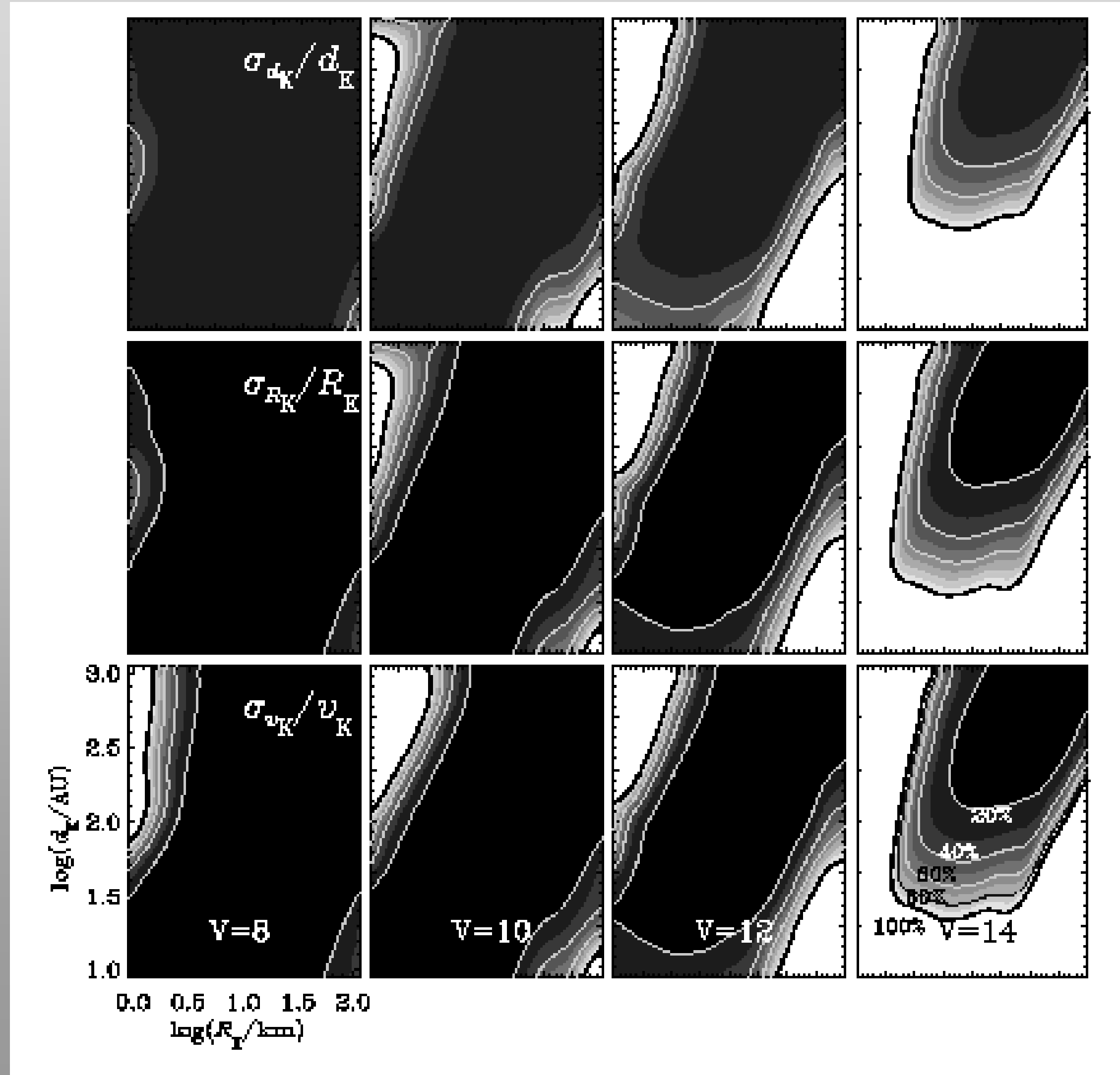
- Weak constraints for faint sources



Parameter Uncertainties

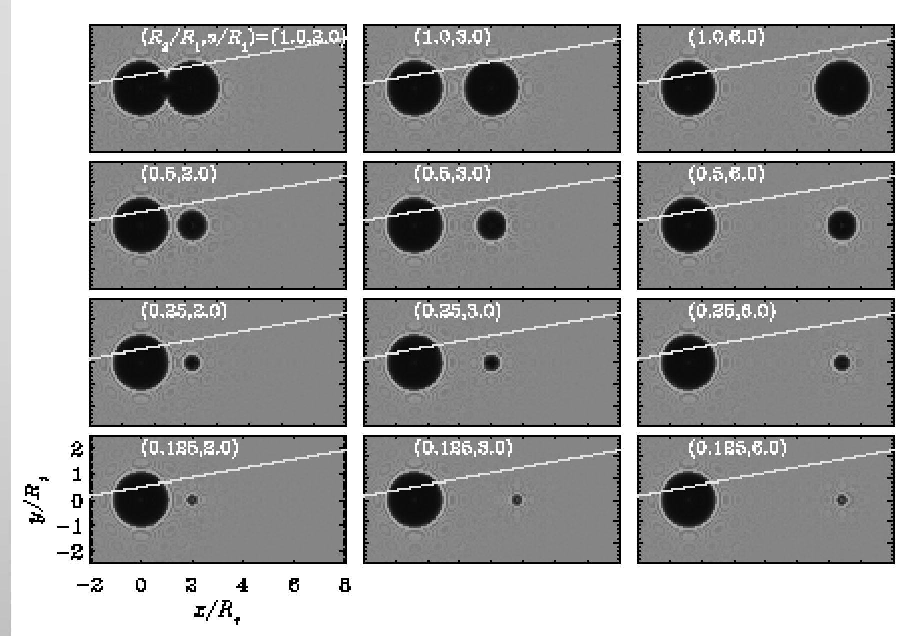
- "Next Generation"
- Experiment
  - 3% (V=14)
  - 30 Hz sampling

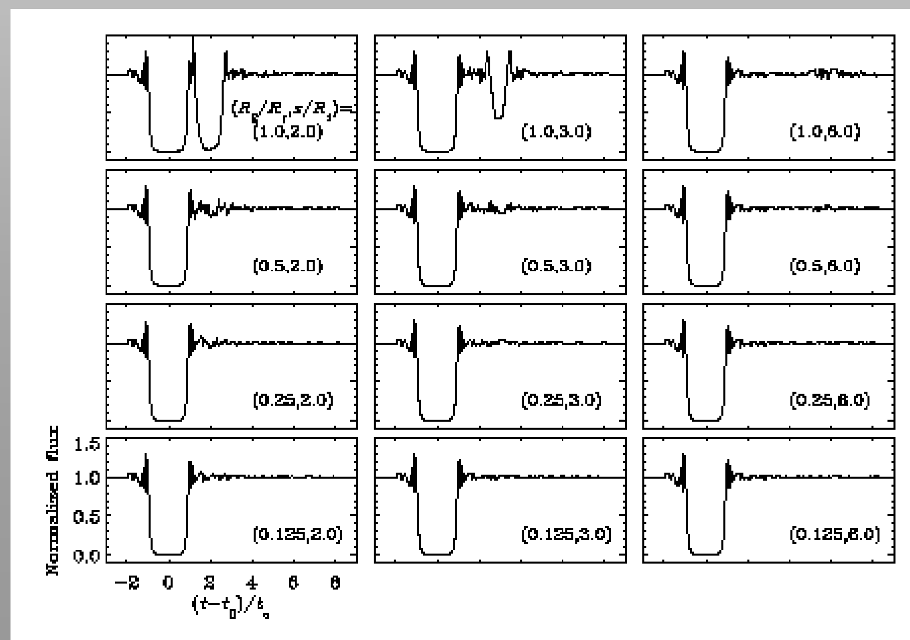
- Good constraints



Occutations by Binaries

- Detection Rate?
- Binary properties
  - Primary size
  - Size ratio
  - Separation
- Photometric properties
  - Sampling rate
  - Photometric errors

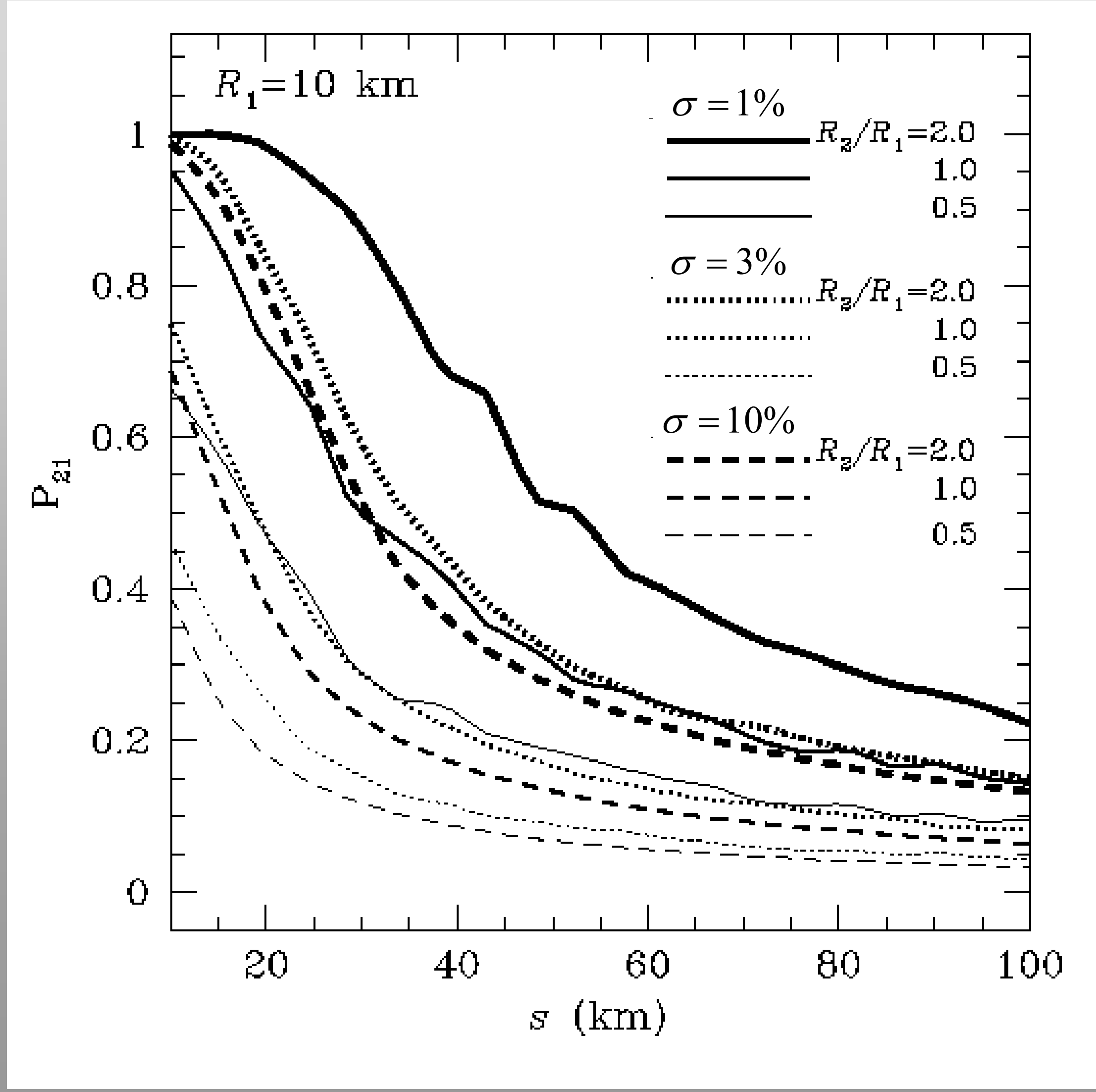




Occutations by Binaries

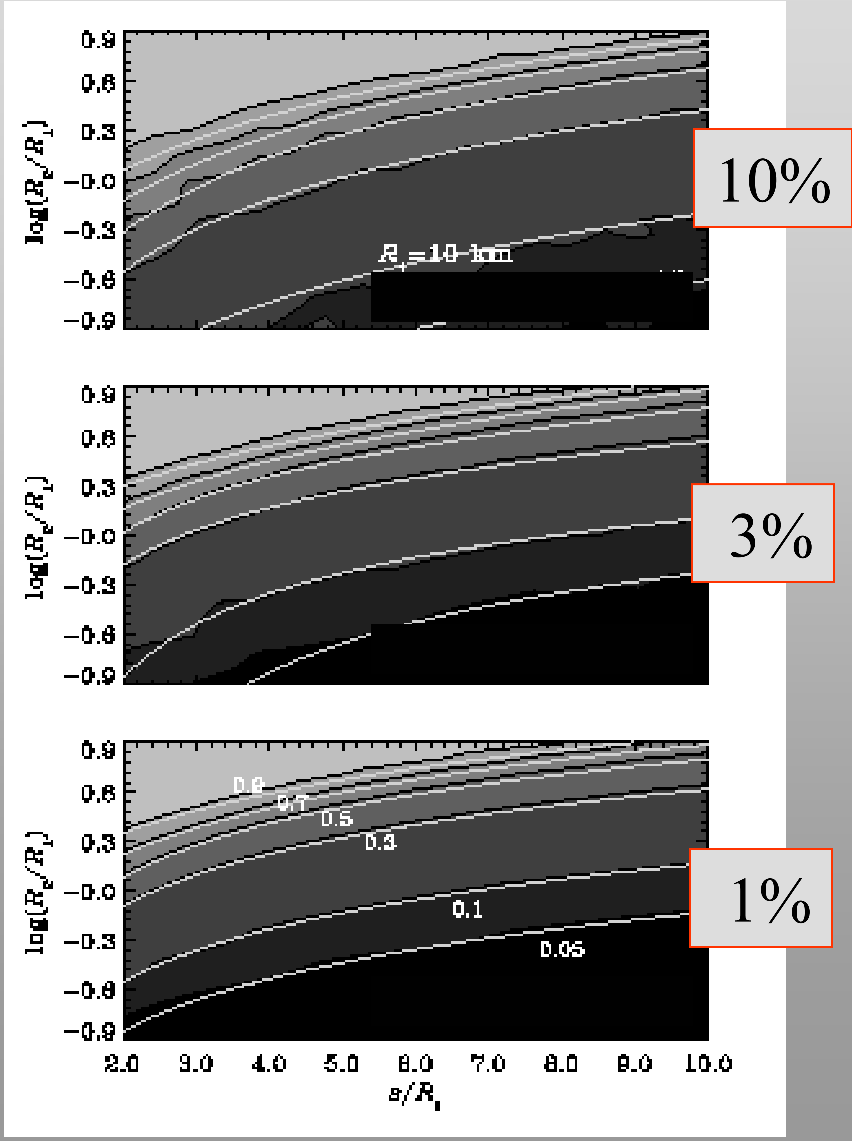
$$t_K, t_0, b$$

- Conditional prob.
  - 10 Hz
  - S/N>10



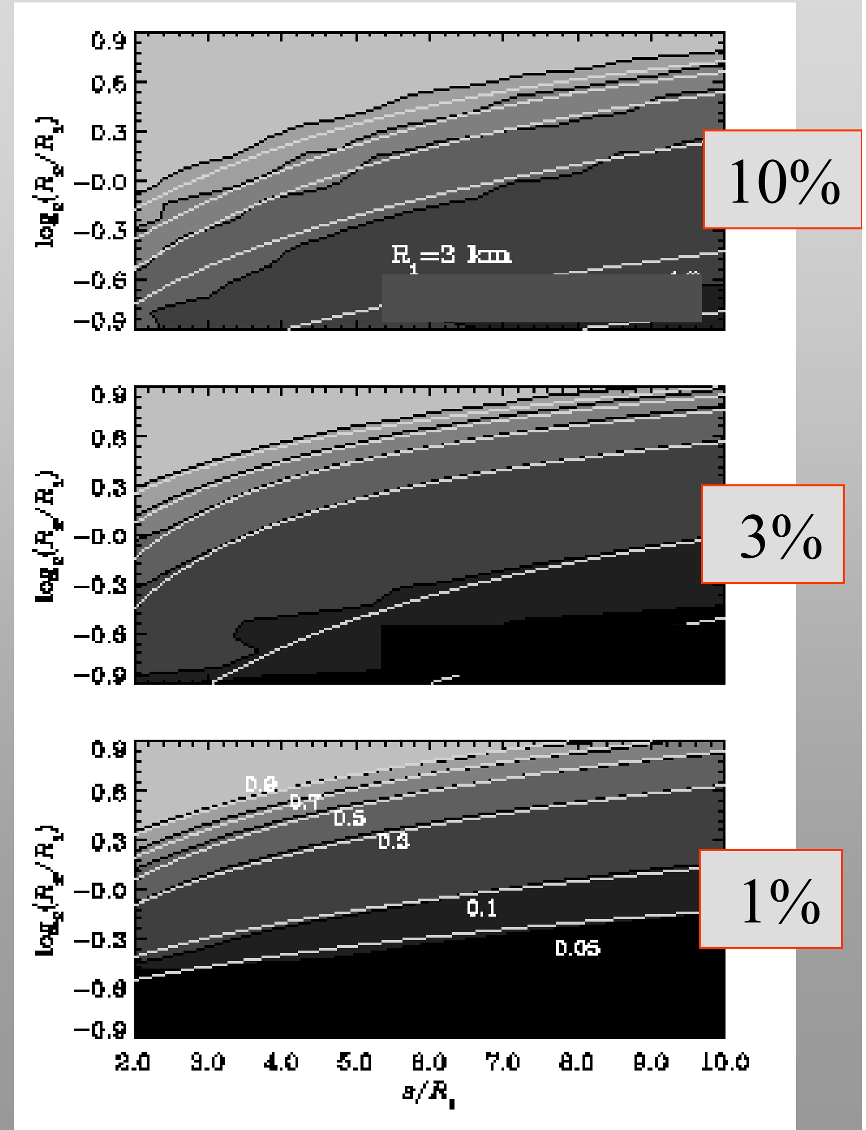
Occutations by Binaries

- Can detect:
  - 50% of equal-sized binaries with d/R < few
  - 10% of equal-sized binaries with d/R < 10



Occutations by Binaries

- Improved precision can dramatically increase rate
  - Especially for small objects



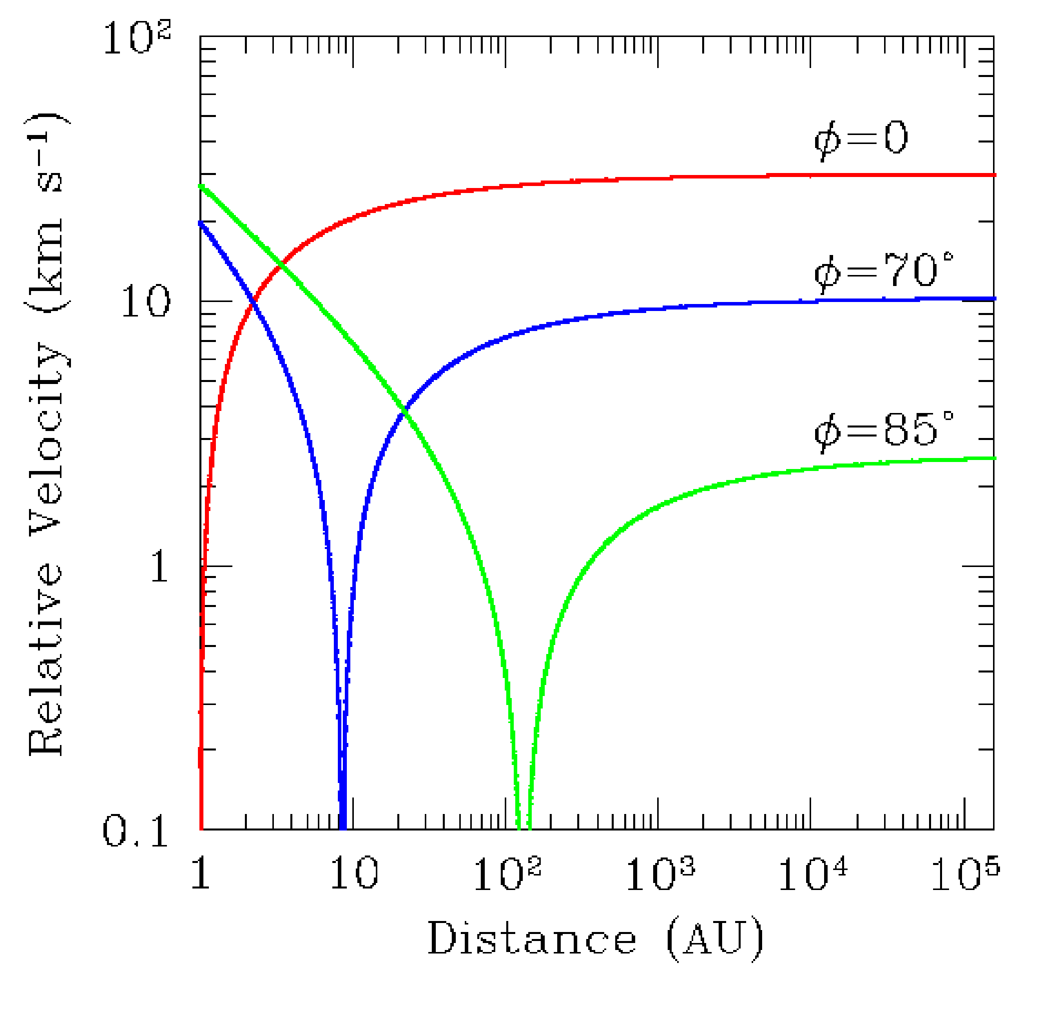
Occutation Surveys

- Challenges
  - Short event duration

$$\Delta t \approx 0.6\text{s}\left(\frac{R}{10\text{km}}\right)\left(\frac{v}{30\text{ km s}^{-1}}\right)^{-1}$$

  - Low event rate

$$\Gamma = \int dr 2\theta\mu\Sigma$$



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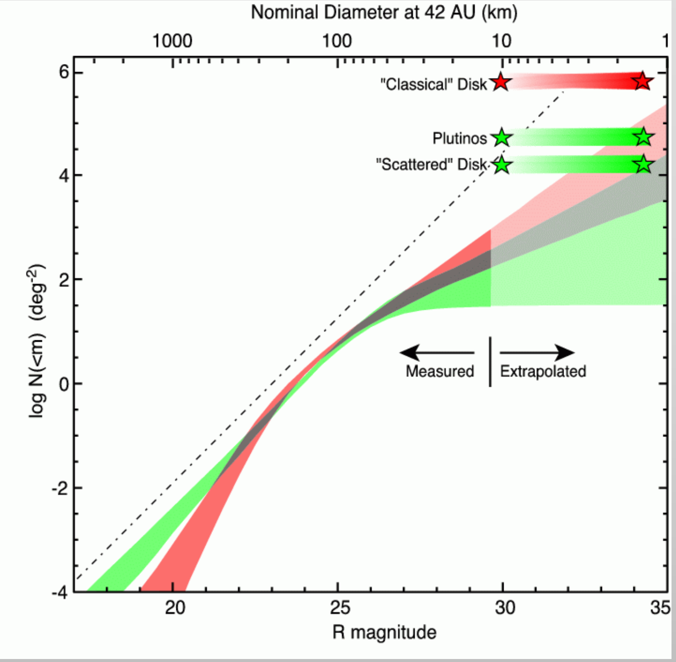
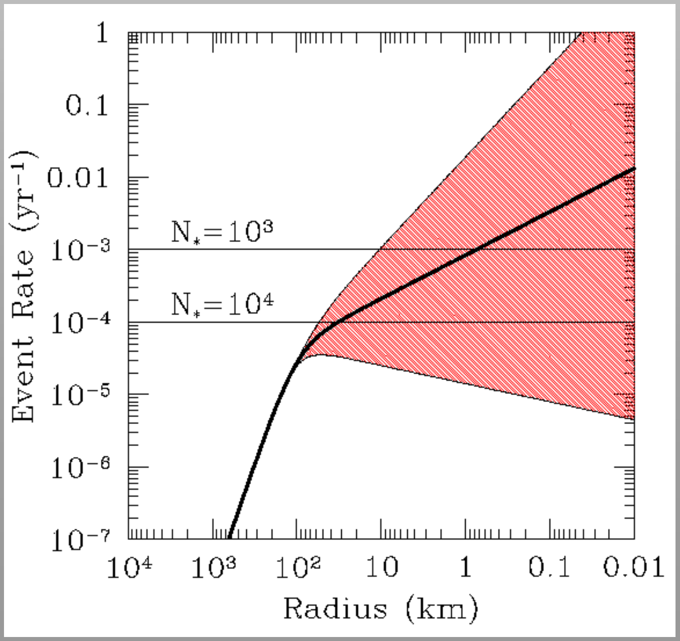
  - Low event rate

$$\Gamma = \int dr\, 2\theta\mu\Sigma$$

$$\approx 10^{-5} - 10^{-3}\,\mathrm{yr}^{-1} \text{ (R<10km)}$$

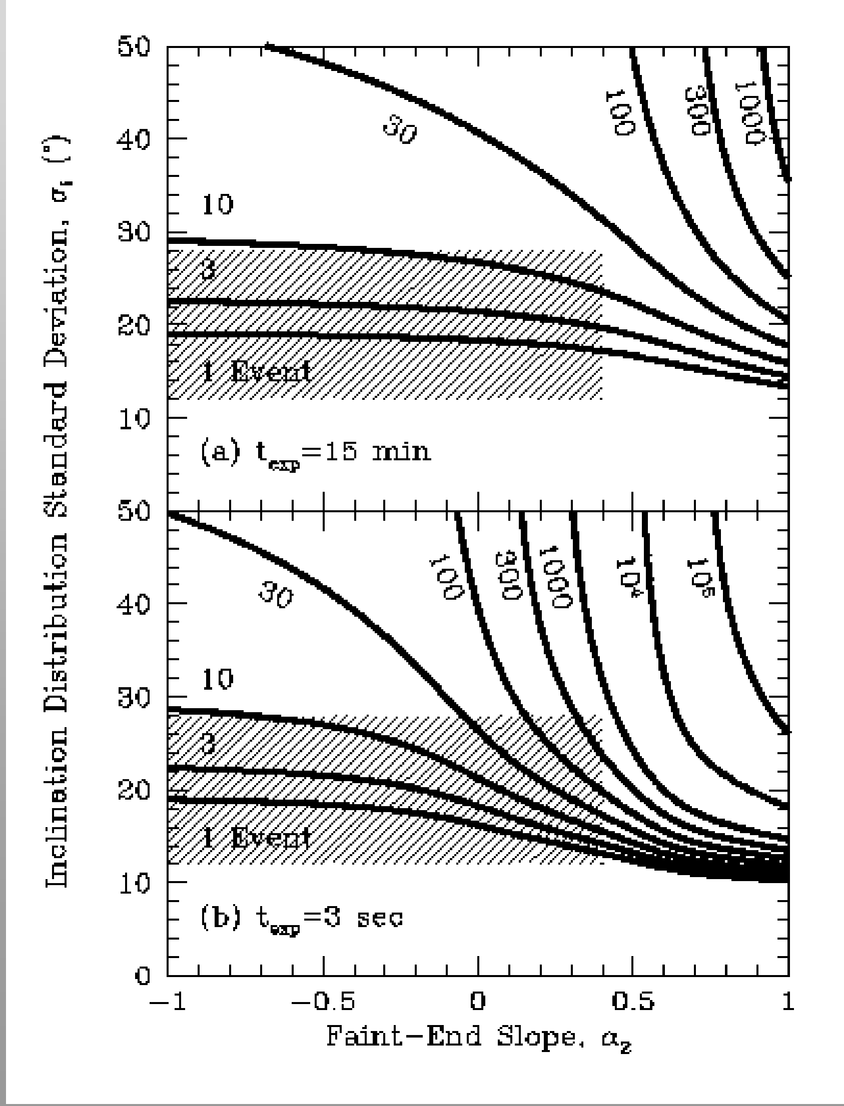
  - Monitor >1000 stars





Occutation Surveys

- *Kepler*
  - 100,000 stars
  - μmag precision
  - Long exposure times
  - High ecliptic latitude



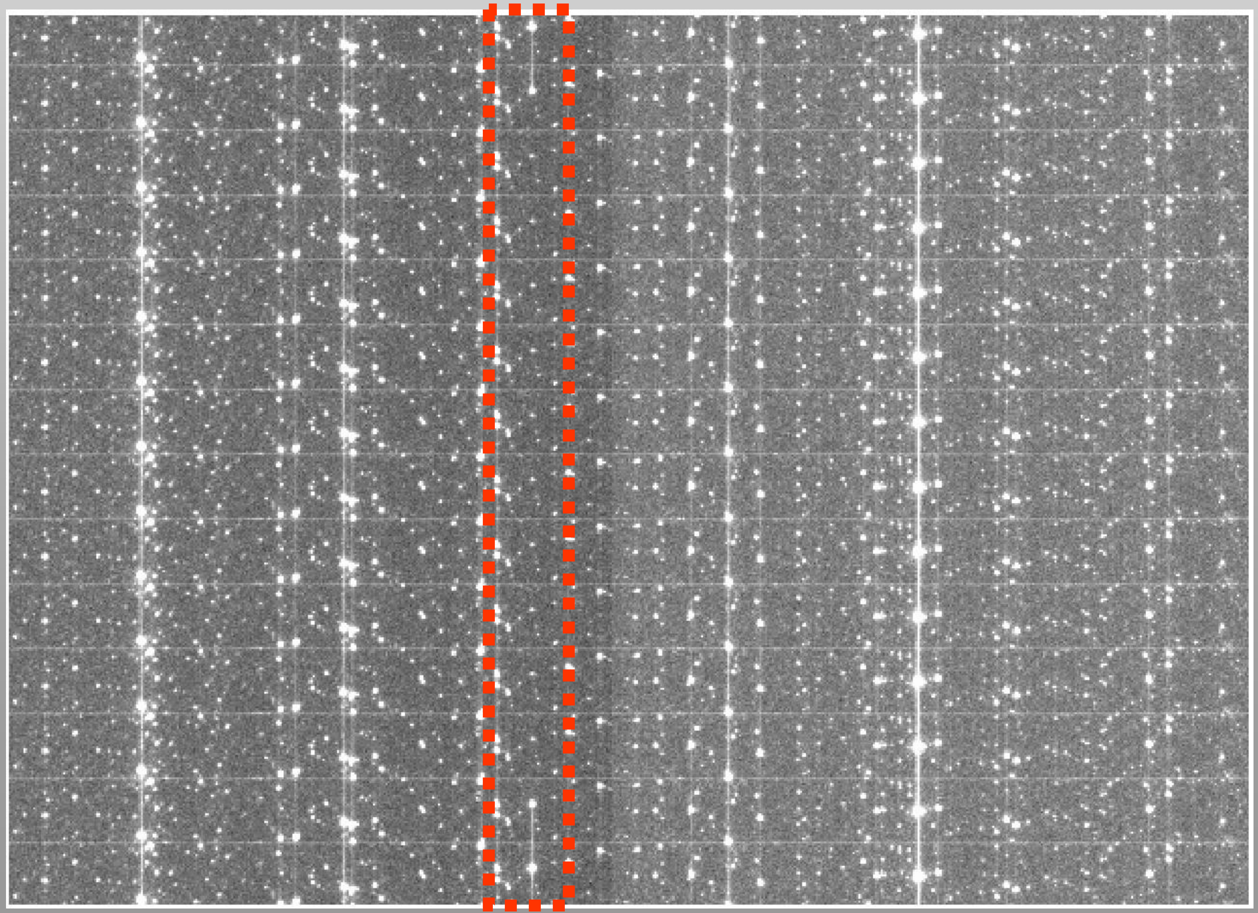
Occutation Surveys

Taiwanese-American Occultation Survey (TAOS)

- Telescopes & Hardware
  - Four 50 cm robotic telescopes
  - f/1.9
  - 2 square degree 2Kx2K cameras
  - Jade Mountain, Taiwan
- Data
  - 2000 stars
  - 5Hz
  - 10% precision
  - Short exposure times

Occutation Surveys

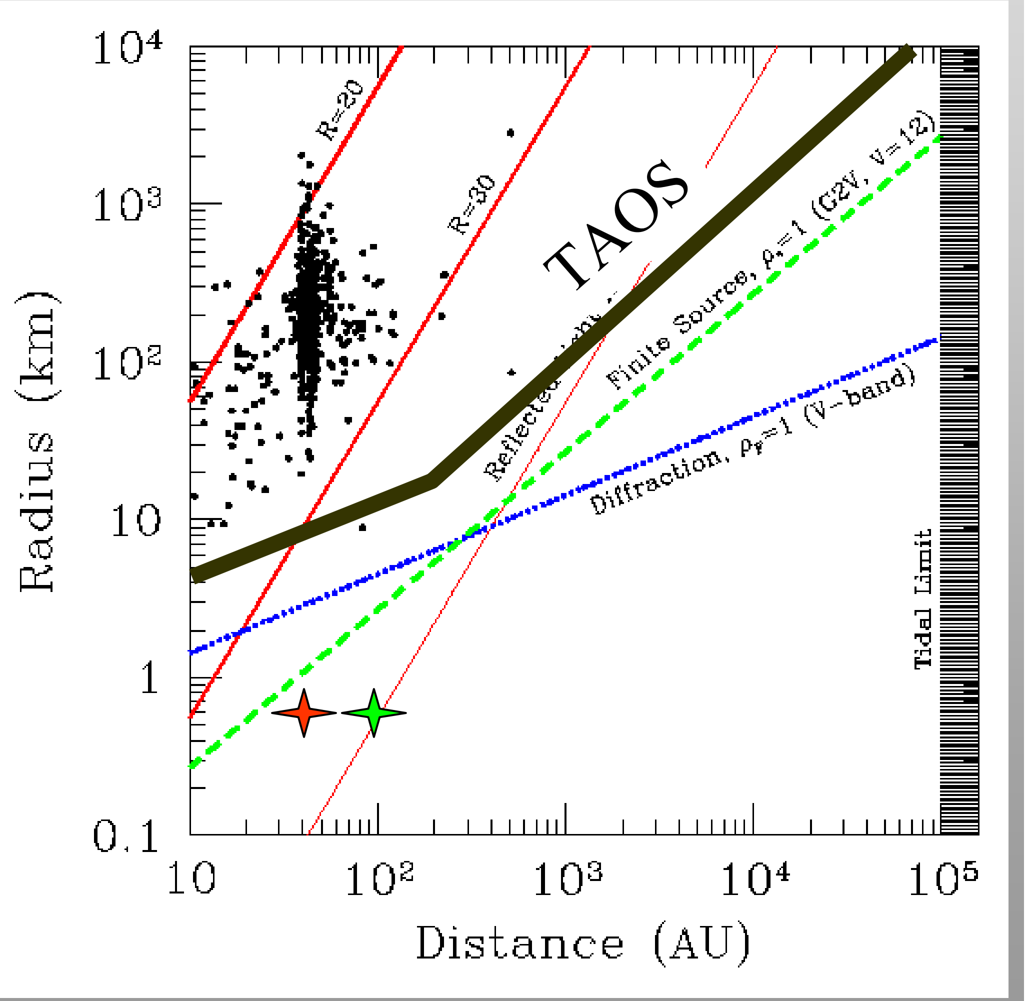
- Shutterless “Zipper” mode



Occutation Surveys

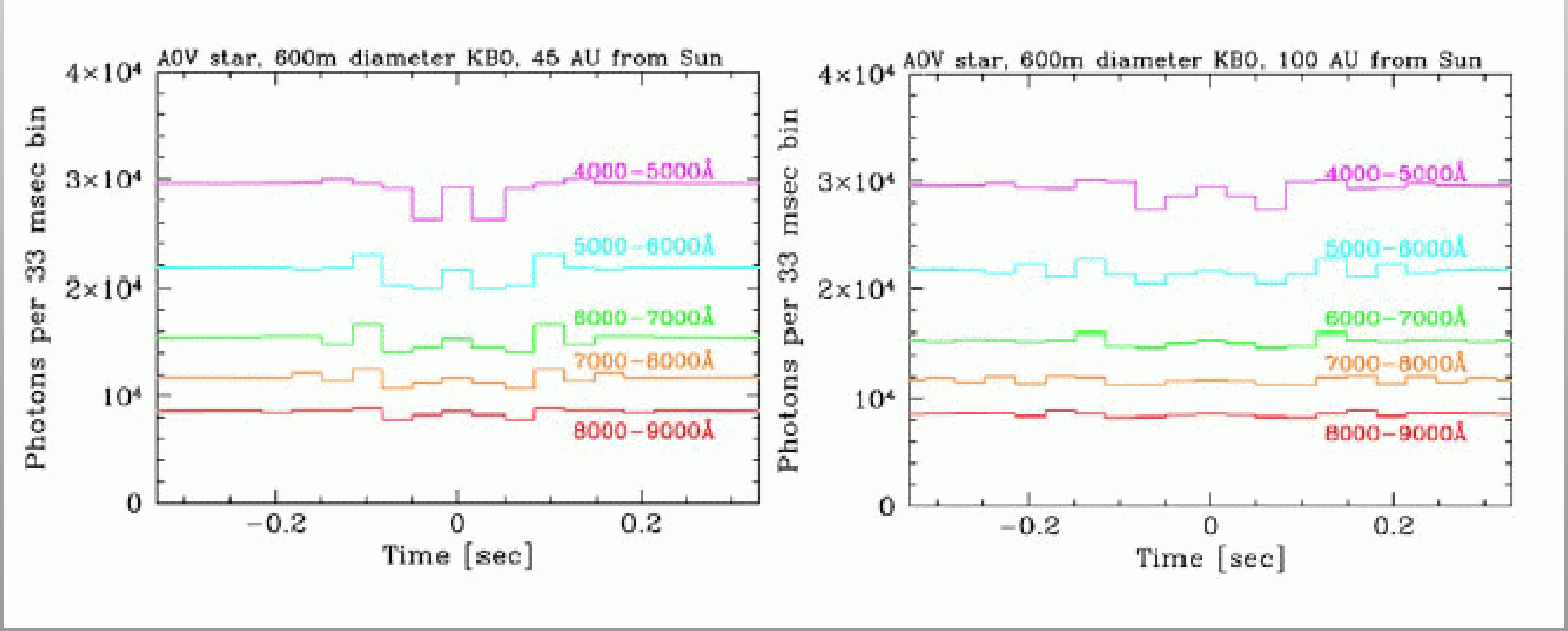
Next Generation Survey

- Requirements
  - Higher cadence
  - Improved photometry (reduced sky background)
  - Color information
- Space based
  - Modeled after *Kepler*
  - Prism



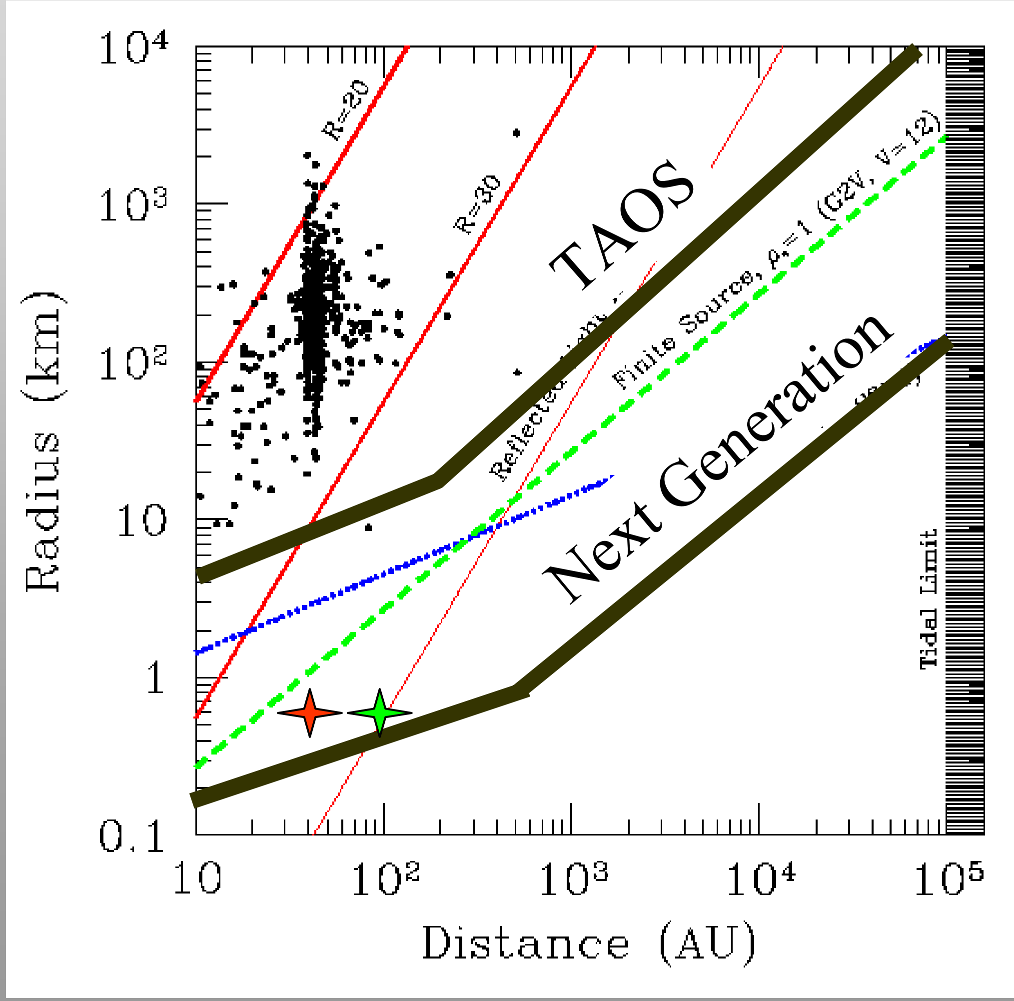
Occutation Surveys

Next Generation Survey



600m at 45 AU   600m at 100 AU

Occutation Surveys



Summary

- Many unanswered questions about the Kuiper belt.
- Outer solar system largely unexplored.
- Reflected light detections limited
- Occultation light curves subject to degeneracies
  - Additional parameters enable parameter measurement
  - High cadence and accurate photometry needed
- Binaries detected via occultations
- Occultation surveys are challenging
  - Short duration
  - Low event reate