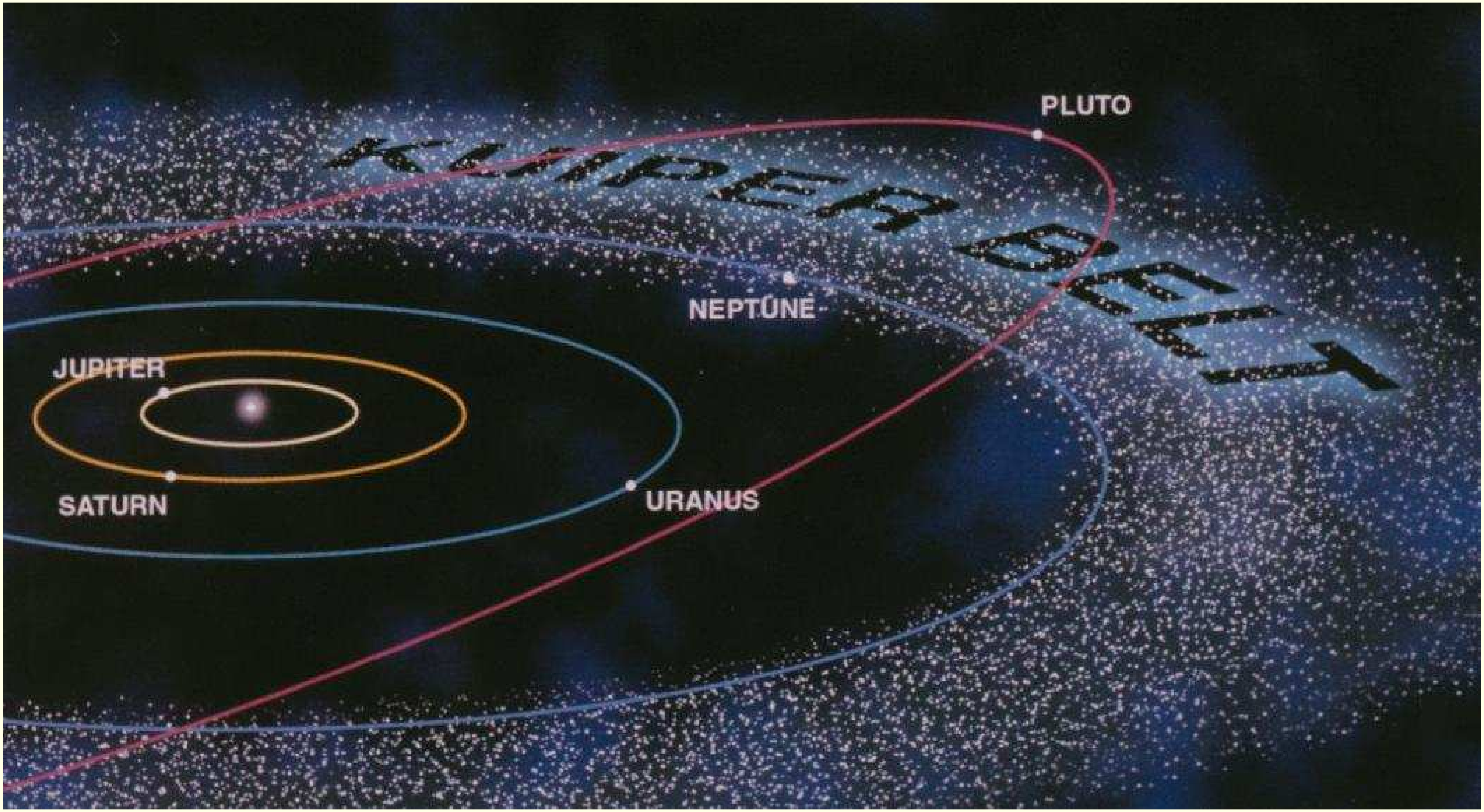
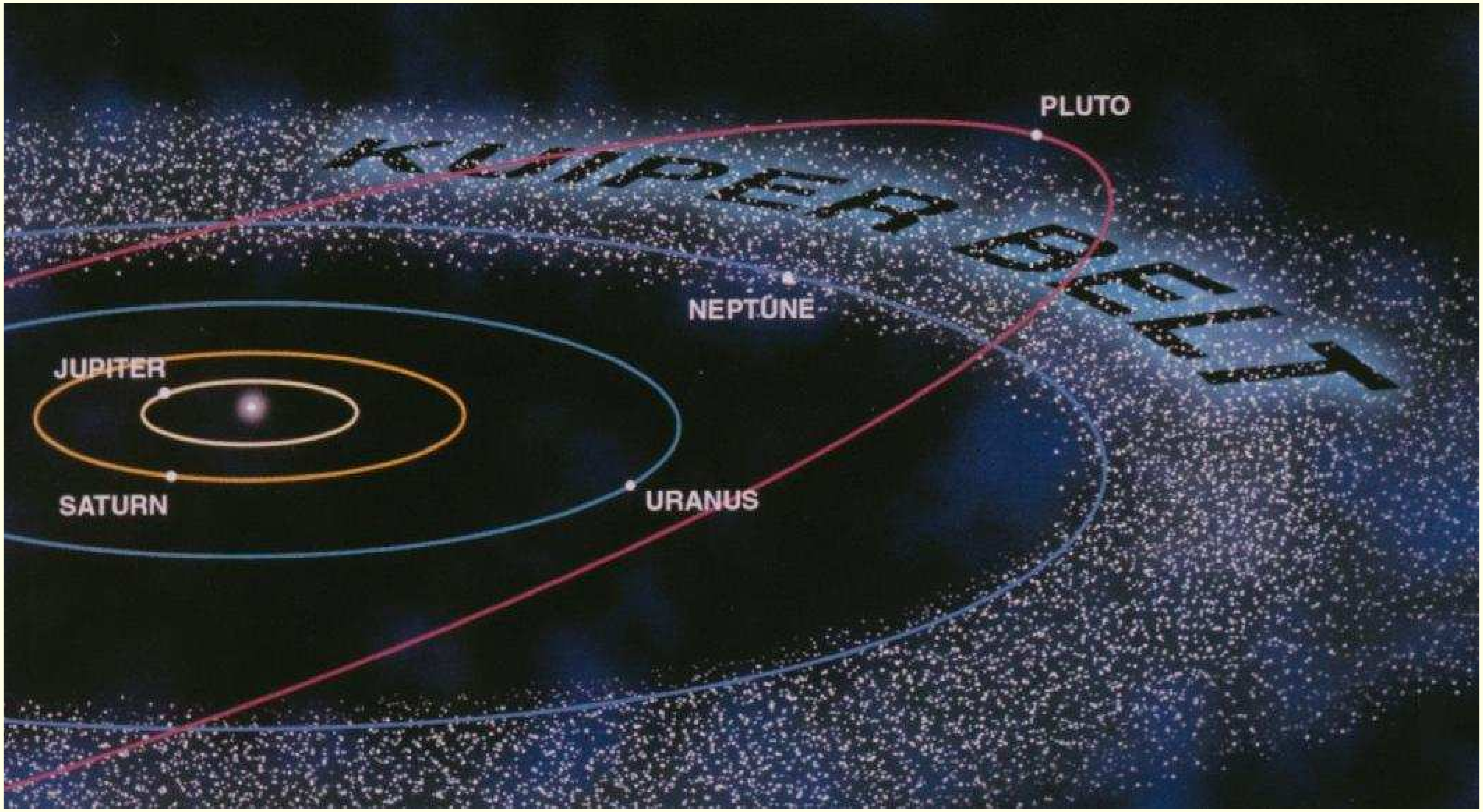
The Kuiper Belt,
and the Early Evolution of the Outer Solar System

Joseph M. Hahn

Saint Mary's University—Institute for Computational Astrophysics (ICA)



What is the Kuiper Belt?

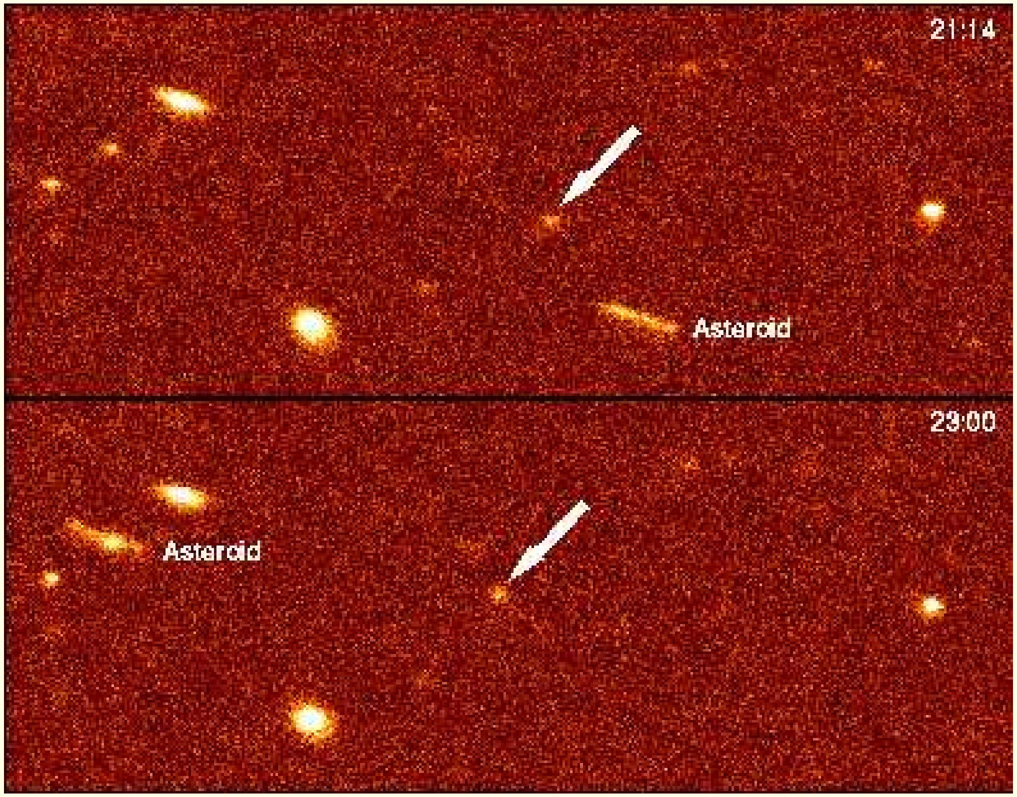


- a vast swarm of giant comets orbiting just beyond Neptune
  - debris that failed to coalesce into another planet

- nomenclature isn't settled:
  Kuiper Belt, Edgeworth–Kuiper Belt, Trans–Neptunian Belt, etc.

- members are: KBOs, EKOs, TNOs, etc.

1992 QB1: the first known KBO?

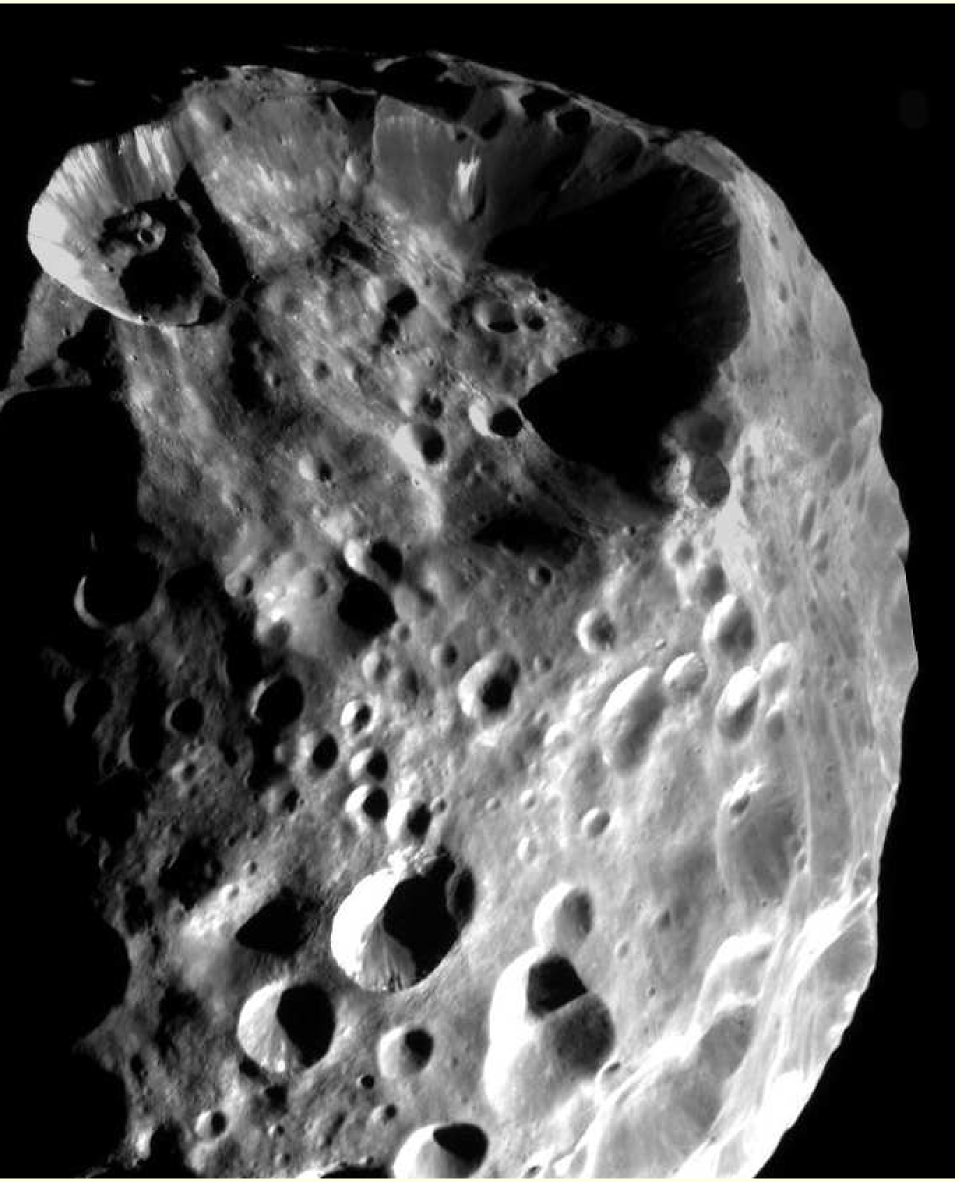


from David Jewitt's website

- discovered in 1992
  by David Jewitt & Jane Luu
- $\mathbf{m = 23}$ at $\mathbf{r \sim 45}$ AU
- apparent motion of $\mathbf{3''}$/hour on sky due to parallax from *Earth's* orbital motion

- ...or was the first KBO discovered in 1930 by Clyde Tombaugh?

What does a KBO look like?



from CICLOPS: Cassini Imaging page.

- KBOs are distant, ice–rich debris that were left over from when Solar System first formed

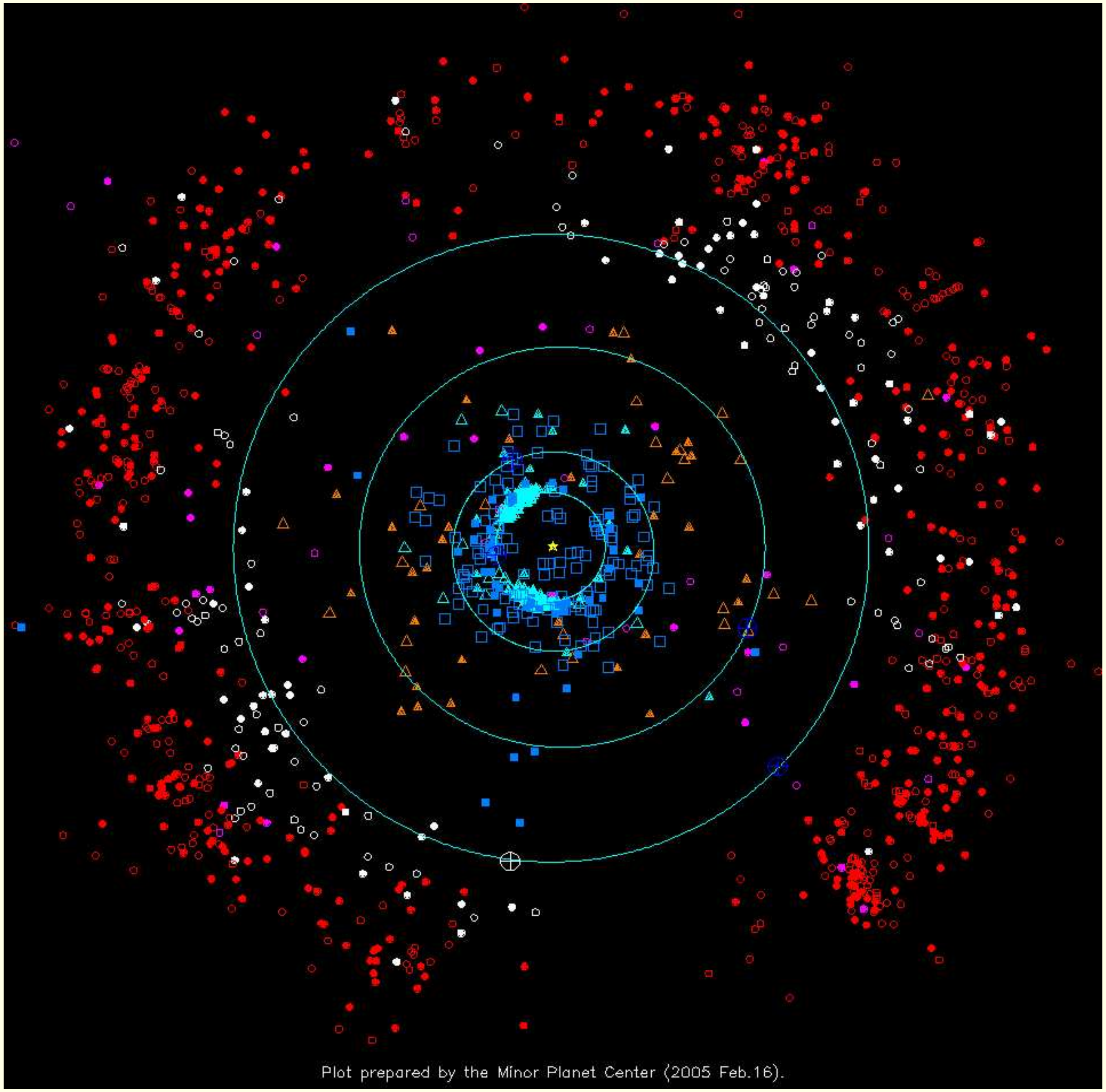
- likely heavily cratered
  due to impacts w/other KBOs,

  $\Leftarrow$perhaps like Phoebe?

  – which is NOT a KBO...

- nonetheless, this pic' of Phoebe might be a representative of a typical KBO

Kuiper Belt Statistics



from the Minor Planet Center

- $\sim \mathbf{1000}$ known KBOs
- observable population has $\mathbf{20} \lesssim \boldsymbol{D} \lesssim \mathbf{1000}$ km, masses $< \frac{\mathbf{1}}{\mathbf{5}}\mathrm{M}_{\mathrm{moon}}$
- estimated population: $\boldsymbol{N}(\boldsymbol{D} > \mathbf{100}\mathrm{km}) \sim \mathbf{200,000}$ total mass $\boldsymbol{M} \sim \mathbf{0.02}\mathrm{M}_{\oplus}$
- $\sim \mathbf{10}$–$\mathbf{100}\times$ asteroid belt

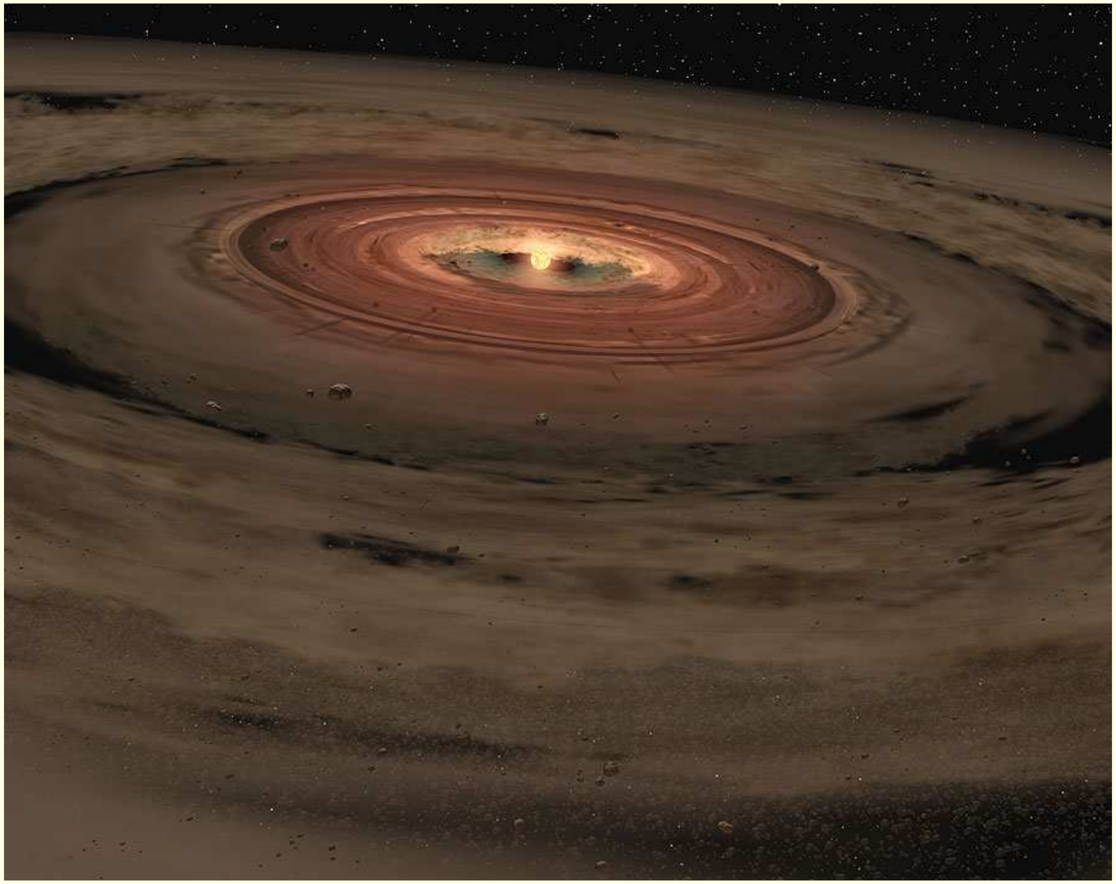
Formation of planets, comets, asteroids...and the Kuiper Belt

- Planet formation is a by-product of star formation

- first, an interstellar cloud of gas & dust collapses due to its gravitational self–attraction

  - $\sim 99\%$ of the cloud forms young Sun

  - $\sim 1\%$ of the cloud forms a disk orbiting the Sun, the *solar nebula*



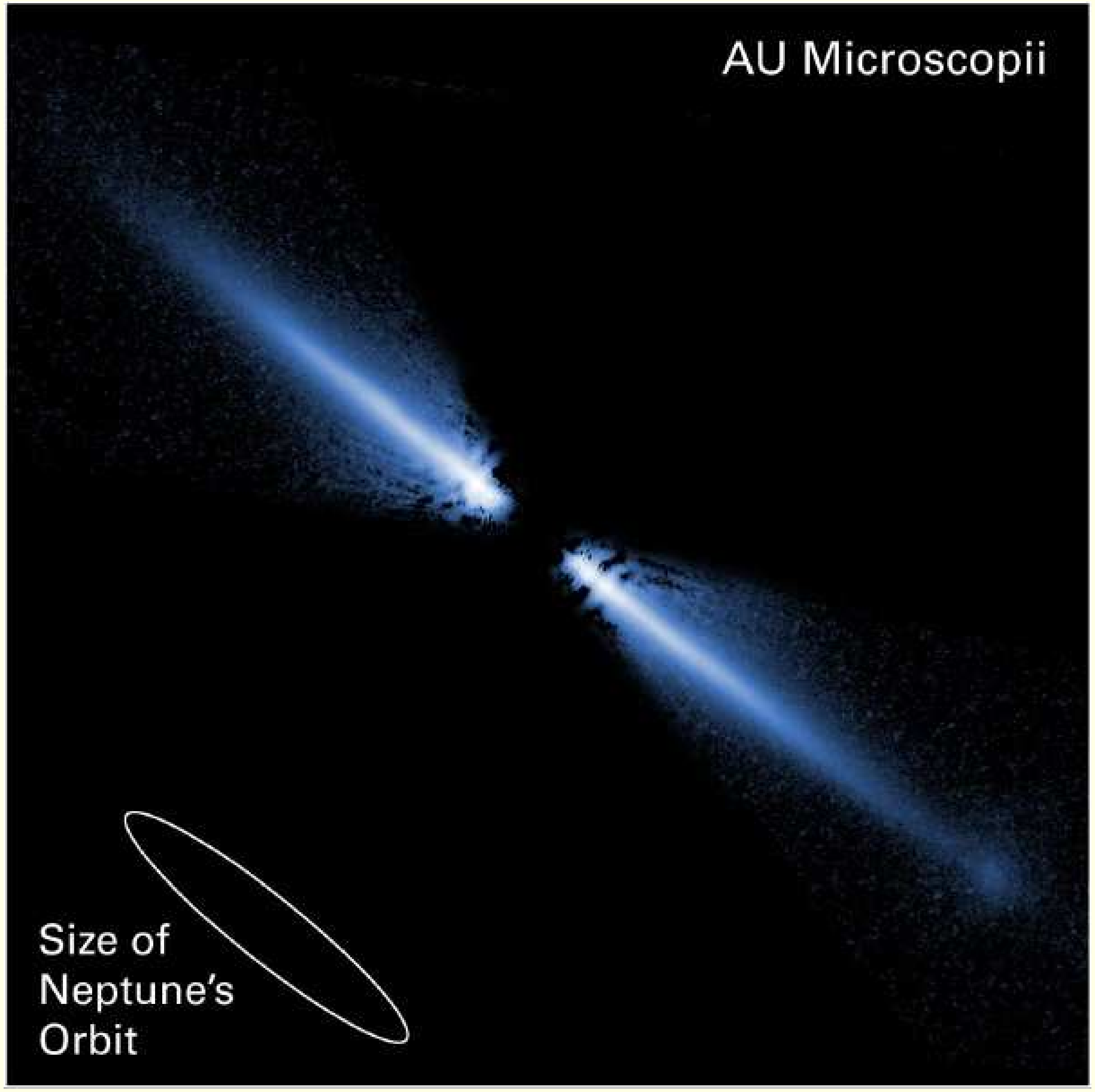
collapsing cloud forms star + disk

- dust grains are concentrated in the solar nebula disk
  - dust grains collide & stick to form larger objects
  - over time, dust grow, form planetesimals (the building blocks of the planets)

cartoon showing growing planetesimals

- regions where $r \lesssim 5$ AU, the nebula temperature $T \gtrsim 200$ K (about -70 C)
  - these planetesimals are rock–rich, ice–poor (too warm!)
    * they will later collide & form the rocky terrestrial planets (M,V,E,M)
    * any left-over planetesimals will become asteroids that live at $r \sim 3$ AU
- where $r \gtrsim 5$ AU & $T \lesssim 200$ K
  - these cooler planetesimals are ice–rich
    * they will form the cores of the gas giant planets (J,S,U,N)
    * any left-over planetesimals will become comets in Kuiper Belt & Oort Cloud

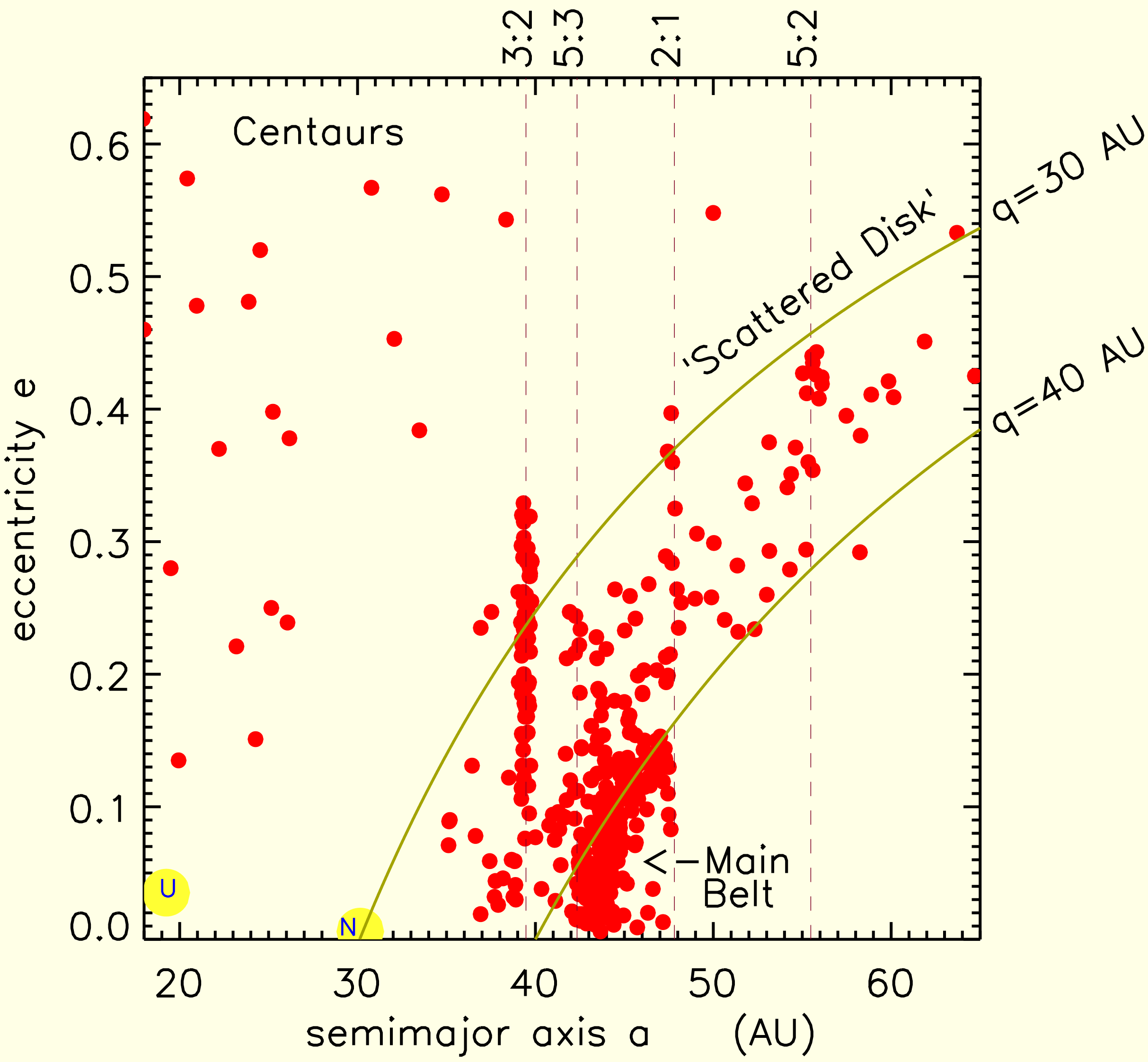
KBO Accretion models



Hubble Space Telescope image by Krist et al.

- KBO accretion models tell us:
  - the KBO 'seeds' were initially in nearly circular orbits
  - you need $\sim \mathbf{30}\mathrm{M}_\oplus$ of matter in order to form Pluto–sized KBOs in 4.5 billion years
- current KB mass is $\sim \mathbf{0.02}\mathrm{M}_\oplus$
  - the KB's mass was *depleted* by factor of $\times\mathbf{1500}$!
- depletion due to collisions among KBOs?
  - collisions generate dust
  - dust is removed by starlight
    - ∗ radiation pressure or PR drag

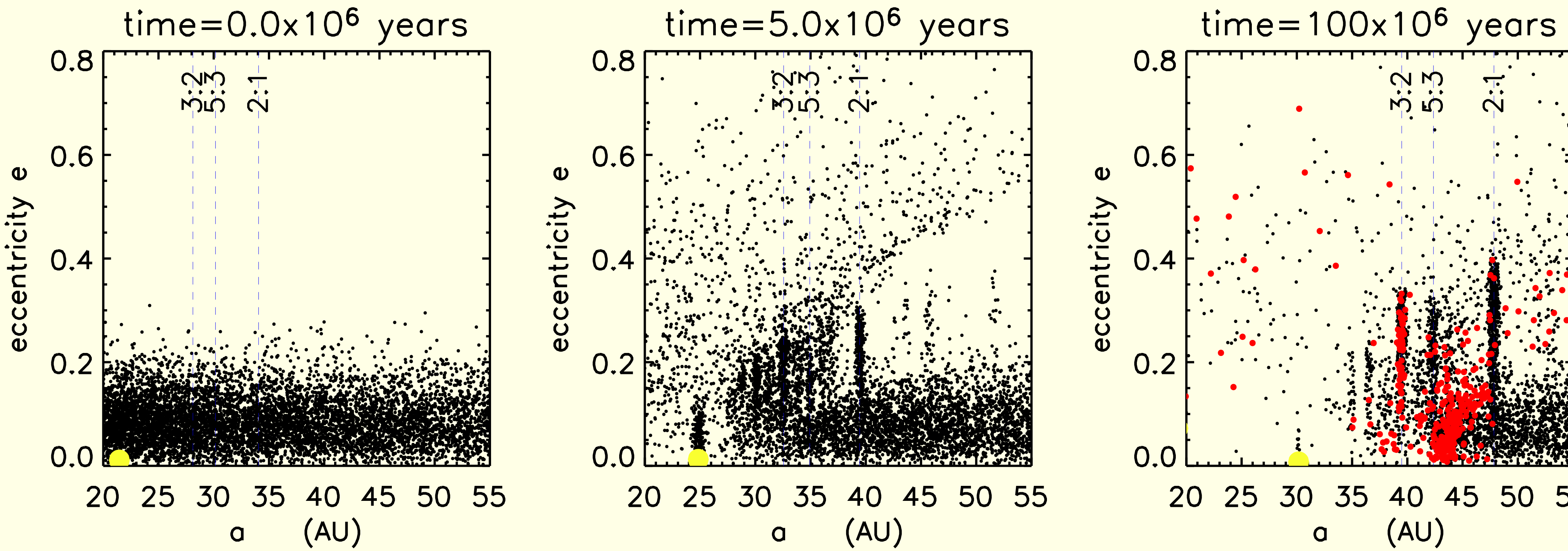
KBO Orbits—anything but circular!



orbits from Minor Plant Center.

- accretion models predict nearly circular orbits, ie, $e \simeq 0$
- but astronomer find KBOs in orbits with eccentricities of $\sim \mathbf{0.1}$–$\mathbf{0.3}$
- something has disturbed the Kuiper Belt since formation!
- note KBOs at Neptune's 3:2
  - site where a KBO gets 'kicked' every 330 years
  - e's get pumped up here
  - KBOs were 'parked' here
    - $*$ possibly due to *planet migration*

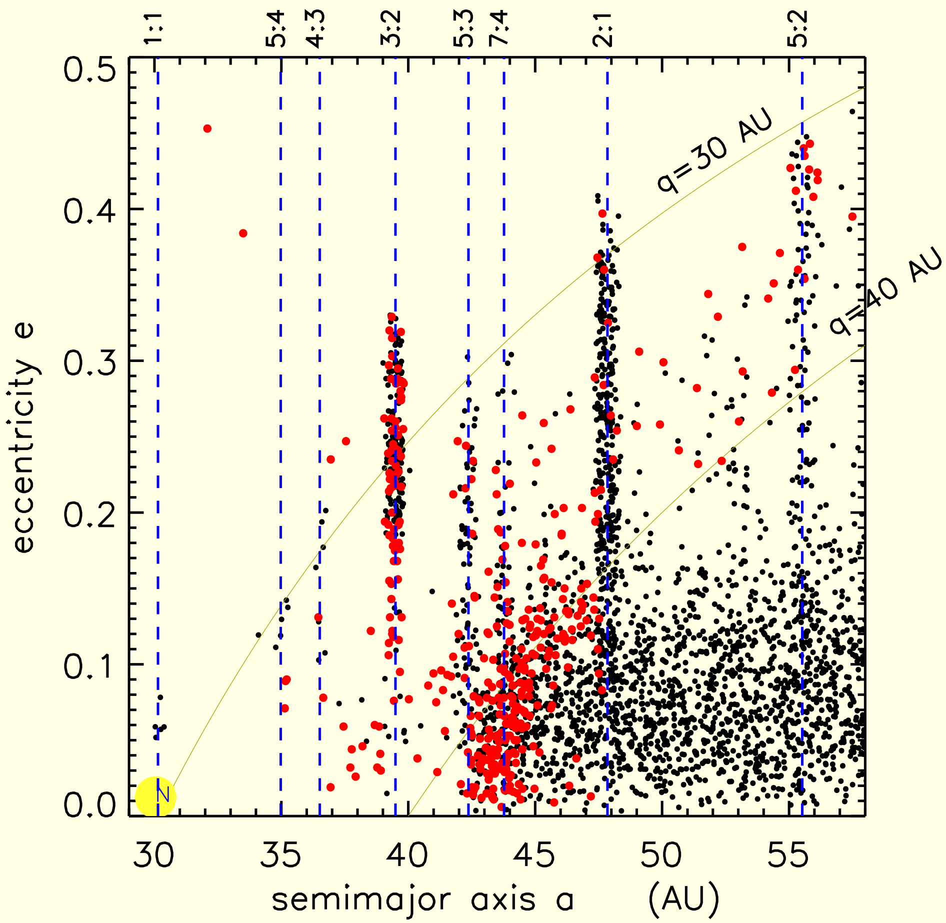
The 3:2—Evidence for Planet Migration?



Nbody simulations show that as Neptune migrates outwards,

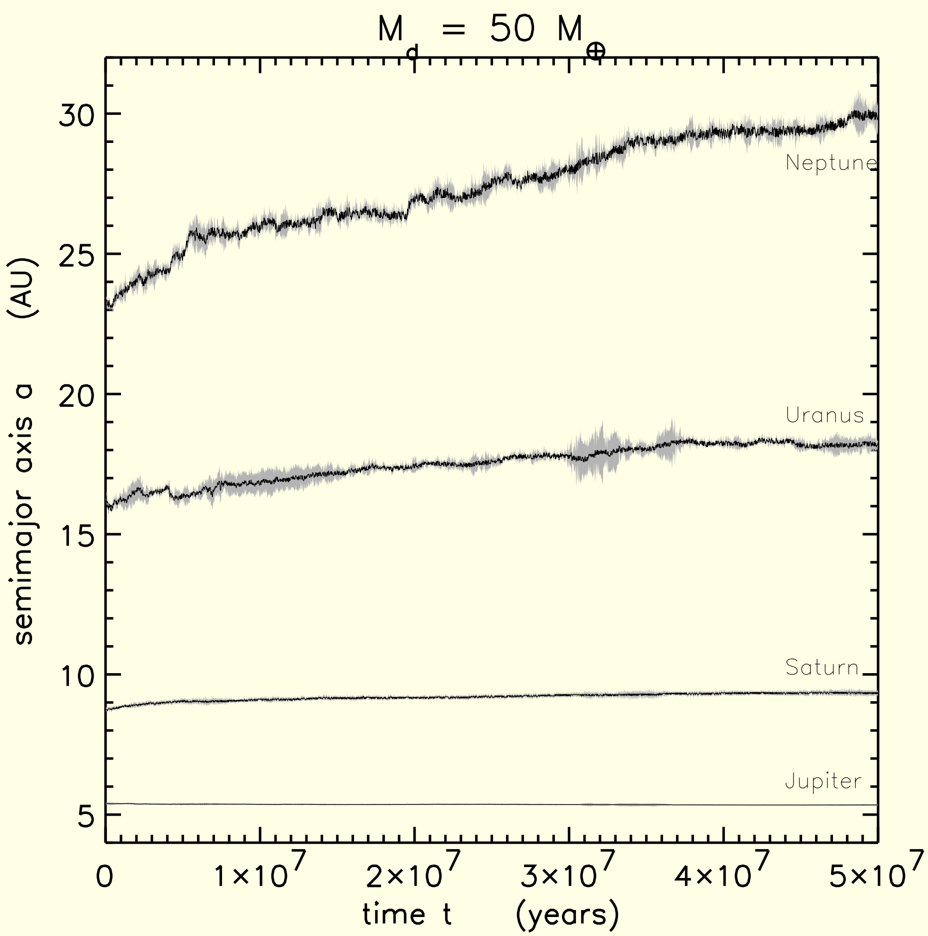
- Neptune's *resonances* can capture KBOs
  - this drags the captured KBOs outwards
  - pumps up their eccentricities e
- astronomers have detected many KBOs at Neptune's 3:2, 5:3, 2:1, 5:2, etc, which suggests that Neptune's orbit did expand outwards

How far did Neptune migrate?



- e–pumping at 3:2 varies with Neptune's migration distance $\Delta \mathbf{a}$
- achieving $\mathbf{e} \sim \mathbf{0.33}$ at 3:2 requires Neptune migrating $\Delta \mathbf{a} \simeq \mathbf{9}$ AU

Why would the giant planets migrate?

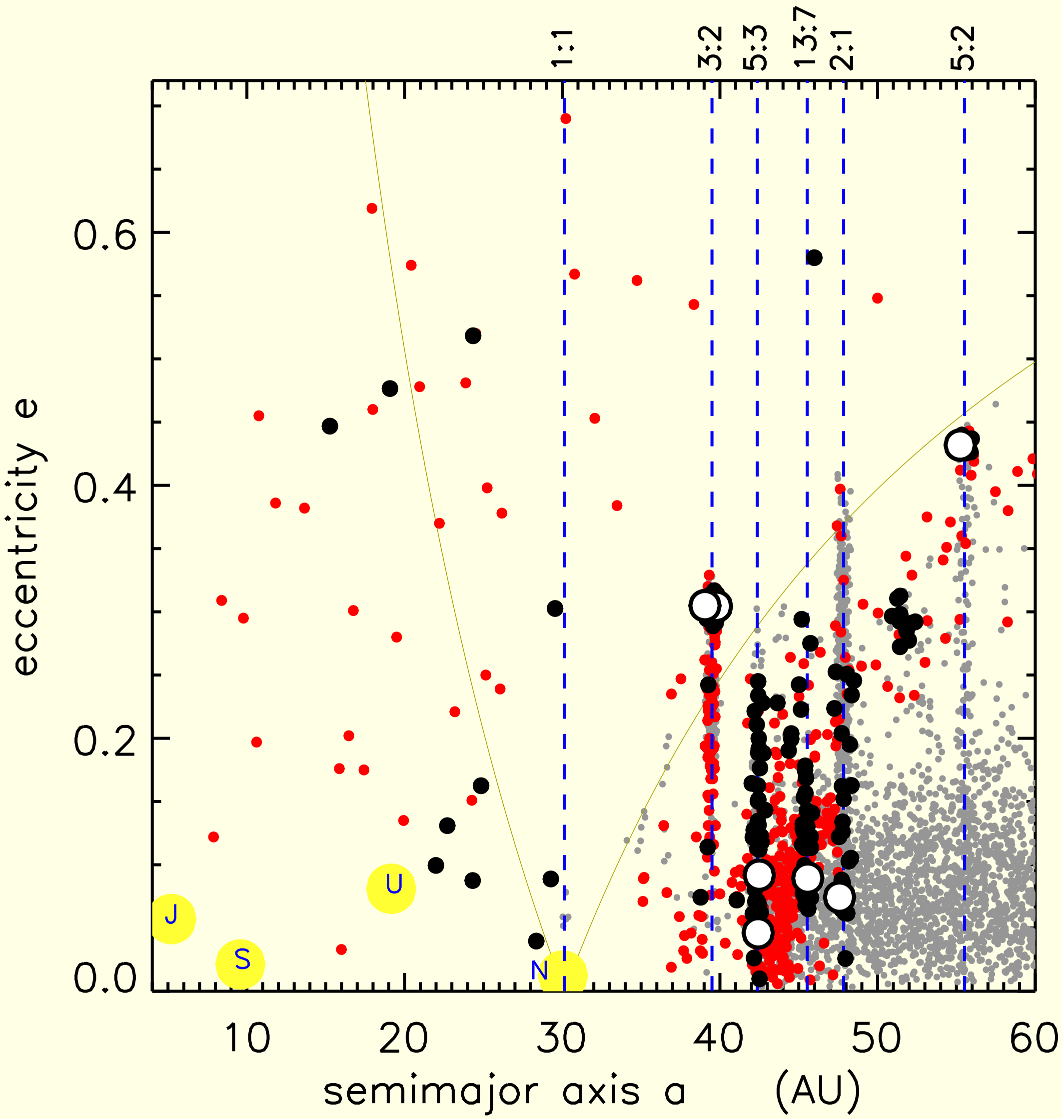


from Hahn & Malhotra (1999)

- cores of giant planets formed within a planetesimal disk
- planet–formation was likely not 100% efficient
  - residual planetesimal debris is left over
- recently–formed planets scatter the planetesimal debris, exchange $\mathbf{L}$ with planetesimal disk
- Nbody simulations (Fernandez & Ip 1984, Hahn & Malhotra 1999, Gomes, Morby, Levison 2004) show planets evolve away from each other, ie, Jupiter inwards, Neptune outwards

- driving Neptune $\Delta \mathbf{a}_{\mathbf{Nep}} \simeq \mathbf{9}$ AU requires debris mass $\mathbf{M_D} \sim \mathbf{30}$ $M_\oplus$, enough to build $\sim \mathbf{2}$ more Neptune's...planet formation was quite ineffi cient

Centaurs, and the origin of Short Period Comets



- Centaurs have $\mathbf{a} < \mathbf{a}_{\mathbf{Neptune}}$ (eg, Pholus, Chiron, Nessus, etc)
- often found in KB surveys, due to their proximity to Sun
- Centaurs are *escapees* from the Kuiper Belt
  - model shows they pop out of resonances,
  - get scattered about Solar System by giant planets

- some Centaurs get tossed within $r \lesssim 2$ AU, where they become visible as an active, short–period comet (aka, a Jupiter–family comet)

What is a comet?

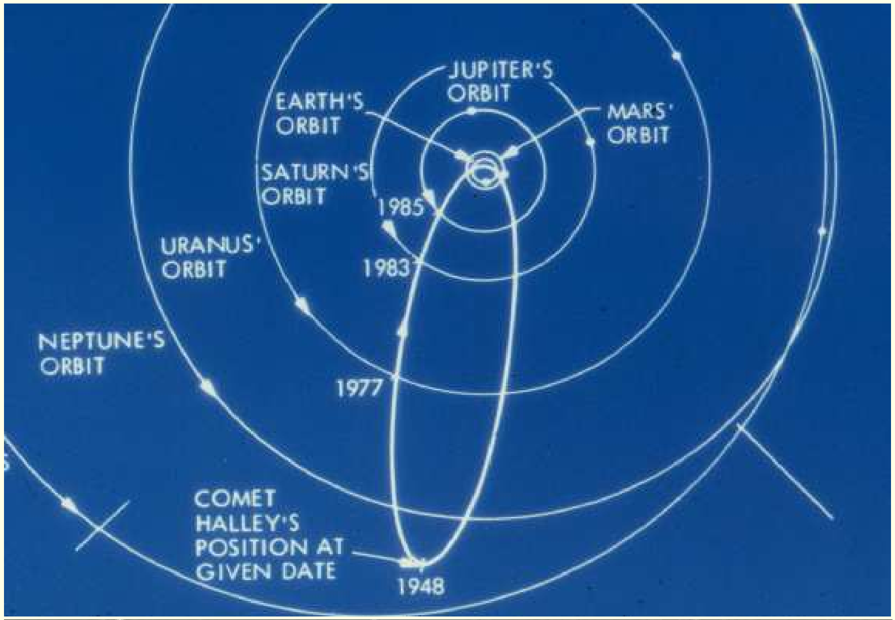
- a comet is an icy planetesimal, eg, a dirty snowball, composed of:

- mostly water ice + trace CHON:
  - CO, CO_2, CH_3OH, HCN, NH_3, … and dust

Comet Wild–2 photographed by Stardust

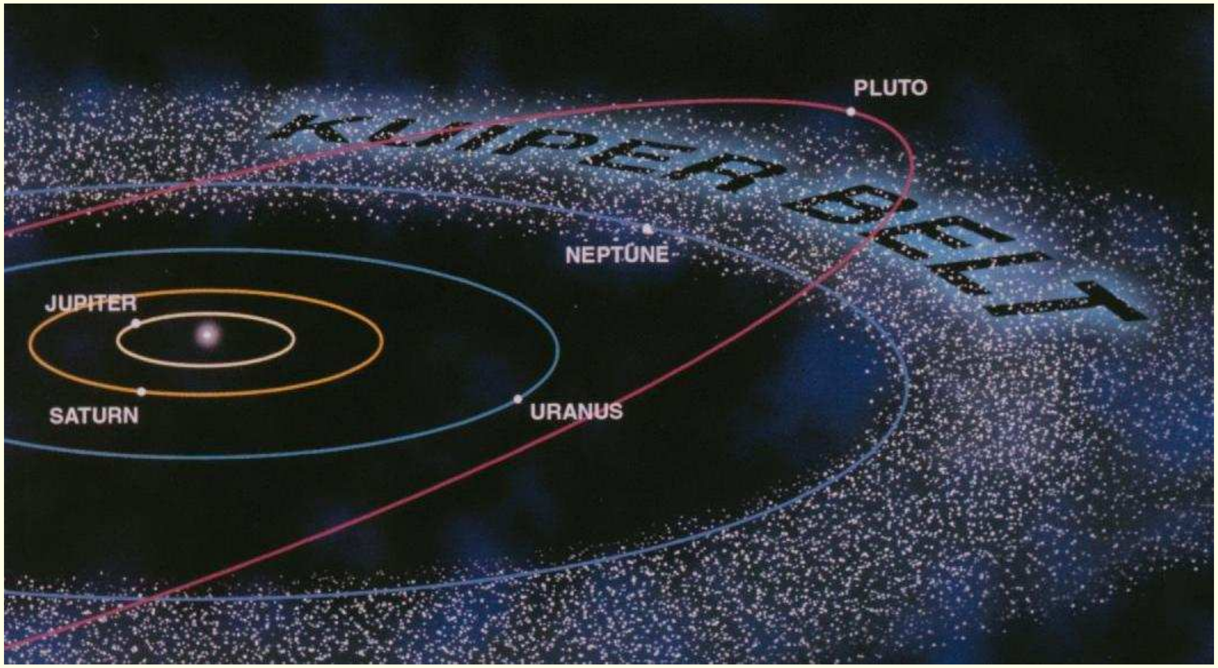
Why do comets have tails?

- comets travel in wide, looping orbits about the Sun
- when $r \lesssim 2$ AU of Sun, their icy surfaces sublimate (eg., boil off)
  - releases gas & dust into coma, a $r \sim 10^5$ km cloud
  - solar wind & radiation sweeps gas & dust into tail $\ell \sim 10^{6\text{ to }7}$ km
  - all this from a comet nucleus with diameter 1–10 km
- most comets reside at $r > 2$ AU, where they are inactive, so they are dark and unseen...



Comet Hale Bopp

if Centaurs/Short–Period Comets come from the Kuiper Belt...

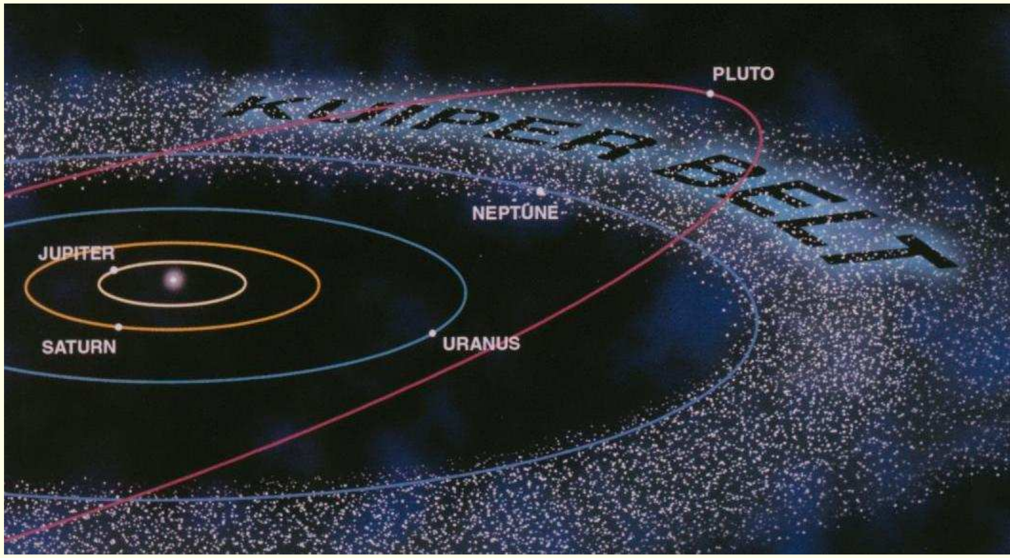


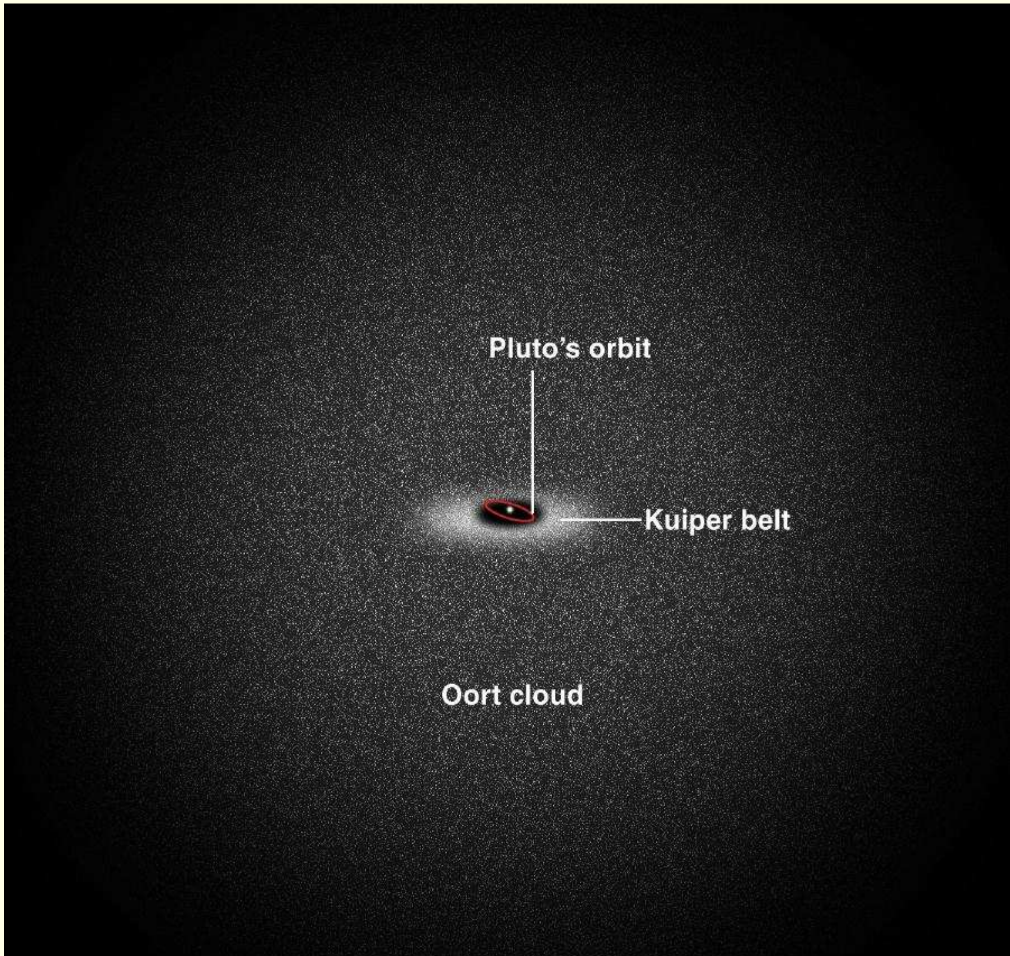
where do Oort Cloud comets come from?

- from within the donut hole...
  - they probably formed *among* the giant planets
  - who accreted some of the planetesimal debris there
  - but also flung icy planetesimals into wide orbits about the Sun

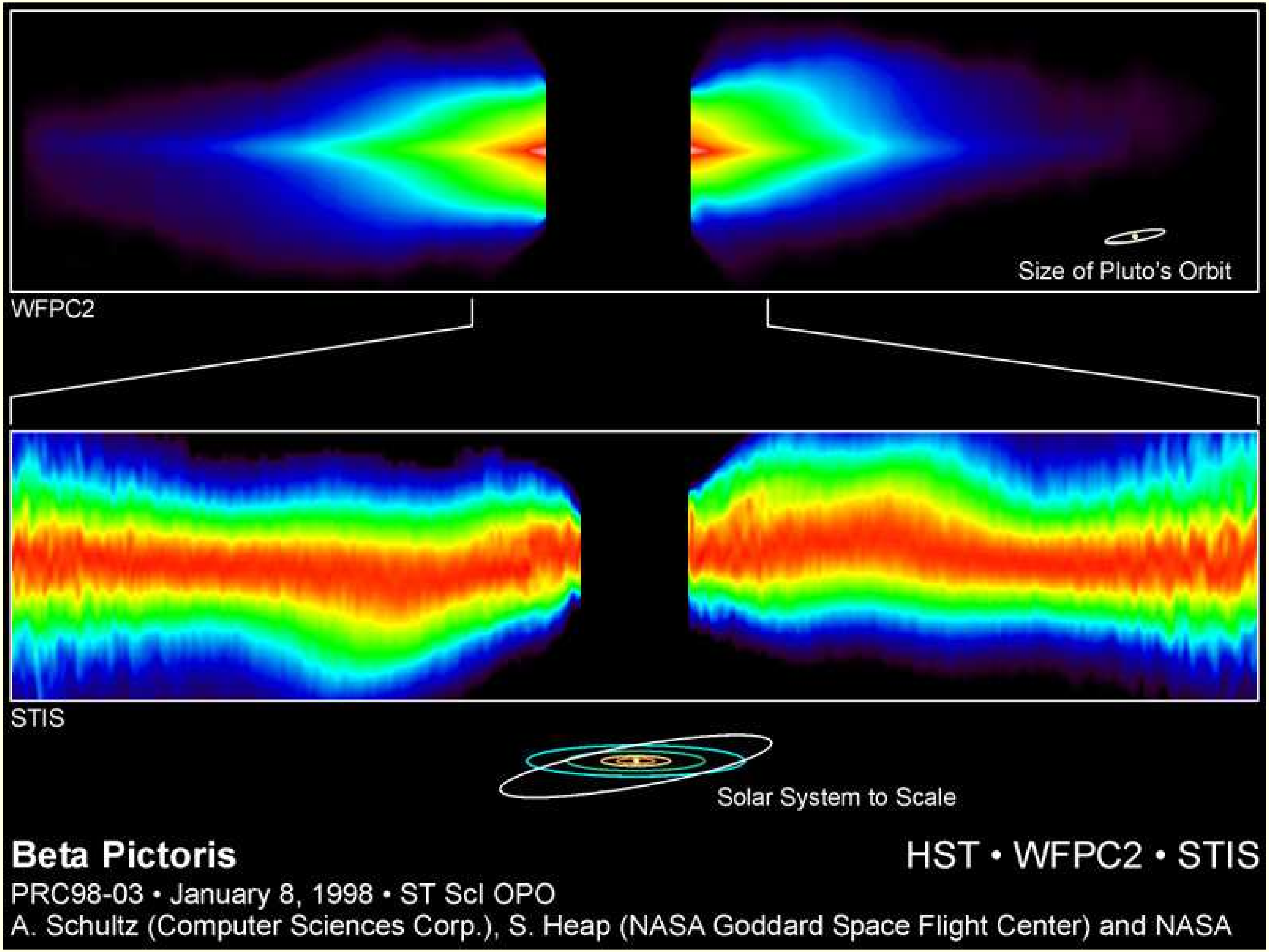
The Oort Cloud is *huge*

- Oort cloud comets can travel as far out as $r \sim 50,000$ AU, which is about 25% of distance to nearest star



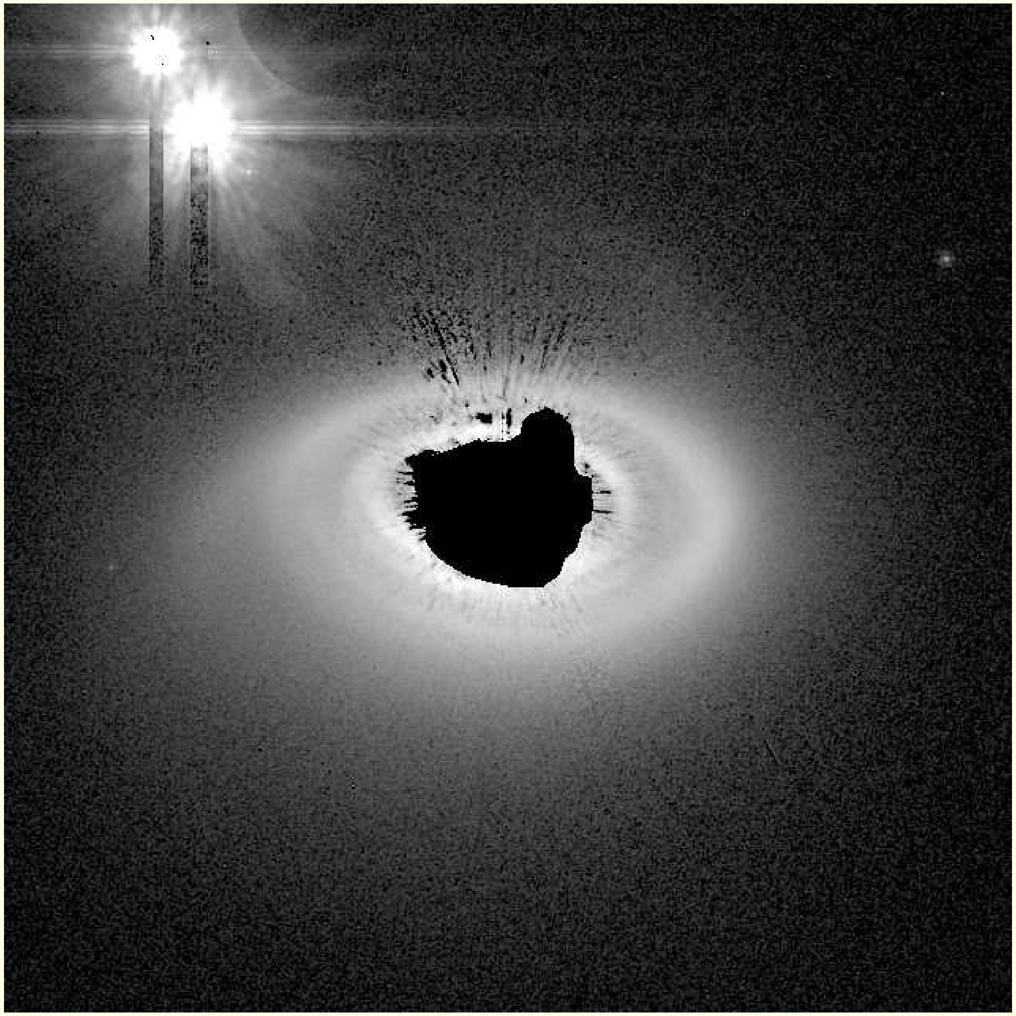


Do other stars have Kuiper Belts?



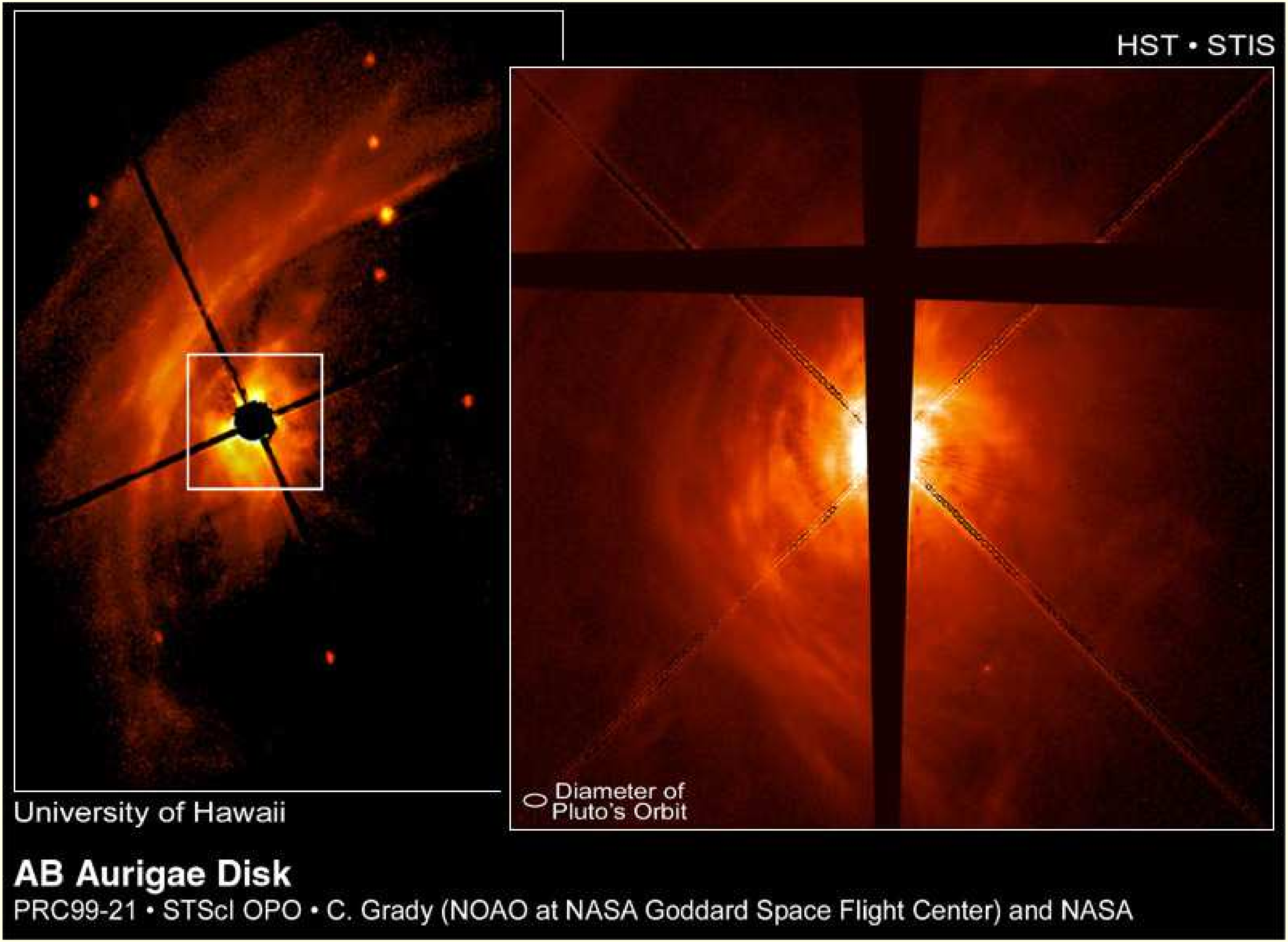
Short dust lifetimes imply unseen KBOs!

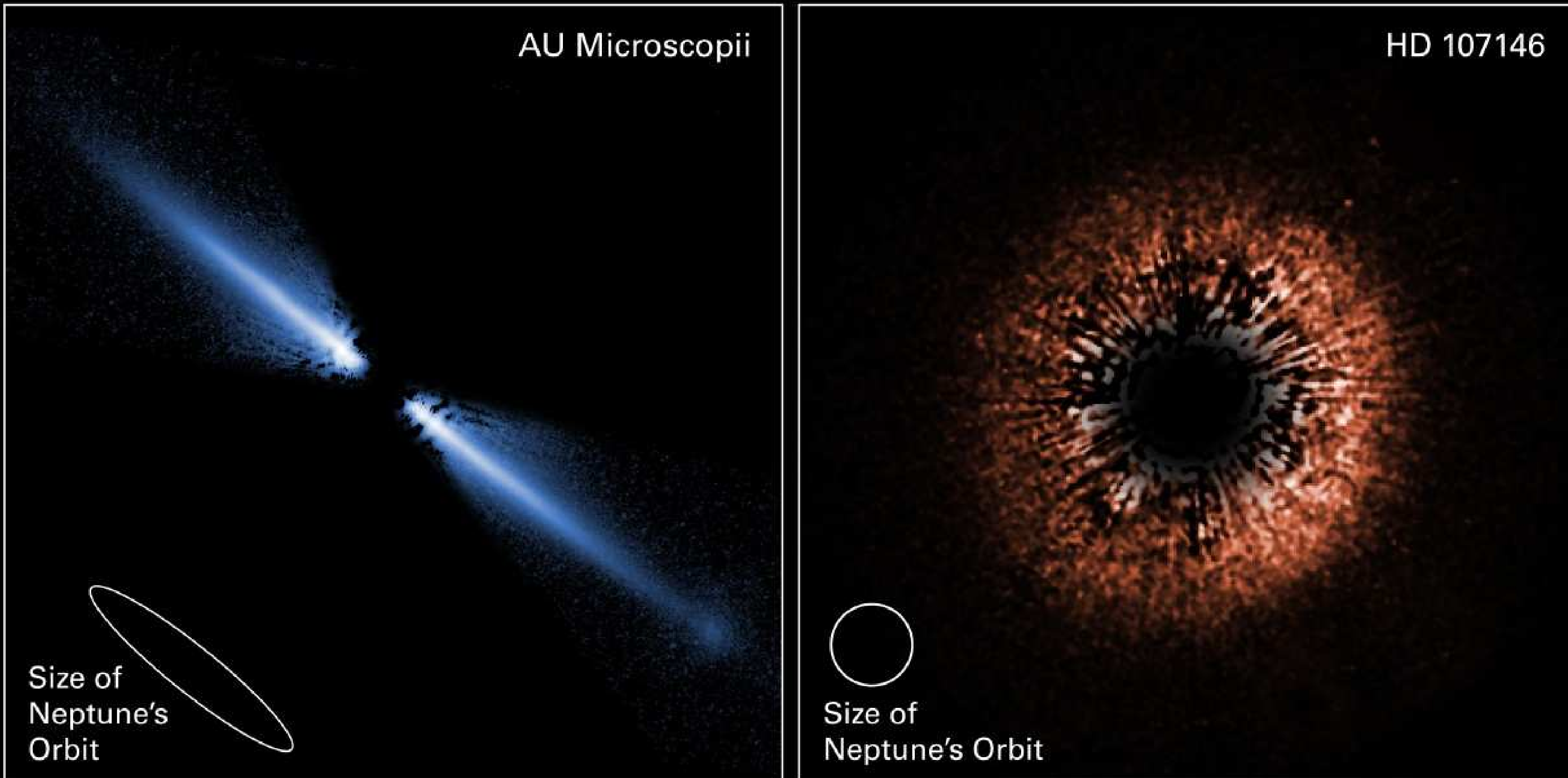
- star HD 141569
- circumstellar dust is quickly destroyed, perhaps in millions of years?
  - due to collisions,
    radiation pressure, PR drag
- dust lifetimes are $\ll$ age of star



HST image by M. Clampin

- must be an *unseen source of dust orbiting star*
  - most likely culprit: KBOs that collide & generate dust


HST • STIS
University of Hawaii
Diameter of
Pluto's Orbit
AB Aurigae Disk
PRC99-21 • STScI OPO • C. Grady (NOAO at NASA Goddard Space Flight Center) and NASA



Circumstellar Debris Disks
Hubble Space Telescope • ACS HRC

NASA, ESA, J. Krist (STScI/JPL), D.R. Ardila (JHU), D.A. Golimowski (JHU), M. Clampin (NASA/Goddard), H. Ford (JHU), G. Hartig (STScI), G. Illingworth (UCO-Lick) and the ACS Science Team

STScI-PRC04-33a

Summary

- the Kuiper Belt is a debris disk—
  a relic that was left–over from when the giant planets formed

- this Belt is interesting, since it appears to preserve evidence of planet migration

  – the KBOs trapped at Neptune's resonances suggest that Neptune's orbit expanded $\sim \mathbf{30}\%$

- the Kuiper Belt is also the source of the short–period comets,
  which are samples of the Solar System's outer edge

  – interestingly, long–period comets from the Oort Cloud probably formed closer to the Sun that the short–period comets

- circumstellar dust-disks have been detected in orbit about many nearby stars

  – these disks are often interpreted as evidence for extra–solar Kuiper Belts

  – the warps & gaps seen in these disks also suggest the presence of unseen planets orbiting within