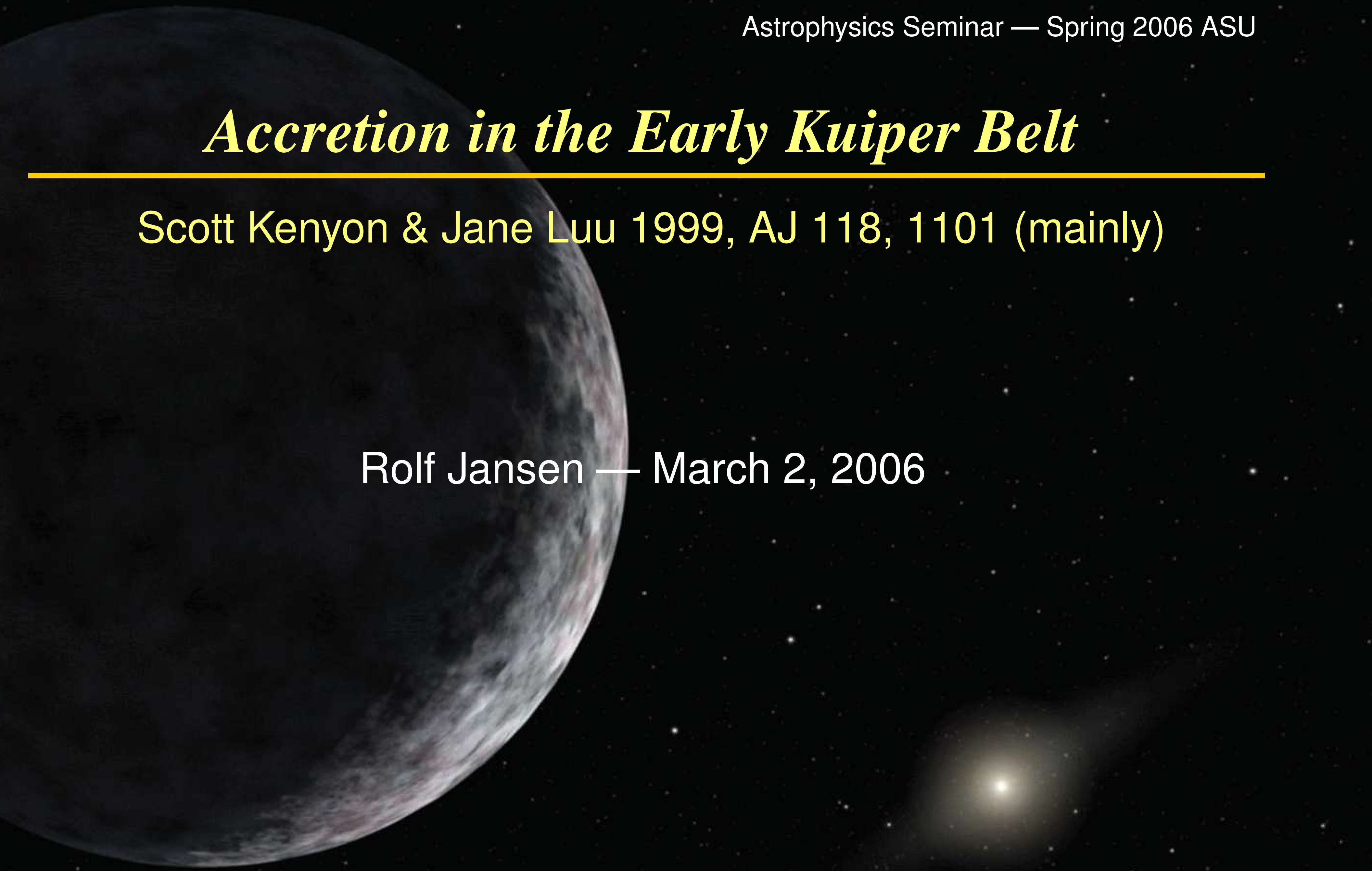
# *Accretion in the Early Kuiper Belt*

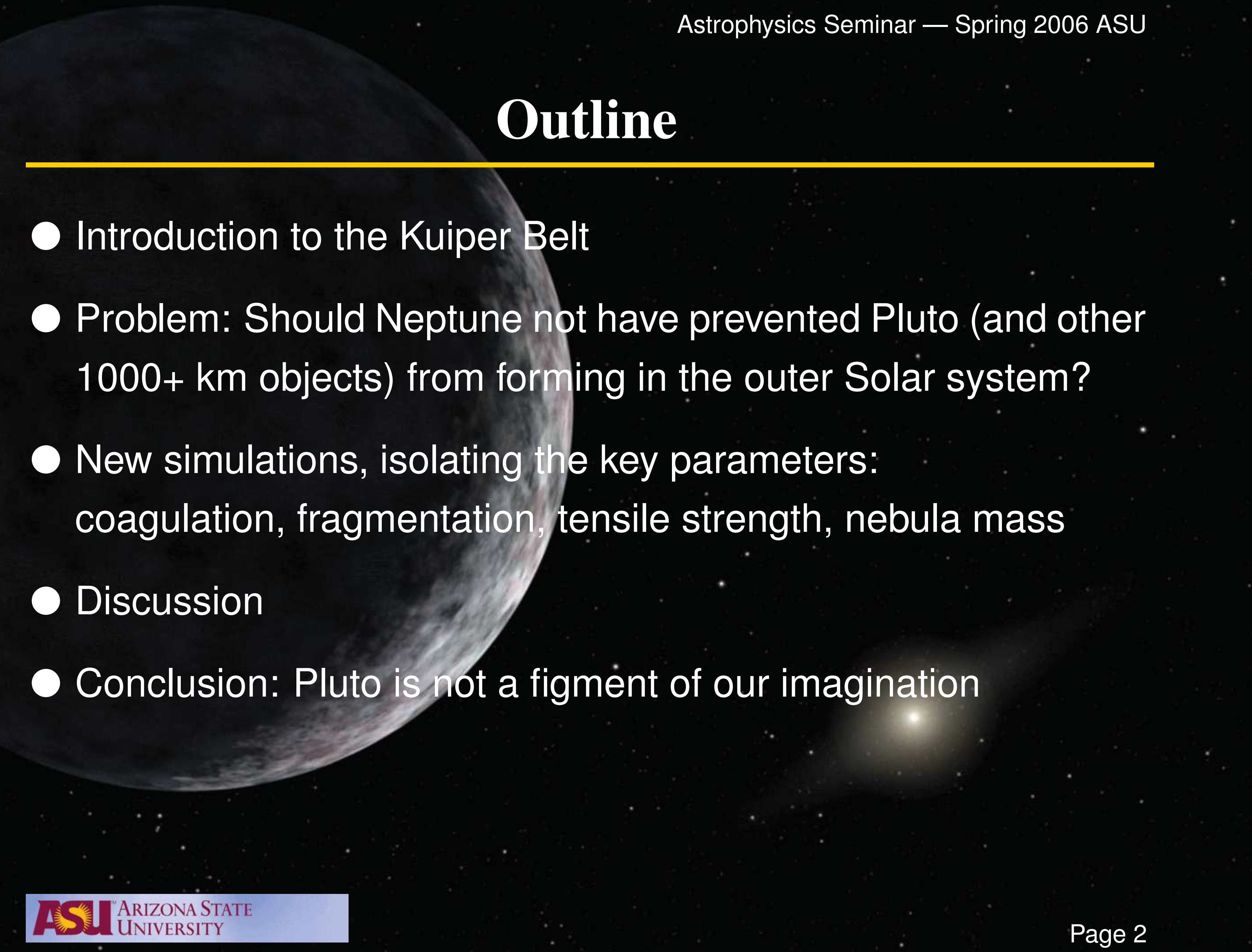
Scott Kenyon & Jane Luu 1999, AJ 118, 1101 (mainly)

Rolf Jansen — March 2, 2006



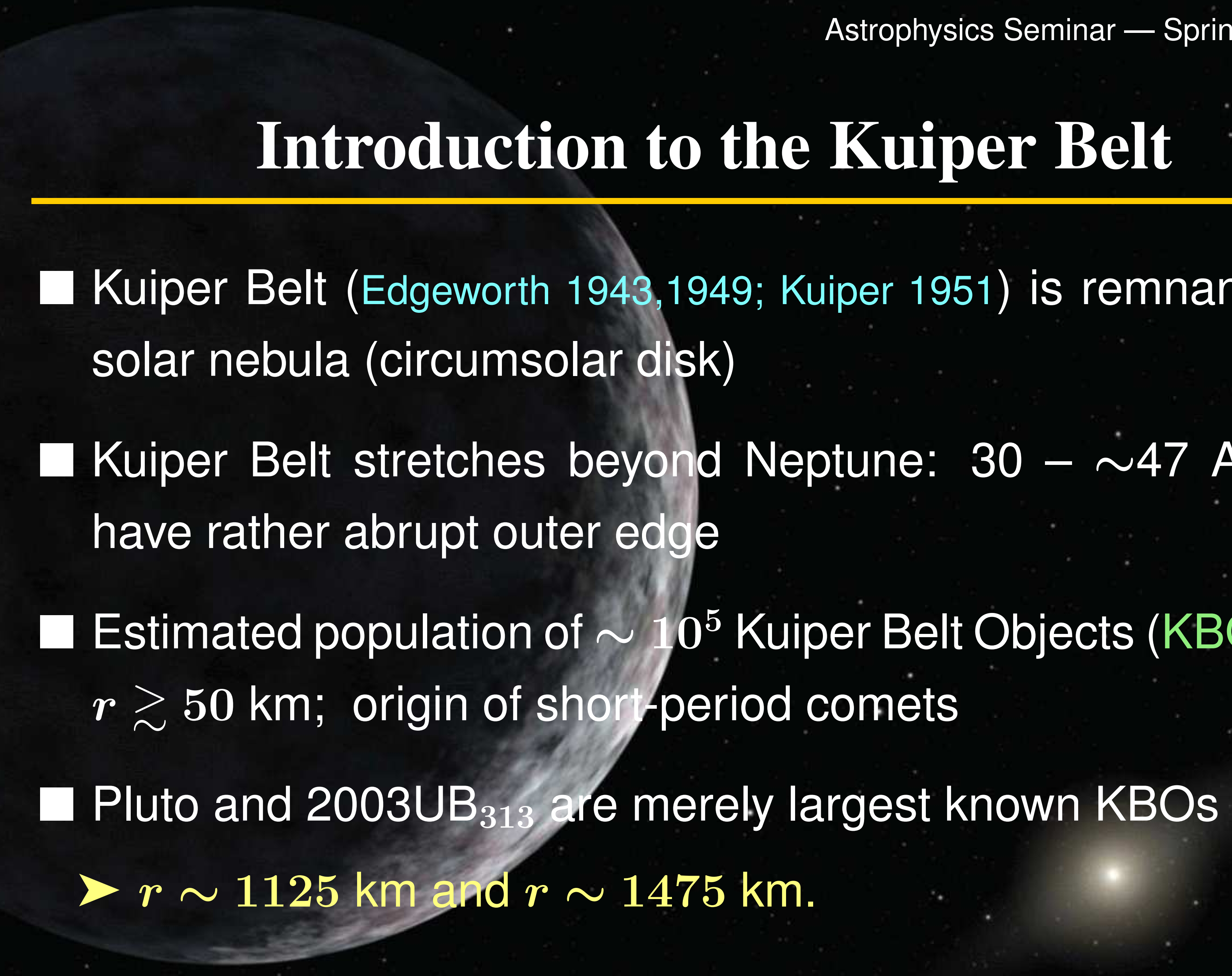
*Artist rendering of 2003UB$_{313}$ set against a background of the distant Sun and inner solar zodiacal disk — Robert Hurt (IPAC)*

# Outline

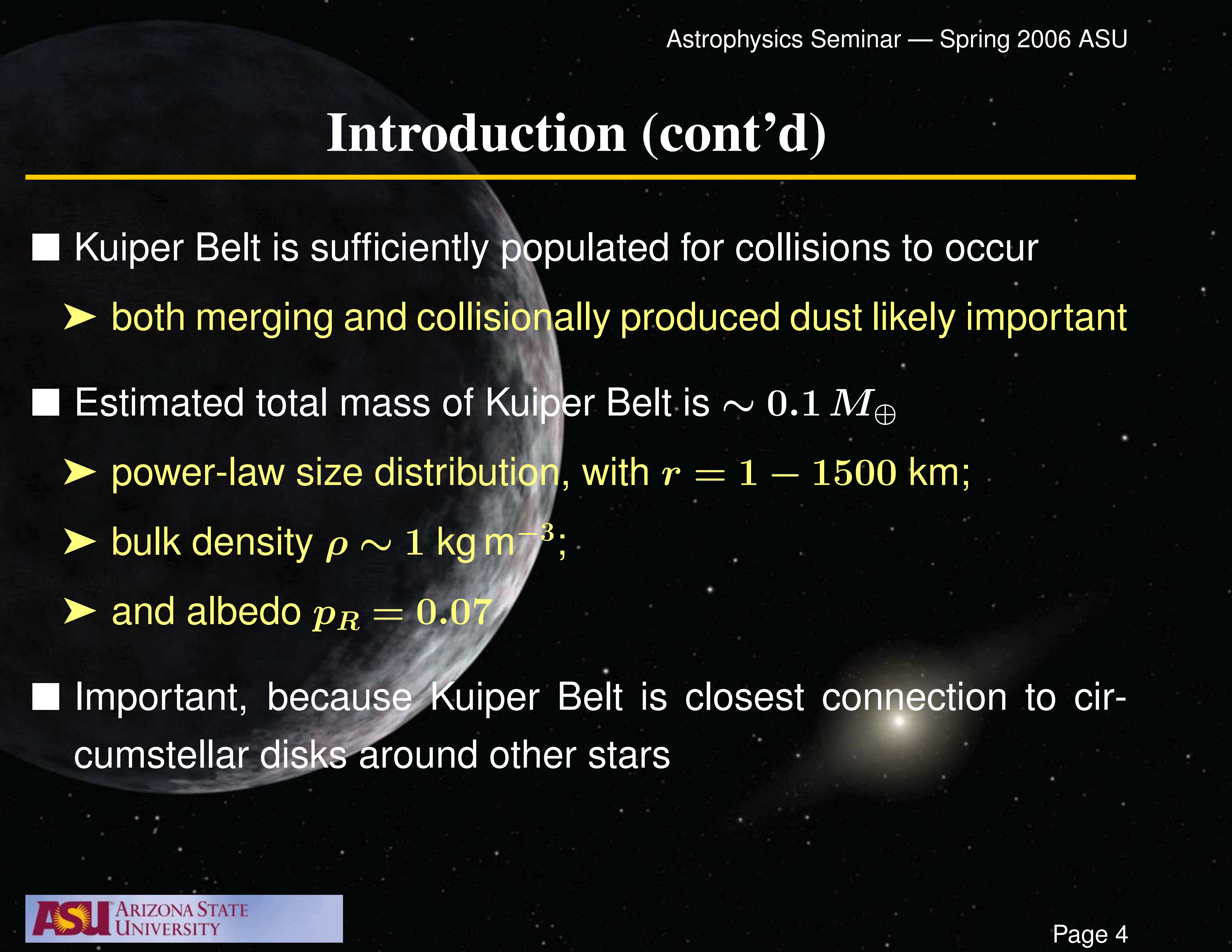


- Introduction to the Kuiper Belt
- Problem: Should Neptune not have prevented Pluto (and other 1000+ km objects) from forming in the outer Solar system?
- New simulations, isolating the key parameters: coagulation, fragmentation, tensile strength, nebula mass
- Discussion
- Conclusion: Pluto is not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

# Introduction to the Kuiper Belt



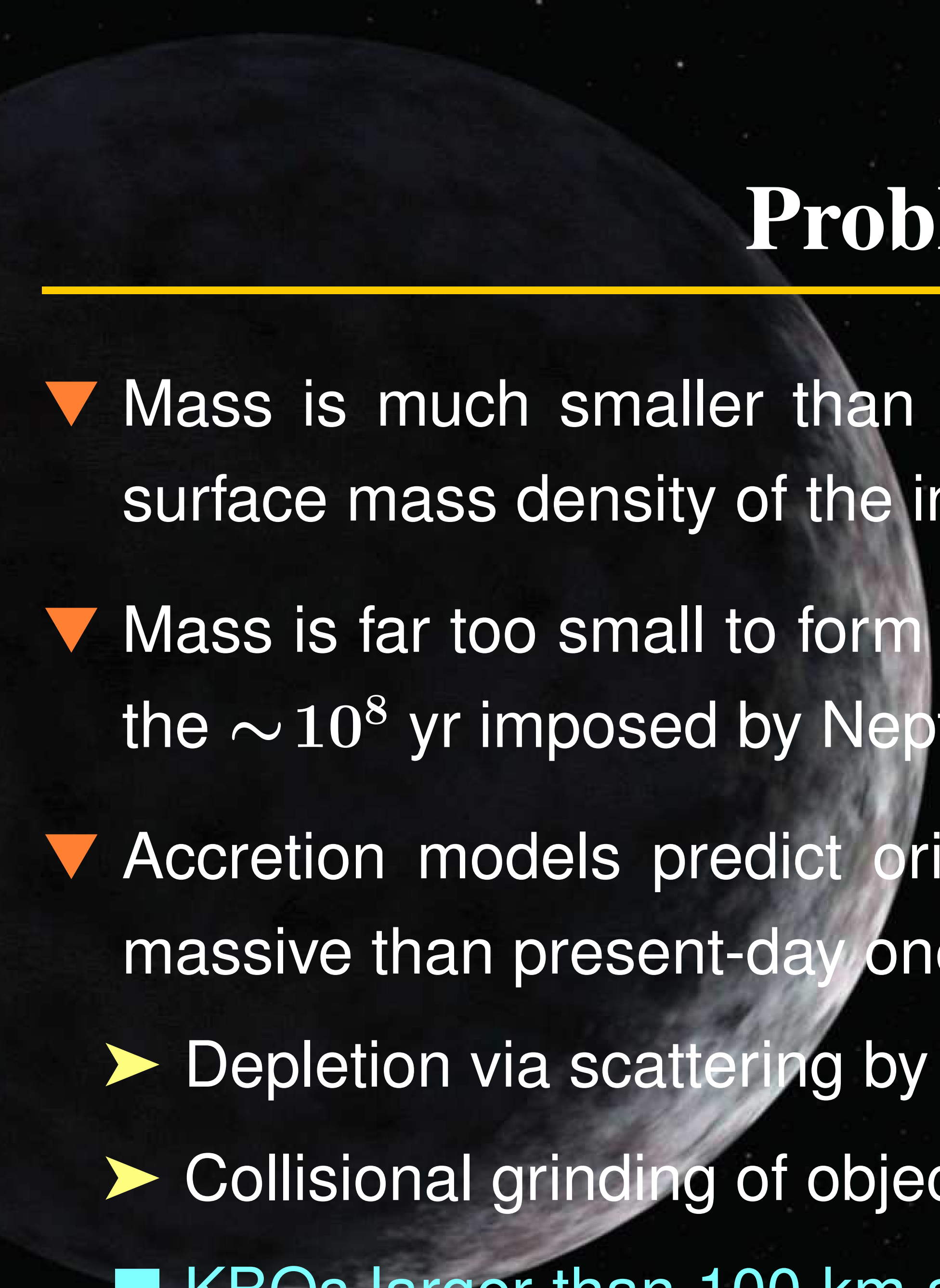
- Kuiper Belt (Edgeworth 1943,1949; Kuiper 1951) is remnant of the solar nebula (circumsolar disk)
- Kuiper Belt stretches beyond Neptune: 30 – ∼47 AU, may have rather abrupt outer edge
- Estimated population of $\sim 10^5$ Kuiper Belt Objects (KBOs) with $r \gtrsim 50$ km; origin of short-period comets
- Pluto and 2003UB$_{313}$ are merely largest known KBOs
  - ➤ $r \sim 1125$ km and $r \sim 1475$ km.



# 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?

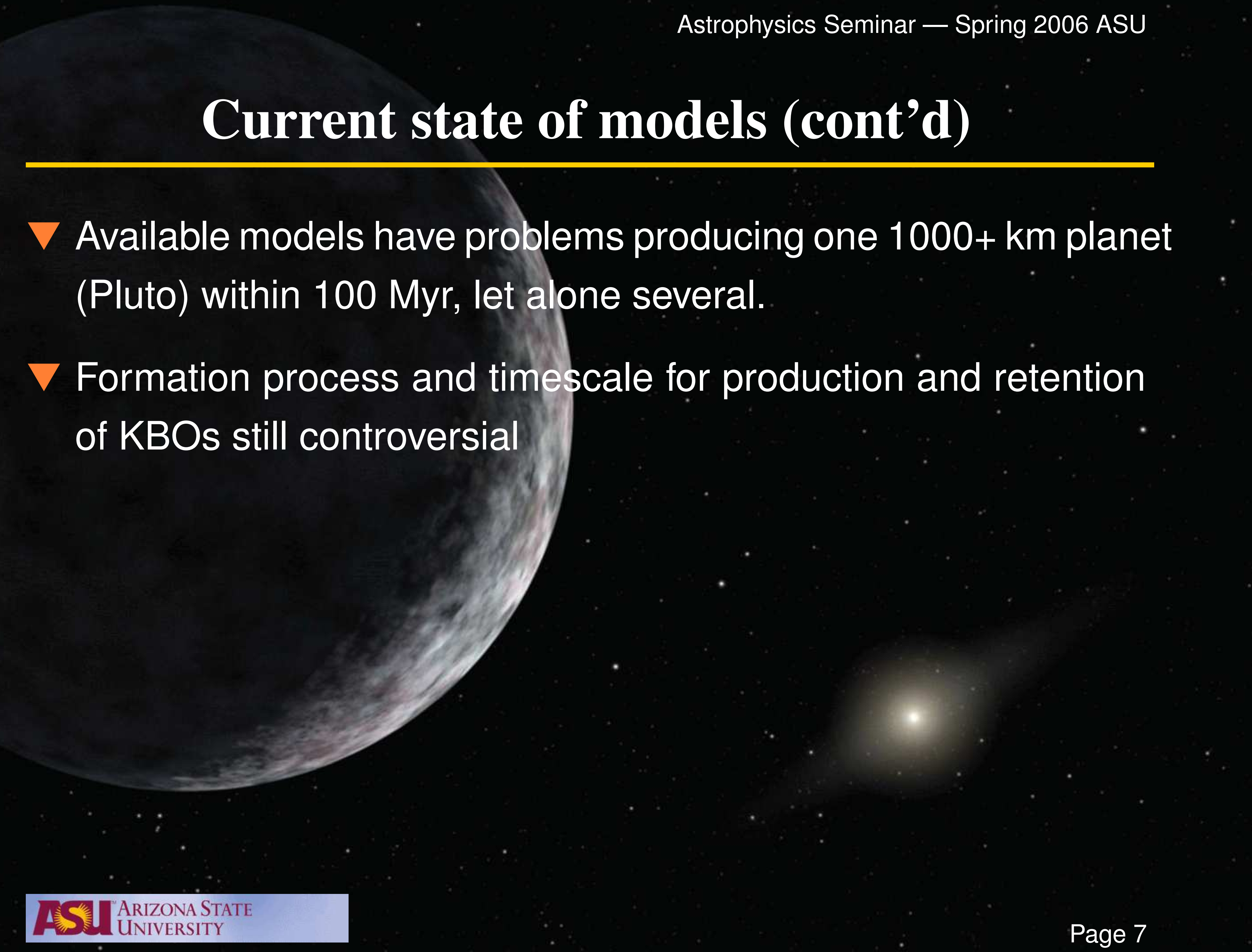


- Mass is much smaller than expected from extrapolating the surface mass density of the inner solar system
- Mass is far too small to form the larger observed KBOs within the $\sim 10^8$ yr imposed by Neptune accreting nearby
- Accretion models predict original Kuiper Belt $\sim 100\times$ more massive 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

# New simulations — Step 1: velocity evolution

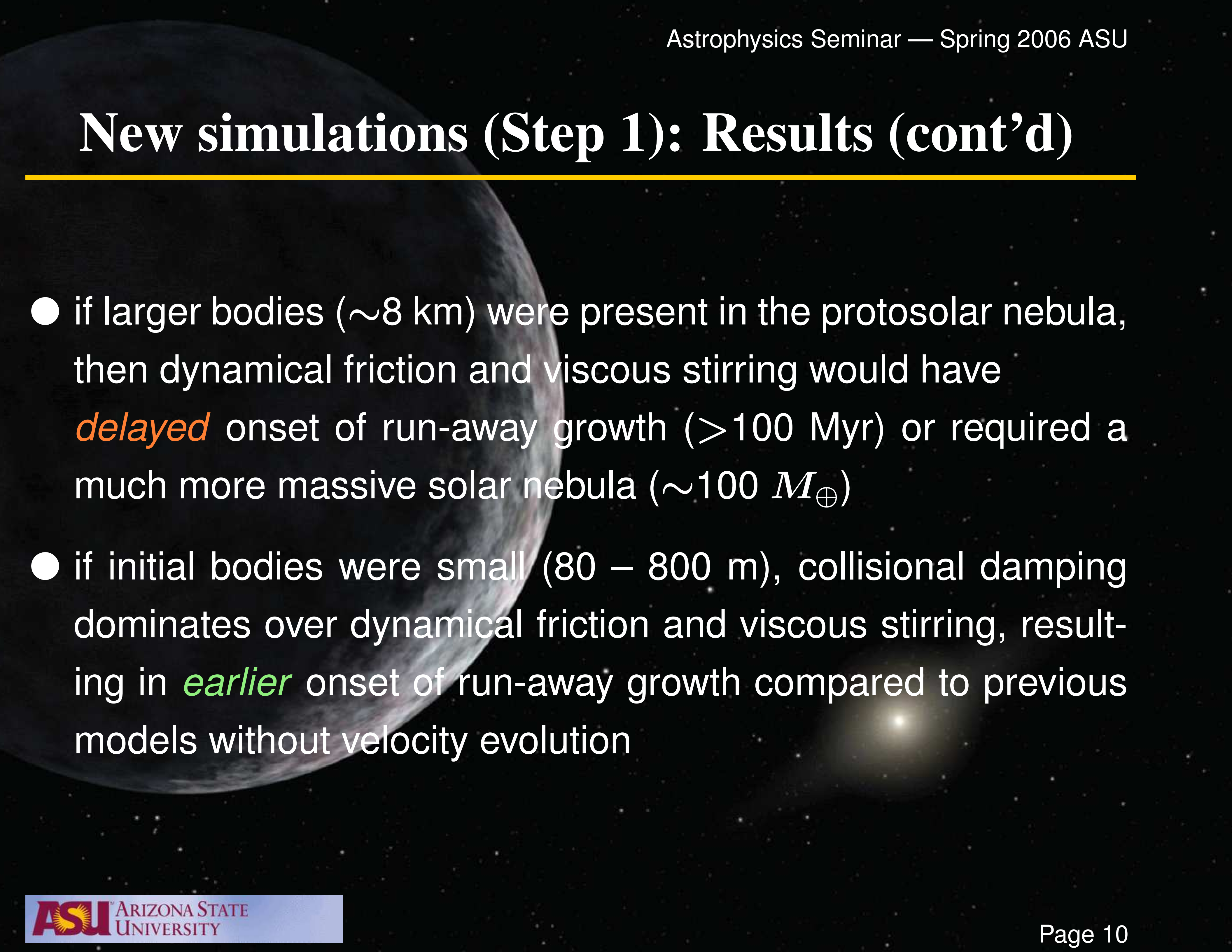
Kenyon & Luu 1998, AJ 115, 2136 [Paper I]

- 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, $e \lesssim 0.01$, 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 $M_{\text{dust}}$ = 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)



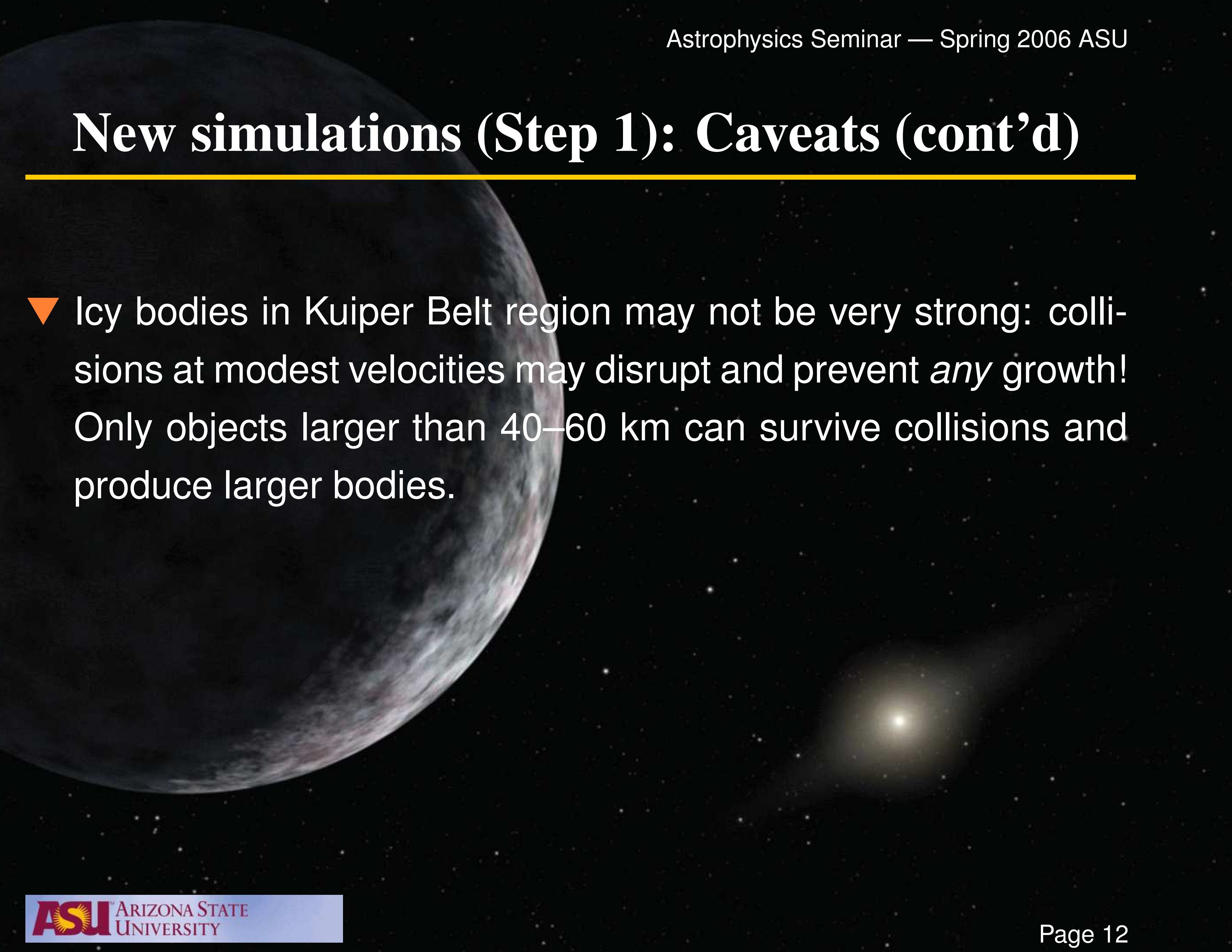
- if larger bodies ($\sim$8 km) were present in the protosolar nebula, then dynamical friction and viscous stirring would have *delayed* onset of run-away growth ($>$100 Myr) or required a much more massive solar nebula ($\sim$100 $M_\oplus$)
- if initial bodies were small (80 – 800 m), collisional damping 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:**

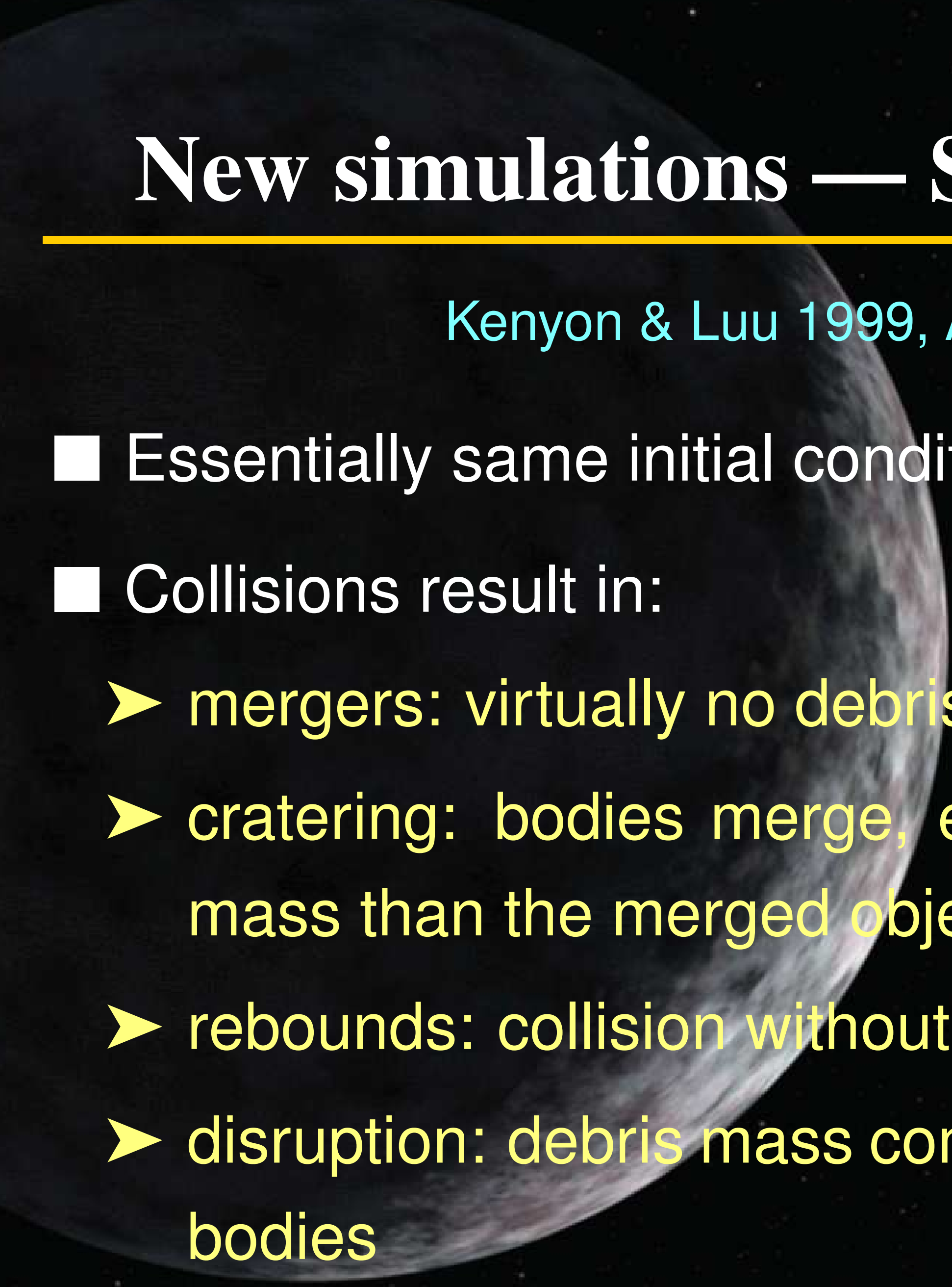
- Assumption of homogenous spatial distribution of planetesimals with small velocities relative to their keplerian orbital velocity breaks down in late stages of run-away growth [hence: simulation were ended at that stage]
- Timescale to run-away is sensitive to the *minimum* radius/mass of objects, 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)



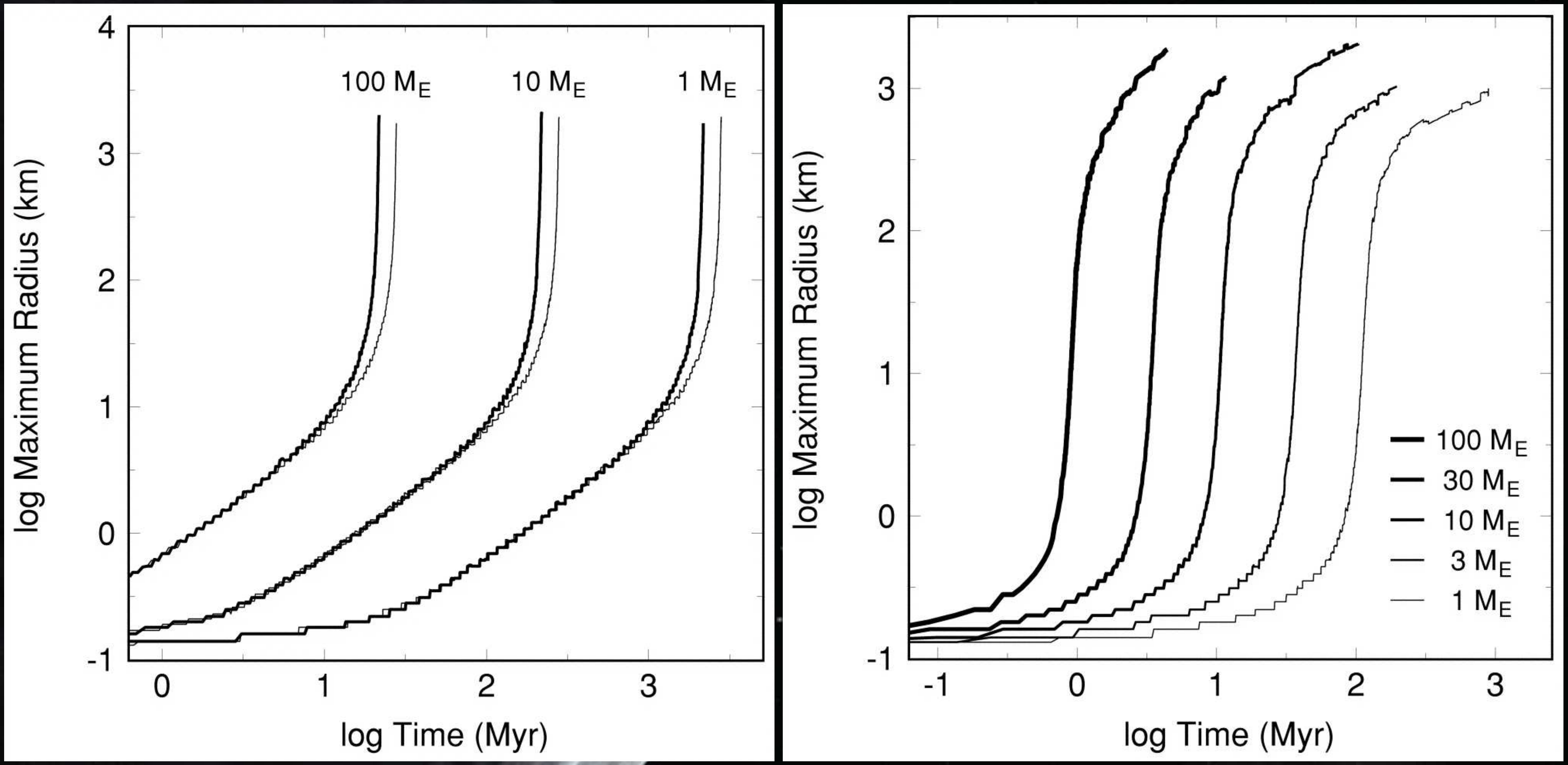
- Icy bodies in Kuiper Belt region may not be very strong: collisions at modest velocities may disrupt and prevent *any* growth! Only objects larger than 40–60 km can survive collisions and produce larger bodies.

# New simulations — Step 2: fragmentation

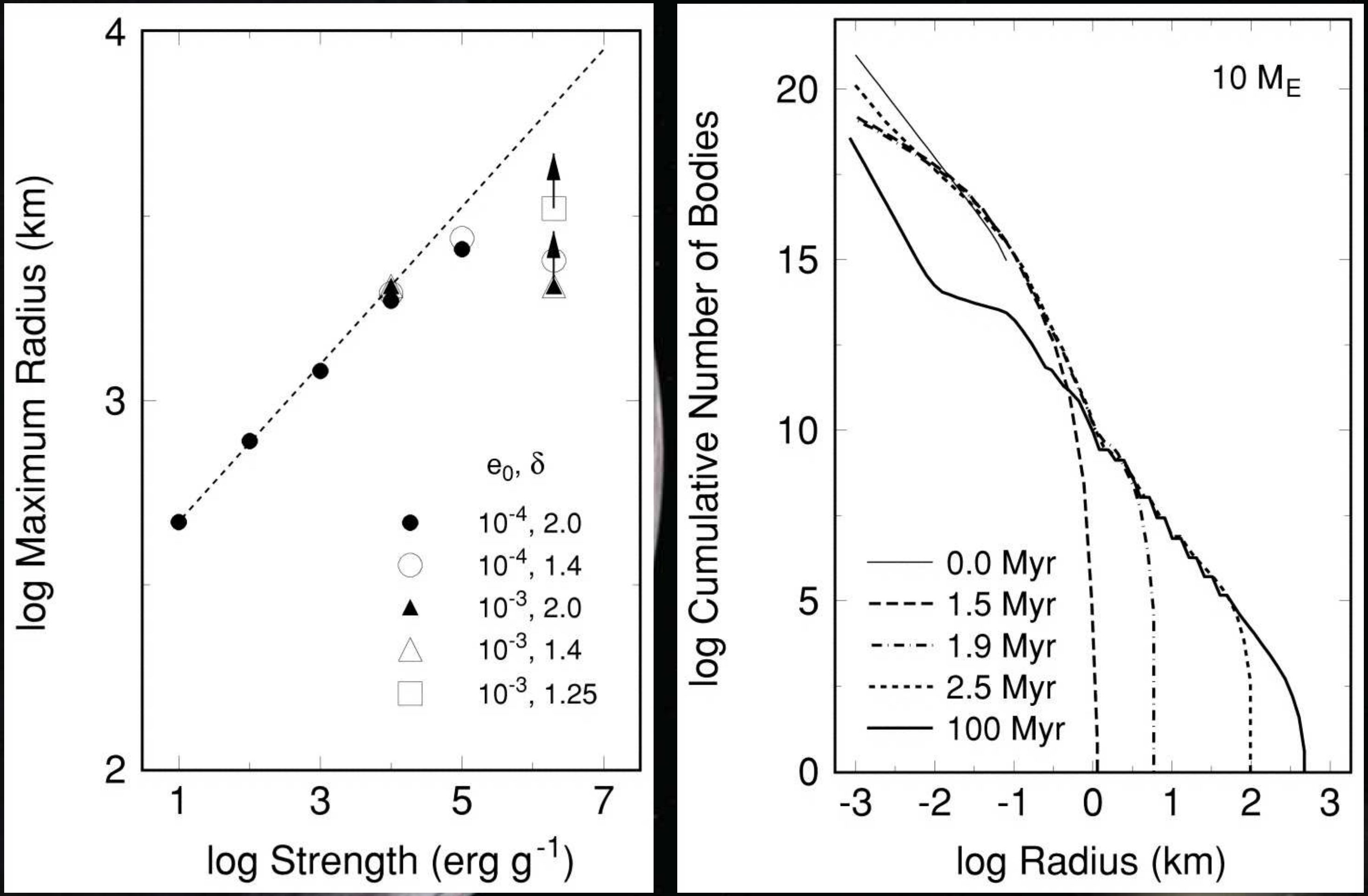


Kenyon & Luu 1999, AJ 118, 1101 [Paper II]

- 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)

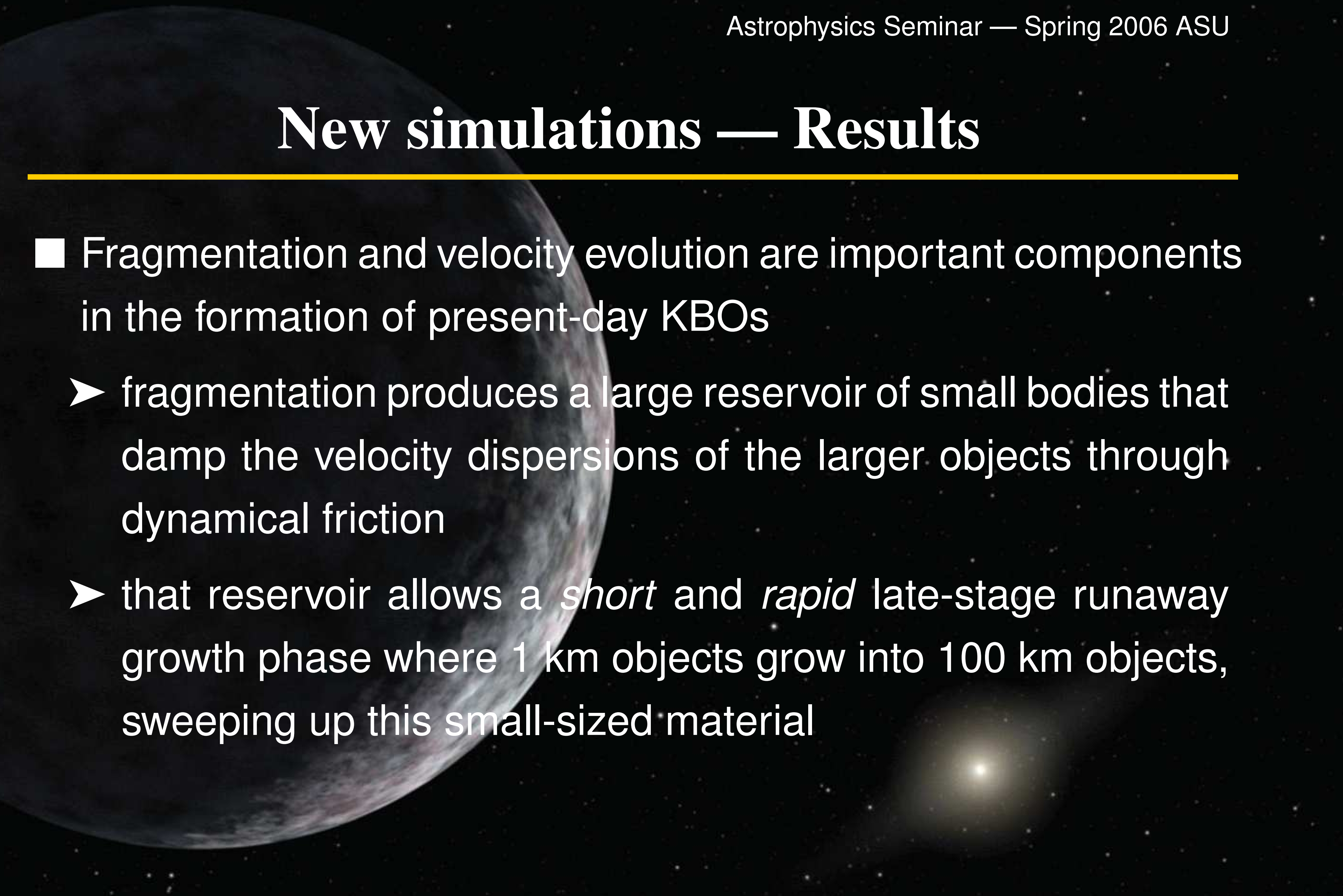


Maximum radius as a function of time for [LEFT] no or limited velocity evolution, and [RIGHT] full velocity evolution. The time to runaway growth decreases with increasing $M_0$. Fragmentation delays onset of runaway growth, producing more 0.1–10 km objects during this delay, and then more rapidly grows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



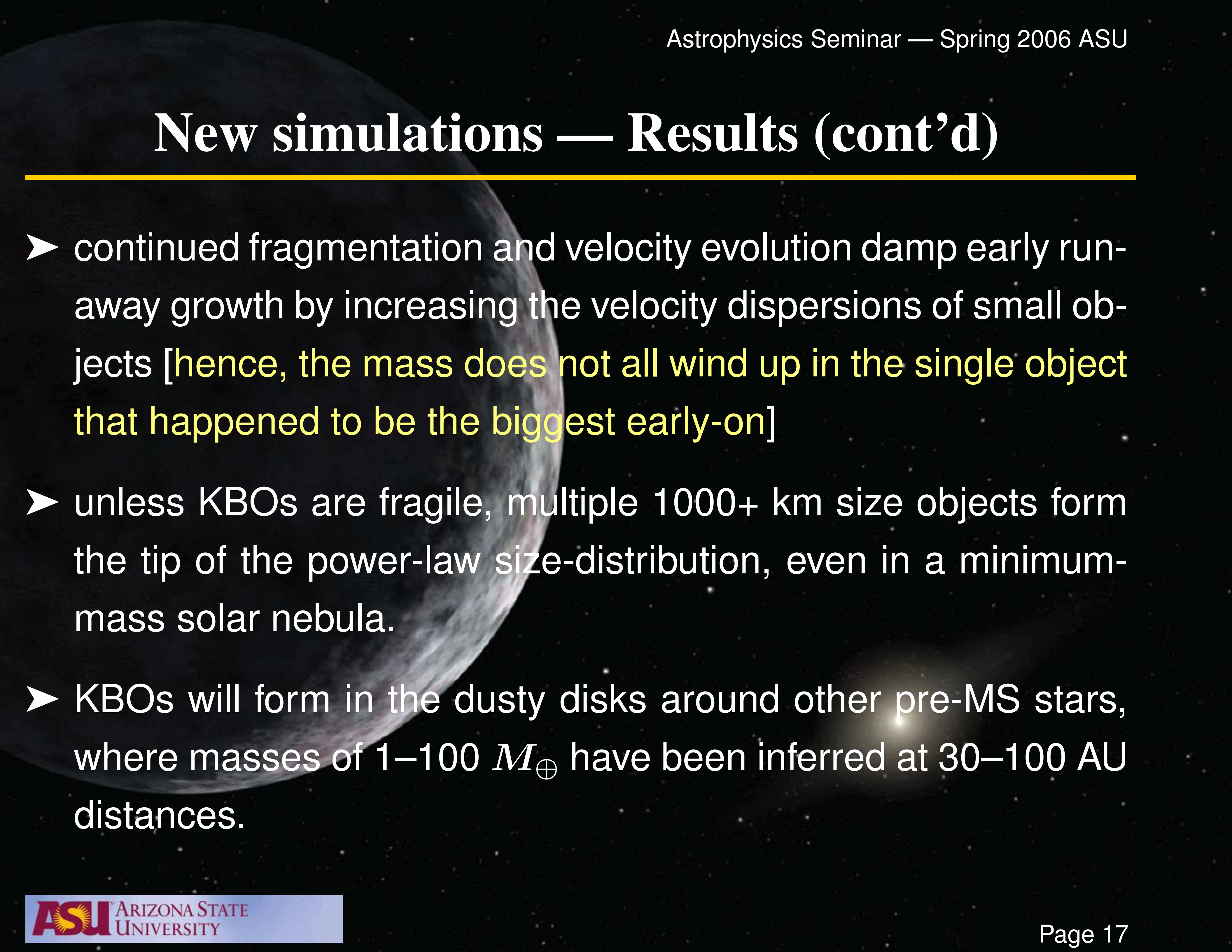
[LEFT] Maximum radius as a function of strength of the KBOs for $M_0 = 10 M_\oplus$. Weak KBOs fail to grow to Pluto sizes. [RIGHT] Cumulative size distributions for a model with fragile KBOs ($S_0$=100 ergs g$^{-1}$). Altough runaway growth produces 100 km objects, objects $>$400 km are catastrophically 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



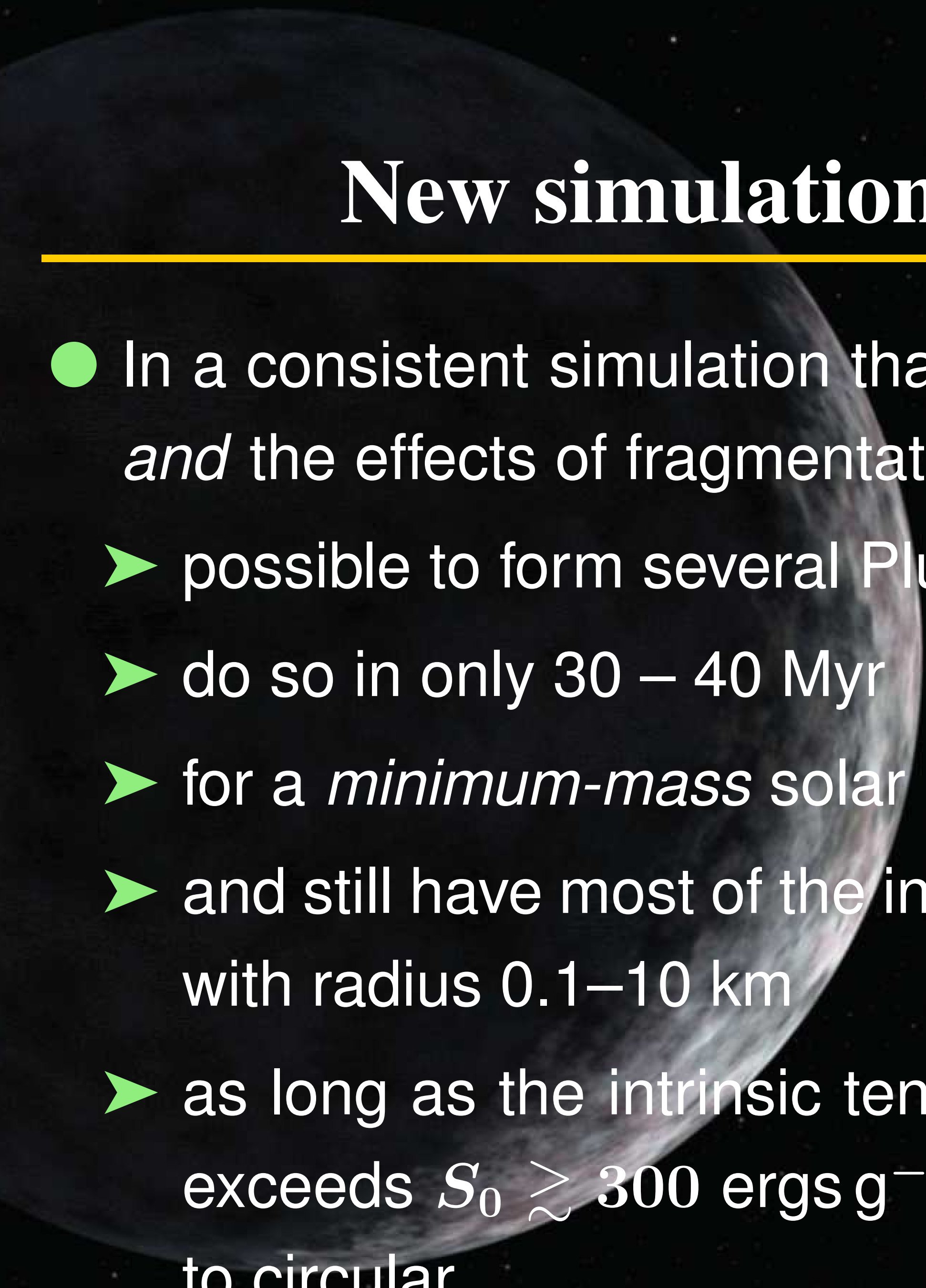
- Fragmentation and velocity evolution are important components in the formation of present-day KBOs
  - fragmentation produces a large reservoir of small bodies that damp the velocity dispersions of the larger objects through dynamical friction
  - that reservoir allows a *short* and *rapid* late-stage 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 runaway 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

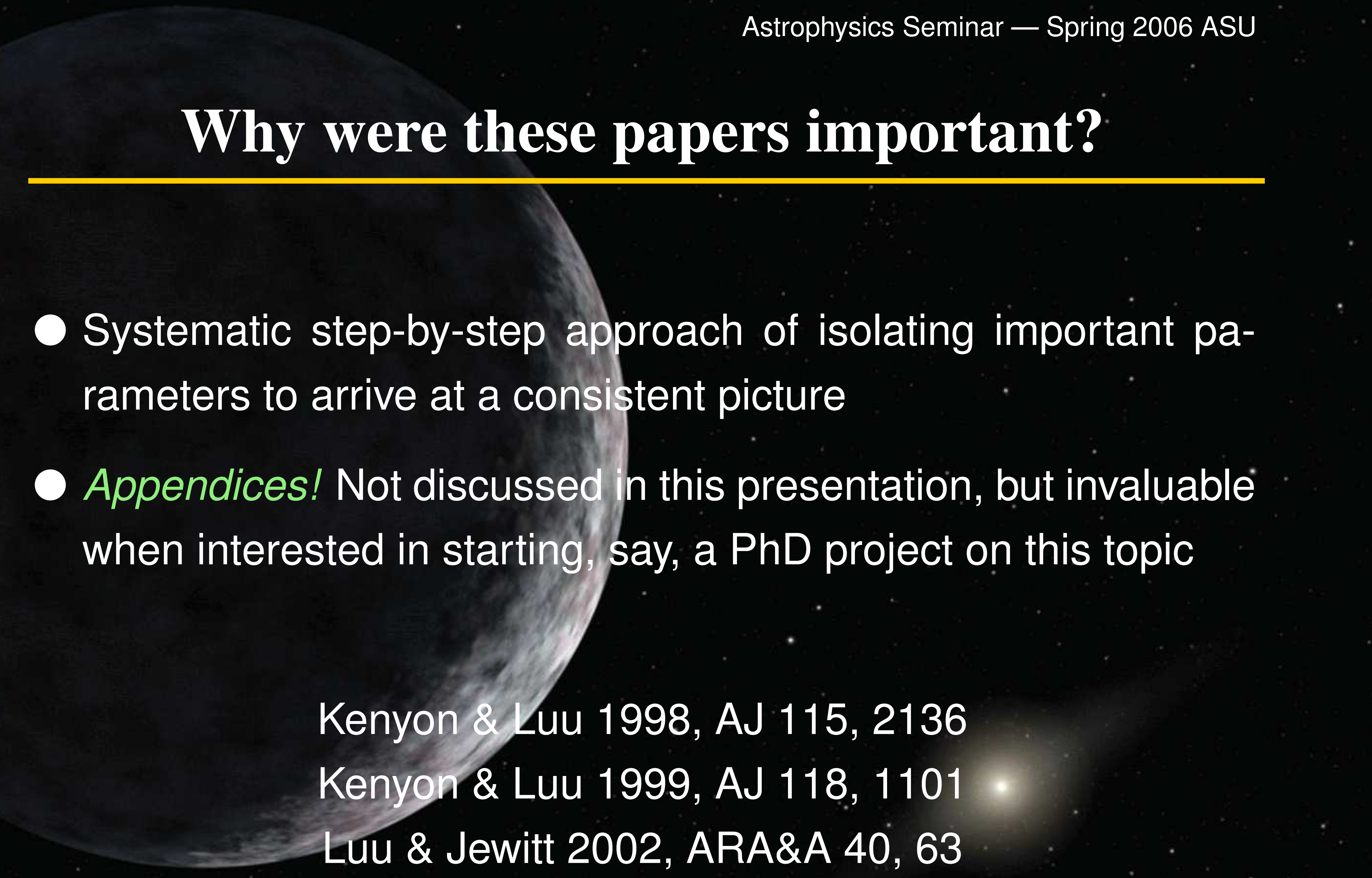


- In a consistent simulation that includes *both* velocity evolution *and* the effects of fragmentation, it is:
  - possible to form several Pluto-sized objects at 32–38 AU
  - do so in only 30 – 40 Myr
  - for a *minimum-mass* solar nebula
  - and still have most of the initial mass locked in $\sim 10^5$ objects with radius 0.1–10 km
  - as long as the intrinsic tensile strength of these icy objects exceeds $S_0 \gtrsim 300$ ergs $\mathrm{g}^{-1}$ 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., $2003UB_{313}$, Pluto, $2005FY_{9}$, Sedna, $2003EL_{61}$ and Quaor are all larger than 1500 km in diameter) in a *small-mass* Kuiper Belt

# 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