Sedna and Beyond

Explorations of the Outer Solar System

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The Known Solar System

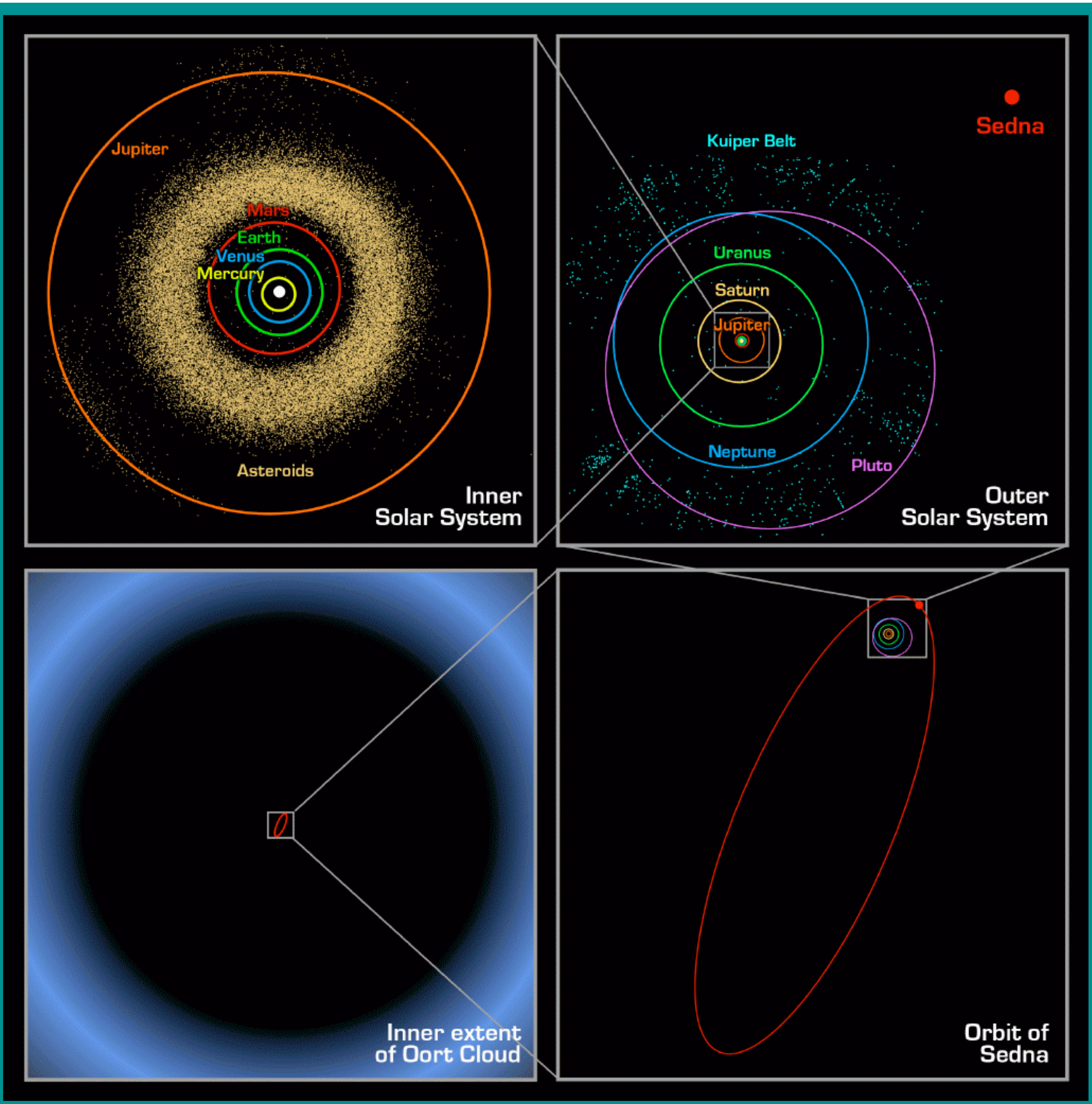
- How big is the solar system?

$$a_{tidal} \approx R_0 \left(\frac{M_{Sun}}{M_{Galaxy}} \right)^{1/3} \approx 200,000\,\text{AU}$$

- How big is the *observed* solar system?

Pluto, Kuiper Belt, $a_{KB} \approx 50\,\text{AU}$

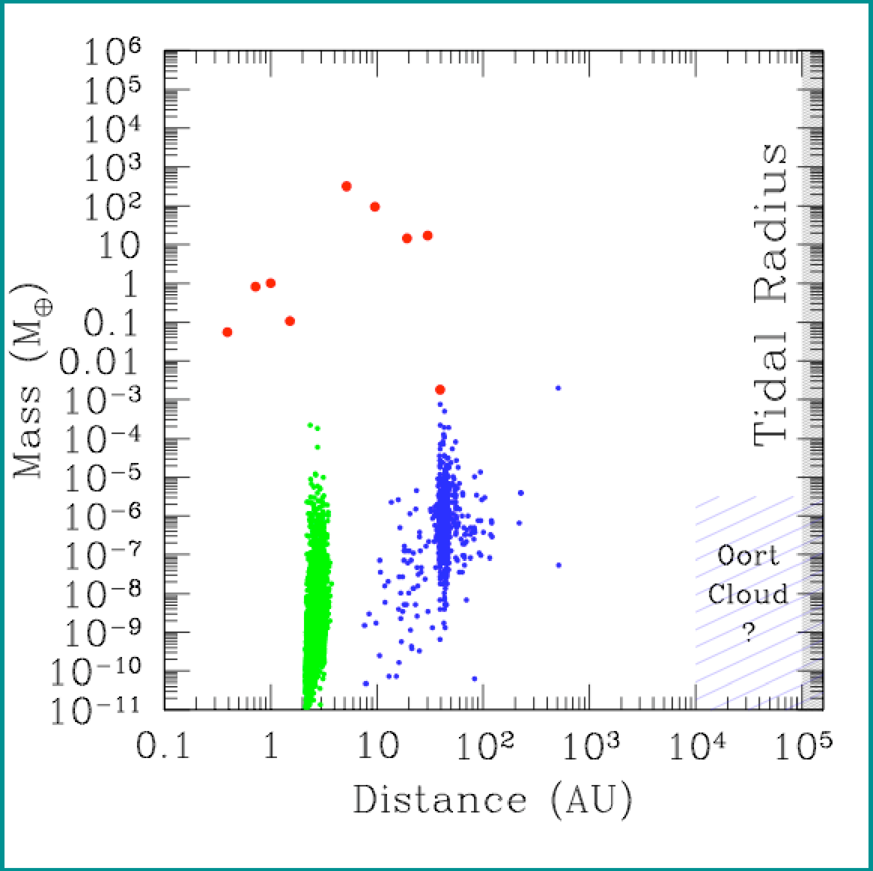
Sedna, $a_{Sedna} \approx 500\,\text{AU}$!



Jupiter
Mars
Earth
Venus
Mercury
Asteroids
Inner
Solar System
Sedna
Kuiper Belt
Uranus
Saturn
Jupiter
Neptune
Pluto
Outer
Solar System
Inner extent
of Oort Cloud
Orbit of
Sedna

The Known Solar System

- The observed portion of the solar system constitutes ~ one billionth of its entire volume!

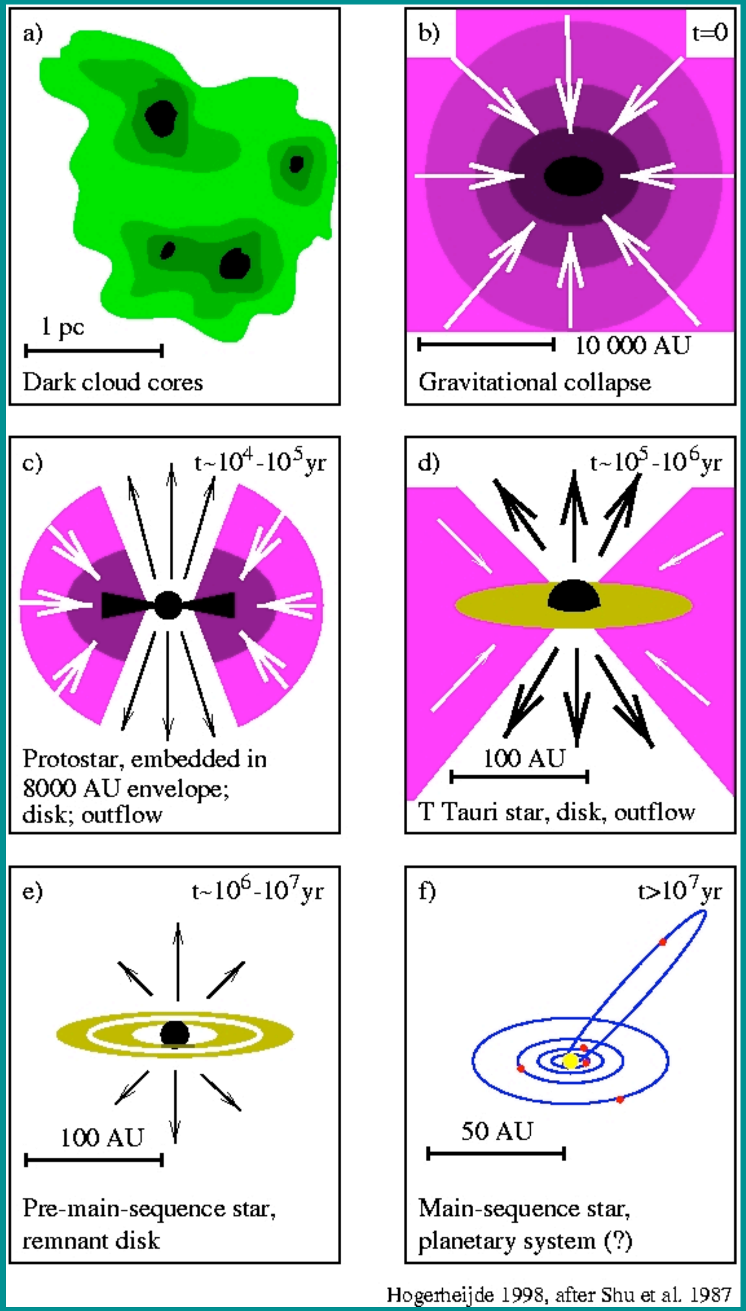


The Known Solar System

- What do we know about the solar system?
- Where did all this stuff come from?
- Why do we care?

Star Formation 101

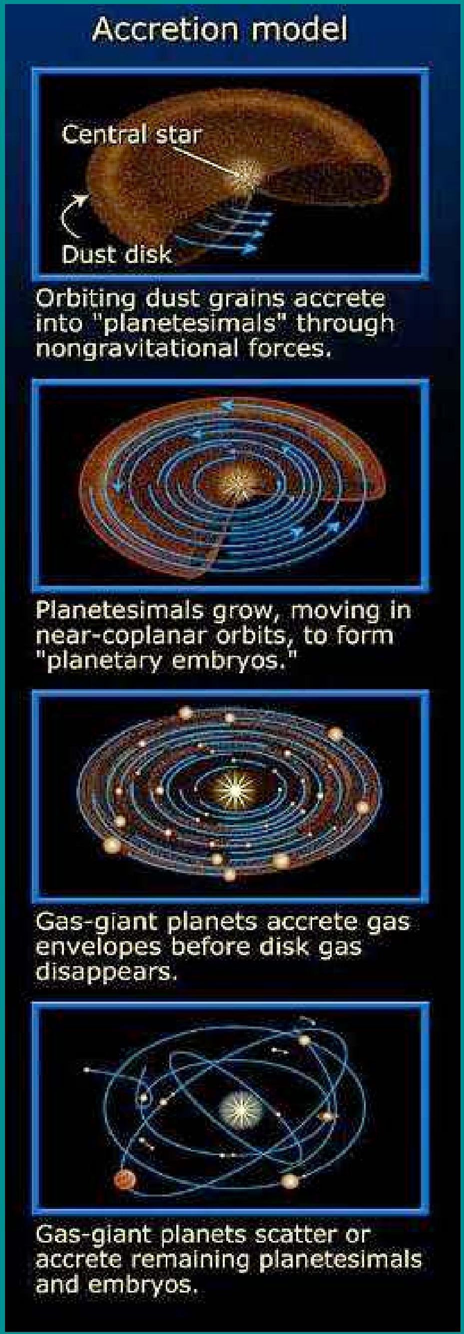
- Molecular Cloud
- Cores
- Collapse
- Ignition/Outflow
- Protoplanetary Disk
- Planetary System



Hogerheijde 1998

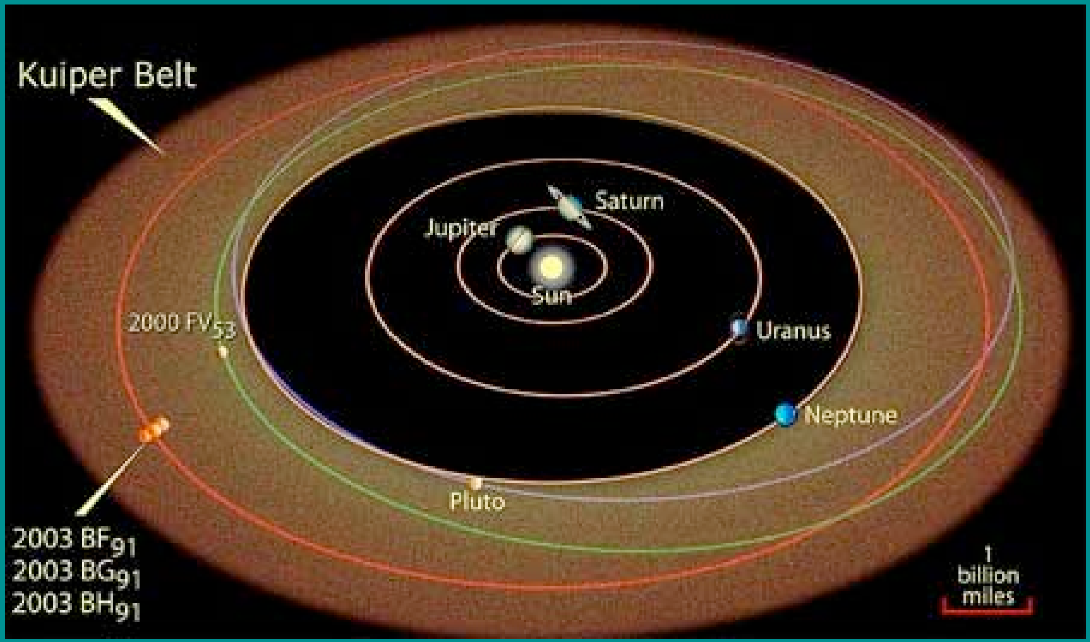
Planet Formation 101

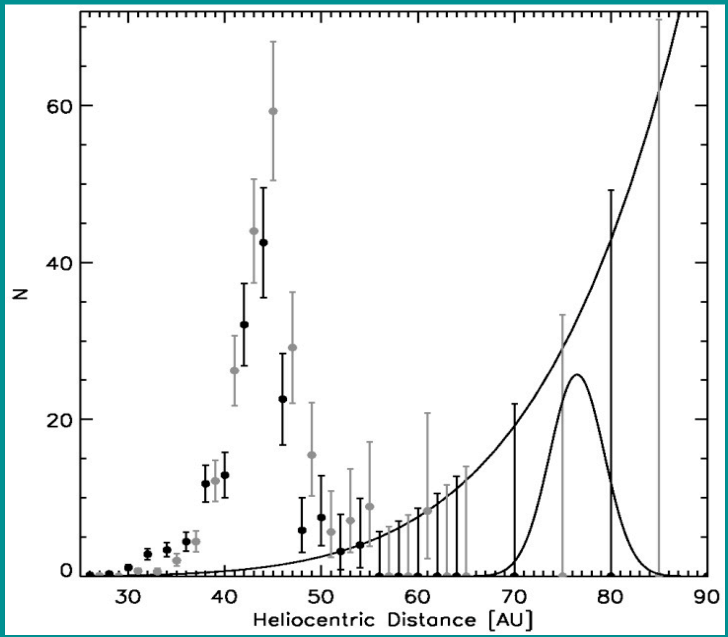
- Core-accretion Model
- Dust → Planetesimals (non G)
- Planetesimals → Protoplanets
- Protoplanets → Terrestrial Planets
  Inner Solar System (<3AU)
- Protoplanets → Gas Giants
  Outer Solar System (3AU-40AU)
- Protoplanets → Planetoids
  Distant Solar System (> 40AU)



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.

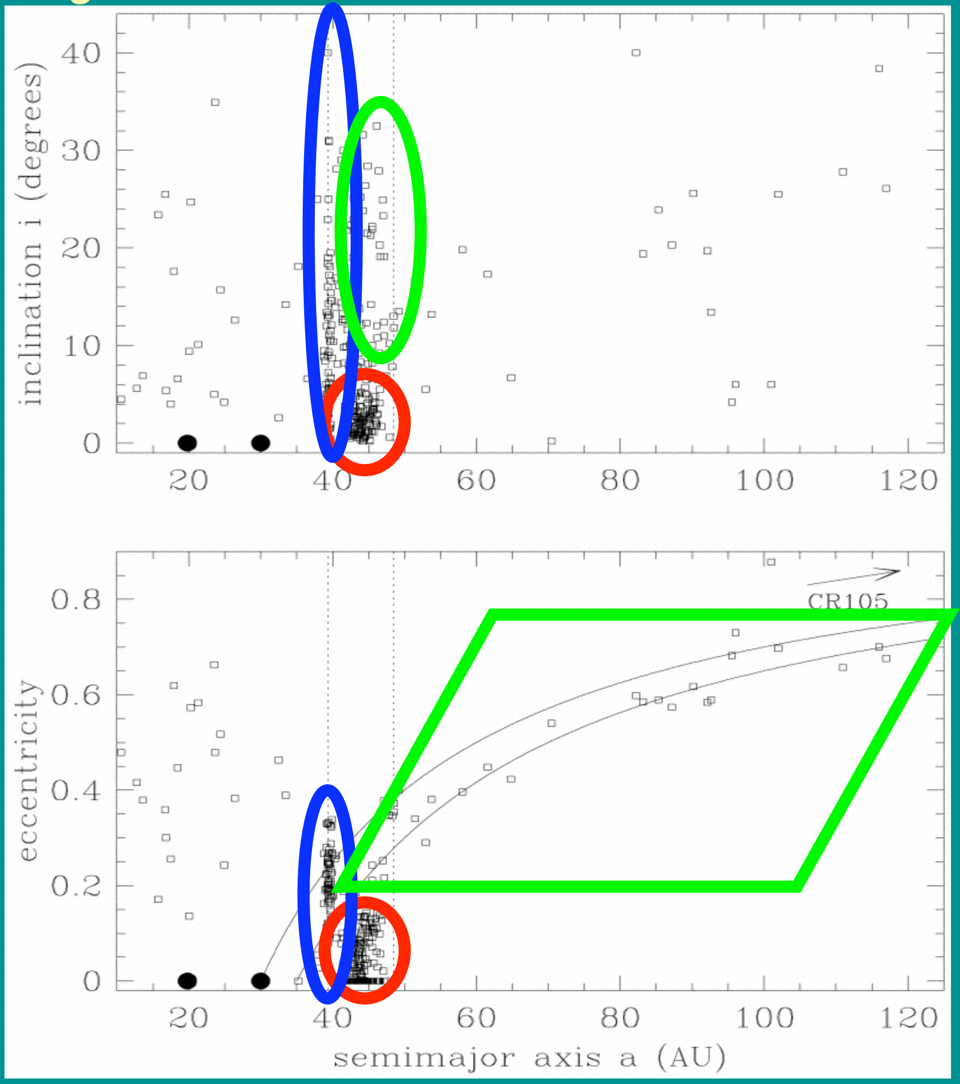




(Trujillo & Brown 2001)

The Kuiper Belt – Dynamical Classes

- Classical
- Resonant
- Scattered
- Extended Scattered??



(Gladman et al. 2001)

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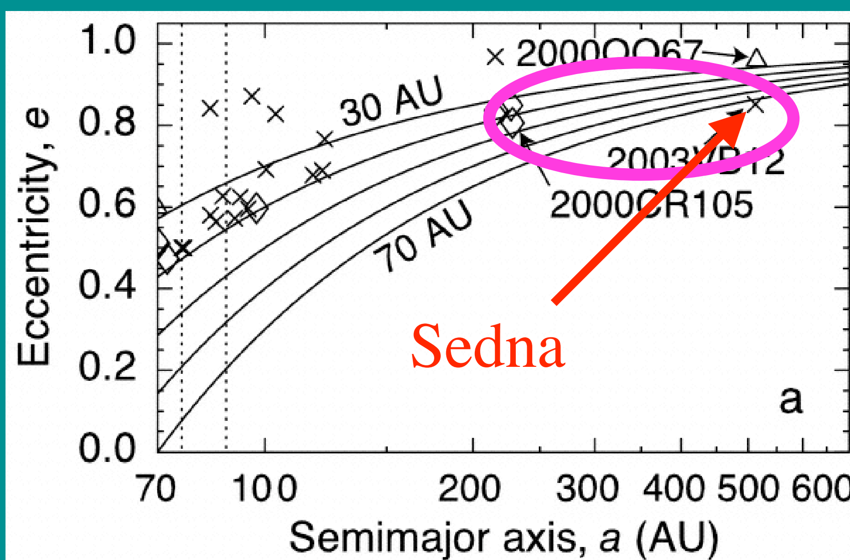
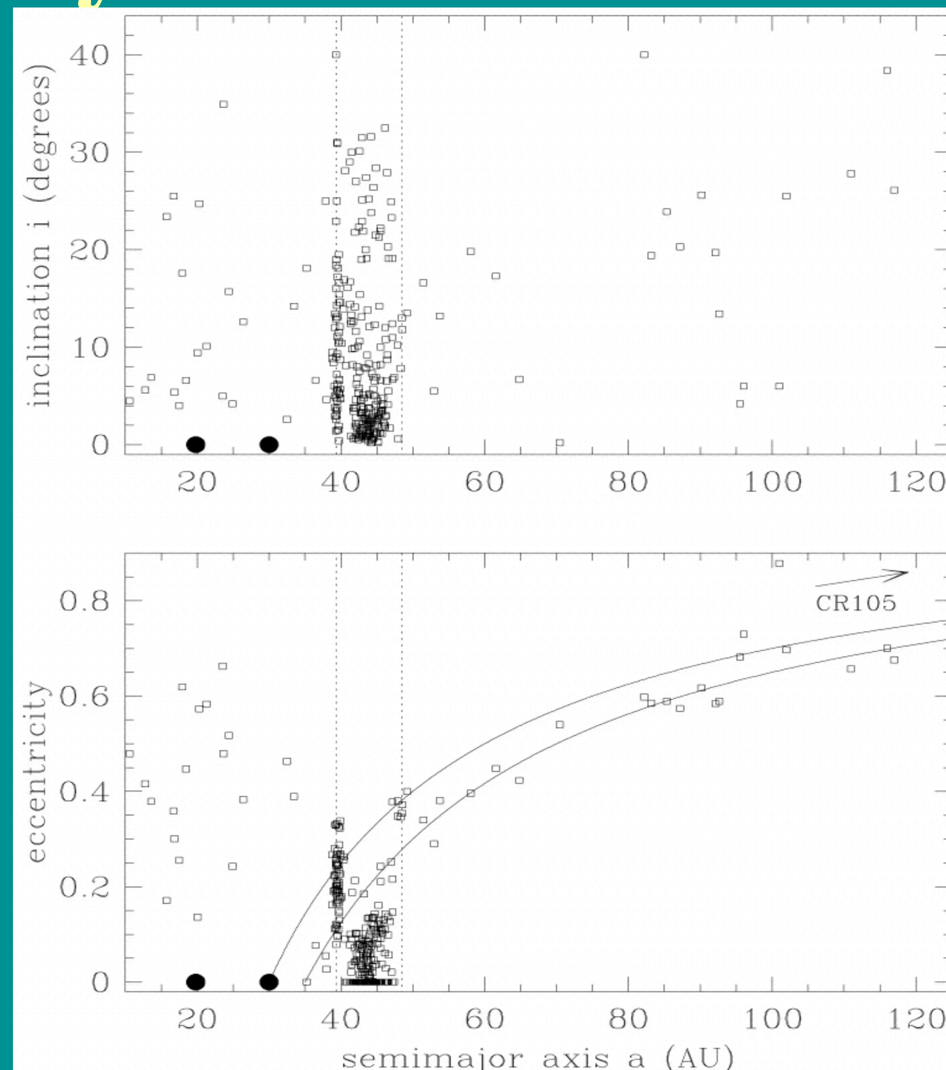


(Elliot et al. 2005)



(Gladman et al. 2001)

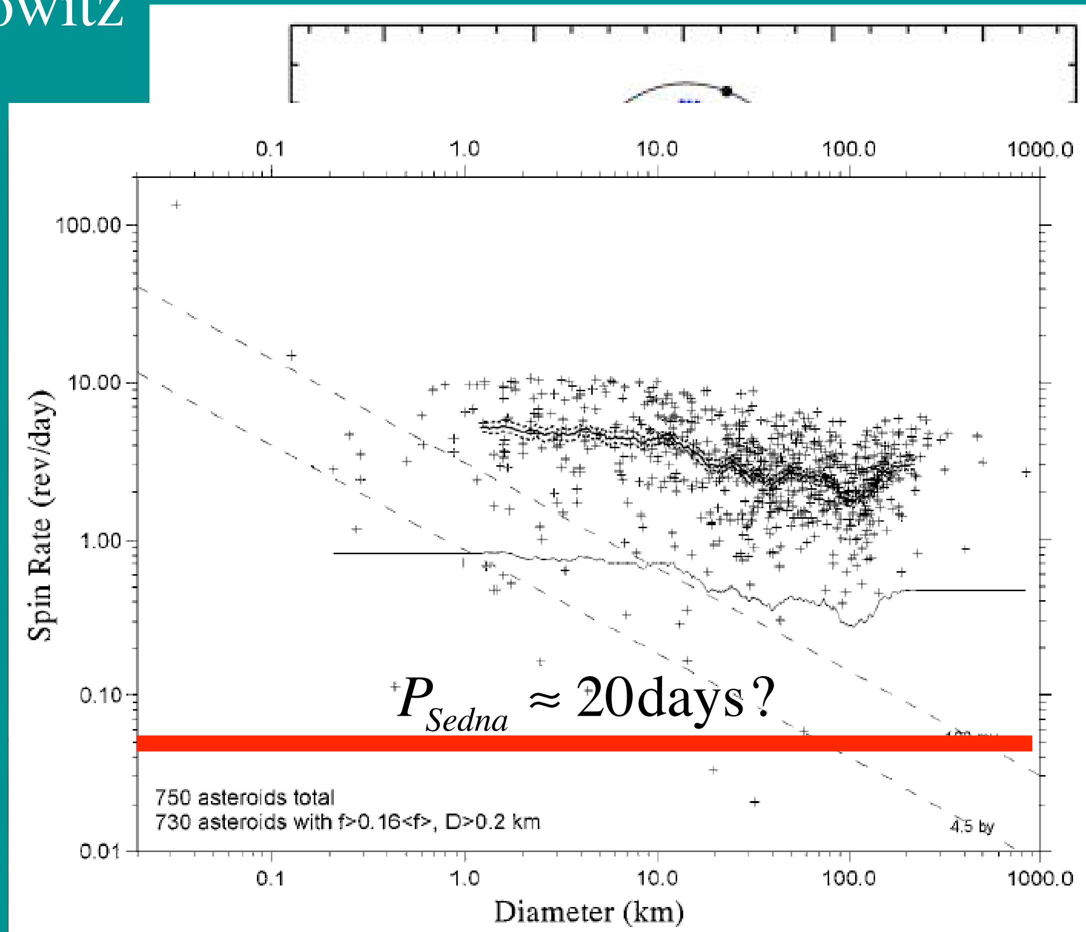
Sedna — The Last Outpost

Discovered in 2003

- by Brown, Trujillo, Rabinowitz

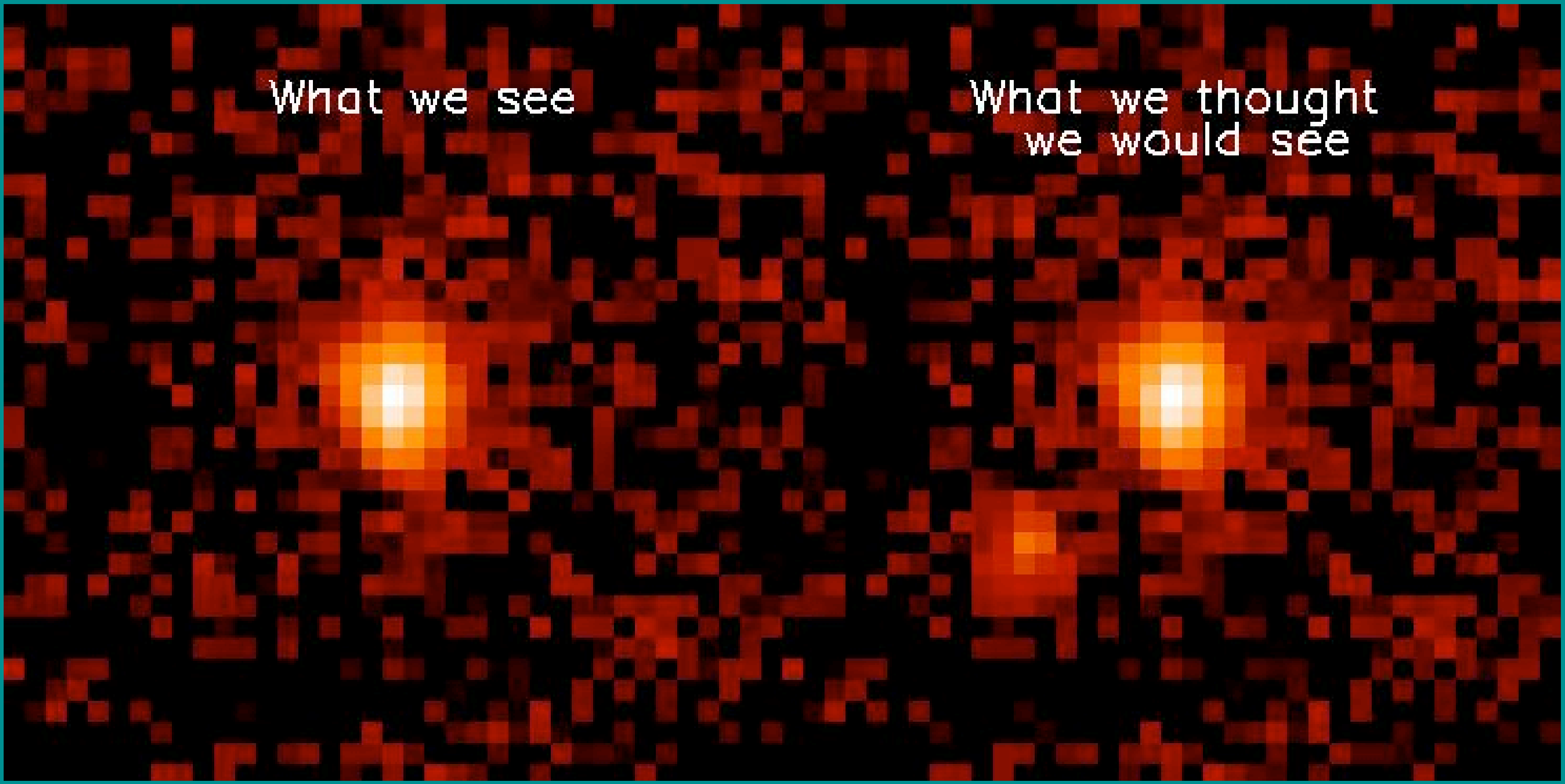
Usual Properties

- Orbit
  - Semimajor axis a ~ 500 AU
  - Perihelion q ~ 80 AU
- Size
  - Diameter ~ 1500 km
- Color
  - Very Red
- Slowly Rotating?
  - Period P ~ 20 days?
  - Companion?



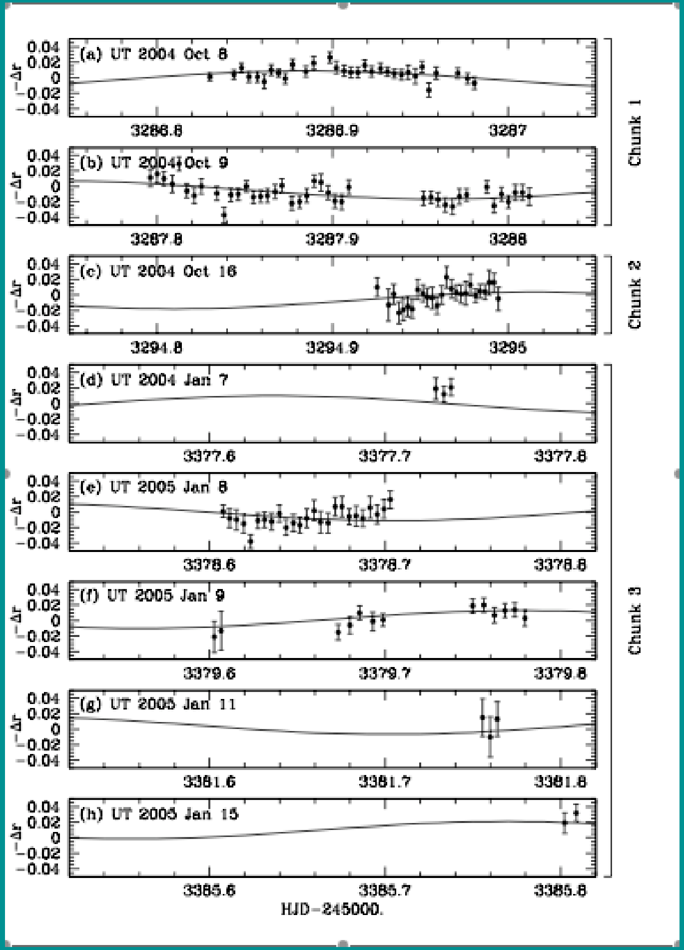
Sedna – A Binary? No!

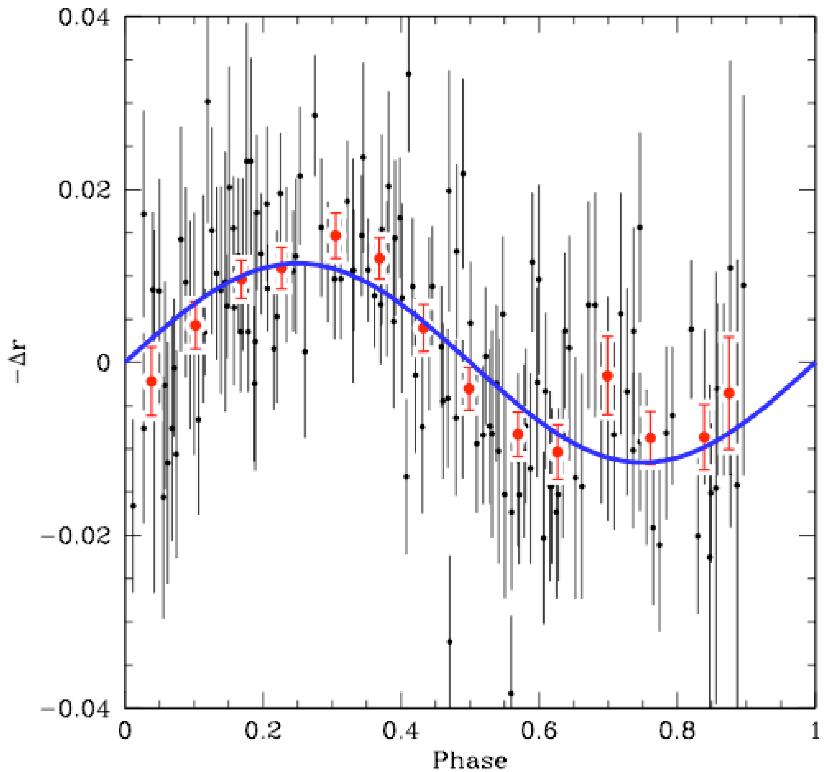
- At least 5%-10% of KBOs in binaries
- What about Sedna?



Sedna – A Better Light Curve

- Used the 6.5m MMT telescope
- Kris Stanek, Matt Holman, Joel Hartman, Brian McLeod

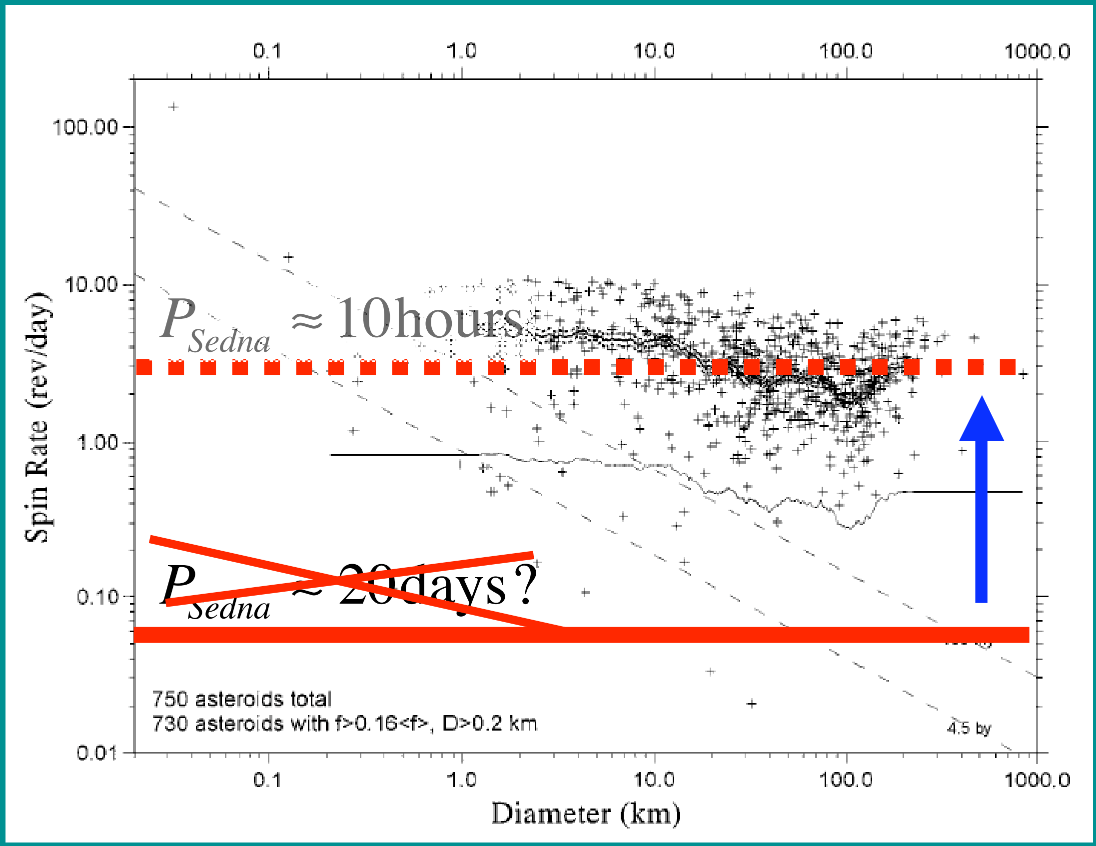




$P_{Sedna} \approx 10\text{hours}$

Sedna – A Better Light Curve

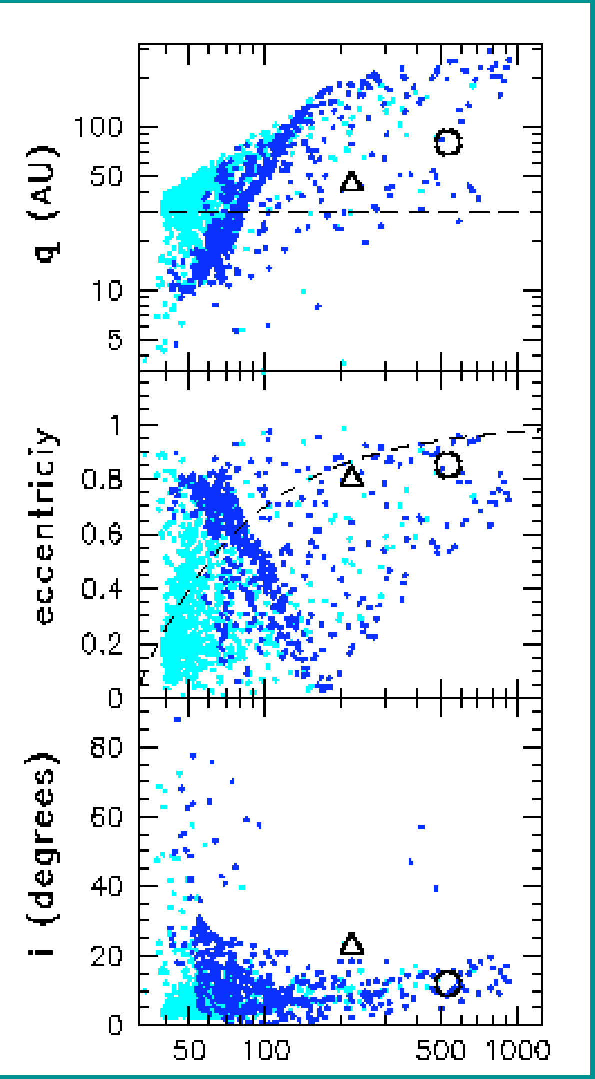
- Used the 6.5m MMT telescope
- Kris Stanek, Matt Holman, Joel Hartman, Brian McLeod
- Normal!



Sedna – Open Questions

Extended Scattered Disk?

- How did it get there?
  - Passing Star?
  - Rogue Planet?
- How many more are out there?
  - Could have only found Sedna over ~1% of its orbit



semimajor axis (AU)

(Kenyon & Bromley 2005)

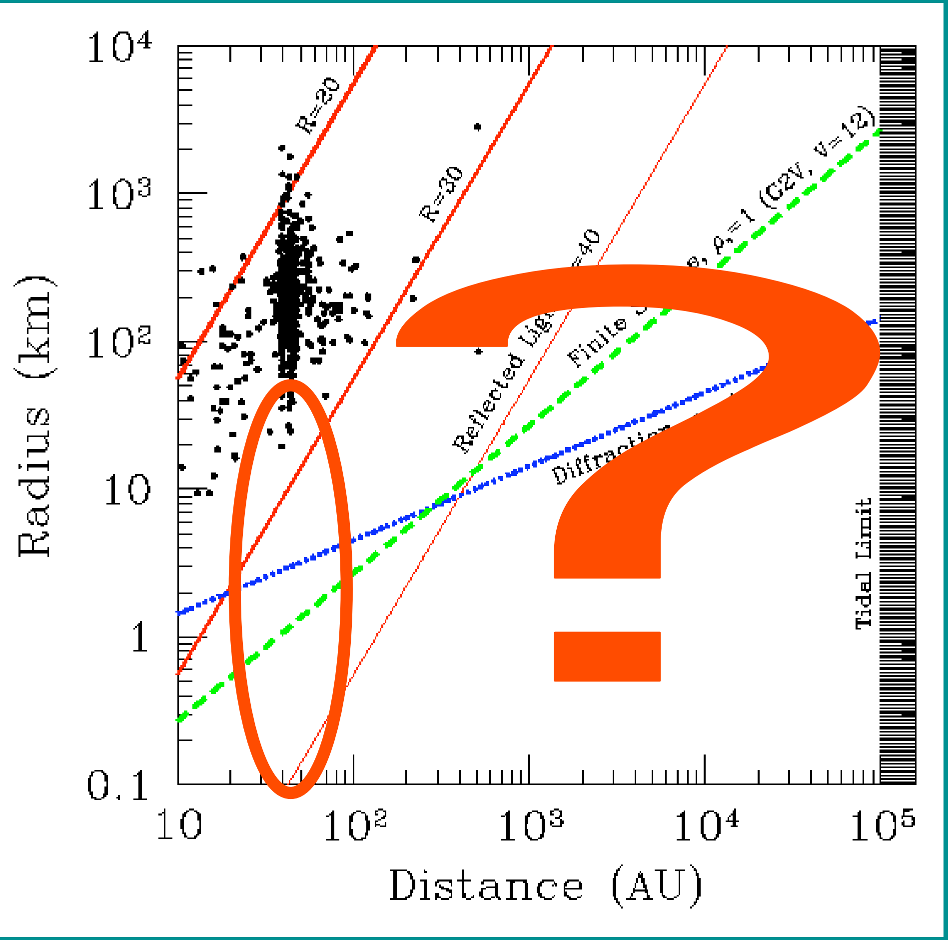
Limitations of Direct Measurements

- Strong scaling with size and distance

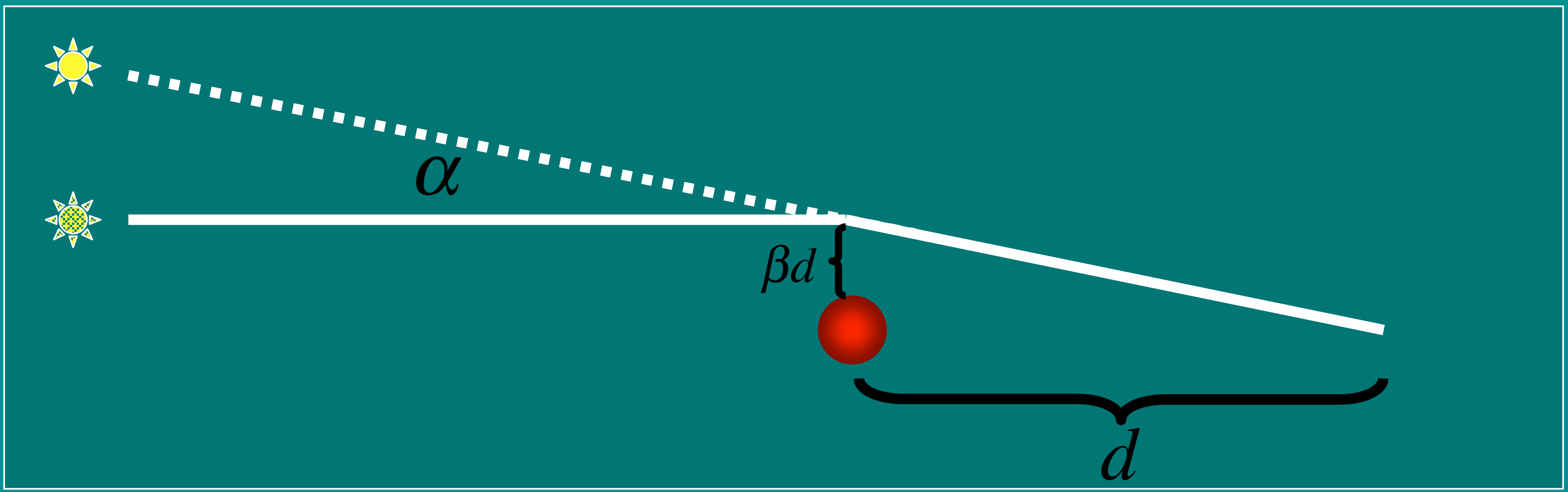
$$\text{Flux} \propto R^2 d^{-4}$$

Detection without Light?

- Gravitational Lensing
  - Gaudi & Bloom (2005)
- Occultations
  - Bailey (1976)
  - Dyson (1992)
  - Brown & Webster (1997)
  - Roques & Moncuqeut (2000)

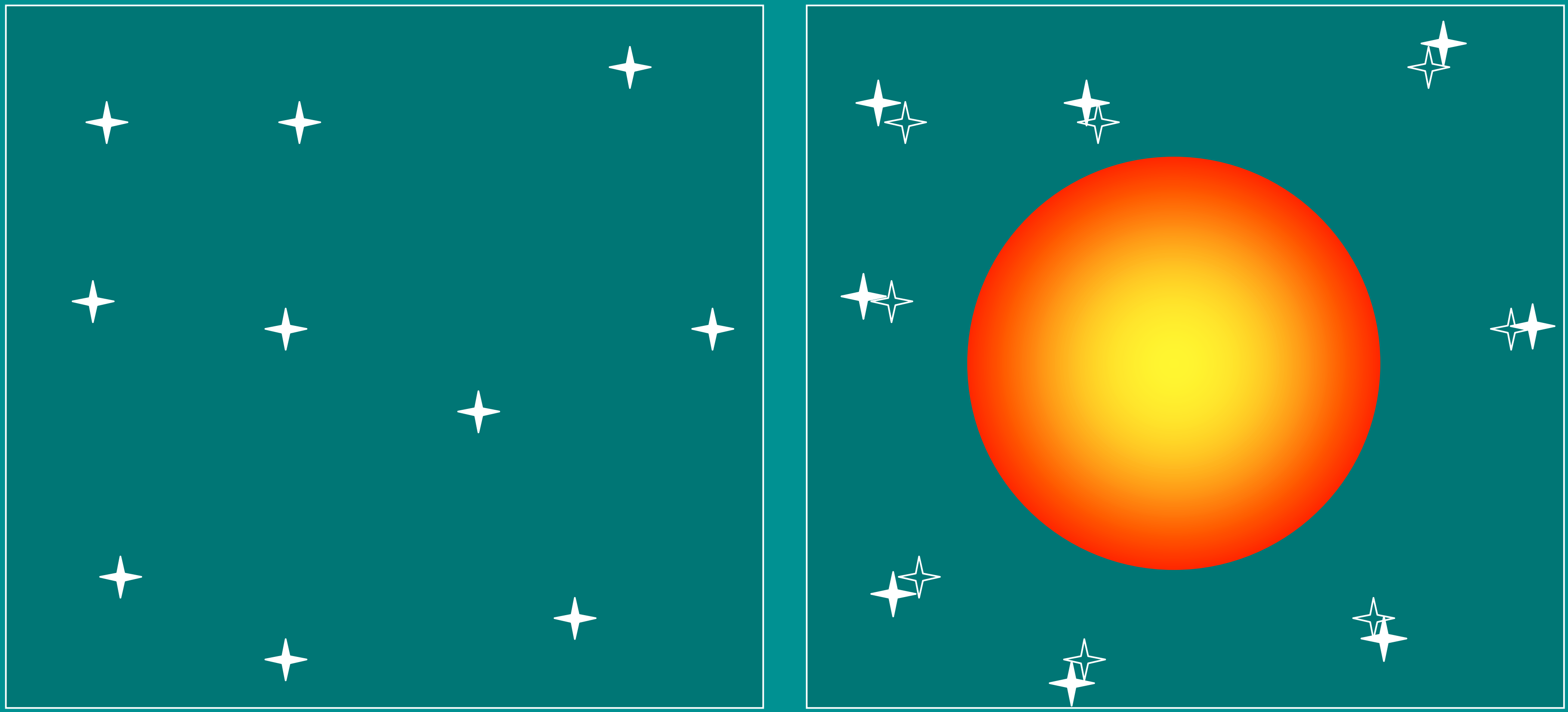


Gravitational Lensing



$$\alpha = \frac{4GM}{\beta d c^2}$$

Gravitational Lensing



$$\alpha = 50\,\mu\text{as}\left(\frac{M}{M_\oplus}\right)\left(\frac{d}{100\,\text{AU}}\right)^{-1}\left(\frac{\beta}{1''}\right)^{-1}$$

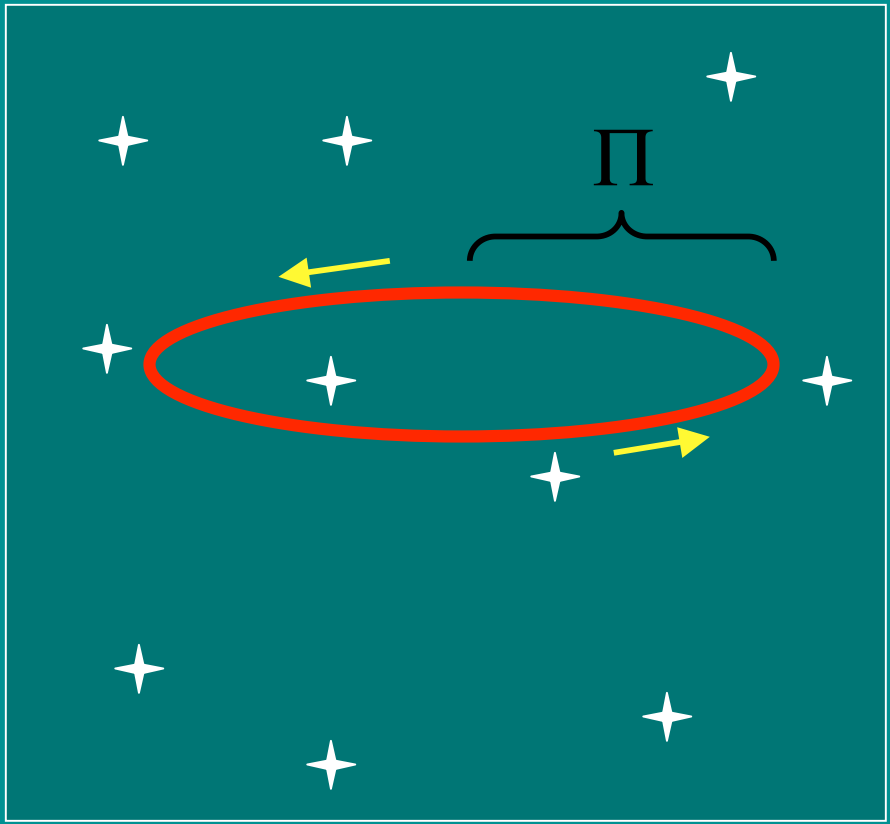
Gravitational Lensing

Requirements

- Moving object
- Dense Star Field
  - Faint Stars
- Precise Astrometry
- Time Series

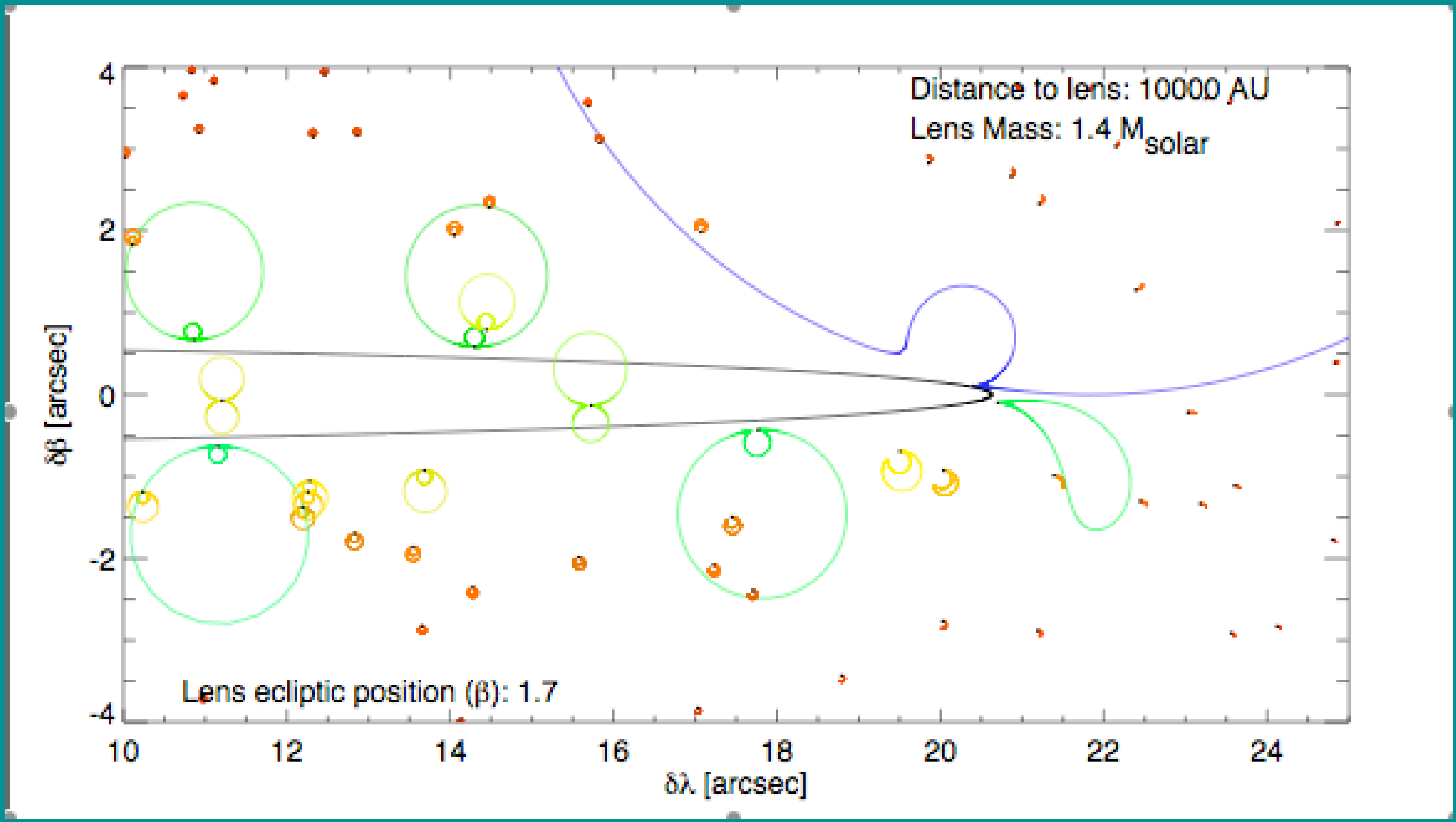
Discovery

- All-Sky Synoptic Survey



$$\Pi = 30'\left(\frac{d}{100\,\mathrm{AU}}\right)^{-1}$$

Gravitational Lensing



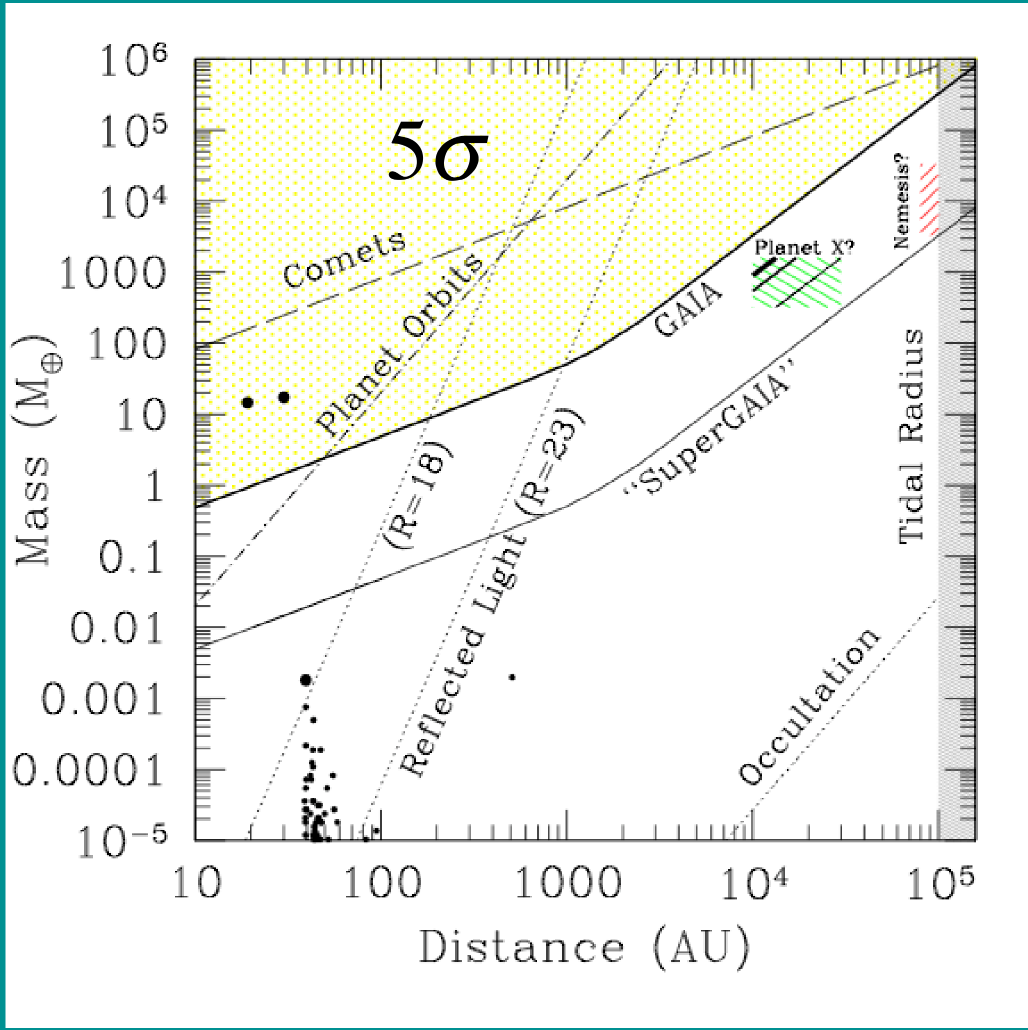
(Gaudi & Bloom 2005)

Gravitational Lensing

(Gaudi & Bloom 2005)

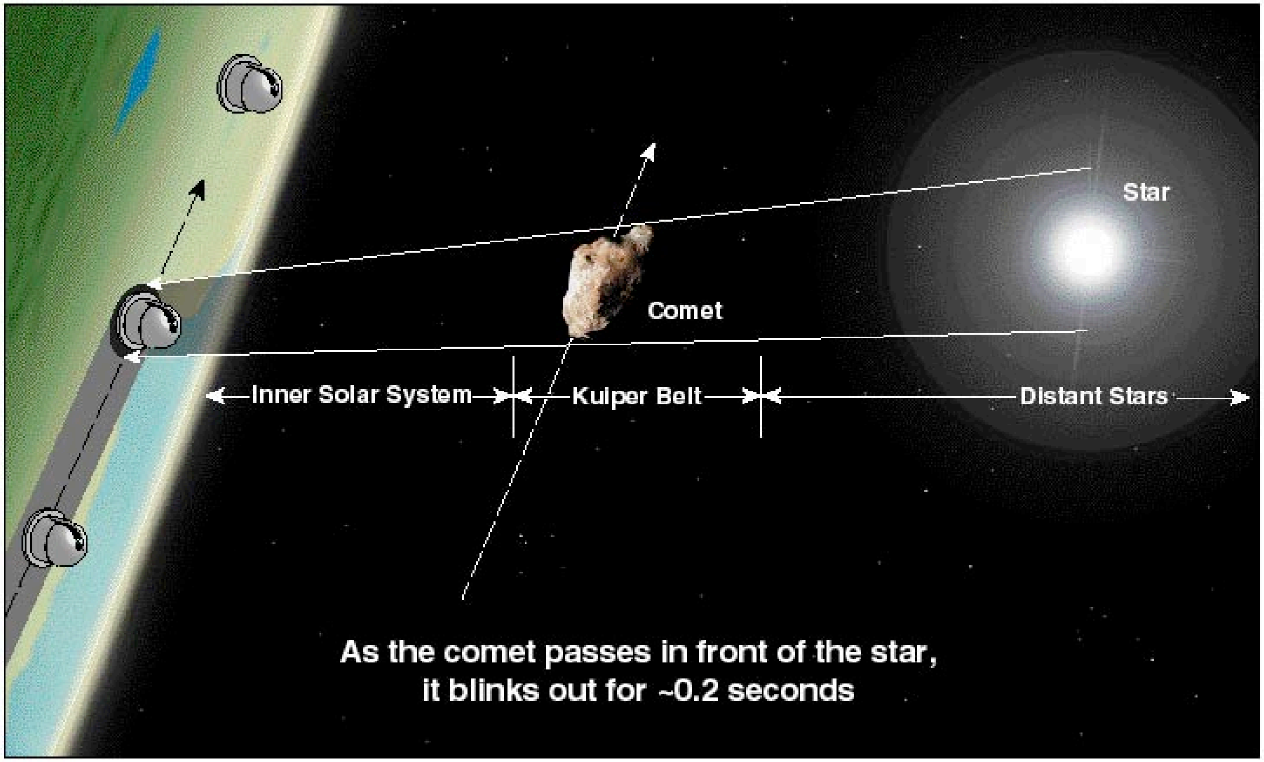
GAIA

- All-Sky Astrometric Mapper
- All stars down to V~20 (one billion stars!)
- Astrometric accuracy
  - Bright Stars: ~30 μas
  - Faint Stars: ~1400 μas
- Measure each star ~50 times



Occultations

Counting Kuiper Belt objects using occultations



36723-K.Belt-001

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

$$v = v_{\oplus}\left(\cos\varphi - \sqrt{\frac{\text{AU}}{d}}\right) \approx 27\text{km s}^{-1} \text{ at opp.}$$

  - 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

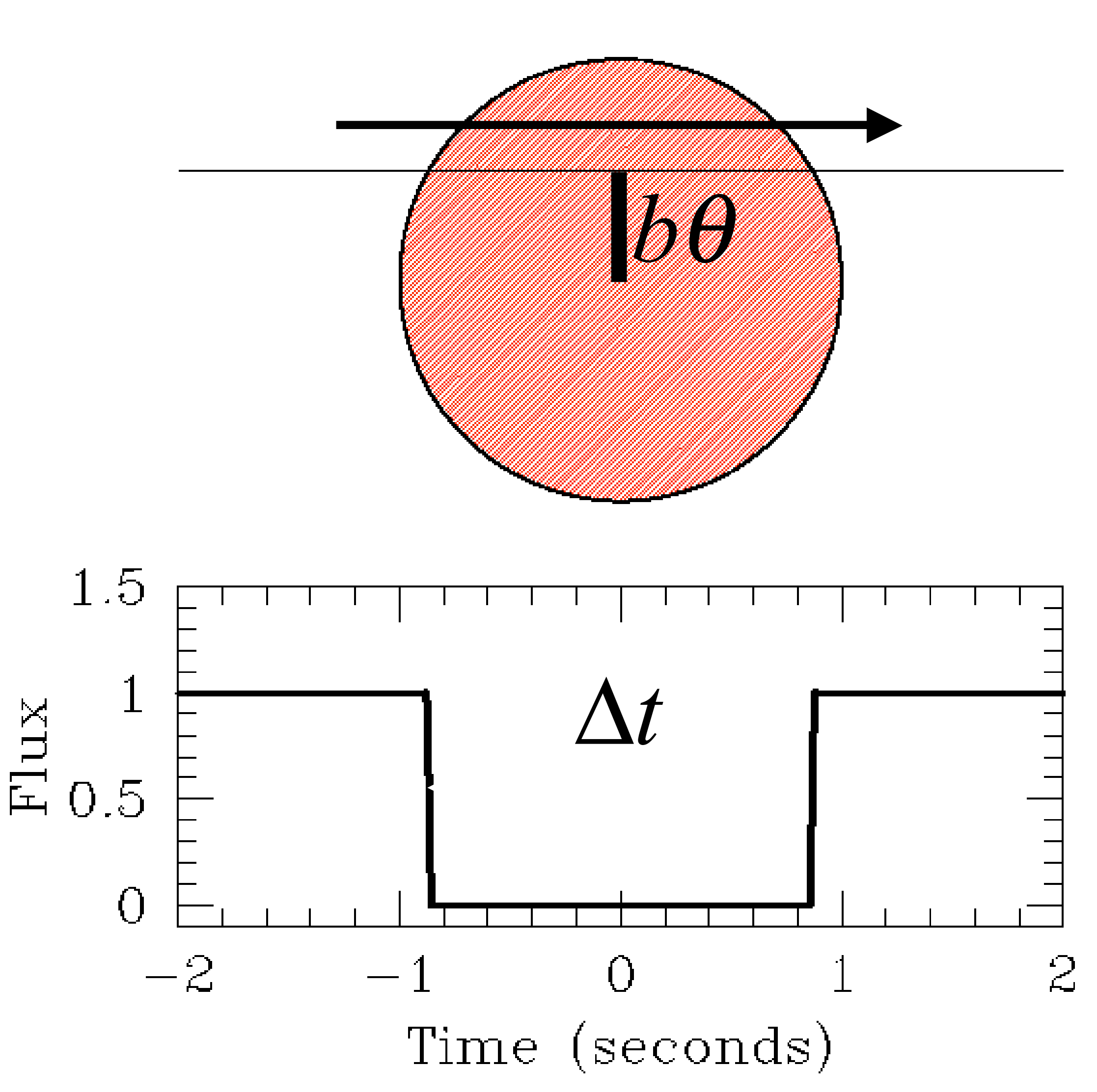
- Observables
  - Duration Δt

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

  - 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



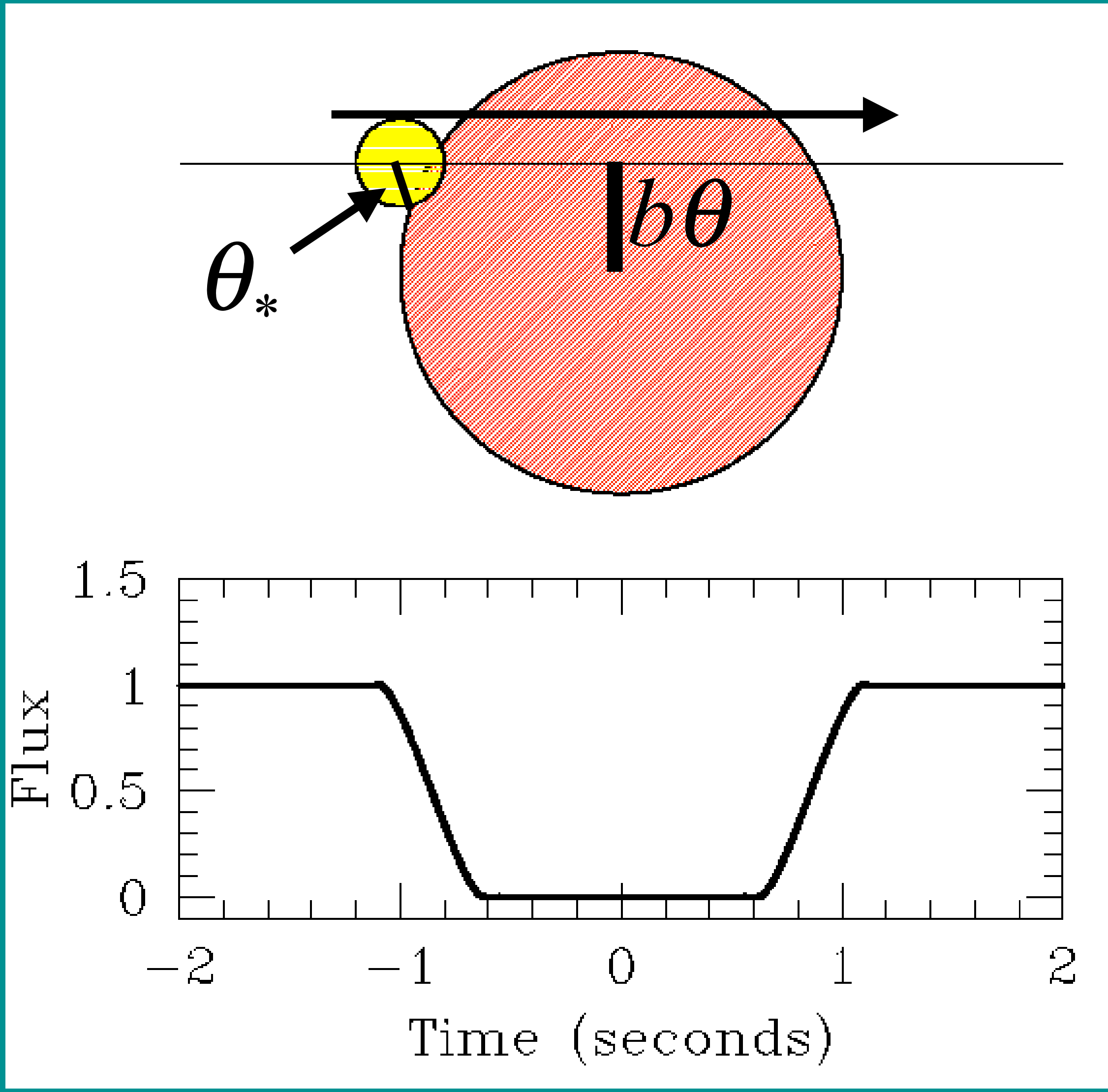
Principles of Occultations

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

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

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

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



Principles of Occultations

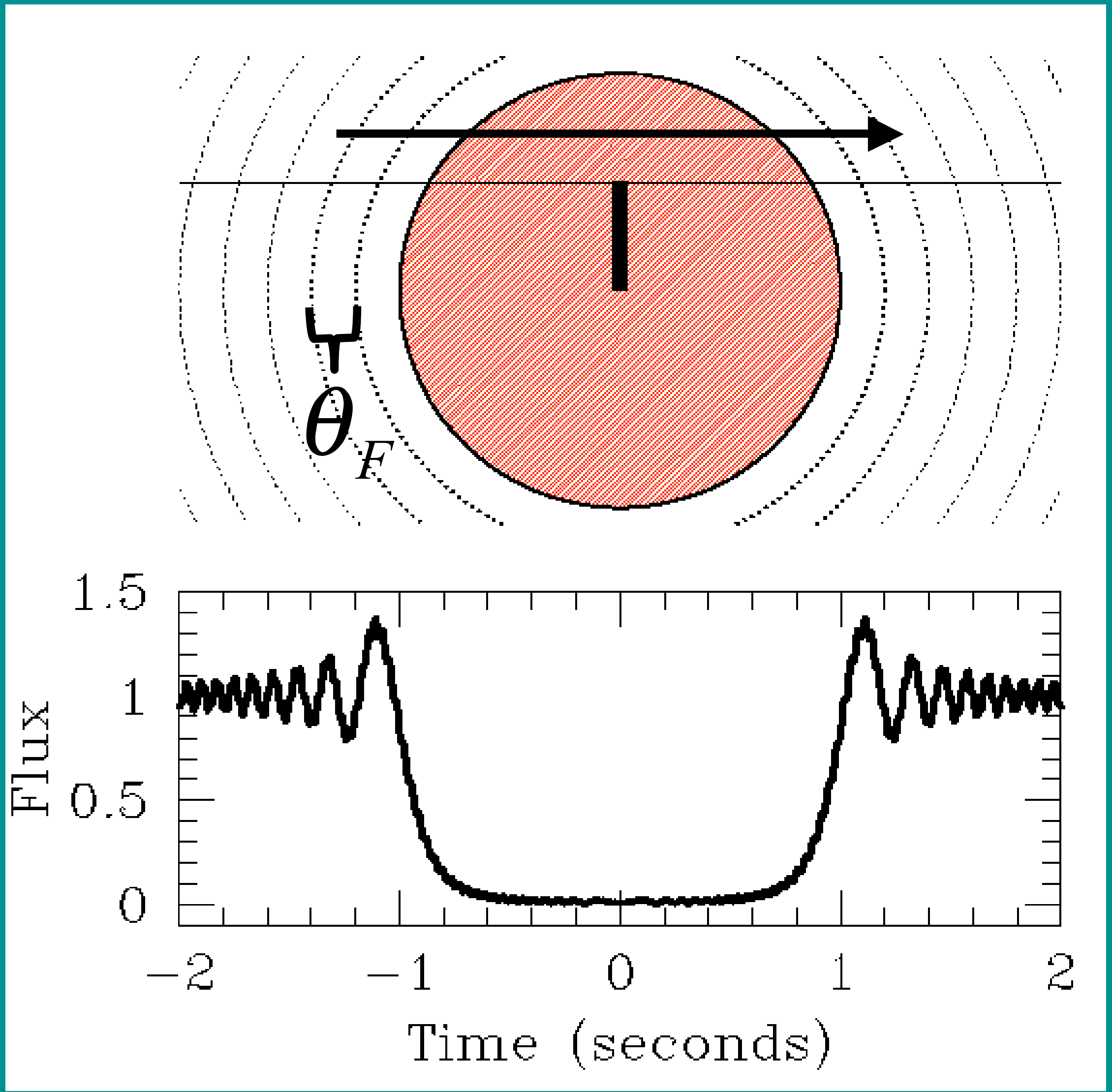
- Observables
  - Fringe Spacing
  - Dimensionless Fresnel angle

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

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

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

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



Principles of Occultations

- Observables

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

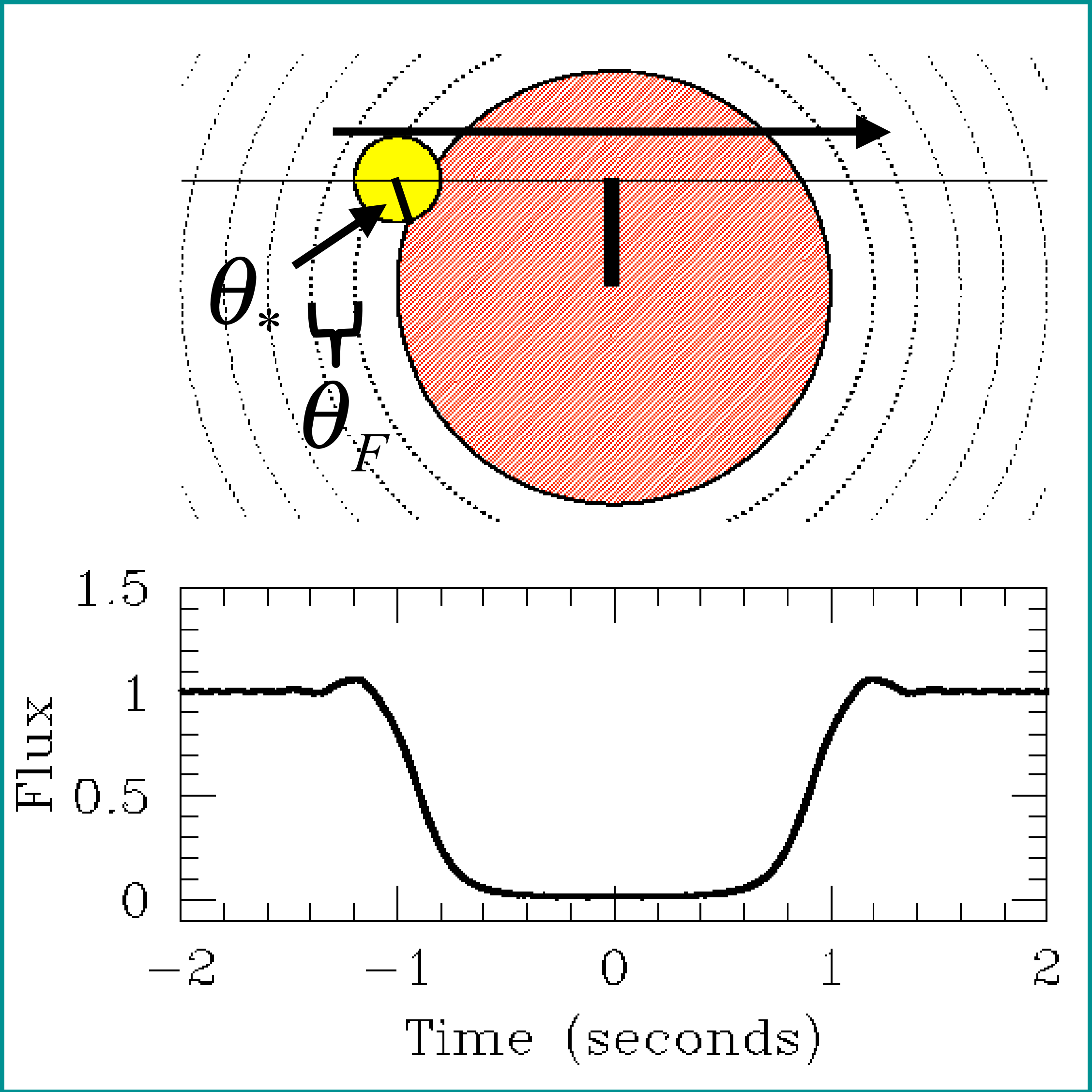
- Parameters

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

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

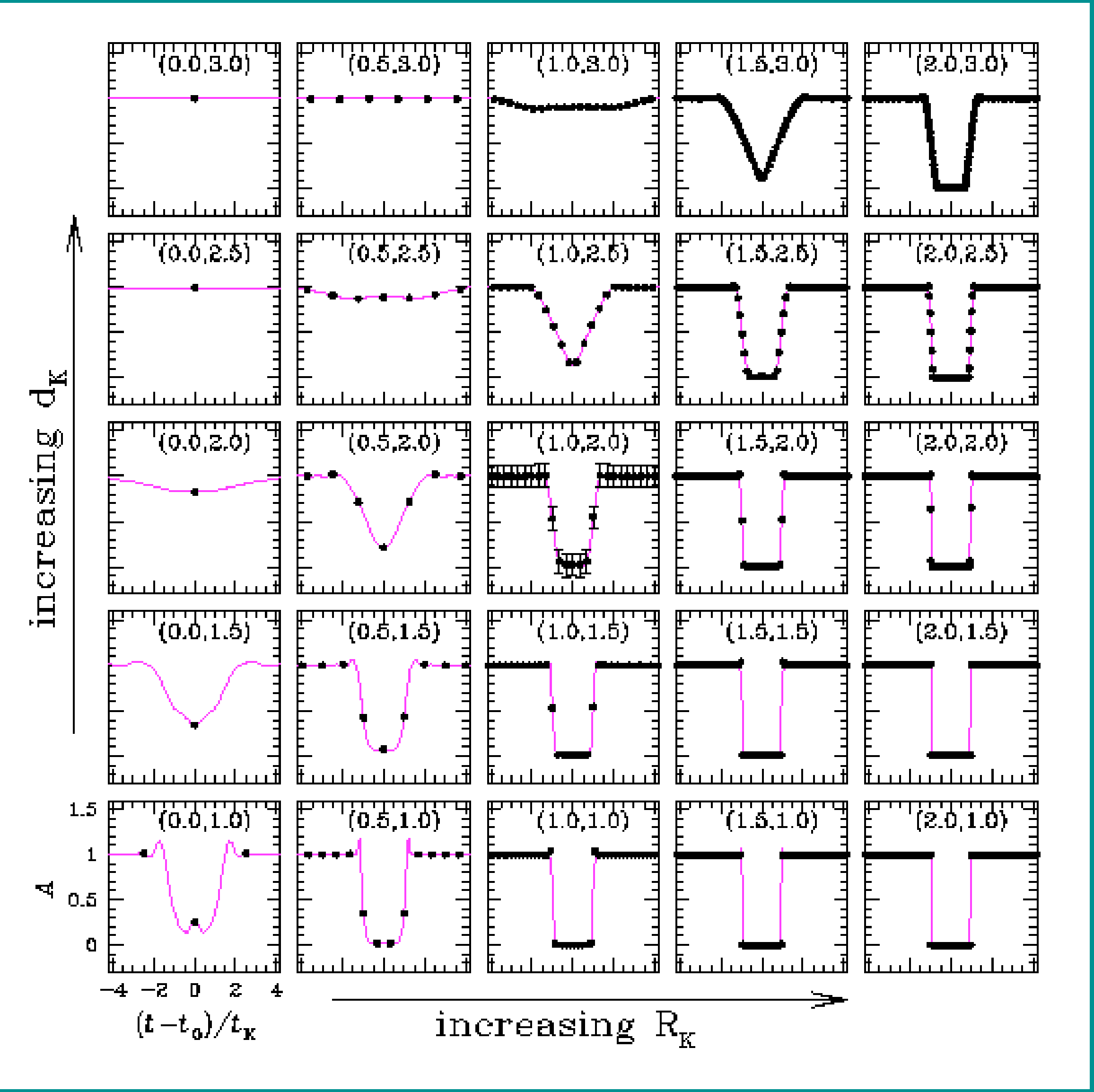
$$v = \frac{\lambda}{2\theta_*}\frac{\rho_*}{\rho_F^2}\frac{1}{t_K}$$

$$\longrightarrow R, d, v$$



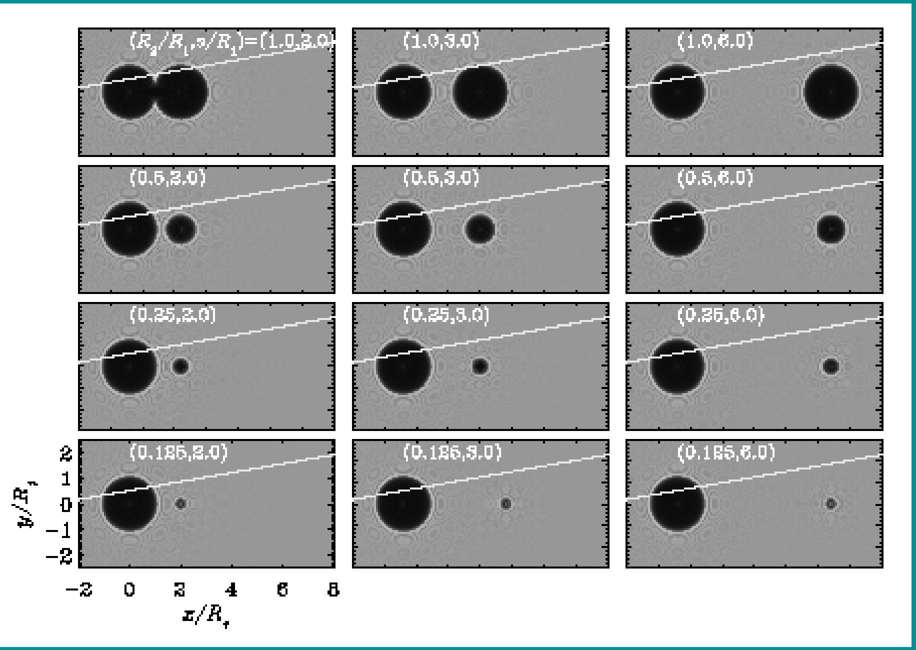
Example Lightcurves

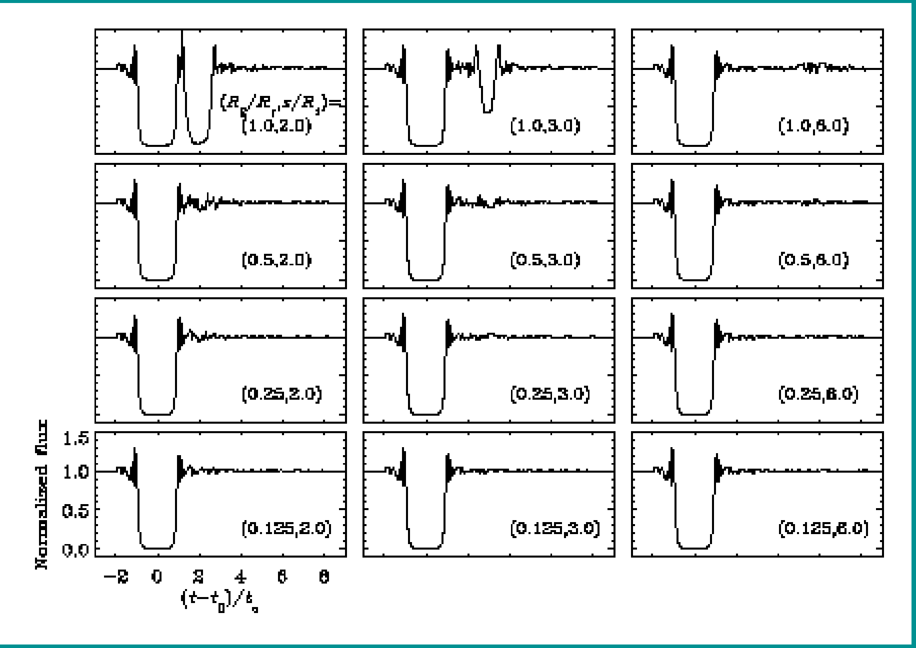
- Light curves
  - 10% errors (V=14)
  - 5 Hz sampling



Occutations by Binaries

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





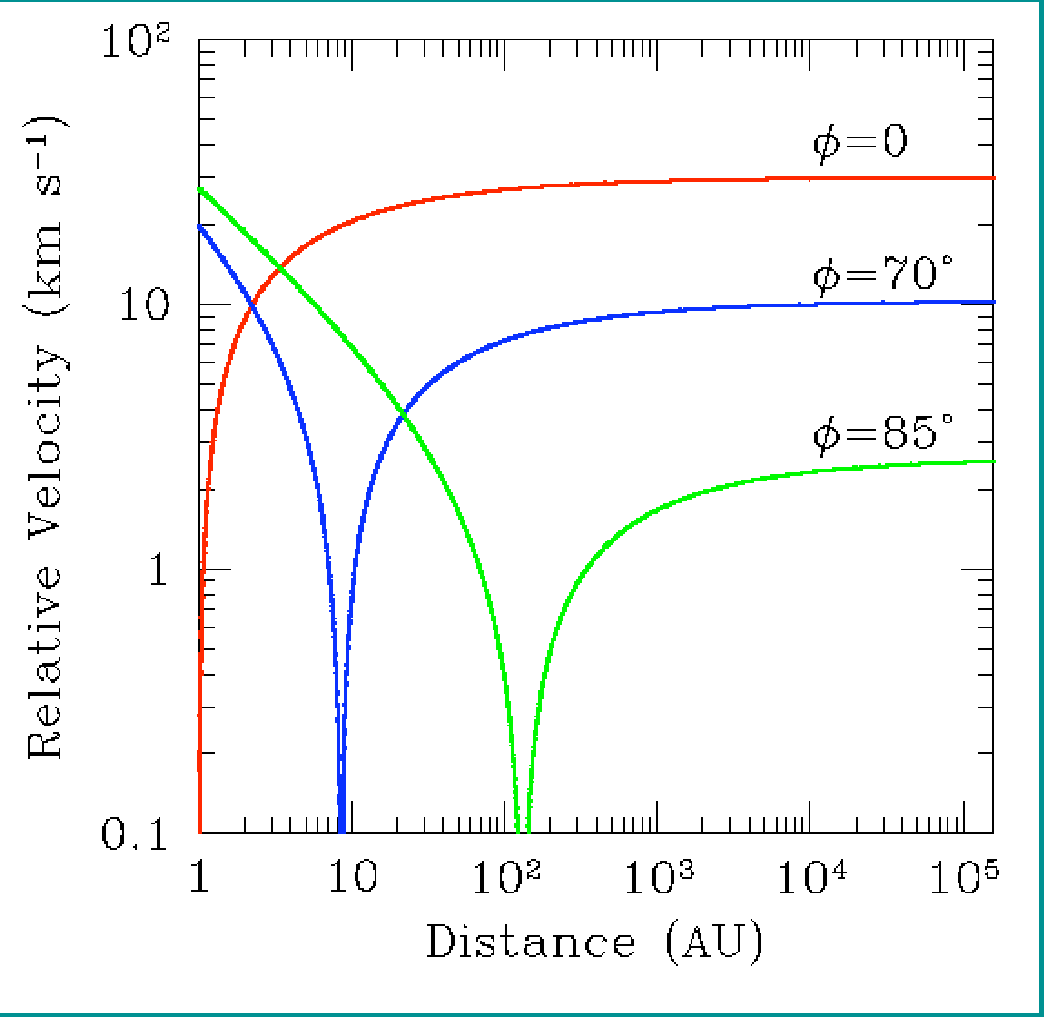
Occutation Surveys

- 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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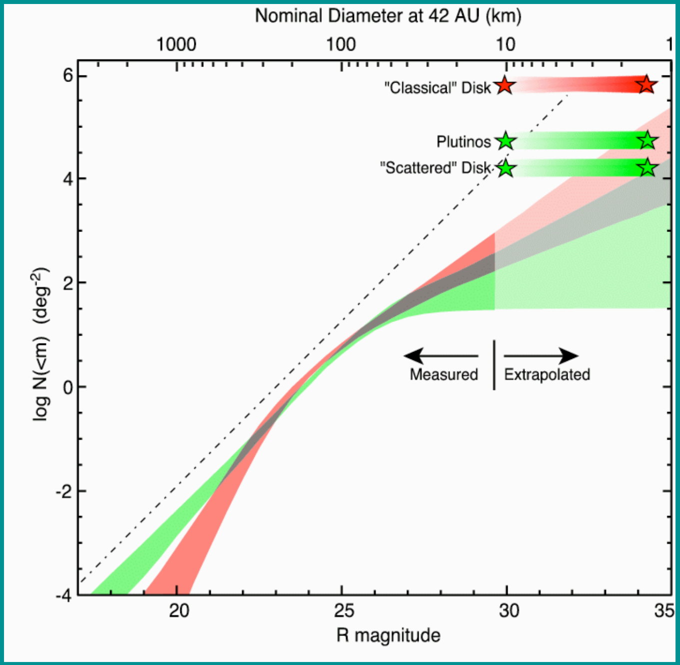
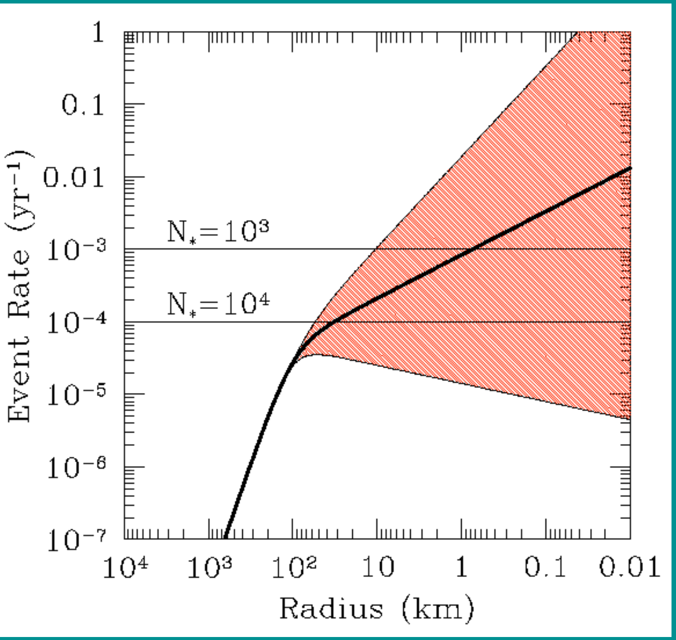
  - Low event rate

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

  - Monitor >1000 stars

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





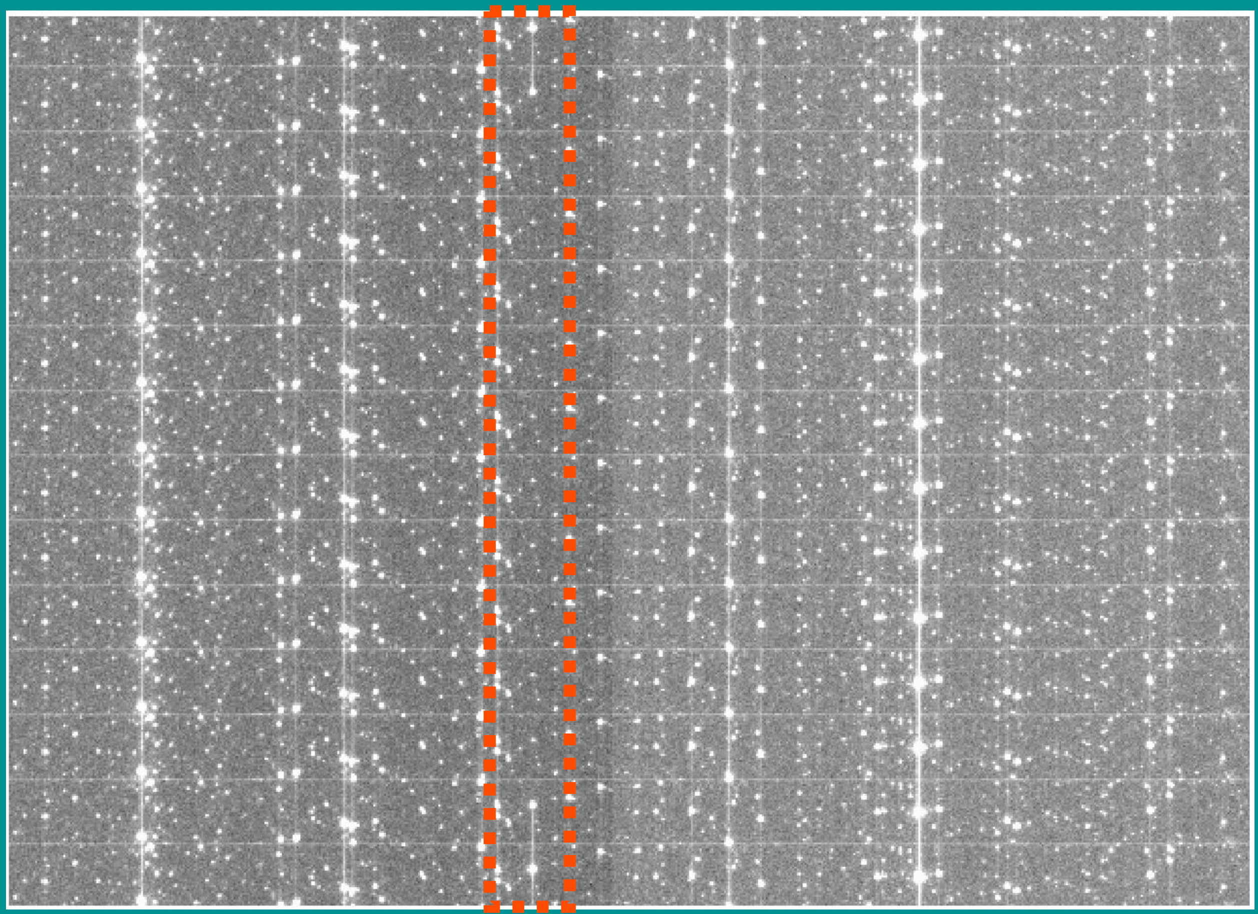
Occutation Surveys

Taiwanese-American Occultation Survey (TAOS); **Charles Alcock, PI**

- 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

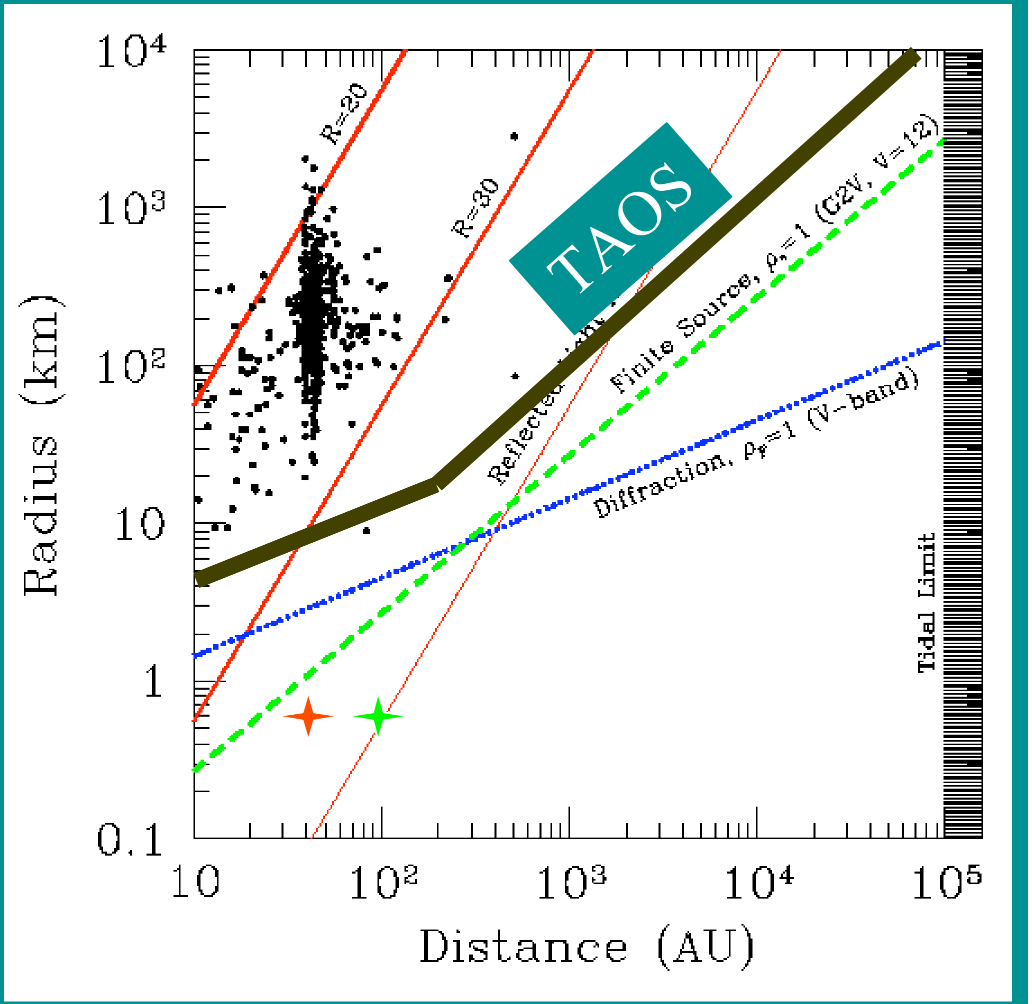
- Shutterless "Zipper" mode



Occutation Surveys

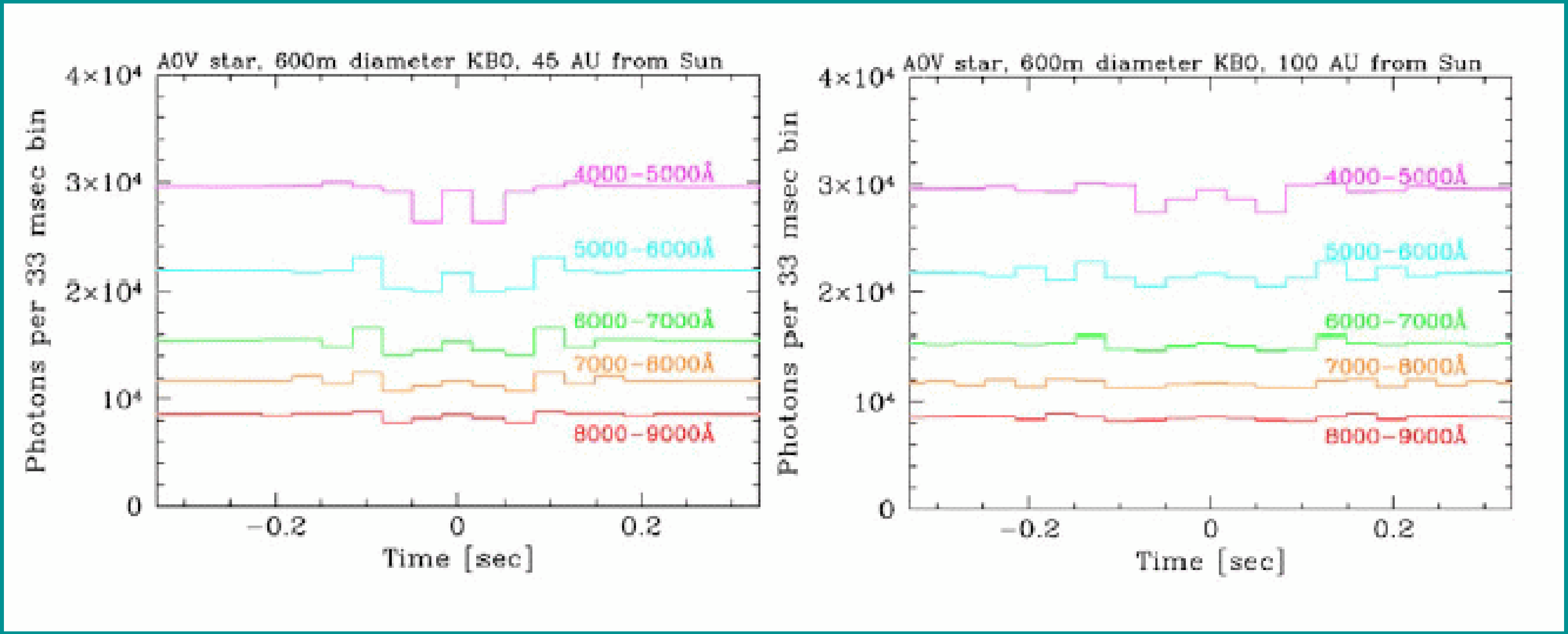
Next Generation Survey

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



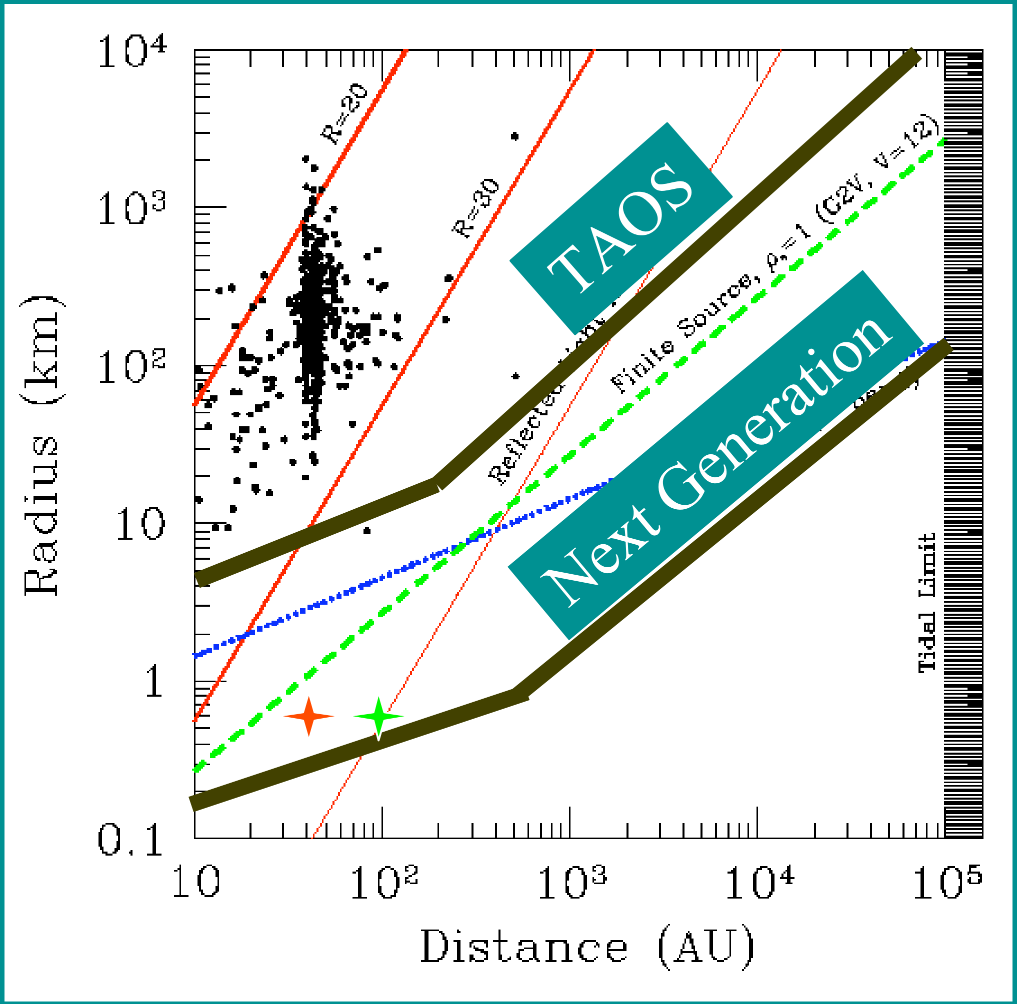
Occutation Surveys

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.
- Sedna is weird in many ways, but not its rotation period.
- Reflected light detections limited.
- Can detect dim or dark but massive objects with GAIA.
- Occultation can be used to detect distant, small objects.
  - Light curves subject to degeneracies
  - Additional parameters enable parameter measurement
  - High cadence and accurate photometry needed
- Binaries can be detected via occultations
- Occultation surveys are challenging
  - Short duration
  - Low event reate