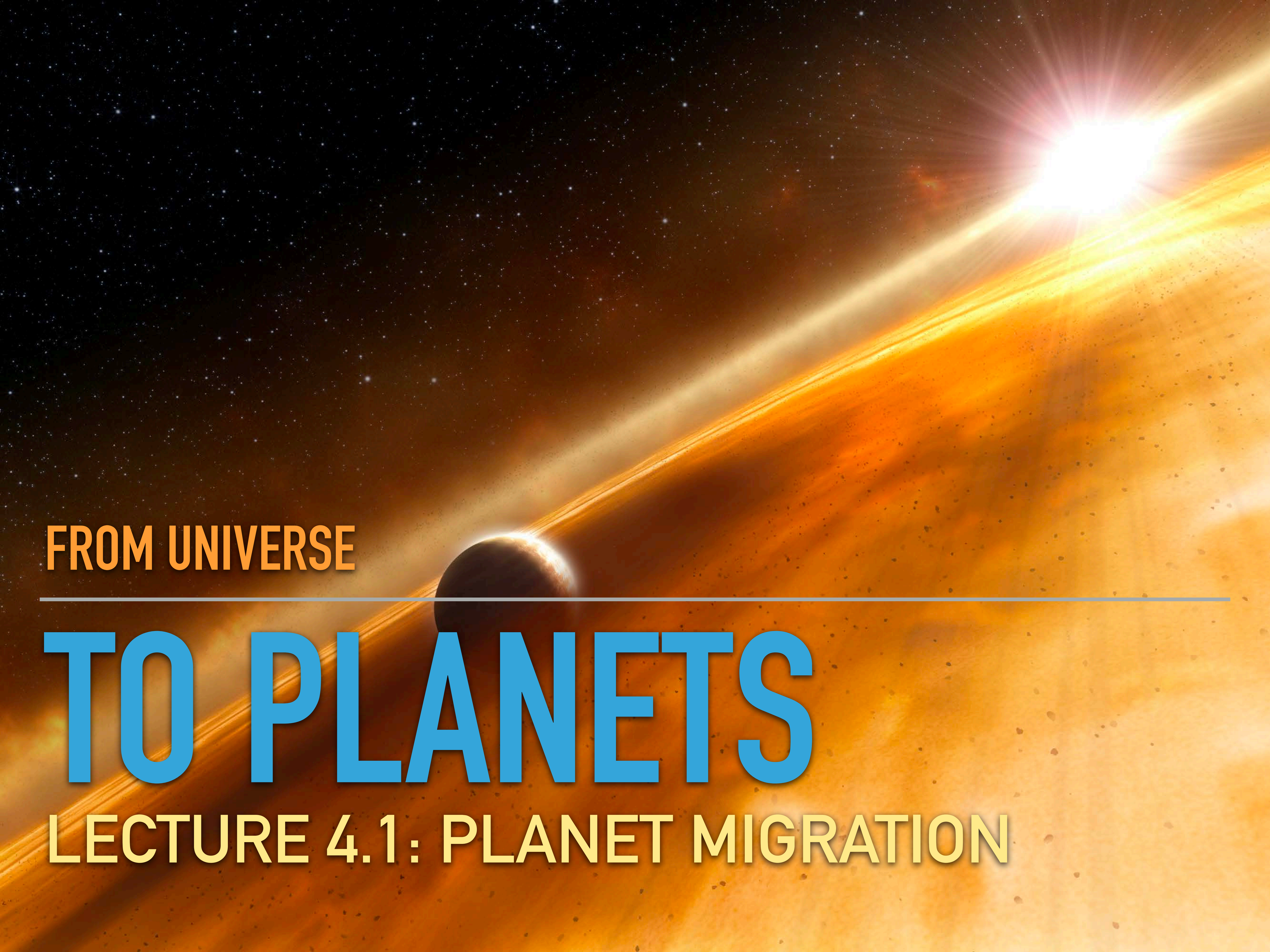
FROM UNIVERSE

TO PLANETS

LECTURE 4: PLANETARY DYNAMICS

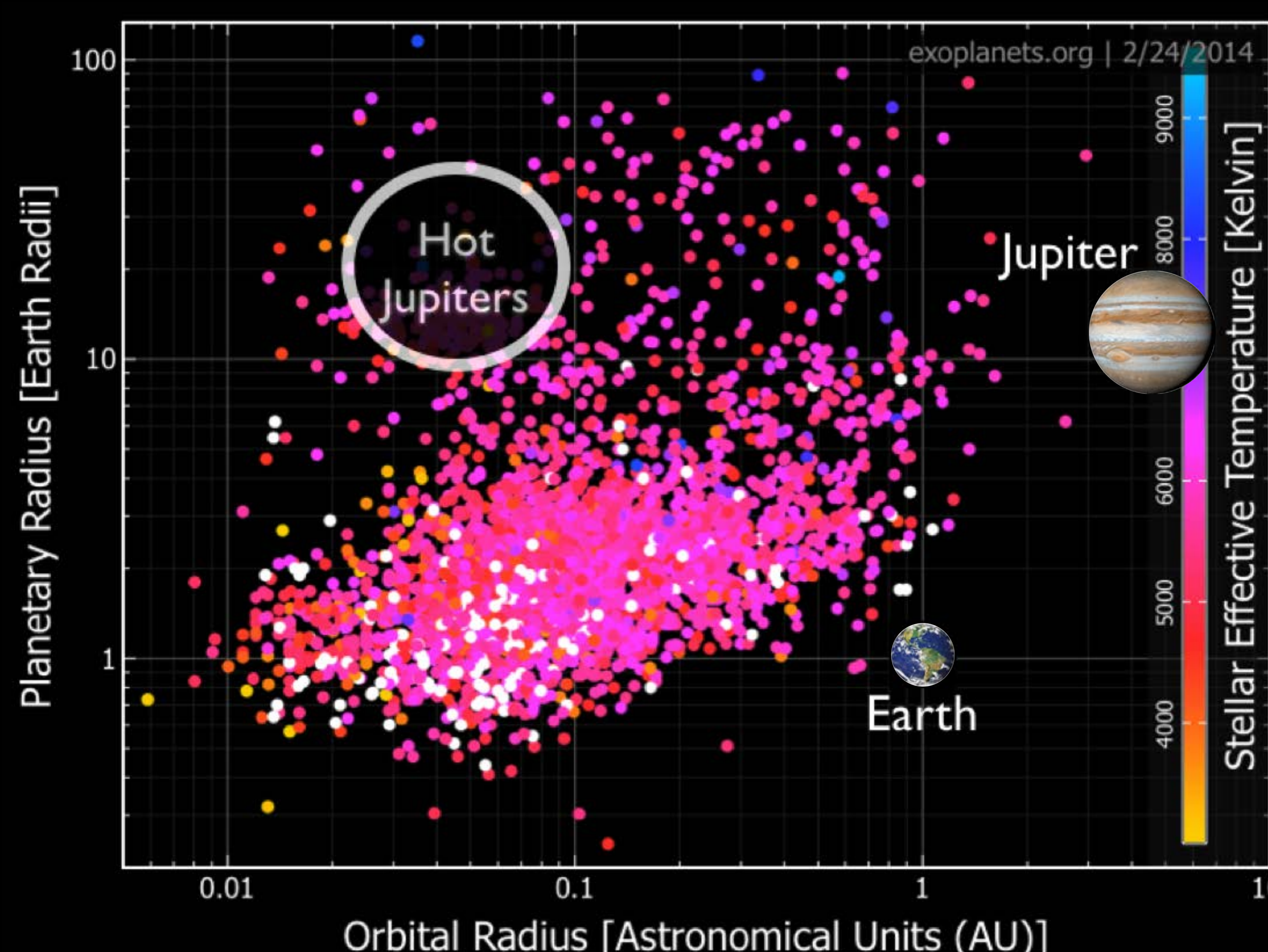

FROM UNIVERSE
TO PLANETS
LECTURE 4.1: PLANET MIGRATION

MIGRATION

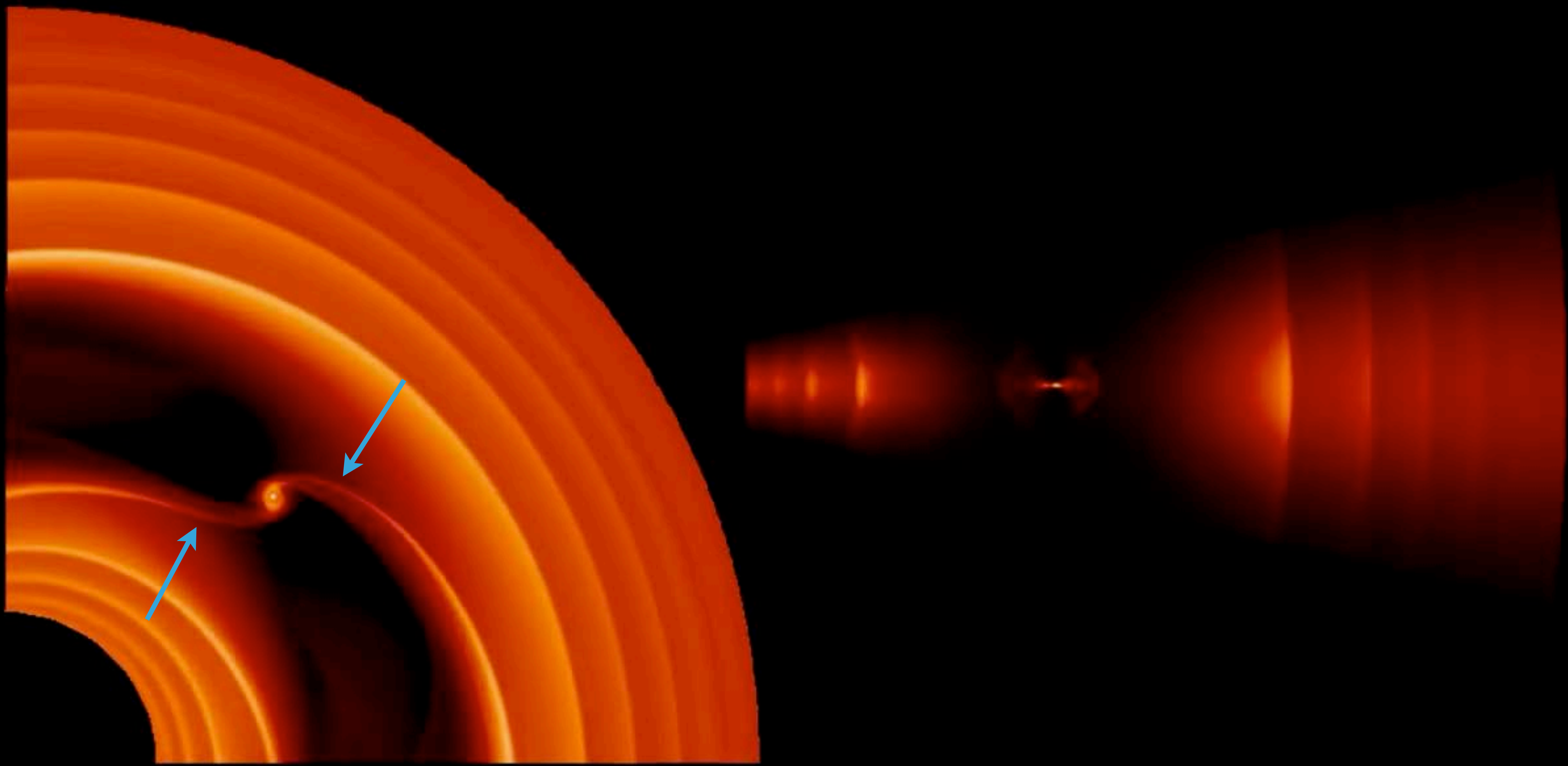
- Disc migration: interactions with the gas disc.
    - Type I: low mass planet.
    - Type II: massive planet in a gap.
    - Type III: turbulent migration (intermediate special case for massive disks).
- Tidal migration: planets whose orbit (or partial orbit) takes it close to the star → causing a bulge on the star.
- Gravitational scattering: interactions with other planets (particularly giant planets) or large number of planetesimals.
- Kozai cycles and tidal friction: planets that are inclined relative to the plane of a binary star (or other planets).

DISC MIGRATION

- Planets create non-axisymmetric, time-dependent gravitational potentials that make density waves in the gas disc (spiral waves).
- These density waves feedback onto the planet through gravitational torques, leading to angular momentum transport and migration.
- Orbital decay due to direct gas drag is negligible at planetary masses.
- Helps explain how hot Jupiters can exist so close to the host star when they preferentially form beyond the snow line.



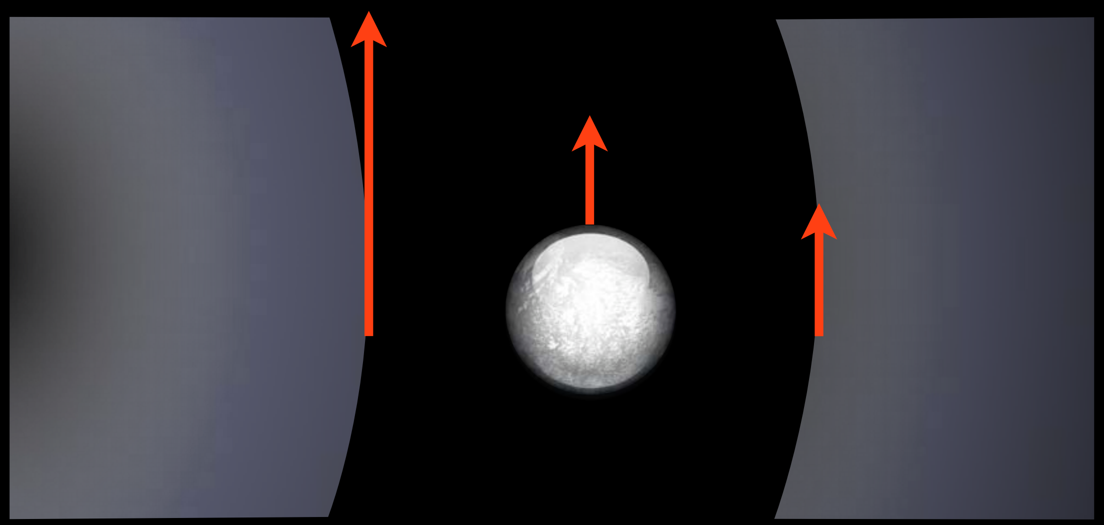
DISC MIGRATION



- The leading density enhancement pulls the planet forward (leading to outward migration), while the trailing density enhancement pulls the planet backwards (leading to inward migration).

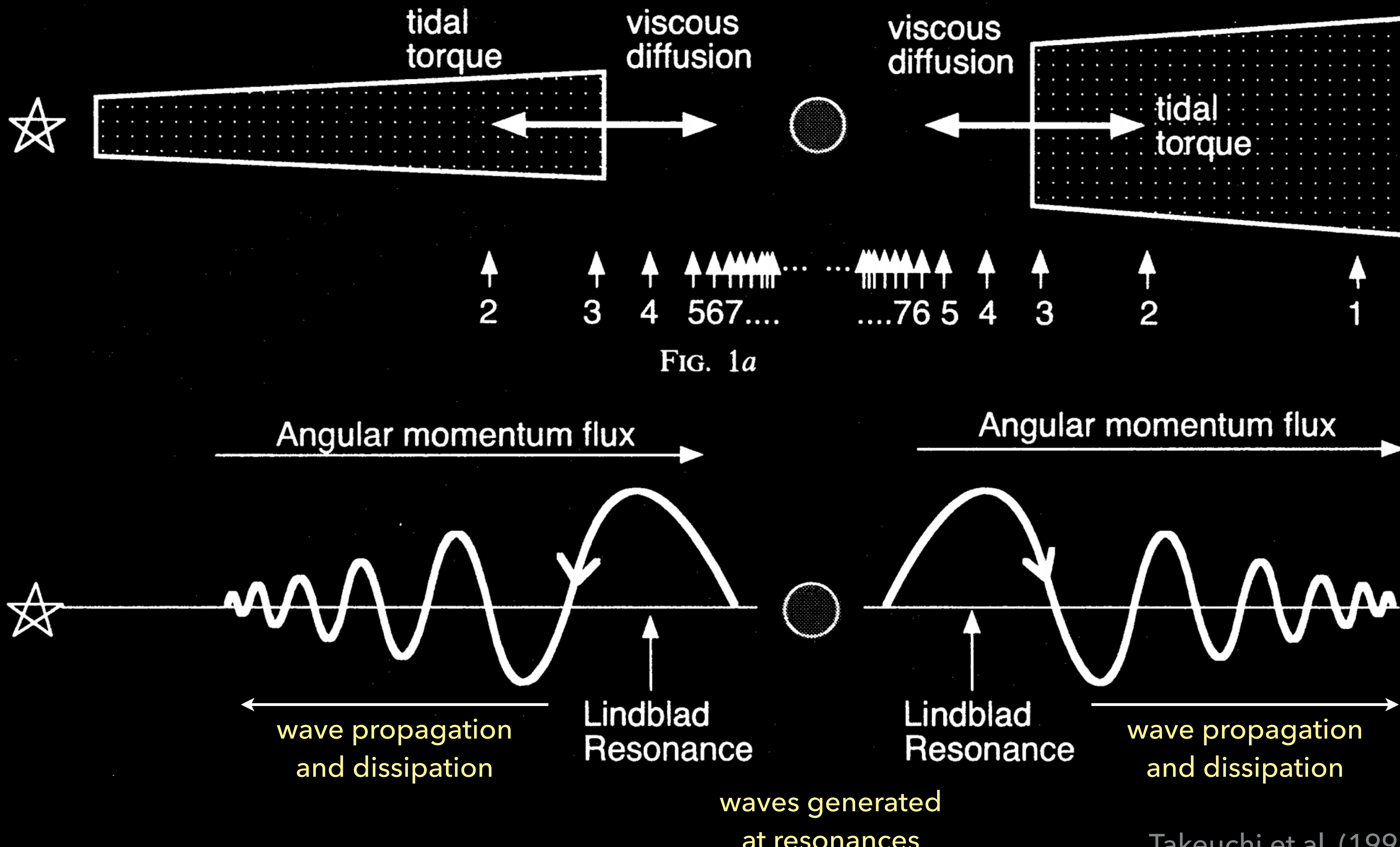
DISC MIGRATION: IMPULSE APPROXIMATION

- Gas interior overtakes the planet → net gain in angular momentum. Gas exterior to the planet is overtaken by the planet → net loss.



- The interaction is frictional with the net direction of migration depending on the difference between the interior and exterior torques.
- We are assuming linear trajectories (approximately true to circular orbits). Deflections cause departures from this geometry, so we assume disc viscosity is able to restore the geometry by the subsequent pass.

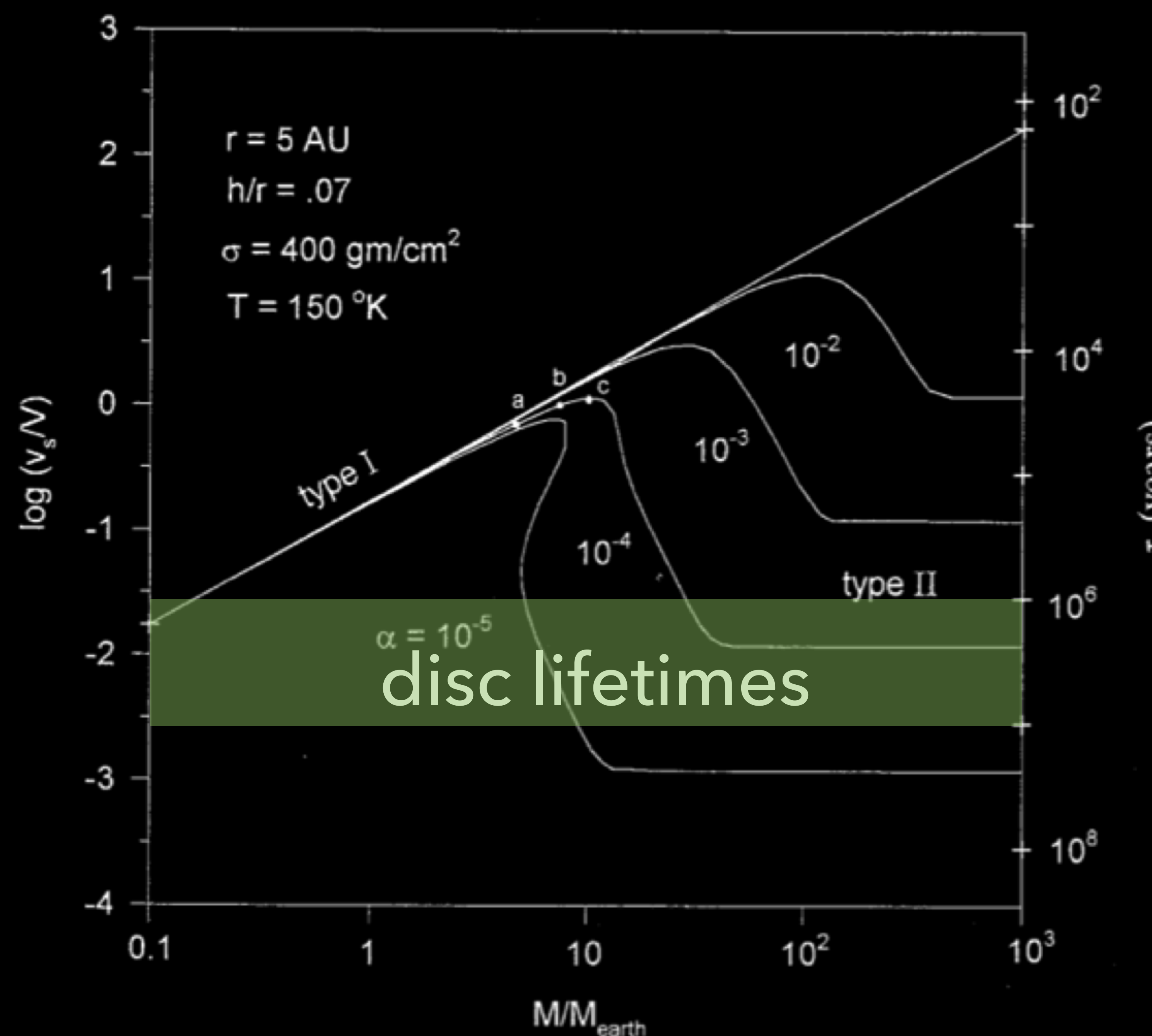
DISC MIGRATION: IMPULSE APPROXIMATION



Takeuchi et al. (1996)

DISC MIGRATION: SUMMARY

- Type I migration timescales are very short ($\sim 10^4$ yrs).
- Type II migration is 1-2 orders of magnitude longer.
- Suggests that planets should all fall into the star within the lifetime of the disc.



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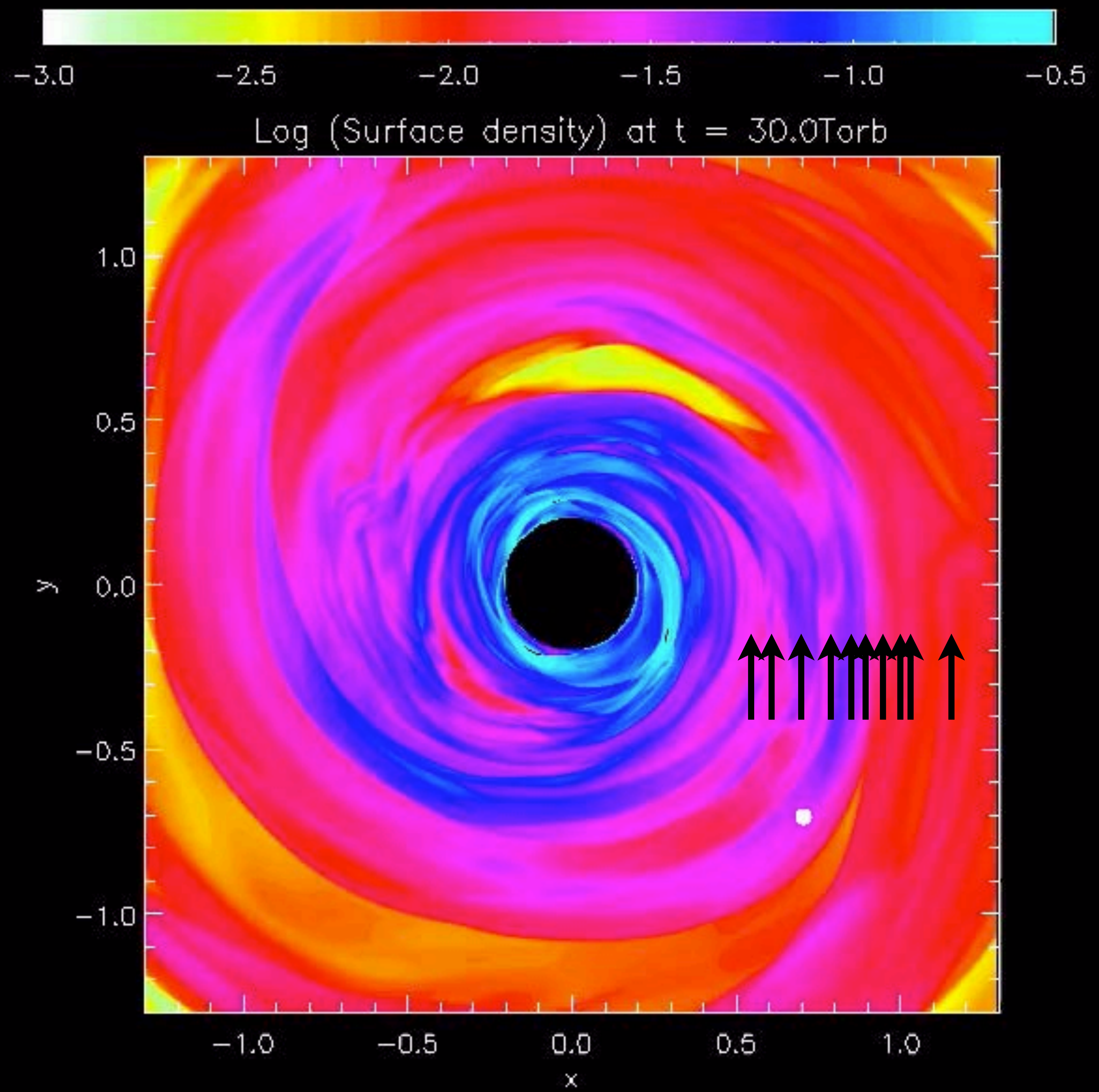

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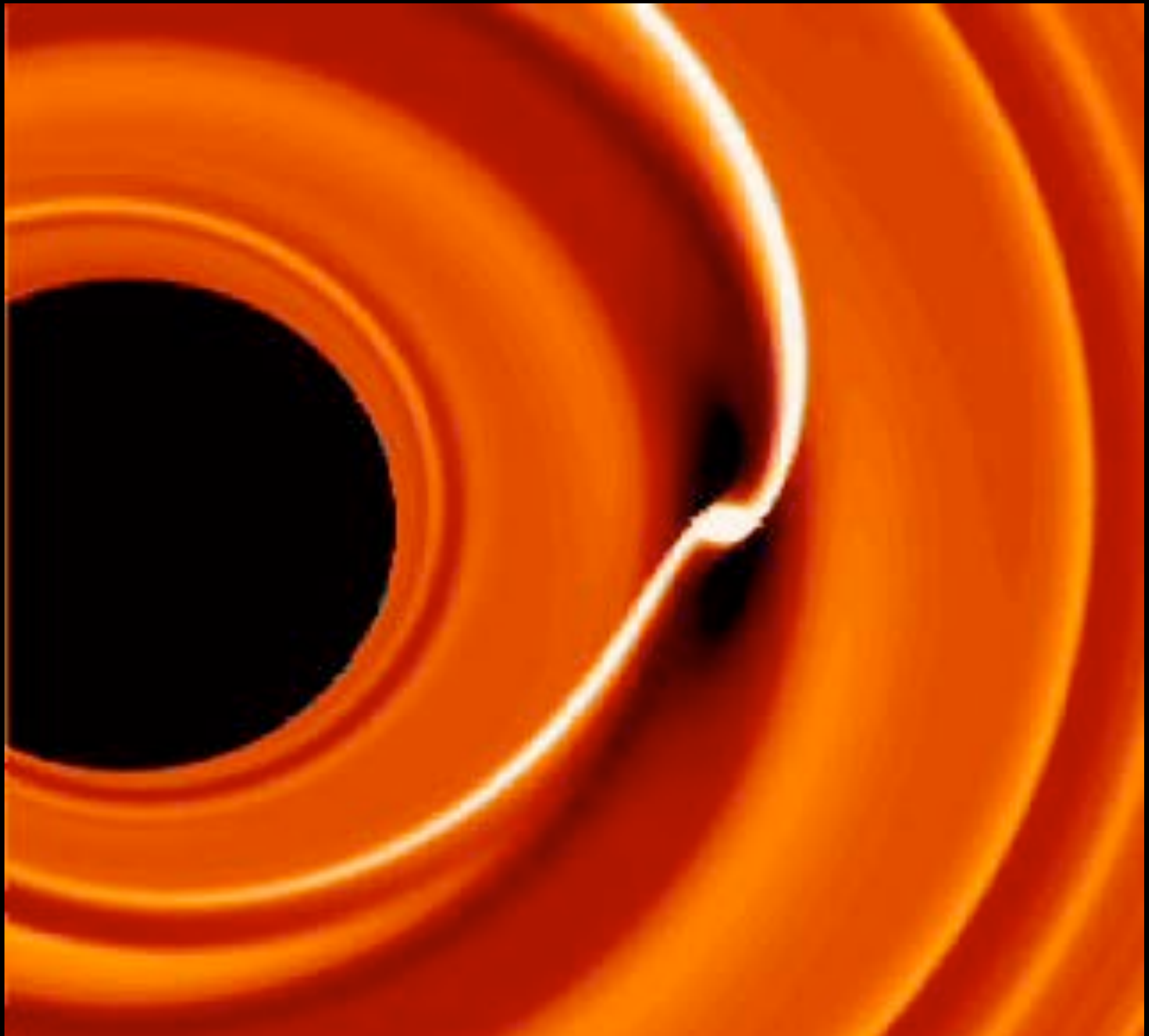

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- Type II migration is 1-2 orders of magnitude longer.
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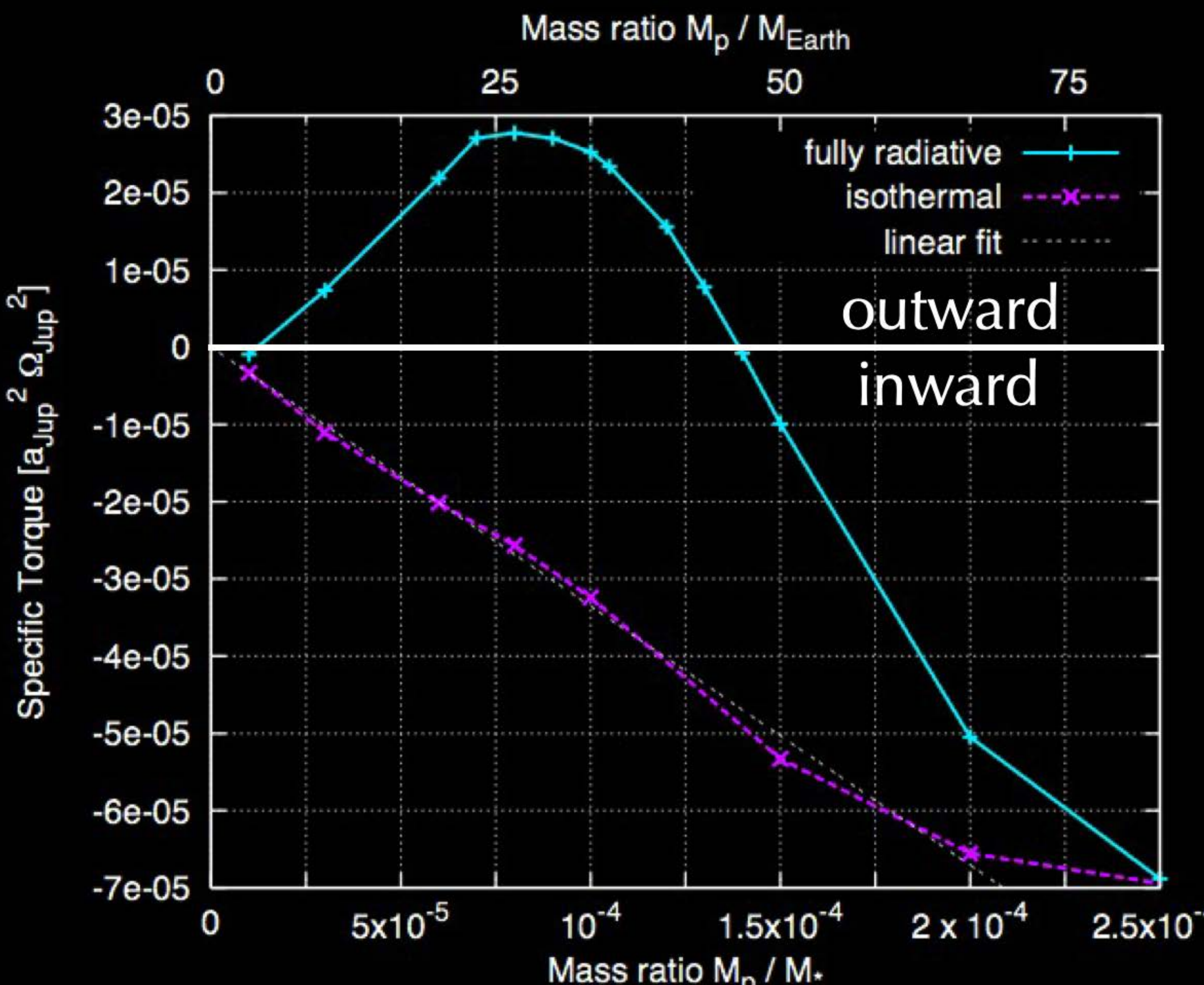
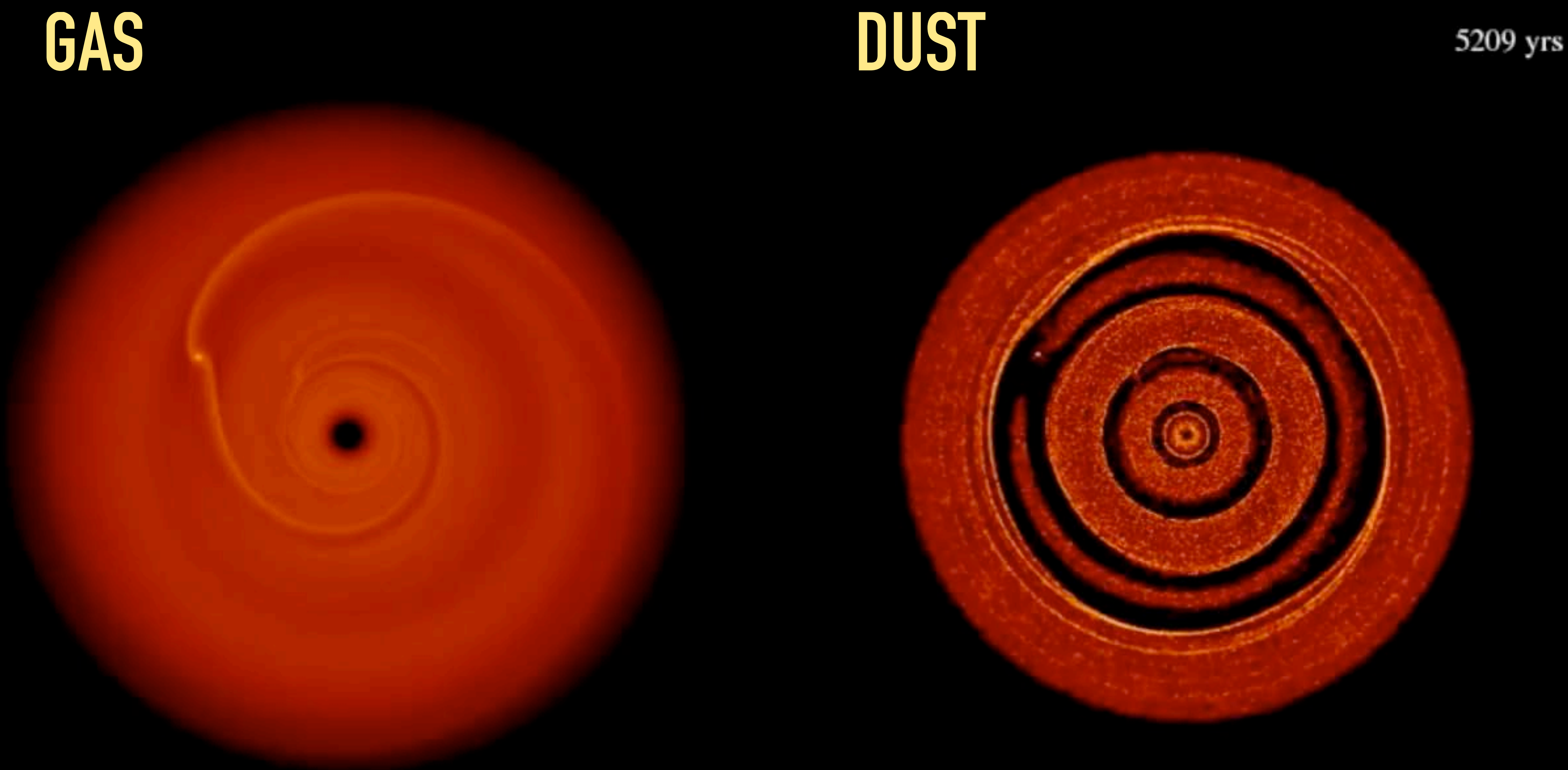
- Not as effective in gravito-turbulent discs or for asymmetric gaps (Type III migration).
- Thermodynamics is an important factor



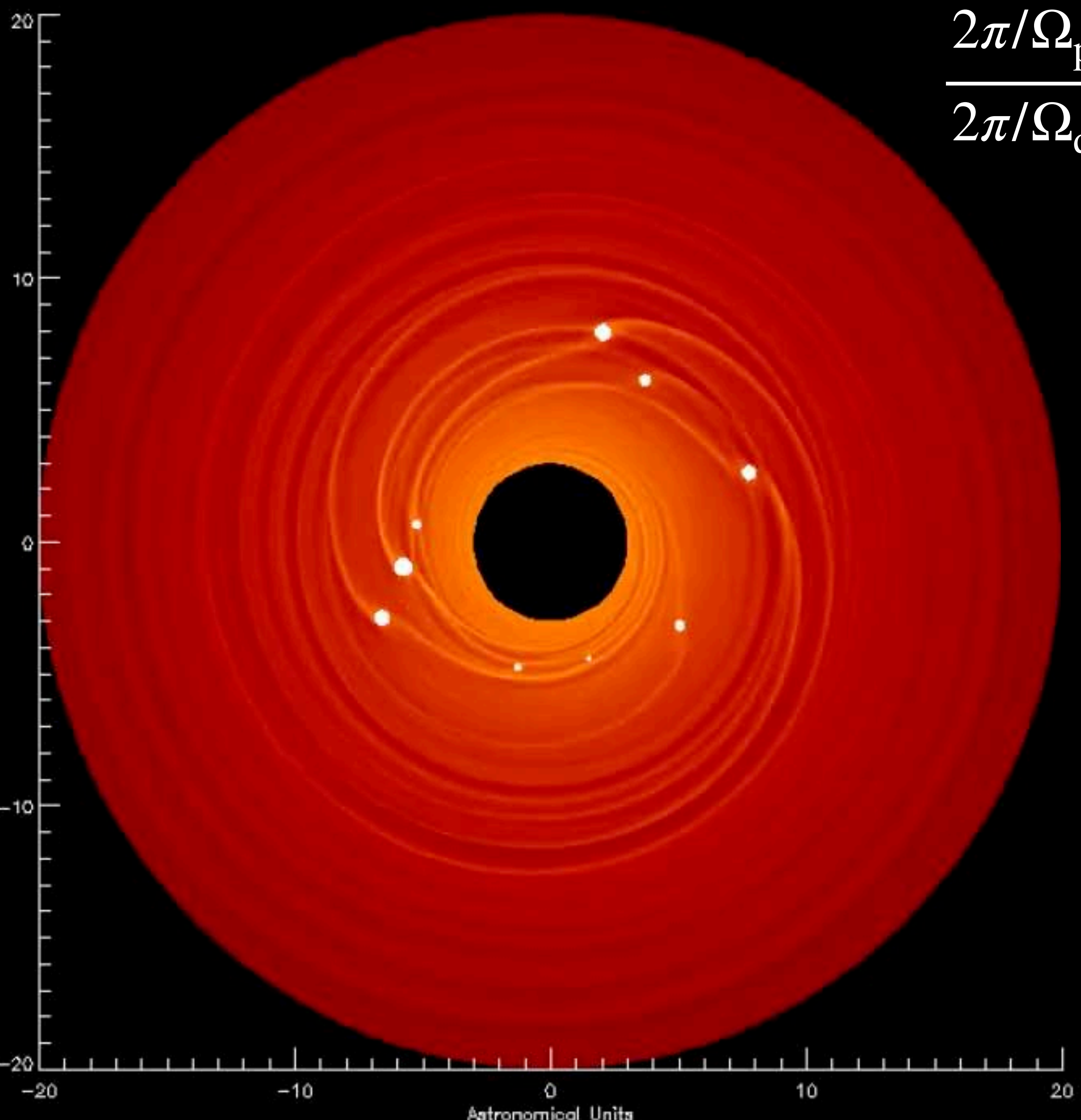
EFFECTS ON DUST



Dipierro, Price, Laibe, Hirsh, Cerioli and Lodato

- Plant gaps prevent large dust grains from migrating past the planet. Only small grains that are well coupled to the gas can still cross. Can affect the grain size distribution in the inner disc.

MEAN MOTION RESONANCES (MMR)

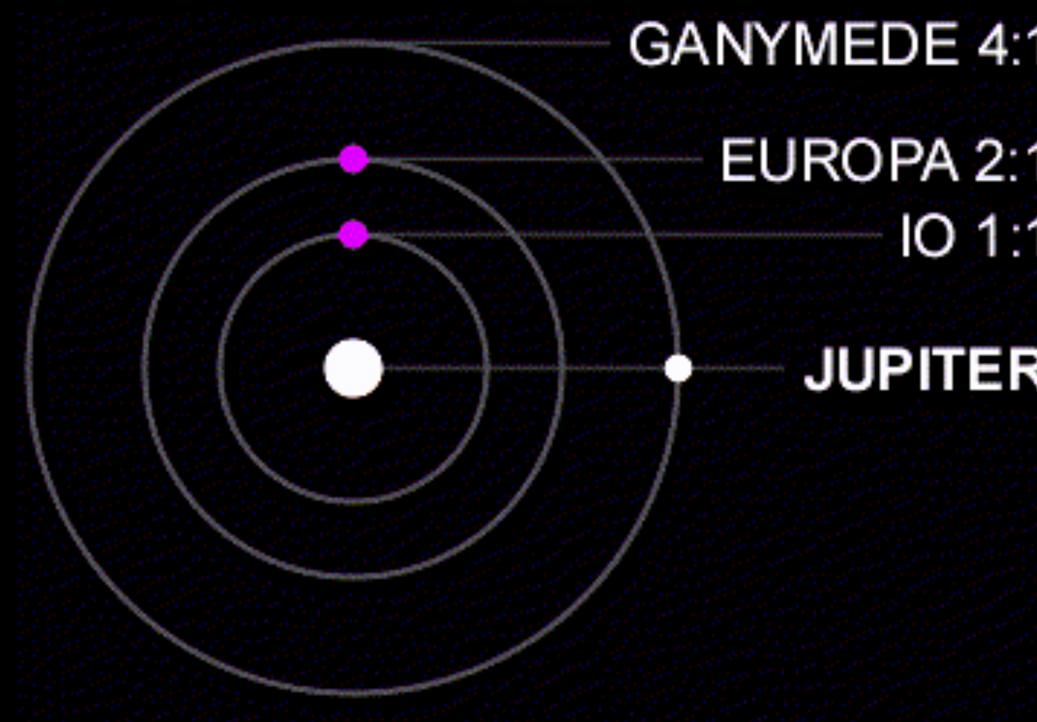


$$\frac{2\pi/\Omega_\mathrm{p}}{2\pi/\Omega_\mathrm{q}} = \frac{P_\mathrm{p}}{P_\mathrm{q}} = \frac{n}{m} \quad \text{where } [n, m] = 1, 2, 3, \ldots$$

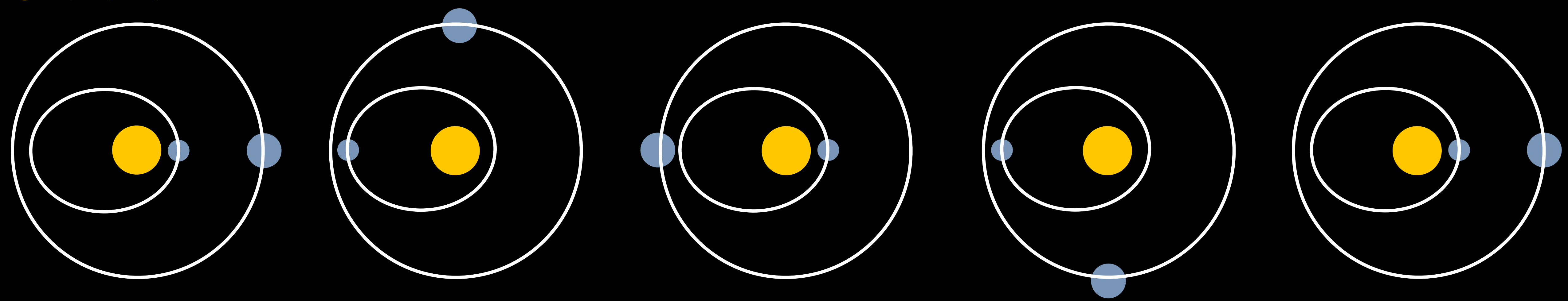
- Multiple planet systems often form resonant chains as inner planets catch migrating planets behind them.

MEAN MOTION RESONANCES (MMR)

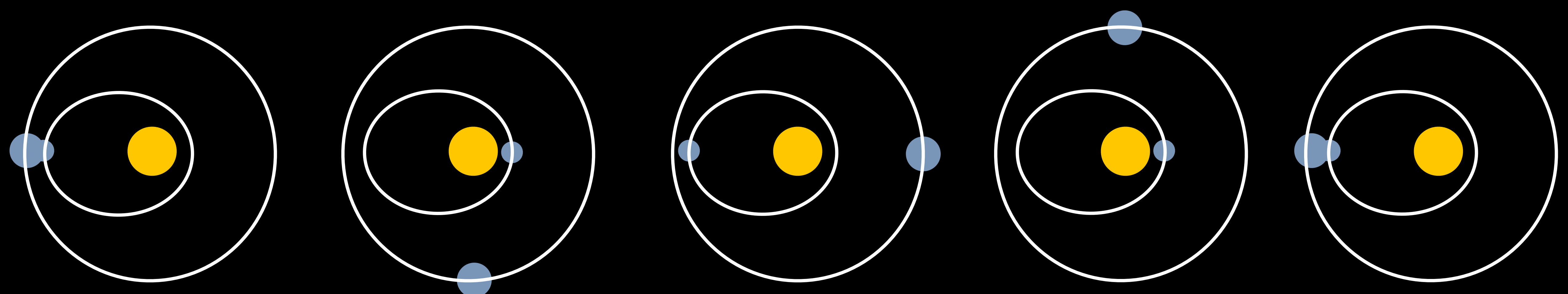
- Similar to finding the natural frequency on a swing. Pushing at the right time is important for stable motion.



Stable

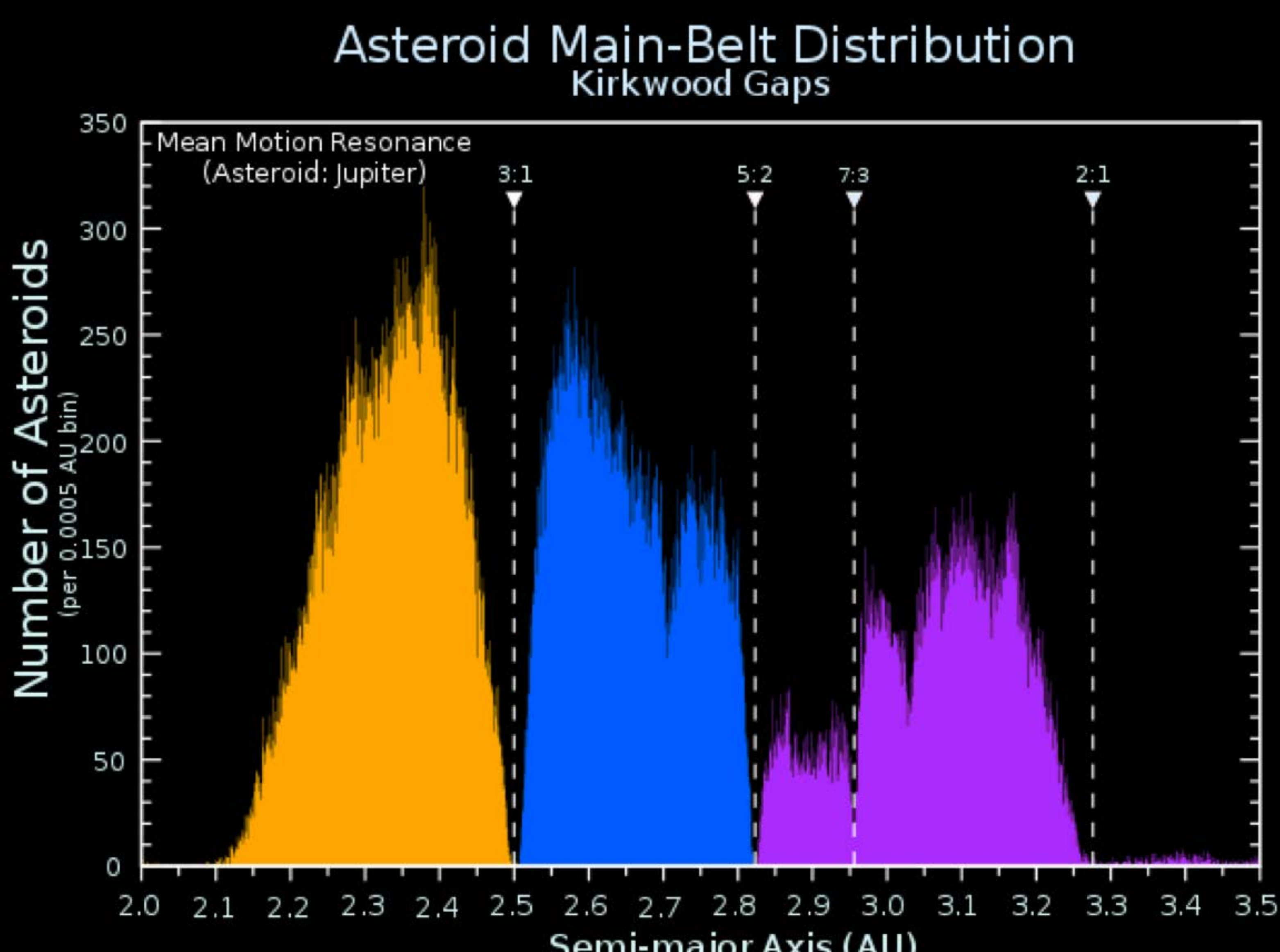


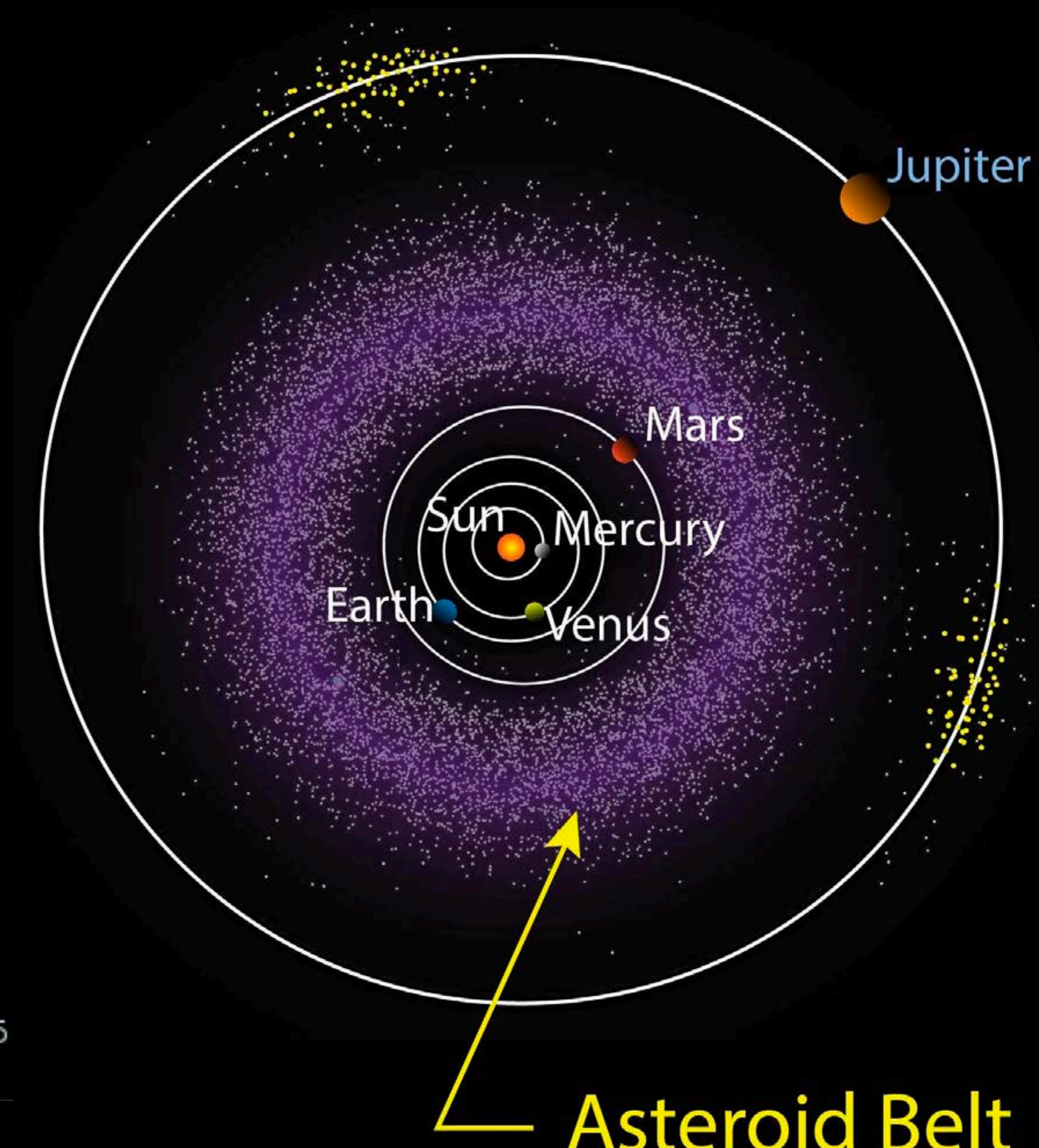
Unstable



MEAN MOTION RESONANCES (MMR)

- Structure in the astroid belt revealed when plotting the mean orbits (instantaneous snapshots don't show this because of the random eccentricities of the astroids). Similar effect in Saturn's rings.





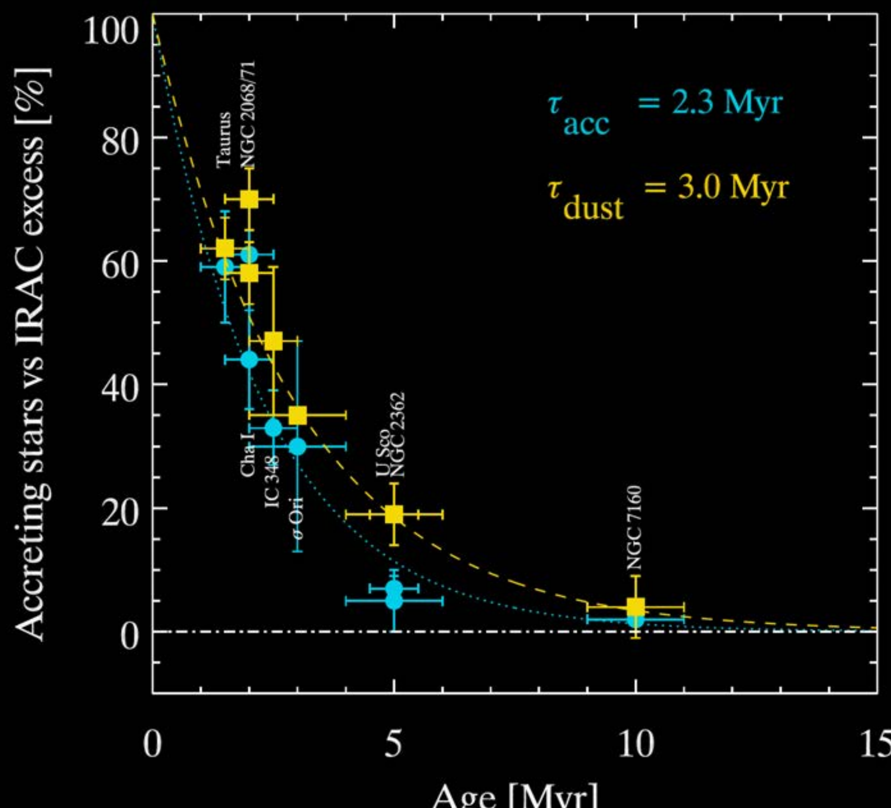
FROM UNIVERSE

TO PLANETS

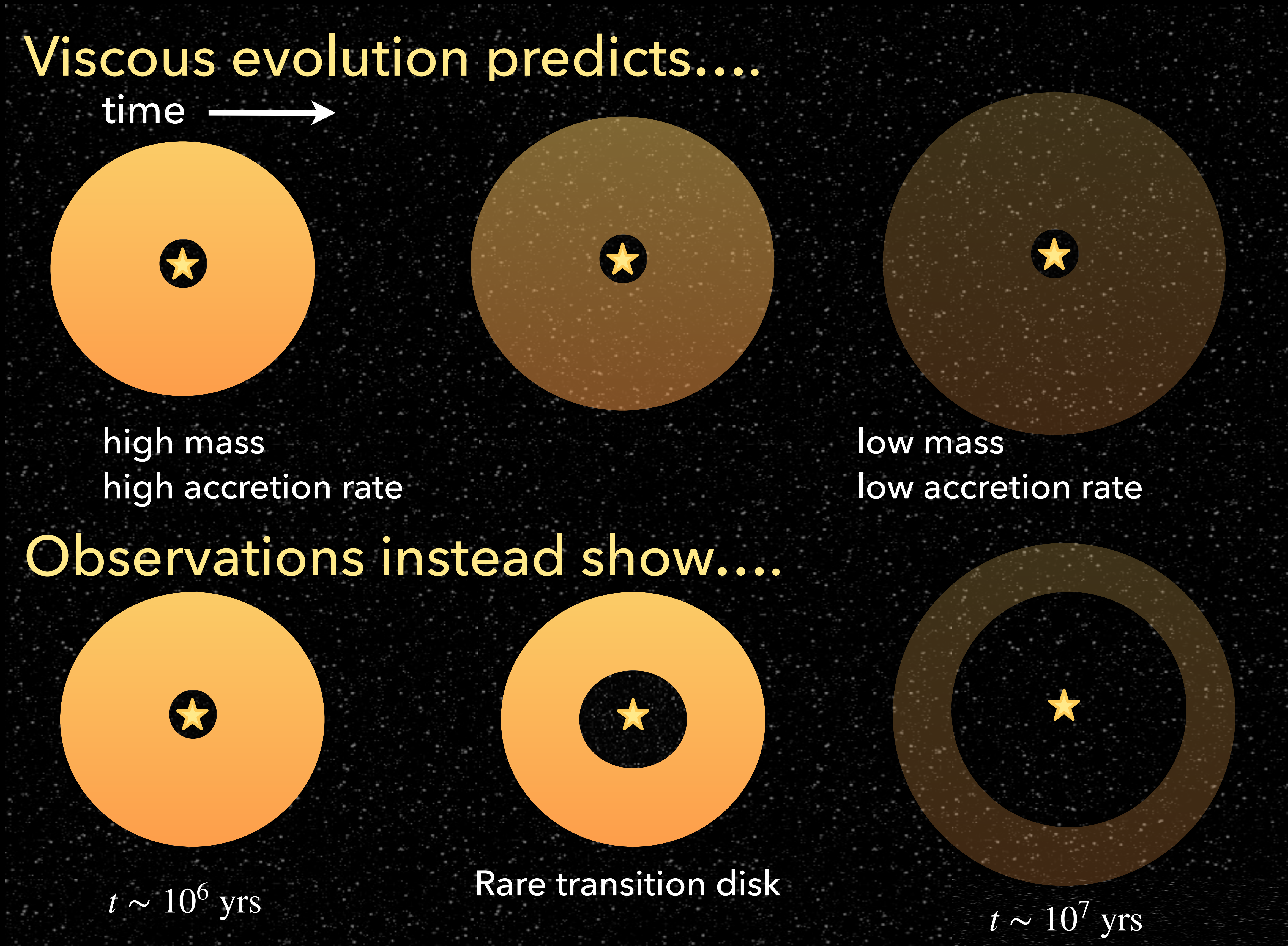
LECTURE 4.2: PHOTOEVAPORATION

VISCOUS EVOLUTION

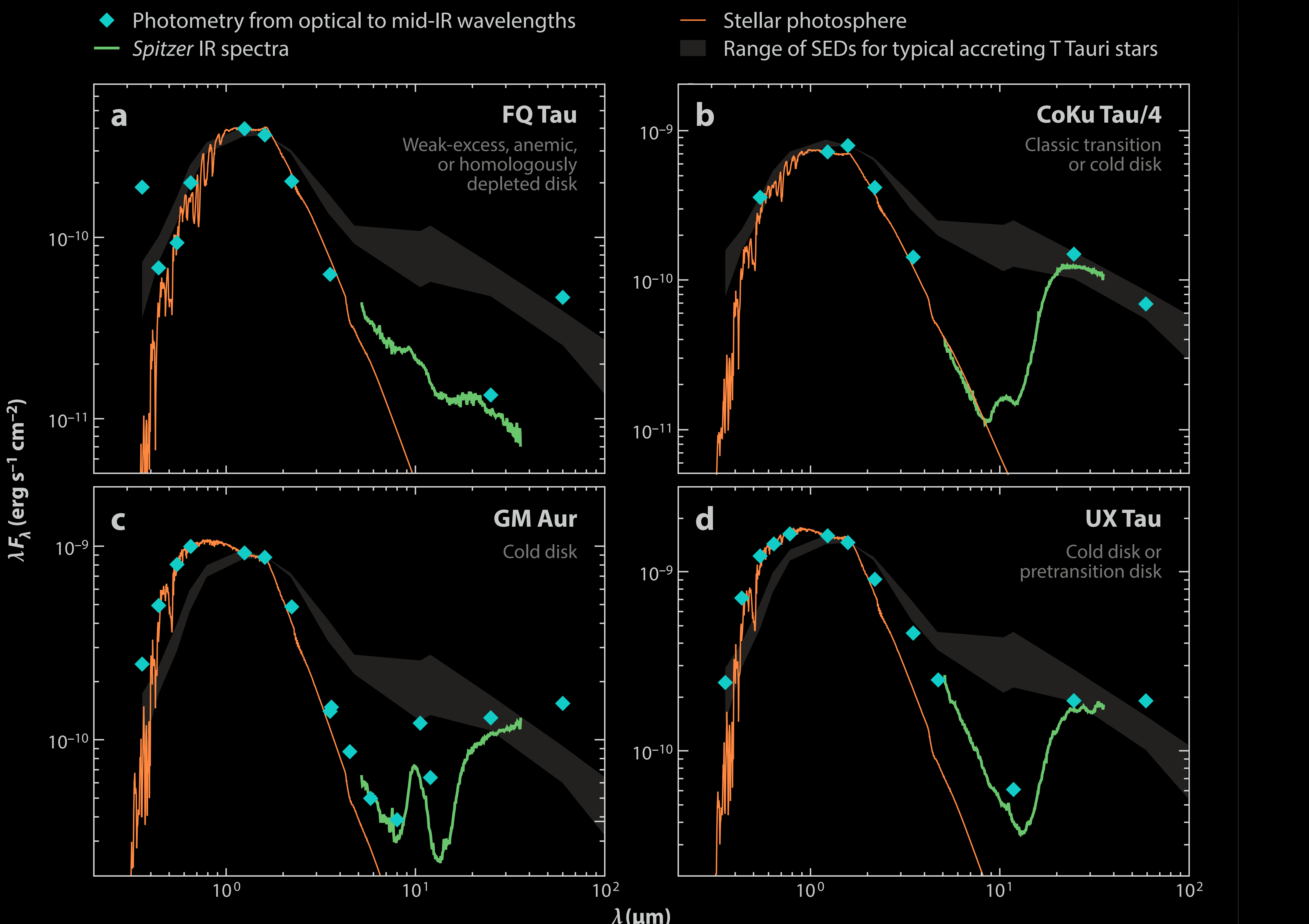
- Viscous evolution theory predicts:
  - Long disc lifetimes (~10–100 of Myr).
  - Discs should go progressively optically thin at all radii due to viscous accretion and spreading.
  - We should see many discs in "transition" phase.
- Observations show:
  - Discs are dispersed in ~1–10 Myr, with a e-folding time of ~3-5 Myr.
  - Very few transition discs (~10%).
  - Clearing must be fast (~0.5 Myrs).



VISCOUS EVOLUTION



TRANSITION DISCS



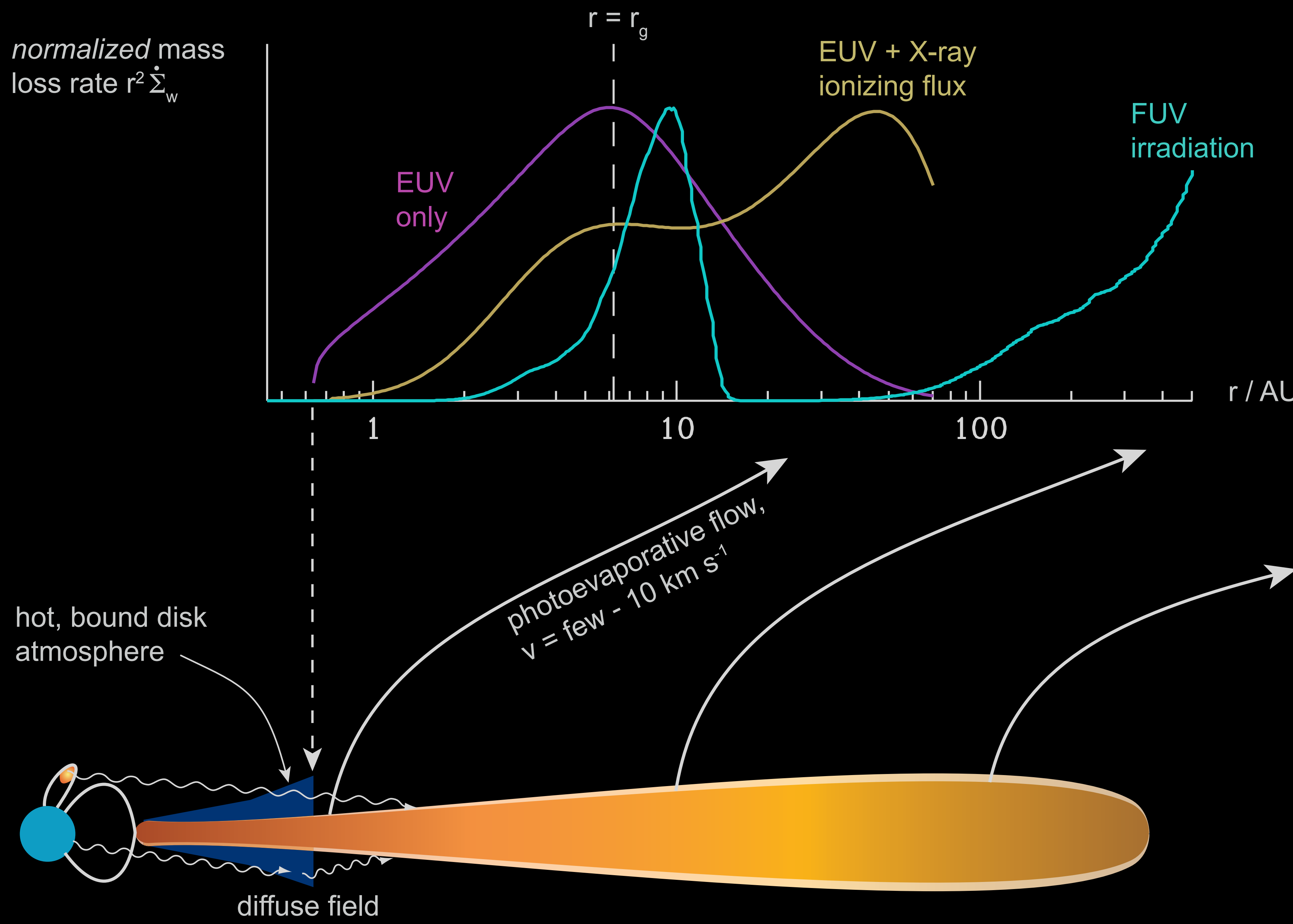
PHOTOEVAPORATION

- Thermal winds are produced by absorption of high energy radiation. Gas can escape if $c_\mathrm{s} > v_\mathrm{esc} = \sqrt{2GM/R}$.
- Naively:

$$R_\mathrm{g} = \frac{GM_*}{c_\mathrm{s}^2}$$
$$\sim 5\text{–}10 \text{ au}$$

- Bernoulli flow:

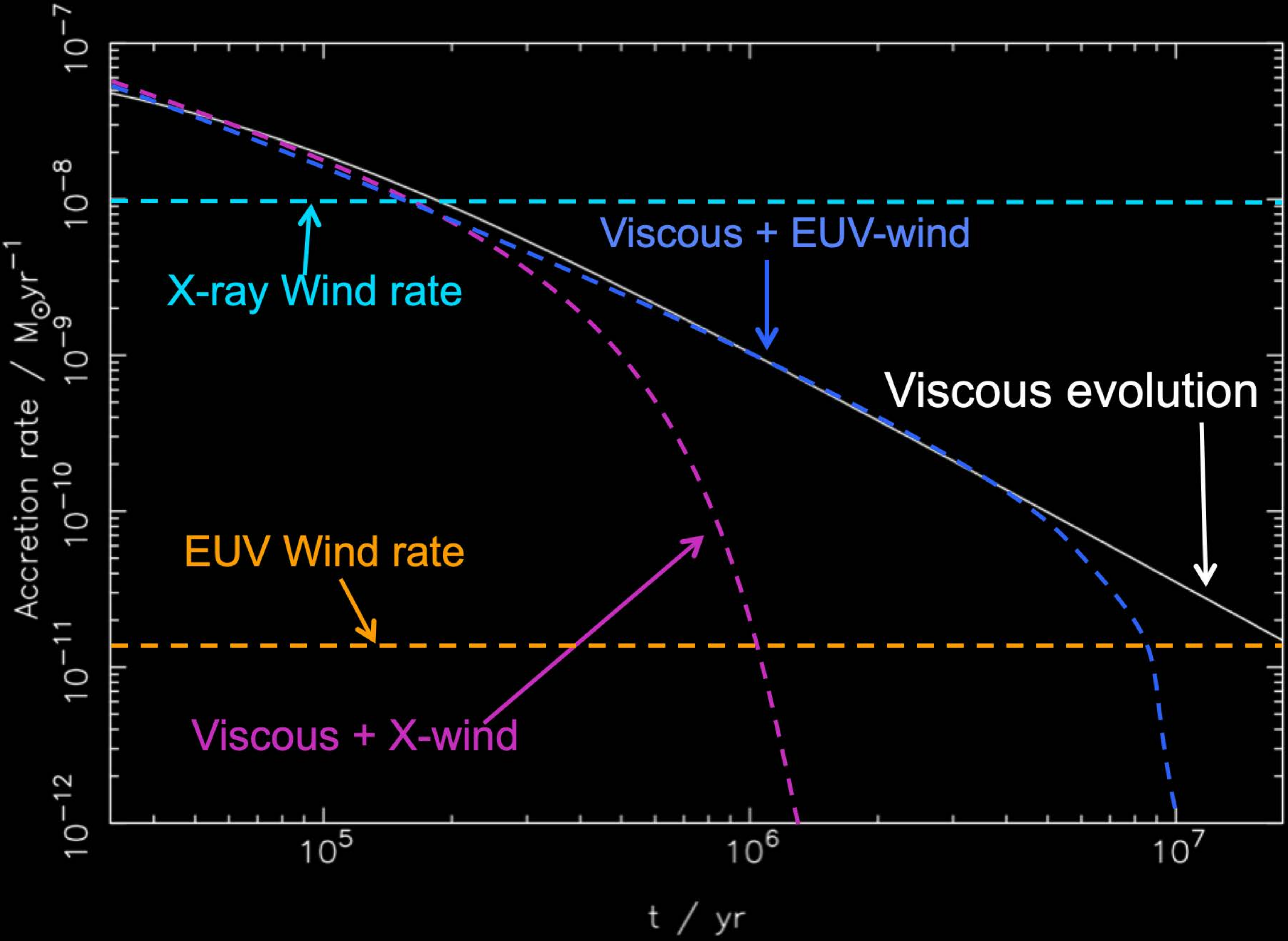
$$R_\mathrm{c} \approx \frac{R_\mathrm{g}}{5}$$
$$\sim 1\text{–}2 \text{ au}$$



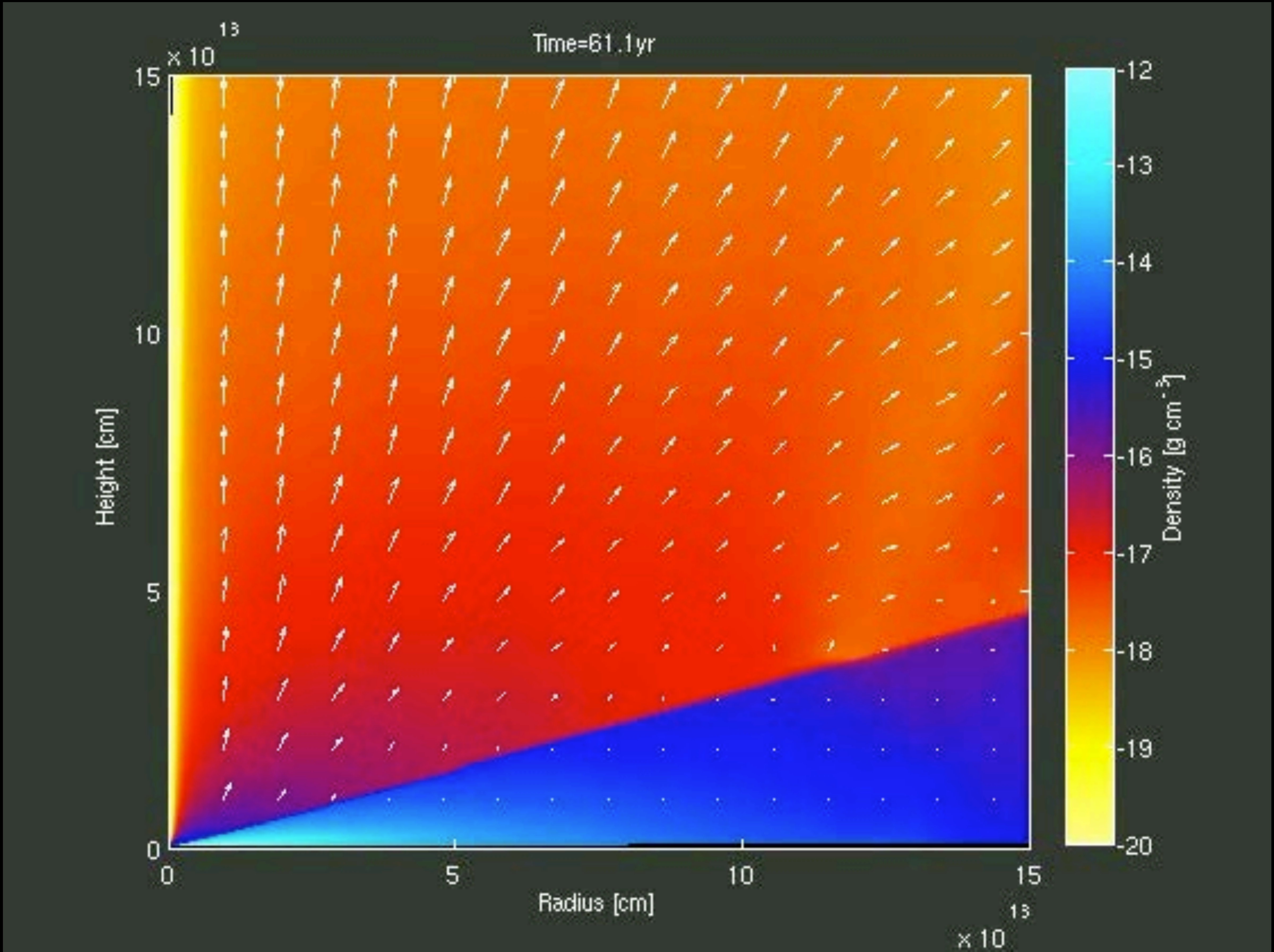
PHOTOEVAPORATION

- X-EUV radiation ionises and heats the disc atmosphere:
  - Bound atmosphere at $R < R_{\rm g}$.
  - Thermal wind at $R > R_{\rm g}$ (large portion of the disc). Total mass loss rates $\sim 10^{-10}$–$10^{-8}\ M_\odot\ {\rm yr}^{-1}$ (can be comparable to viscous accretion).
- Once accretion rates drop below the wind mass-loss rate at a given radius, a gap opens (typically near $R_{\rm g}$).
  - The outer and the inner disc become decoupled. The inner disc is starved.
- Inner disc (viscously) drains rapidly onto the star producing a transition disc. Direct EUV and X-ray flux photoevaporate the outer disc from the inside out.

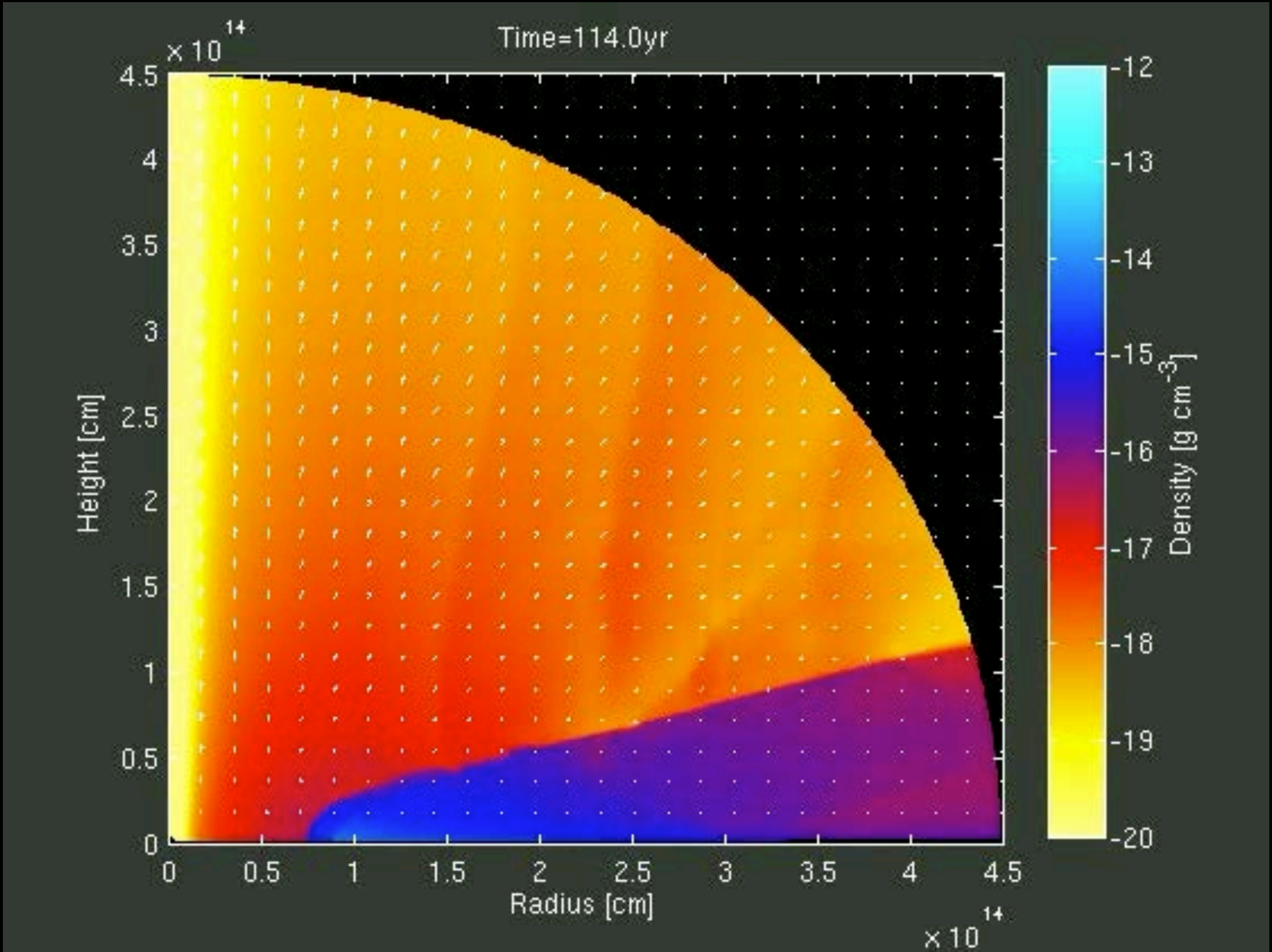
PHOTOEVAPORATION



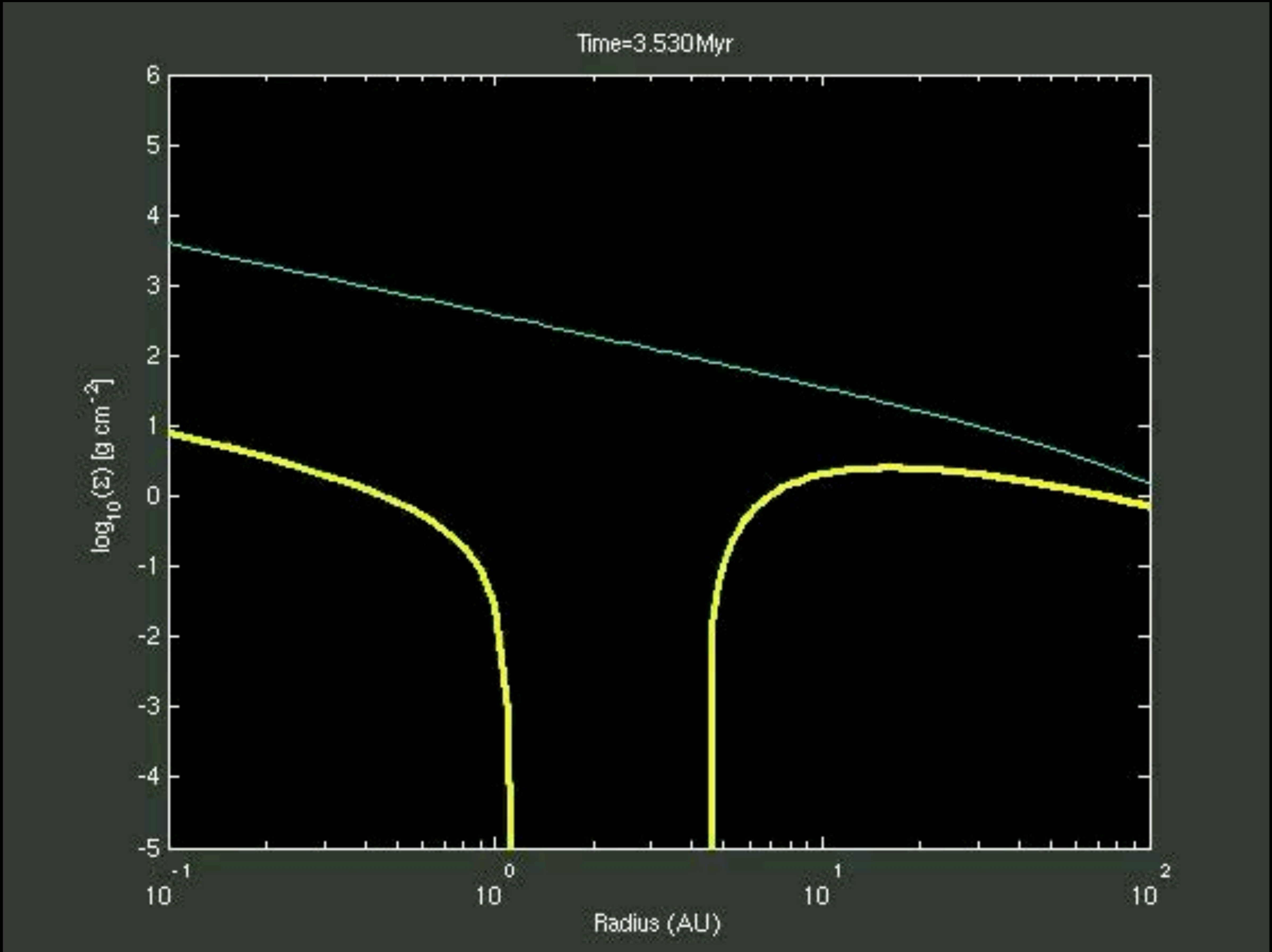
PHOTOEVAPORATION



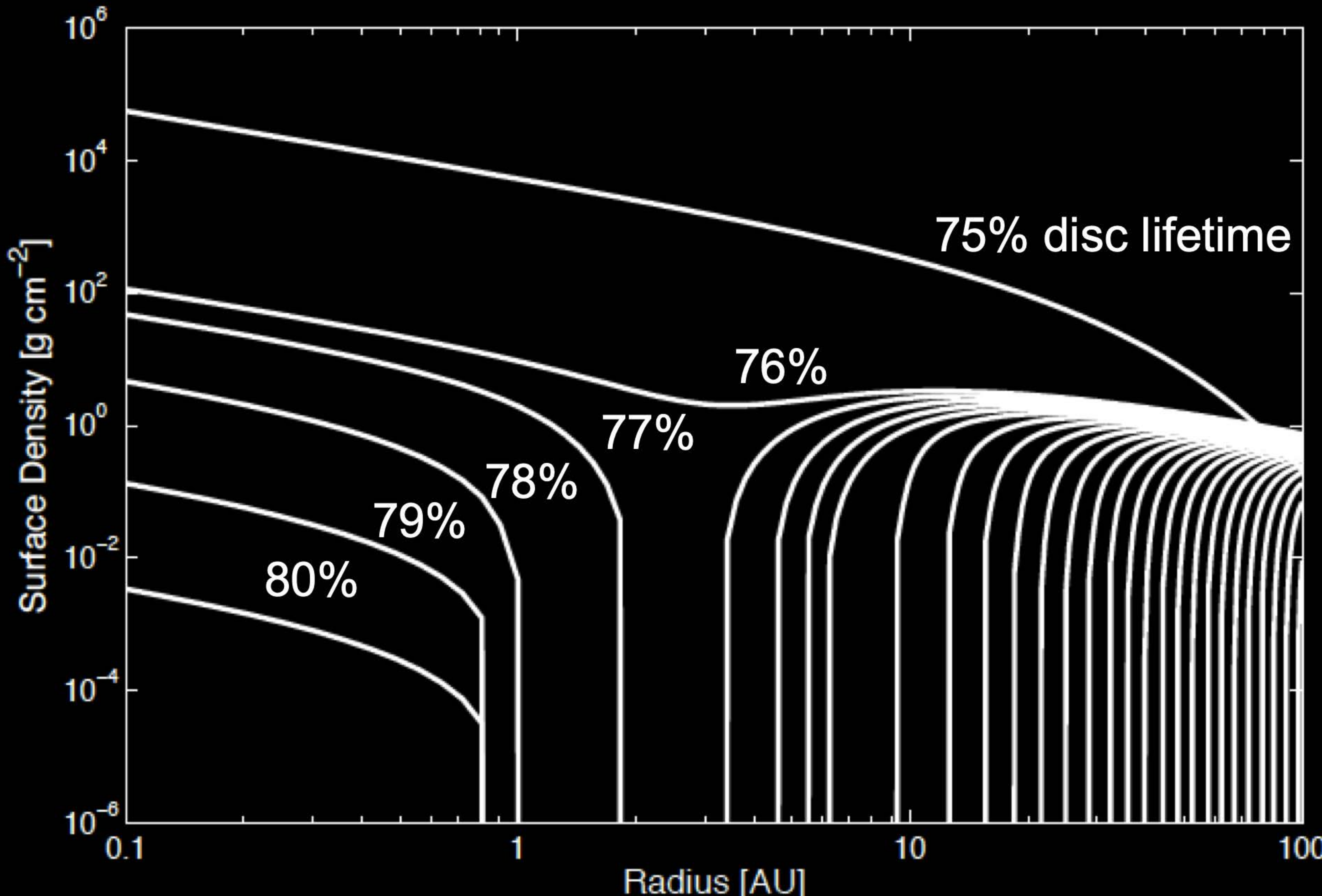
PHOTOEVAPORATION



PHOTOEVAPORATION

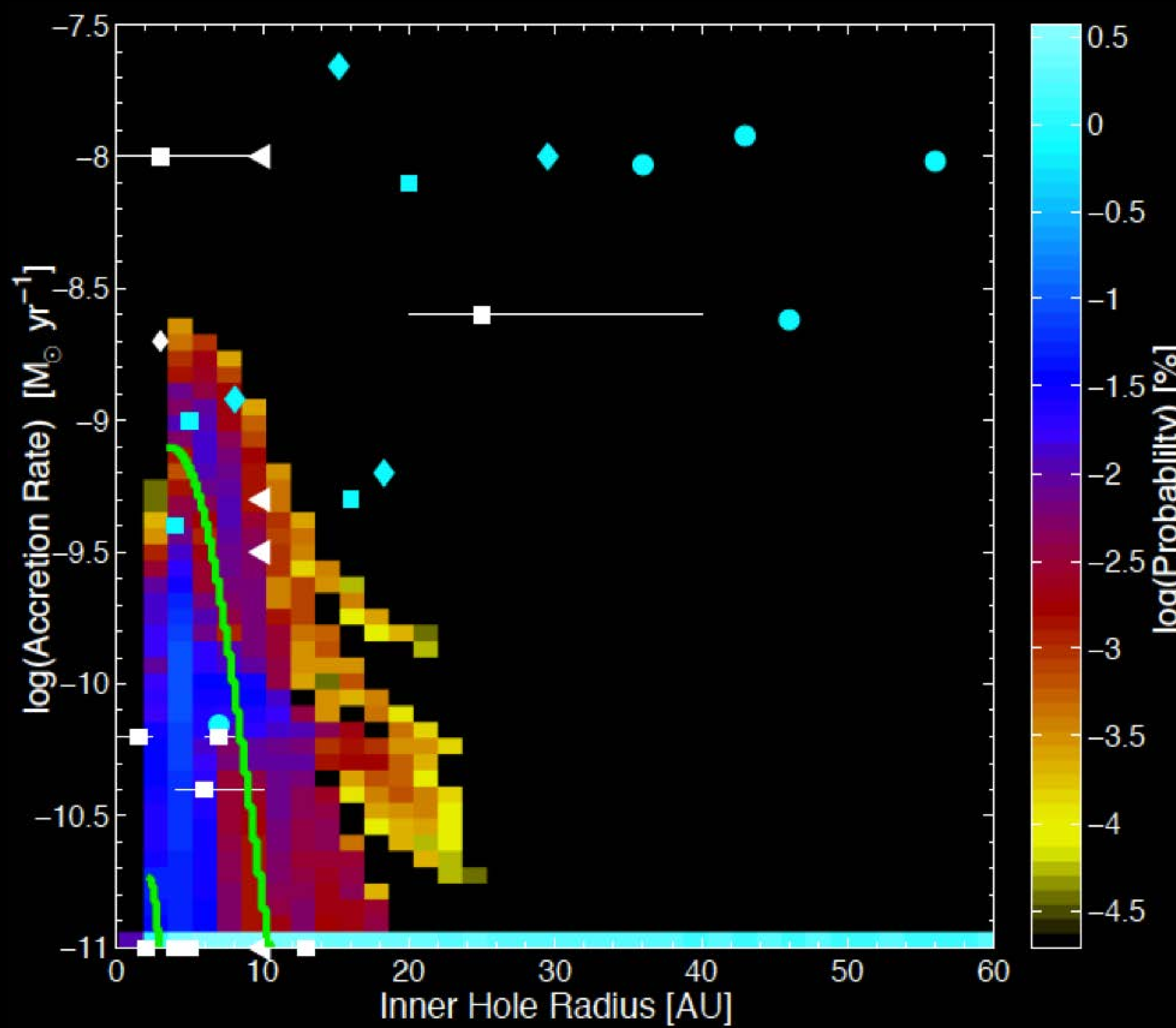


PHOTOEVAPORATION



PHOTOEVAPORATION OR GIANT PLANETS?

- Struggles to produce transition discs with large gaps and high accretion rates. By the time that the disc gap is large enough the accretion rates in the inner disc have slowed or even quenched.
- Probably caused by giant planets, but grain growth can partially mimic this effect too.



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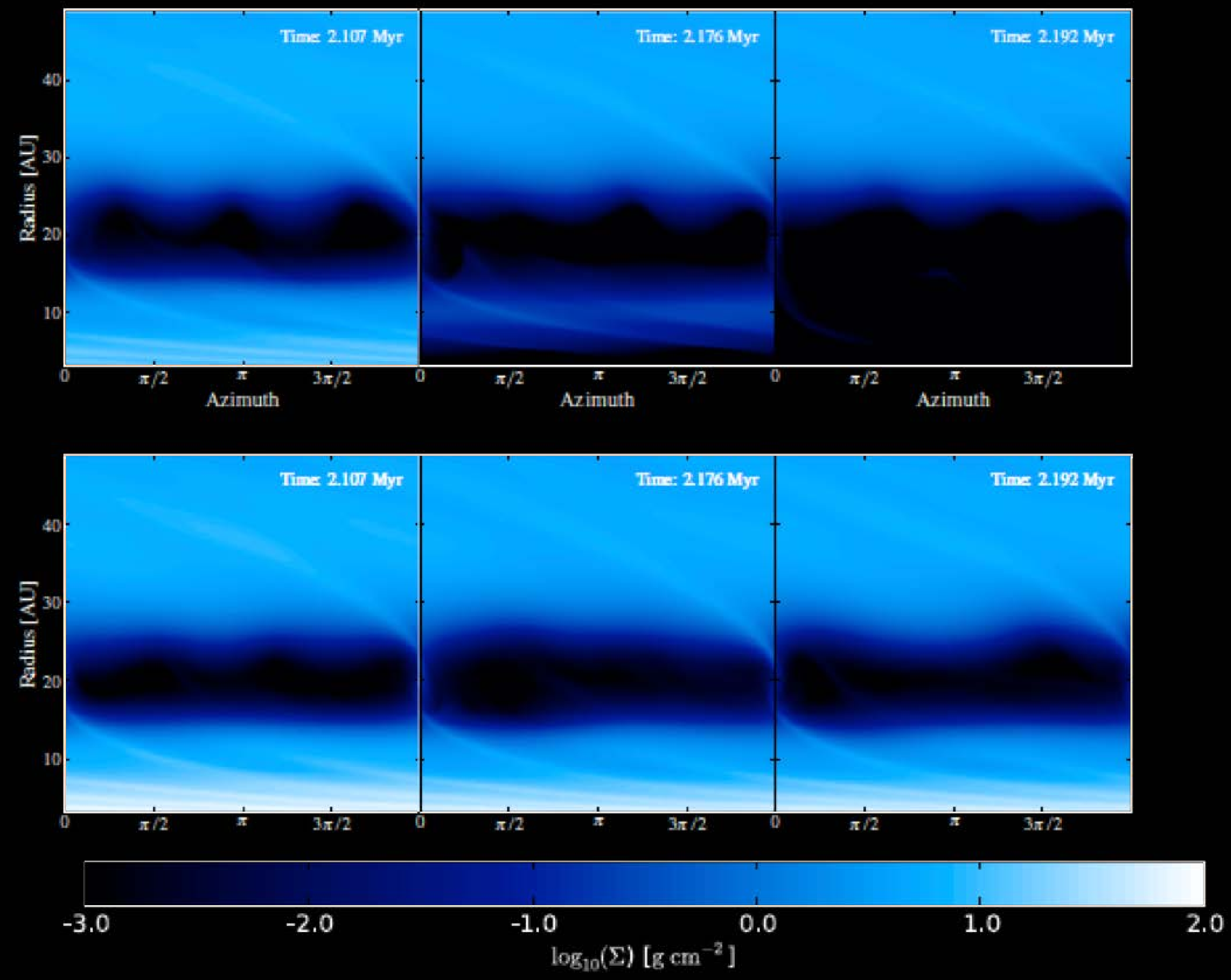
- Combination of the two: planet-induced photoevaporation

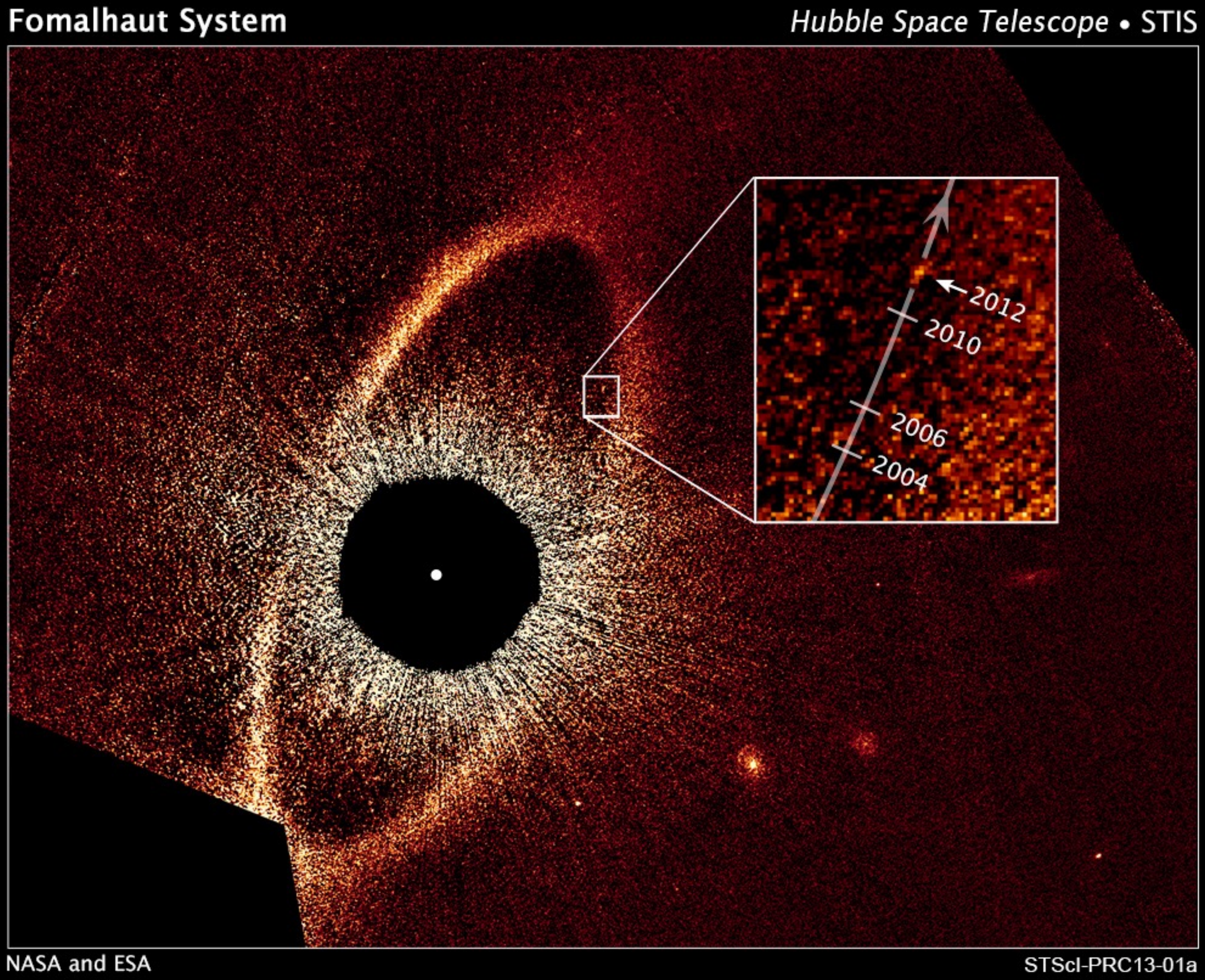


FROM UNIVERSE

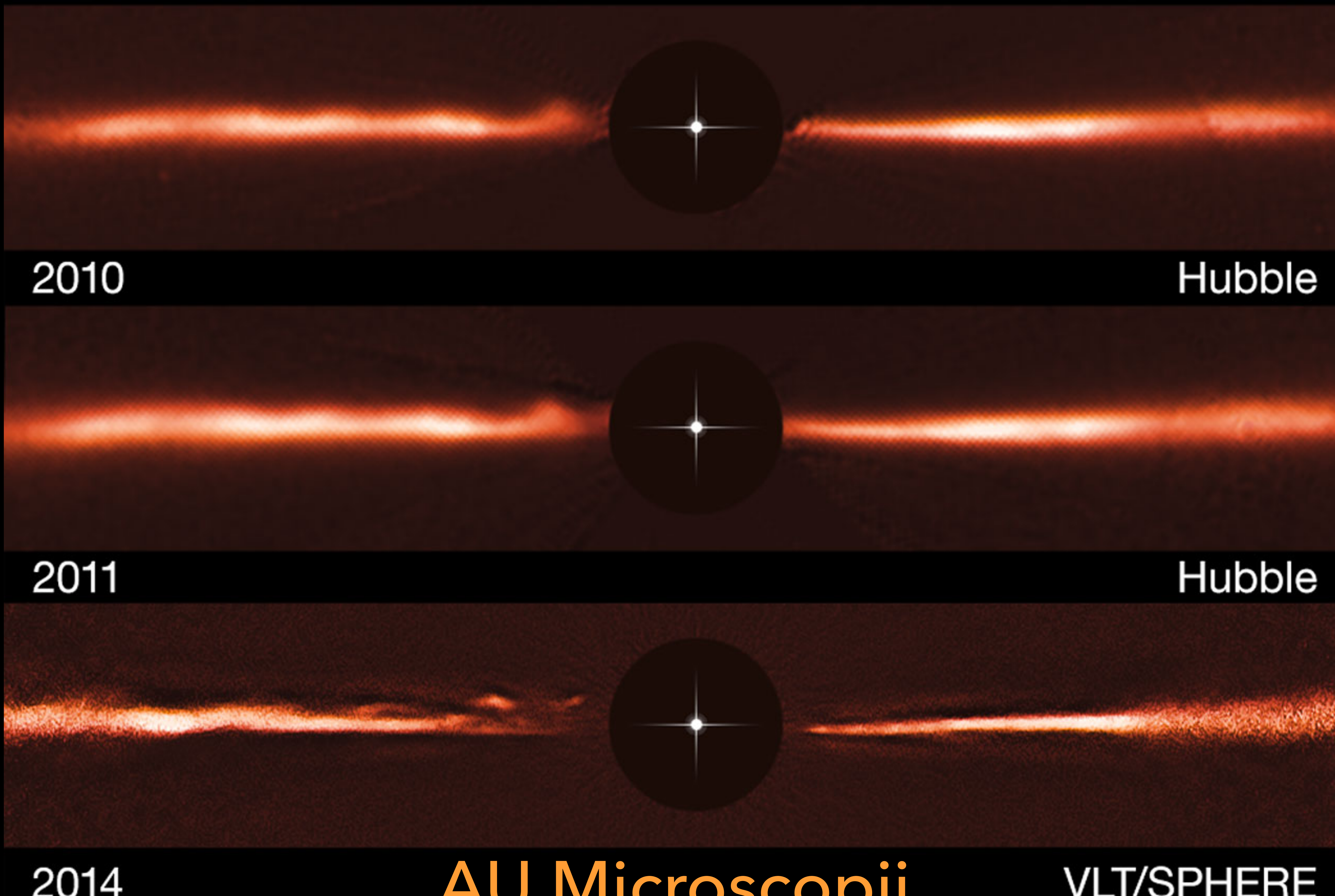
TO PLANETS

LECTURE 4.3: DEBRIS DISCS & COLLISIONS

DEBRIS DISCS

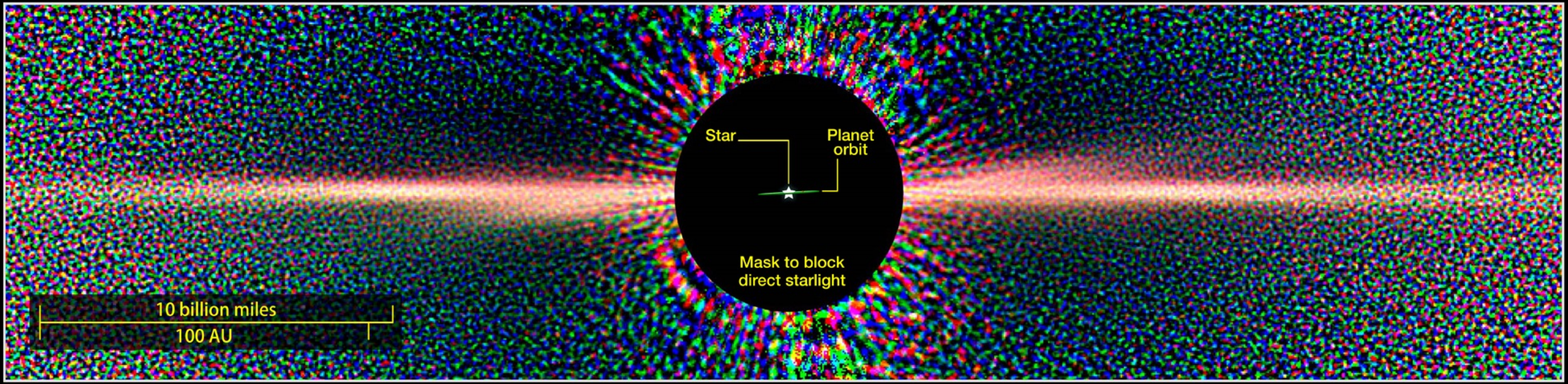


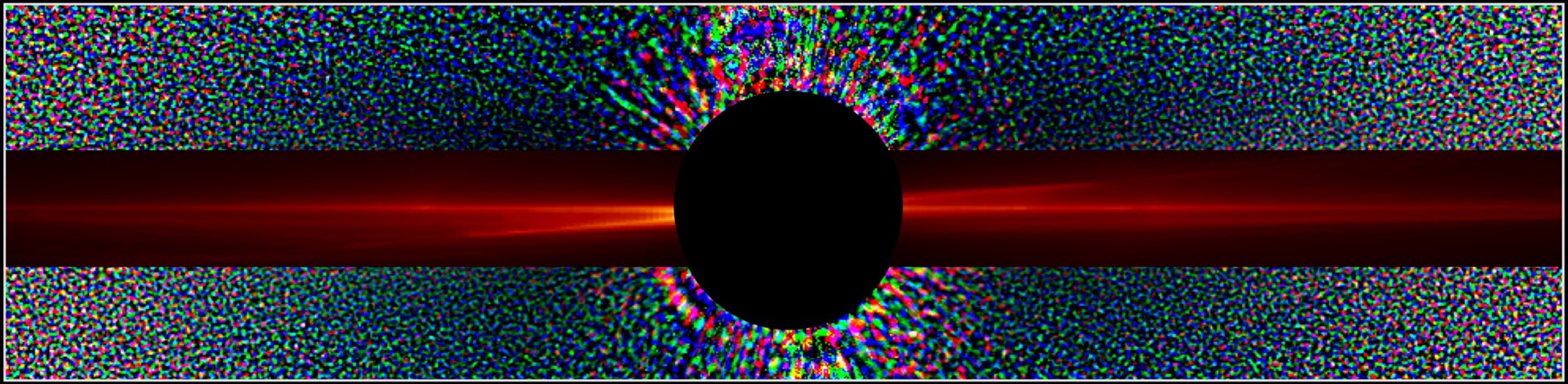
DEBRIS DISCS



AU Microscopii

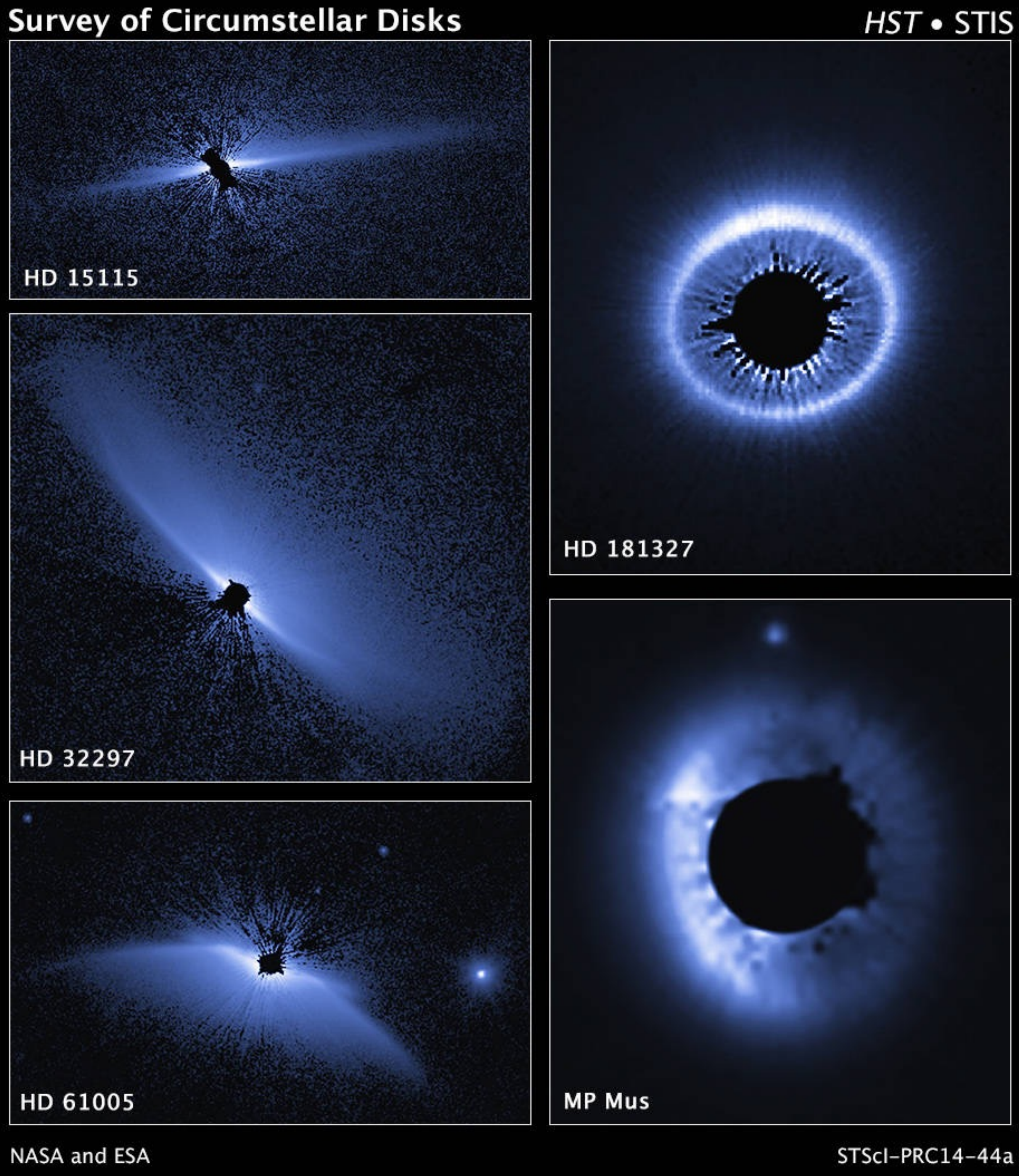
DEBRIS DISCS



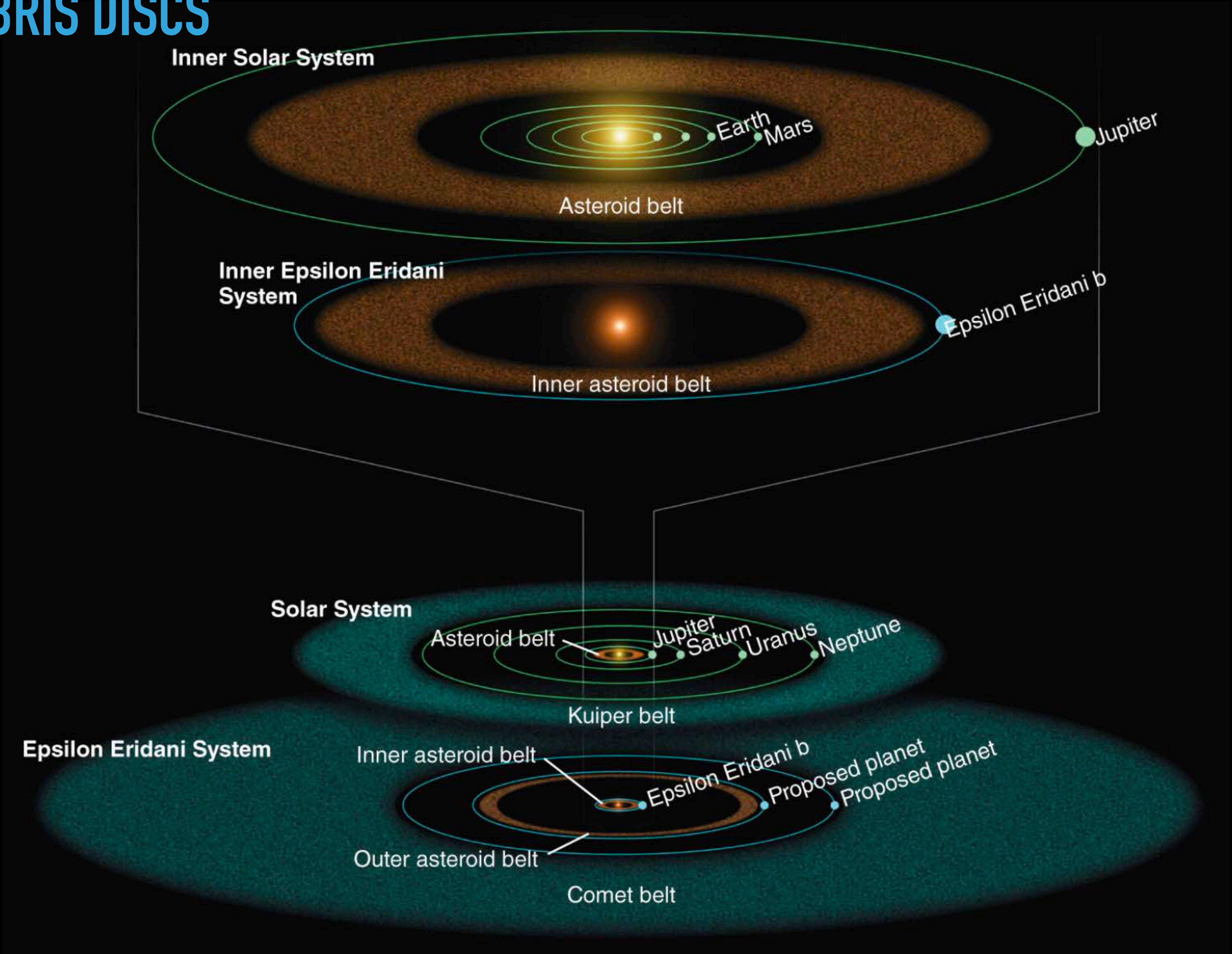


Beta Pictoris

DEBRIS DISCS



DEBRIS DISCS

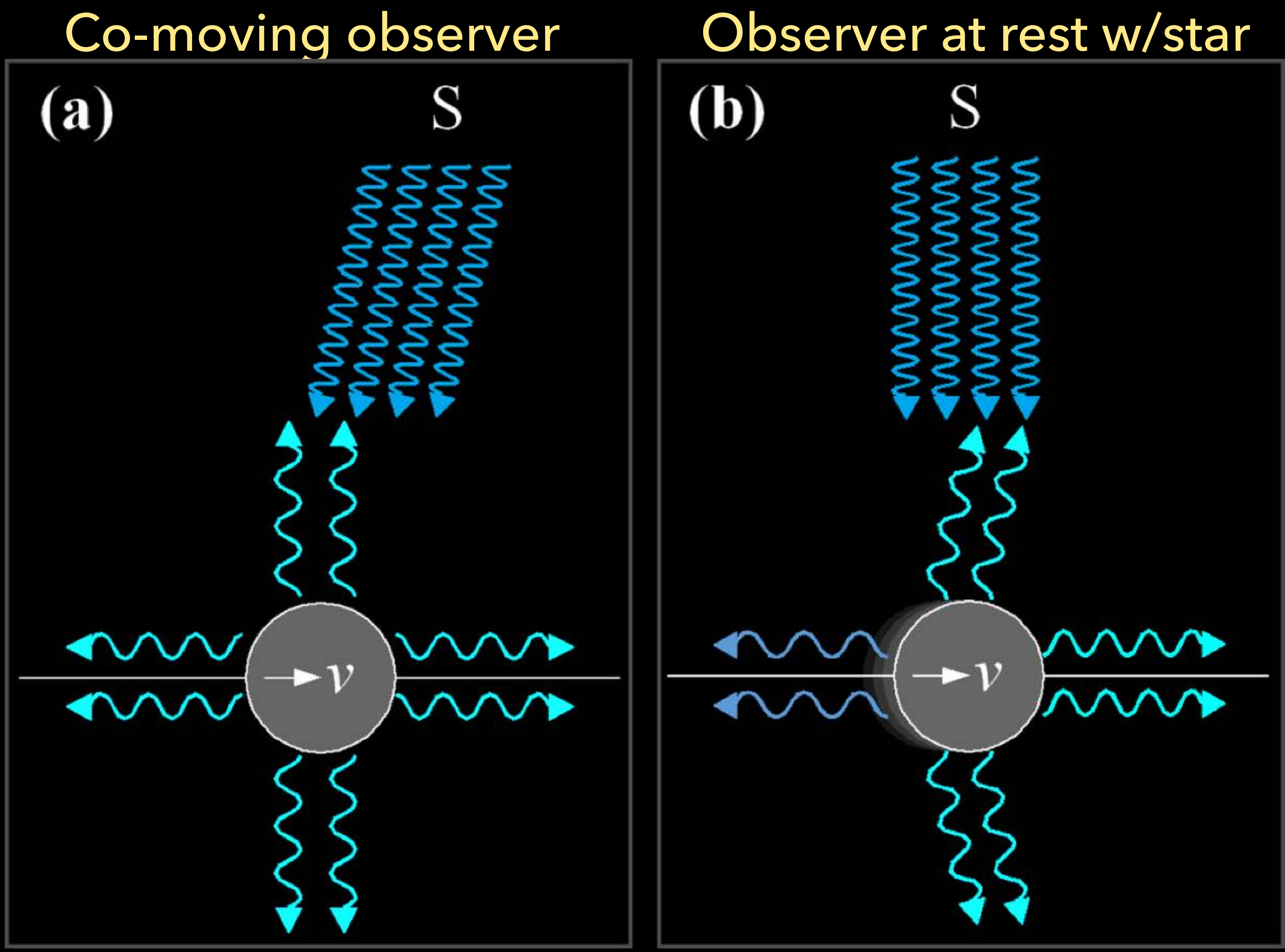


DEBRIS DISCS

- Debris discs are made from collisional grinding of leftover km-sized planetesimals.
- Collisions are destructive, producing a collisional cascade that repopulates small grain sizes (observable).
- $M_{\rm disc} \ll 0.01 M_*$
- $L_{\rm disc} \ll L_*$
- Dust and gas dynamics decoupled ($M_{\rm gas} < 10\ M_{\rm dust}$).
- Lifetimes depend on the stability of the system, size of the remnant disc, and the amount of stirring (Myr–Gyr).

DEBRIS DISCS

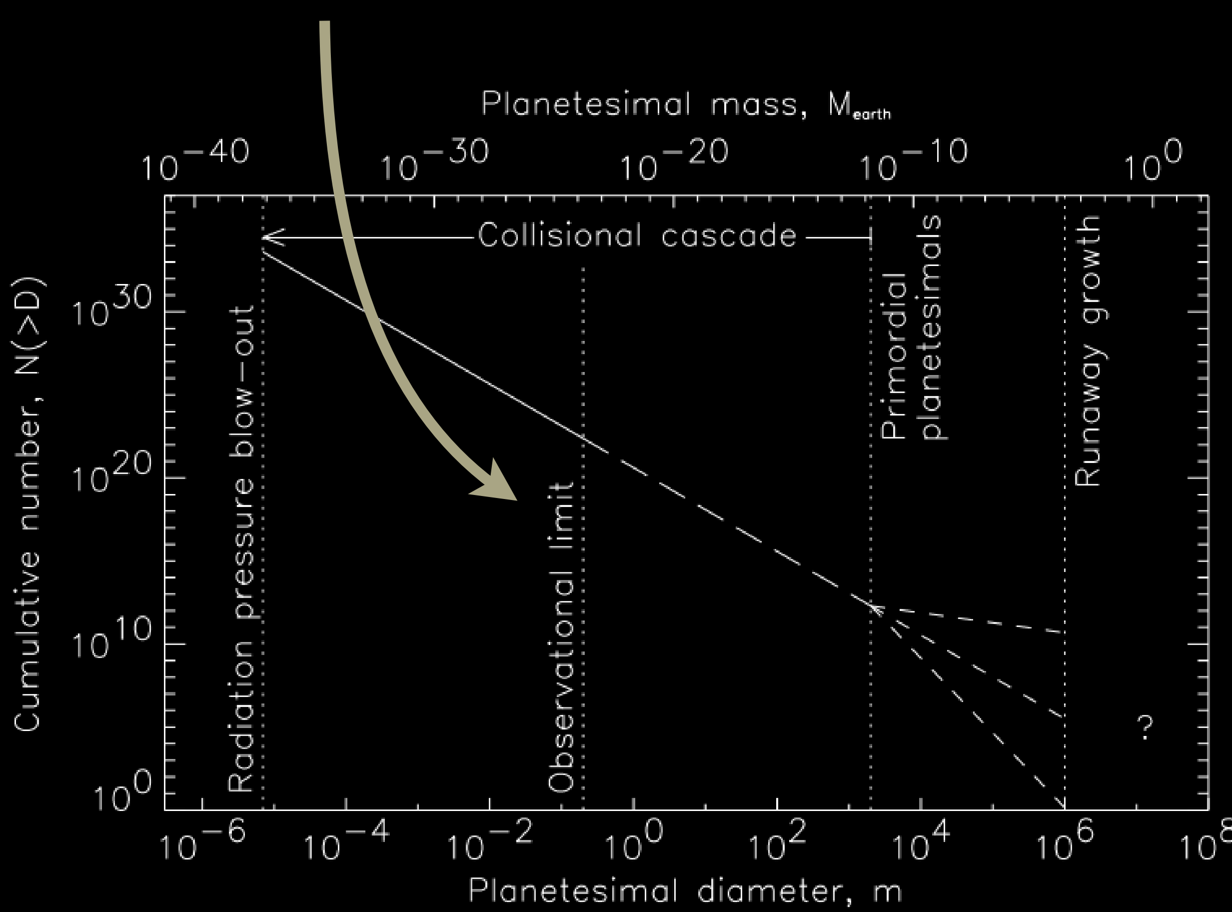
- Poynting–Robertson drag: stellar radiation causes a dust grain orbiting a star to lose angular momentum → radial drift. This is related to radiation pressure tangential to the grain's motion.
- (a) Stellar radiation comes from forward direction, but grain radiates isotropically.
- (b) Stellar radiation hits the grain laterally, but the grain appears to radiate more in the forward direction.



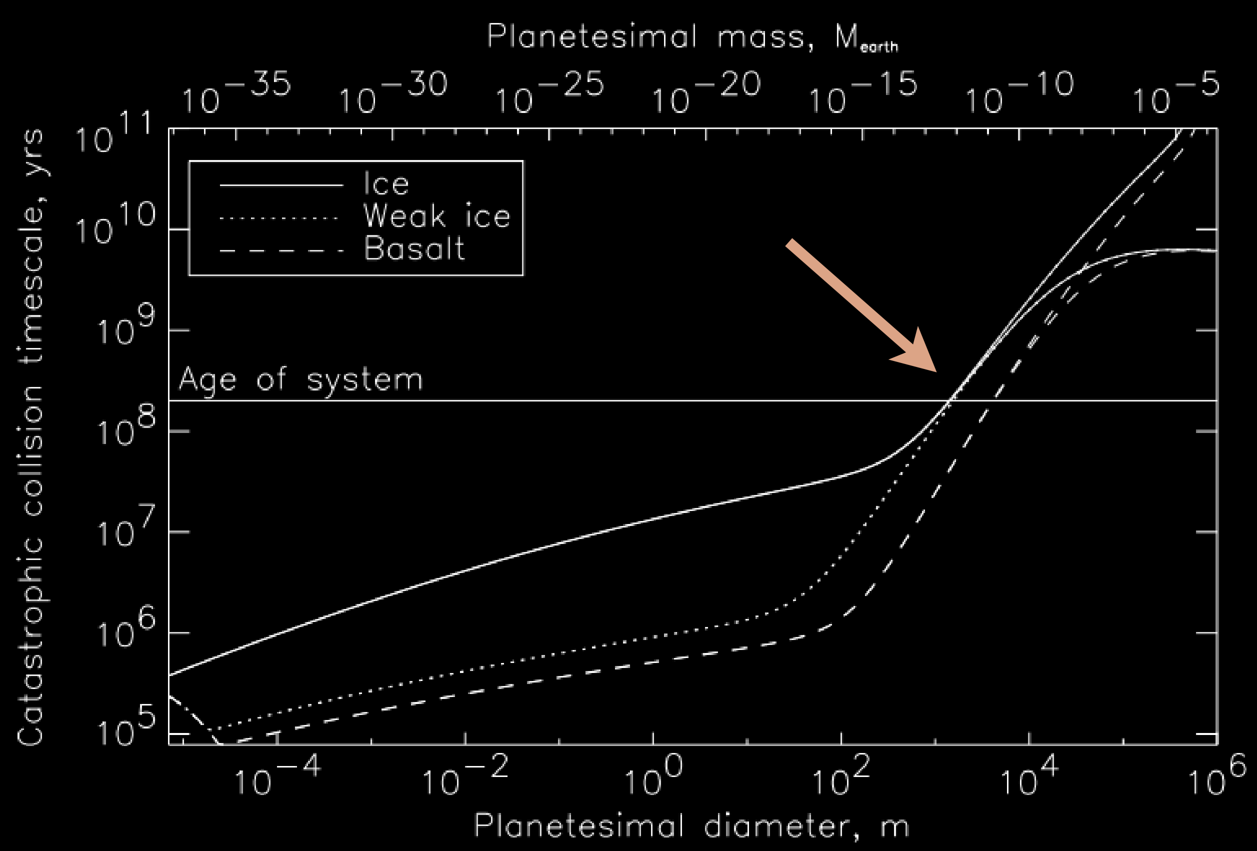
DEBRIS DISCS

- Large grains and planetesimals contain most of the mass, but contribute little to no flux.
- Must characterise the invisible population of eroding parent bodies through modelling.

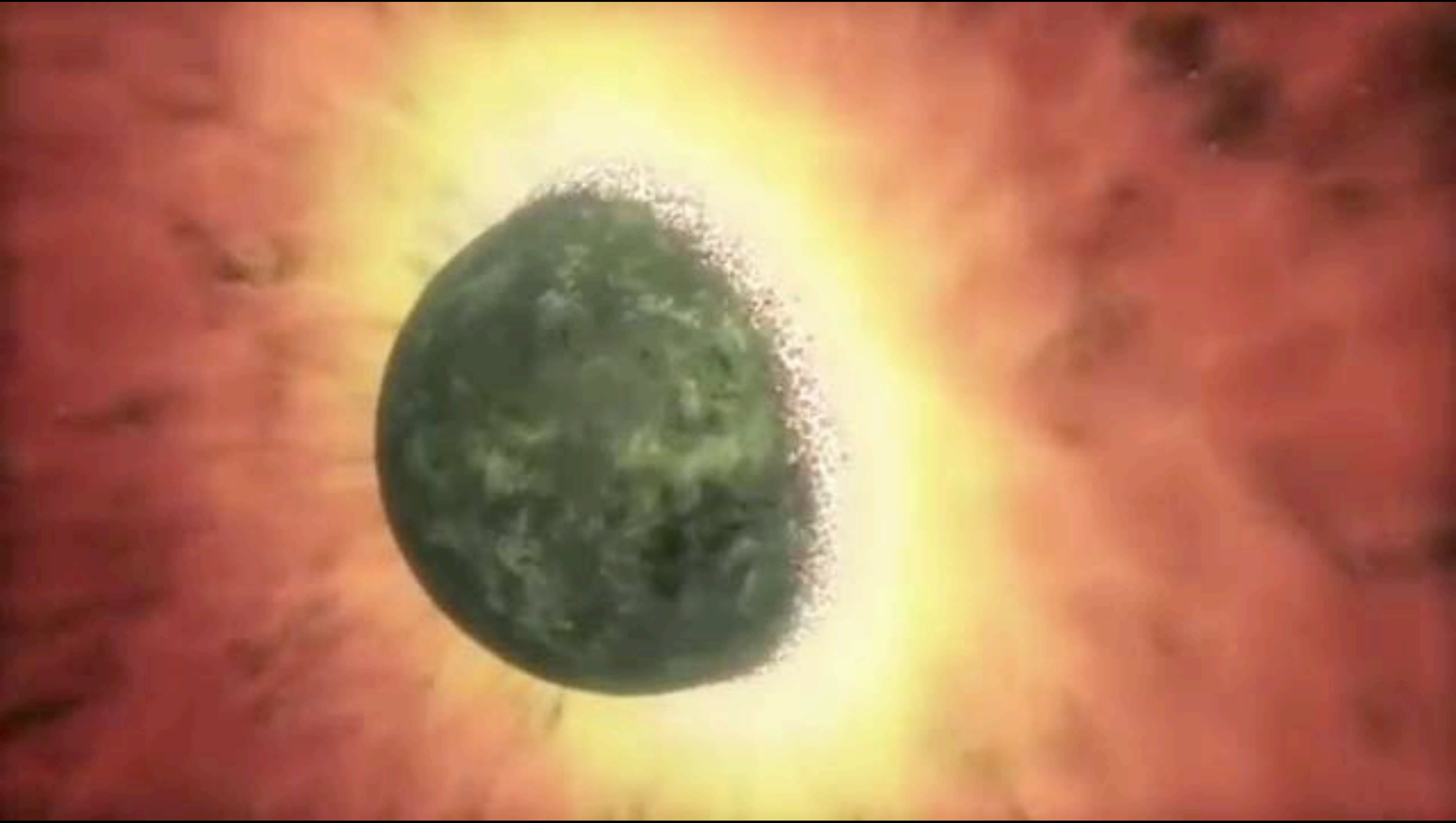
The observable portion of the collisional cascade extends up to 20 cm



Without larger objects, small grains would disappear in ~1 Myr; 440 Myr age of Fomalhaut implies planetesimals ~4 km feed the cascade

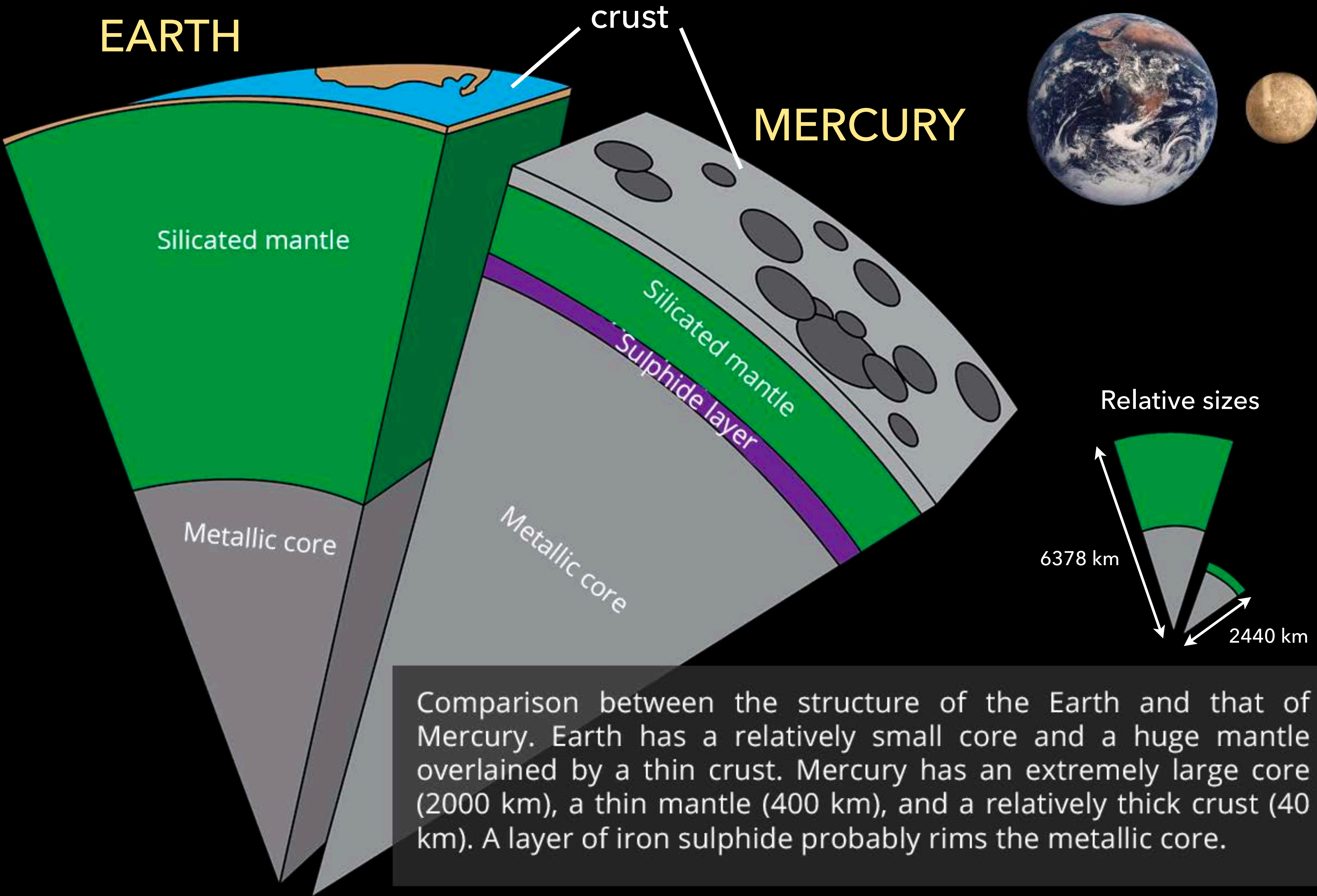


GIANT IMPACTS

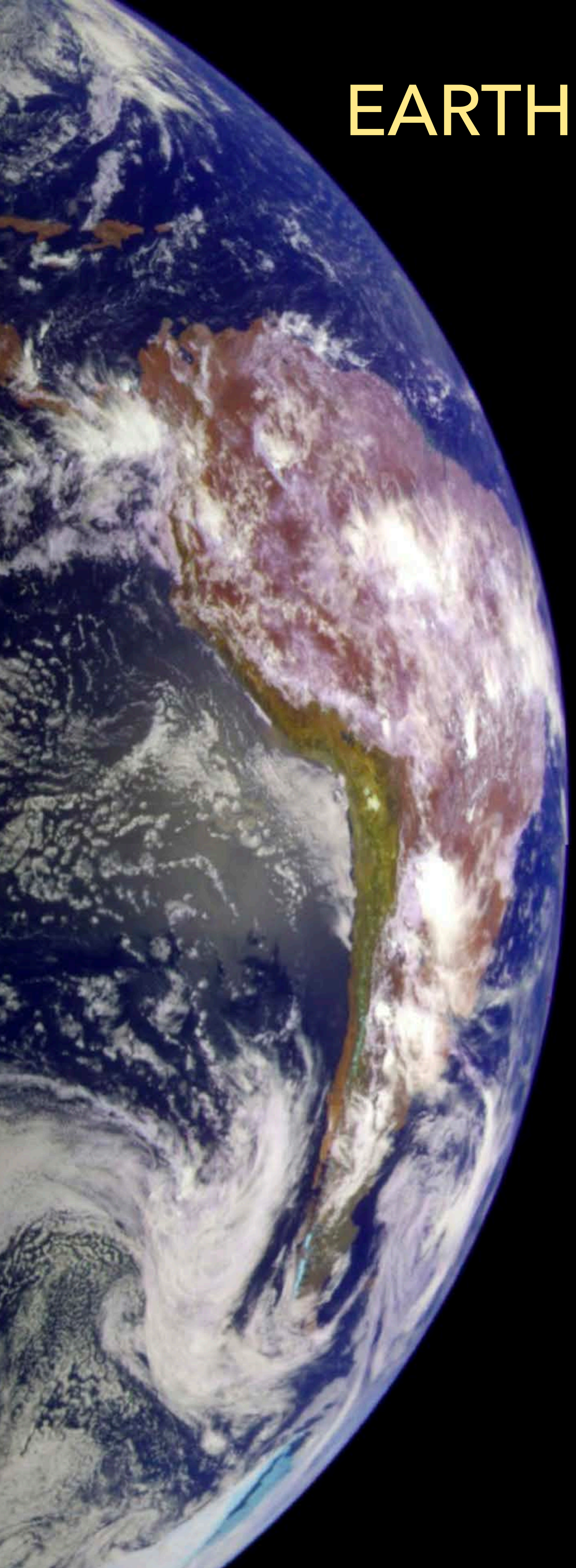


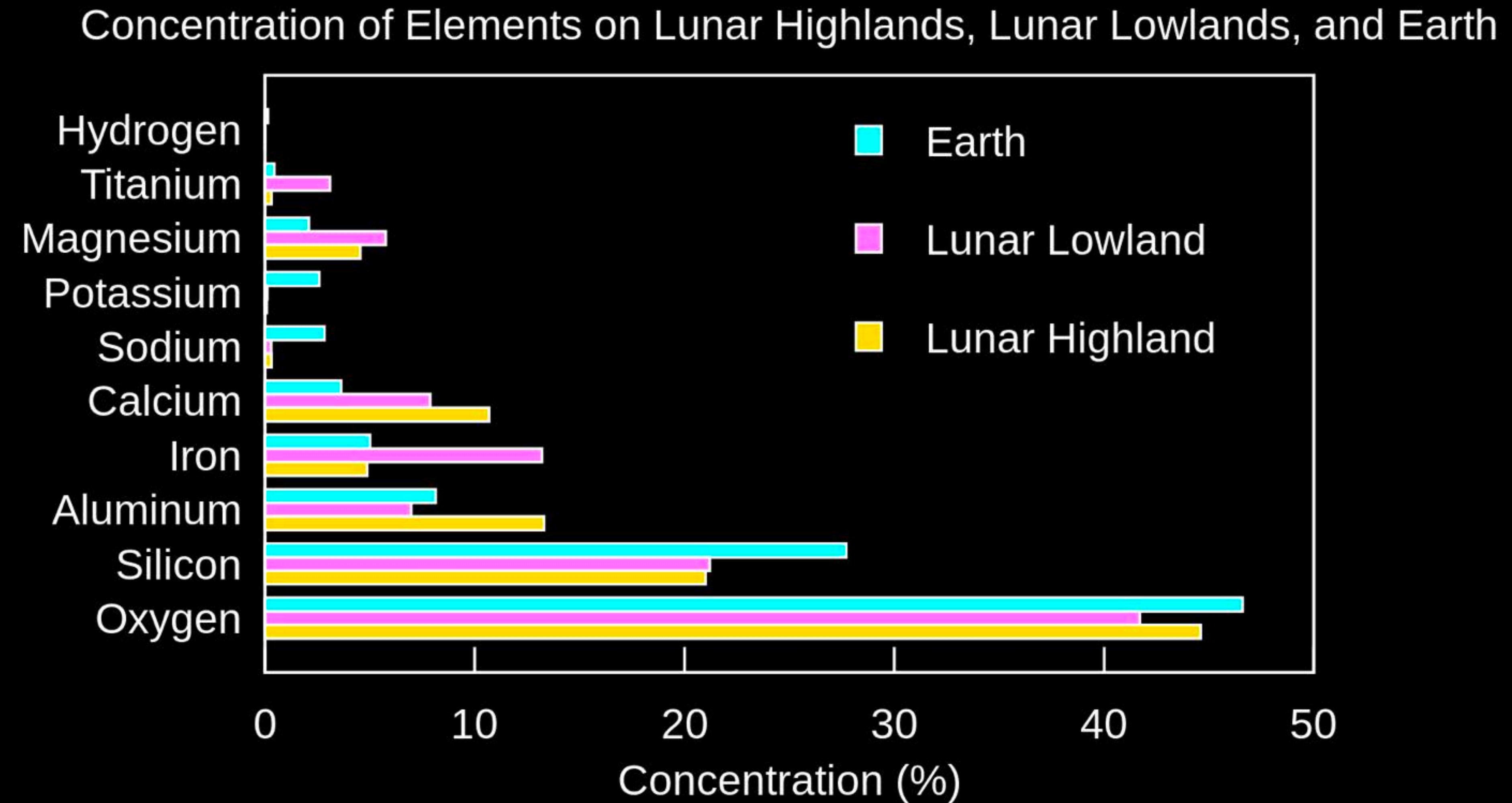
GIANT IMPACTS

- The late stages of the collisional accretion of planets involves collisions between planetary-sized bodies. These giant impacts involve enormous amounts of energy and are probably responsible for a number of particularities in the solar system:
    - Anomalous density of Mercury
    - Earth-Moon similarities
    - The topography of Mars
    - Tilt of Uranus' rotation axis
    - Existence of Chiron (Pluto's moon).
- It is the last giant impact that leaves traces. The geological clock is reset in the impact region (molten surface).



Comparison between the structure of the Earth and that of Mercury. Earth has a relatively small core and a huge mantle overlained by a thin crust. Mercury has an extremely large core (2000 km), a thin mantle (400 km), and a relatively thick crust (40 km). A layer of iron sulphide probably rims the metallic core.





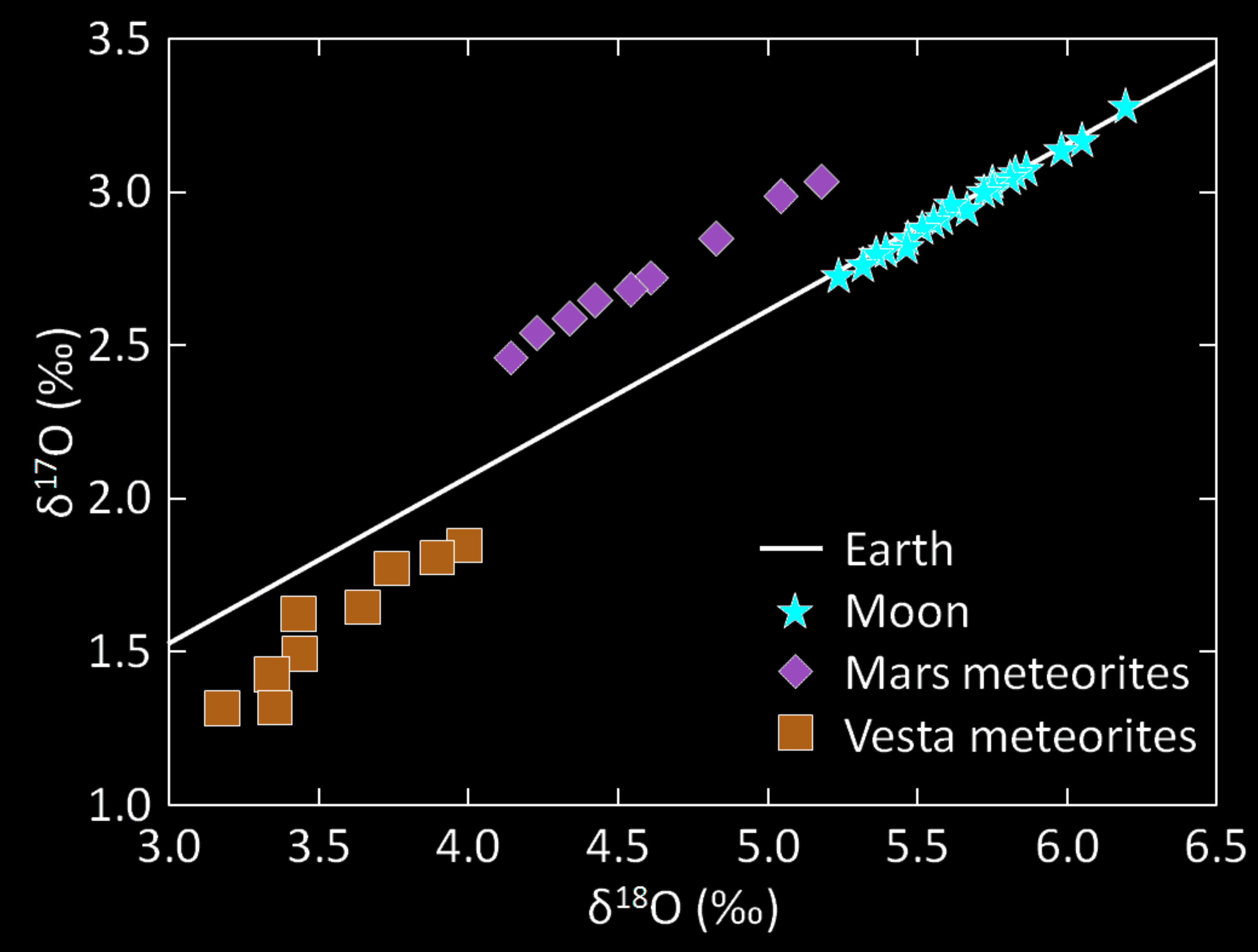
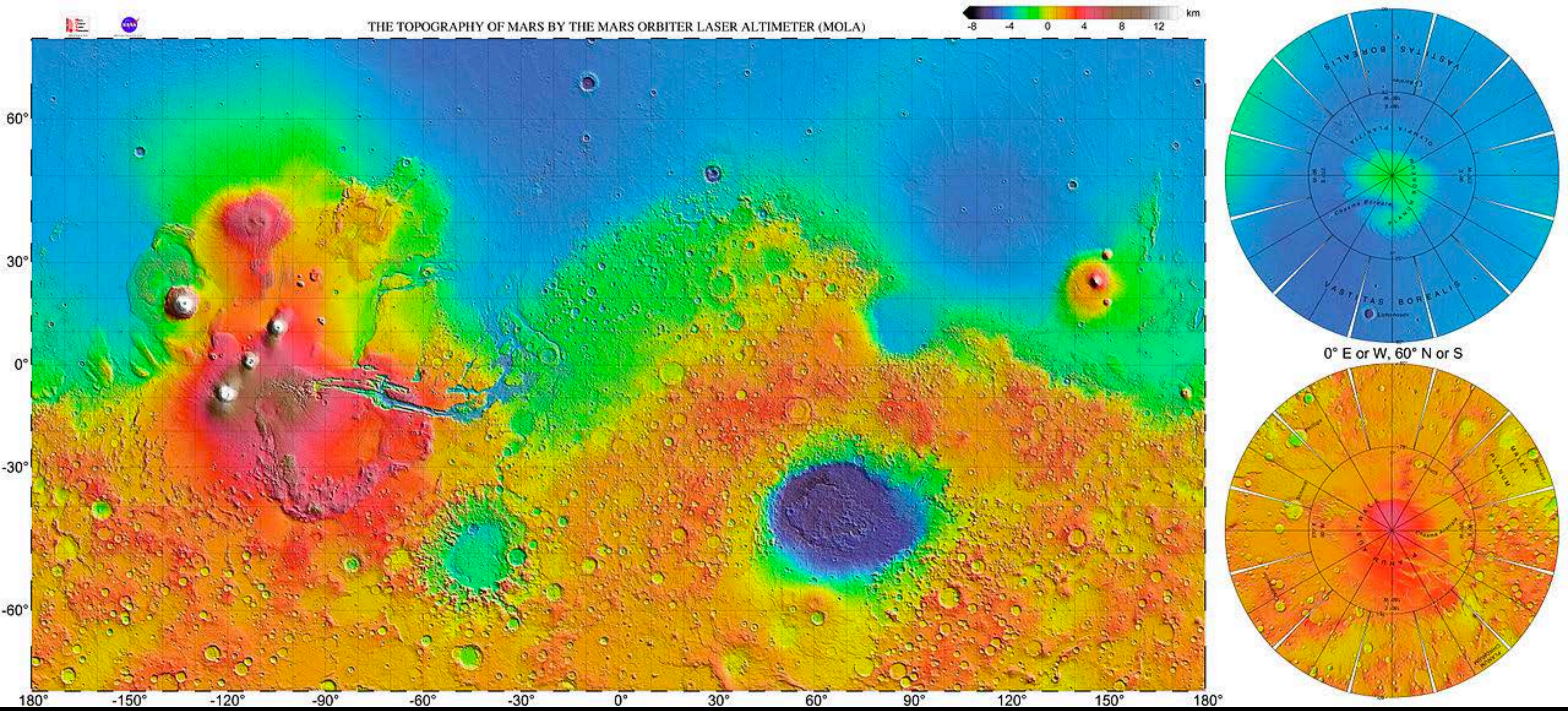
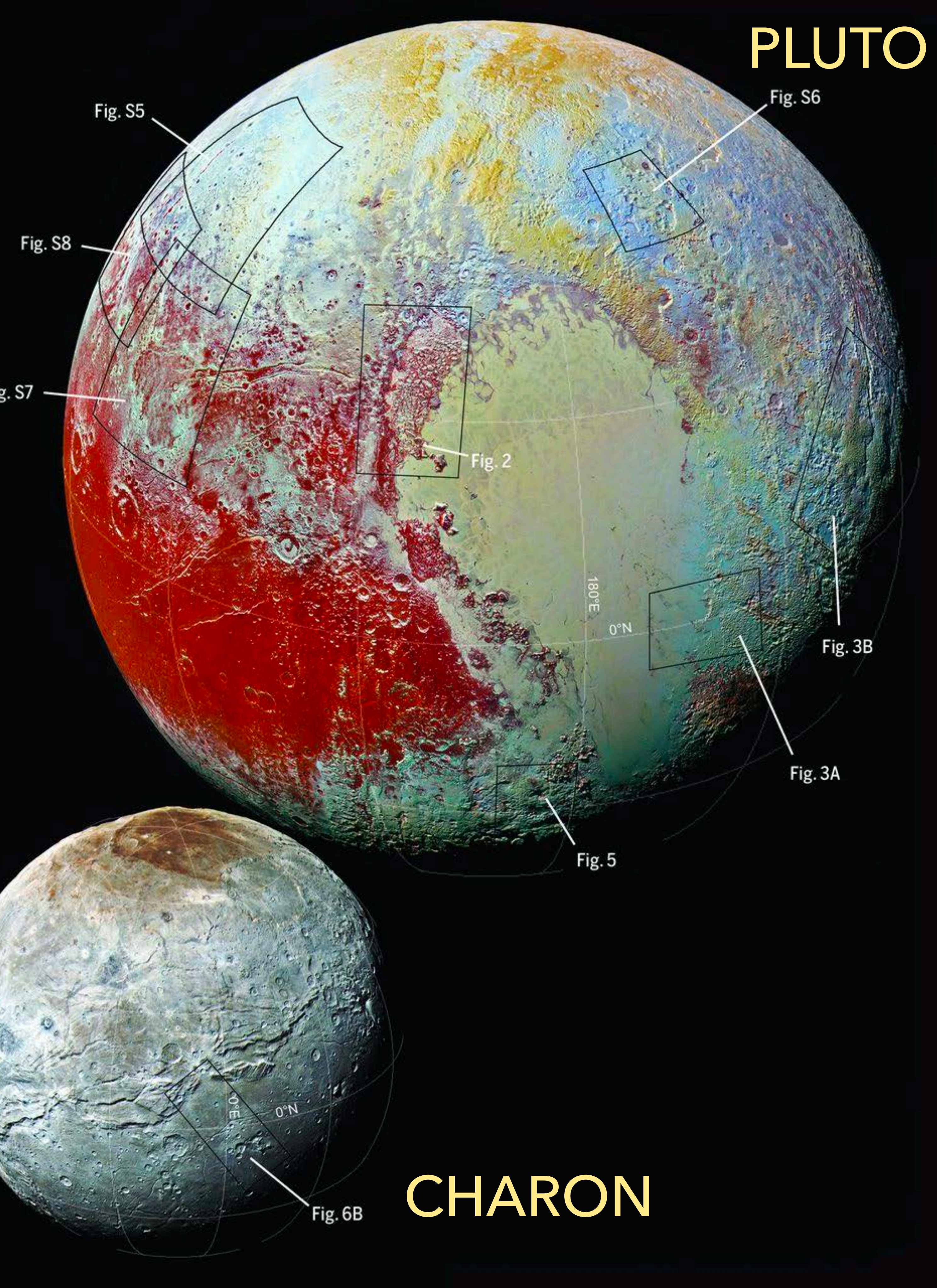


Image Credit: NASA/JPL/USGS

MARS

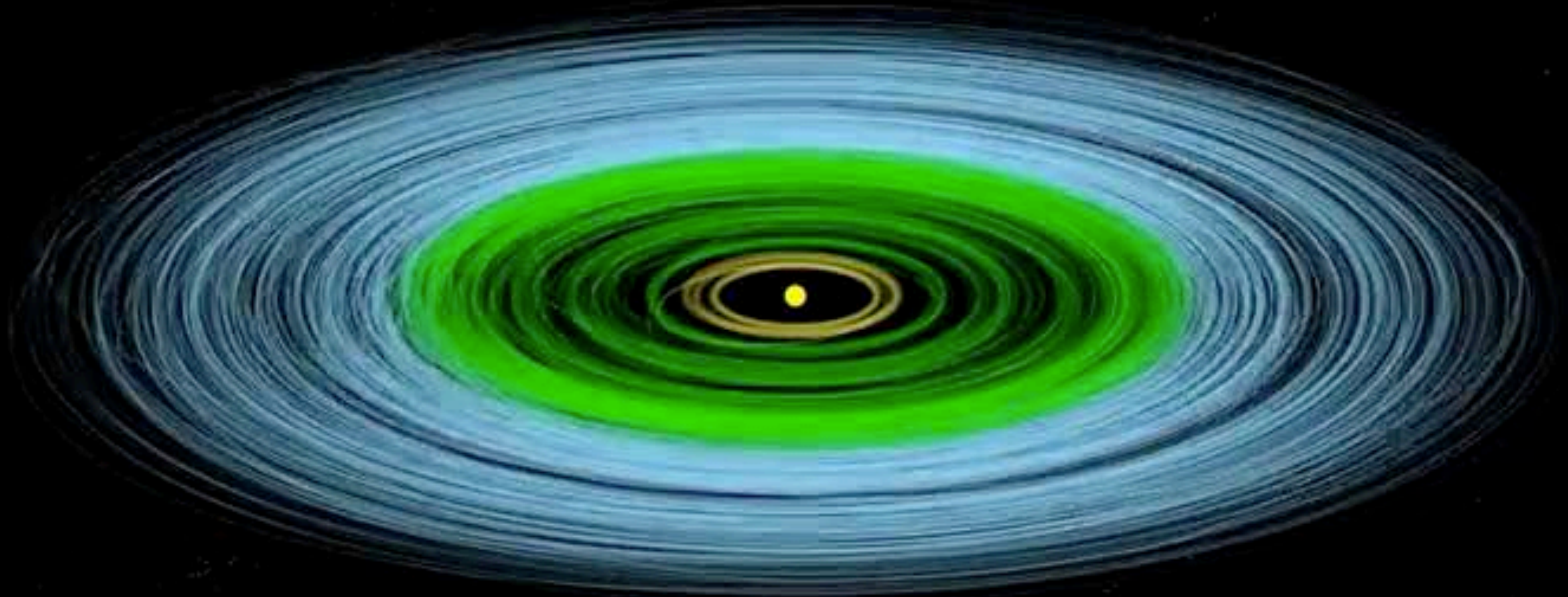


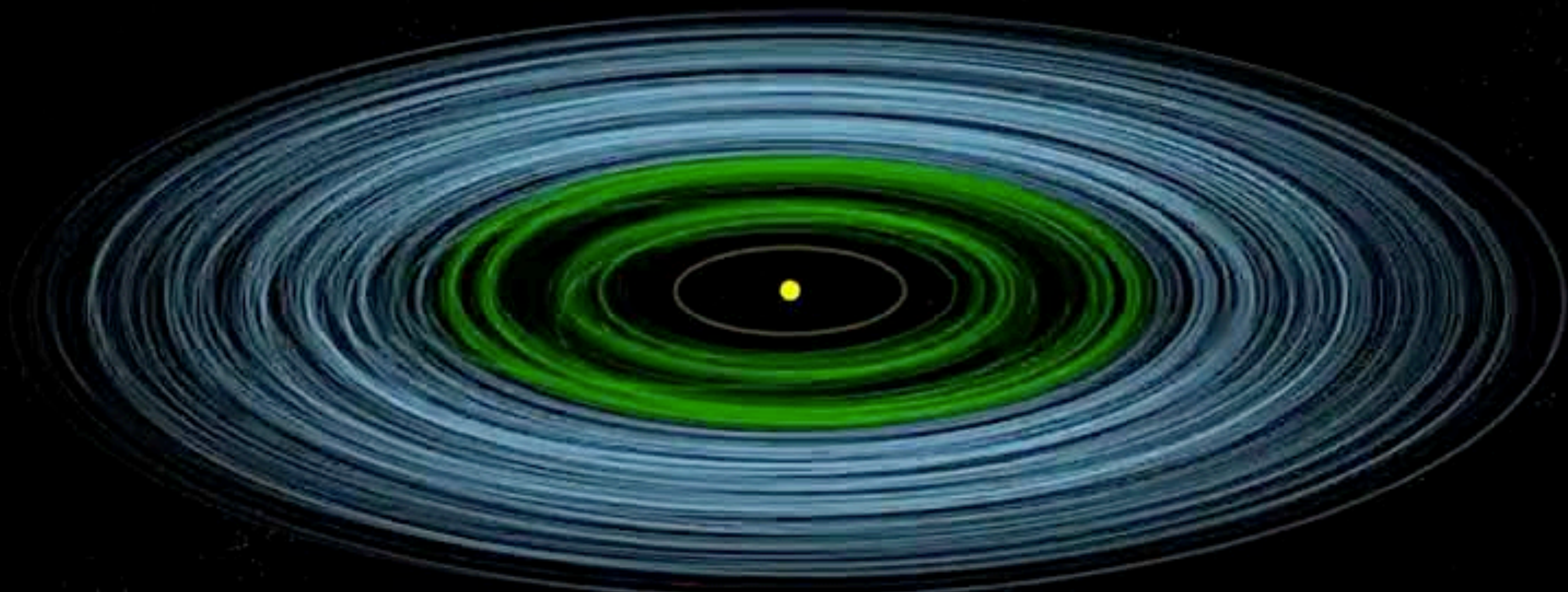
THE TOPOGRAPHY OF MARS BY THE MARS ORBITER LASER ALTIMETER (MOLA)
km
-8
-4
0
4
8
12
60°
30°
0°
-30°
-60°
180°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
180°
VASTITAS BOREALIS
0° E or W, 60° N or S

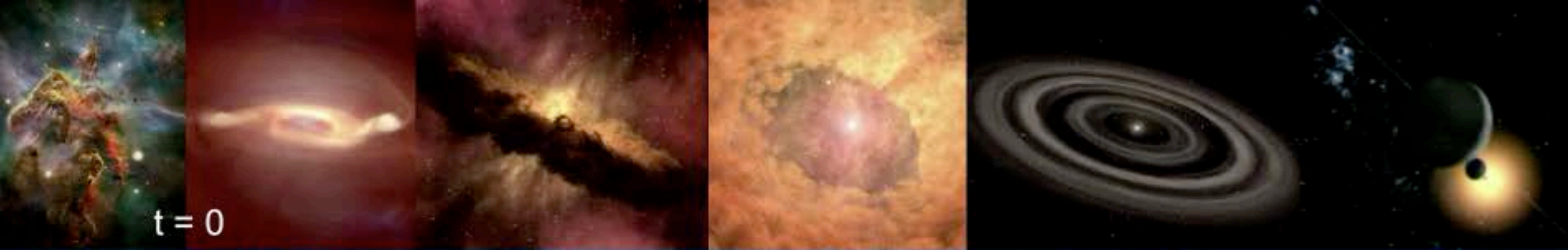

PLUTO
Fig. S5
Fig. S6
Fig. S8
g. S7
Fig. 2
180°E
0°N
Fig. 3B
Fig. 3A
Fig. 5
0°E
0°N
Fig. 6B
CHARON


Mercury
0°
Venus
177°
Earth
23°
Mars
25°
Jupiter
3°
Saturn
27°
Uranus
98°
Neptune
28°
URANUS
Planets not to scale

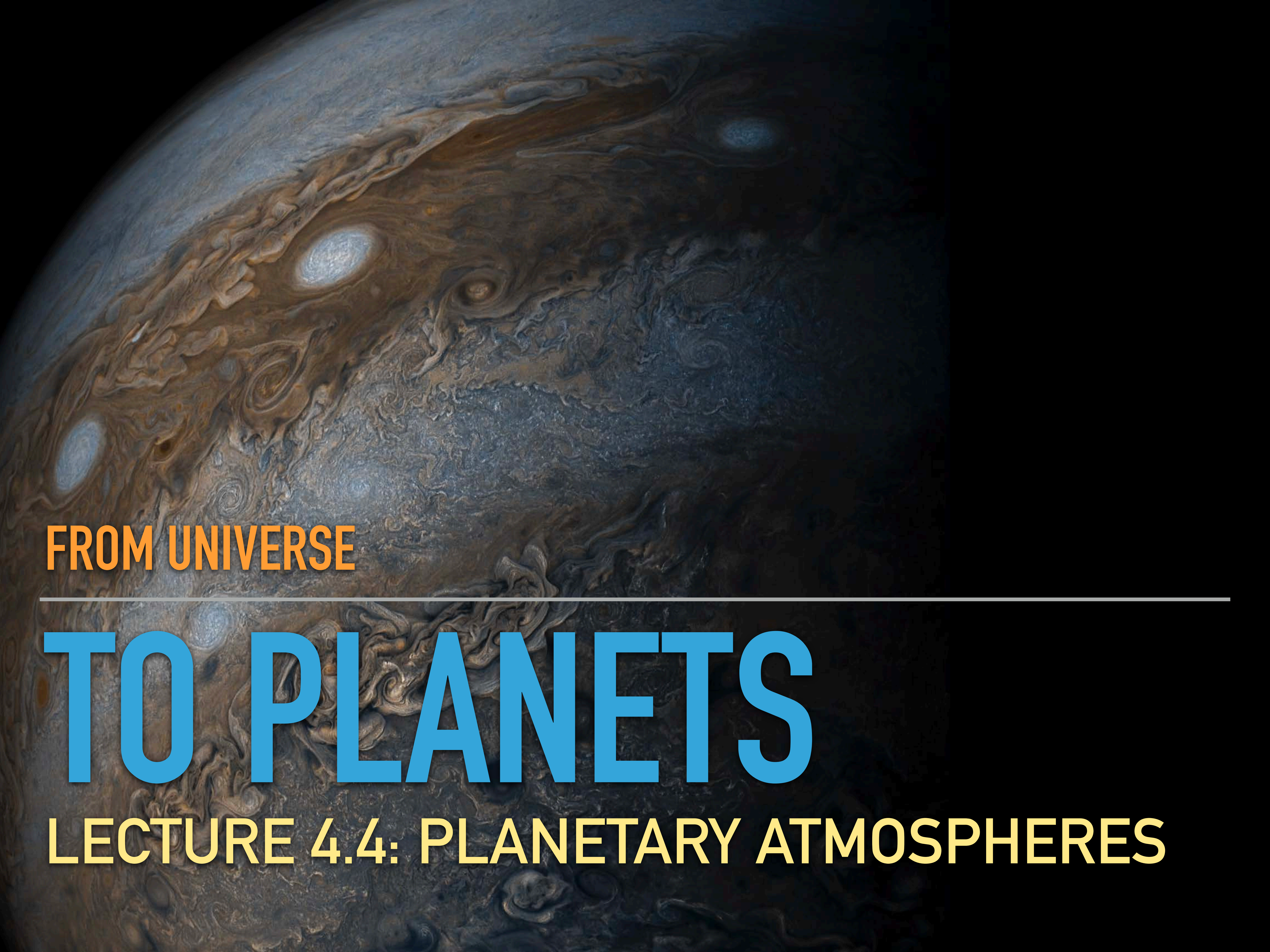
LONG TERM EVOLUTION







~Myr | ~10,000 yr ~0.5 Myr ~1–5 Myr ~10–100 Myr ~Gyr



FROM UNIVERSE

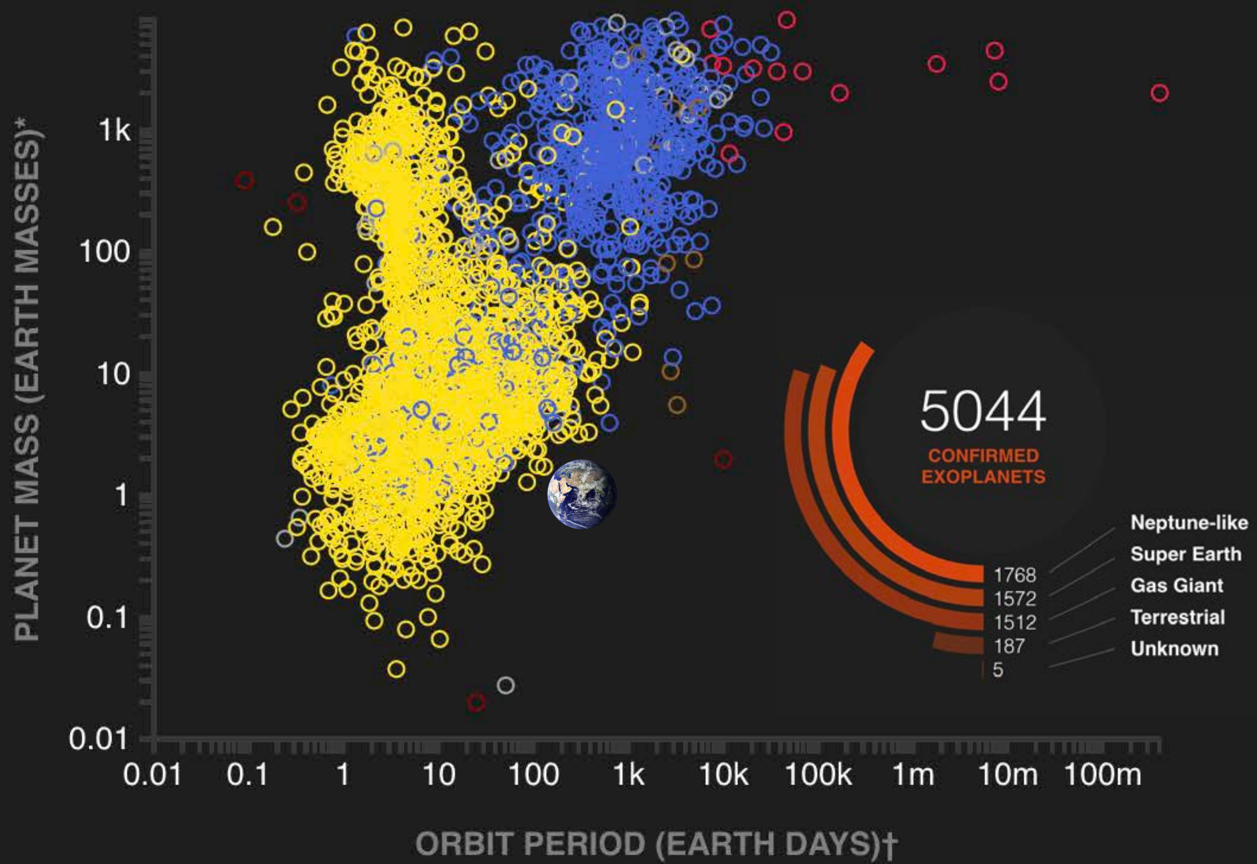
TO PLANETS

LECTURE 4.4: PLANETARY ATMOSPHERES

Exoplanet Census

Display limited to planets with both measured or estimated orbital period and mass

Transit (3835) Radial Velocity (926) Microlensing (9)
Imaging (14) Pulsar Timing (6) Other (48)



YEAR **2022** | DISCOVERIES‡ **5044**

1989 2022

k=thousand,m=million
*Masses and orbital periods are estimated for some planets based on other parameters
†Orbit period is equal to one trip around the star
‡Does not include discoveries where mass or orbit period is unknown or mass in Jupiters is > 25

https://exoplanets.nasa.gov/

By Method

76.6% Transit

When a planet passes directly between its star and an observer, it dims the star's light by a measurable amount.

18.4% Radial Velocity

Orbiting planets cause stars to wobble in space, causing an observable shift in the color of the star's light.

2.6% Microlensing

Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.

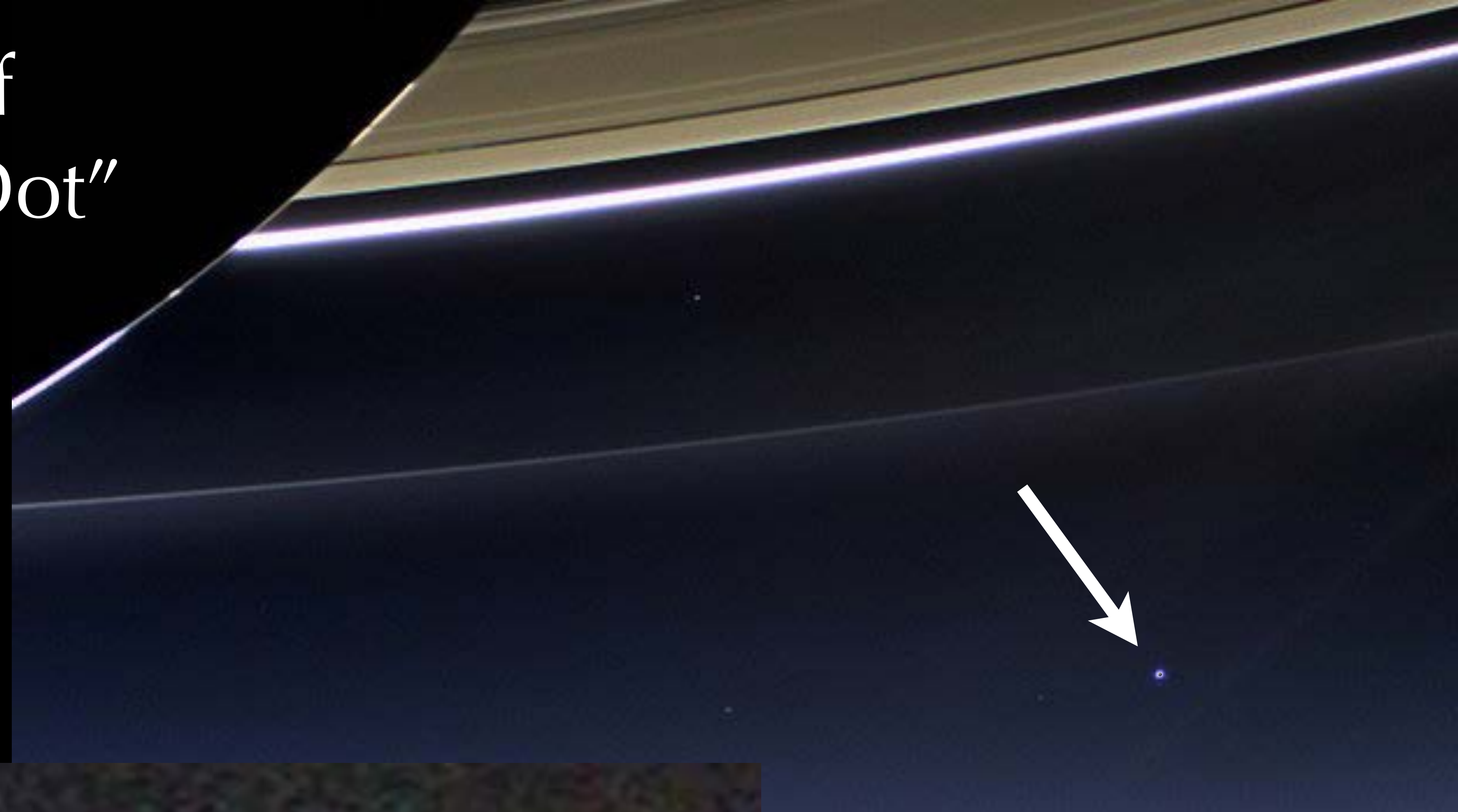
1.2% Imaging

Astronomers can take pictures of exoplanets using techniques that remove the overwhelming glare of the stars they orbit

0.44% Transit Timing Variations, 0.36% Eclipse Timing Variations, 0.18% Orbital Brightness Modulation, 0.14% Pulsar Timing, 0.04% Pulsation Timing Variations, 0.02% Disk Kinematics, 0.02% Astrometry

What would Earth look like from far away?

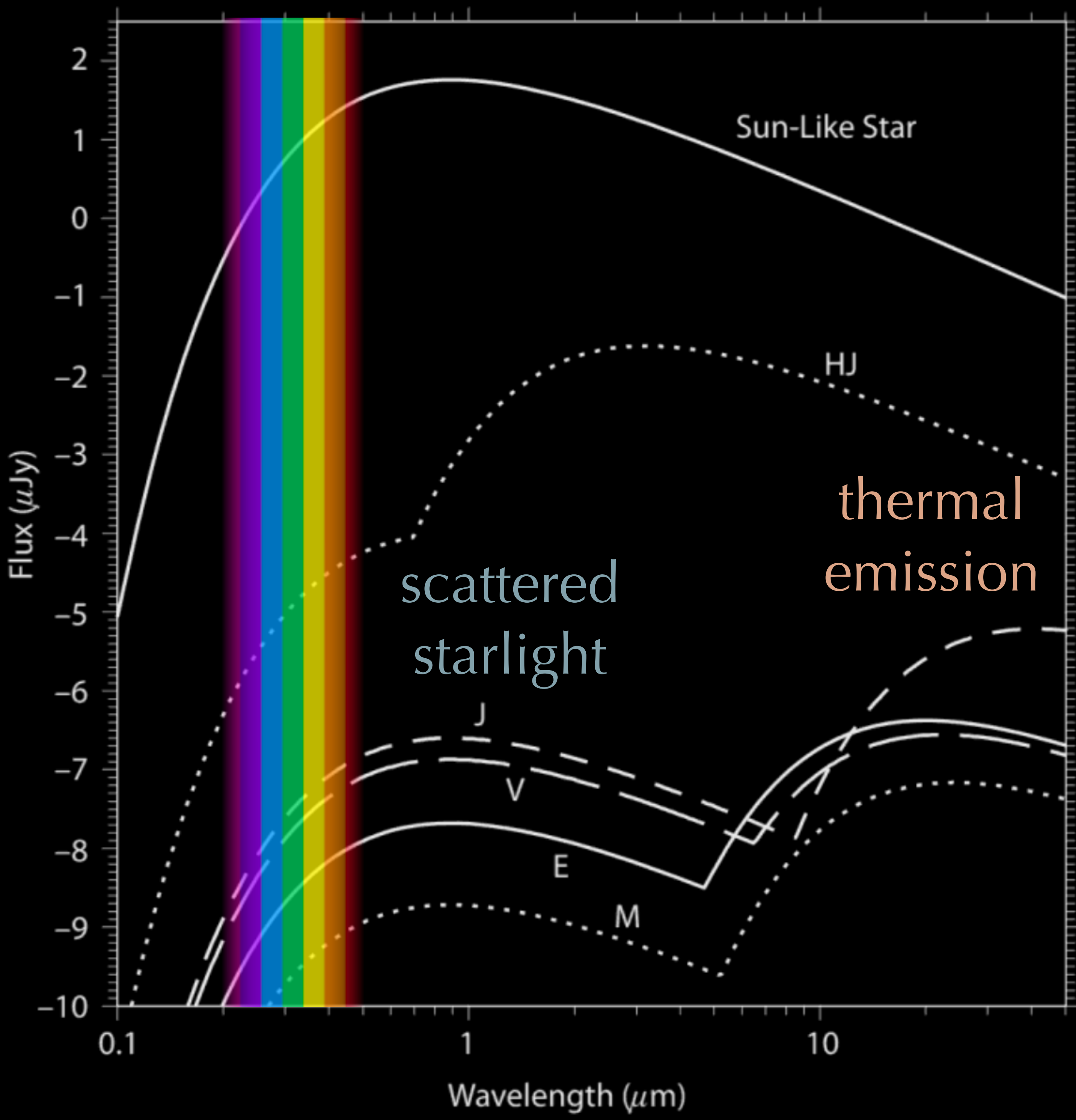
Cassini Image of
the “Pale Blue Dot”



Voyager I Image

Planet-Star Flux Ratio

- Exoplanets are no fainter than the faintest galaxies, but…
- ENORMOUS planet-star contrast is a major impediment to observation
- Hot Jupiters are much more favourable
    - Temperatures: 1000–2500 K
    - IR contrast only 10^{-3}



Observing Atmospheres

- Even in our own solar system it is difficult to resolve objects, so resolving atmospheres of exoplanets is not very feasible
- Instead, exoplanetary atmospheres are studied through their photometry (total light/brightness) and spectra (# of photons per wavelength)

VIS – NIR

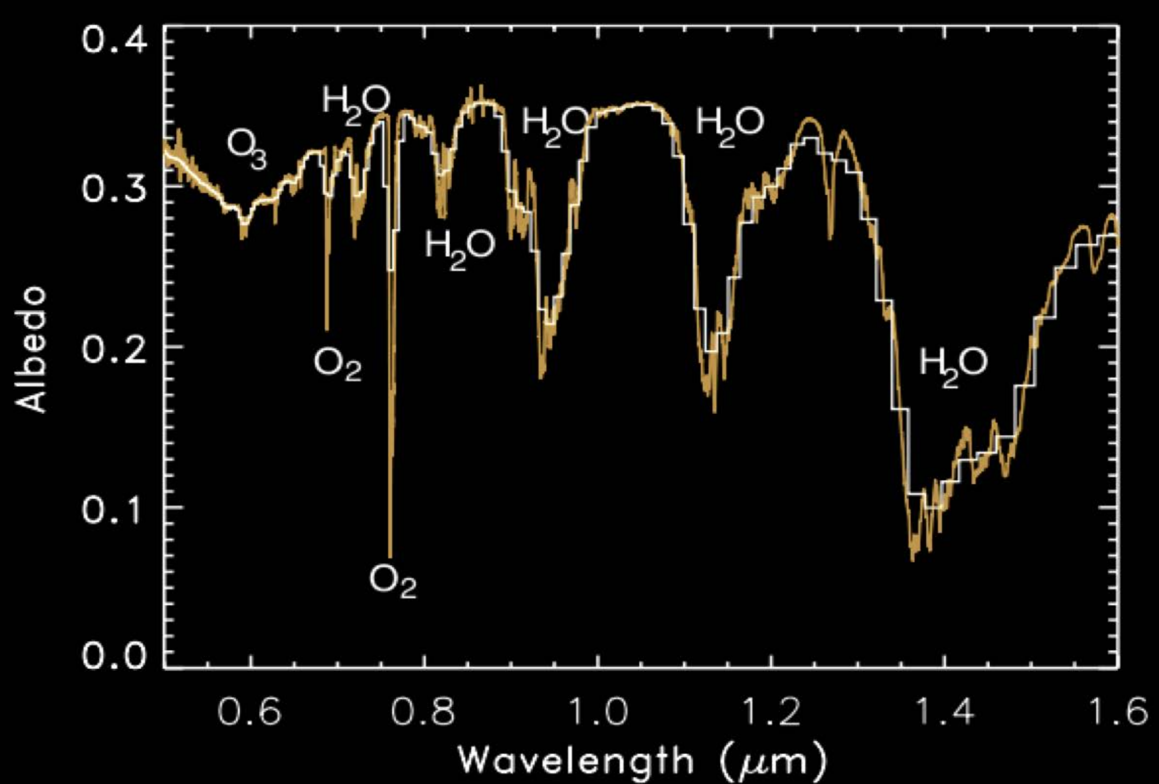


FIG. 1. Synthetic disk-averaged spectra of the Earth in the VIS-NIR, highly resolved (blue line) and at spectral resolution $R = 70$ (black line), simulating the TPF-C detection.

MIR

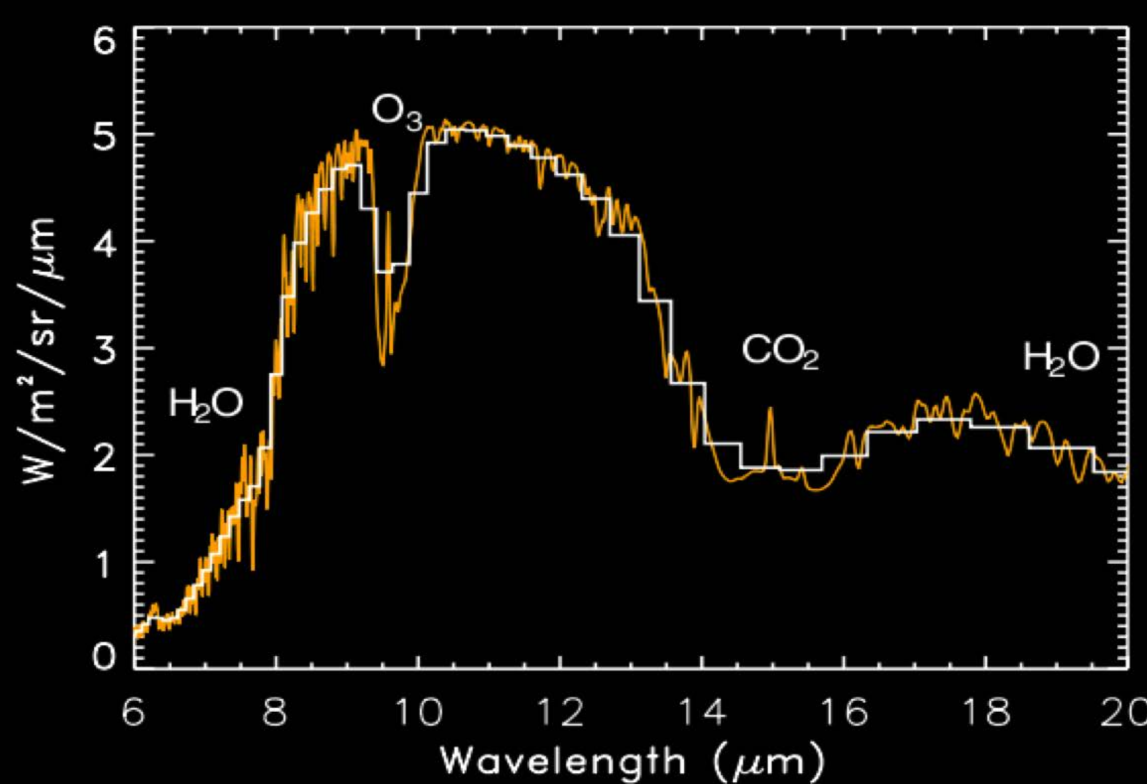


FIG. 2. Synthetic disk-averaged spectra of the Earth in the MIR, highly resolved (blue line) and at spectral resolution $R = 20$ (black line), simulating the TPF-I detection.

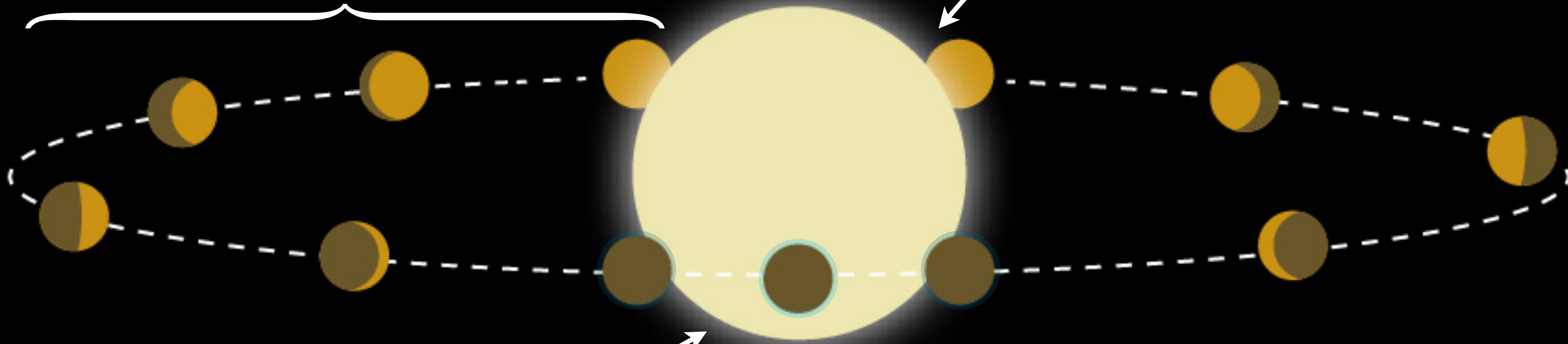
Tinetti et al. (2006)

Phase Curves

- Atmospheric circulation
- Weather patterns (e.g. clouds)

Secondary Eclipse

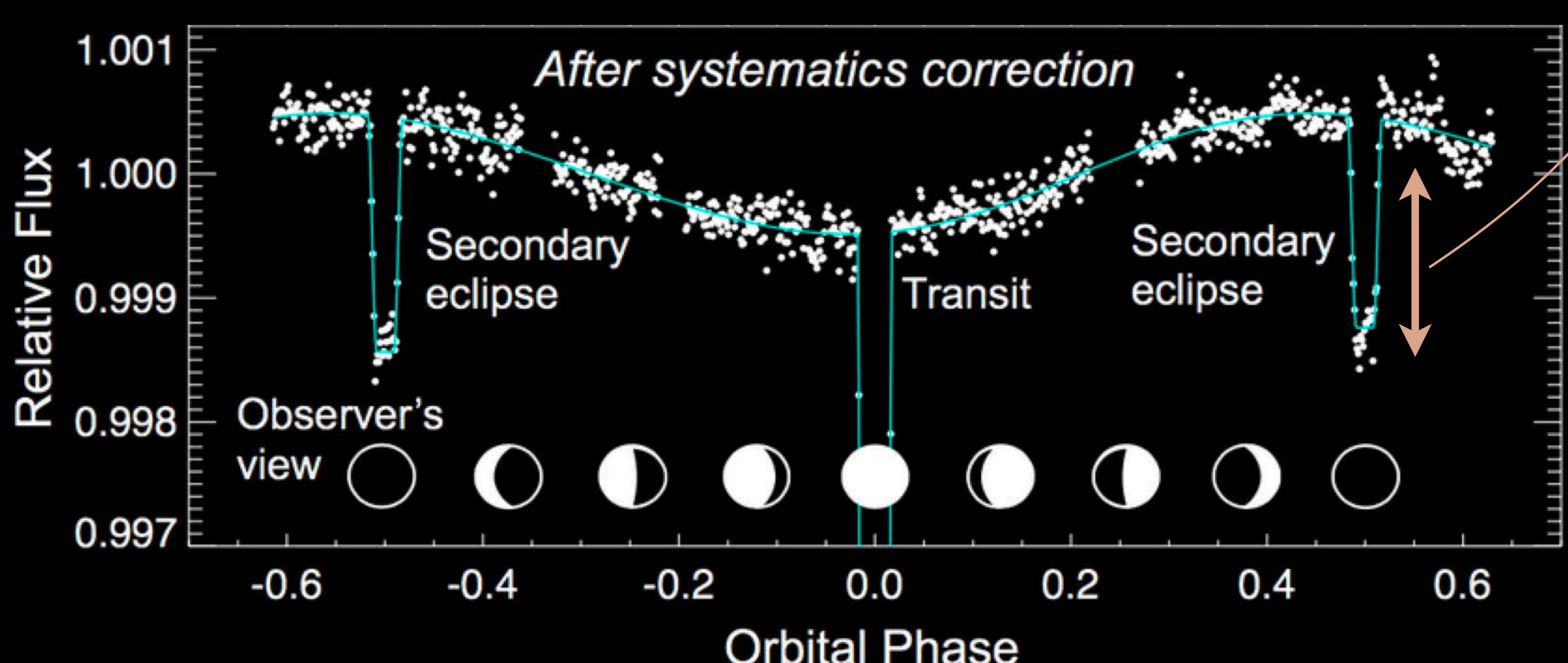
- Thermal radiation of planet



Primary Eclipse

- Tells us about the size of planet
- Transmission spectra

Brightness temperature from depth of secondary transit



55 Cancri e

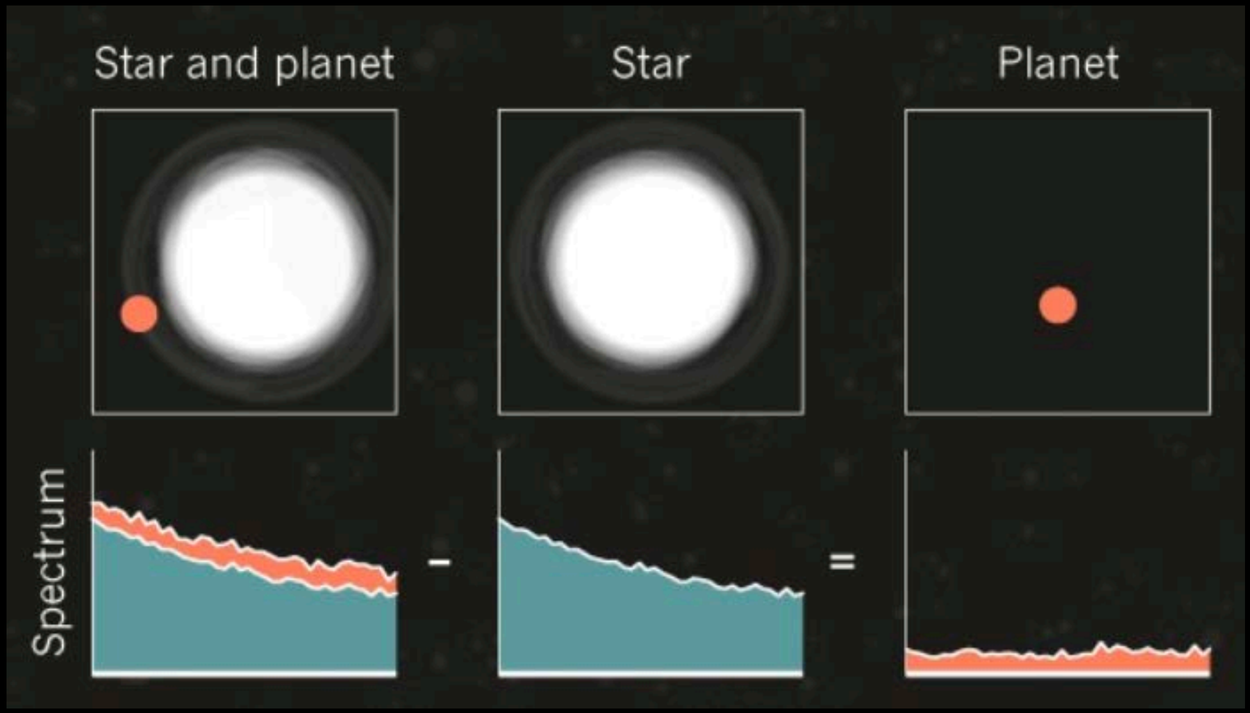
Day-side: 2,700 K

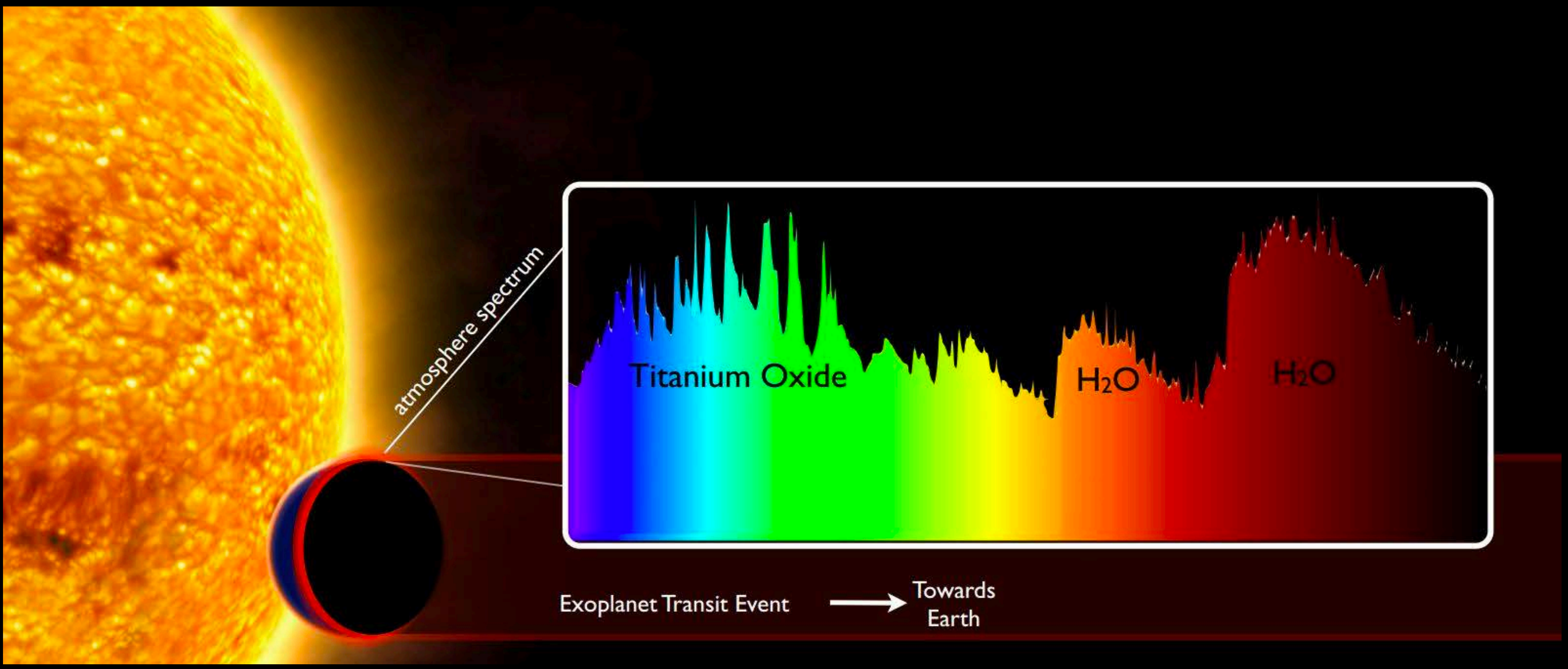
Credits: NASA/JPL-Caltech

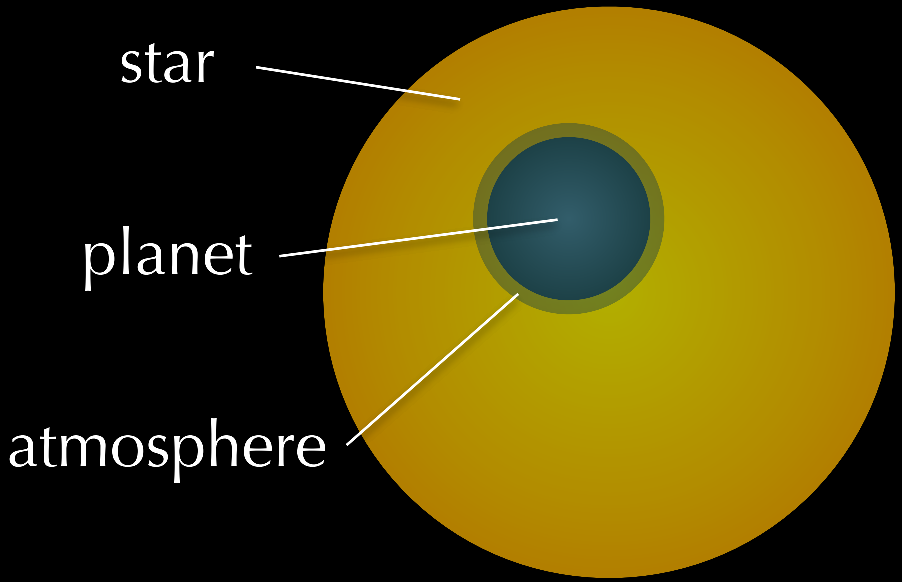
Night-side: 1,400 K

Transmission Spectrum

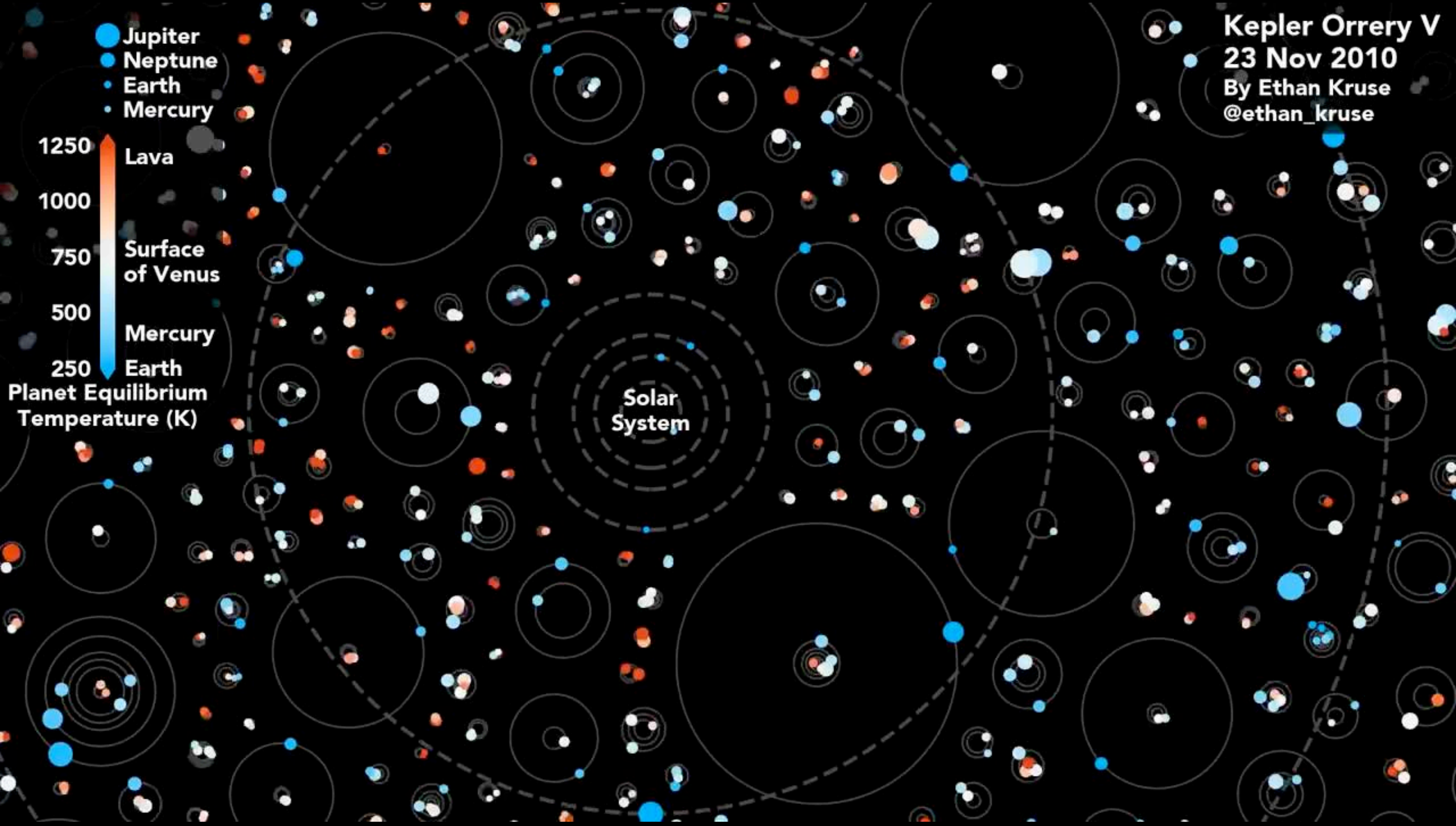
- Stellar radiation passing through the optically thin (upper) atmosphere
- Differencing the spectra from in and out of transit allows us to isolate the spectral features of the atmosphere





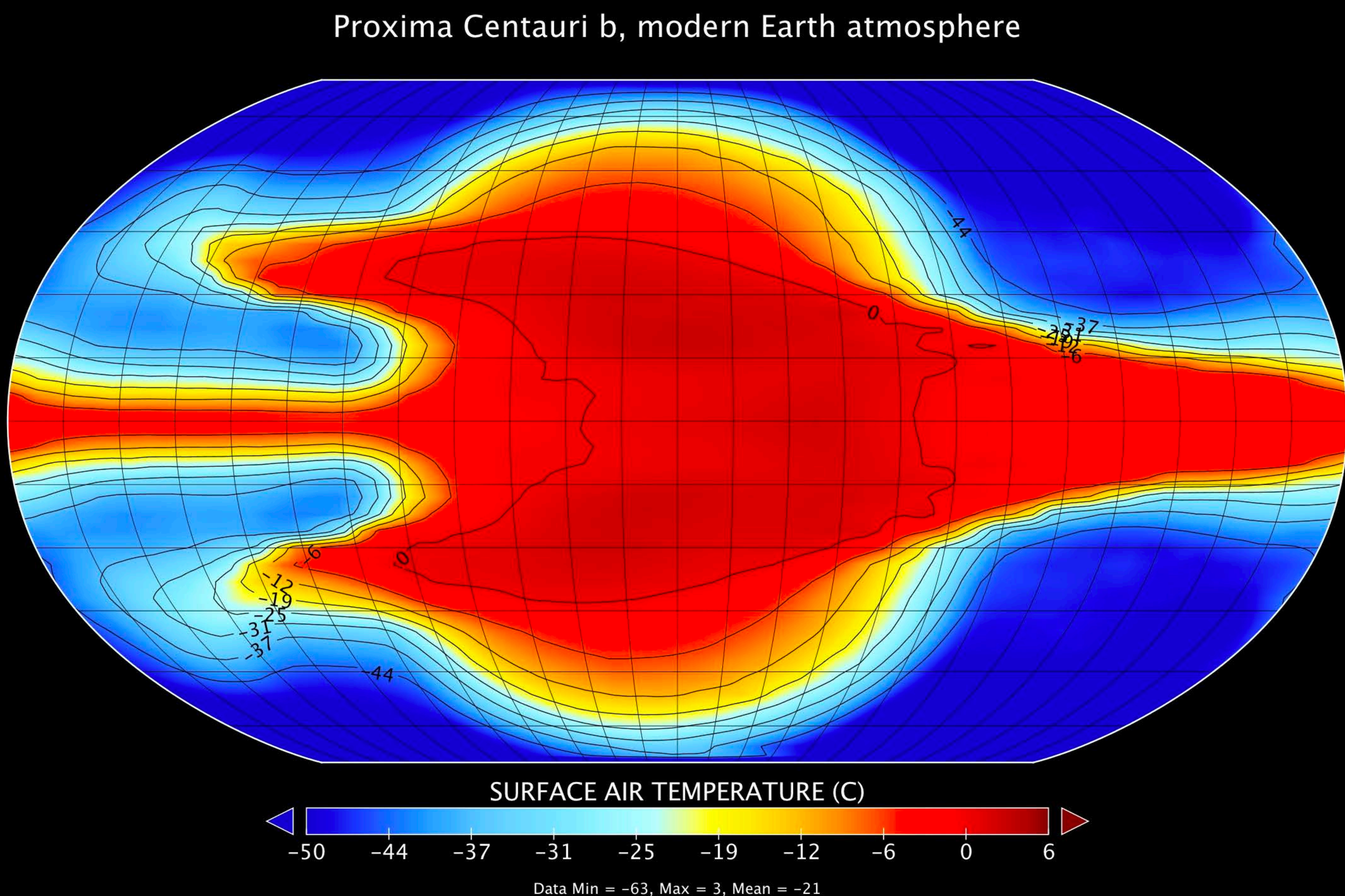


Diversity of Planets



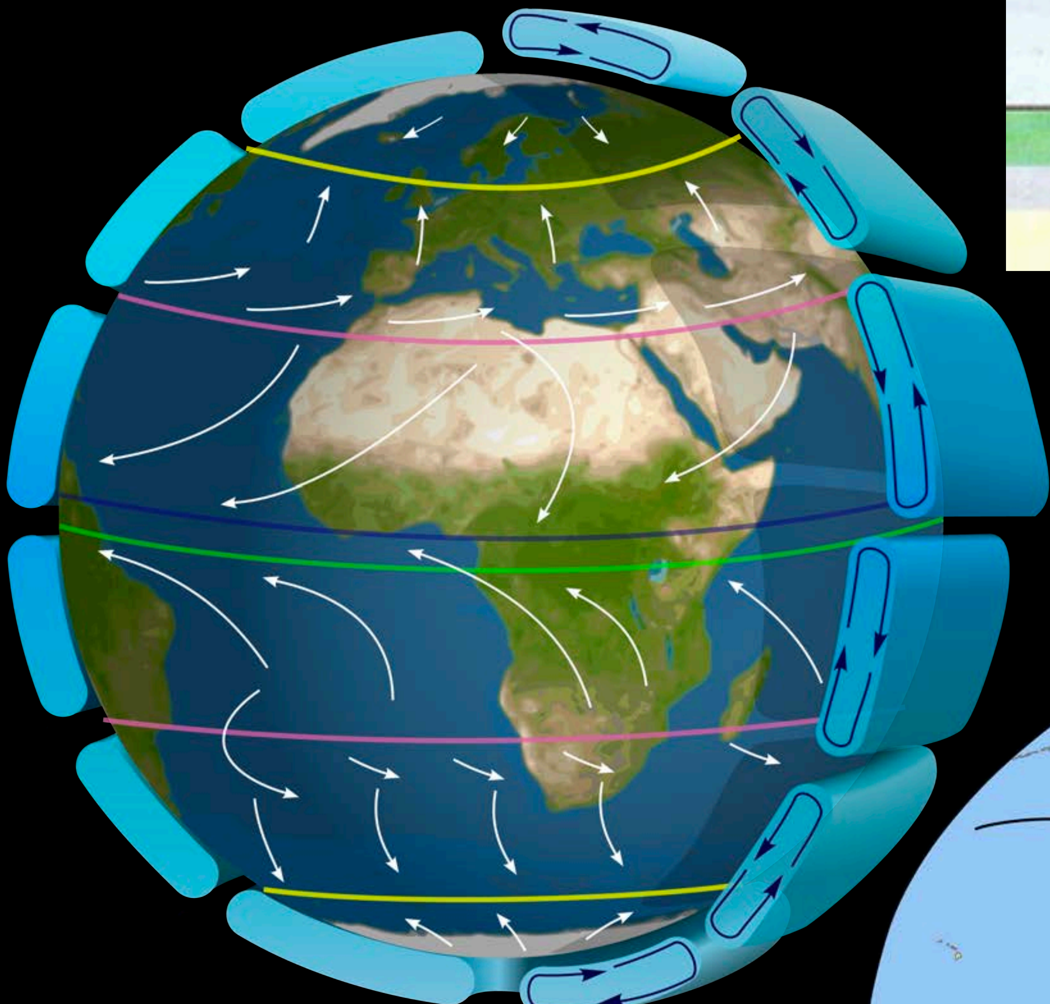
Diversity of Planets
=
Diversity of Atmospheres

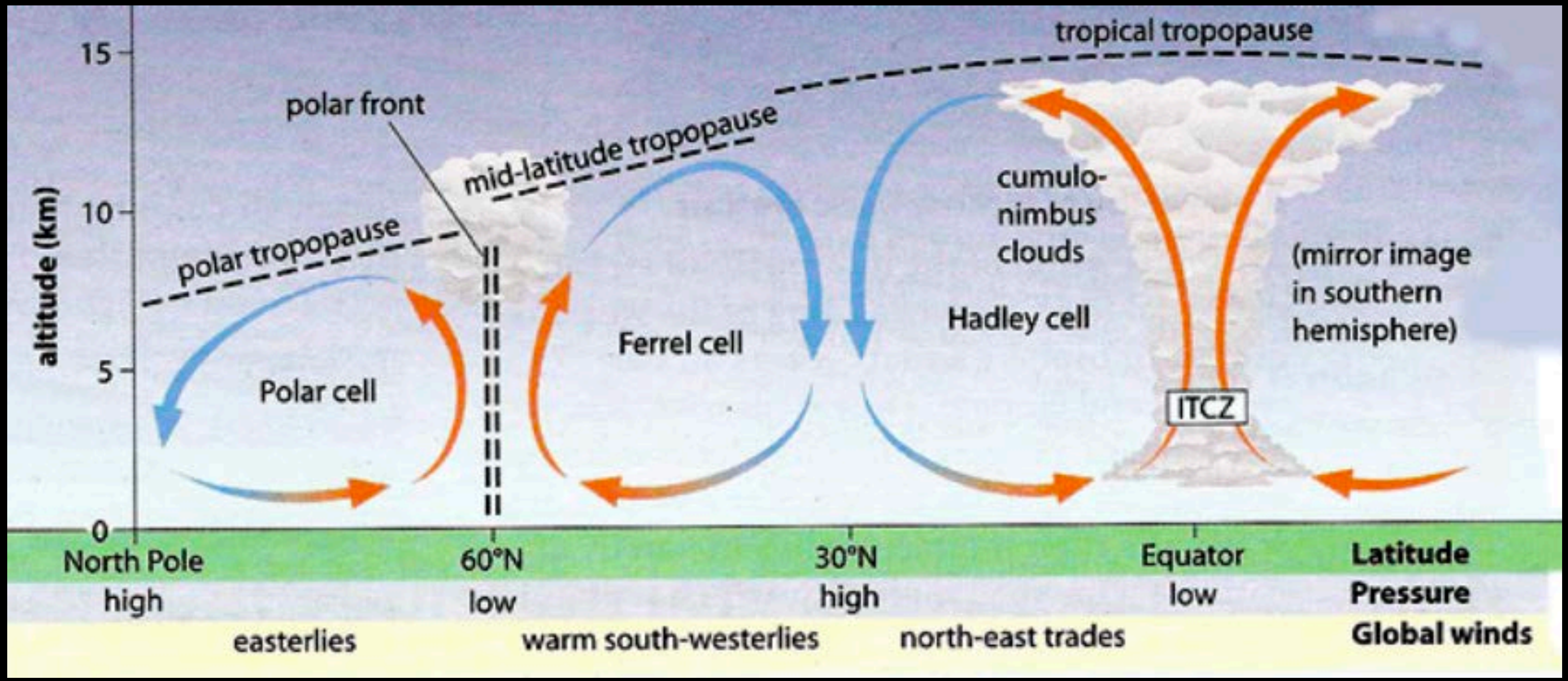
- The final atmosphere will be the result of
  - Gains: accretion from the disc (location dependent) and outgassing
  - Losses: atmospheric escape and sequestering of gases in oceans
- Terrestrial planets: have thin atmospheres that are replaced or acquired by outgassing during early evolution or gas-surface reactions
- Giant planets: have thick atmospheres captured directly from the protoplanetary disc on formation (approximately primordial)

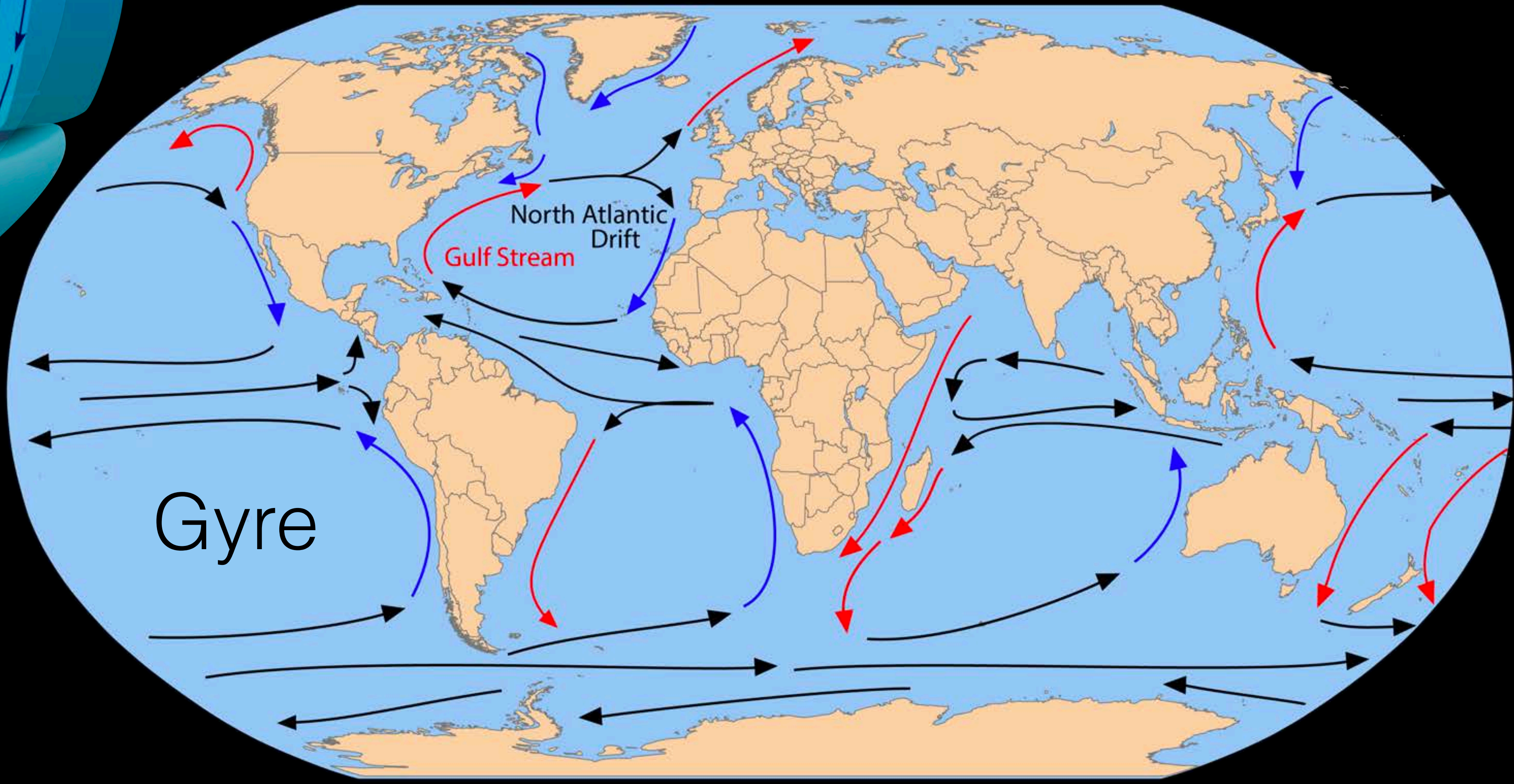


- Note it is possible to have a tidally locked core with a thick mobile atmosphere

Atmospheric Circulation



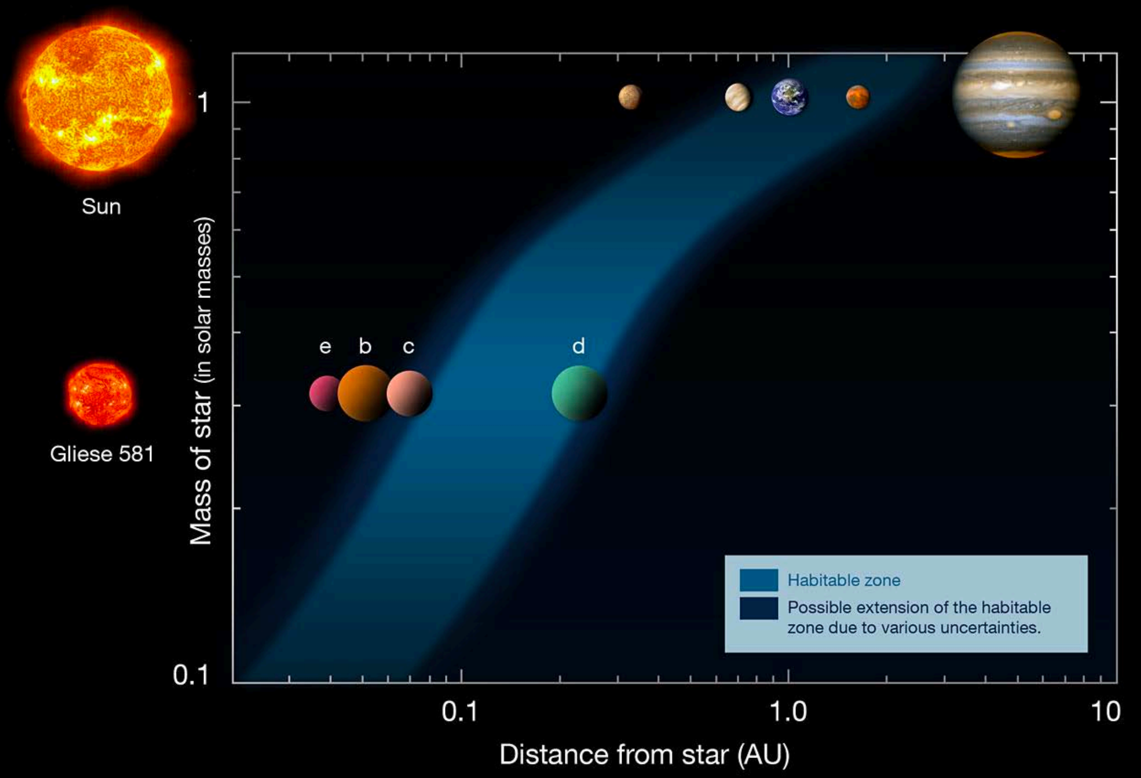


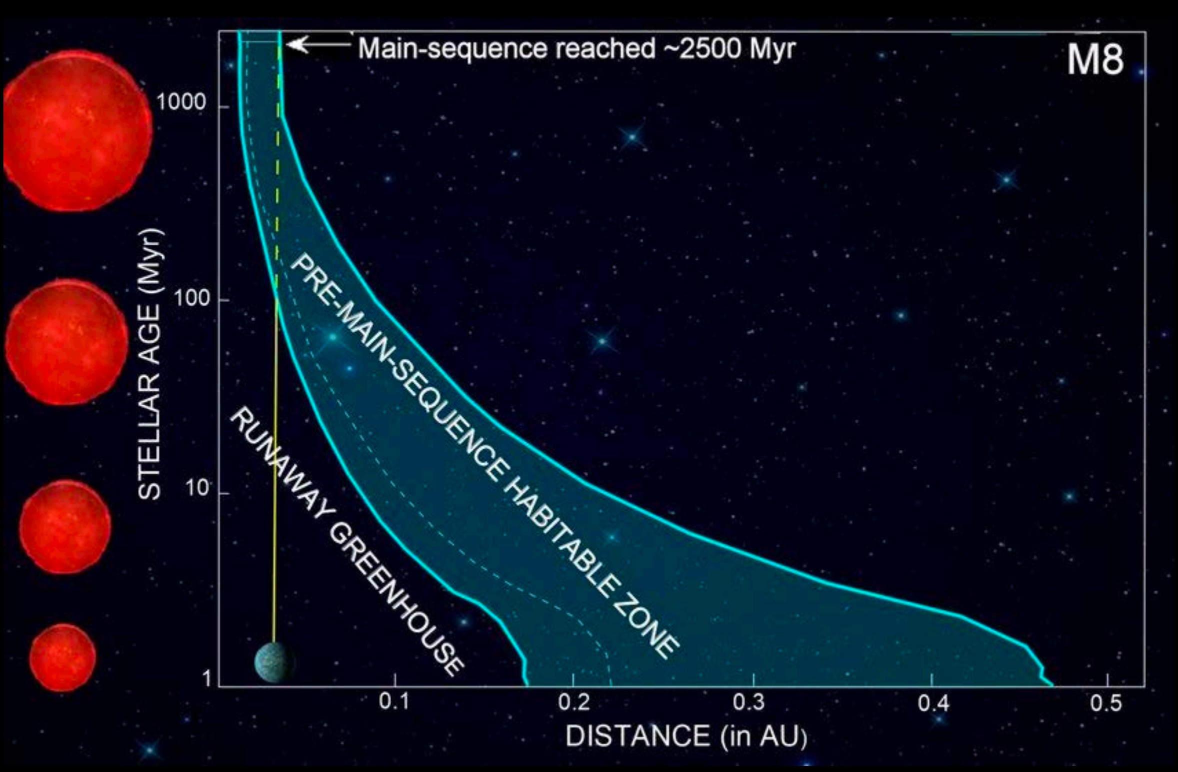


Vertical Thermal Structure of a Planetary Atmosphere

- Temperature is key to habitability (determines whether complex molecules and liquid water exist)
- Temperature-pressure structure is needed to compute (non-)equilibrium chemistry of an atmosphere
  - Chemistry determines the spectral features
- If we know the total amount of energy passing through a planet atmosphere we can derive the temperature profile
  - Energy is neither created or destroyed in an atmosphere, which means that the net flux through the atmosphere must be constant (must hold for every layer, but NOT for each frequency)
  - The radiative equilibrium temperature profile is the temperature profile that satisfies this flux constraint
- Note atmospheric temperatures vary in the horizontal direction as well (especially true for tidally locked exoplanets)

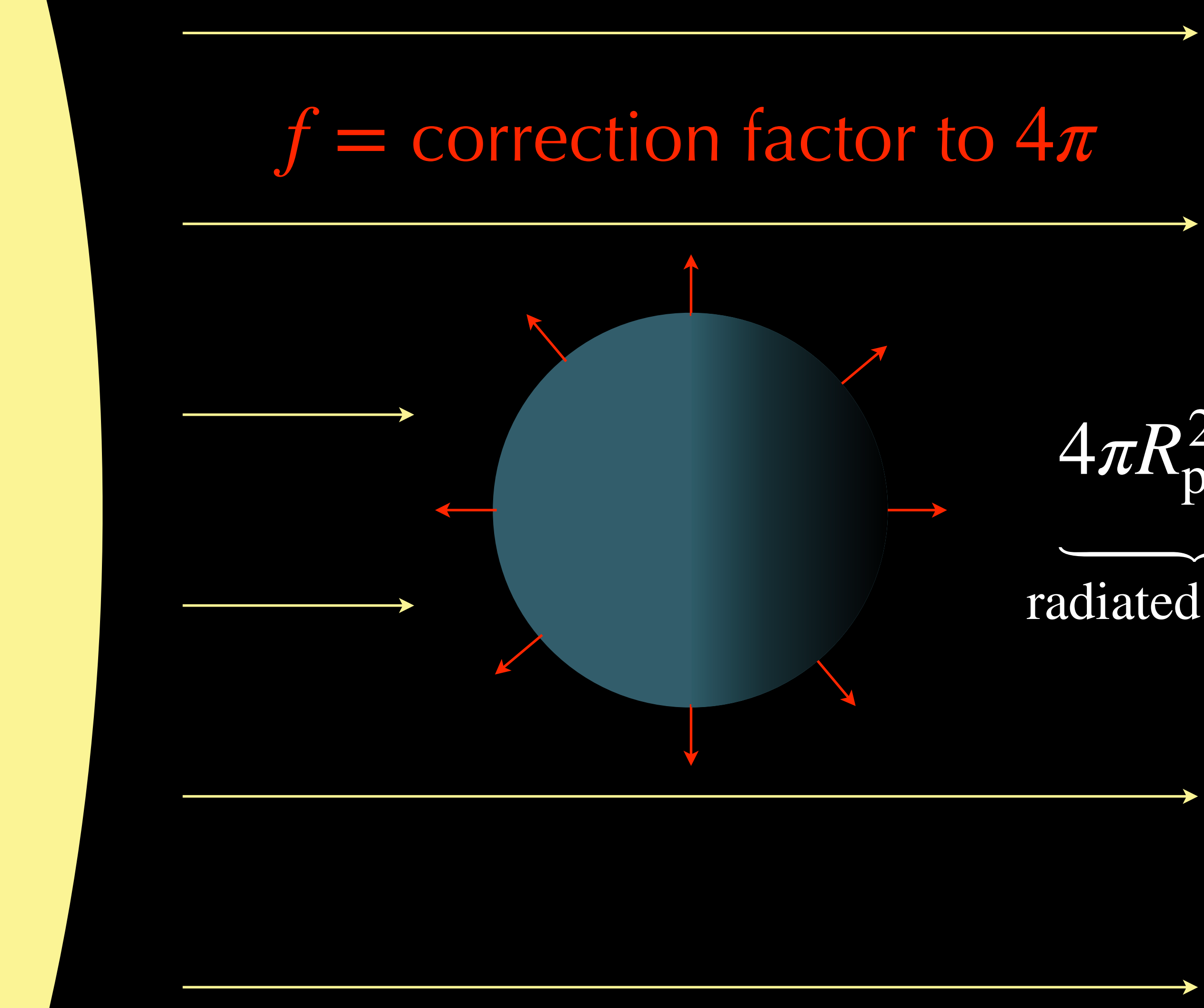
Habitable Zone





- The orbital region around a star where liquid water may exist
- Usually based on flux calculations at different extremes (e.g. runaway greenhouse vs absence of greenhouse)
- Important factors include:
  - Stellar mass, age, proximity, activity
  - Atmospheric composition
    - Photochemistry, escape, outgassing, hazes/clouds
  - Atmospheric/oceanic circulation
  - Alternative heating sources (e.g. radioactive decay, tidal heating)

Energy Balance



Albedo

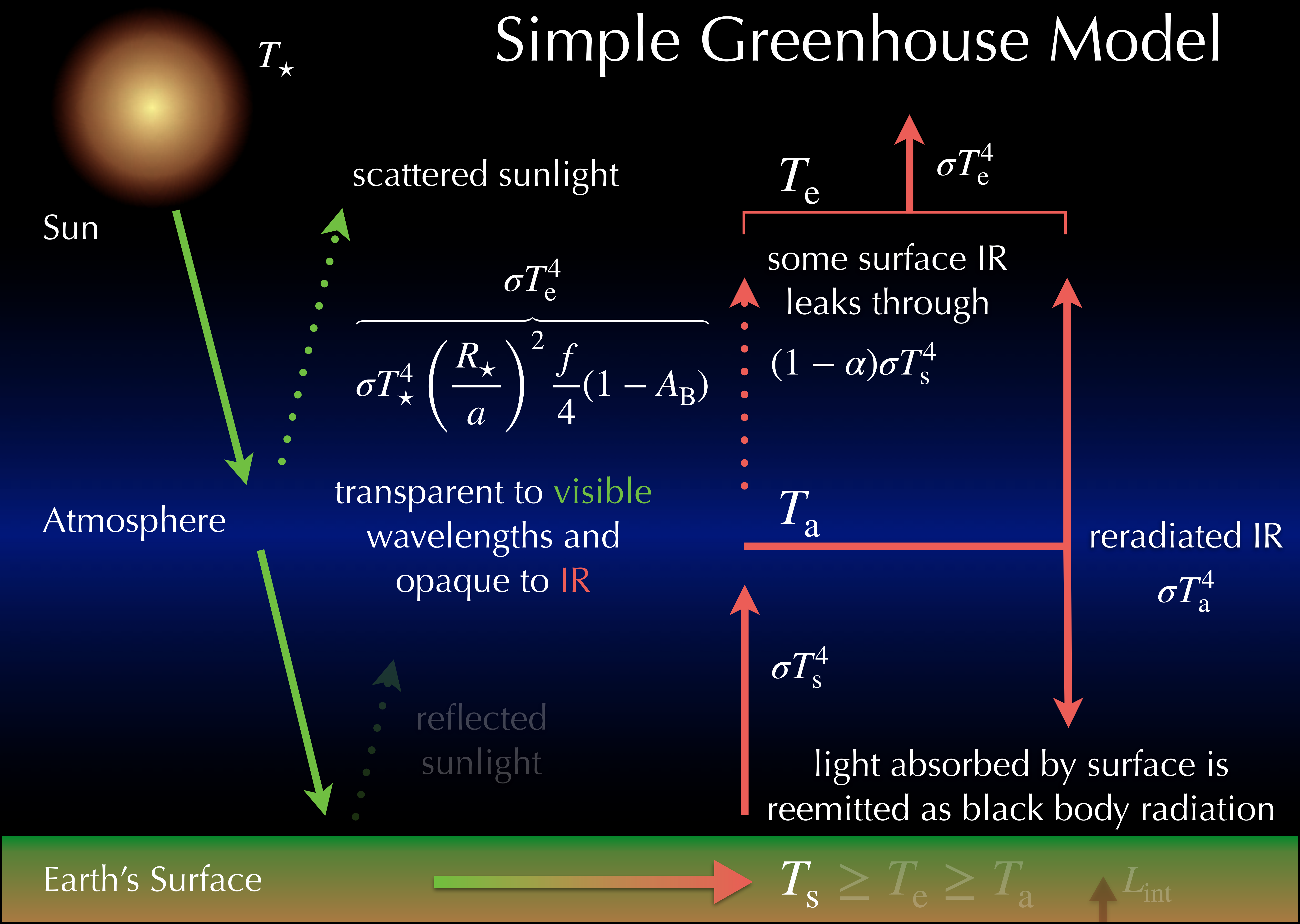
$$\underbrace{4\pi R_{\rm p}^2 F_{\rm S,p}}_{\text{radiated energy}} = \underbrace{(1 - A_{\rm B}) F_{\rm S,\star} \left(\frac{R_\star}{a}\right)^2 f \pi R_{\rm p}^2}_{\text{incident energy}} + \cancel{\underbrace{L_{\rm p,int}}_{\text{internal}}}$$

$$F_{\rm s,\star} = \sigma T_{\rm eff,\star}^4$$
$$F_{\rm s,p} = \sigma T_{\rm eq}^4$$

$$\longrightarrow \quad T_{\rm eq}^4 = T_{\rm eff,\star}^4 \left(\frac{R_\star}{a}\right) \frac{f}{4} (1 - A_{\rm B})$$

- In the context of an idealised planetary atmosphere, the equilibrium temperature is essentially the temperature at the layer where most of the radiation is emitted (i.e. $T_{\rm eq} \sim T_{\rm e}$)

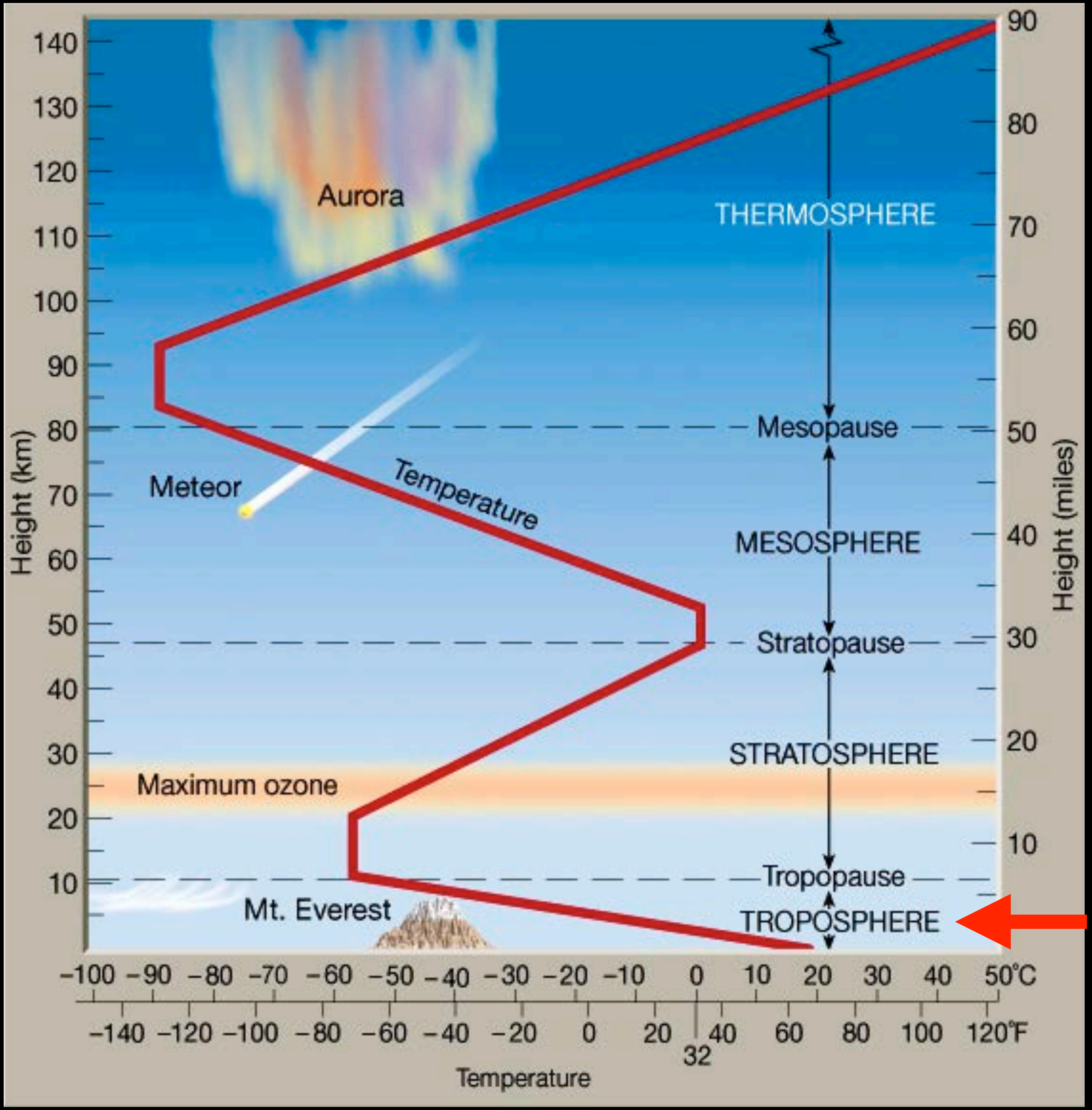
Simple Greenhouse Model



Simple Greenhouse Model

- In equilibrium, energy conservation requires that the energy radiated must equal the energy absorbed (neglecting the internal energy of the planet)
  - Surface: $$\sigma T_s^4 = \underbrace{\sigma T_\star^4 \left(\frac{R_\star}{2a}\right)^2 (1 - A_B)} + \sigma T_a^4 = \underbrace{\sigma T_e^4} + \sigma T_a^4$$
  - Atmosphere: $$\sigma T_e^4 = \sigma T_a^4 + \sigma T_s^4 (1 - \alpha)$$ fraction of surface emission absorbed by the atmosphere
  - Substituting one into the other and solving for the surface temperature $$T_s^4 = T_e^4 + \left[T_e^4 - T_s^4(1-\alpha)\right] \quad \rightarrow \quad T_s = \left(\frac{2}{2-\alpha}\right)^{1/4} T_e$$
  - Two extremes (for Earth):
    $$\alpha = 0 \; :: \; T_s = T_e \quad \sim 255 \text{ K}$$
    $$\alpha = 1 \; :: \; T_s = 2^{1/4} T_e \quad \sim 303 \text{ K}$$
    $$T_{s,\text{actual}} \sim 280 \text{ K}$$
    could generalise by using many α's
  - Atmosphere always tends to warm/insulate the surface: $T_s \geq T_e \geq T_a$

Earth's Vertical Atmospheric Structure



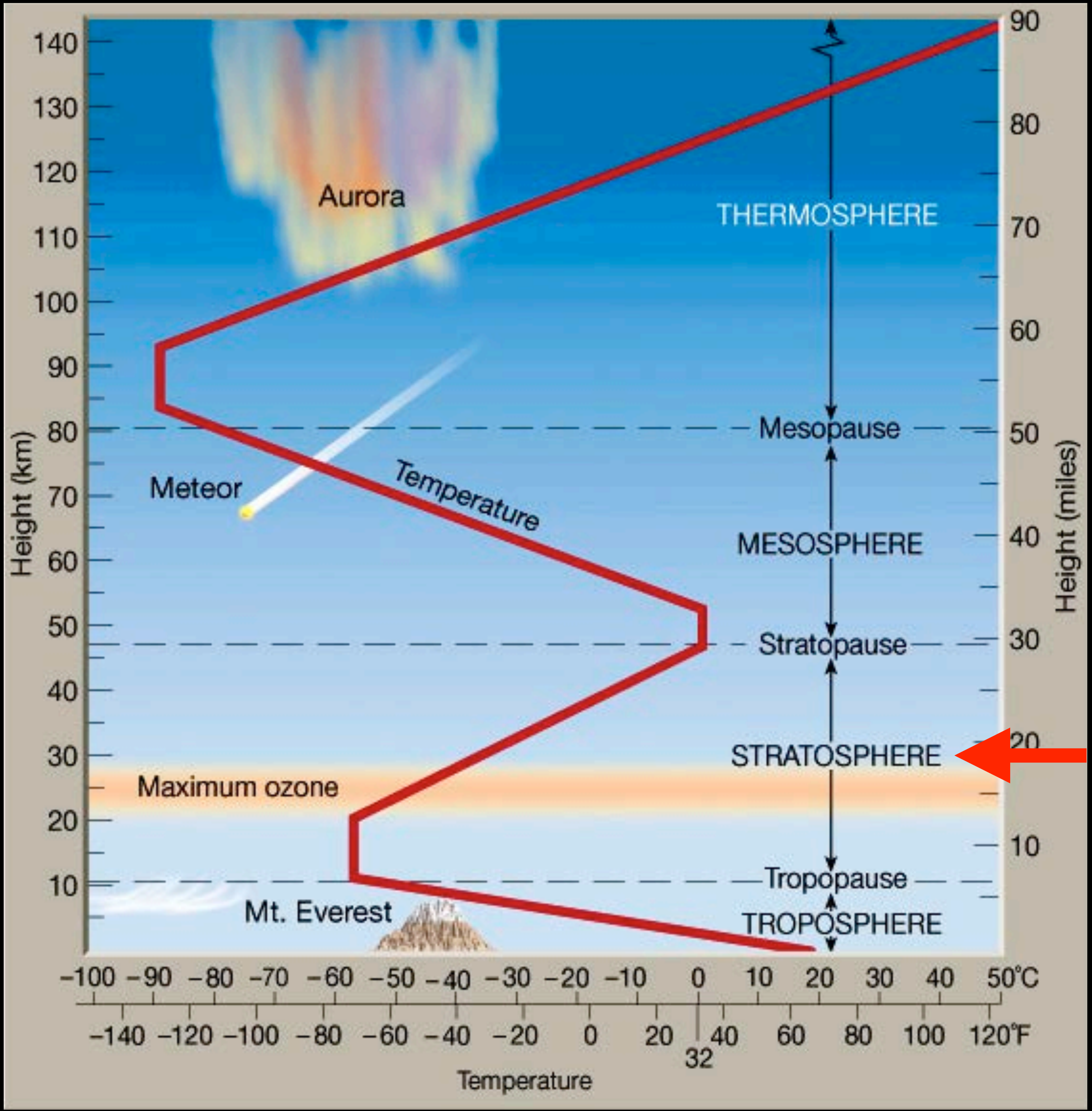
Troposphere:
Responsible for the majority of Earth's:

- Weather
- Atmospheric mass (~85%)
- Spectral features in visible and IR

Exponentially decreasing density caused by hydrostatic equilibrium

Heated from the surface which absorbs majority of visible radiation from the sun

Earth's Vertical Atmospheric Structure

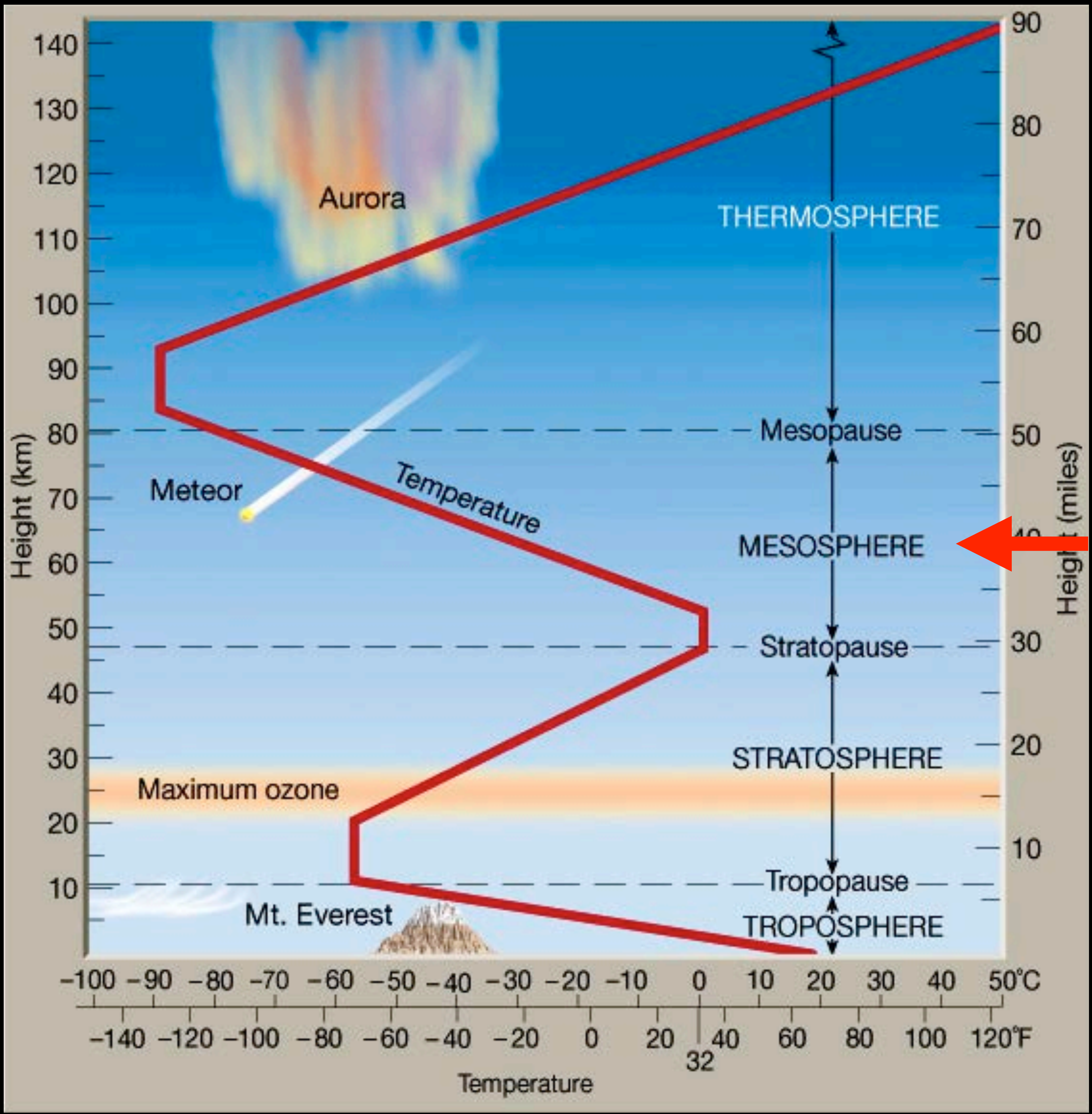


Thermosphere:
Temperature inversion due to absorption of highly energetic solar radiation

Mesosphere:
Ozone level decreases causing the temperature to decrease with height

Stratosphere:
Heated from above (absorption of UV solar radiation by ozone) causing a temperature inversion

Earth's Vertical Atmospheric Structure



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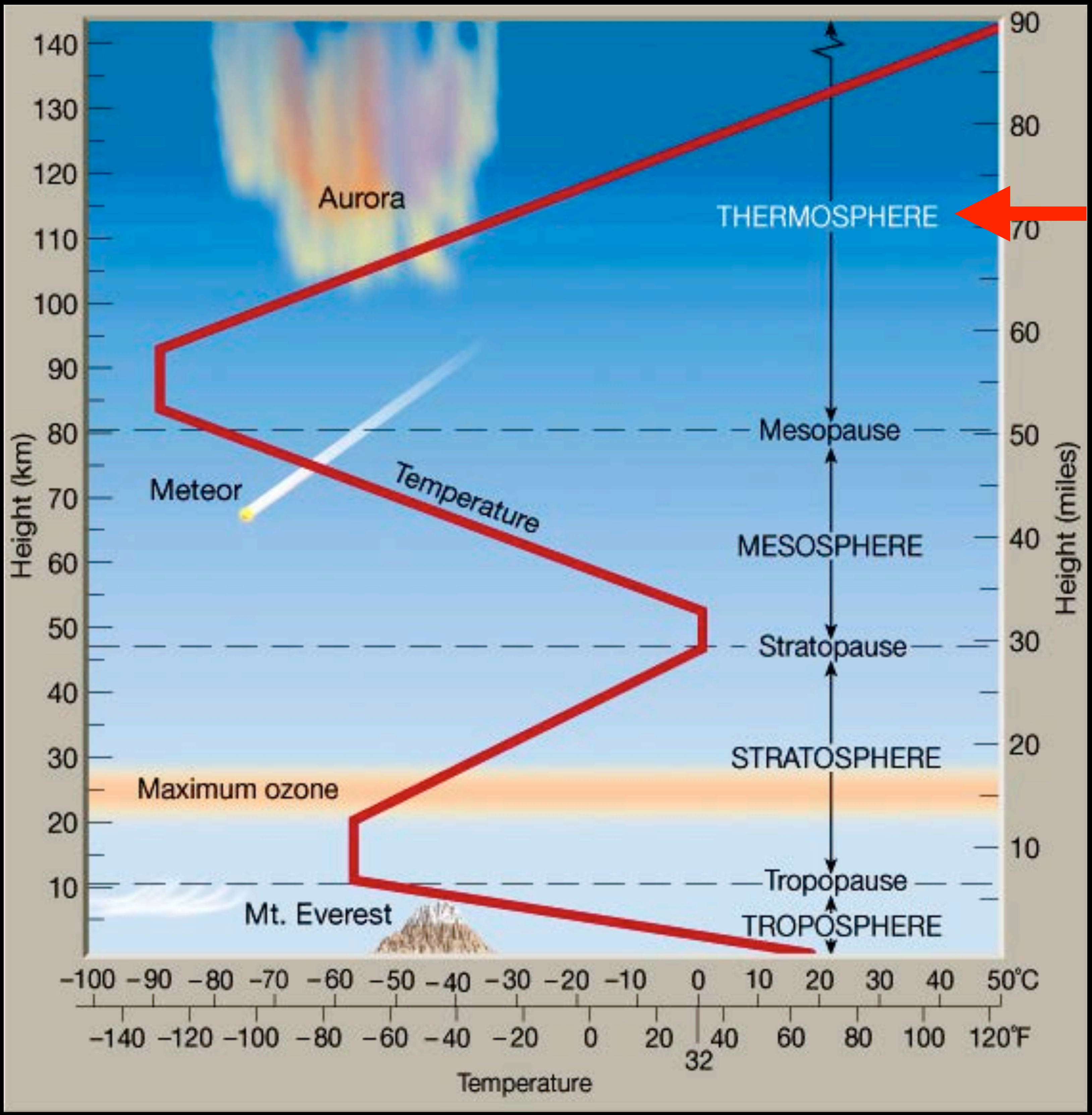

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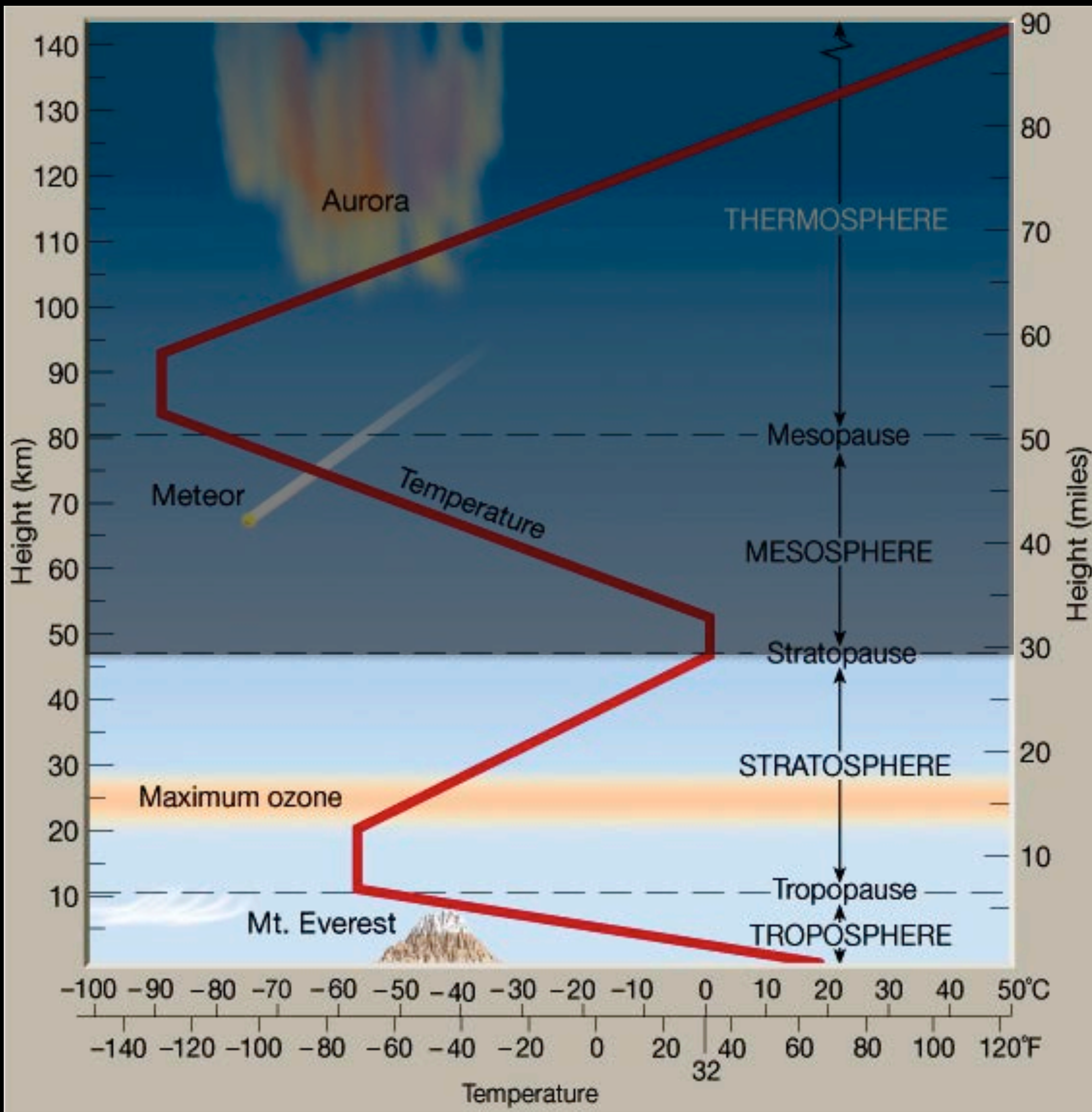


Photochemistry
Atmospheric escape

Thermosphere:

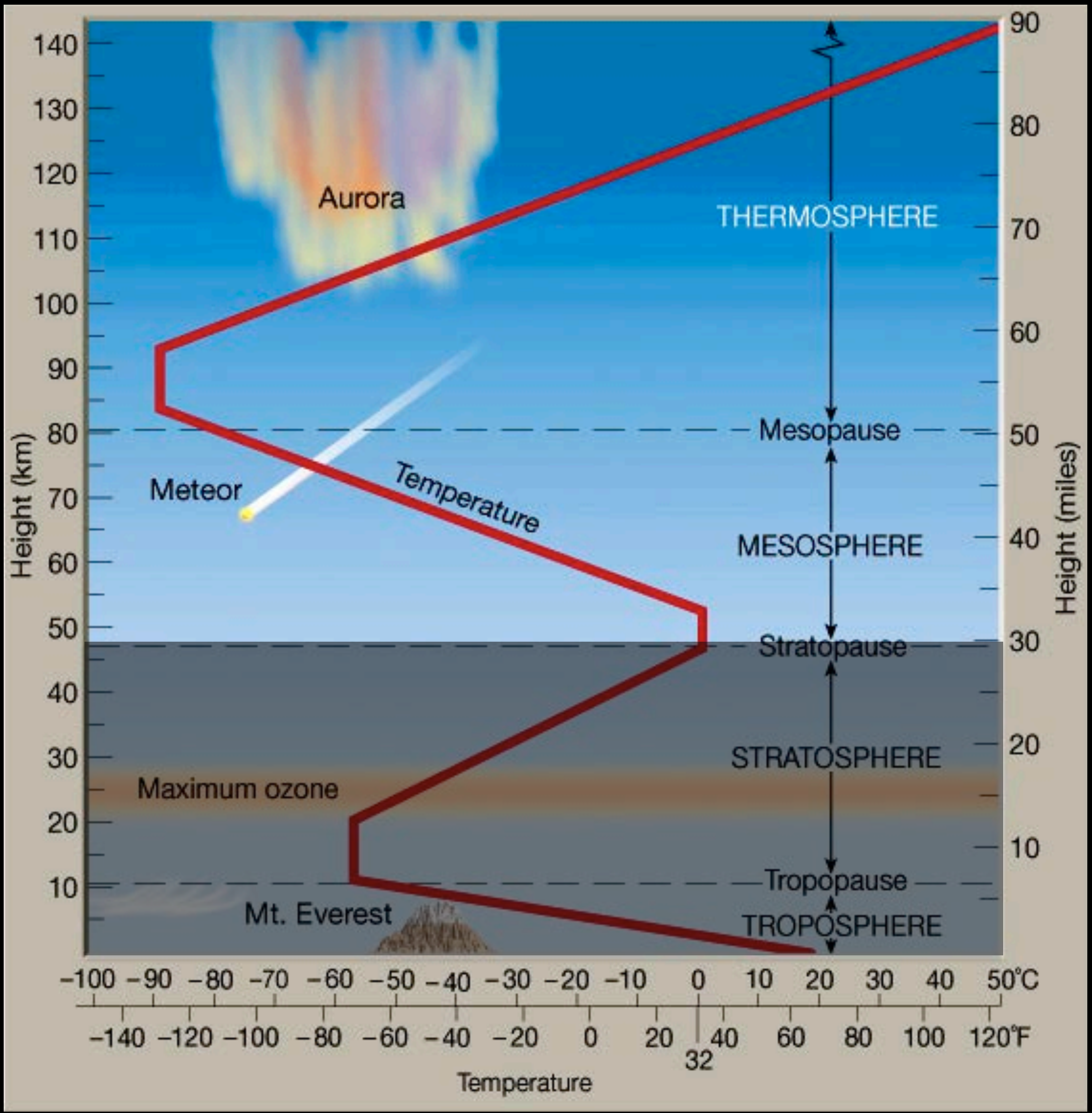
Mesosphere:

Stratosphere:

Troposphere:

Most relevant for spectral features

Earth's Vertical Atmospheric Structure



Photochemistry
Atmospheric escape

Thermosphere:

Mesosphere:

Stratosphere:

Troposphere:

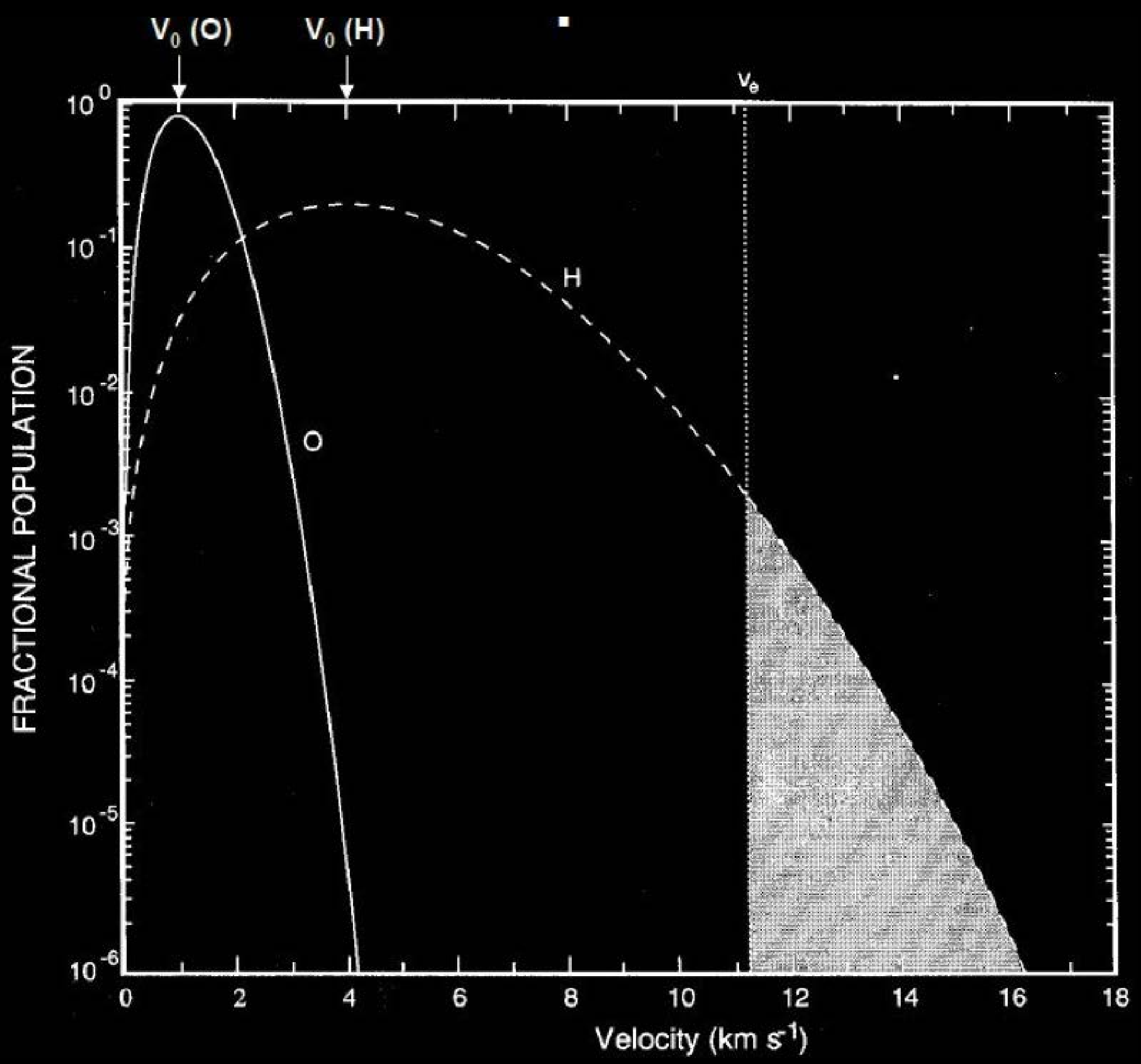
Most relevant for spectral features

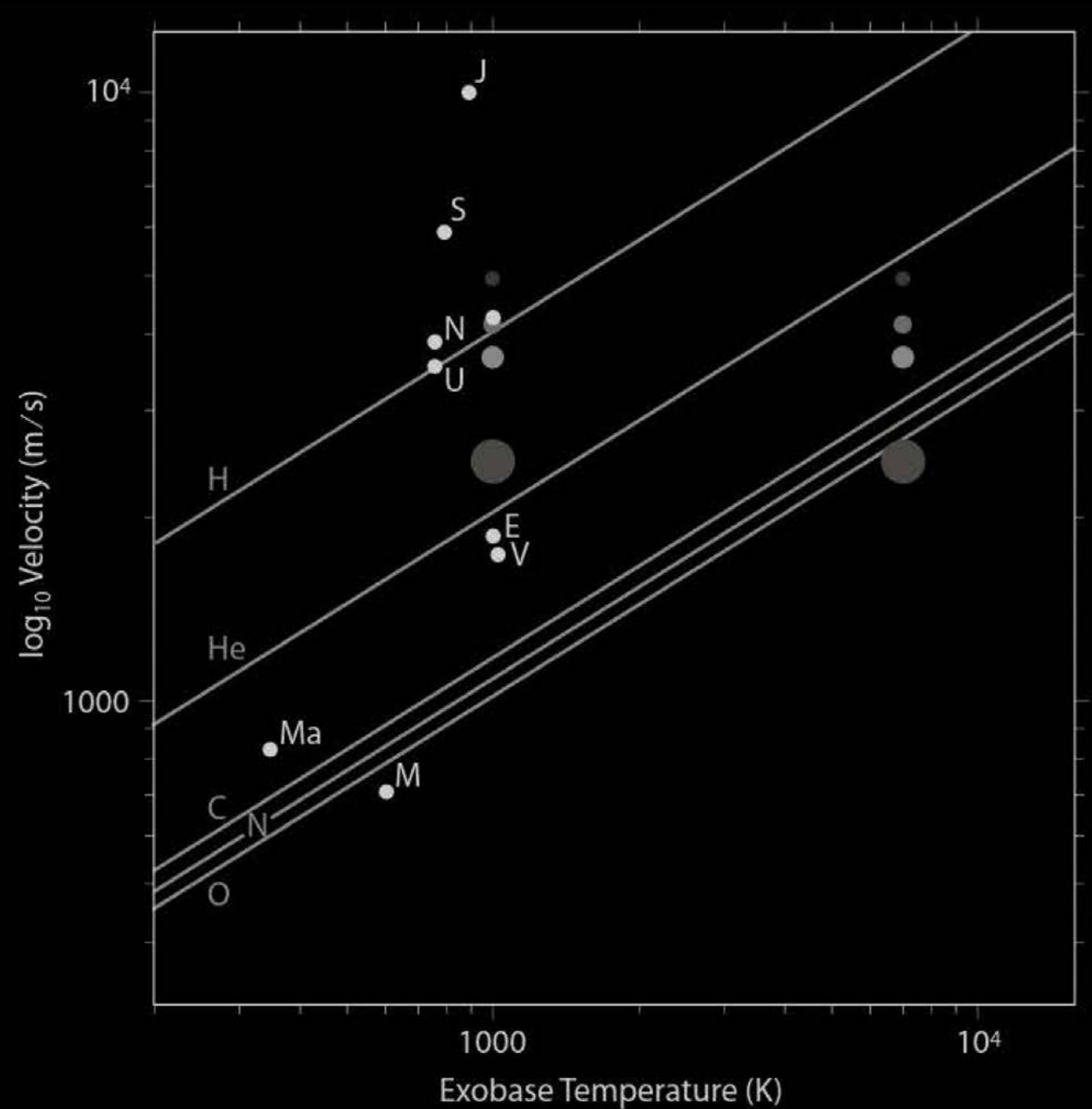
Atmospheric Escape

- Usually light gases, but also heavier elements (perhaps the whole atmosphere) if a terrestrial planet is close to the star.
- Three stages:
  1. Transport from lower to upper atmosphere
  2. Conversion from molecular to atomic/ionic form
  3. The actual escape process:
     - Thermal hydrostatic escape
     - Thermal hydrodynamic escape
     - Non-thermal escape
- Depends on planet mass, composition, temperature, magnetic field, distance to star, and stellar type.

Hydrostatic Escape

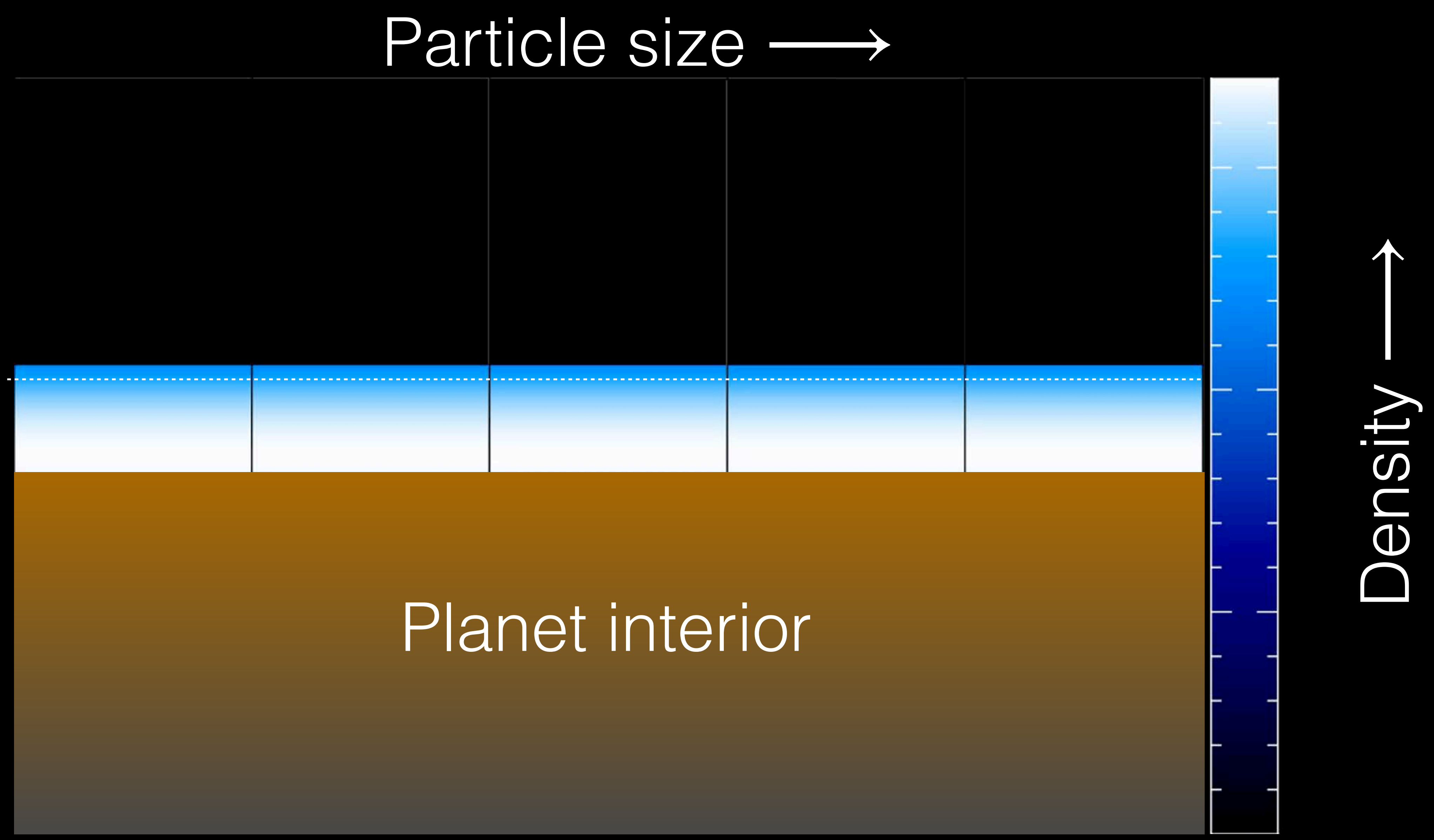
- Thermal hydrostatic escape occurs when an atom's or molecule's thermal escape velocity exceeds the escape velocity of the planet.





Hydrodynamic Escape

- Thermal hydrodynamic escape occurs when the outflow behaves as a dense fluid (as opposed to individual particles). Typically driven by stellar irradiation.

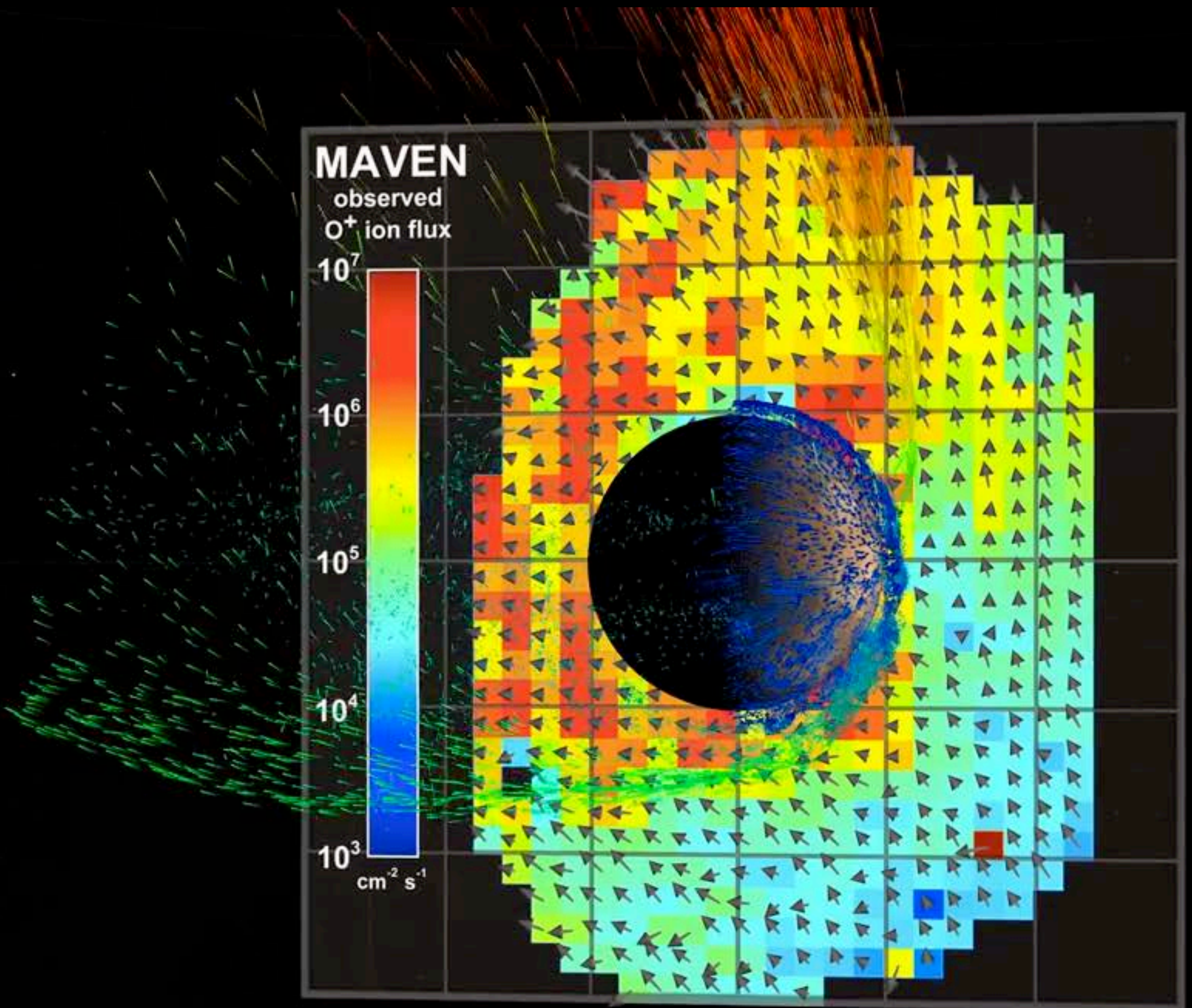


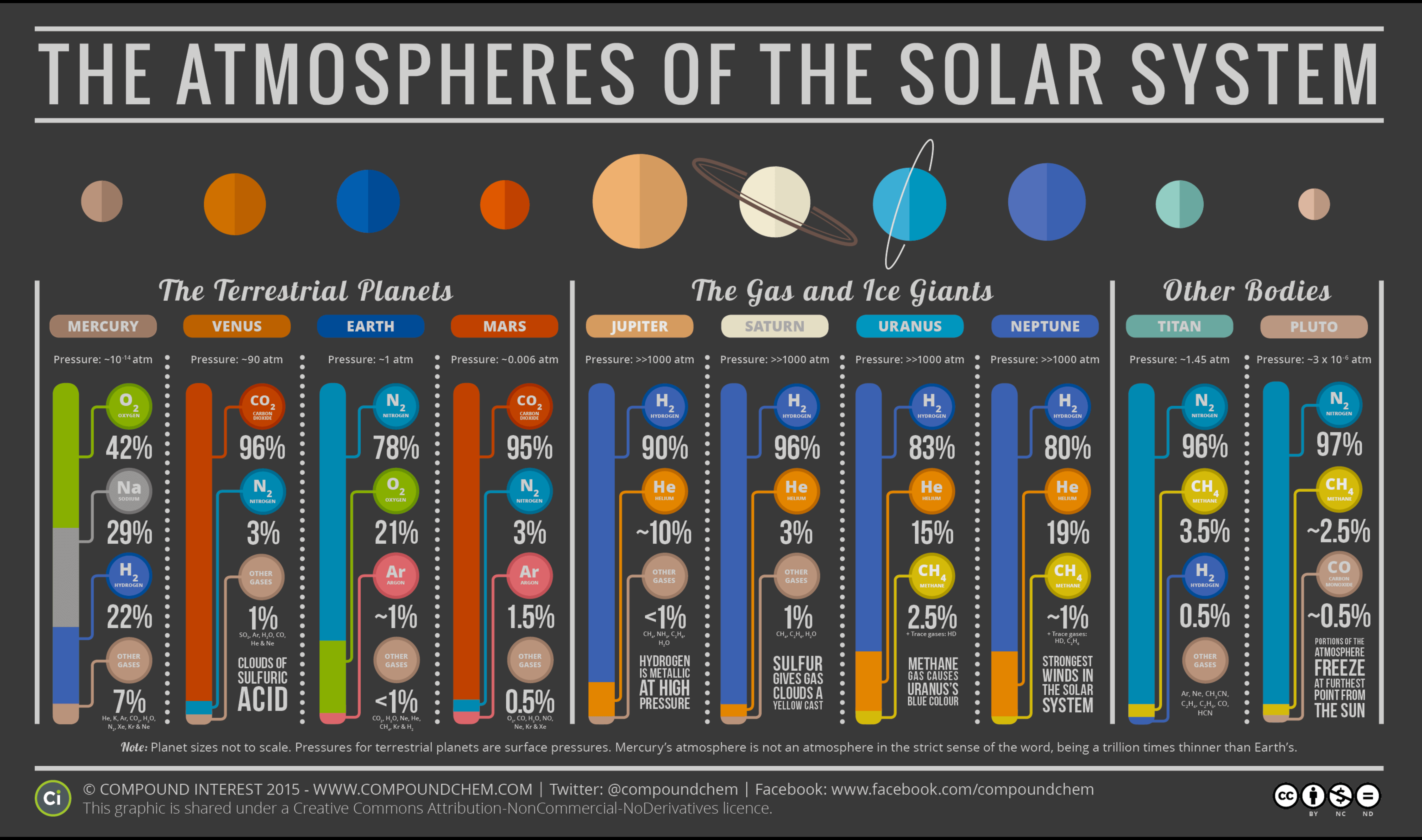
Non-thermal Escape

- Collisional processes with charged species → atoms acquire enough energy to escape (even heavier elements)
- Umbrella term for many processes:

Process	Examples	Planet (gas) example
Charge exchange	$H + H^{+*} \rightarrow H^+ + H^*$	Earth (H, D)
	$O + H^{+*} \rightarrow O^+ + H^*$	Venus (He)
Dissociative	$O_2^+ + e \rightarrow O^* + O^*$	Mars (O), E, G, C (O)
recombination	$OH^+ + e \rightarrow O + H^*$	Venus (H), Mars (N), Titan (H_2)
Impact dissociation	$N_2 + e^* \rightarrow N^* + N*$	Mars (N), Titan (N)
Photodissociation	$O_2 + h\nu \rightarrow O^* + O^*$	
Ion-Neutral reaction	$O^+H_2 \rightarrow OH^+ + H^*$	
Sputtering or	$Na + S^+ \rightarrow Na^* + S^{+*}$	Io (Na, K)
knockon	$O^* + H \rightarrow O^* + H^*$	Venus (H)
Solar-wind pickup	$O + h\nu \rightarrow O^+ + e$ then O^+ picked up	Mercury (He, Ar)
Ion escape	H^{+*} escapes	Earth (H, D, He)
Jeans escape		Earth (H, D), Mars (H, H_2), Titan (H, H_2), Pluto (CH_4)

The * represents excess kinetic energy. The Jeans escape is a thermal process but is included in this table for completion. Adapted from [16].


MAVEN
observed
O+ ion flux
10^7
10^6
10^5
10^4
10^3
cm^-2 s^-1


THE ATMOSPHERES OF THE SOLAR SYSTEM
The Terrestrial Planets
The Gas and Ice Giants
Other Bodies
MERCURY
Pressure: ~10^{-14} atm
O_2 OXYGEN 42%
Na SODIUM 29%
H_2 HYDROGEN 22%
OTHER GASES 7%
He, K, Ar, CO_2, H_2O, N_2, Xe, Kr & Ne
VENUS
Pressure: ~90 atm
CO_2 CARBON DIOXIDE 96%
N_2 NITROGEN 3%
OTHER GASES 1%
SO_2, Ar, H_2O, CO, He & Ne
CLOUDS OF SULFURIC ACID
EARTH
Pressure: ~1 atm
N_2 NITROGEN 78%
O_2 OXYGEN 21%
Ar ARGON ~1%
OTHER GASES <1%
CO_2, H_2O, Ne, He, CH_4, Kr & H_2
MARS
Pressure: ~0.006 atm
CO_2 CARBON DIOXIDE 95%
N_2 NITROGEN 3%
Ar ARGON 1.5%
OTHER GASES 0.5%
O_2, CO, H_2O, NO, Ne, Kr & Xe
JUPITER
Pressure: >>1000 atm
H_2 HYDROGEN 90%
He HELIUM ~10%
OTHER GASES <1%
CH_4, NH_3, C_2H_6, H_2O
HYDROGEN IS METALLIC AT HIGH PRESSURE
SATURN
Pressure: >>1000 atm
H_2 HYDROGEN 96%
He HELIUM 3%
OTHER GASES 1%
CH_4, C_2H_6, H_2O
SULFUR GIVES GAS CLOUDS A YELLOW CAST
URANUS
Pressure: >>1000 atm
H_2 HYDROGEN 83%
He HELIUM 15%
CH_4 METHANE 2.5%
+ Trace gases: HD
METHANE GAS CAUSES URANUS'S BLUE COLOUR
NEPTUNE
Pressure: >>1000 atm
H_2 HYDROGEN 80%
He HELIUM 19%
CH_4 METHANE ~1%
+ Trace gases: HD, C_2H_6
STRONGEST WINDS IN THE SOLAR SYSTEM
TITAN
Pressure: ~1.45 atm
N_2 NITROGEN 96%
CH_4 METHANE 3.5%
H_2 HYDROGEN 0.5%
OTHER GASES
Ar, Ne, CH_3CN, C_2H_4, C_2H_6, CO, HCN
PLUTO
Pressure: ~3 x 10^{-6} atm
N_2 NITROGEN 97%
CH_4 METHANE ~2.5%
CO CARBON MONOXIDE ~0.5%
PORTIONS OF THE ATMOSPHERE FREEZE AT FURTHEST POINT FROM THE SUN
Note: Planet sizes not to scale. Pressures for terrestrial planets are surface pressures. Mercury's atmosphere is not an atmosphere in the strict sense of the word, being a trillion times thinner than Earth's.
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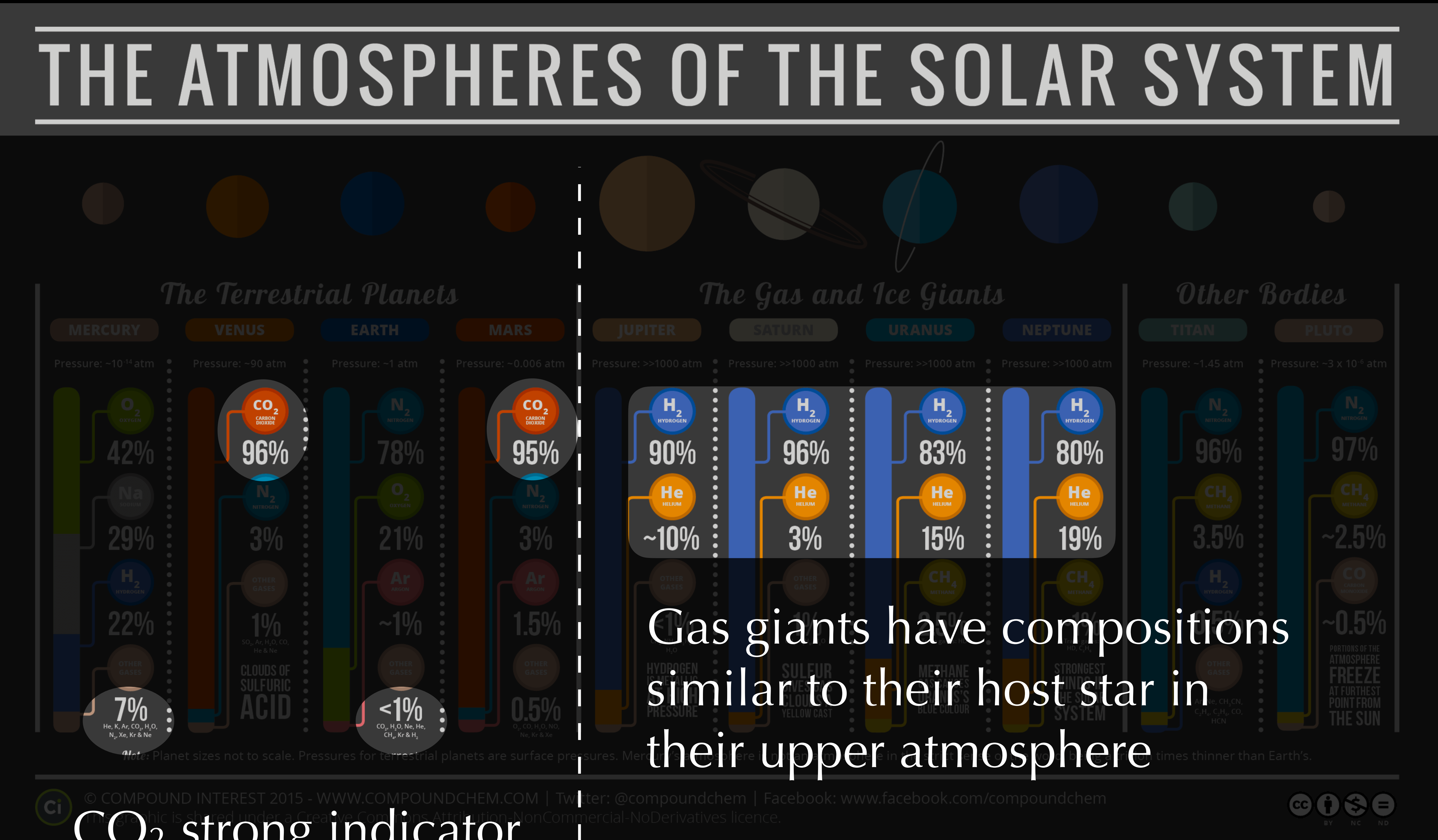
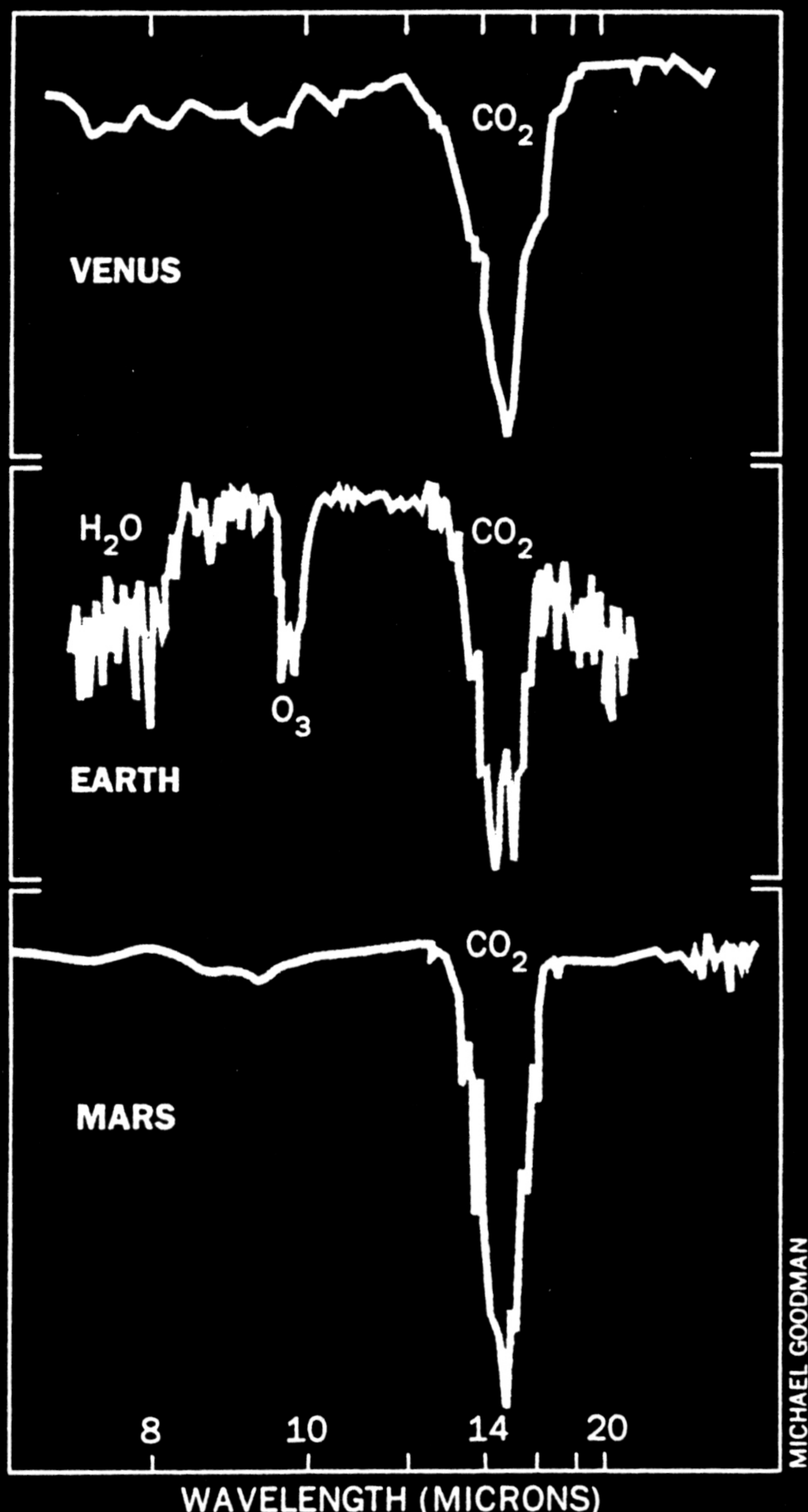


Gas giants have compositions similar to their host star in their upper atmosphere

CO_2 strong indicator of terrestrial planets

Atmosphere Composition

- Planetary spectra are the main observable for exoplanets because they probe into the atmosphere. Dominated by a handful of molecules:
  - CH_4 in gas giants
  - CO_2 in terrestrial planets
- Cannot always see abundant gases that have weak or no absorption/emission features.
- Absorbing power depends on the number density times the absorption cross section.
- Homonuclear molecules (e.g. N_2 and O_2) have weak absorption cross sections while molecules composed of different atoms have much larger absorption cross sections.



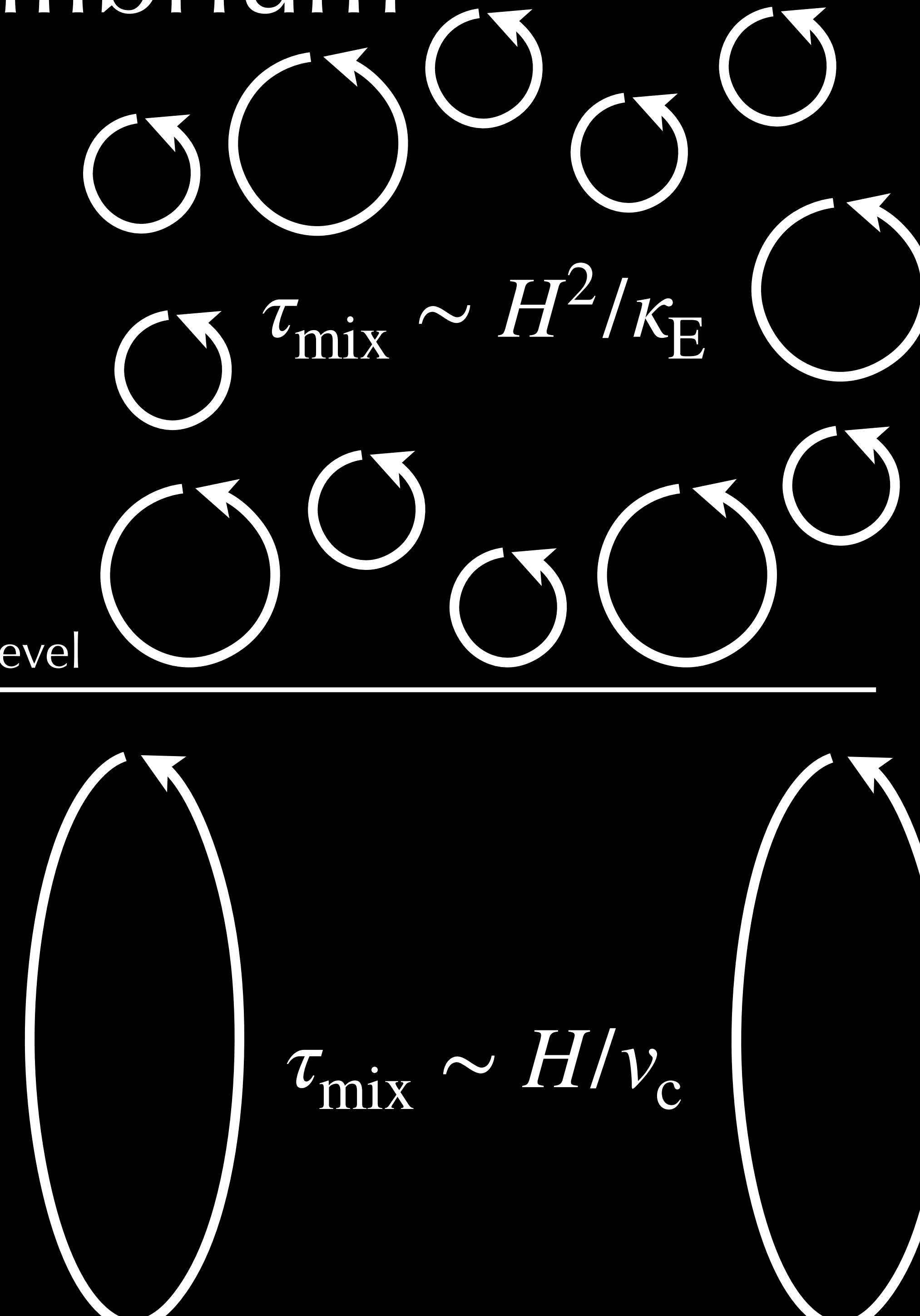
Chemical Disequilibrium

$\tau_{\rm chem} \gg \tau_{\rm mix}$ — Cool, upper atmosphere
Radiative zone
(non-equilibrium)

↑ ↑ ↑ ↑ ratios above set by quench level

$\tau_{\rm chem} = \tau_{\rm mix}$ — Quench Level

$\tau_{\rm chem} \ll \tau_{\rm mix}$ — Hot interior
Convective zone
(equilibrium)



Different molecular species have their own quench level

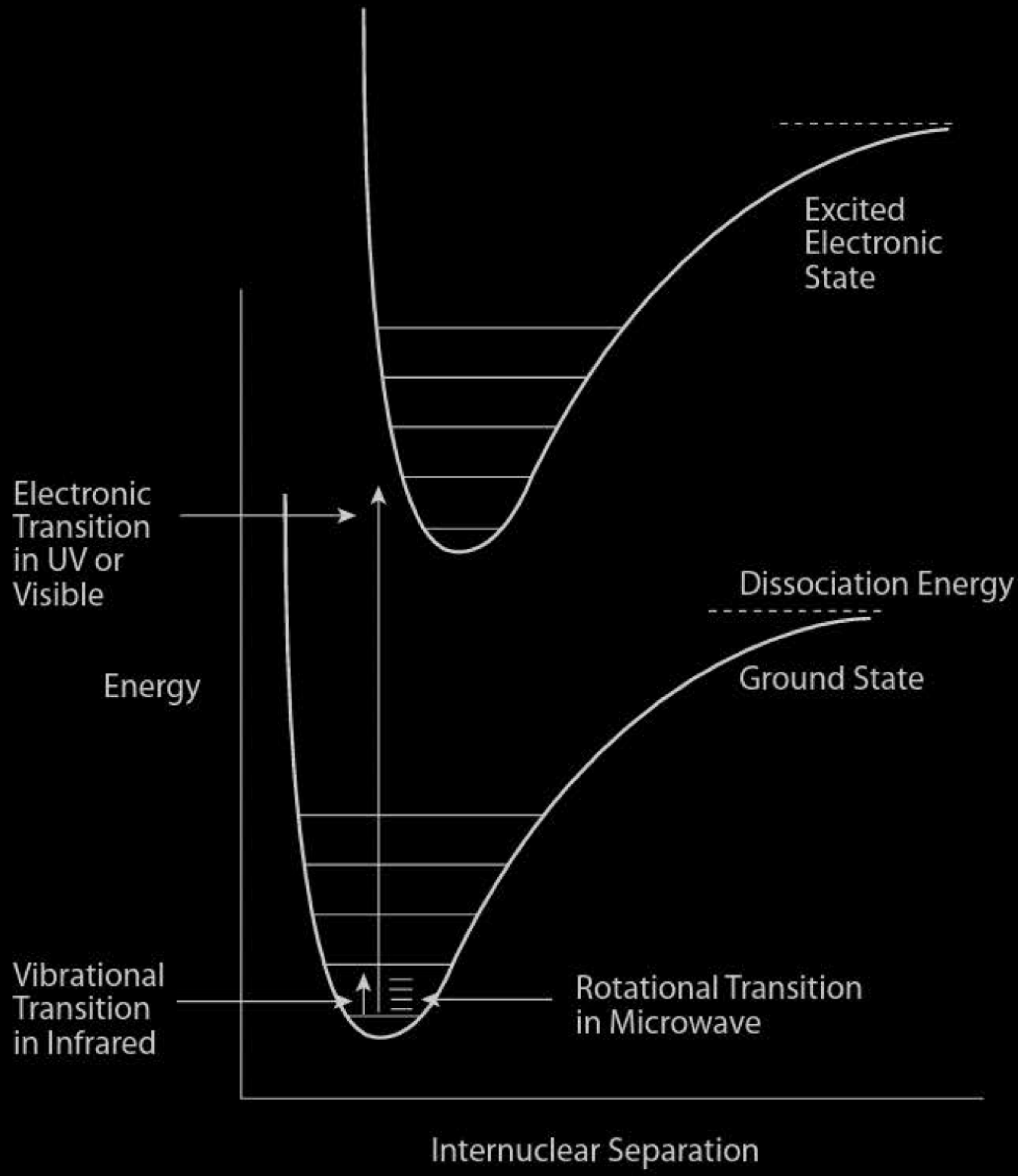
$$\tau_{\rm chem} = \tau_{\rm mix}$$

Photochemistry

- Stellar irradiation photo dissociates molecules in the upper atmosphere. The atoms can then either escape to space or recombine to form other molecules.
- Photochemistry is important for terrestrial planets atmospheres more than giant planets atmospheres.
  - Atmospheric escape is negligible in gas giants and the fast reaction rates occurring in the deeper layers can replenish the dissociated molecules.
- Early Venus: photochemistry led to water escape by dissociating water vapour in the atmosphere allowing H to escape.
- Jupiter/Saturn: photochemistry creates hazes that mute the blue part of the spectrum (UV radiation photodissociates CH_4 and the resulting C combines with the H to make haze).

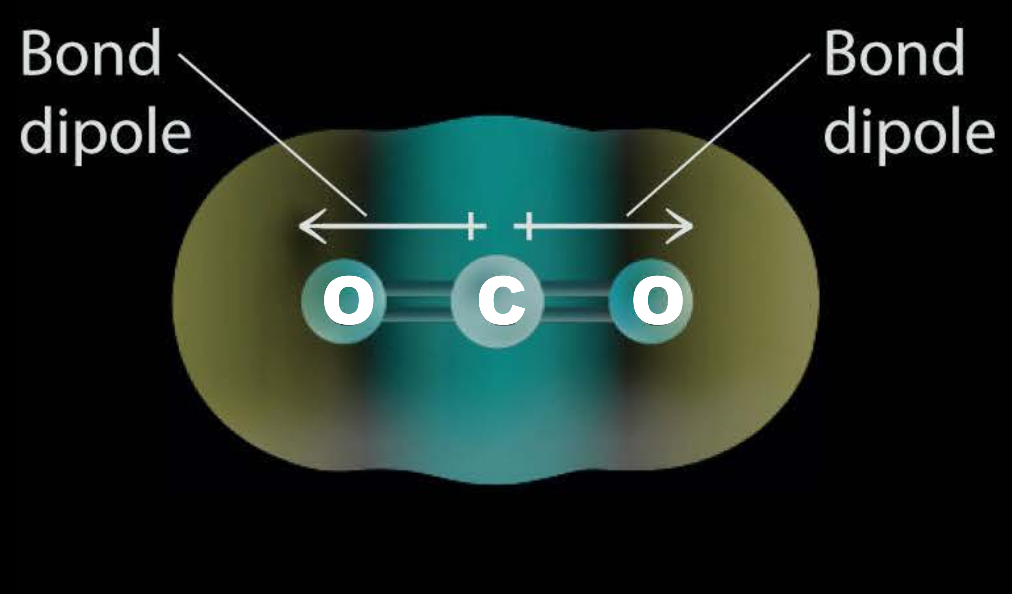
Molecules

- Like atoms, molecules can also undergo electronic transitions
- Additionally they also have rotational and vibrational transitions giving rise to complex molecular bands.
    - For example, H_2O has hundreds of millions of lines from combined ro-vibrational transitions!
- Molecular spectral lines blend together to form molecular bands.

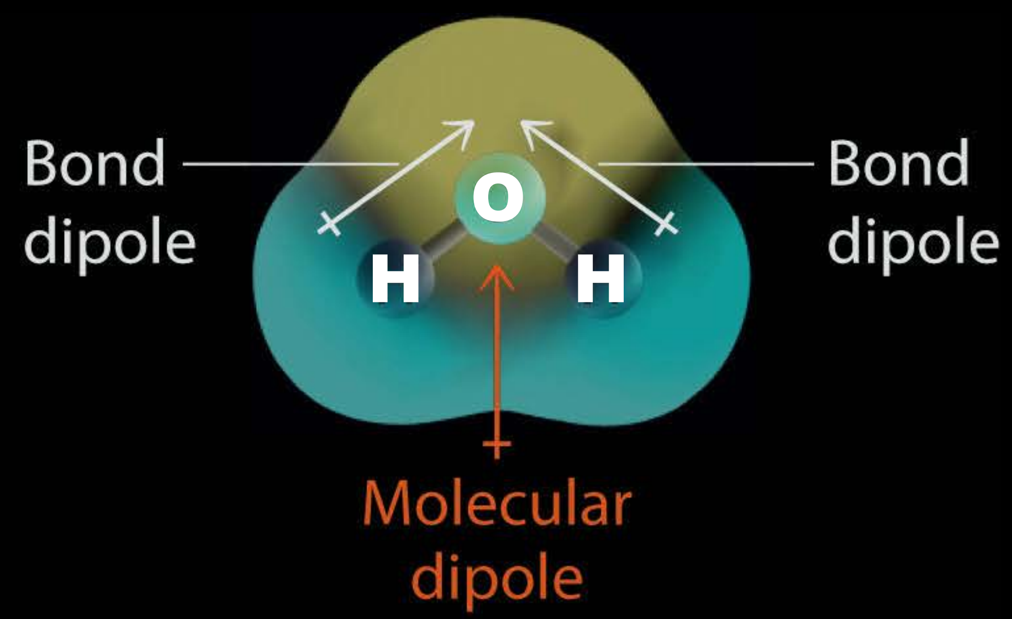


Molecules

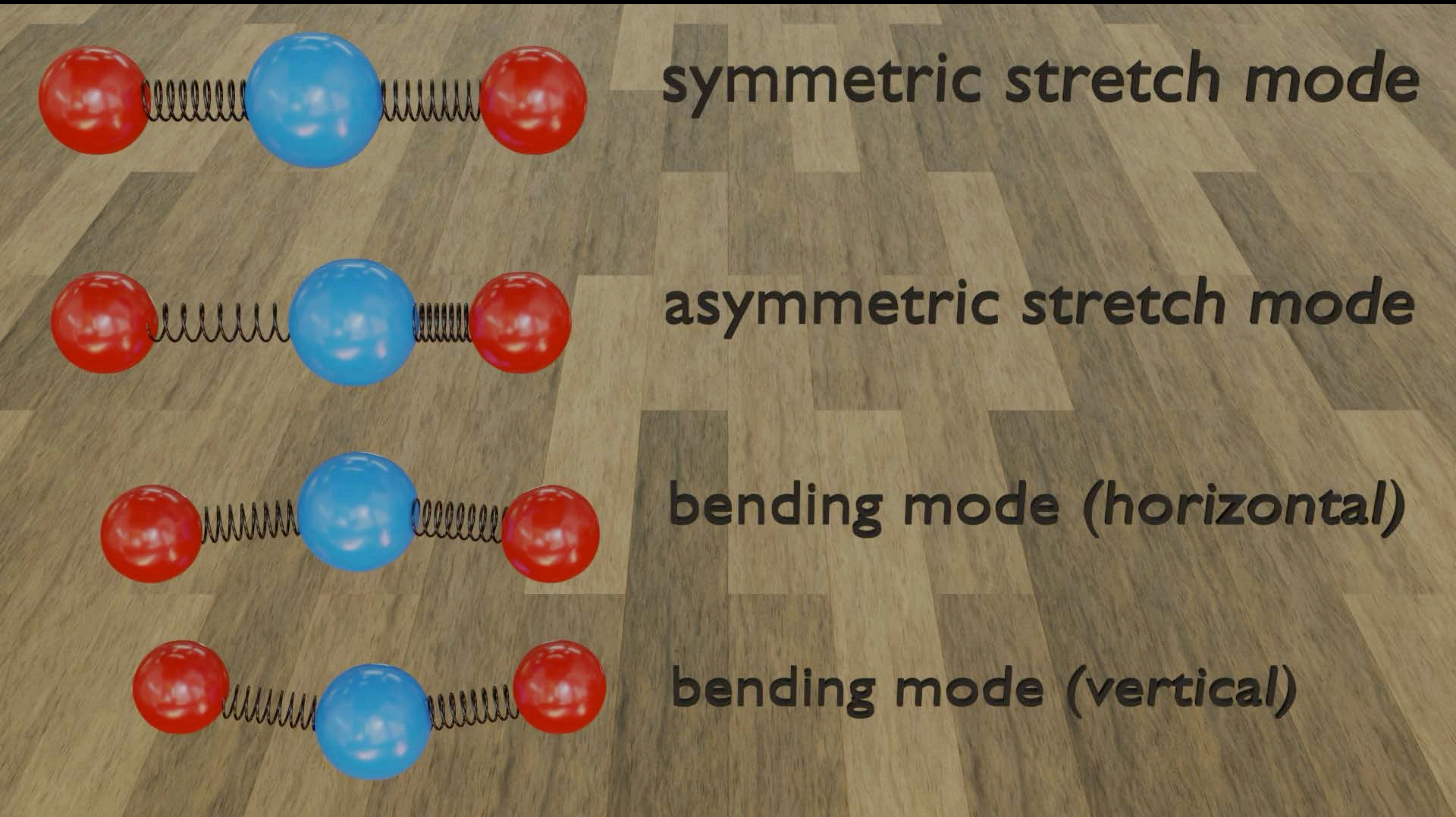
- Ro-vibrational transitions occur when the molecule couples with the an electromagnetic field — generally the electric dipole moment (i.e. when the effective centres of the negative and positive charges are displaced and the centres of mass and charge differ).
- Rotational motion is always induced when vibration occurs.
- Temporary dipole moments can be induced (e.g. through asymmetric bending/stretching). Also electric quadrupole or magnetic dipole moments can cause vibrational transitions.



(a) No net dipole moment

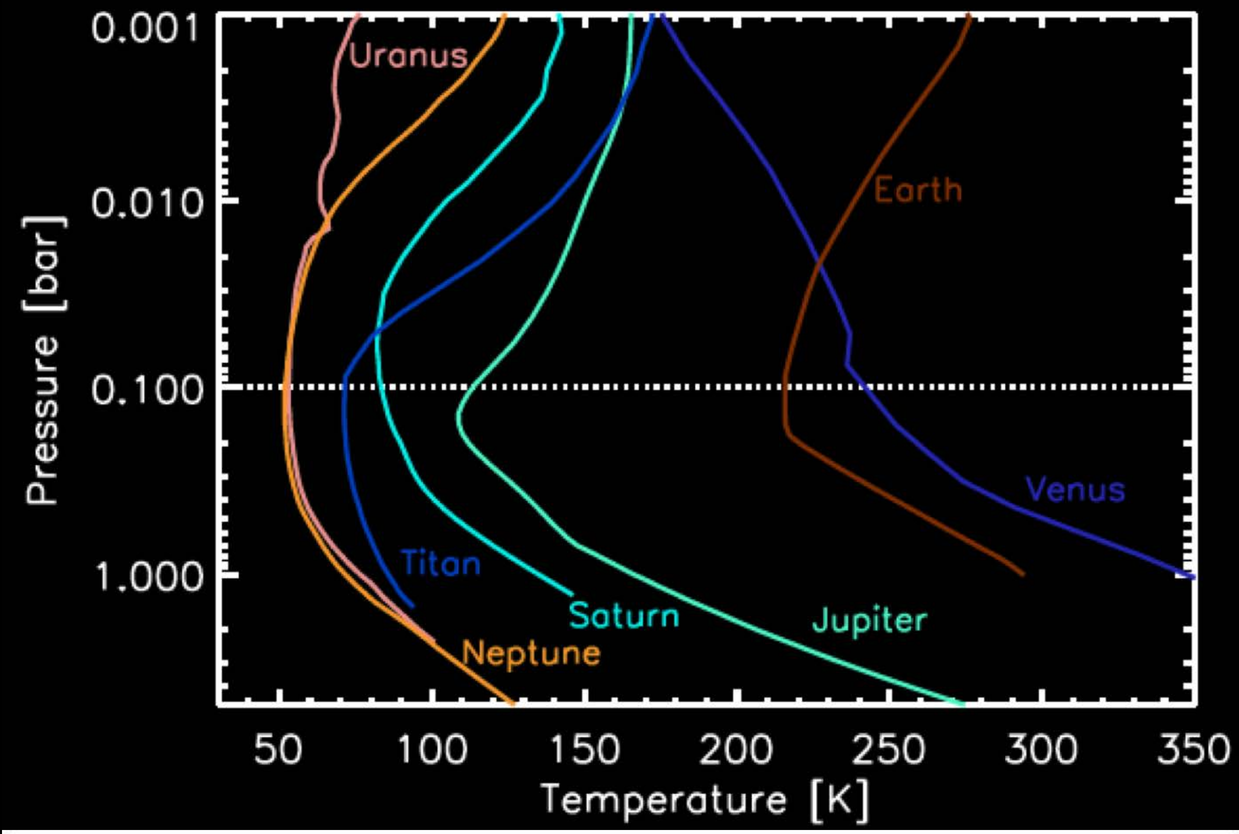


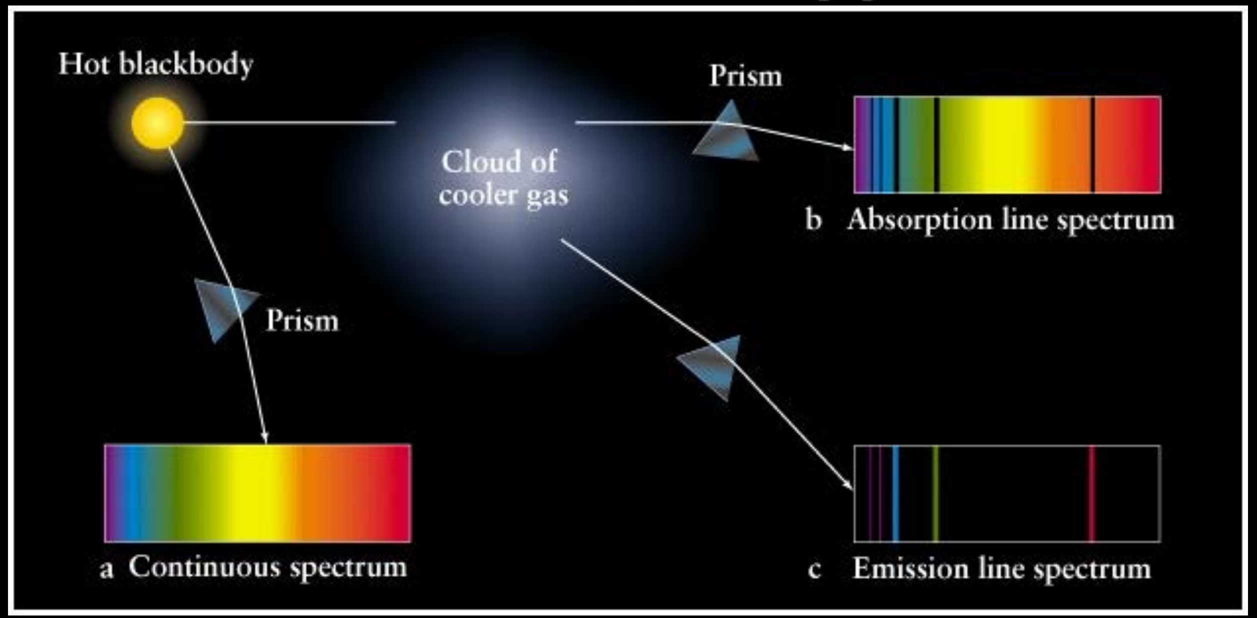
(b) Net dipole moment

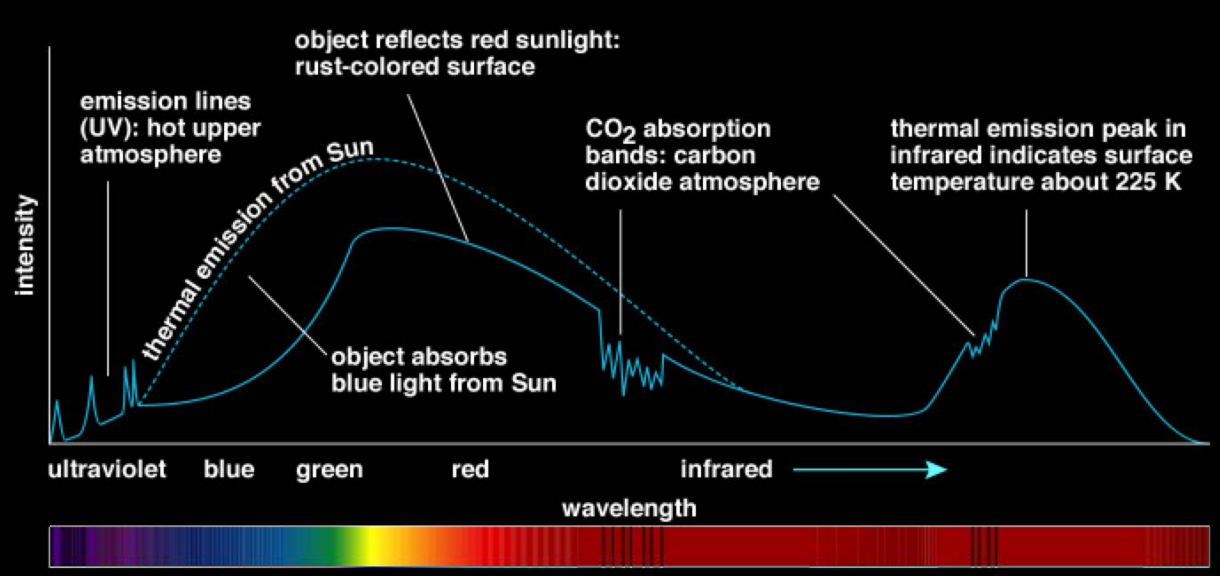

symmetric stretch mode
asymmetric stretch mode
bending mode (horizontal)
bending mode (vertical)

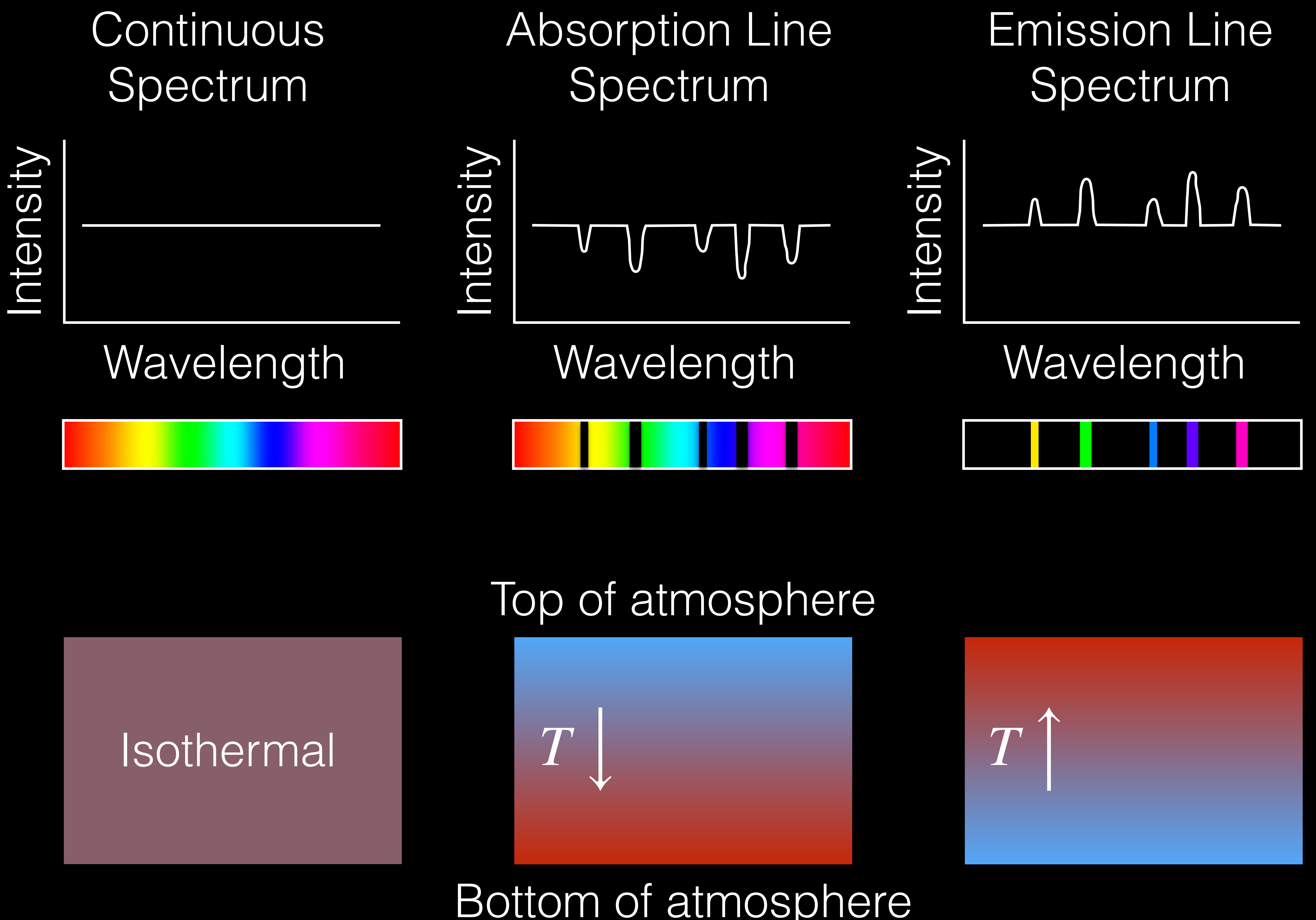
Thermal Spectrum

- The thermal spectrum is composed of a combination of an absorption and emission line spectrum depending on the temperature stratification of the atmosphere.
- Cooler layers in front of hotter layers → absorption lines.
- Temperature inversions → emission lines.
- Isothermal atmosphere → continuous spectrum (e.g. a black body with no absorption or emission features).

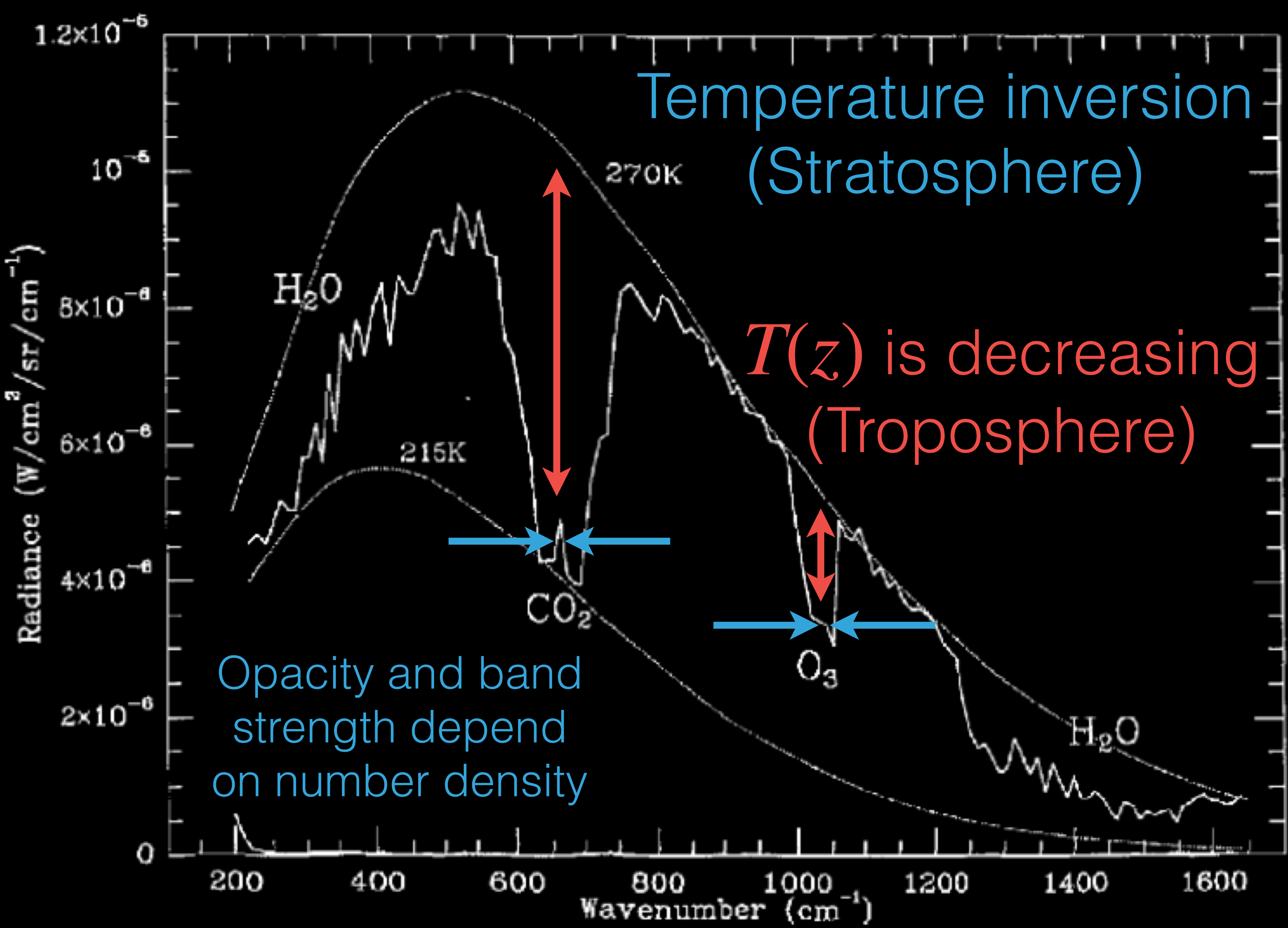






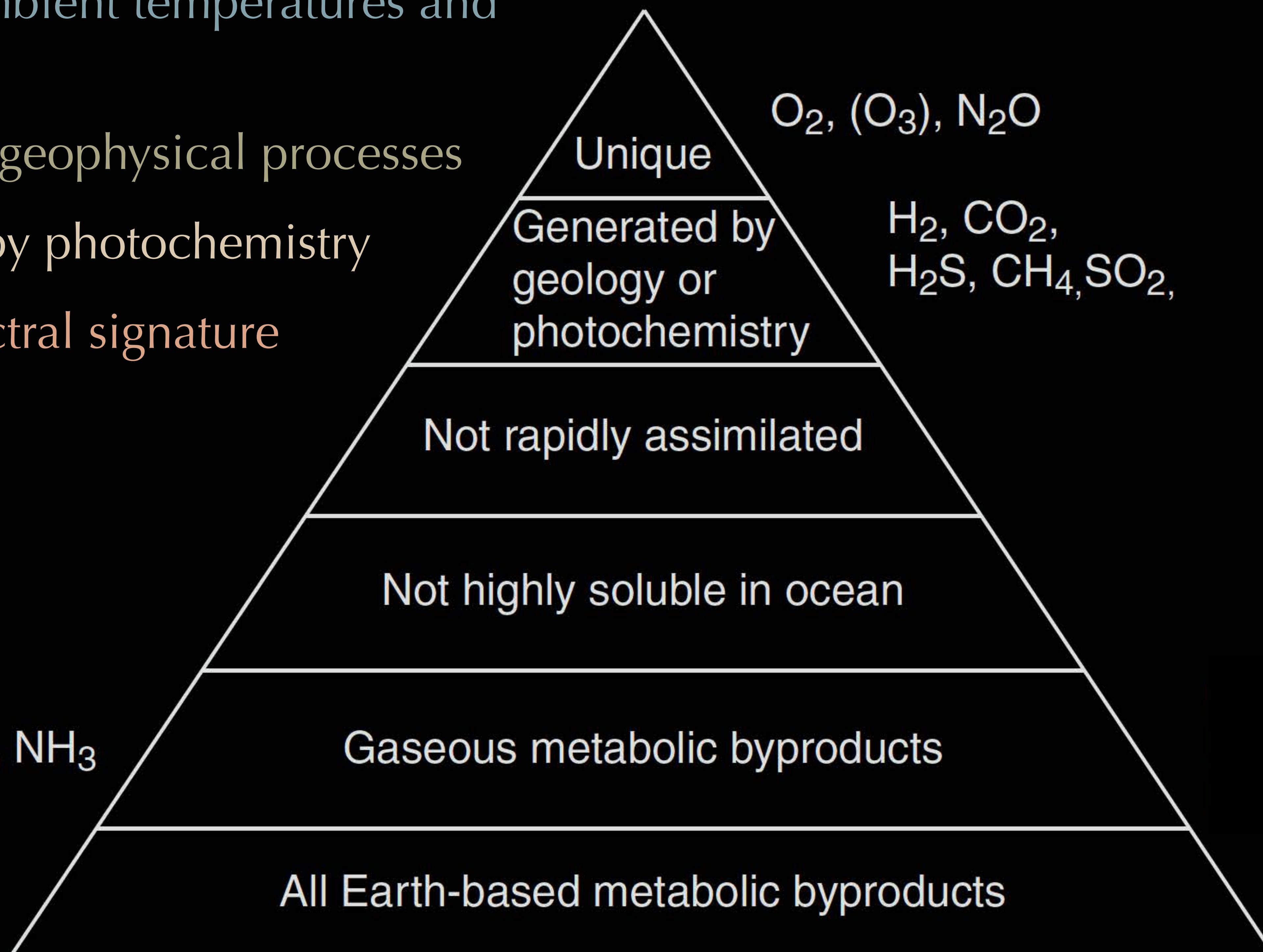

Continuous Spectrum
Absorption Line Spectrum
Emission Line Spectrum
Intensity
Intensity
Intensity
Wavelength
Wavelength
Wavelength
Top of atmosphere
Isothermal
T ↓
T ↑
Bottom of atmosphere

- What can the Earths' spectrum tell us about the temperature structure of our atmosphere ?



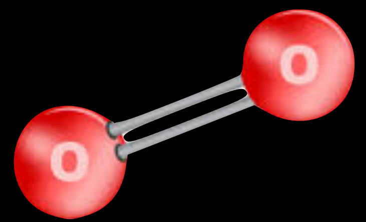
Ideal Characteristics for a Biosignature Gas

1. Does not exist naturally in the planetary atmosphere at ambient temperatures and pressures
2. Is not created by geophysical processes
3. Is not produced by photochemistry
4. Has a strong spectral signature

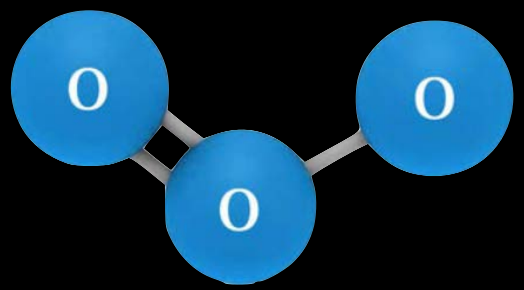


Earth's Most Robust Biosignature Gases

- Earth is a natural reference point when looking for suitable conditions for life on exoplanets…but you never know what else may be out there
- Oxygen (O_2):

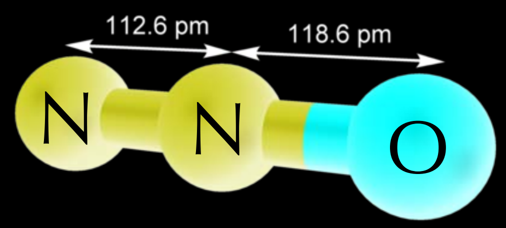


  - Satisfies all four criteria
  - Makes up 21% of atmosphere, but is highly reactive (must be continually produced)
  - Generated by plants/photosynthetic bacteria as a metabolic by-product
  - No continuous abiotic sources (in large quantities)
- Ozone (O_3):
  - Photolytic product of O_2 being split by UV radiation
  - Inherits biosignature qualities from O_2



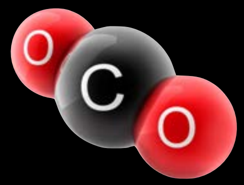
Earth's Semi-Robust Biosignature Gas

- Nitrous oxide (N_2O):
  - Satisfies three of the four criteria
  - N is important for plants (major component of chlorophyll, amino acids, ATP, and DNA) and used in fertilisers
  - Produced during microbial oxidation-reduction (redox) reactions in soil
    - Relatively small quantities compared to O_2
  - Strong greenhouse gas (298 × stronger than CO_2)

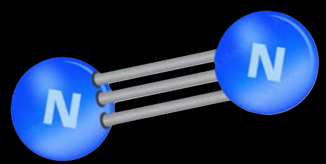


Earth's Not-So-Robust Biosignature Gases

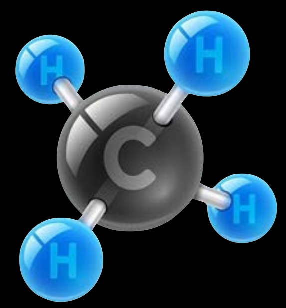
- Carbon dioxide (CO_2):



  - Indicative of a terrestrial atmosphere
  - Very strong mid-IR spectral feature
  - 0.035% of air on Earth, but 97% on Venus/Mars
    - Considered a major planetary atmosphere gas (not useful)
- Nitrogen (N_2):



  - Makes up 78% of air on earth (not useful)
  - Homonuclear (no spectral signatures in visible/IR)



- Methane (CH_4) and various (H_2, H_2S, SO_2, NO, NO_2):
  - Released by volcanism and produced by photochemistry (non-unique)
  - Produced in trace amounts (a-)biotically (lacks detectable spectral signatures for remote observers)

Potential Alternatives to Biosignature Gases

- Excess amounts of gas that cannot be explained by abiotic processes
- Atmospheres that are out of chemical equilibrium (especially redox disequilibrium)
- Photometric variation: most likely from clouds (possibly from liquid water oceans), but could also be from continents and oceans
  - Red edge: evolutionary trait to prevent overheating, which causes chlorophyll to degrade
  - The reflection spectrum of photosynthetic vegetation has a sudden rise (factor of ~10) in albedo at ~750 nm