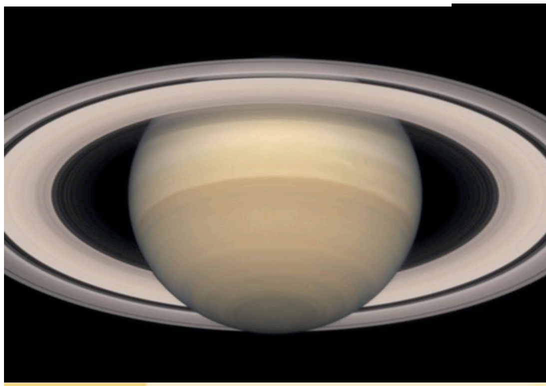
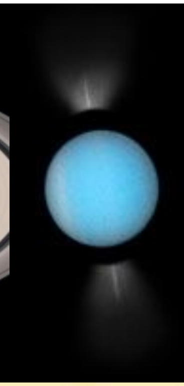
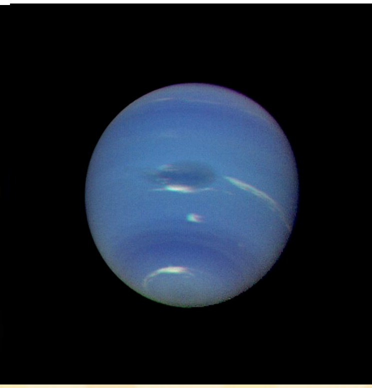
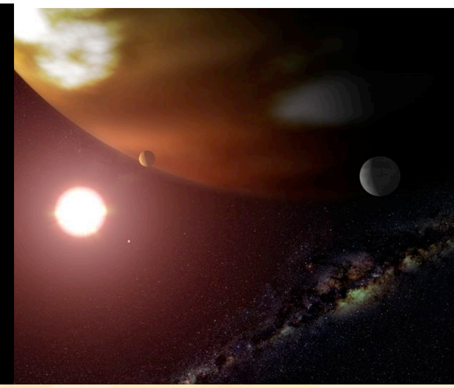
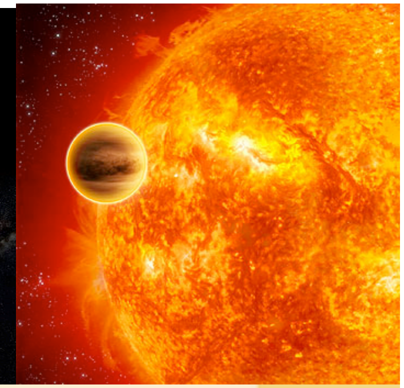
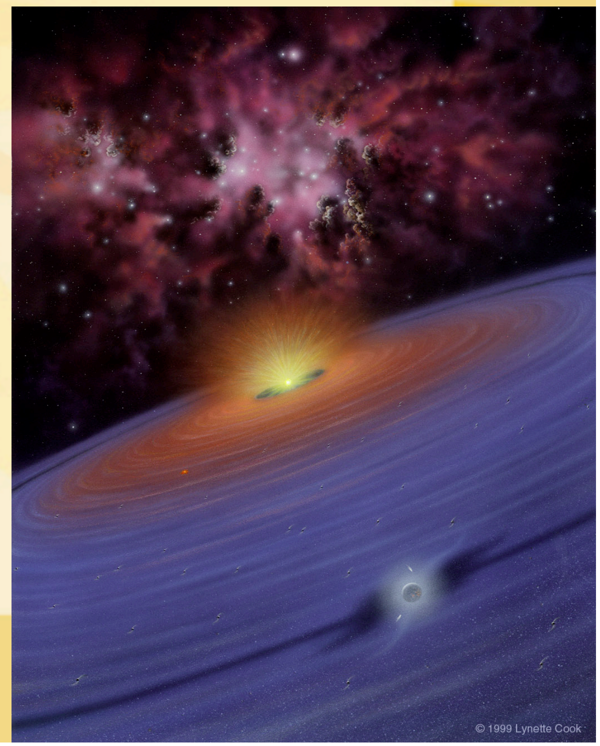
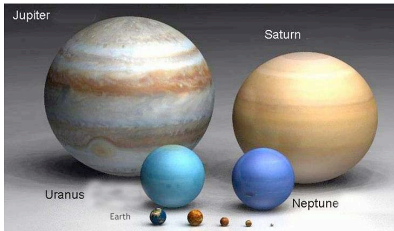
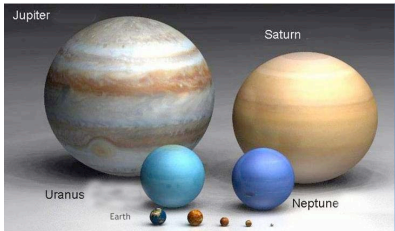






Giant Planet Formation
via Core-Nucleated Accretion

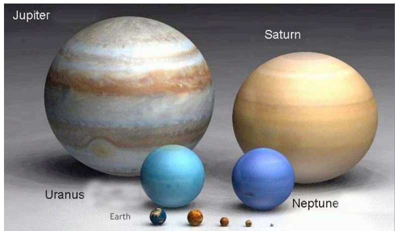
Jack J. Lissauer
NASA Ames



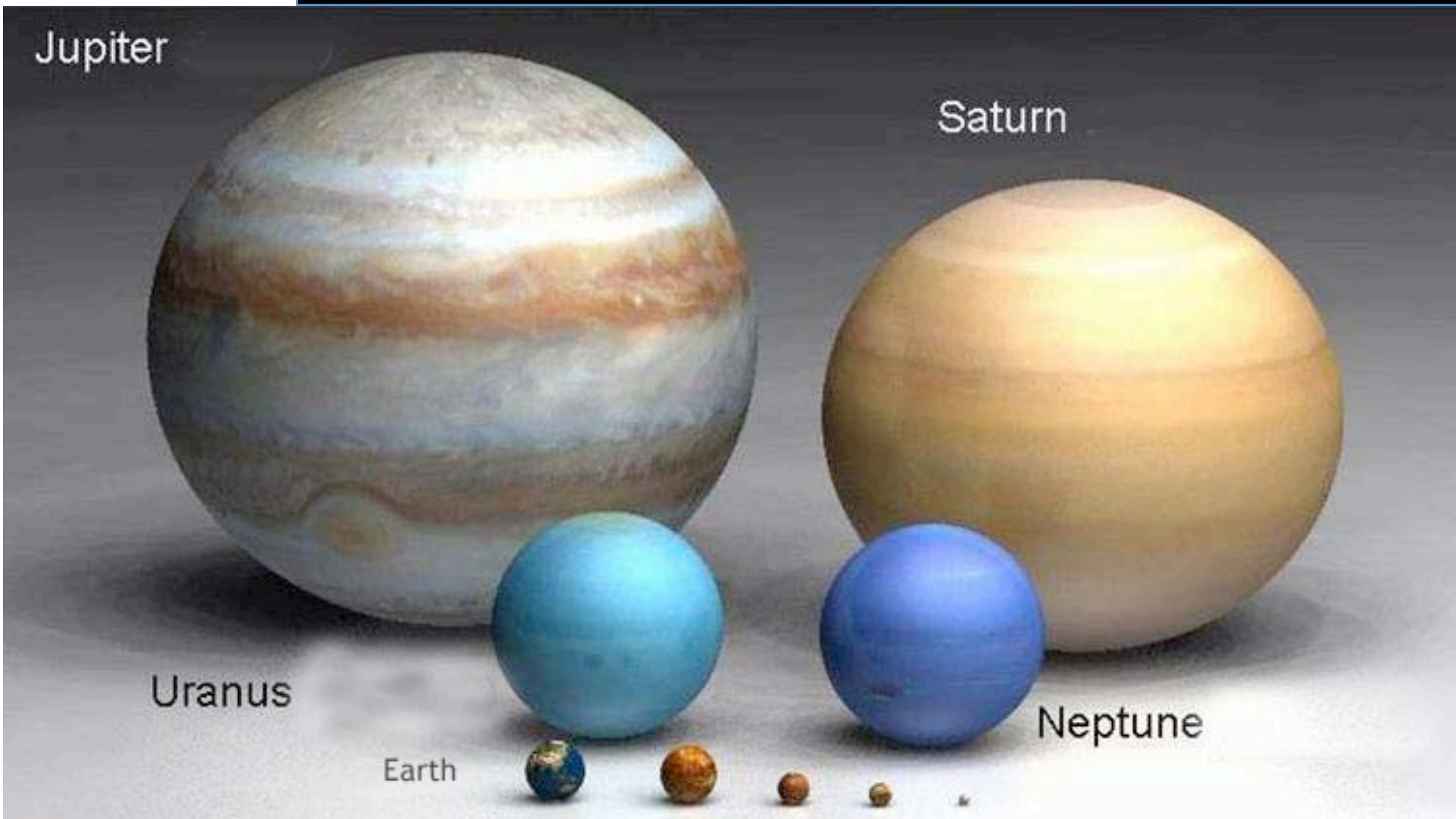

Jupiter
Saturn
Uranus
Neptune
Earth

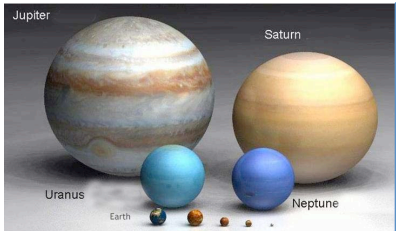


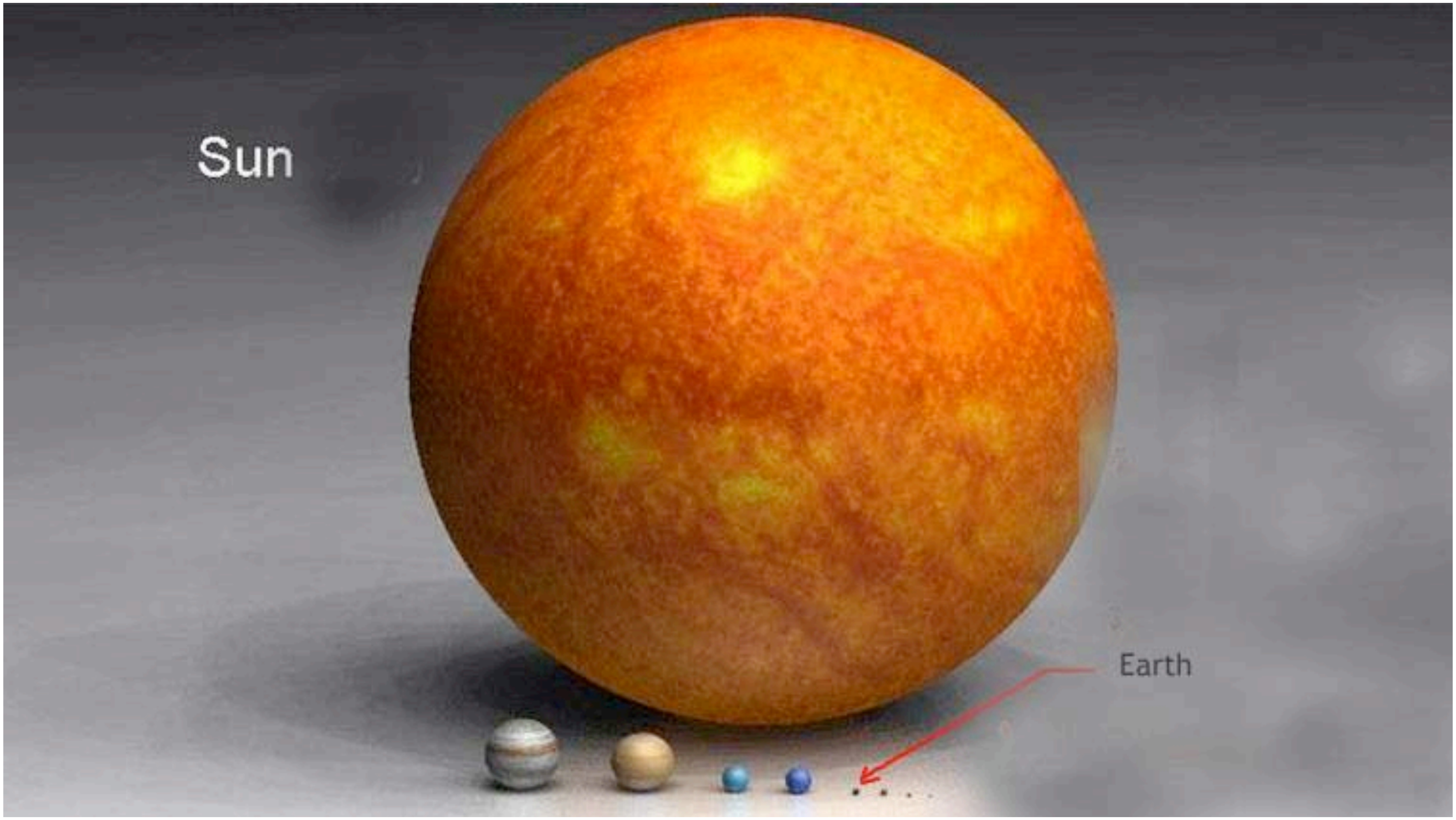
– Largest bodies most gas-rich

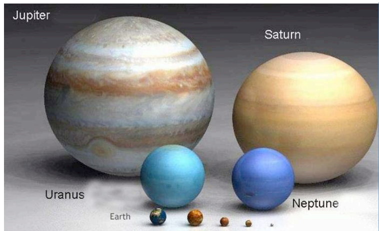

Jupiter
Saturn
Uranus
Neptune
Earth

[redacted]

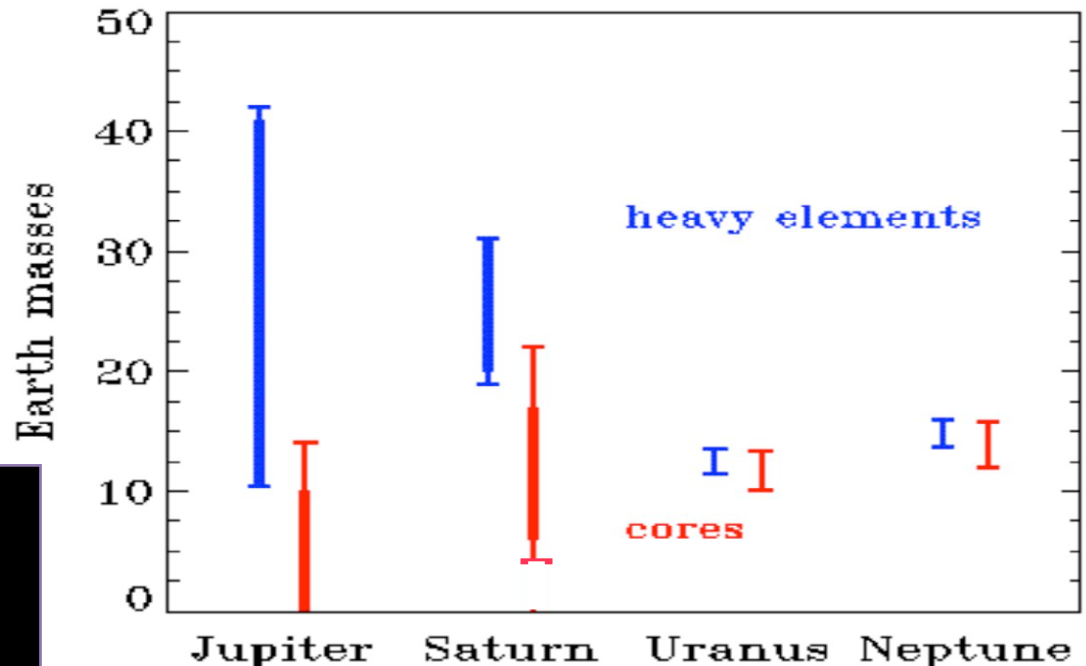

Jupiter
Saturn
Uranus
Neptune
Earth


Jupiter
Saturn
Uranus
Neptune
Earth


Sun
Earth

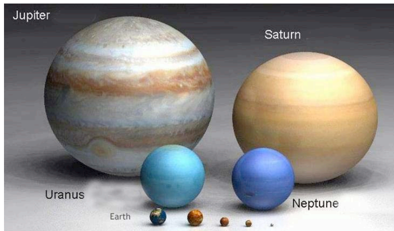


Core total heavy element



[redacted]

[redacted]

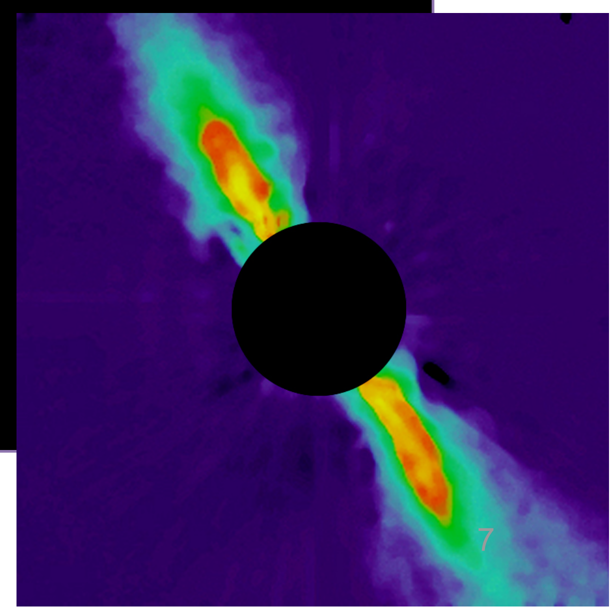


[redacted]

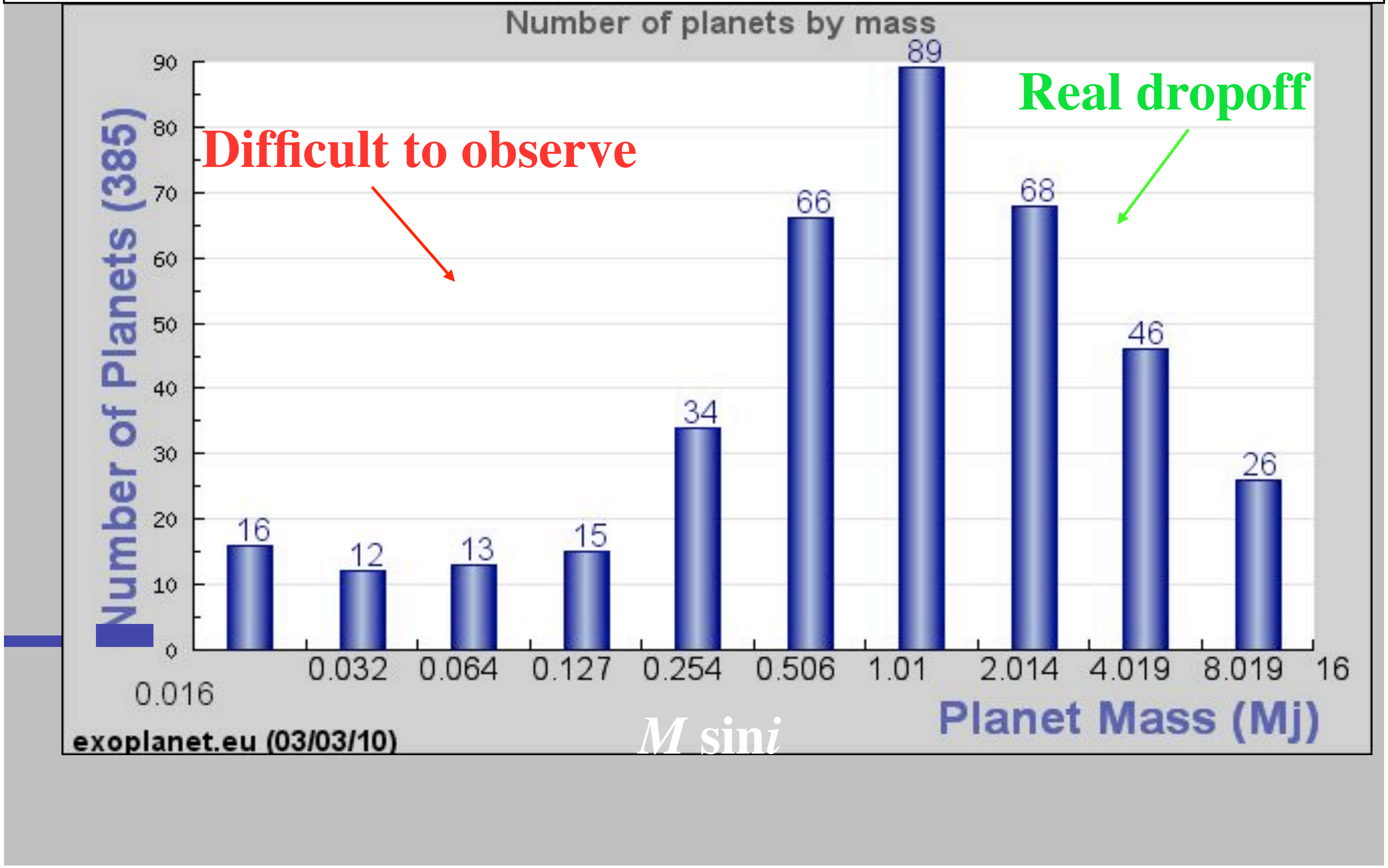
[redacted]

– **Typical mass ~ 0.01 - 0.1 M_{Sun}**
– **Lifetime (dust) < 10 Myr**

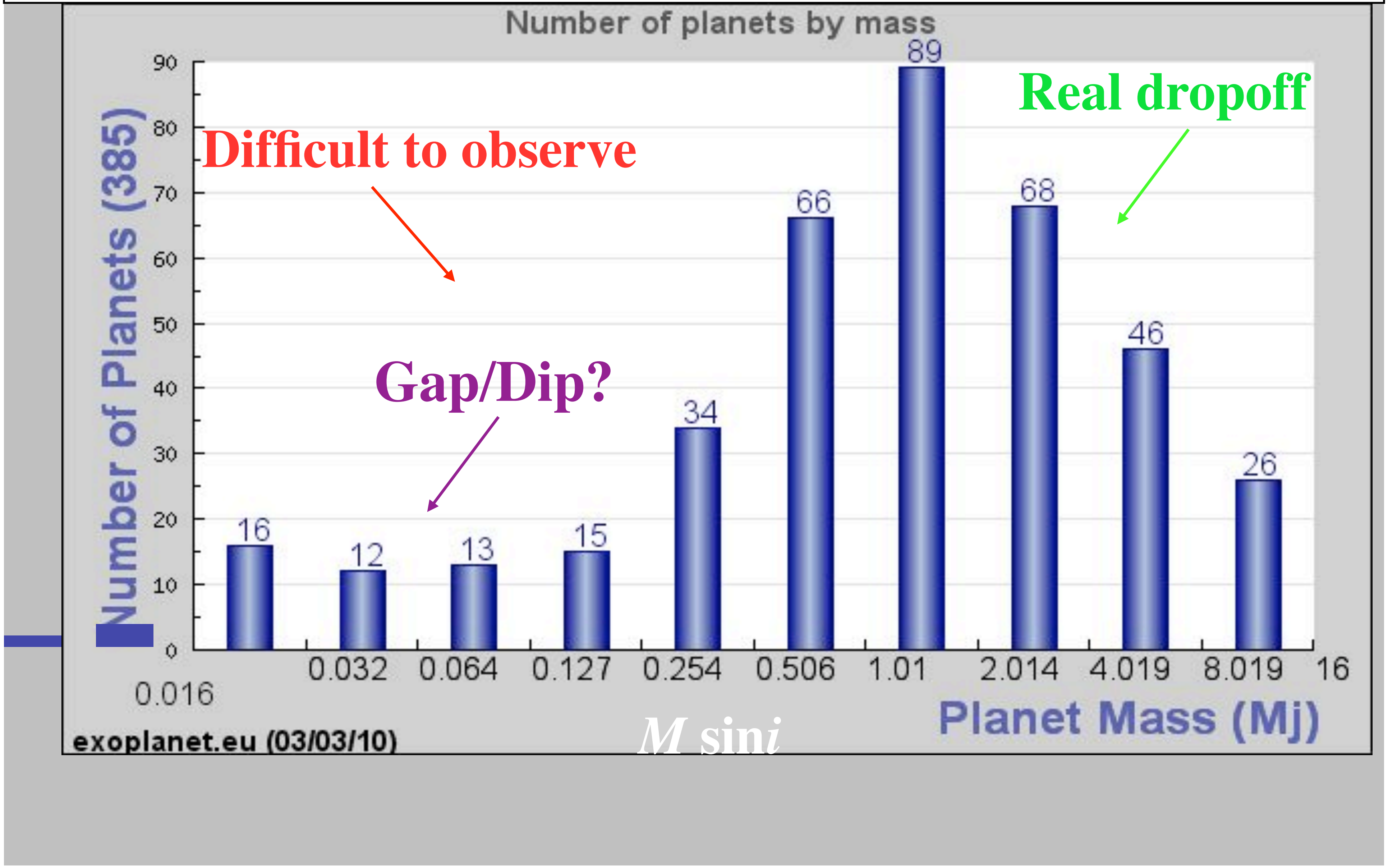
[redacted]

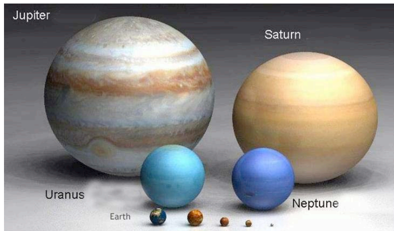


Mass Distribution of Planets
Detected by Doppler Method

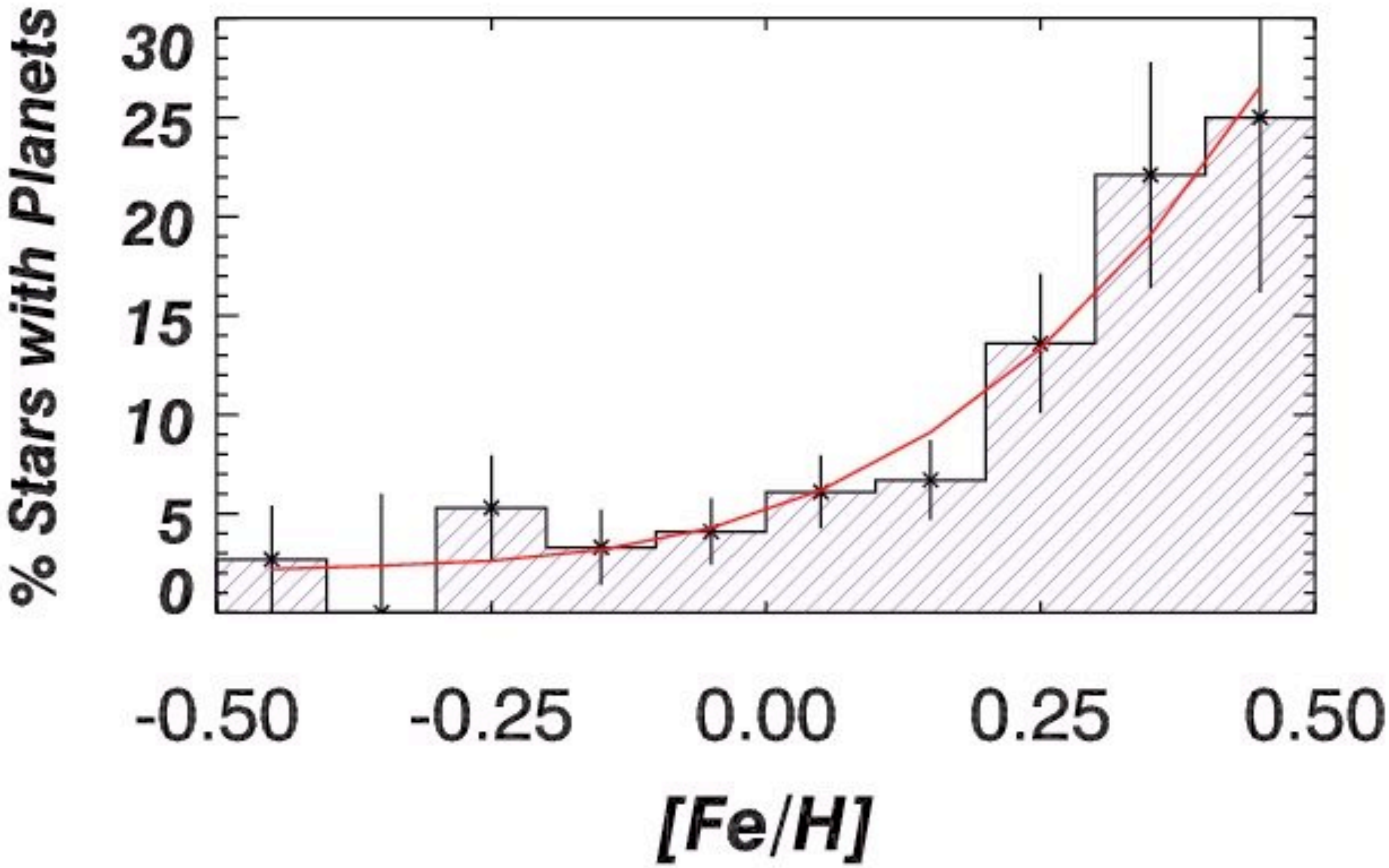


Mass Distribution of Planets
Detected by Doppler Method



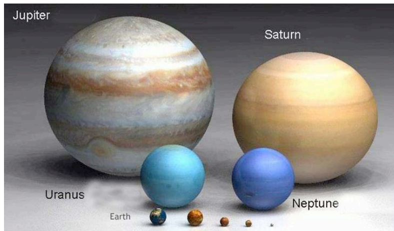

Jupiter
Saturn
Uranus
Earth
Neptune

[redacted]


% Stars with Planets
30
25
20
15
10
5
0
-0.50
-0.25
0.00
0.25
0.50
[Fe/H]

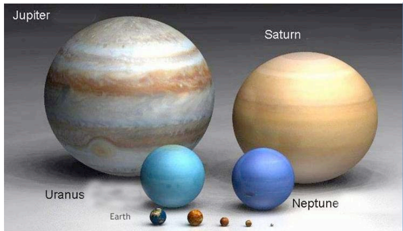
High-Resolution Images of First Three Planets Discovered by *Kepler*

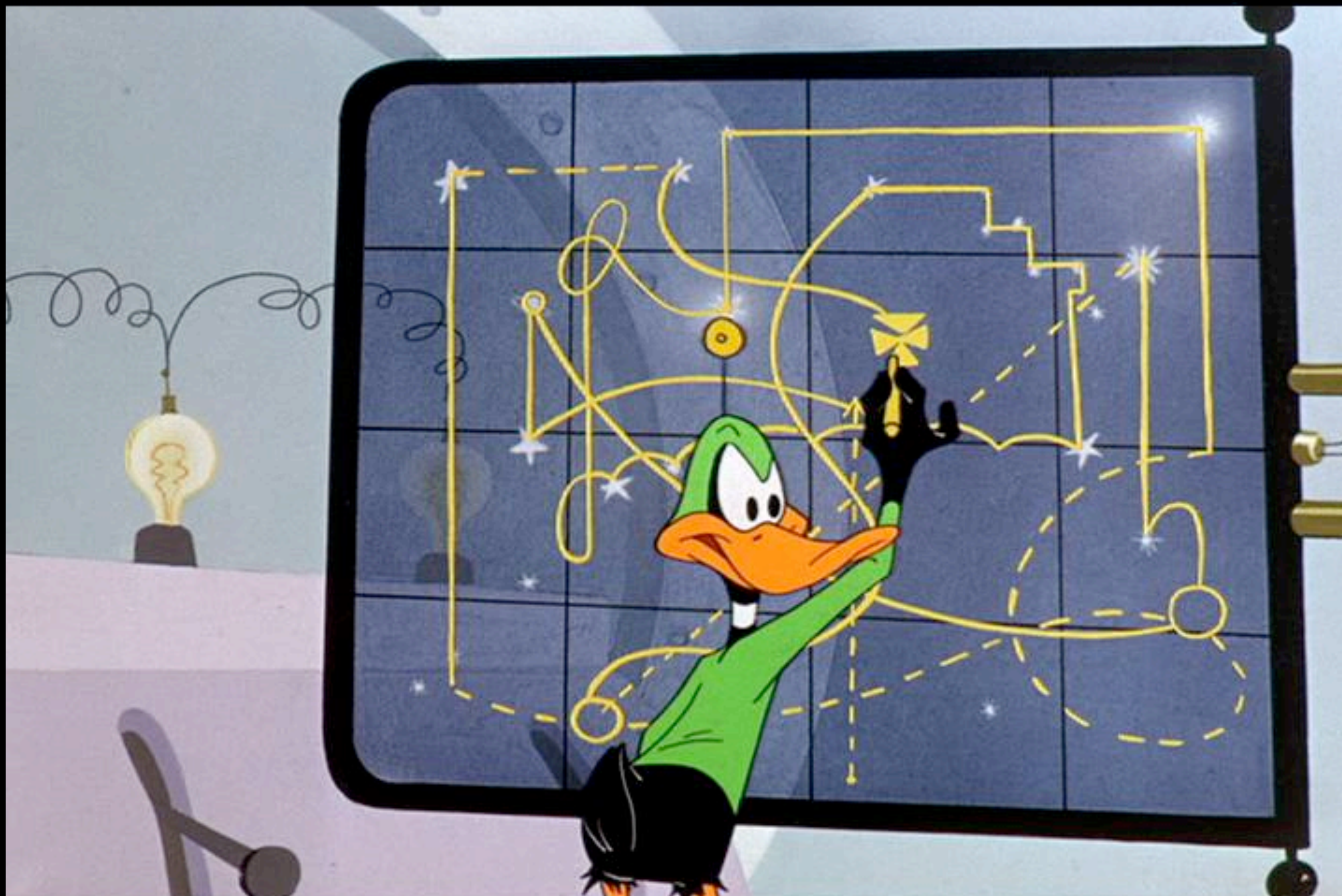

Small, dry planet
Earth
Ocean-covered world
April Fools!
Lissauer 1999

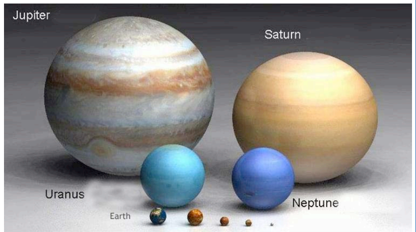


Key Findings

- Few planets are much more massive than Jupiter
- More (giant) planets around stars with more metals
- Mass-radius relationship ~ Solar System
- Larger fraction of more massive stars have giant planets within 2 AU


Jupiter
Saturn
Uranus
Neptune
Earth





[redacted]

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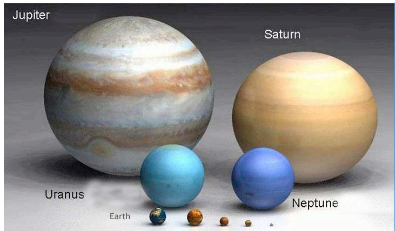

[redacted]

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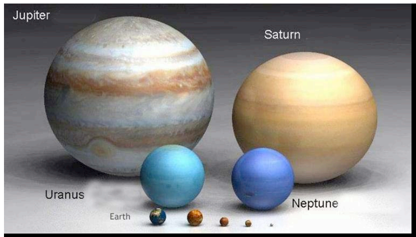
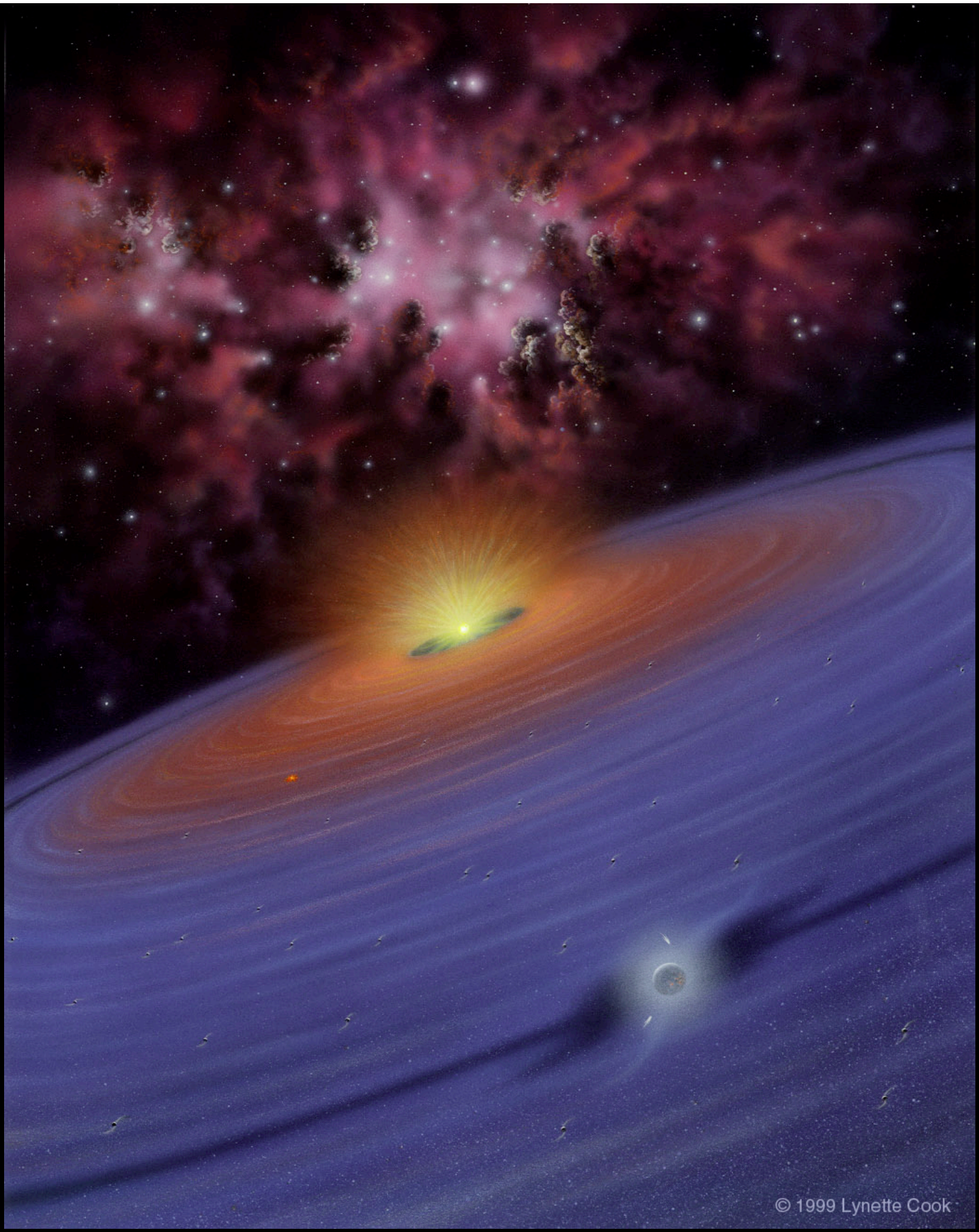
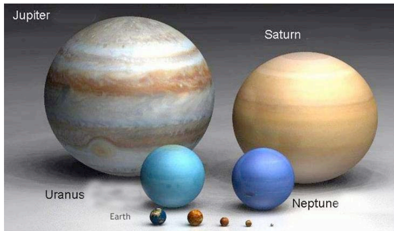
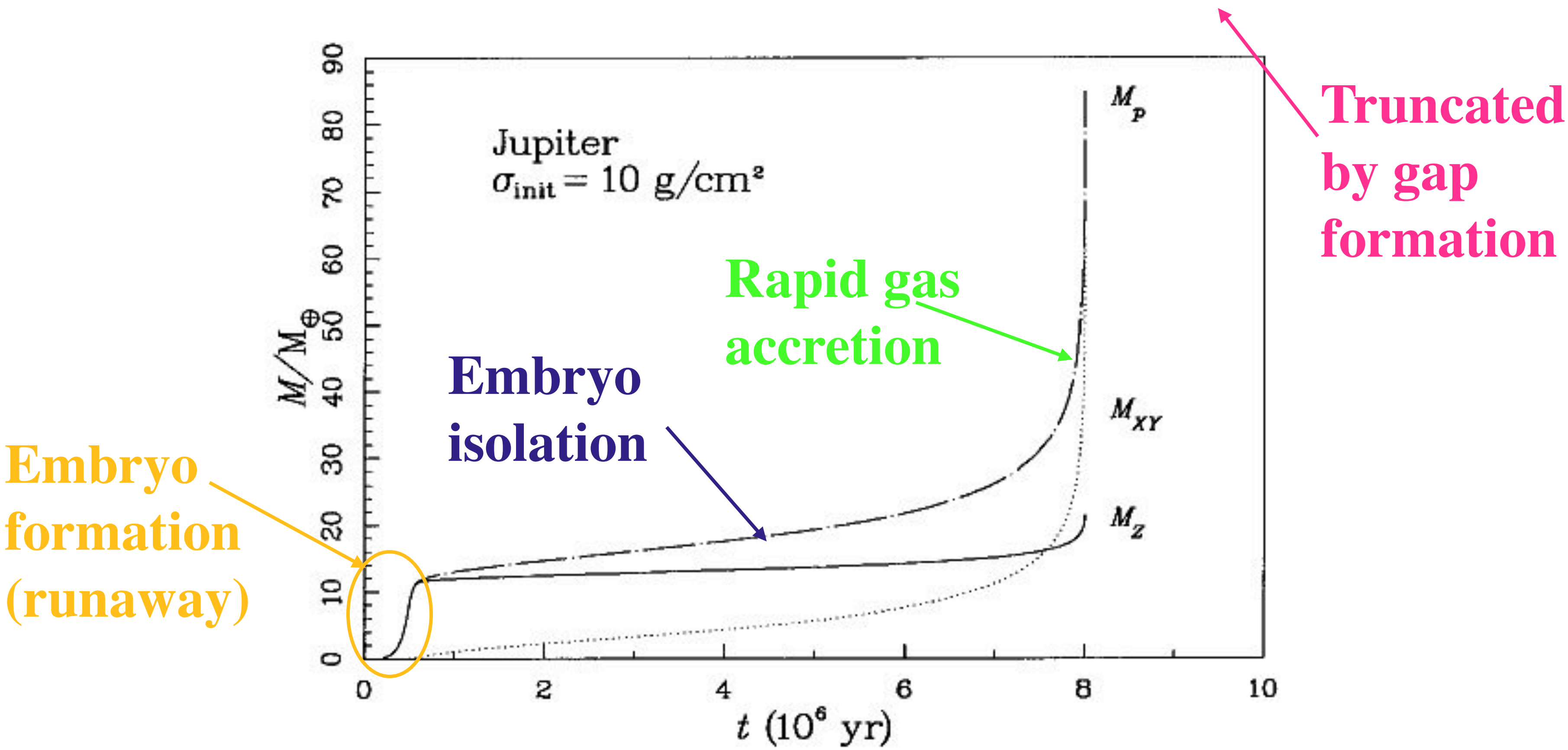


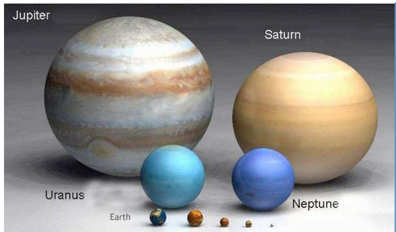


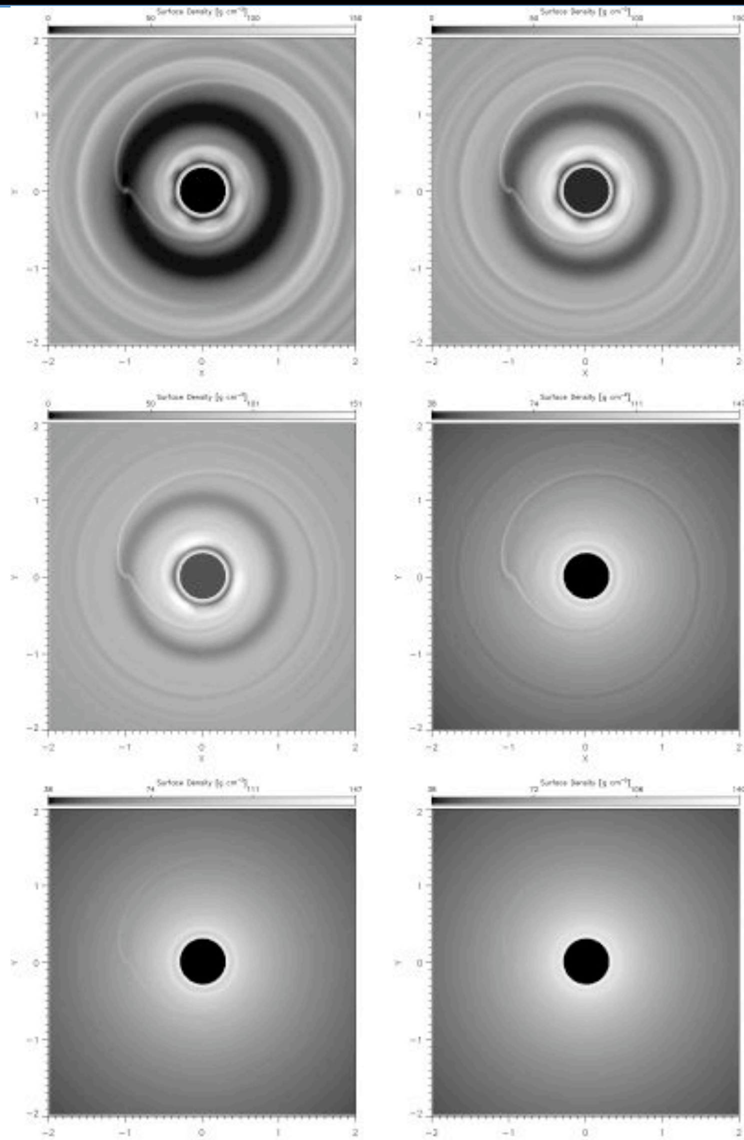
Giant Planets



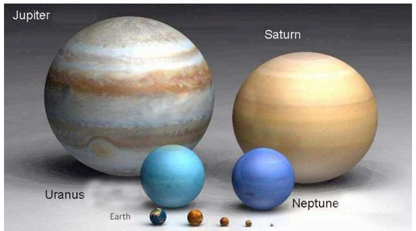


Pollack *et al*. 1996





Giant Planets



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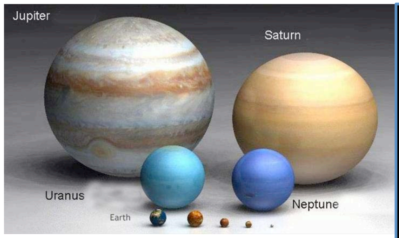
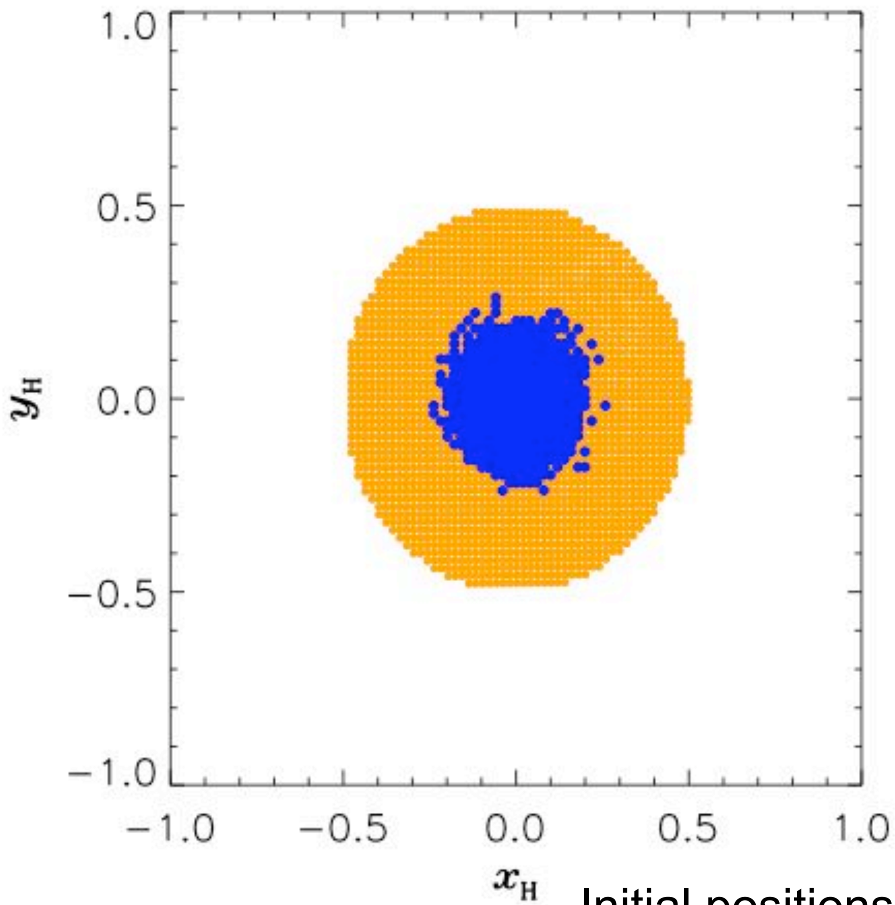
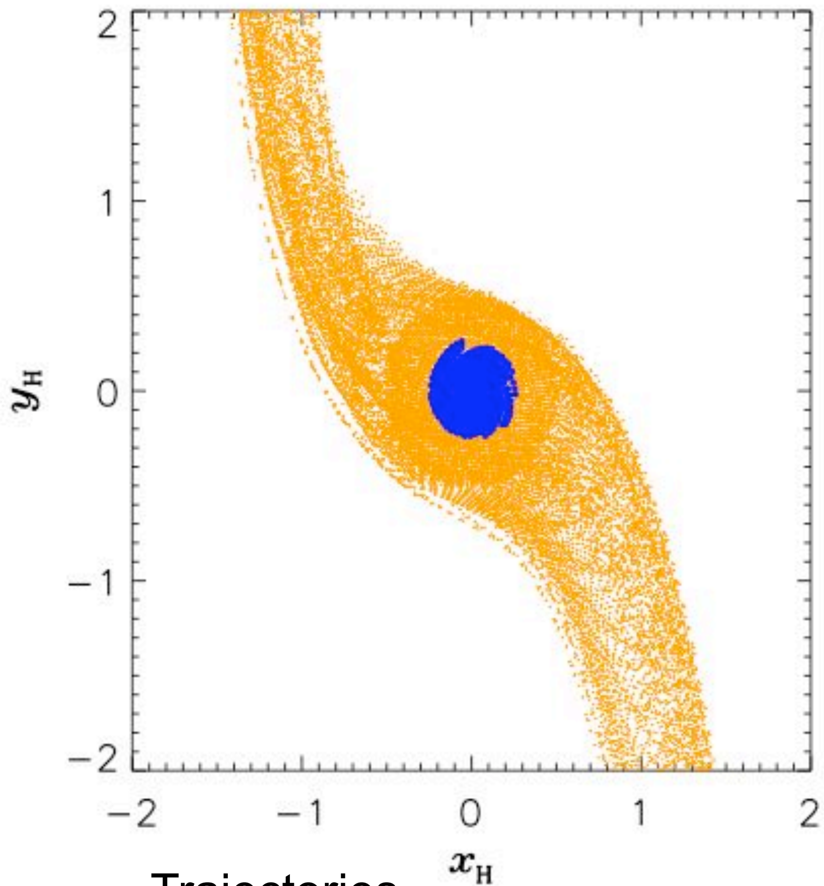


Bound Unbound

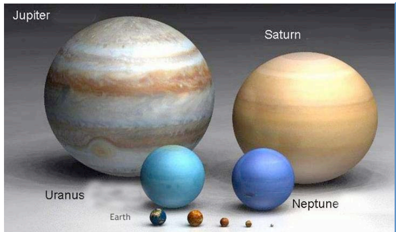


Initial positions

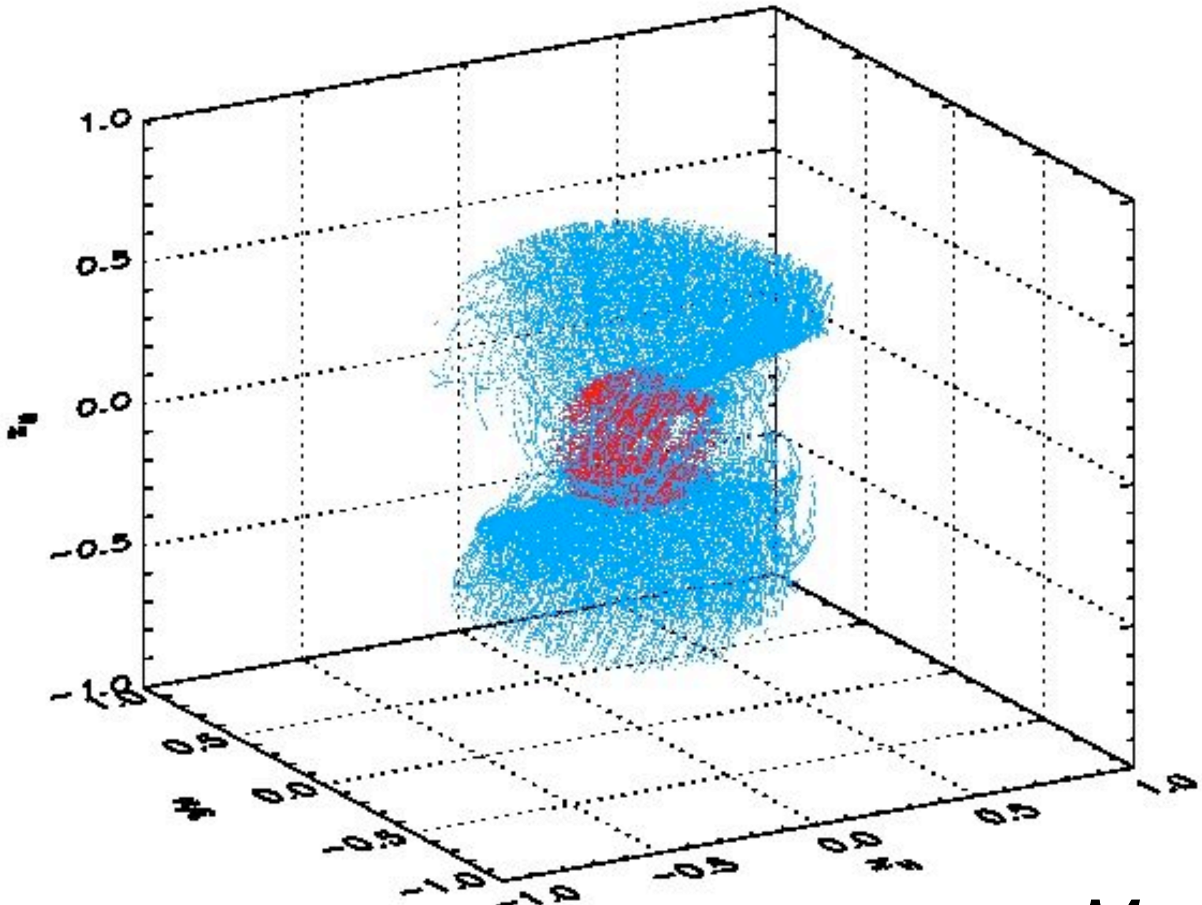


Trajectories

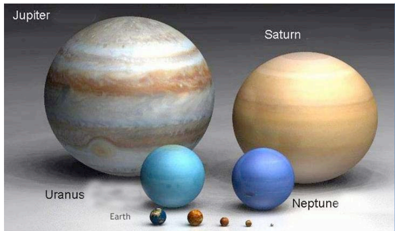
$M_p = 10\ M_{Earth}$



Near Far

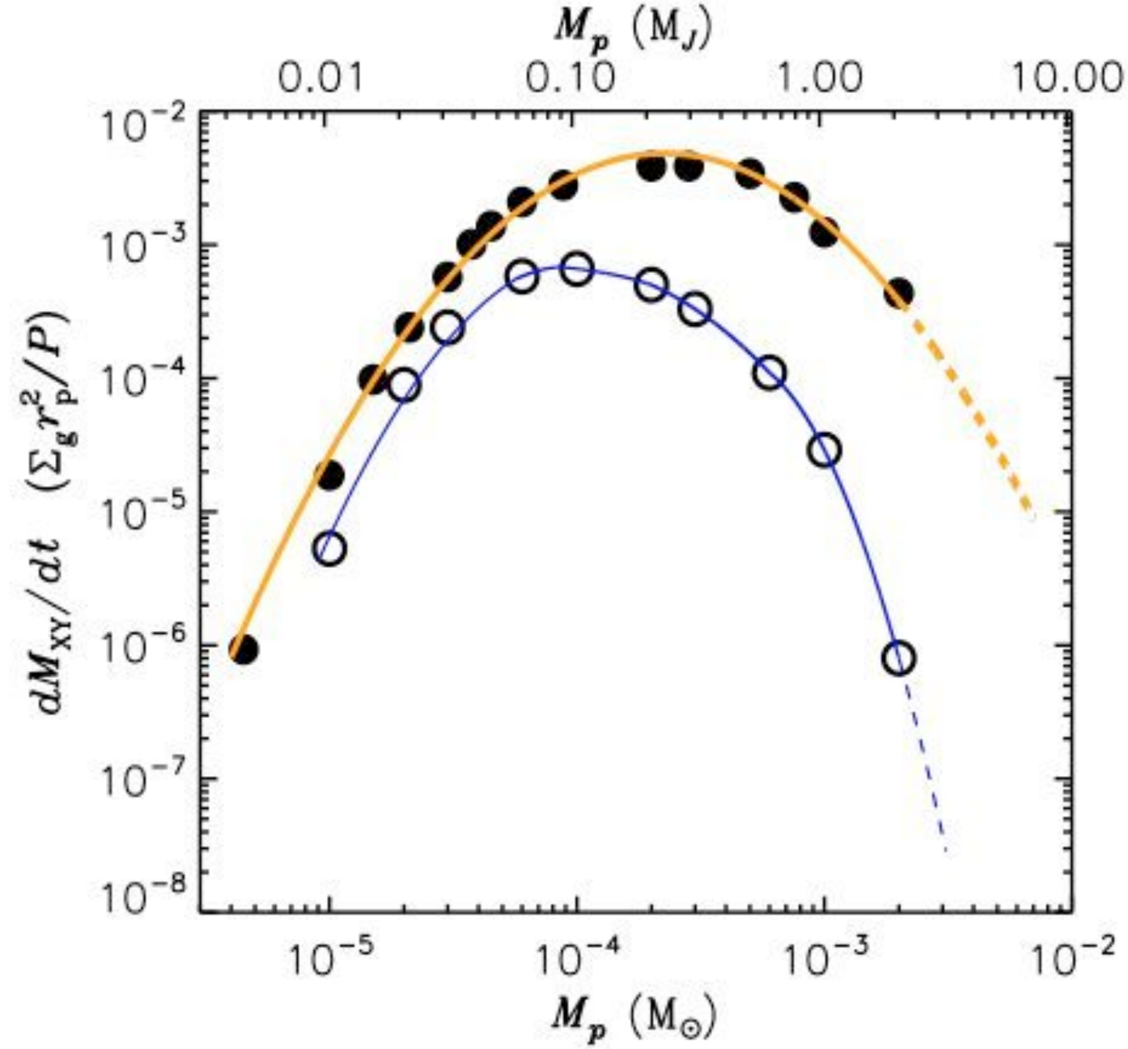


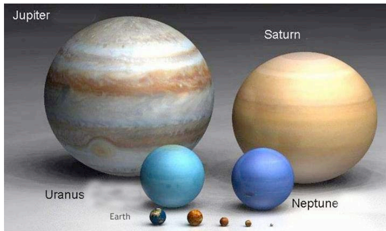
$M_p = 10\ M_{Earth}$



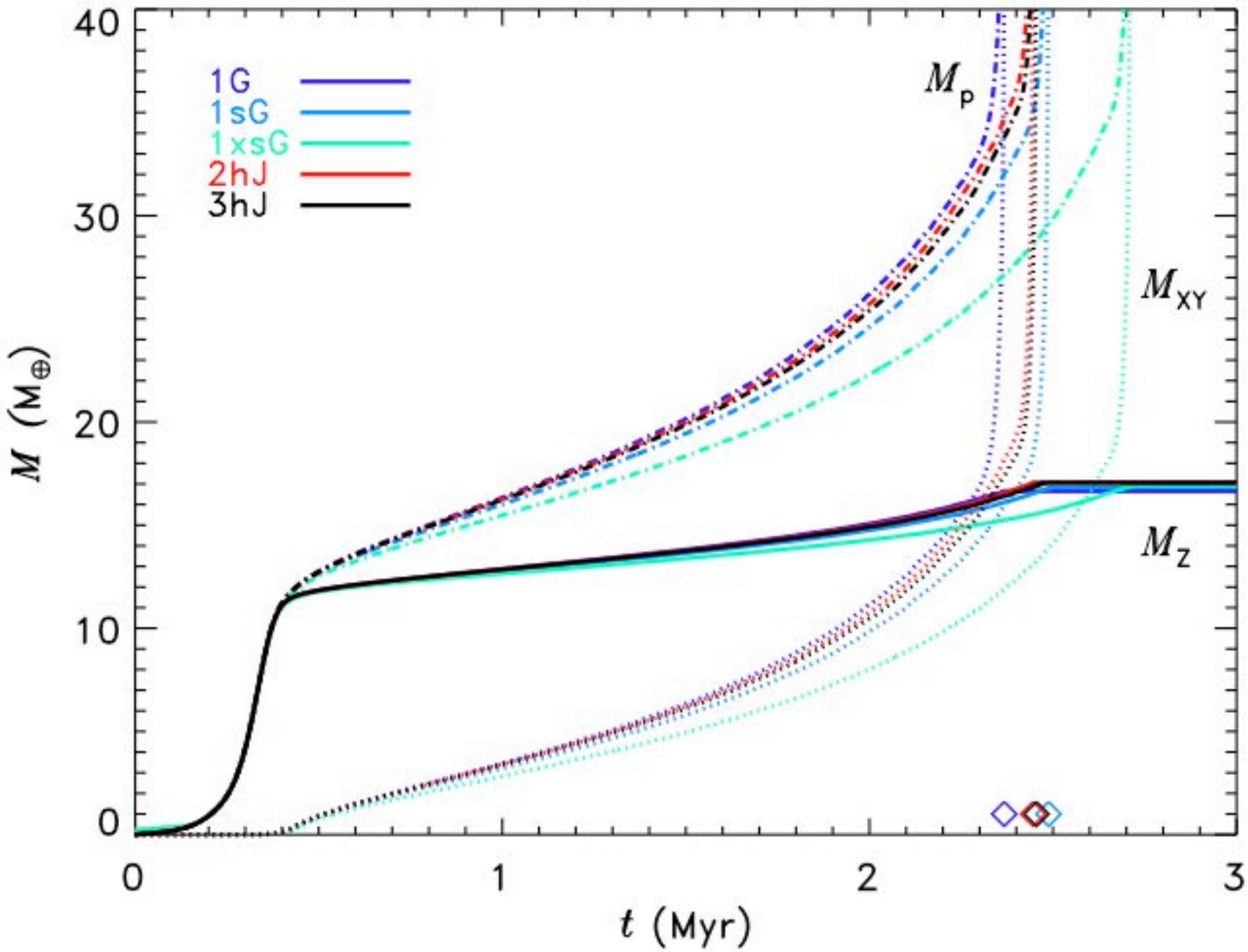
[redacted]

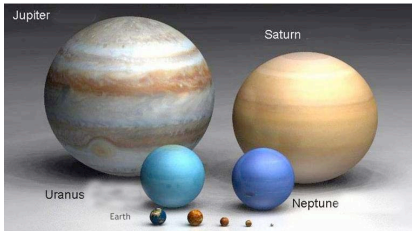
[redacted] points [redacted]
points [redacted]



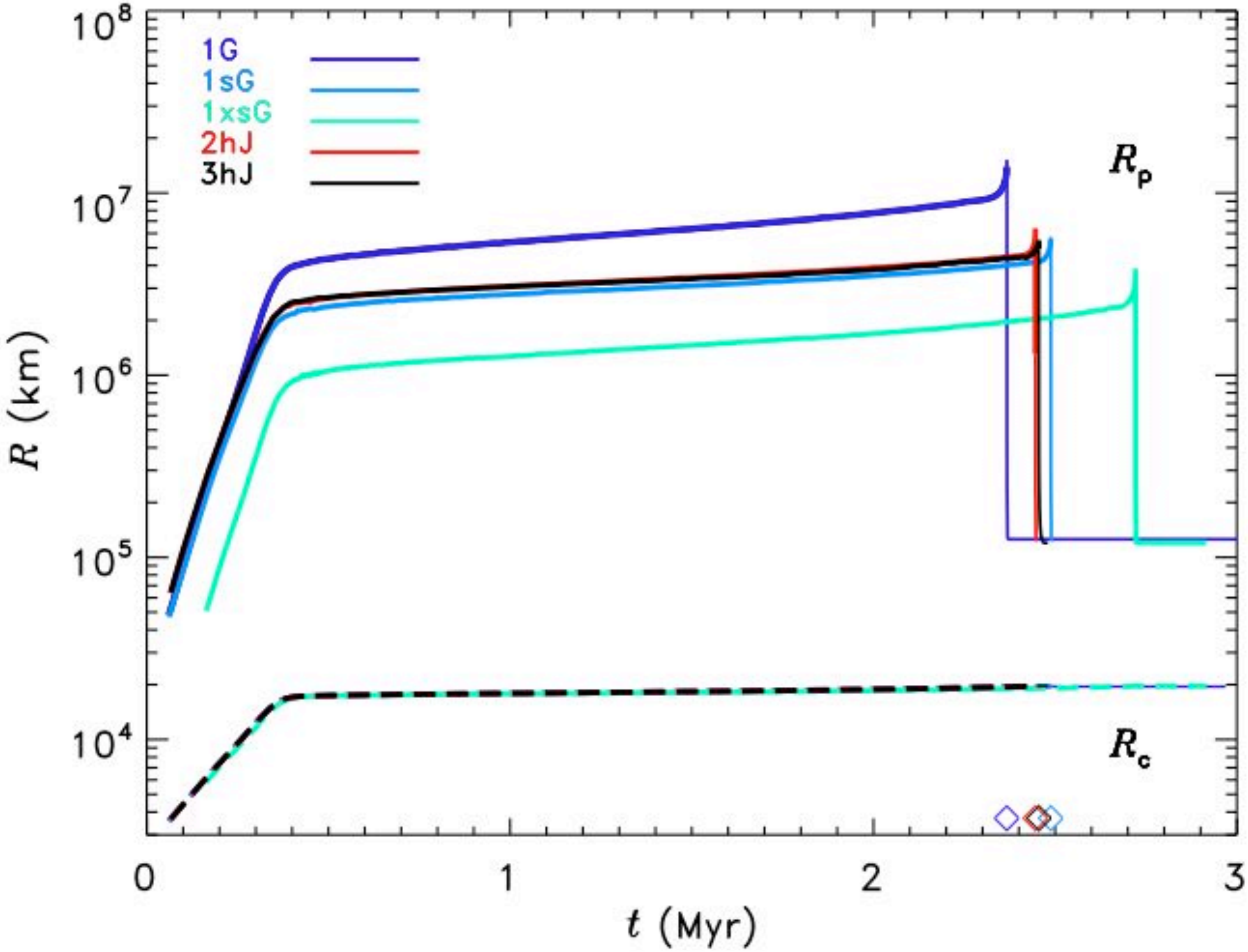

Jupiter
Saturn
Uranus
Neptune
Earth

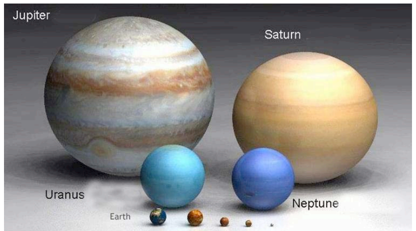
[redacted]


1G
1sG
1xsG
2hJ
3hJ
M_p
M_{XY}
M_Z
M ($M_\oplus$)
t (Myr)
0
10
20
30
40
0
1
2
3

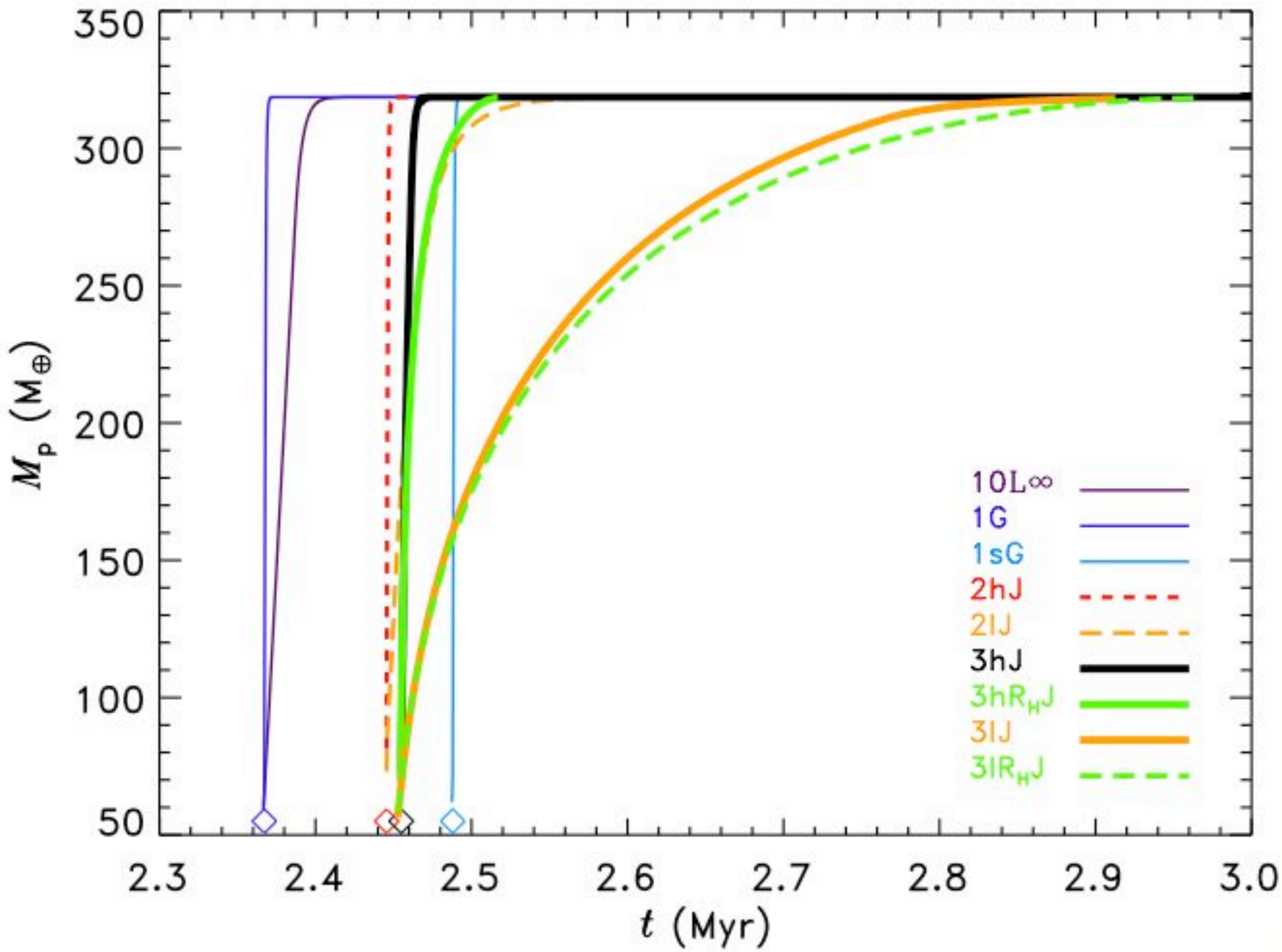

Jupiter
Saturn
Uranus
Earth
Neptune

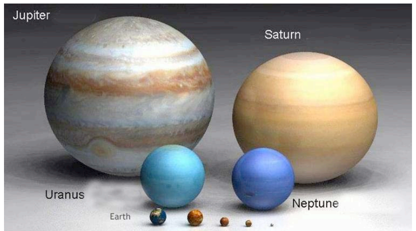
[redacted]


1G
1sG
1xsG
2hJ
3hJ
R_p
R_c
10^8
10^7
10^6
10^5
10^4
R (km)
0
1
2
3
t (Myr)

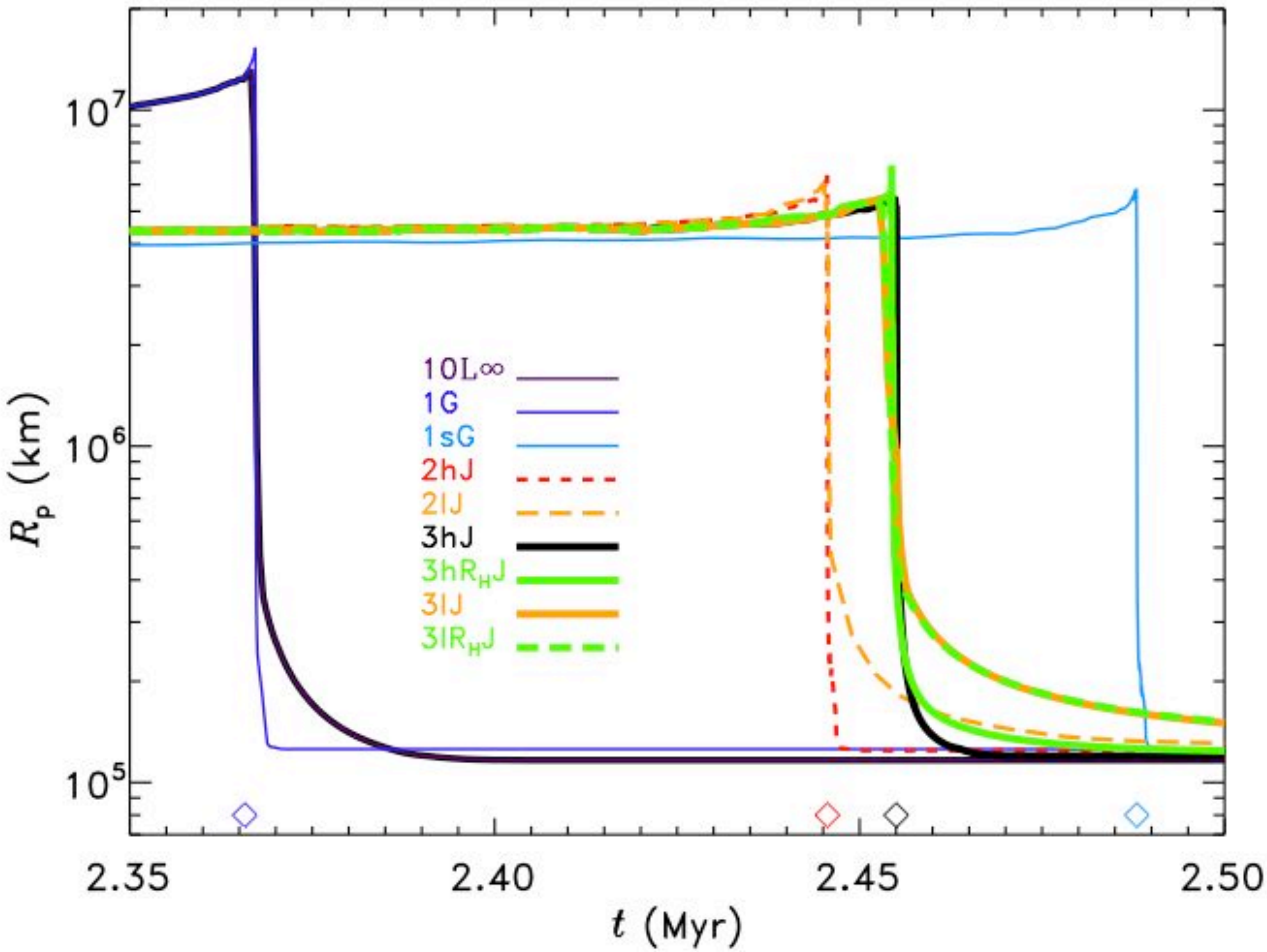

Jupiter
Saturn
Uranus
Neptune
Earth

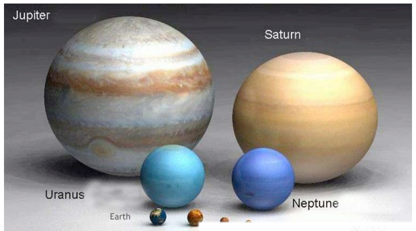
[redacted]


350
300
250
200
150
100
50
M_p ($M_\oplus$)
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
t (Myr)
10L∞
1G
1sG
2hJ
2lJ
3hJ
$3hR_HJ$
3lJ
$3lR_HJ$

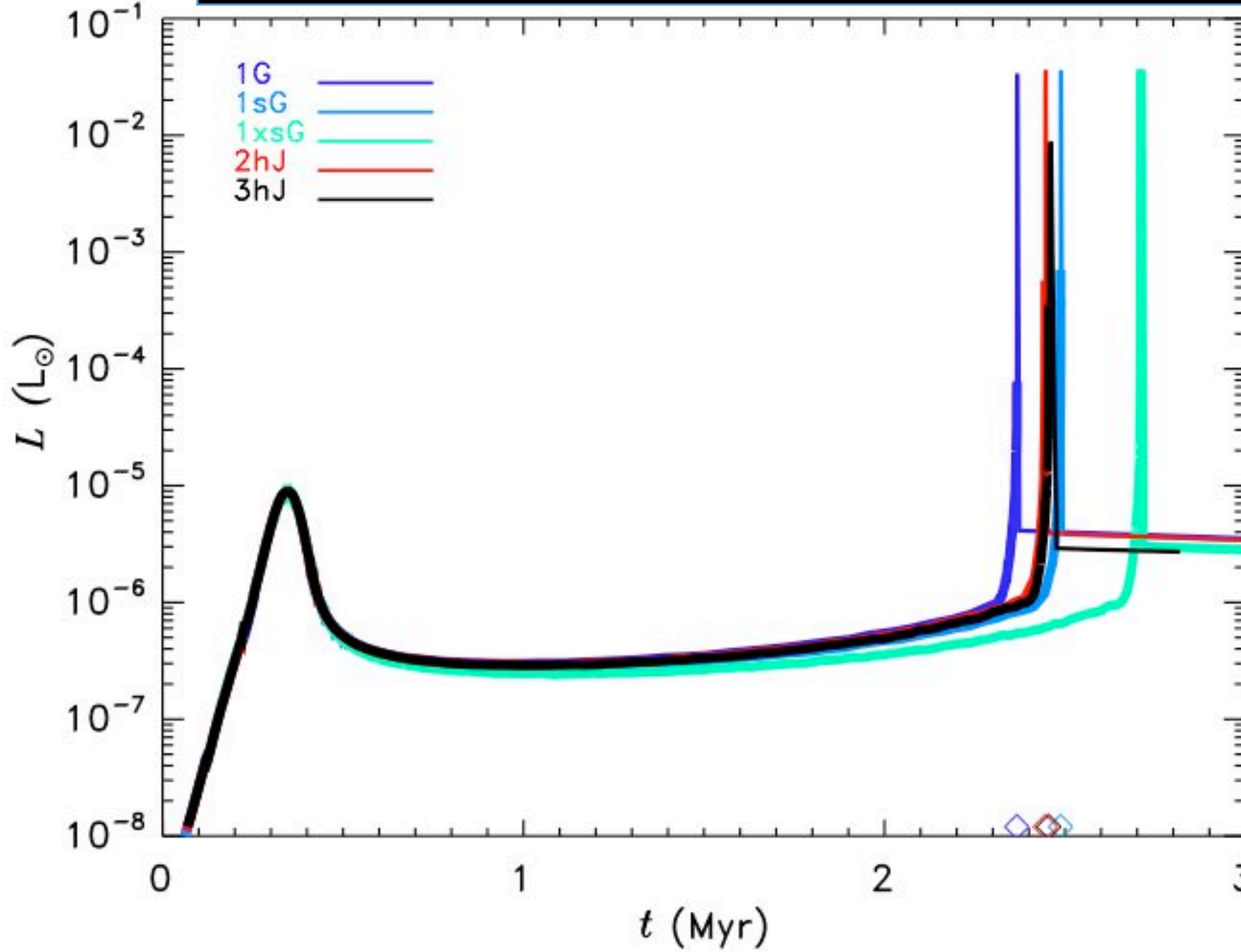

Jupiter
Saturn
Uranus
Earth
Neptune

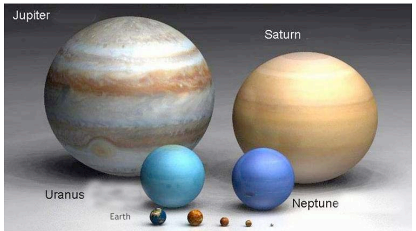
[redacted]


10L∞
1G
1sG
2hJ
2lJ
3hJ
3hR$_H$J
3lJ
3lR$_H$J
R_p (km)
10^7
10^6
10^5
2.35
2.40
2.45
2.50
t (Myr)

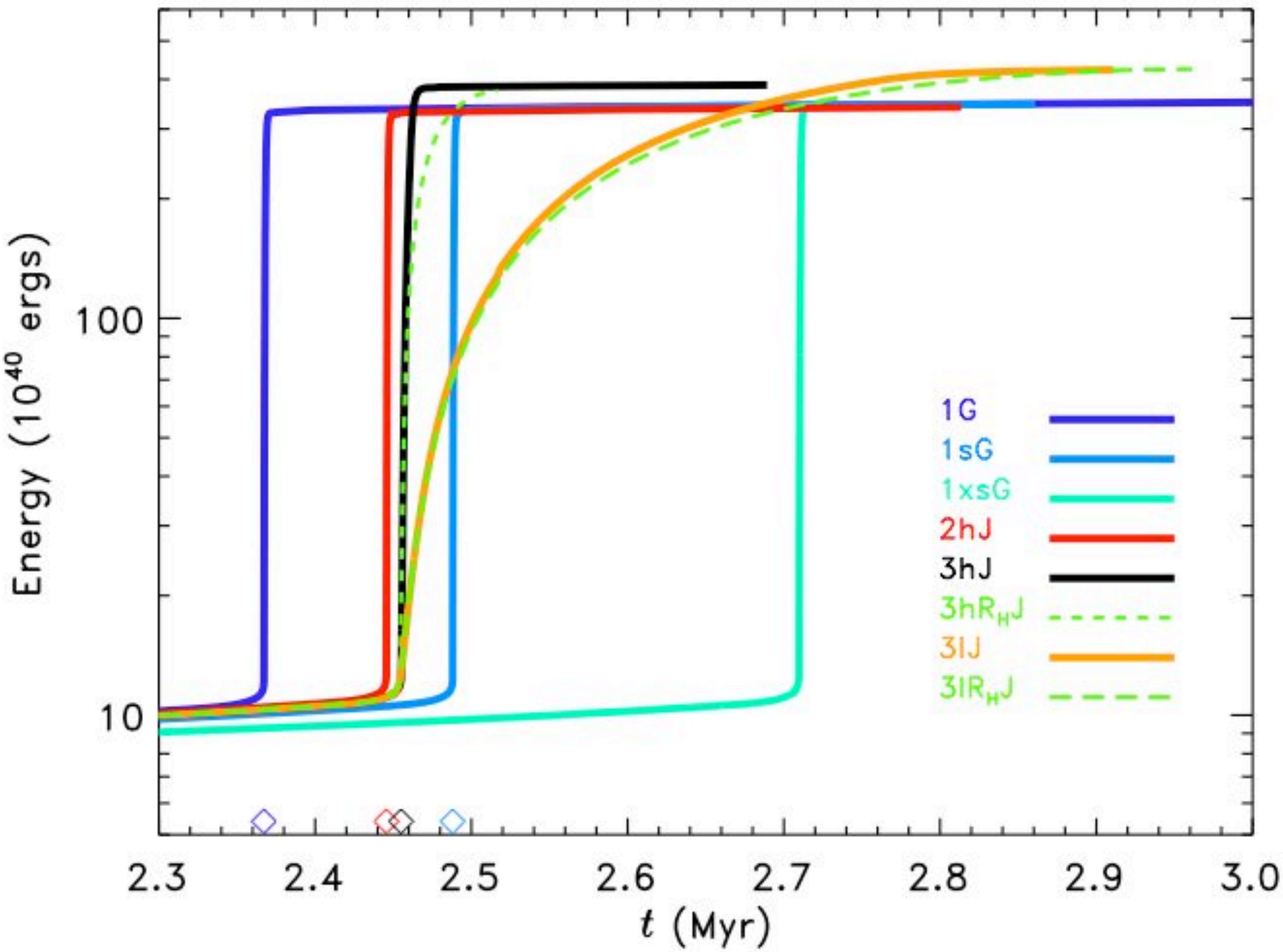

Jupiter
Saturn
Uranus
Neptune
Earth

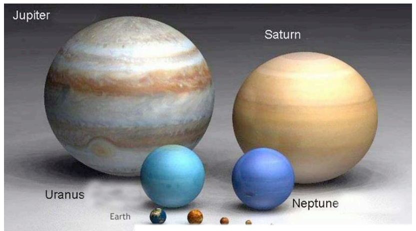
[redacted]


1G
1sG
1xsG
2hJ
3hJ
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
L ($L_\odot$)
0
1
2
3
t (Myr)


Jupiter
Saturn
Uranus
Neptune
Earth

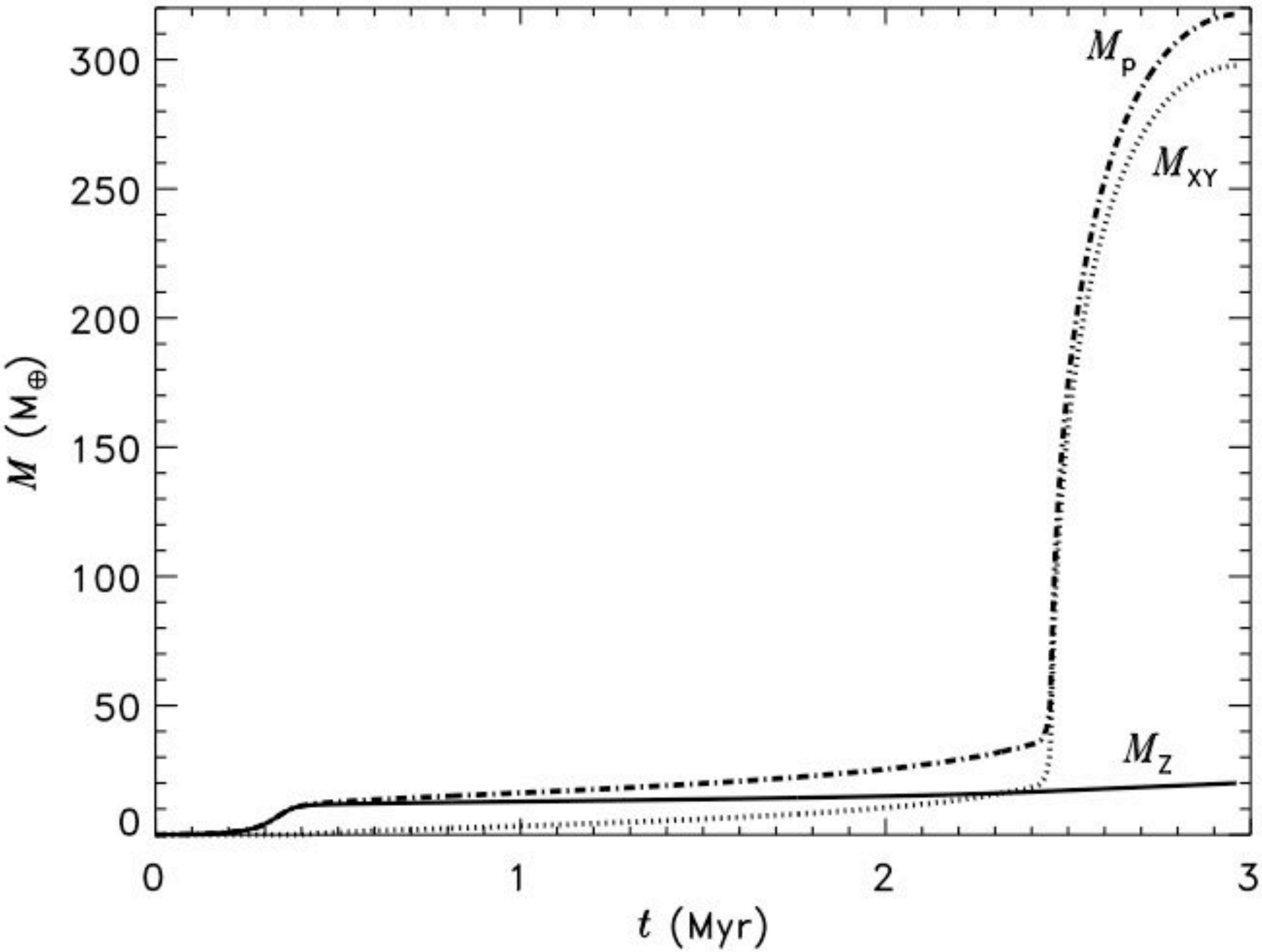
[redacted]


Energy (10^40 ergs)
100
10
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
t (Myr)
1G
1sG
1xsG
2hJ
3hJ
3hR_HJ
3IJ
3IR_HJ

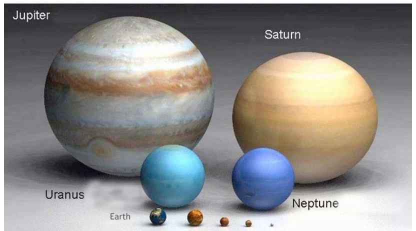


Jupiter
Saturn
Uranus
Neptune
Earth

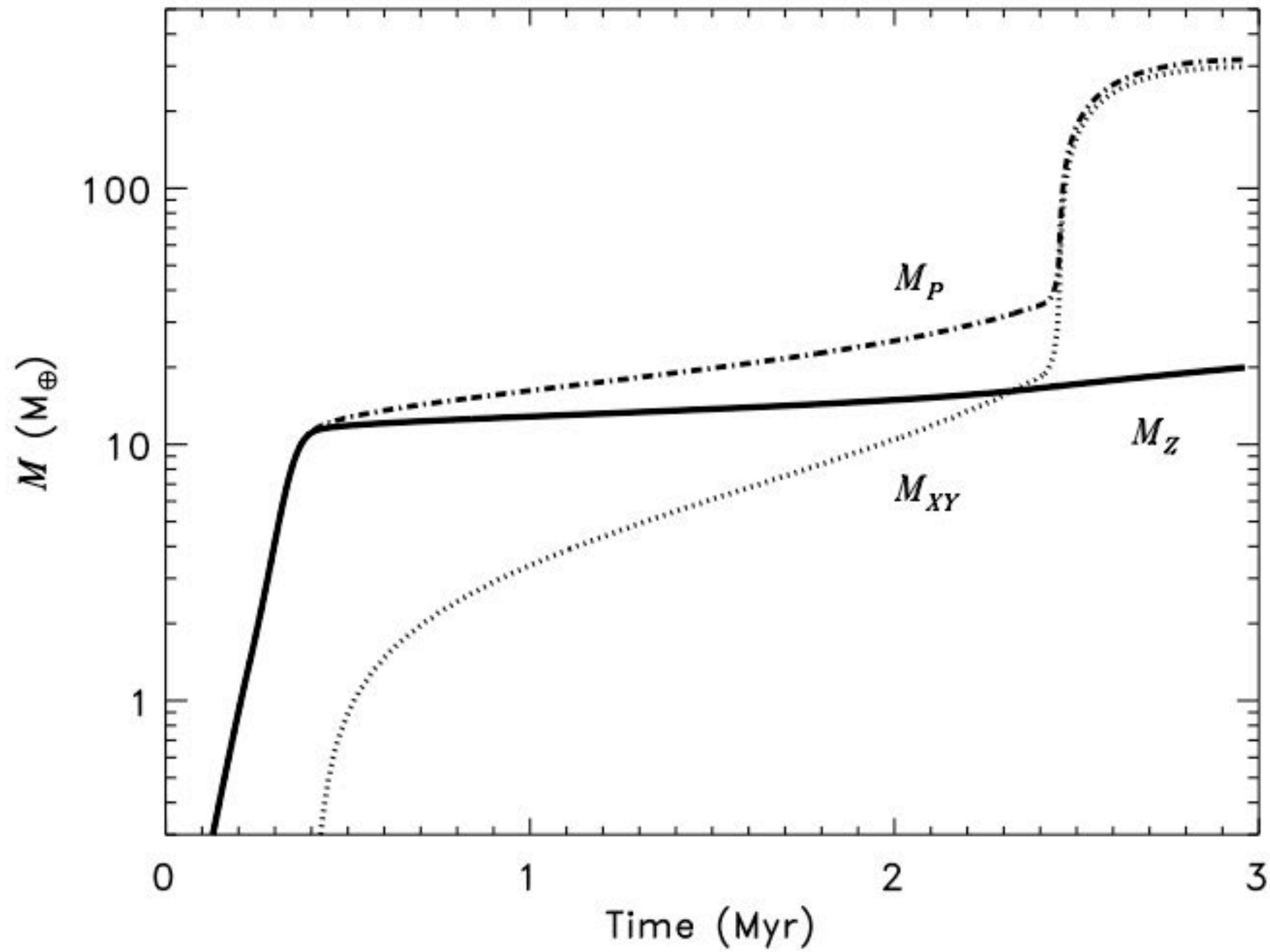
[redacted]

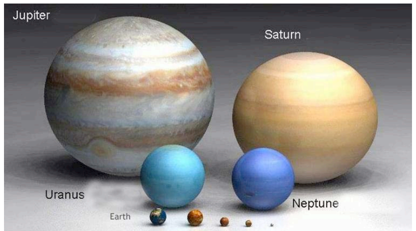


M_P
M_{XY}
M_Z
300
250
200
150
100
50
0
0
1
2
3
M ($M_\oplus$)
t (Myr)


Jupiter
Saturn
Uranus
Neptune
Earth

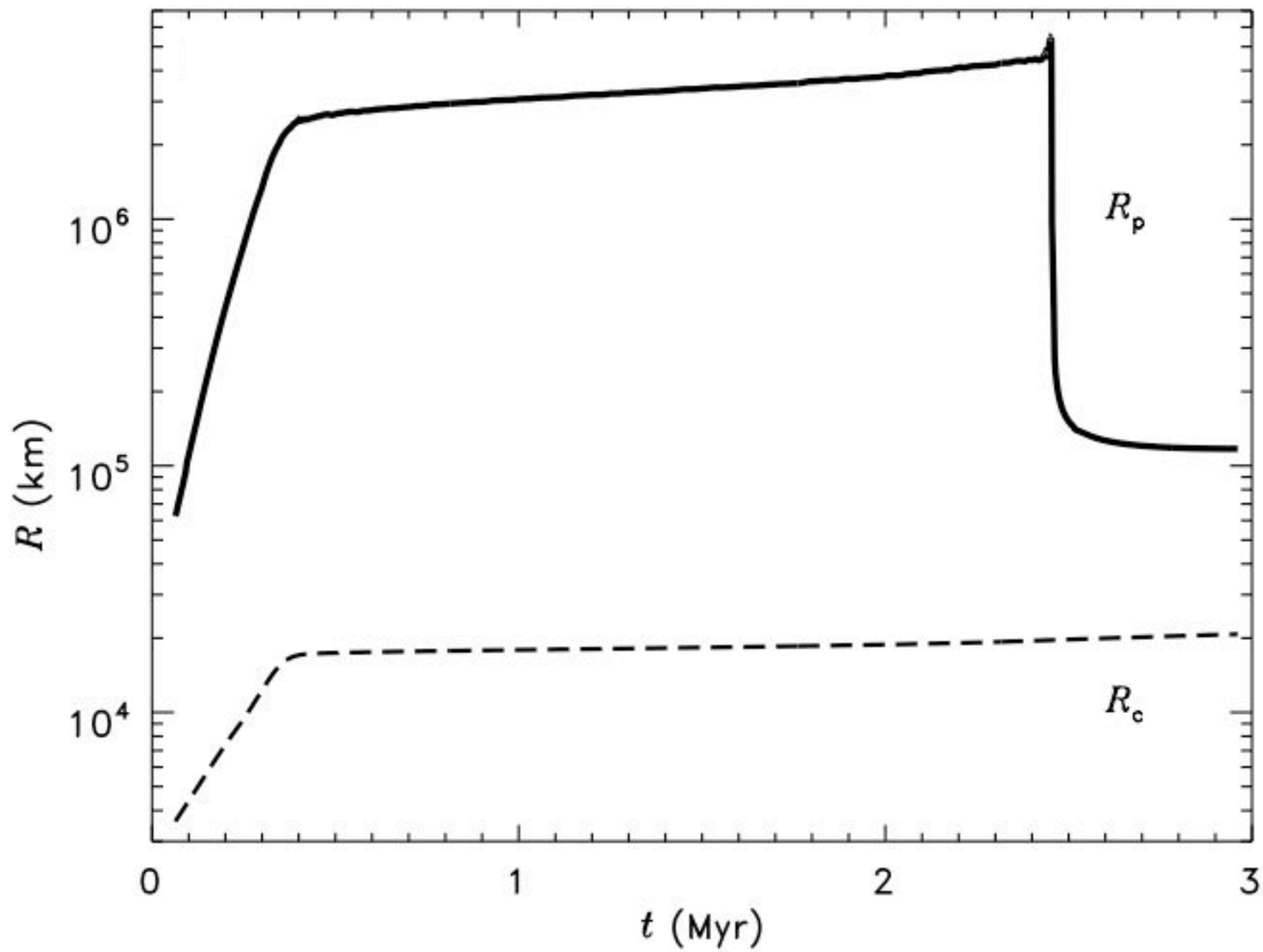
[redacted]


100
10
1
0
1
2
3
M_P
M_Z
M_{XY}
M ($M_\oplus$)
Time (Myr)

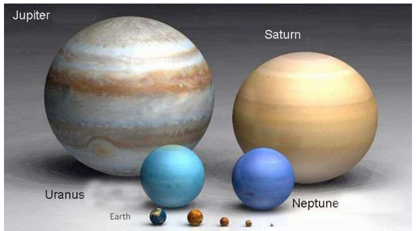


Jupiter
Saturn
Uranus
Neptune
Earth

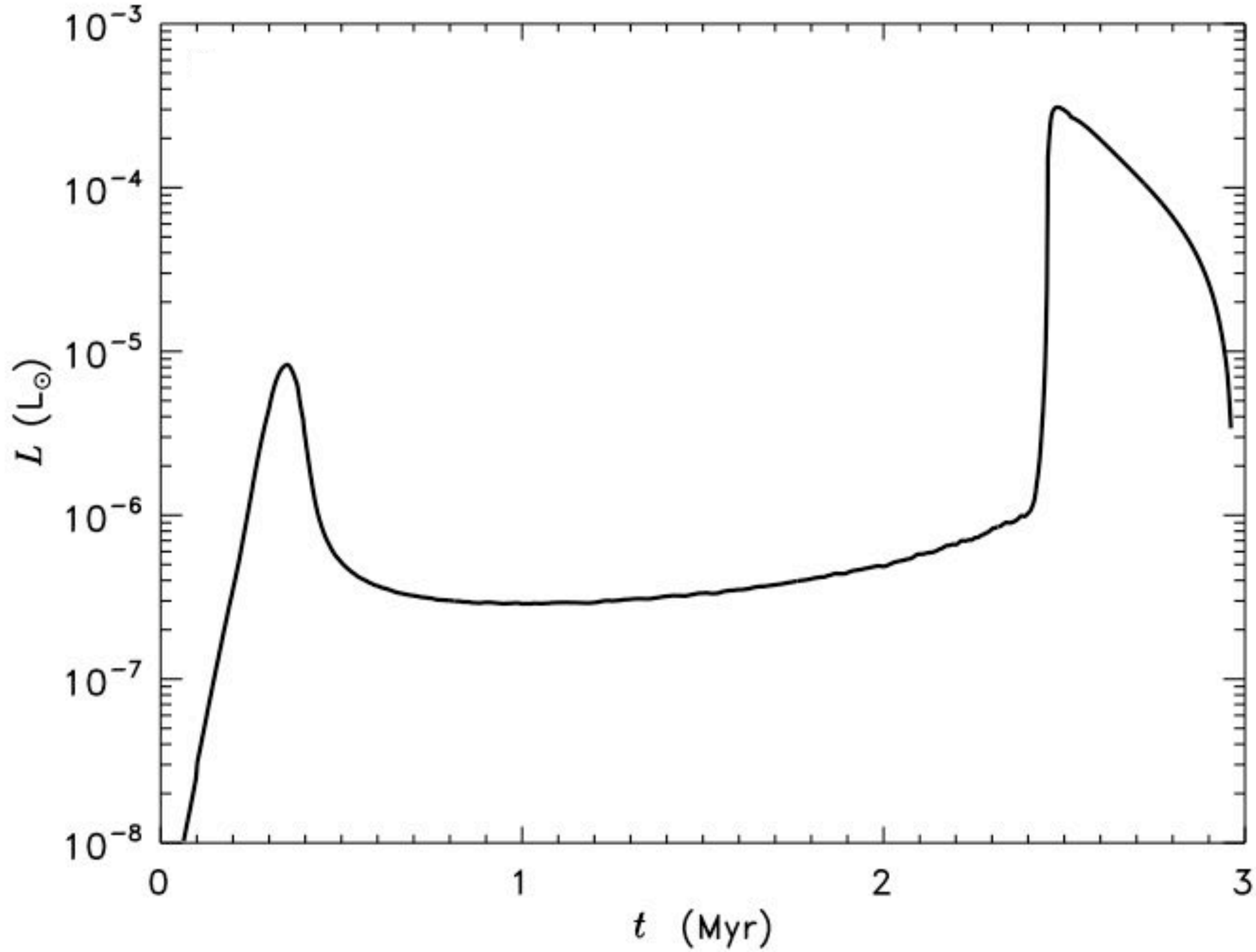
[redacted]

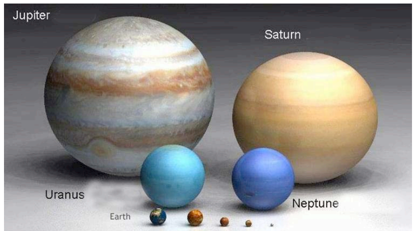


10^6
10^5
10^4
R (km)
R_p
R_c
0
1
2
3
t (Myr)

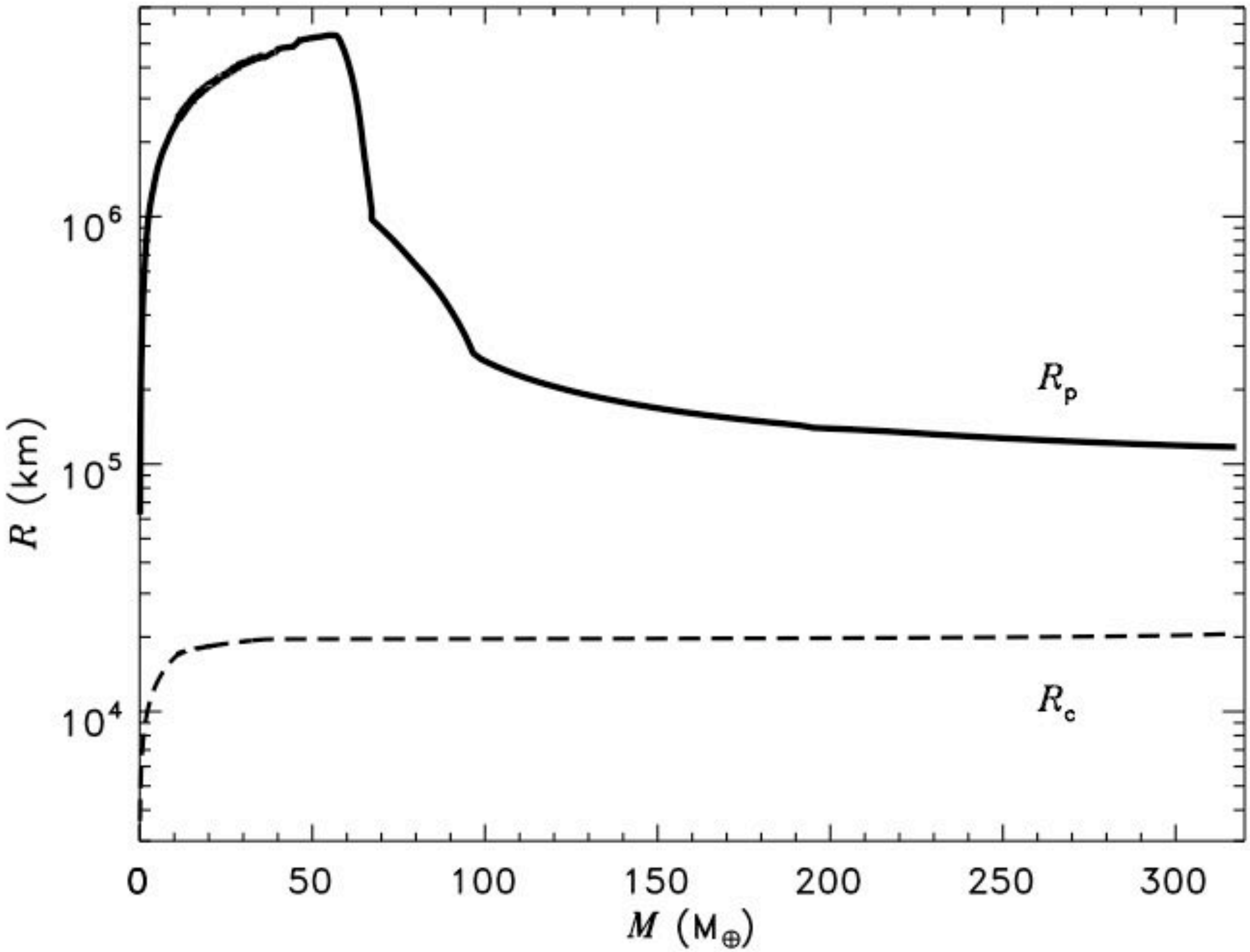

Jupiter
Saturn
Uranus
Neptune
Earth

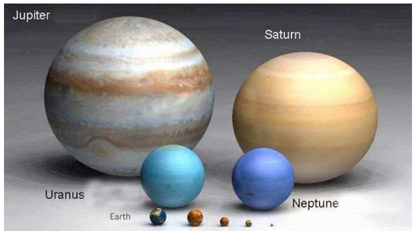
[redacted]


10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
L ($L_\odot$)
0
1
2
3
t (Myr)


Jupiter
Saturn
Uranus
Neptune
Earth

[redacted]


10^6
10^5
10^4
R (km)
R_p
R_c
0
50
100
150
200
250
300
M ($M_\oplus$)



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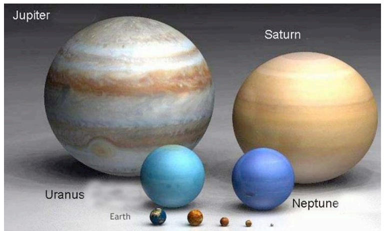
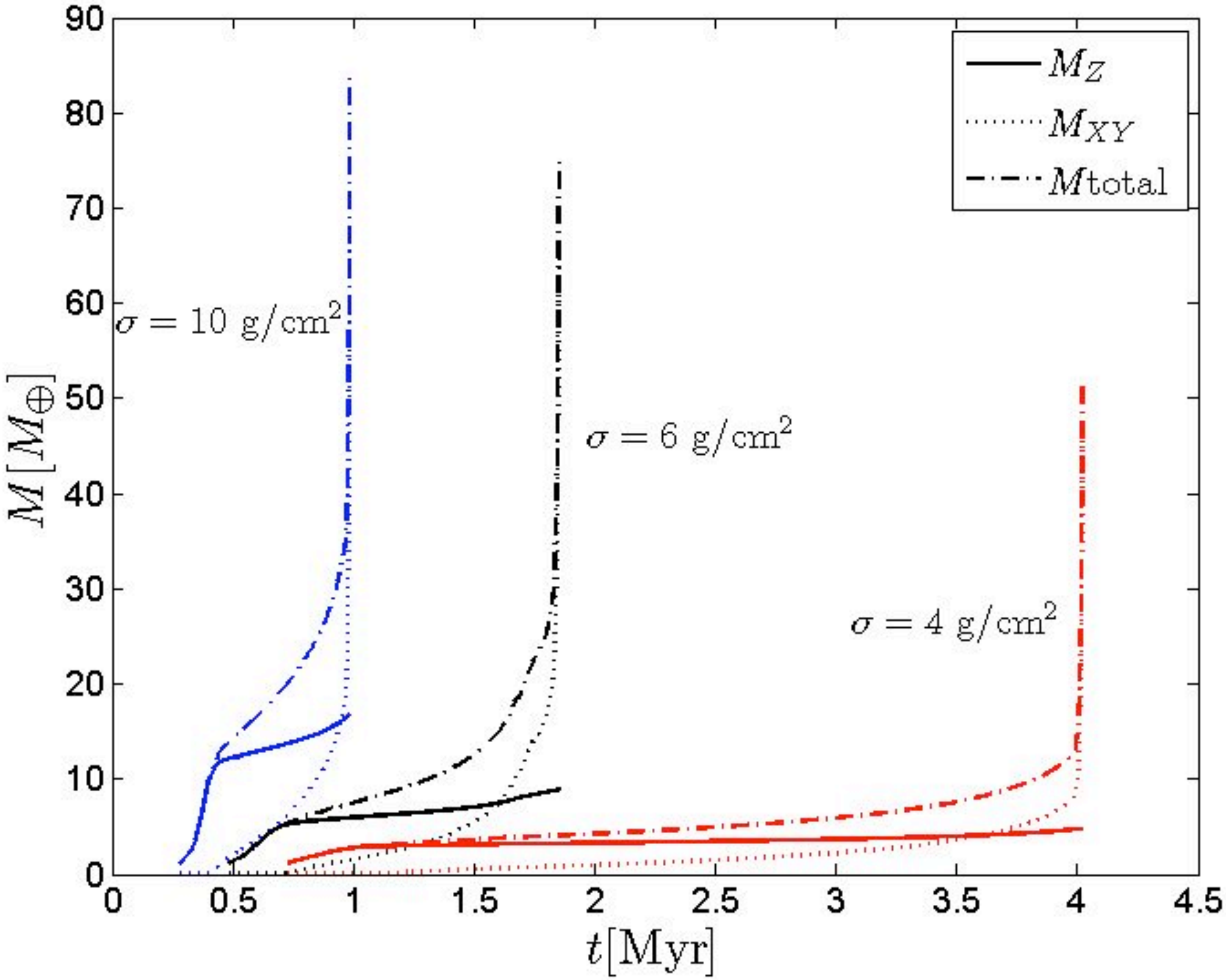
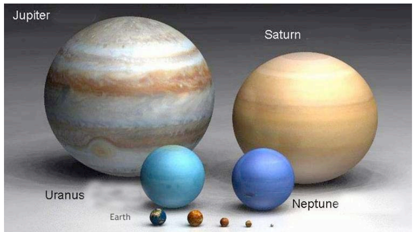
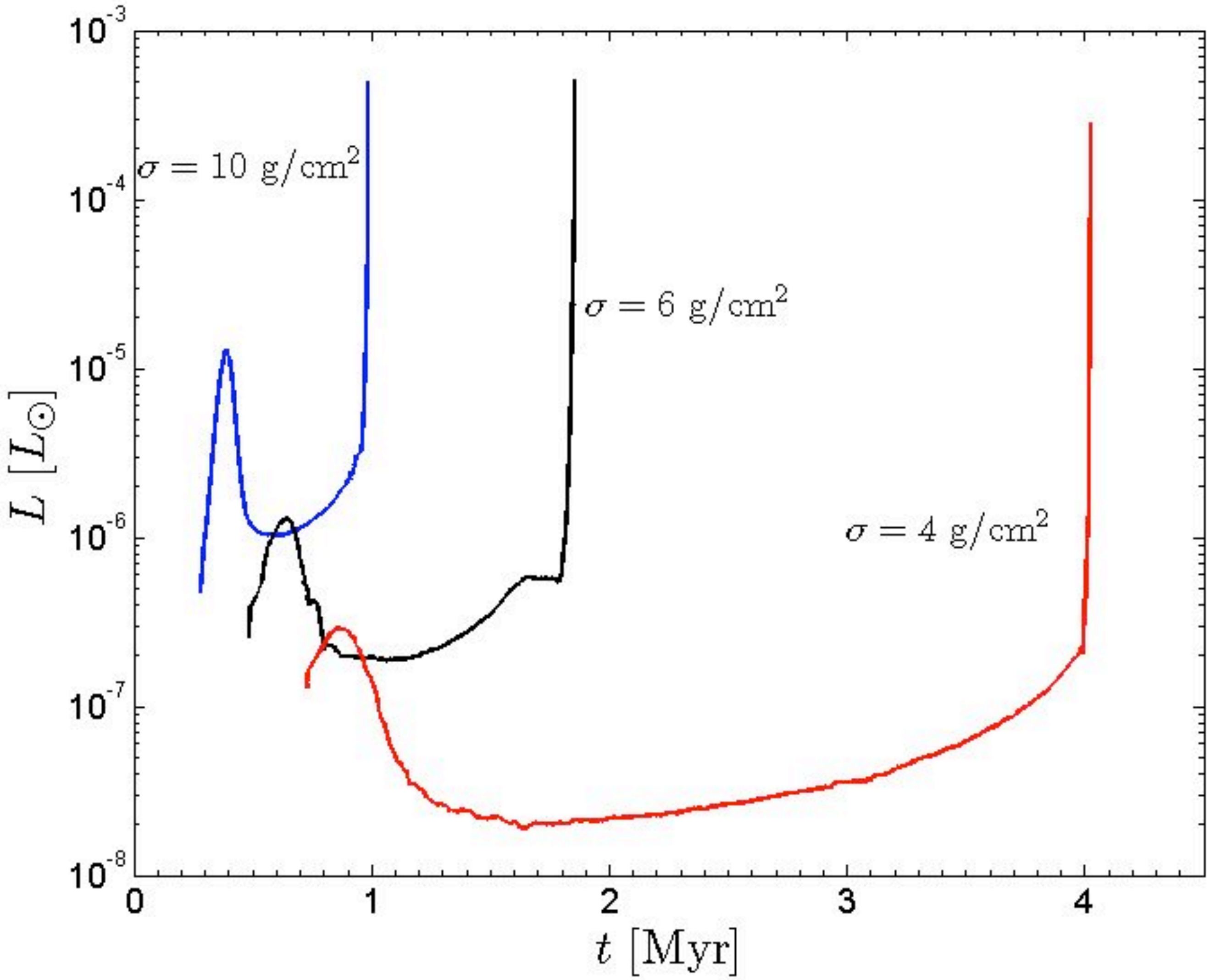


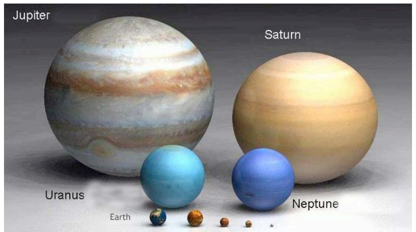
Jupiter
Saturn
Uranus
Neptune
Earth

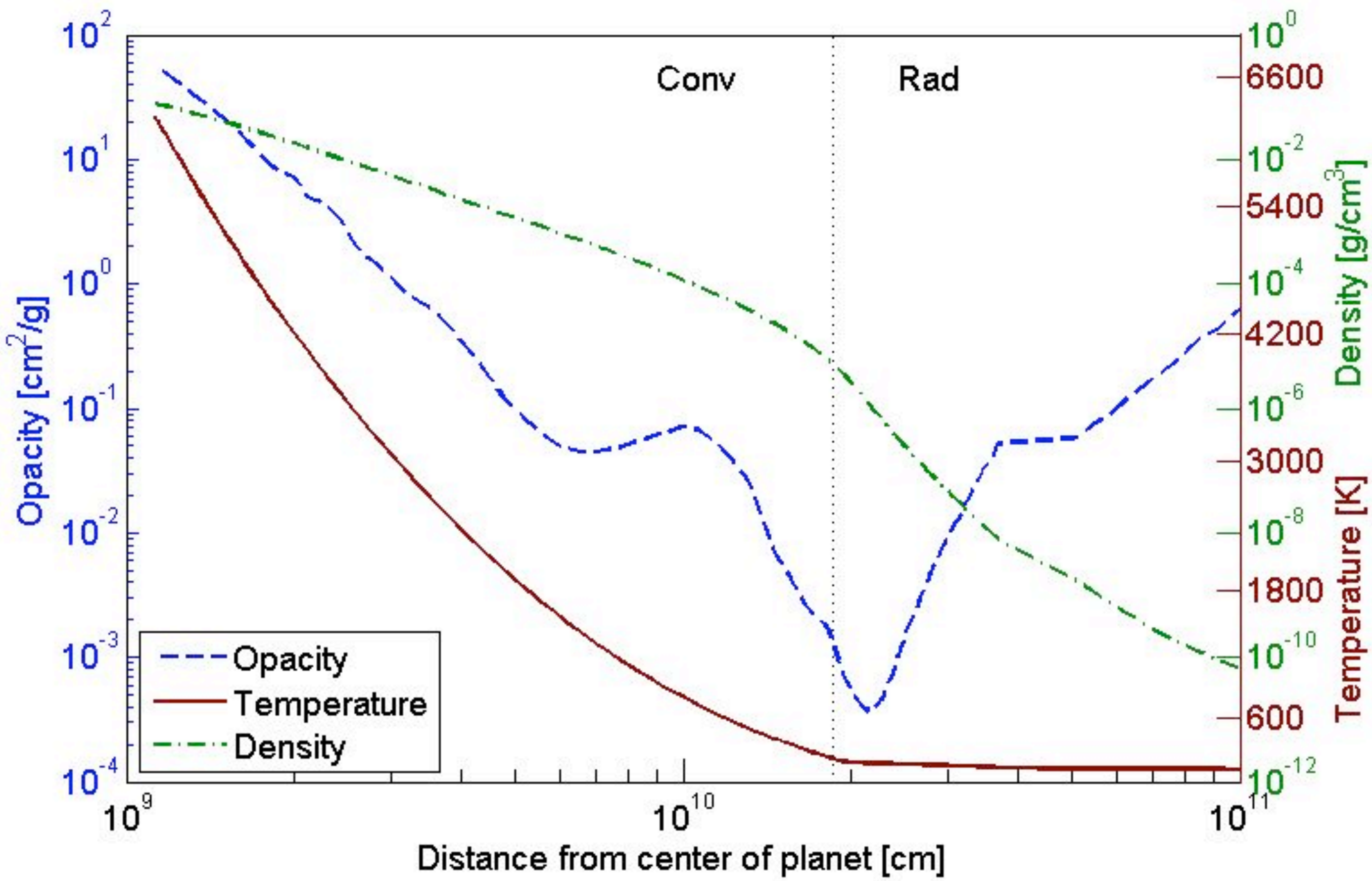


M_Z
M_{XY}
Mtotal
$\sigma = 10$ g/cm^2
$\sigma = 6$ g/cm^2
$\sigma = 4$ g/cm^2
$M[M_\oplus]$
t[Myr]
0
10
20
30
40
50
60
70
80
90
0.5
1
1.5
2
2.5
3
3.5
4
4.5

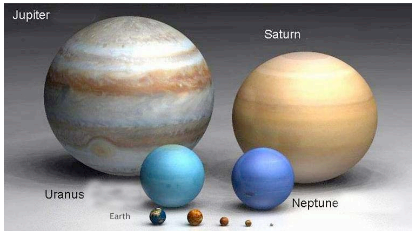

Jupiter
Saturn
Uranus
Neptune
Earth

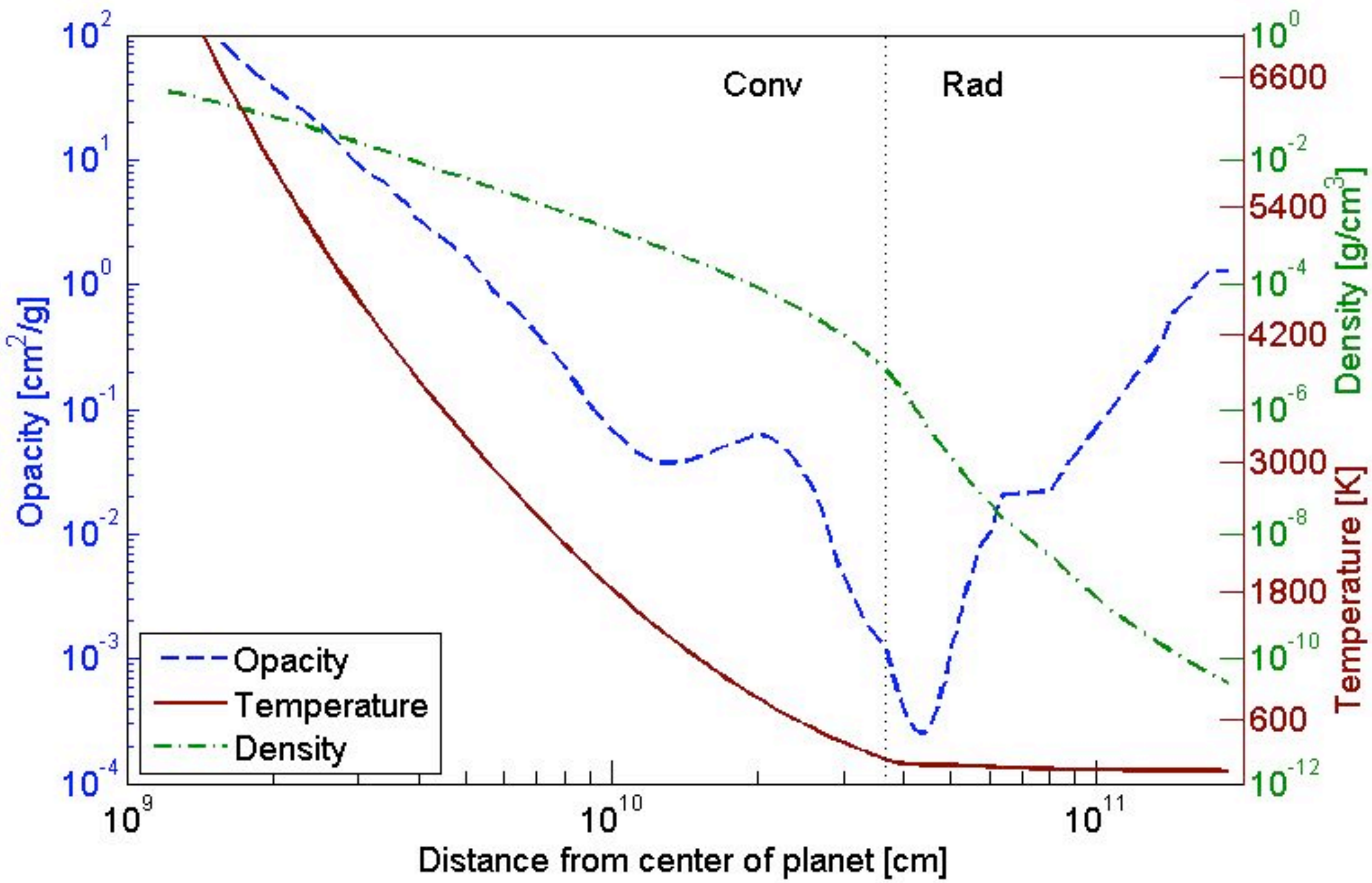

$\sigma = 10$ g/cm^2
$\sigma = 6$ g/cm^2
$\sigma = 4$ g/cm^2
$L\ [L_\odot]$
t [Myr]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
1
2
3
4



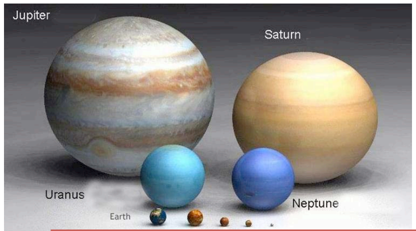


$\sigma = 4\ \mathrm{g/cm^2}$; $t = 1.2 \times 10^6$ yr ; $M_Z = 3.2\ \mathrm{M_{Earth}}$; $M_{XY} = 0.74\ \mathrm{M_{Earth}}$





$\sigma = 4\ \mathrm{g/cm^2}$; $t = 3 \times 10^6$ yr ; $M_Z = 4.1\ \mathrm{M_{Earth}} = M_{XY}$



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Core-nucleated accretion: Big rocks accumulated gas

One model for rocky planets, jovian planets, moons, comets…

Explains composition vs. mass

Detailed models exist

Takes millions of years (depends on M_{core}, atmosphere opacity)

Fragmentation during collapse: Planets form like stars

Rapid

Binary stars are common

Mass gap

Requires $M > 7\ M_J$

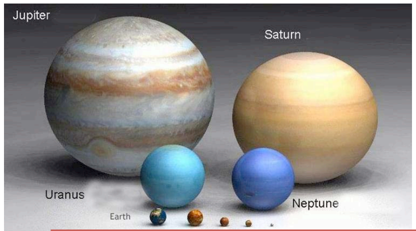
Separate model for solid bodies; no model for Uranus/Neptune

Gravitational instability in disk: Giant gaseous protoplanets

Rapid growth, *but cooling rate limits contraction*

Requires unphysical initial conditions (density waves stabilize)

Separate model for solid bodies; no good model for Uranus/Neptune



[redacted]

Core-nucleated accretion: Big rocks accumulated gas

One model for rocky planets, jovian planets, moons, comets…

Explains composition vs. mass

Detailed models exist

Takes place within typical disk lifetime

Fragmentation during collapse: Planets form like stars

Rapid

Binary stars are common

Mass gap

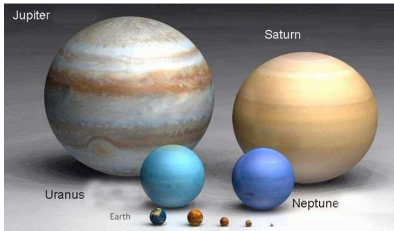
Requires $M > 7\ M_J$

Separate model for solid bodies; no model for Uranus/Neptune

Gravitational instability in disk: Giant gaseous protoplanets

Rapid growth, **but cooling rate limits contraction**

Suitable physical conditions may exist far from stars - HR 8799



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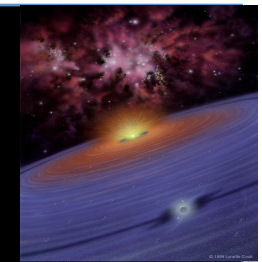

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- *Kepler* will greatly expand our data on terrestrial and giant exoplanets