The Collisional Evolution of Small Bodies in the Solar System

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Invited Review
CD '07 – Alicante, Spain

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Overview

- Collisional evolution is important for small-body populations
  - Shapes their size distributions
  - Reduces mass of the population by grinding material down to dust
- Dynamical evolution also important
  - Can give a large mass depletion by ejecting material from the Solar System
  - Emplaces bodies in their current location (eg. scattered disk and Oort cloud)

Overview

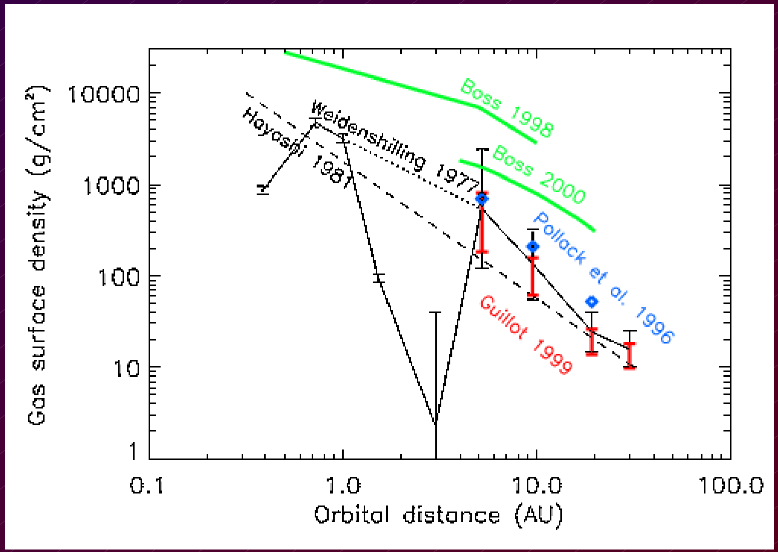
- In reality, collisional and dynamical processes occur simultaneously

- Significant recent advances have come from models that combine collisional and dynamical evolution...

  ...and many issues still remain to be addressed!

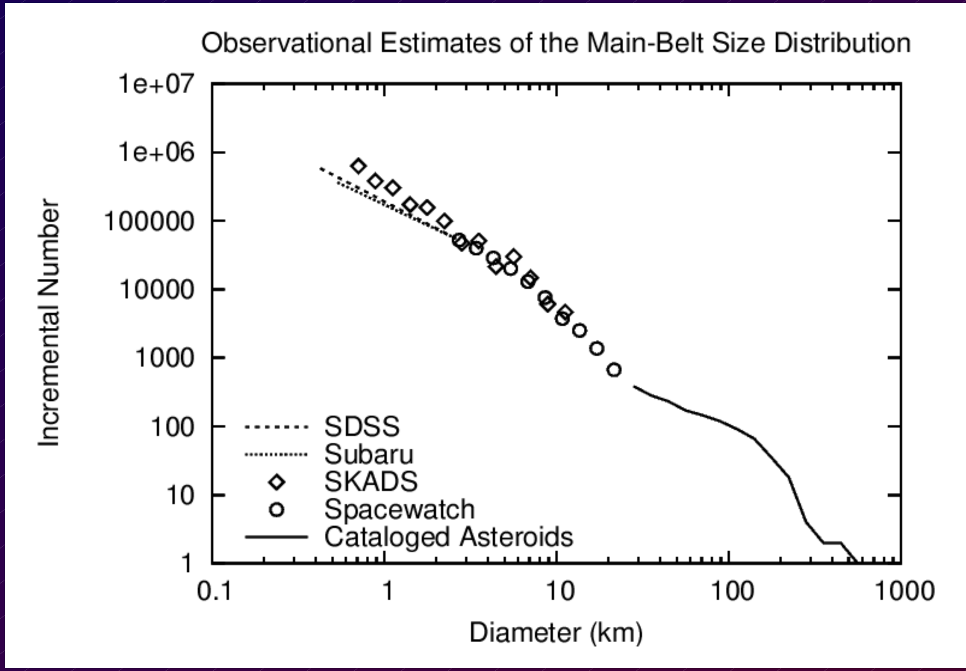
Asteroid Belt

- Early asteroid belt was much more massive than today (by >100X)
  - Needed to accrete asteroids on short timescales
  - Consistent with smooth primordial distribution of mass in the Solar System

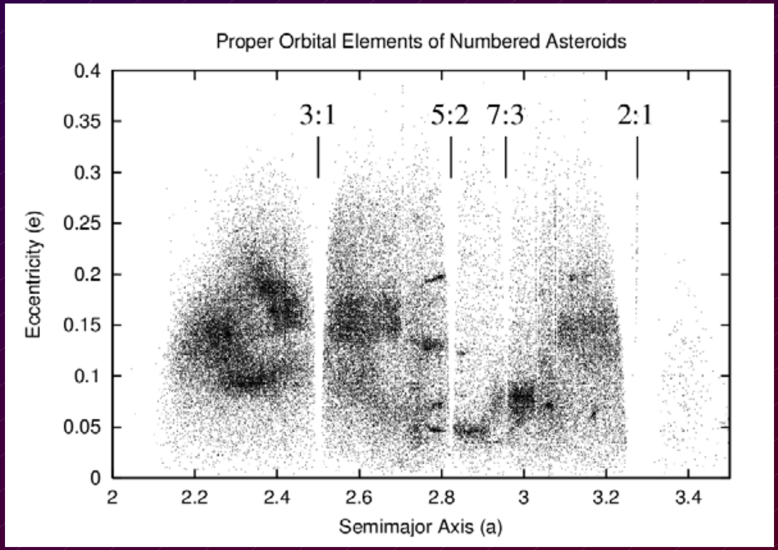


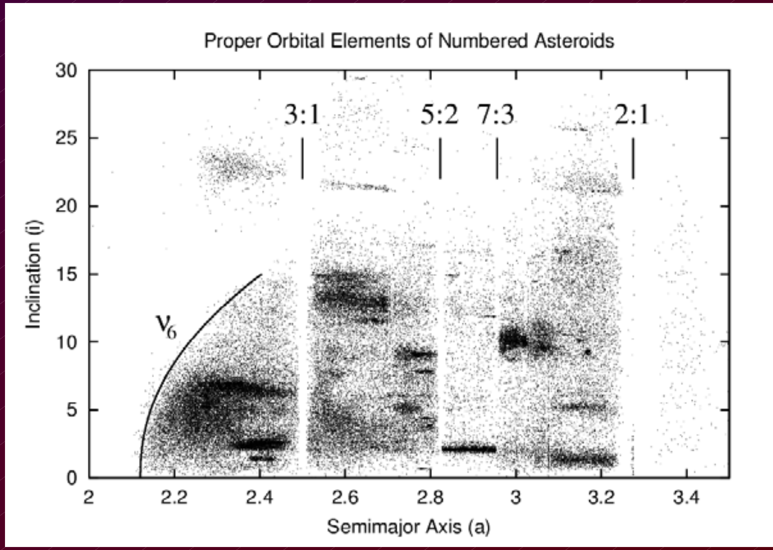
- Shows evidence for significant collisional sculpting
  - 'Wavy' size distribution
  - Asteroid families

Constraints



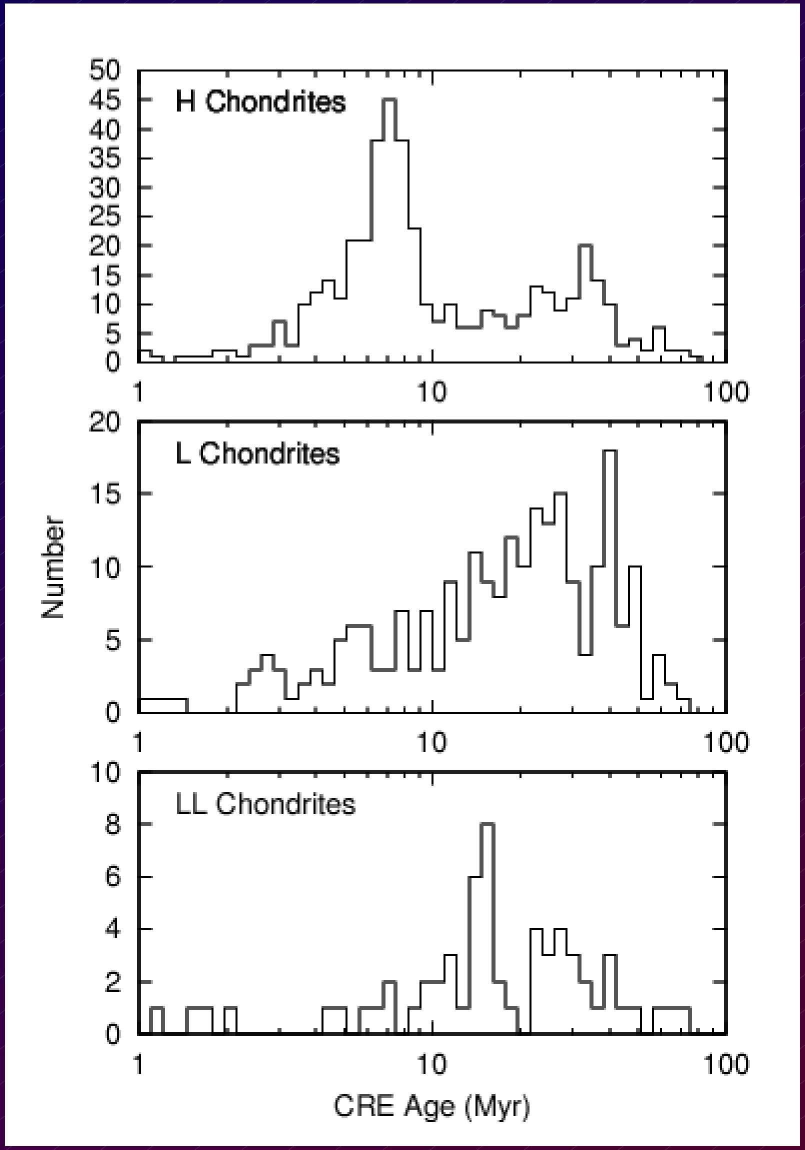
Size Distribution





Families

Constraints



Meteorite CRE Ages

Vesta's Basaltic Crust

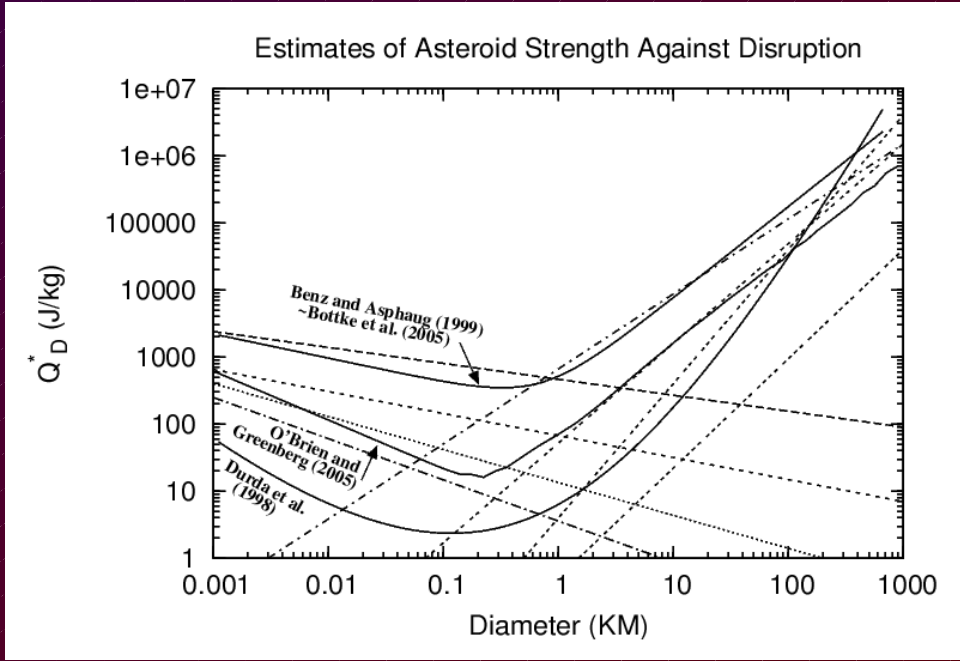
Collisional Evolution Modeling

- What is a collisional evolution model?
  - Tracks the evolution of the size distribution of a population of colliding bodies*
- Collisional cascade
  - Small bodies break up larger bodies
  - Large bodies break up into smaller bodies
  - Break-ups governed by collision probability, impact velocity, and strength
  - Also need estimate of initial size distribution

* Large body of work by Davis, Farinella, Durda, Dohnanyi, Tanaka, Wetherill, Marzari, Petit, Campo-Bagatin, O'Brien, Greenberg, Cheng....

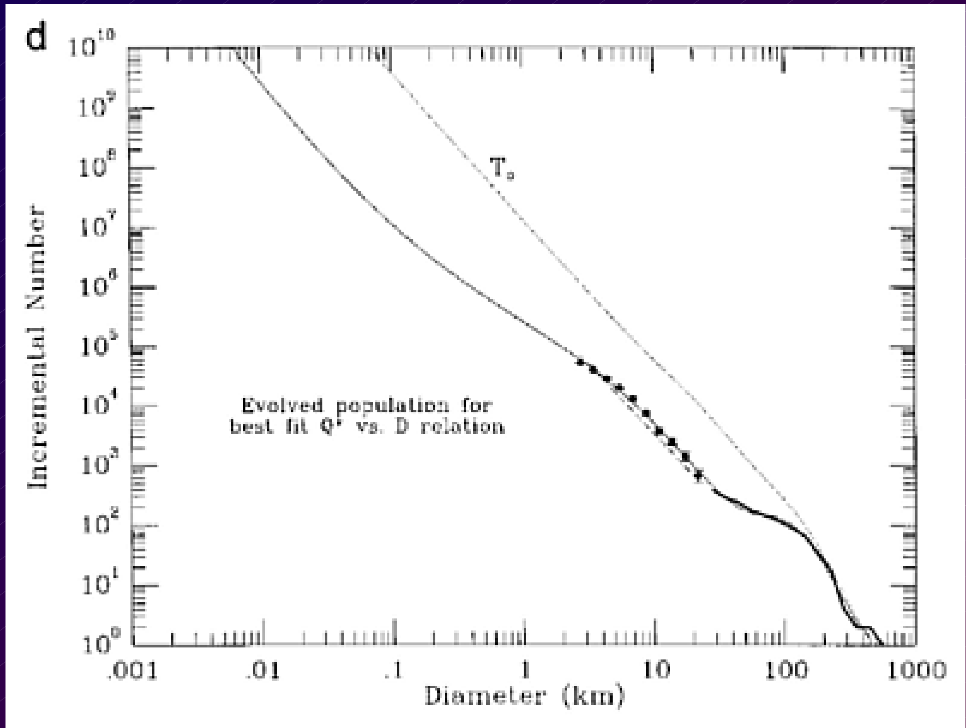
Asteroid Strength

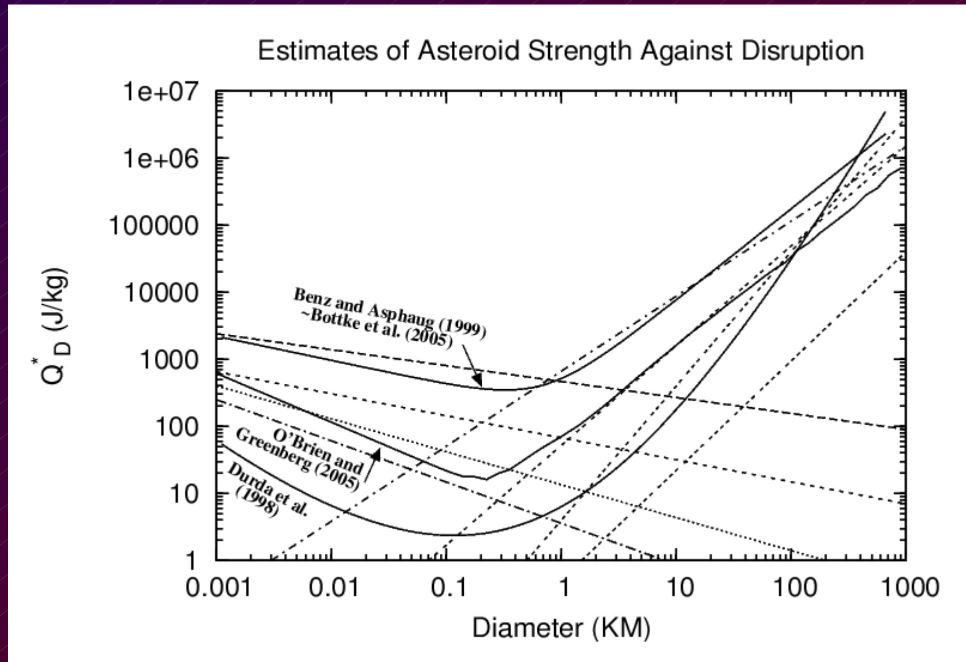
- Wide range of estimates
- Still need better understanding of porous/rubble-pile bodies
- Given enough constraints, one can construct a model and 'solve' for Q*



Durda et al. (1998)

- Able to fit to the main-belt size distribution





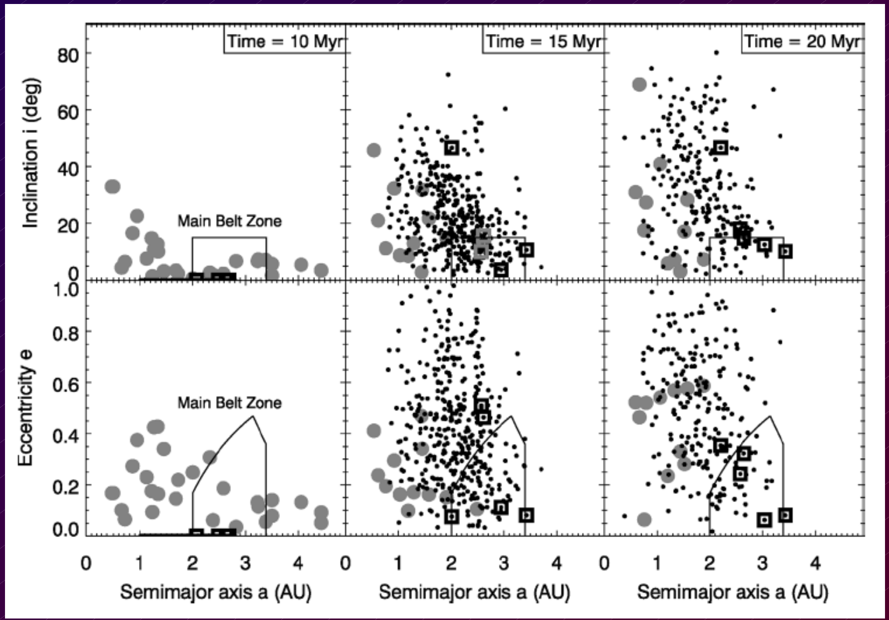
- Inconsistent with other constraints
  - CRE ages and families

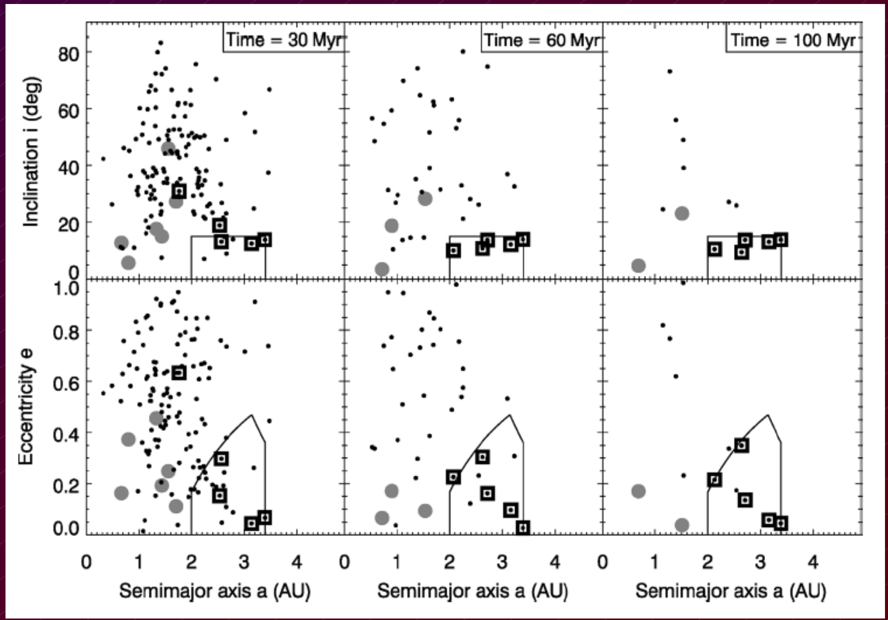
Bottke et al. (2005)

- Used multiple constraints
  - Main belt size distribution
  - Asteroid families
  - Survival of Vesta's crust
  - Meteorite CRE ages
- Incorporates dynamical evolution of the primordial asteroid belt
- Solves for both Q* and the initial size distribution

Main Belt Primordial Evolution

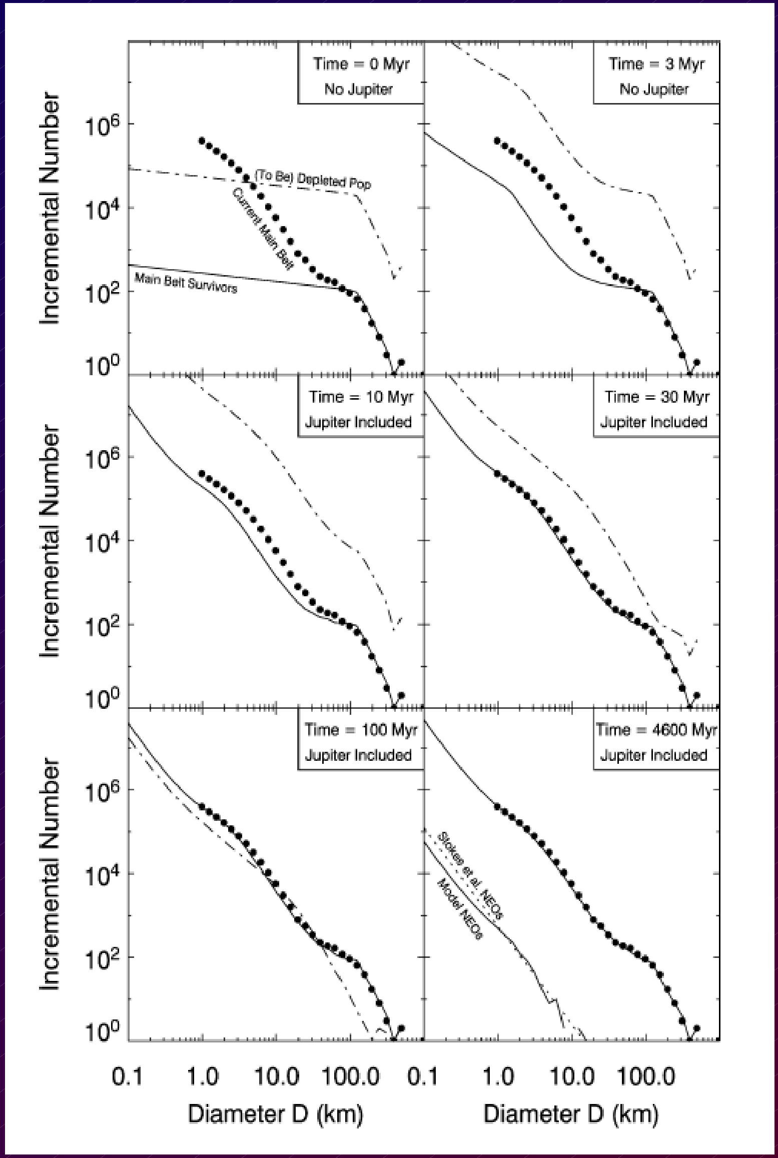
- Planetary embryos embedded in primordial belt*
  - Excited by Jupiter
  - Push asteroids (and one-another) into resonances
  - Significantly deplete main-belt mass

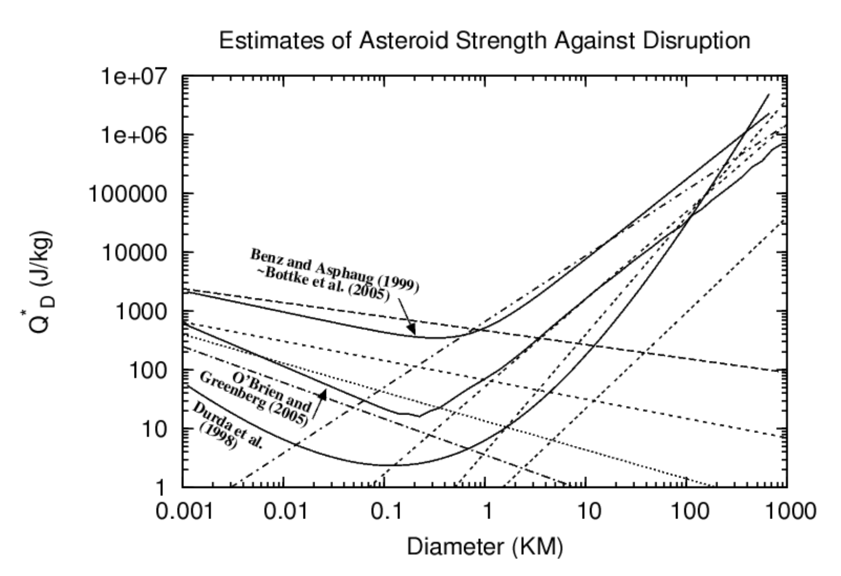




*Wetherill (1992), Petit et al. (2001)

Bottke et al. (2005)

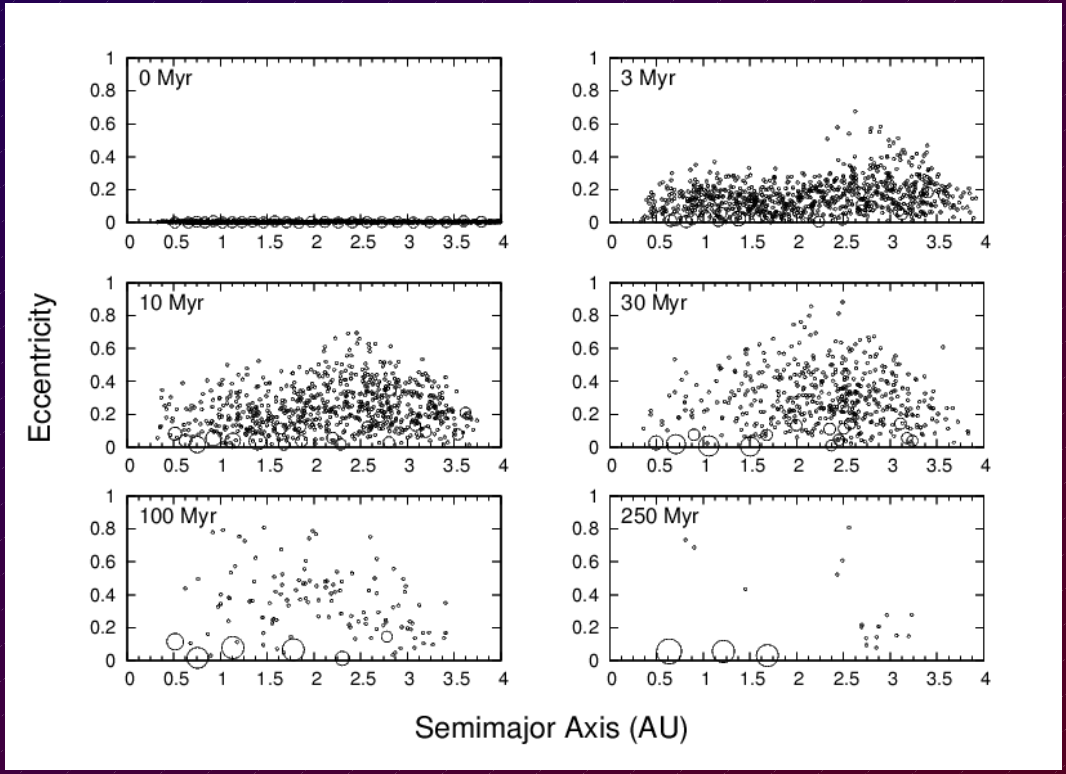


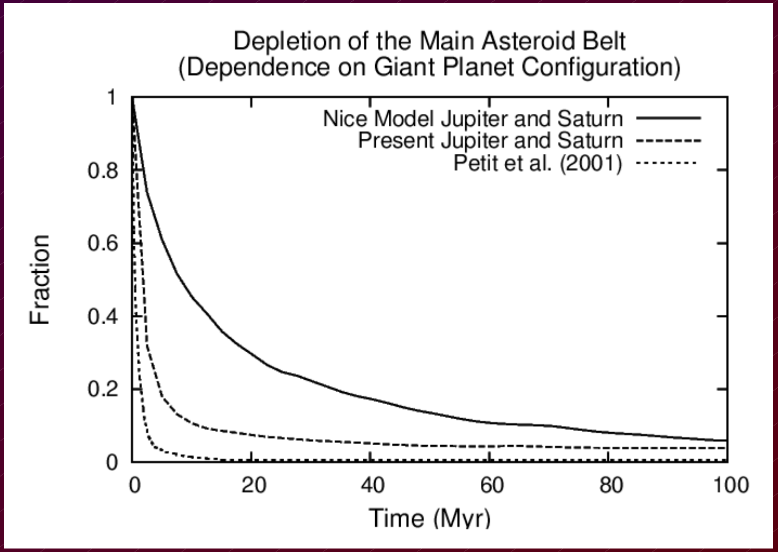


- Good fit to all constraints used!
- Q* law close to that of Benz and Asphaug (1999)

Asteroid Belt Summary

- Coupled collisional-dynamical model gives good fit to numerous constraints
- Future work will incorporate more advanced dynamical simulations





O'Brien et al. (2006,2007)

TNOs - Observational Evidence

- There are several observables that can be used to constrain models of TNO collisional evolution
  - Total mass of TNO population
  - Size distribution of TNO population

Mass of TNO Population

- Weissman and Levison (1996) - 0.1-0.4 Me
- Gladman et al. (2001) - ~0.1 Me
- Bernstein et al. (2004) - 0.01-0.1 Me

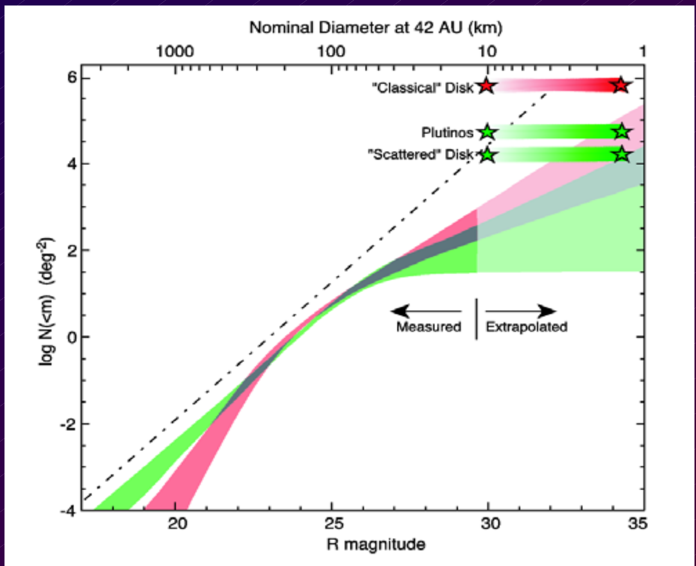
Lower than expected from a minimum-mass solar nebula by factor of 100-1000 or more

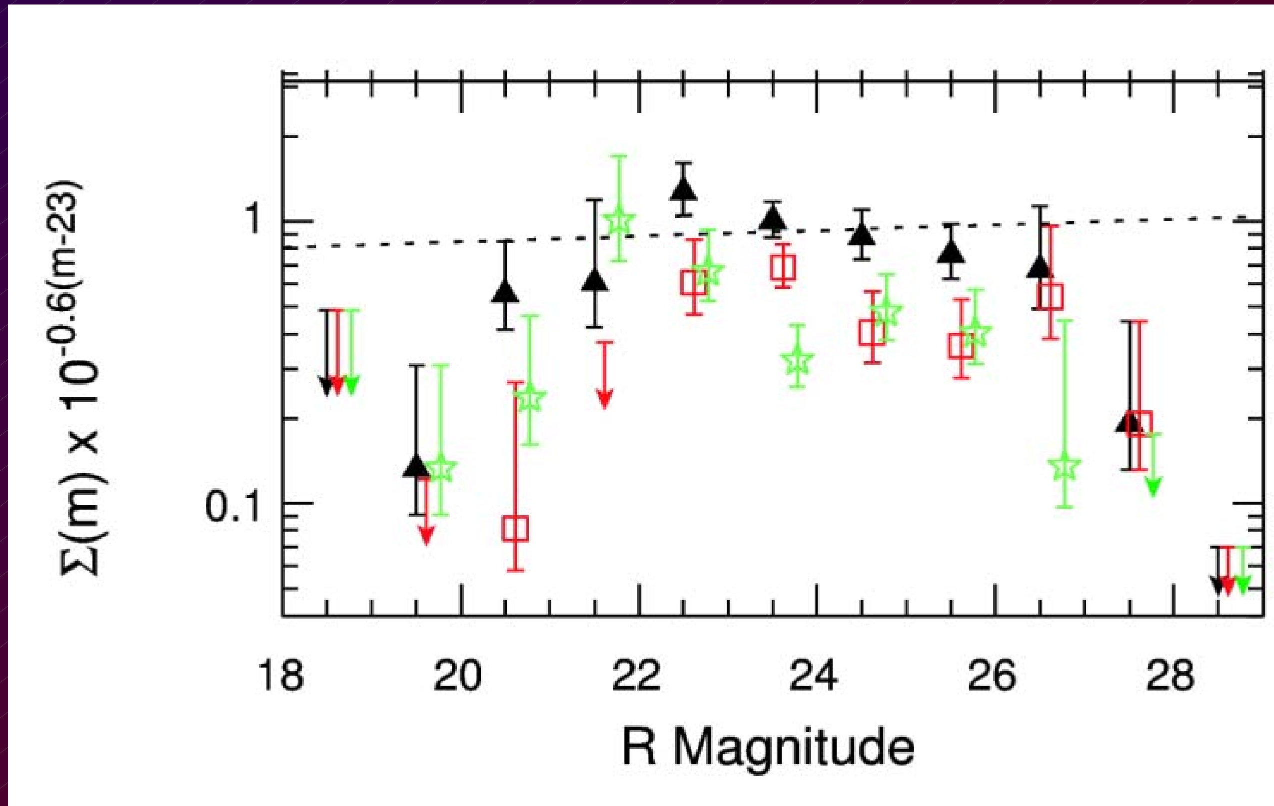
Size Distribution of TNOs

- Large bodies (~100 km and above)
  - Trujillo et al. (2001) : q = 4 (+/-.5)
  - Gladman et al. (2001) : q = 4.4 (+/- 0.3)
- Too steep to be collisionally relaxed
  => Must be primordial
- Slope <u>must</u> flatten at some size
  - Otherwise, infinite mass

Size Distribution -- Continued

- Bernstein et al. (2004) found:
  - Different q for 'classical' and 'excited' populations
  - Slope flattens above R=24 (D ~ 100 km)



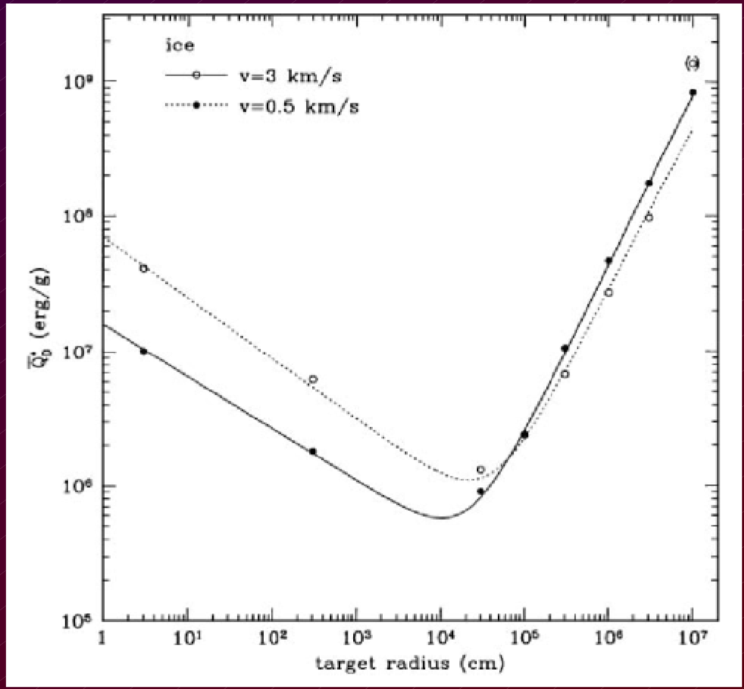


Size Distribution -- Continued

- Rollover in size distribution potentially a signature of collisional erosion
  - More collisional erosion = rollover at larger diameter
  - Could also just be an accretional signature

Strength of TNOs

- Benz and Asphaug (1999) hydrocode models for solid ice
- Predicts stronger small targets than lab experiments
- Hydrocode simulations for large porous bodies needed!
  - Large rubble-piles or micro-porous bodies could behave differently than solid targets



Accretion of TNOs

- To accrete large bodies (>100-km scale) between 30 and 50 AU:
  - Need 10-50 M_e of material
  - Tens - hundreds of Myr
  - Low eccentricity (<0.01)

- May require Neptune to form late to keep e low
  - Most recent models can form large TNOs in <100 Myr

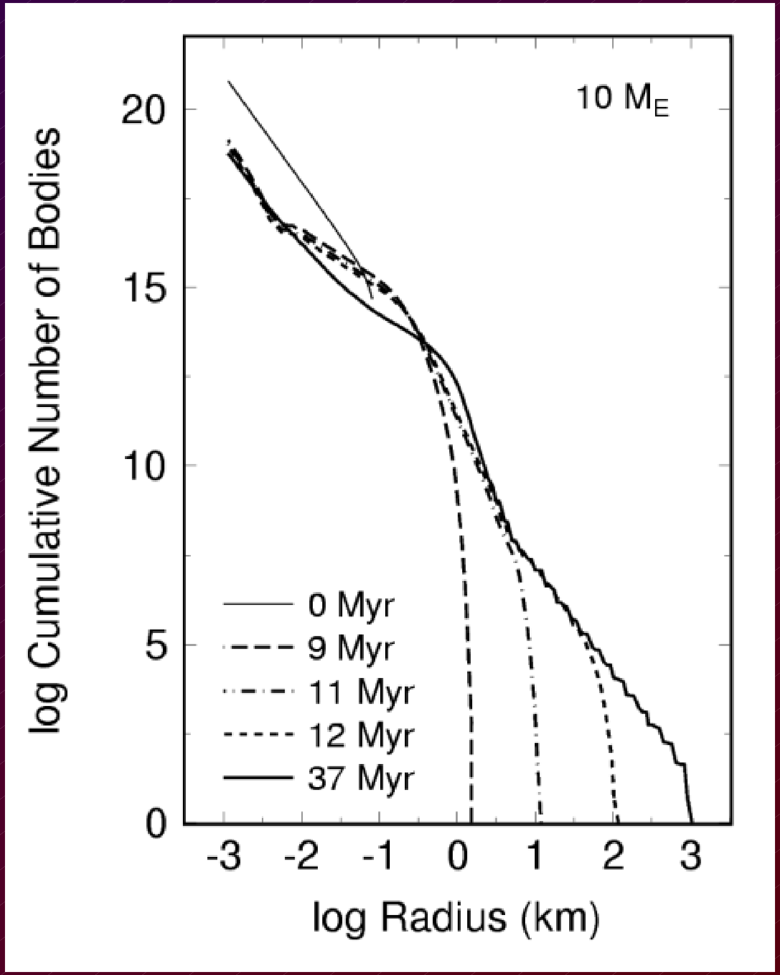
Stern (1995, 1996), Stern and Colwell (1997), Kenyon and Luu (1998, 1999)

Accretion -- Continued

- Slope of the primordial population
  - q ~ 4-4.5 for larger bodies
  - Consistent with observations

Primordial TNO population was 100 -1000X more massive than today

?? Where did the mass go ??



Kenyon and Luu (1999)

Collisional Grinding

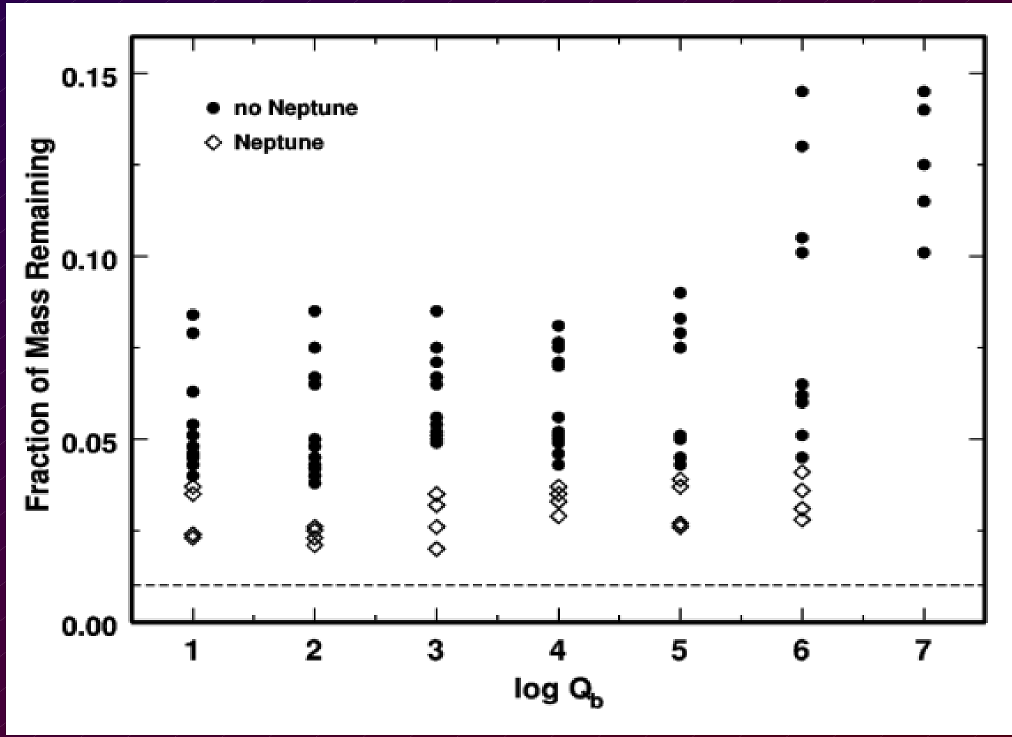
- Collisions have been proposed to
  - Reduce the primordial TNO population to its current mass
  - Shape the current size distribution (eg. turn-over point)

- Significant collisional activity starts when
  - Bodies grow large and start exciting others
  - Neptune forms (excites out to ~50 AU)

Stern (1996), Stern and Colwell (1997), Davis and Farinella (1997)
Kenyon and Bromley (2004), Pan and Sari (2005)

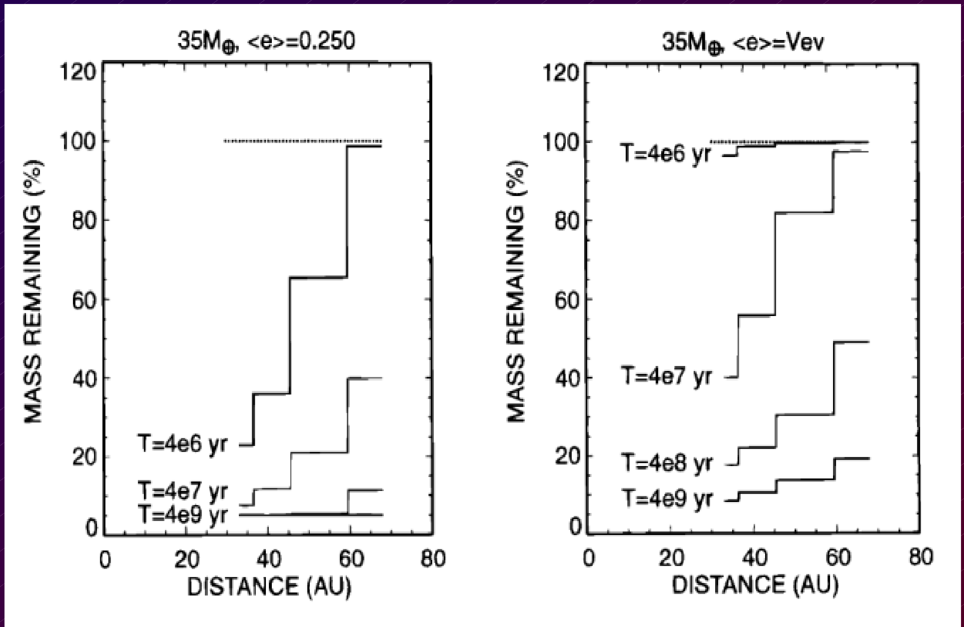
Collisional Grinding -- Continued

Does it work?



Kenyon and Bromley (2004)

Stern and Colwell (1997)

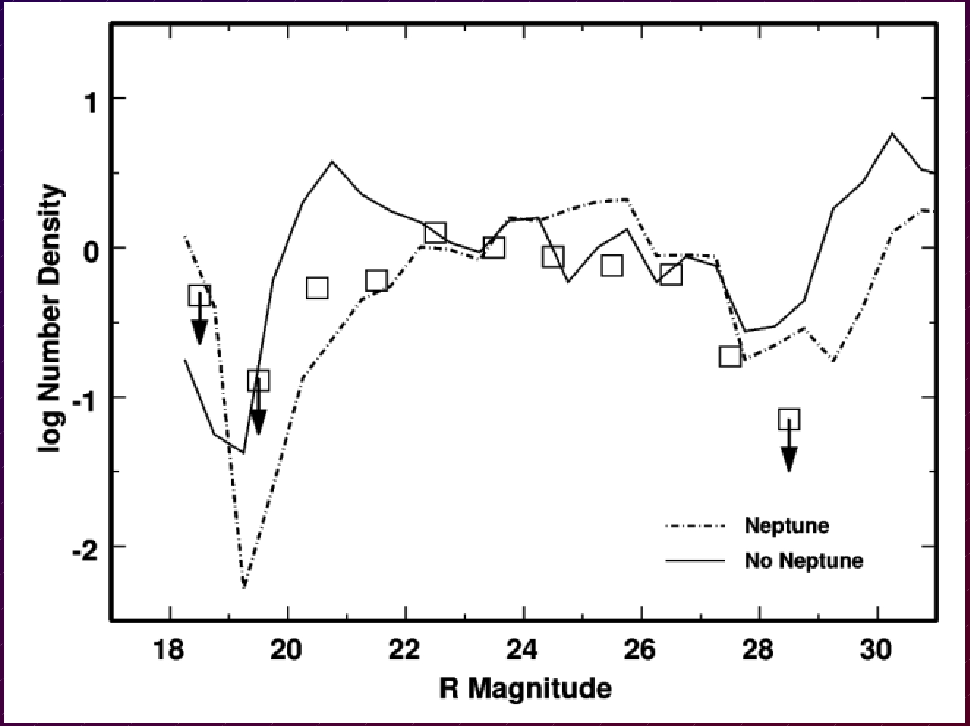


Collisional Grinding -- Continued

- Mass can be reduced significantly by collisional grinding, but:
  - Requires most mass to be in small bodies
  - May require weak bodies
  - Still can't explain all mass loss
  - Some dynamical loss mechanism still needed
- Region beyond ~50 AU would experience little mass loss
  - If there was material there in the past, there should still be a lot now

Collisional Grinding -- Continued

- All simulations and analytical models find break in size distribution < ~100 km diameter
  - Kenyon and Bromley (2004) ~1-30 km
  - Pan and Sari (2005) ~40 km



Kenyon and Bromley (2004)

Reasonably consistent with observations

Collisional Grinding -- Summary

- Collisional grinding can remove at least some of the primordial TNO mass
  - Requires most mass to be in small bodies
  - Some dynamical mechanism likely still necessary to match current mass
- Collisional grinding can (reasonably) reproduce the current size distribution
  - Break location close to observed/estimated size

The Dynamical Environment

- The history of the outer Solar System is dynamically complex
- Giant planet migration injects bodies into the scattered disk and Oort cloud populations
  - Kuiper belt, scattered disk and Oort cloud originate from same disk of planetesimals
  - Those populations can constrain each other's collisional and dynamical evolution

Dynamics -- Continued

- Gomes et al. (2005) – The 'Nice Model'
  - Significant migration of outer planets delayed for ~700 Myr
  - Massive primordial trans-Neptunian disk needs to survive against collisions for ~700 Myr

- New collisional models need to take these dynamical issues into account

Definitions

- Kuiper Belt
  - TNOs with a~40-50 AU that don't come too close to Neptune (low e)
- Scattered Disk
  - Moderately eccentric TNOs that have perihelia close to Neptune
- Oort Cloud
  - Bodies ejected from the Jupiter-Saturn zone onto orblts that nearly escape the Solar System
  - A spherical distribution with r~10,000 AU

Coupling Collisions and Dynamics

- Two examples:
  - Is collisional depletion of the Kuiper Belt consistent with the number of comets in the Oort cloud and scattered disk?
  - Can the trans-Neptunian disk survive for ~700 Myr in the Nice model?

Collisions and the Comet Supply

- Stern and Weissman (2001)
  - If Kuiper Belt was collisionally depleted of its mass, then the Oort cloud should be deficient in comets
- Charnoz and Morbidelli (2007)
  - What scenario for Kuiper Belt evolution is consistent with estimates of comets in the Oort cloud and scattered disk?
    - Mass depletion through collisional grinding?
    - Mass depletion through dynamical mechanism?

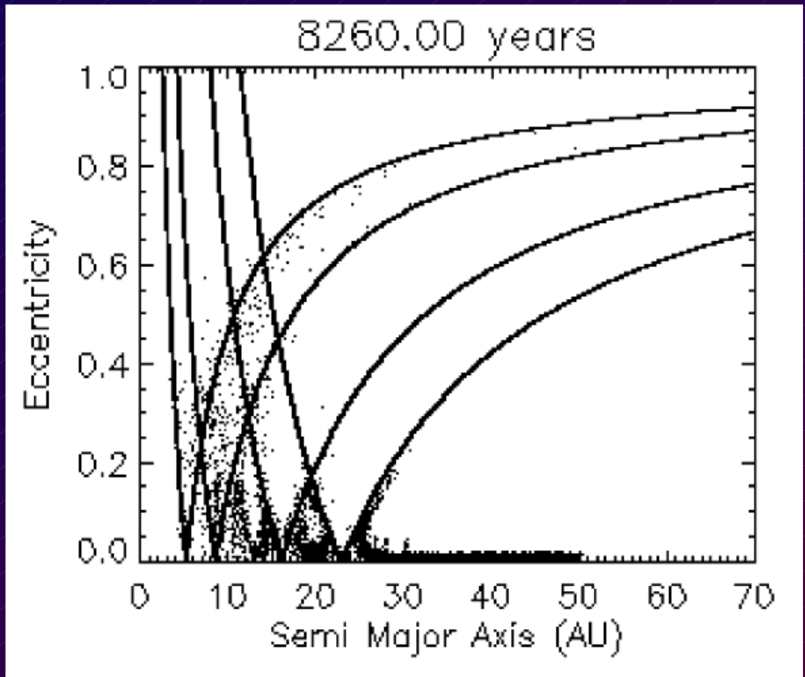
Collisions and Comets

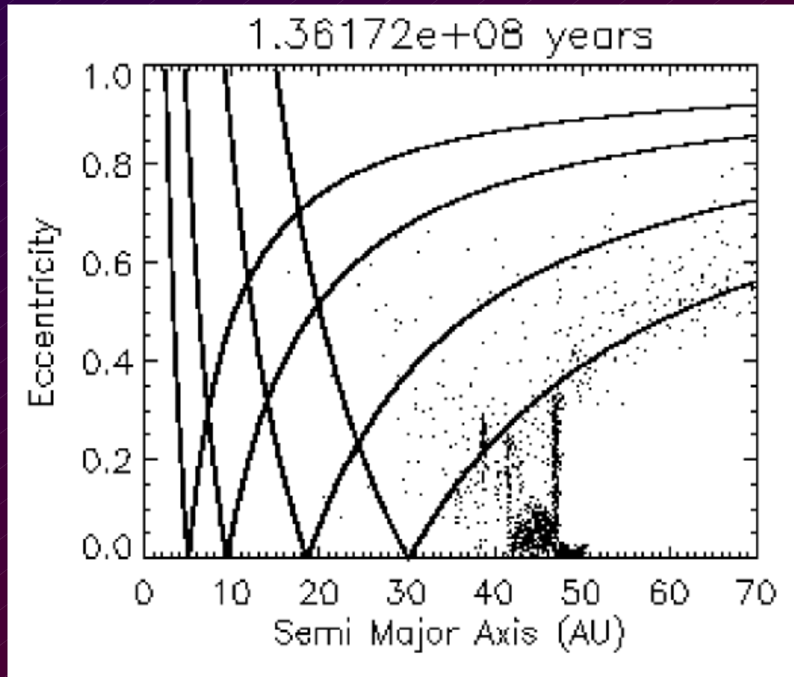
Charnoz and Morbidelli (2007)

- Hybrid model
- First: performs orbital integration w/o collisions
- Second: calculates collisional evolution occurring during the integration

- Tracks evolution of Kuiper Belt, Oort cloud, and scattered disk during giant planet migration
  - Assume constant size distribution throughout disk
  - Migration as in Malhotra (1993,1995)

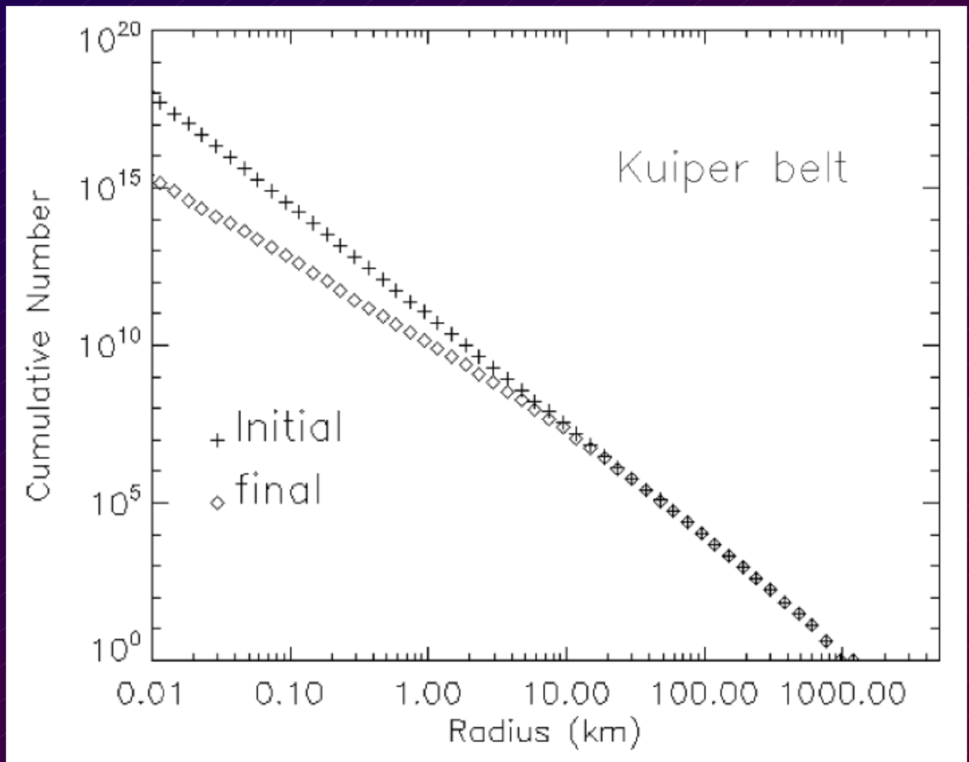
Dynamical Simulations





Collisions and Comets

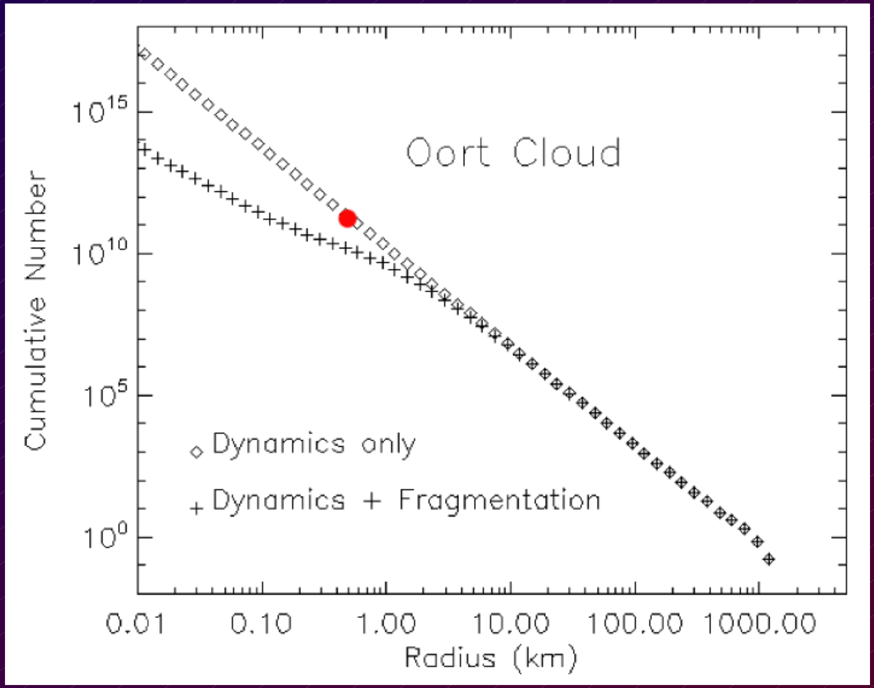
- Case 1
  - Most mass initially in small bodies
  - Easy to erode away collisionally

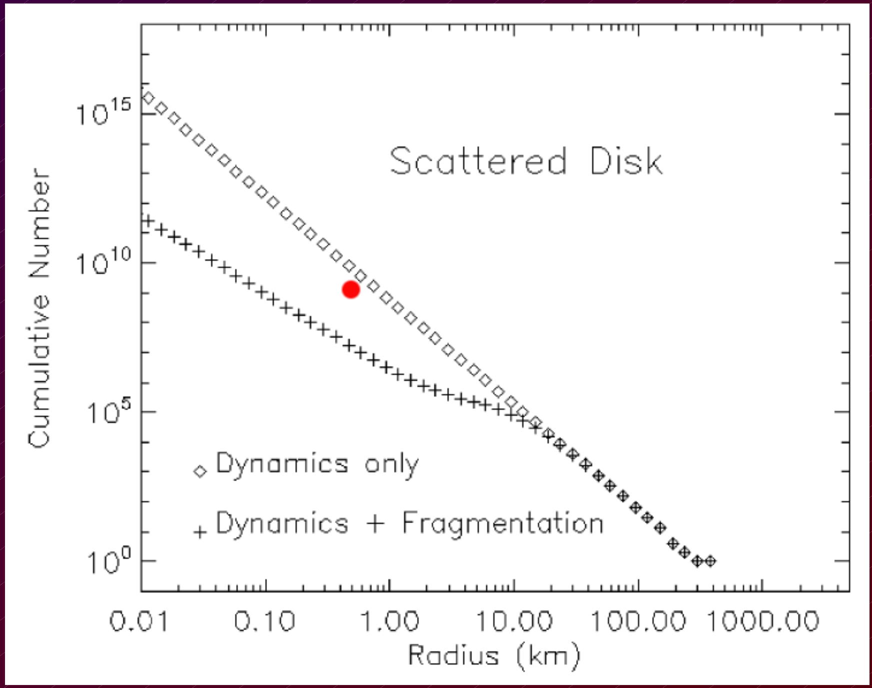


Mass and size distribution of KB reproduced!

Collisions and Comets

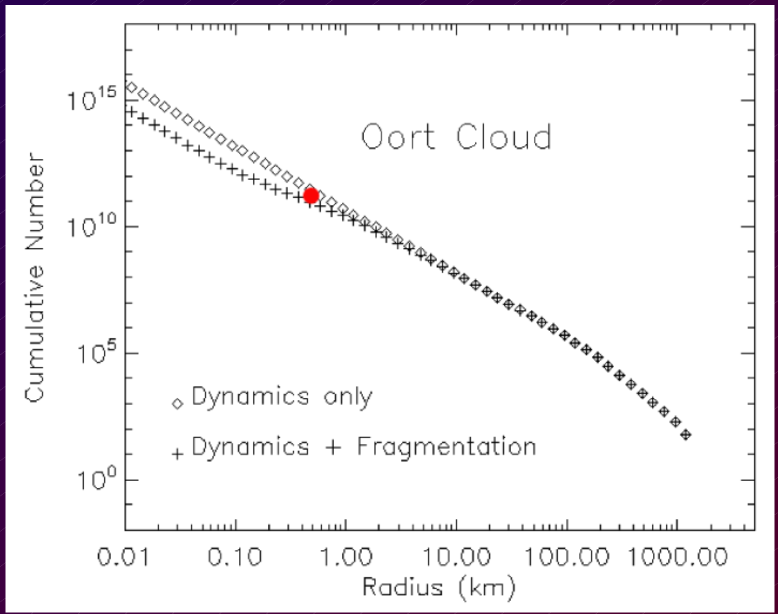
- Case 1
  - Too few ~1 km comet precursors in Oort cloud and scattered disk (compared to Heisler (1990) and Duncan and Levison (1997) estimates)

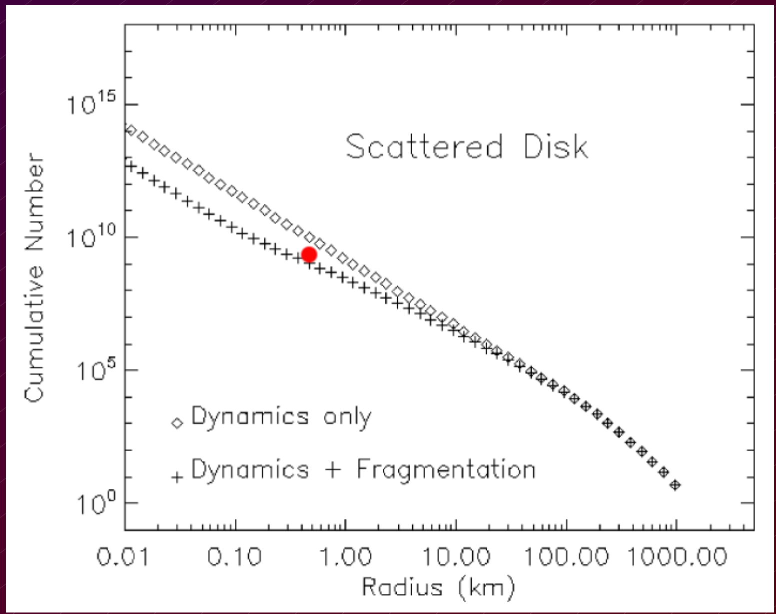




Collisions and Comets

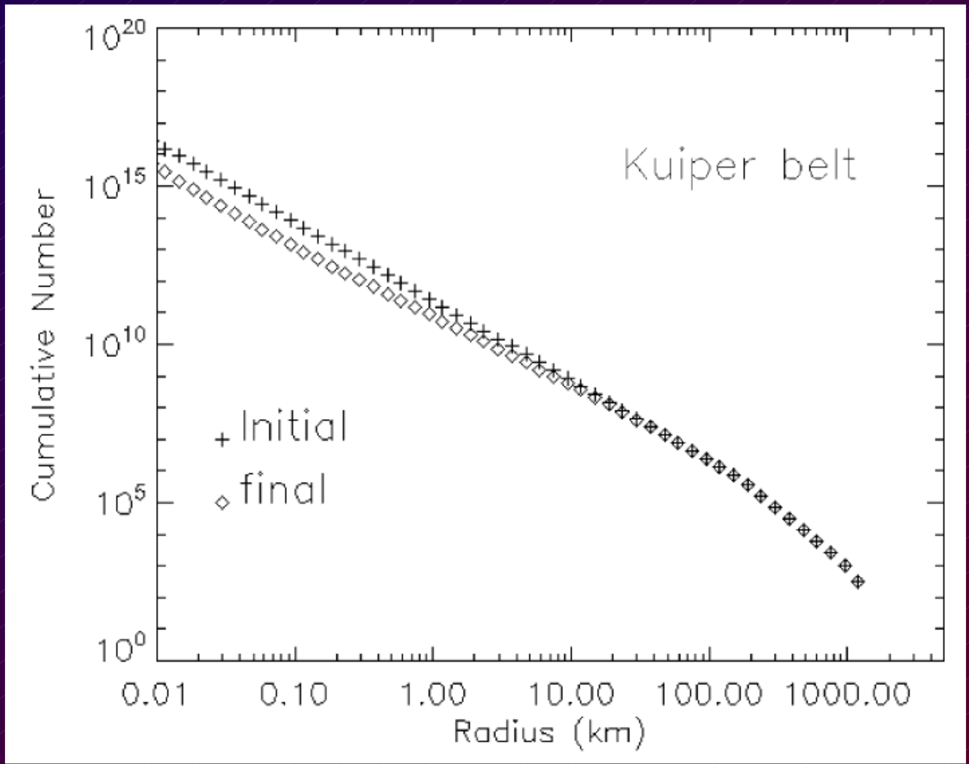
- Case 2
  - Most mass initially in large bodies
  - Difficult to erode away collisionally
  - Better match to ~1 km comet precursors in Oort cloud and scattered disk





Collisions and Comets

- Case 2
  - Size distribution of Kuiper Belt is reproduced
  - Mass is larger by ~100x



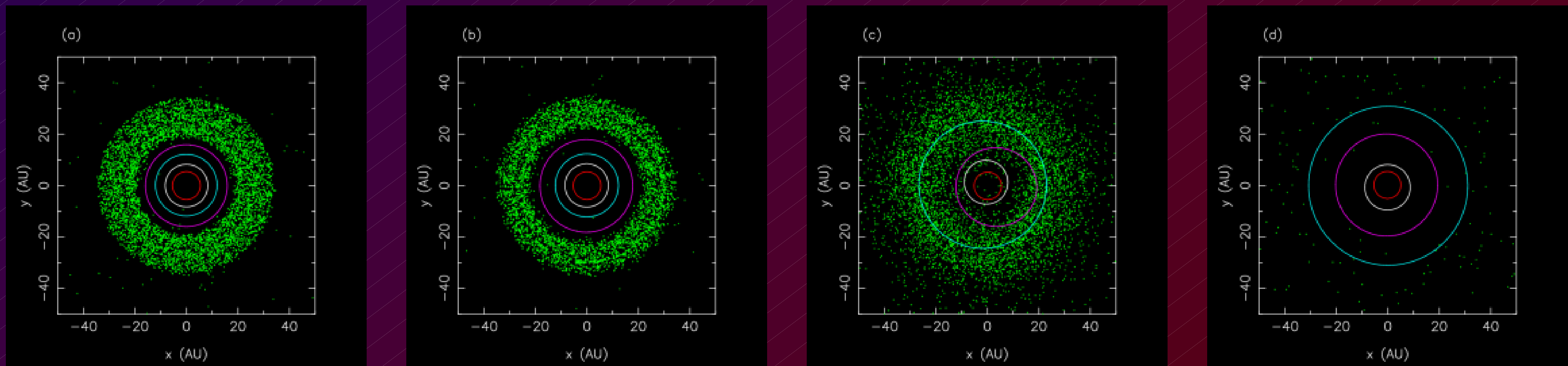
Dynamical depletion event is needed!

Collisions and Comets

- Having enough comets requires that most of the initial TNO mass was in large bodies
  - Kuiper belt must have been dynamically depleted
- Accretion models predict a population with most of the mass in small bodies
  - Kenyon and Luu (1999) find break at ~100 m diameter
- Need to re-evaluate accretion models
  - Can we form populations with most of the mass in large bodies?

The Nice Model*

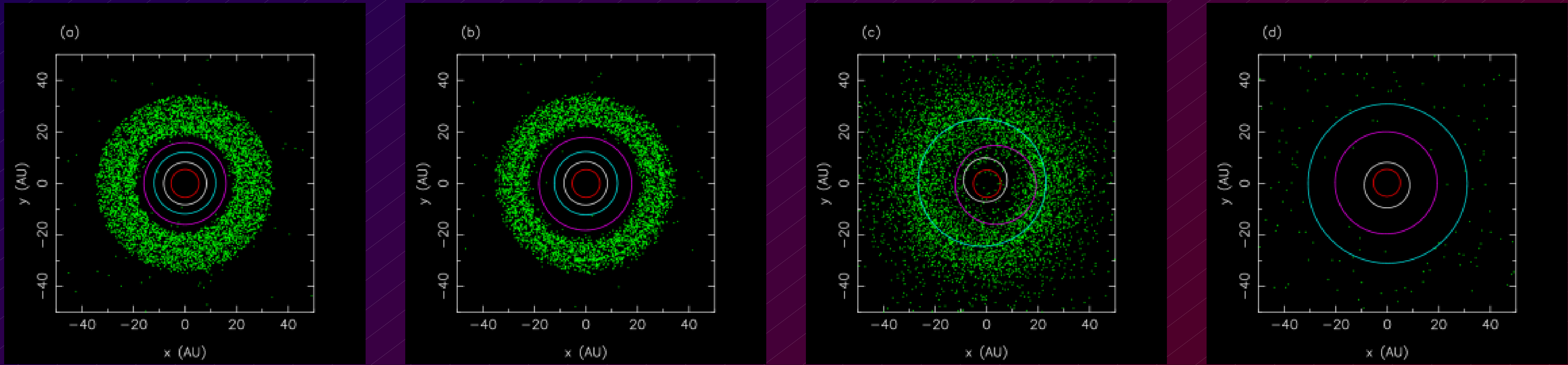
- Initially compact outer-planet system
  - Planetesimal disk extending beyond Neptune
- Slow migration for ~700 Myr
- 1:2 Jup/Sat resonance crossing
  - Triggers LHB
  - Causes rapid migration to current orbital configuration



*Tsiganis et al (2005), Morbidelli et al (2005), Gomes et al (2005)

Collisions in the Nice Model

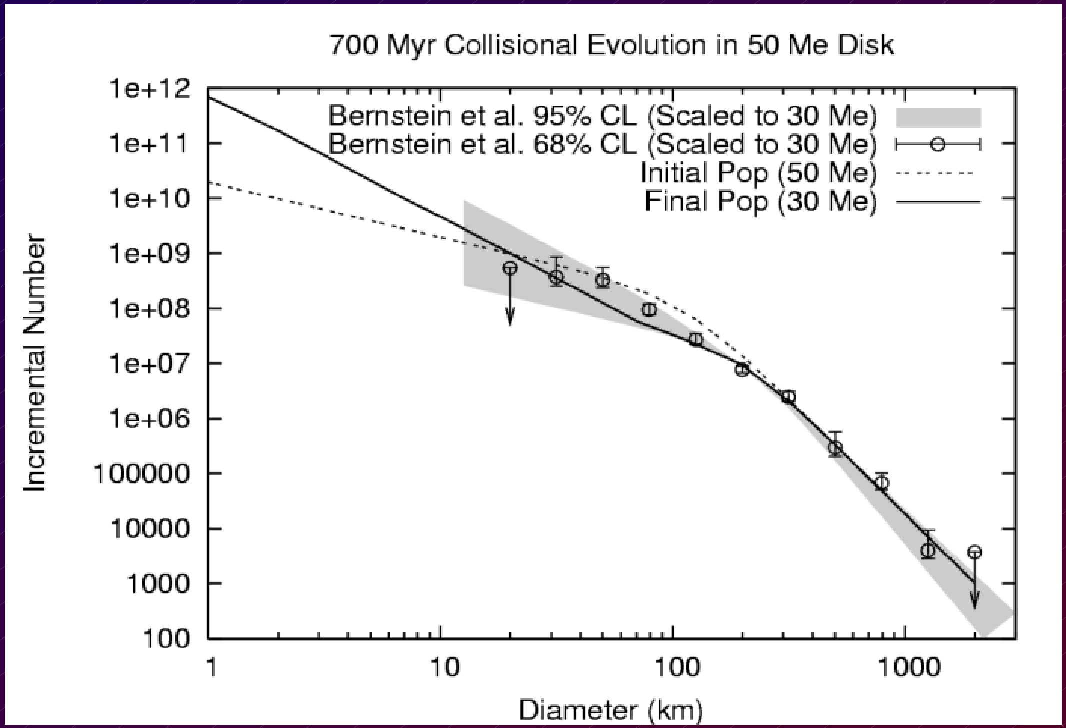
- Nice Model requires ~30 M_e trans-Neptunian disk to survive for ~700 Myr



- Can a disk from ~15-30 AU survive against collisions for that long?

Collisions in the Nice Model

- Simple collisional model
  - Start w/ 50 M_e between 15 and 30 AU, e ~ 0.04
  - Assume Benz and Asphaug (1999) strength law



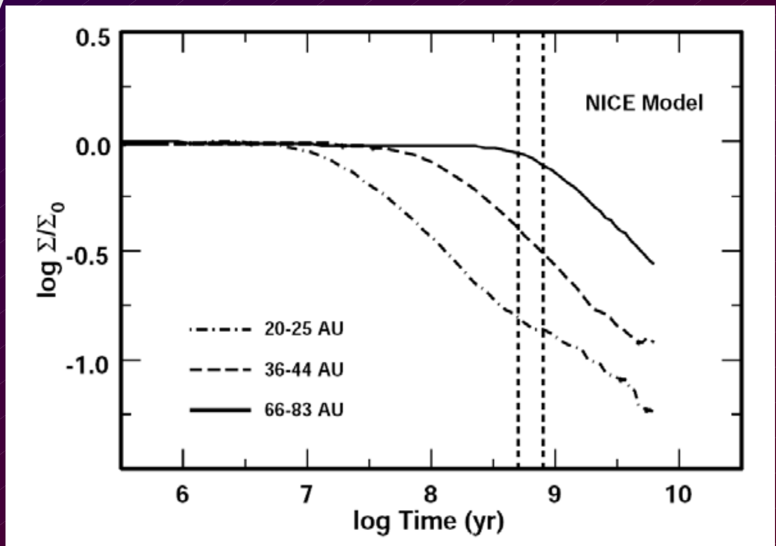
O'Brien el al. (DPS 2005)

30 M_e can survive!

Final size distribution roughly consistent with Bernstein et al.

Collisions in the Nice Model

- Kenyon et al (2007)
  - Accretion plus collisional grinding
- Bodies don't grow large fast enough to avoid collisional disruption
  - ~80-90% of the mass would be collisionally eroded away



Collisions in the Nice Model

- Can accretion efficiency be increased?
  - Concentrate more mass in large bodies, better survival against collisional grinding?
- More work necessary to draw solid conclusions

Summary

- Collisional and dynamical evolution are important for small-body populations
  - Must be considered simultaneously
- Asteroid belt
  - Initially massive (100-1000X current mass)
  - Dynamically depleted
  - Most collisional evolution occurred during early, massive phase
  - Collisional/dynamical model provides good match to numerous constraints (Bottke et al. 2005)

Summary -- Continued

- Important results from TNO accretion and collisional modeling
  - Initial TNO population was much more massive than current population
  - Collisional grinding can be effective, but probably not sufficient

Summary -- Continued

- Collisional+Dynamical modeling* of TNOs suggests that
  - Significant collisional grinding inconsistent with constraints from scattered disk and Oort cloud comets
  - Initial TNO size distribution had most of its mass in large bodies
  - Kuiper belt was dynamically depleted of most of its initial mass

*Charnoz and Morbidelli (2007)

Summary -- Continued

- Nice Model
  - Amount of erosion sensitive to initial size distribution in planetesimal disk
  - For enough mass to survive, most mass must be initially in large bodies

- These lines of evidence suggest that
  - Accretion in TNO region may be more efficient than predicted by current models