# The Formation of Planets from the Direct Accretion of Pebbles

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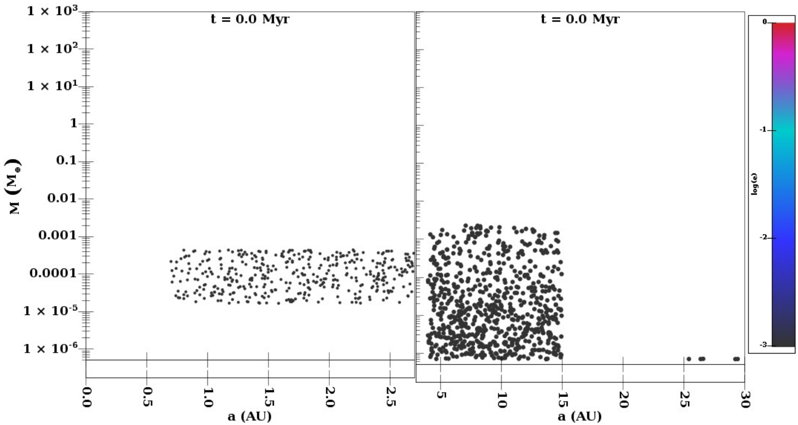
*An Apple- and Microsoft-Free Presentation*

## A Pair Simulations

- Our Disk: $\Sigma = \Sigma_o r^{-1}$, $h/r \propto r^{9/7}$, $\alpha = 3 \times 10^{-4}$
  - $\Sigma_0 = 5 \times \mathrm{MMSN}$.
  - Gas exponentially decays with half-life of 2 Myr.
  - Solar Solid-to-Gas Ratio.
- Split the simulation into 2 parts at the snow-line ($2.7$ AU).
- Convert some fraction ($f$) solids to planetesimals:
  - Outer: $f = 10\%$
    $100 < R < 1350$ km (roughly Pluto size), $n(R)dR \propto R^{-4.5}$.
  - Inner: $f = 0.8\%$ ($50 \times \Sigma(\mathrm{AB})$),
    $200 < R < 600$ km (slightly $>$ Ceres size), $n(R)dR \propto R^{-3.5}$.
- *Slowly* create pebbles:
  - Spatially and temporally follows $\Sigma$ out to $30$ AU.
  - $\tau_S \sim P_{orb}/t_{drag} = 0.1$ – 0.6.
    - Have $R \sim 4$ — $\sim 50$ cm depending on $a$.
  - Assume that pebbles can't cross snow-line.
- Follow evolution with new dynamical/collisional code *LIPAD*.
  - Modified to include just about everything.

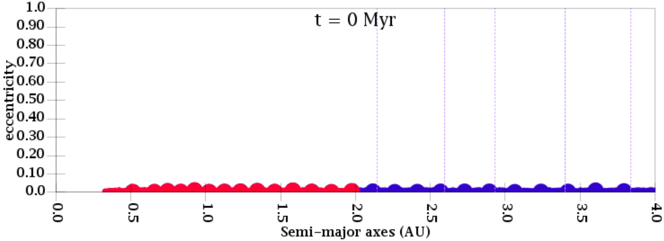
# Two Example Simulations




- First calculations to reproduce the structure of the Solar System!
  - Normal Earth and Venus, a small Mars, a low mass asteroid belt, and the gas giant planets.

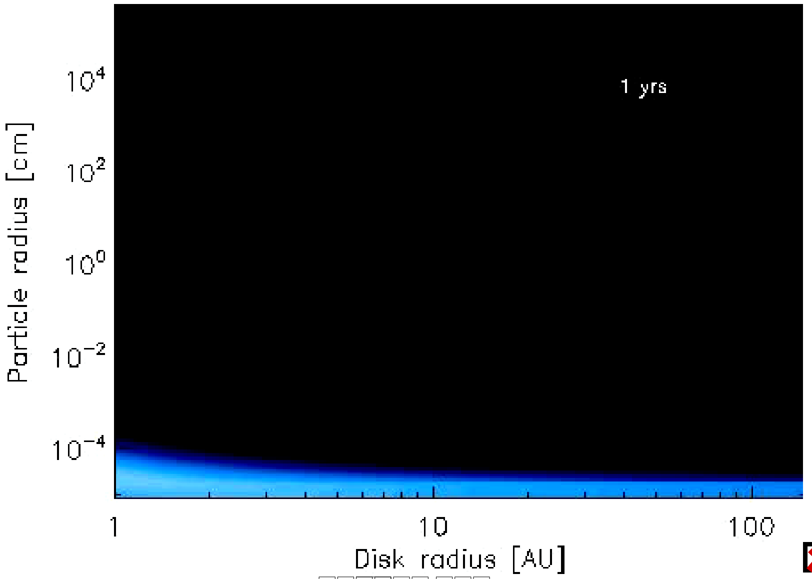
## Well Known Issues in Standard Planet Formation Models

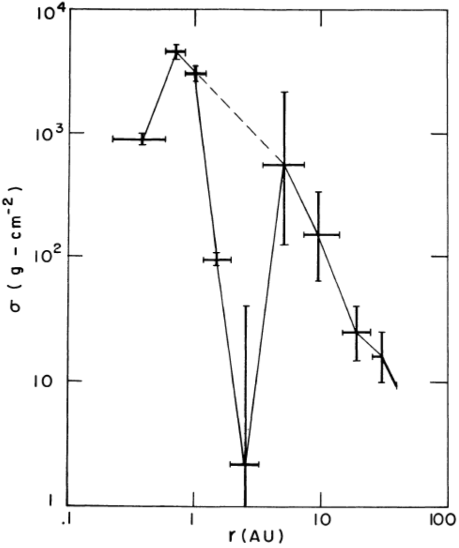
1. The Meter Barrier:
   - Small objects stick due to electrostatic forces.
   - Large objects can be held together by gravity.
   - But it is not clear that $\sim 1\,\text{m}$ will stick.
2. The Giant Planet Core Time-Scale Problem:
   - Cores of Jupiter and Saturn have to form before the gas goes away.
     - Disks last 3-5 Myr. (Earth took between 50 and $100\,\text{Myr}$ to form!)
   - Standard model cannot build the core fast enough.
3. Mars is TOOOOOOOOOOOOOO small:
   - Standard model predicts that Mars should be larger than the Earth.




   - But, Mars is part of a gap in the distribution of material in the Solar System.

Example from Brauer, Dullemond, & Henning (2008)





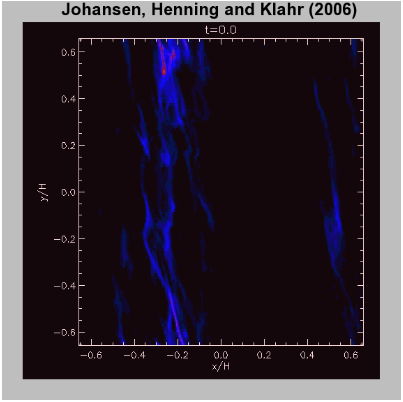
10^4
10^3
10^2
10
1
σ ( g - cm^-2 )
.1
1
10
100
r (AU)

# The Basic Story

1. Dust particles begin to settle and grow in disk.
2. The presence of settling dust causes turbulence in the gas.
3. $10\,$cm — $10\,$m *pebbles* concentrate due to streaming instability or turbulence $\Longrightarrow$ gravitational instabilities.

   *(Youdin & Goodman; Cuzzi et al.)*

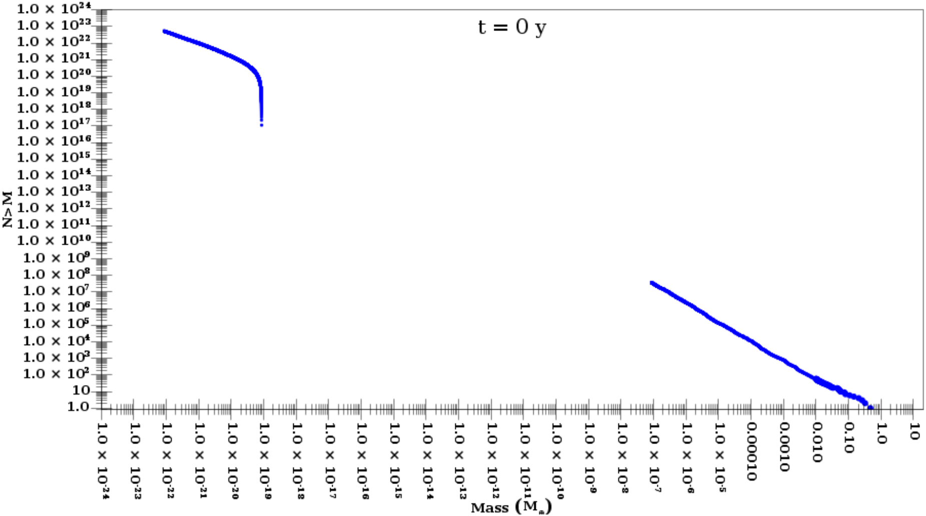
   - Predicts the first planetesimals are $\sim 100$ — $\sim 1000\,$km.
   - Only converts 10 – 50% of pebbles to planetesimals.
   - So, we have a bimodal distribution of objects.




4. Large planetesimals can accrete pebbles **verrrrrrry** effectively.

   *(Ormel & Klahr; Lambrechts & Johansen)*

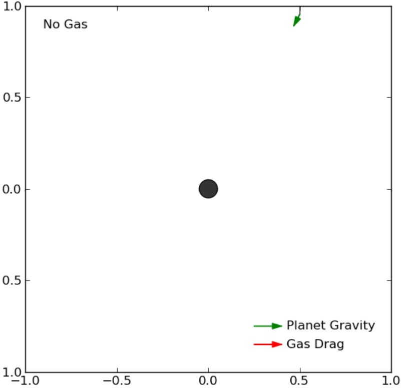
   - Because strong gas drag leads to pebbles becoming captured.
   - Leads to HUGE cross section ($> r_H$).
   - Only effective for large planetesimals.

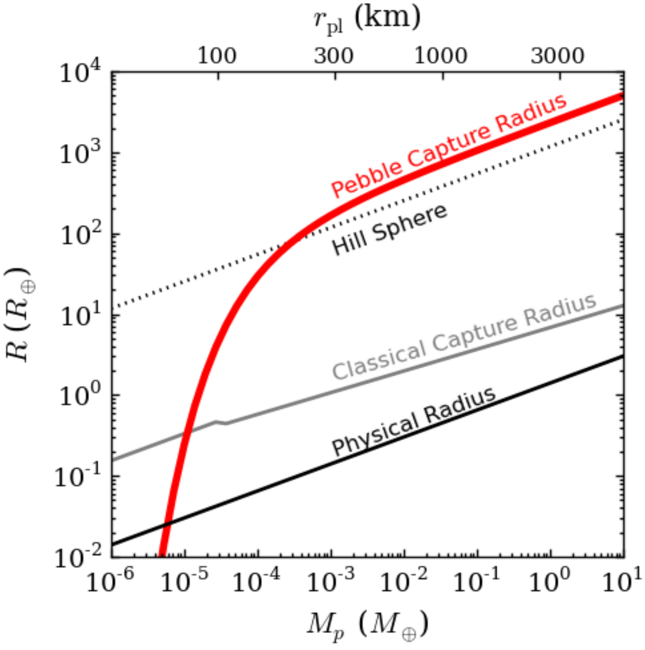


t = 0 y
N>M
Mass (M⊕)

# Pebble Accretion

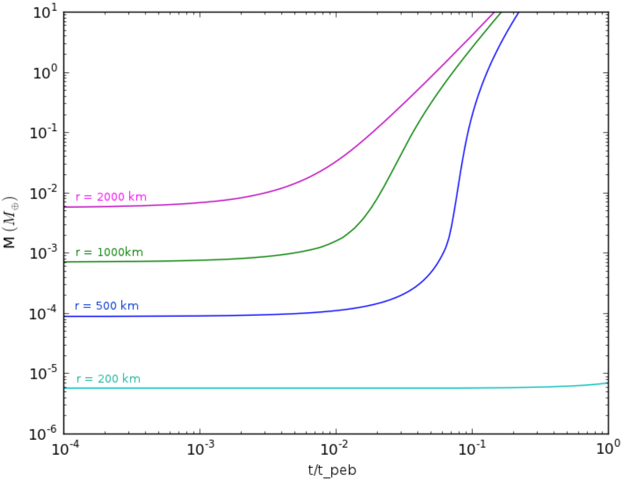
*(Lambrechts & Johansen)*





$r_{pl}$ (km)
100
300
1000
3000
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$R\ (R_\oplus)$
Pebble Capture Radius
Hill Sphere
Classical Capture Radius
Physical Radius
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$M_p\ (M_\oplus)$

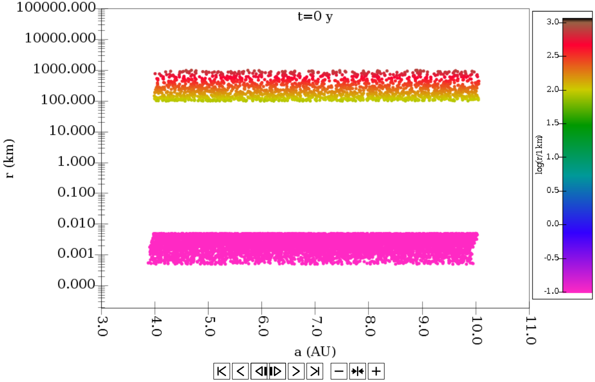
A single planetary embryo embedded in a disk of pebbles:



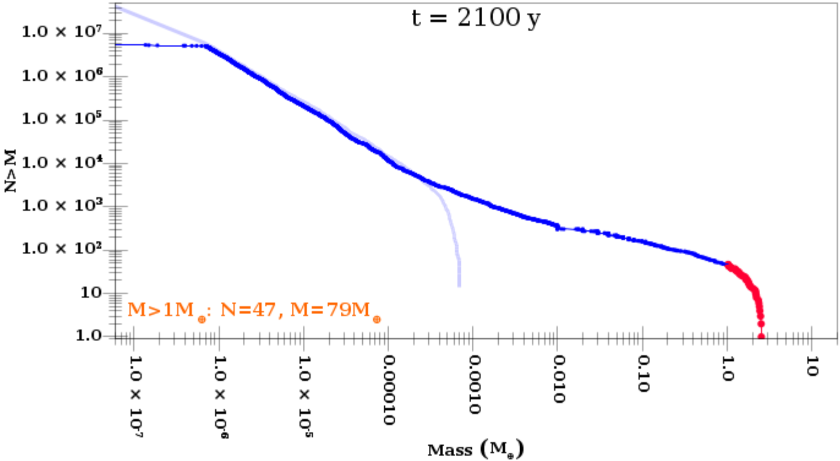

- Small objects cannot grow because encounters happen too fast for the gas to matter.

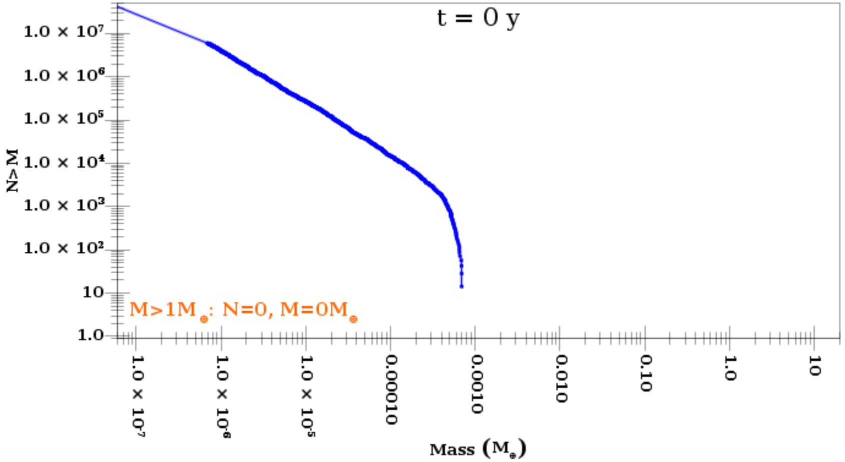
# The Problem with Fast Pebble Creation

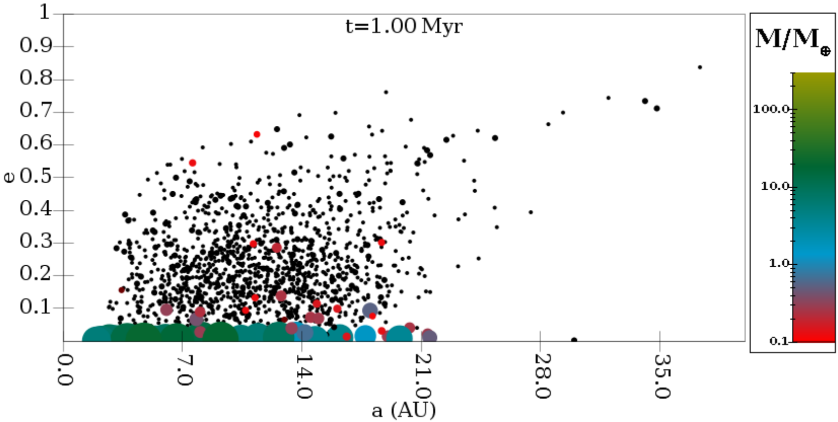
- The simplest assumption is that all the pebbles and planetesimals formed together. *(Lambrechts & Johansen)*



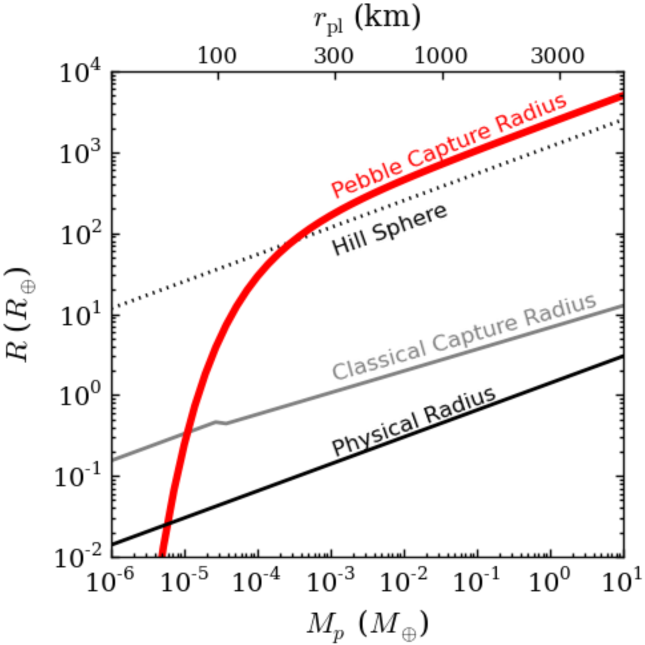

- Large planets grow in ∼1000 years! ✓
- But, we end up with ∼100 Earth-mass objects. *(Kretke & Levison)*
  - We get gas giants, but earths scatter through the system, destroying the Kuiper belt and terrestrial region.
  - This occurs because the capture cross section scales with $R_H$.
    - So, $R \sim R_H \Rightarrow \dot{M} \propto M^{2/3}$.
    - the largest objects become roughly the same size.


t = 2100 y
N>M
1.0 × 10^7
1.0 × 10^6
1.0 × 10^5
1.0 × 10^4
1.0 × 10^3
1.0 × 10^2
10
1.0
M>1M⊕: N=47, M=79M⊕
1.0 × 10^-7
1.0 × 10^-6
1.0 × 10^-5
0.00010
0.0010
0.010
0.10
1.0
10
Mass (M⊕)


t = 0 y
N>M
1.0 × 10^7
1.0 × 10^6
1.0 × 10^5
1.0 × 10^4
1.0 × 10^3
1.0 × 10^2
10
1.0
M>1M⊕: N=0, M=0M⊕
1.0 × 10^-7
1.0 × 10^-6
1.0 × 10^-5
0.00010
0.0010
0.010
0.10
1.0
10
Mass (M⊕)



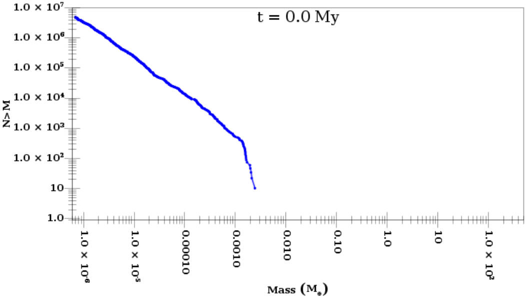
t=1.00 Myr
e
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
7.0
14.0
21.0
28.0
35.0
a (AU)
M/M⊕
100.0
10.0
1.0
0.1



$r_{pl}$ (km)
100
300
1000
3000
Pebble Capture Radius
Hill Sphere
Classical Capture Radius
Physical Radius
$R\ (R_\oplus)$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$M_p\ (M_\oplus)$

# Slow Pebble Accretion

- If we let pebbles form slowly:

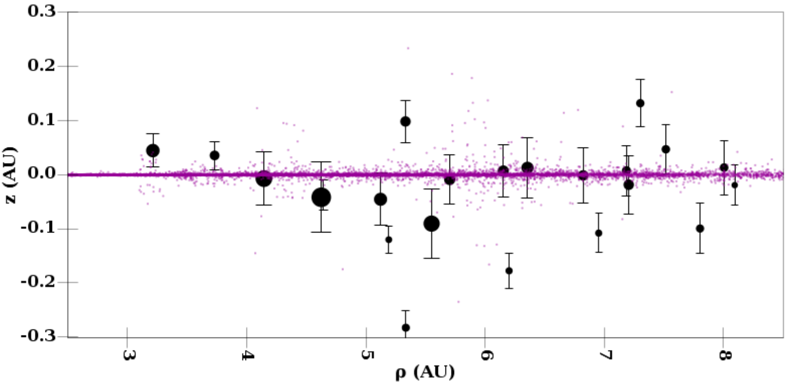


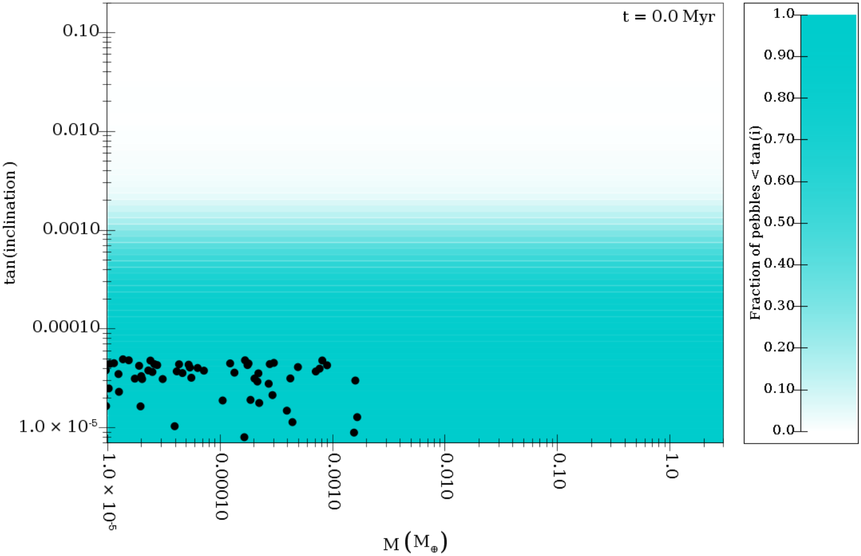

- In original runs, planets grow before they interact.
  - System stays cold and then BOOM!
- However in this case, the planets excite one another as the grow.
  - Smaller planets spend most of their time above the pebble disk.

$\Longrightarrow$ They can't grow.

  - Larger planets can feed most of the time, so they can grow.
- We end up with a few cores and a lot of small things.

So, this process can effectively make the giant planets.

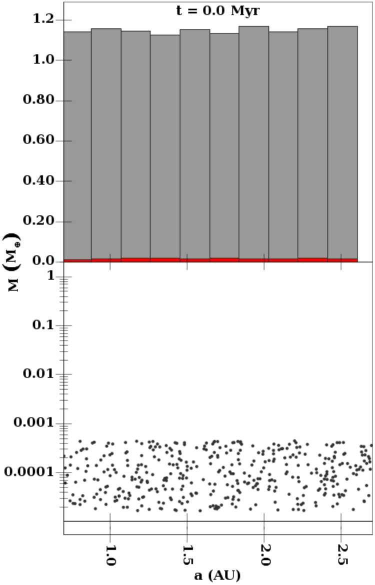

0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
z (AU)
3
4
5
6
7
8
ρ (AU)


t = 0.0 Myr
tan(inclination )
0.10
0.010
0.0010
0.00010
1.0 × 10-5
1.0 × 10-5
0.00010
0.0010
0.010
0.10
1.0
M (M⊕)
Fraction of pebbles < tan(i)
1.0
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.0

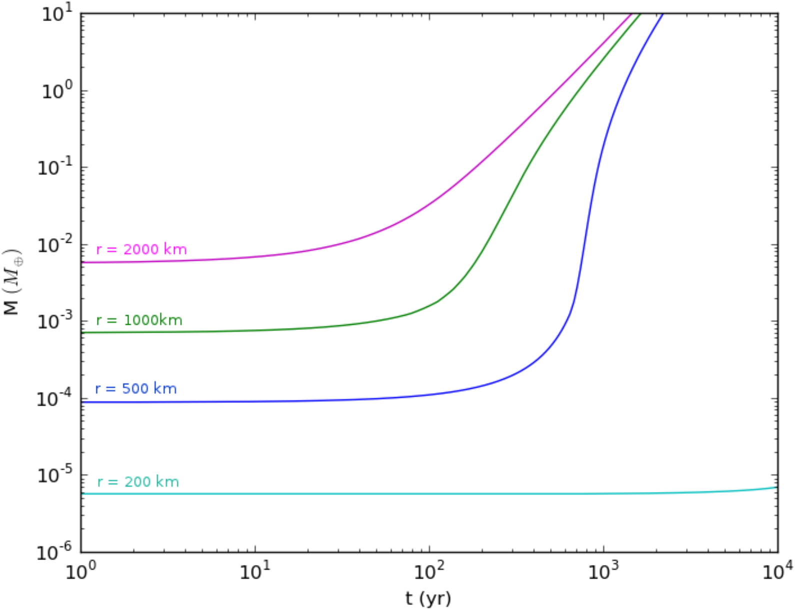
# Slow Pebble Accretion and Terrestrial Planets

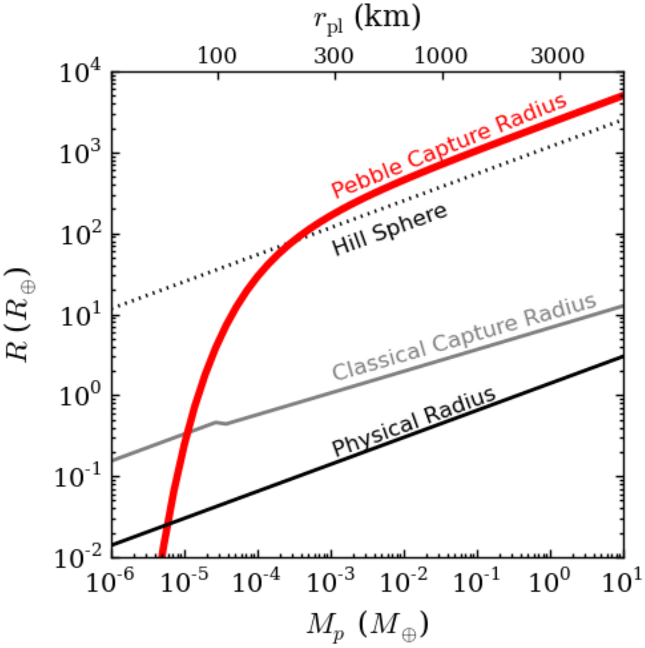
Let's look at what happens with slow pebble accretion:
We find that the terrestrial planets form in 2 stages.

- **Pebbles Stage:**
  - Little mass near $1.5$ AU and almost none beyond $2$ AU!
  - Closer to the Sun $\Rightarrow$ smaller objects can grow.
  - For this disk, Ceres-sized objects can only grow to $\sim 1.5$ AU.
- **Bamm-Bamm Stage:**
  1. Eat all planetesimals w/ $a \lesssim 1$ AU.
  2. Settle into a system of $\sim 20$ small planets.
  3. Suffer an instablity of 10s Myr $\Rightarrow$ giant impacts.
- So, we have a single physical process that can make:
  1) Earth and Venus.
  2) Low-mass Mars,
  3) Low-mass asteroid belt.



A single planetary embryo embedded in a disk of pebbles:





$r_{\rm pl}$ (km)
100
300
1000
3000
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$R\ (R_\oplus)$
Pebble Capture Radius
Hill Sphere
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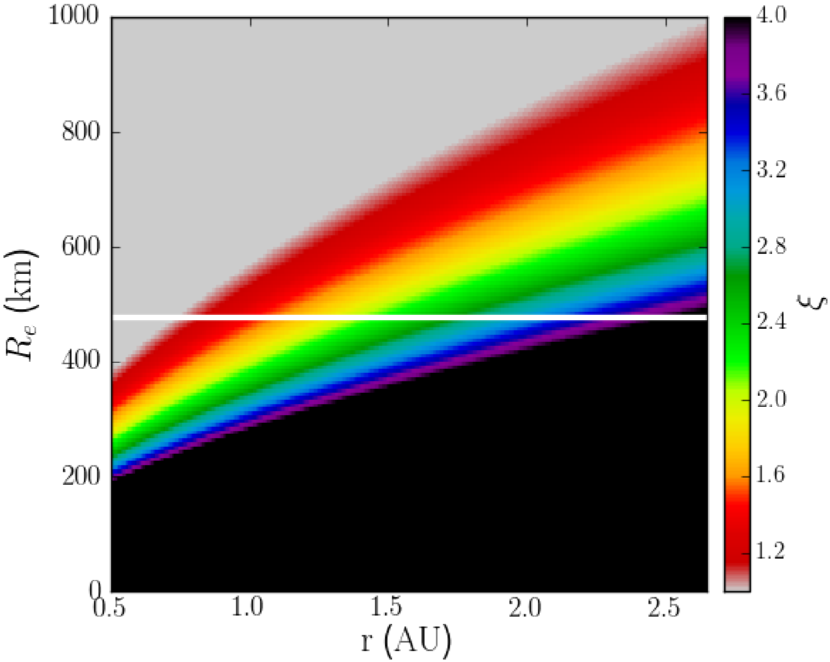
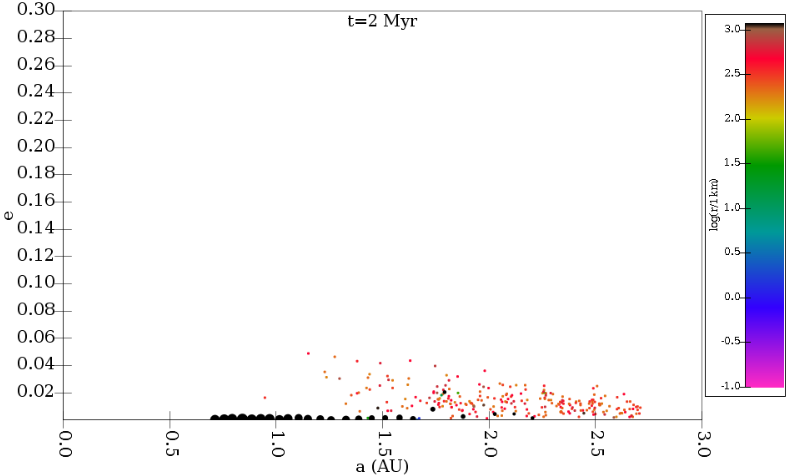
Physical Radius
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$M_p\ (M_\oplus)$

To zeroth order $R_c \propto R_H e^{-\xi}$, where $\xi$ is $\mathrm{func}(R, M_p, \Sigma, h)$. So:





t=2 Myr
e
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.0
0.5
1.0
1.5
2.0
2.5
3.0
a (AU)
log(r/1 km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0

## Conclusions

- There are some issues with the classical model of planet formation.
  1. Cannot grow beyond ∼1 m.
  2. Cores of giant planets take too long to form.
  3. Mars is too small and the asteroid belt is nearly empty.
- We argue that slow pebble accretion might solve these problems.
- In particular, we present a new scenario:
  - A small number of planetesimals initially form.
  - Pebbles grow on a timescale of 100,000 y — 1 Myr.
- This one scenario can reproduce most of the structure of the planetary system!

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This talk can be found at www.boulder.swri.edu/∼hal/talks.html.
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