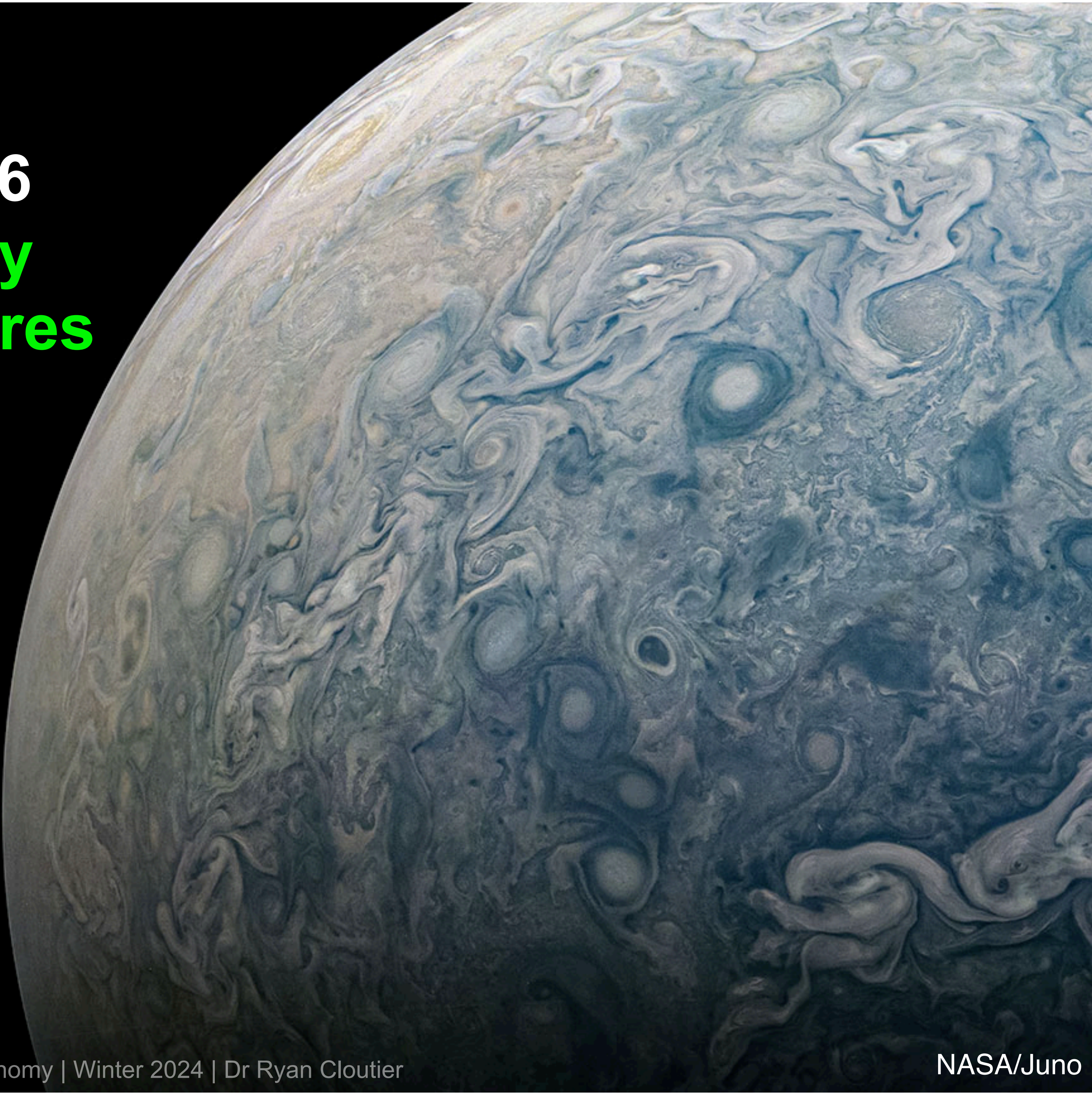
Lecture 6
Planetary Atmospheres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Learning Objectives -
Planetary Atmospheres

1) Derive the expression for hydrostatic equilibrium and use it to derive to pressure and density profiles of an Earth-like planet's atmosphere
2) Describe the energy sources that dictate the thermal structure of a planet's atmosphere
3) Understand the conditions that lead to atmospheric convection and evaluate where atmospheres are convective based on their thermal structures
4) List the main chemical constituents of the planetary atmospheres in the solar system and on exoplanets from transmission spectroscopy
5) Outline the physics behind the cloud formation process
6) Outline the physics behind winds in the solar system and beyond

Atmospheres

The gaseous outer layers of planets and moons

Terrestrial planet atmospheres
- thin
- mass fractions of $\lesssim 10^{-3}$
- dominated by heavy species N_2, CO_2, and others

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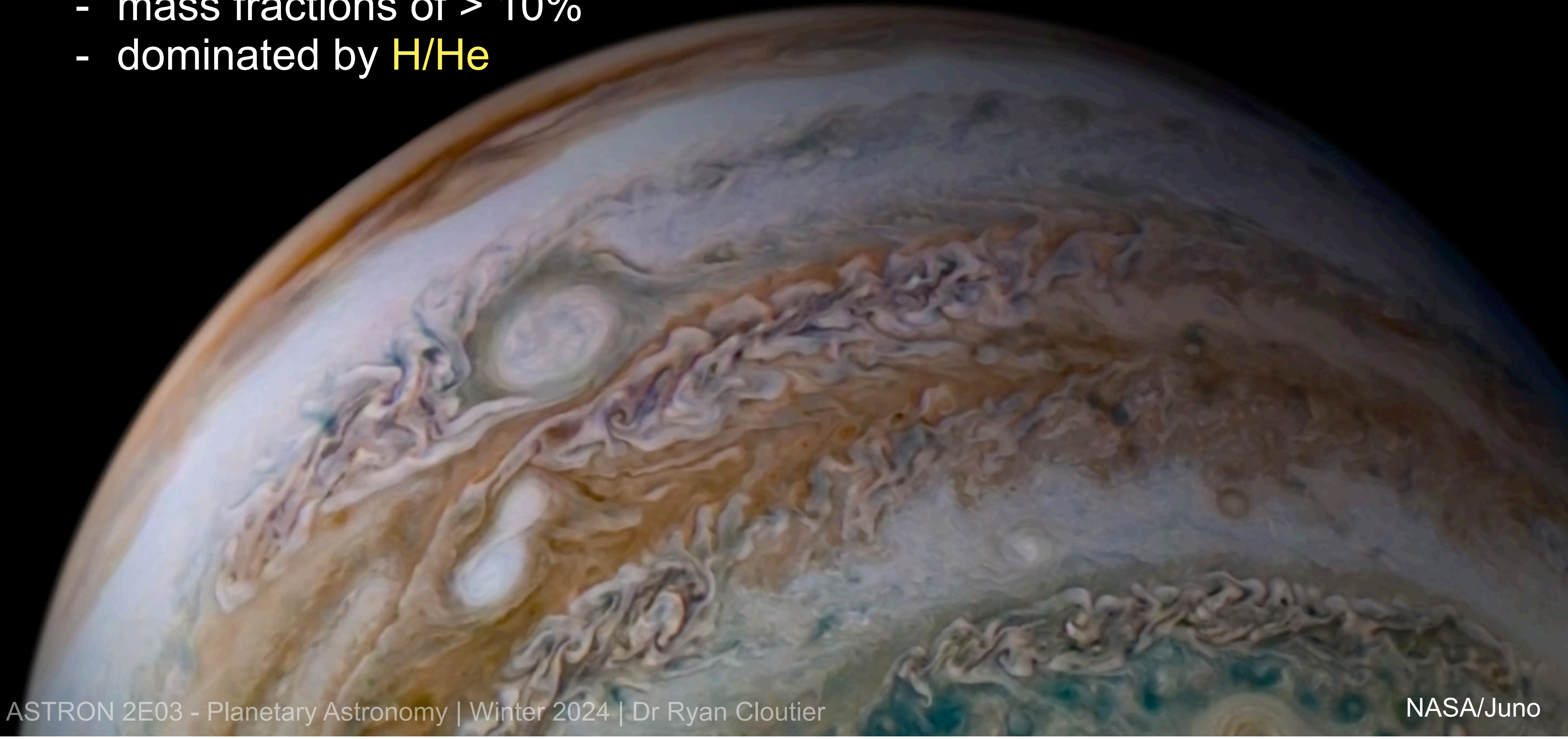
Atmospheres

The gaseous outer layers of planets and moons



Giant planet atmospheres
- deep
- mass fractions of > 10%
- dominated by H/He

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Hydrostatic Equilibrium (HSE)

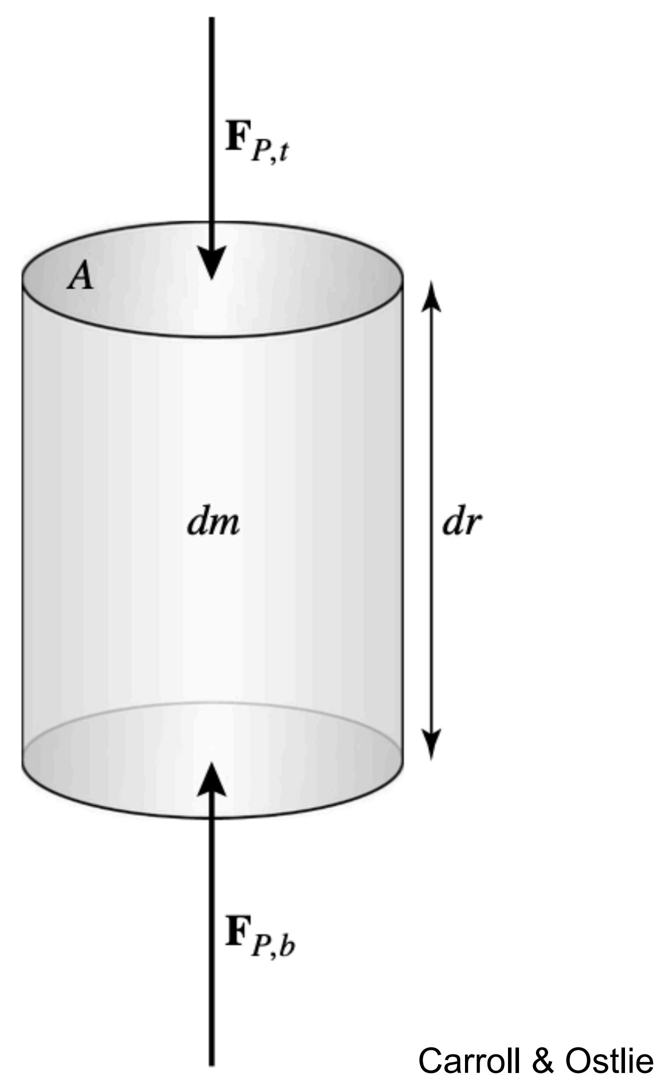
Atmospheres are held up against the

force of gravity F_g

by a gas

pressure gradient

$$\Delta P = \frac{F_{P,t} - F_{P,b}}{\Delta A}$$



Carroll & Ostlie

Hydrostatic Equilibrium (HSE)

In class we'll derive the expression for HSE given below

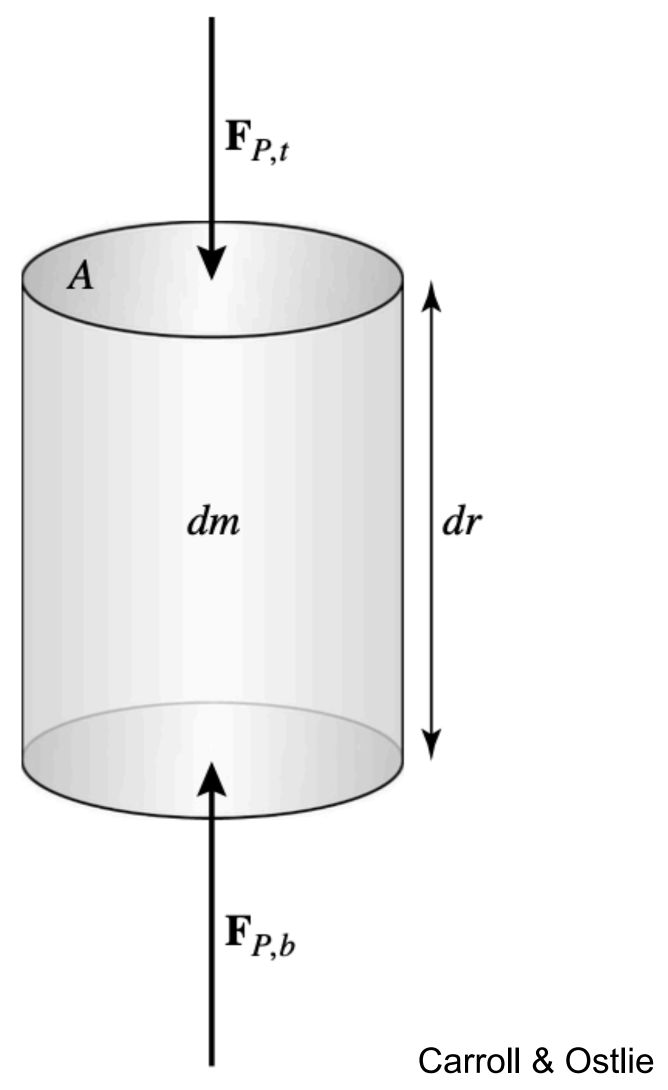
$$\frac{dP}{dr} = -\rho g$$

P: fluid pressure

r: vertical coordinate (i.e. height of the atmosphere)

ρ: fluid density

g: gravitational acceleration



Carroll & Ostlie

Atmospheric structure

We're interested in knowing how the atmospheric pressure changes with height in the atmosphere.

To do this, we need to write down an equation of state (EOS) for the atmospheric gas

$$P(\rho, T)$$

An EOS typically has the form above.

It describes the relationship between a material's pressure, density, and temperature

Atmospheric structure

In low to moderate pressure environments, typical of terrestrial planet atmospheres, the atmosphere is well-described as an ideal gas

$$P = \frac{\rho k_B T}{\mu m_H}$$

P: fluid pressure

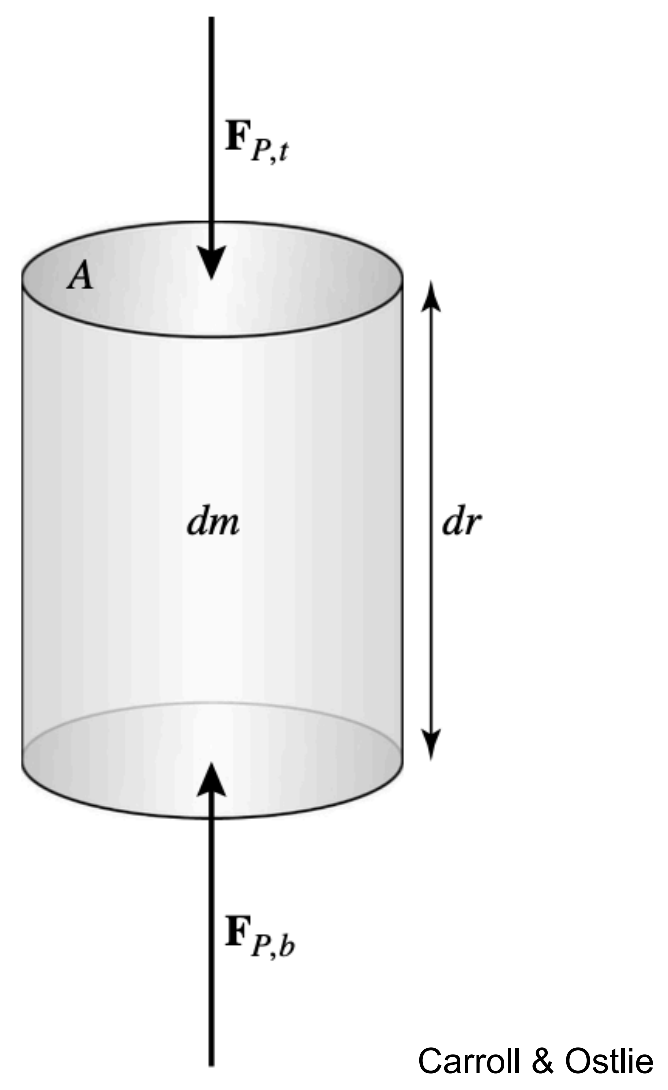
k_B: Boltzmann constant

T: fluid temperature

ρ: fluid density

μ: mean molecular weight

m_H: mass of the hydrogen atom



Carroll & Ostlie

Mean Molecular Weight (μ)

Atomic mass unit ~ the proton mass ~ the neutron mass = 1.67e-27 kg

Gas	Composition	**Mean molecular weight μ**
Molecular nitrogen	N_2 = 2*N	2*14 = **28**
Molecular oxygen	O_2 = 2*O	2*16 = **32**
Water	H_2O = 2*H + O	2*1 + 16 = **18**
Earth atmosphere	78% N_2 + 22% O_2	0.78*28 + 0.22*32 ~ **29**

Atmospheric Structure

In class we'll show that for an atmosphere in HSE and composed of an ideal gas, the atmospheric pressure and density profiles are

$$P(r) = P_0\, e^{-r/H}$$

$$\rho(r) = \rho_0\, e^{-r/H}$$

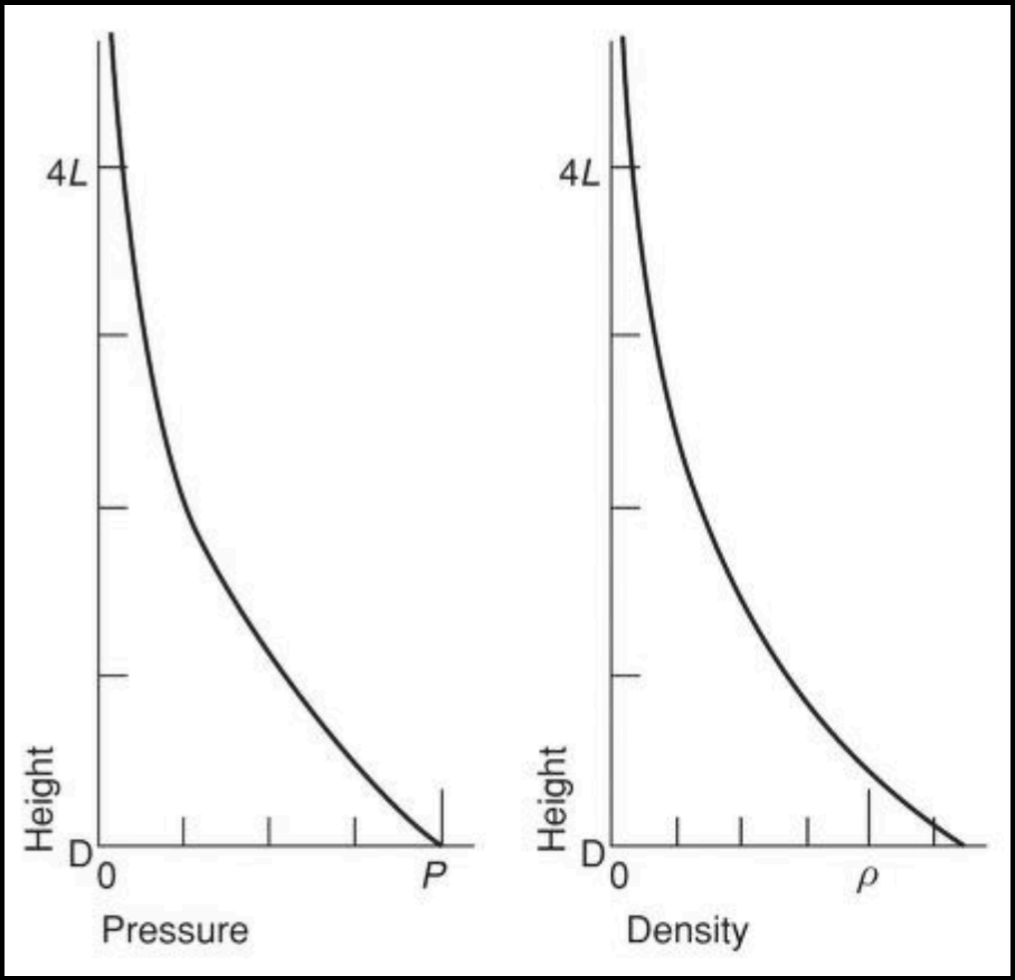
where the subscript 0 indicates the values at the surface and *H* is the atmospheric scale height

$$H = \frac{k_B\, T}{\mu\, m_H\, g}$$

Atmospheric Structure

$$P(r) = P_0\, e^{-r/H}$$

$$\rho(r) = \rho_0\, e^{-r/H}$$



Carroll & Ostlie

where

$$H = 8.3\,\mathrm{km}\left(\frac{T}{288\,\mathrm{K}}\right)\left(\frac{g}{9.8\,\mathrm{m/s}}\right)^{-1}\left(\frac{\mu}{29\,m_H}\right)^{-1}$$

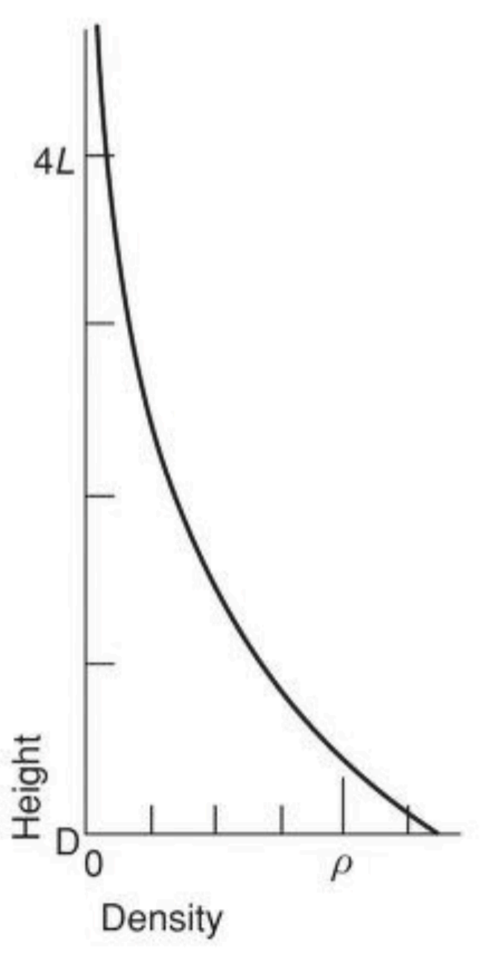
Atmospheric Mass

Note that most of the atmosphere's mass is within one scale height *H*

$$\rho(r) = \rho_0 \, \exp\left(-r/H\right)$$

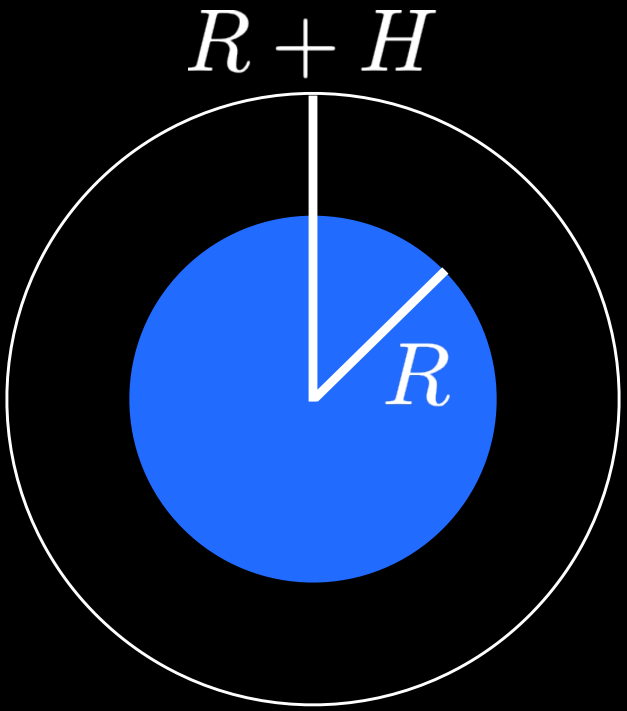
where

$$H = 8.3\,\mathrm{km}\left(\frac{T}{288\,\mathrm{K}}\right)\left(\frac{g}{9.8\,\mathrm{m/s}}\right)^{-1}\left(\frac{\mu}{29\,m_H}\right)^{-1}$$



Carroll & Ostlie

Atmospheric Mass

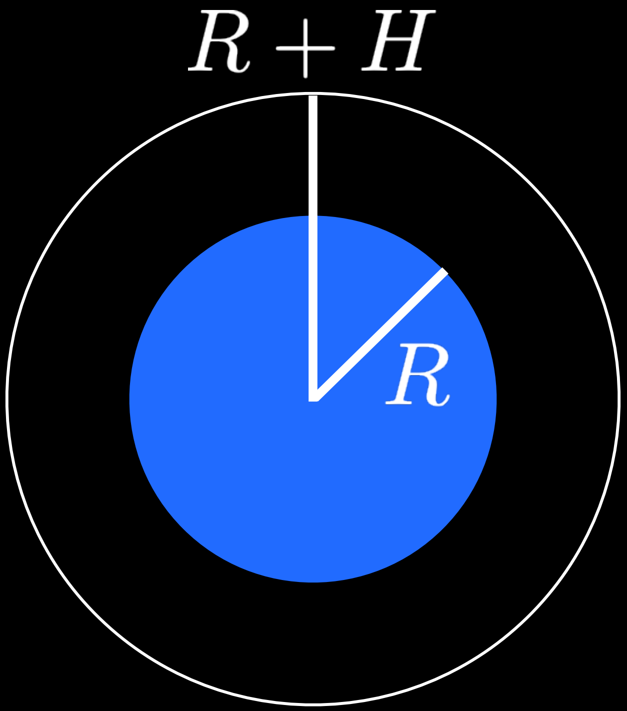


Normally, one would calculate the atmospheric mass by integrating the atmospheric density profile

$$\rho(r) = \rho_0 \, e^{-r/H}$$

from the planet's surface to *H.*
(noting that that ρ_0=1.2 kg/m^3)

Atmospheric Mass



But we can approximate the atmospheric mass by noting that most of the mass is contained within $r < H$, with ρ_0=1.2 kg/m^3.

The atmospheric mass is then

$$\int_0^{M_{atm}} dM \approx \rho_0 \, dV$$

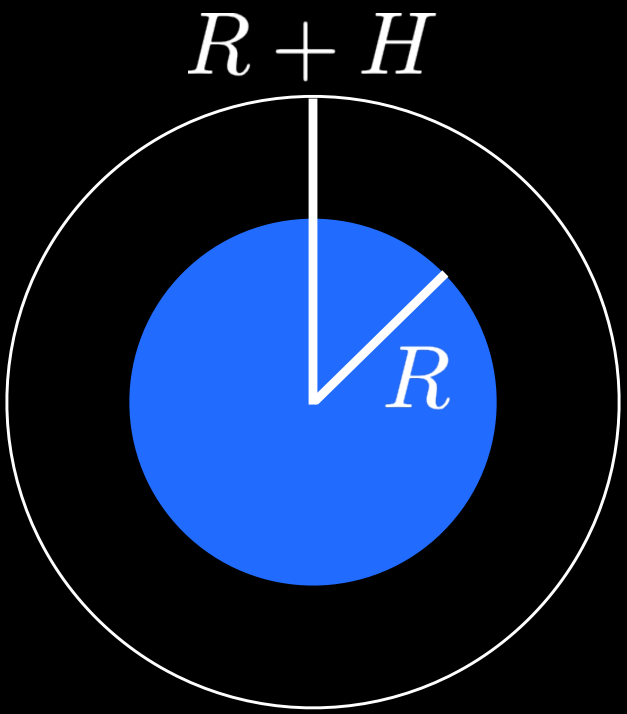
$$M_{atm} \approx \rho_0 \int_R^{R+H} 4\pi r^2 dr$$

$$= \frac{4\pi}{3}\rho_0 \left[(R+H)^3 - R^3\right]$$

$$= 5 \times 10^{18} \, \mathrm{kg}$$

Actual is 5.1 x 10^{18} kg!!

Atmospheric Mass



On terrestrial planets for which $H << R$, the atmospheric mass can be approximated as

$$M_{atm} = M_{atm,\oplus} \left(\frac{\rho}{\rho_\oplus} \right) \left(\frac{H}{H_\oplus} \right)$$

Thermal Structure

Note that in deriving the pressure and density profiles

$$P(r) = P_0\, e^{-r/H}$$

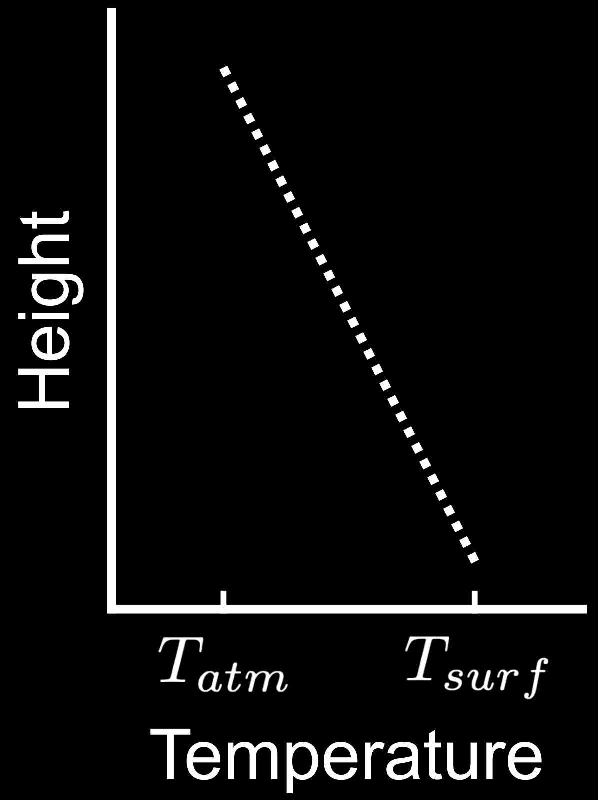
$$\rho(r) = \rho_0\, e^{-r/H}$$

we implicitly assumed that the atmospheric temperature profile was isothermal

Thermal Structure

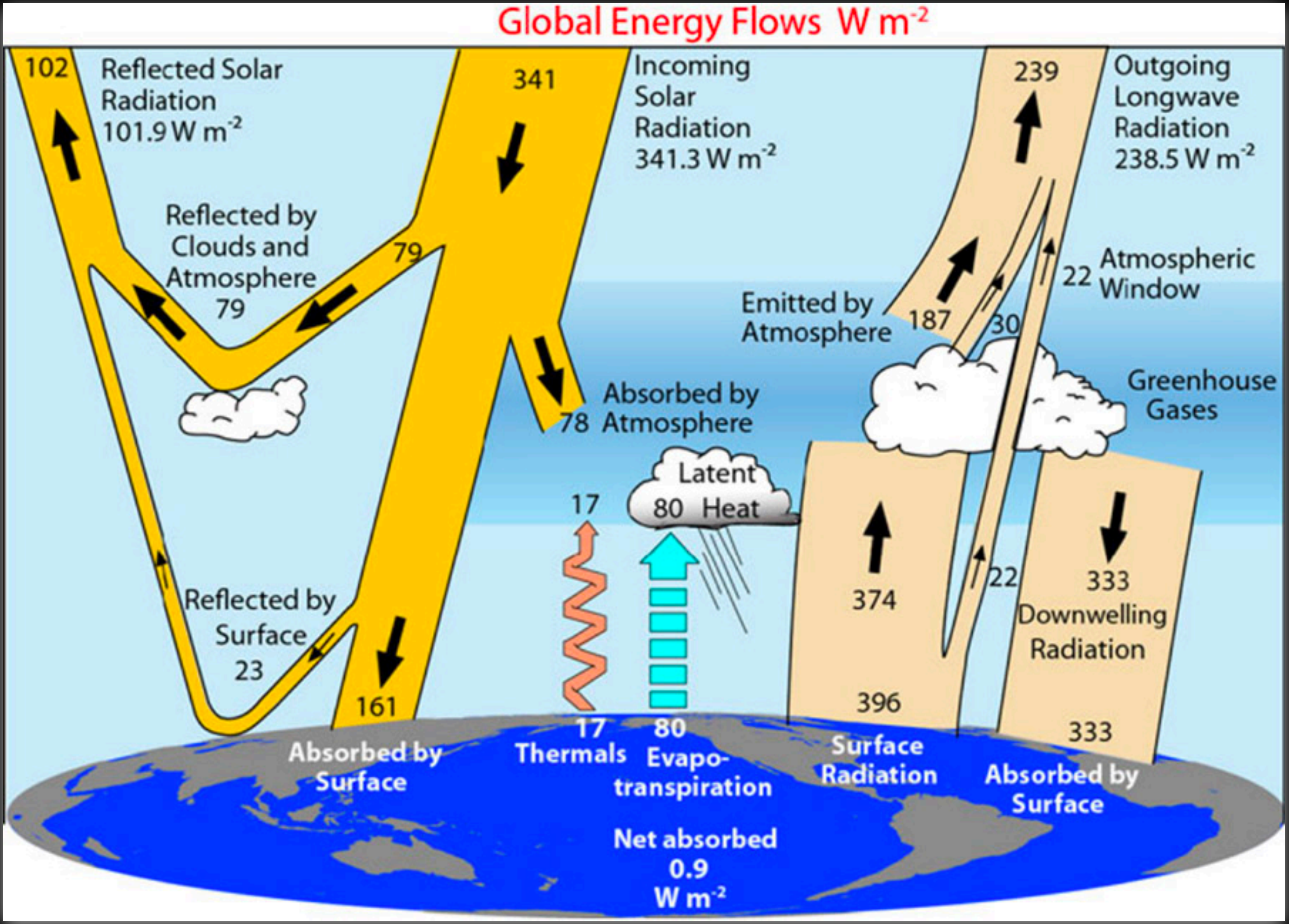
But recall from our discussion of that greenhouse effect that

$$\frac{dT}{dr} < 0$$



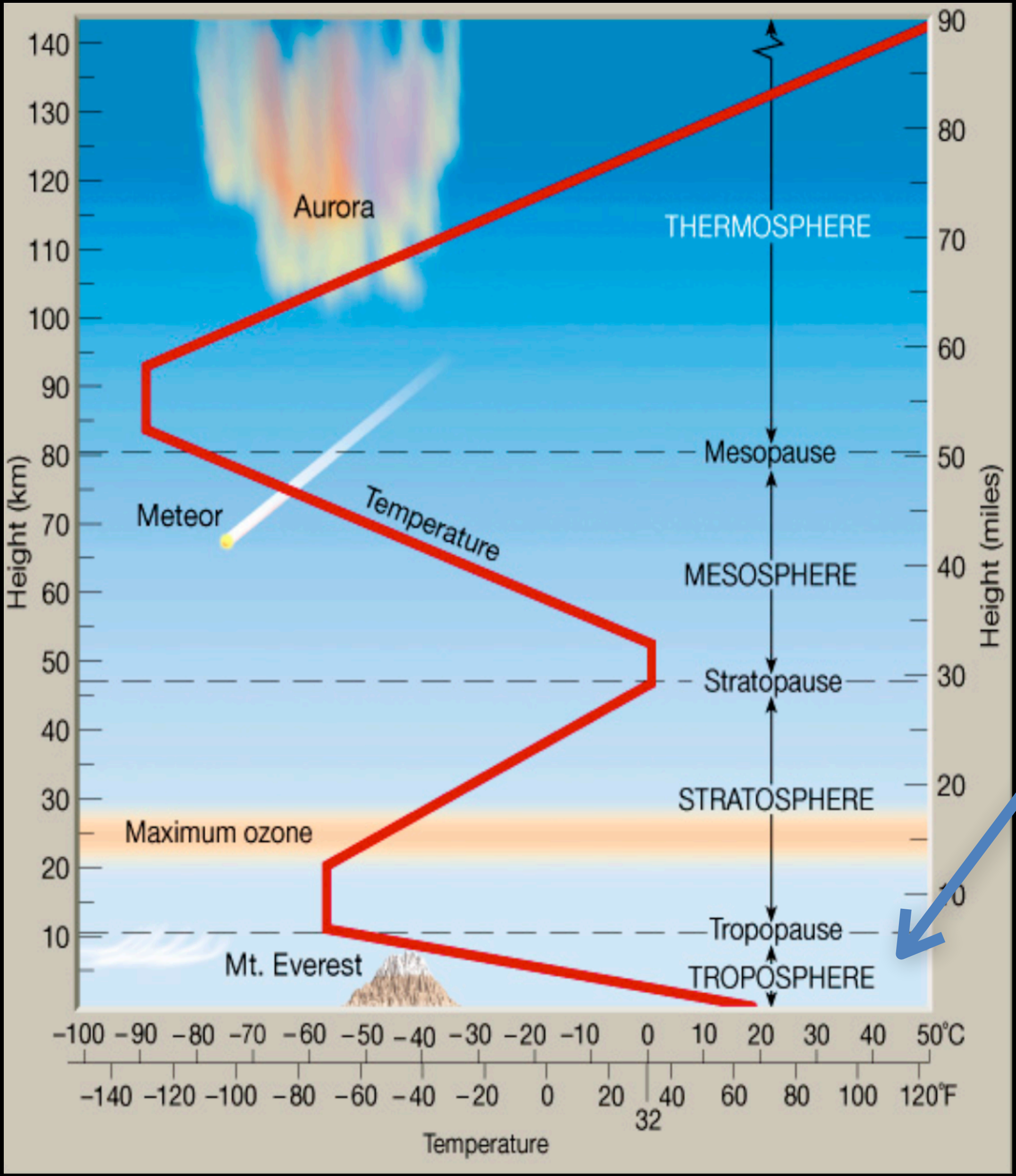
We must consider all available energy sources

Radiative feedback alters the atmospheric temperature profile



Kevin Trenberth, John Fasullo and Jeff Kiehl

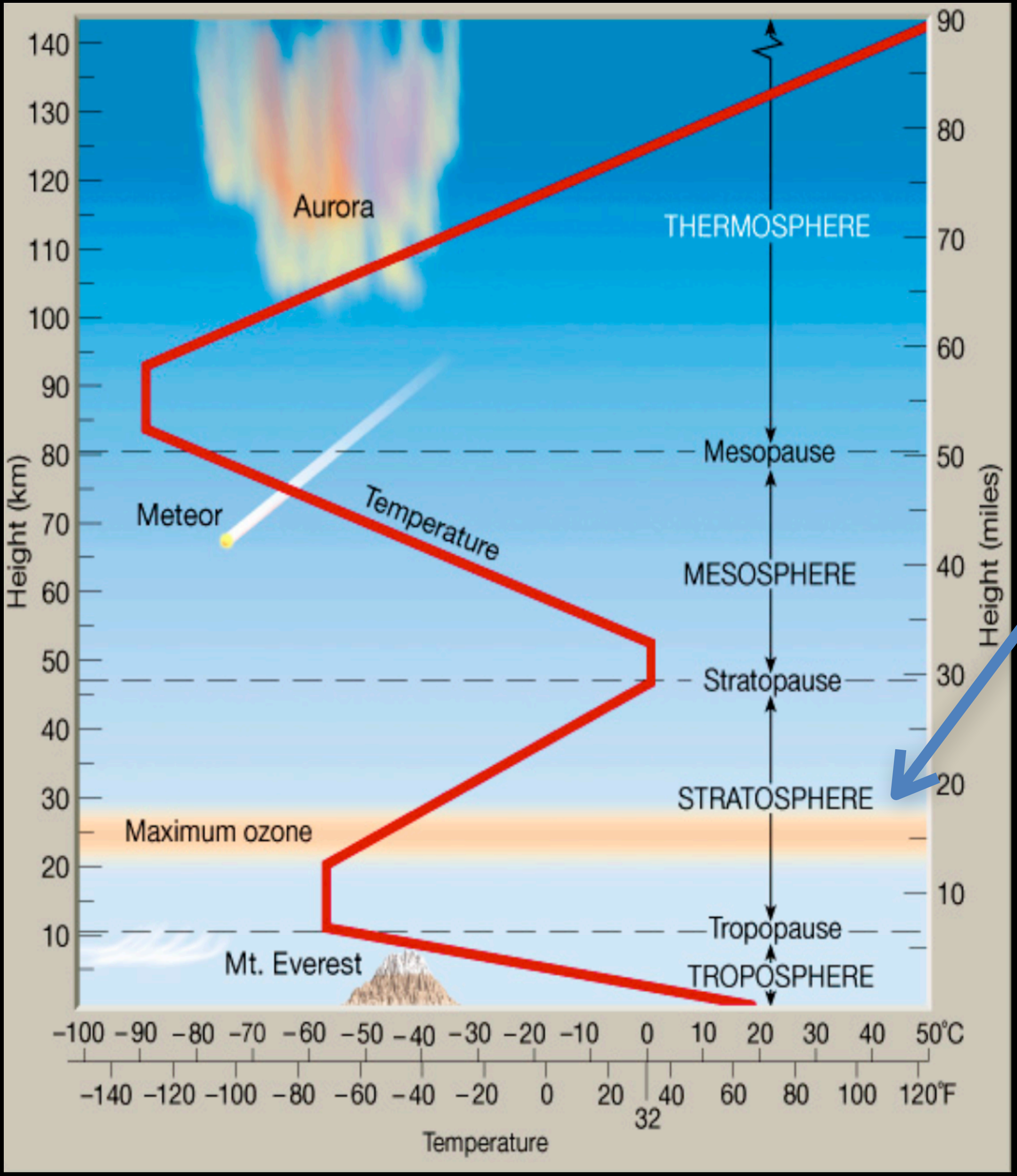
Earth's Atmosphere



TROPOSPHERE

- **Densest portion** containing most of atmospheric mass below *H* = 8.3 km
- Rich in **GH gases** (H_2O, CO_2, CH_4)
- Energy transport is via **convection**

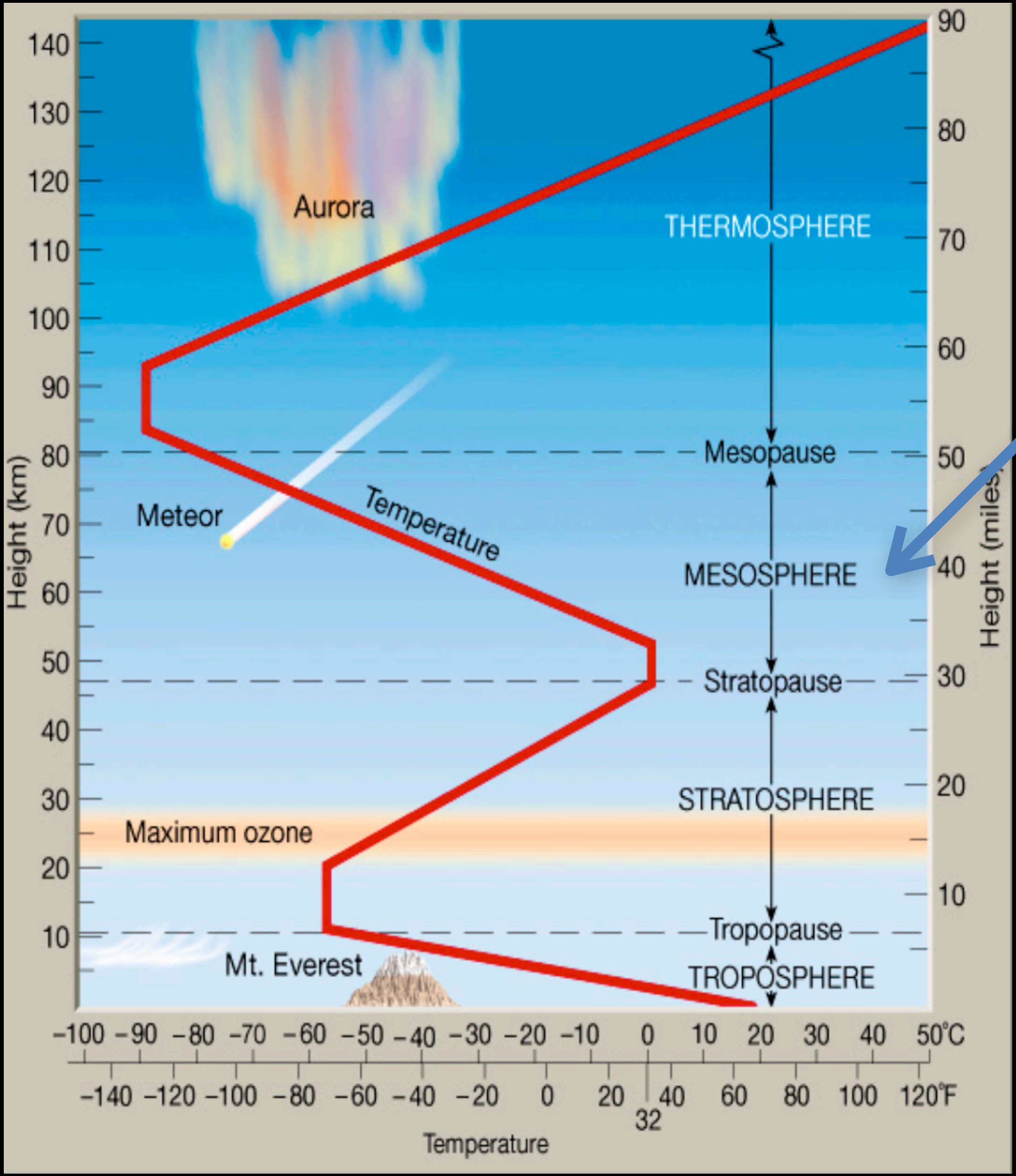
Earth's Atmosphere



STRATOSPHERE

- **Thermal inversion produced by UV absorption of O_3**

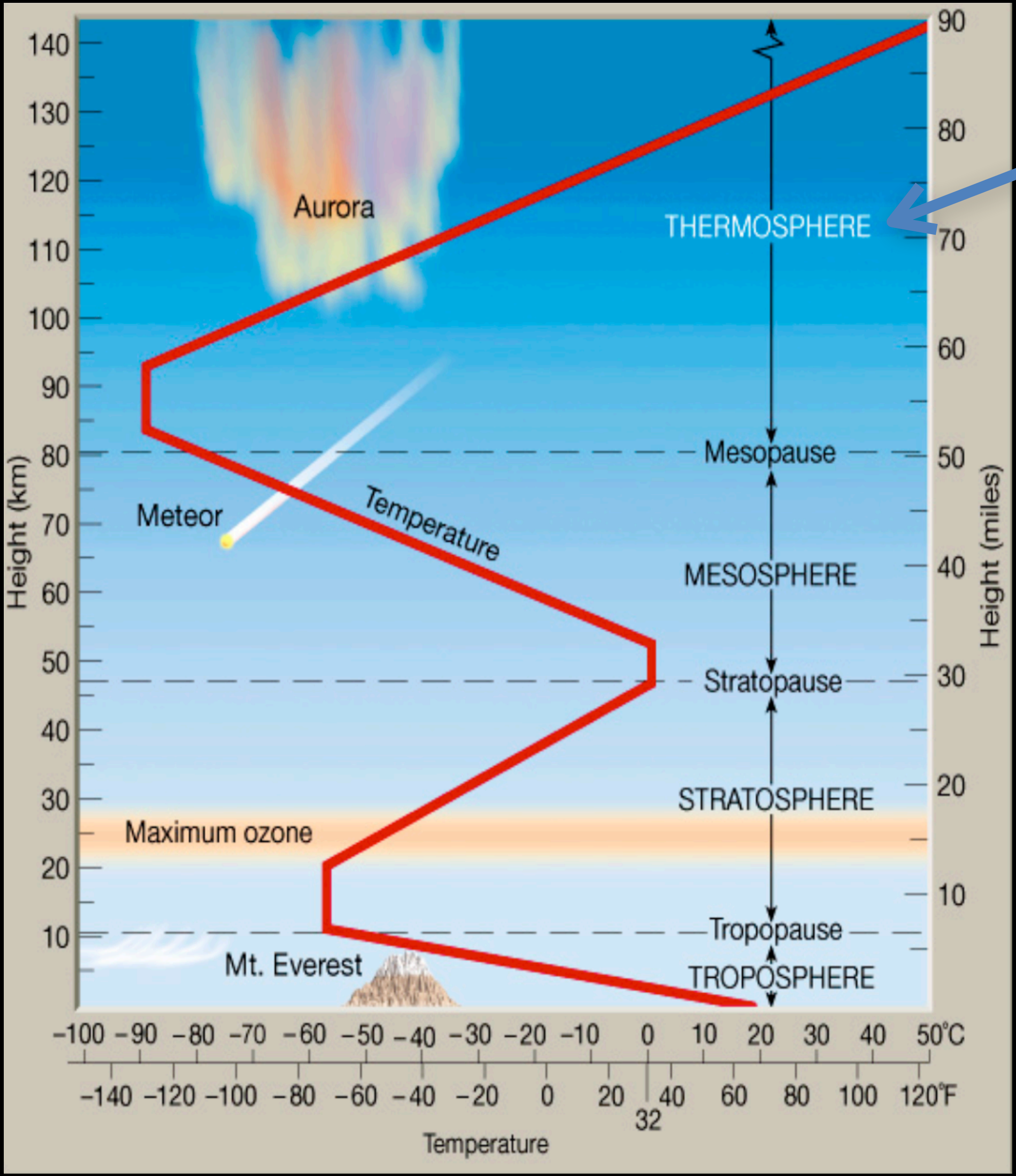
Earth’s Atmosphere



MESOSPHERE

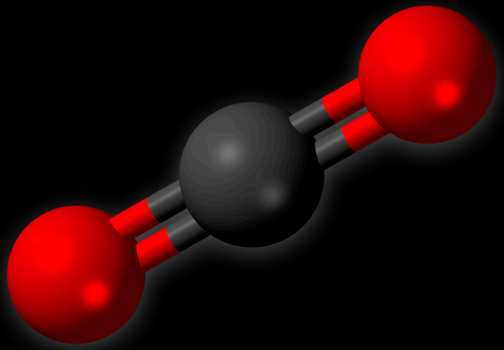
- Lower O_3 abundance results in **inefficient UV heating**
- GH gases do not “see” as much longwave radiation as in the troposphere, such that the **GH effect is weak**

Earth's Atmosphere

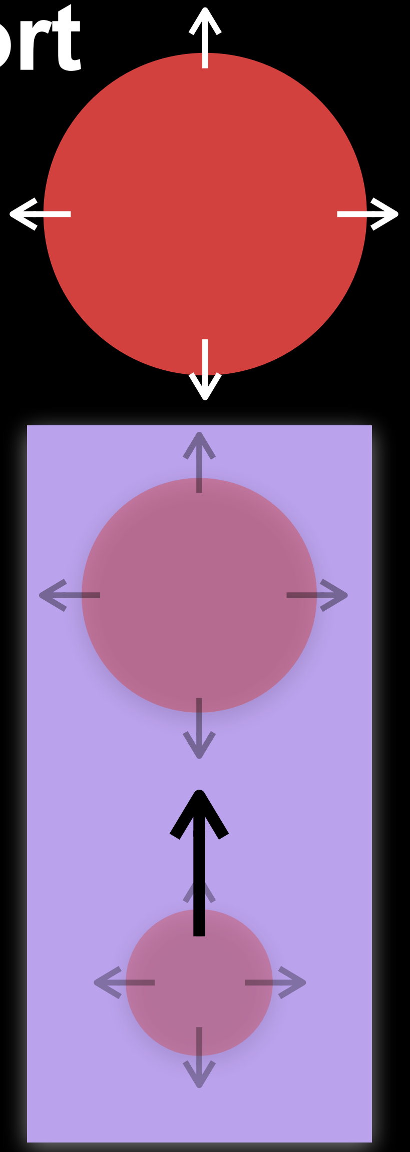


THERMOSPHERE

- **UV heating** by O_2
- **Auroral heating** by the interactions with the solar winds
- Atmosphere density is low such that molecular **cooling is inefficient**



Convective energy transport



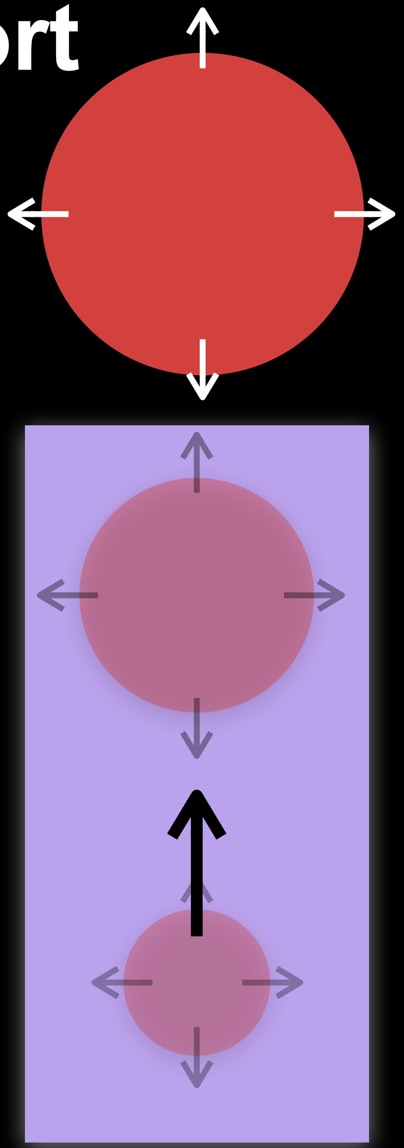
Consider a parcel of air that is hotter than its surroundings

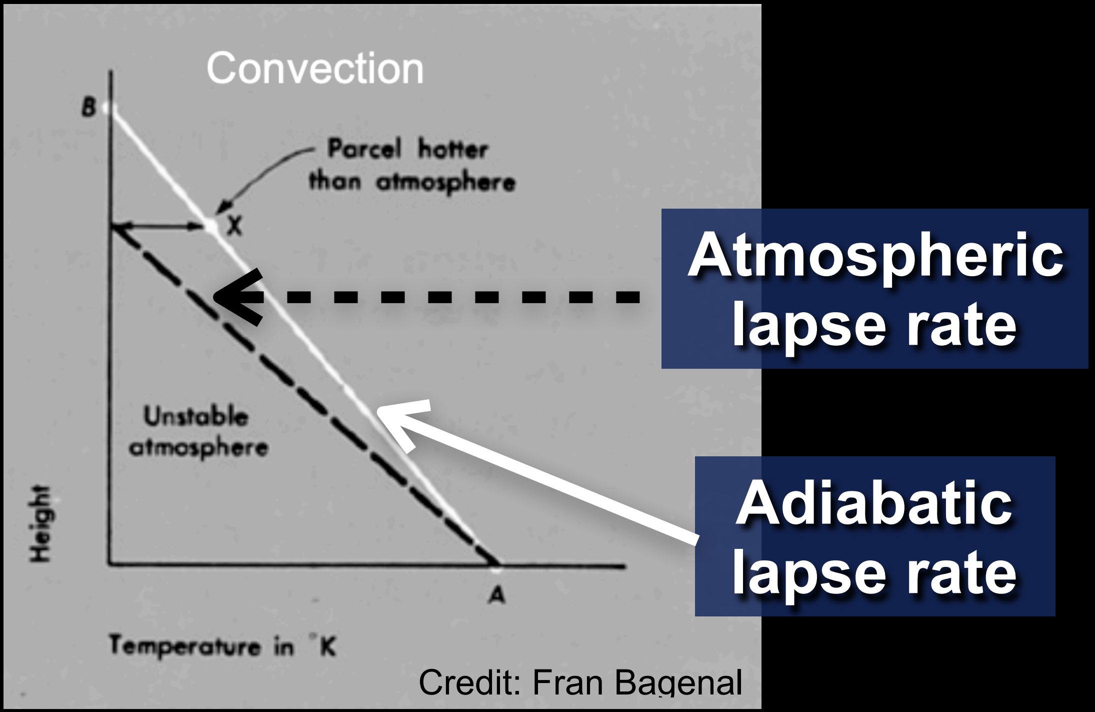
- according to the ideal gas law, $P_{parcel} > P_{surroudings}$ so the parcel expands to reach a pressure balance
- its lower density causes the parcel to rise (buoyancy)
- because P decreases with altitude, the rising parcel continues to expand and cool as it rises
- if cooling is slow, then the parcel will remain warmer than its surroundings and continue to rise, carrying thermal energy with it (i.e. convective heat transport)

Convective energy transport

An atmosphere is said to be **unstable against convection** (i.e. it is convective)

if its temperature drops rapidly with altitude compared to the change in parcel temperature





Atmospheric lapse rate

Adiabatic lapse rate

Credit: Fran Bagenal

Adiabatic lapse rate

The cooling rate of a rising parcel of gas

$$\left(\frac{dT}{dr}\right)_{\rm ad} = -\frac{\gamma - 1}{\gamma}\left(\frac{g\mu m_H}{k_B}\right)$$

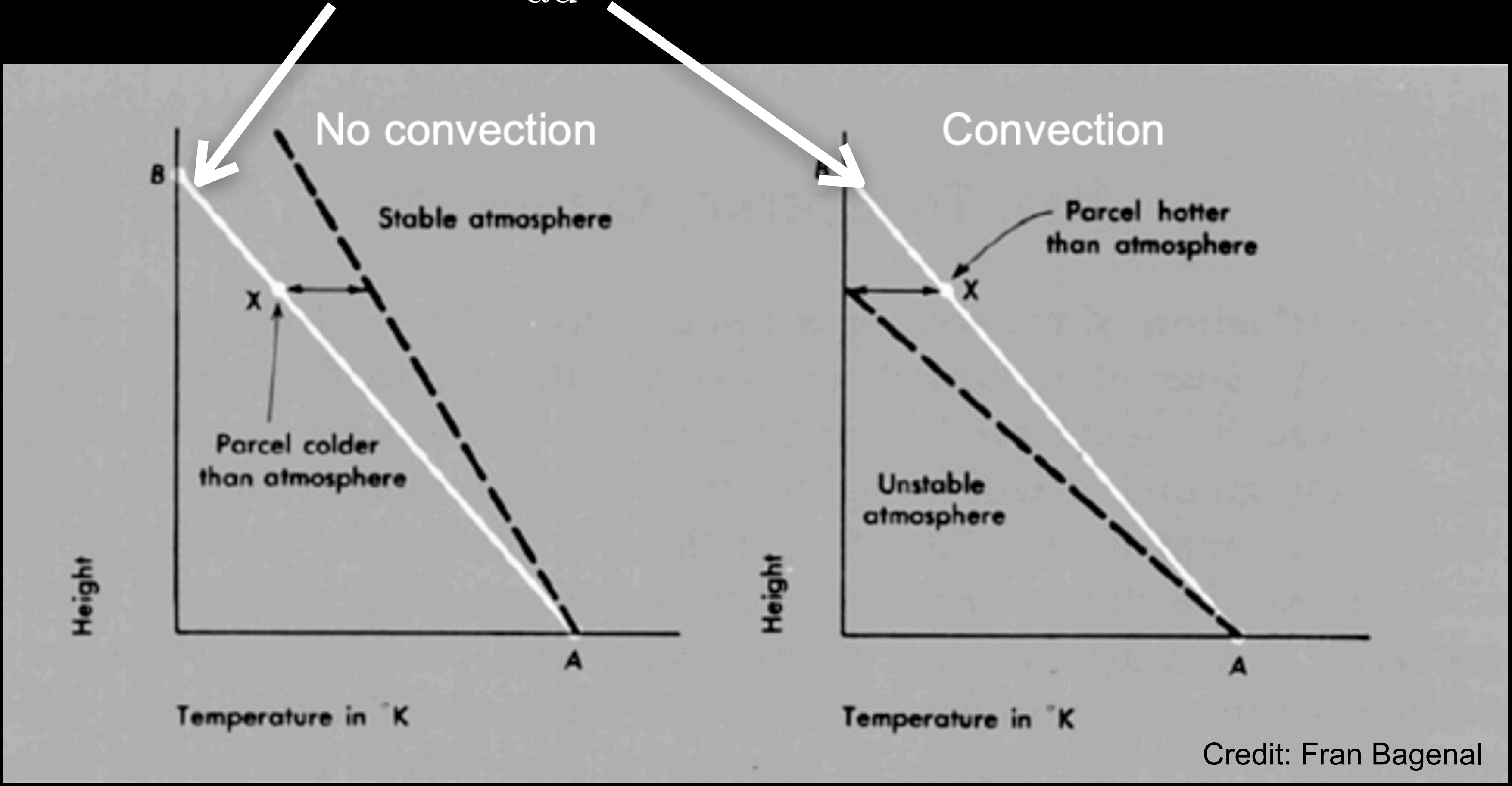
Depends on the planet's surface gravity, mean molecular weight, and the adiabatic index γ describing the heat required to raise the gas temperature at a fixed *P* and *V*.

γ = 5/3, 7/5, 4/3 for monoatomic, diatomic, and polyatomic gases respectively

Adiabatic lapse rate

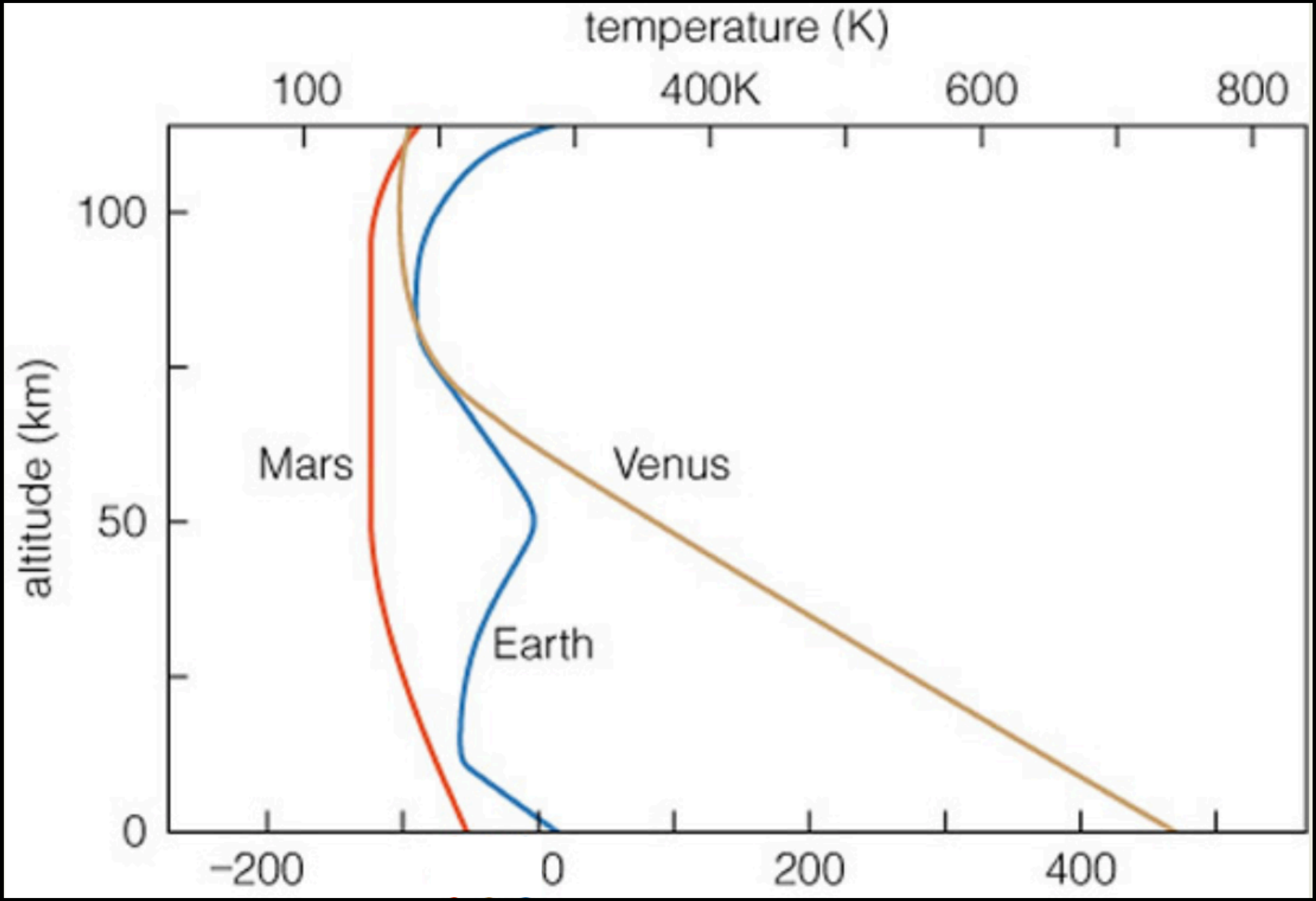
The cooling rate of a rising parcel of gas

$$\left(\frac{dT}{dr}\right)_{\rm ad} = -\frac{\gamma - 1}{\gamma}\left(\frac{g\mu m_H}{k_B}\right)$$

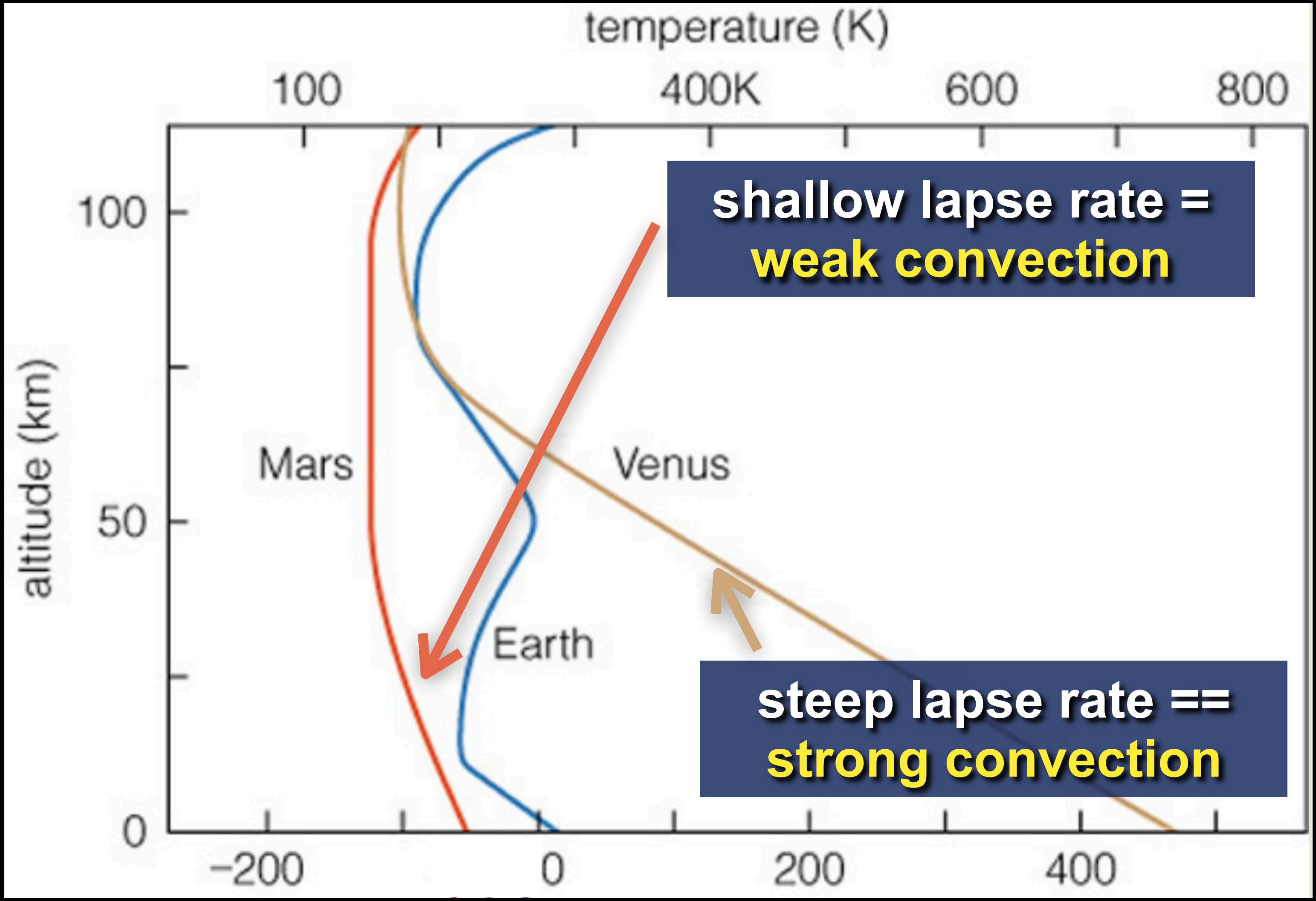


Credit: Fran Bagenal

Comparative Atmospheres



Comparative Atmospheres

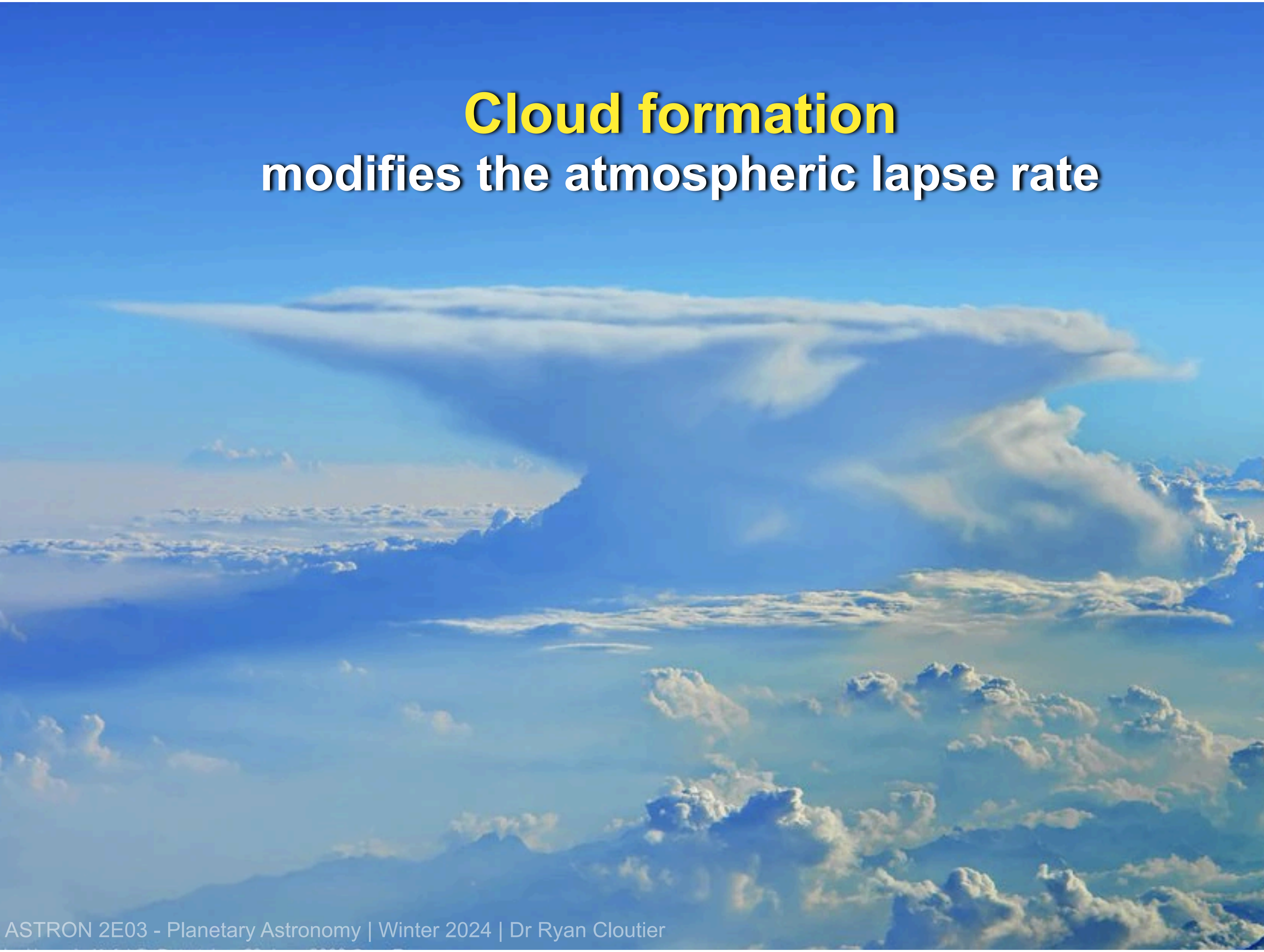


shallow lapse rate = **weak convection**

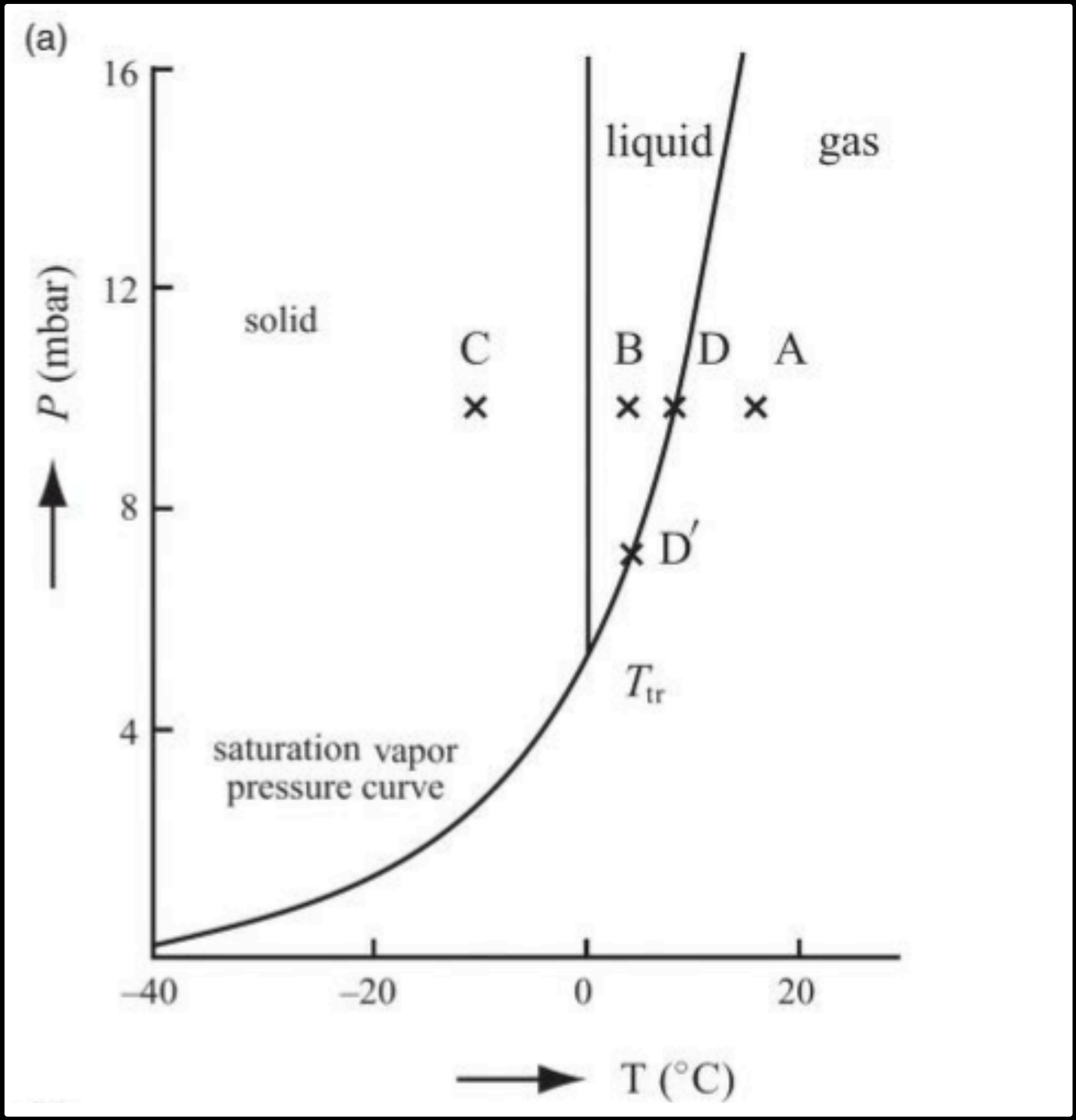
steep lapse rate == **strong convection**

Cloud formation

modifies the atmospheric lapse rate



Cloud Formation



Lissauer & de Pater

At a fixed P and T, air cannot contain more water than the saturation vapour pressure, which is given by the Clausius-Clapeyron EOS

$$P = C_L e^{-L/(R_{gas}T)}$$

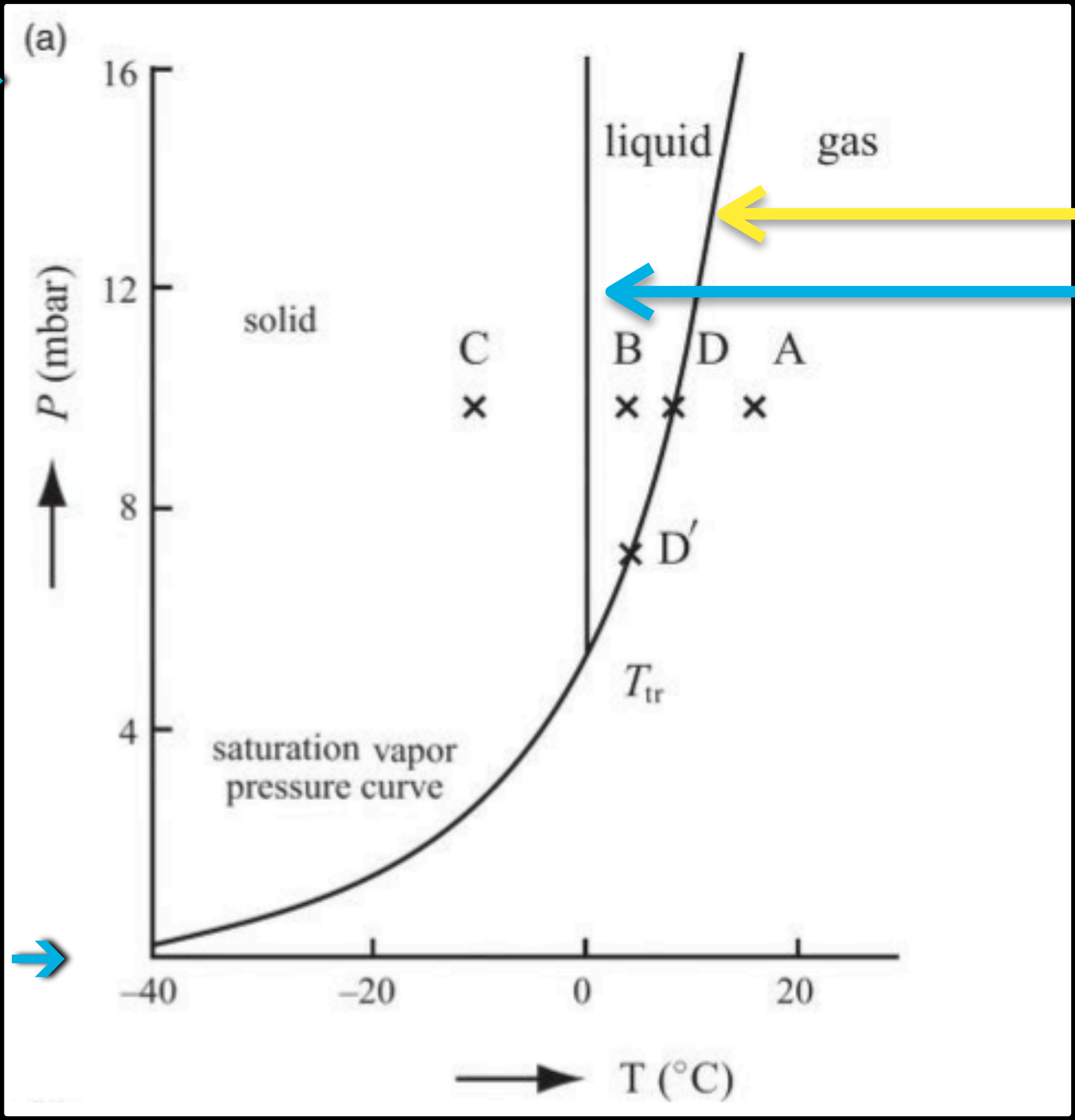
P: saturation vapour pressure of water

C_L, R_{gas}: gas constants

L latent heat

T: air temperature

Cloud Formation



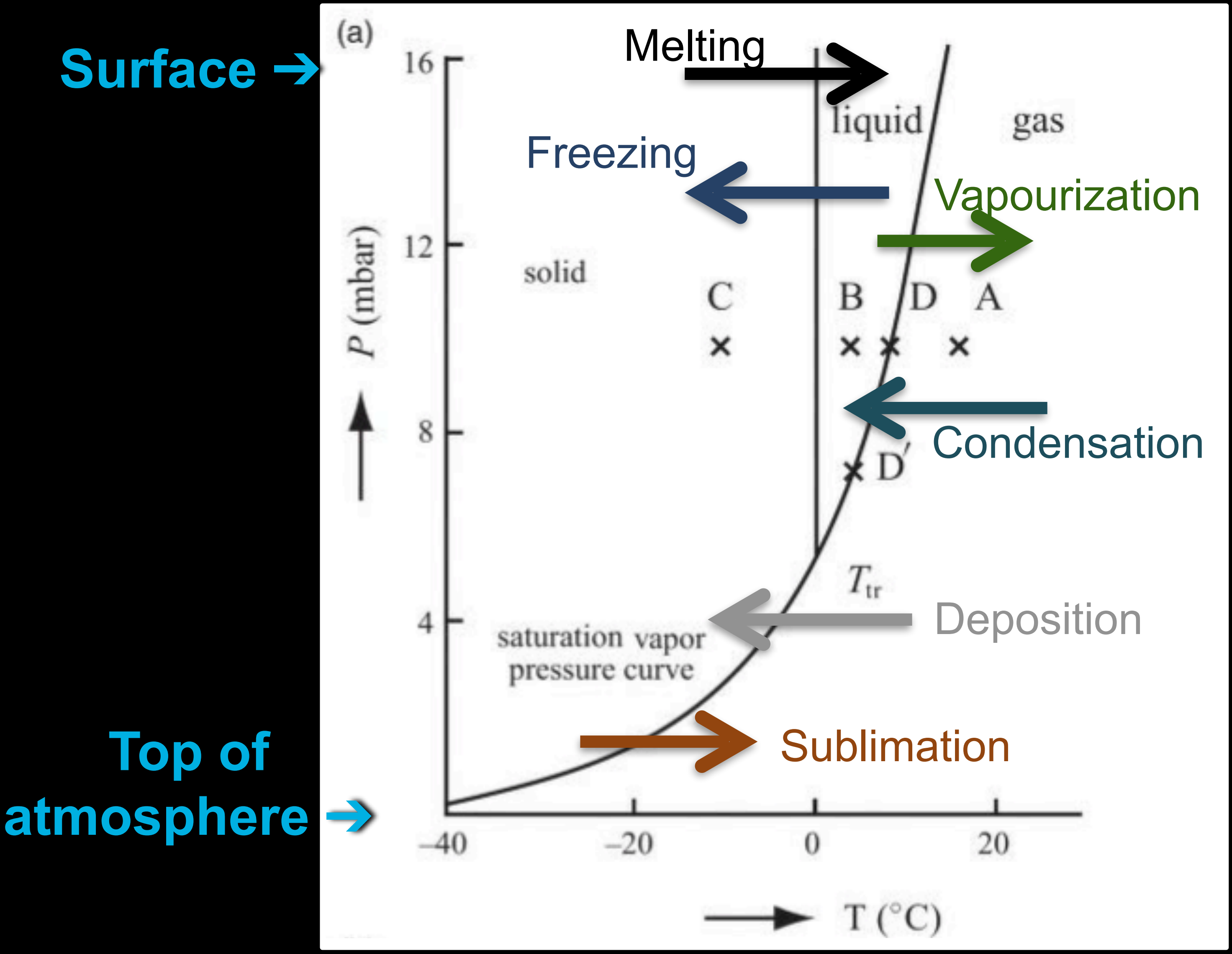
Surface →

Top of atmosphere →

saturation curves for **liquid water** **and ice**

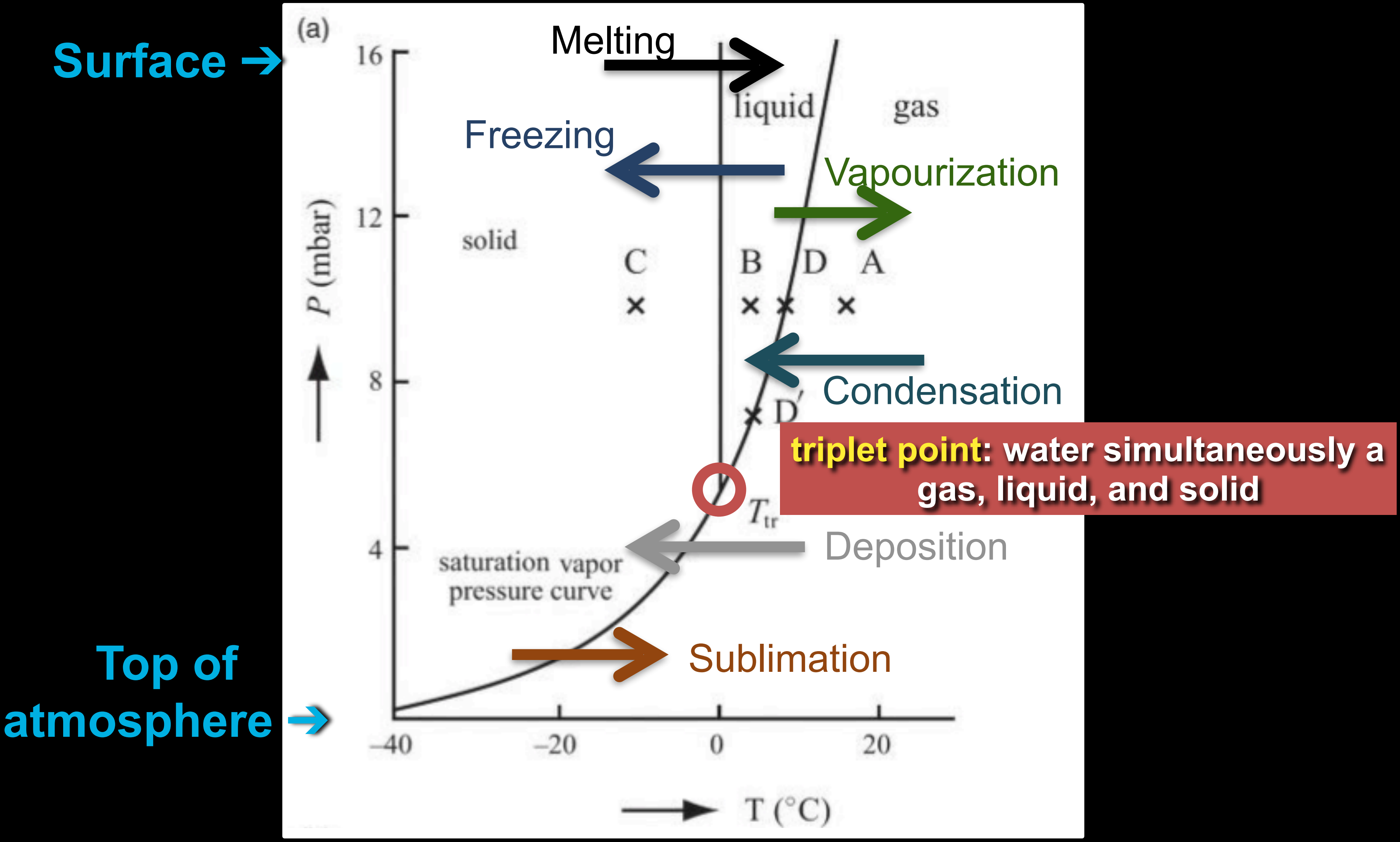
Lissauer & de Pater

Cloud Formation



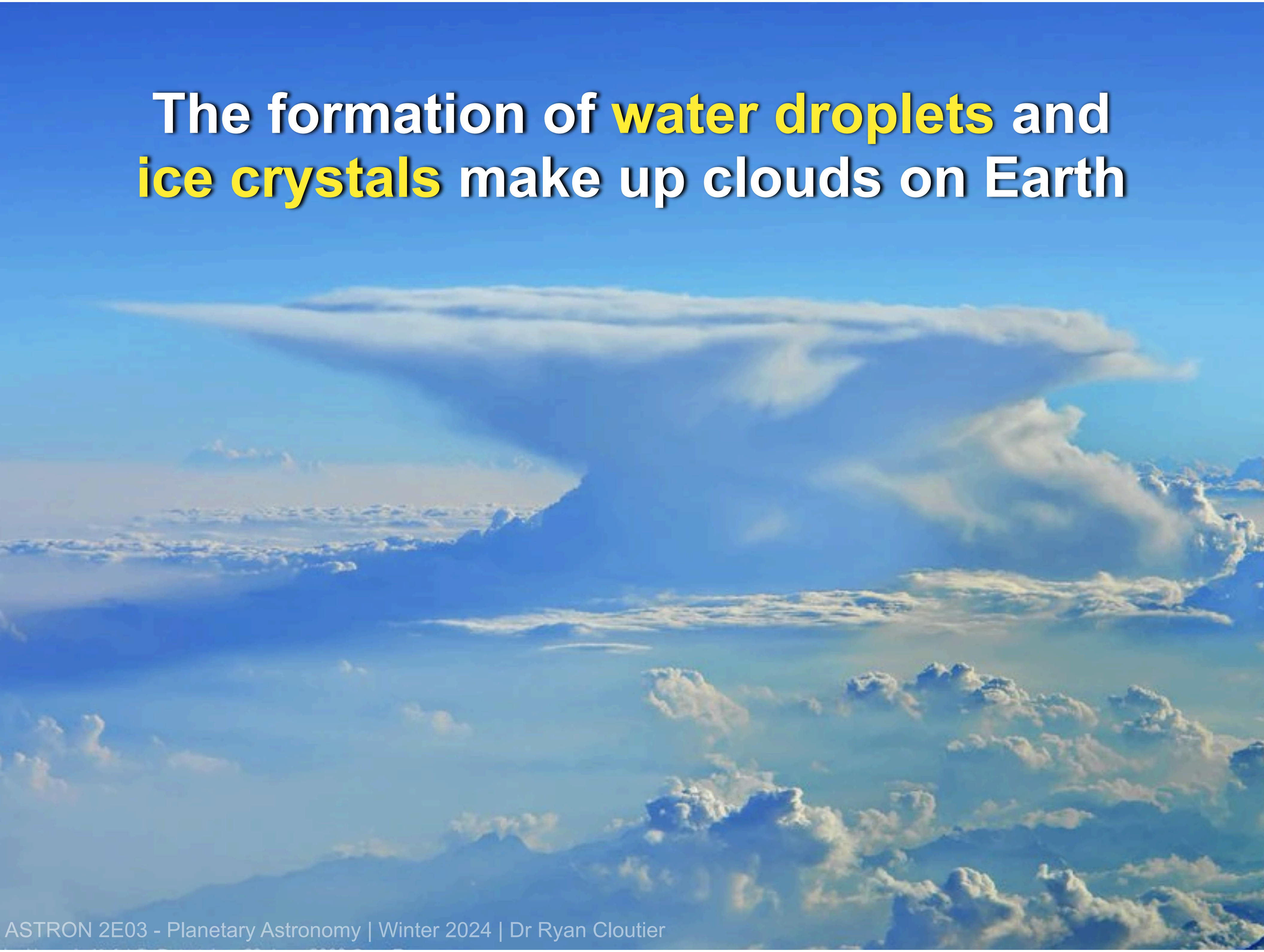
Lissauer & de Pater

Cloud Formation

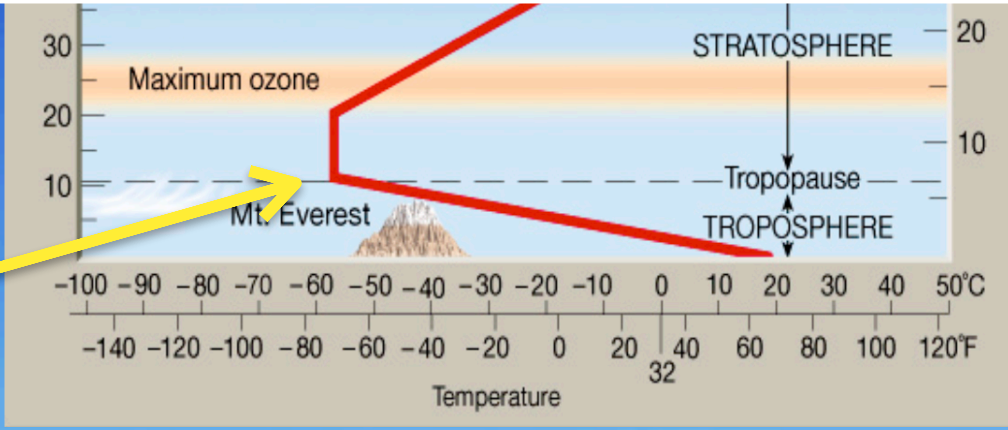


Lissauer & de Pater

The formation of water droplets and ice crystals make up clouds on Earth



Condensation halts at the **tropopause** where the lapse rate turns over



Produces a "cloud anvil"

Clouds in the solar system

Giant planets:

NH_3, H_2S, CH_4

Mars:

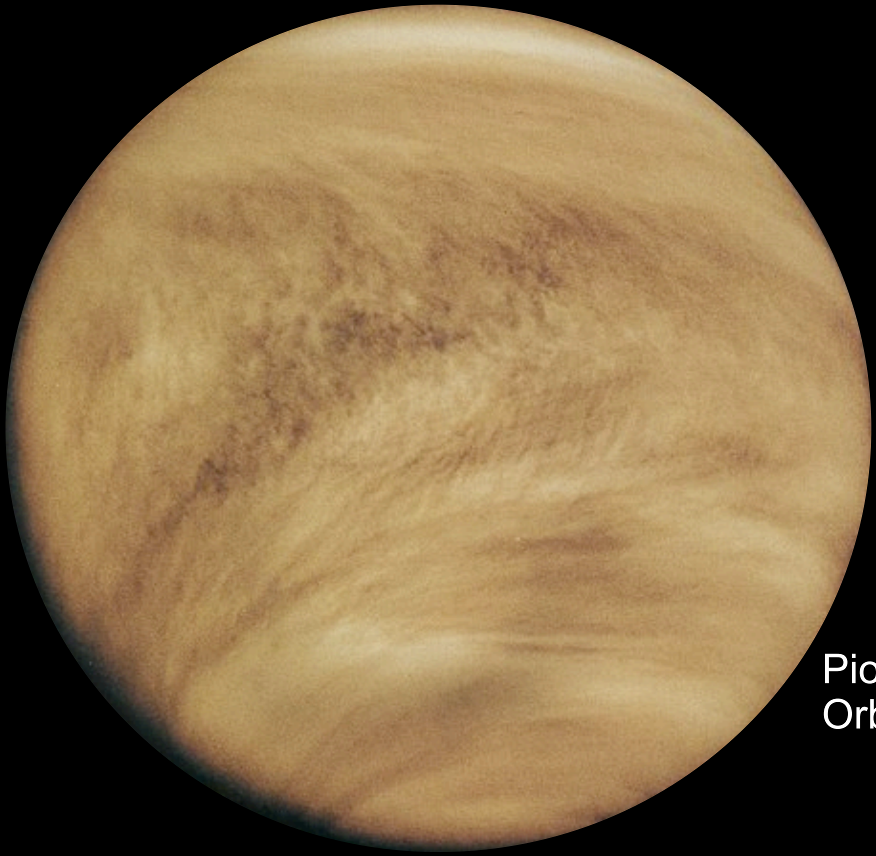
CO_2

Venus:

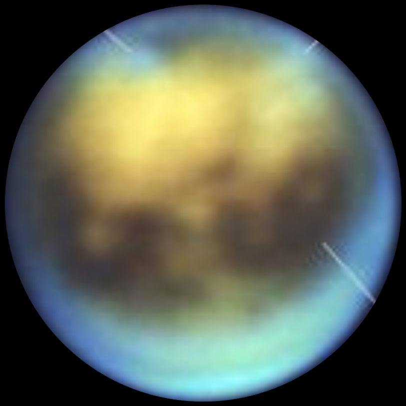
H_2SO_4

Titan (largest of Saturn's moons):

CH_4, C_2H_6, + other complex hydrocarbons



Pioneer Venus Orbiter

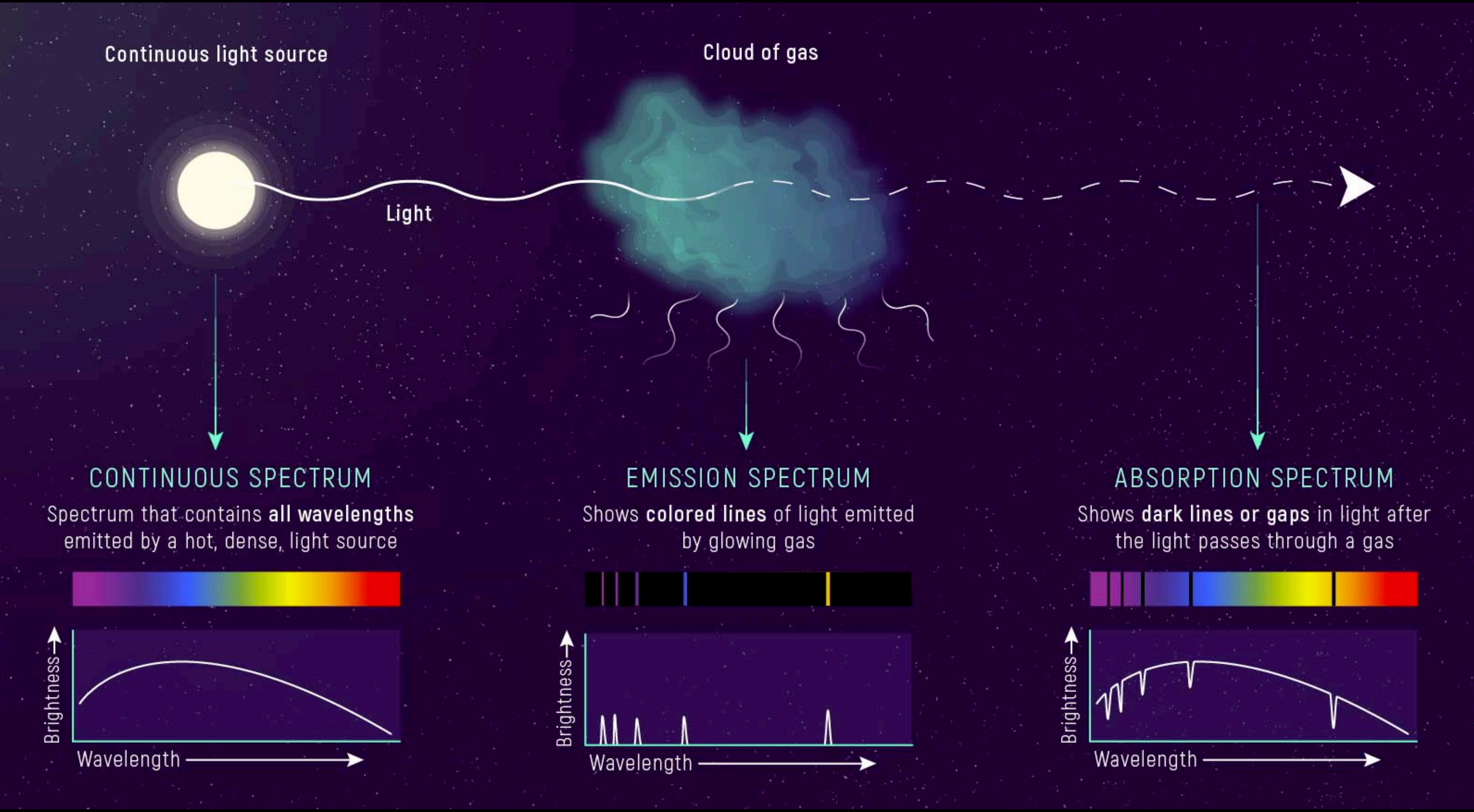


Keck/NIRC2

Can we detect clouds on exoplanets?

Yes, via transmission spectroscopy

Absorption & Emission



CONTINUOUS SPECTRUM

Spectrum that contains **all wavelengths** emitted by a hot, dense, light source

EMISSION SPECTRUM

Shows **colored lines** of light emitted by glowing gas

ABSORPTION SPECTRUM

Shows **dark lines or gaps** in light after the light passes through a gas

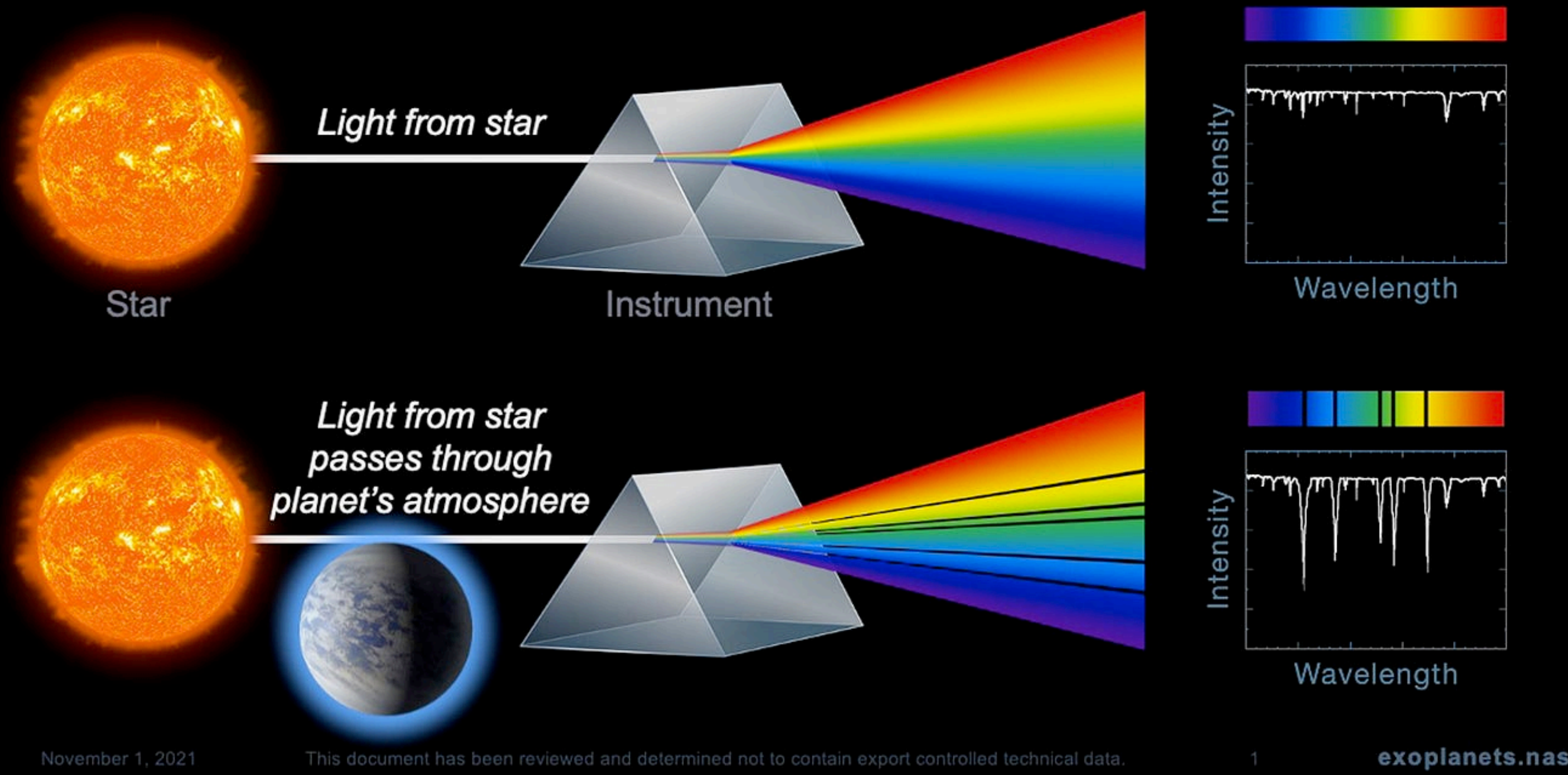
blackbody

Hot gas

Cold gas

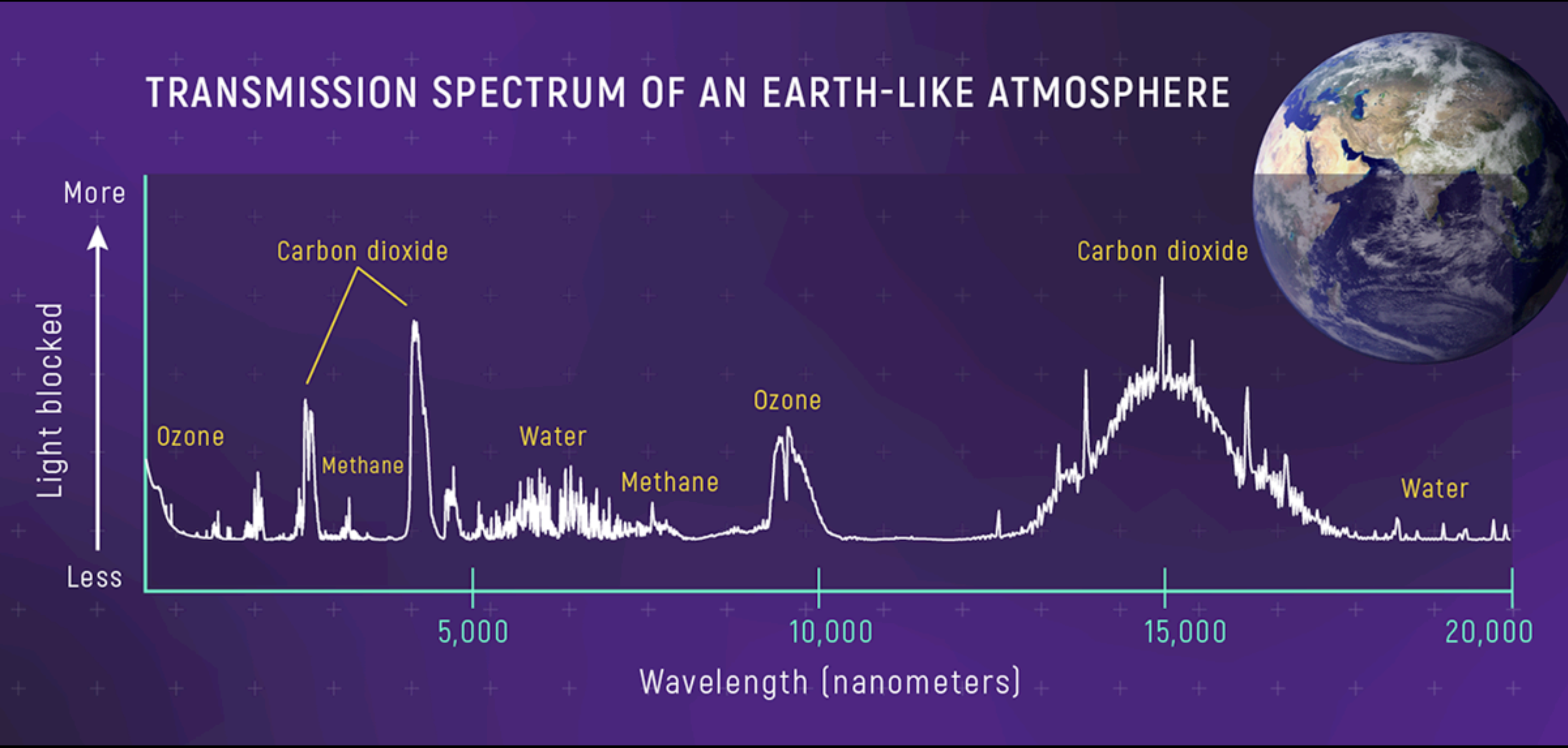
NASA/ESA/CSA

Transmission Spectroscopy



Transmission Spectroscopy

traces atmospheric composition



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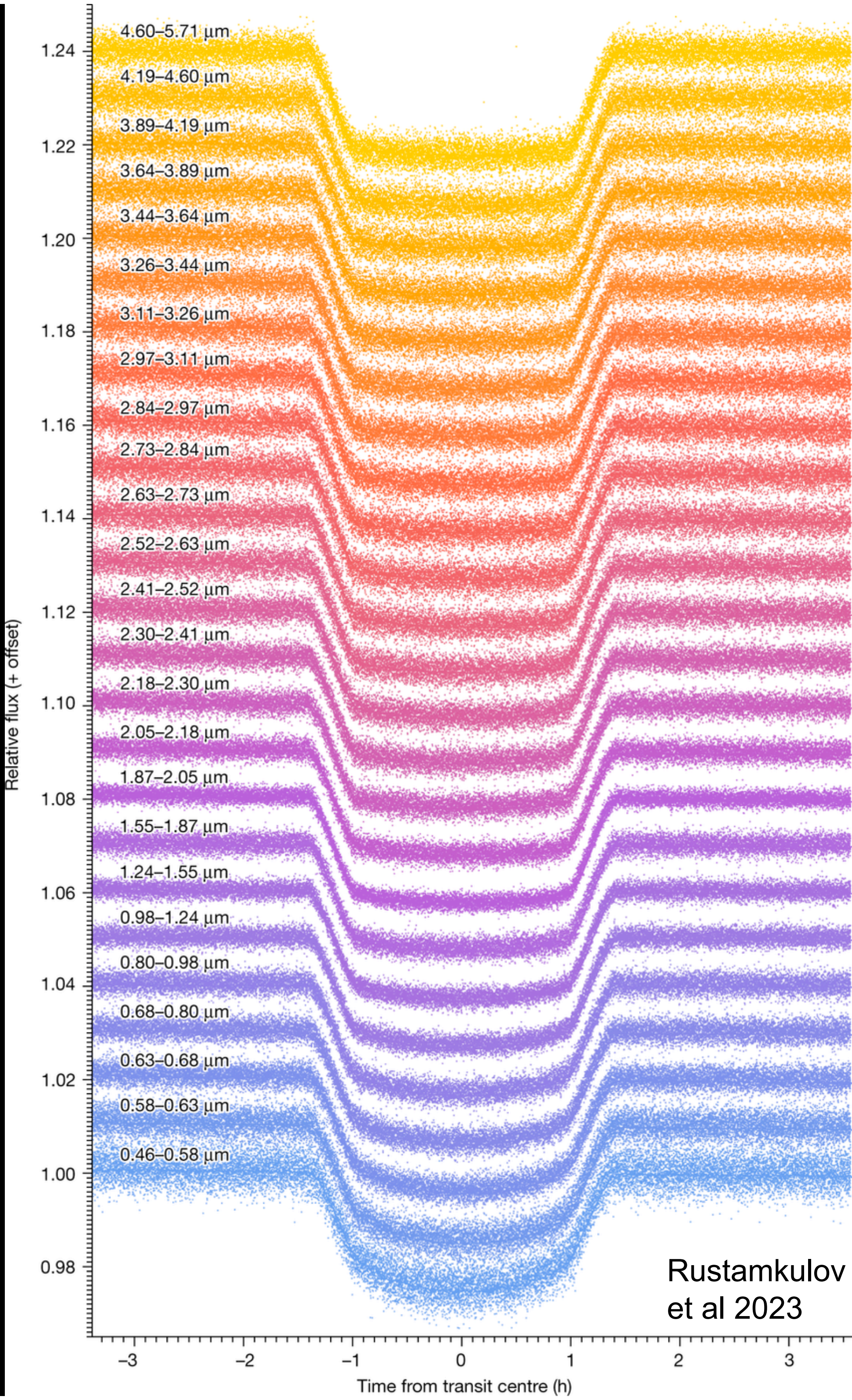
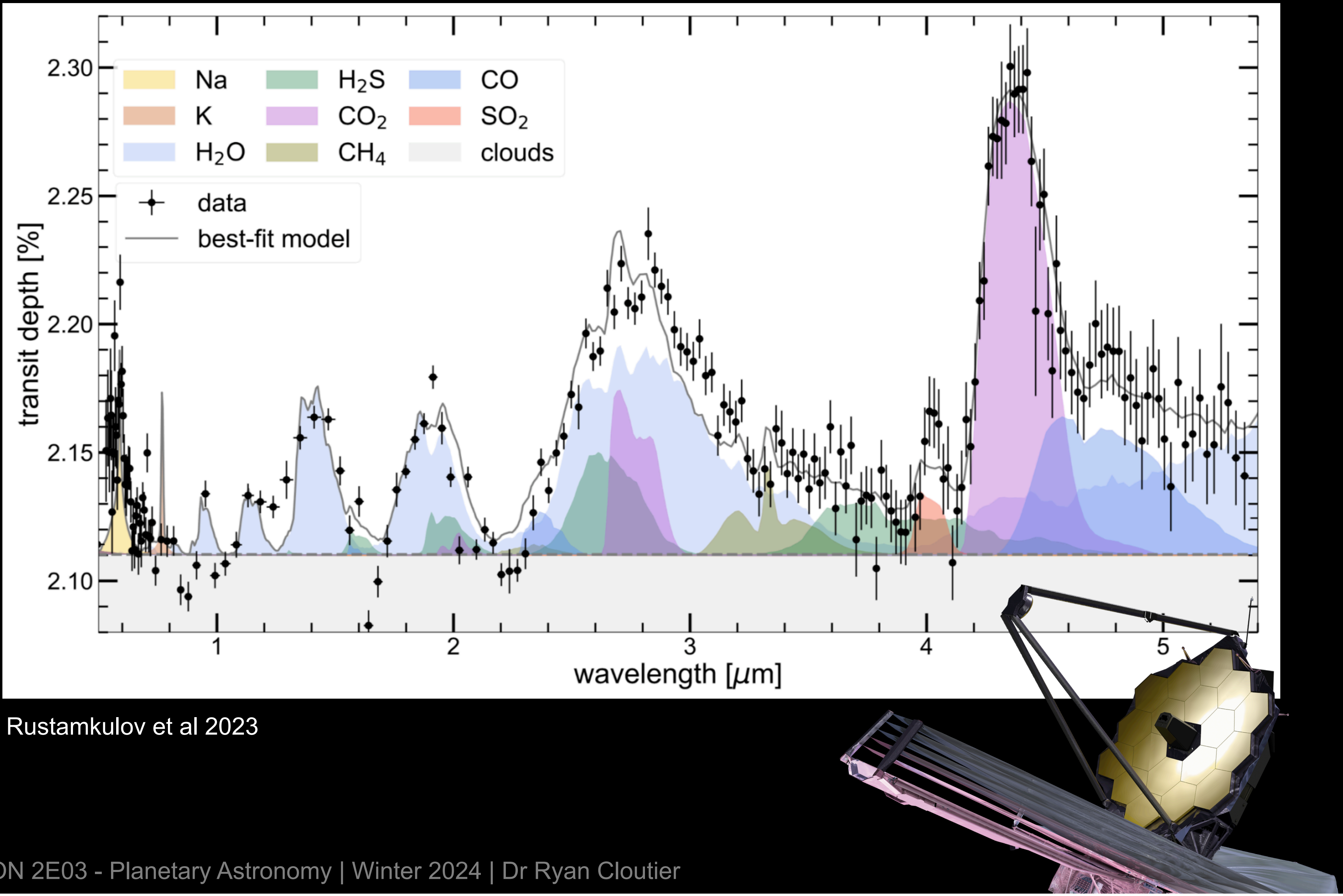
Transmission Spectroscopy = transit depth as a function of wavelength



Rustamkulov et al 2023

Transmission Spectrum
of the hot Jupiter WASP-39 b



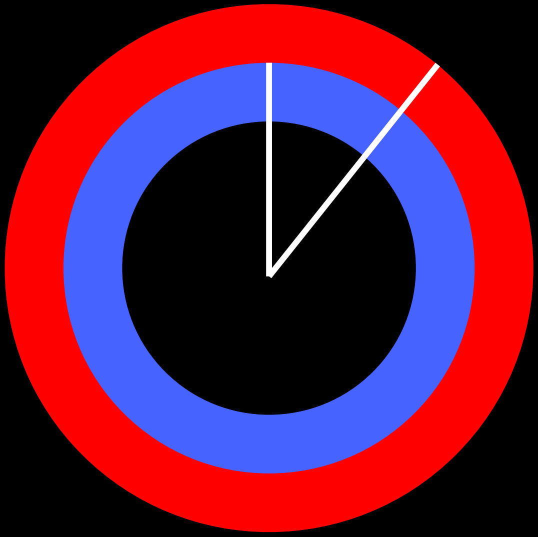
Rustamkulov et al 2023

Absorption depth *ΔZ* scales with atmospheric scale height *H*

$$H = \frac{k_B T}{\mu m_H g}$$

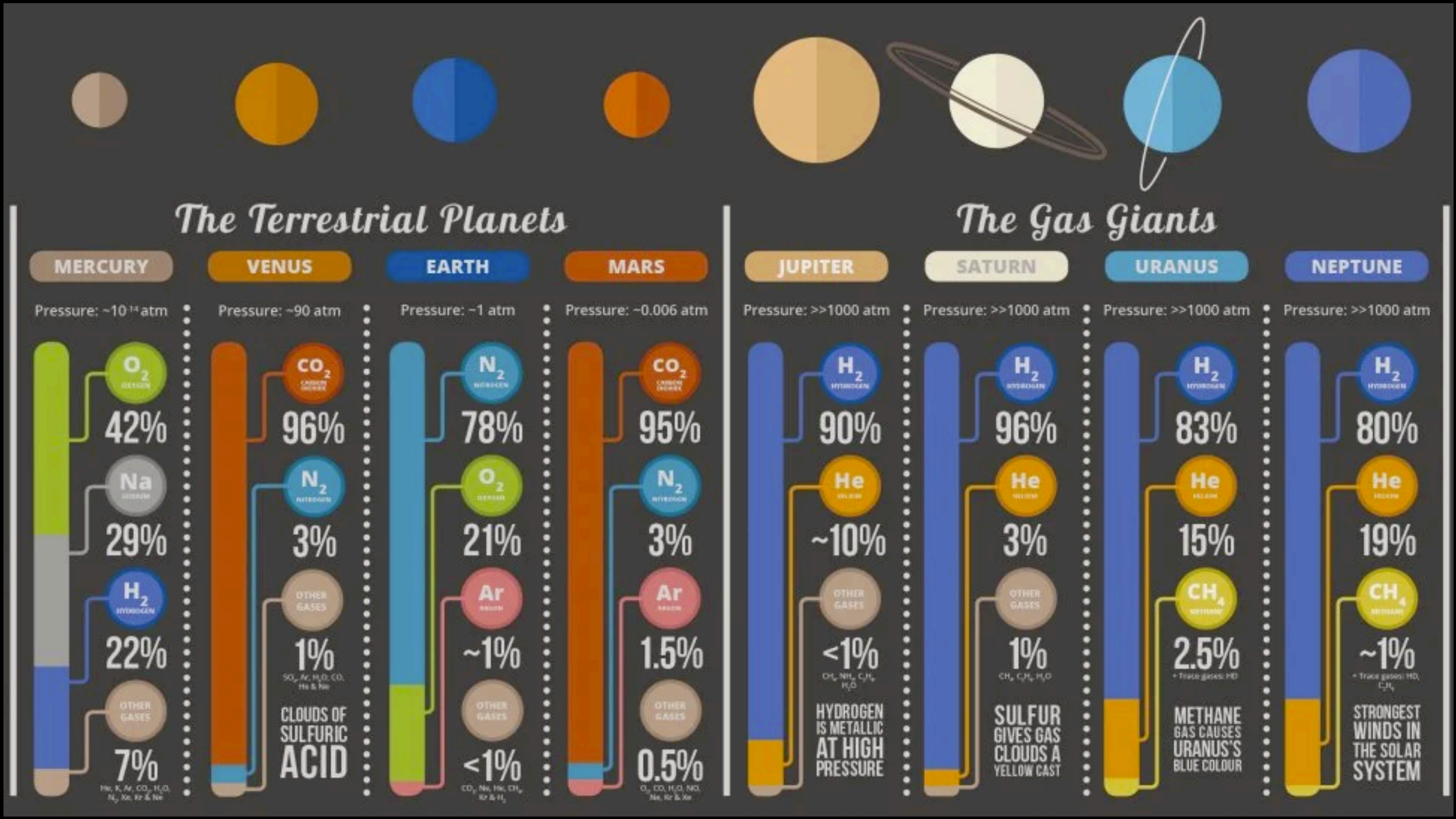
$$\Delta Z = \frac{\pi (R_p + nH)^2}{\pi R_\star^2} - \frac{\pi R_p^2}{\pi R_\star^2}$$

$$\approx 2 \left(\frac{R_p}{R_\star} \right)^2 \left(\frac{nH}{R_p} \right)$$

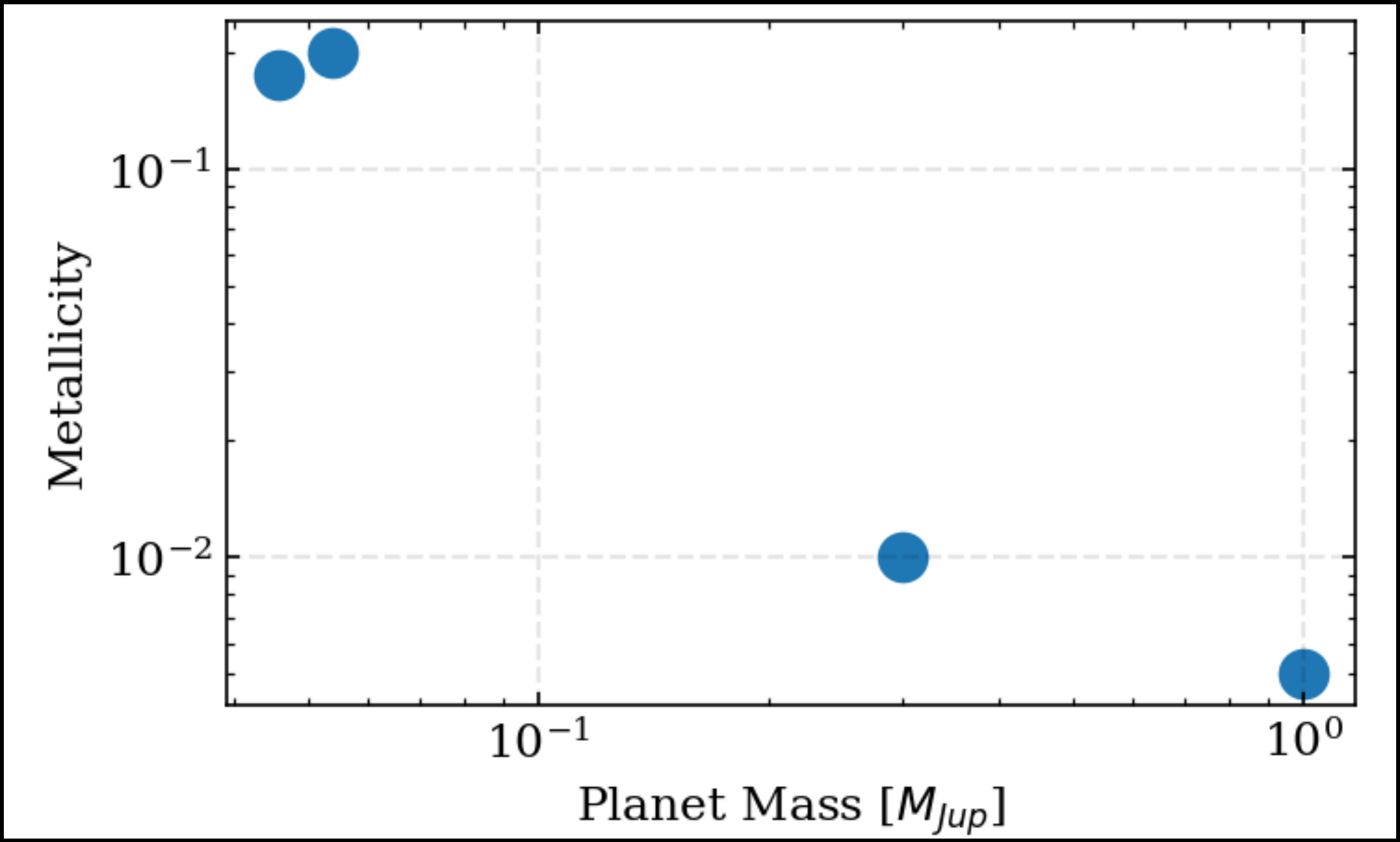


Kempton et al 2016

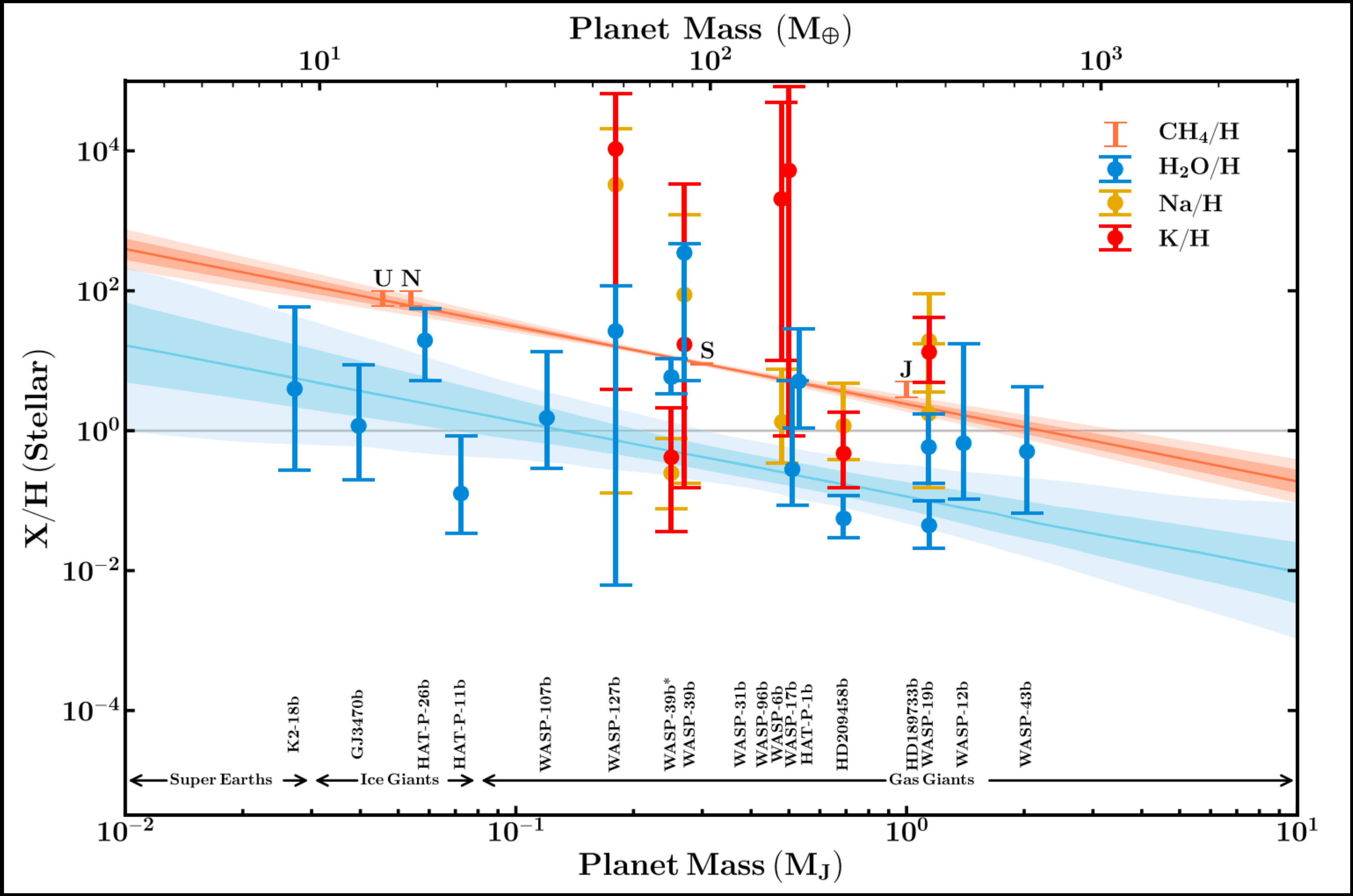
Atmospheric Composition in the solar system



The gas giants in the solar system exhibit a **mass-metallicity trend**



Maybe the **mass-metallicity trend** extends to exoplanets…

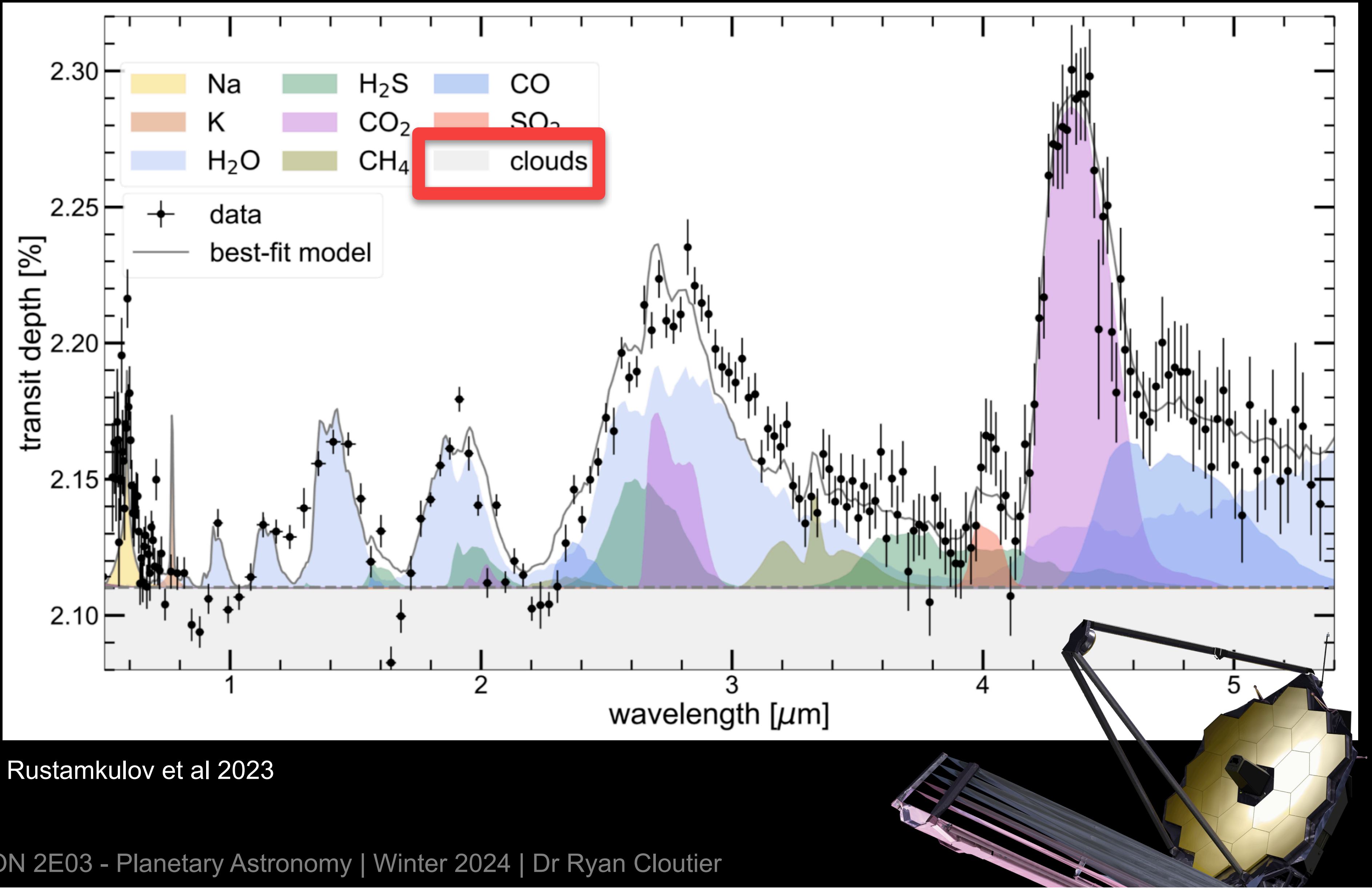


Wellbanks et al 2019

Recall the initial question that started our discussion on transmission spectroscopy…

Can we detect clouds on **exoplanets**?

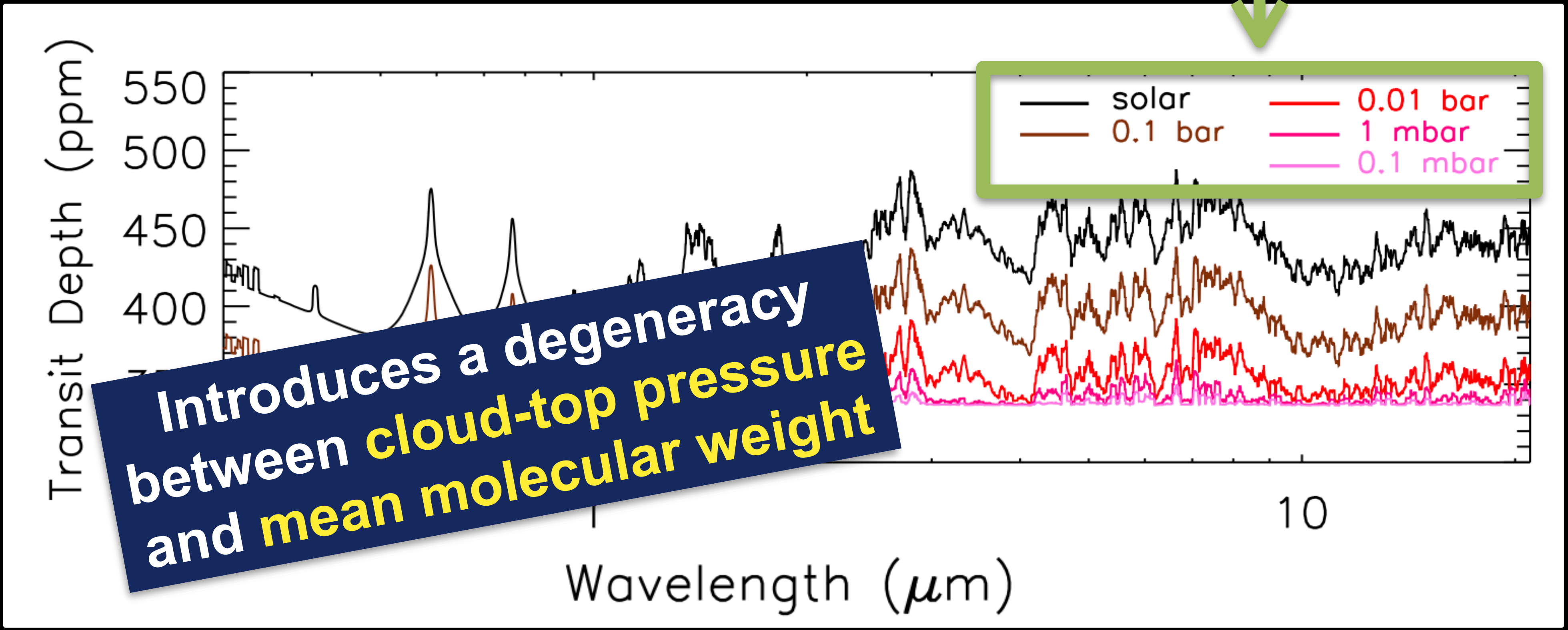
Clouds **suppress** atmospheric chemical signatures



Rustamkulov et al 2023

Clouds **suppress** atmospheric chemical signatures

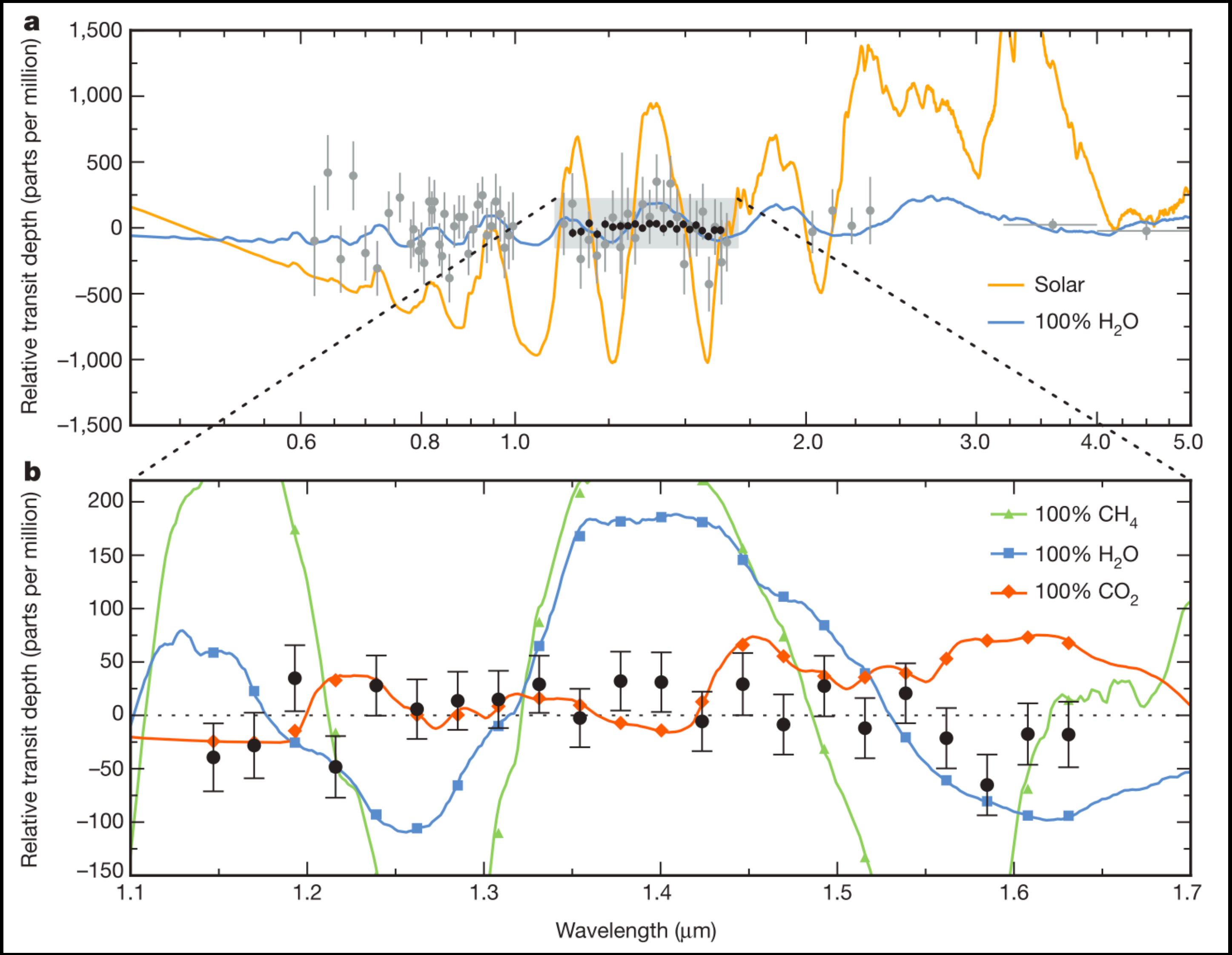
Cloud deck **pressures**



Introduces a degeneracy between cloud-top pressure and mean molecular weight

Kempton et al 2016

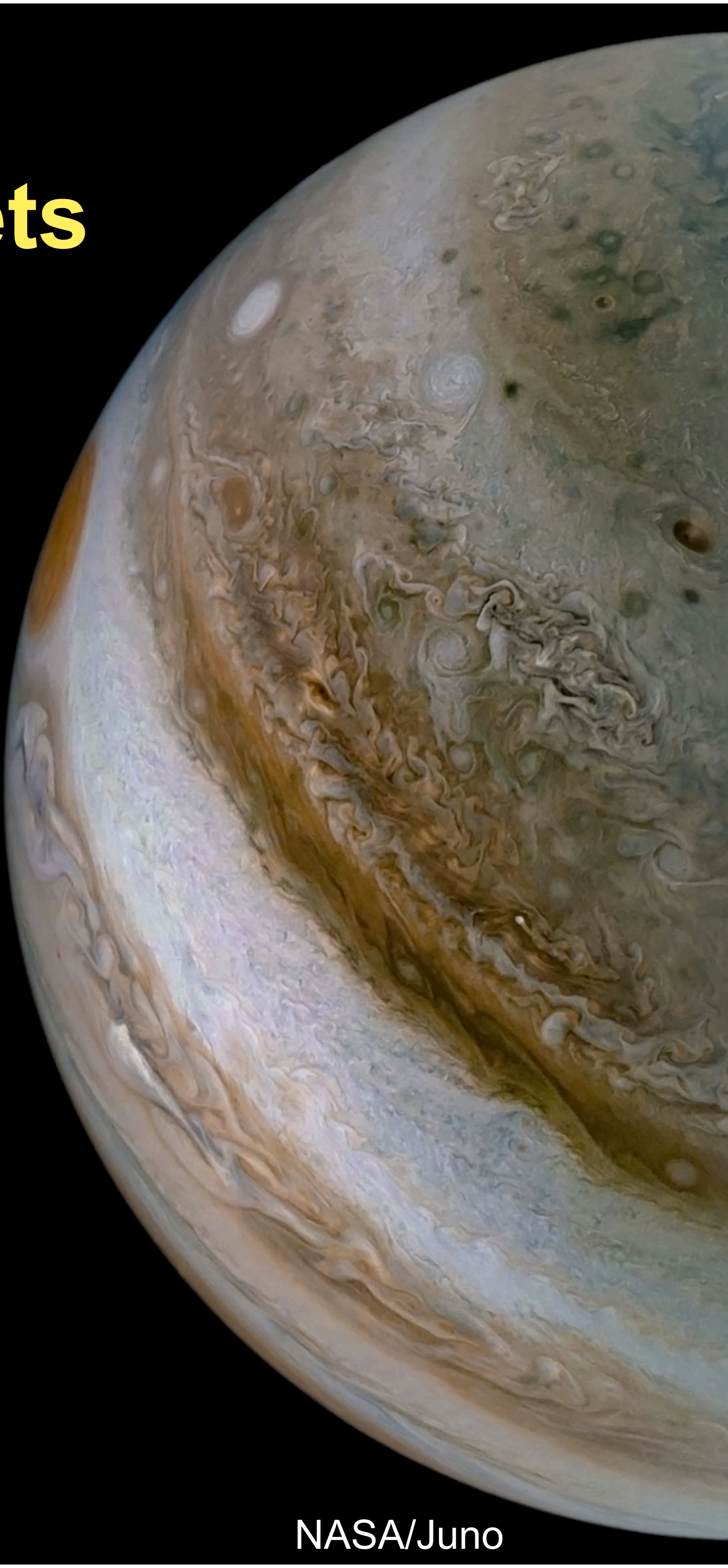
Clouds on the sub-Neptune exoplanet GJ 1214 b



Kreidberg et al 2014

Clouds/winds on Giant Planets

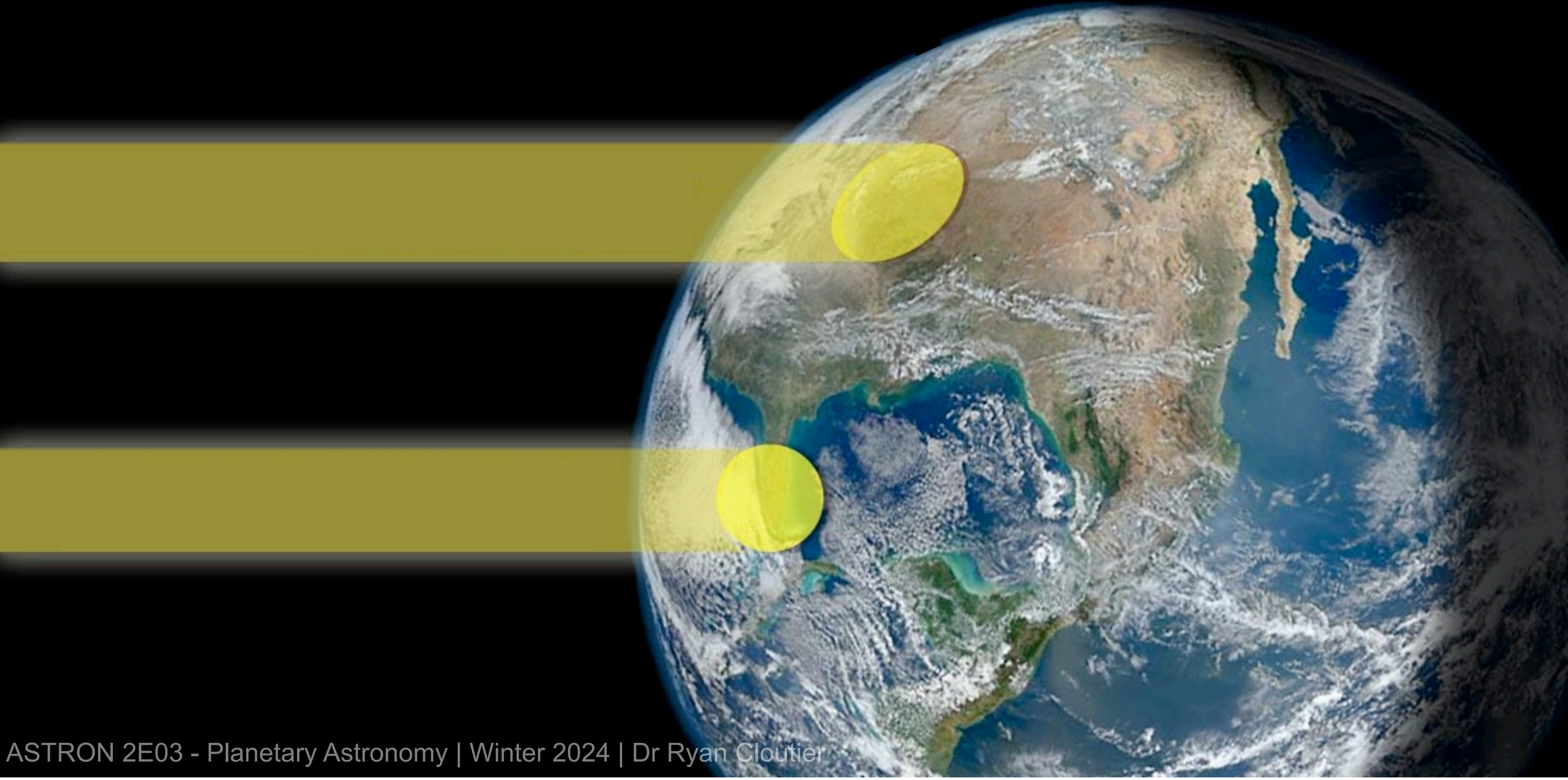
- non-water species (e.g. NH_3, H_2S, CH_4)
- Forms zones and belts. **Why?**



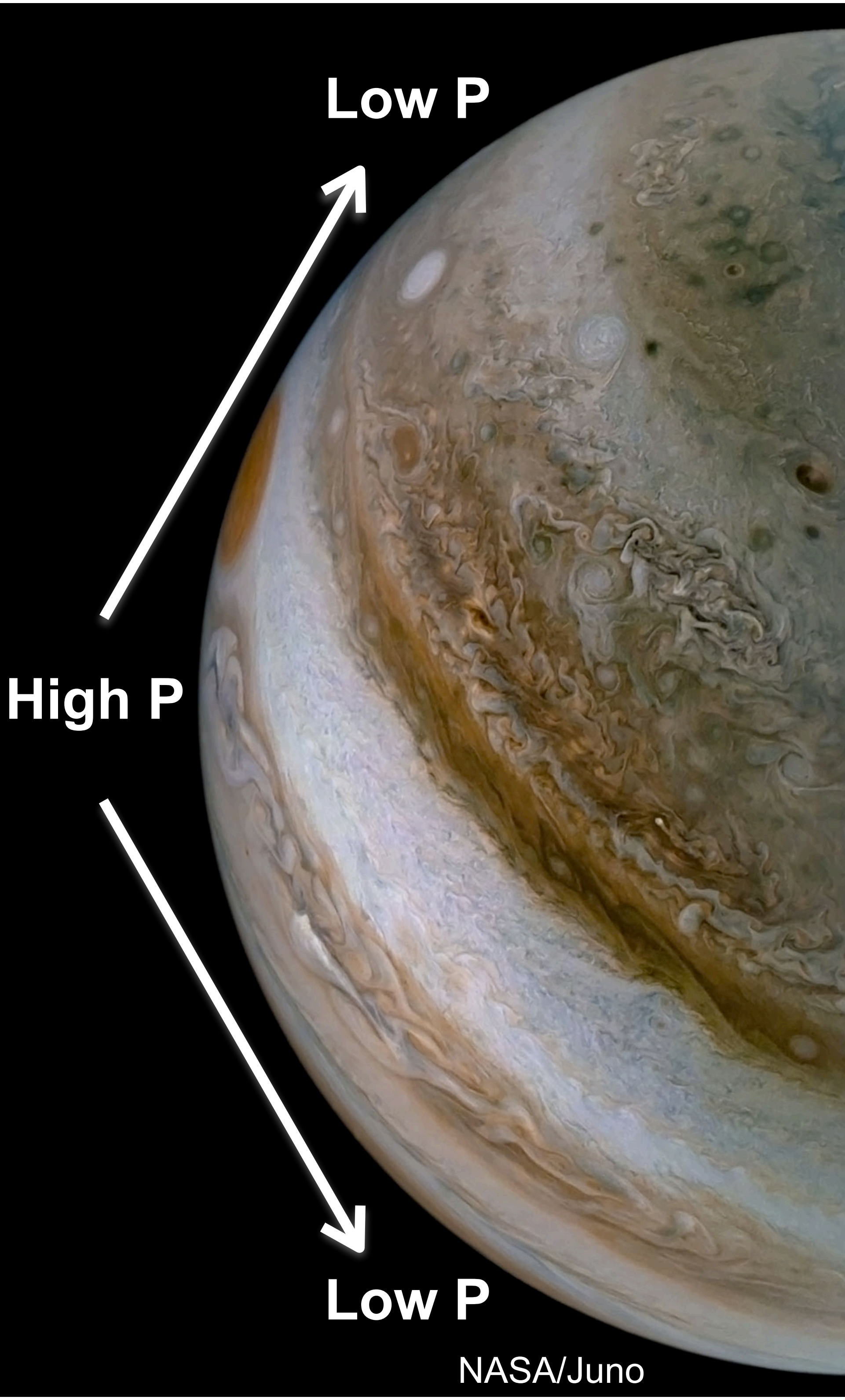
NASA/Juno

Incident flux on a surface patch depends on the **incident angle**

Stronger heating at the equator compared to high latitudes → Pressure gradient that drives winds

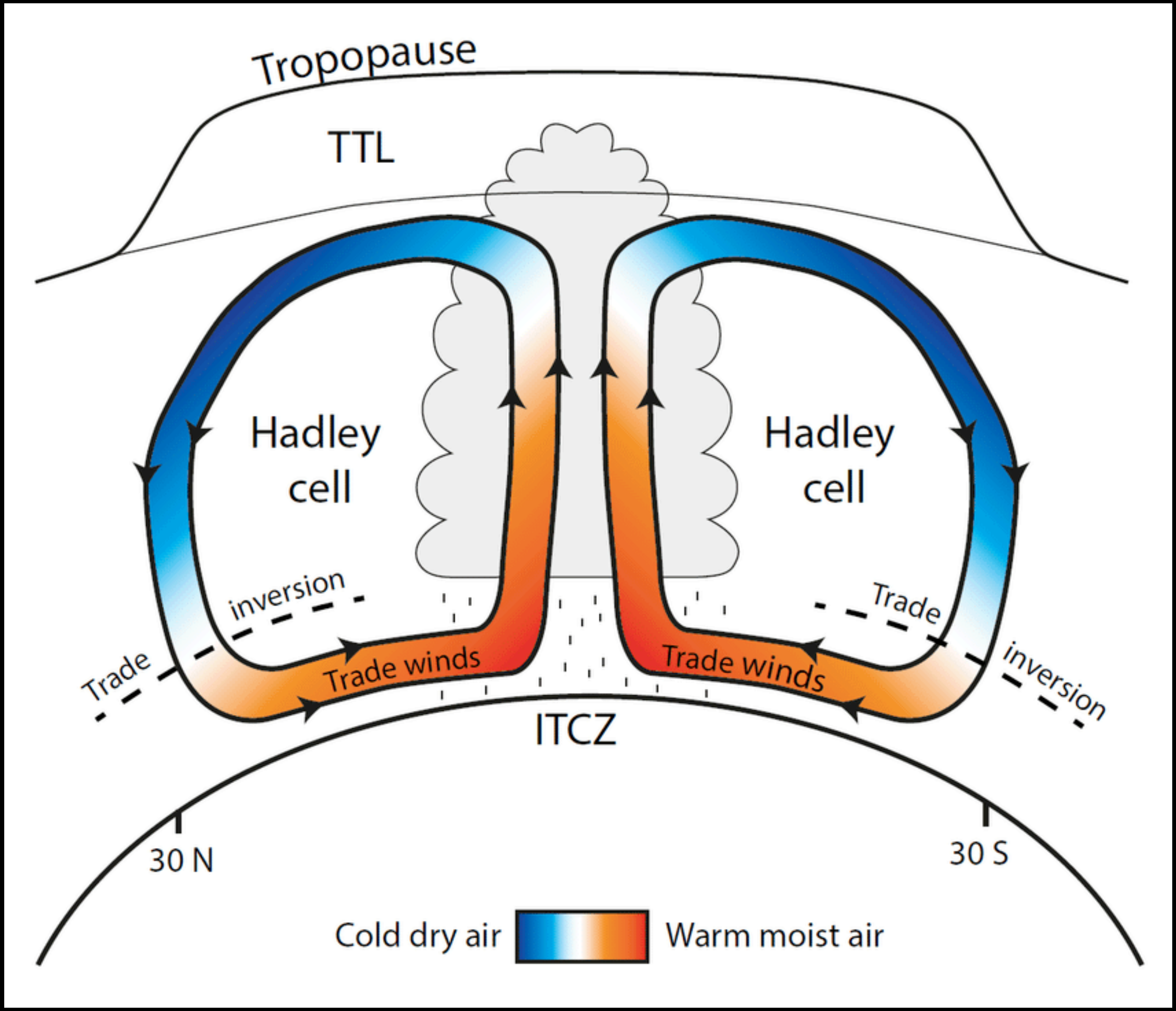


- Hot equatorial air rises and flows toward low pressure regions (i.e. high latitudes)
- Air cools, subsides, and flows back to the equator



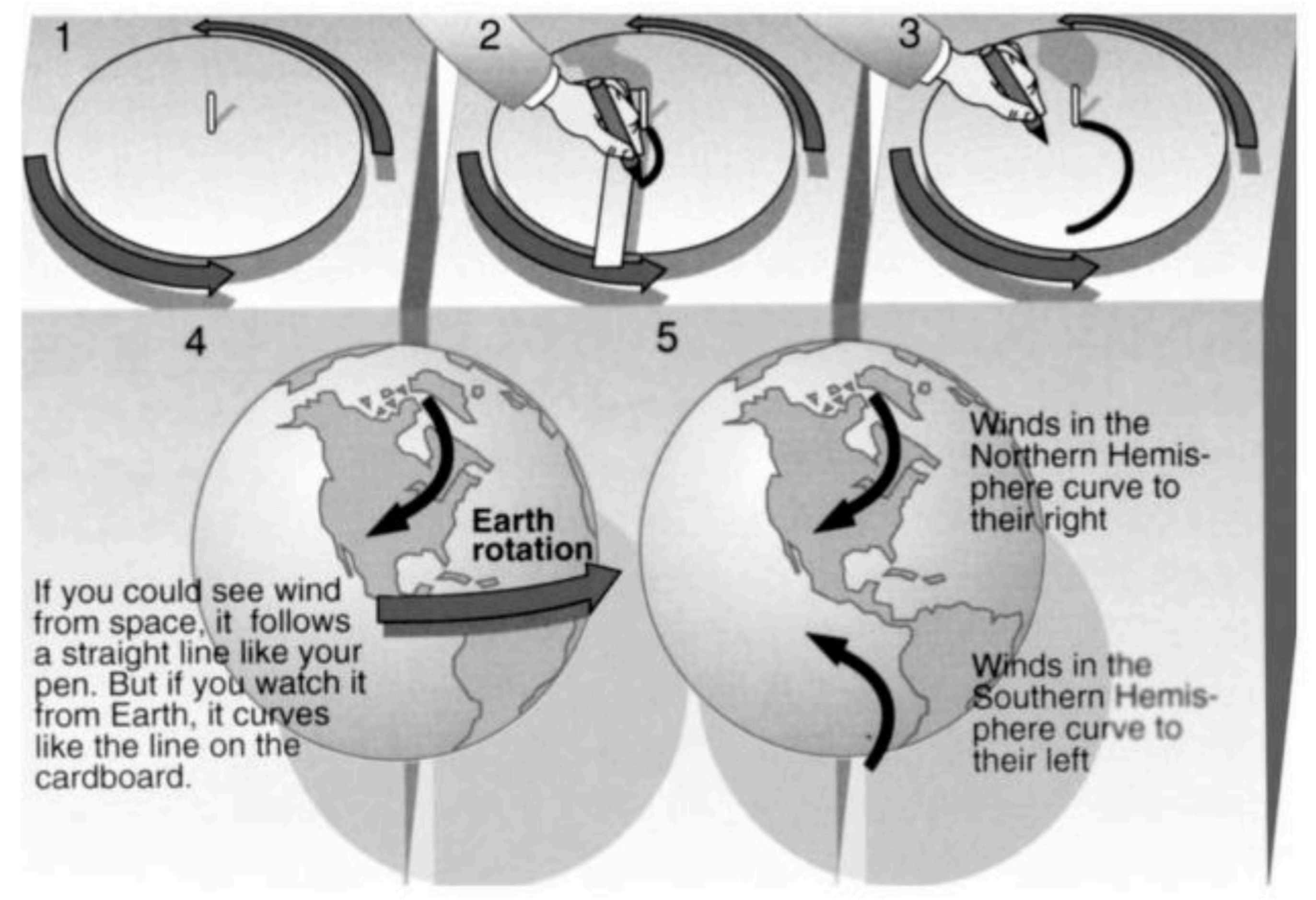
NASA/Juno

- Produces **wind cells**
- e.g. **Hadley cells** on Earth
- But what about the effect of **rotation**?



Credit: Alina Fiehn

Coriolis Effect: winds do not follow a straight trajectory



If you could see wind from space, it follows a straight line like your pen. But if you watch it from Earth, it curves like the line on the cardboard.

Winds in the Northern Hemisphere curve to their right

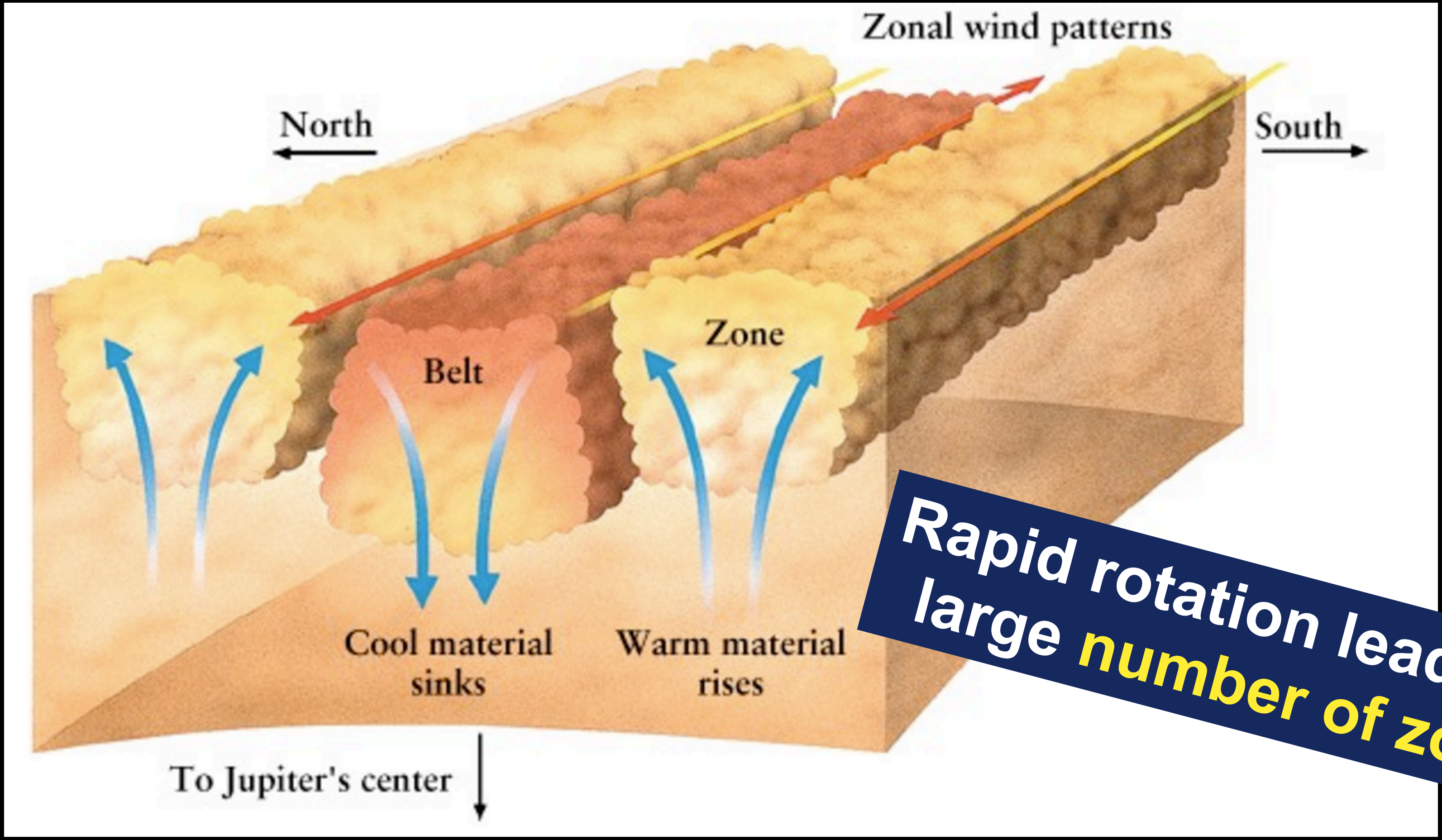
Winds in the Southern Hemisphere curve to their left

Lissauer & de Pater

On a rotating planet, winds traveling from the poles will be deflected to the westward (if the planet's rotation is prograde)

Winds on Giant Planets

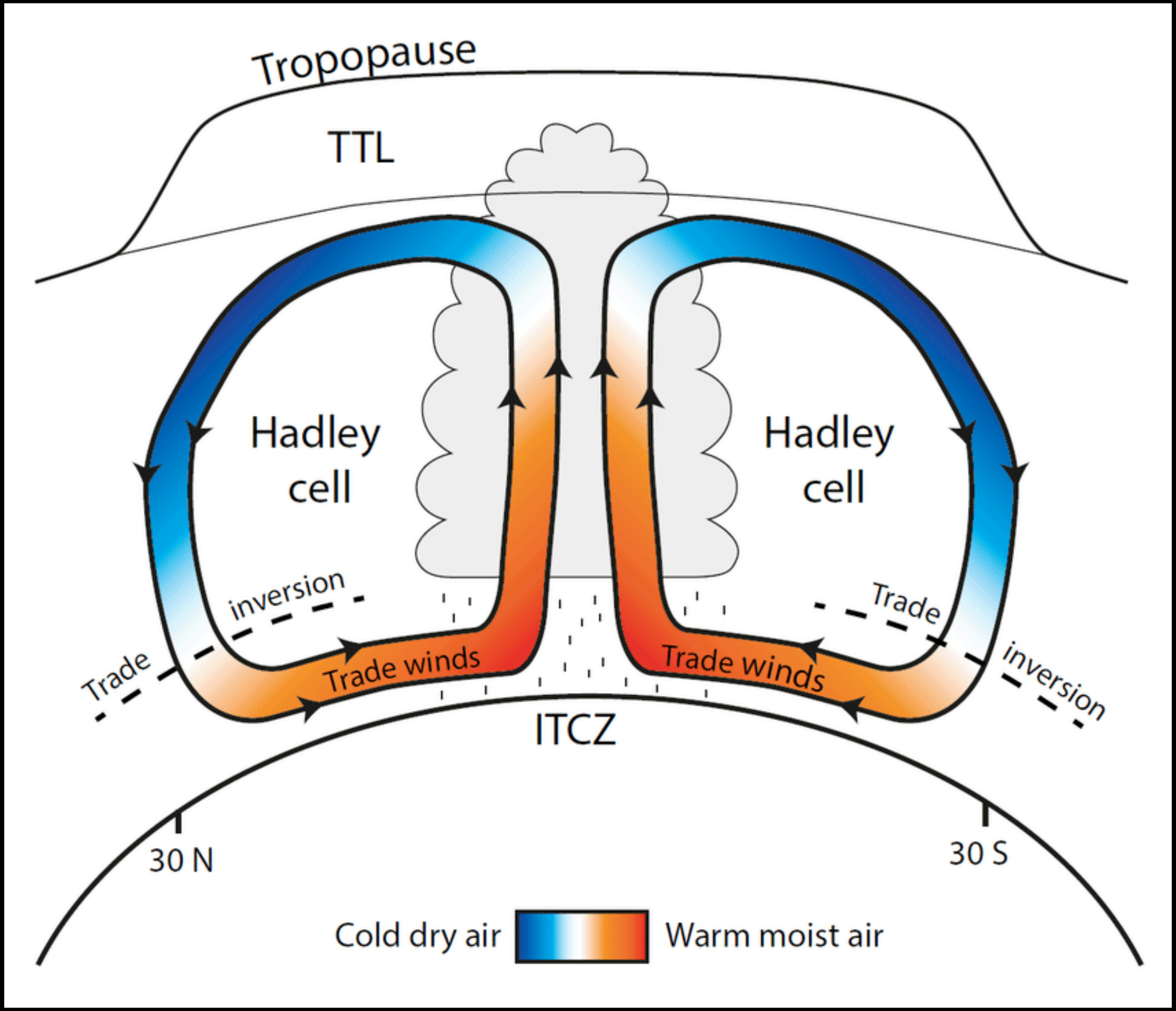
Pressure gradient + rapid rotation → zonal winds



Rapid rotation leads to a large **number of zones**

Winds on **Terrestrial Planets**

- Earth (P_{rot} = 24 hrs) has **three wind cells** per hemisphere
- Venus (P_{rot} = 2802 hrs) has **one large wind cells** per hemisphere



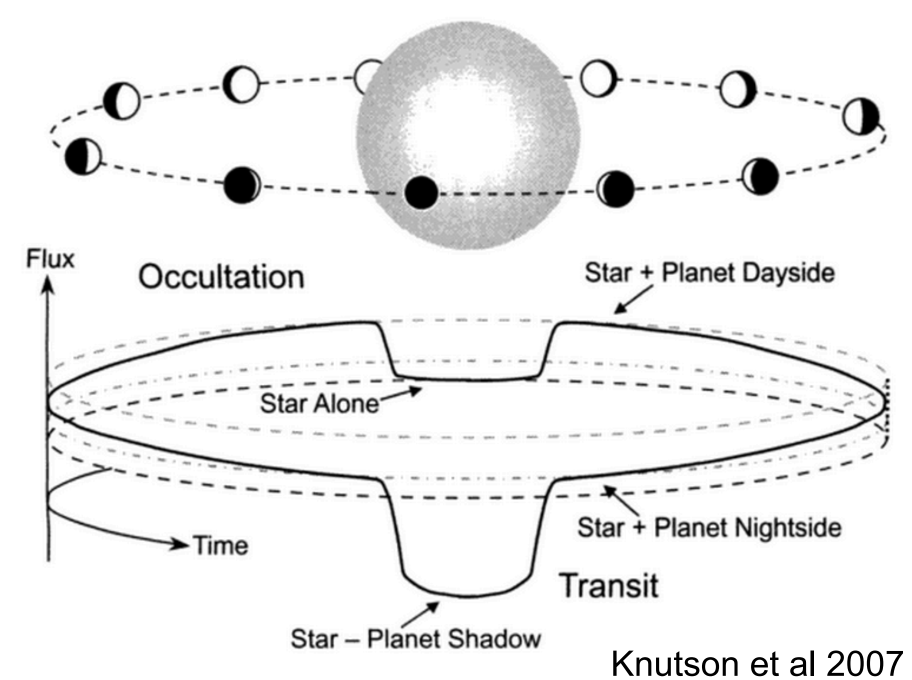
Credit: Alina Fiehn

Winds on Exoplanets

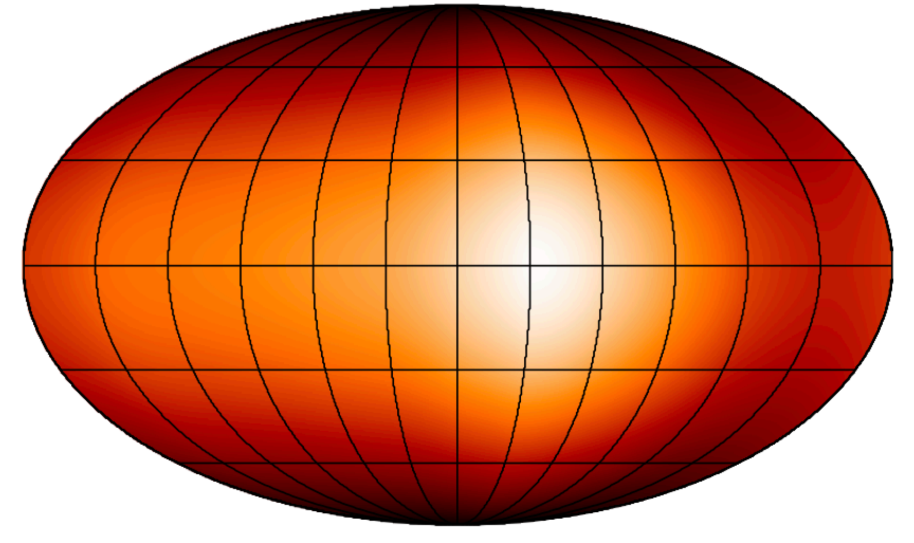
For the majority of exoplanets, planetary rotation rates are not observable,

but there are a couple of techniques that work for certain exoplanets

Winds on tidally-locked exoplanets



Knutson et al 2007



Recall that tidally-locked planets have permanent (i.e. hot) daysides

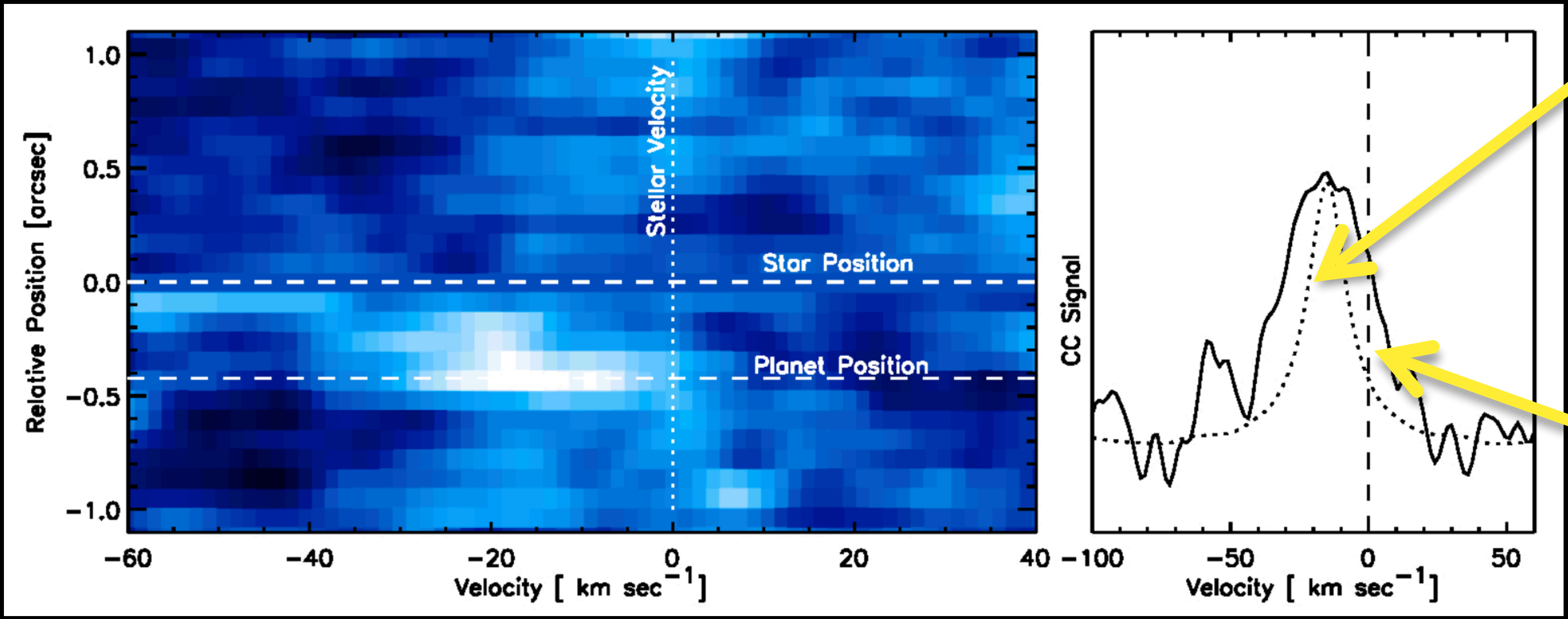
Observations around the secondary eclipse reveal a hot-spot offset

⬇

Atmospheric circualtion

Winds on directly-imaged exoplanets

Rotation broadens spectroscopic signals



Signal for a non-rotating planet

Observed signal shows rotational broadening

Snellen et al 2014