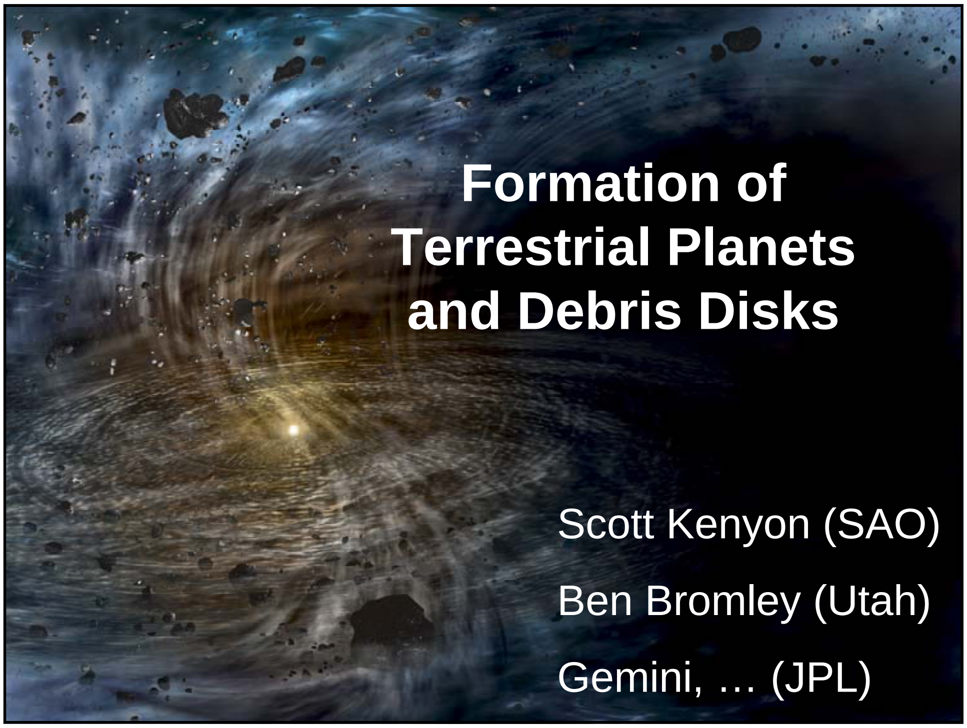


Central Goals

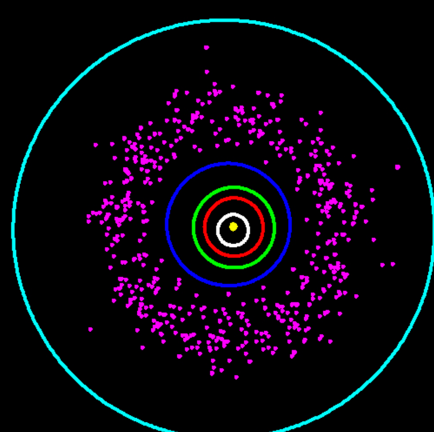
- Simulate an entire solar system
- Links to other solar systems
  - * Terrestrial planets ***
  - * Jovian planets
  - * Icy planets (Pluto, debris disks)

Rocky Planets

- Location
  * close to Sun
- Size of a rocky planet
  * 100-10000 km radius
- Types
  * Planets – Mercury, Venus, Earth, Mars
  * Asteroids – collision fragments
  * Zodiacal light – dusty debris

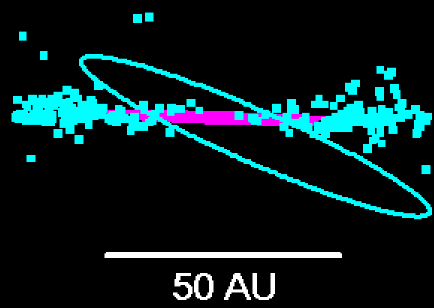
Inner Solar System

Top View



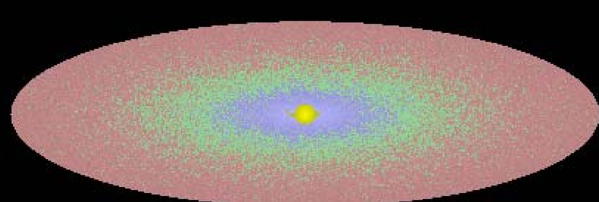
Our Solar System

Side View



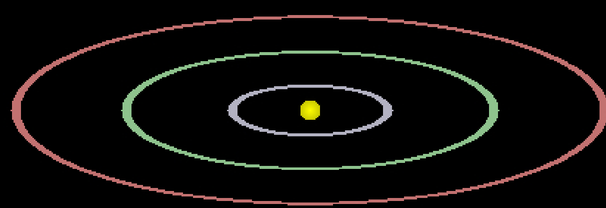
A Dusty Disk

1 Myr



A Solar System

10-100 Myr



1 Myr

HK Tau/c – Stapelfeldt et al

100 Myr

HD 107146 - Ardila at al

Major Issues

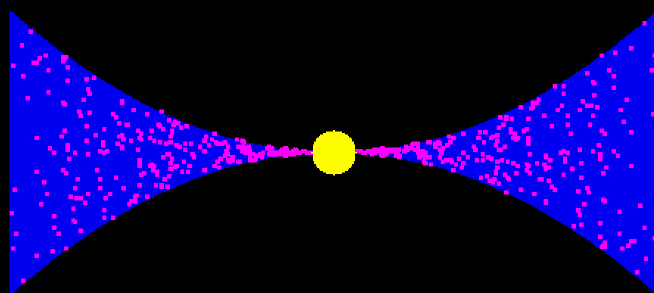
- **Evolution of Gas**
  - * viscosity
  - * evaporation

- **Evolution of Dust** ***
  - * collisions

Planets Grow in a Dusty DIsk

*disk radius = 100-1000 AU

*disk mass = $10^4 – 10^5$ M_{Earth}

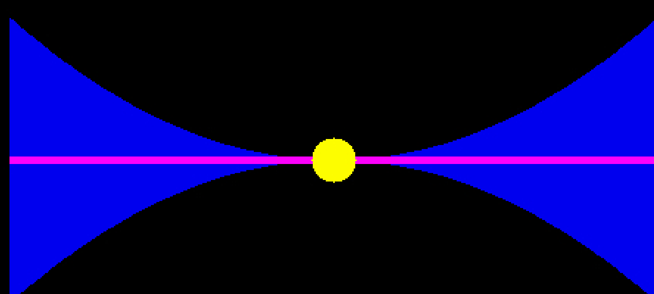


Safronov, Wetherill, Weidenschilling

Dust Settles to Midplane

* 1 mm and larger particles

*circular orbits



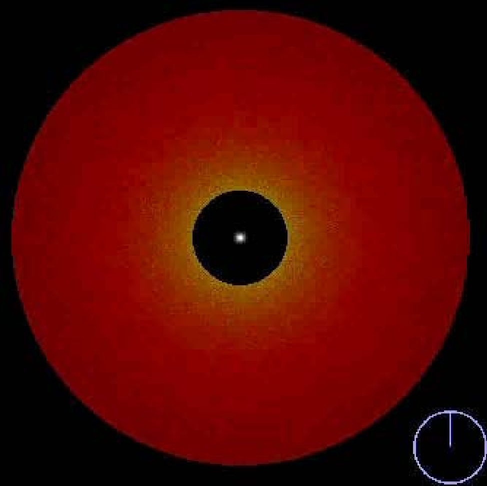
Planet Formation

- Coagulation
  - * dust ➔ planetesimals ➔ planets
  - * make Earths
  - * Earths accrete gas
  - * Earths stir up debris
  - * Debris scatters radiation from star
  - * Scattered radiation is visible
- Wetherill, Weidenschilling, Lissauer, …

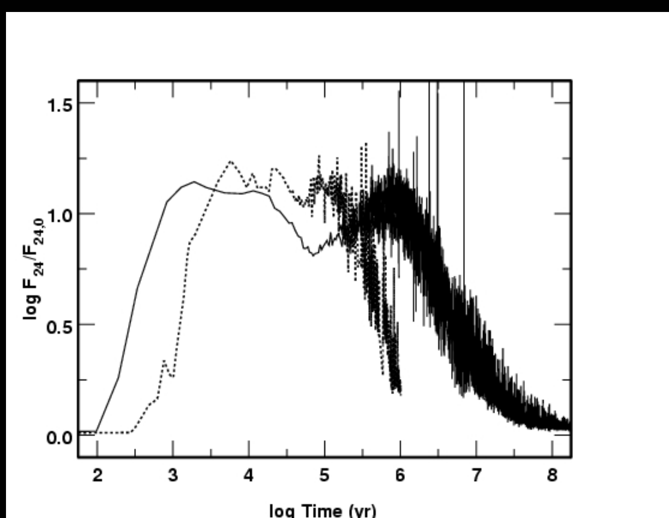
Highlights

- Successes
  - * Earth-like planets in 10-30 Myr
  - * Pluto-like planets in 10-100 Myr
  - * Kuiper Belt properties
  - * Vega-like debris disks
- Challenges
  - *Jupiters are hard
  - * Sedna

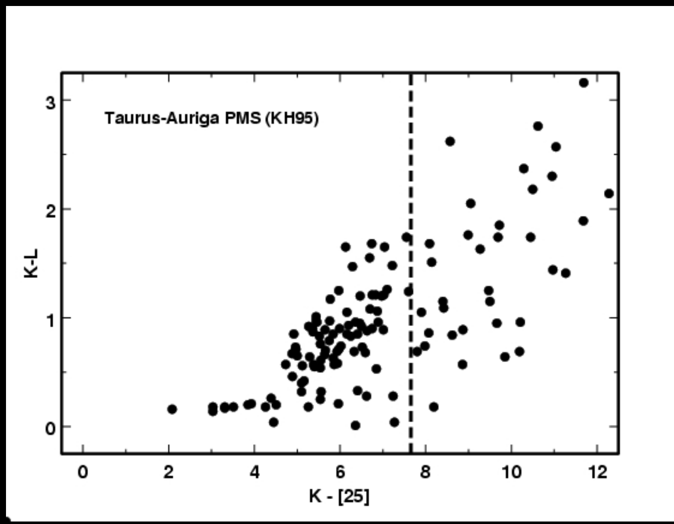
HST: Bright Rings



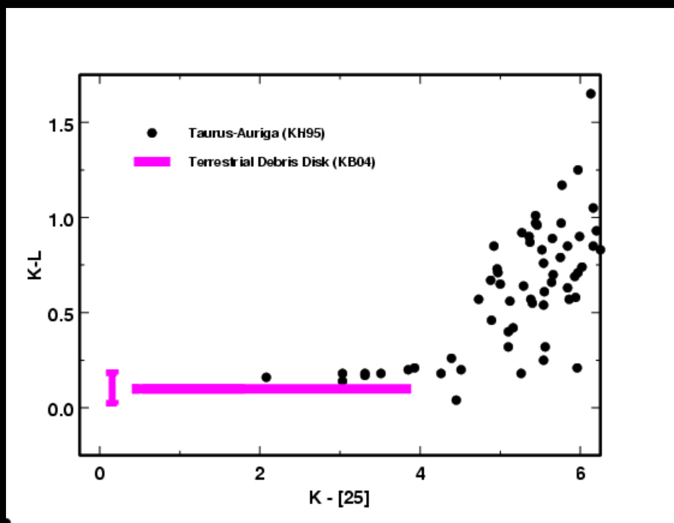
Spitzer: Evolution of Dust



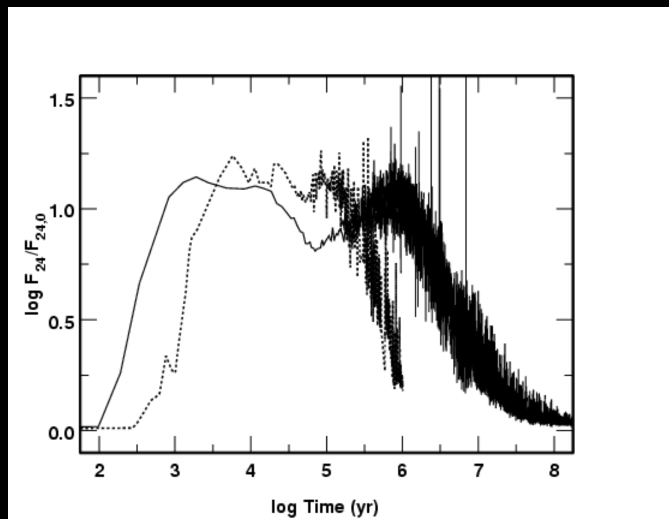
IRAS: Taurus-Auriga



Spitzer: Model Tests

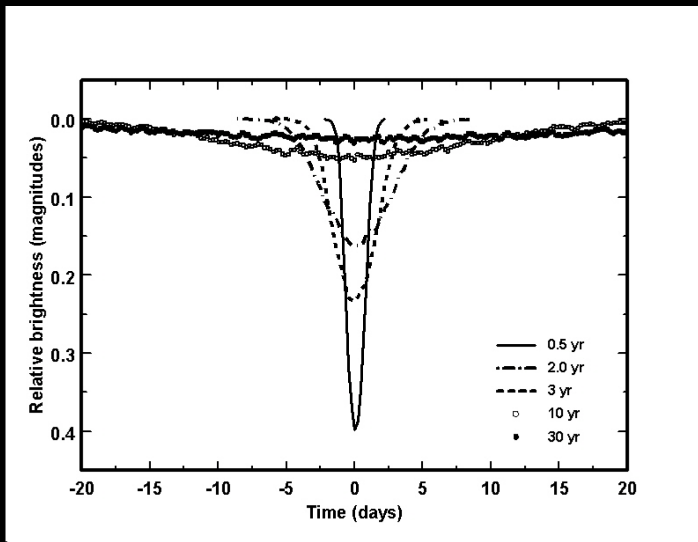


Spitzer: Evolution of Dust



Evolution of Blob of Dust

Kepler: Dust Eclipses



Observational Tests

- HST: disk structure
- Spitzer: IR excesses
- Chandra: dust/gas evolution
  - * Kastner
  - * Testa

Summary

- Terrestrial planets form quickly
  - * 10% of Earth mass in 1 Myr
  - * 1 Earth mass in 10-20 Myr
- Collisions produce IR excess from dust
  - * excess is observable
  - * lasts for 1-100 Myr

Coming Attractions

- Theory: better calculations
  - * Jupiter
  - * Outer solar system
- Observations
  - * FUV/EUV spectra: evolution of gas
  - * JWST: evolution of dust
  - * Kepler: transient events

Collision Outcomes

- Energy scaling algorithm
- Merger
  * collision energy < binding energy
- Disruption
  * collision energy > binding energy

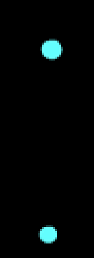
Coagulation

- Statistical mechanics approach
  * collision rate: $N_{ij}\ \sigma\ v\ F_g$
  * N_{ij} bodies of mass M_j
  * near-circular orbits: e_{ij}, i_{ij}
  * multiple annuli (32-64): a_i, Δa_i
- Physics
  * collisions
  * collective velocity motion
  * gas accretion, drag

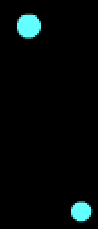
N-Body Code

- Encke method for largest bodies
  - * follows Keplerian orbits
  - * direct force evaluations
  - * hierarchical timesteps
- Coupled to coagulation code
  - * accretion of small bodies
  - * drag from gas and small bodies

Mergers



Disruptions



Velocity Evolution

- Viscous stirring
  - * all velocities increase
- Dynamical friction
  - * small bodies brake large bodies
- Gas, Poynting-Robertson drag
  - * brake small bodies
- Collisions
  - * brake large bodies

Dust

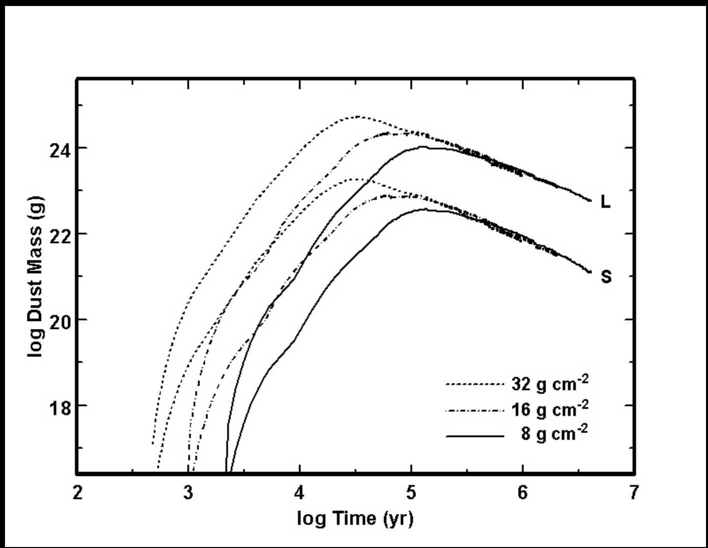
An Asteroid

10^{18} to 10^{21} dust grains

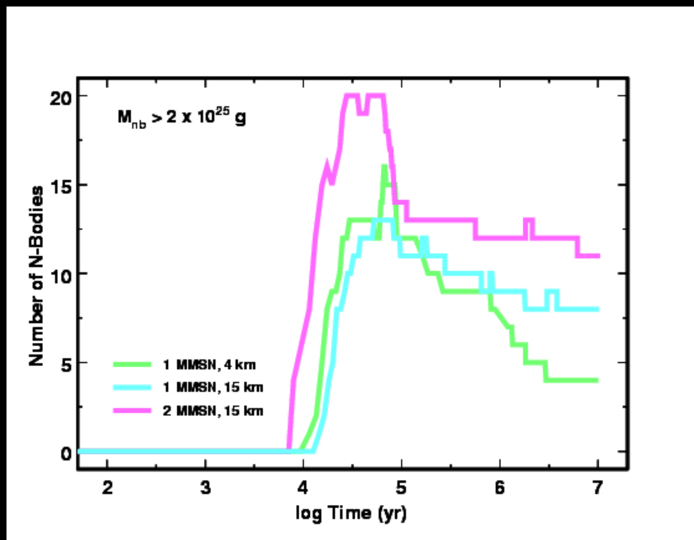
Three Phases of Growth

- Slow growth
  * geometric cross-sections
  * all bodies grow linearly
- Runaway growth
  * gravitational focusing
  * largest bodies grow exponentially
- Oligarchic growth
  * largest bodies grow slowly
  * collisional cascade

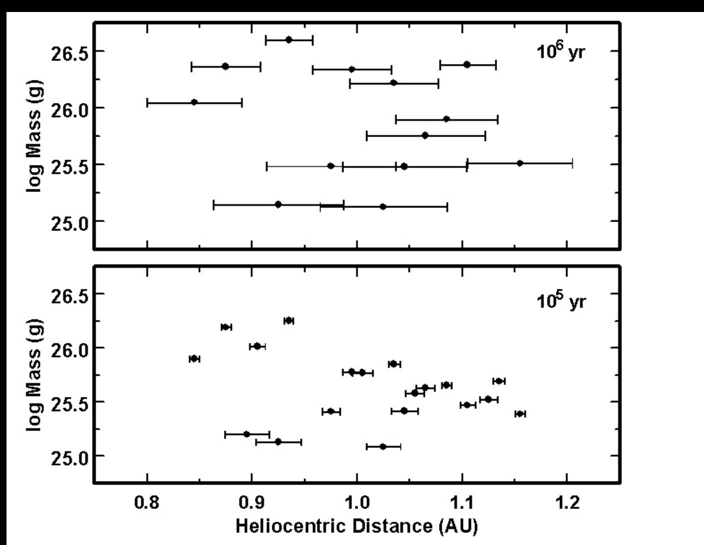
The Dust Mass



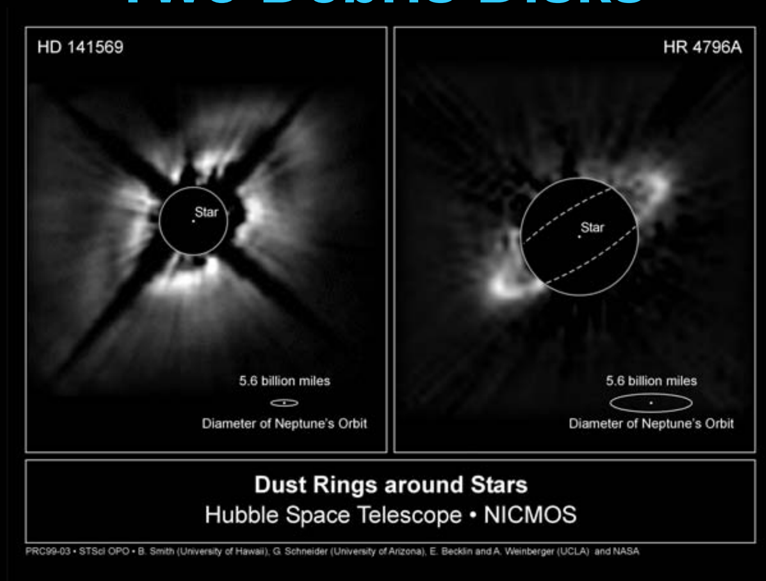
N-Body Number



The Largest Objects



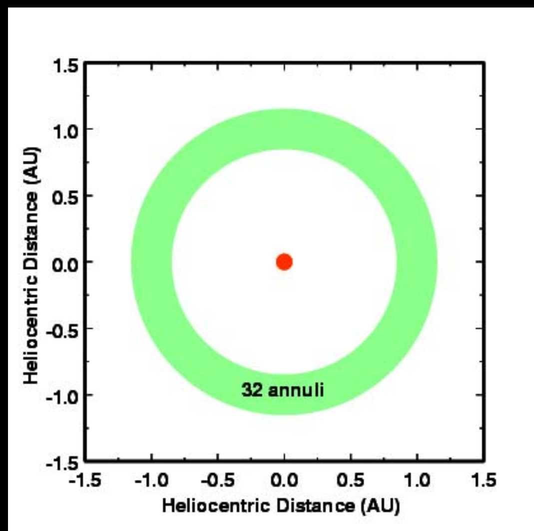
Two Debris Disks



Planet Formation

- **Dynamical instability**
  - * part of disk collapses
  - * gravitational instability
  - * make Jupiters
  - * Jupiters stir up debris
- **Earth and Pluto are impossible**
- **Boss, Cameron, …**

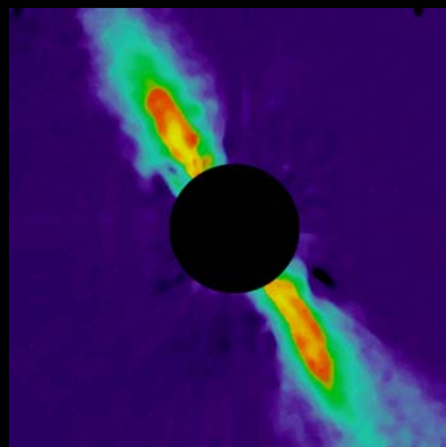
Our Grid



Debris Disks

- **Far-infrared emission**
  - * small dust grains absorb starlight
  - * reradiate at 100 microns
- **Optical and near-infrared emission**
  - * grains scatter starlight
- **Disk-like morphologies**
  - * size of our solar system

β Pictoris



Near-infrared – Lagrange et al

Links to Other Solar Systems

- Our solar system
  - * 1000’s of rocky planets & asteroids
- Other solar systems
  - * 1000’s of debris disks
- Need a robust formation model
  - * numerical simulation of solar system

Our Calculations

- Multiannulus hybrid code
  - * 32-64 concentric annuli at 0.5-1.5 AU
  - * 1 m to 1 km planetesimals
  - * minimum mass solar nebula
- Results after 1-10 Myr
  - * planets: Moon to Earth
  - * rings of dust