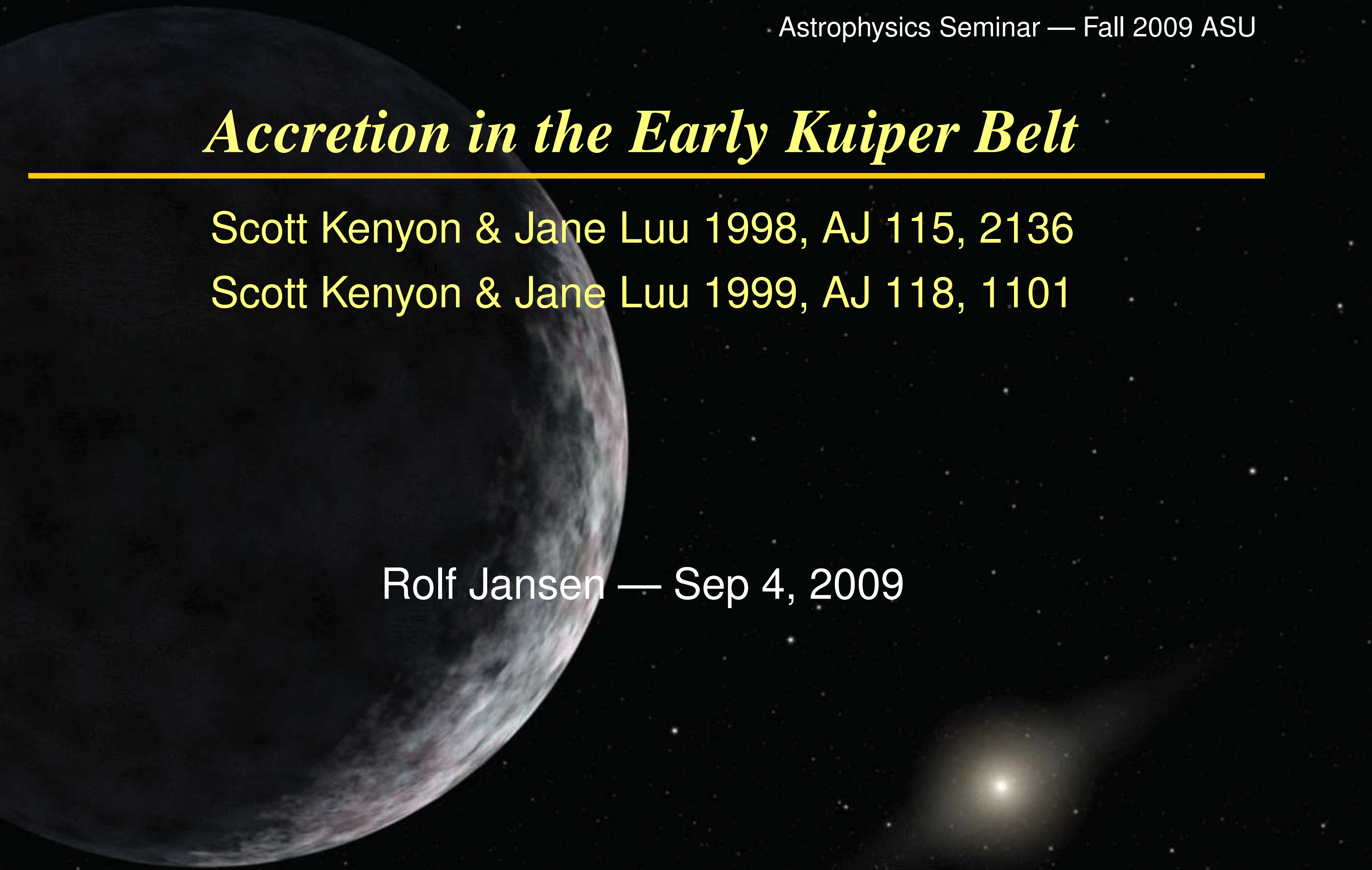
Accretion in the Early Kuiper Belt

Scott Kenyon & Jane Luu 1998, AJ 115, 2136

Scott Kenyon & Jane Luu 1999, AJ 118, 1101

Rolf Jansen — Sep 4, 2009



Artist rendering of Eris (2003 UB_{313}) set against a background of the distant Sun and inner solar zodiacal disk — Robert Hurt (IPAC)

Arizona State University

Outline

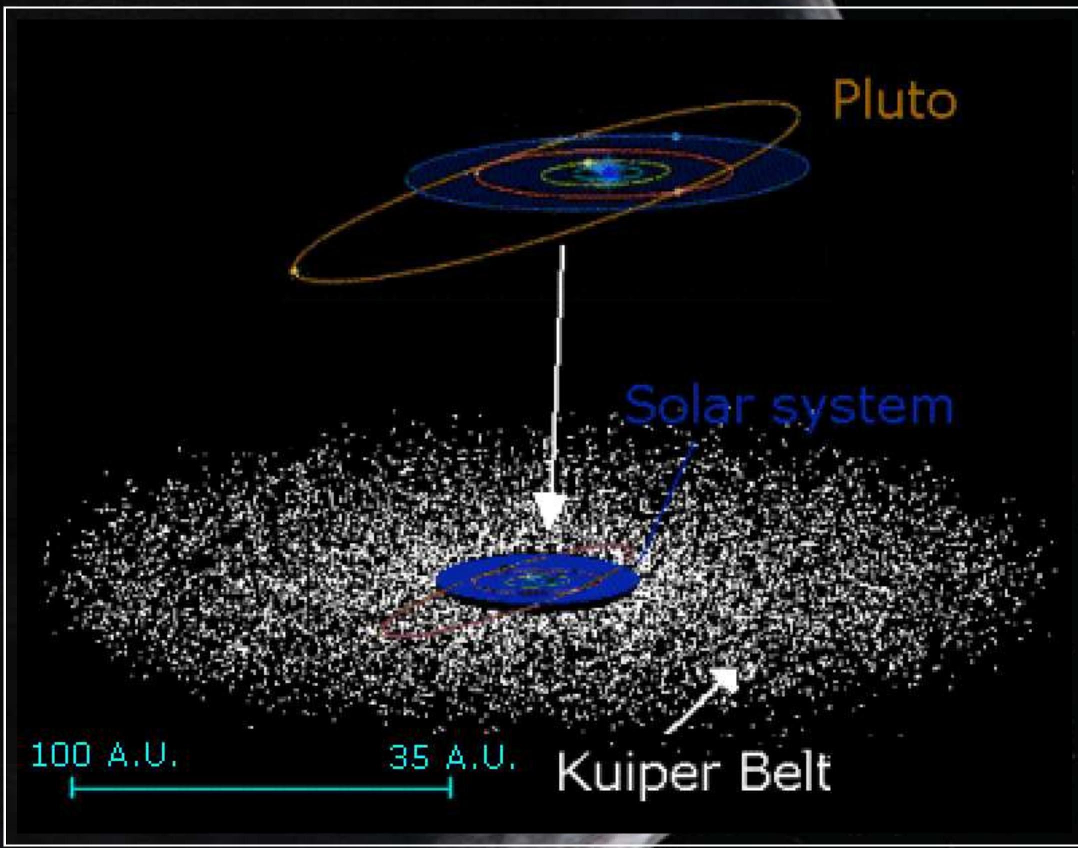
- Introduction to the Kuiper Belt
- Problem: Should Neptune not have prevented Pluto (and other 1000+ km objects) from forming in the outer Solar system?
- New simulations, isolating the key parameters: coagulation, fragmentation, tensile strength, nebula mass
- Discussion
- Conclusion: Pluto is not a figment of our imagination

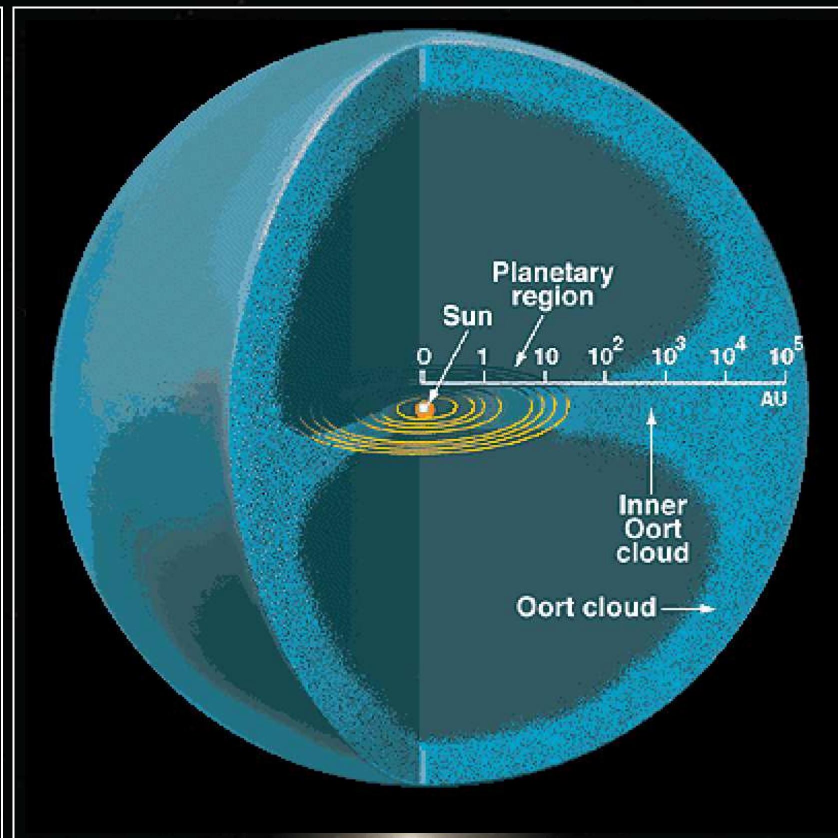
Introduction to the Kuiper Belt (anno 1998)

- Kuiper Belt (Edgeworth 1943,1949; Kuiper 1951) is remnant of the solar nebula (circumsolar disk)
- Kuiper Belt stretches beyond Neptune: 30 – ∼50 (100?) AU, may have rather abrupt outer edge
- Estimated population of $\sim 10^5$ Kuiper Belt Objects (KBOs) with $r \gtrsim 50$ km; origin of short-period comets
- Pluto and Eris (2003UB$_{313}$) are merely largest known KBOs
  - ➤ $r \sim 1125$ km and $r \sim 1475$ km.

ARIZONA STATE UNIVERSITY

Introduction (cont’d)





Cartoon representations of Kuiper Belt and Oort Cloud.
(Courtesy: http://spaceguard.iasf-roma.inaf.it/NScience/neo/)

Introduction (cont'd)

- Kuiper Belt is sufficiently populated for collisions to occur
  - both merging and collisionally produced dust likely important
- Estimated total mass of Kuiper Belt is $\sim 0.1\, M_{\oplus}$
  - power-law size distribution, with $r = 1 - 1500$ km;
  - bulk density $\rho \sim 1$ kg m^{-3};
  - and albedo $p_R = 0.07$
- Important, because Kuiper Belt is closest connection to circumstellar disks around other stars

Problems?

- Mass is much smaller than expected from extrapolating the surface mass density of the inner solar system
- Mass is far too small to form the larger observed KBOs within the $\sim 10^8$ yr imposed by Neptune accreting nearby
- Accretion models predict original Kuiper Belt $\sim 100\times$ more massive than present-day one
  - Depletion via scattering by Neptune
  - Collisional grinding of objects with $r < 50$ km
  - KBOs larger than 100 km should be original remnants from early solar system

Current state of models

- Improve upon previous models that:
  - follow coagulation of large dust grains into larger grains up to km-sized planetesimals
  - follow collission-driven merging into larger bodies
  - do manage to produce a planet-sized object on time-scales roughly compatible with life-time of (proto)solar nebula
  - do not include velocity evolution
  - do not include fragmentation due to collisions of the larger bodies formed

Current state of models (cont'd)

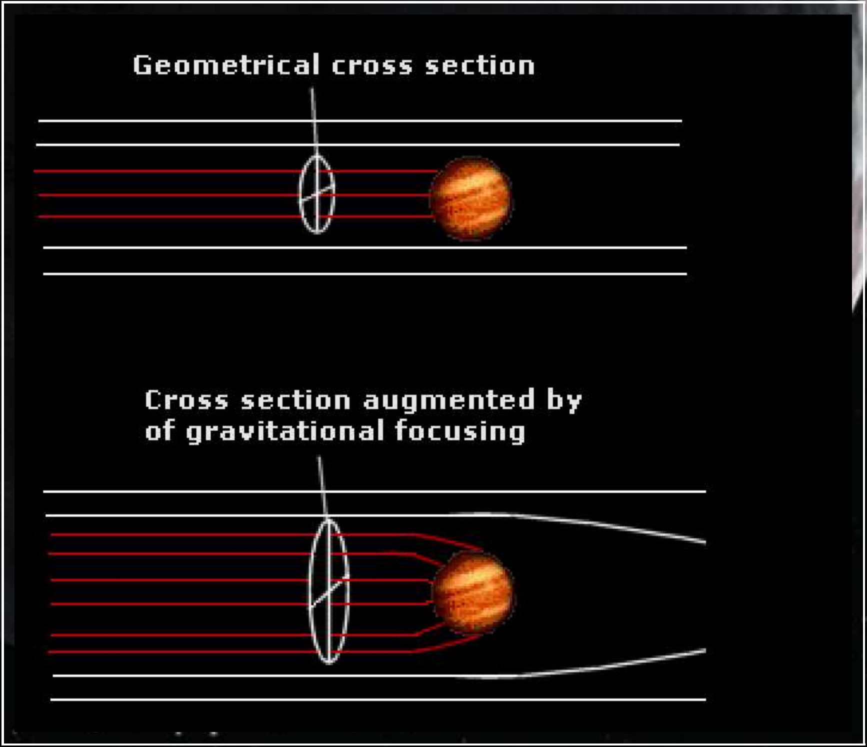
- Available models have problems producing one 1000+ km planet (Pluto) within 100 Myr, let alone several.
- Formation process and timescale for production and retention of KBOs still controversial

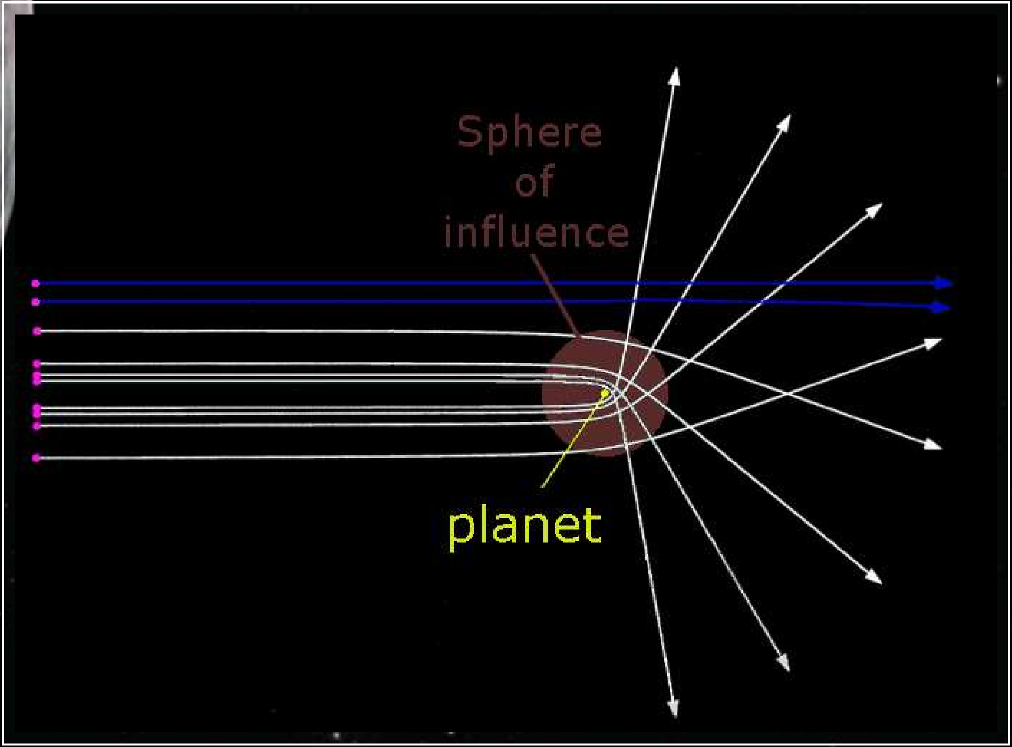
Relevant Dynamical Processes

- Gas drag (decreases particle velocities and causes particles to spiral inward; unimportant: too long a time-scale)
- Dynamical friction (transfers kinetic energy from larger to smaller bodies)
- Viscous stirring (taps Solar gravitational field to increase the velocities of all bodies)
- Collisional damping (inelastic collistions)

Relevant Dynamical Processes (cont'd)

- Gravitational focusing (increases effective cross section of a body; important for all dynamical processes if $r \gtrsim 100\,\mathrm{km}$ and $m \gtrsim 10^{19}\,\mathrm{kg}$) :





New simulations — Step 1: velocity evolution

Kenyon & Luu 1998, AJ 115, 2136 [Paper I]

- ▼ Sanity check of new code at 1 AU (Wetherill & Steward 1993)
- Model annulus at 35 AU with width of 6 AU
- Starting conditions based on observations of other stellar systems and models of the protosolar nebula
- Initial sizes of bodies of either 80 m, 800 m or 8 km
- Small eccentricities, $e \leq 0.01$, and equilibrium ratio of inclination to eccentricity, $\beta = \langle i \rangle / \langle e \rangle = 0.6$ (Barge & Pellat 1990,'91,'93)
- Fixed mass density of each body of 1.5 g cm^{-3}
- Total $M_{\rm dust}$ = 7–15 $M_\oplus$ (from minimum-mass solar nebula)

New simulations (Step 1): Results

- 1000+ km objects can be produced at 35 AU on timescales of 10–100 Myr in a minimum-mass solar nebula, if *small* bodies with initial radii $80 < r < 800$ m were already present and if orbital eccentricities were small ($e \sim 0.001$)
- When velocity evolution is taken into account, run-away growth occurs on a *wide range* of timescales (not just a linear process; not just one single object)

New simulations (Step 1): Results (cont'd)

- if larger bodies ($\sim$8 km) were present in the protosolar nebula, then dynamical friction and viscous stirring would have *delayed* onset of run-away growth ($>$100 Myr) or required a much more massive solar nebula ($\sim$100 $M_\oplus$)
- if initial bodies were small (80 – 800 m), collisional damping dominates over dynamical friction and viscous stirring, resulting in *earlier* onset of run-away growth compared to previous models without velocity evolution

New simulations (Step 1): Caveats

But:

- Assumption of homogenous spatial distribution of planetesimals with small velocities relative to their keplerian orbital velocity breaks down in late stages of run-away growth [hence: simulation were ended at that stage]
- Timescale to run-away is sensitive to the *minimum* radius/mass of objects, hence fragmentation/cratering might have a large impact [see: Paper II]
- Treatment of low-velocity collisions is uncertain approximation, particularly in the later stages: massive bodies have low relative velocities and long gravitional ranges!

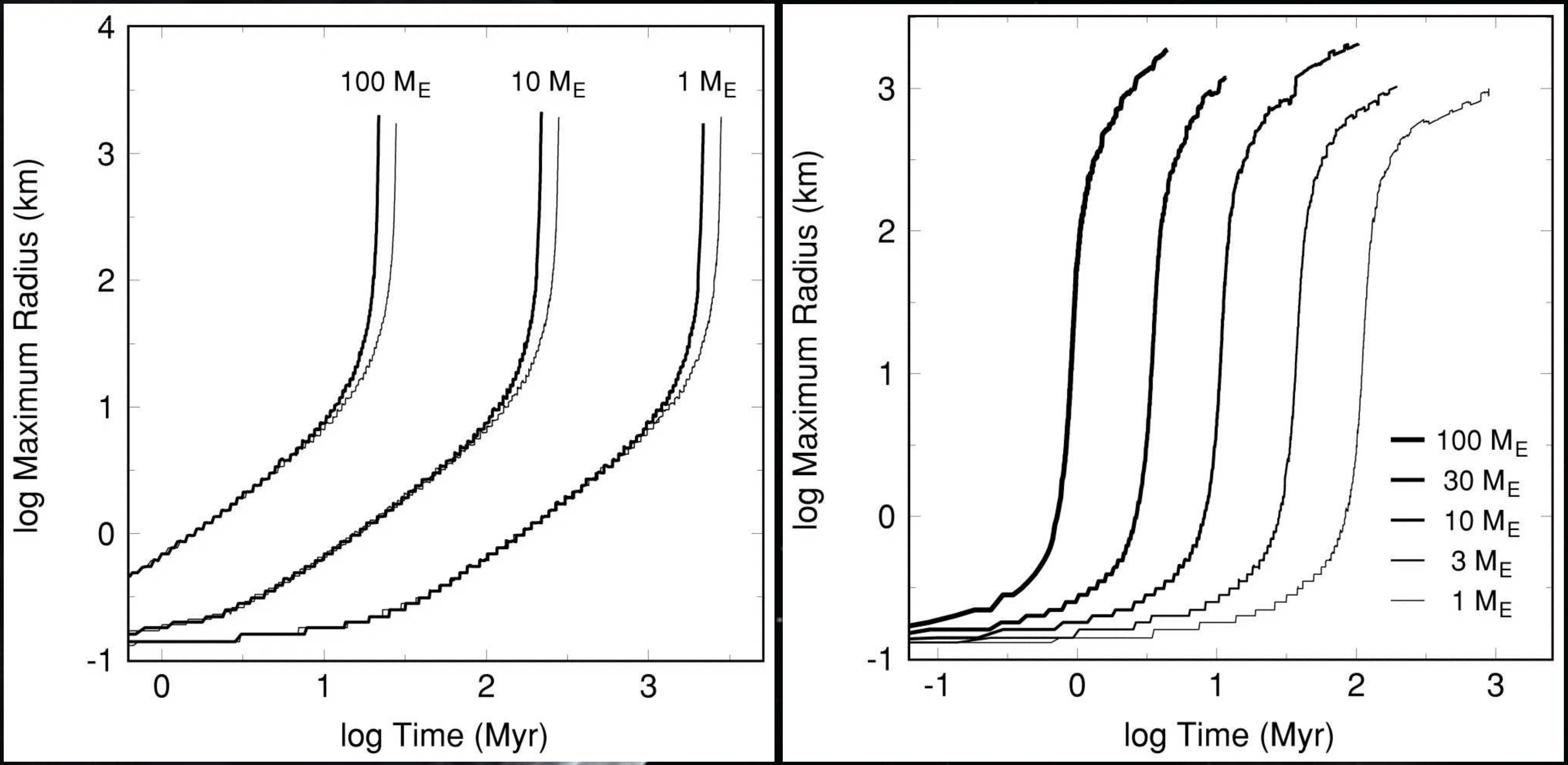
New simulations (Step 1): Caveats (cont’d)

- Icy bodies in Kuiper Belt region may not be very strong: collisions at modest velocities may disrupt and prevent *any* growth! Only objects larger than 40–60 km can survive collisions and produce larger bodies.

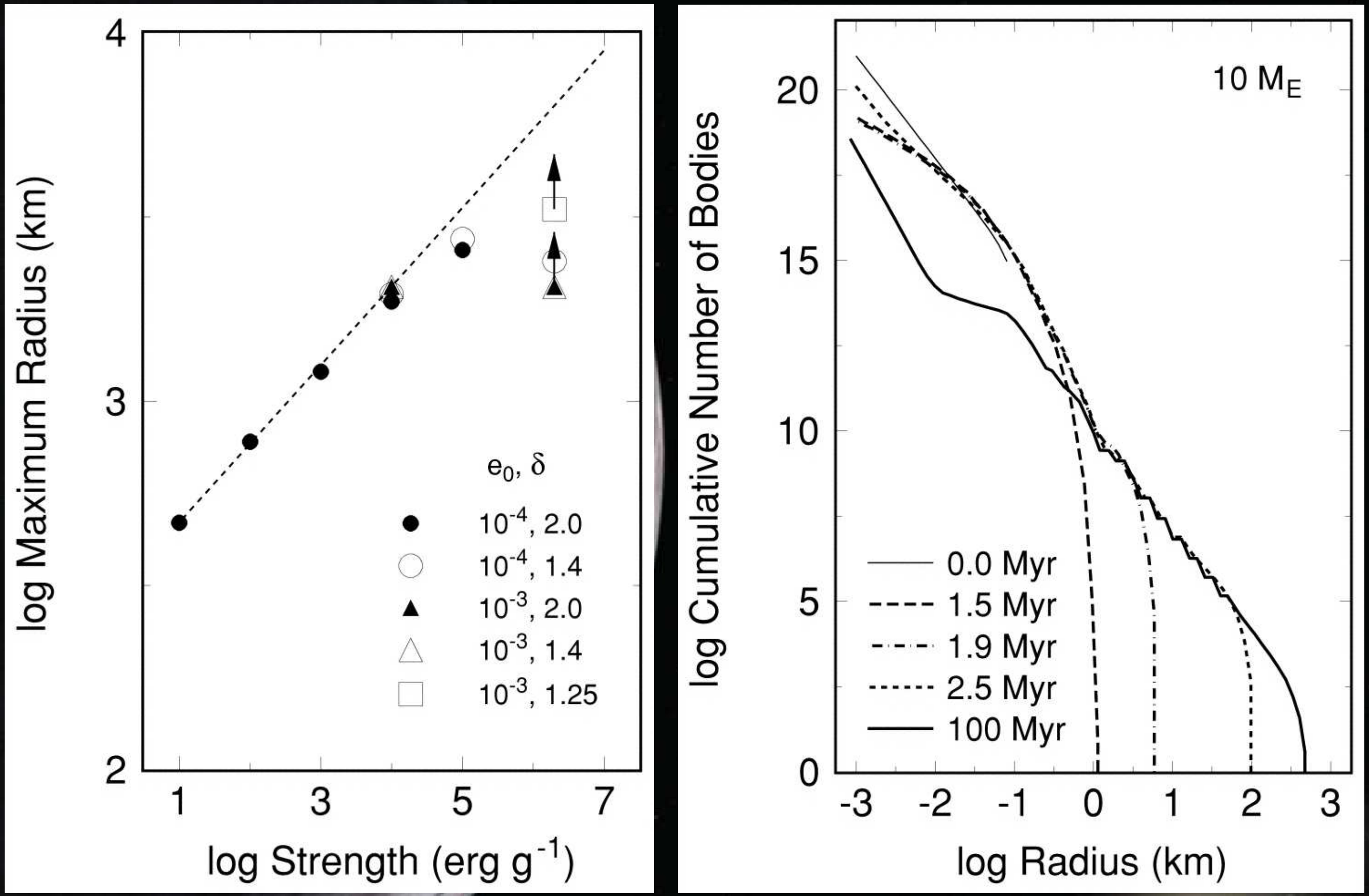
New simulations — Step 2: fragmentation

Kenyon & Luu 1999, AJ 118, 1101 [Paper II]

- Essentially same initial conditions as in Paper I
- Collisions result in:
  - mergers: virtually no debris
  - cratering: bodies merge, ejected debris has much smaller mass than the merged object
  - rebounds: collision without merging, with some debris
  - disruption: debris mass comparable to mass of the two initial bodies
  - (2 algorithms for treatment of cratering and disruption)



Maximum radius as a function of time for [LEFT] no or limited velocity evolution, and [RIGHT] full velocity evolution. The time to runaway growth decreases with increasing M_0. Fragmentation delays onset of runaway growth, producing more 0.1–10 km objects during this delay, and then more rapidly grows 100–1000 km objects, by sweeping up the small debris.



[LEFT] Maximum radius as a function of strength of the KBOs for $M_0 = 10 M_\oplus$. Weak KBOs fail to grow to Pluto sizes. [RIGHT] Cumulative size distributions for a model with fragile KBOs (S_0=100 ergs g^{-1}). Altough runaway growth produces 100 km objects, objects >400 km are catastrophically disrupted. Low-mass objects with $r \lesssim 0.1$ km are either ejected or ground to dust that is removed from the system on short timescales for $t \gtrsim 100$ Myr.

New simulations — Results

- Fragmentation and velocity evolution are important components in the formation of present-day KBOs
  - fragmentation produces a large reservoir of small bodies that damp the velocity dispersions of the larger objects through dynamical friction
  - that reservoir allows a *short* and *rapid* late-stage runaway growth phase where 1 km objects grow into 100 km objects, sweeping up this small-sized material

New simulations — Results (cont'd)

- continued fragmentation and velocity evolution damp early run-away growth by increasing the velocity dispersions of small objects [hence, the mass does not all wind up in the single object that happened to be the biggest early-on]
- unless KBOs are fragile, multiple 1000+ km size objects form the tip of the power-law size-distribution, even in a minimum-mass solar nebula.
- KBOs will form in the dusty disks around other pre-MS stars, where masses of 1–100 $M_\oplus$ have been inferred at 30–100 AU distances.

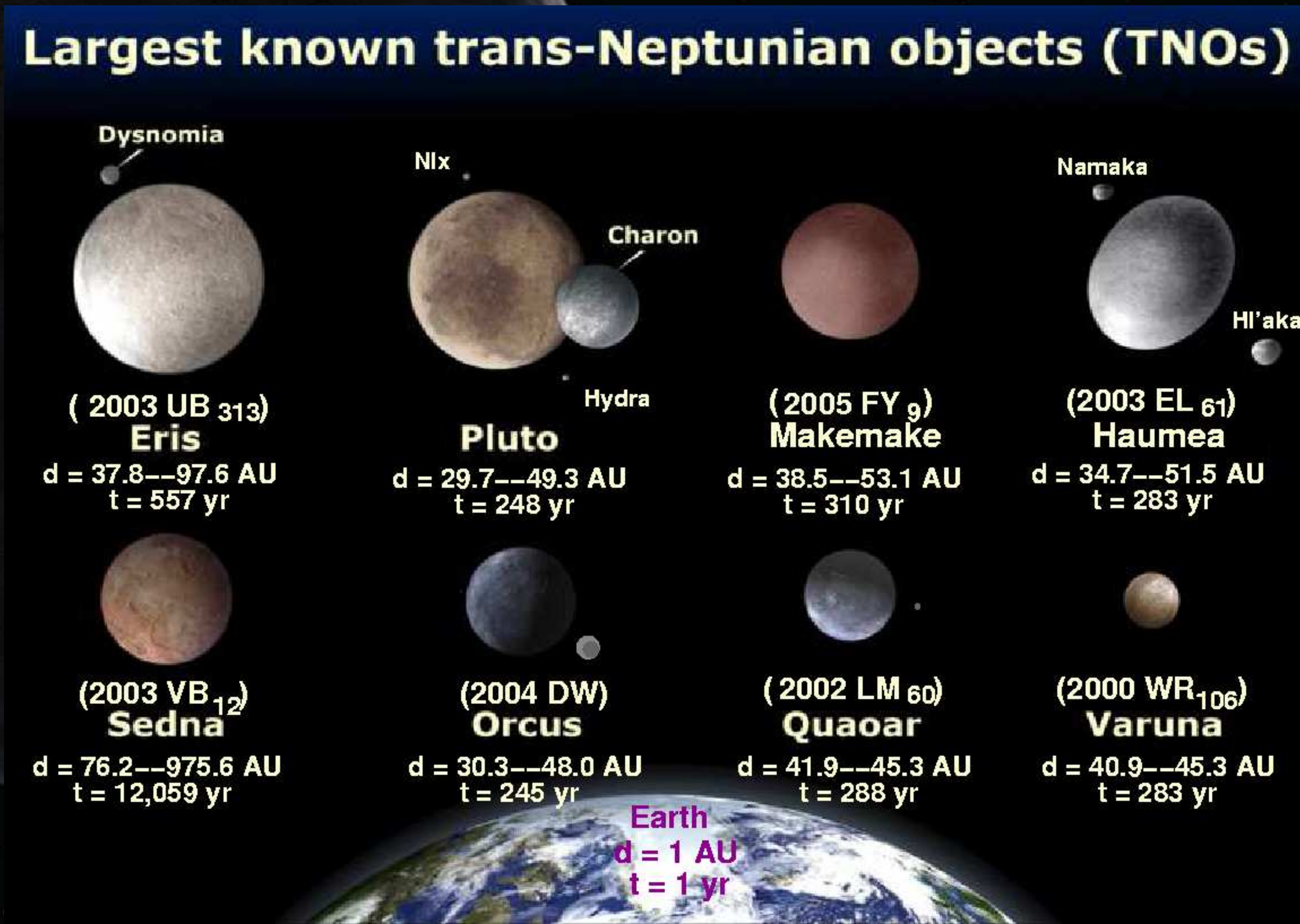
New simulations — Conclusion

- In a consistent simulation that includes *both* velocity evolution *and* the effects of fragmentation, it is:
  - possible to form several Pluto-sized objects at 32–38 AU
  - do so in only 30 – 40 Myr
  - for a *minimum-mass* solar nebula
  - and still have most of the initial mass locked in $\sim 10^5$ objects with radius 0.1–10 km
  - as long as the intrinsic tensile strength of these icy objects exceeds $S_0 \gtrsim 300$ ergs g^{-1} and the initial orbits were close to circular.

New simulations — Conclusion (cont'd)

- Kenyon & Luu, therefore, resolve the apparent paradox of *large* KBOs (e.g., Eris, Pluto, Makemake, Haumea, and Sedna are all larger than 1200 km in diameter) in a *small-mass* Kuiper Belt

The Kuiper Belt (anno 2009)



The Kuiper Belt (anno 2009)

- Thousands of Kuiper Belt objects with $r \gtrsim$ 100 km known (radii and masses often very uncertain; *Spitzer* mid-IR detections helped with mass / size / albedo estimates)
- Not just one or several Pluto's but possibly 104 objects of Pluto-like sizes in Pluto-like orbits at Pluto-like distances (new minor planet sub-class: plutinos)
- Distribution of orbits non-homogenous $\longrightarrow$ (Nice-model): the outer gas giants, particularly Neptune, did not form at their present distance from the Sun but migrated outward, trapping KBOs in resonances (2:1, 3:2, 4:3, 5:3 etc..), explaining Trojan populations of Neptune and also the capture of Triton.

The Kuiper Belt (anno 2009) (cont’d)

- Many of the larger discovered KBOs have satellites
- Objects like Sedna may originate from outside our Solar system; or the Kuiper Belt and formation of large bodies may (somehow) extend all the way to the inner Oort Cloud.

Why were these papers important?

- Systematic step-by-step approach of isolating important parameters to arrive at a consistent picture
- *Appendices!* Not discussed in this presentation, but invaluable when interested in starting, say, a PhD project on this topic

Kenyon & Luu 1998, AJ 115, 2136

Kenyon & Luu 1999, AJ 118, 1101

Luu & Jewitt 2002, ARA&A 40, 63

Artist impression of a collision, resulting in at least *some* debris, in the Kuiper Belt — Illustration credit: Dan Durda