Gas Drag-Induced Capture of Planetesimals in the Proto-Atmosphere of a Growing Giant Planet

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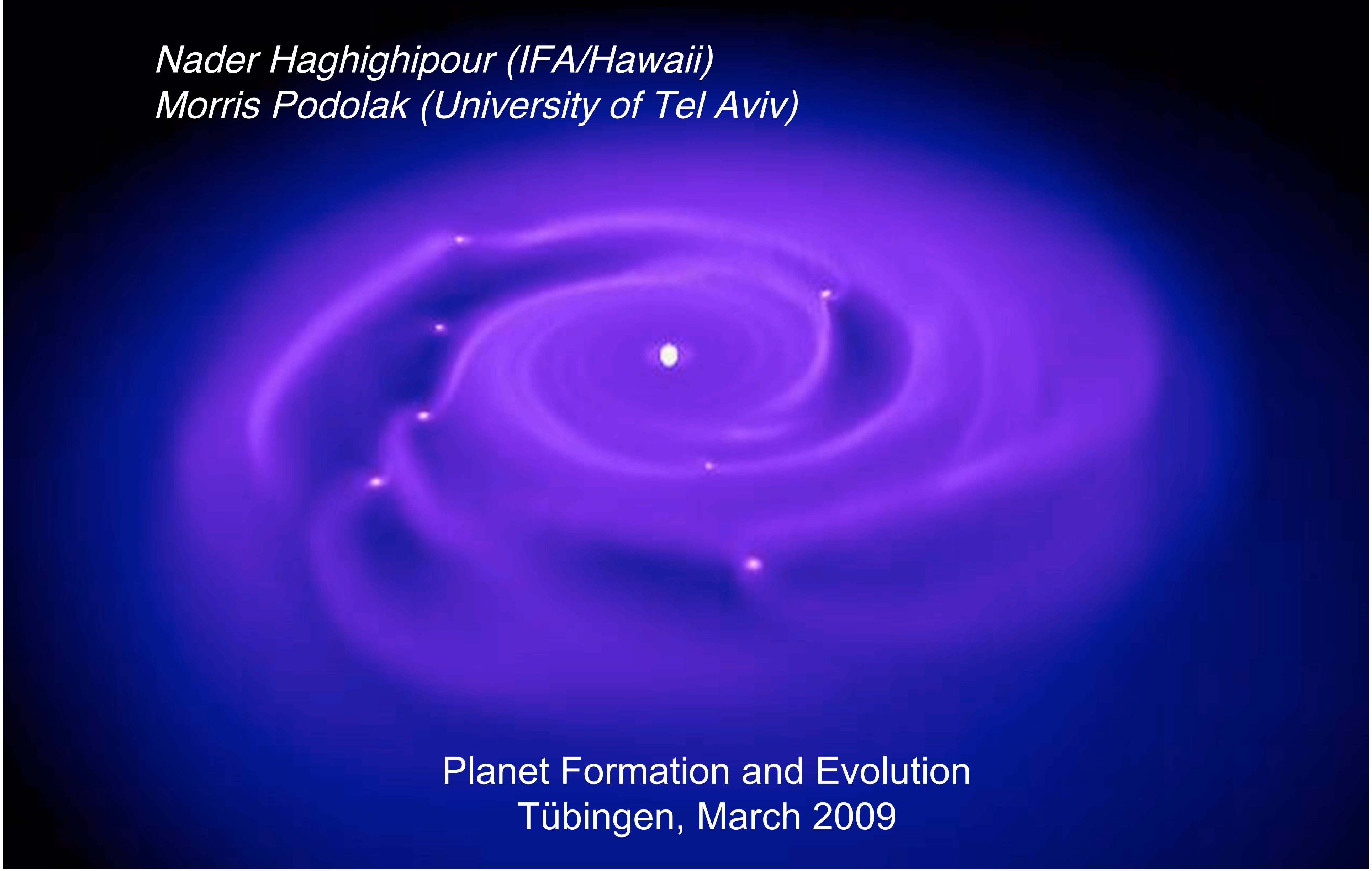
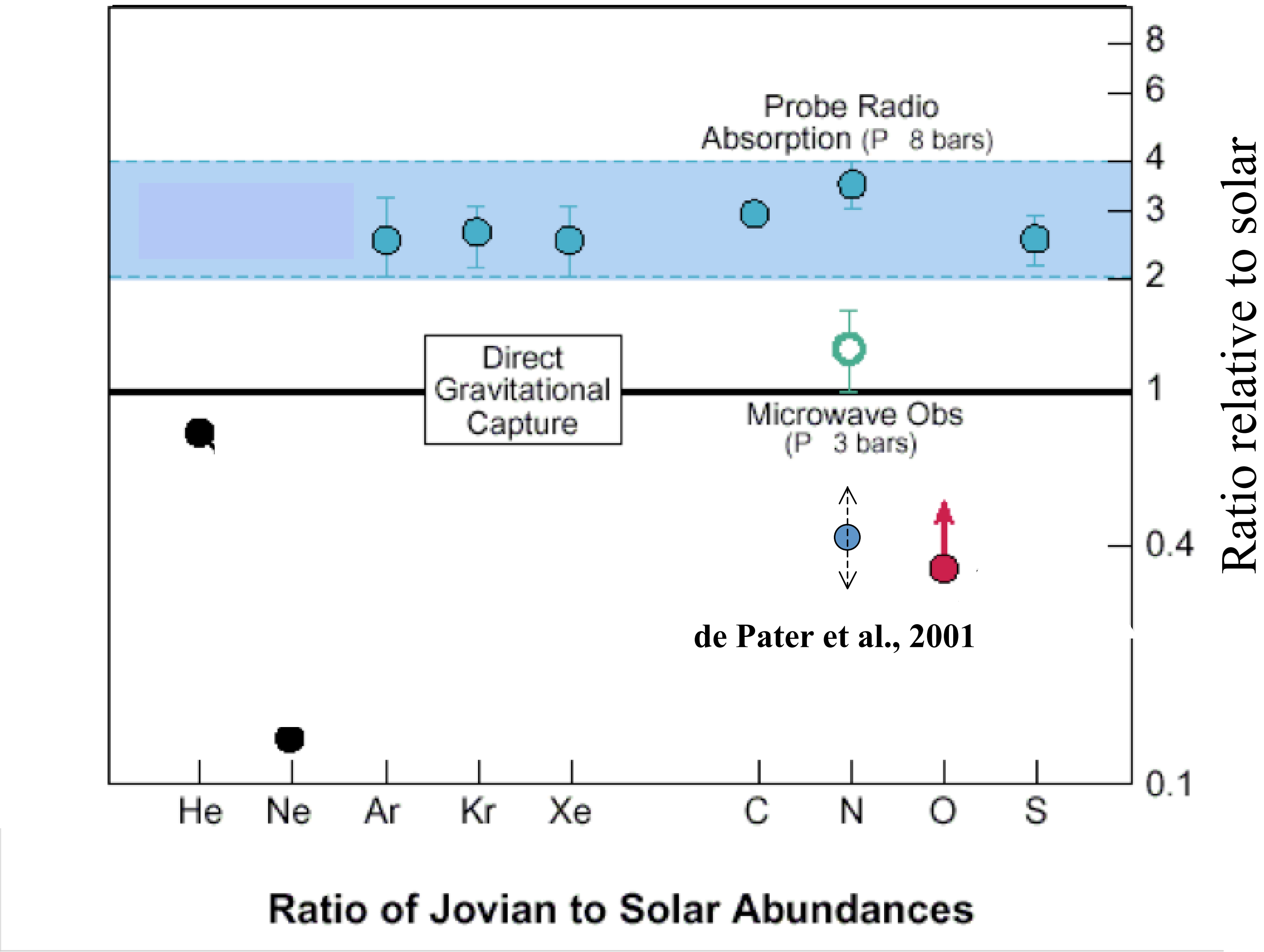


Planet Formation and Evolution
Tübingen, March 2009

Heavy element abundances in Jupiter from Galileo Probe mass spectrometer (Modified from Owen et al. 1999)

(Courtesy of J. Lunine)



Motivation

- Gravitational perturbation of (growing) Jupiter scatters out planetesimals in it vicinity

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If Jupiter was originally of solar composition, it would stay with the same composition

- Abundance of high Z material in Jupiter is several times larger than solar (consistent with atmospheric measurements with Galileo)

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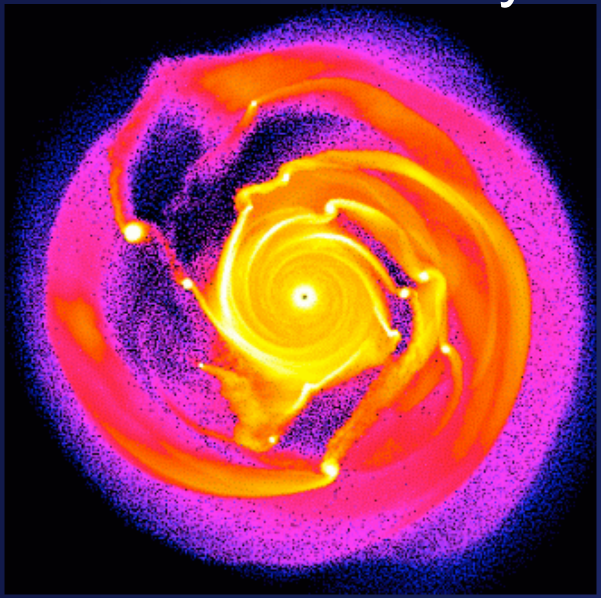
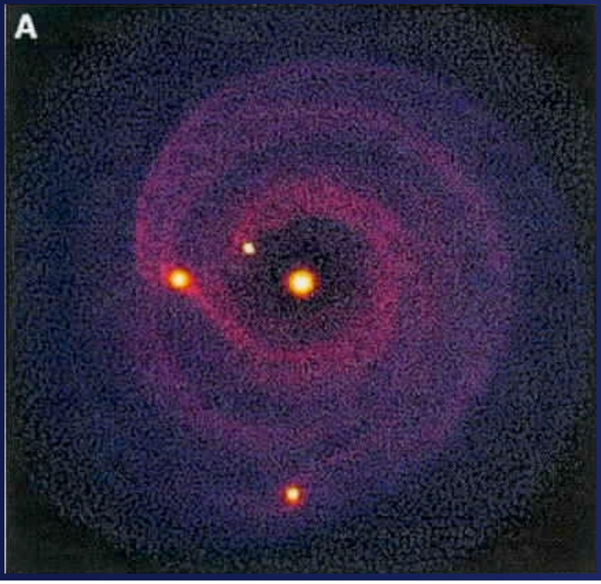
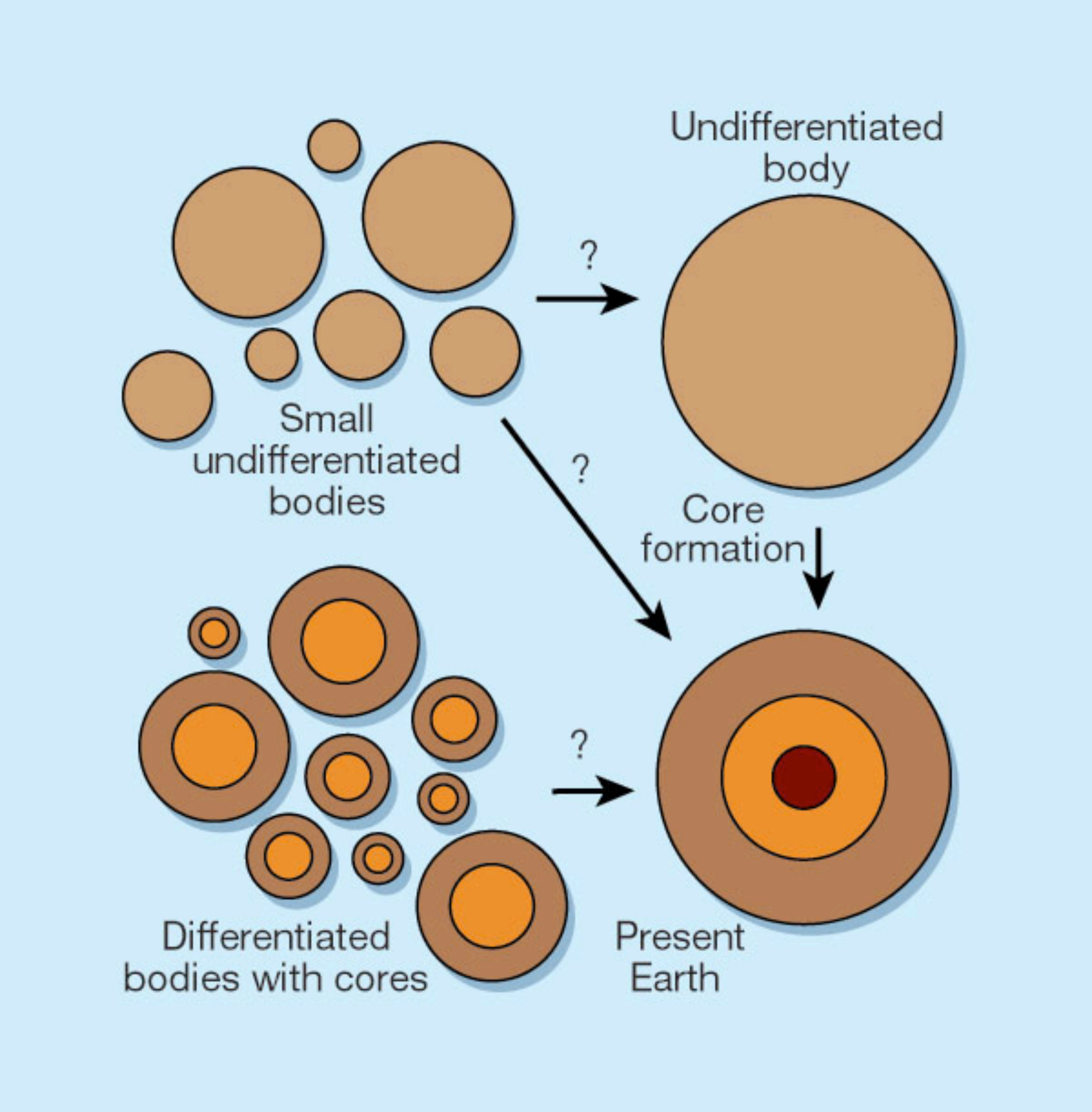
Giant Planet Formation

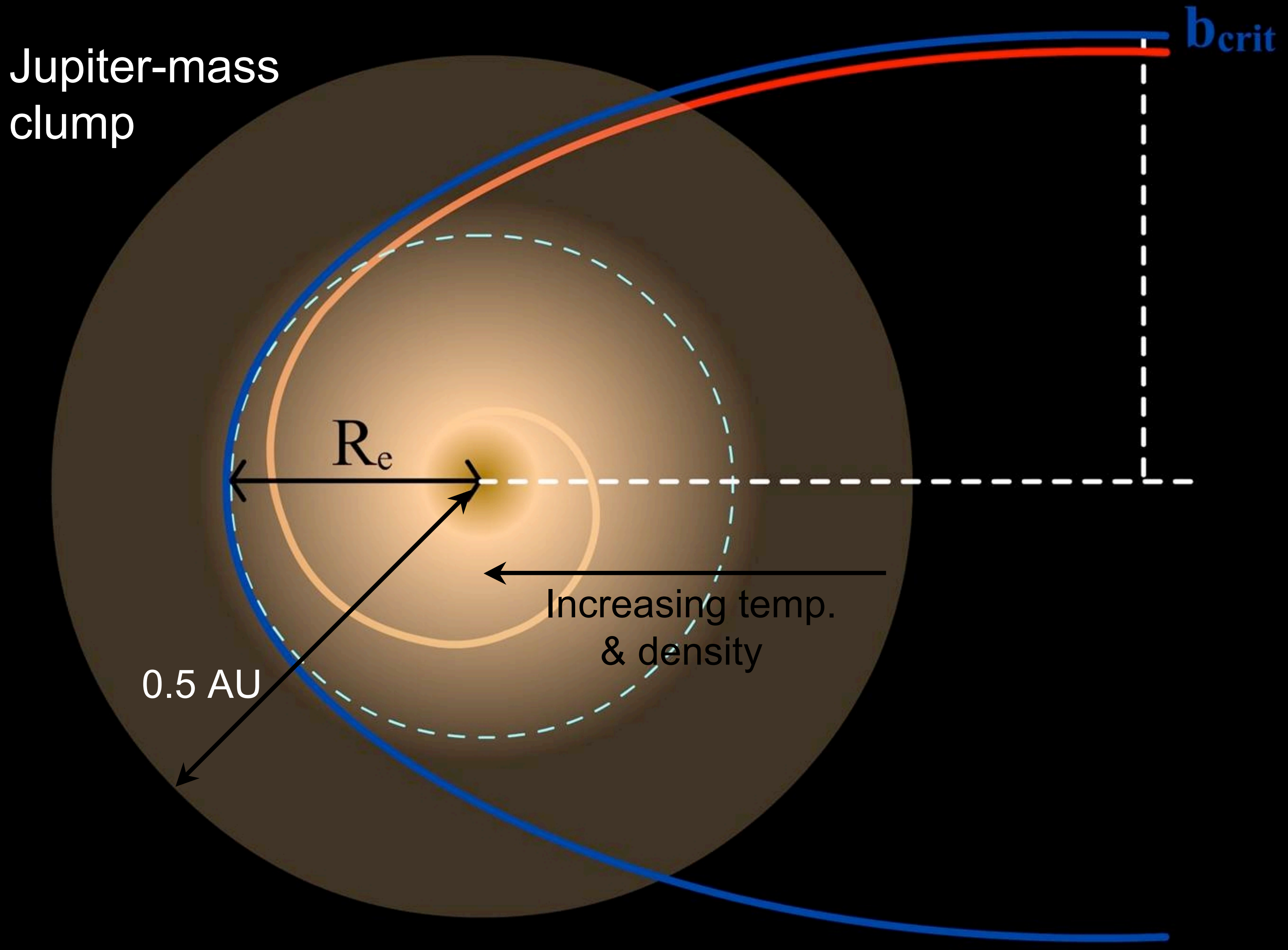
Disk Instability





Core accretion





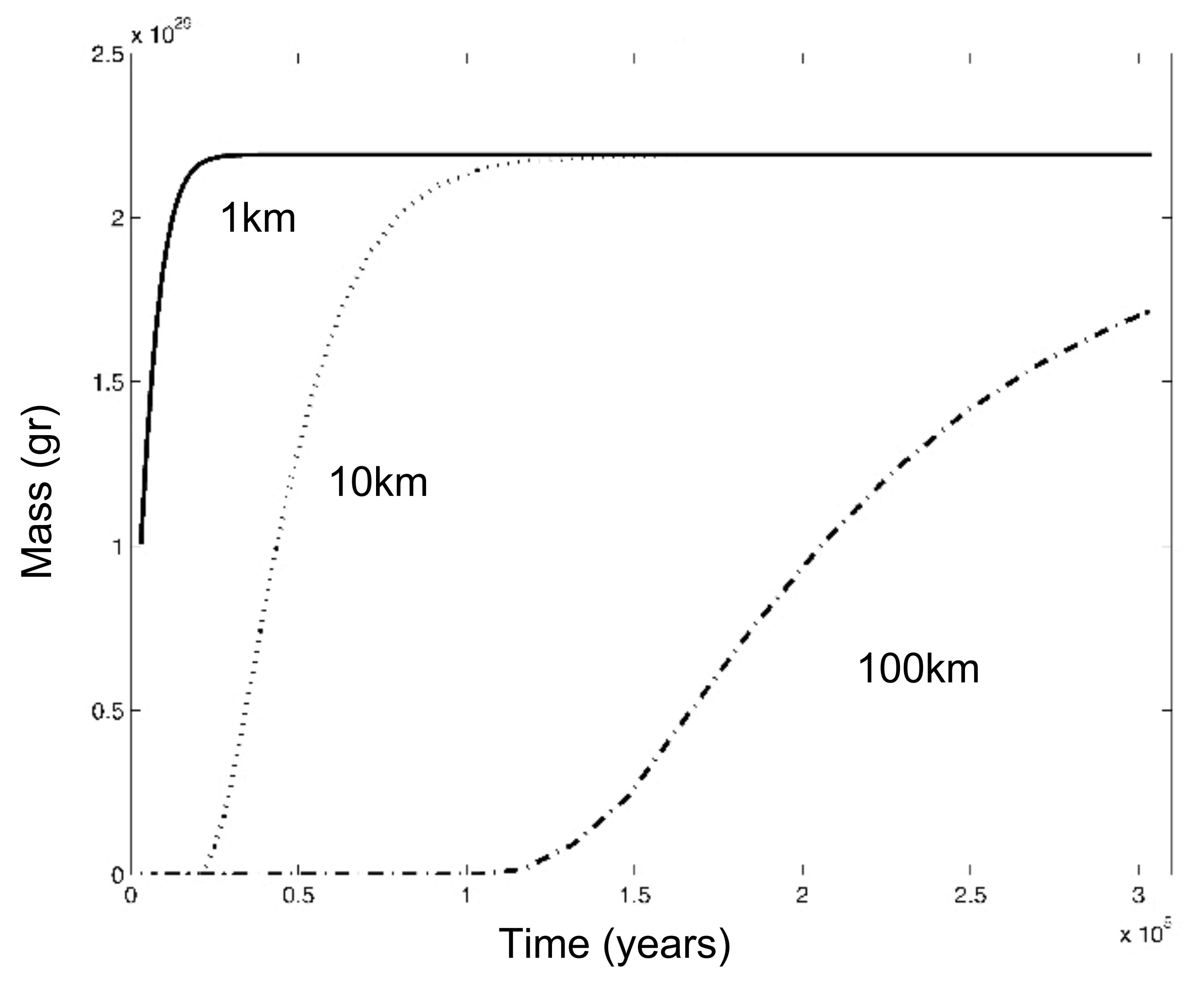
Helled, Podolak, Kovetz (2006)

-Two-body system

- Uniform distribution of planetesimals

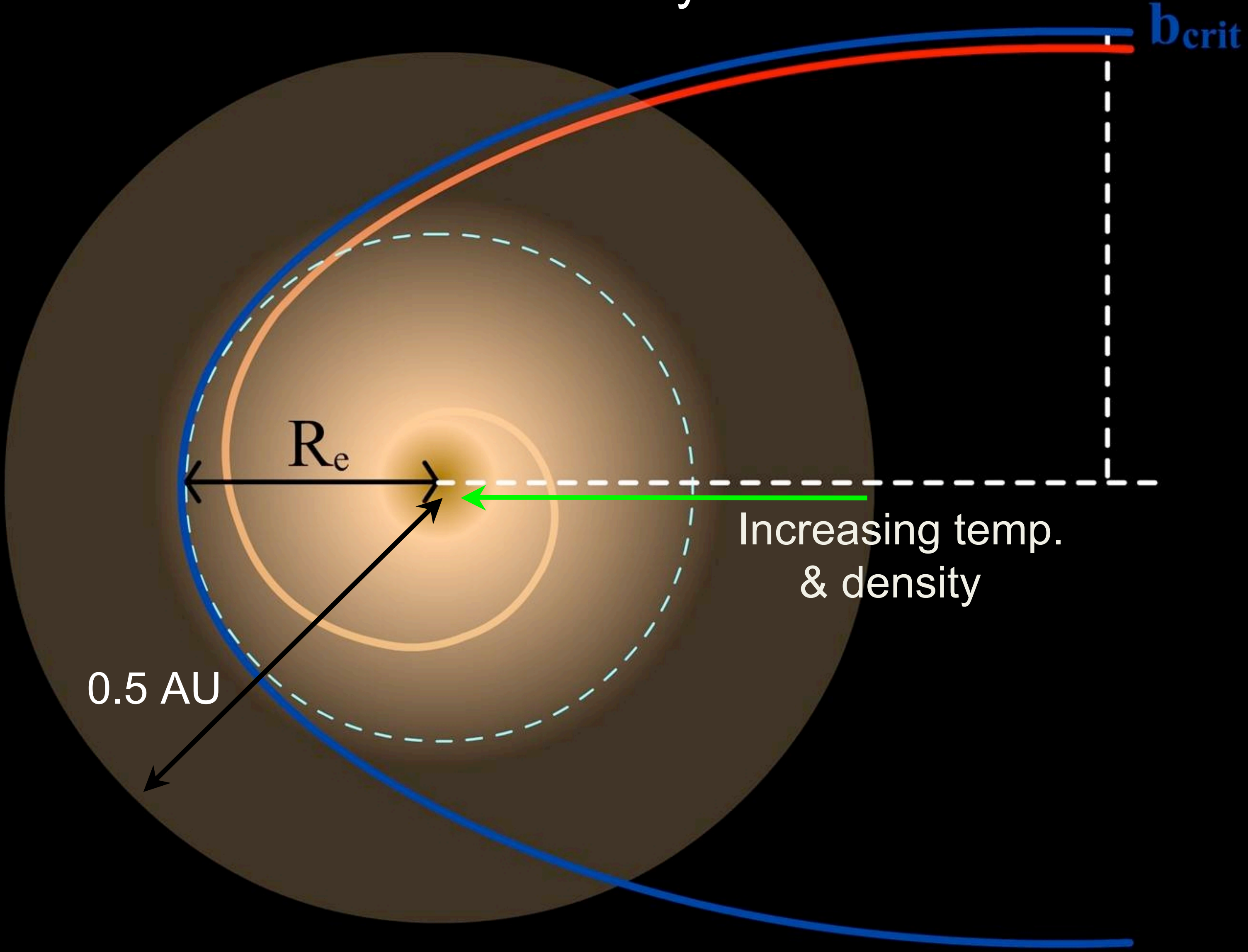
-$V_{\infty} = 1$ km/s

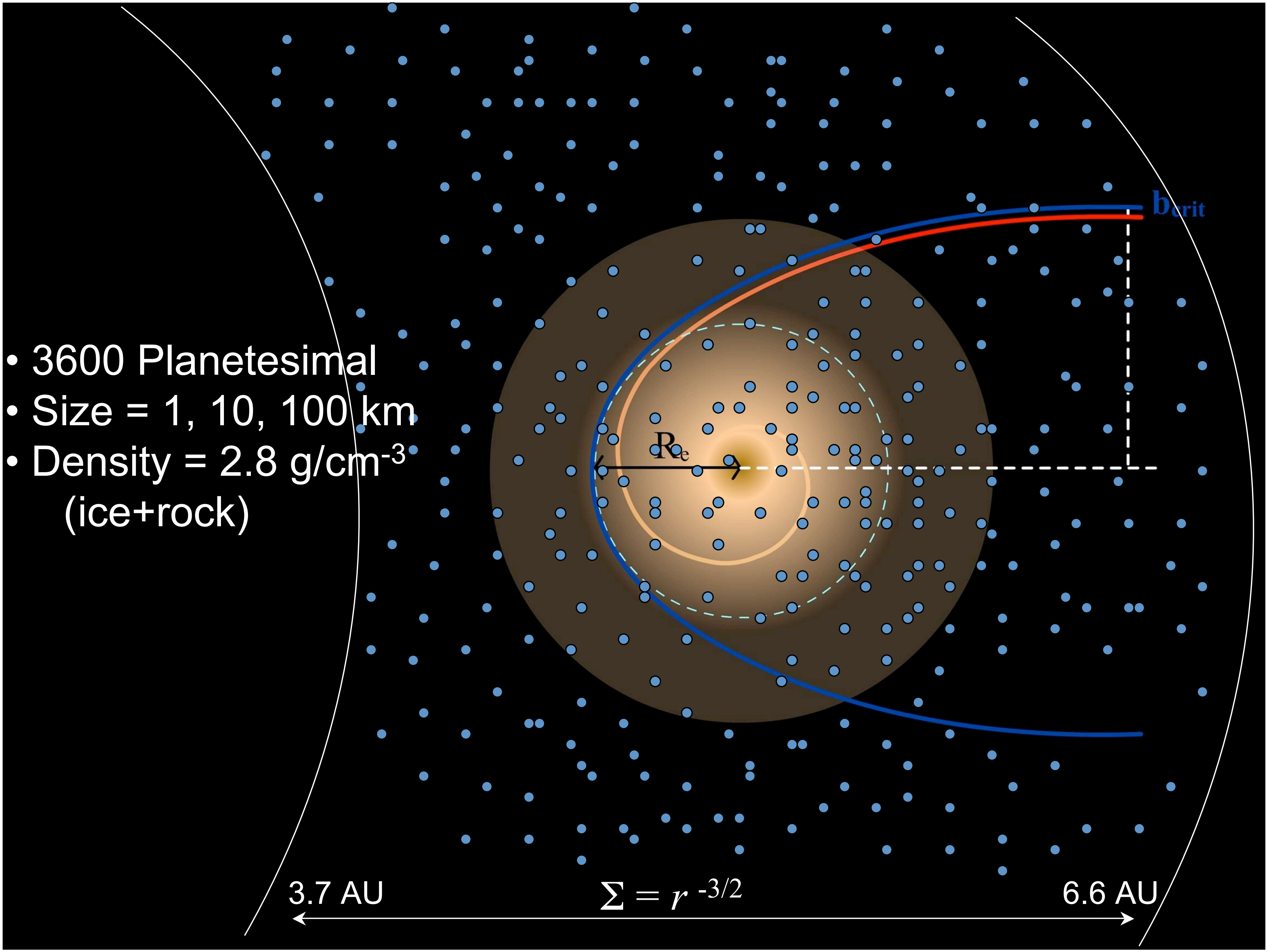
-No planetesimal is ejected.



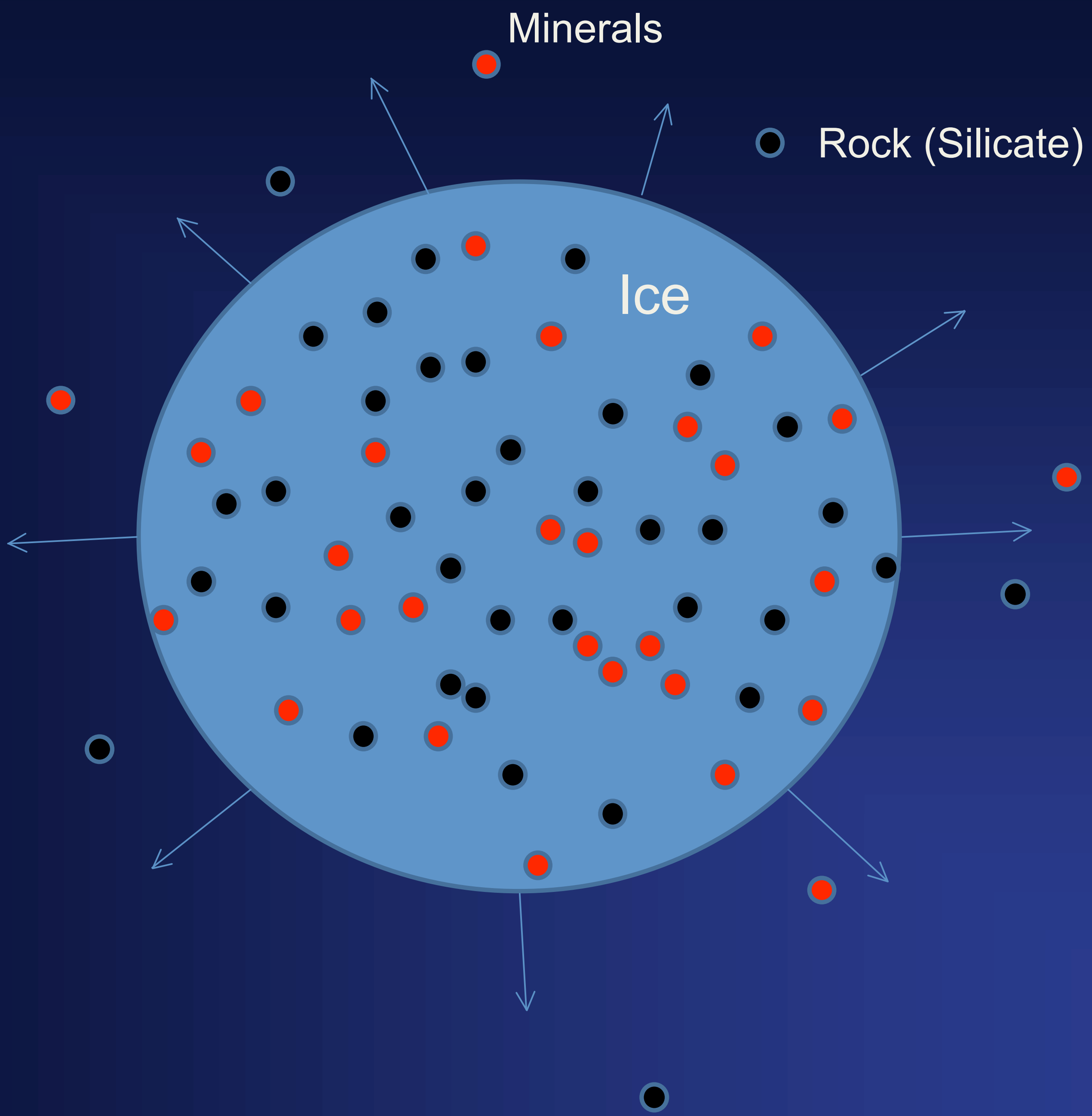
Helled, Podolak, Kovetz (2006)

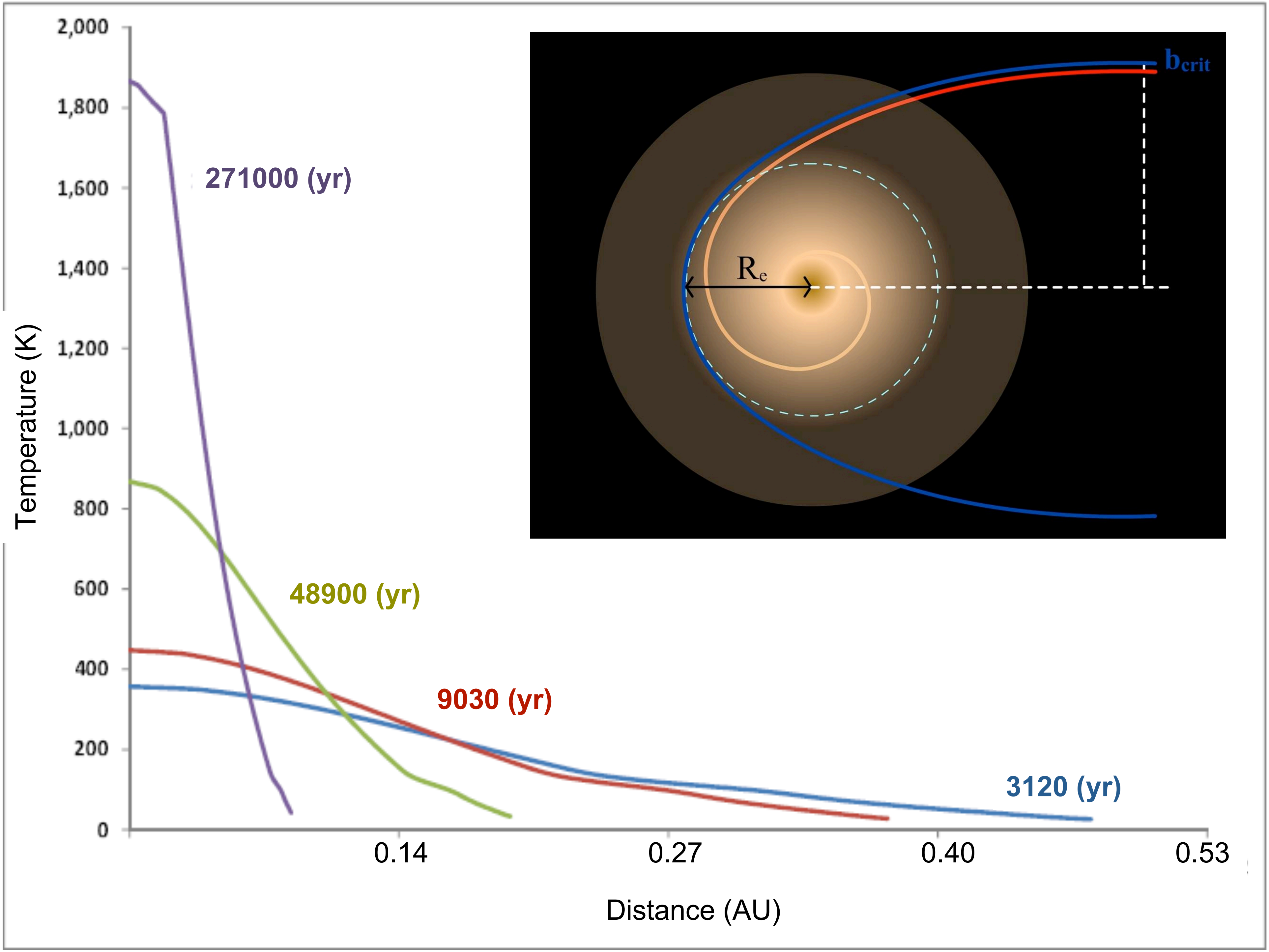
- Jupiter-mass envelope/clump
- Initial radius = 0.5 AU
- Duration of contraction = 2.71 x 10^5 years





- 3600 Planetesimal
- Size = 1, 10, 100 km
- Density = 2.8 g/cm^{-3} (ice+rock)


Minerals
Rock (Silicate)
Ice


271000 (yr)
48900 (yr)
9030 (yr)
3120 (yr)
Temperature (K)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0.14
0.27
0.40
0.53
Distance (AU)
b_{crit}
R_e

Gas Drag

$$F_{Drag} = C_{\mathrm{D}} \frac{1}{2} \pi a^2 \rho v^2$$

C_{D} is the drag coefficient which depends on the Knudsen number, the Reynolds number, and the Mach number.

Aerodynamic Heating

$$E_D = \frac{1}{2} \Im \rho v^3$$

$\Im = C_D/2$ in the limit of large Knudsen number, and in the limit of supersonic flow (for a cap of shock-heated gas). We assume this is approximately true everywhere.

Dynamical Breakup

$$P_{dyn} = \frac{1}{2}\rho v^2$$

(Ram Pressure)

If this pressure exceeds the compressional strength of the material it will fracture unless held together by self-gravity.

$$a_{dyn} = \sqrt{\frac{5v^2\rho}{8\pi\rho_b^2 G}}$$

Heating

- Aerodynamic heating
- Radiation from ambient atmosphere

$$E_D = \frac{1}{2}\Im\rho v^3$$

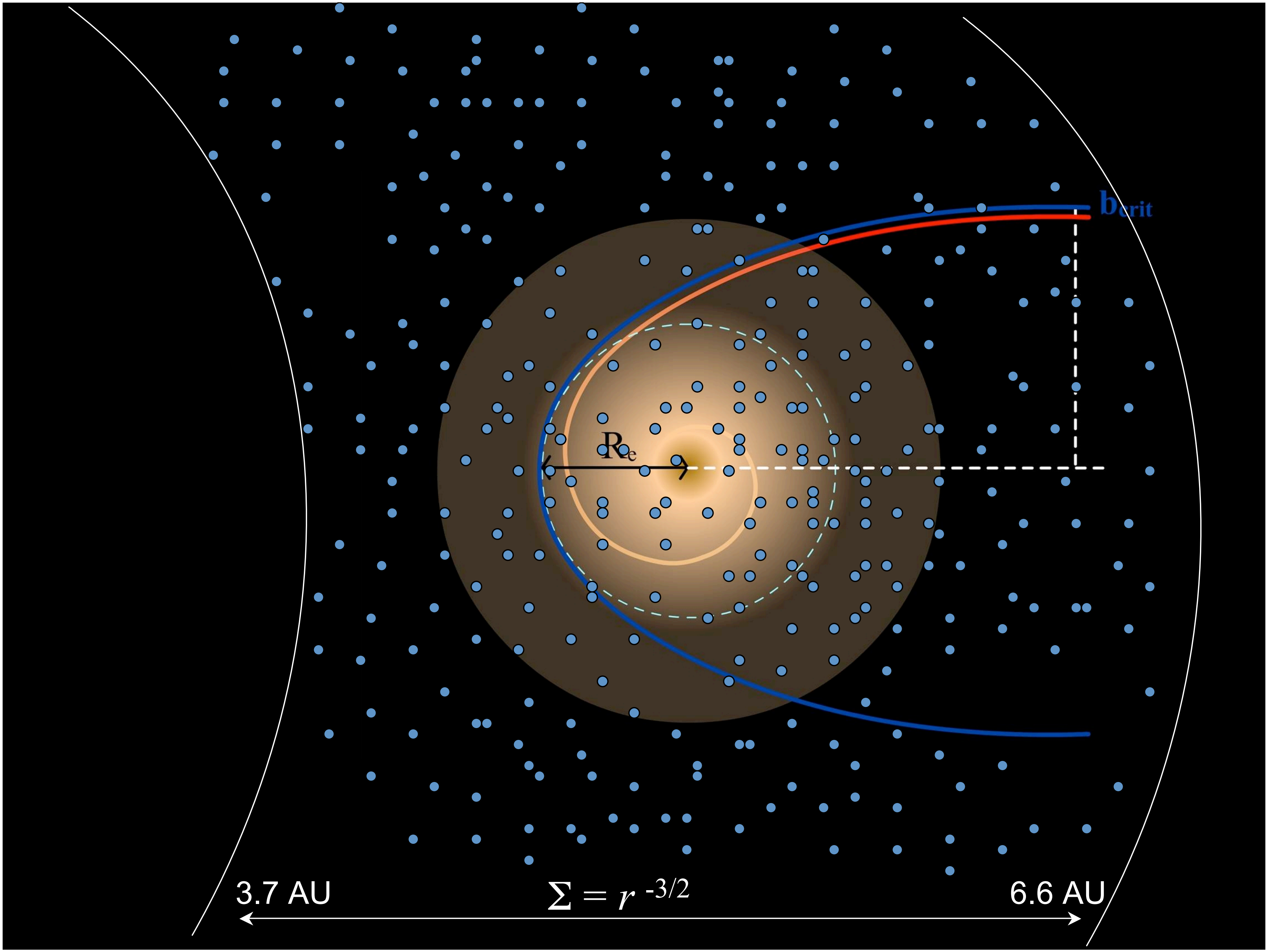
$$E_{atm} = \sigma T_{atm}^4$$

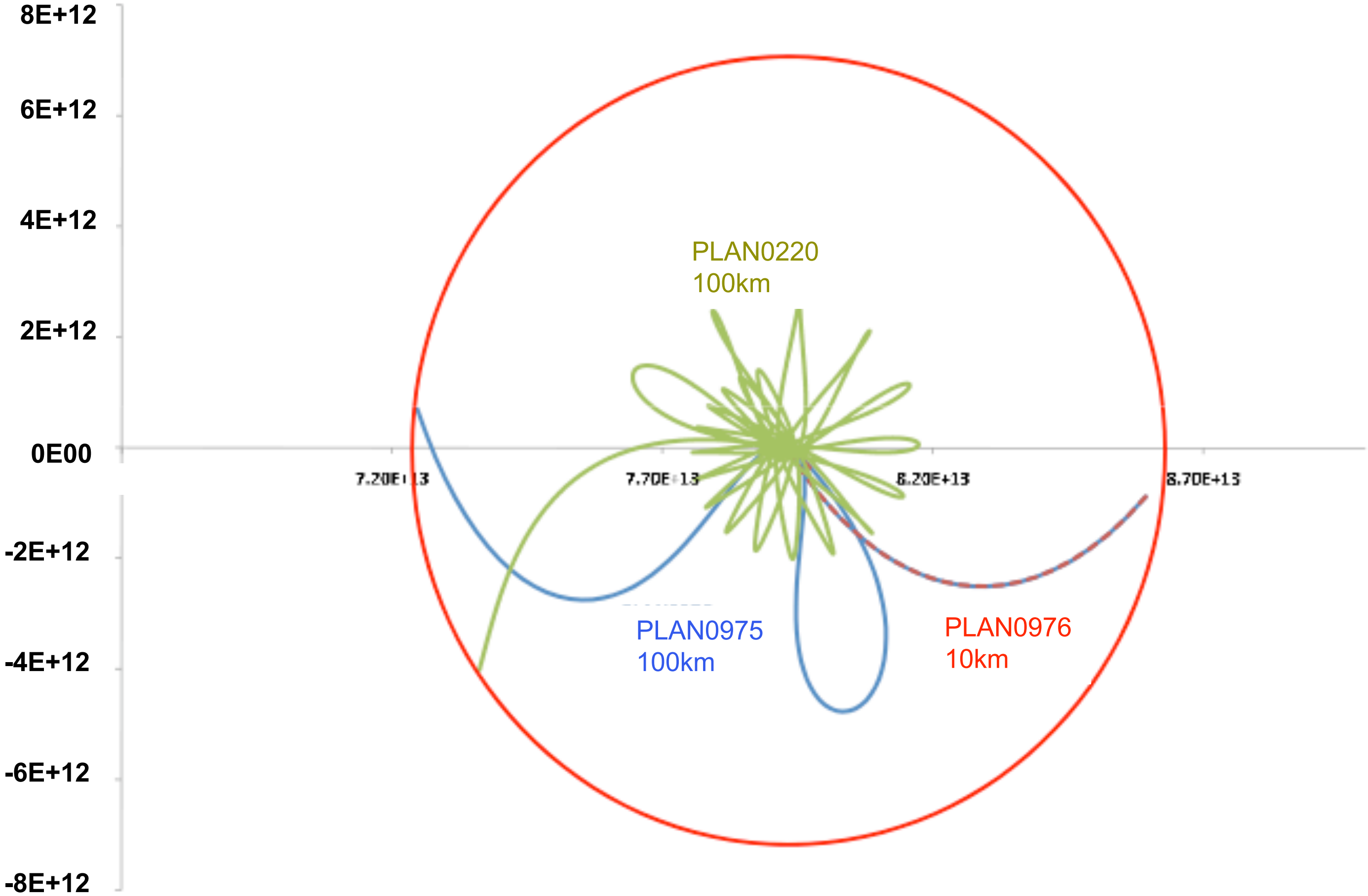
Cooling

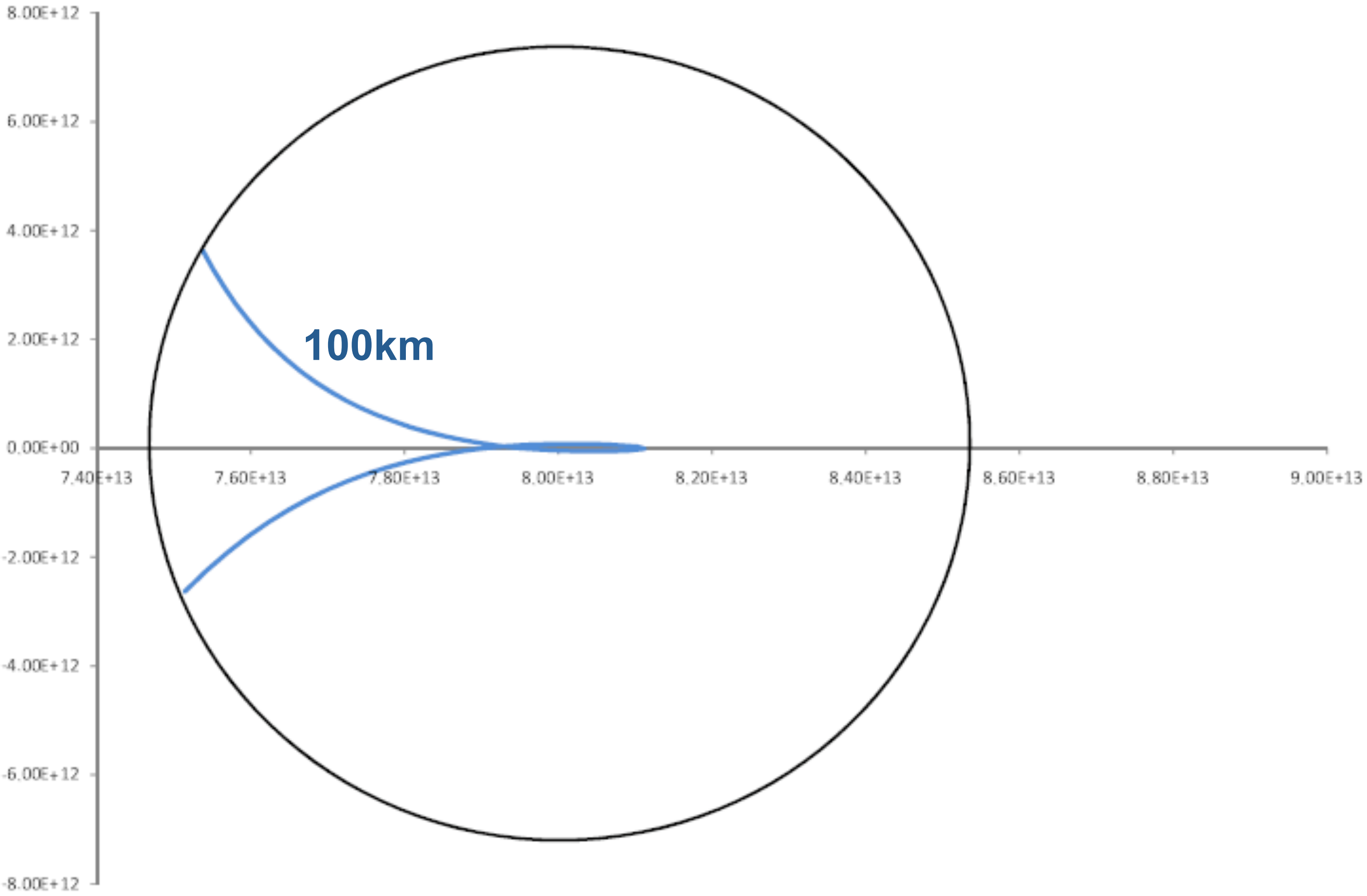
- Radiative cooling
- Evaporative cooling

$$E_{rad} = \sigma T_{surf}^4$$

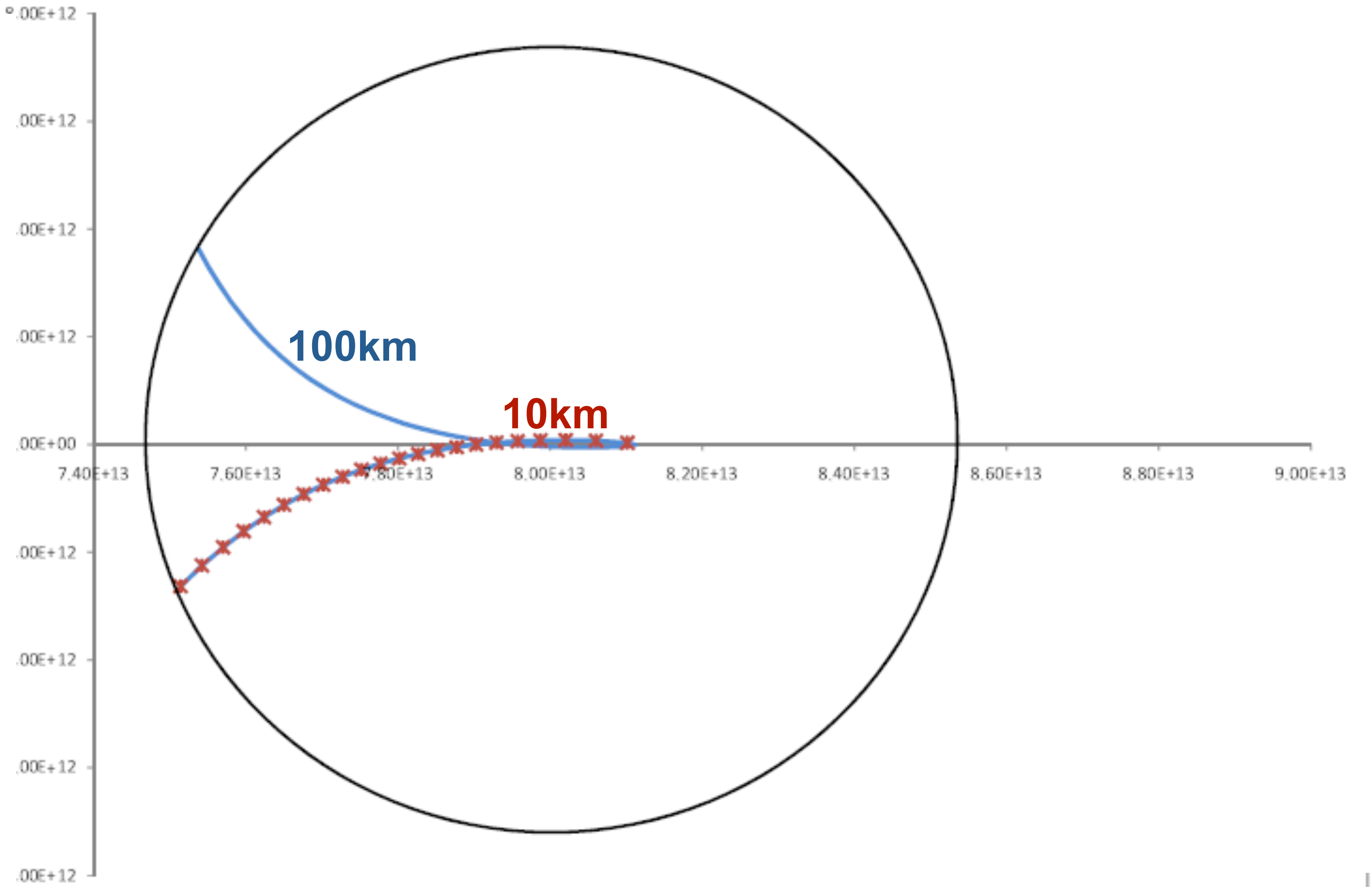
$$E_{vap} = qP_{vap}(T_{surf})\sqrt{\frac{\mu}{2\pi N_A k T_{surf}}}$$

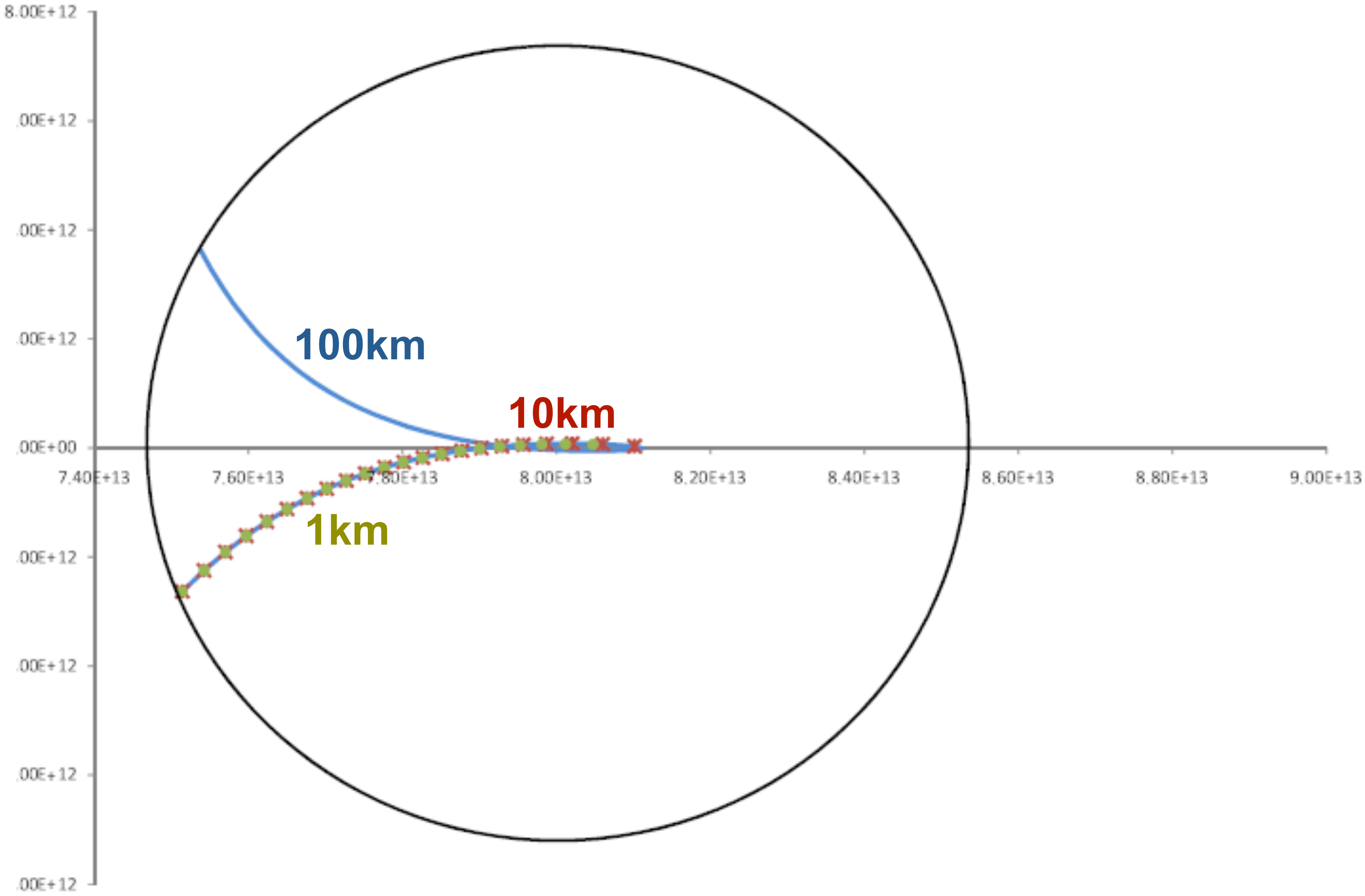

b_{crit}
R_e
3.7 AU
$\Sigma = r^{-3/2}$
6.6 AU

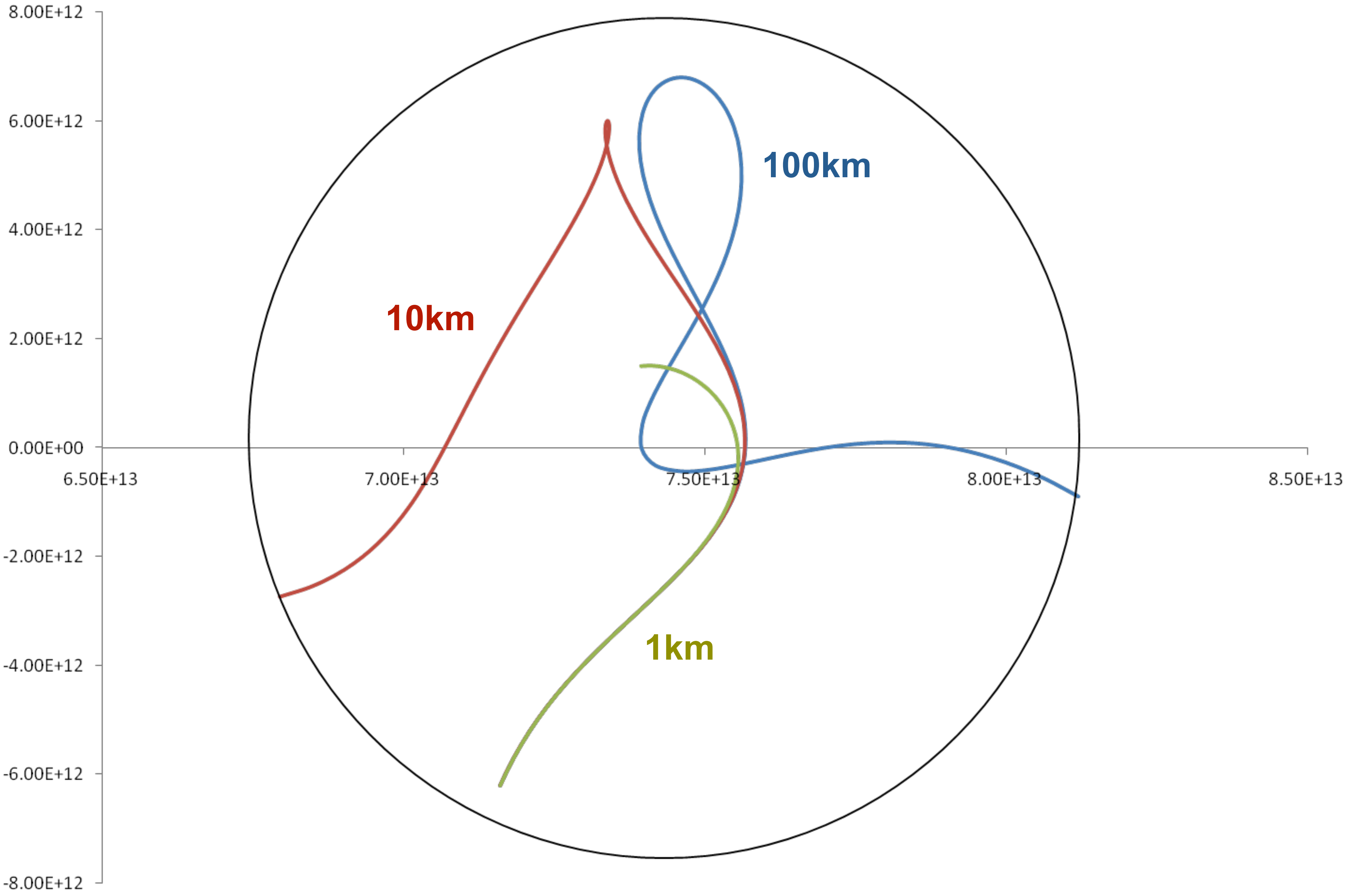

8E+12
6E+12
4E+12
2E+12
0E00
-2E+12
-4E+12
-6E+12
-8E+12
7.20E+13
7.70E+13
8.20E+13
8.70E+13
PLAN0220
100km
PLAN0975
100km
PLAN0976
10km

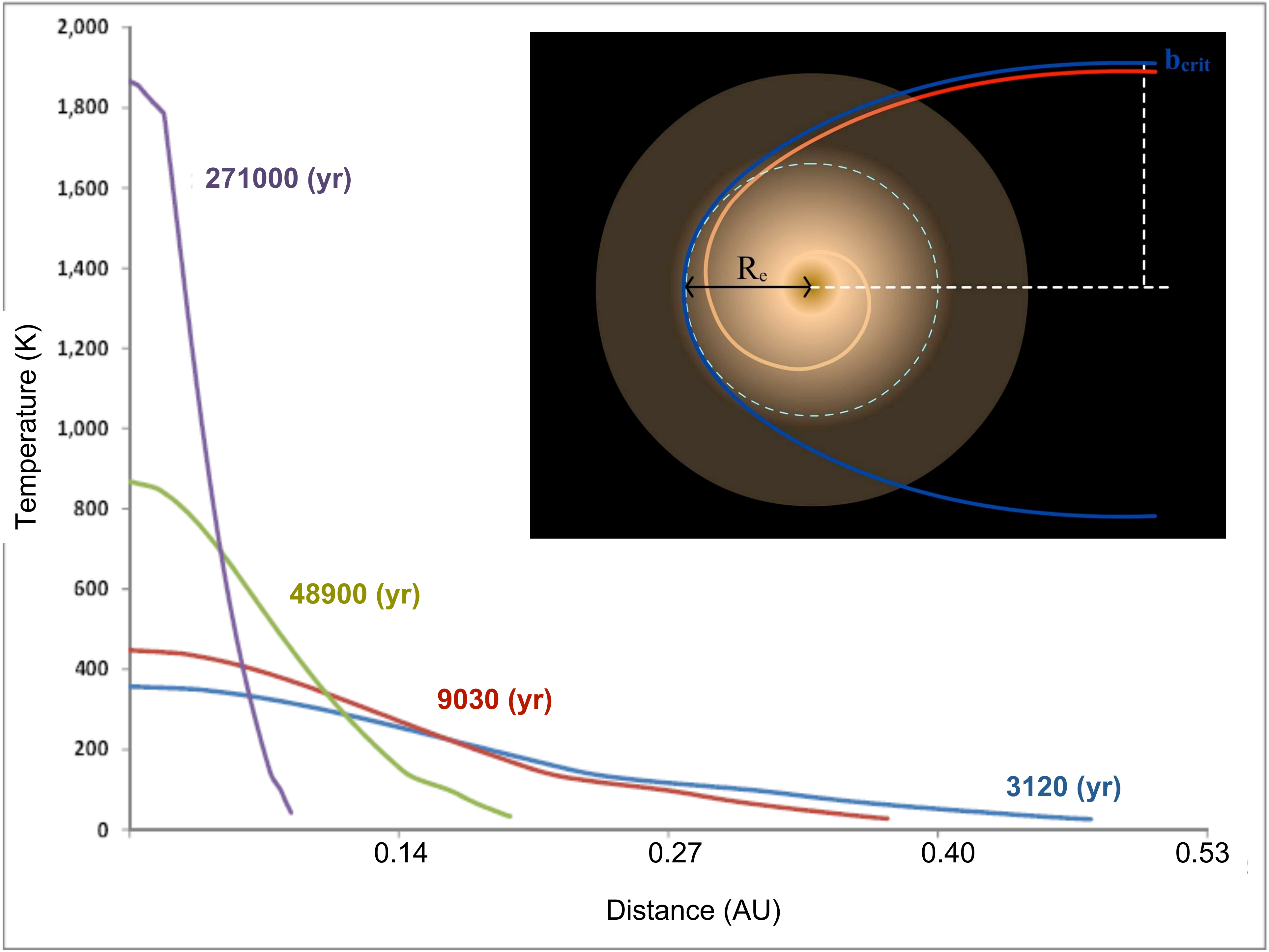


8.00E+12
6.00E+12
4.00E+12
2.00E+12
0.00E+00
-2.00E+12
-4.00E+12
-6.00E+12
-8.00E+12
7.40E+13
7.60E+13
7.80E+13
8.00E+13
8.20E+13
8.40E+13
8.60E+13
8.80E+13
9.00E+13
100km

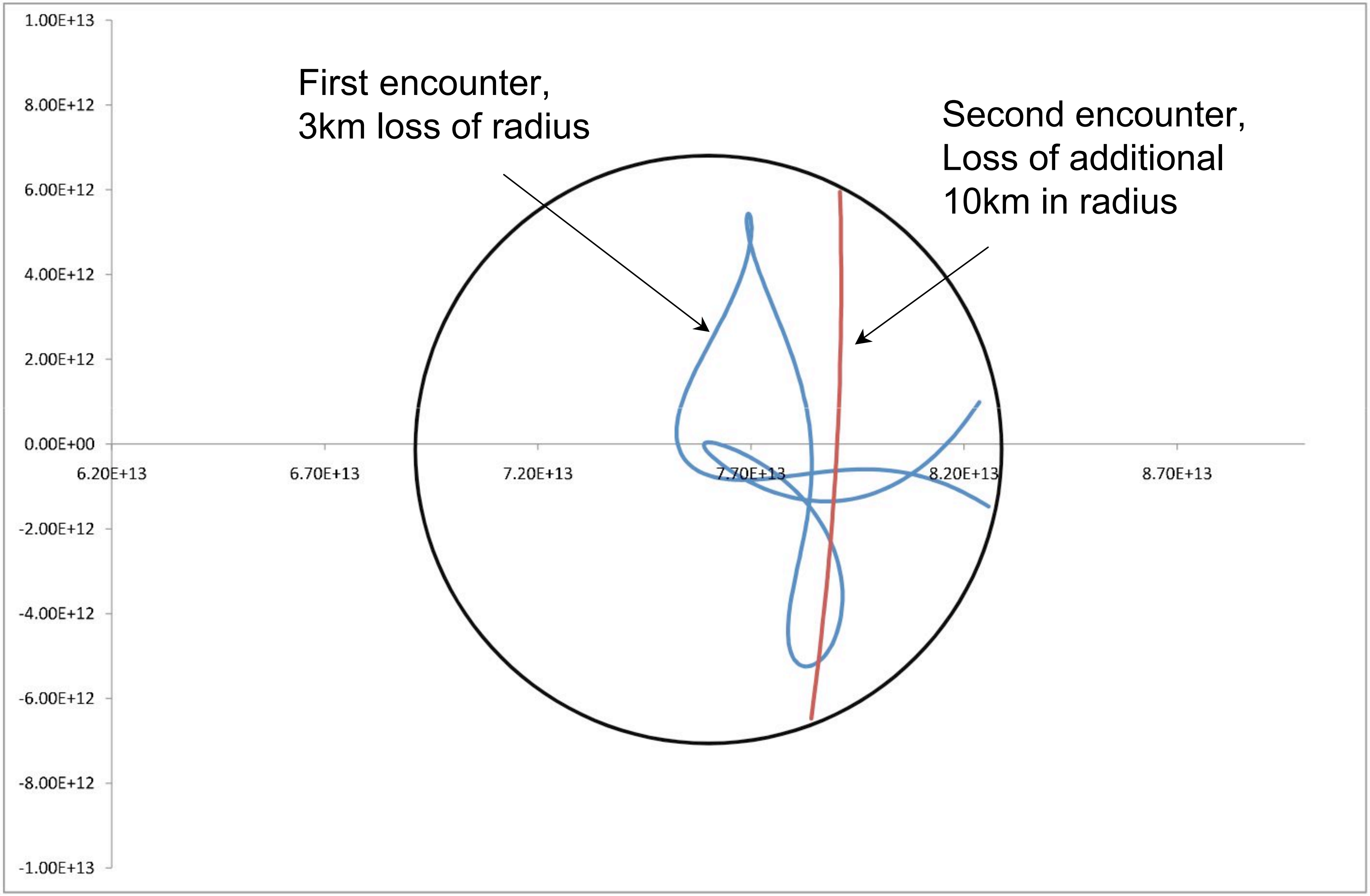

.00E+12
.00E+12
.00E+12
.00E+12
.00E+00
.00E+12
.00E+12
.00E+12
.00E+12
7.40E+13
7.60E+13
7.80E+13
8.00E+13
8.20E+13
8.40E+13
8.60E+13
8.80E+13
9.00E+13
100km
10km


8.00E+12
.00E+12
.00E+12
.00E+12
.00E+00
.00E+12
.00E+12
.00E+12
.00E+12
7.40E+13
7.60E+13
7.80E+13
8.00E+13
8.20E+13
8.40E+13
8.60E+13
8.80E+13
9.00E+13
100km
10km
1km


8.00E+12
6.00E+12
4.00E+12
2.00E+12
0.00E+00
-2.00E+12
-4.00E+12
-6.00E+12
-8.00E+12
6.50E+13
7.00E+13
7.50E+13
8.00E+13
8.50E+13
100km
10km
1km

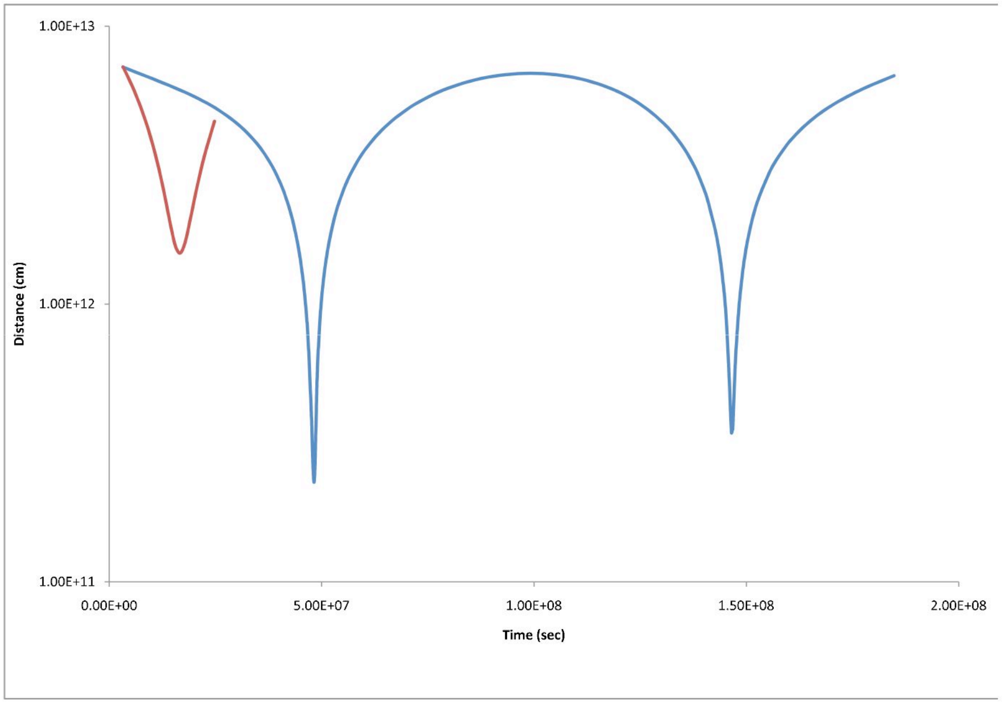

2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Temperature (K)
271000 (yr)
48900 (yr)
9030 (yr)
3120 (yr)
0.14
0.27
0.40
0.53
Distance (AU)
b_{crit}
R_e

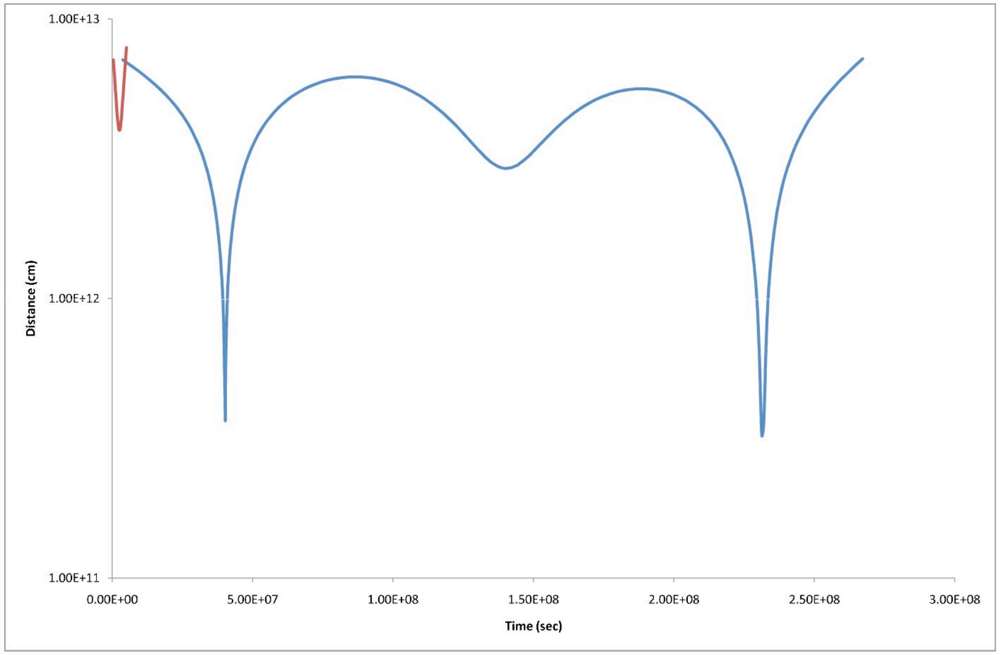
100km Planetesimal



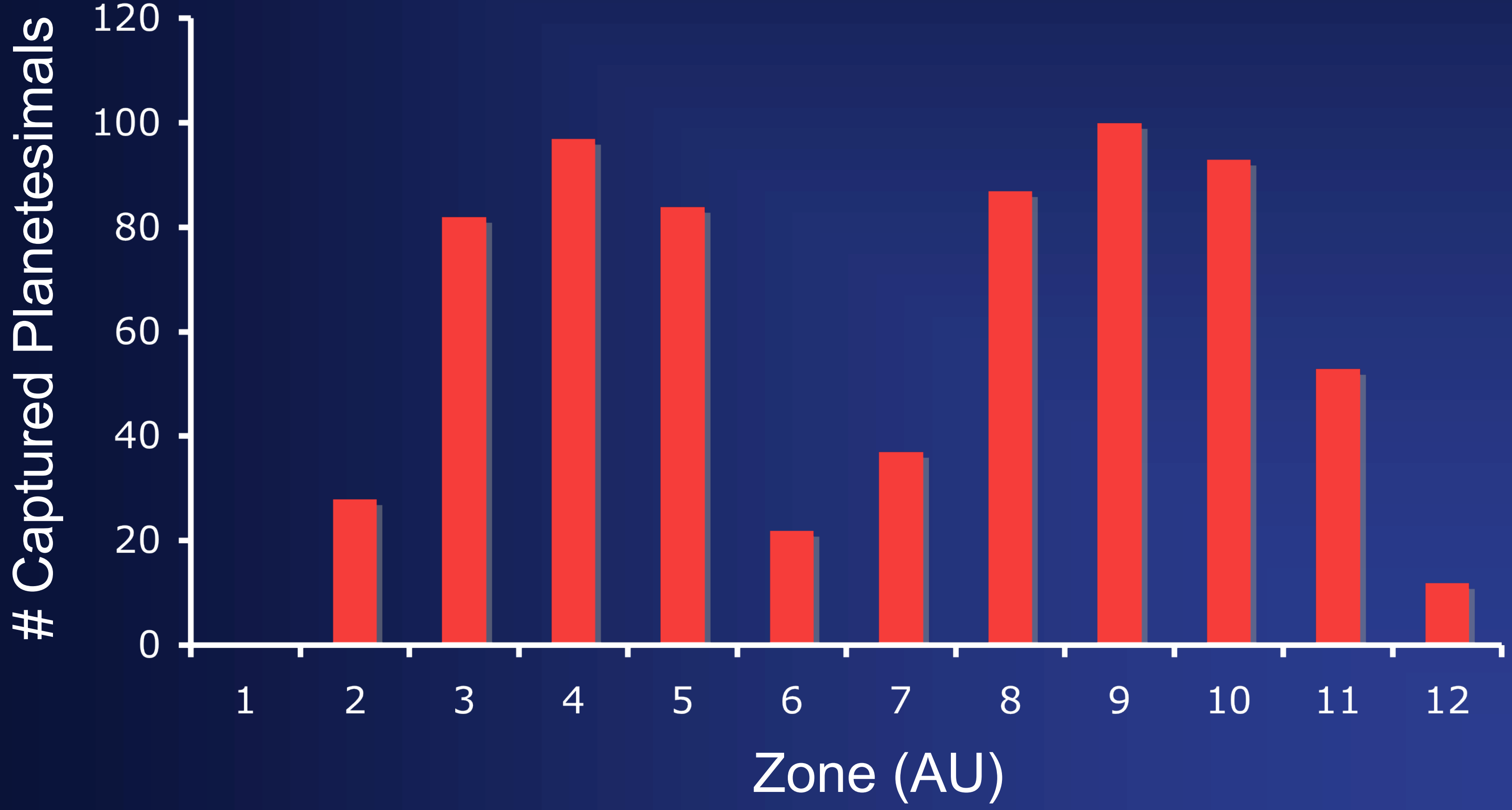
First encounter,
3km loss of radius

Second encounter,
Loss of additional
10km in radius


1.00E+13
1.00E+12
1.00E+11
Distance (cm)
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
Time (sec)


1.00E+13
1.00E+12
1.00E+11
Distance (cm)
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
2.50E+08
3.00E+08
Time (sec)

1= 3.73 - 3.98
2= 3.98 - 4.23
3= 4.23 - 4.48
4= 4.48 - 4.73
5= 4.73 - 4.98
6= 4.98 - 5.23
7= 5.23 - 5.48
8= 5.48 - 5.73
9= 5.73 - 5.98
10= 5.98 - 6.23
11= 6.23 - 6.48
12= 6.48 - 6.66



Gas Drag

$$F_{Drag} = C_{\mathrm{D}} \frac{1}{2} \pi a^2 \rho v^2$$

Density

Velocity relative to gas

Drag force of the gas is larger on objects with higher densities and larger velocities relative to the gas.

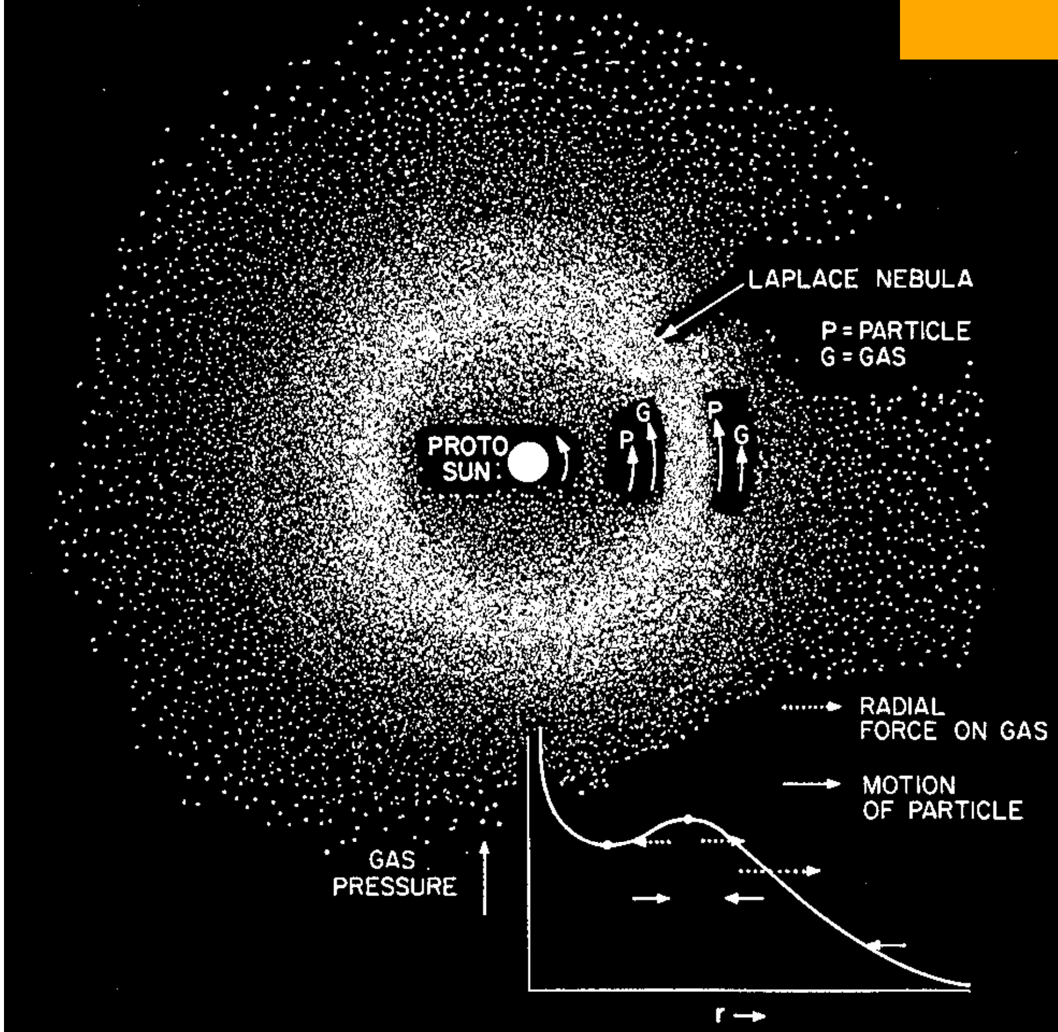
Gas angular frequency

Gas Pressure

$$r\omega_g^2 = r\omega_K^2 + \frac{1}{\rho_g(\vec{R})}\frac{\partial P_g(\vec{R})}{\partial r}$$

Keplerian frequency

Gas density



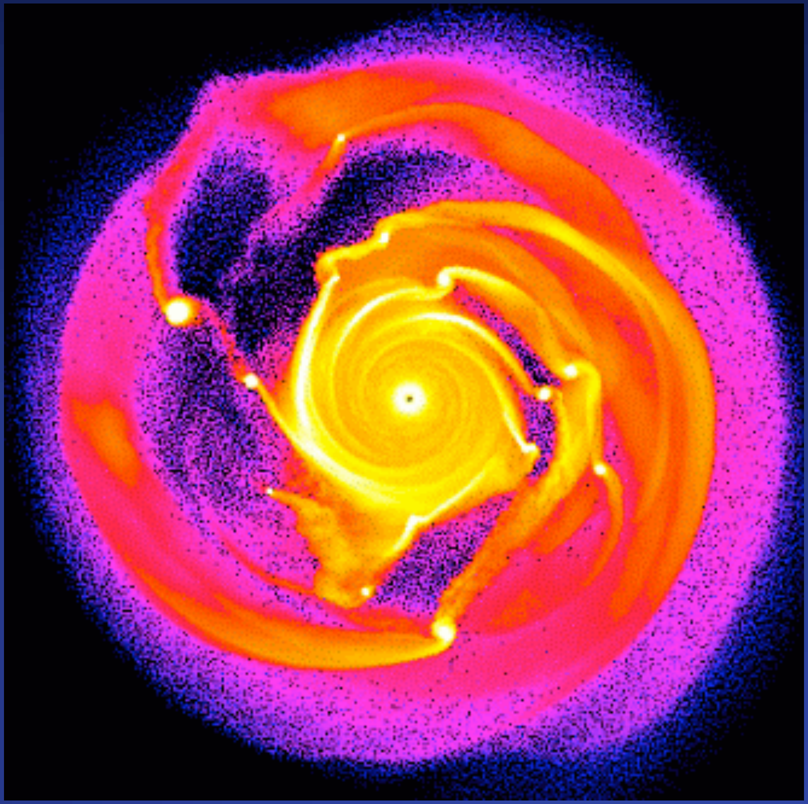
Objects outside the maximum pressure feel a headwind and spiral toward the star, whereas objects inside feel a tailwind and spiral out.

Self-Gravitating Disks

-Pressure gradient changes sign across spiral structures.

-Dust grains/small planetesimals can drift both inwards and outwards (Haghighipour & Boss 2003)

-Net effect: Solid object approach the center of the structures.



Conclusions

- Smaller planetesimals are captured in shorter times

- Multiple passages of larger planetesimals through the envelope results in more capture and more mass deposit

- Accumulation of high density planetesimals around gas-pressure structures in the envelope enhances the rate of the capture of these objects.