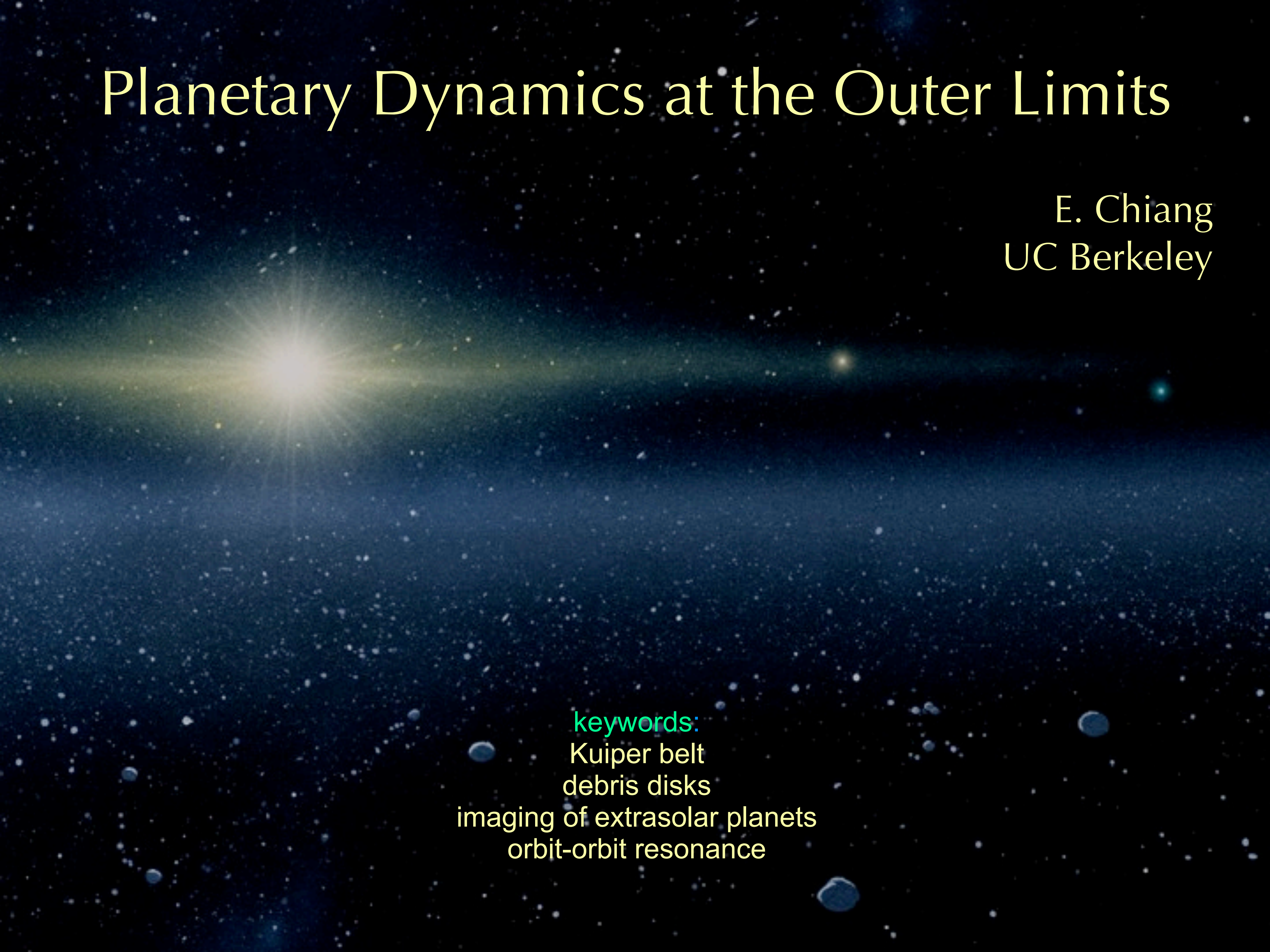
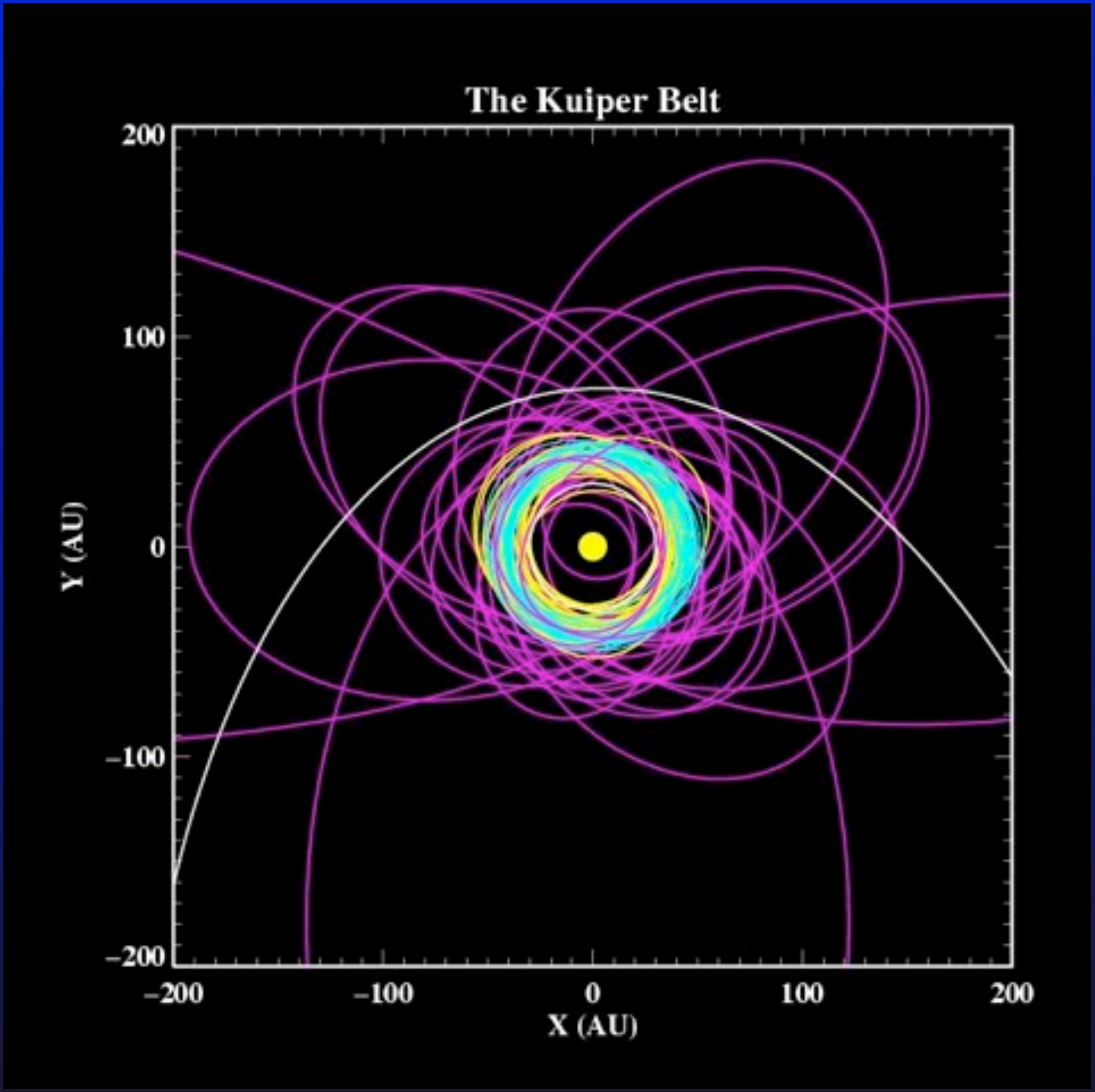


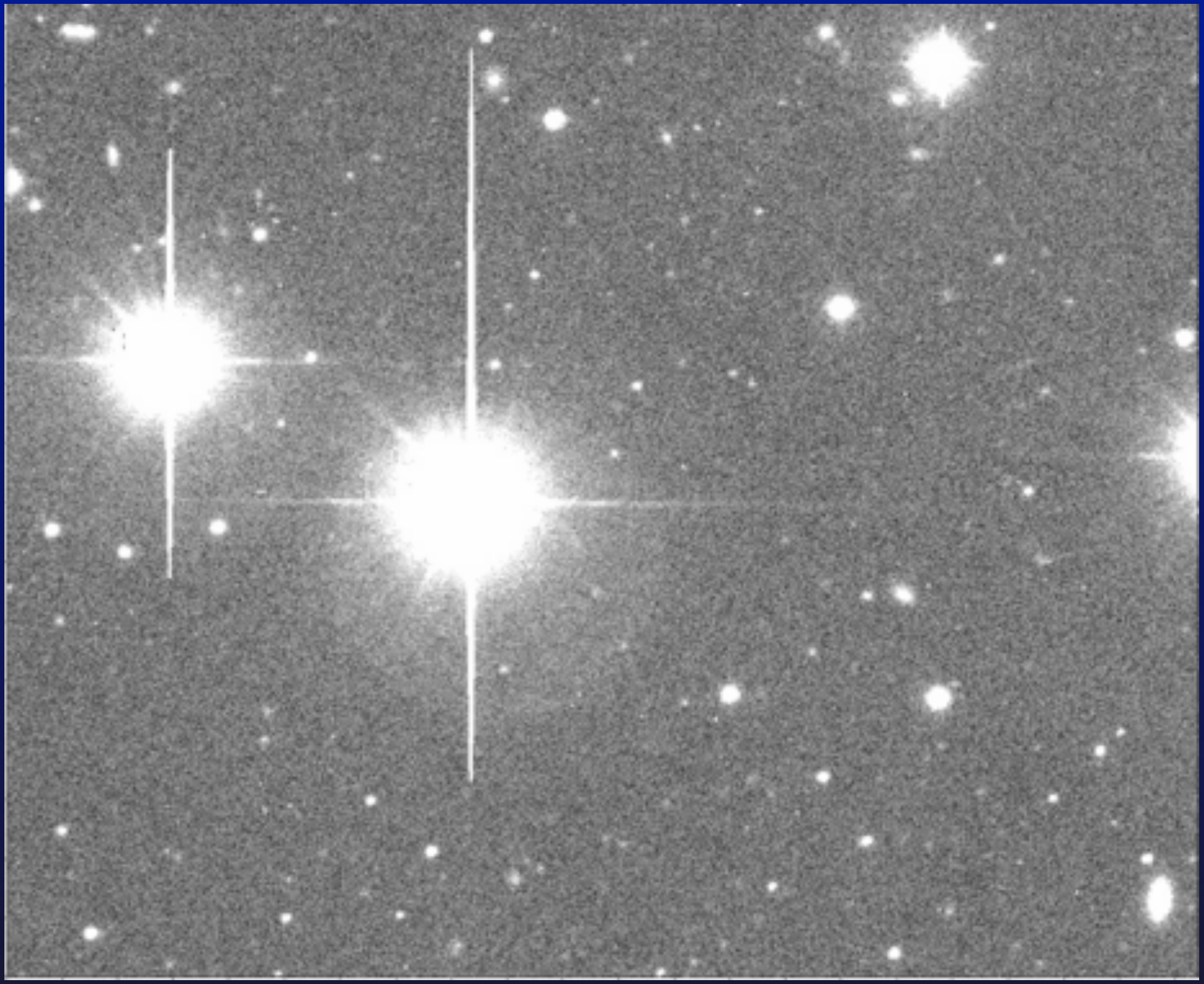
Planetary Dynamics at the Outer Limits

E. Chiang
UC Berkeley

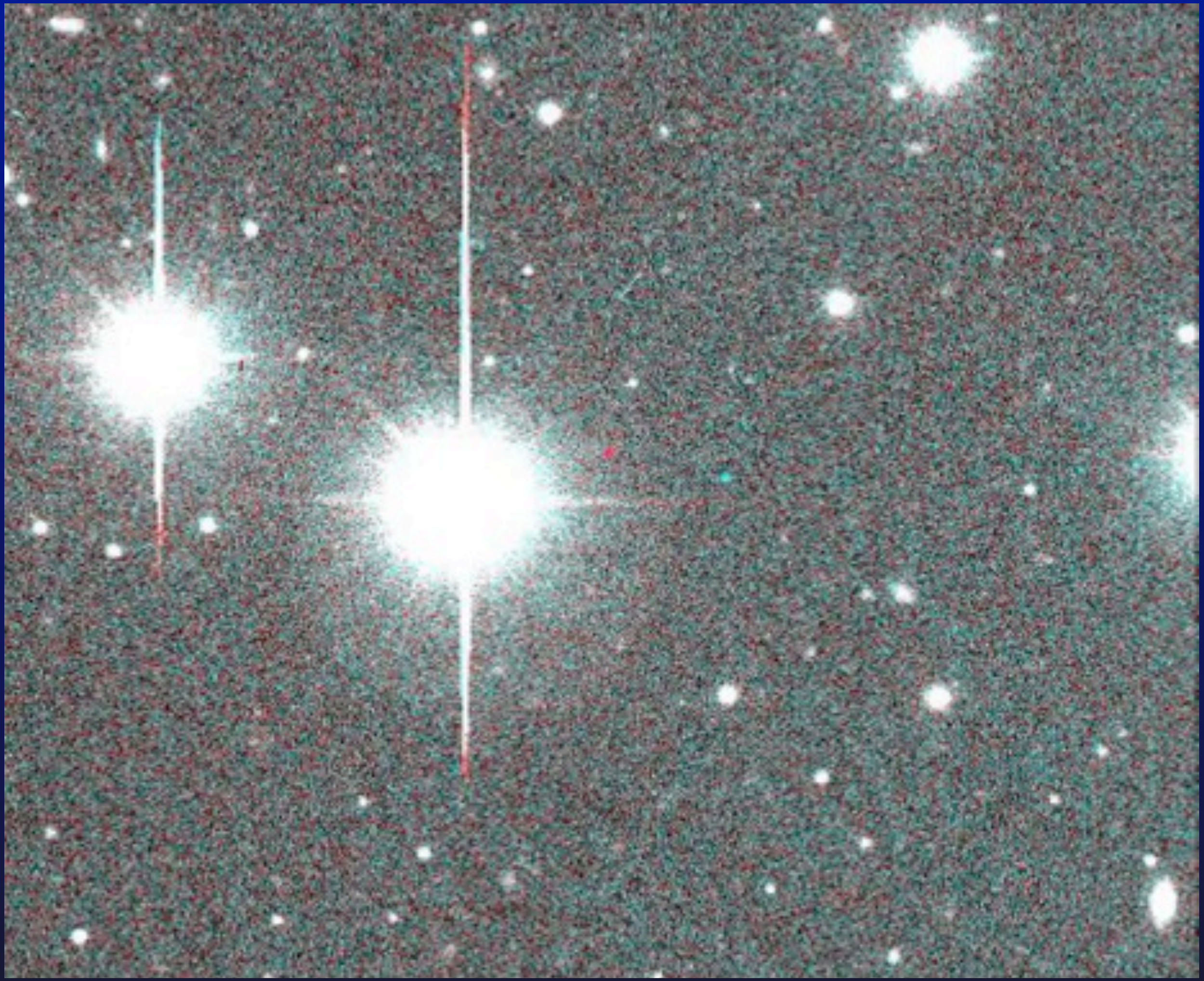
keywords:
Kuiper belt
debris disks
imaging of extrasolar planets
orbit-orbit resonance

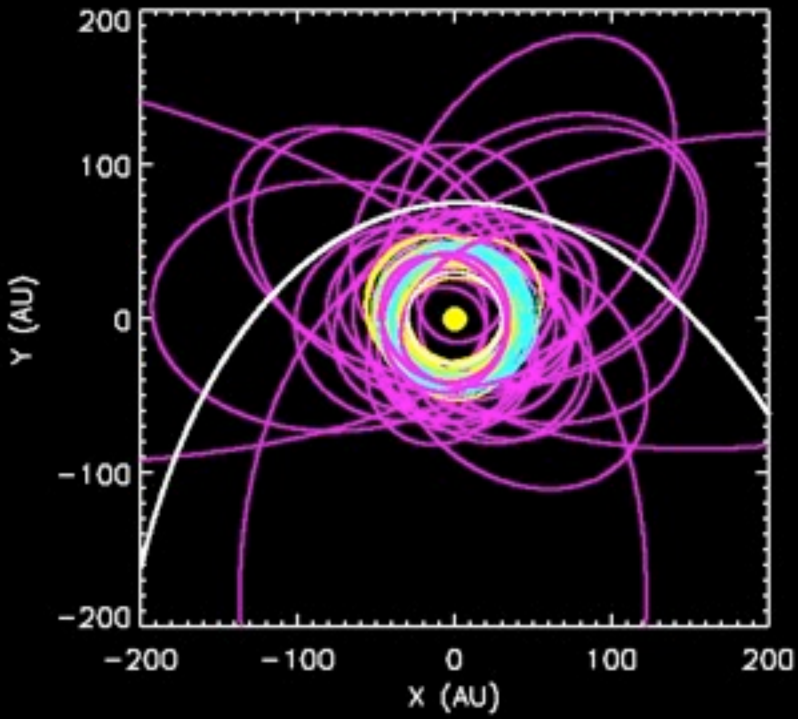

The Kuiper Belt
200
100
0
−100
−200
Y (AU)
−200
−100
0
100
200
X (AU)

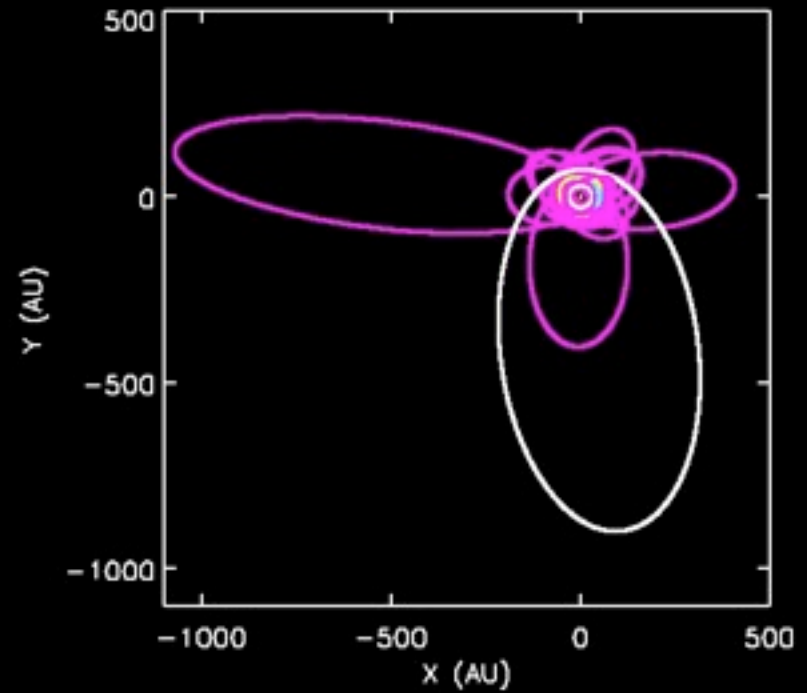
Sample Blinking

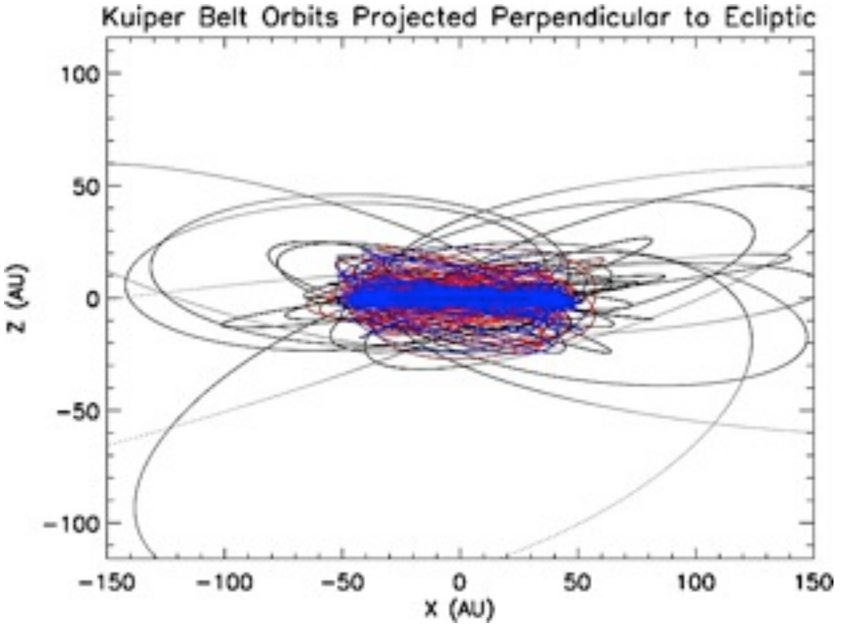


Sample Blinking









$$M \sim 0.1\ M_\oplus$$

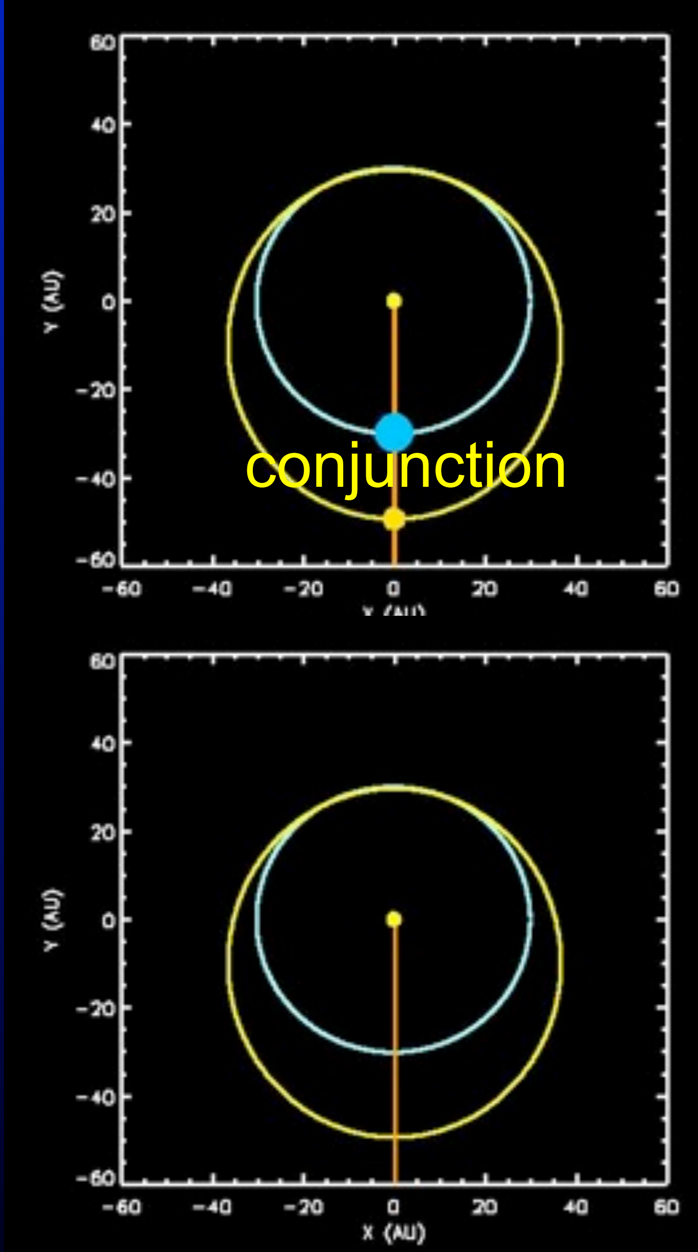
$$t_{collision} \sim \frac{1}{n\,\sigma\ v_{rel}} \sim 10^{12}\ \text{yr}$$

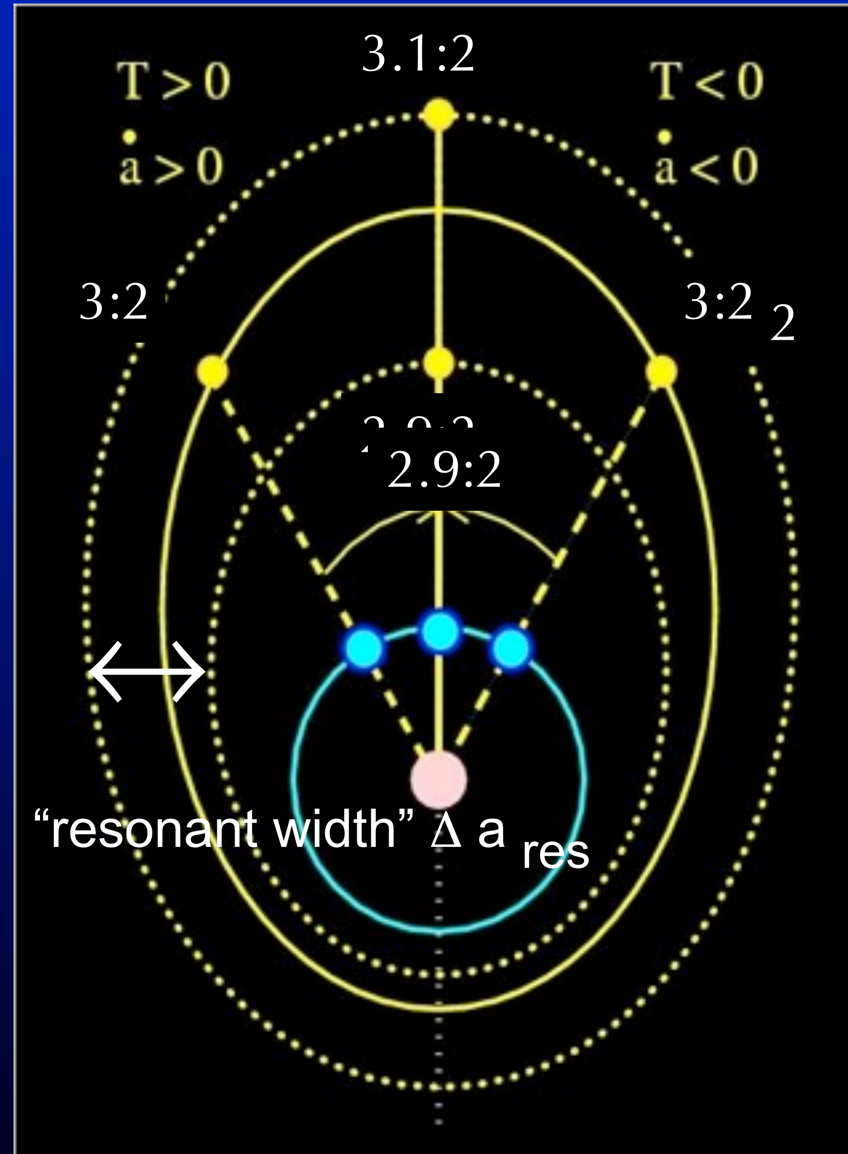
n: 3 AU^{-3}

σ: π (100 km)^2

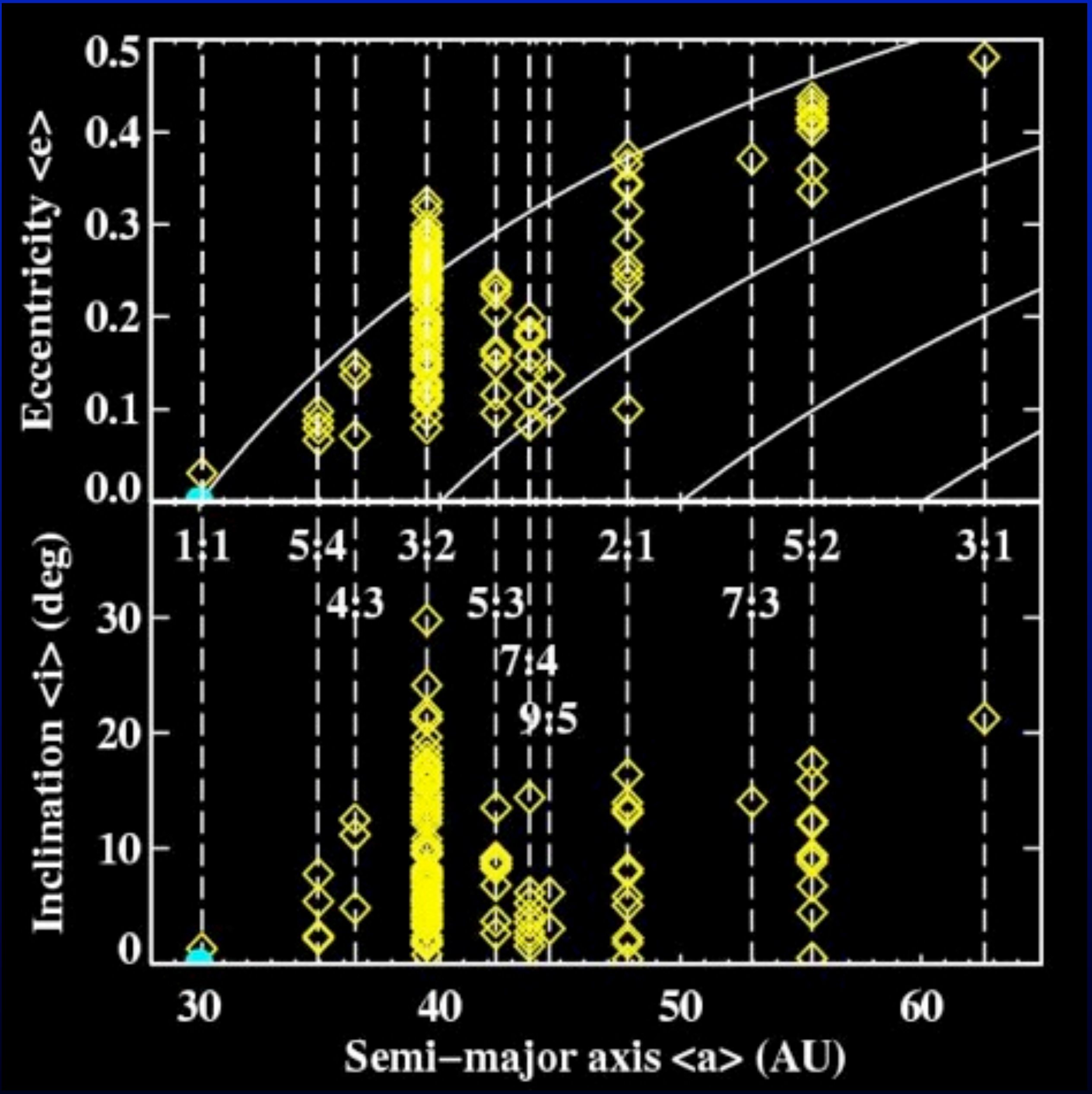
v_{rel}: 1 km s^{-1}

KBOs = test particles



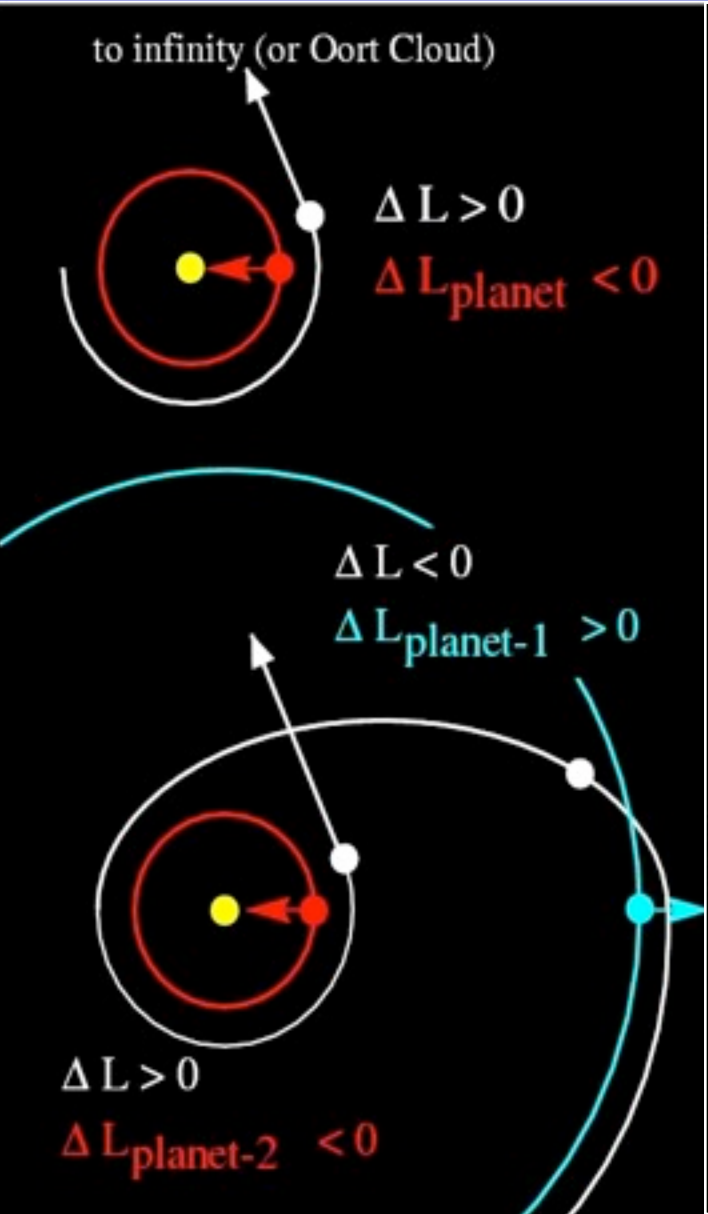


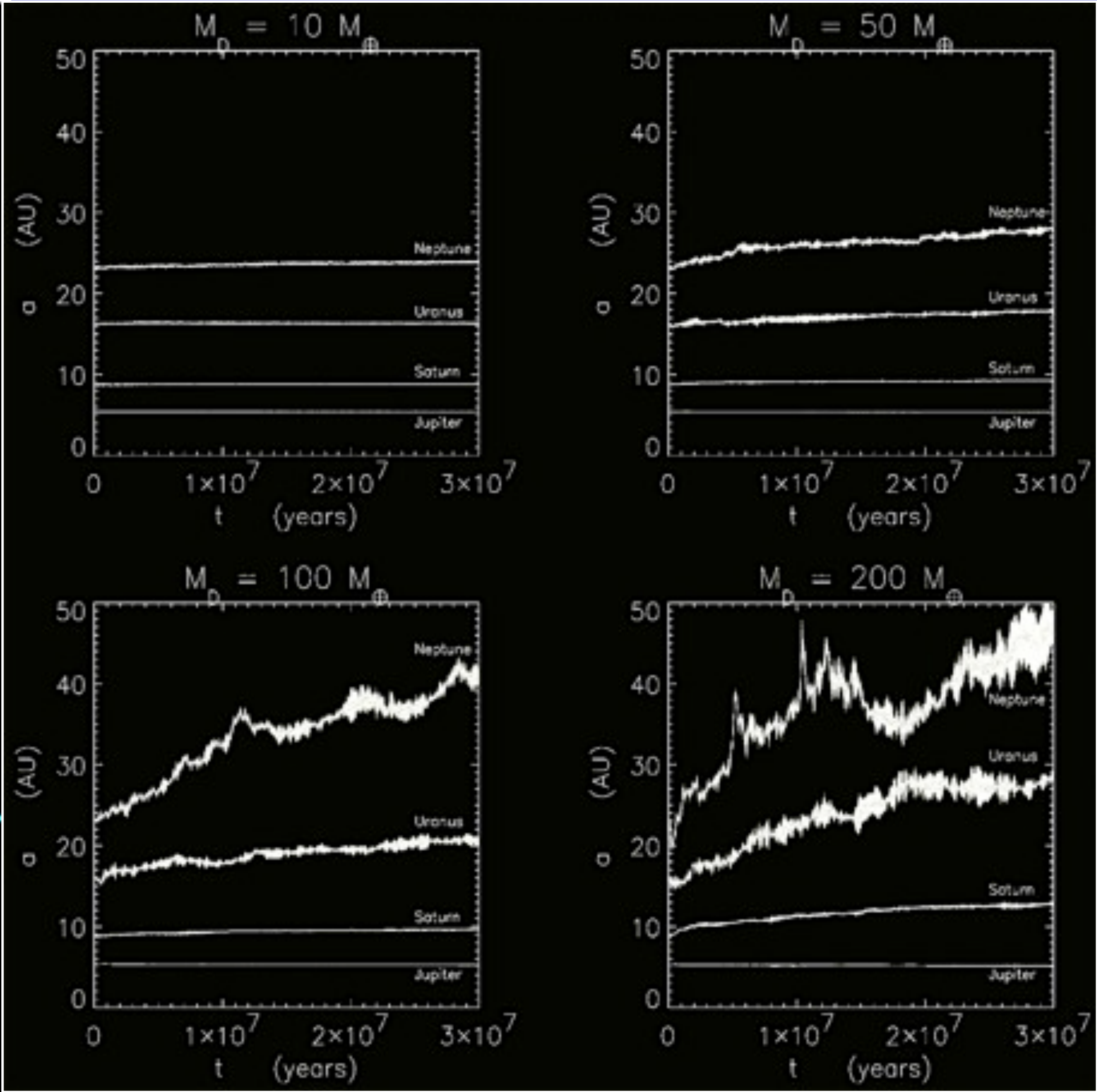
Neptune-Pluto Orbit-Orbit Resonance



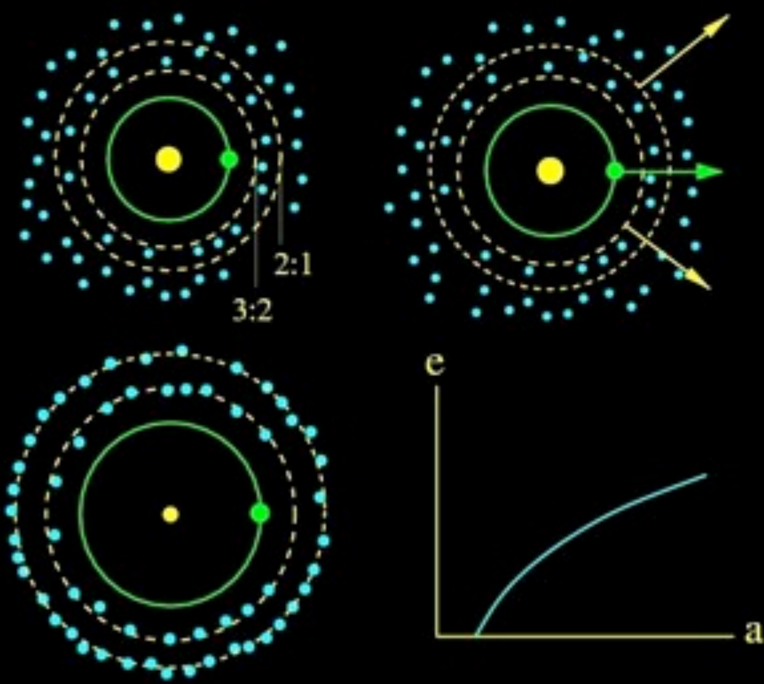
Resonant KBOs (~26%)

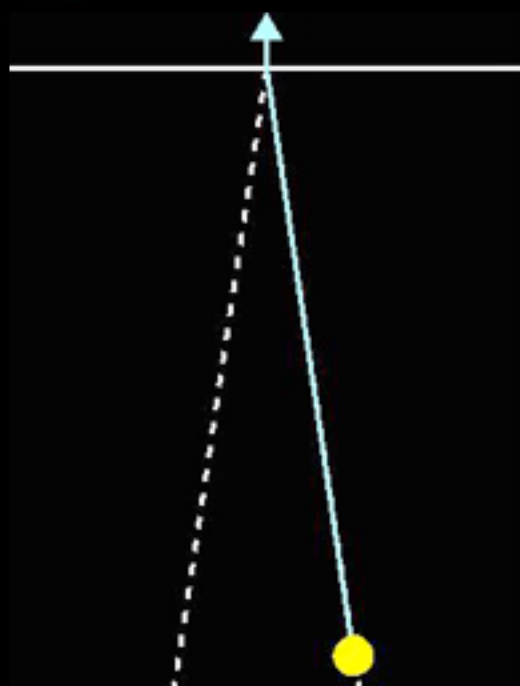
Orbital Migration by Planetesimal Ejection

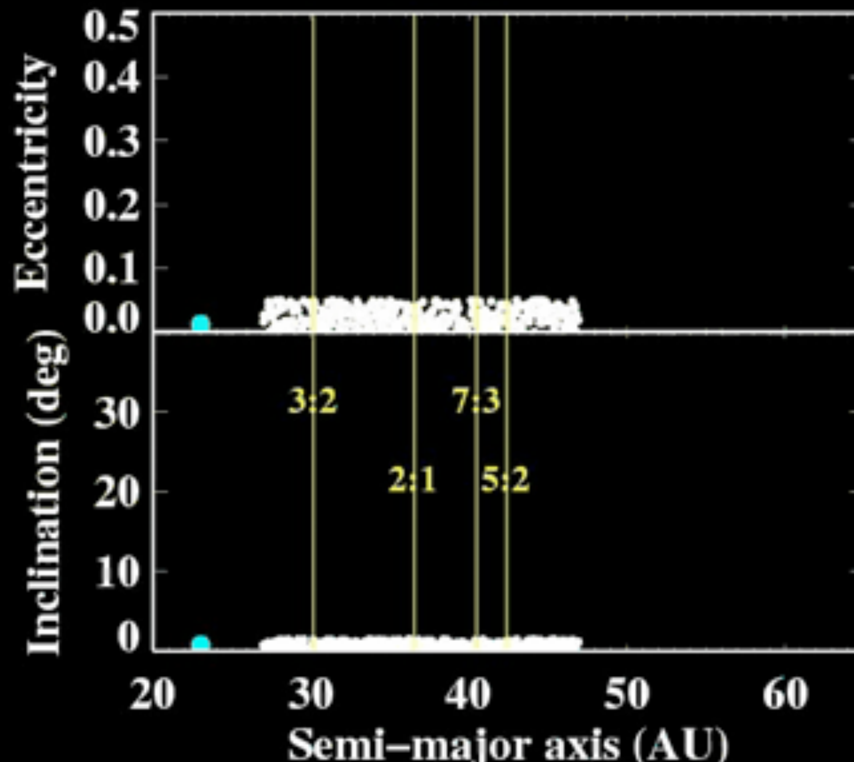




Resonance Sweeping





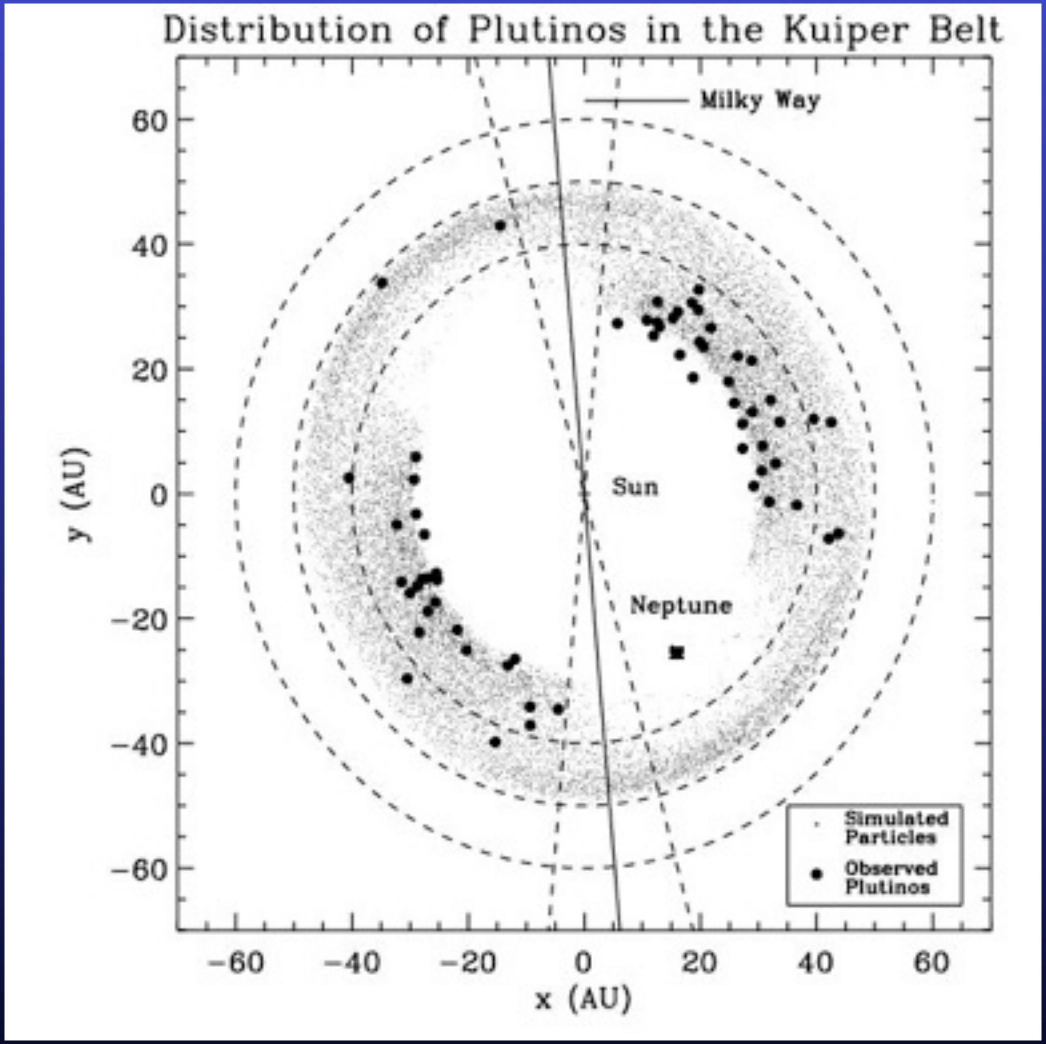


$\Gamma = \oint p \, dq =$ conserved

$\Gamma_1 =$ adiabatic invariant over synodic period

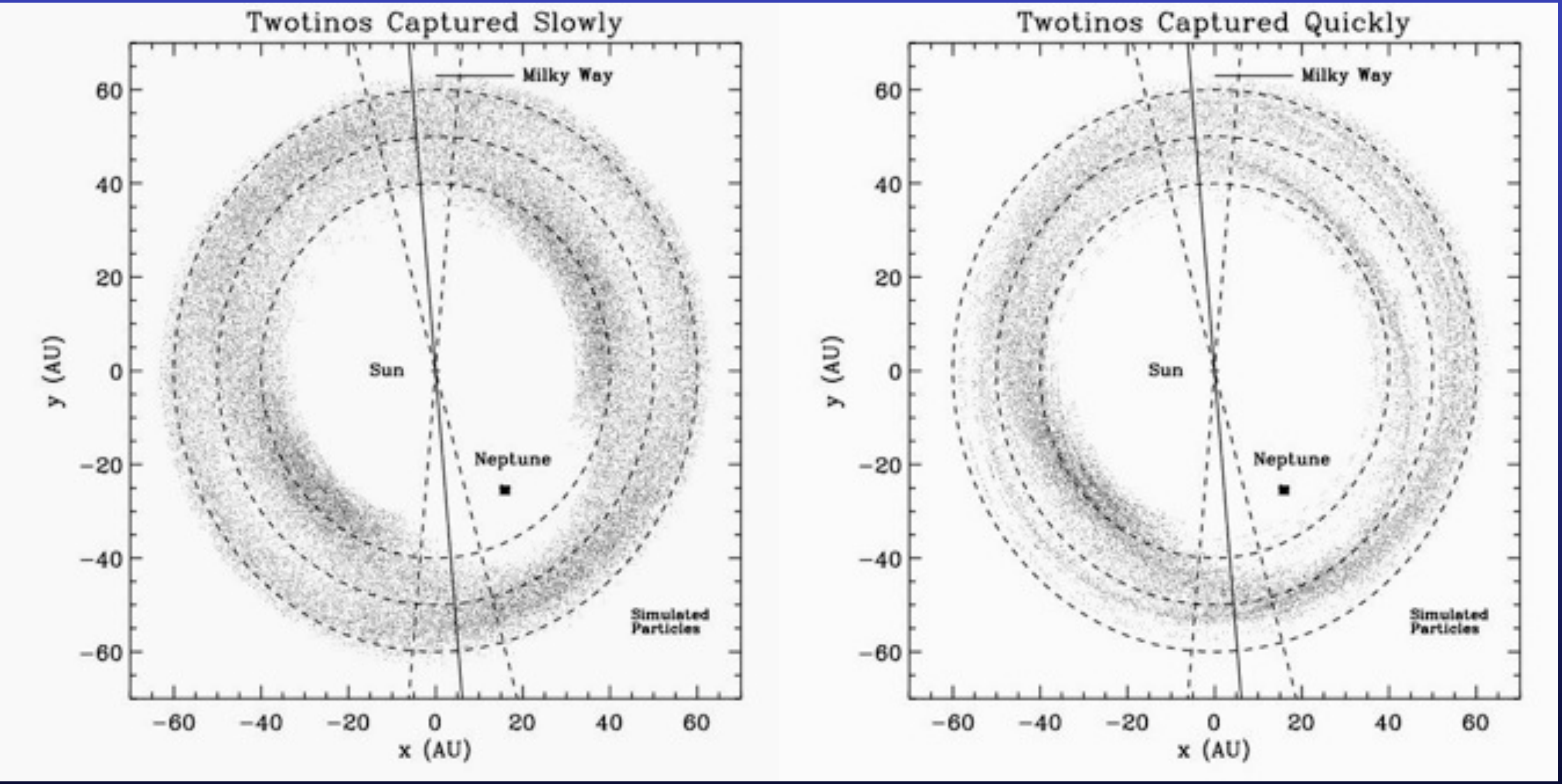
$\Gamma_2 =$ adiabatic invariant over libration period

Plutino (3:2) Snapshot



Wave pattern rotates rigidly with Neptune

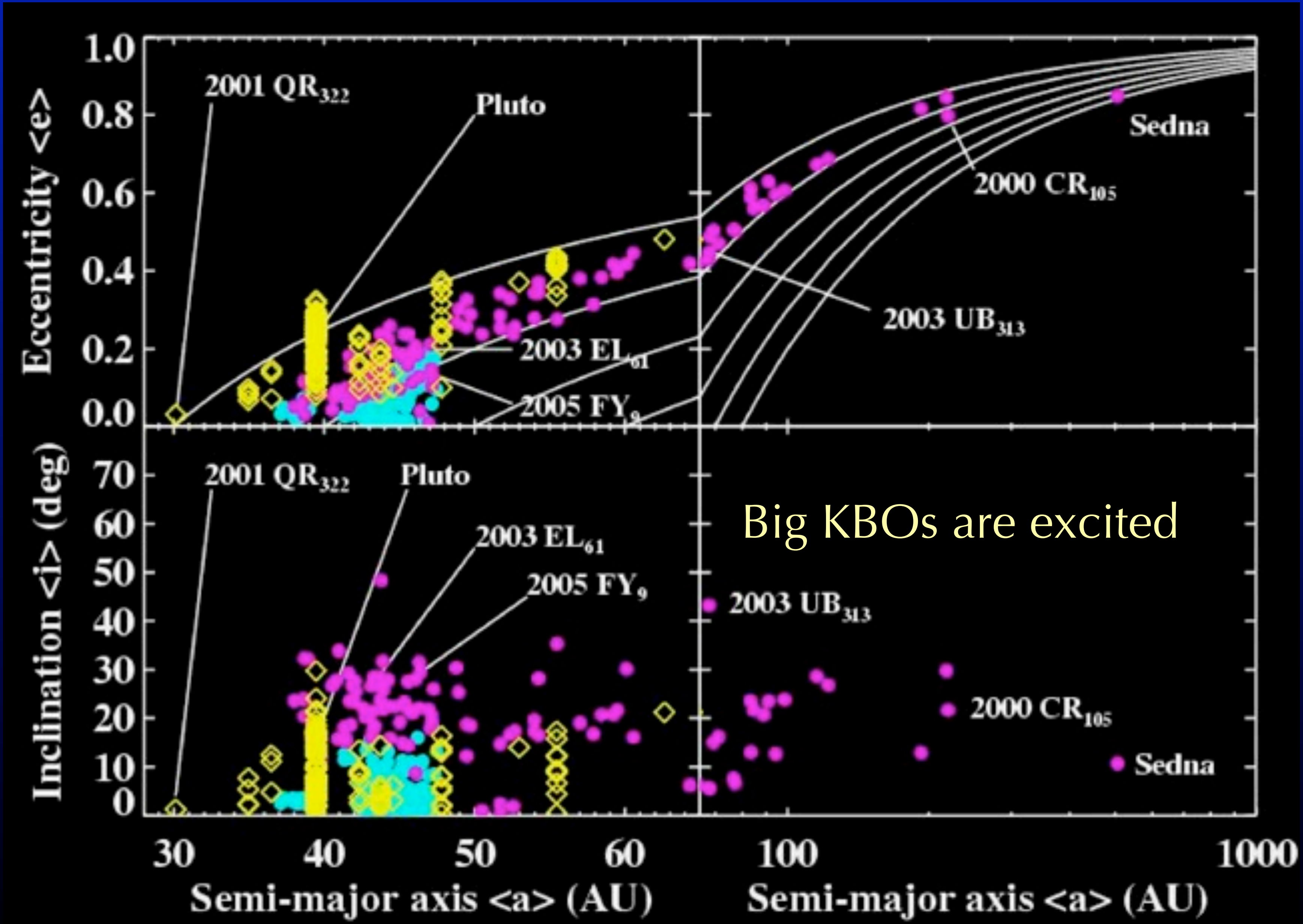
2:1 = Planetary Speedometer



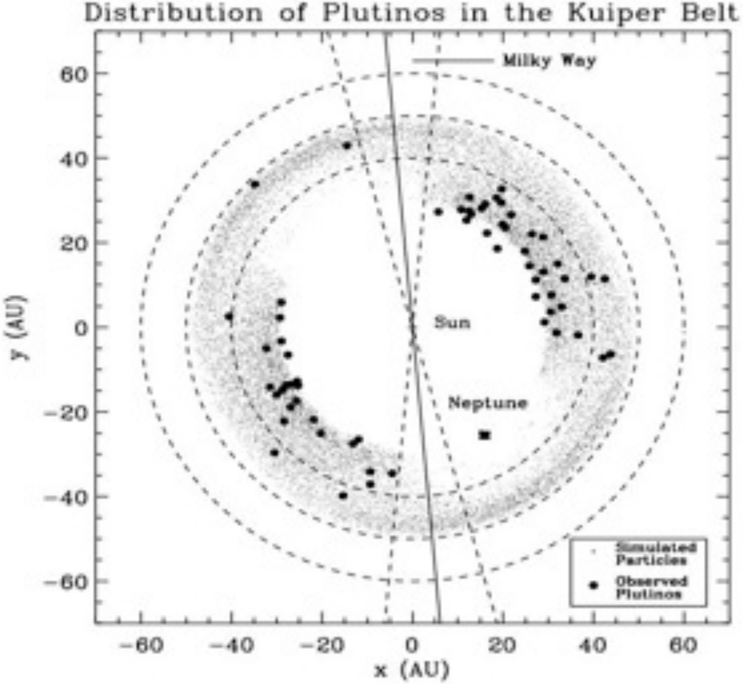
$t_{\rm migrate} \equiv a/(da/dt) \geq 10^7$ yr

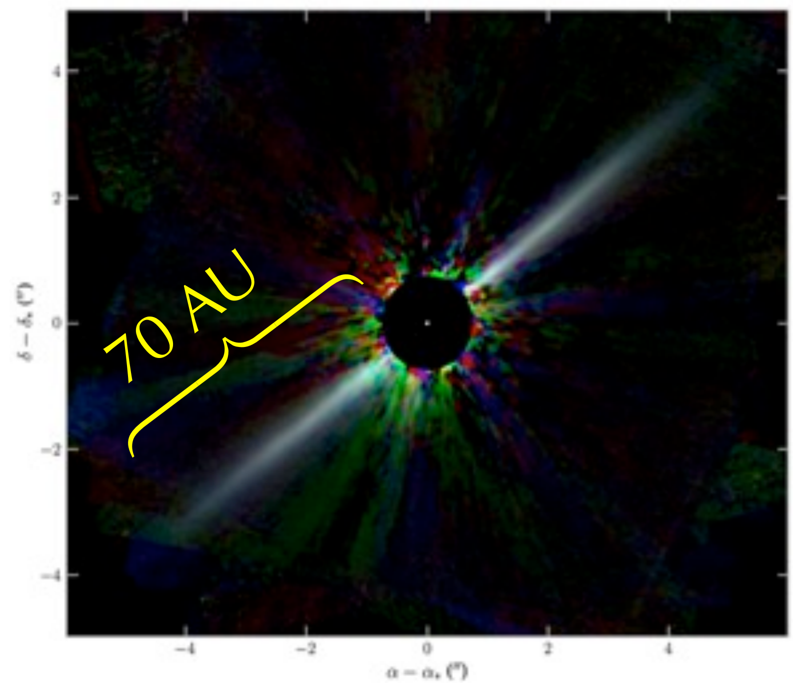
$t_{\rm migrate} = 10^6$ yr

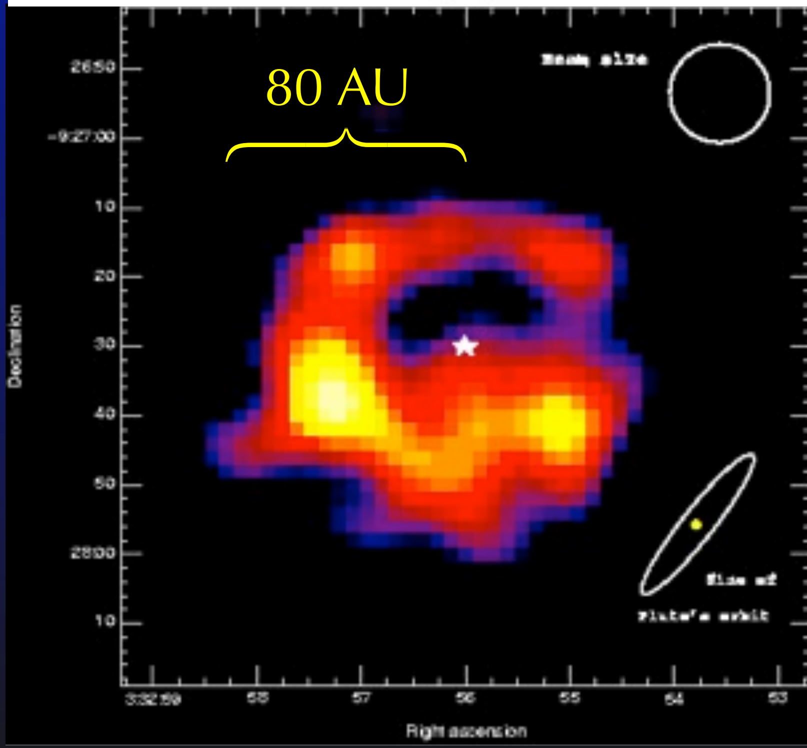
The Kuiper Belt: The Global View

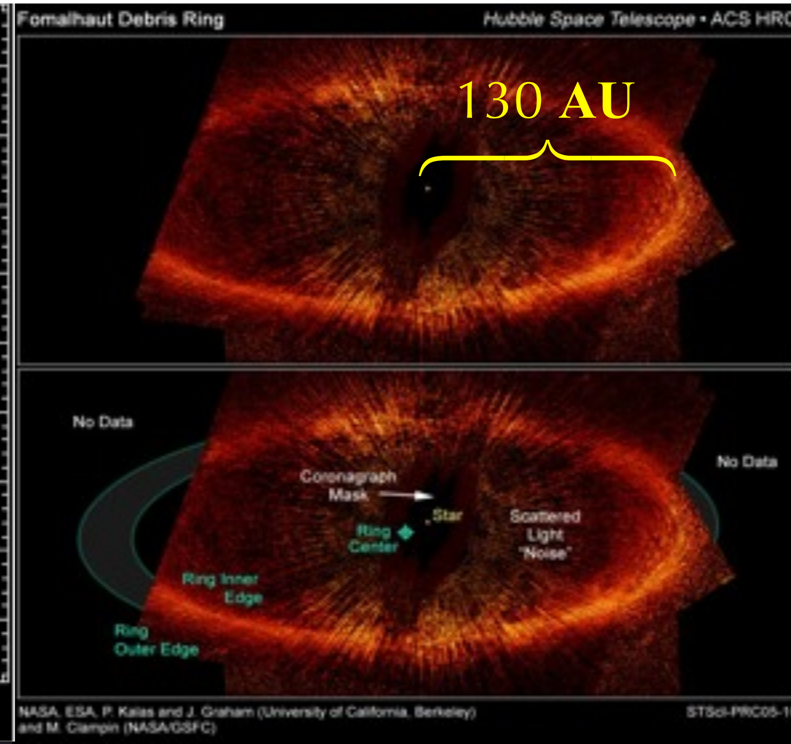


Big KBOs are excited


Distribution of Plutinos in the Kuiper Belt
Milky Way
Sun
Neptune
Simulated Particles
Observed Plutinos
y (AU)
x (AU)
60
40
20
0
−20
−40
−60

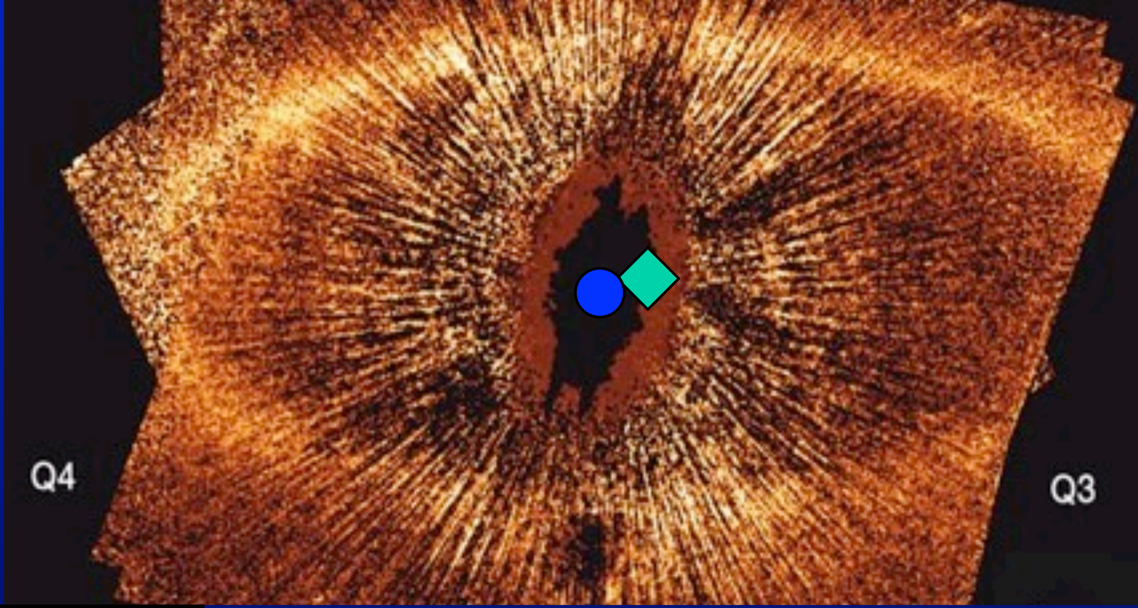

70 AU

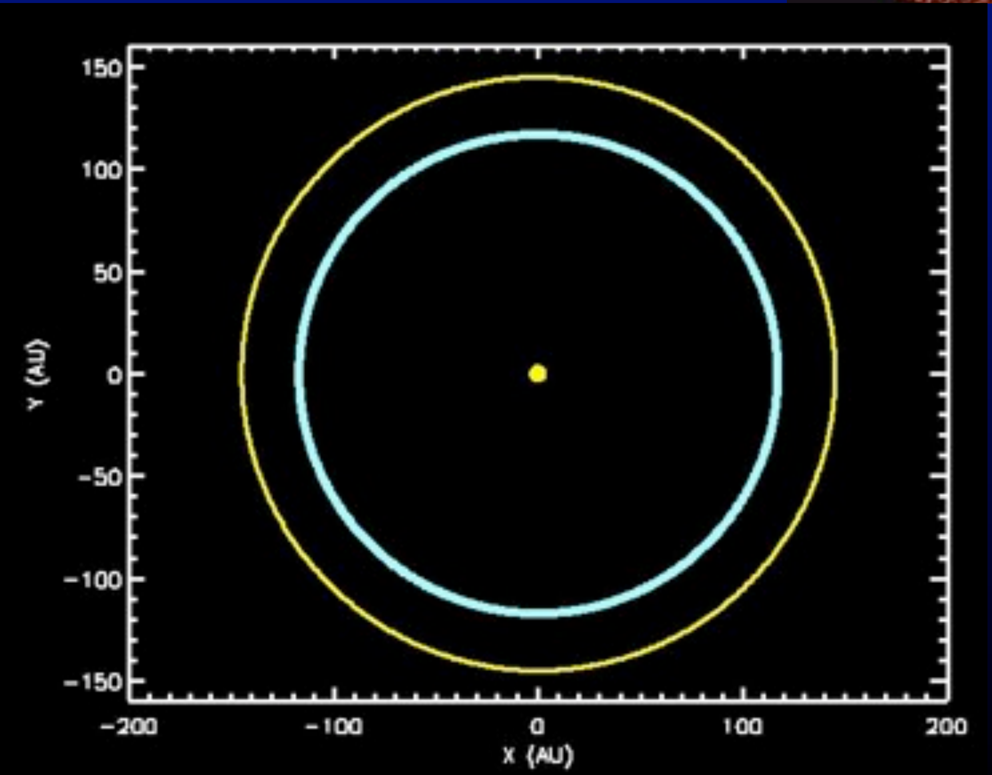

80 AU
Declination
Right ascension


Fomalhaut Debris Ring
Hubble Space Telescope • ACS HRC
130 AU
No Data
No Data
Coronagraph Mask
Star
Ring Center
Scattered Light "Noise"
Ring Inner Edge
Ring Outer Edge
NASA, ESA, P. Kalas and J. Graham (University of California, Berkeley) and M. Clampin (NASA/GSFC)
STScI-PRC05-10

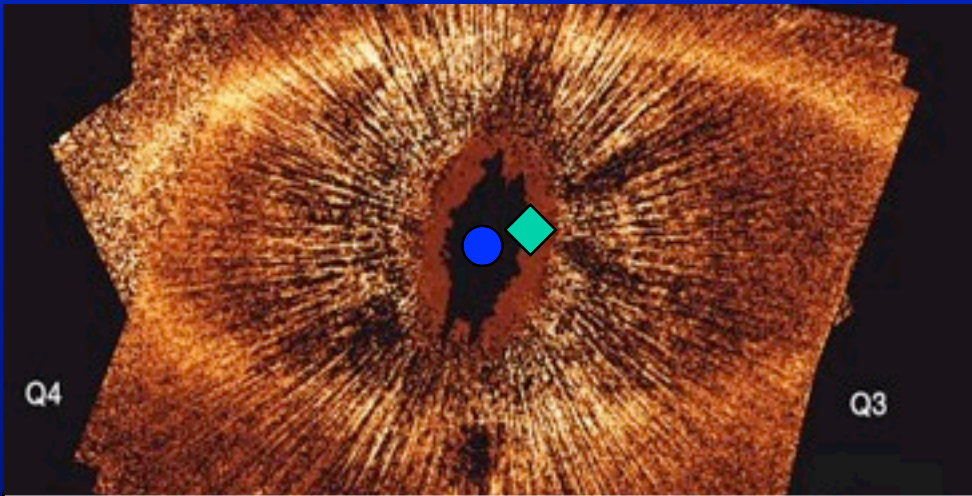
Fomalhaut

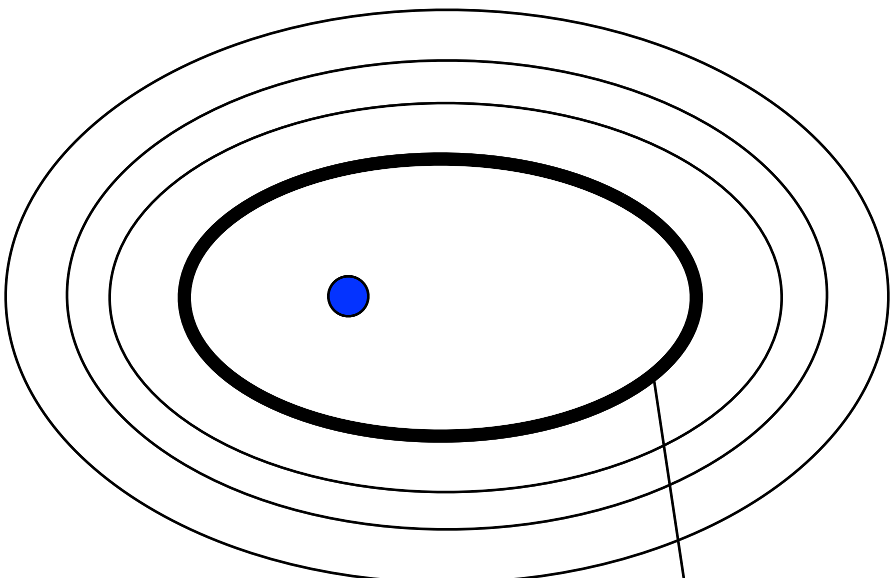
Eccentric planet begets eccentric ring





Equilibrium belt orbits are eccentric and aligned with the planet's orbit





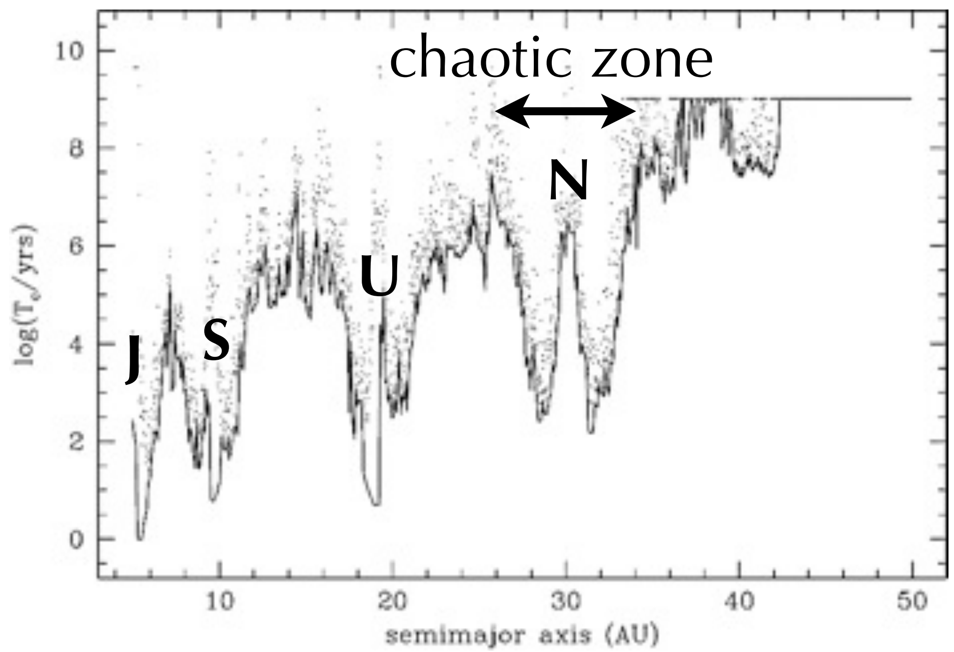
Dissipative relaxation of parent bodies onto non-crossing (forced eccentric) orbits

Relaxation occurs during:

- Present-day collisional cascade
- Prior coagulation

$$e_{\rm forced}(a) = \frac{b_{3/2}^{(2)}(a_{\rm planet}/a)}{b_{3/2}^{(1)}(a_{\rm planet}/a)} e_{\rm planet}$$

Wyatt et al. 99
Kalas et al. 05

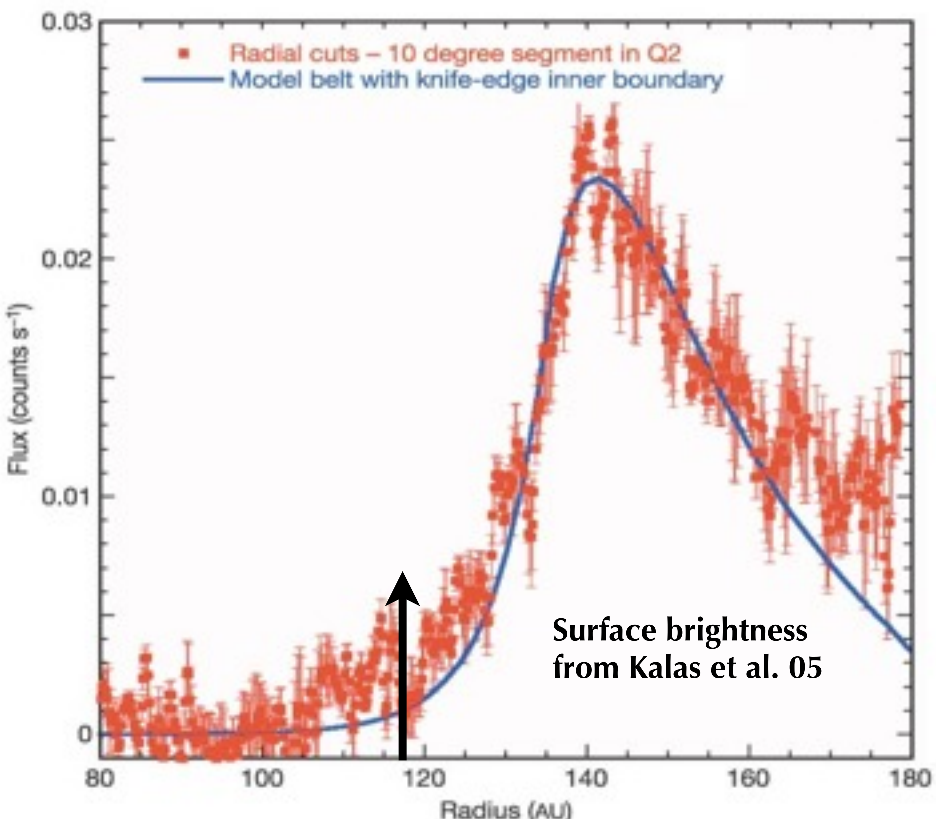


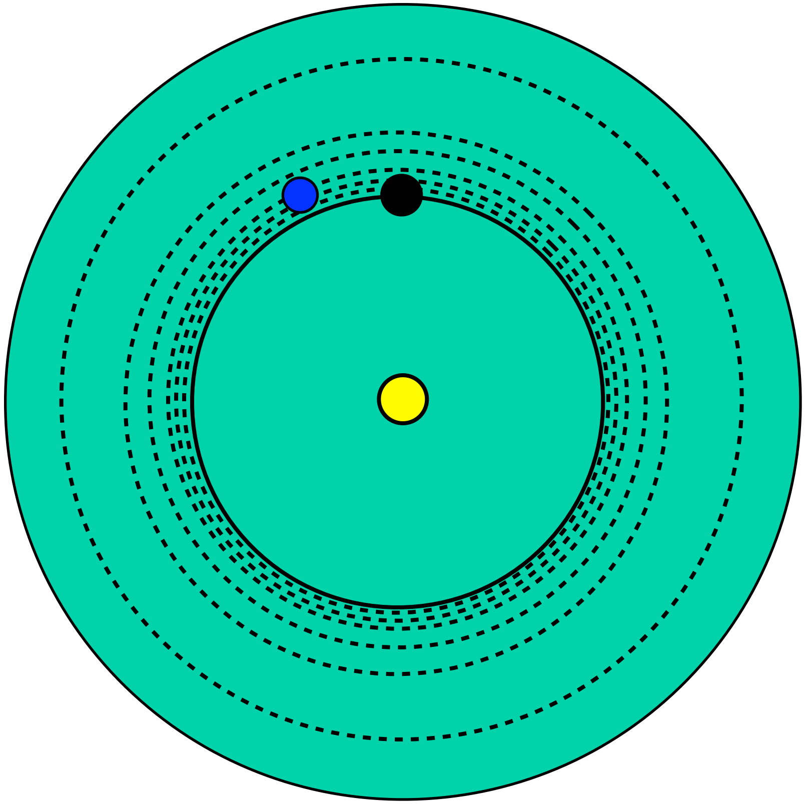
Lecar et al. 2001

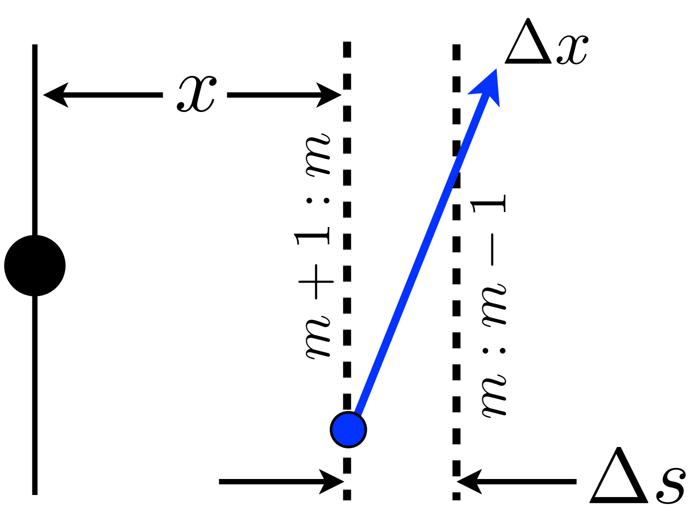
Constraining a_p and M_p using the sharp inner belt edge

Inner belt edge = Outer edge of planet's "chaotic zone"

Chaotic zone width ~ $(M_{planet}/M_{star})^{2/7}\ a_{planet}$

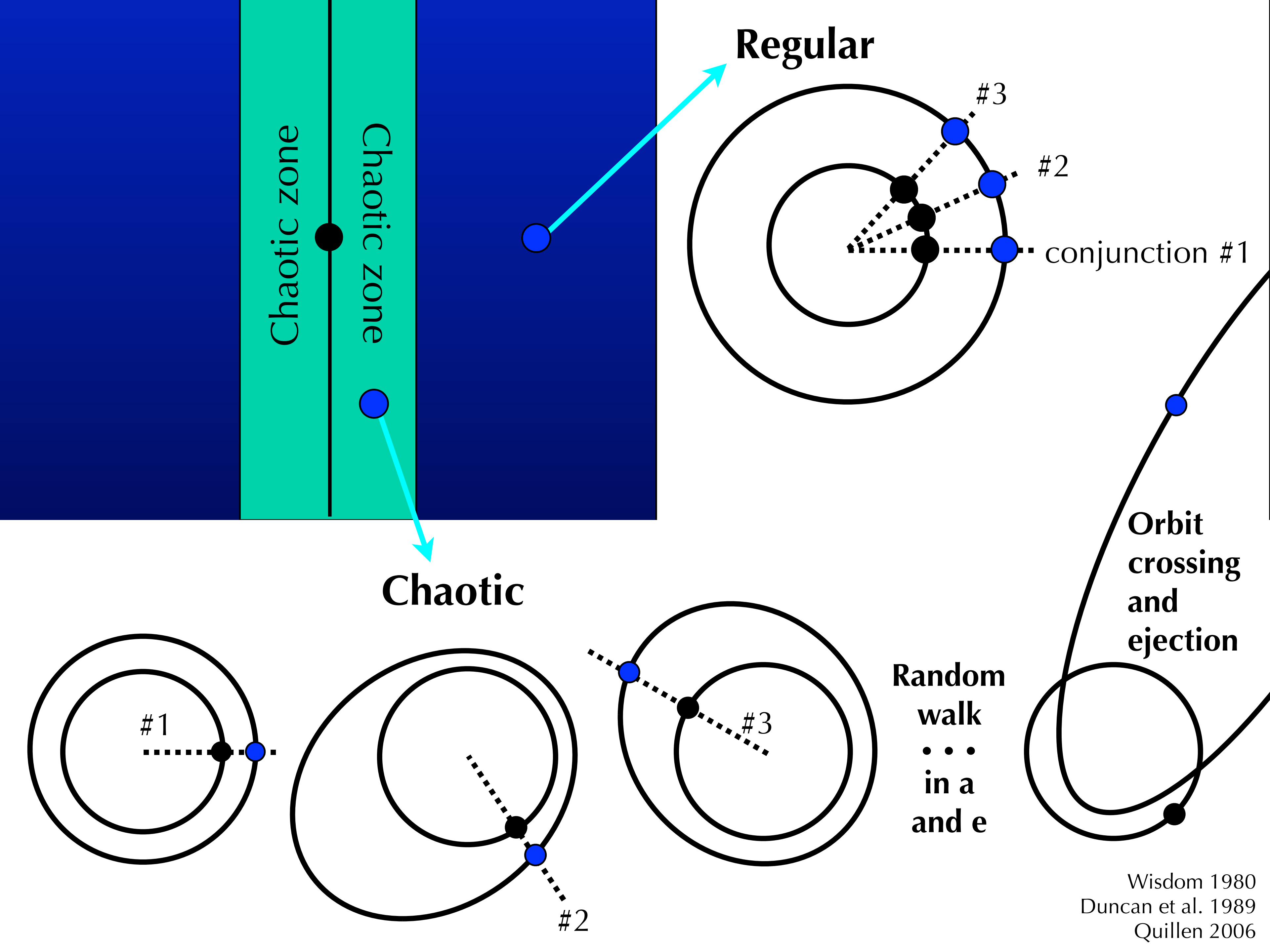


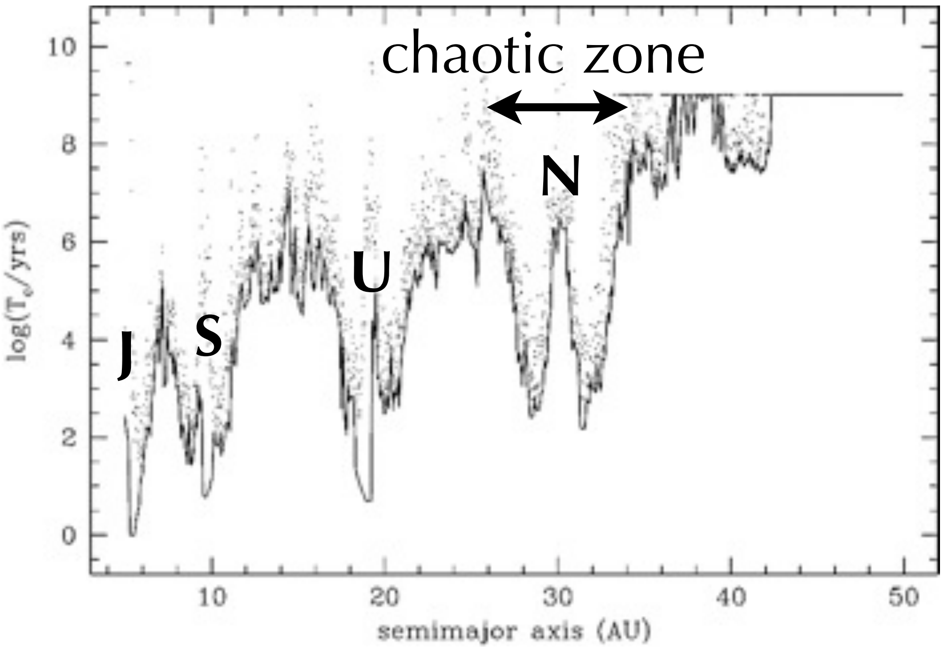




Planetary chaotic zone

= Region where first-order resonances overlap


Regular
#3
#2
conjunction #1
Chaotic zone
Chaotic zone
Chaotic
#1
#2
#3
Random
walk
. . .
in a
and e
Orbit
crossing
and
ejection
Wisdom 1980
Duncan et al. 1989
Quillen 2006



Lecar et al. 2001

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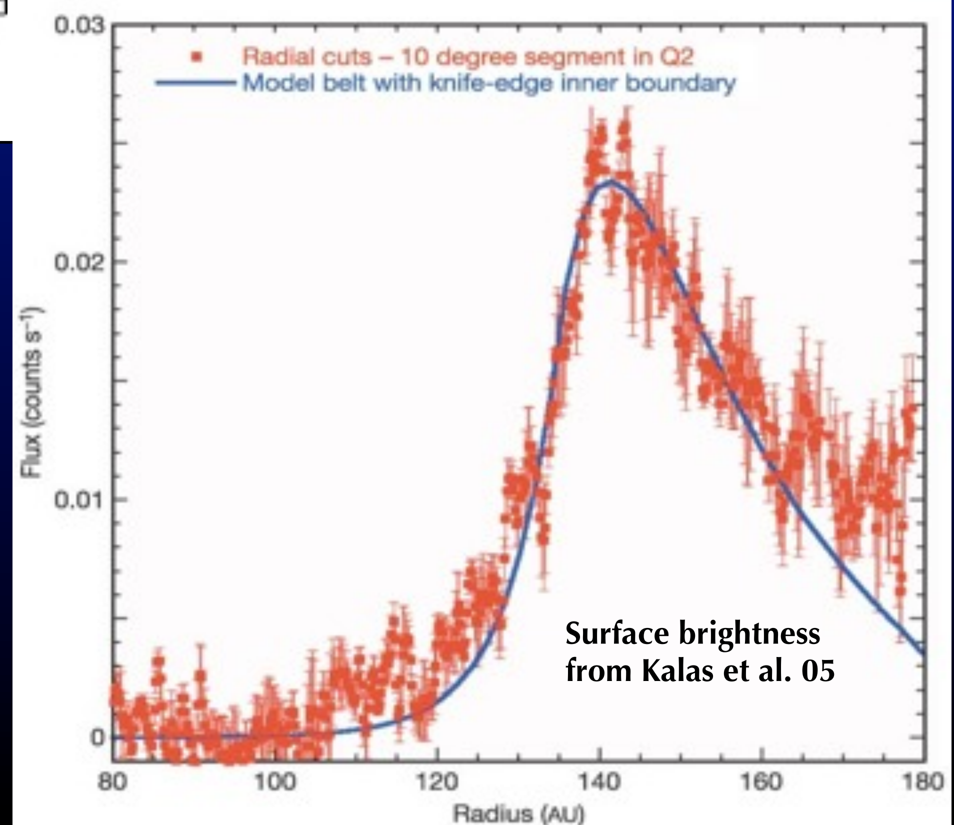
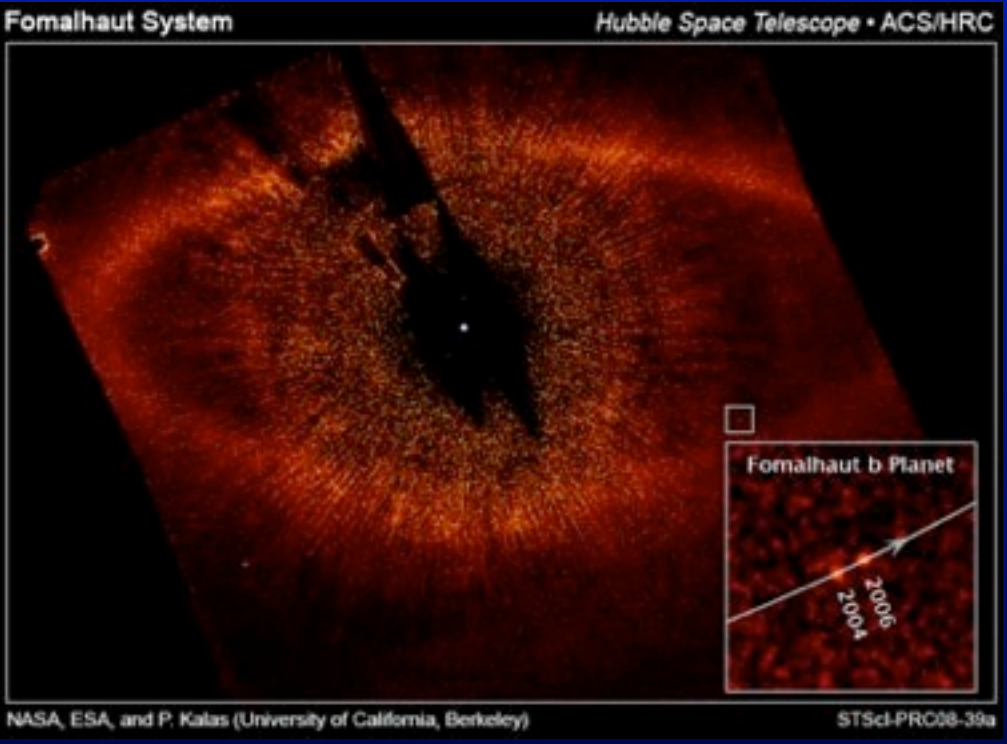
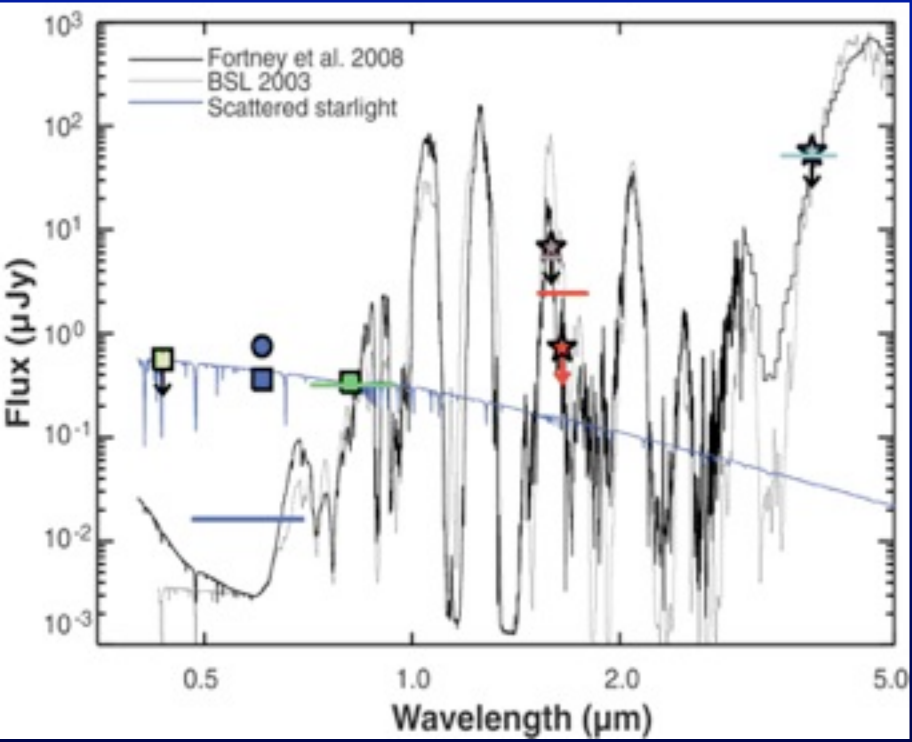


Candidate planet (0.5 Jupiter mass)





not confirmed: only 2 epochs

not thermal emission from planetary atmosphere

40 R_J reflective dust disk?

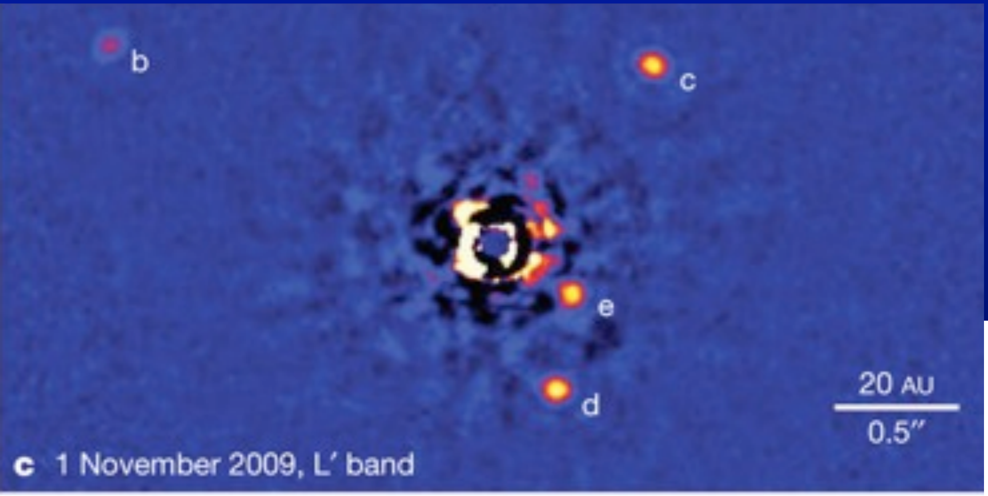
Variable Hα emission?

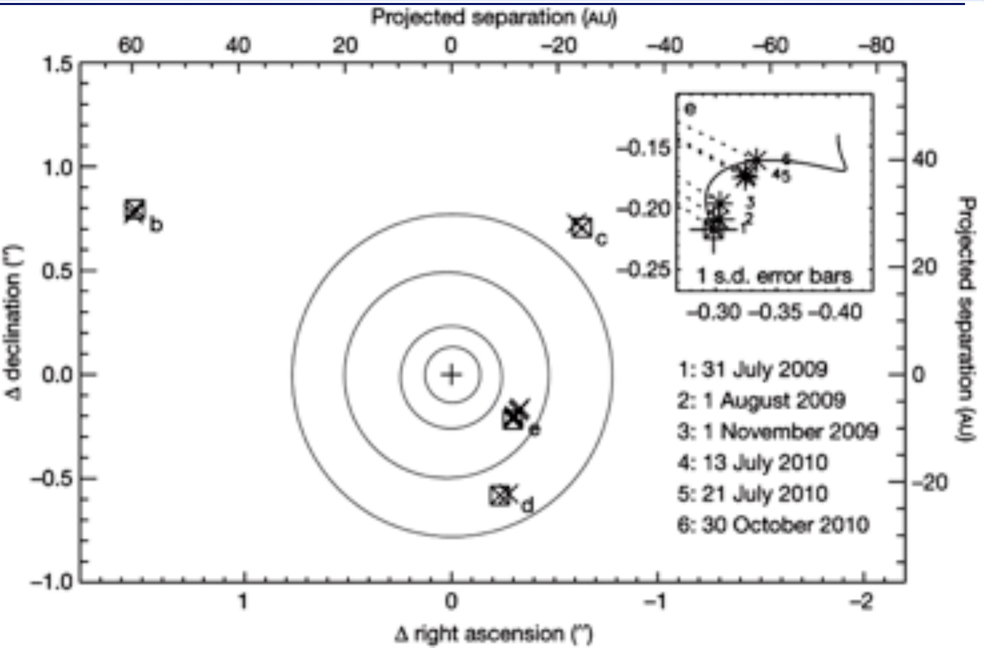
HR 8799
A-type star 30-60 Myr old
with 4 Super-Jupiters

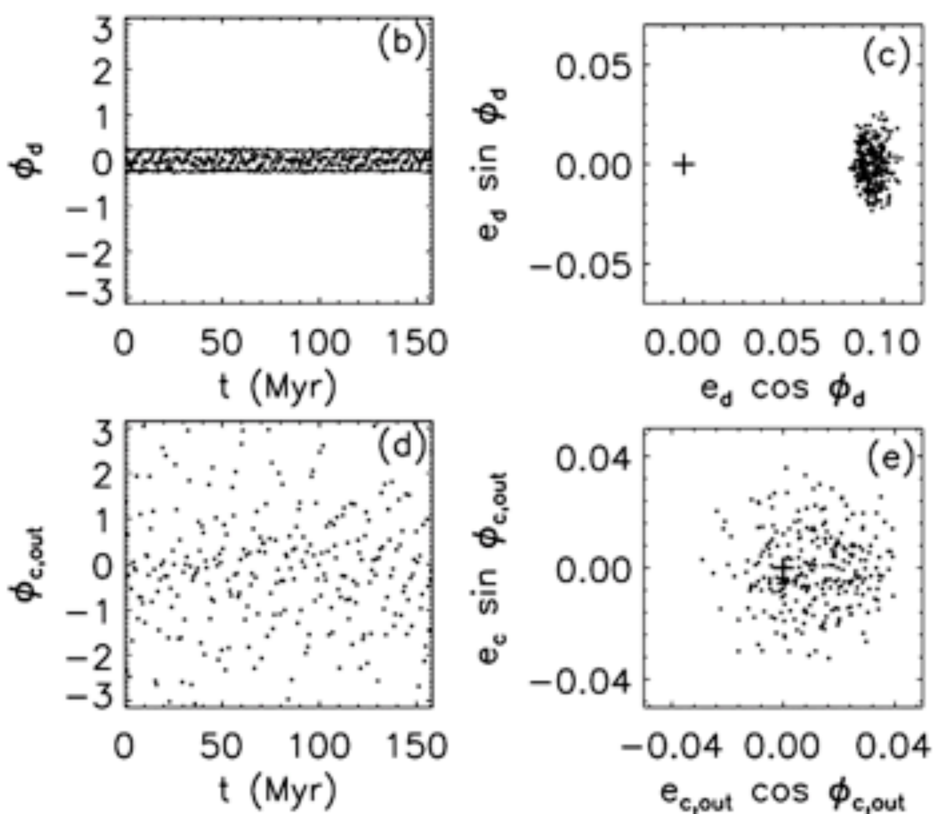
Orbital resonances afford stability
d:c = 2:1 resonance

Other possibilities include
d:c:b = 4:2:1
e:d:c = 4:2:1

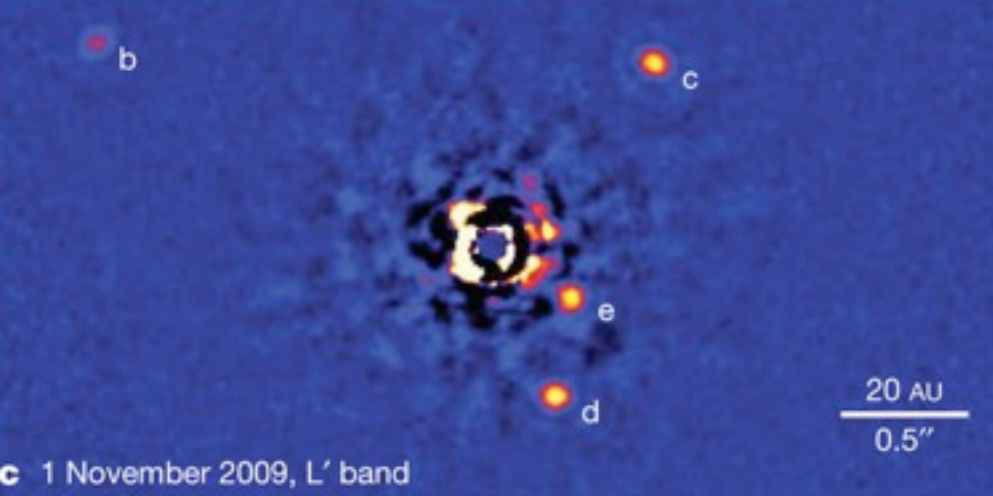
dynamical masses < 20 Jupiter masses each

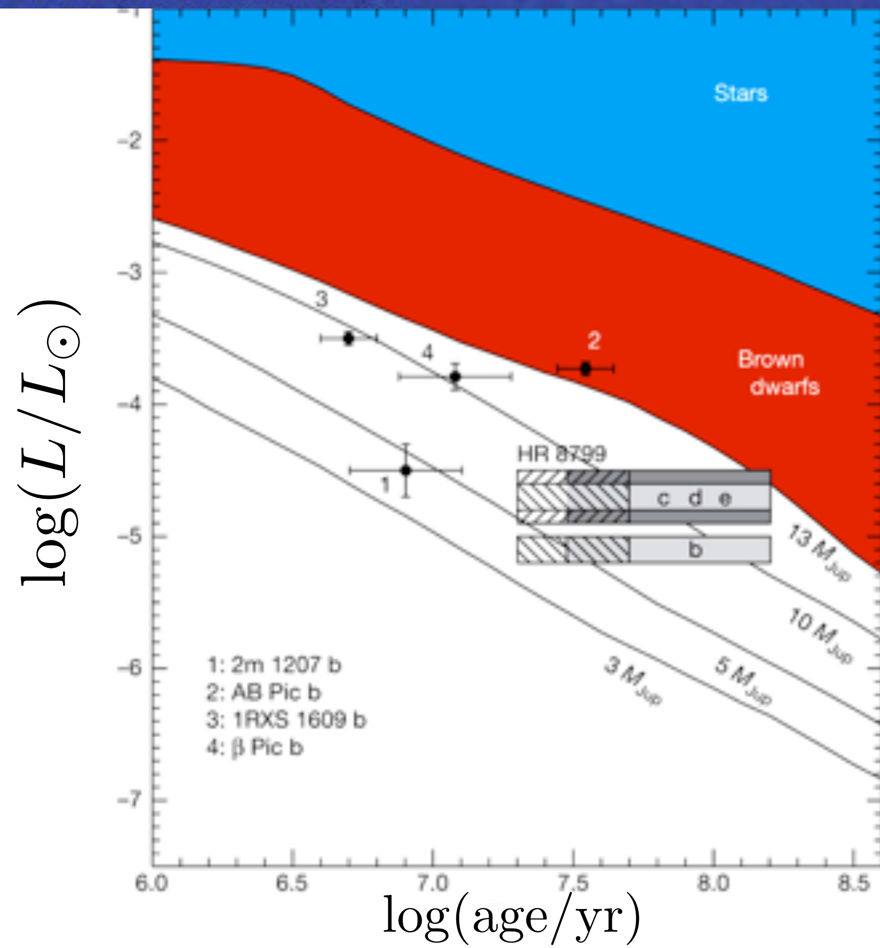


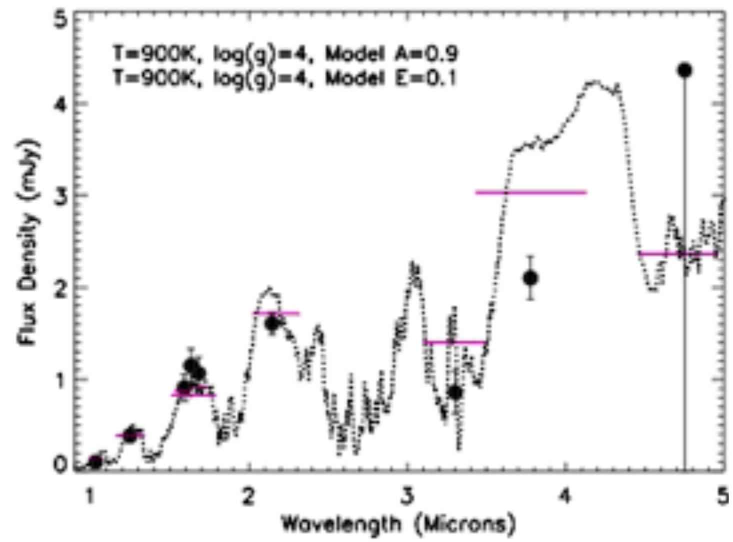




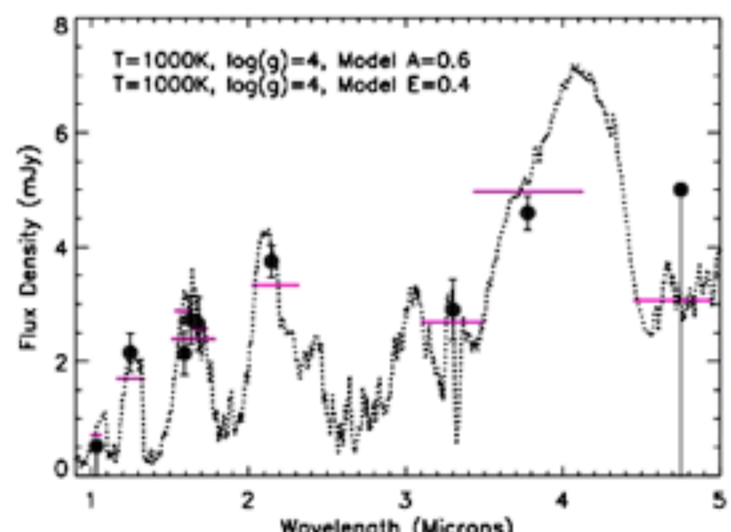
Cloudy spectra unlike brown dwarfs







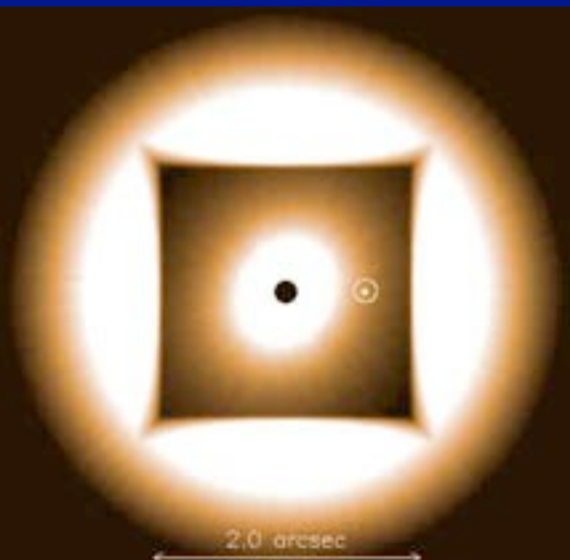
6-7 M_J

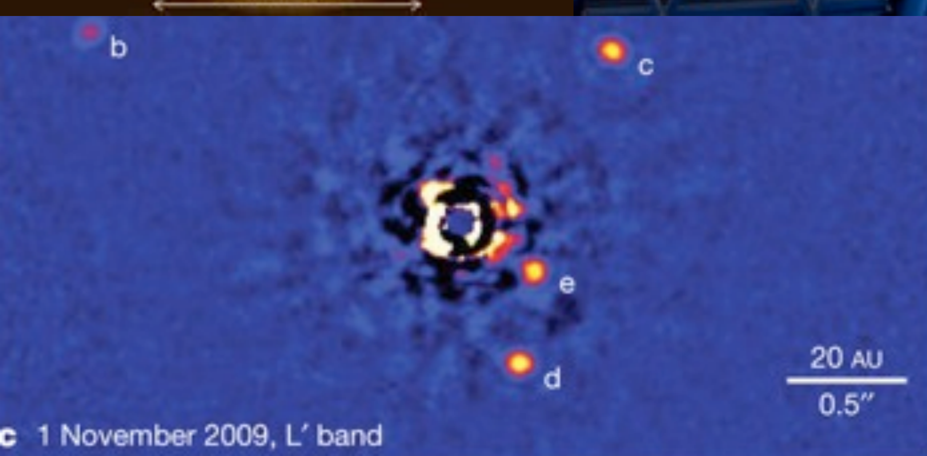


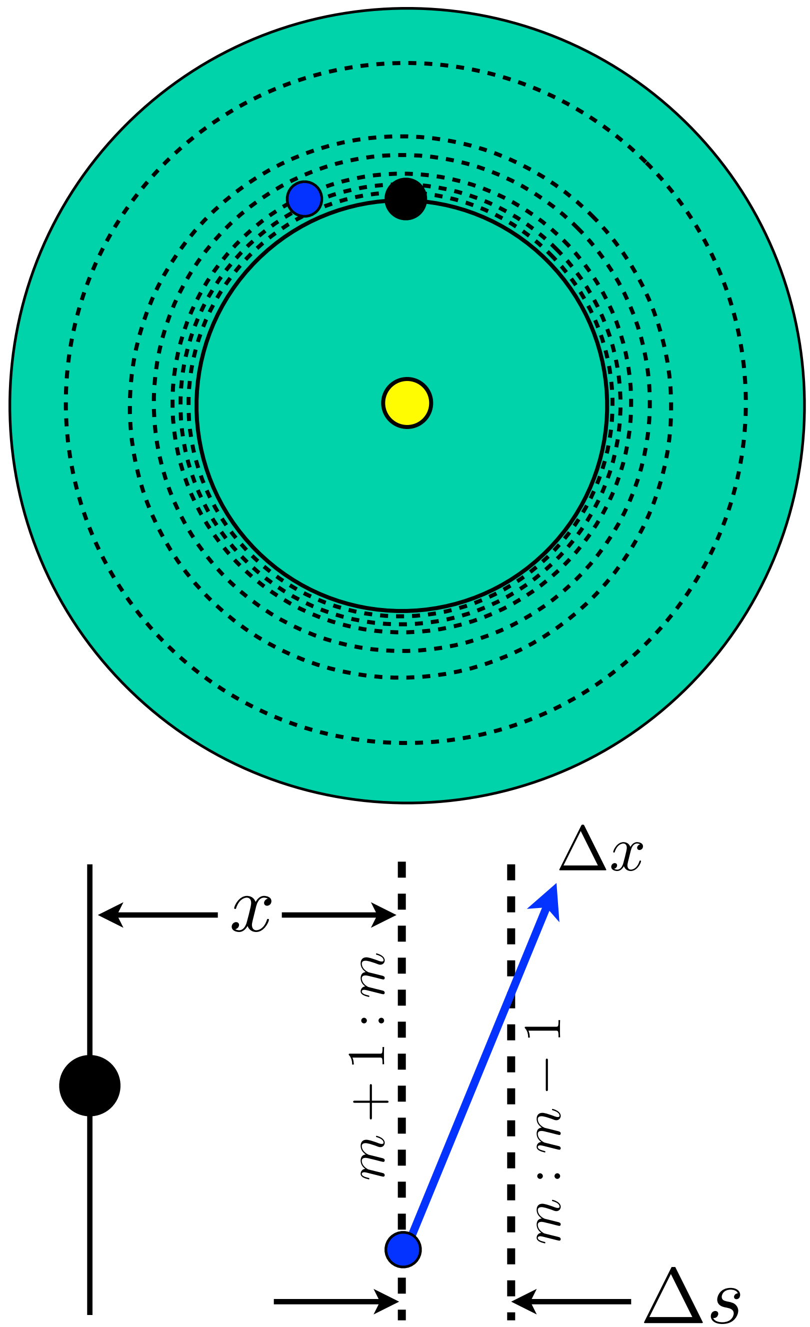
7-10 M_J

Gemini Planet Imager (GPI)
2012

Pan-STARRS (once a week, mag 24)
and LSST (once every few days, mag 24.5)







Deriving the chaotic zone width

Resonance overlap

Resonance spacing

$$\frac{\Delta s}{a} \sim \left(\frac{x}{a}\right)^2$$

if $\Delta x > \Delta s$

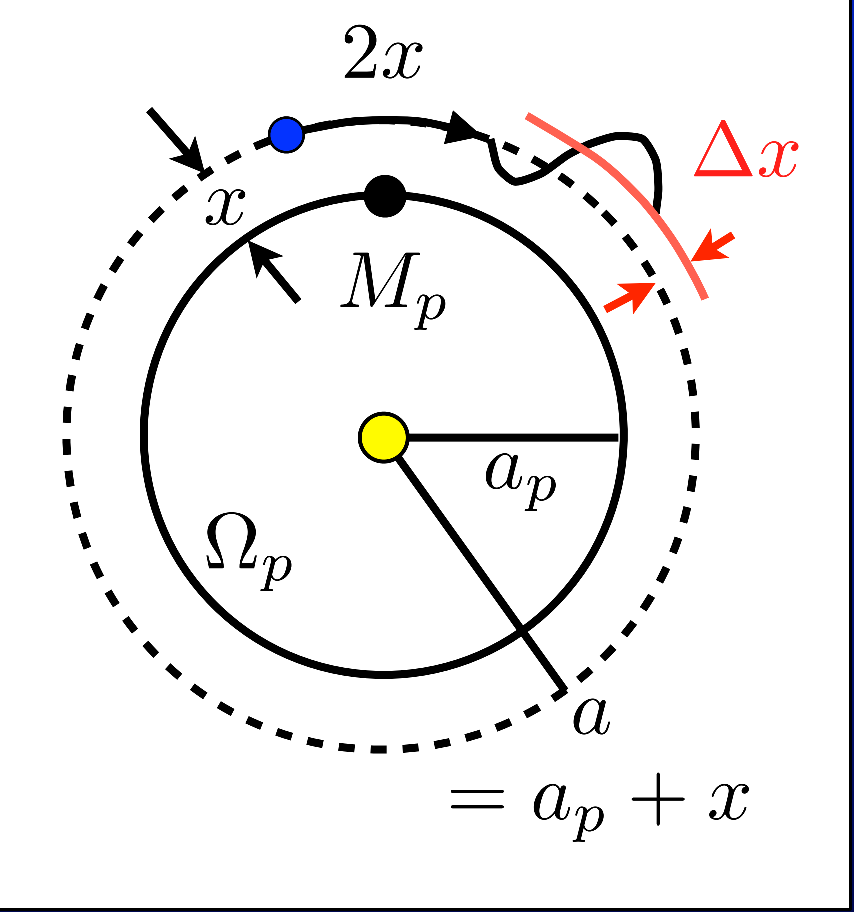
i.e., if $x < \left(\frac{M_p}{M_*}\right)^{2/7} a$

then chaos

Deriving the chaotic zone width

I. The kick at conjunction

$$x \ll a$$



Kick in eccentricity Δe

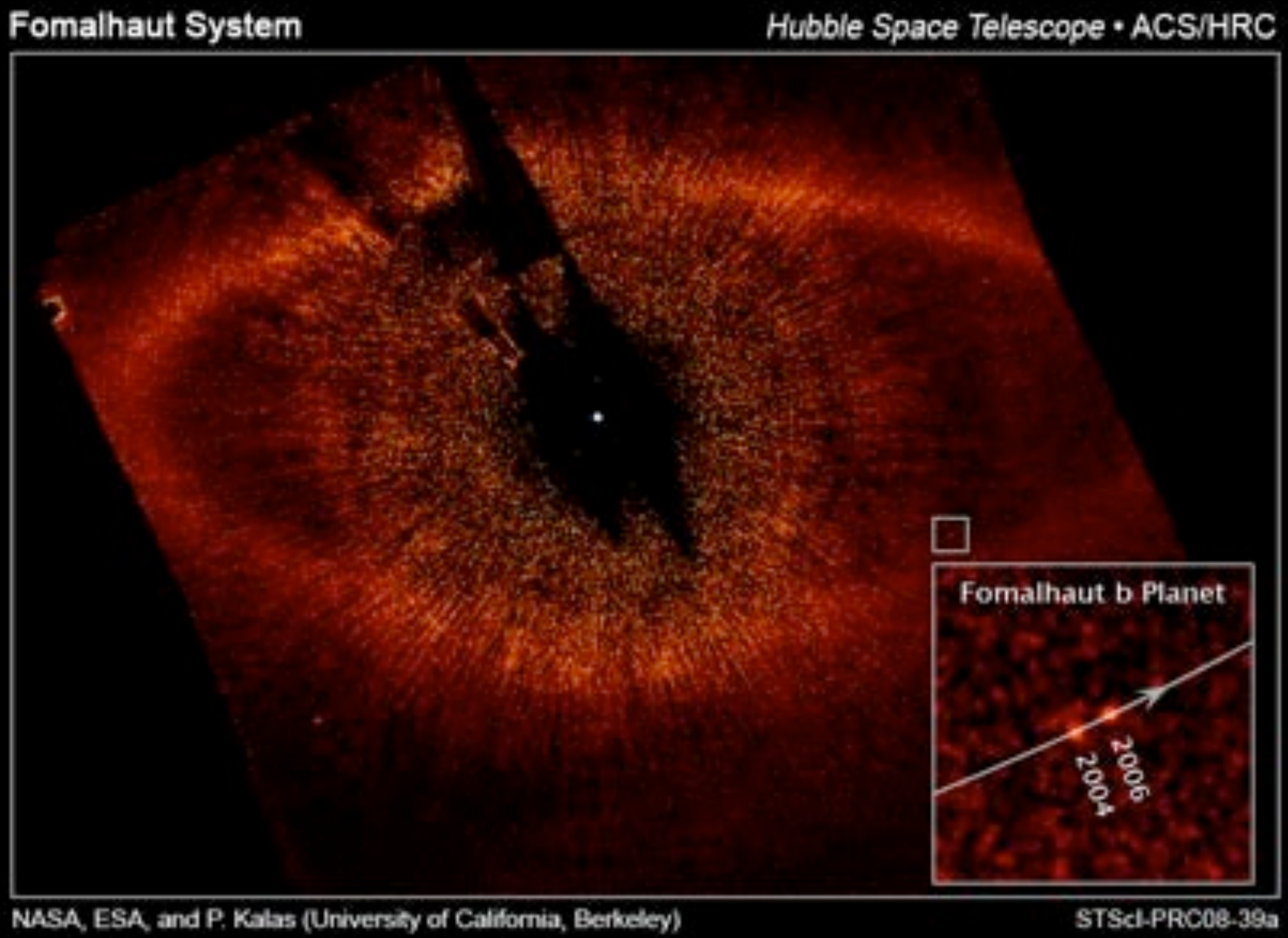
$$\Delta e \sim \frac{\Delta v}{v} \sim \frac{1}{v}\frac{GM_p}{x^2}\Delta t$$

$$\sim \frac{M_p}{M_*}\left(\frac{a}{x}\right)^2$$

Kick in semimajor axis Δx

Use Jacobi constant: $C_J \approx -\frac{GM_*}{2(a+x)} - \Omega_p\sqrt{M_*(a+x)(1-e^2)}$

$$\Rightarrow \frac{x\Delta x}{a^2} \sim (\Delta e)^2 \Rightarrow \frac{\Delta x}{a} \sim \left(\frac{M_p}{M_*}\right)^2\left(\frac{a}{x}\right)^5$$



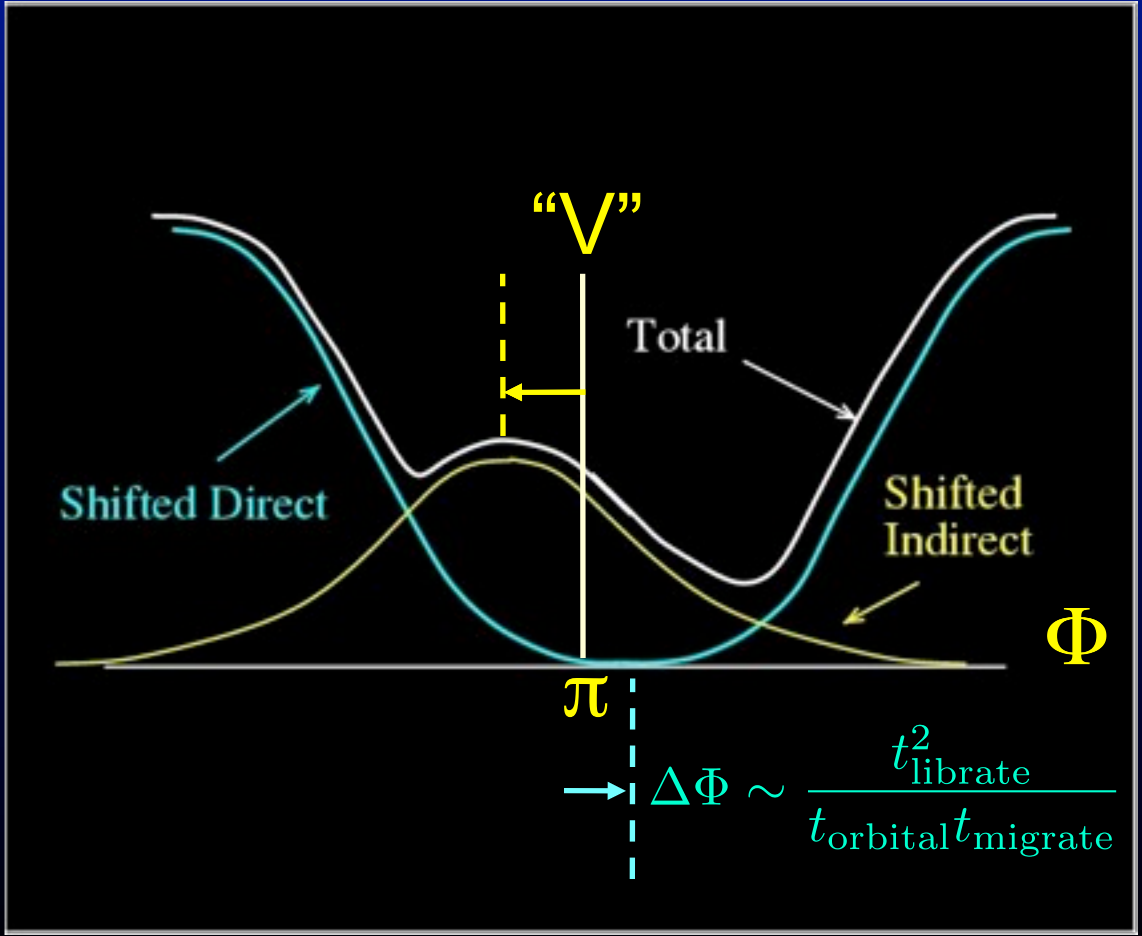
if $\omega_{\text{planet}} = \omega_{\text{belt}}$ (nested ellipses)

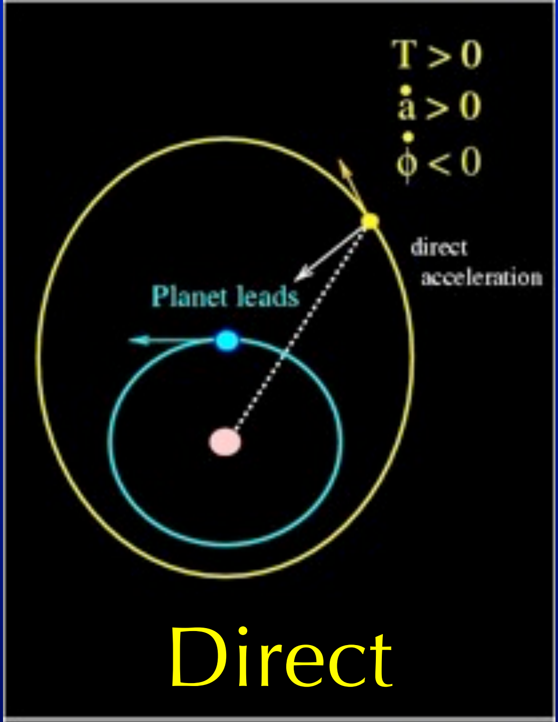
then
$$a_{\text{planet}} = 115\,\text{AU}$$
$$e_{\text{planet}} = 0.12$$
$$M_{\text{planet}} = 0.5 M_{\text{J}}$$

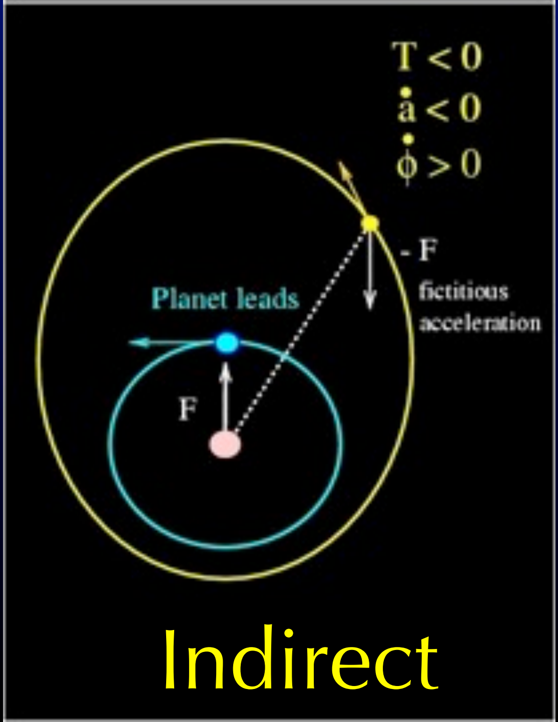
$$M_{\text{belt}} > M_{\text{parent bodies}} \sim 3 M_{\oplus}$$

Enough material for gas giant core

Asymmetric capture: Migration-shifted potentials







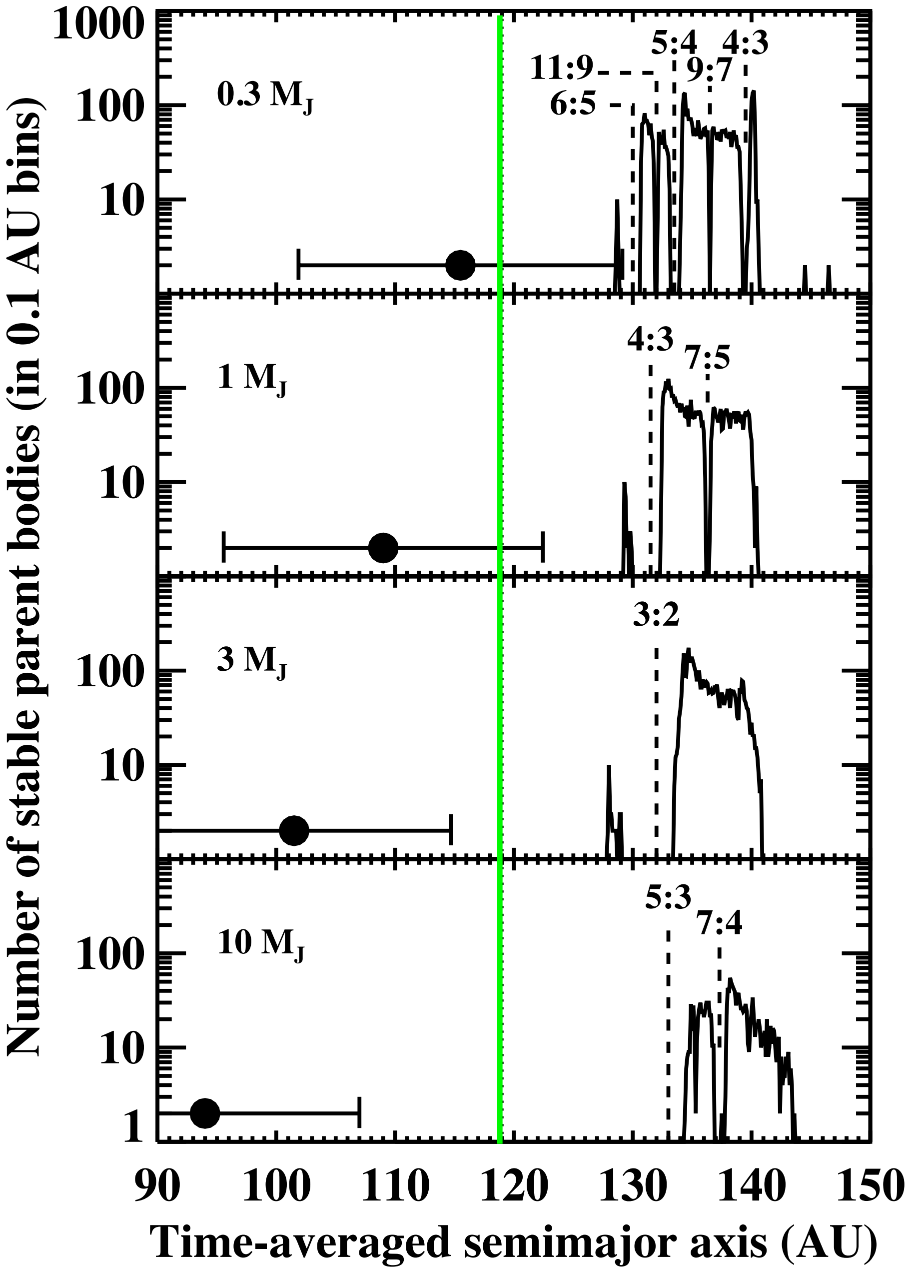
Results

- If $M_{\text{planet}} \uparrow$ then $a_{\text{planet}} \downarrow$

  Planet position too far from dust belt

  $\therefore\ M_{\text{planet}} < 3\,M_{\text{J}}$

- Planet also evacuates Kirkwood-type gaps



Chiang et al. 2008
Kalas et al. 2008

Results

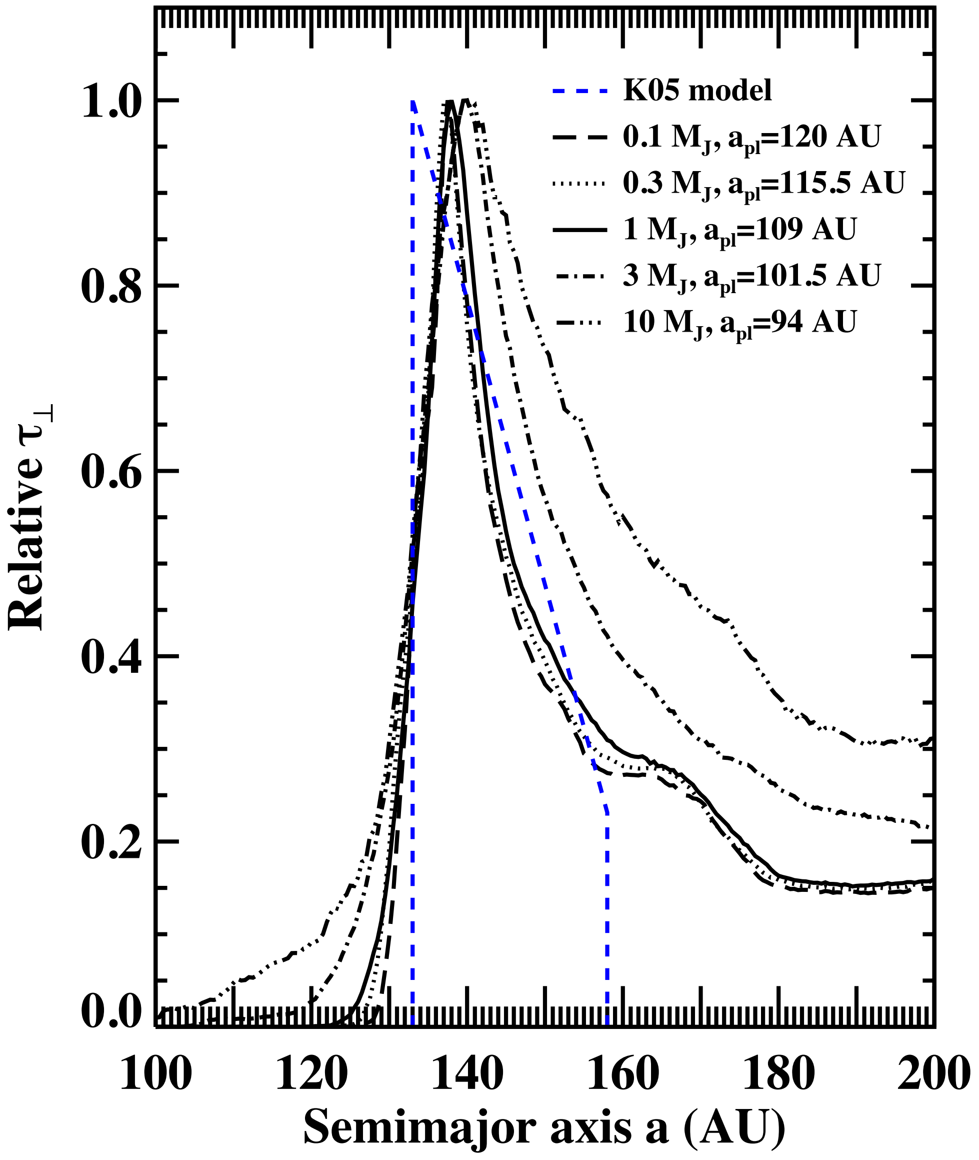
- If $M_{\rm planet}\uparrow$ then $e_{\rm dust}\uparrow$

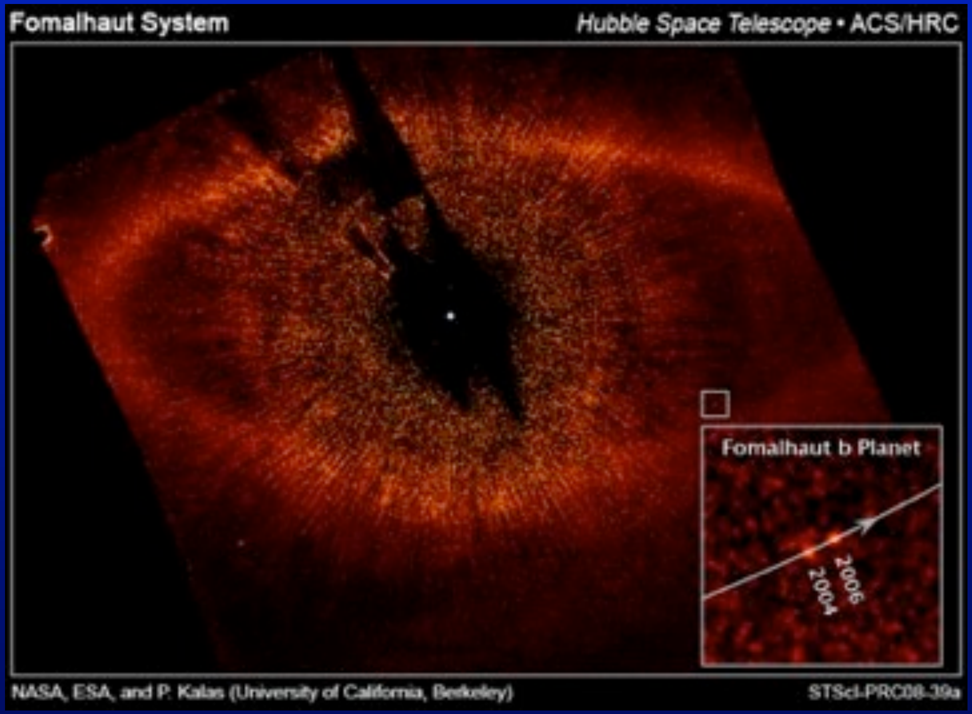
  Surface brightness profiles broaden too much

  $\therefore\ M_{\rm planet} < 3\,M_{\rm J}$

- $M_{\rm belt} > M_{\rm parent\ bodies} \sim 3M_\oplus$

  Enough material for gas giant core



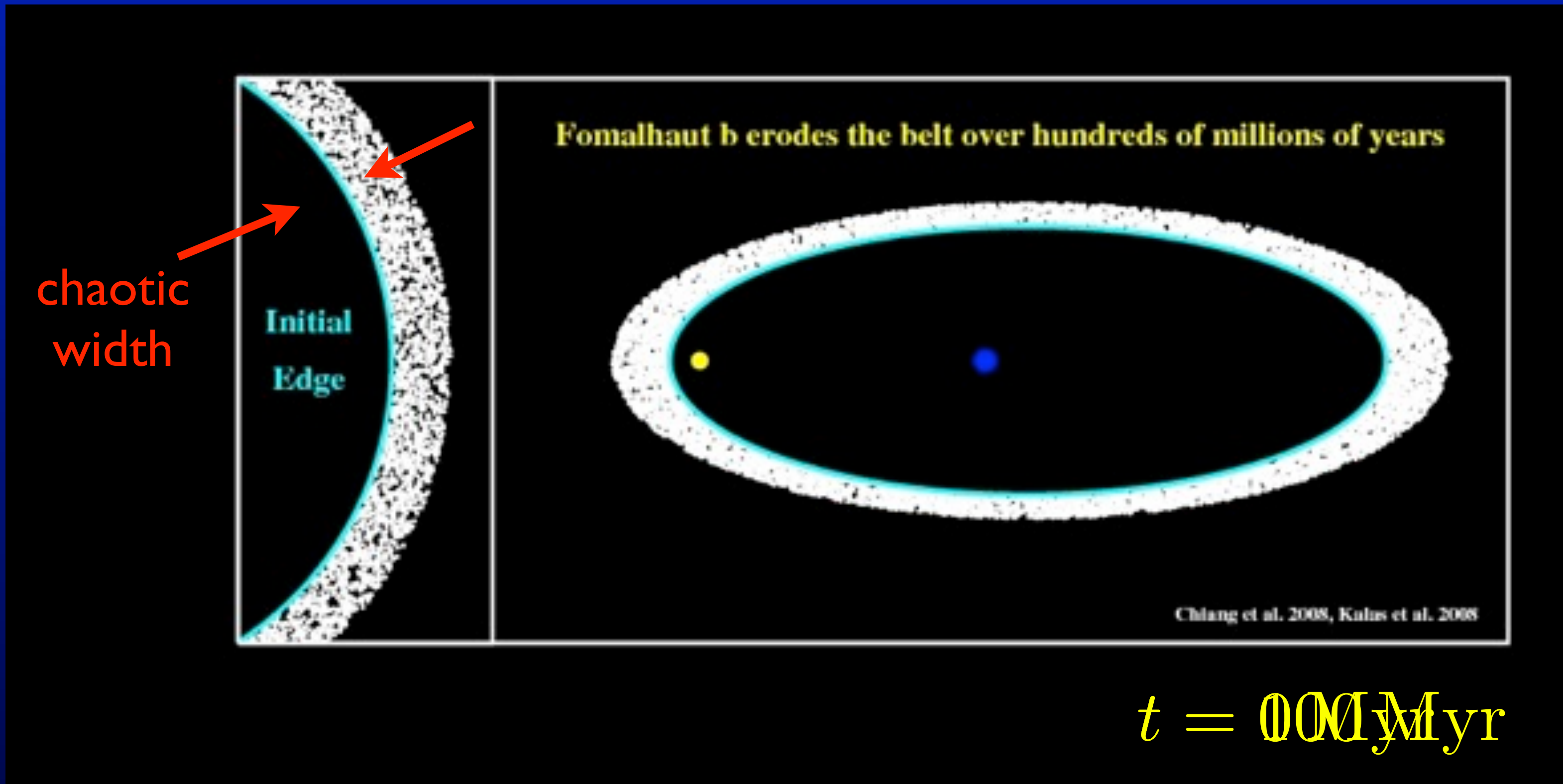


$$\text{if } \omega_{\text{planet}} = \omega_{\text{belt}} \text{ (nested ellipses)}$$

$$\text{then} \quad \begin{aligned} a_{\text{planet}} &= 115\,\text{AU} \\ e_{\text{planet}} &= 0.12 \\ M_{\text{planet}} &= 0.5 M_{\text{J}} \end{aligned}$$

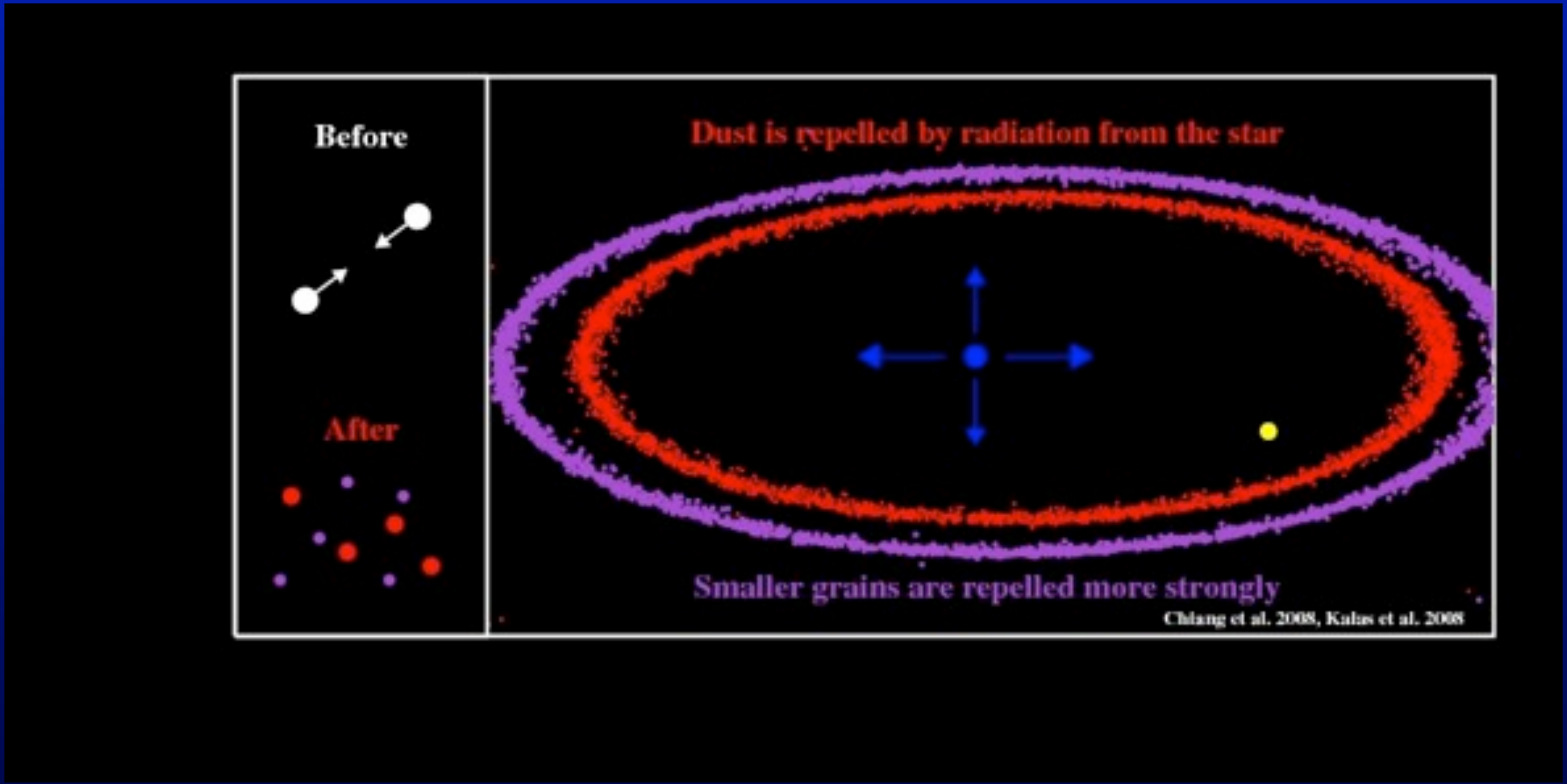
- The Kuiper belt comprises tens of thousands of icy, rocky objects having sizes greater than 100 km
- Many KBOs occupy highly eccentric and inclined orbits that imply a violent past
- Pluto and other Resonant KBOs share special gravitational relationships with Neptune
- Extrasolar debris disks are nascent Kuiper belts
- Belts are gravitationally sculpted by planets

Fomalhaut b: Planet-Debris Disk Interaction

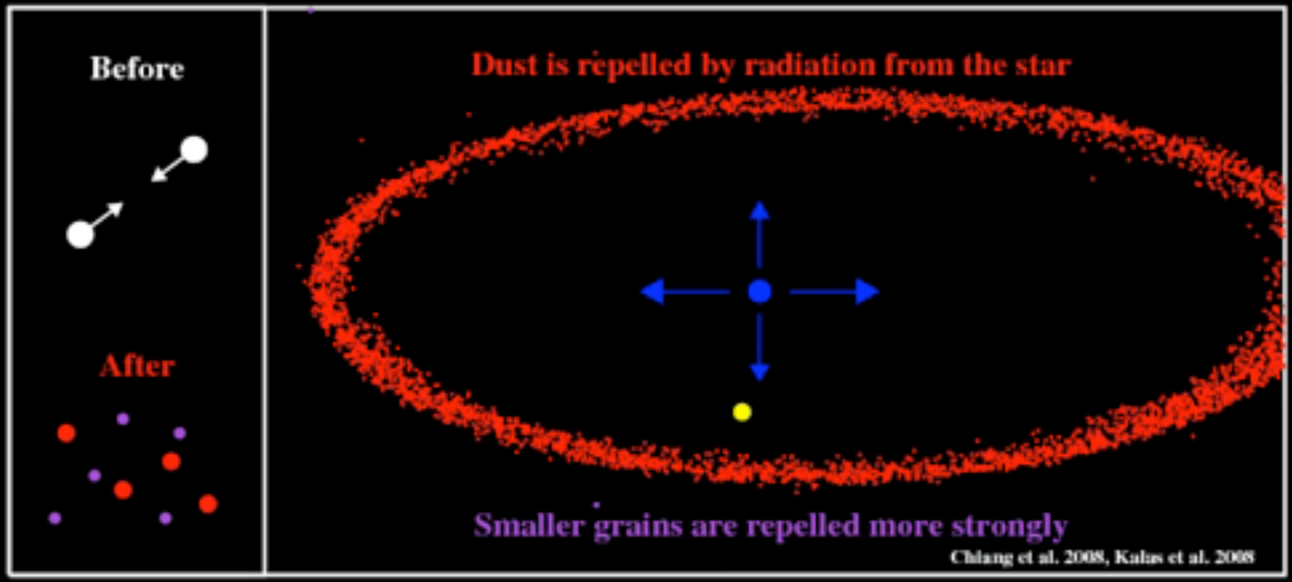


Step 1: Screen parent bodies for gravitational stability

$$t_{\rm age} \sim 10^8 \text{ yr}$$



Step 2: Replace parent bodies with dust grains



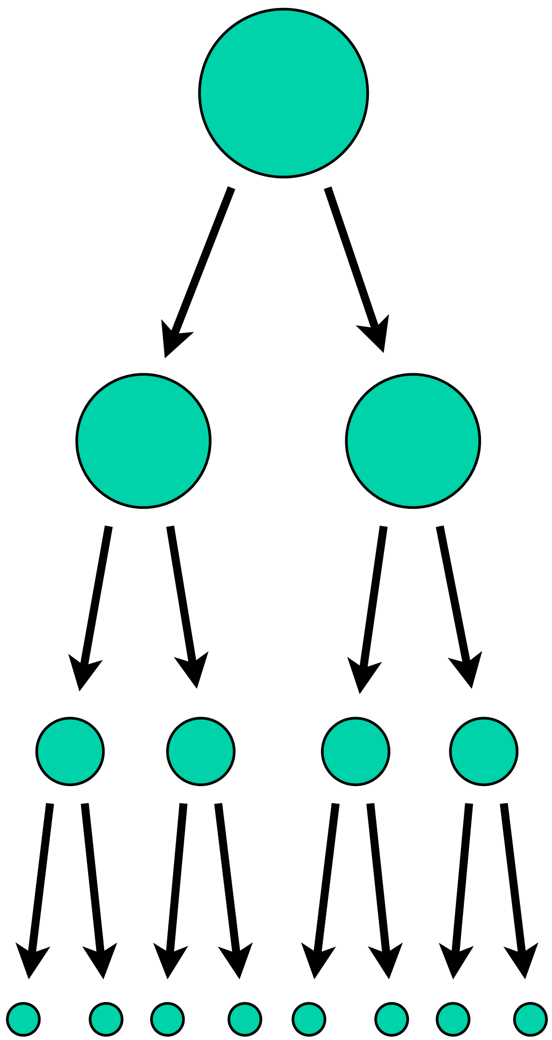
$$\Delta t = t_{\rm collision} = 0.1 \ {\rm Myr}$$

Step 3: Integrate dust grains with radiative force for collisional lifetime

$$t_{\rm collision} \sim t_{\rm orb}/\tau \sim 0.1 \ {\rm Myr}$$

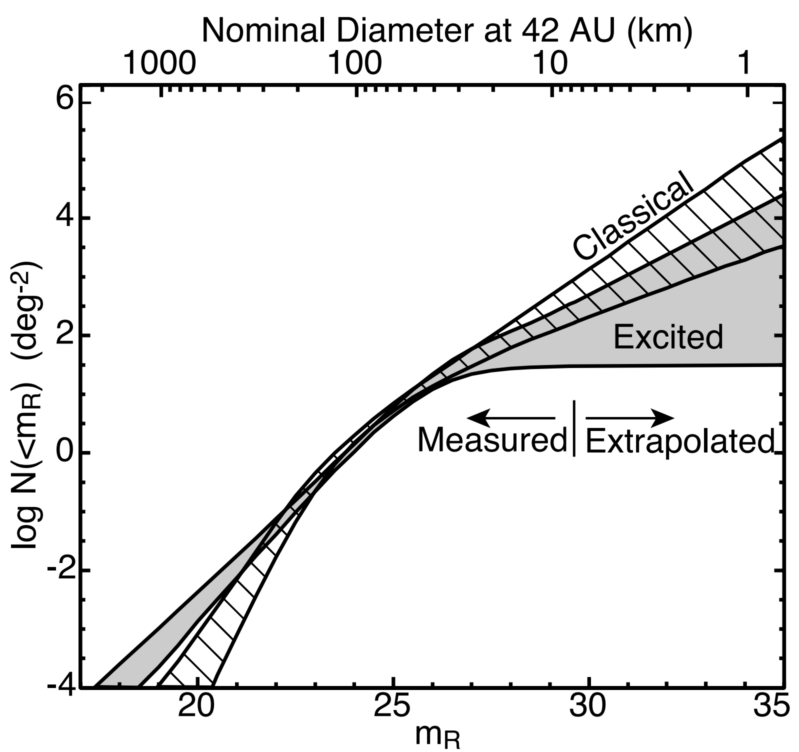
Collisional Cascade

Parent bodies collide once in system age



Most visible grains are just large enough to avoid stellar blow-out

Distribution of sizes of Kuiper belt objects



Results

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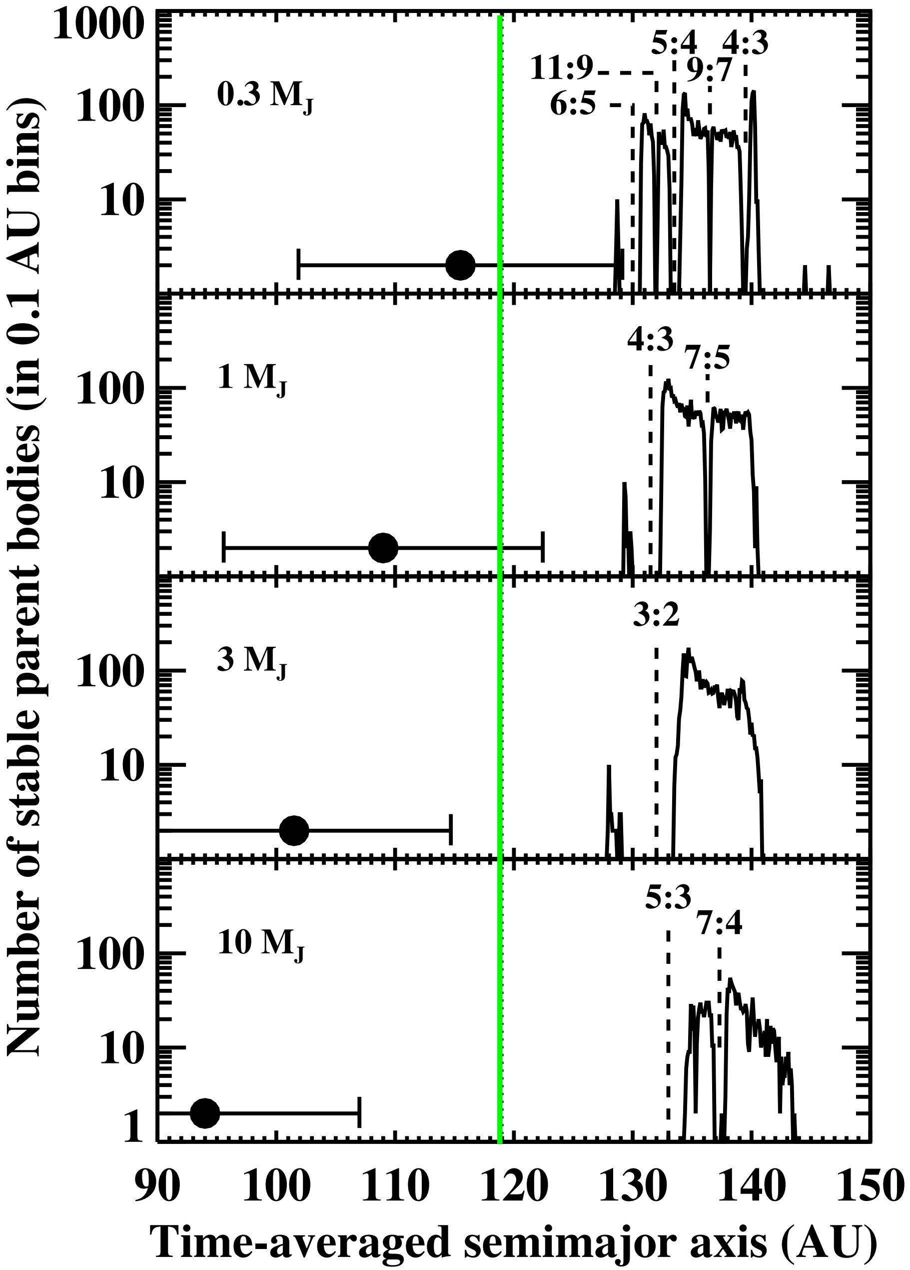
  Planet position too far from dust belt

  $$\therefore\ M_{\text{planet}} < 3\, M_{\text{J}}$$

- Planet also evacuates Kirkwood-type gaps

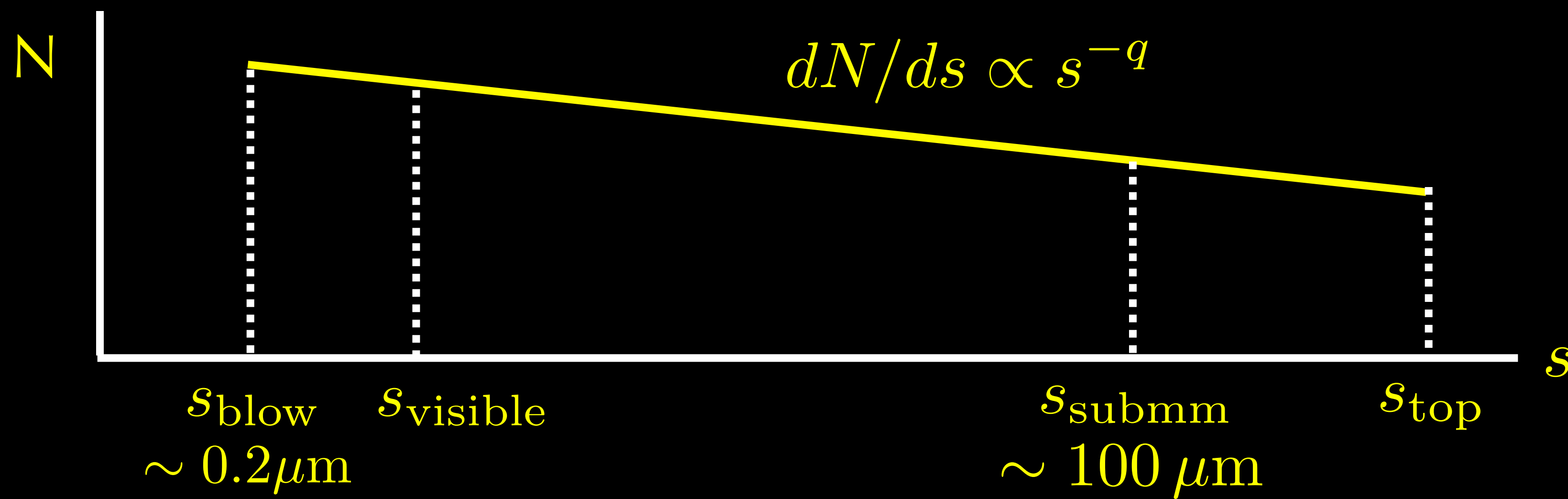
- $M_{\text{belt}} > M_{\text{parent bodies}} \sim 3 M_{\oplus}$

  Enough material for gas giant core



Chiang et al. 2008
Kalas et al. 2008

Measuring Debris Disk Masses



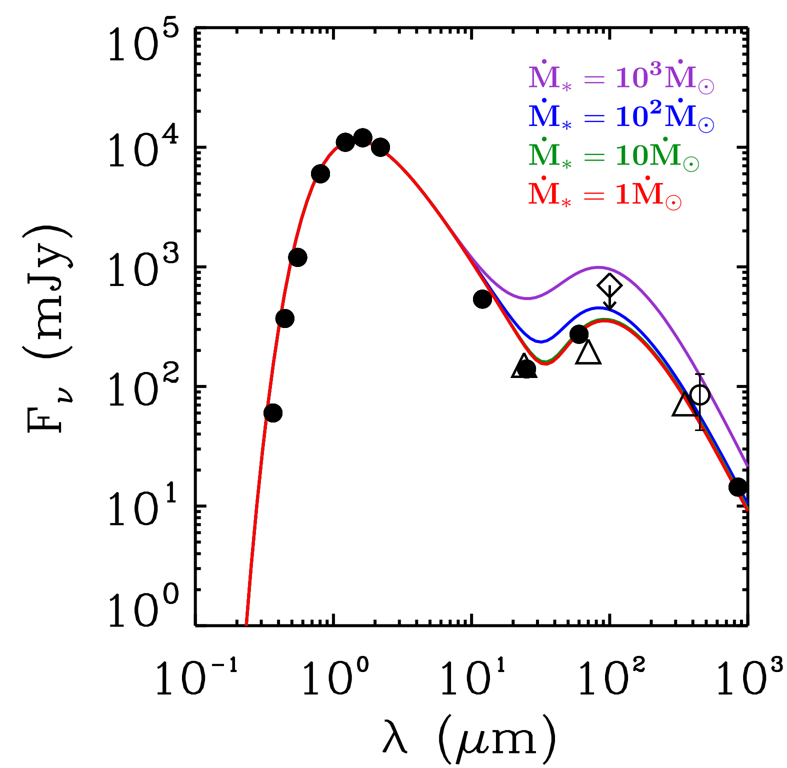
850 μm flux consistent w/

$M_{\rm SED}(s_{\rm top}) \sim 0.01 M_\oplus$

$q = 7/2$(Dohnanyi)

$s_{\rm top} \sim 10$ cm

[from $t_{\rm collision}(s_{\rm top}) \sim t_{\rm age}$]



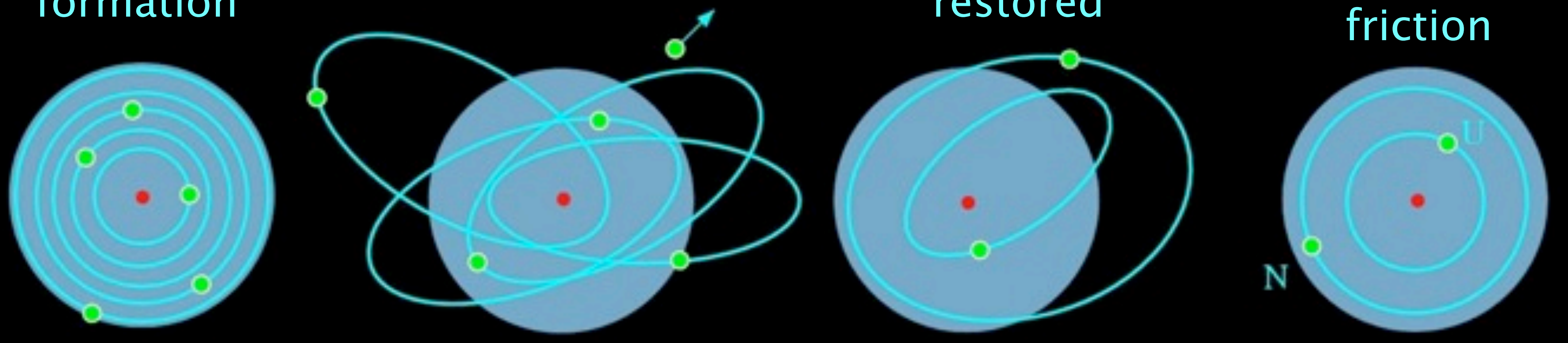
Packed planetary systems

Packed formation

Instability and ejection

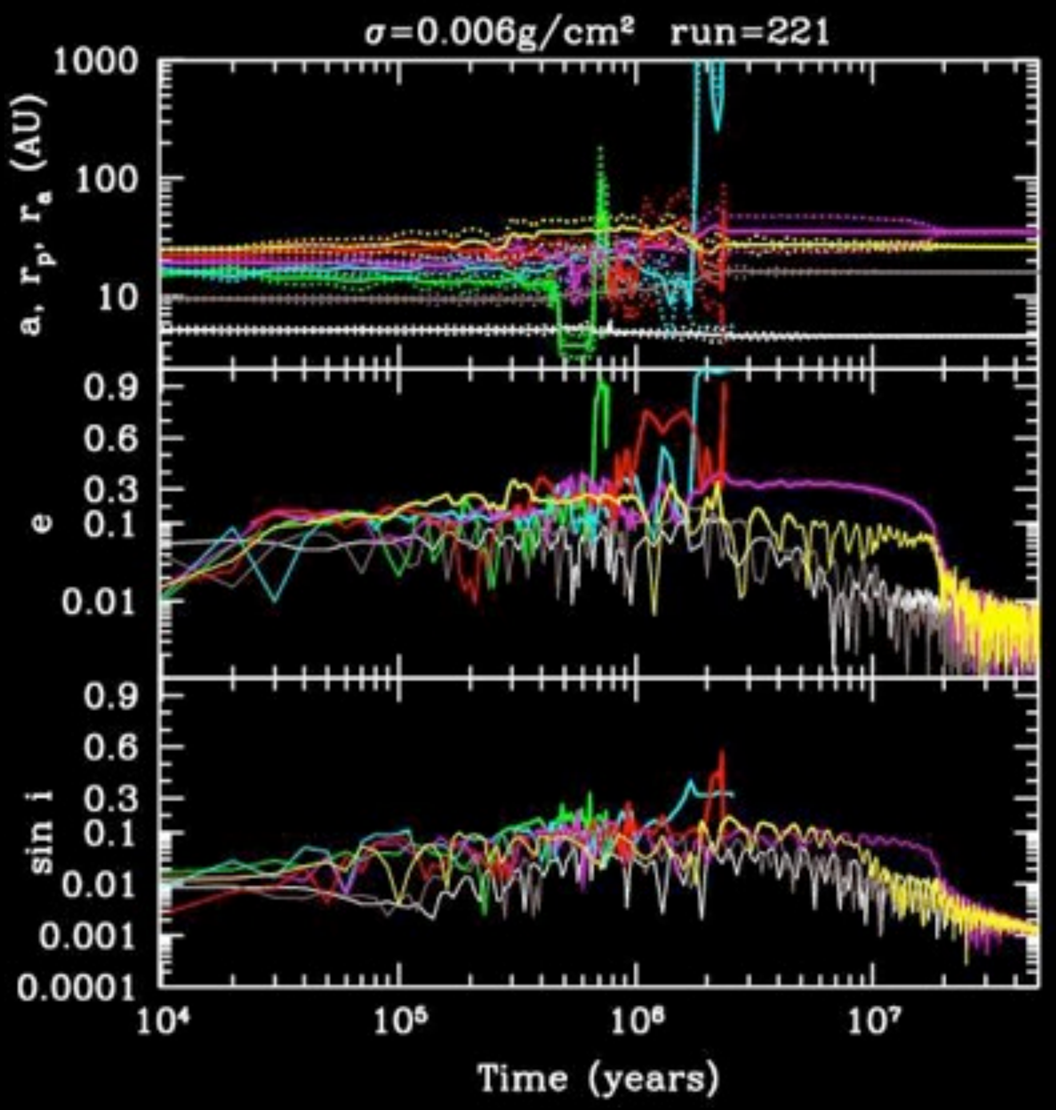
Stability restored

Regularization by dynamical friction

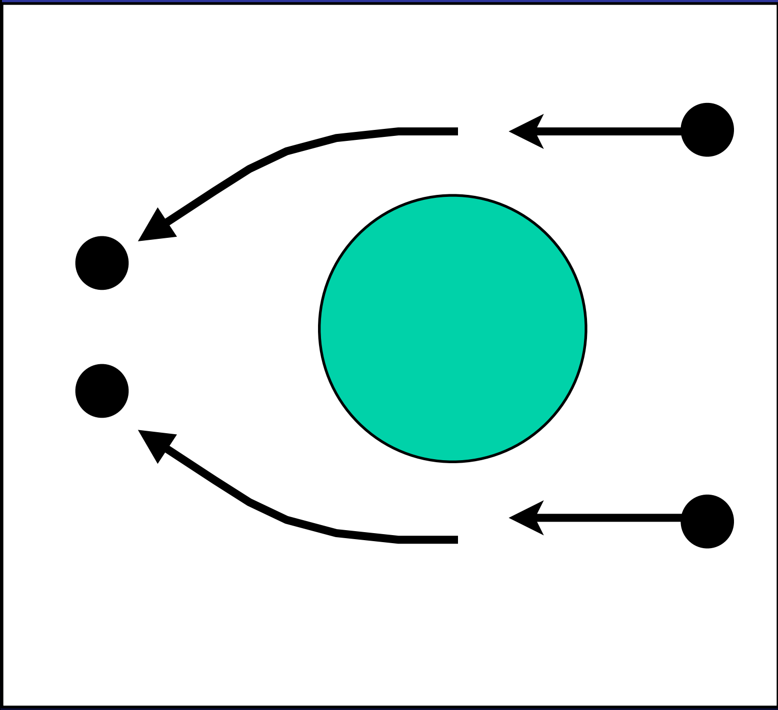


occurs when planets outweigh parent disk

Signature recorded in Kuiper belt

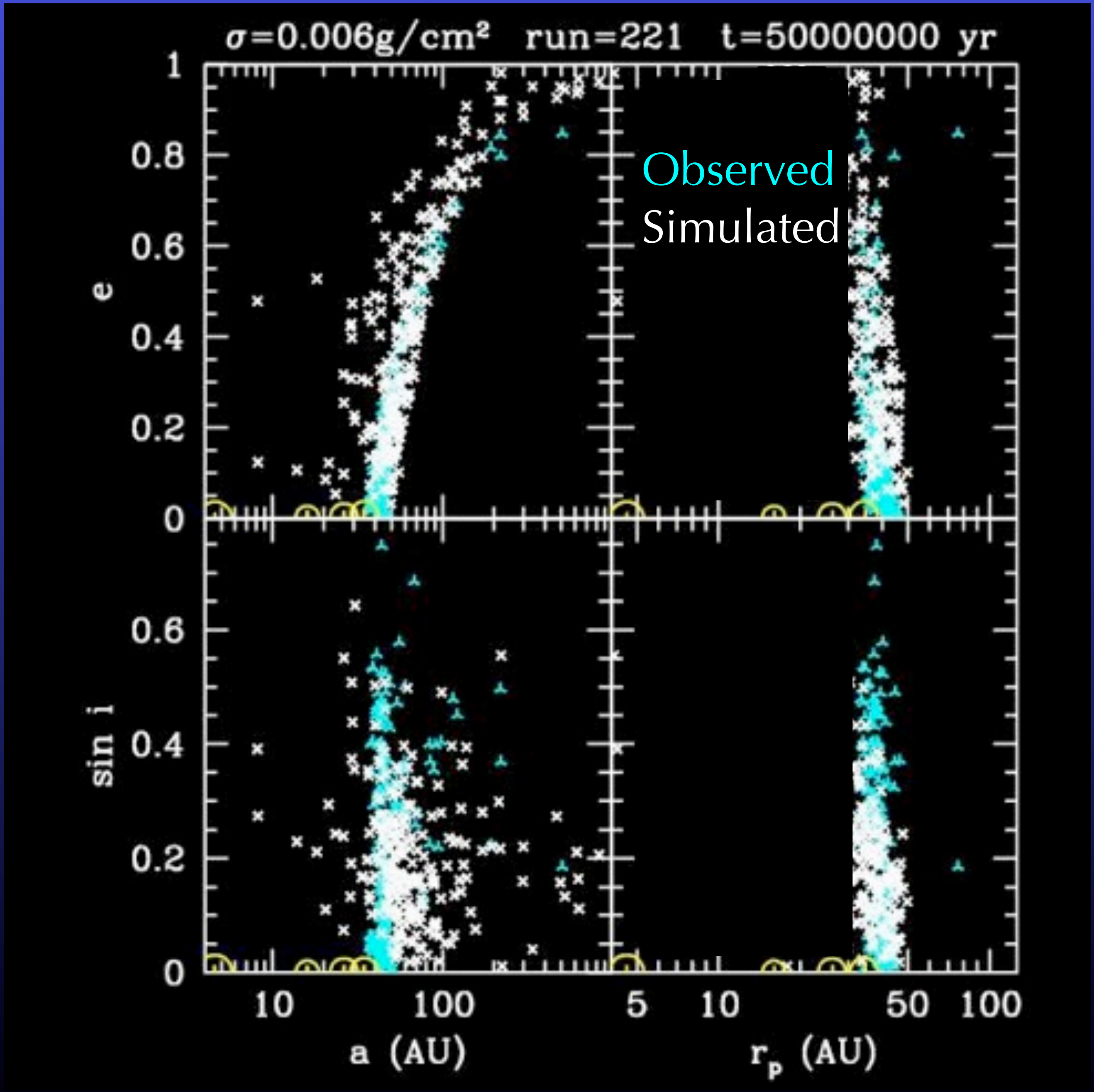


Dynamical friction:
Small bodies slow
big bodies



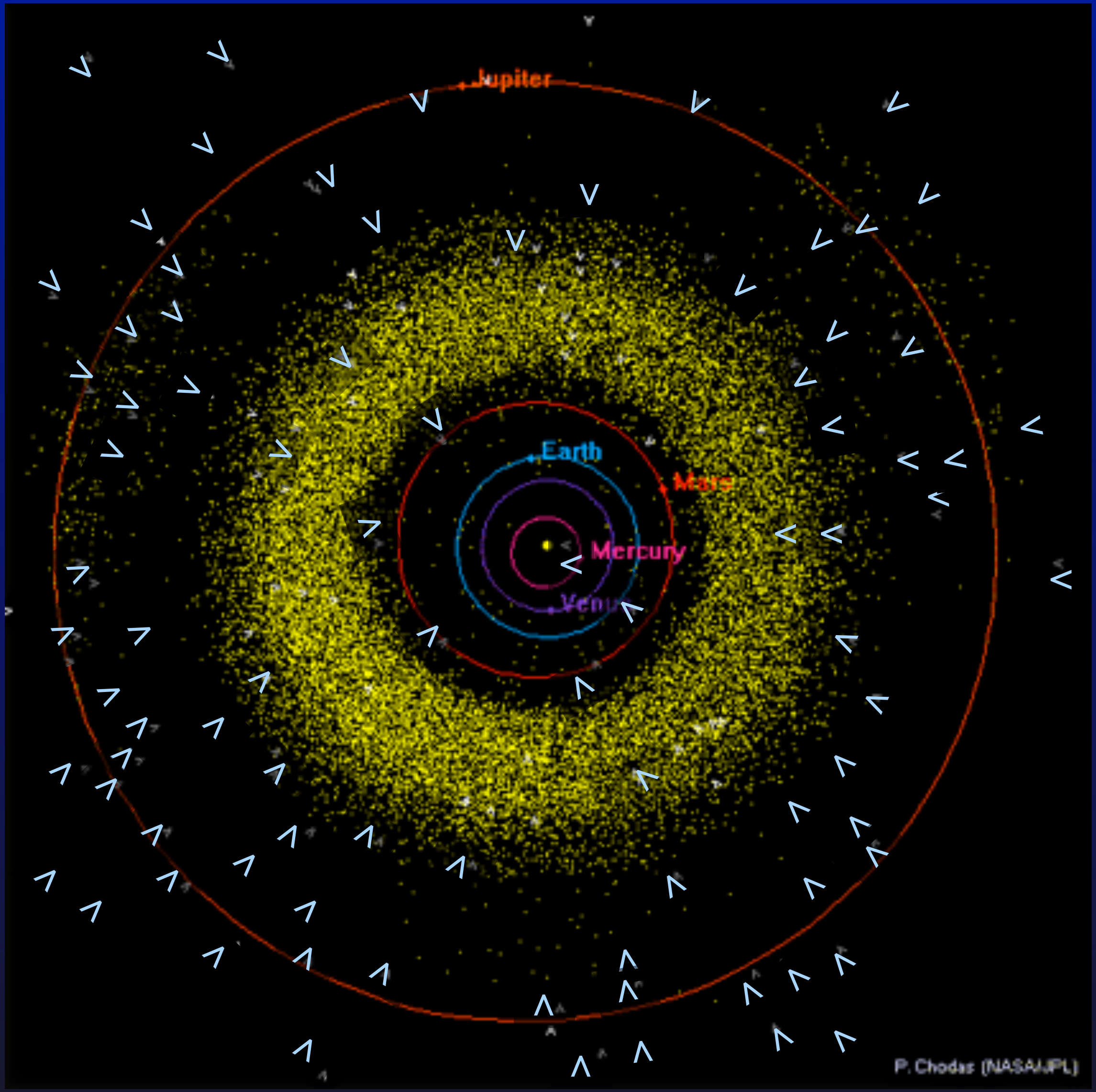
Numerical simulations of packed planetary systems

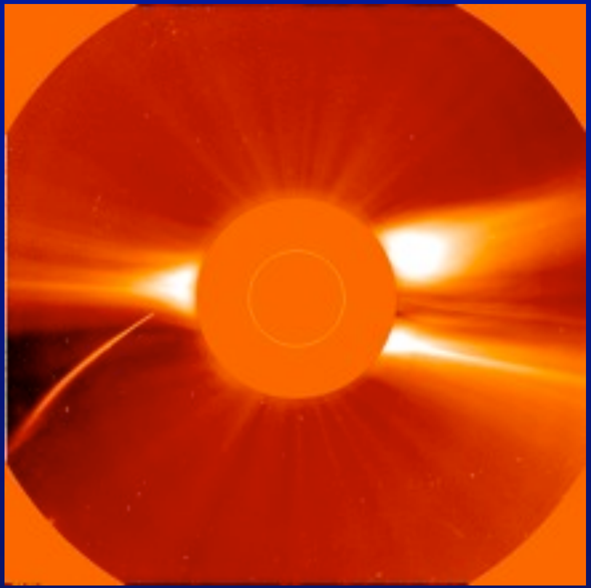
Solar system-like outcomes emerge from chaos



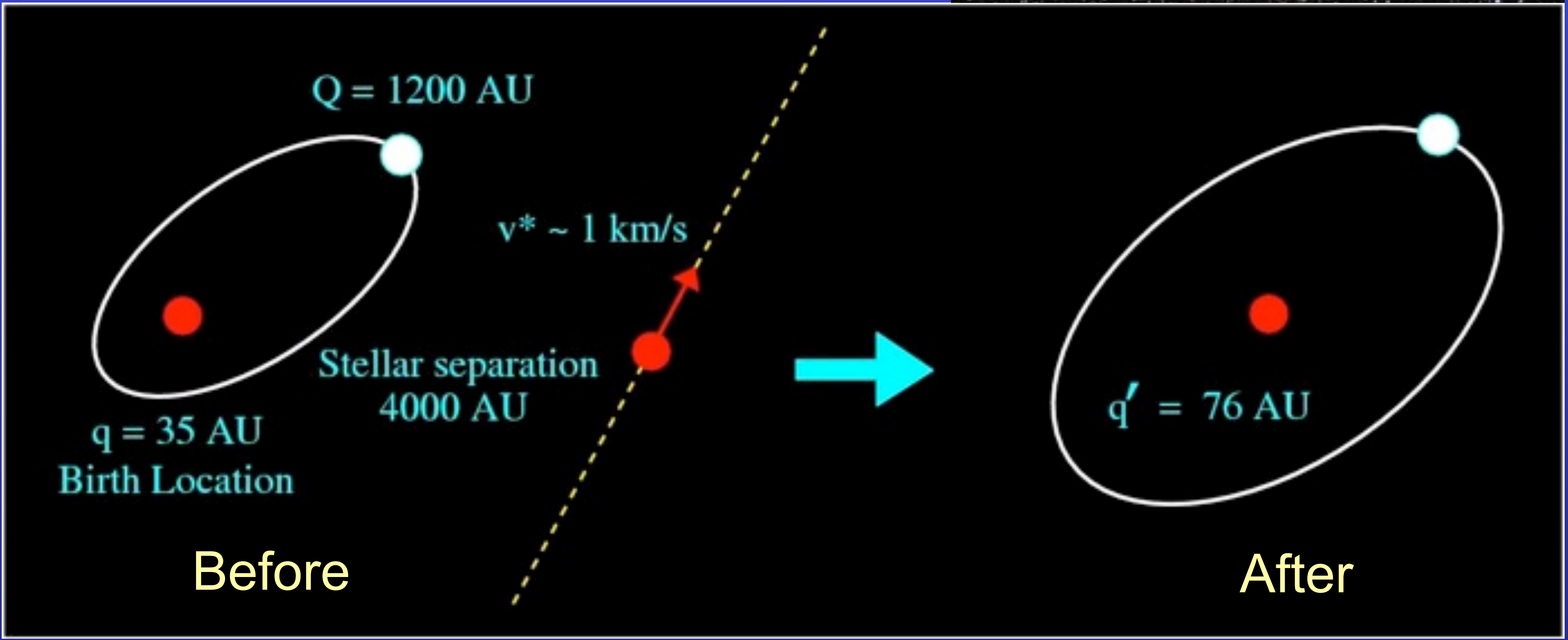
Stirring of KBOs by Rogue Ice Giants

Short-Period Comets





Raising Sedna's Peri by Stellar Encounters

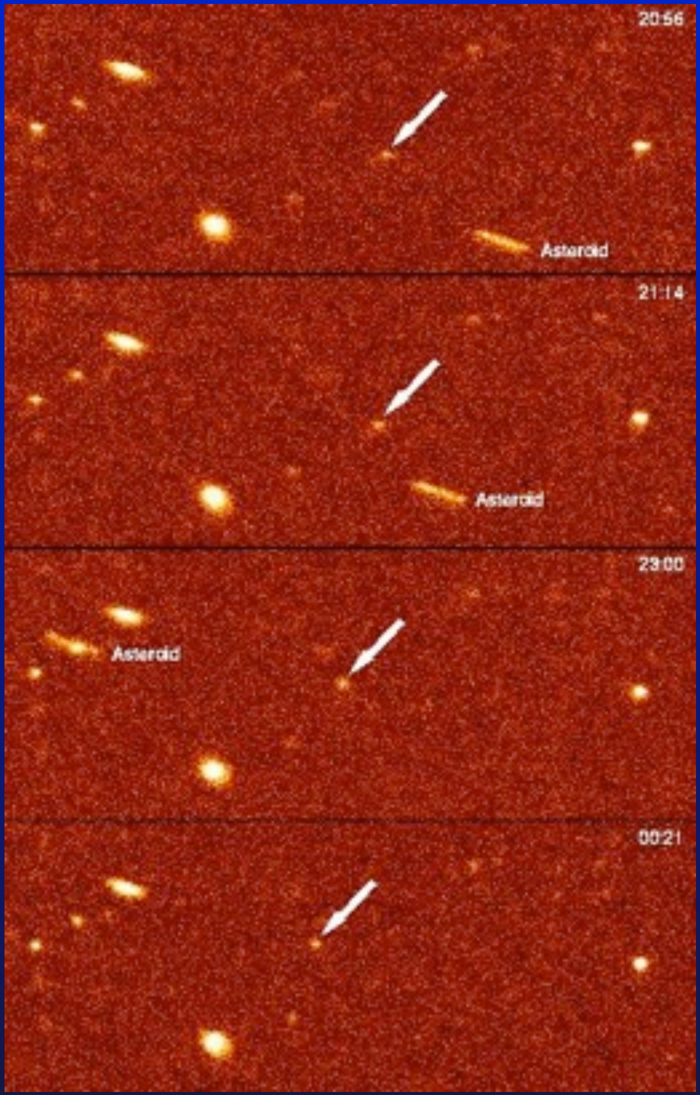


Typical open cluster

- $n_* \sim 4\,\mathrm{stars/pc^3}\ \ (R_{1/2} \sim 2\,\mathrm{pc})$
- $t \sim 200\,\mathrm{Myr}$
- $\langle v_*^2 \rangle^{1/2} \sim 1\,\mathrm{km/s}$

Fernandez & Brunini 00

Discovery of Kuiper Belt Object (KBO) #3

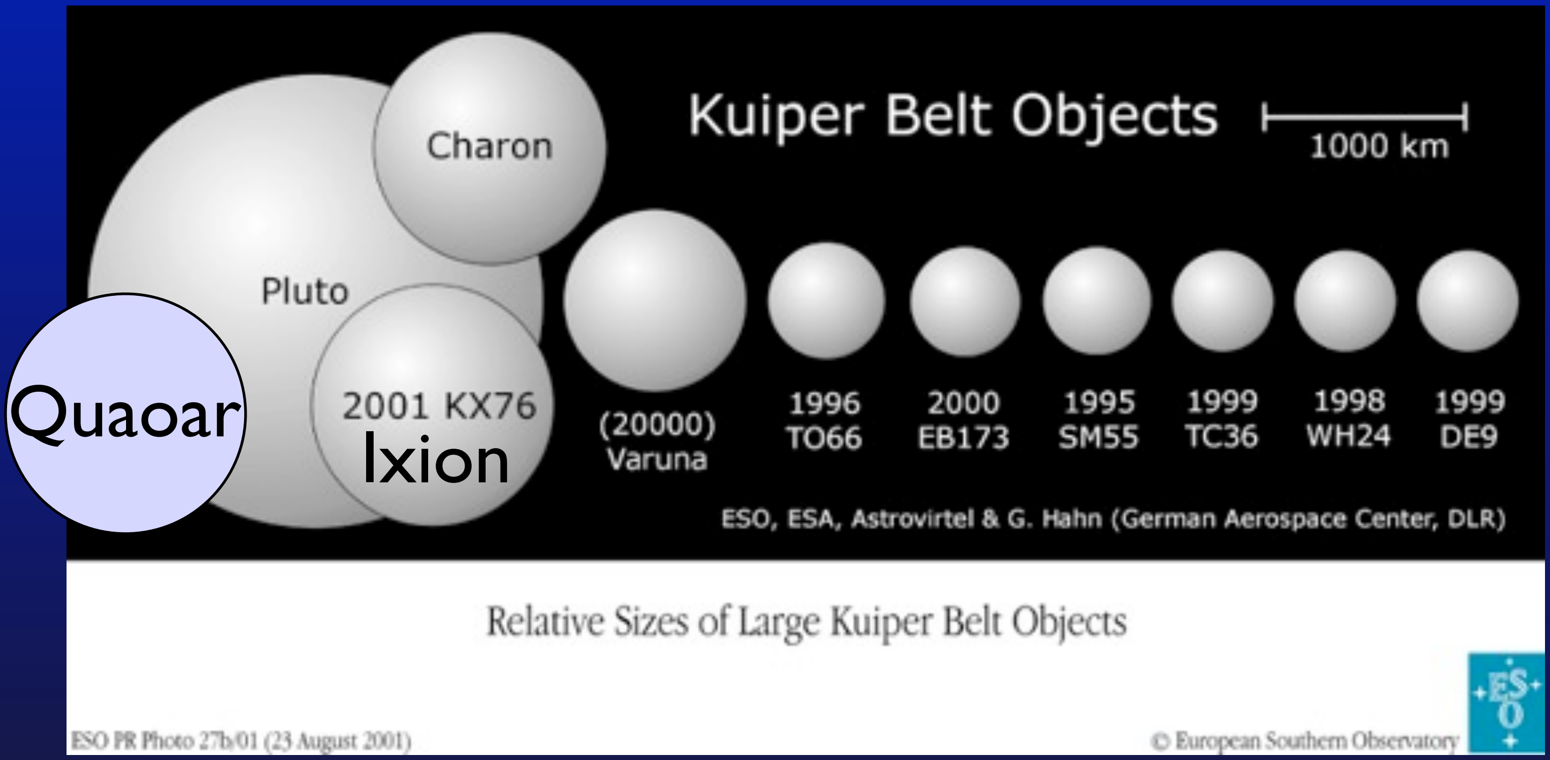


1992 QB1: "Smiley"

Figure 4.1 Jane Luu and Dave Jewitt. The picture was taken in the control room of the UKIRT telescope in 1994. (Jane Luu.)

David Jewitt (U Hawaii)
Jane Luu (UC Berkeley)

Size depends on observed brightness and intrinsic reflectivity (albedo)

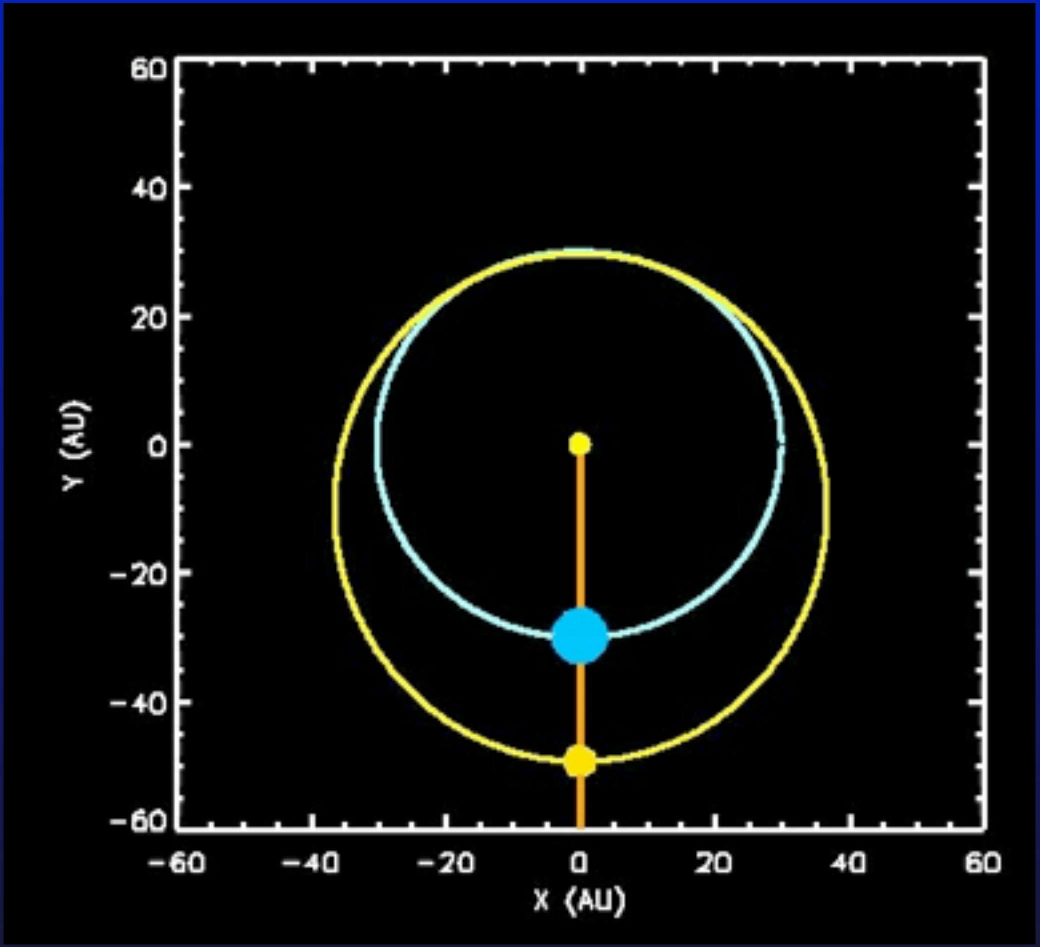


Planetary Protection Mechanism: Orbit-Orbit Resonance

Neptune makes 3 orbits

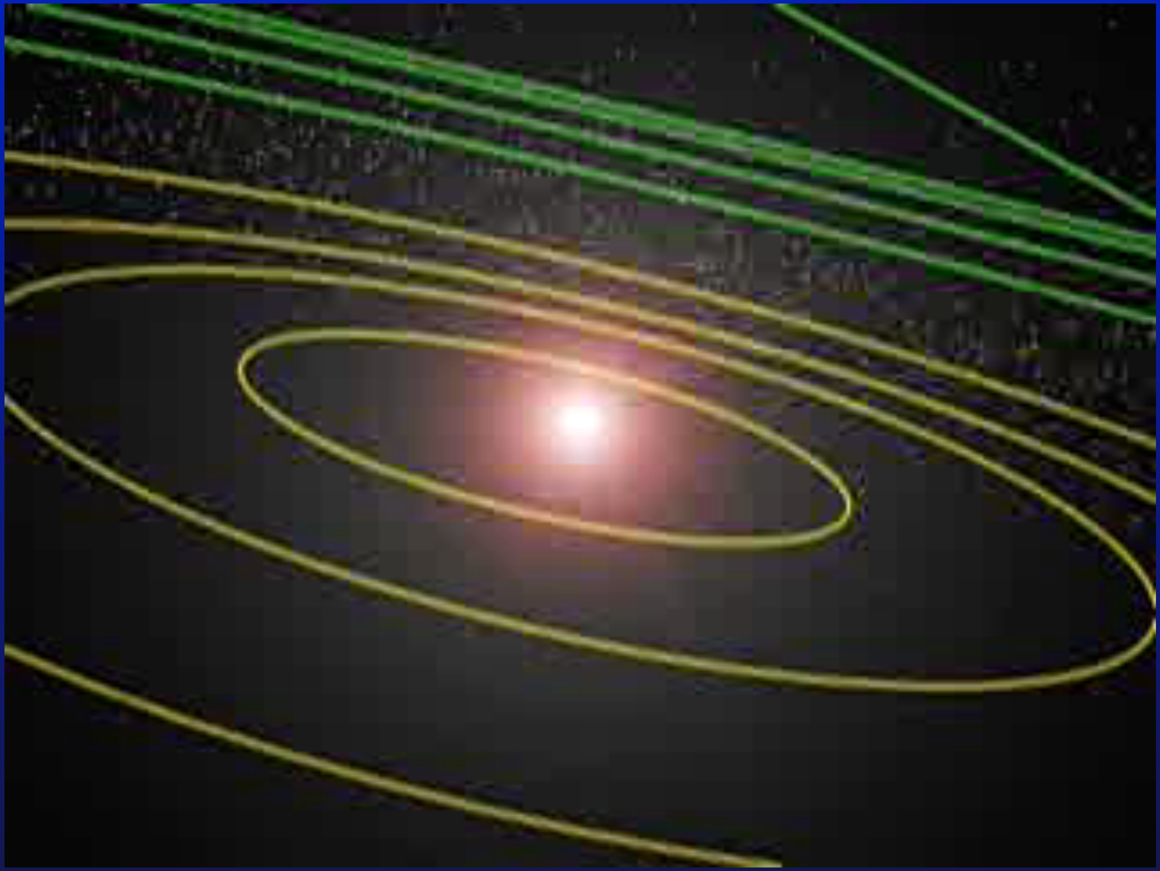
for every

2 orbits of Pluto

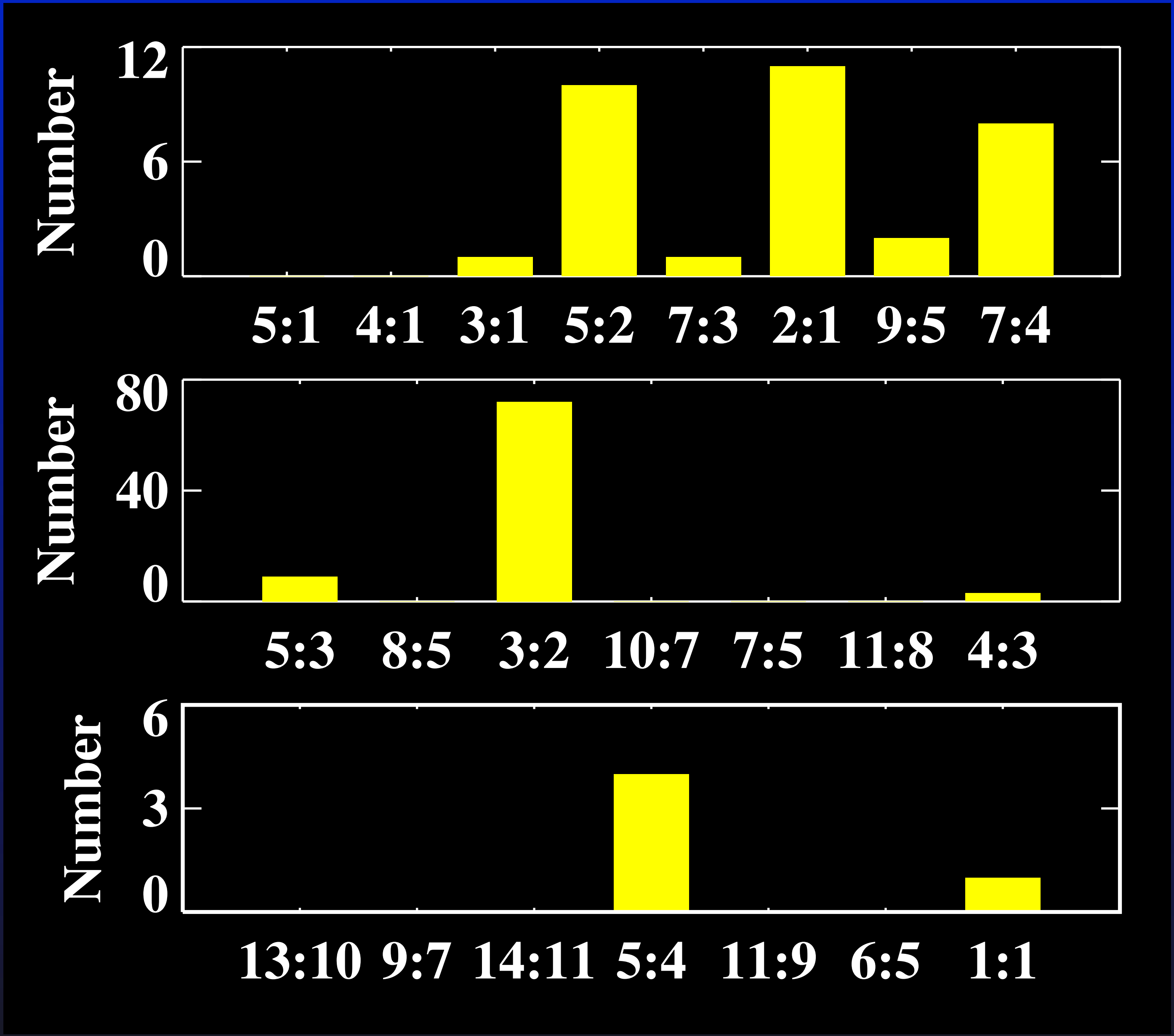


"Dance of the Plutinos"

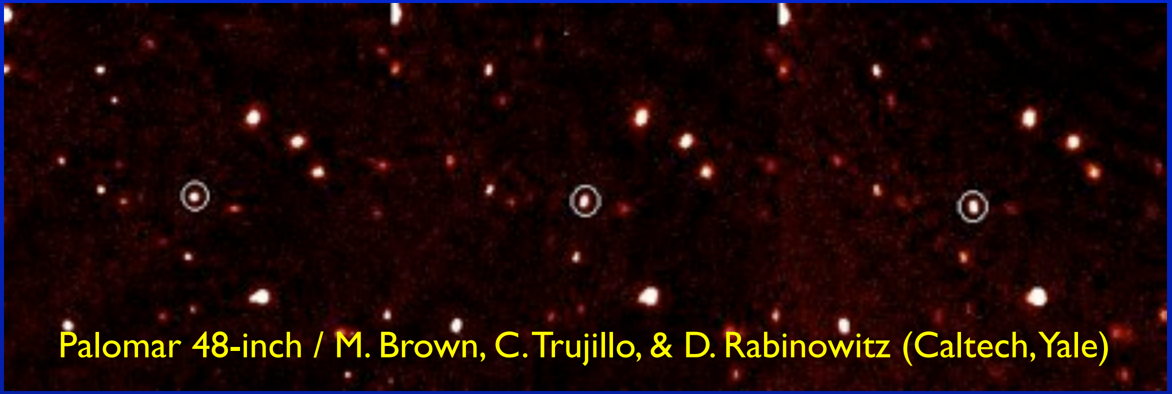
The Orbit of Sedna

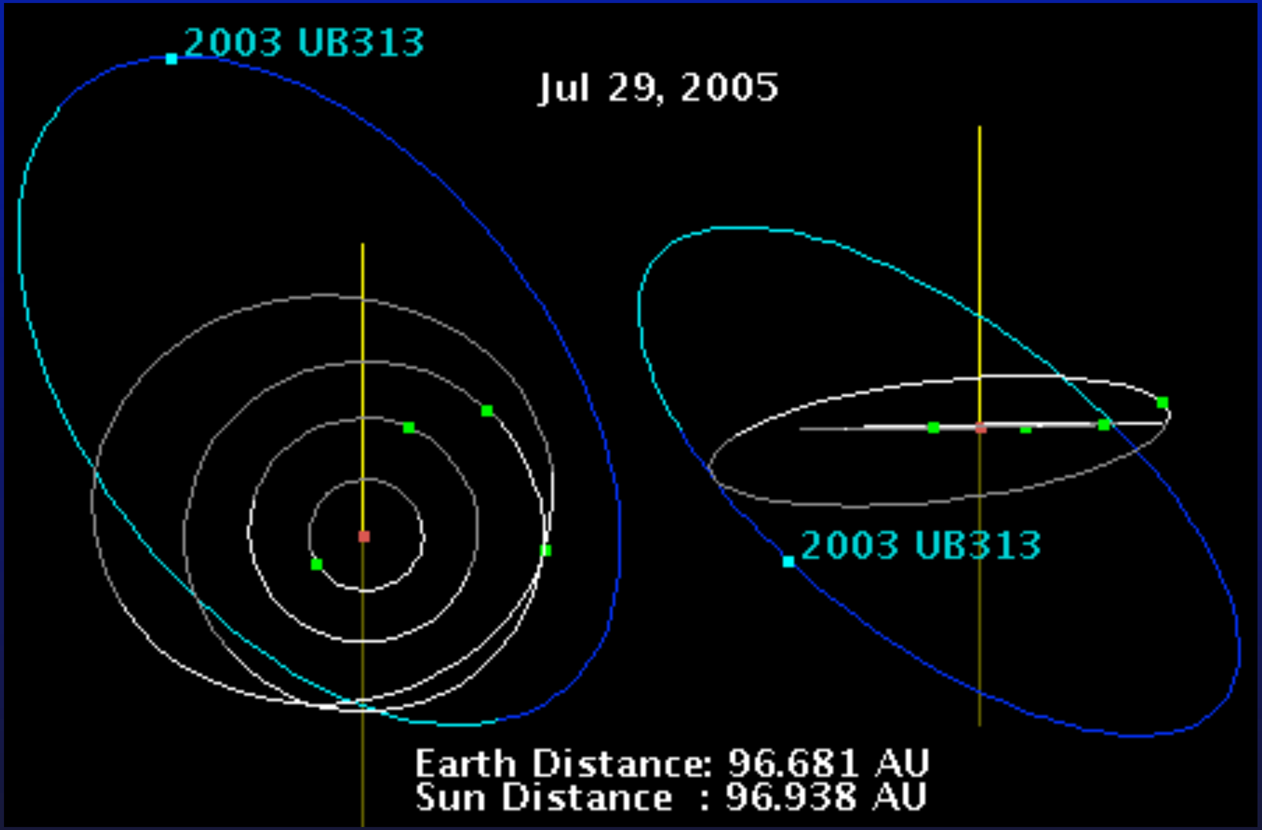


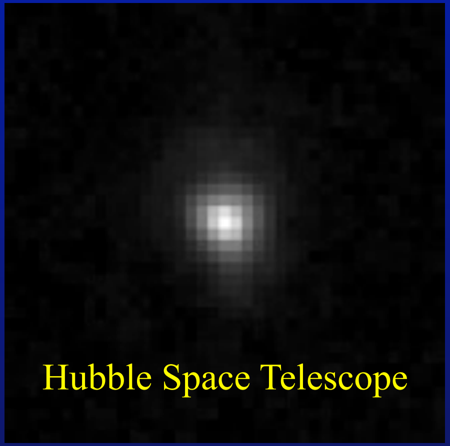
Resonant KBOs



2003 UB_{313}
"Xena"
Bigger than Pluto







2003 UB_{313} (m_{app} = 19)
Diameter = 2397±100 km

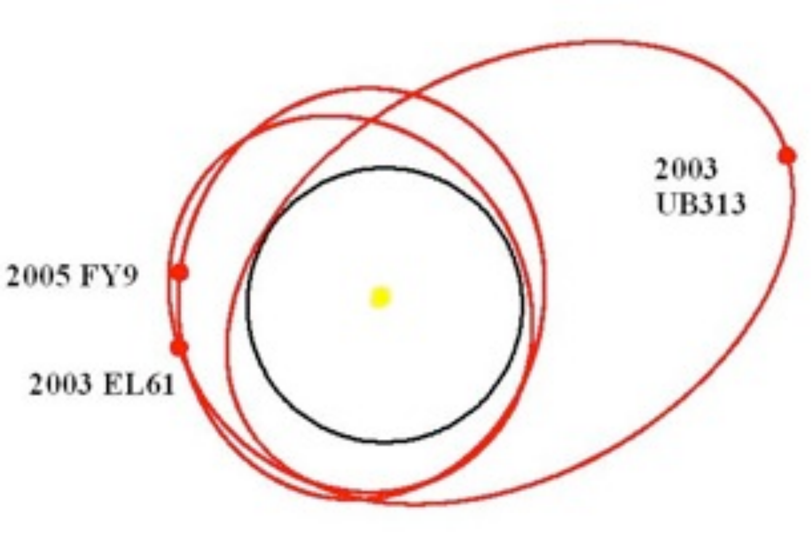
vs.

Pluto
Diameter = 2274 km

"Dwarf Planets"

I.A.U. definition

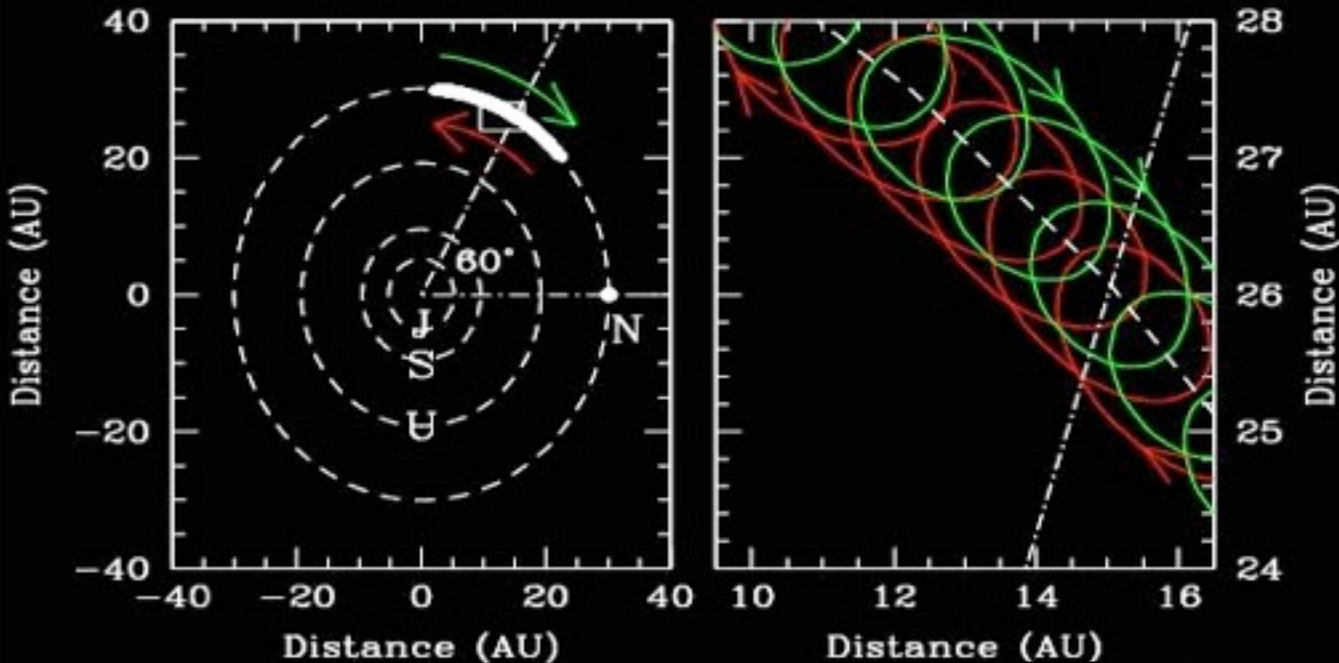
(a) orbits the Sun
(b) hydrostatic (round) shape
(c) not a satellite
(d) not cleared its neighborhood

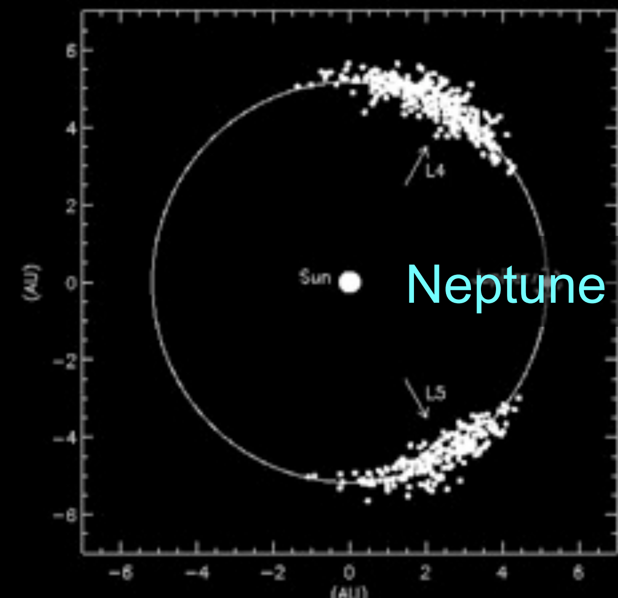


What we know:

- The Kuiper belt comprises tens of thousands of icy, rocky objects having sizes greater than 100 km
- The Kuiper belt is the source of short-period comets
- Pluto and other Resonant KBOs share special gravitational relationships with Neptune
- Many KBOs, especially large ones, occupy highly eccentric and inclined orbits that imply a violent past
- Other star systems have their own Kuiper belts

First discovered Neptune Trojan (1:1)





1 “Large” Neptune Trojan in 60 □°

⇒ ~10-30 Large Neptune Trojans

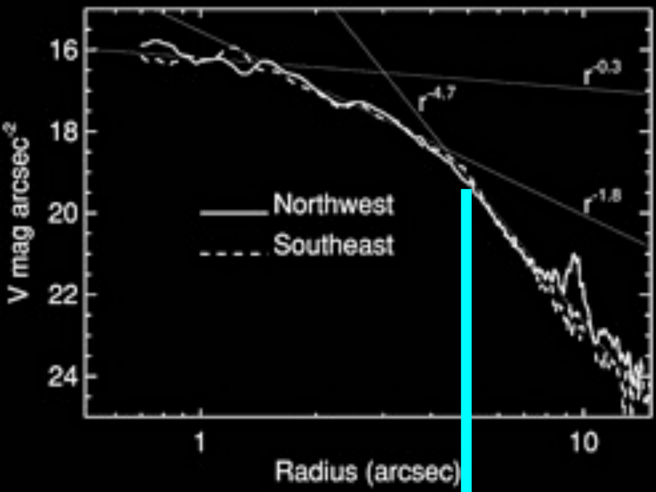
vs. ~1 Large Jovian Trojan

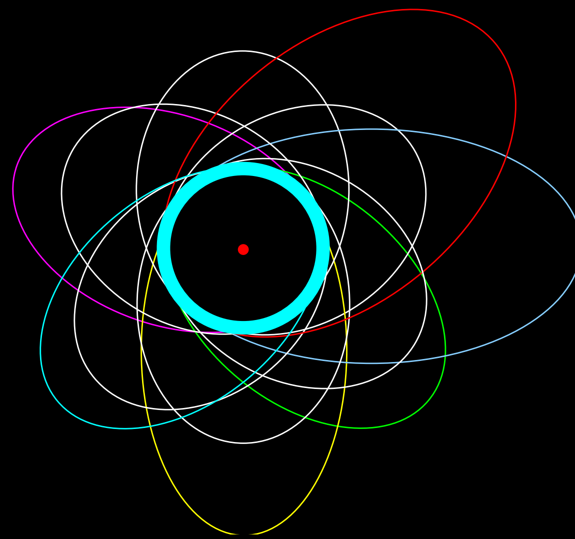
(“Large” ≡ 130-230 km diameter
assuming 12-4% visual albedo)

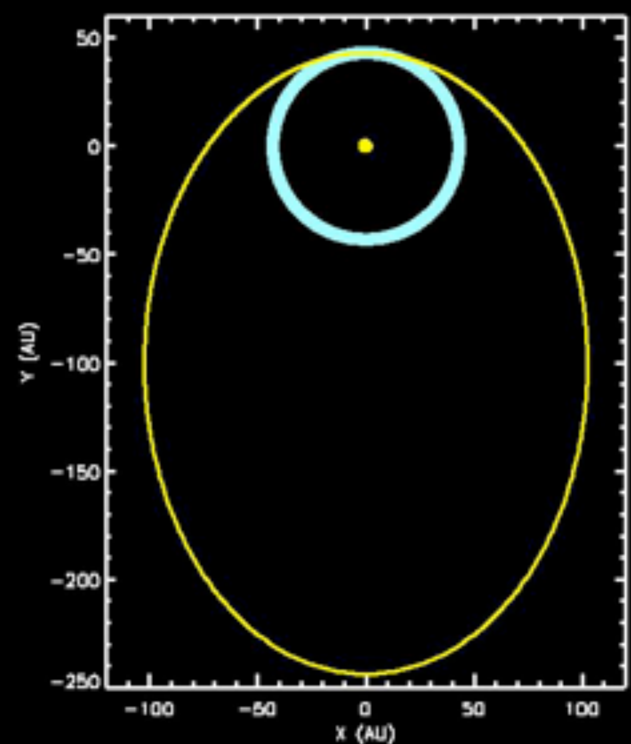
based on Mike Brown's survey limits:
1 Earth mass at less than 200 AU
1 Neptune at less than 500 AU
1 Jupiter (in reflected light) at less than 1000 AU

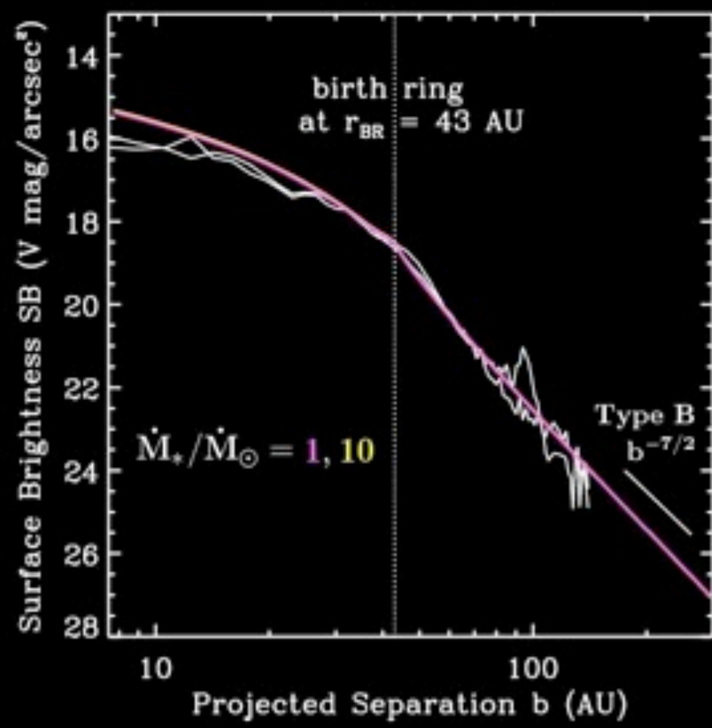
based on Hipparcos and Tycho-2
cannot be a self-luminous main-sequence star above the hydrogen burning limit

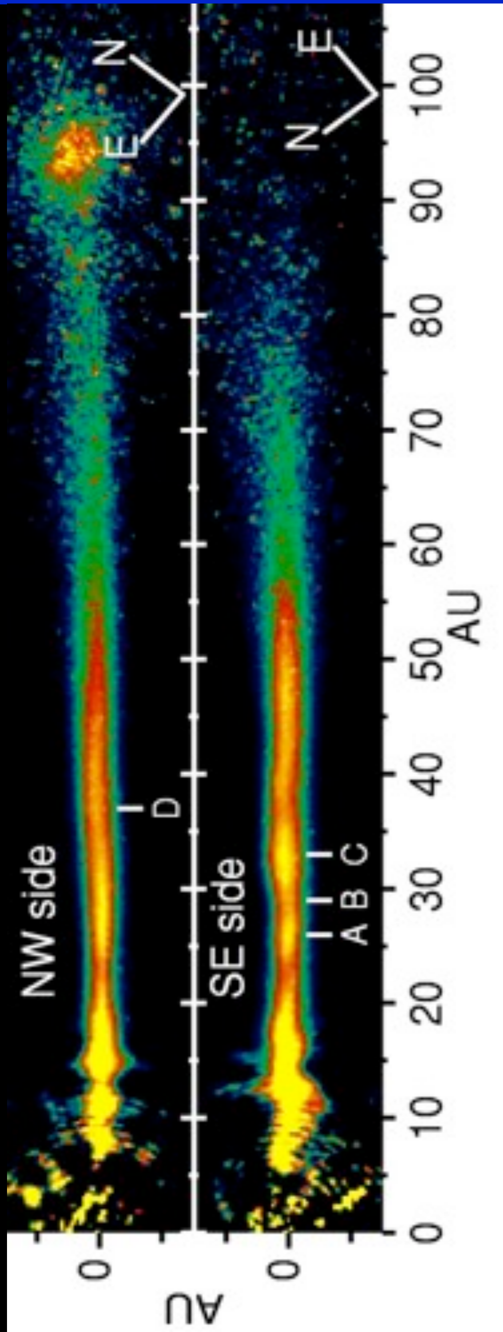
infrared detection of a Jupiter or brown dwarf could be interesting


V mag arcsec^{-2}
Radius (arcsec)
$r^{-0.3}$
$r^{-4.7}$
$r^{-1.8}$
Northwest
Southeast
16
18
20
22
24
1
10

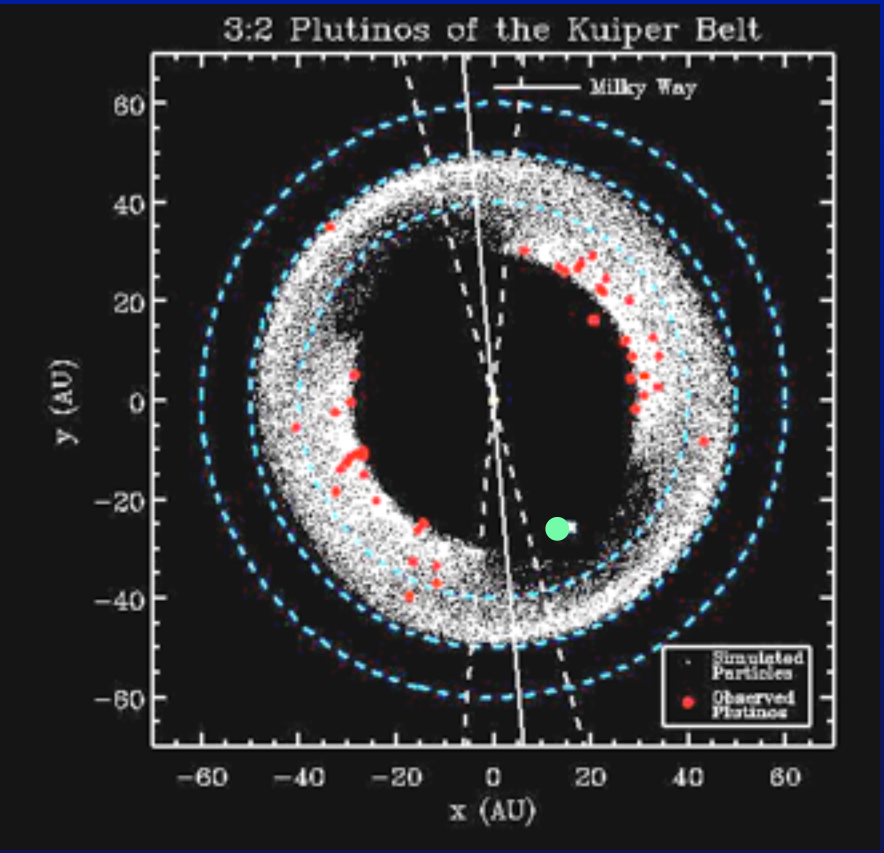



Y (AU)
X (AU)
50
0
-50
-100
-150
-200
-250
-100
-50
0
50
100

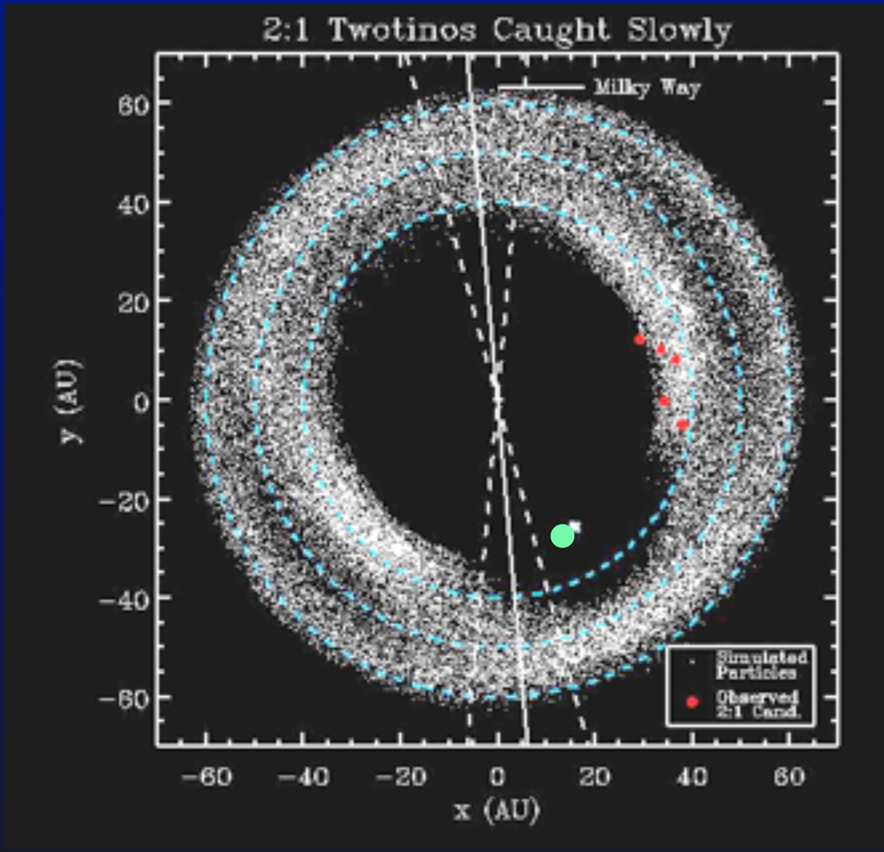

Surface Brightness SB (V mag/arcsec^2)
Projected Separation b (AU)
birth ring
at r_{BR} = 43 AU
$\dot{M}_*/\dot{M}_\odot = 1, 10$
Type B
$b^{-7/2}$
14
16
18
20
22
24
26
28
10
100


NW side
SE side
N
E
D
A
B
C
AU
0
10
20
30
40
50
60
70
80
90
100

Theoretical Snapshots of Resonant KBOs



⇐ Plutinos 3:2



Twotinos 2:1 ⇒

Chiang & Jordan 2002

Observational Facts and Theoretical Deductions

1. Pluto is the largest known member of a swarm of billions of outer solar system bodies that supply new comets.
2. Pluto and the Plutinos are locked in an orbital resonance established by Neptune.
3. The orbits of many Kuiper Belt Objects are dynamically excited.
4. Pluto is not alone in having an orbital companion.