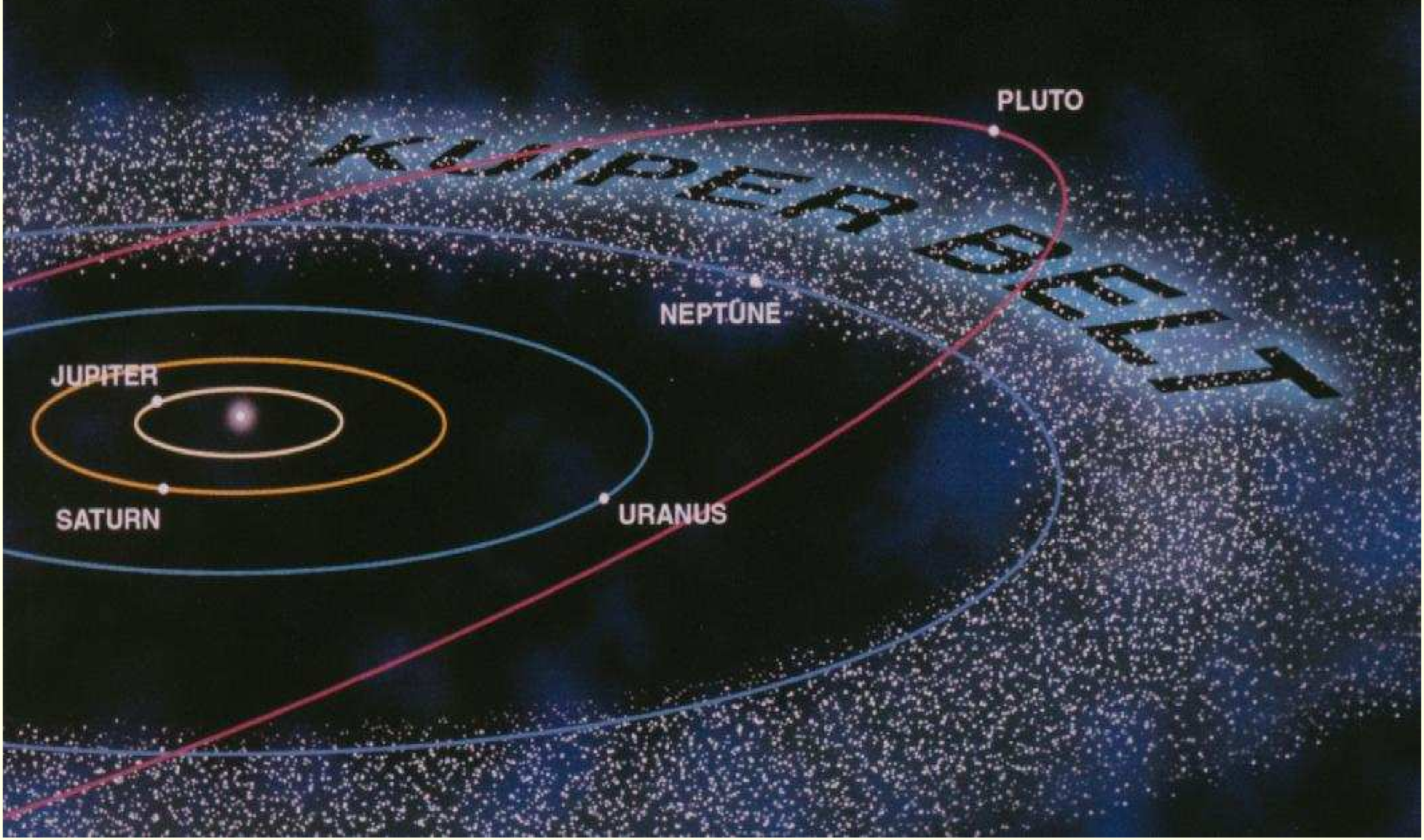
# Extraterrestrial Snowballs from the Solar System's Outer Frontier

*Joe Hahn*



# What is a comet?

comet = dirty snowball, composed of:

- mostly water ice + trace CHON:
  - $CO$, $CO_2$, $CH_3OH$, HCN, $NH_3 \ldots$
  - plus dust

- Note that comets carry the essential ingredients for organic chemistry
  - some comet scientists argue that comet impacts delivered chemistry that to started life on early Earth
  - but this claim is still being investigated & debated

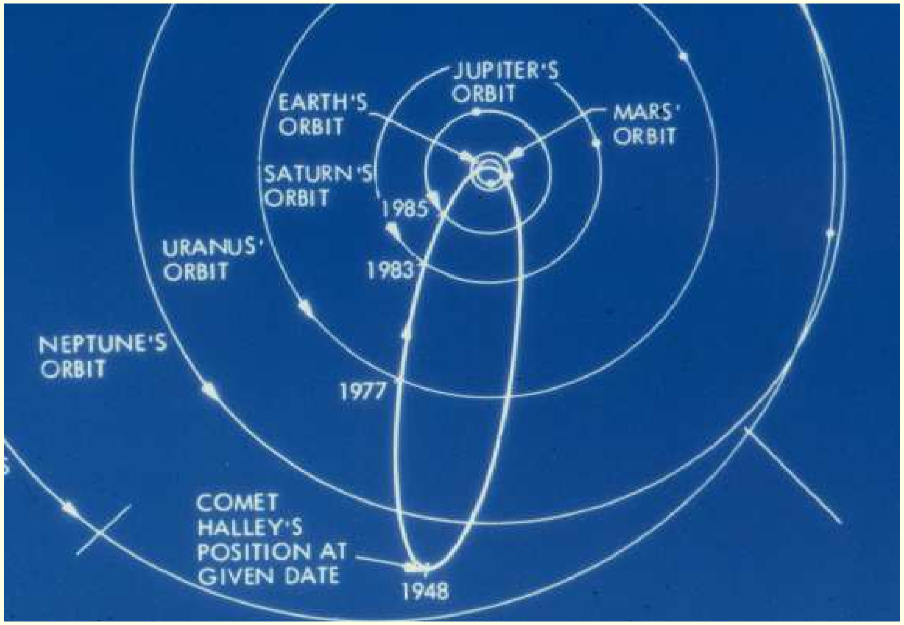
Comet Wild–2 photographed by Stardust

# What 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., boils off)
  - releases gas & dust into coma, $R \sim 10^5$ km cloud
  - solar wind & radiation sweeps gas & dust into tail $\ell \sim 10^{6 \text{ to } 7}$ km
  - all this from a comet having a typical size $R \sim 1$ km

- most comets live beyond $r > 2$ AU, where they are inactive, so they are dark and unseen...




Comet Hale Bopp

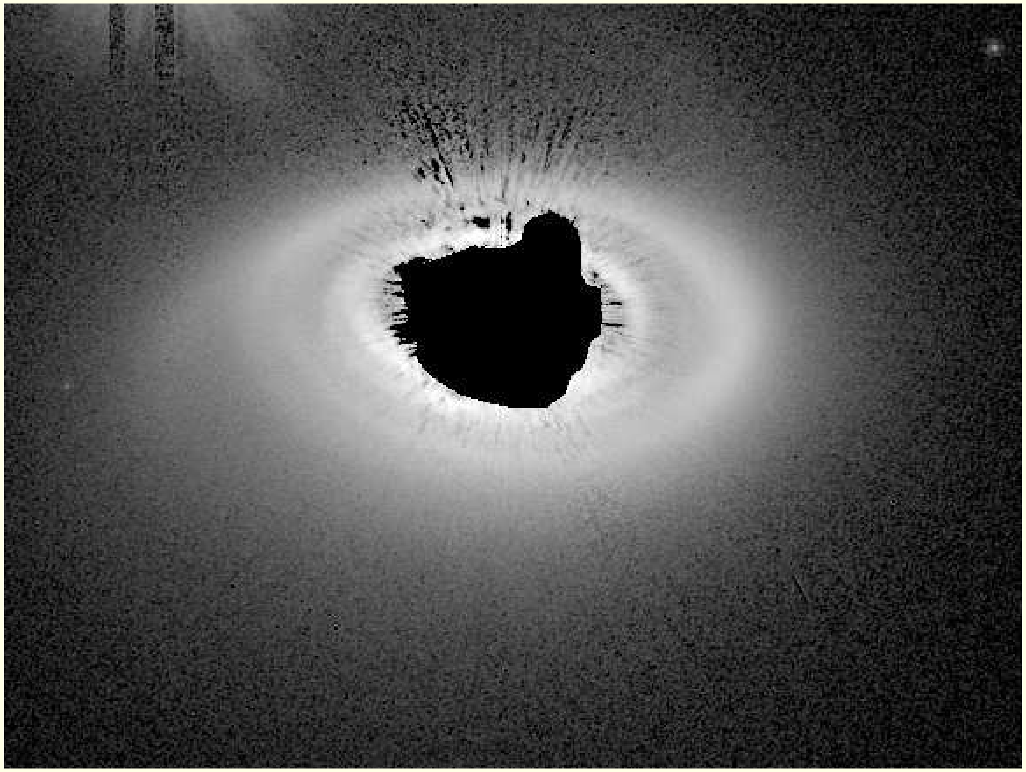
# Why are comets interesting?

- comets are pristine remnants left–over from when planets formed

- their chemistry tells us the composition of that initial planet-forming 'cradle'

- that 'cradle' = solar nebula
  - the disk of gas & dust that formed concurrent with the young Sun

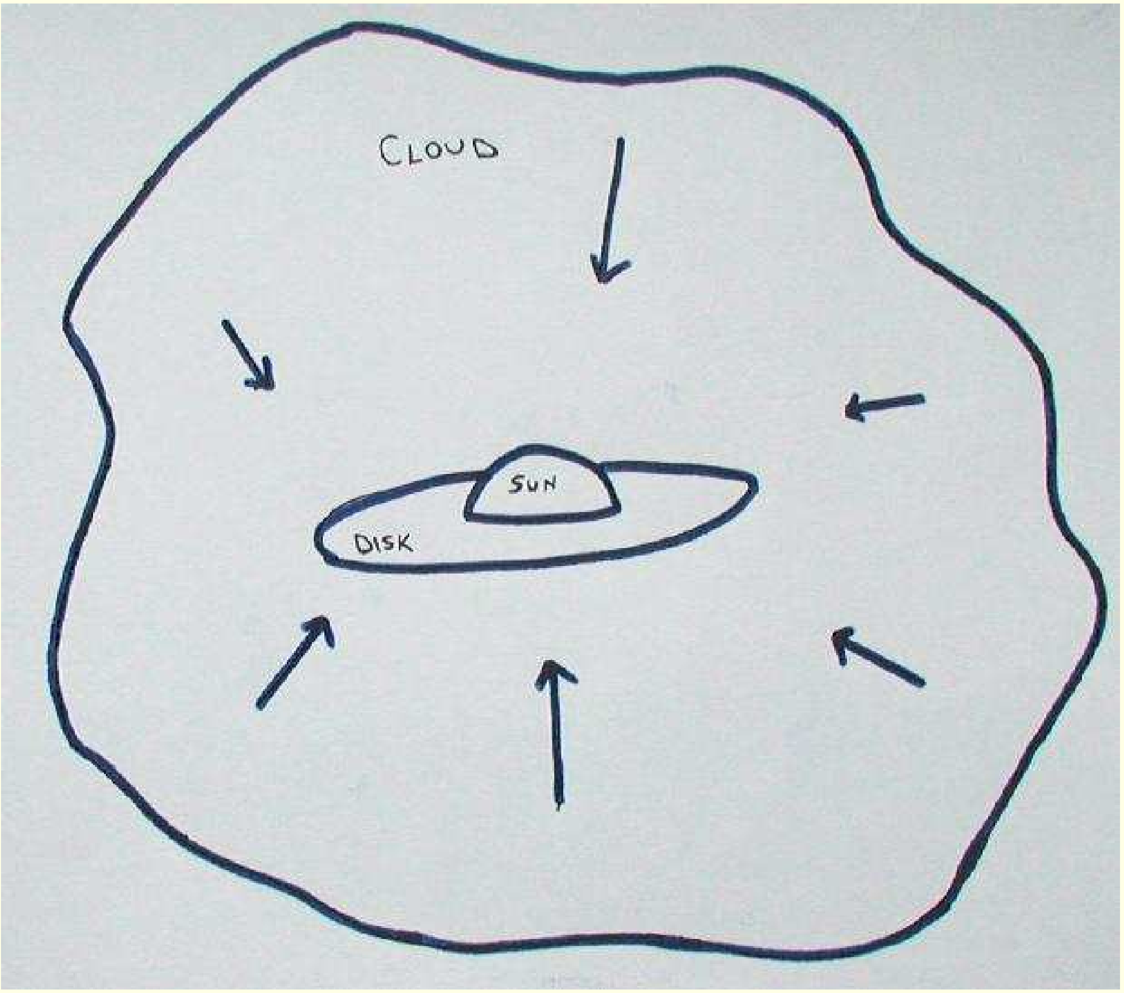
- cometary orbits tell us about the dynamical evolution of the solar nebula
  - ie, how the solar nebula's dust coagulated into 9 planets + asteroids + comets



artist's solar nebula (above) & HD 141569

# Comets & Planet Formation 101

- Planet formation is a byproduct of star formation
  - first, an interstellar cloud of gas & dust collapses due to its gravitational self–attraction
    - $\sim \mathbf{99\%}$ of the cloud forms young Sun
    - $\sim \mathbf{1\%}$ of the cloud forms a disk orbiting the Sun (consequence of $\boldsymbol{L}$ conservation)



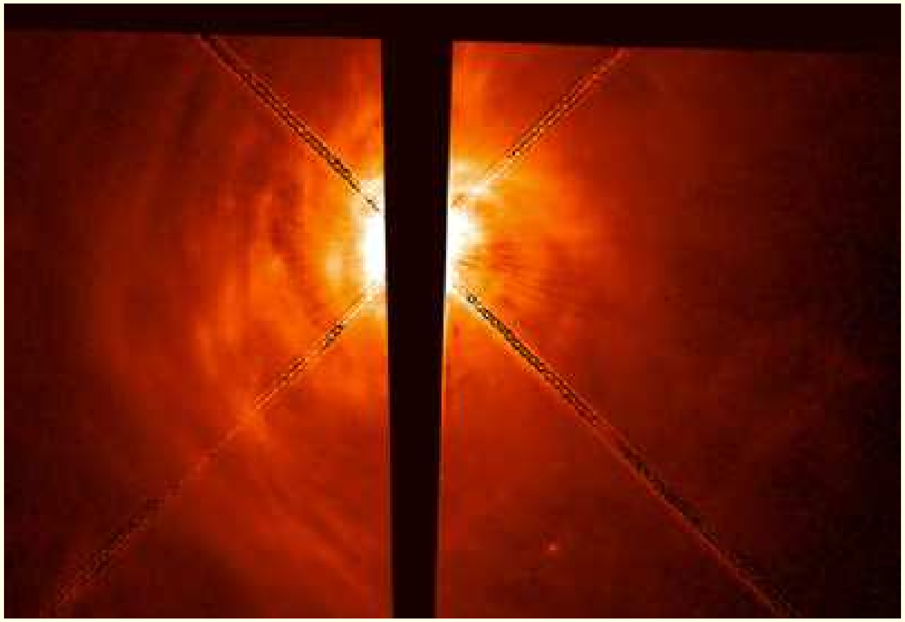

collapsing cloud forms star + disk

- dust grains are concentrated in the solar nebula disk
  - many grains collide, & some stick to form larger objects
  - over time, dust grow $\longrightarrow$ planetesimals, which are the building blocks of the planets

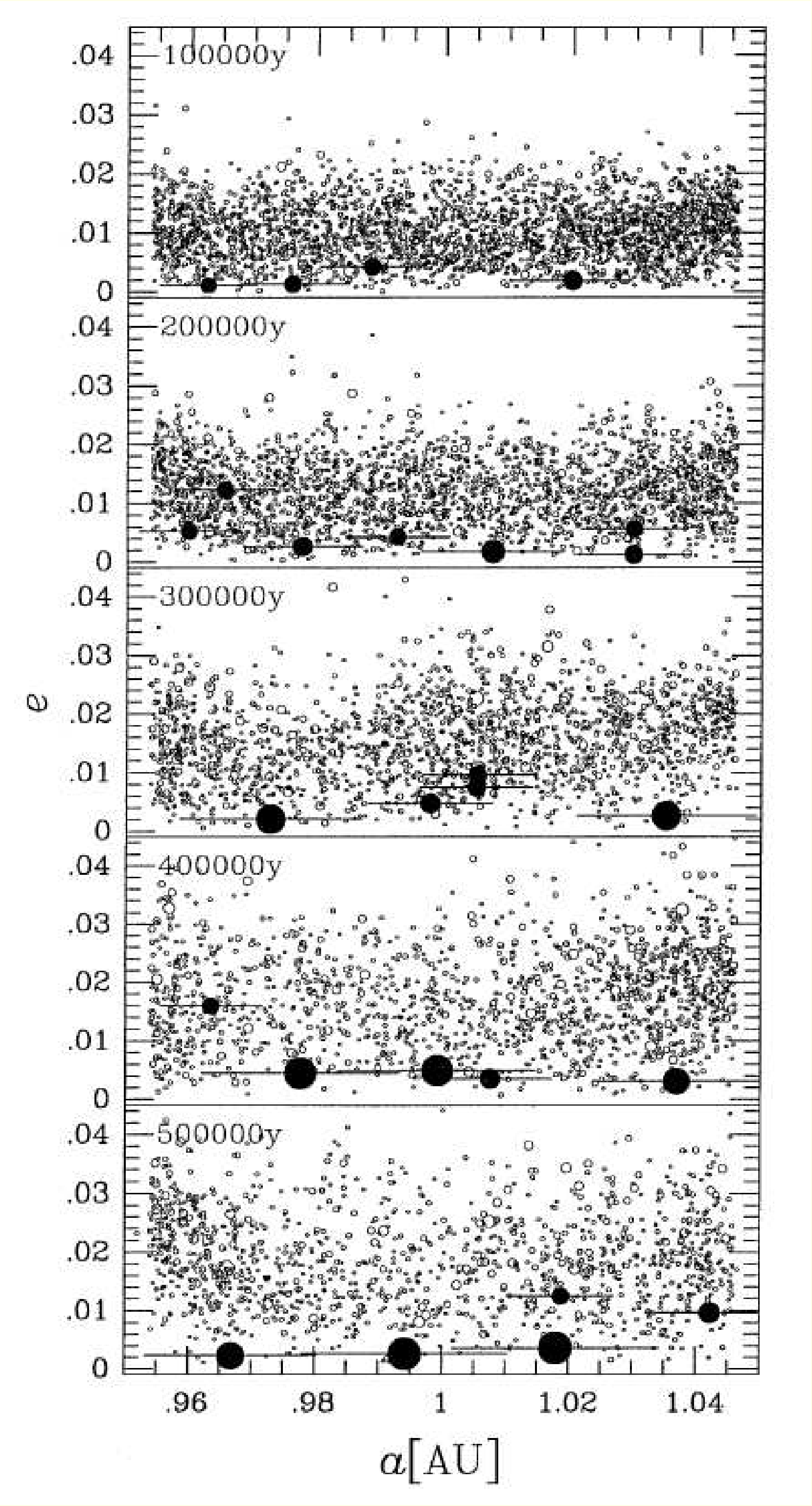

cartoon showing growing planetesimals

- regions where $r \lesssim 5$ AU, the nebula temperature $T \gtrsim 200$ K
  - 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

- computer Nbody simulations have confirmed these planetformation theories
  - show that protoplanetary cores do form from swarms of smaller planetesimals
  - however this is only *partial* confirmation; they have not been confirmed by astronomical observations
  - that must await for later generation of telescopes to observe *in–situ* planet formation

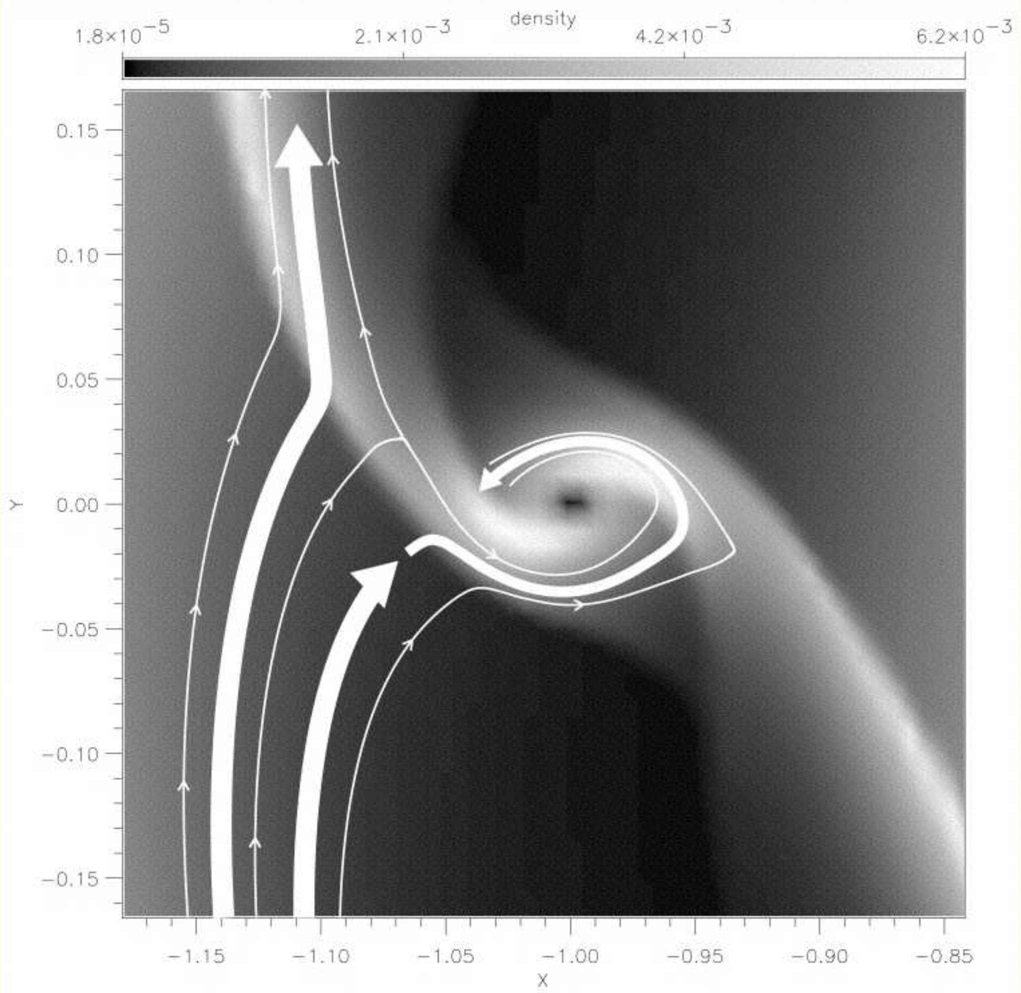


AB Aurigae



# Formation of the Giant Planets

- when the giant planets' cores achieve $M_{core} \sim 10\, M_{\oplus}$, they start to accrete gas directly from solar nebula
  - important, Jupiter is $\sim 90\%$ gas
  - observations show that disk's dissipate in $\tau_{disk} \sim 10^{6 \text{ to } 7}$ years
  - implies that giant–planet formation must be complete by time $t < \tau_{disk}$.



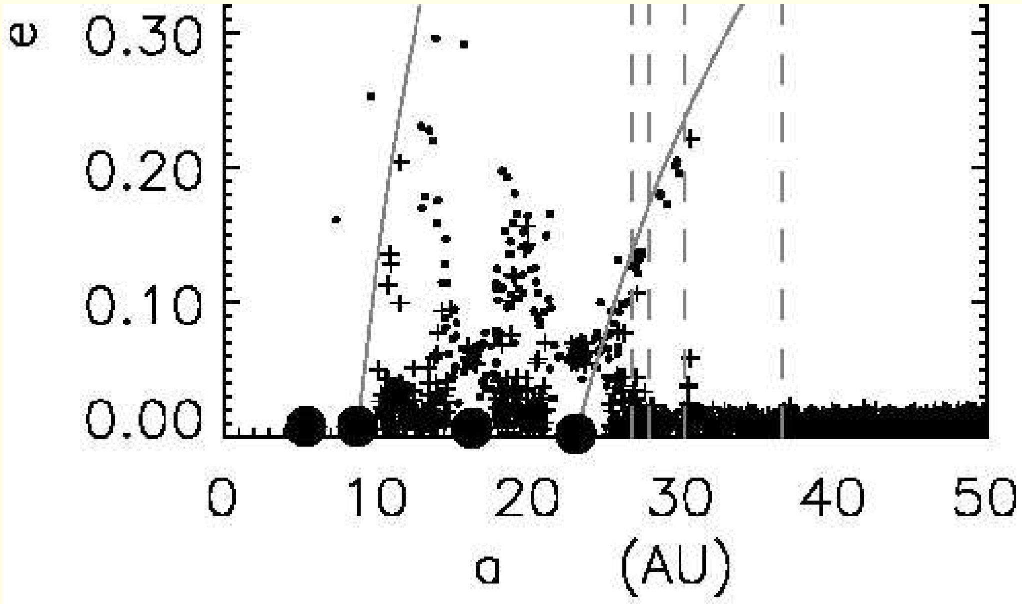

simulation of Jupiter's gas accretion

# Endgame—Final Cleanup

- initial stages of planet formation provides you with:
  - 4 terrestrial planets
  - 4 giant planets
  - lots of debris orbiting between and beyond the planets

- thus the final stage involves cleaning the SS of this residual debris

- Nbody simulations show that the giant planets are effective at:
  - accreting some of this debris
  - gravitationally scattering some debris into wide orbits $r \sim 10^4$ AU
  - or ejecting debris from the Solar System




Nbody simulation of final cleanup

# What is an Nbody Integrator?

very useful code used to study dynamical systems

begin loop over all times $t_n$

begin loop over all particles $i$

$$\mathbf{a}_{ij} = \frac{Gm_j}{r_{ij}^2}\hat{\mathbf{r}}_{\mathbf{ij}} = \text{ i's acceleration due to j}$$

$$\mathbf{a}_i = \sum_j \mathbf{a}_{ij} = \text{ i's total acceleration}$$

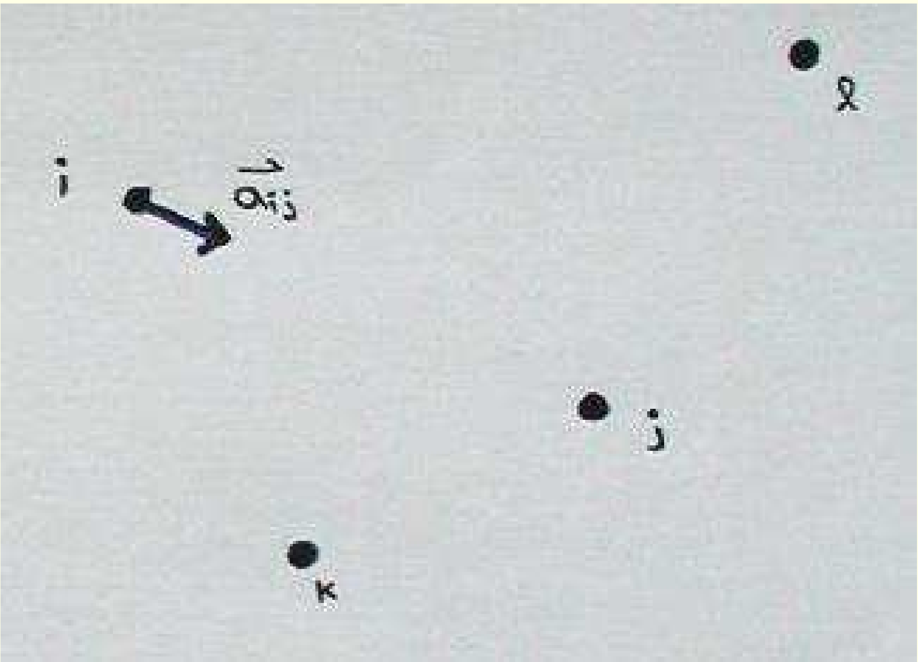
as time advances as $t_n \rightarrow t_n + \Delta t$

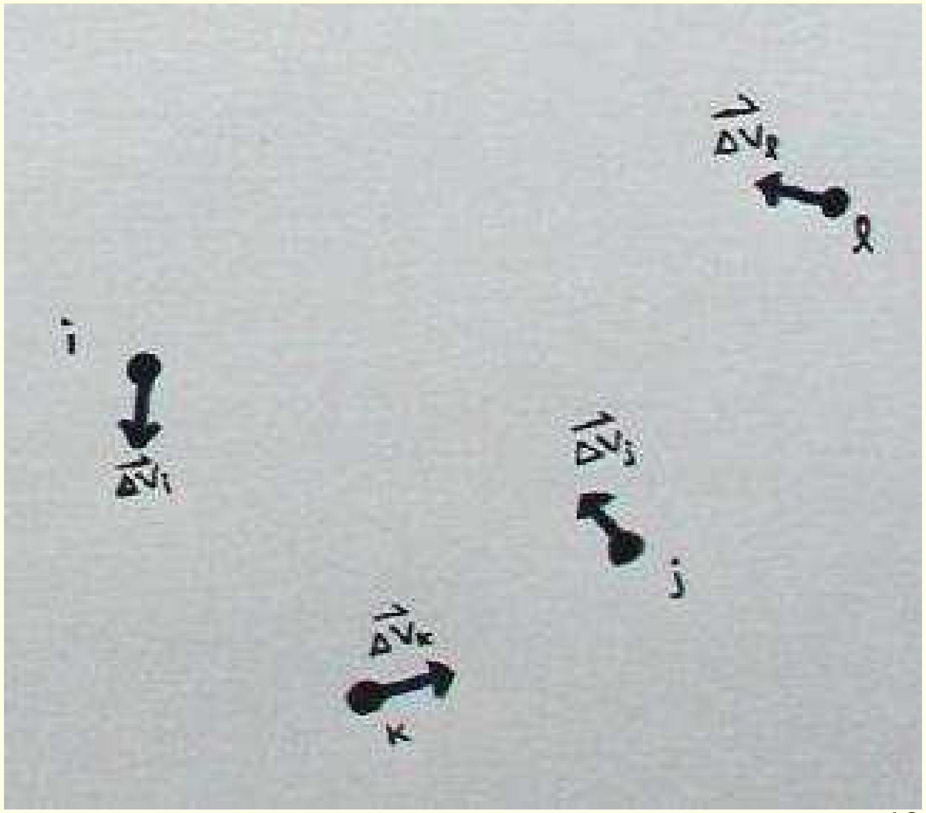
$\mathbf{\Delta v_i = a_i \Delta t} =$ i's velocity kick

end loop over all particles $i$

end loop over all times $t_n$

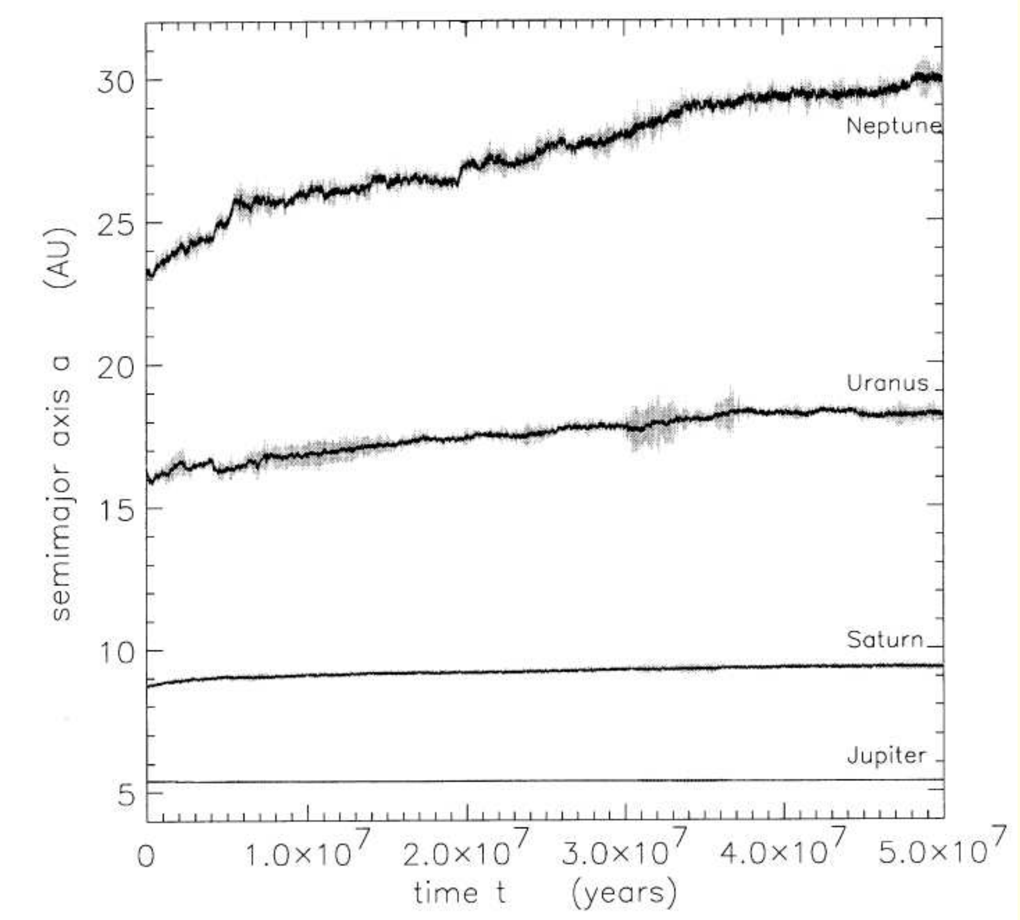
⇒Nbody integrator 'kicks' particles along their trajectories





- these same Nbody simulations show that the final cleanup also causes the orbits of the planet's to *migrate*

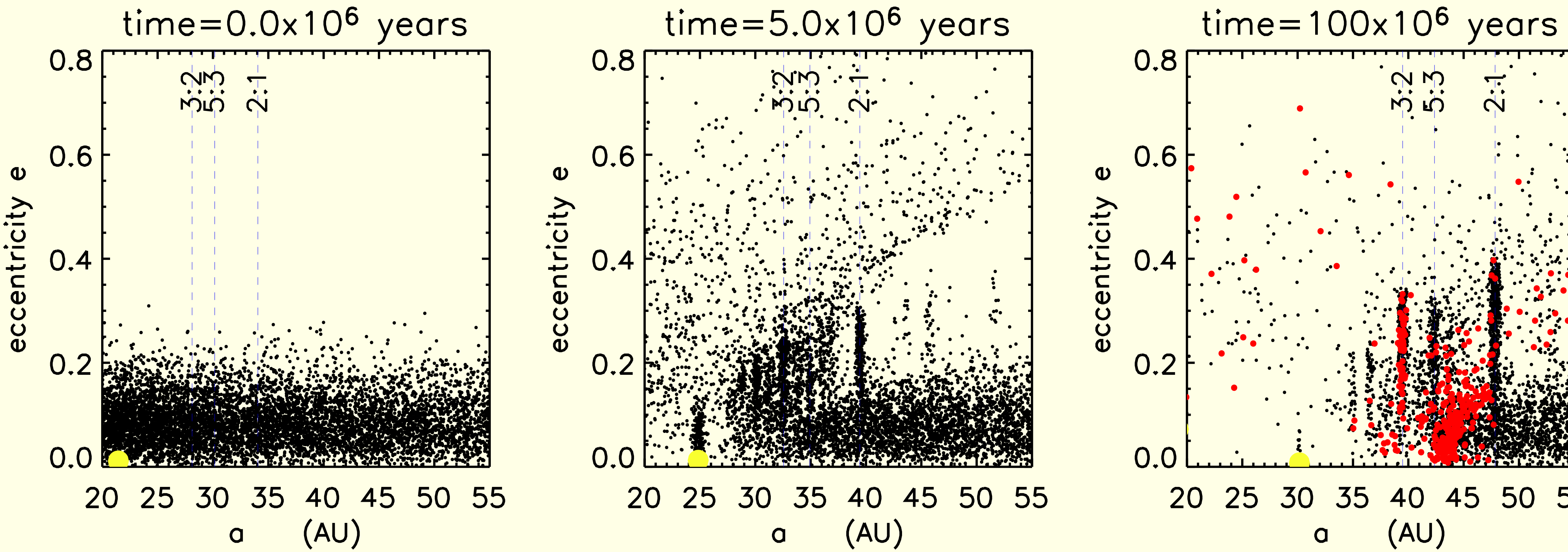
- this is due to an angular momentum exchange with the debris–disk
  - the outer giant planets acquire $\boldsymbol{L}$ from nearby planetesimals
  - early planets' orbits were *mobile*, & not fixed!
  - Neptune's orbit probably expanded $\sim \mathbf{50\%}$, from $\mathbf{20} \rightarrow \mathbf{30}$ AU




Nbody simulation of planet migration

# Is there Evidence for Planet Migration—or is this all a Fairy Tale?

The evidence is preserved in the Kuiper Belt:

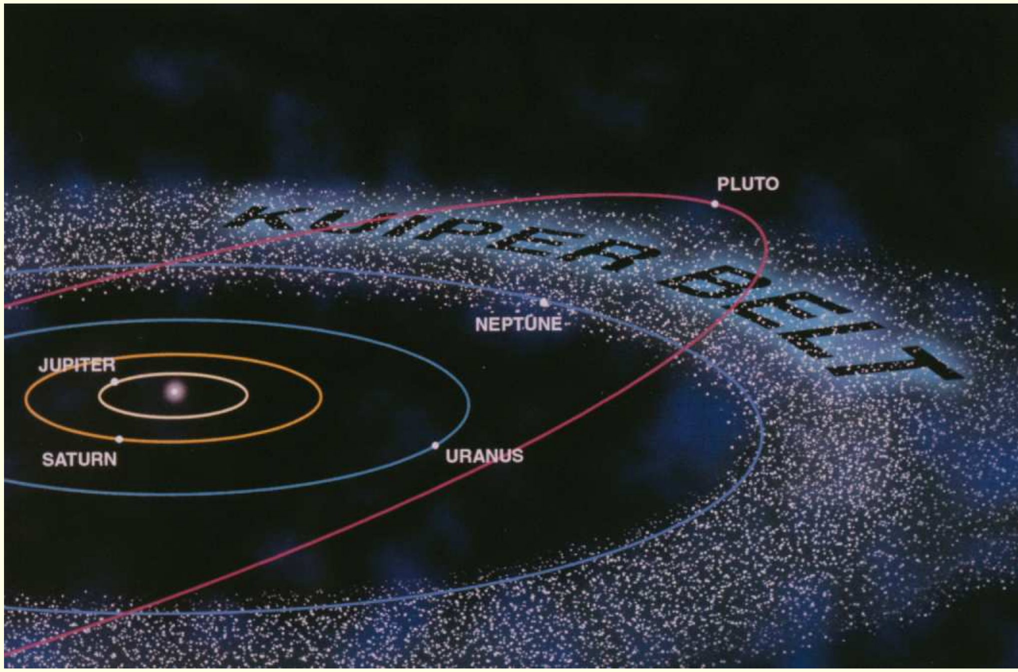


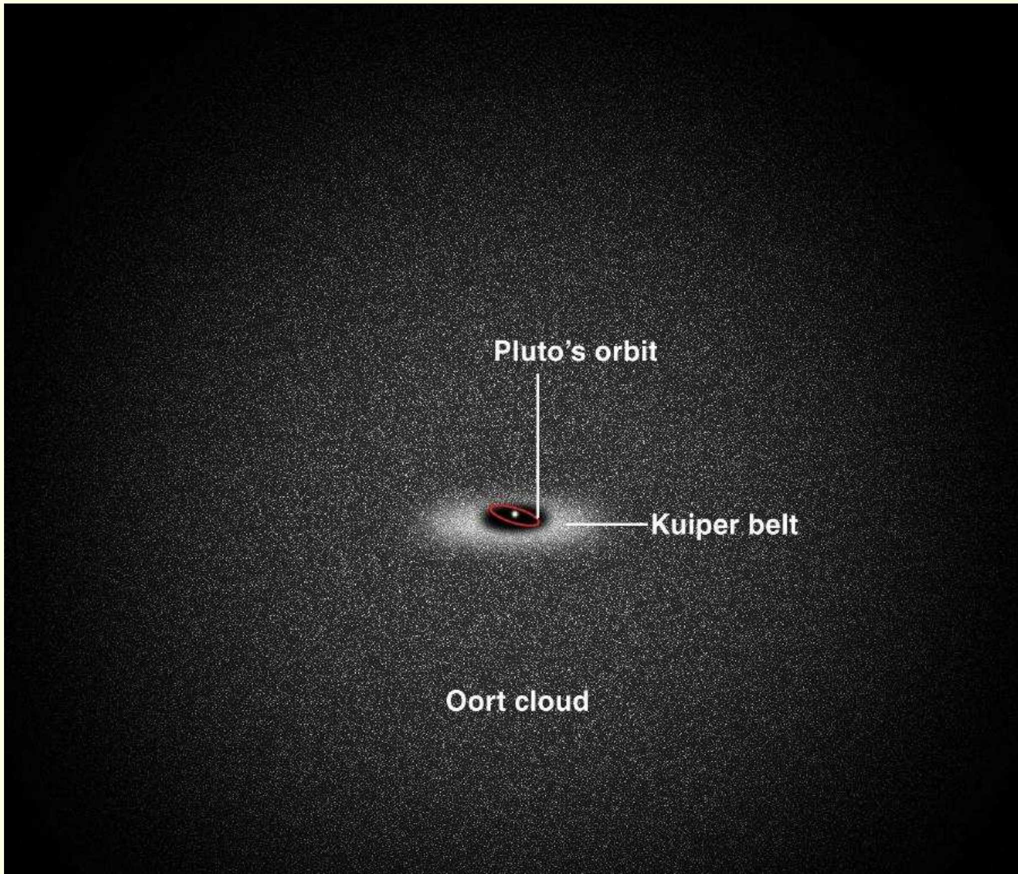

Nbody simulations show that as Neptune migrates outwards,

- Neptune's *resonances* 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.
  - good agreement is regarded as strong evidence for Neptune's migration

# Where Do Comets Come From?

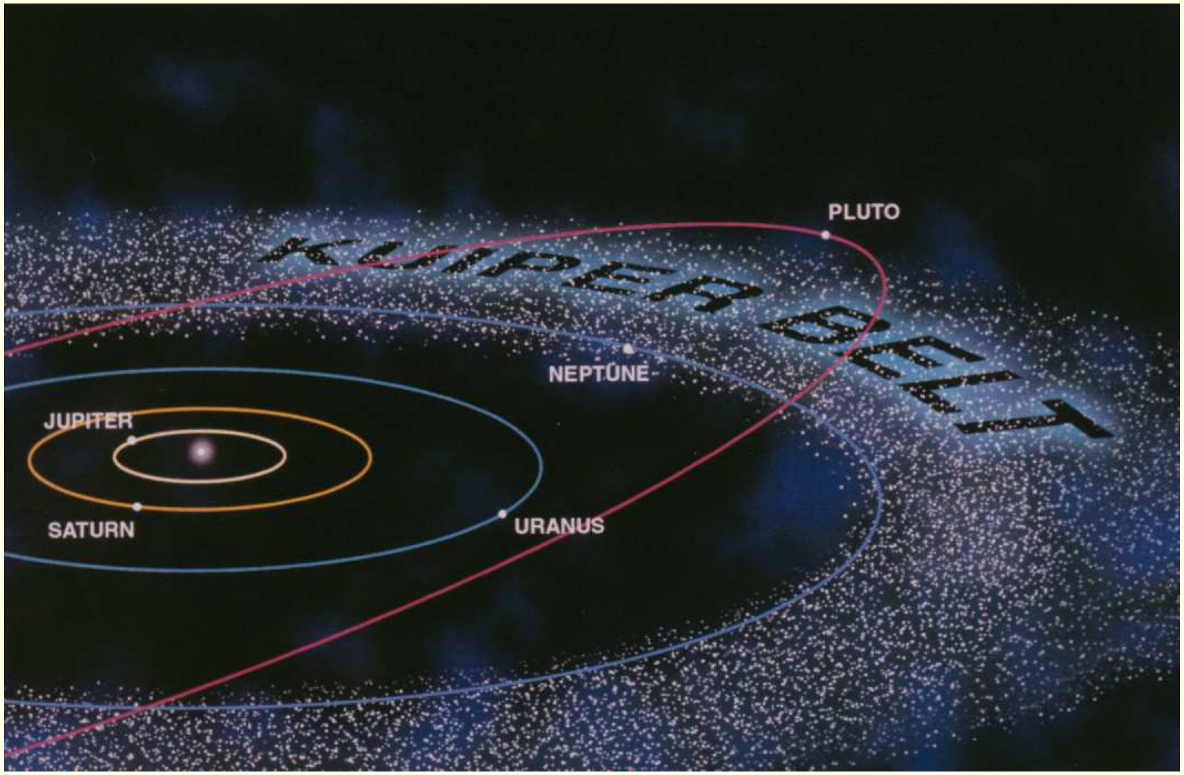
- comets slowly trickle out of 2 reservoirs, then get tossed about the Solar System by the giant planets
  - low–inclination comets come from Kuiper Belt
  - high–inclination comets come from Oort Cloud
  - most comets are dark and invisible since $r \gg 2$ AU
  - only the lucky few reach $r \lesssim 2$ AU, become warm and active enough to be *visible*

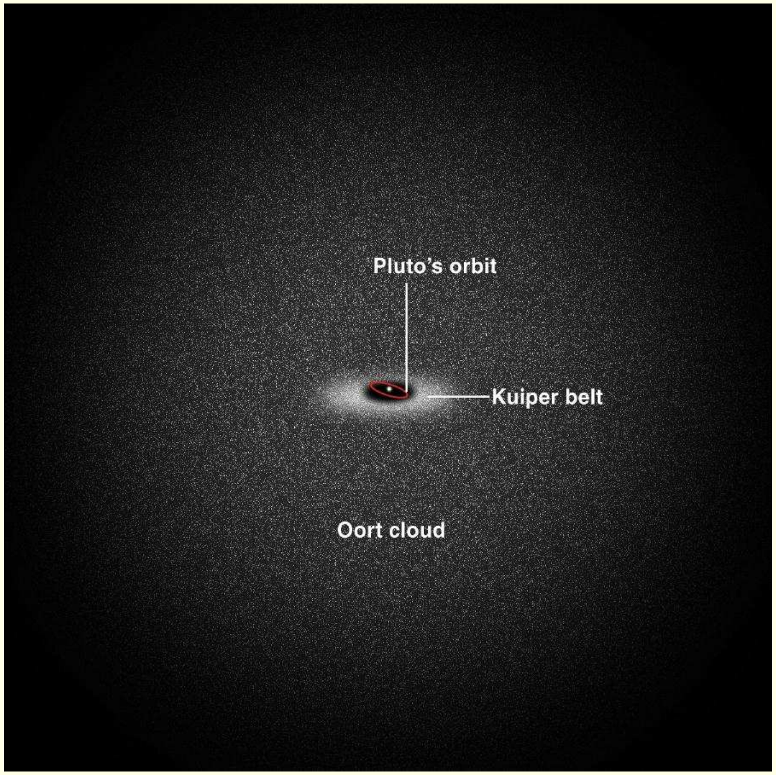


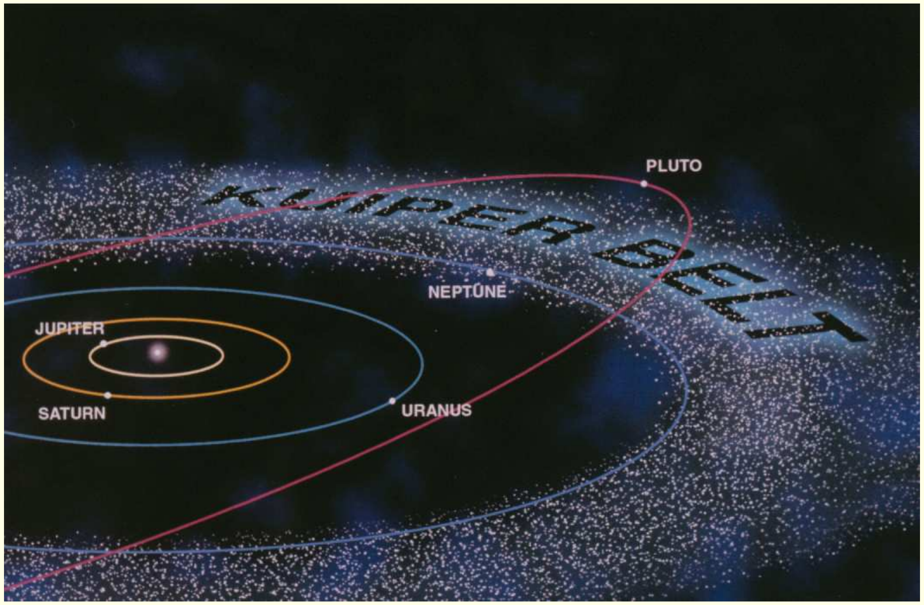
# Summary

- Comets and asteroids are ancient relics—debris that was left–over from when the planets first formed.
- the composition of comets preserve important clues about the initial conditions (namely, temperature & chemistry) in the early planet–forming solar nebula
- of particular interest to me is the dynamics of the Kuiper Belt and the Oort Cloud

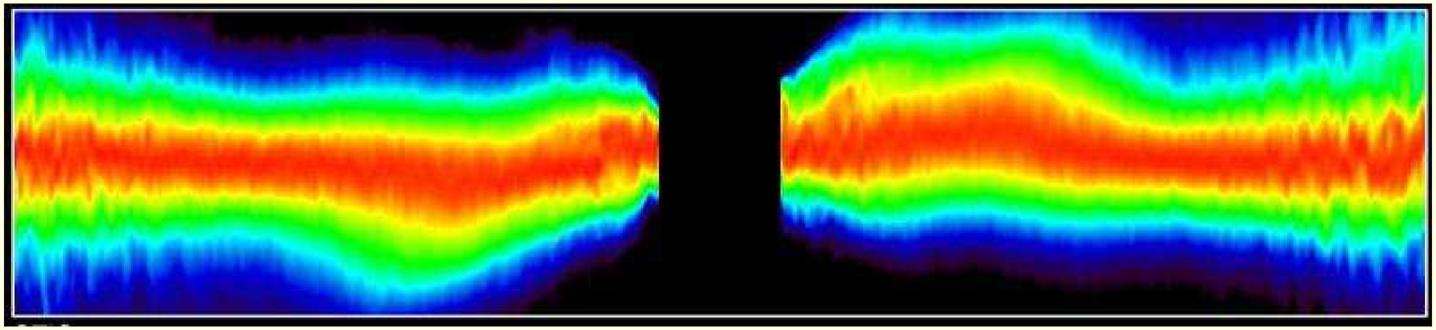


- the Kuiper Belt and the Oort Cloud are sources of the ‘active’ comets we see at $r \lesssim 2$ AU




- Kuiper Belt also provides insight into the early history of the outer Solar System
  - dynamical structure observed in the Kuiper Belt indicates Neptune’s orbit expanded $\sim 50\%$ during the ‘final cleanup’ stage
  - this probably happened during the Solar System’s first $t \sim 10^{7 \text{ or } 8}$ years
- Kuiper Belt studies may help us understand dust–disks observed at other stars



HST image of dust–disk orbiting $\beta$ Pictoris