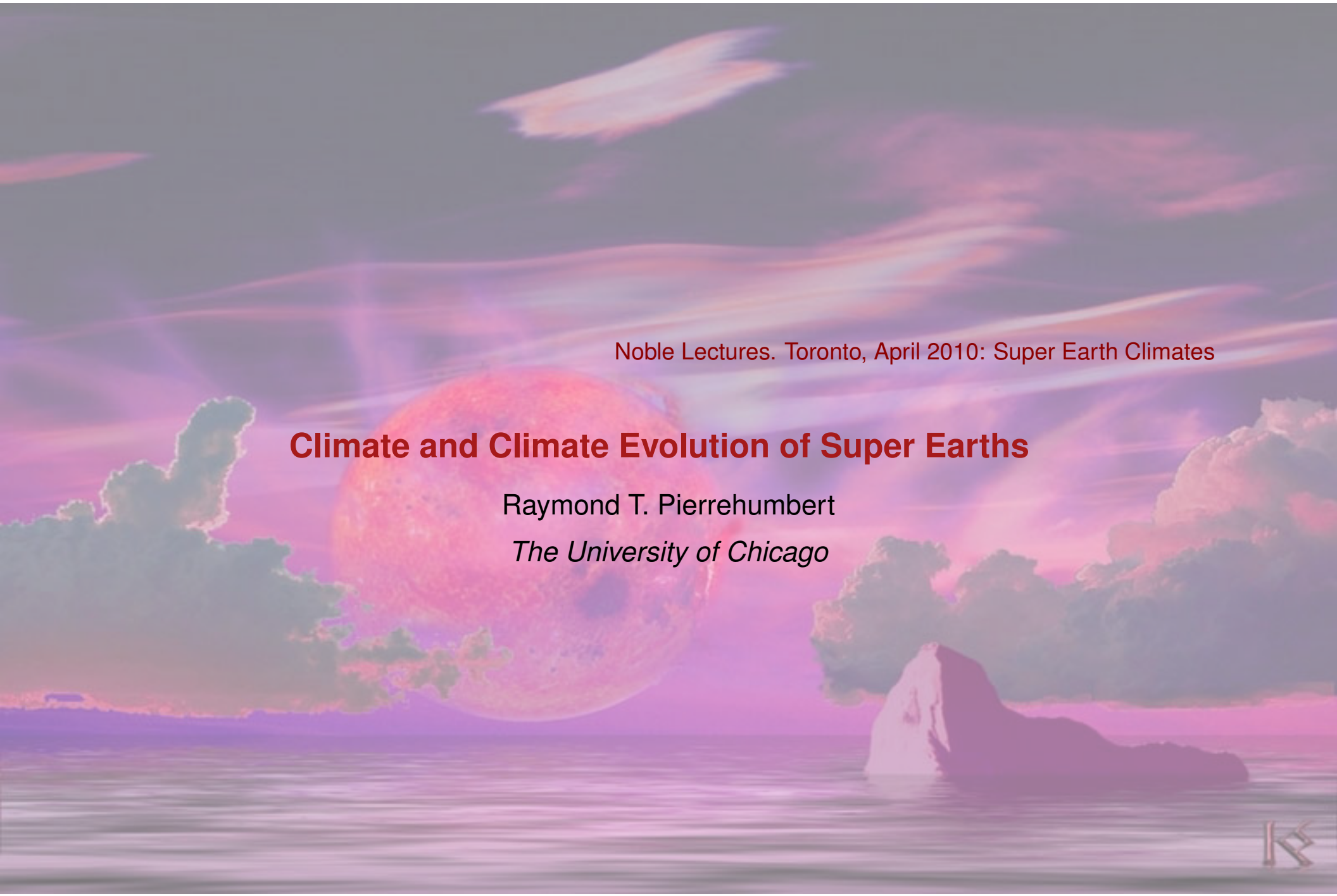
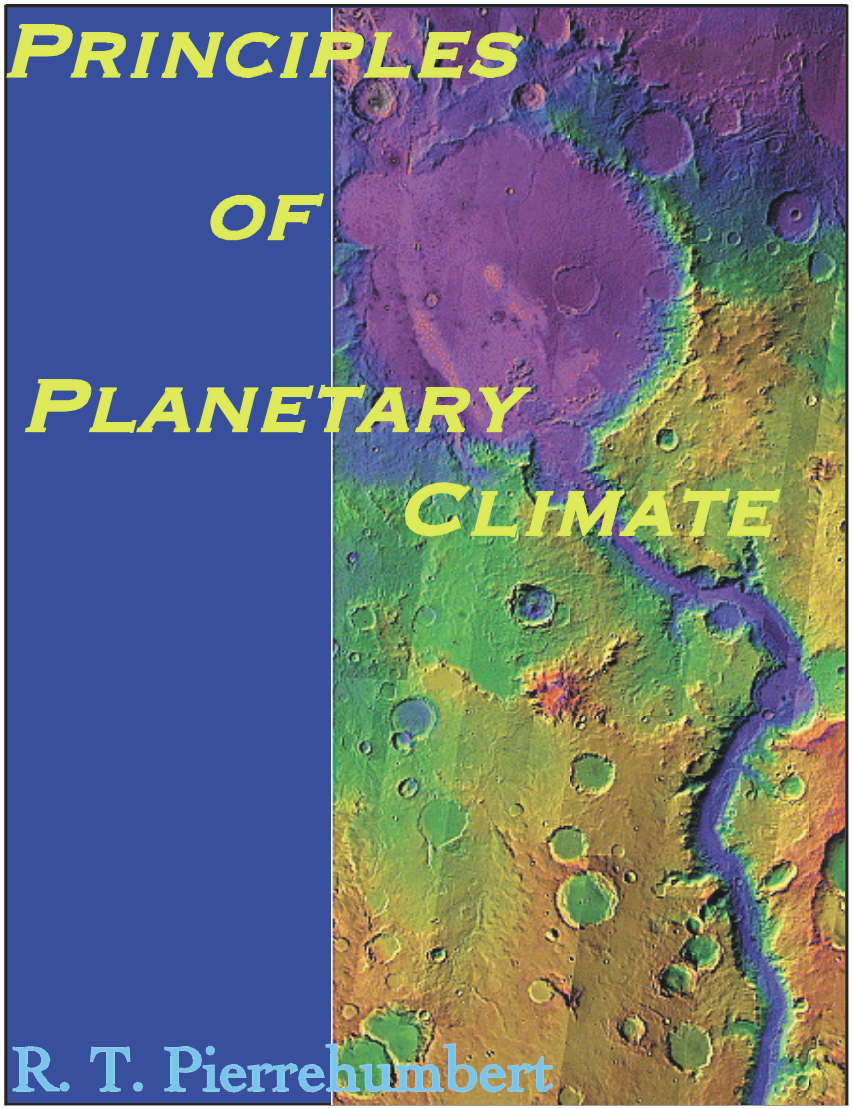


Climate and Climate Evolution of Super Earths

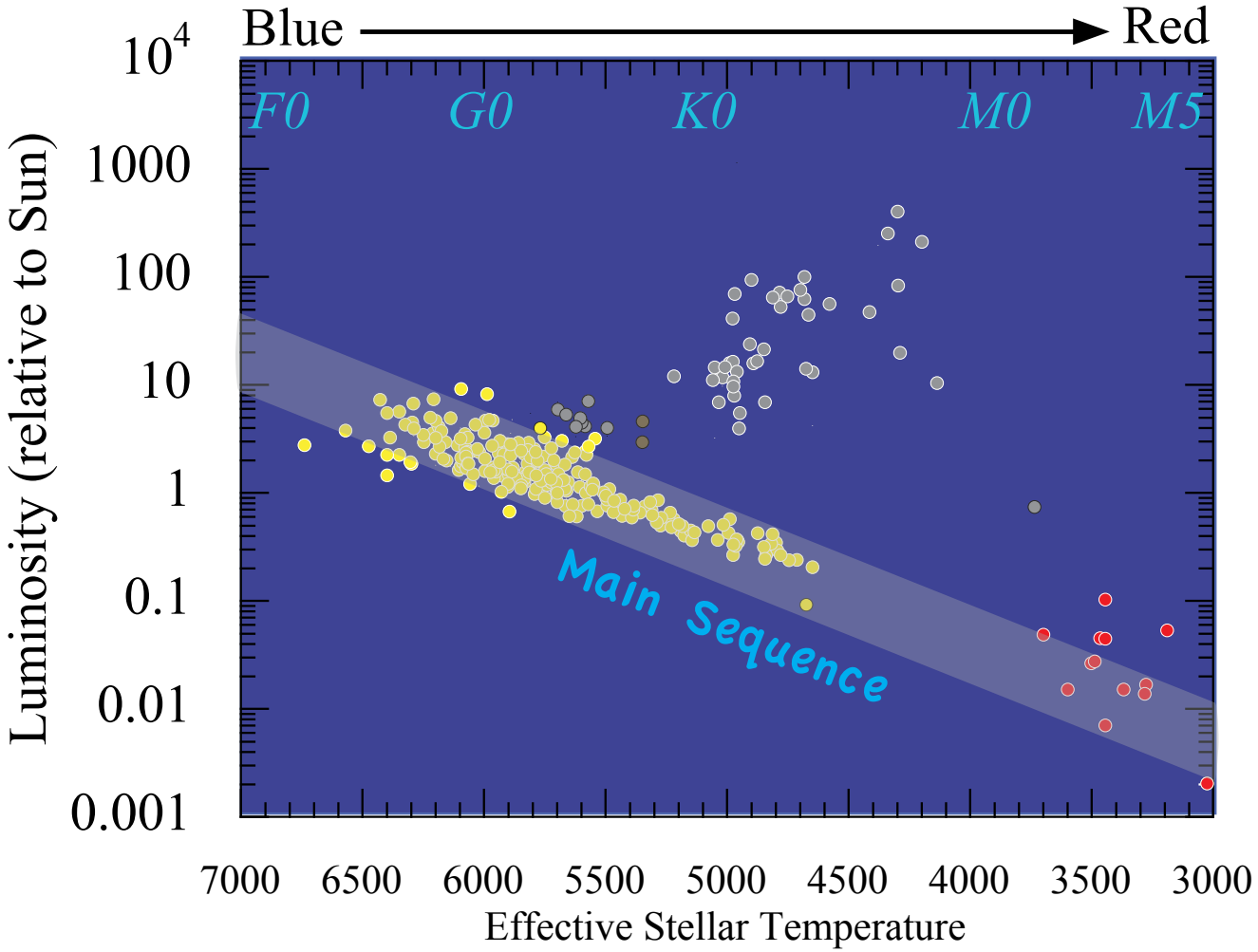
Raymond T. Pierrehumbert

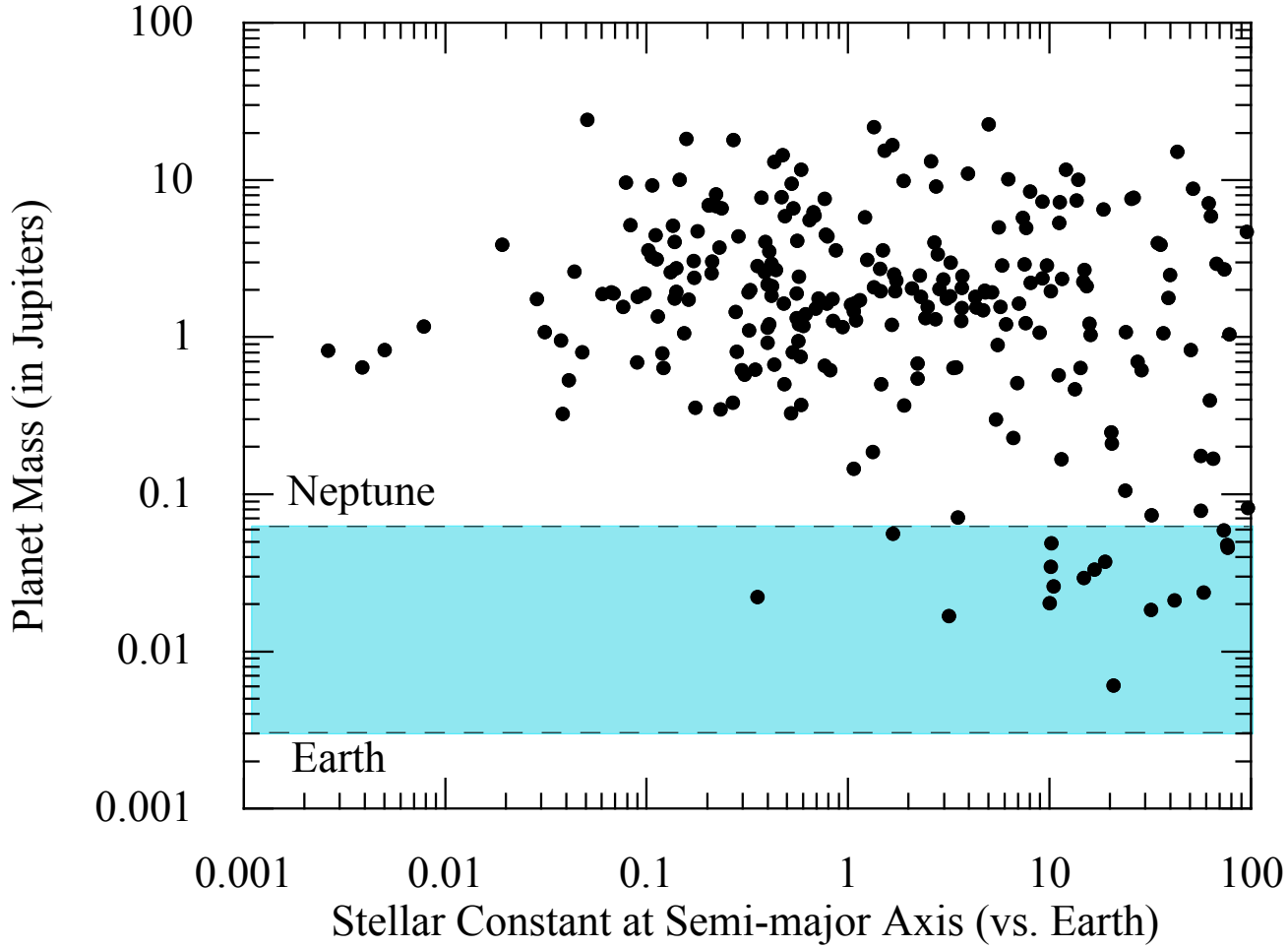
The University of Chicago

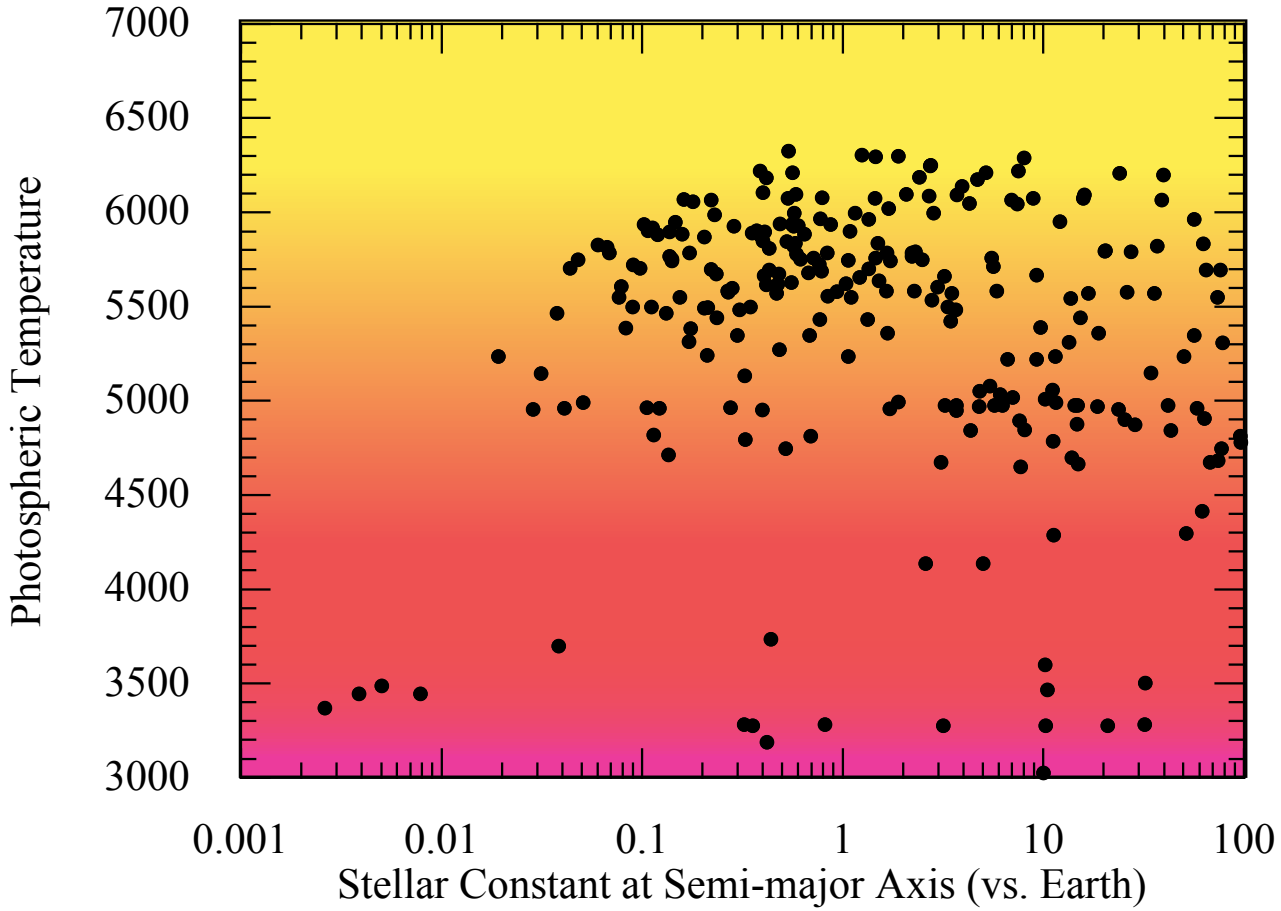


June, 2010

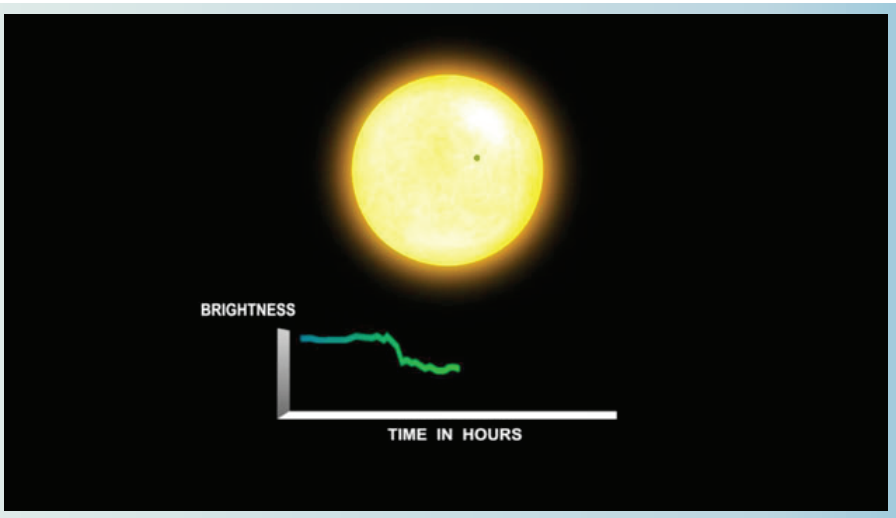
Cambridge
University
Press

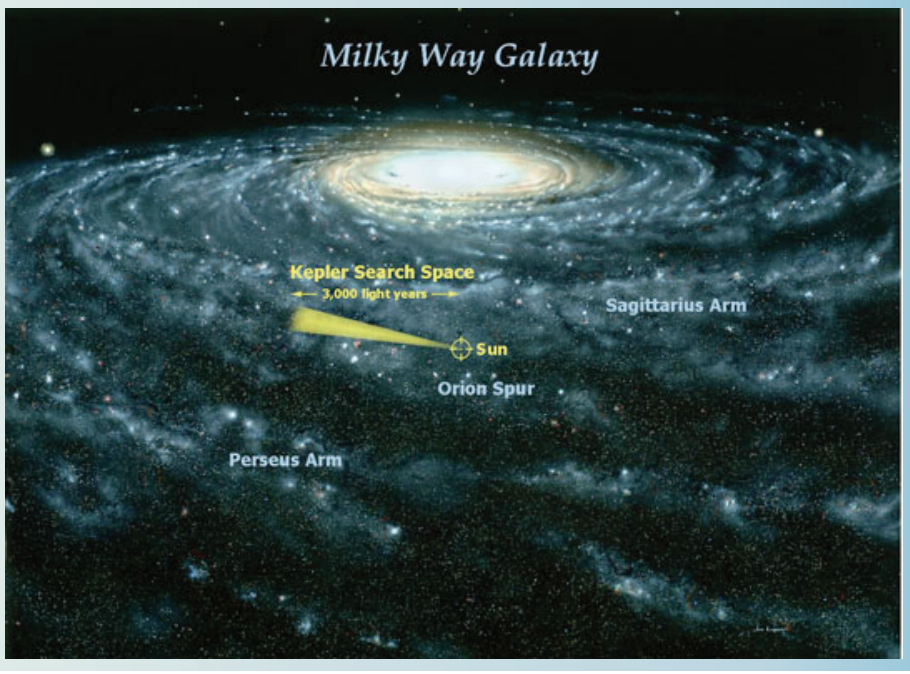

Blue
Red
F0
G0
K0
M0
M5
Main Sequence
Luminosity (relative to Sun)
10^4
1000
100
10
1
0.1
0.01
0.001
7000
6500
6000
5500
5000
4500
4000
3500
3000
Effective Stellar Temperature


100
10
1
0.1
0.01
0.001
Planet Mass (in Jupiters)
Neptune
Earth
0.001
0.01
0.1
1
10
100
Stellar Constant at Semi-major Axis (vs. Earth)

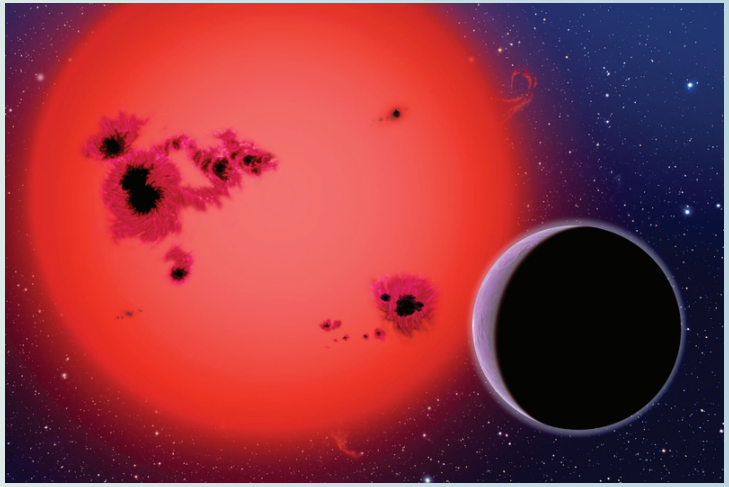

Photospheric Temperature
7000
6500
6000
5500
5000
4500
4000
3500
3000
0.001
0.01
0.1
1
10
100
Stellar Constant at Semi-major Axis (vs. Earth)

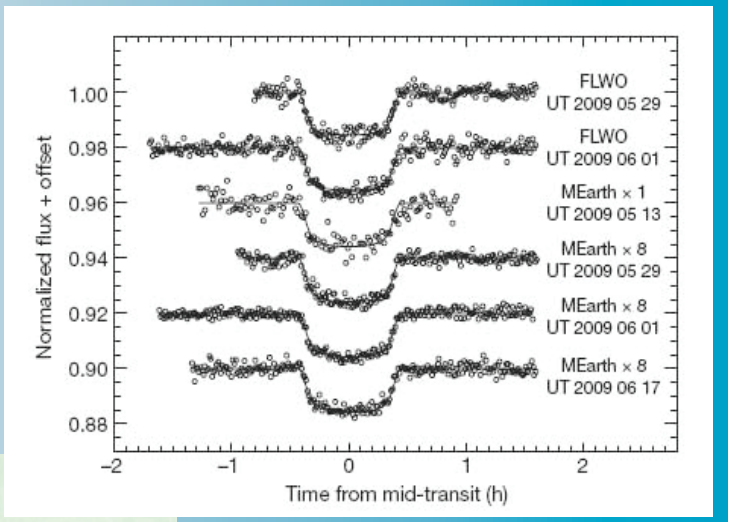
Kepler will fill in Earth-mass window for G stars





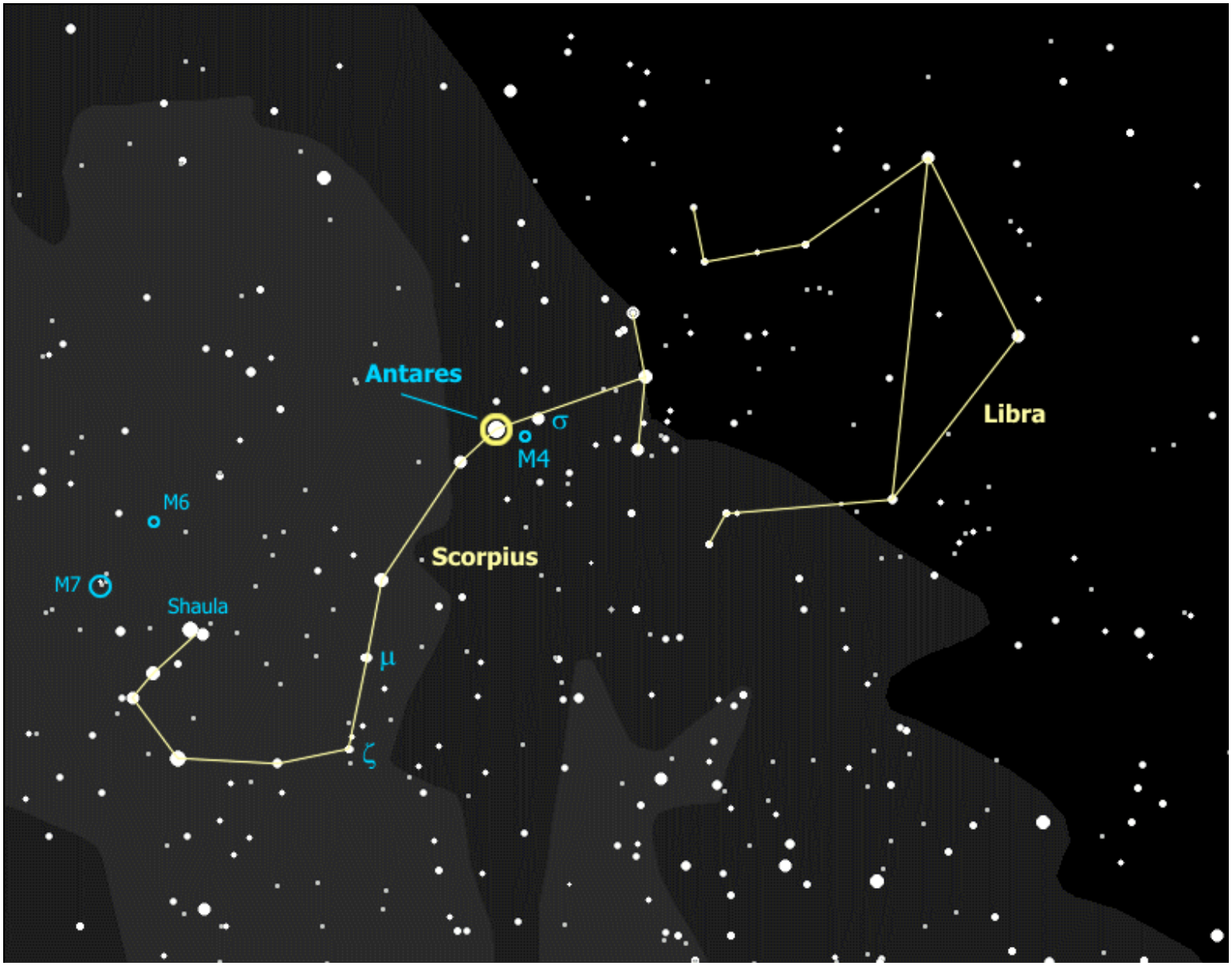
... and MEarth for M stars

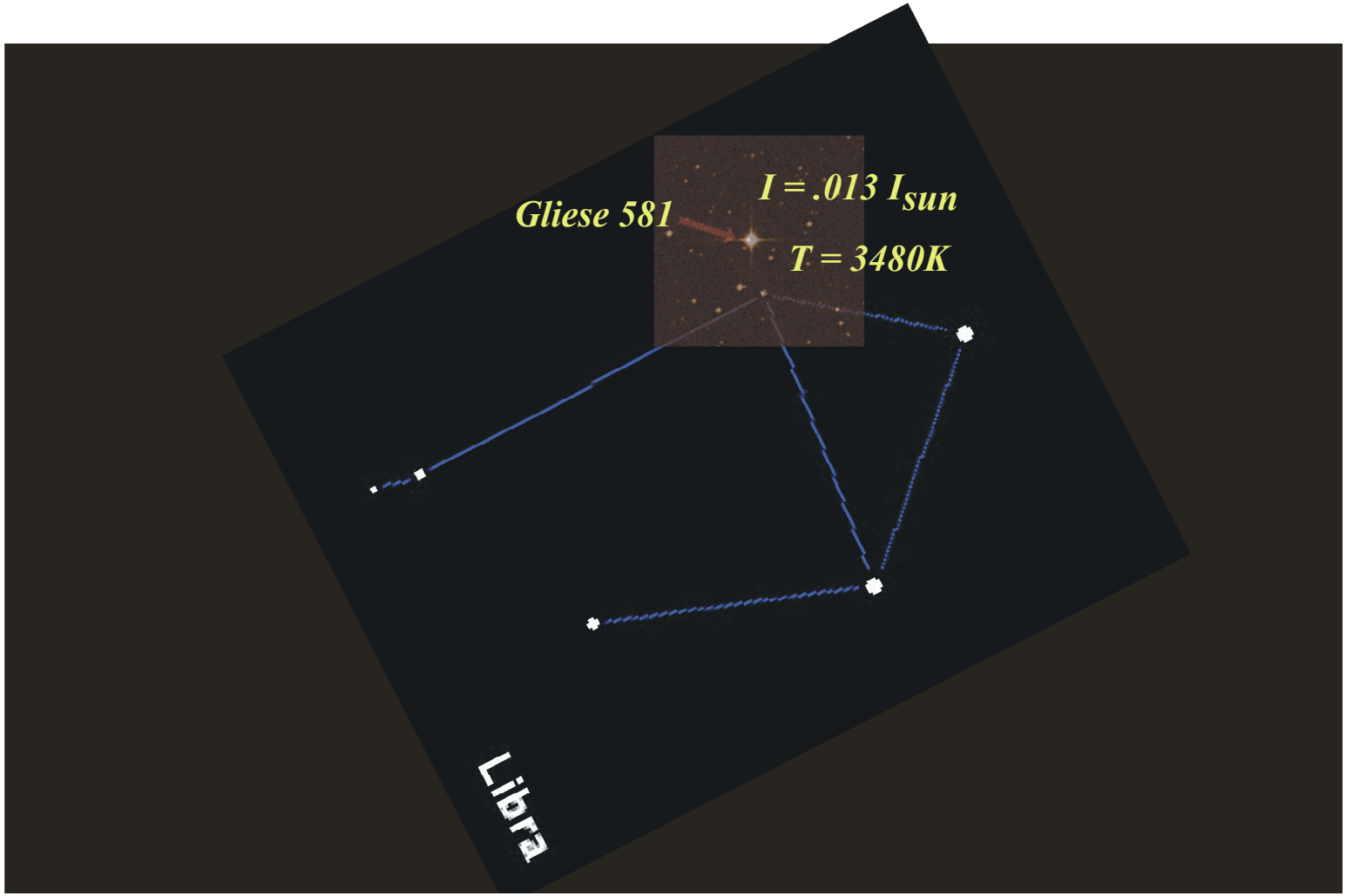


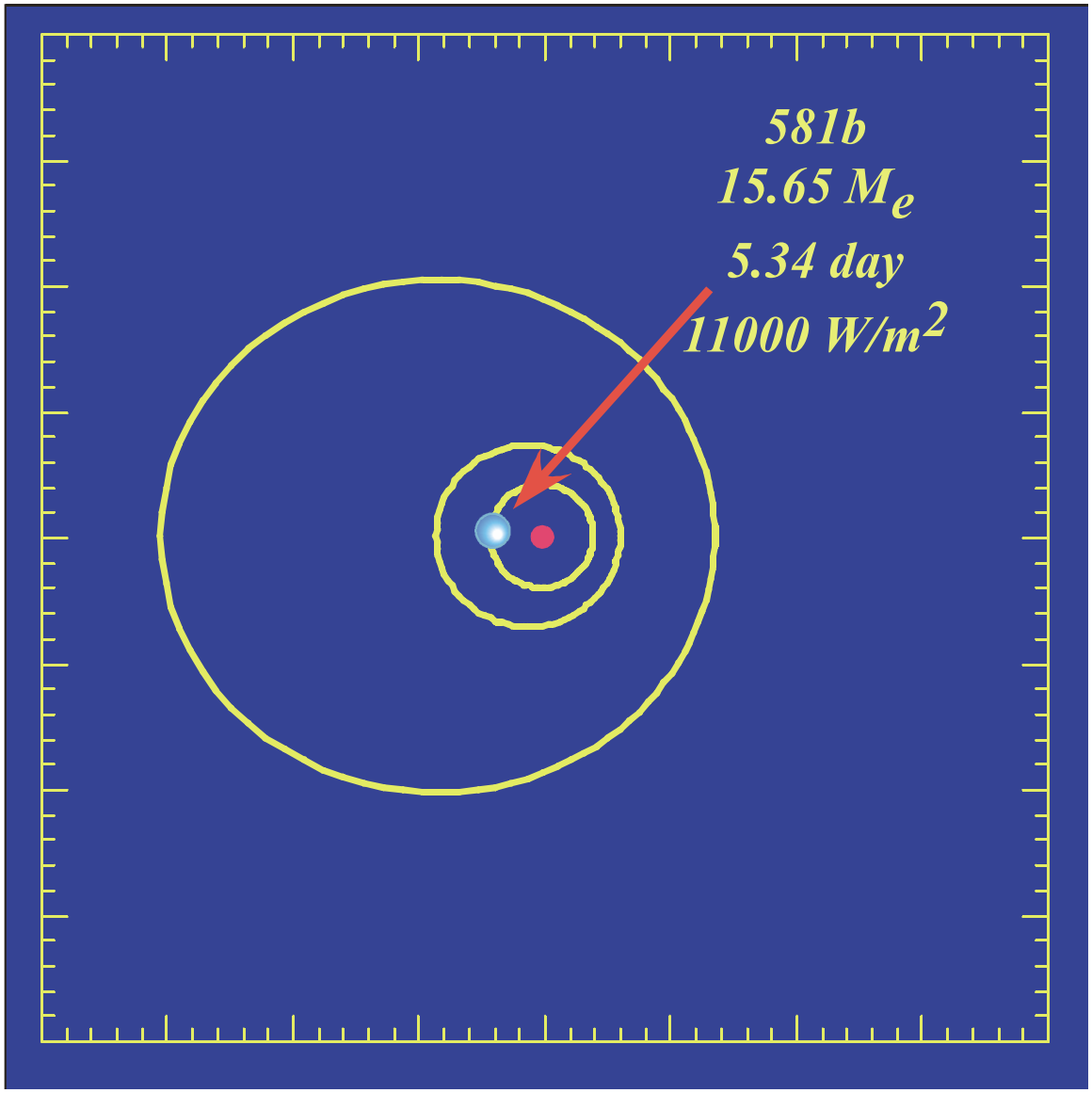


To convert this to climate you need...

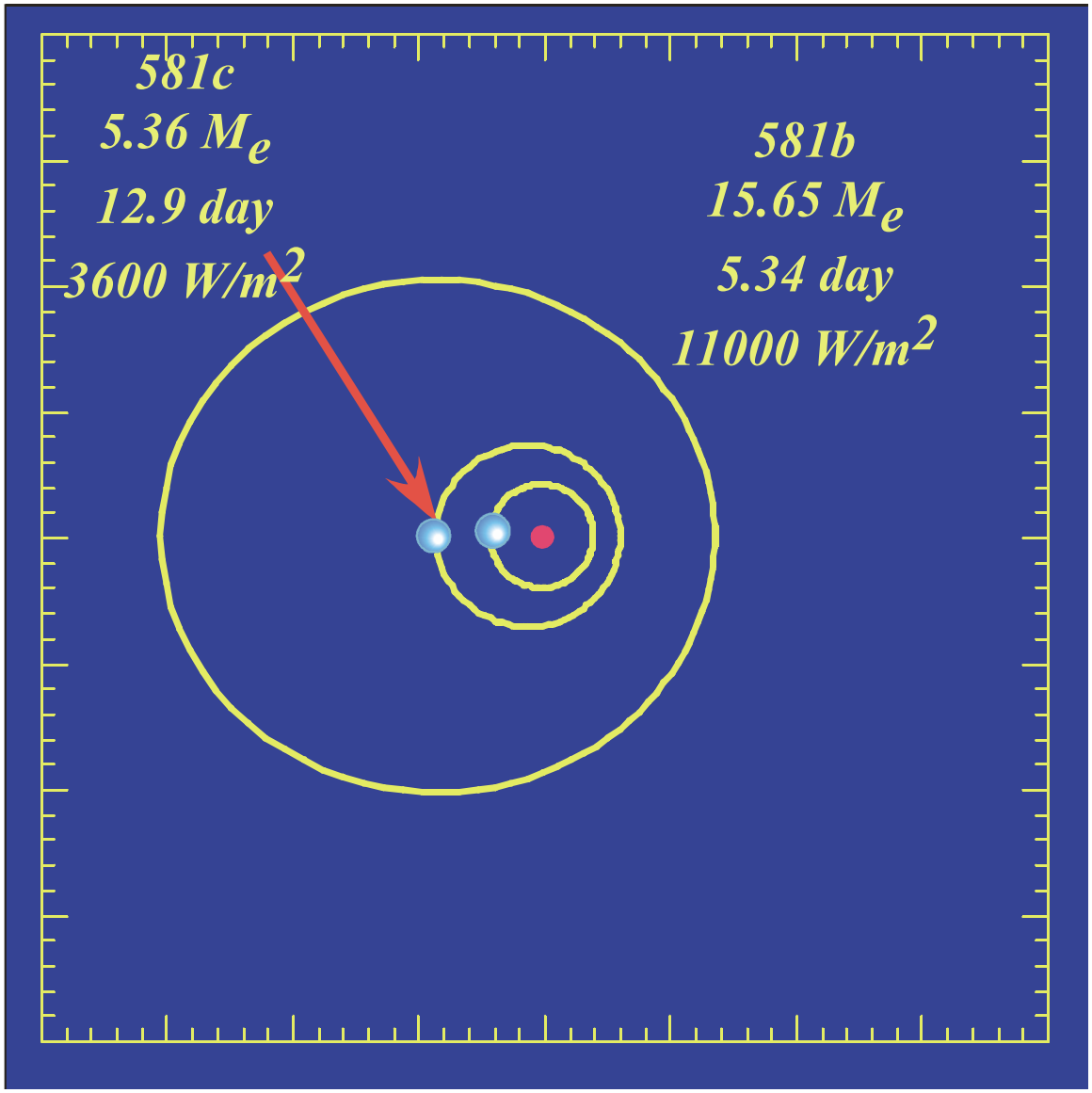
- Atmospheric composition
  - Greenhouse Effect
  - What condenses, if anything?
- Thermal inertia of land and ocean
- Albedo (What freezes? What snows out?)


Antares
σ
M4
Libra
M6
Scorpius
M7
Shaula
μ
ζ

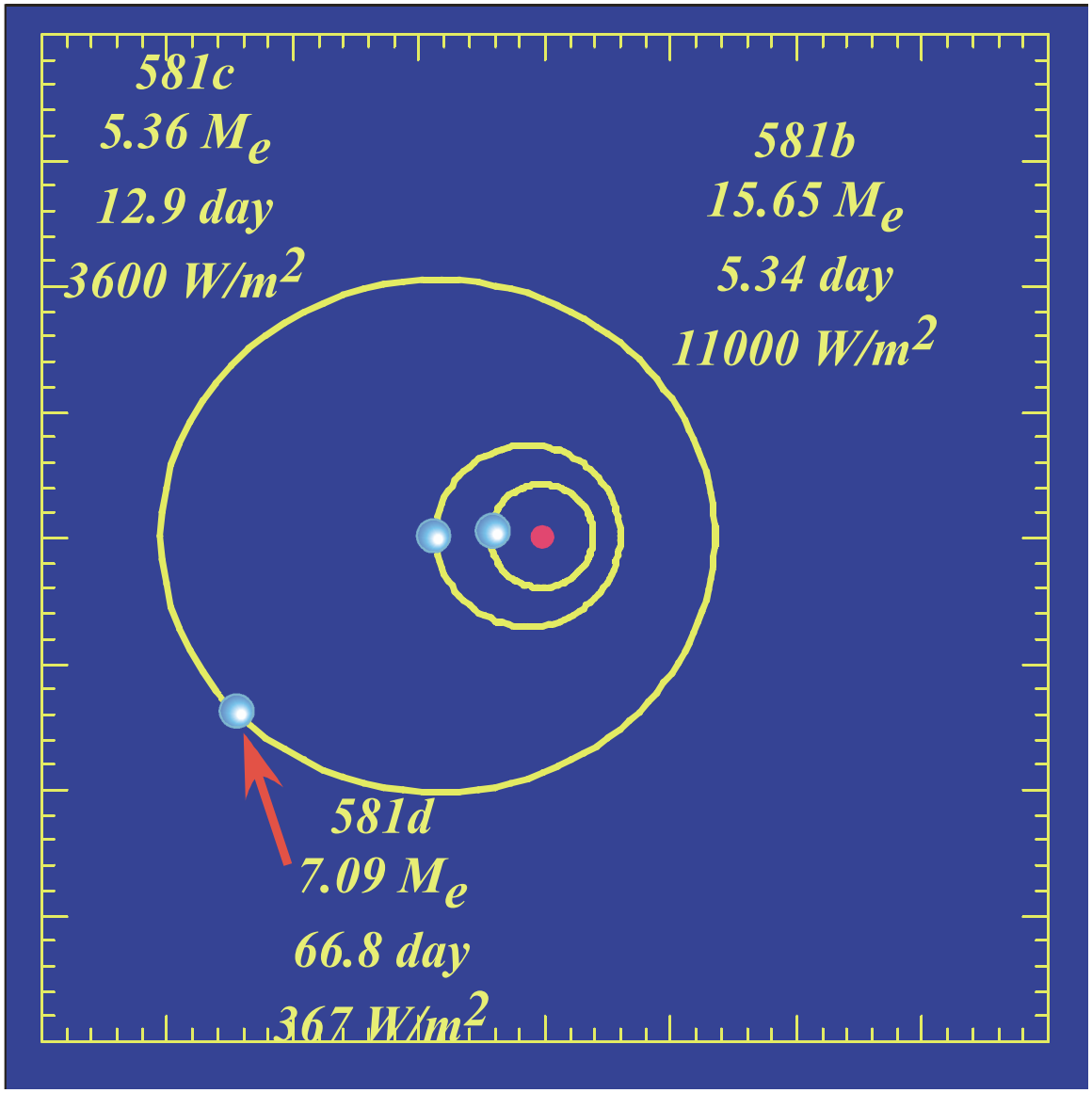

Gliese 581
I = .013 I sun
T = 3480K
Libra



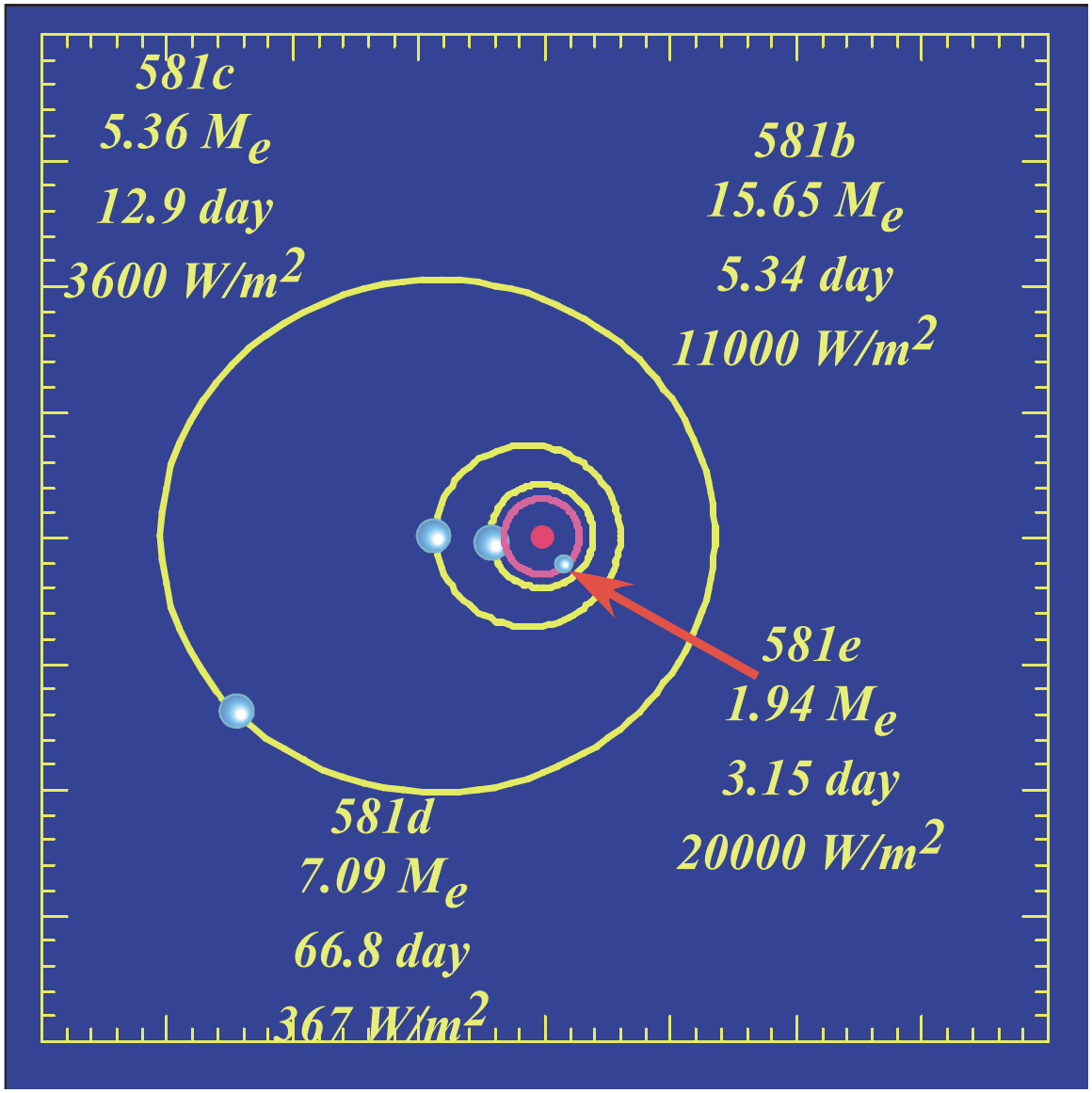
(vs. 2613W/m^2 Venus, 1367W/m^2 Earth, 589W/m^2 Mars



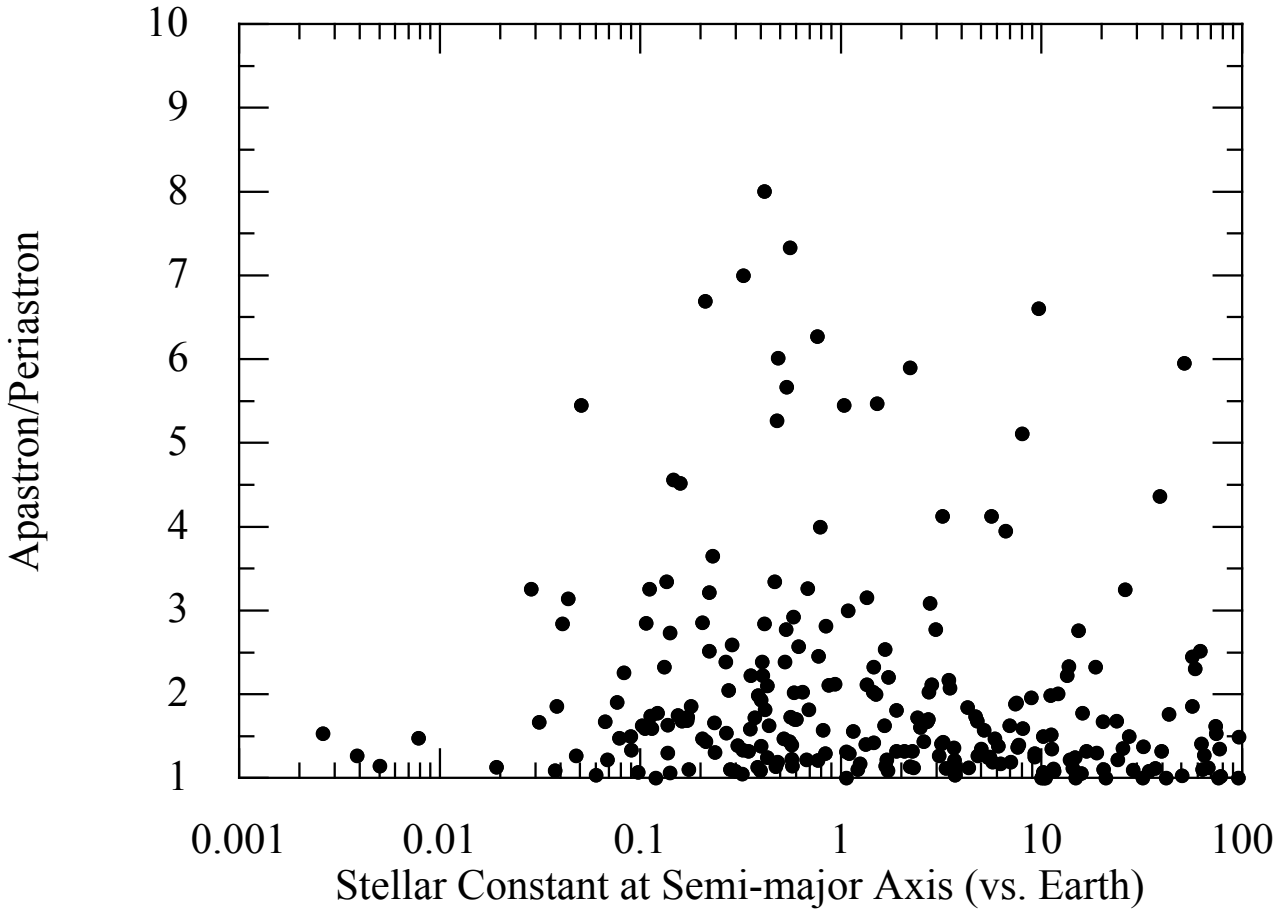
(vs. 2613W/m^2 Venus, 1367W/m^2 Earth, 589W/m^2 Mars



(vs. 2613W/m^2 Venus, 1367W/m^2 Earth, 589W/m^2 Mars

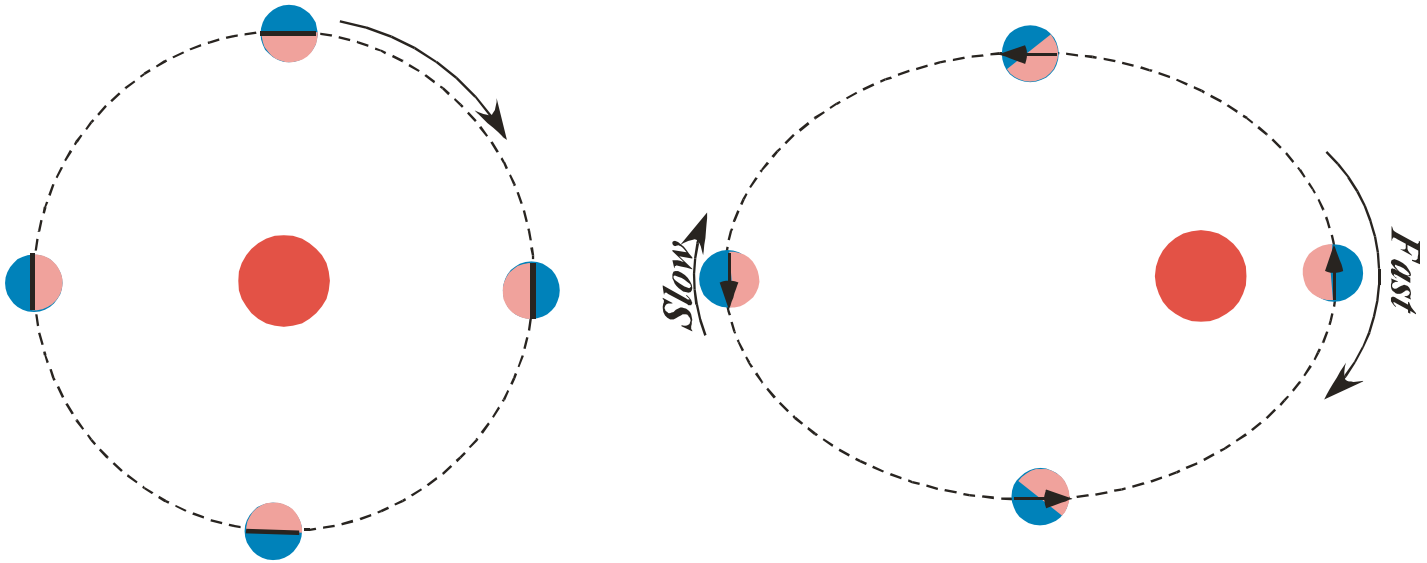


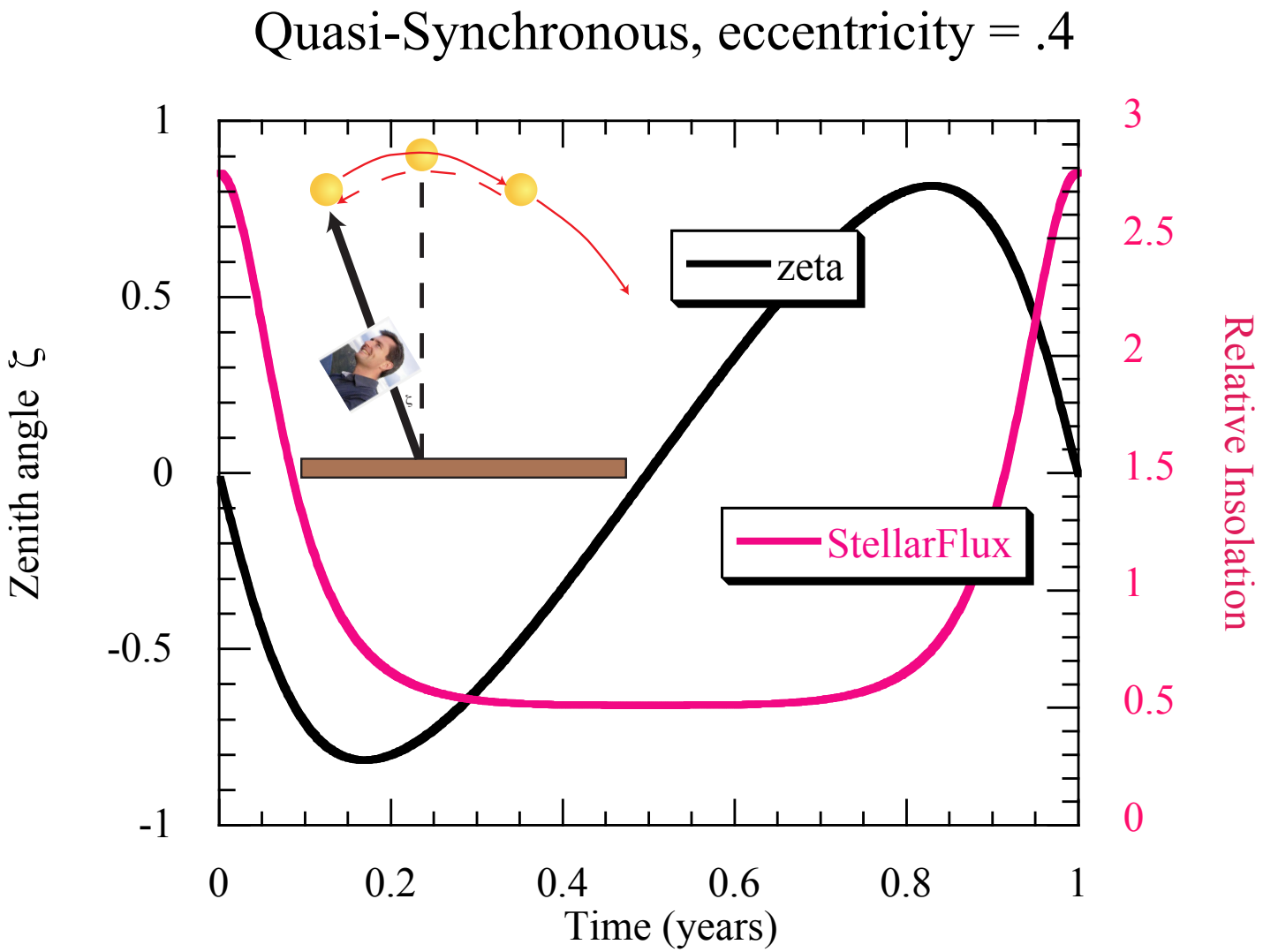
(vs. 2613W/m^2 Venus, 1367W/m^2 Earth, 589W/m^2 Mars


Apastron/Periastron
10
9
8
7
6
5
4
3
2
1
0.001
0.01
0.1
1
10
100
Stellar Constant at Semi-major Axis (vs. Earth)

Exotic Orbits and Spin States

(*Exotic for Solar System, not Universe!*)




Quasi-Synchronous, eccentricity = .4
Zenith angle ζ
Relative Insolation
Time (years)
zeta
StellarFlux
1
0.5
0
-0.5
-1
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1

Basic physical issues

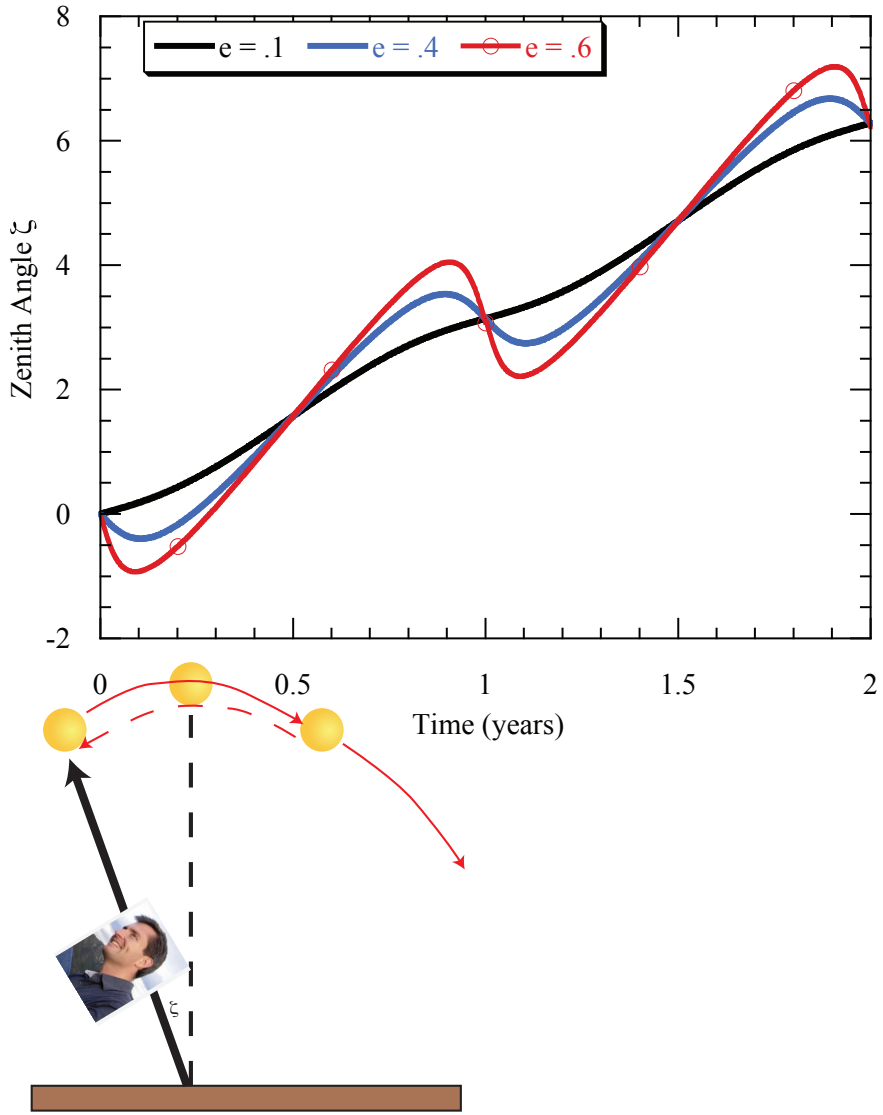
- Low Coriolis force implies efficient atmospheric heat transport. Free atmosphere temperature horizontally uniform (cf. Venus, Titan).
- But weak coupling to surface allows significant surface temperature variation
- Ocean thermal inertia evens out seasonal extremes from highly eccentric orbit or high obliquity. Even a 50m deep ocean can do this.
- Continents will experience extreme *surface* seasonal cycle.

Thermal inertia time scales

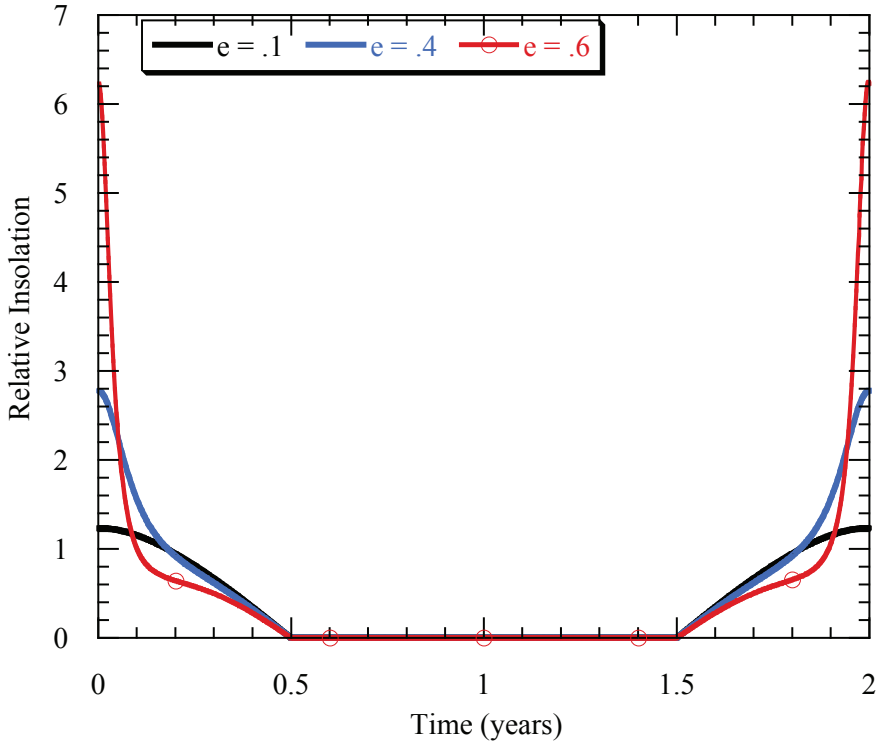
- $\tau = \rho c_p H/b \approx .13 H/b$ (years)
- b is radiative emission coeff. $4\sigma T^3$ if no atmosphere. 2 $\mathrm{W/m^2K}$ for Earthlike atmosphere
- Hence for 50 m mixed layer, $\tau \approx 3$ Earth years
- Convection of cooling water into deep ocean can increase this by two orders of magnitude
- Over land, surface seasonal cycle attenuated at depths $> \sqrt{Dt_y}$ (Fourier's solution)

Full GCM Simulations

- Earthlike $CO_2/N_2/H_2O$ atmosphere.
- Global mixed-layer ocean, no continents



Three:Two Spin-orbit Resonance



Additional climate determinants

- Gravity – p_s/g (mass path) vs p_s (condensation, chemistry)
- Gravity and size (gr determines escape of light elements)
- Size (Dynamical regime – large planet like faster rotaton)
- Stellar spectrum (Atmos. surface absorption)
  More on this Friday

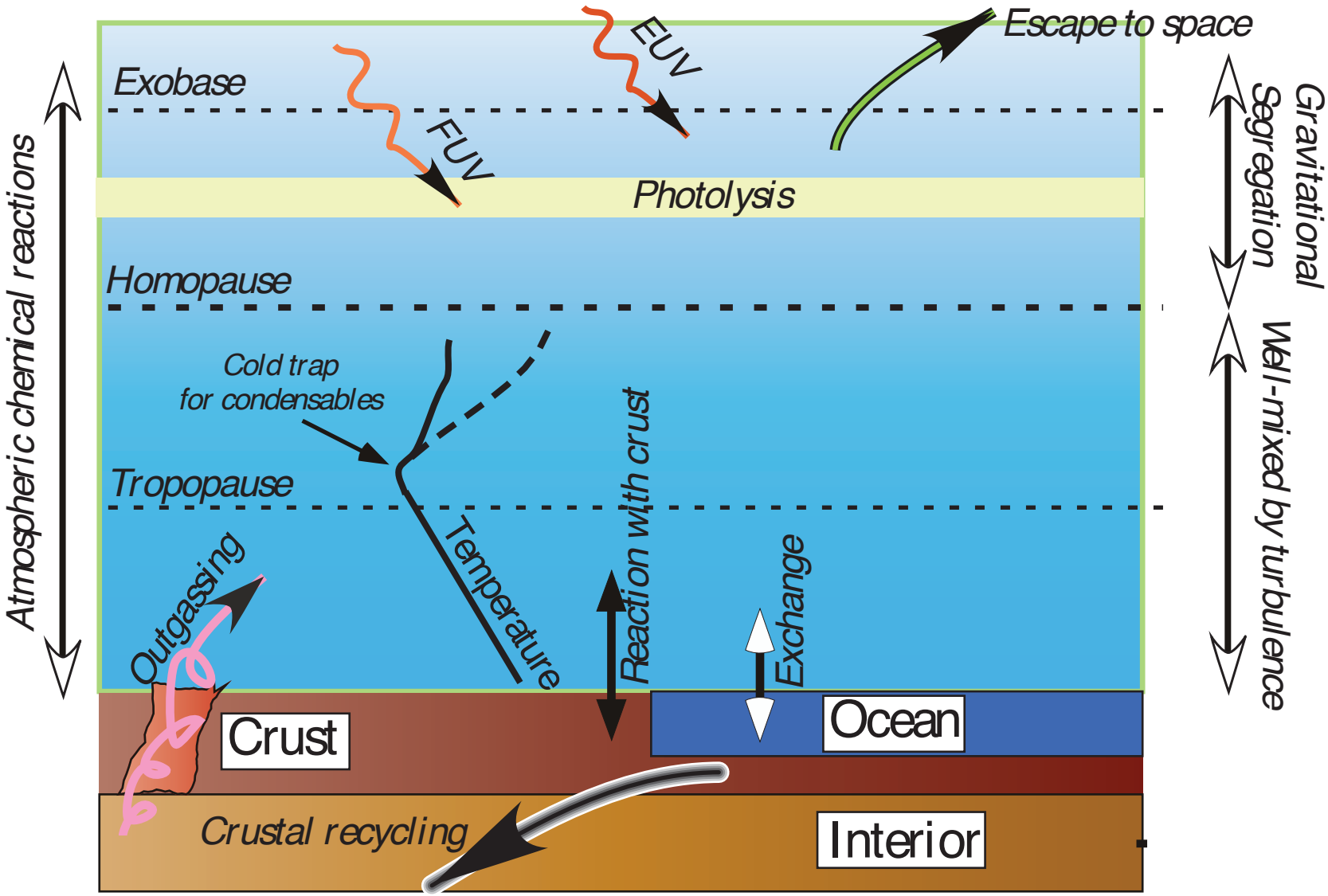
Stellar activity

- M-stars have proportionately higher EUV output relative to net luminosity
- Feeds atmospheric escape
- FUV is subthermal, implying weaker photochemistry

Climate Evolution: Faint Young Sun

- Luminosity of main sequence stars increases over their lifetime
- 30% over 4 billion years for G star
- Not so much of an issue for M stars

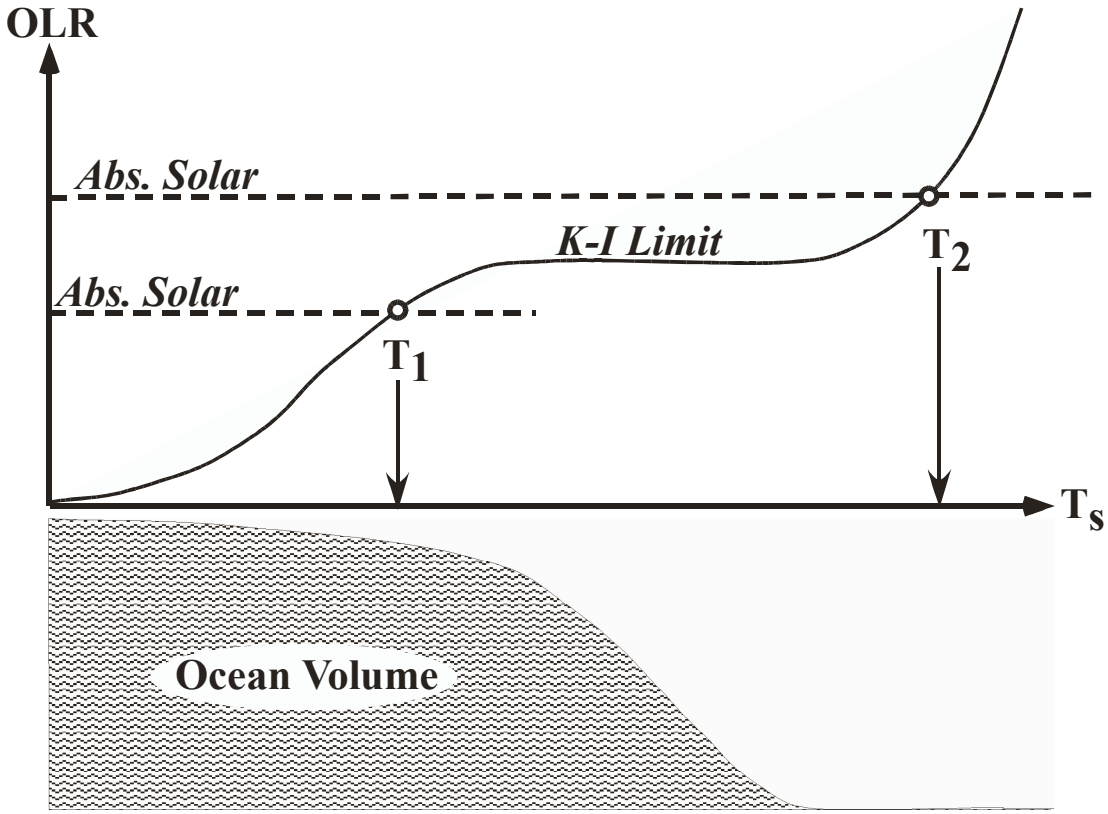
But there's a lot more to climate evolution than that!


Escape to space
EUV
Exobase
FUV
Photolysis
Homopause
Cold trap
for condensables
Tropopause
Temperature
Reaction with crust
Exchange
Outgassing
Crust
Ocean
Crustal recycling
Interior
Atmospheric chemical reactions
Gravitational Segregation
Well-mixed by turbulence

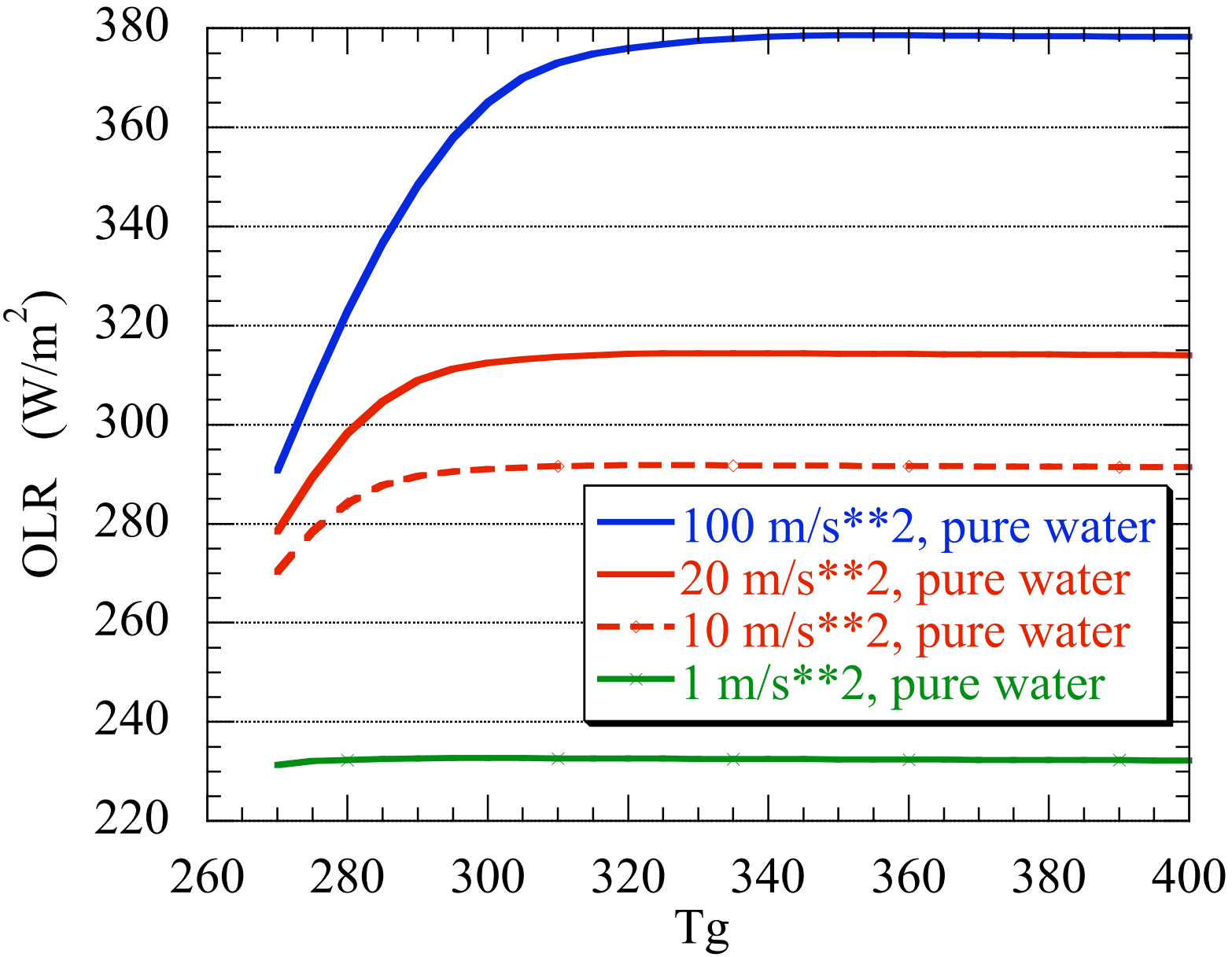
Let's focus in on hot Super-Earth evolution

i.e. is Gliese 581d a Super Venus or something completely different?

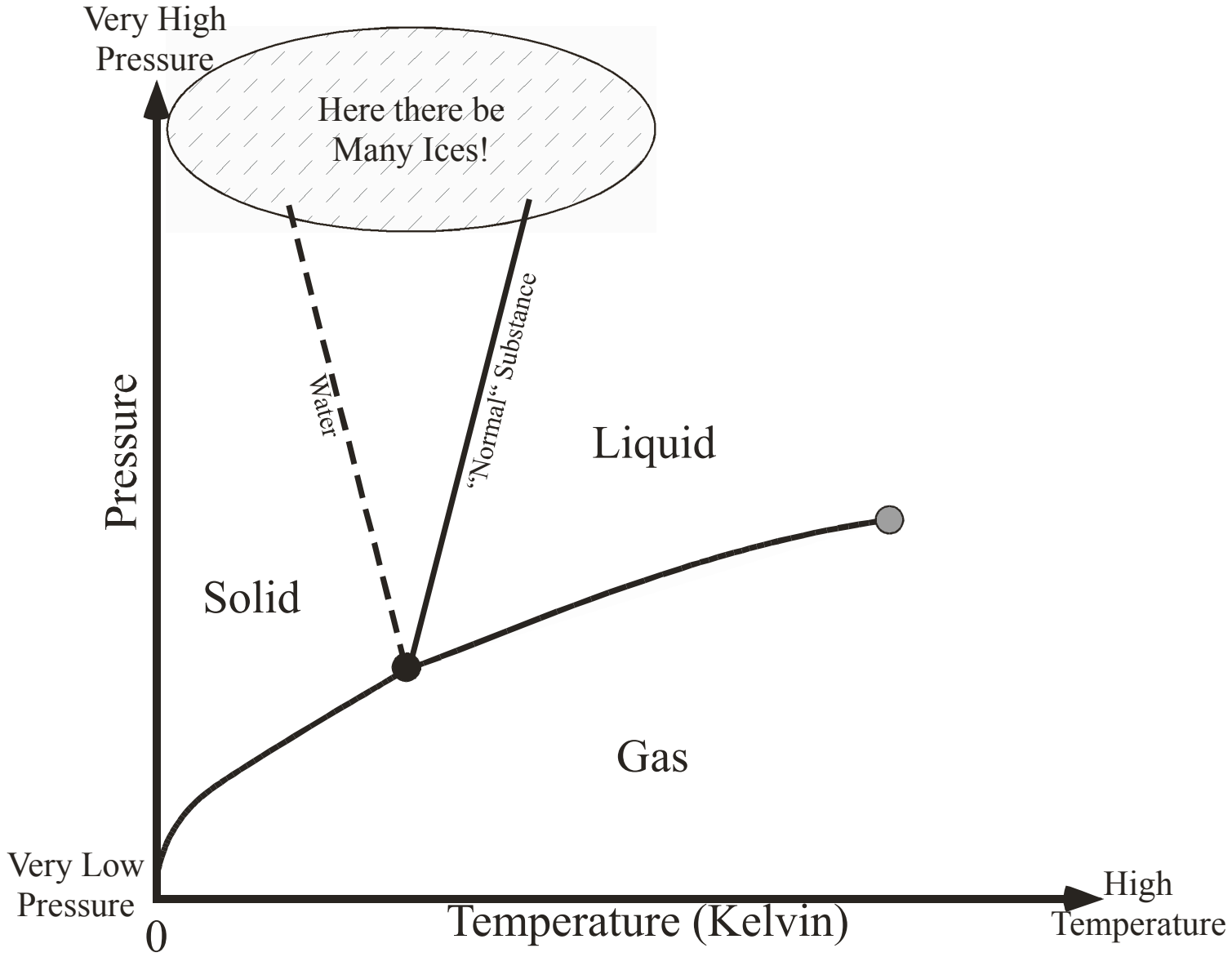
Runaway greenhouse in a nutshell



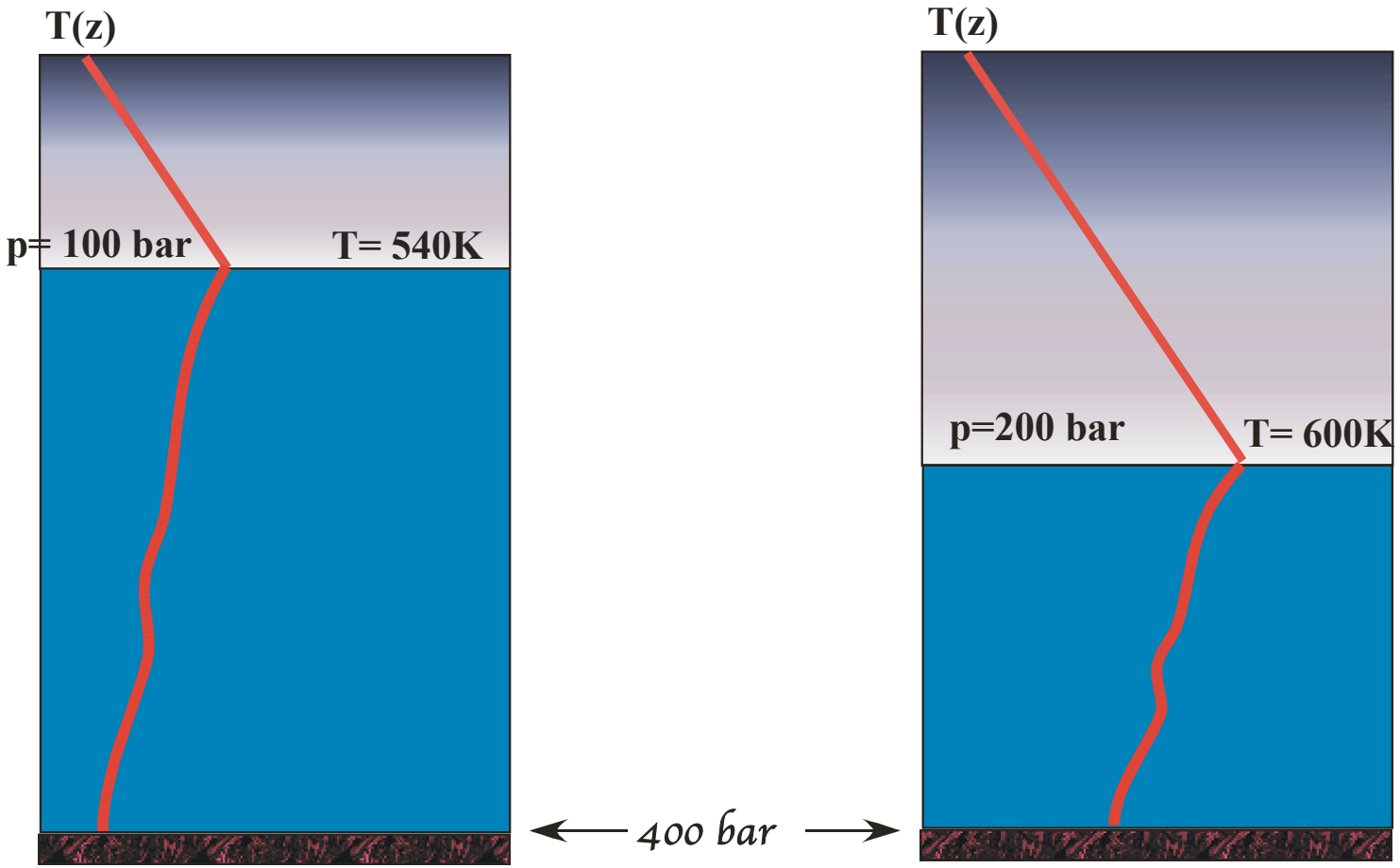
Noble Lectures. Toronto, April 2010: Super Earth Climates


380
360
340
320
300
280
260
240
220
OLR (W/m^2)
260
280
300
320
340
360
380
400
Tg
100 m/s**2, pure water
20 m/s**2, pure water
10 m/s**2, pure water
1 m/s**2, pure water

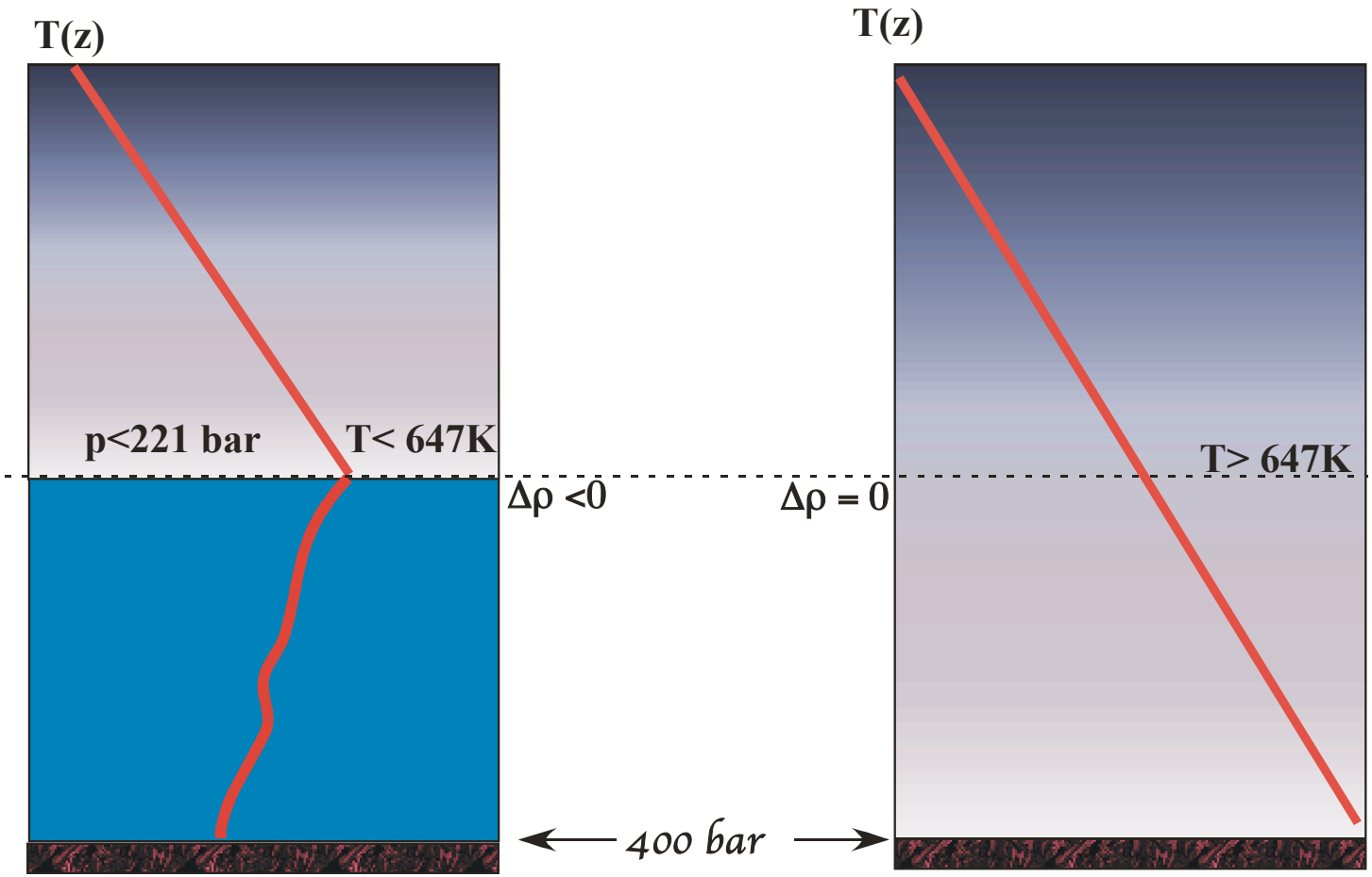
The Critical Point



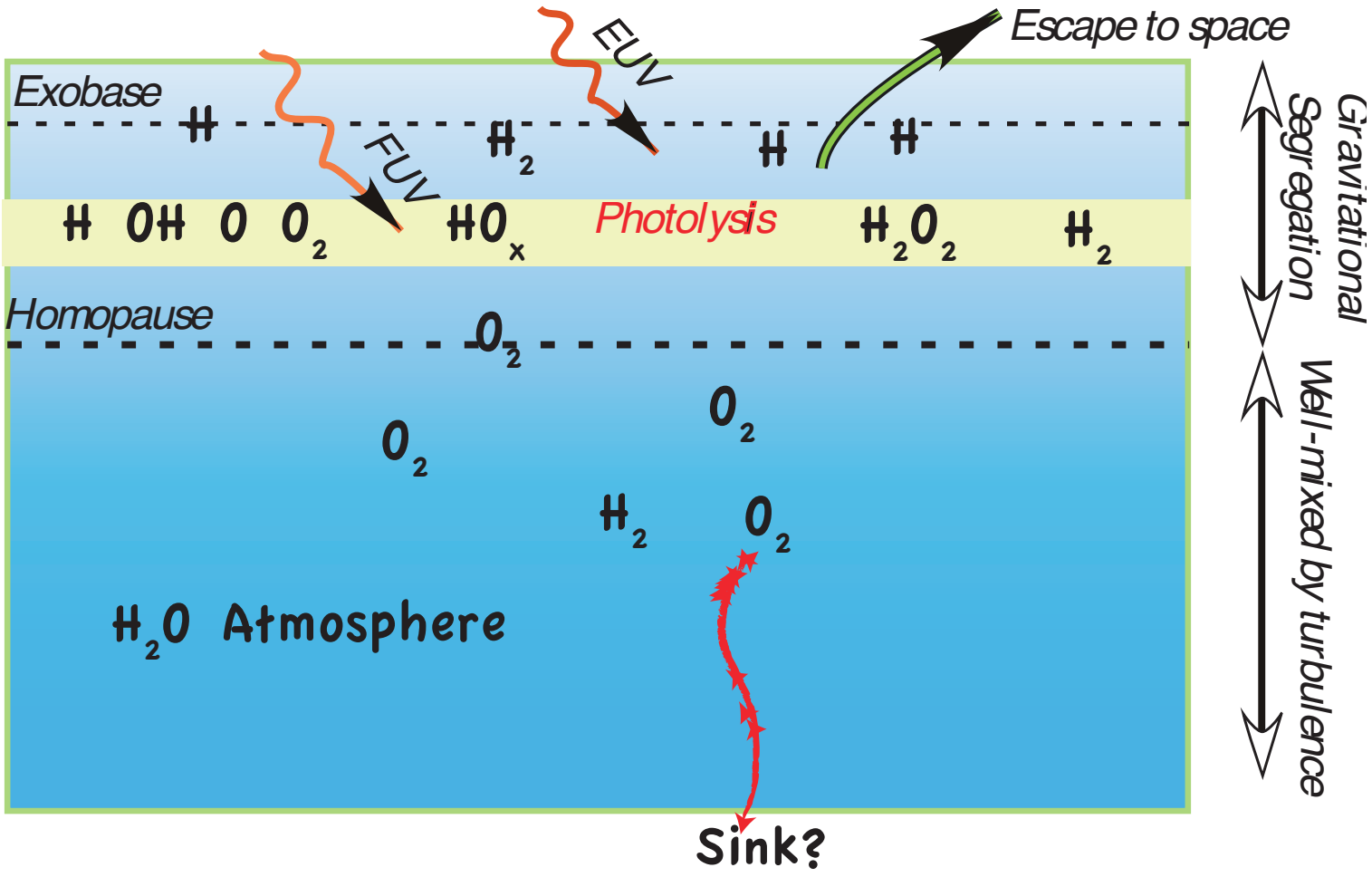
The Critical Point and Super-Earth Runaway

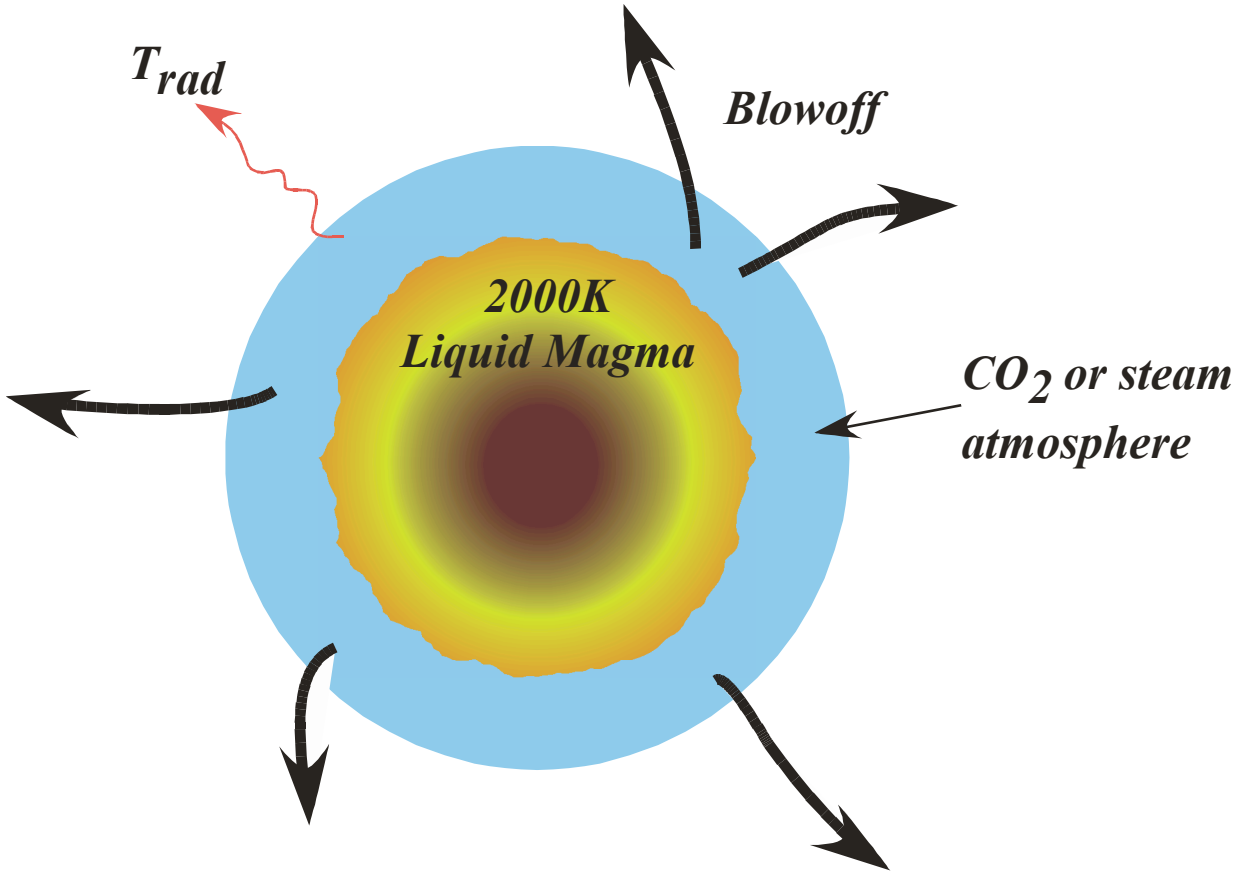


The Critical Point and Super-Earth Runaway



Need oxygen sink for irreversible water loss




T_{rad}
Blowoff
2000K
Liquid Magma
CO_2 or steam
atmosphere

The Critical Point and Magma Oceans

- Work with Diana Valencia
- How long does a magma ocean last?
- Could we detect an extrasolar magma ocean?
- High temperatures $\longrightarrow$ hydrodynamic blowoff $\longrightarrow$ very extended atomic H corona.

Implications

- Note: liquidus for basalt $\approx 2000K$
- Supercritical, so OLR not limited by K-I limit
- We compute the OLR using non-ideal equation of state for water, down to the magma ocean surface
- $OLR \approx 10000 W/m^2$ for 200 bar water inventory.
- Greater cooling $\rightarrow$ shorter magma ocean lifetimes than Norm Sleep's upper bound. (i.e. $<$ 100Kyr, depending on water inventory)
- A pity, since spectrum of extrasolar magma ocean planets would be readily identifiable
- OLR starts to increase once T_s reaches $637K$, not when you evaporate the whole ocean.

Some parting remarks

- Exotic orbits are not much of a threat to habitability
- Need for GCM simulations which handle optically thick atmospheres and major constituent condensation.
- For ice cover problem, need dynamic ocean simulations
- Discovery of an atmosphere – any atmosphere – about a Gliese-581c class planet would be big news.
- We are on the brink of discovery of planets with the potential for truly Earthlike climates
- The next few years will be very interesting

Additional parting remarks

- Note that I didn't say anything about clouds
- Clouds are the bete noir (blanche?) of all climate theory
- (Did I mention that I didn't say anything about clouds?)