Greenhouse

Global Warming Science, EPS101

Camille Hankel and Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

Class objectives

- How natural greenhouse gases keep the Earth from freezing
- How human-added greenhouse gasses lead to warming
- How can such small changes in CO_2 concentration (currently 420 ppmv ≈ 0.04% by volume) make such a big difference
- How greenhouse gases work on the molecular level
- The water vapor feedback
- The logarithmic dependence of warming on CO_2
- How important are other greenhouse gasses relative to CO_2

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RF is the net increase in the energy input to the climate system due to greenhouse gas increase, in watts/m^2.

(IPCC AR5, 2013)

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Observed radiative forcing increases

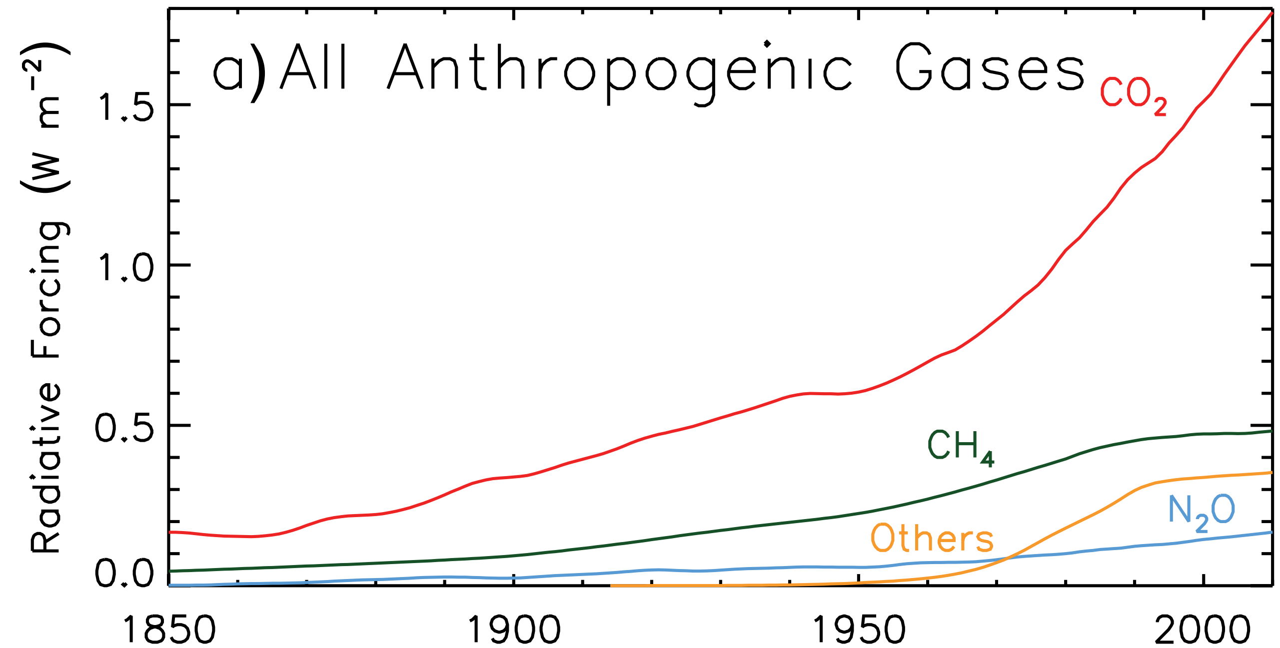

Figure 8.6 | (a) Radiative forcing (RF) from the major well-mixed greenhouse gases (WMGHGs) and groups of halocarbons, 1850-2011, (b) as (a) but with a log scale.

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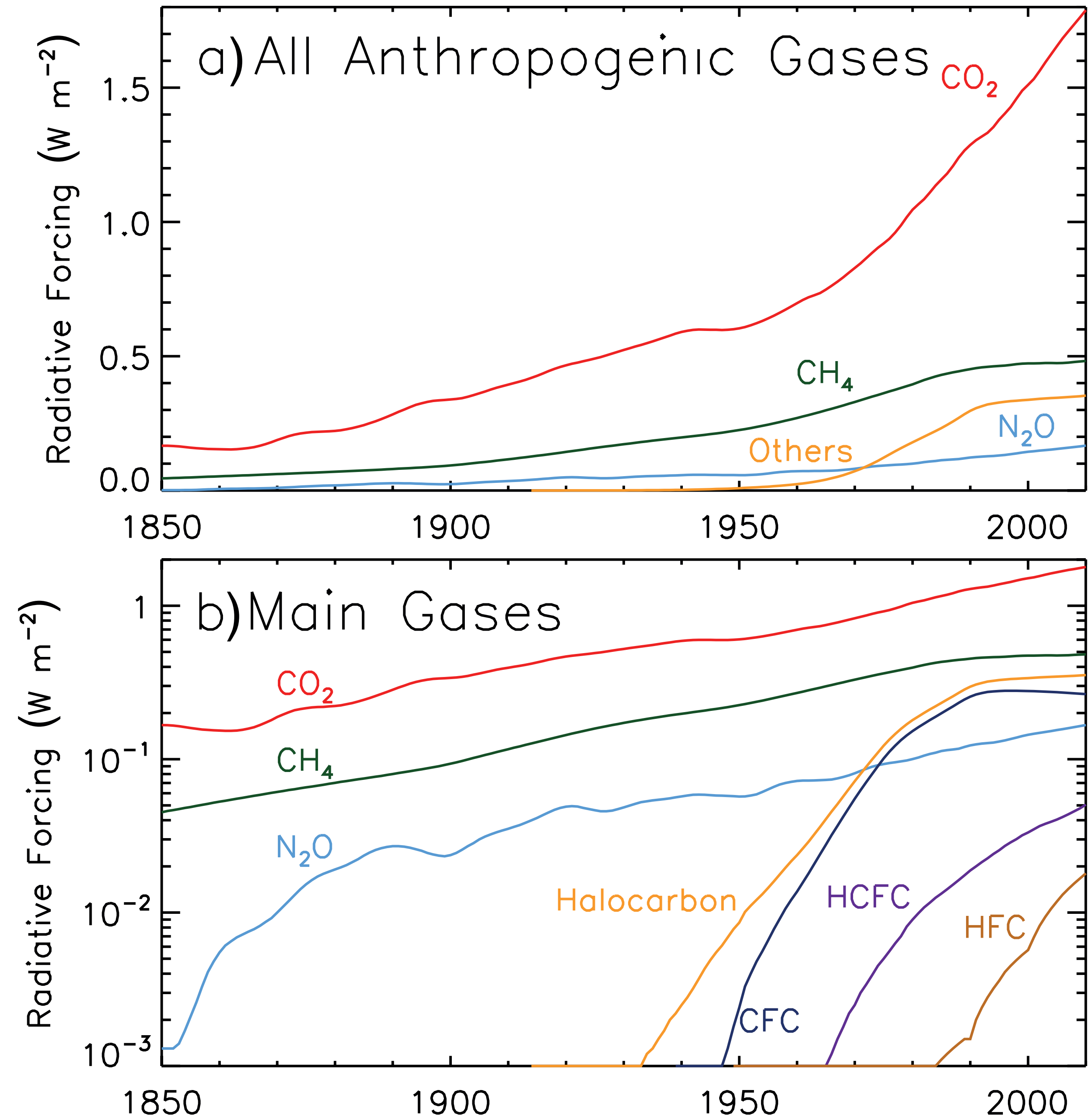

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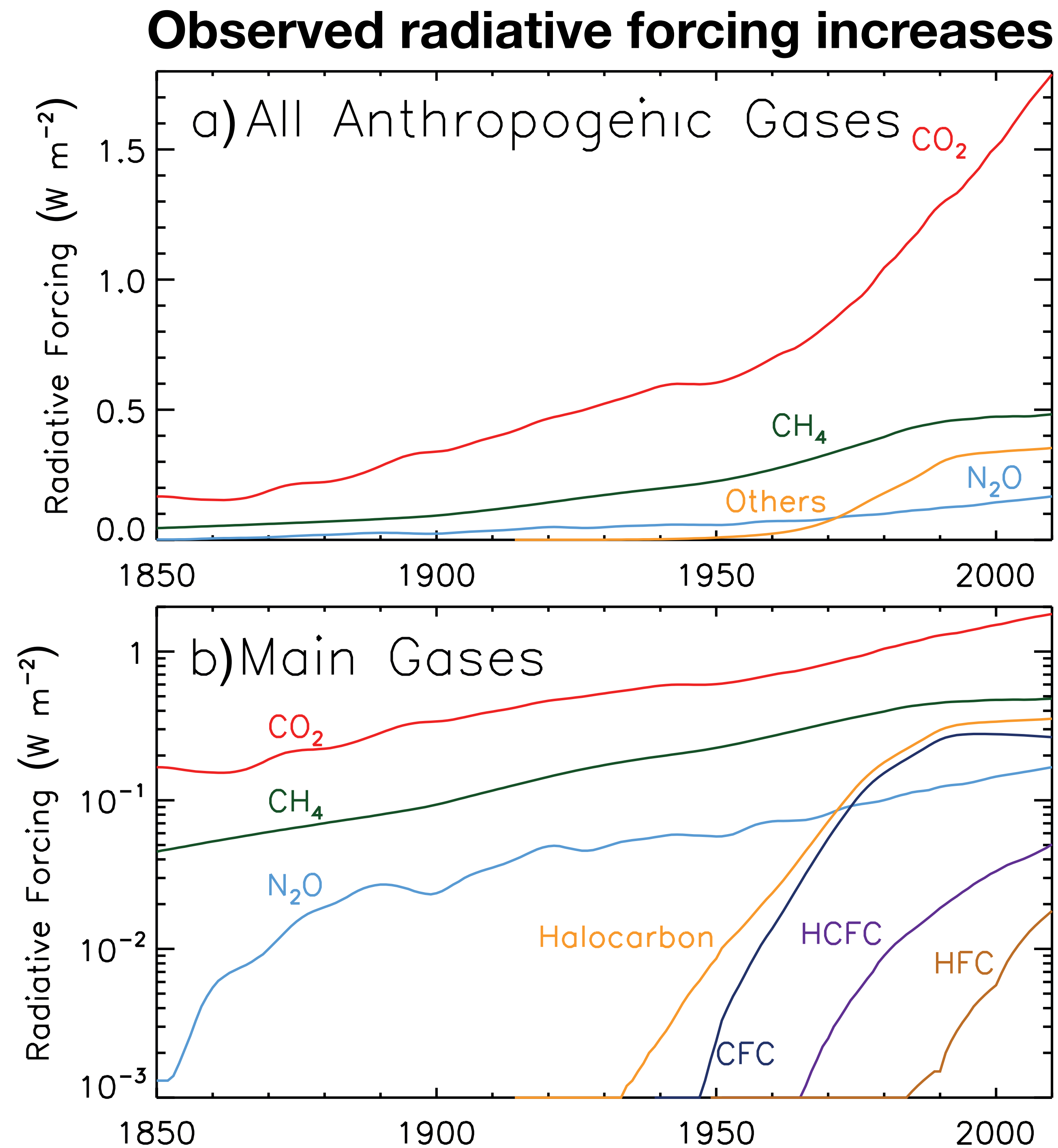
More specifically: (IPCC AR5, 2013)
RF: the change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures, and water vapor and cloud cover, fixed at the unperturbed values.



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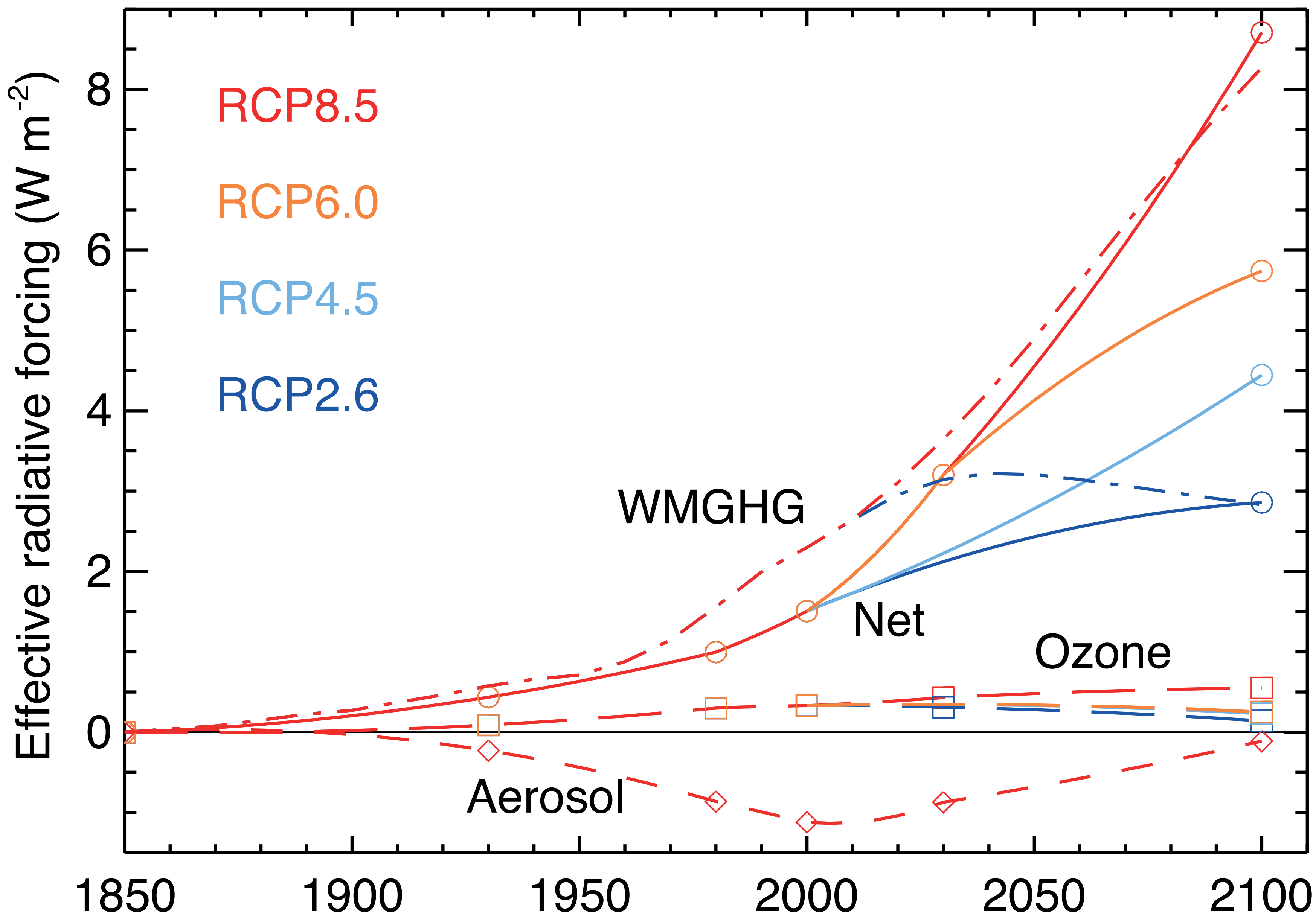
(IPCC AR5, 2013)

Future scenarios for radiative forcing: The Representative Concentration Pathway (RCP)

Future scenarios.
RCP8.5: worst-case scenario/ business as usual



(IPCC AR5, 2013)

Figure 8.22 | Global mean anthropogenic forcing. (solid lines with circles are net; long dashes with squares are ozone; short dashes with diamonds are aerosol; dash-dot are WMGHG; colors: RCPs with **red for RCP8.5, orange RCP6.0, light blue RCP4.5, and dark blue RCP2.6**). Symbols: times of ACCMIP simulations were performed.

Workshop #1:
Observed and projected increase in greenhouse gasses

Observations & projections of CO_2 concentration

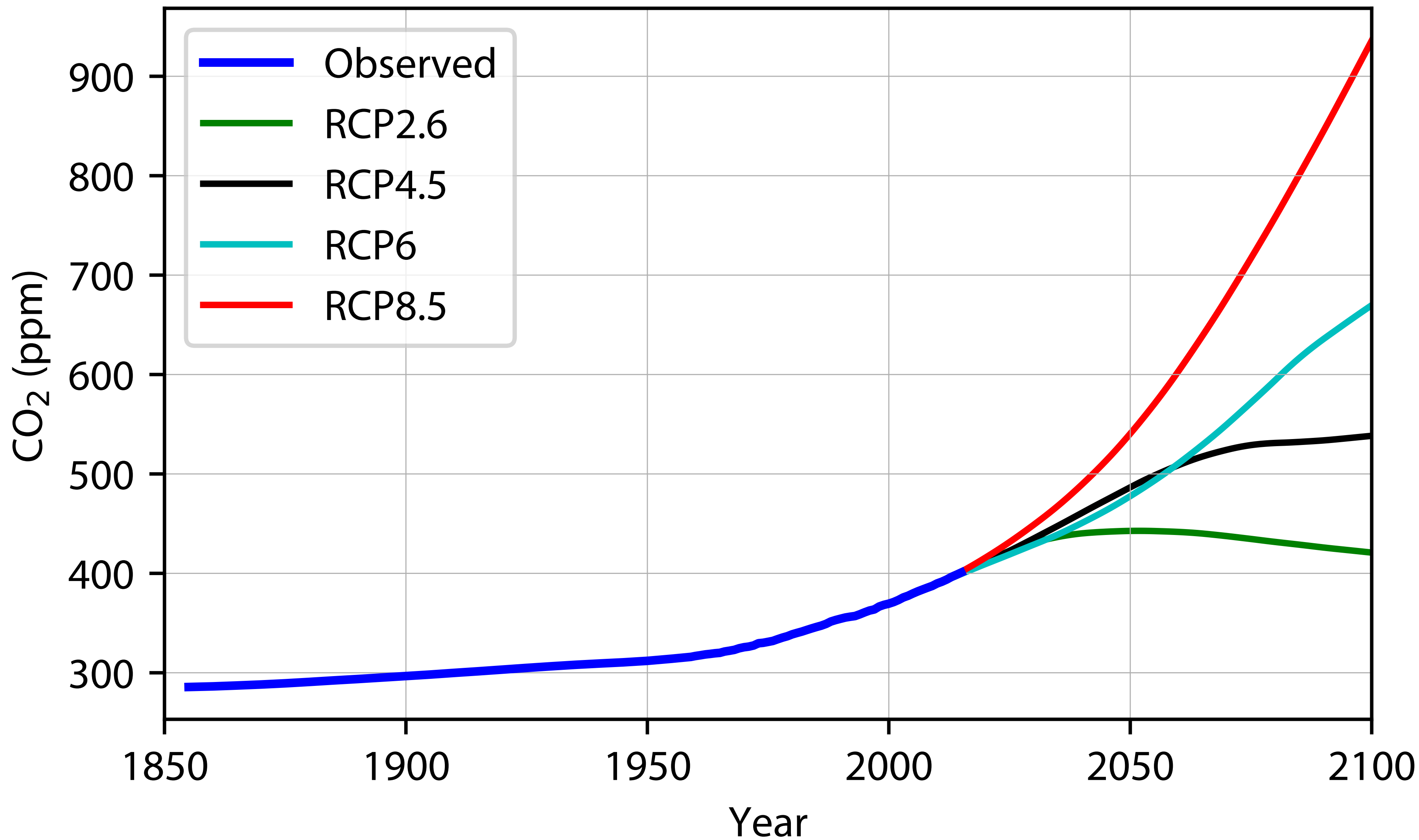


Figure 2.1: CO_2 time series.

Annually averaged CO_2 concentration, observed and projected according to different RCP scenarios.

Observed vs projected CO_2 concentrations

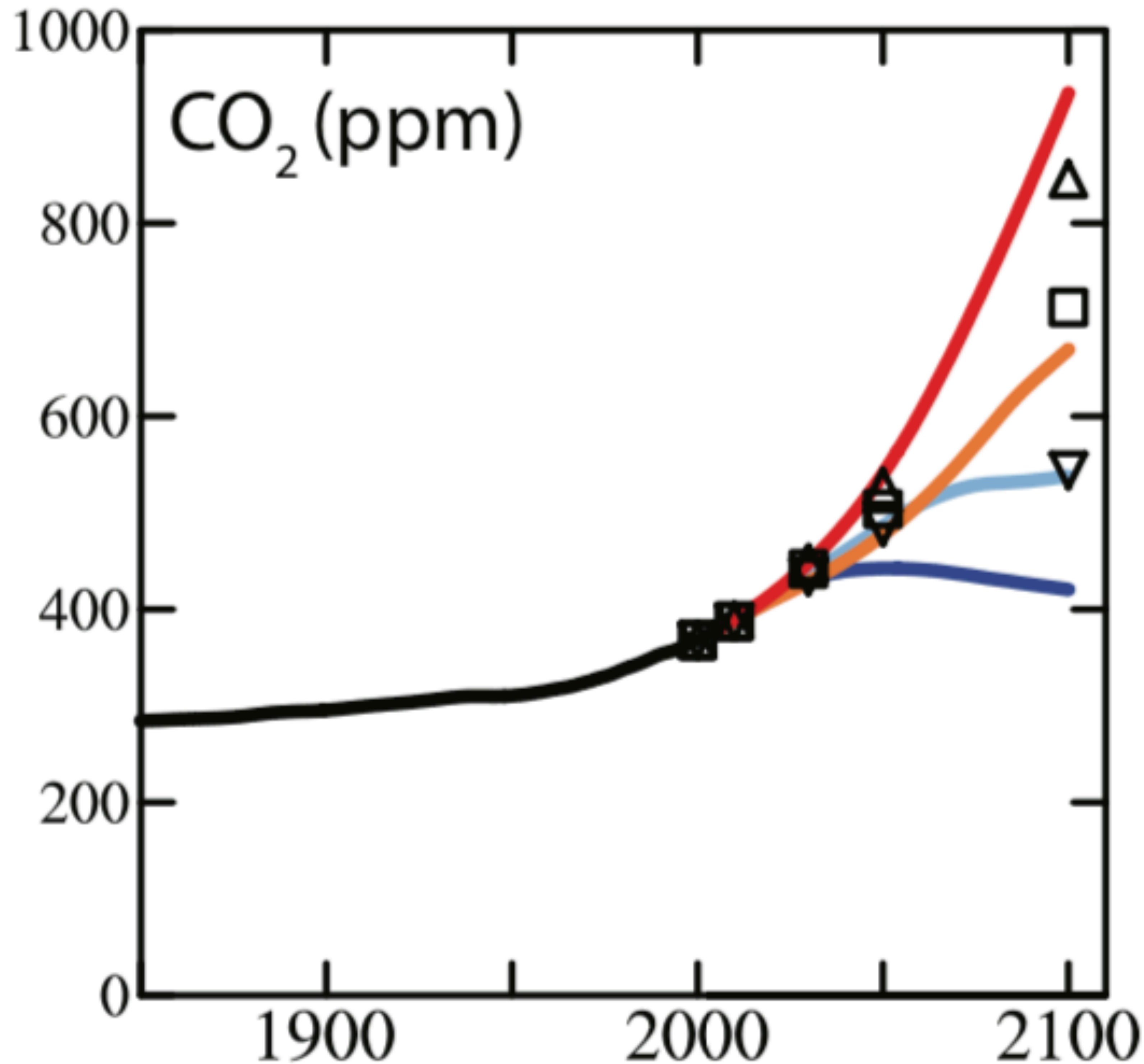
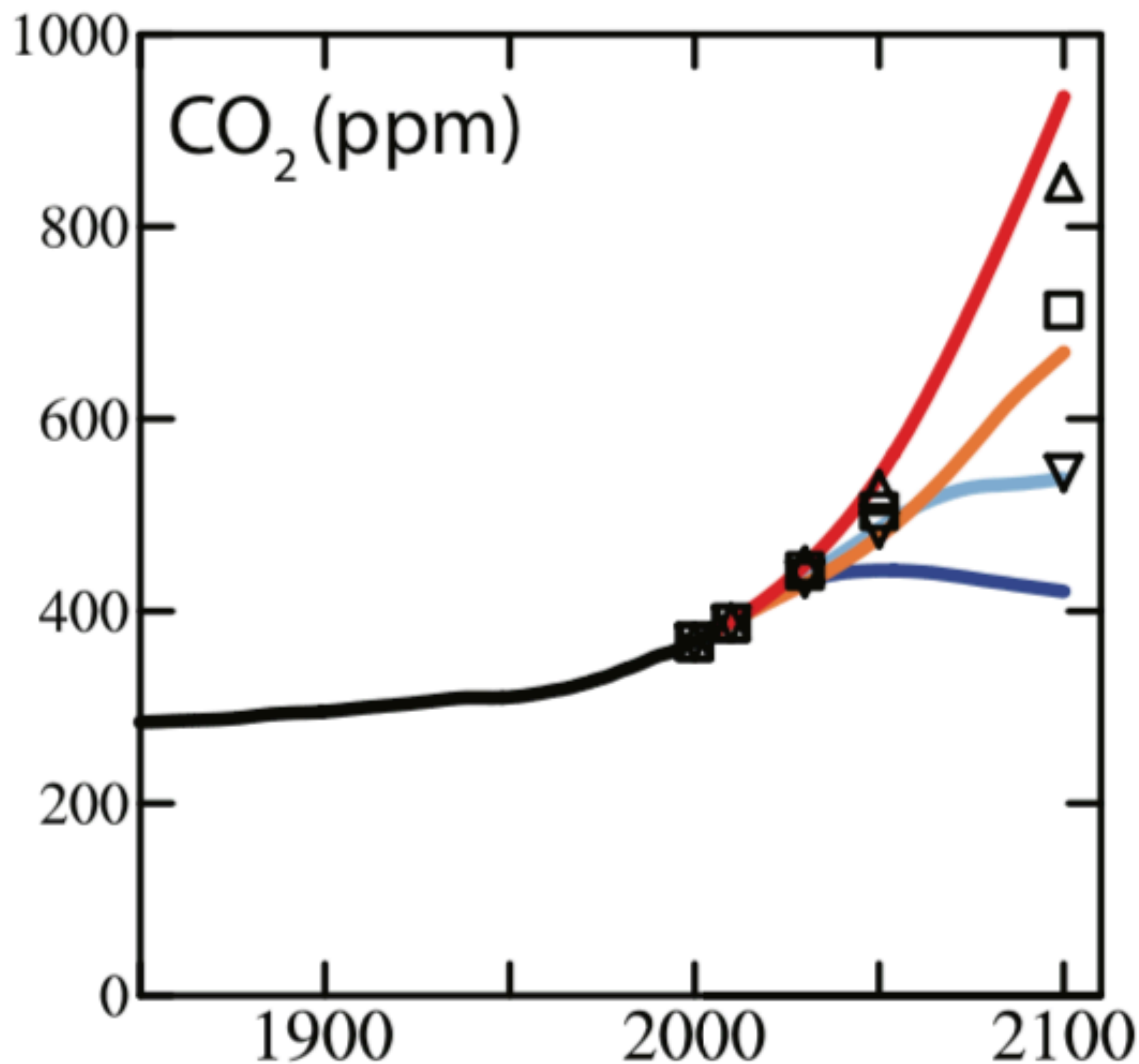


Figure 8.5 (above) Time evolution of global-averaged mixing ratio of long-lived species1850–2100 following each RCP; blue (RCP2.6), light blue (RCP4.5), orange (RCP6.0) and red (RCP8.5). (Meinshausen et al., 2011b)

Observed vs projected CO_2 concentrations

worse than RCP8.5
business as usual
considered in 2011



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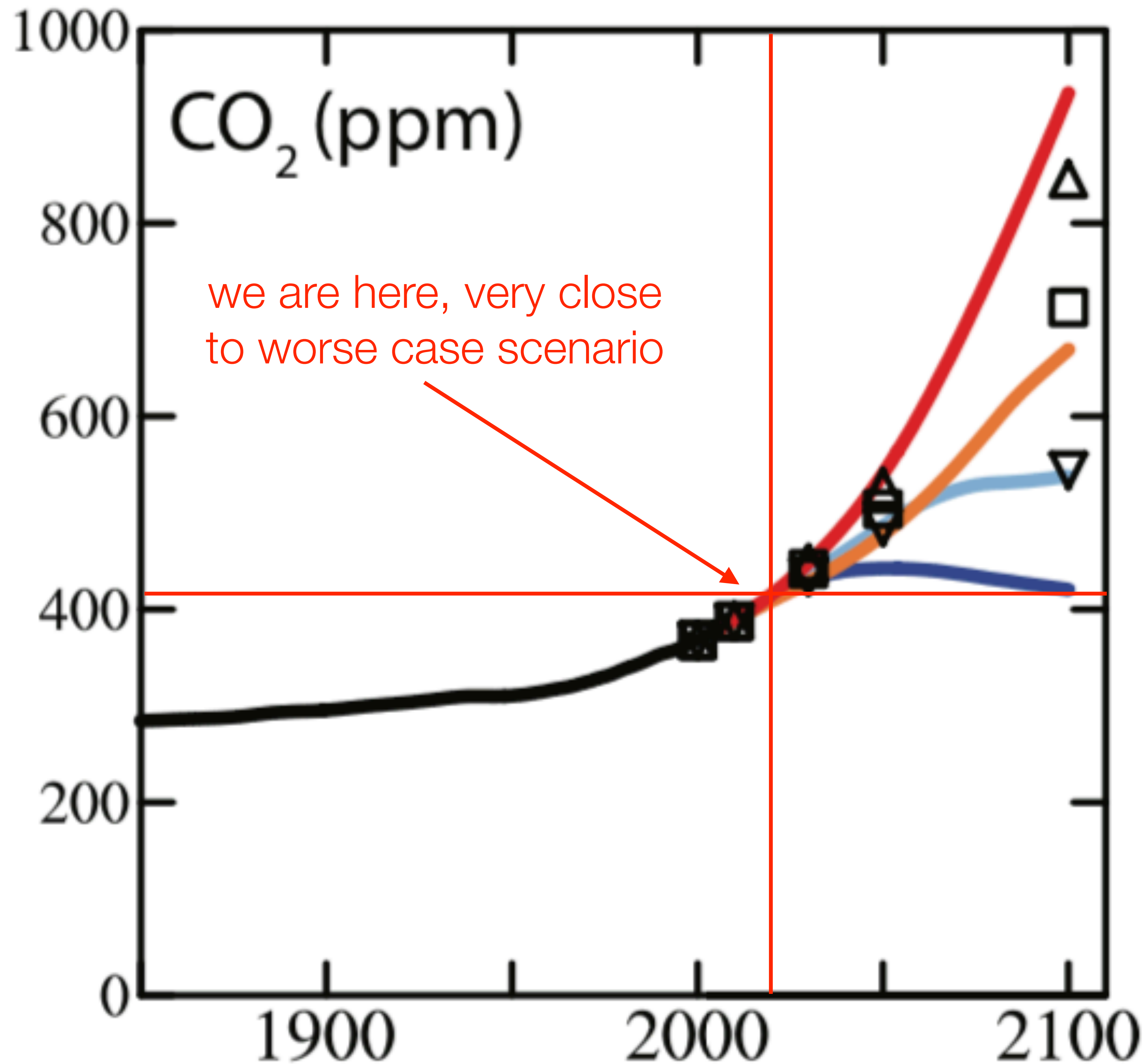

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Energy balance: Albedo, greenhouse

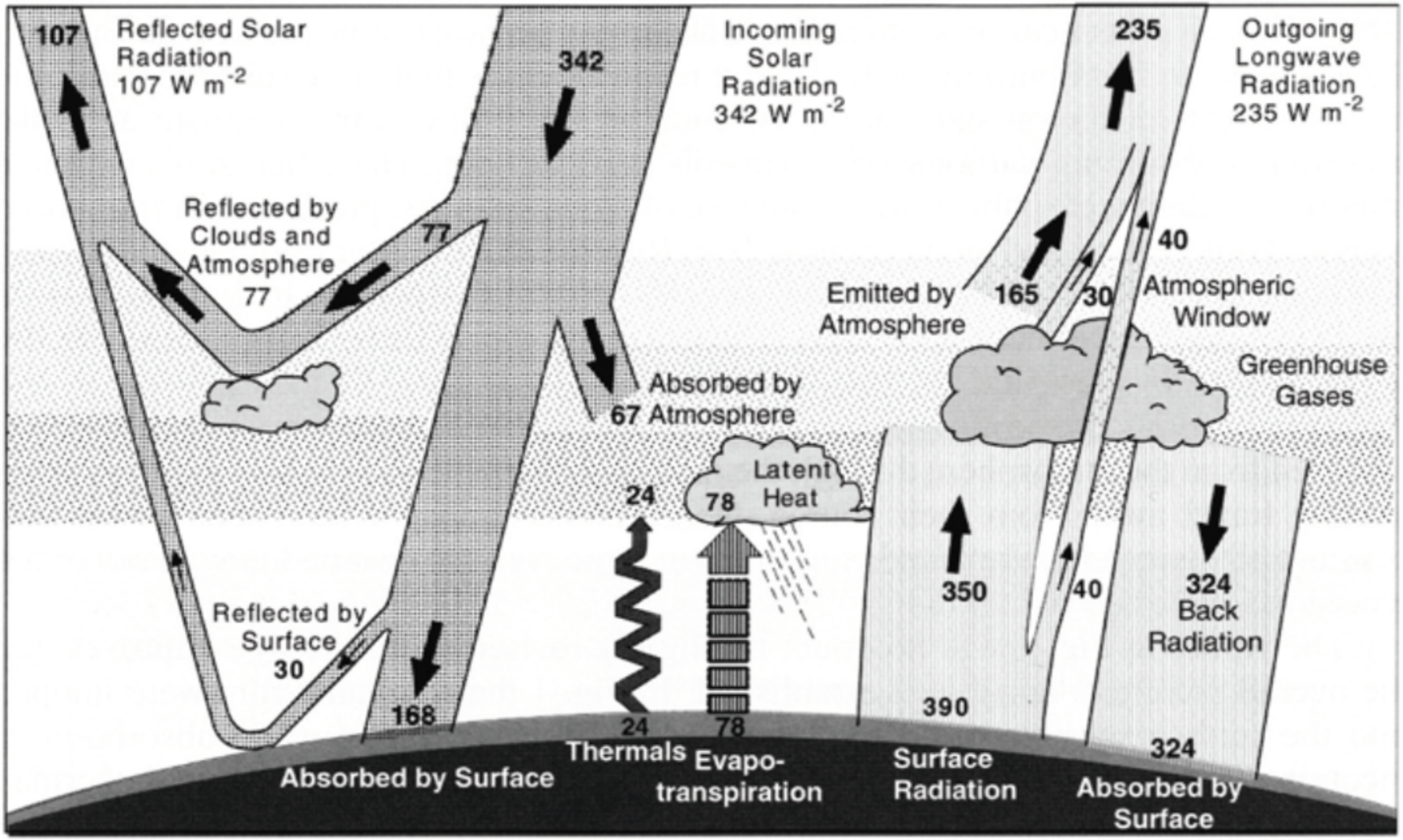


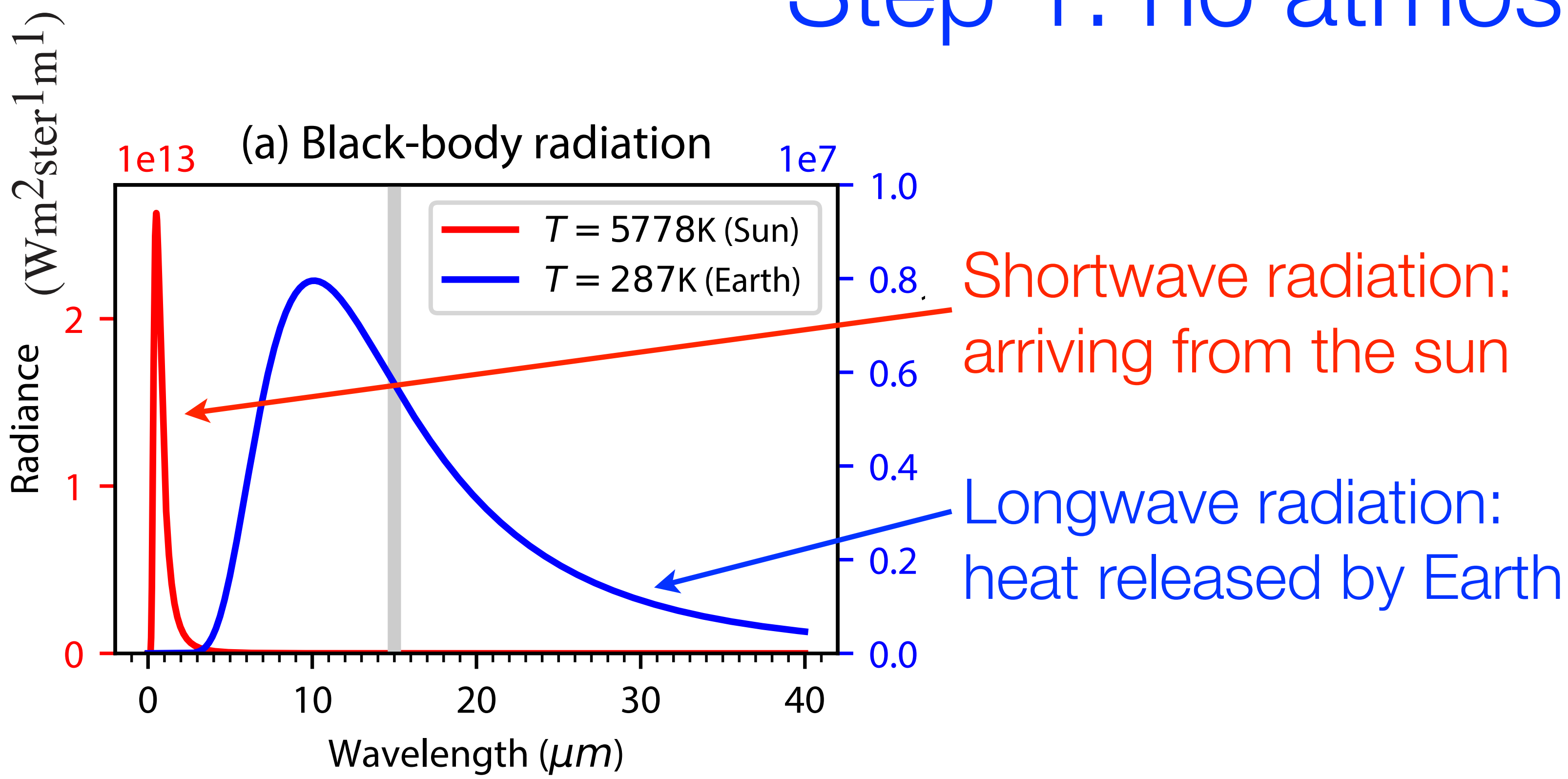
FIGURE 9.4. Earth's energy balance (from Trenberth, K.E., and D.P. Stepaniak, 2004: The flow of energy through the Earth's climate system. **Q.J.R.Meteorol.Soc., 130**, 2677-2701).

Notes sections 2.1.1, 2.1.2, 2.1.3:
Energy balance, 2-layer model, continuous temperature profile and level of last absorption

(use next three slides)

Energy balance of the Earth

Step 1: no atmosphere!!



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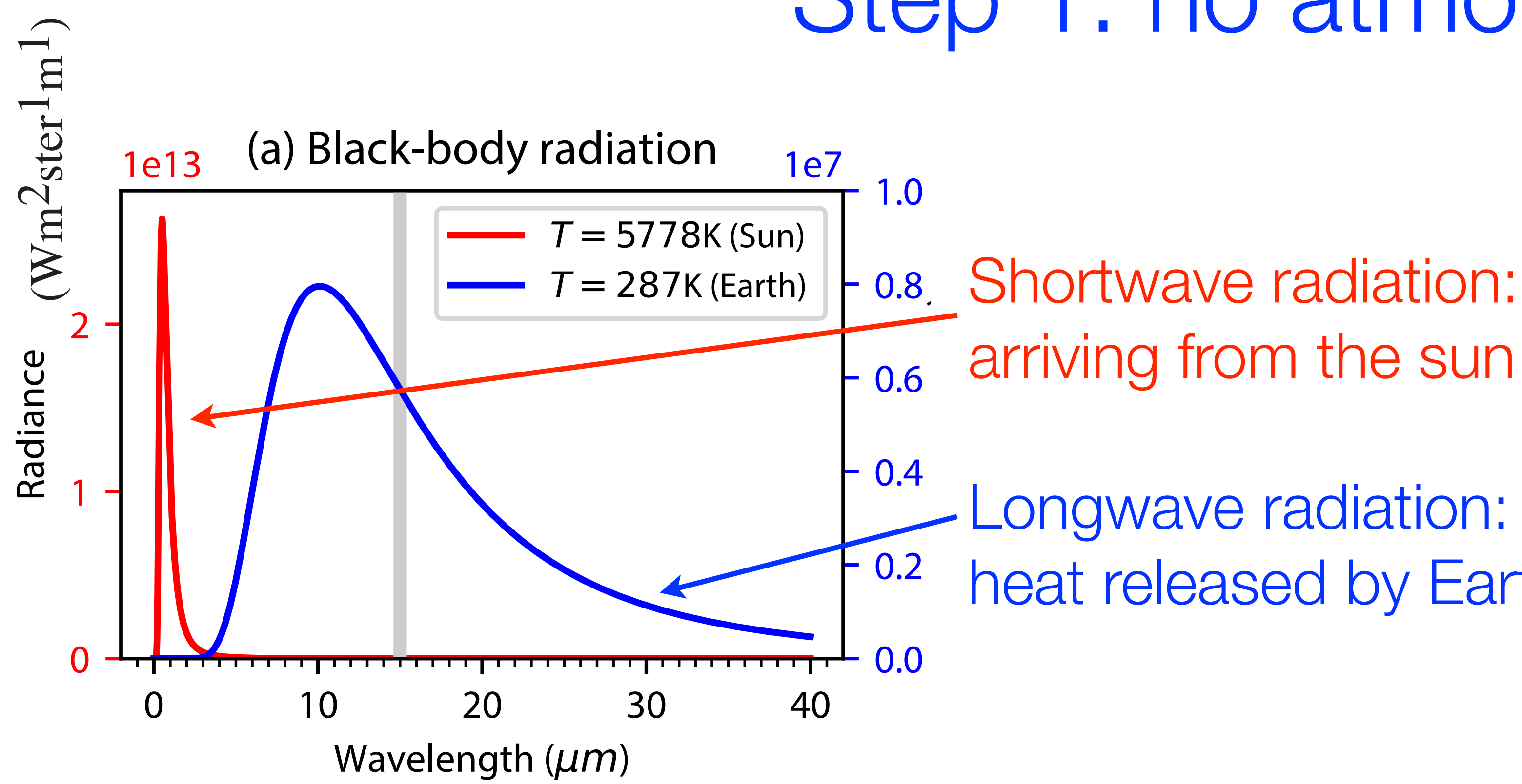

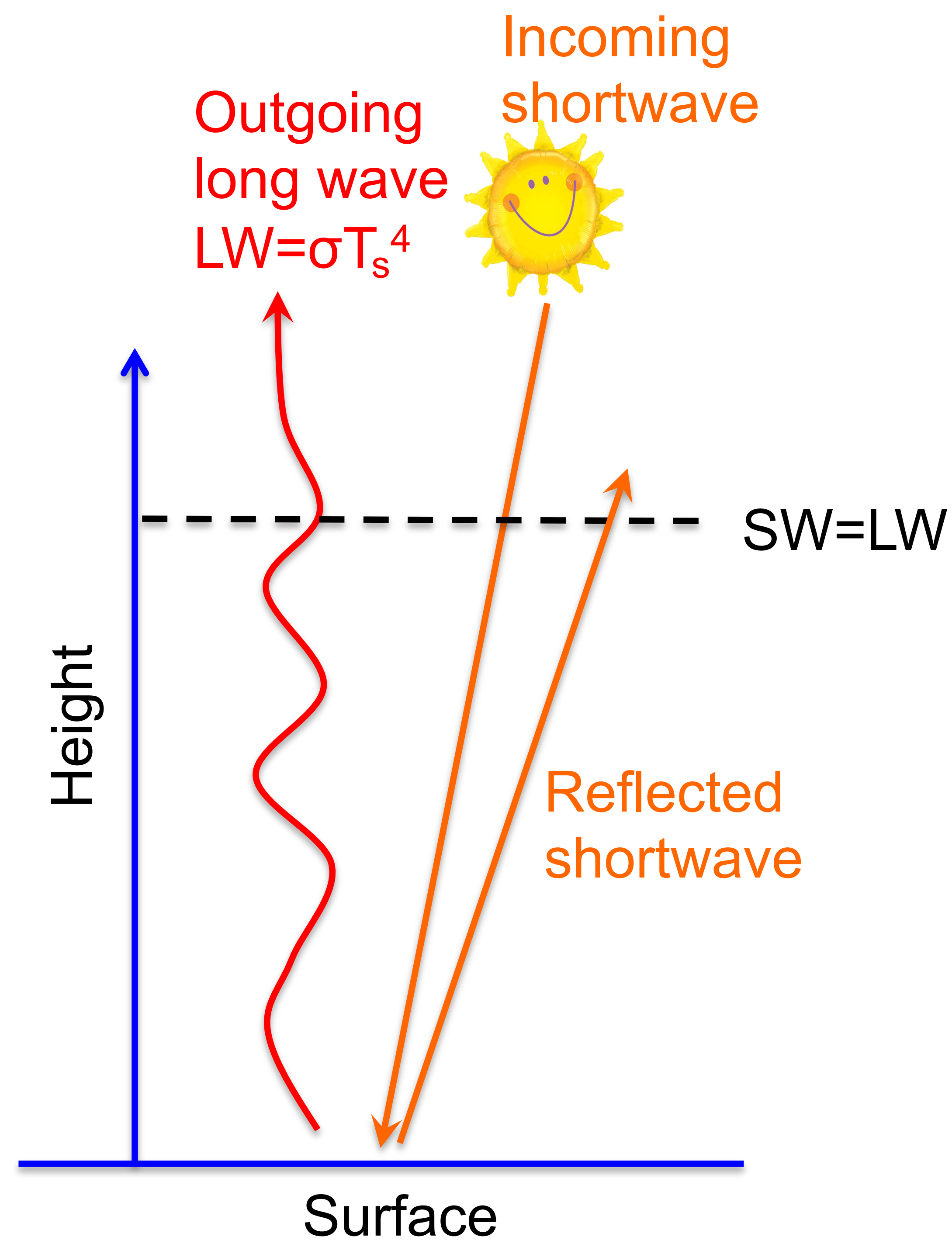

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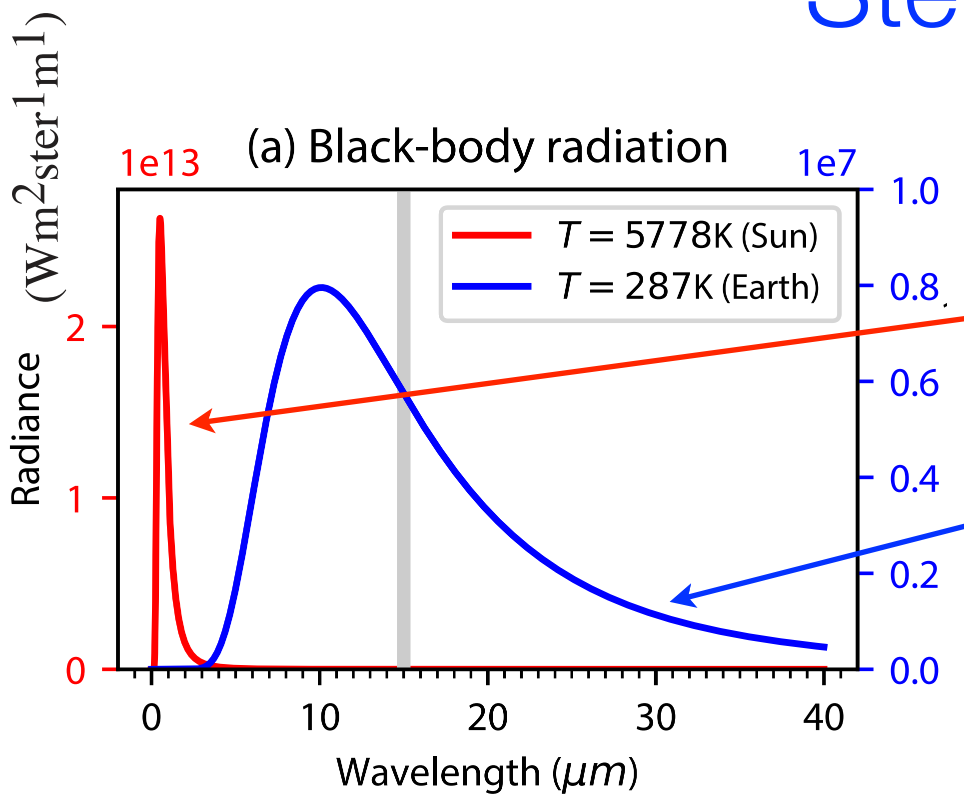
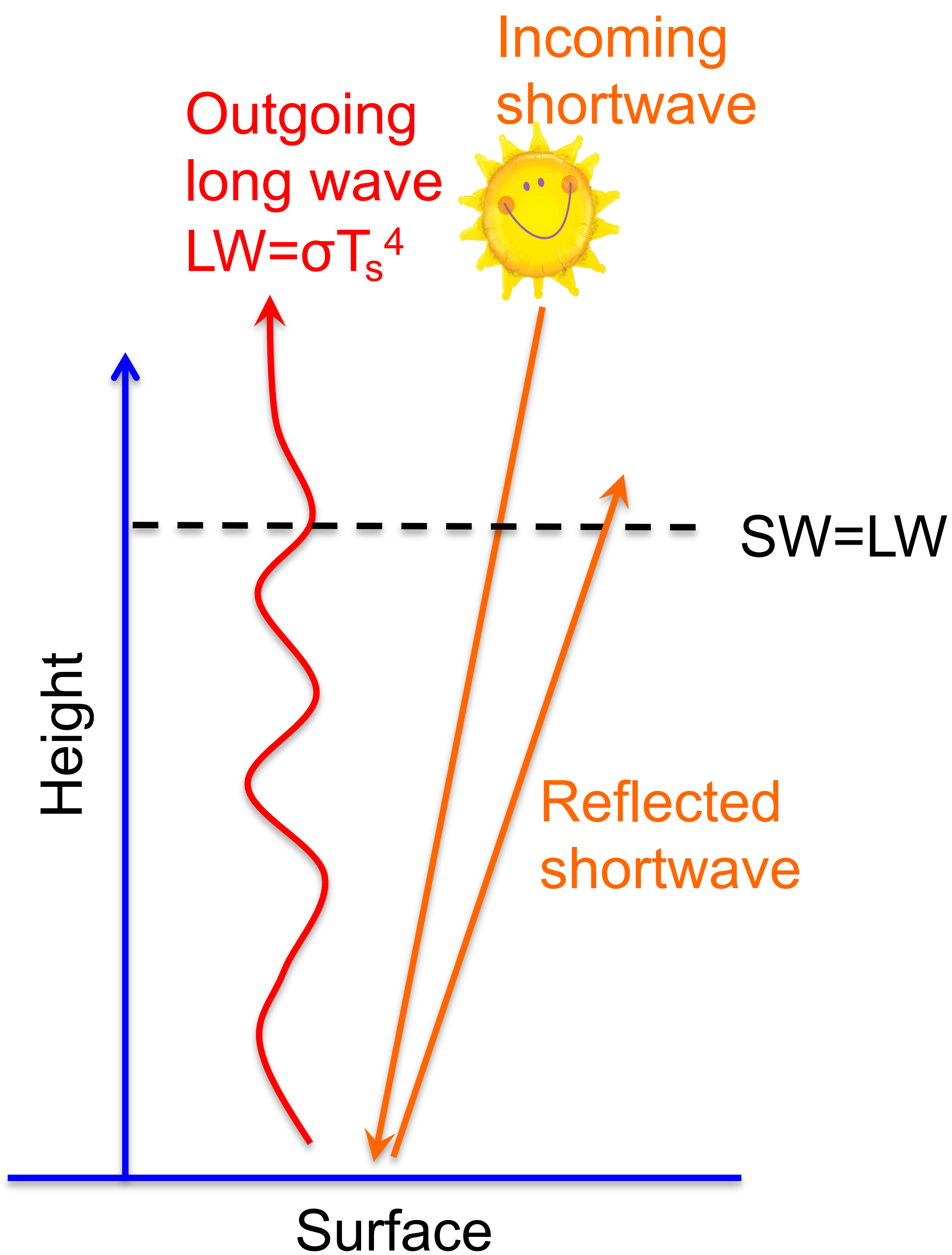
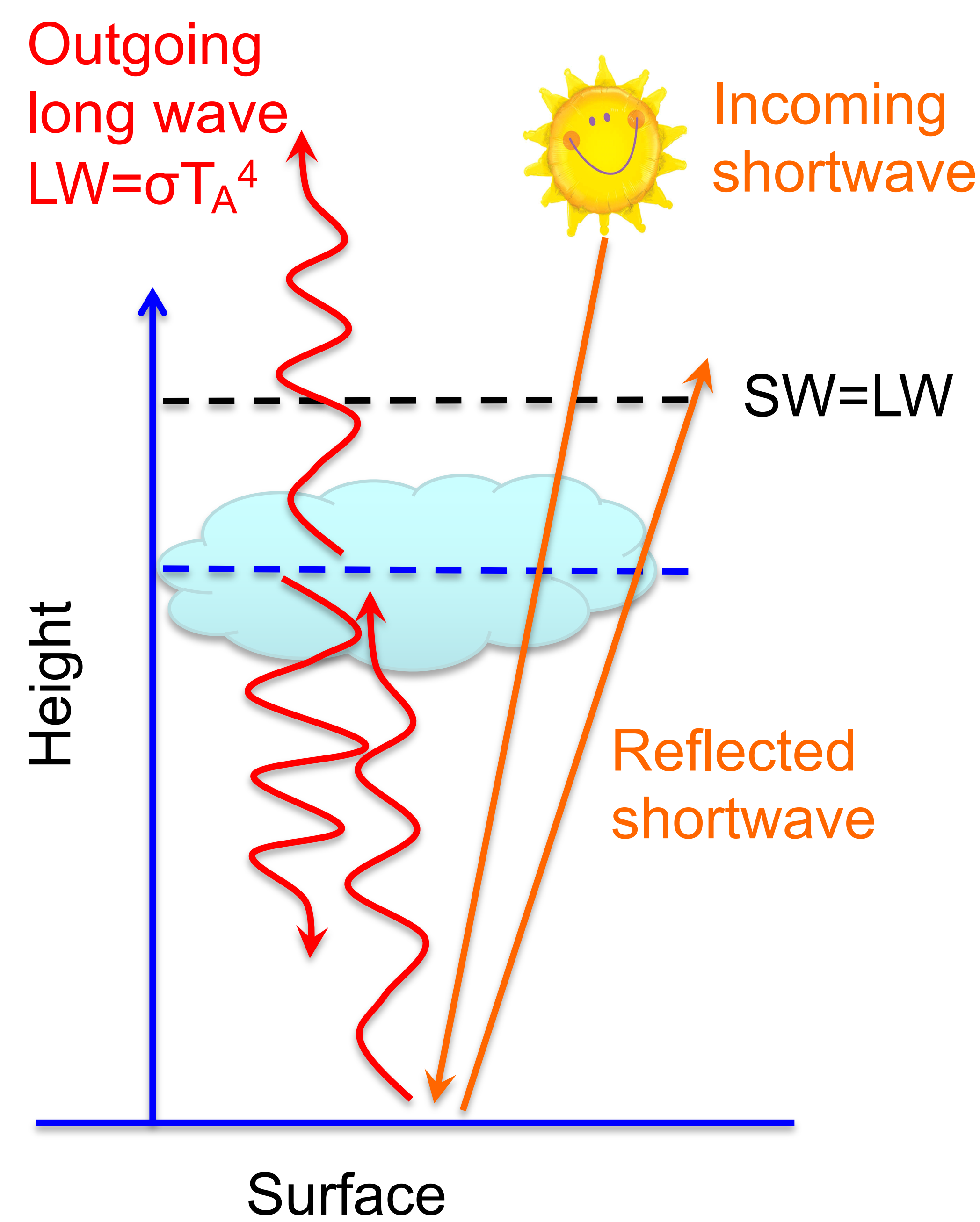




- Energy conservation: incoming **SW** radiation to Earth = outgoing **LW** radiation to space
- Incoming **SW** $= \dfrac{S_o}{4}(1-\alpha)$
- α = albedo = proportion SW reflected
- Outgoing **LW** $= \sigma T^4$
- Set incoming = outgoing ➡ $T = \left(\dfrac{(S_0/4)(1-\alpha)}{\sigma}\right)^{1/4} = 255\,\mathrm{K} = -18\,^{\circ}\mathrm{C} \equiv T_0.$

The Greenhouse Effect

Step 2: add a 1-layer atmosphere



The Greenhouse Effect

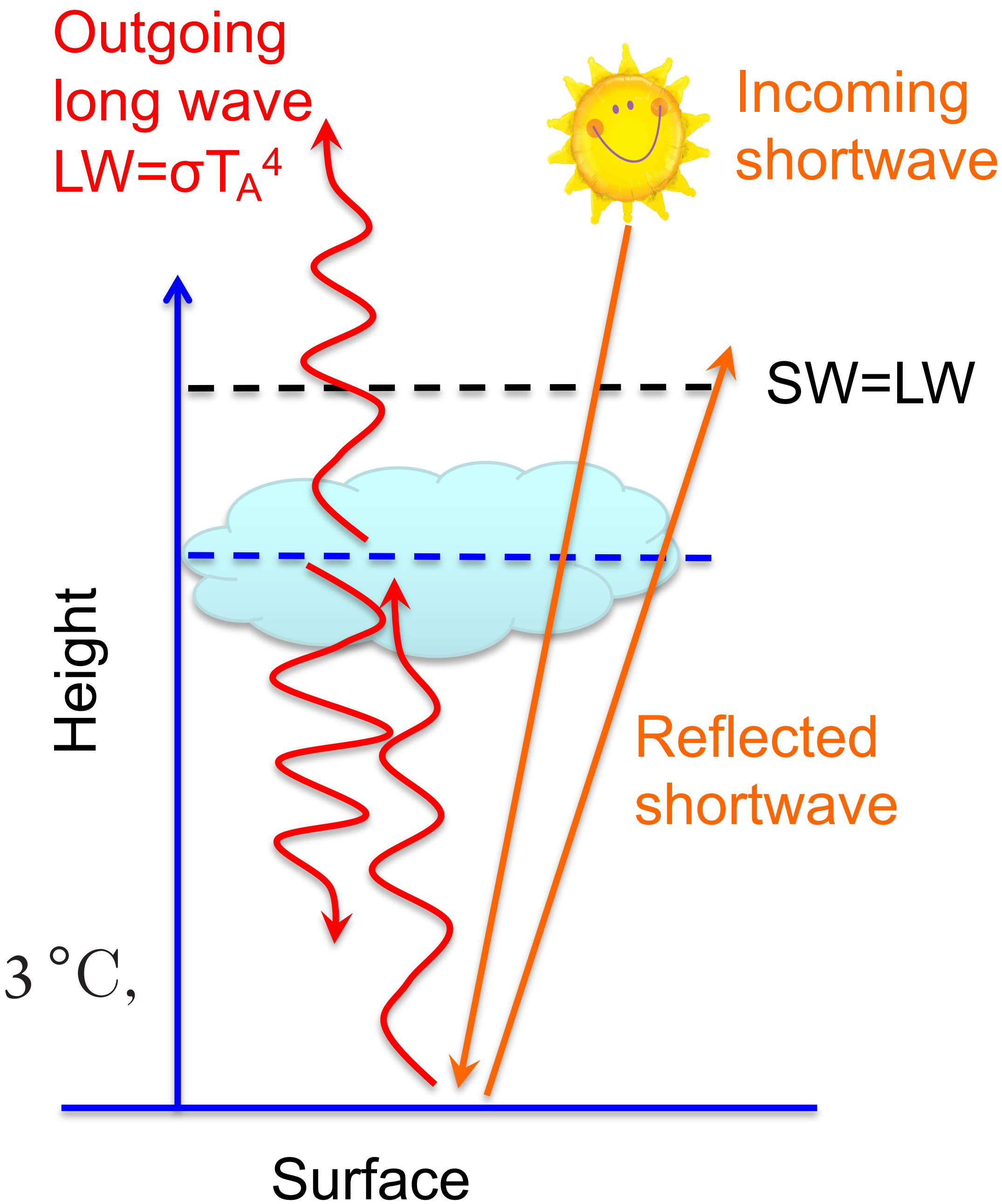
Step 2: add a 1-layer atmosphere

- Add an atmospheric layer which absorbs and re-emits LW radiation, transparent to SW
- Two unknowns: surface temperature T and (mid) atmospheric temperature T_a. Two equations (energy balance at the surface and at mid-atmosphere):

$$\frac{S_0}{4}(1-\alpha)+\epsilon\sigma T_a^4=\sigma T^4$$

$$\epsilon\sigma T^4=2\epsilon\sigma T_a^4.$$

$$T=\left(\frac{(S_0/4)(1-\alpha)}{\sigma(1-\epsilon/2)}\right)^{1/4}=T_0(1-\epsilon/2)^{-1/4}=284\,\mathrm{K}=13\,^{\circ}\mathrm{C},$$

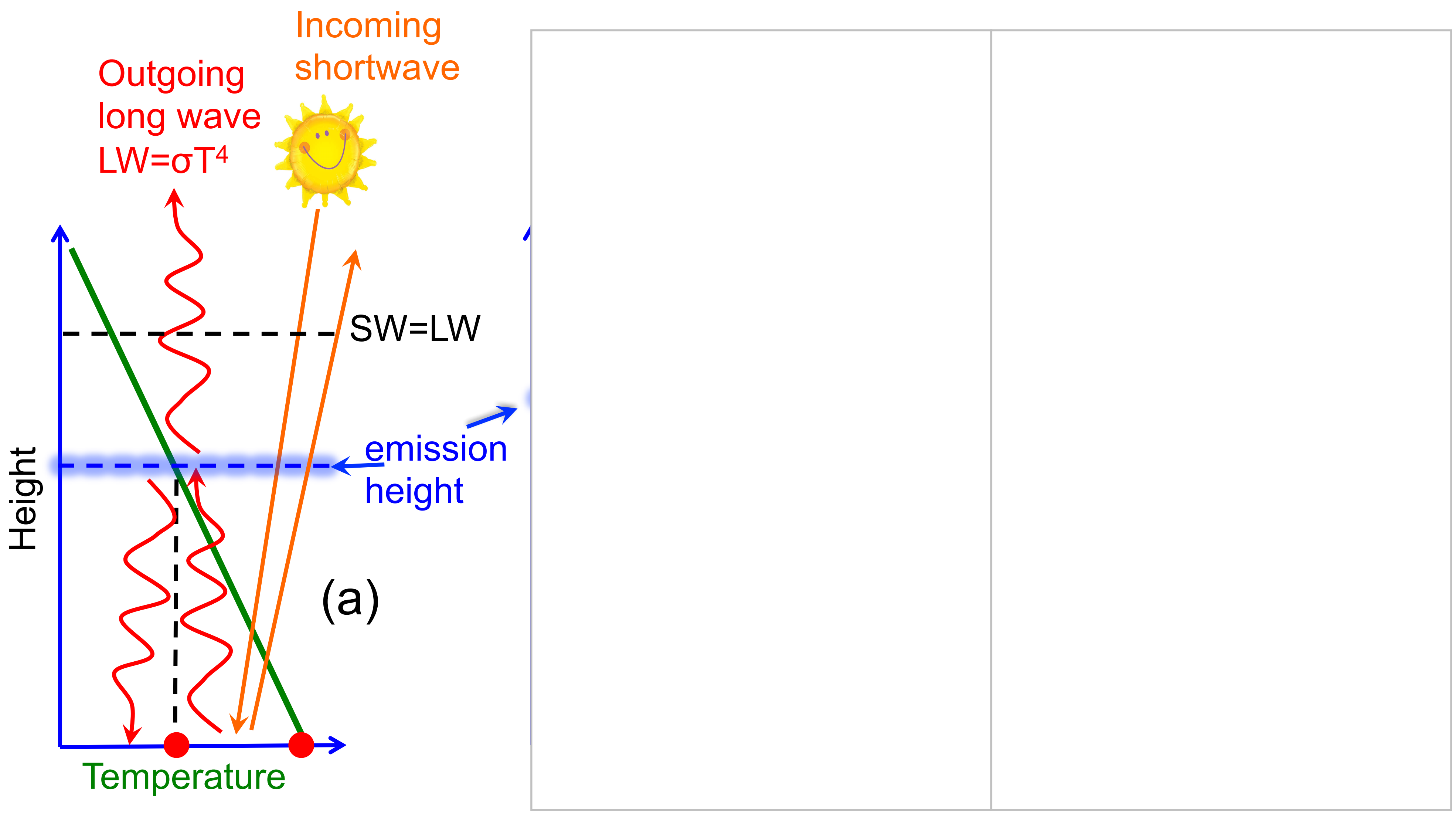


- Result: surface temperature increases due to the "greenhouse effect"

Workshop #2 a,b:
2-layer energy balance model

The Anthropogenic Greenhouse Effect

Step 3: add a continuous atmospheric temperature profile



- Level of last absorption: where most of the radiation emitted upward escapes to space, without getting absorbed again
- Increasing greenhouse gas ➨ Rising level of last absorption ➨ Earth radiates from a colder temperature ➨ Energy balance is broken: LW < SW ➨ The temperature must adjust

The Anthropogenic Greenhouse Effect

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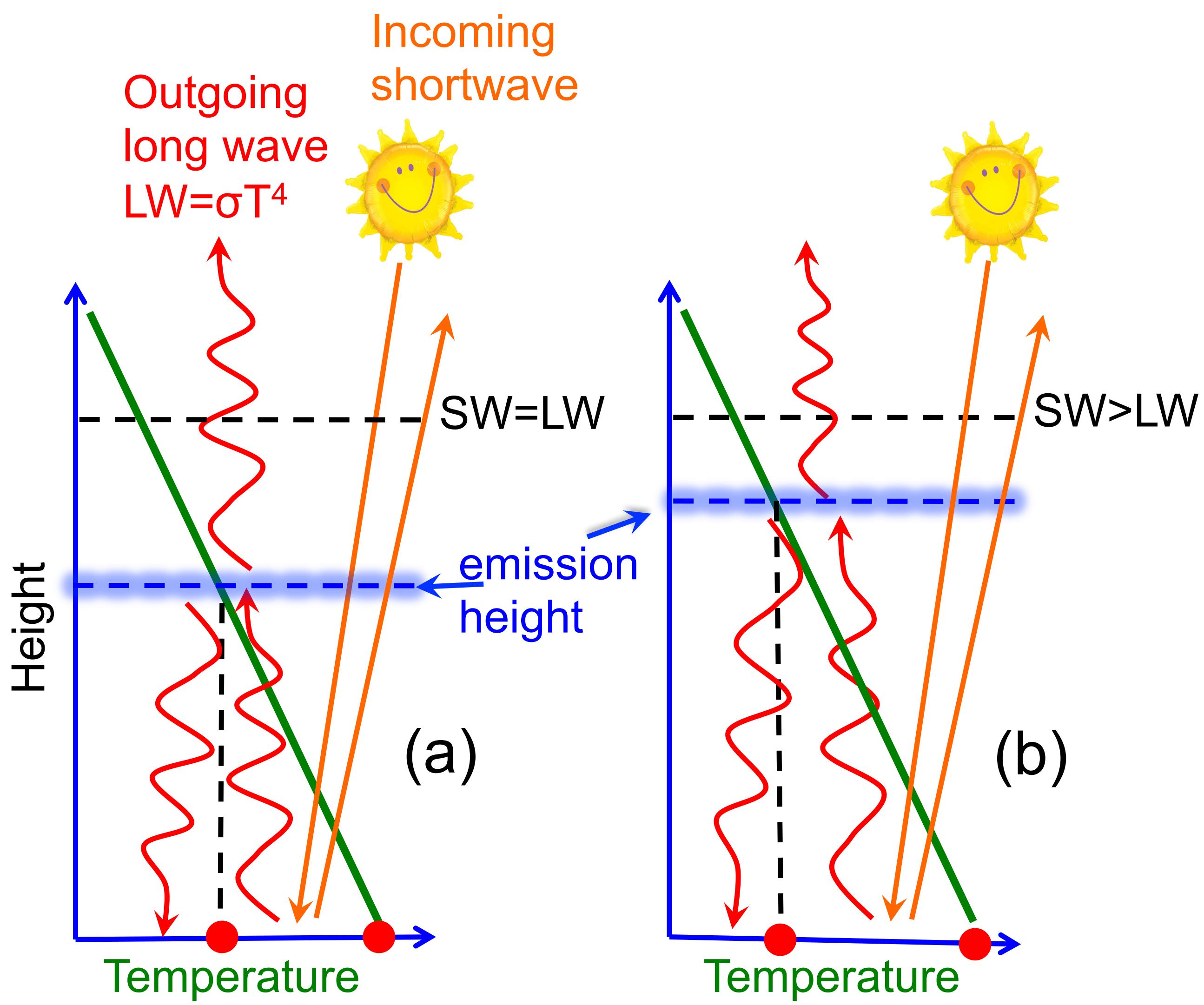

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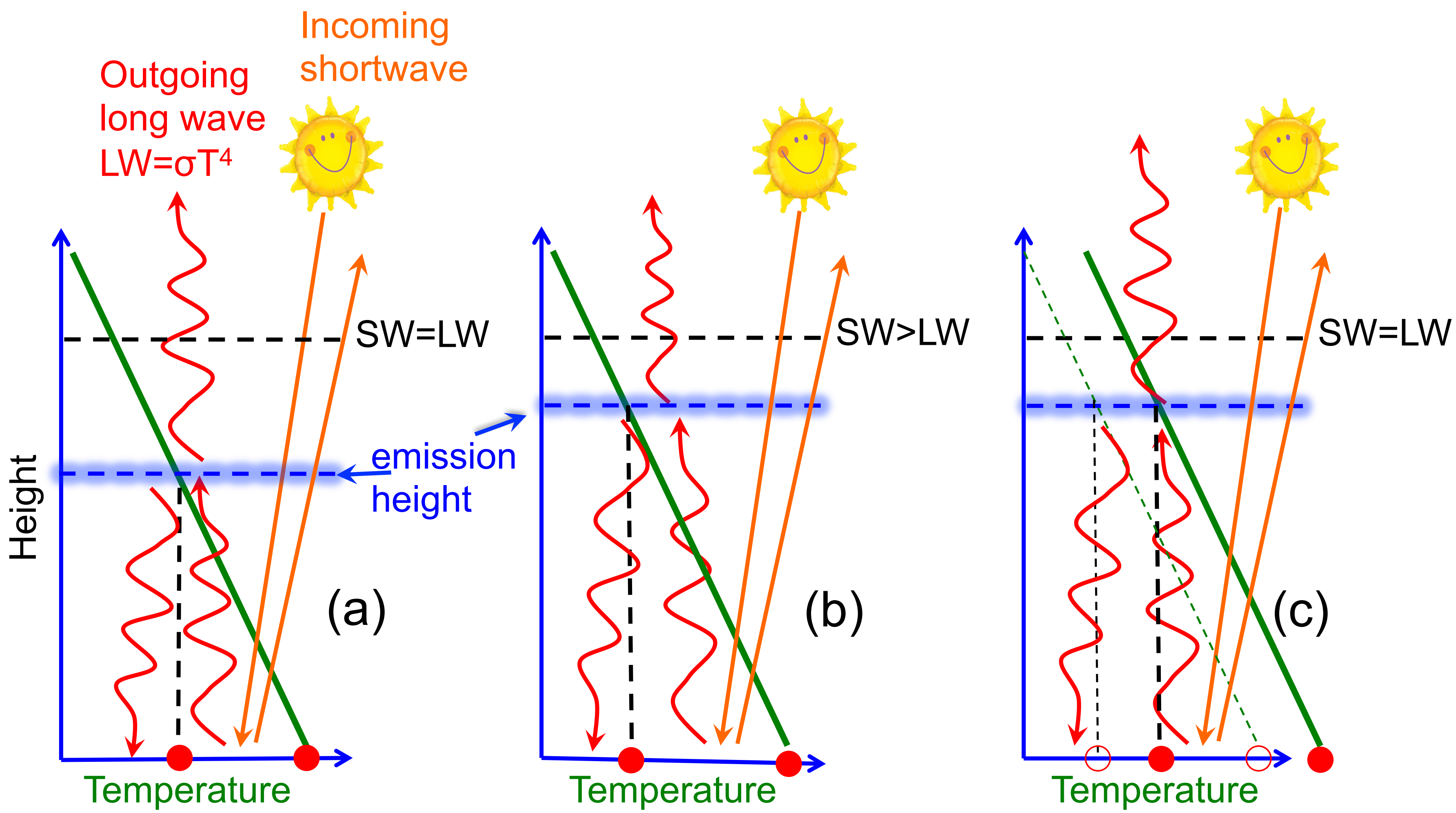

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Workshop #2 c:
emission height: leave for HW

How greenhouse gasses work:
wavelength-dependent radiation & molecular energy levels

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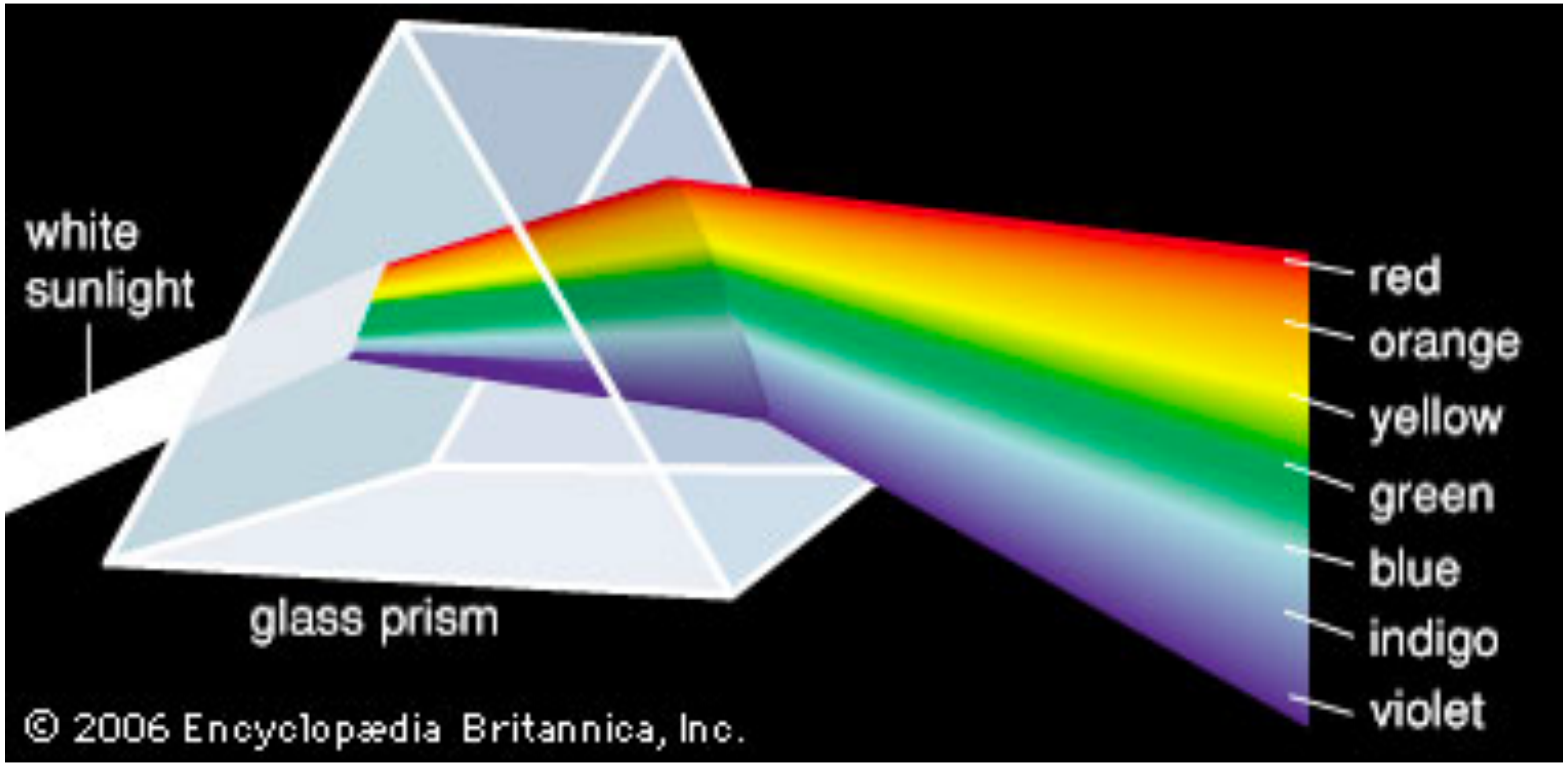
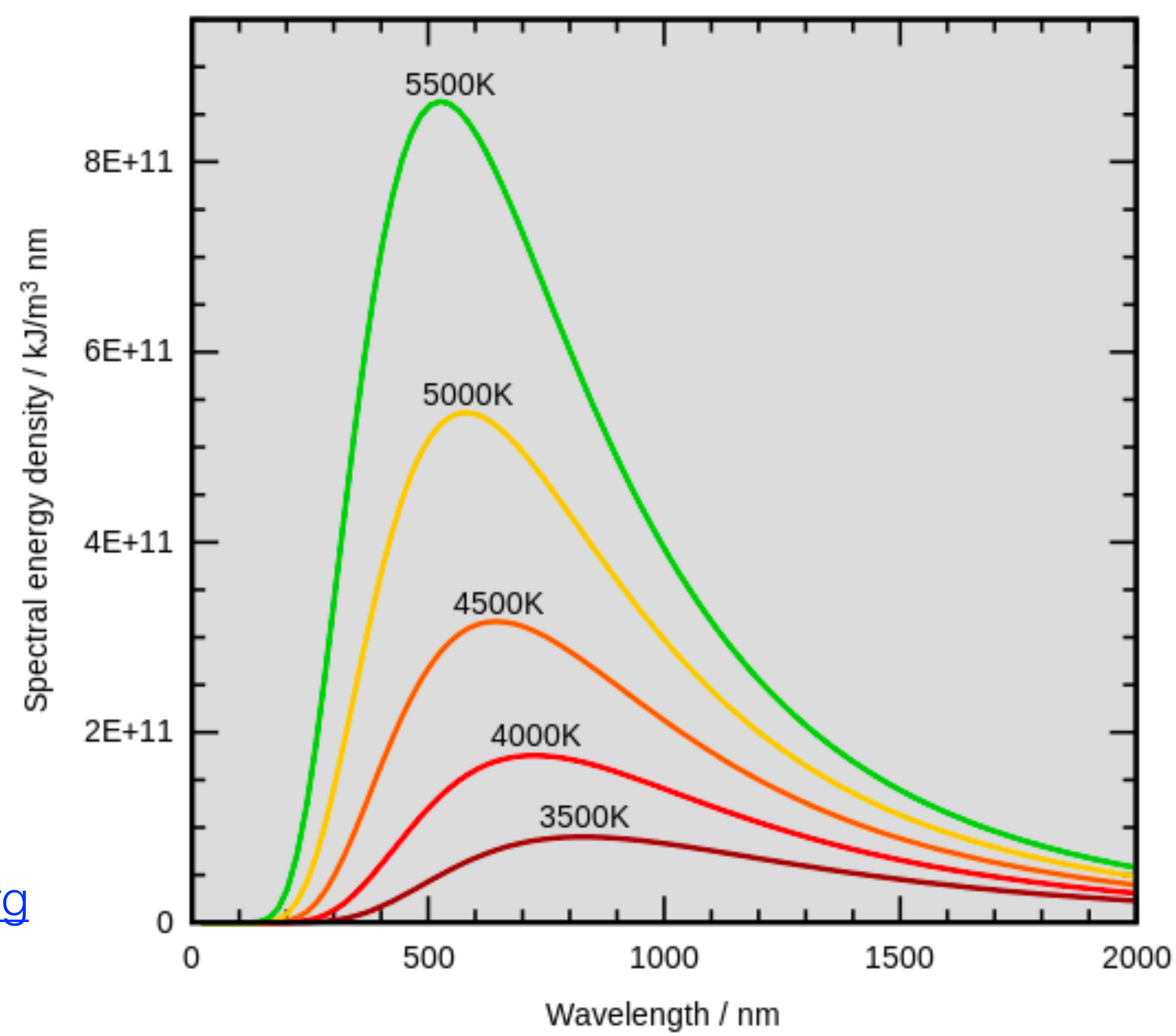


Black body radiation

Planck's law of black-body radiation: $$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

$B(\lambda,T)d\lambda$ is the energy per area/ time/ angle emitted between wavelengths λ & $\lambda+d\lambda$; T=temperature; h=Planck's const; c=speed of light; k=Boltzmann's const.

Total emitted radiation per area/ time: σT^4 Stefan–Boltzmann constant:
$\sigma = 5.670367 \times 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$



https://en.wikipedia.org/wiki/File:Wiens_law.svg

Shortwave vs longwave radiation

Earth's surface and the sun both emit blackbody radiation according to Planck's function — they radiate over the full spectrum

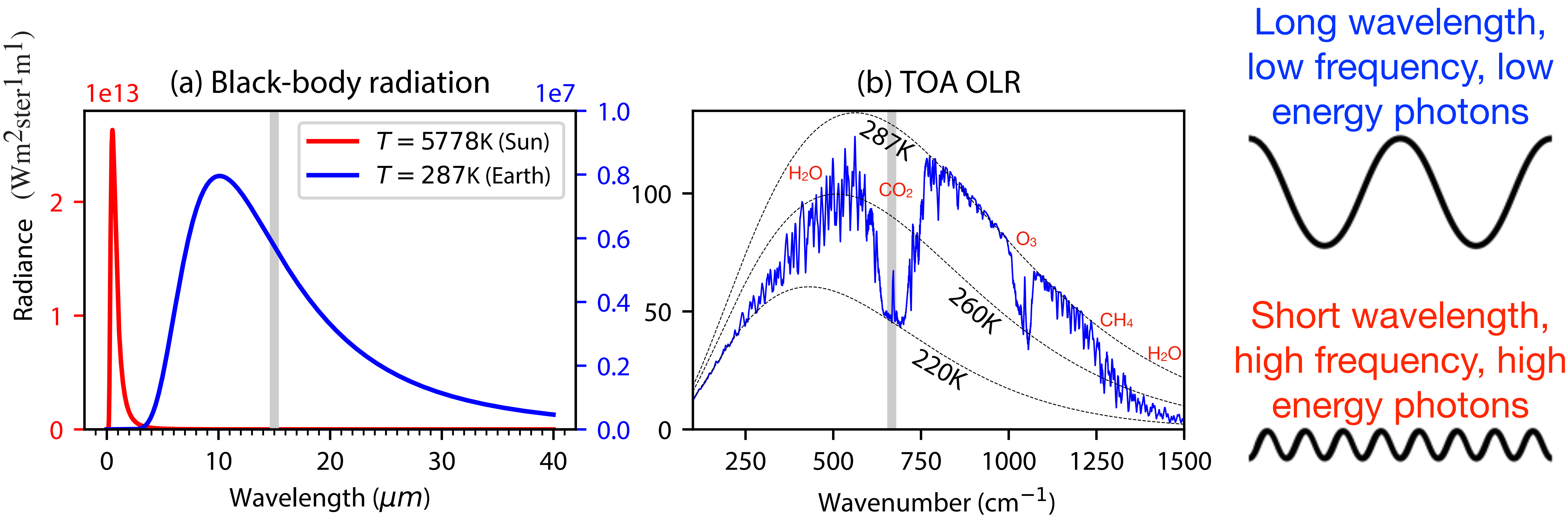
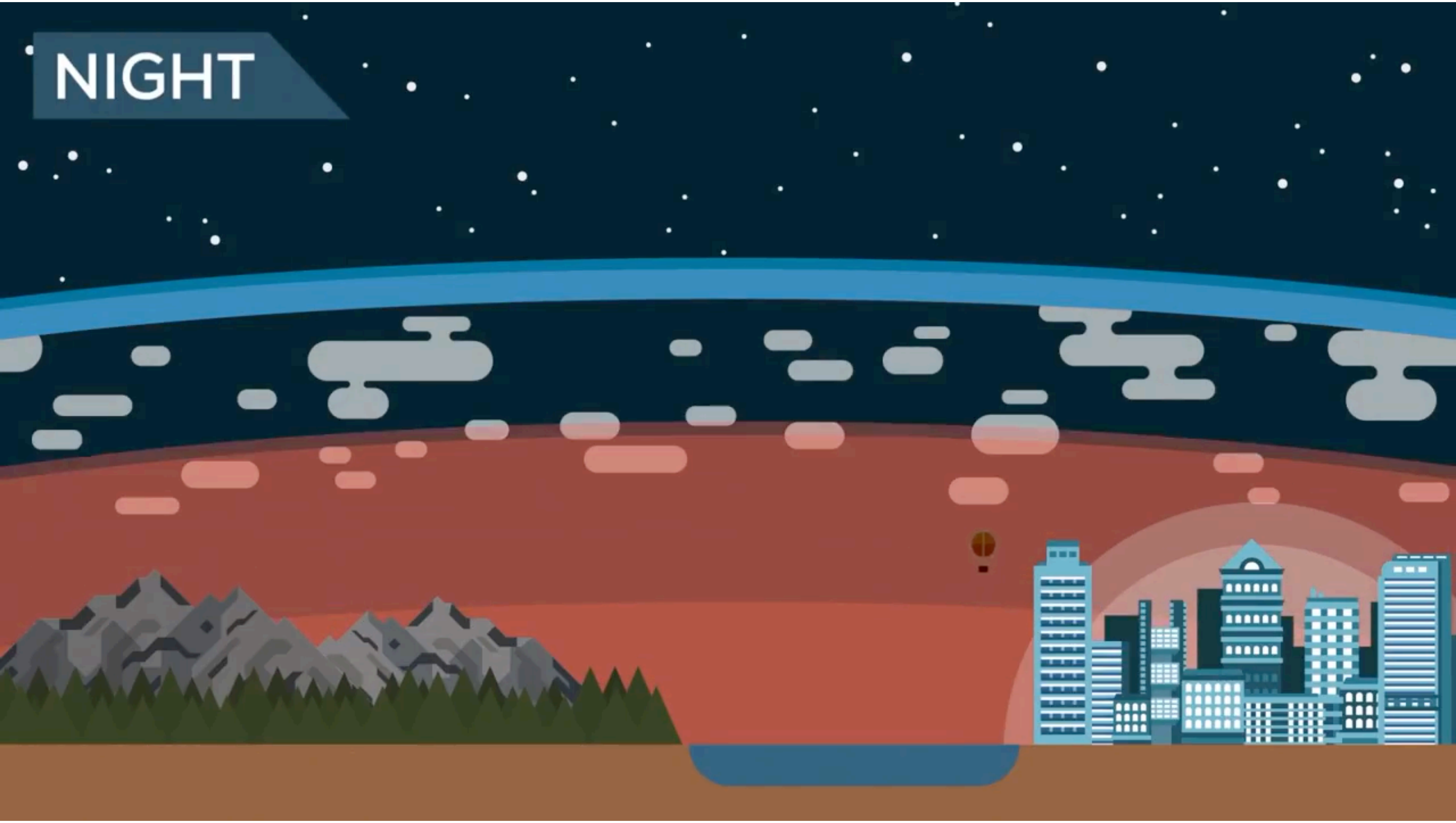


Figure 2.5: Blackbody radiation.
(a) Planck's black-body spectral radiance for the emission temperatures of the Earth (blue) and Sun (red), as a function of wavelength. (b) blue curve shows estimated outgoing longwave radiation at the top of the atmosphere as a function of wavenumber, with black-body radiation curves at different temperatures shown by dashed lines. The deviations from the 287 K black body radiation curve indicate absorption bands due to CO_2, CH_4, H_2O, and O_3; the central CO_2 absorption line is shown on both panels as a vertical gray bar.

How do greenhouse gases work?



https://youtu.be/sTvqIijqvTg

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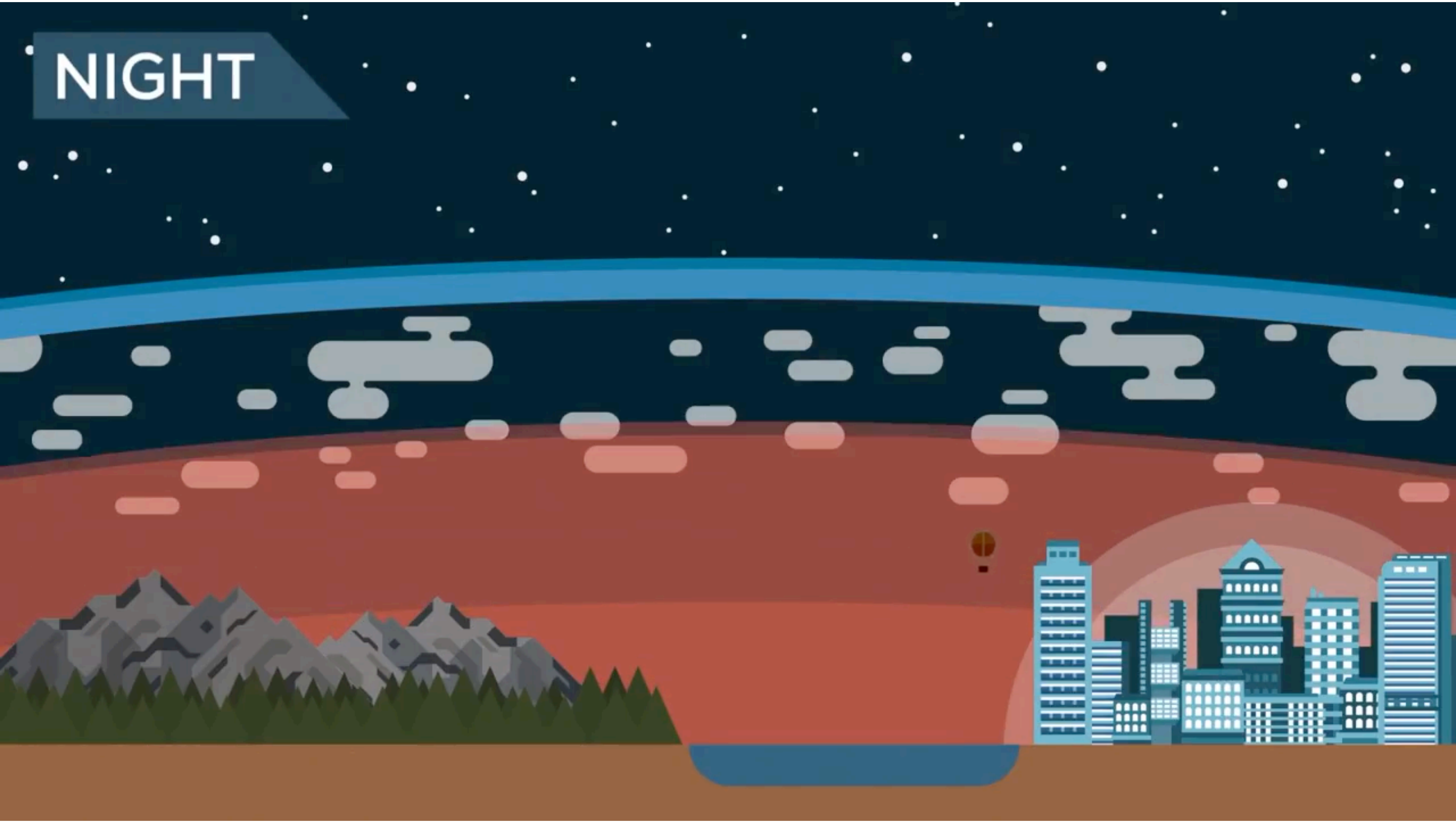

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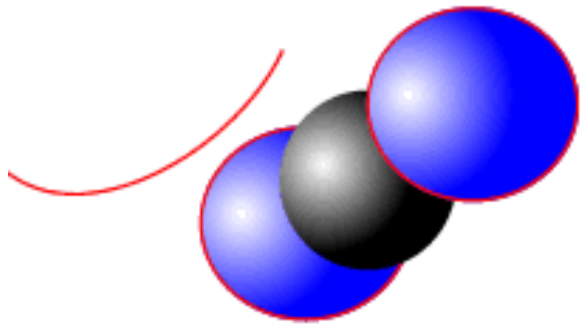
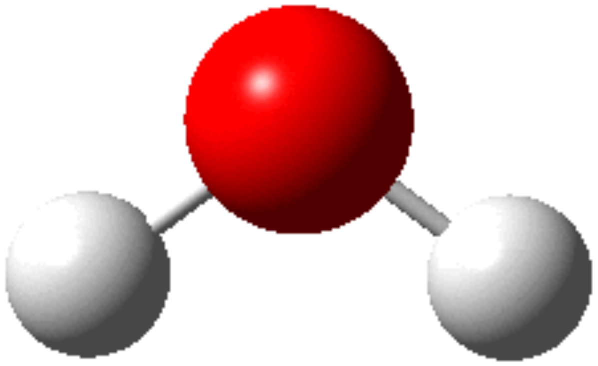
Vibration energy levels of CO_2 & H_2O



CO_2

http://www.dynamicscience.com.au/tester/solutions1/chemistry/greenhouse/co2andtheghe.htm

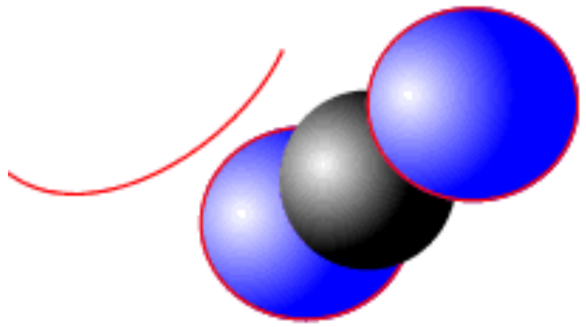


H_2O

http://davidobru.blogspot.com/2017/01/some-animations.html

The vibration energy levels determine the frequency of absorption

Vibration energy levels of CO_2 & H_2O



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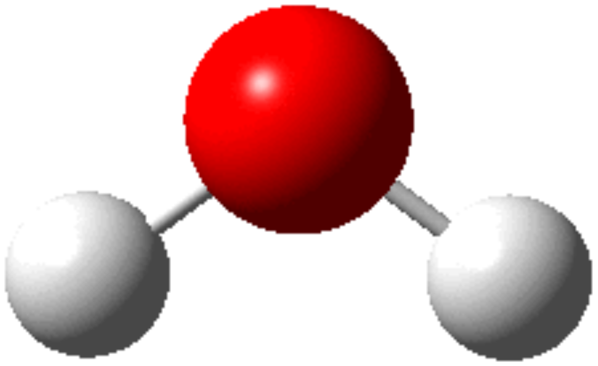

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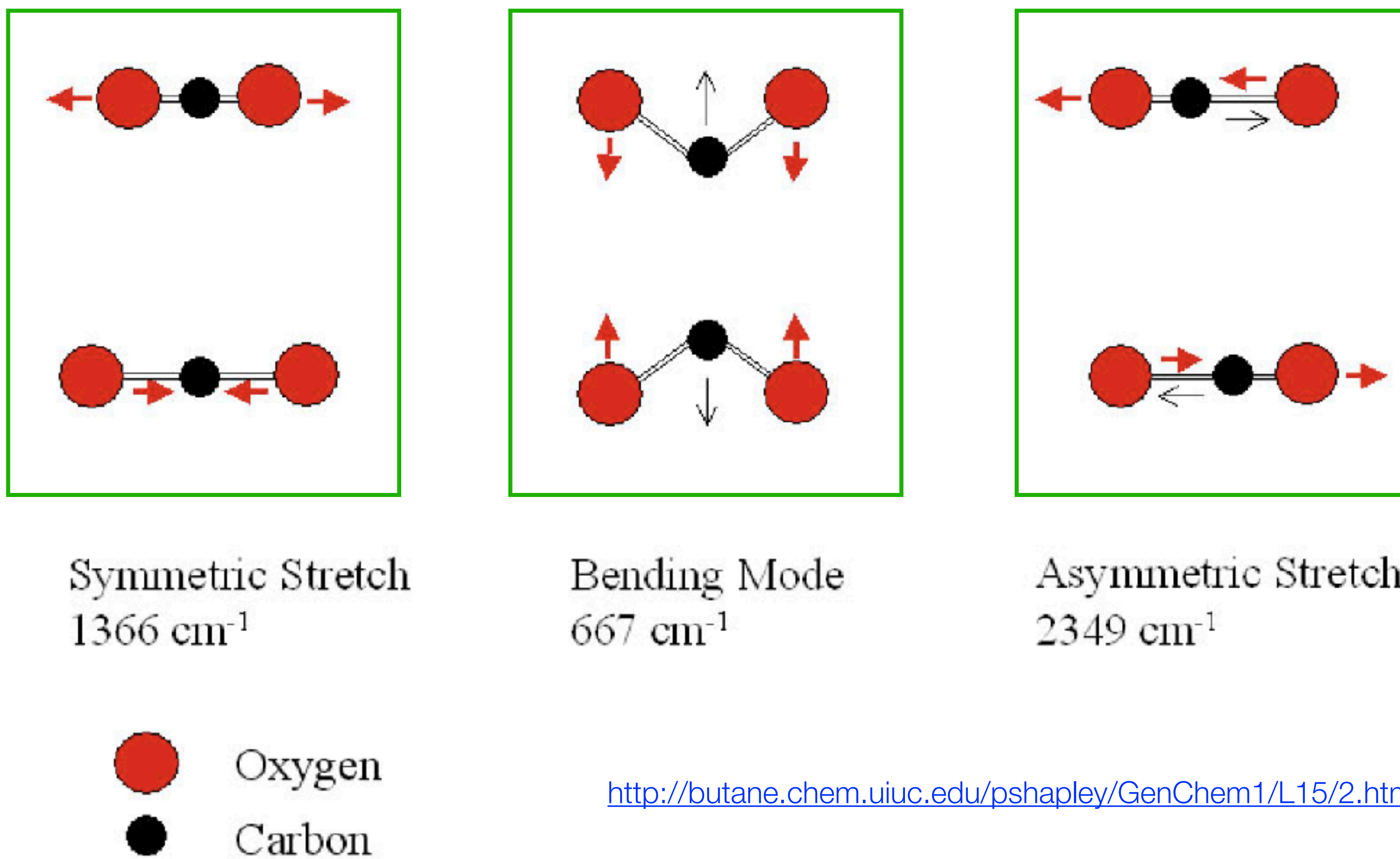
The vibration energy levels determine the frequency of absorption

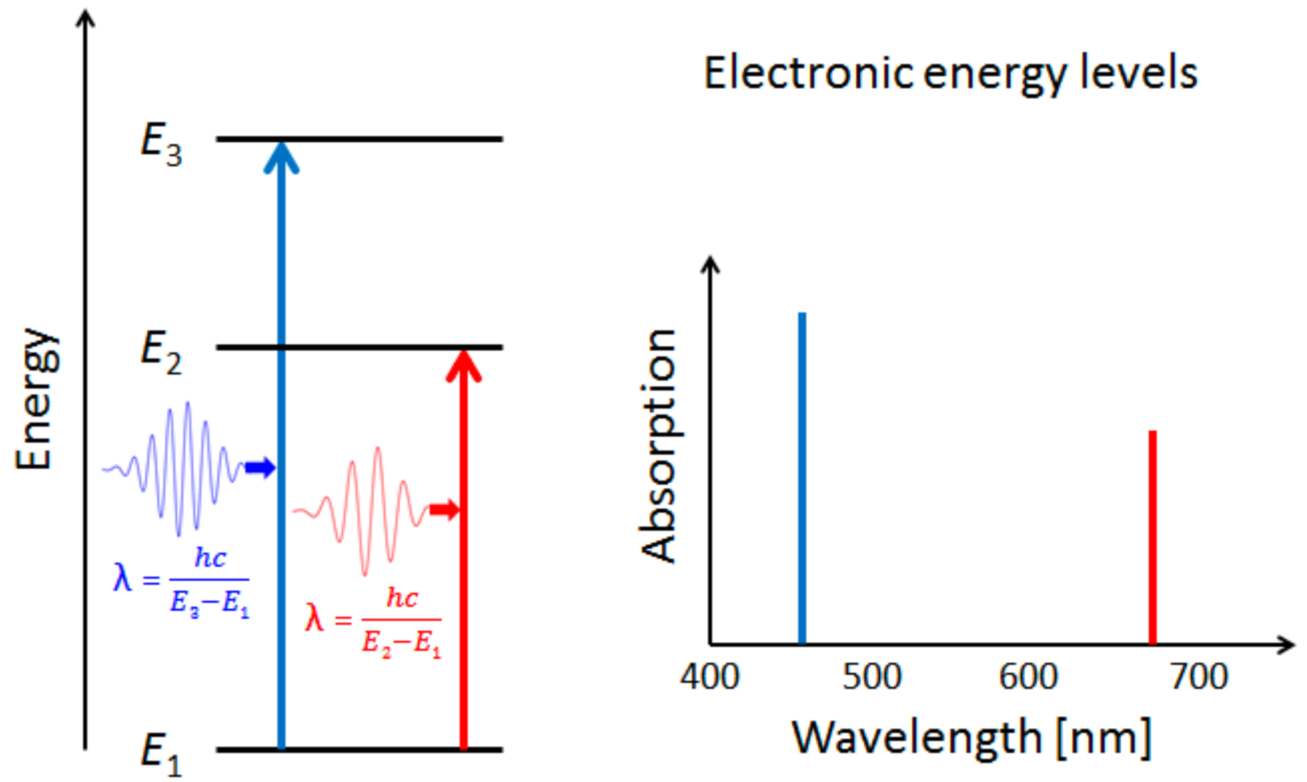
Greenhouse gasses vibration modes

- Discrete wavelengths excite molecular transitions in greenhouse gas molecules
- This results in absorption and re-emission of radiation of that wavelength
- The “transition wavelengths” for various greenhouse gases have been measured in lab experiments



http://butane.chem.uiuc.edu/pshapley/GenChem1/L15/2.html

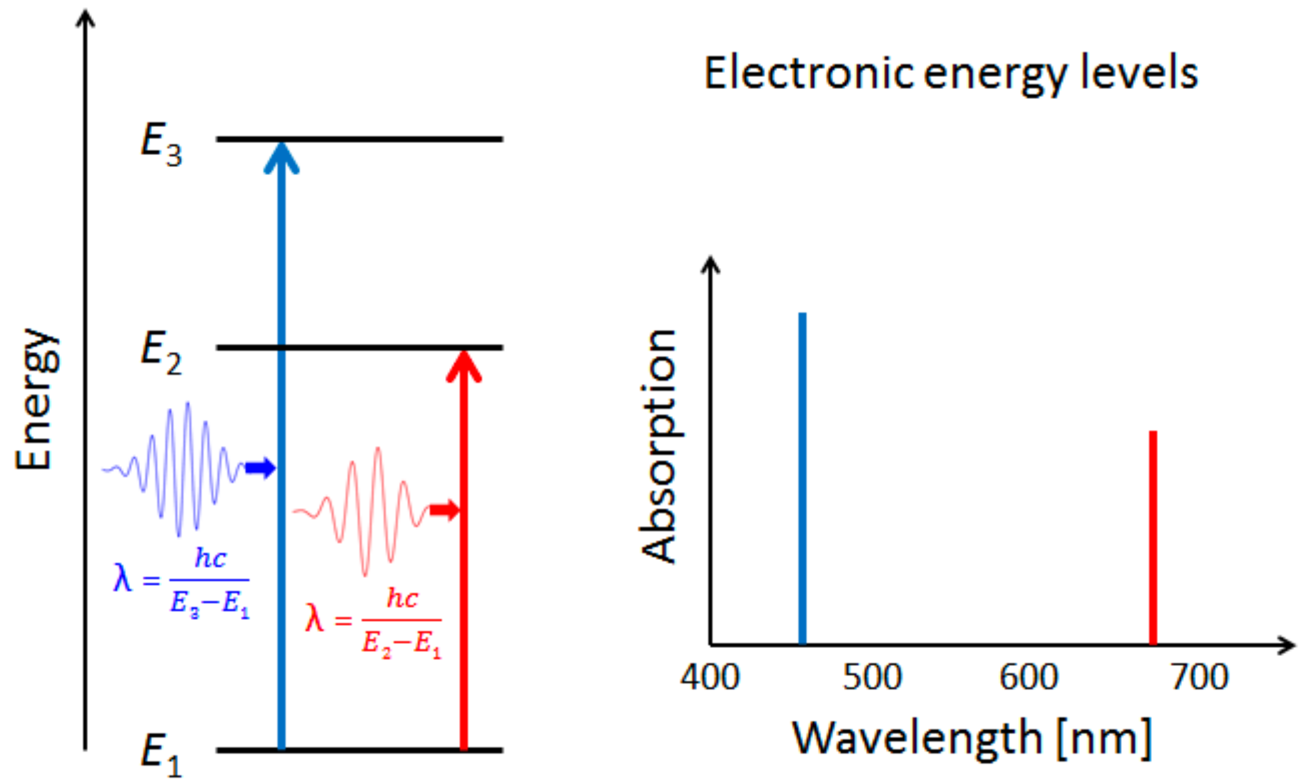
Molecular vibration/rotation energy levels & photon absorption



Photon energy: $E = h\nu = hc/\lambda$ where h is Planck's constant, c is the speed of light, ν the frequency, and λ the wavelength. Note: $\nu = c/\lambda = 1/T$, where T is the wave period.

From "ocean optics" web book,
https://www.oceanopticsbook.info/view/absorption/physics-of-absorption

Molecular vibration/rotation energy levels & photon absorption



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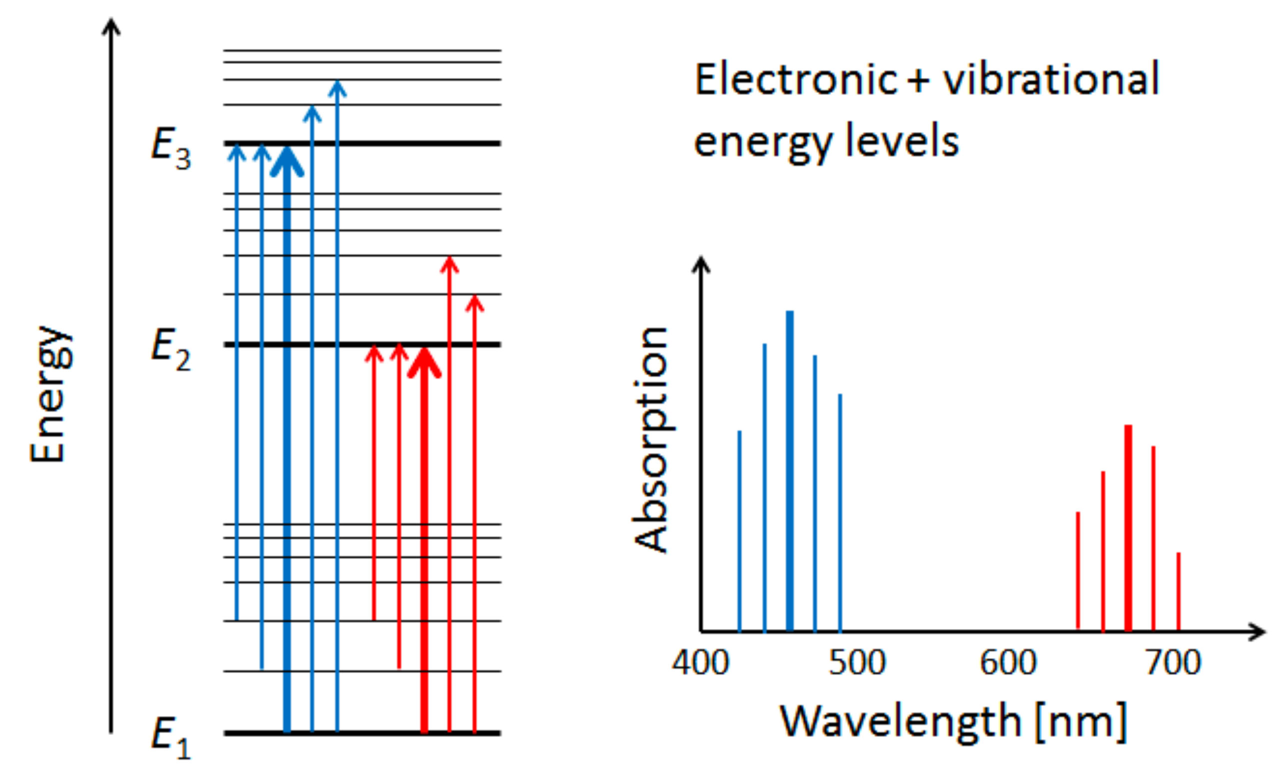

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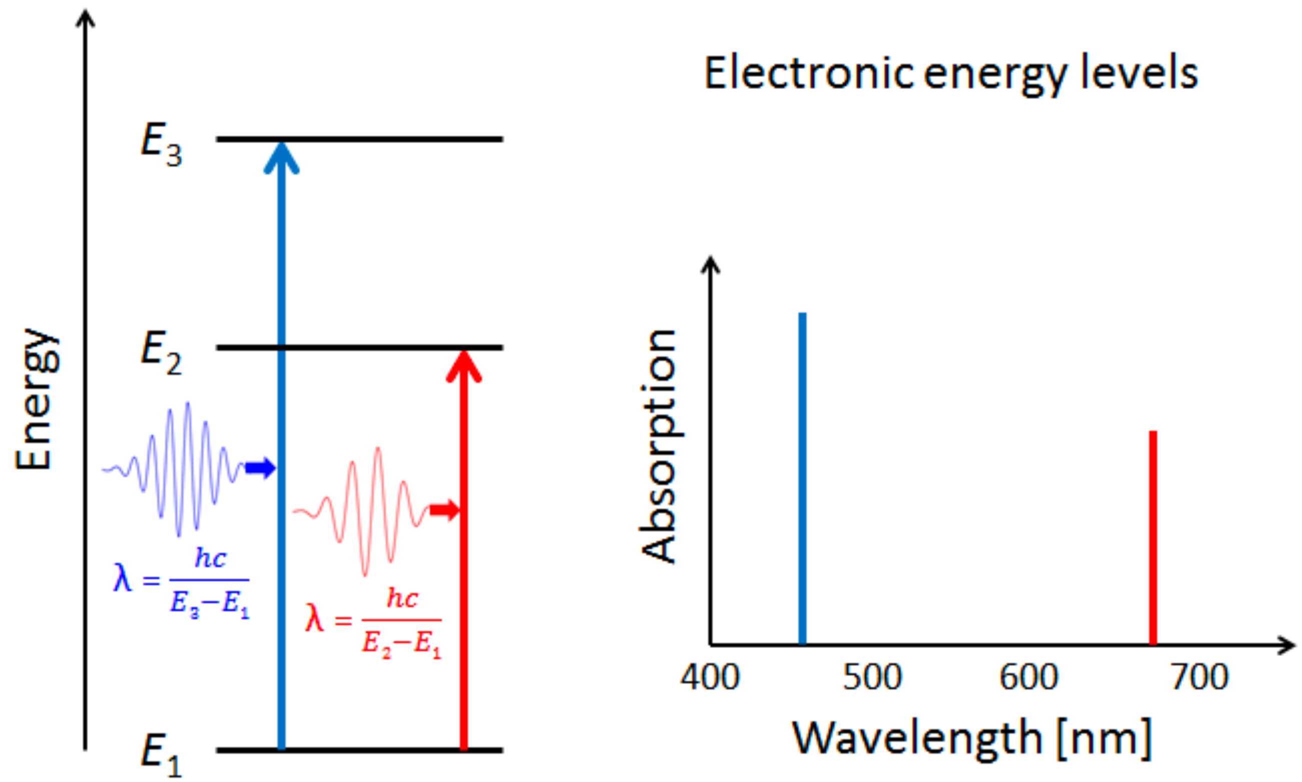

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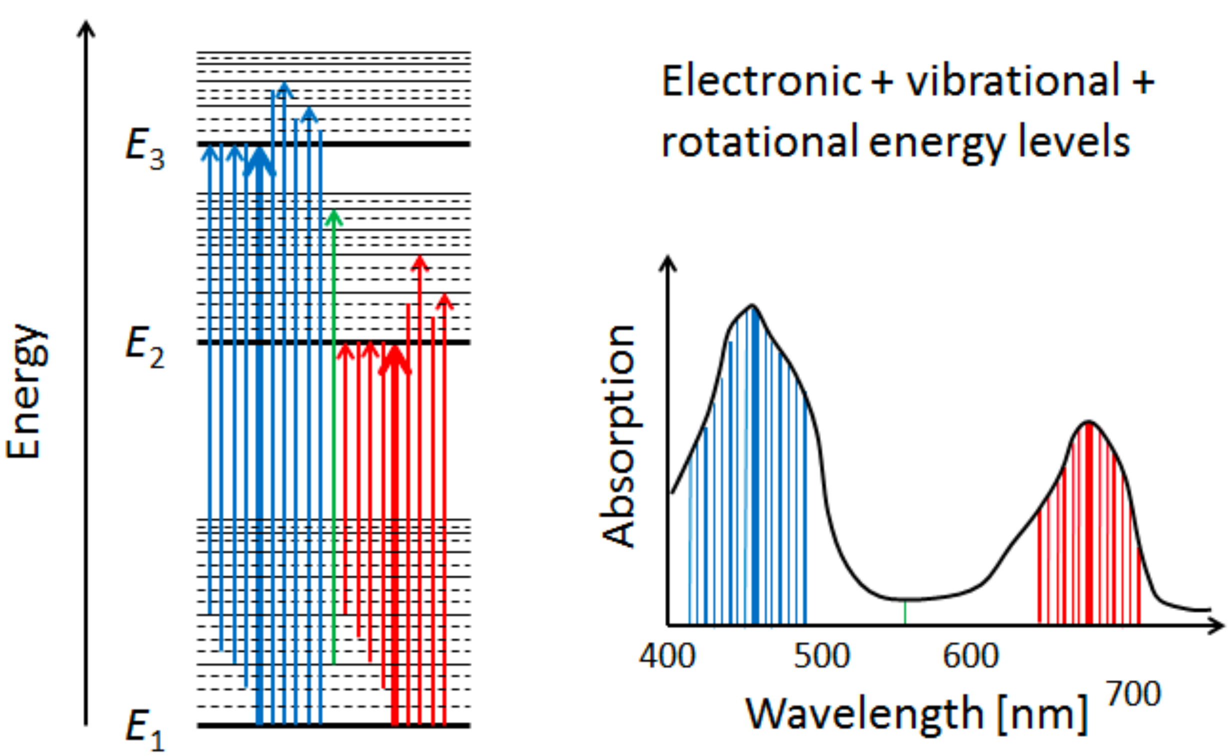
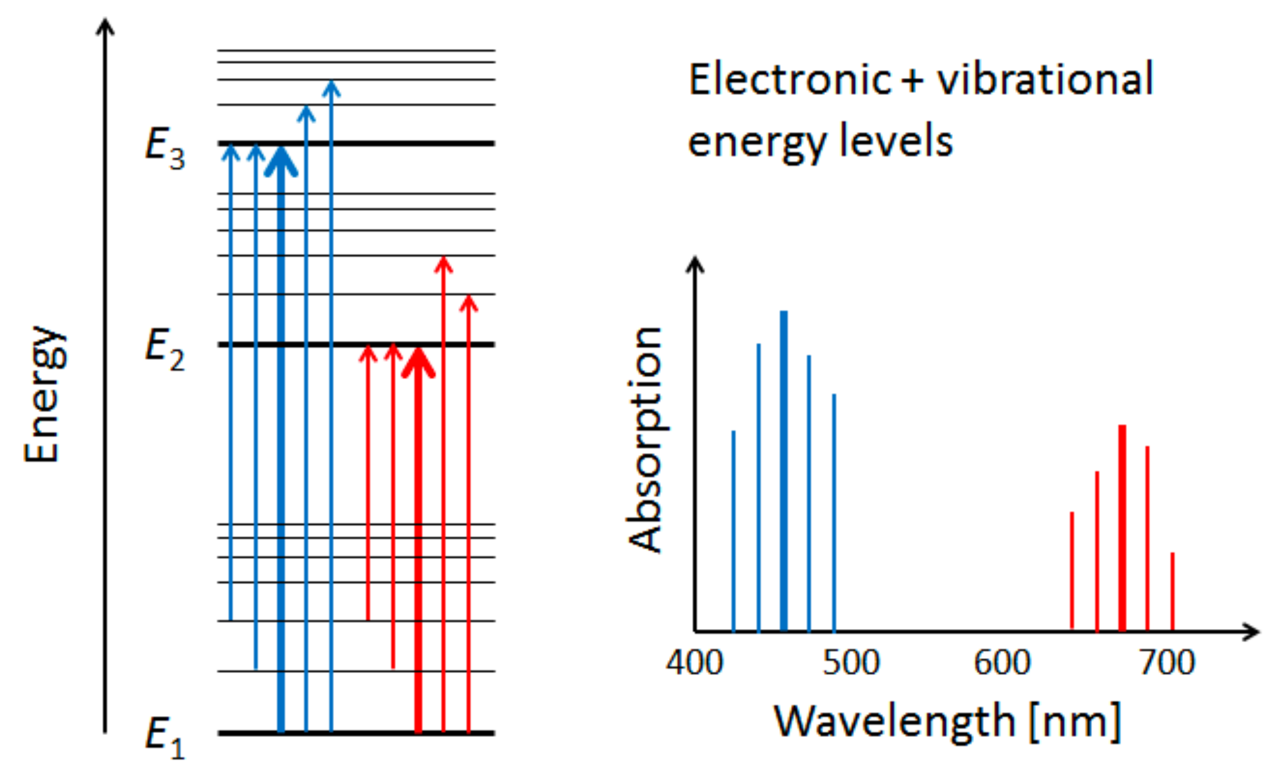
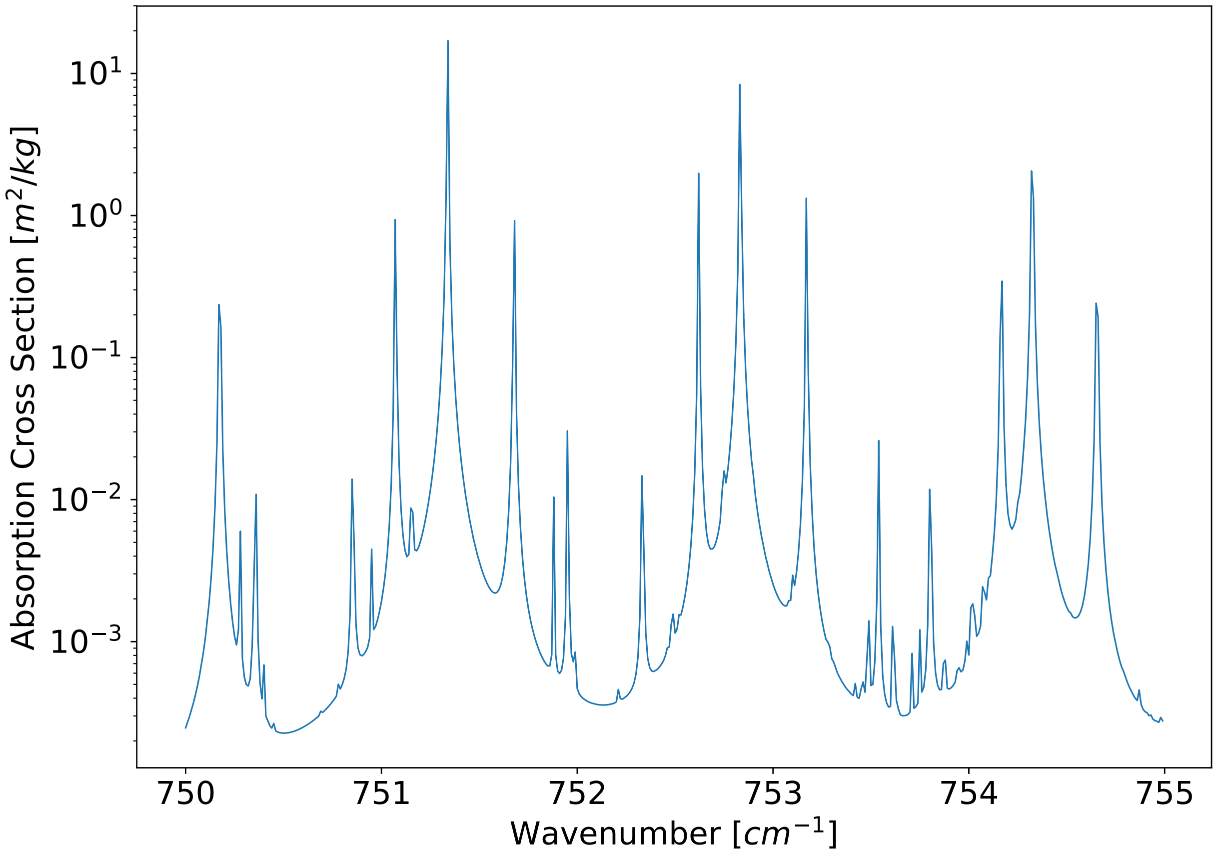




From "ocean optics" web book, https://www.oceanopticsbook.info/view/absorption/physics-of-absorption

Absorption cross-section

- Spike in absorption "efficiency" i.e. cross-section at wavenumber that excites a molecular transition: spikes called absorption lines
- Absorption "lines" look like Gaussian/Lorentzian $(\alpha_L/\pi)/\left((\nu-\nu_0)^2+\alpha_L^2\right)$ profiles due to "line broadening"
  - Pressure broadening due to molecular collisions
  - Doppler broadening due to gaussian distribution of particle velocities
- All individual lines calculated and broadened in radiative transfer code to give "absorption spectrum" for a greenhouse gas



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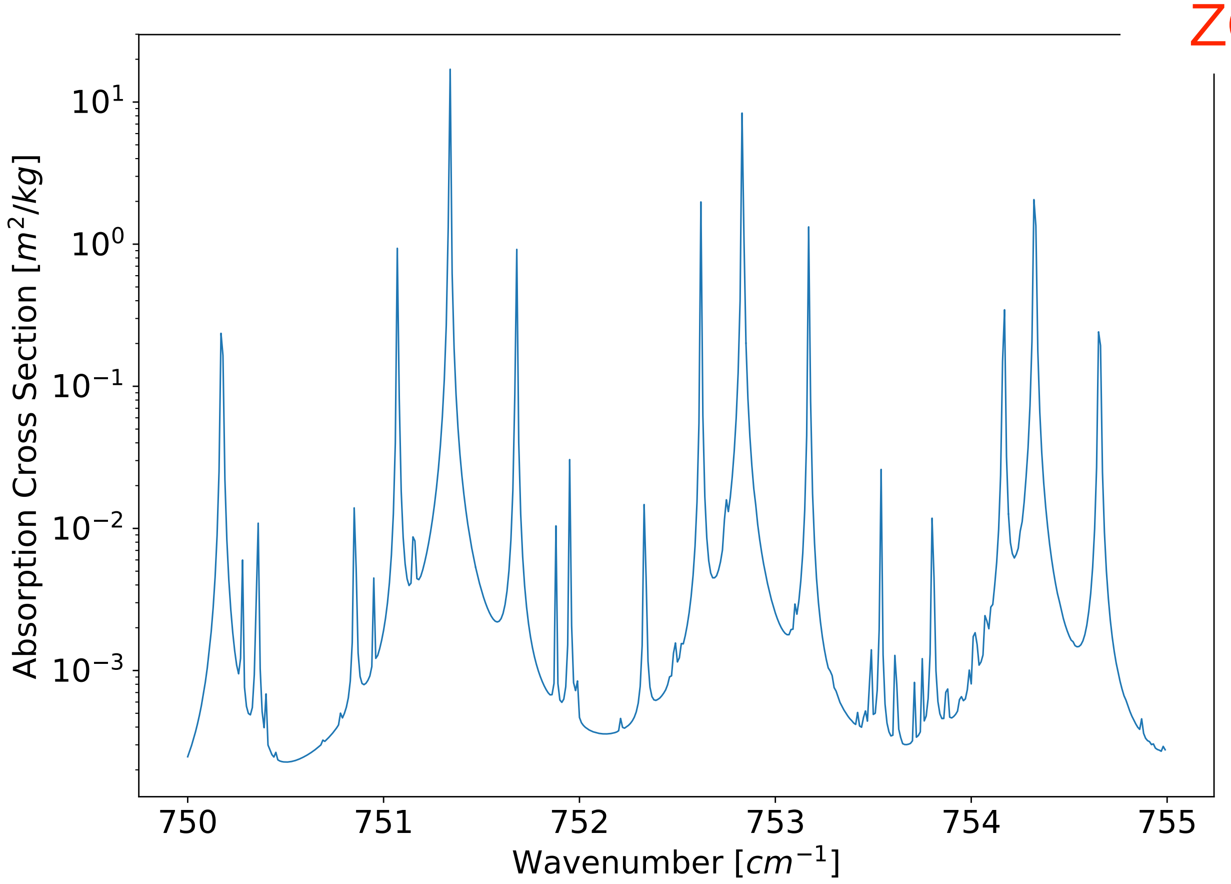
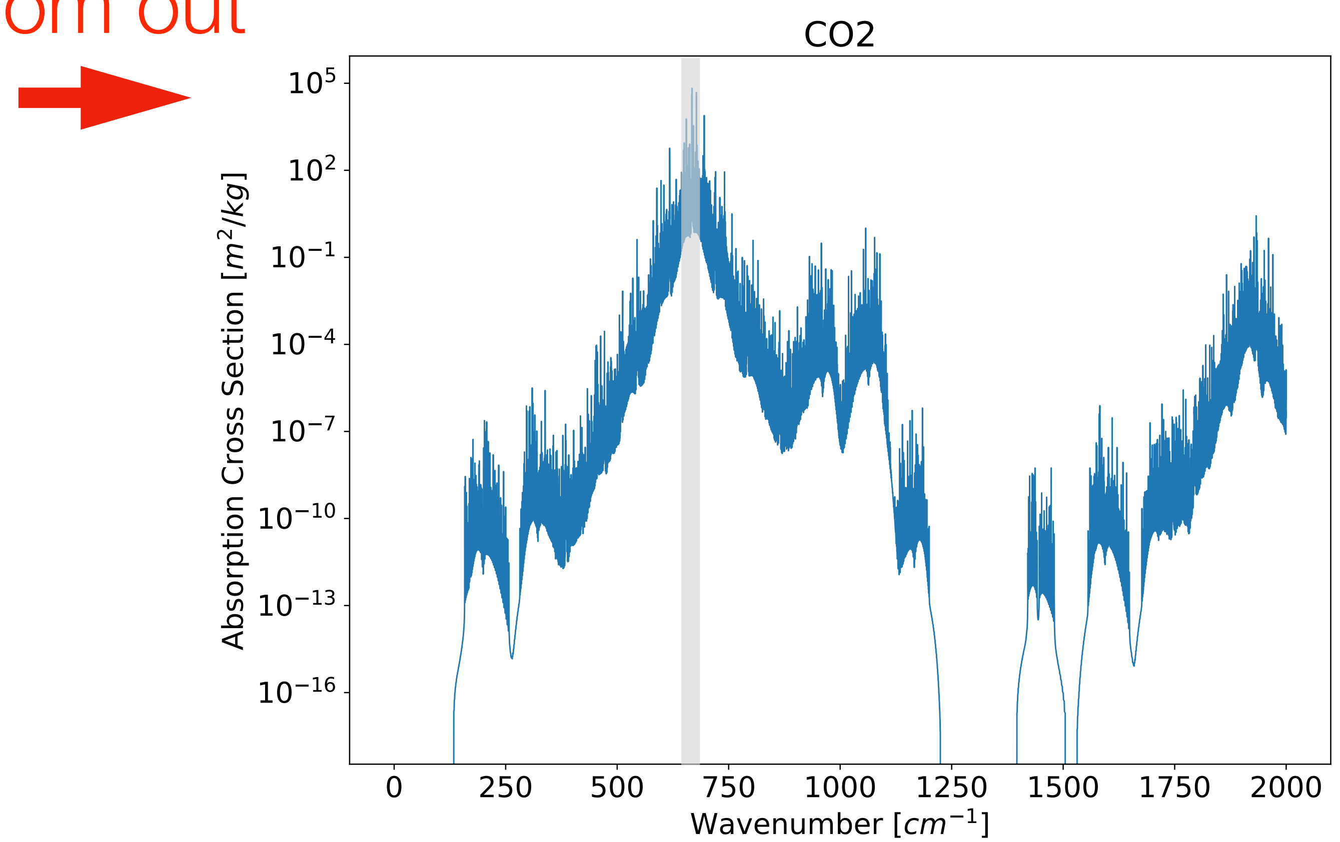


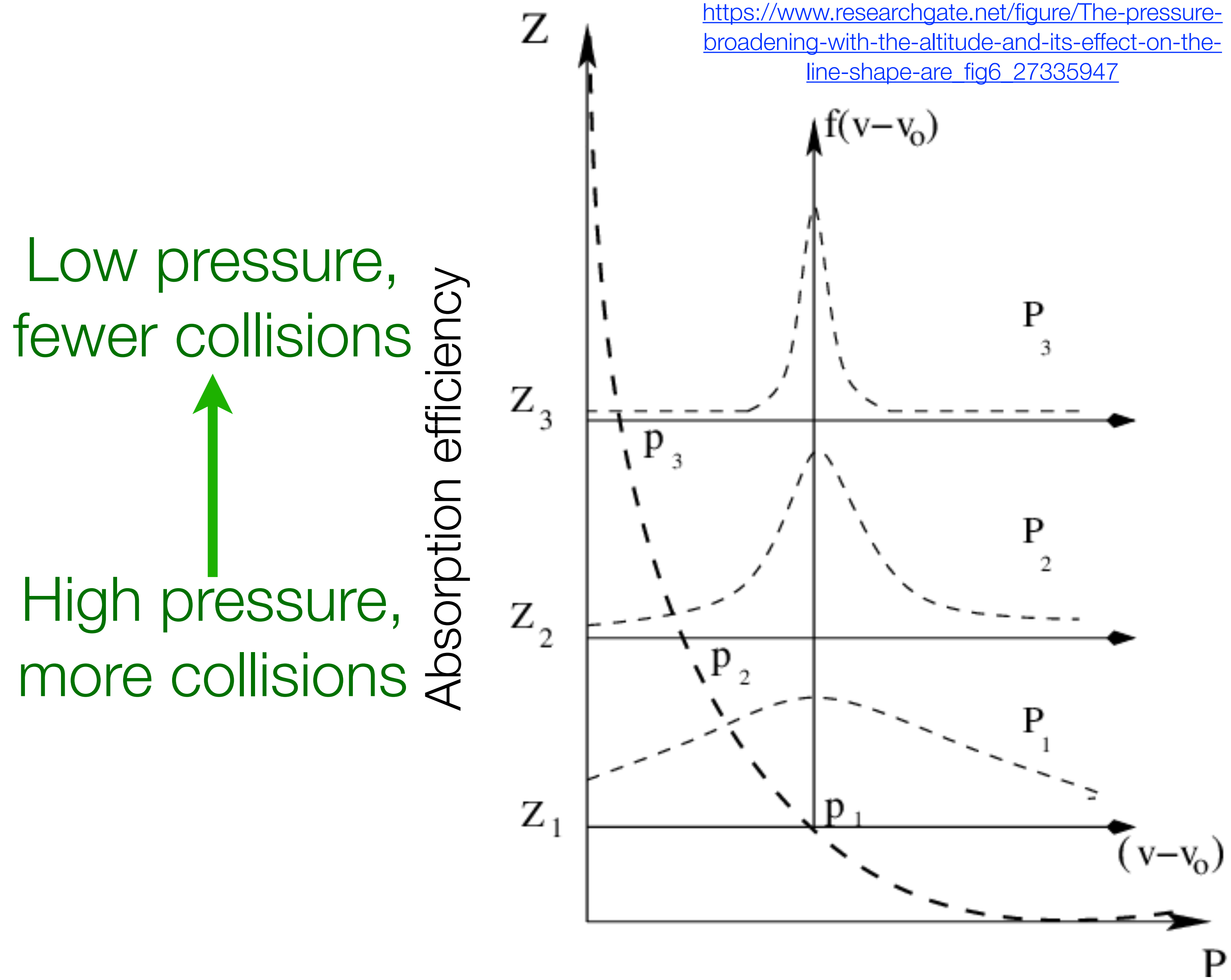
zoom out



Notes section 2.2.3: Broadening

(use next three slides)

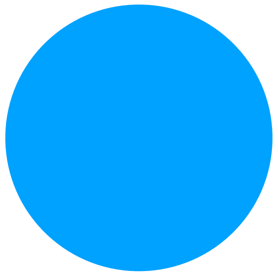
Pressure/Collisional Broadening



https://www.researchgate.net/figure/The-pressure-broadening-with-the-altitude-and-its-effect-on-the-line-shape-are_fig6_27335947

The collisions of gas molecules cause the widening of absorption lines: If the arriving photon has slightly more energy than needed for energy level transition, the excess energy can be transferred to the colliding molecule, allowing to absorb photons that are not exactly at the right frequency/ energy

Pressure/Collisional Broadening



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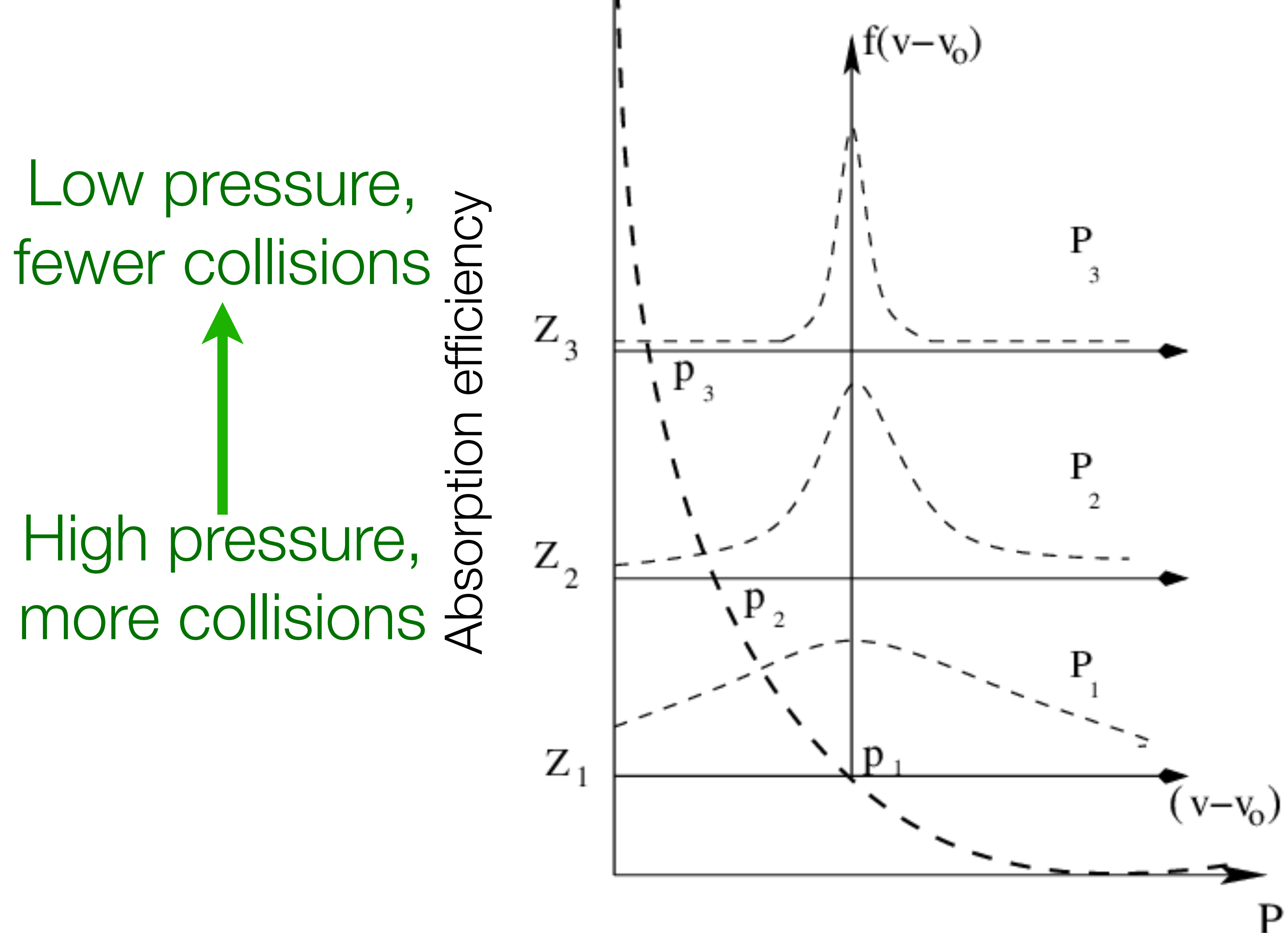

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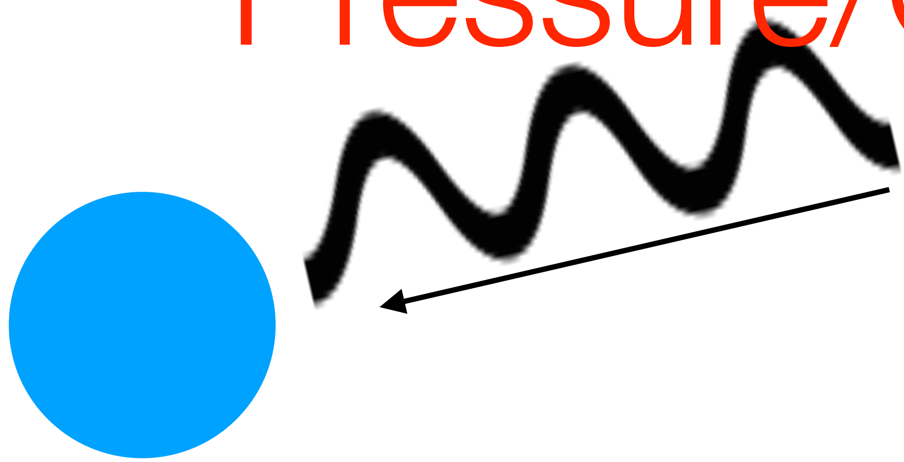

Low pressure, fewer collisions

High pressure, more collisions

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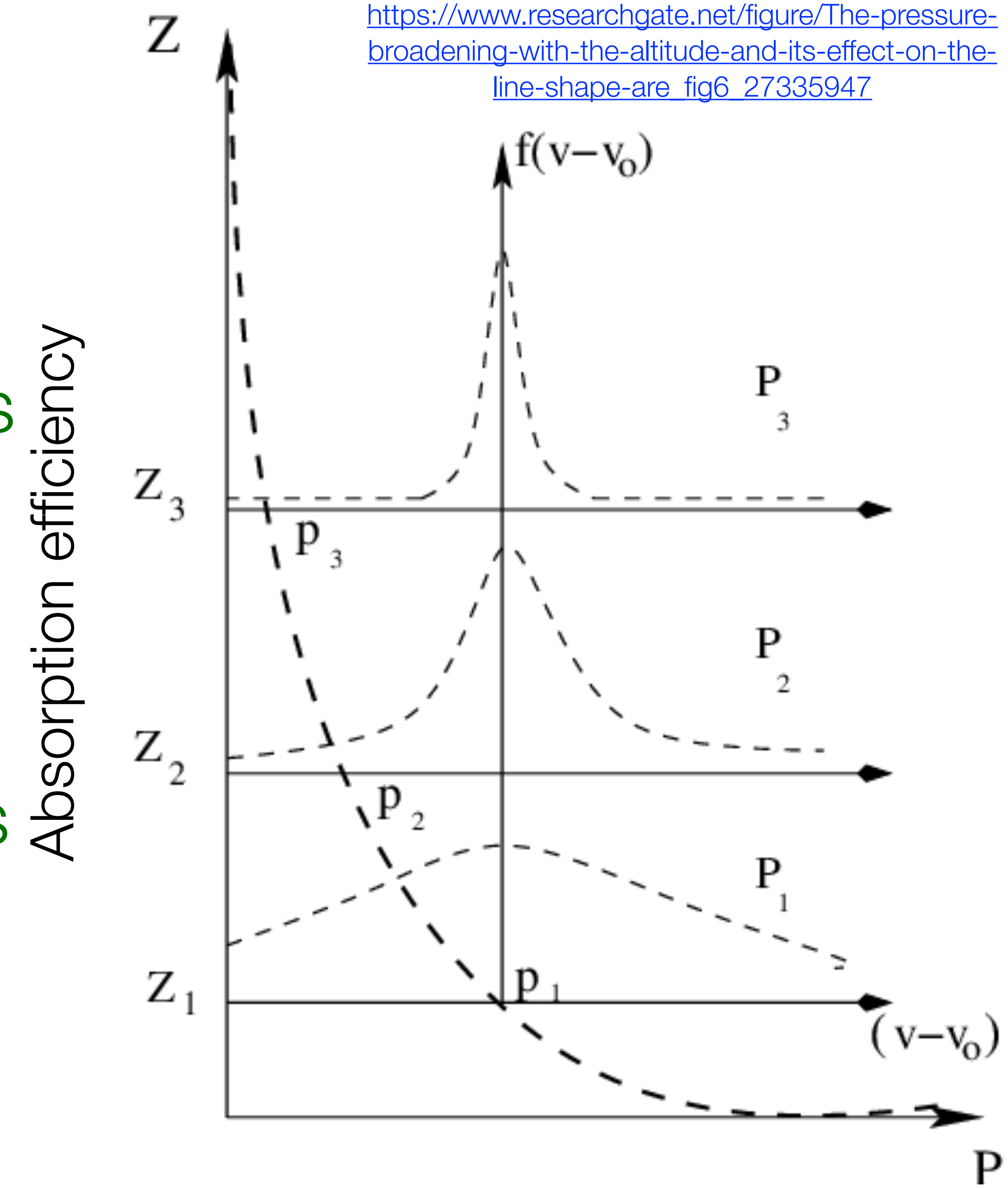

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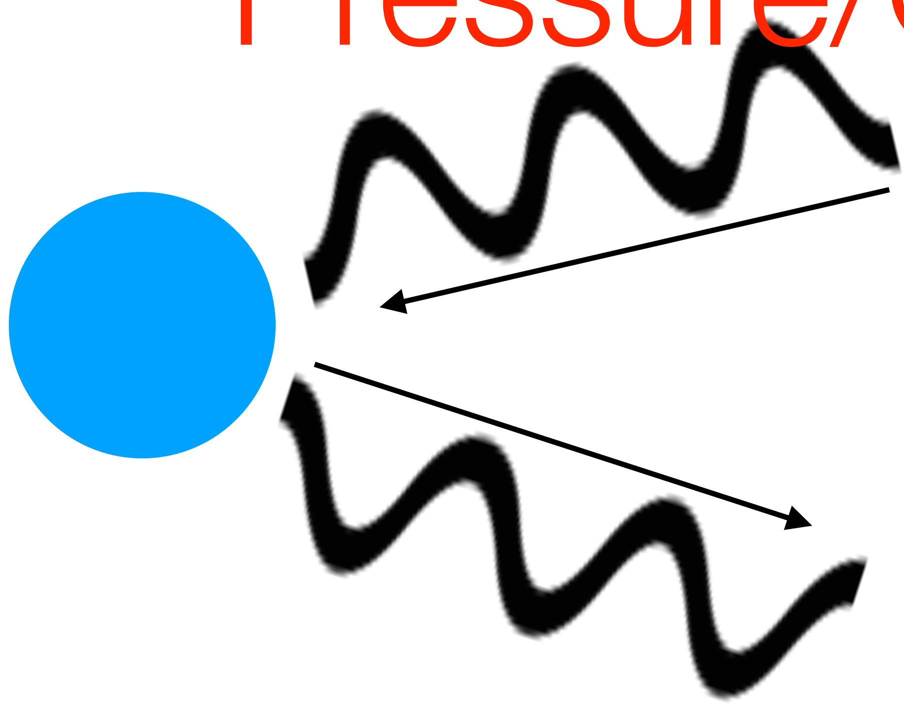
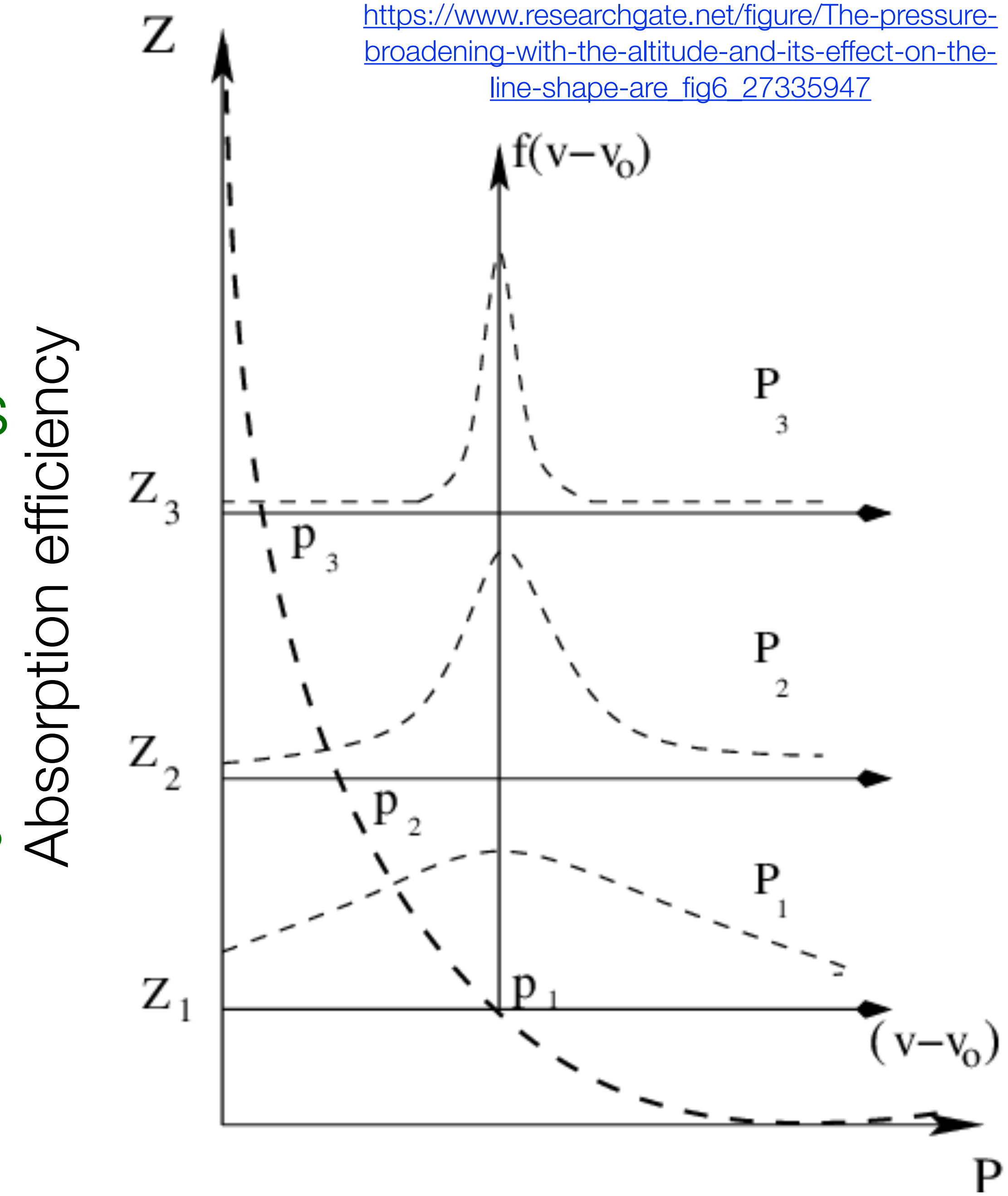


Low pressure,
fewer collisions

↑

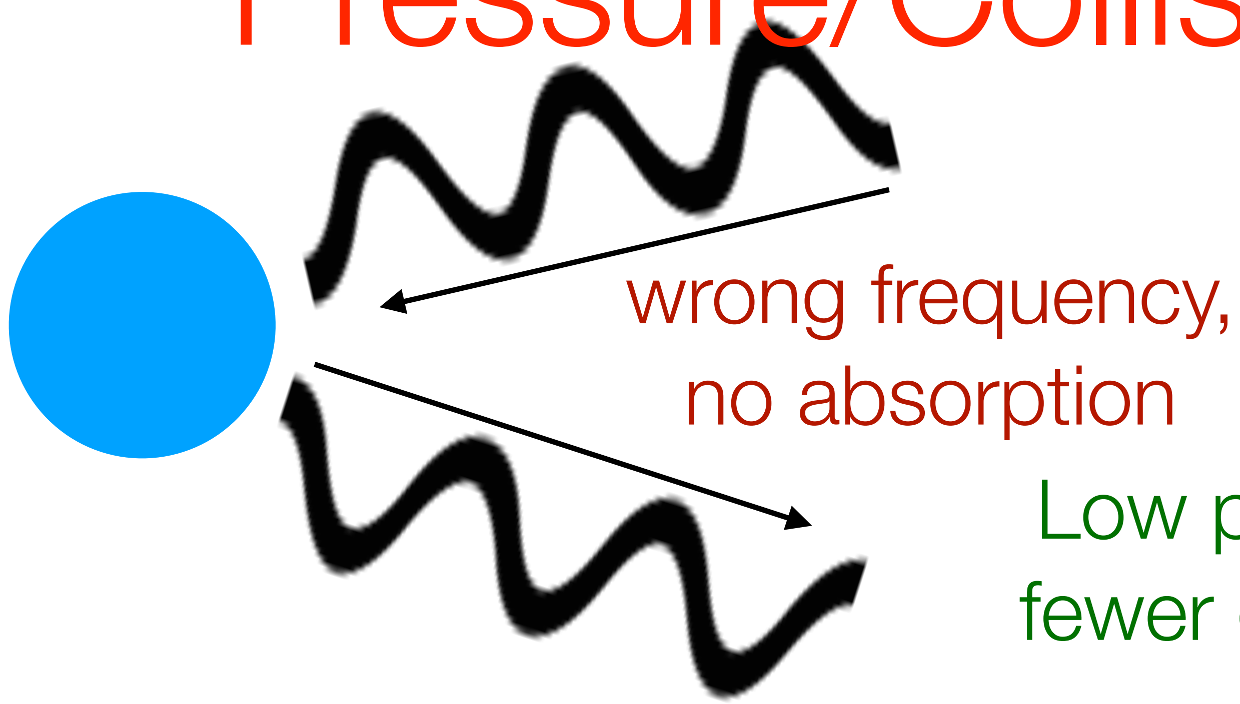
High pressure,
more collisions



https://www.researchgate.net/figure/The-pressure-broadening-with-the-altitude-and-its-effect-on-the-line-shape-are_fig6_27335947

The collisions of gas molecules cause the widening of absorption lines:
If the arriving photon has slightly more energy than needed for energy level transition, the excess energy can be transferred to the colliding molecule, allowing to absorb photons that are not exactly at the right frequency/ energy

Pressure/Collisional Broadening



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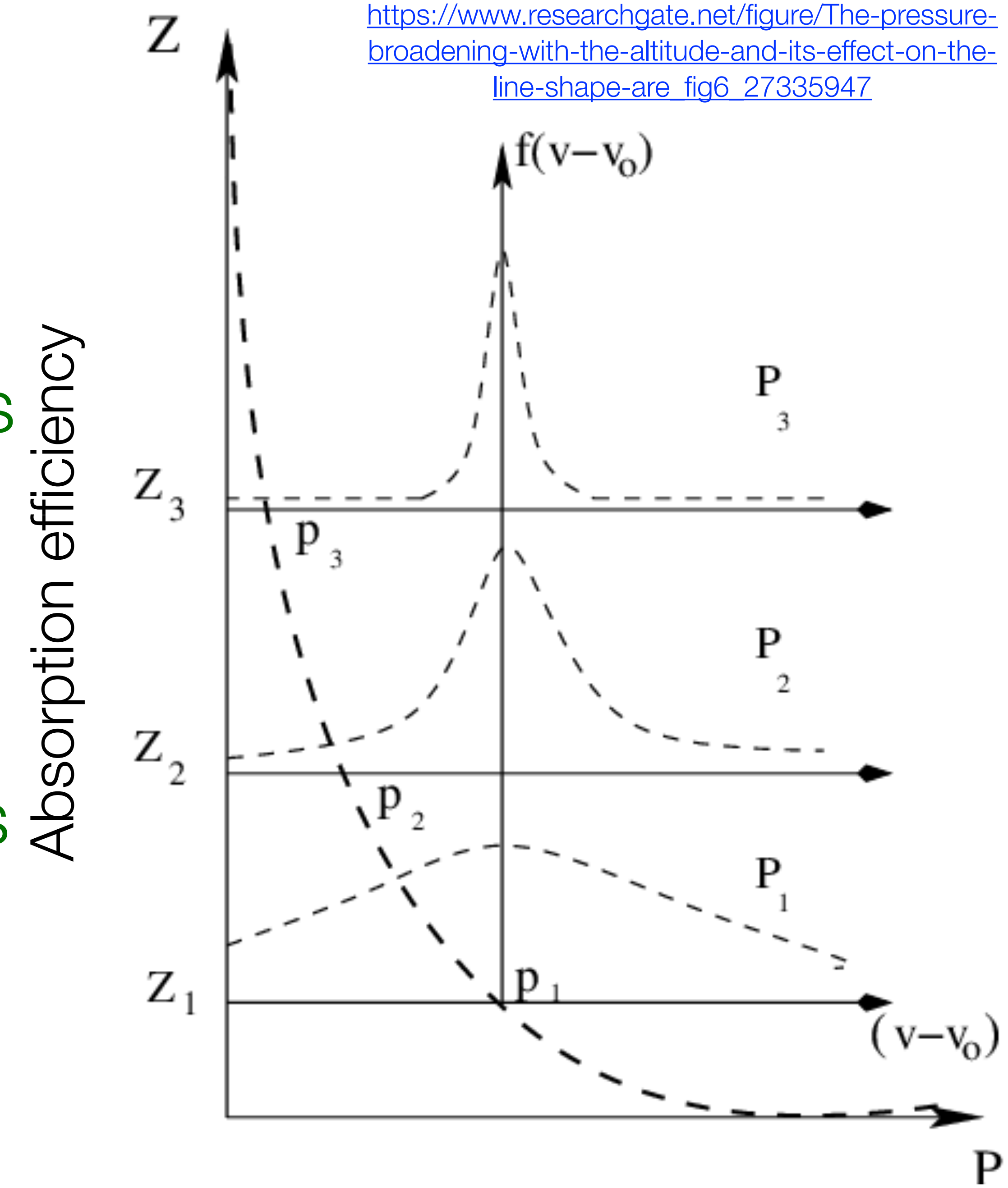

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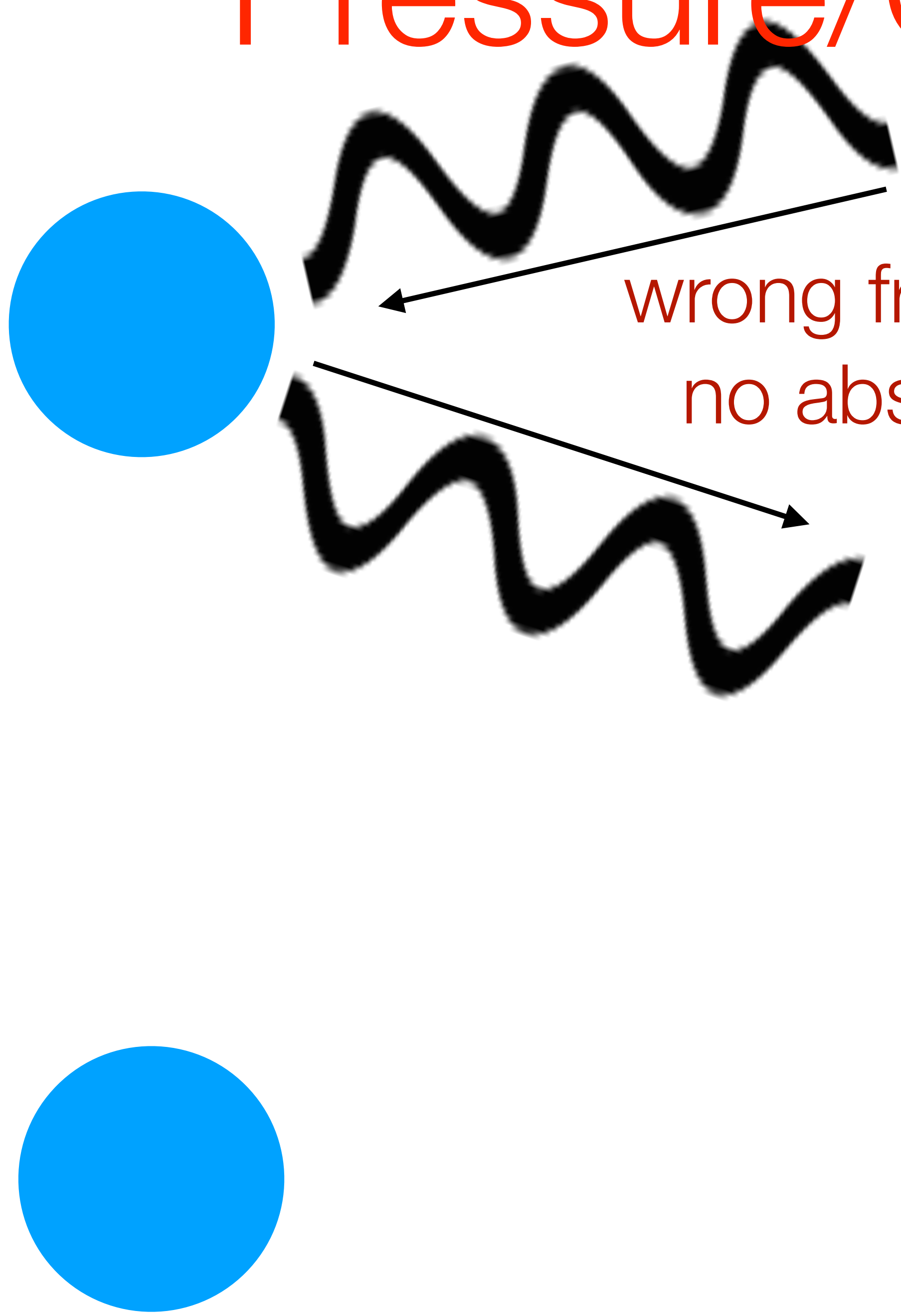

wrong frequency, no absorption

Low pressure, fewer collisions

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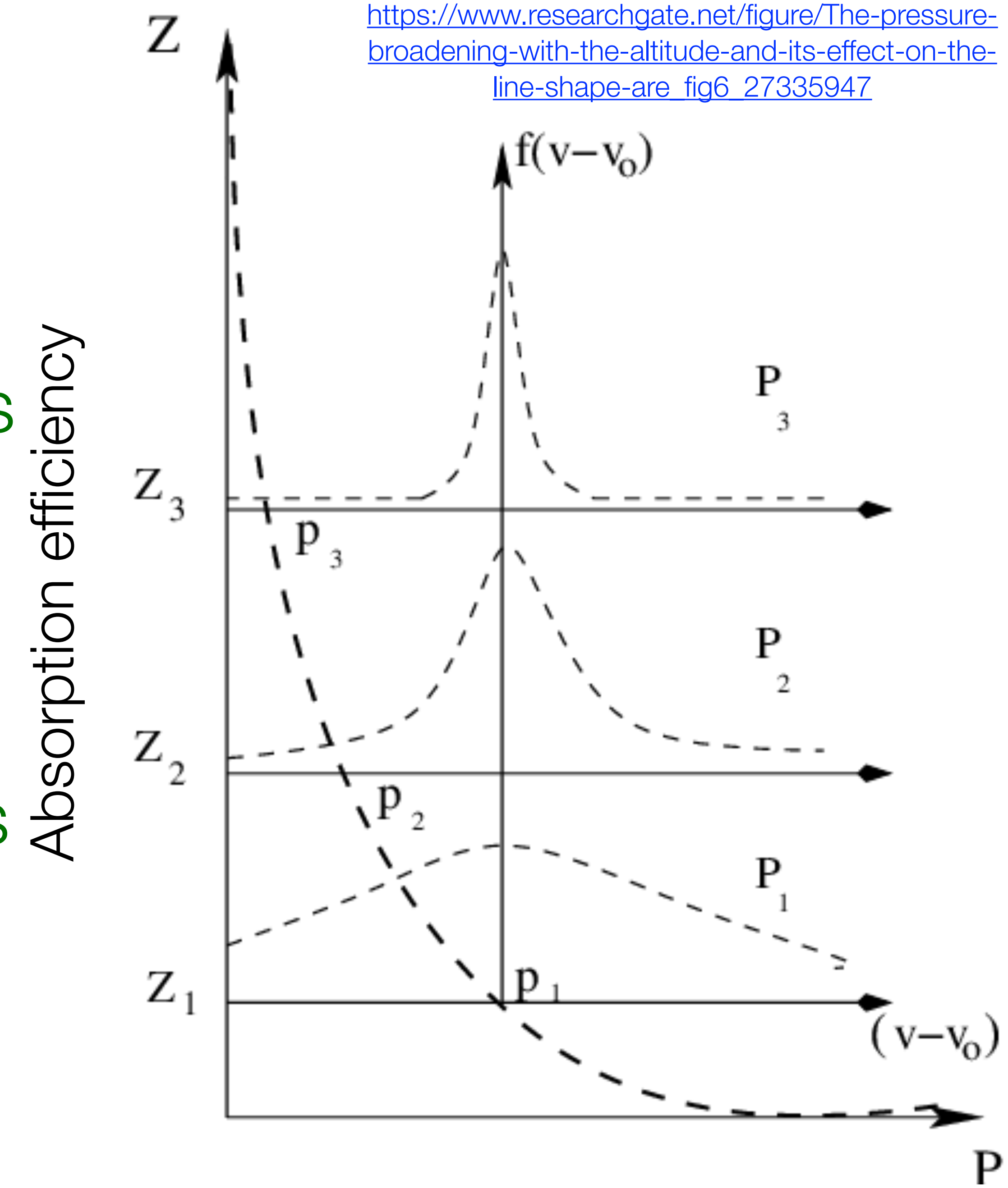

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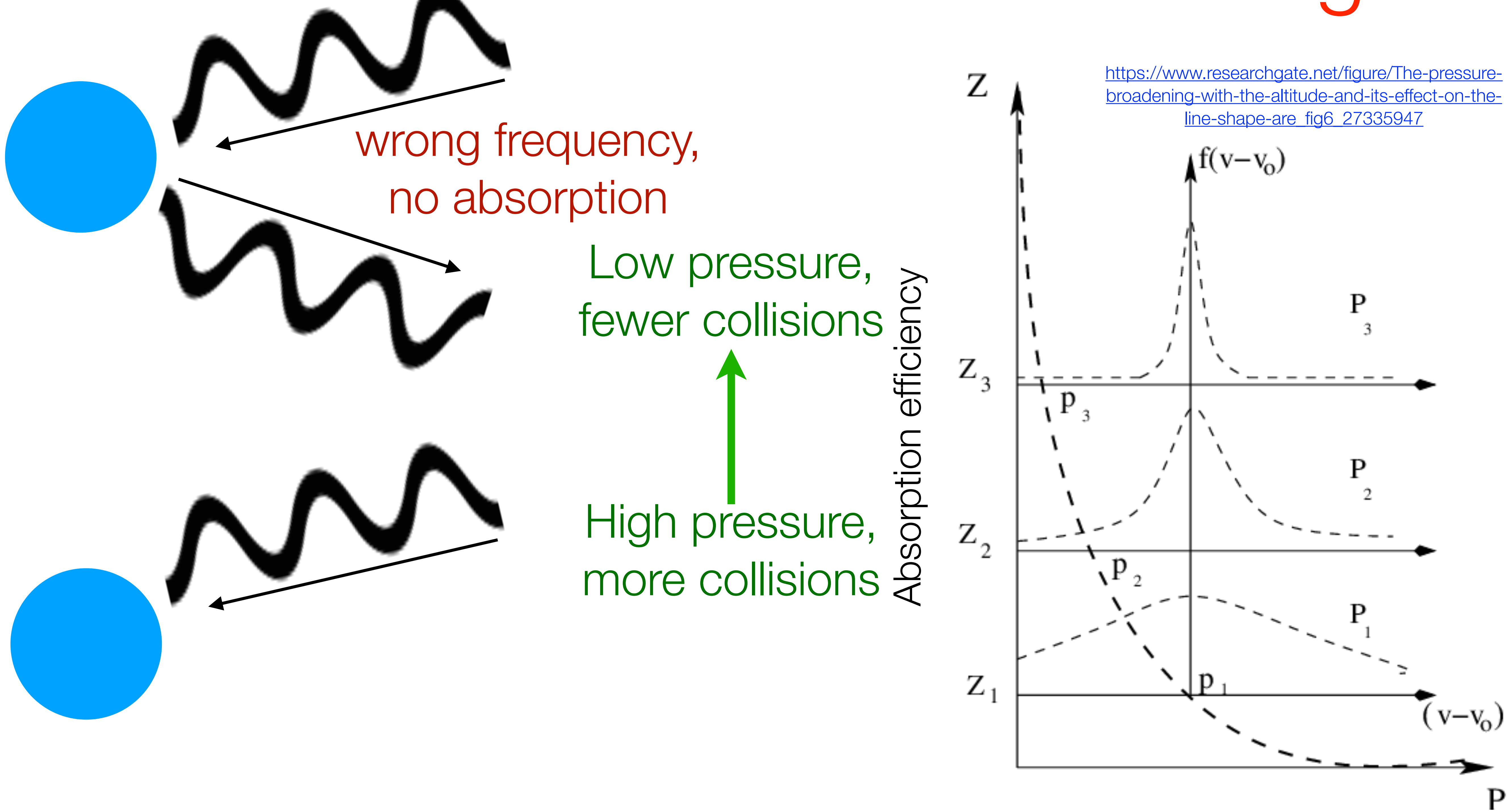

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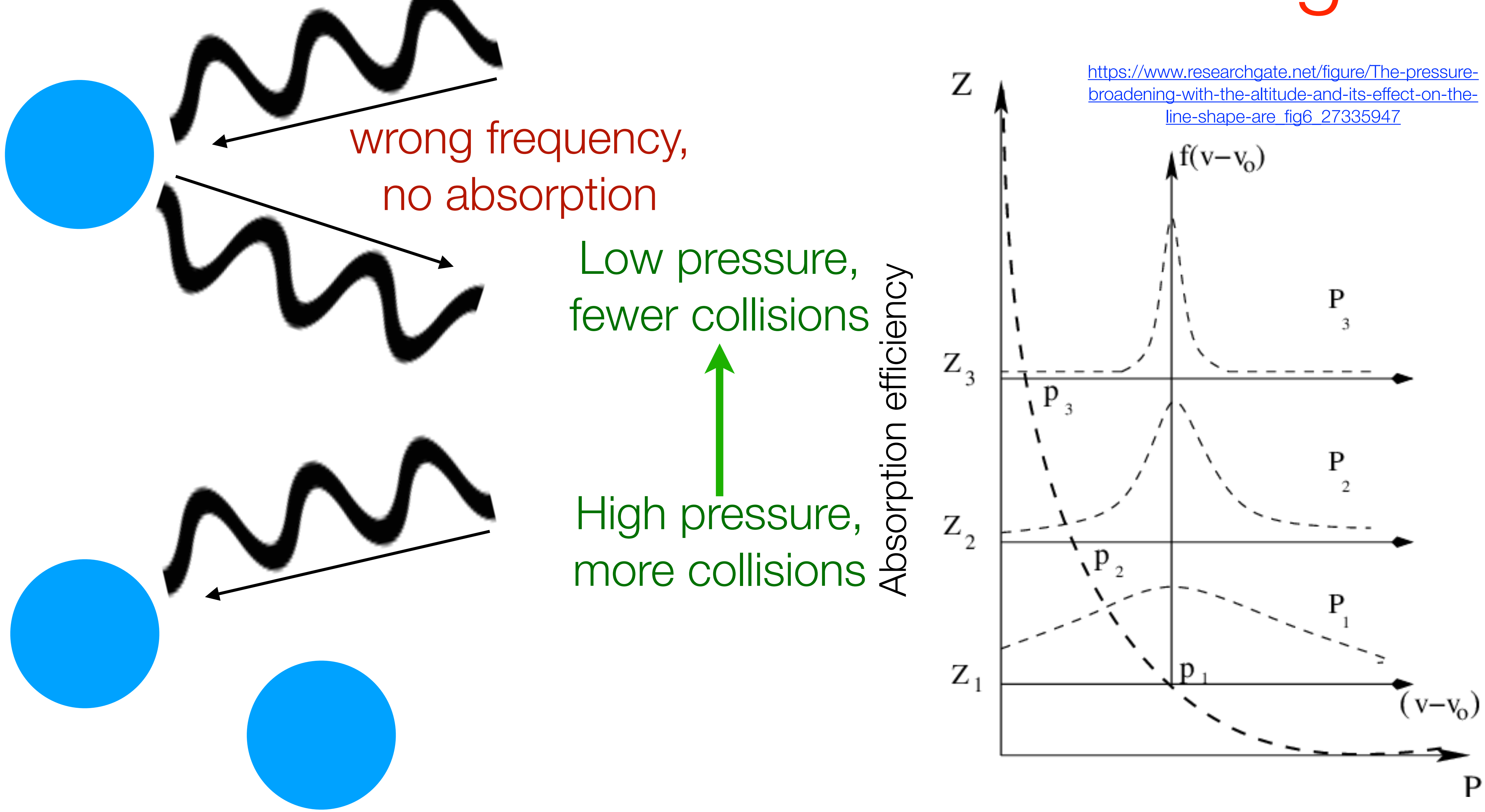

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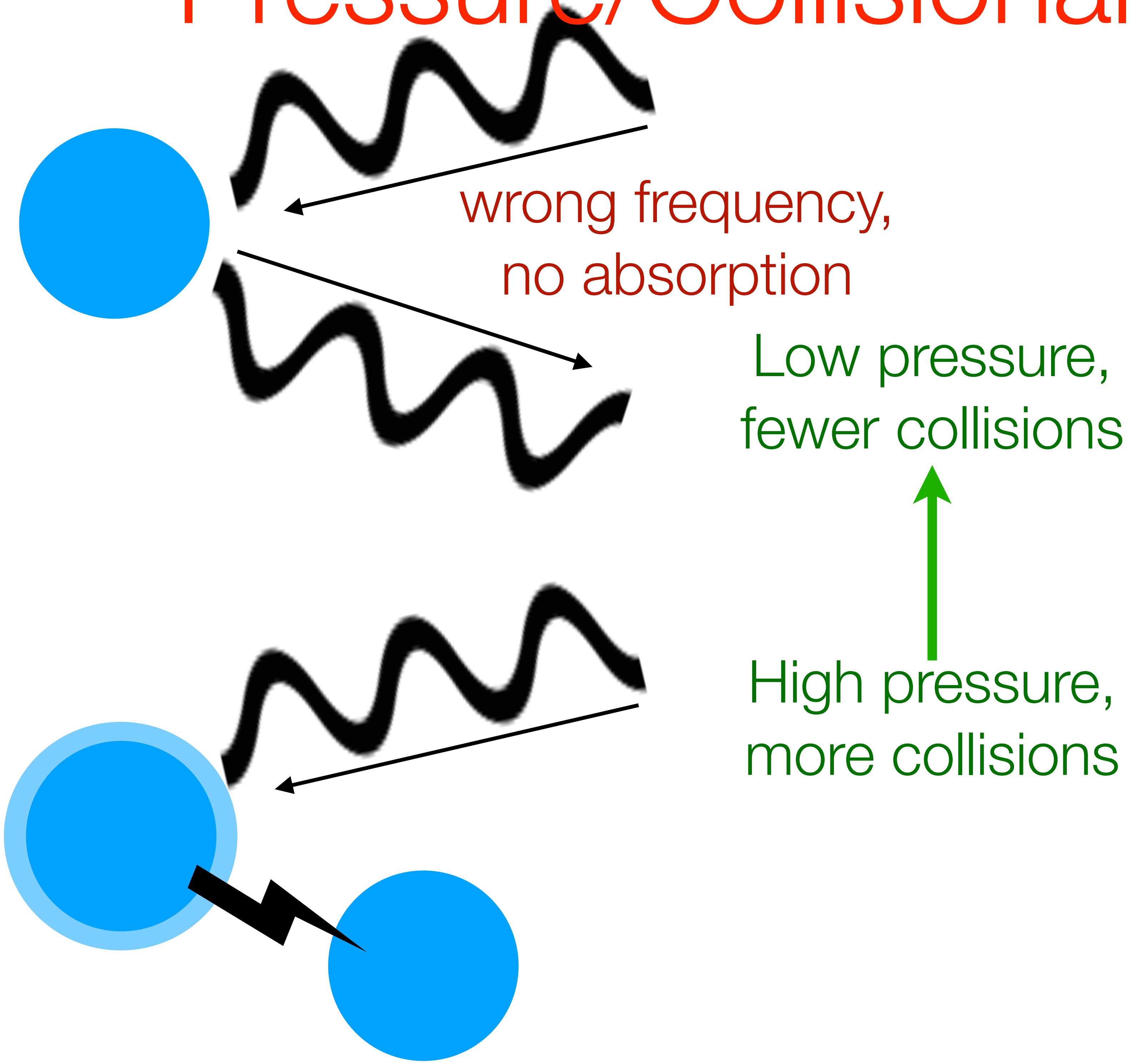

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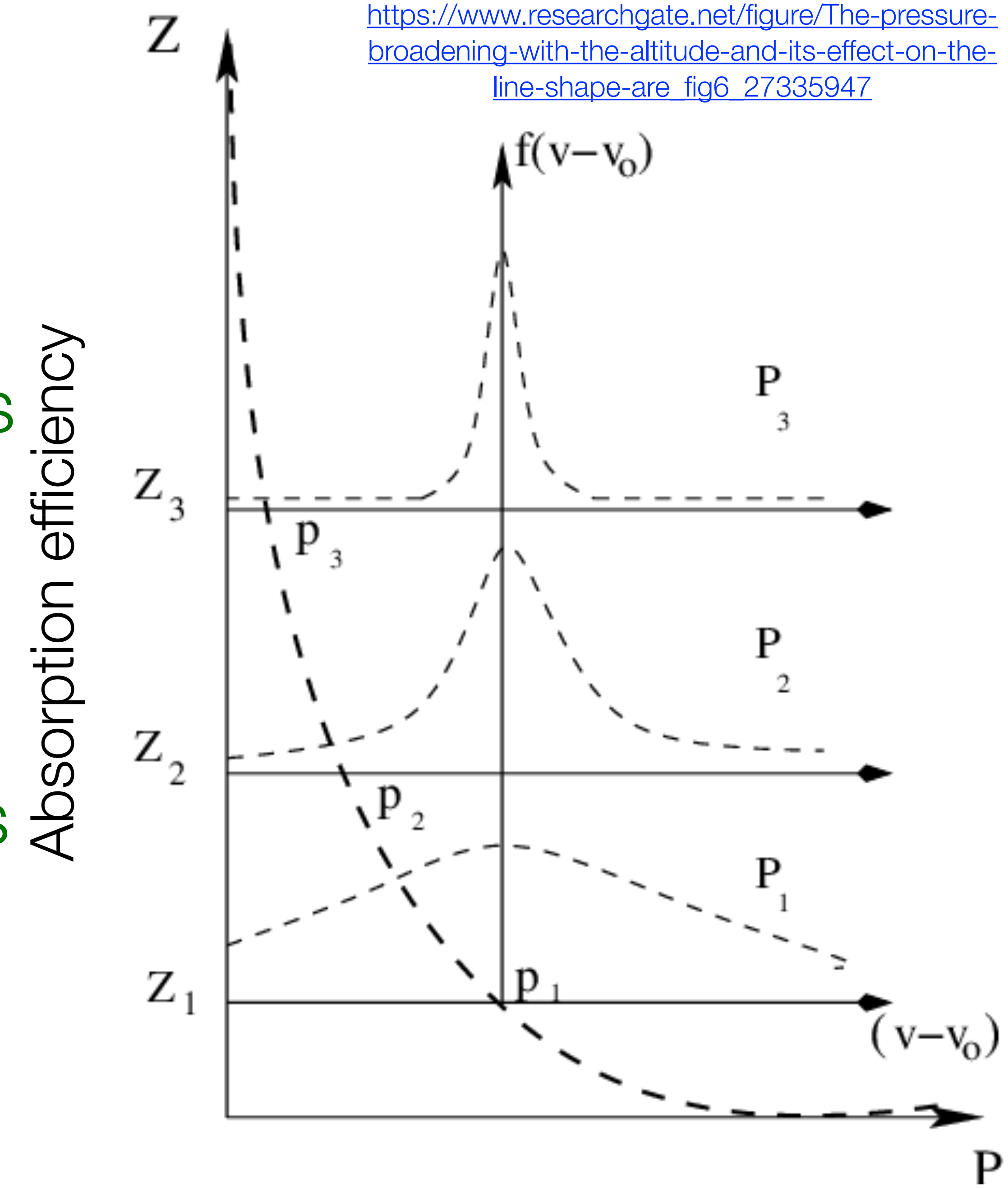

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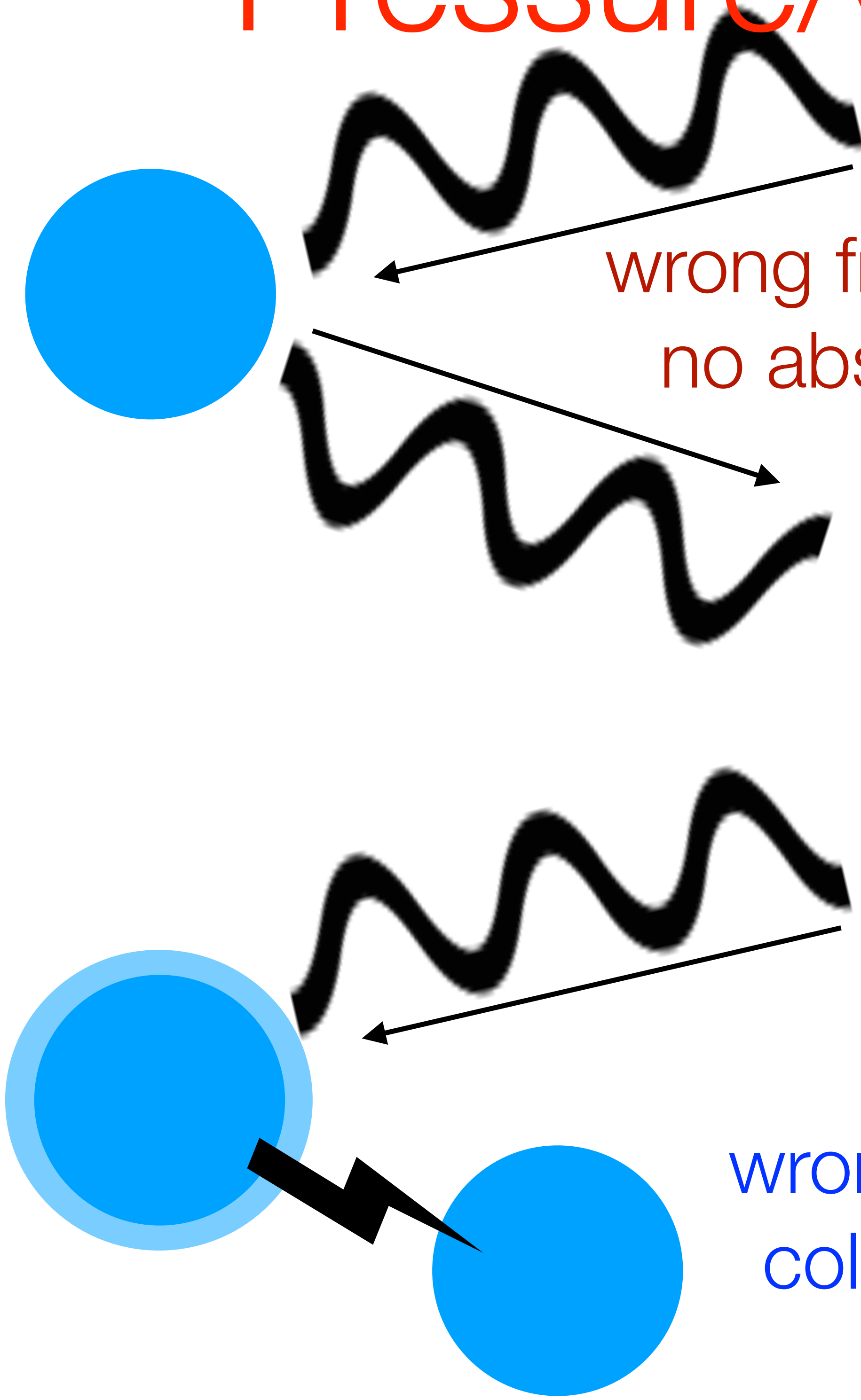

wrong frequency, no absorption

Low pressure, fewer collisions

High pressure, more collisions

wrong frequency, with collision, absorption possible

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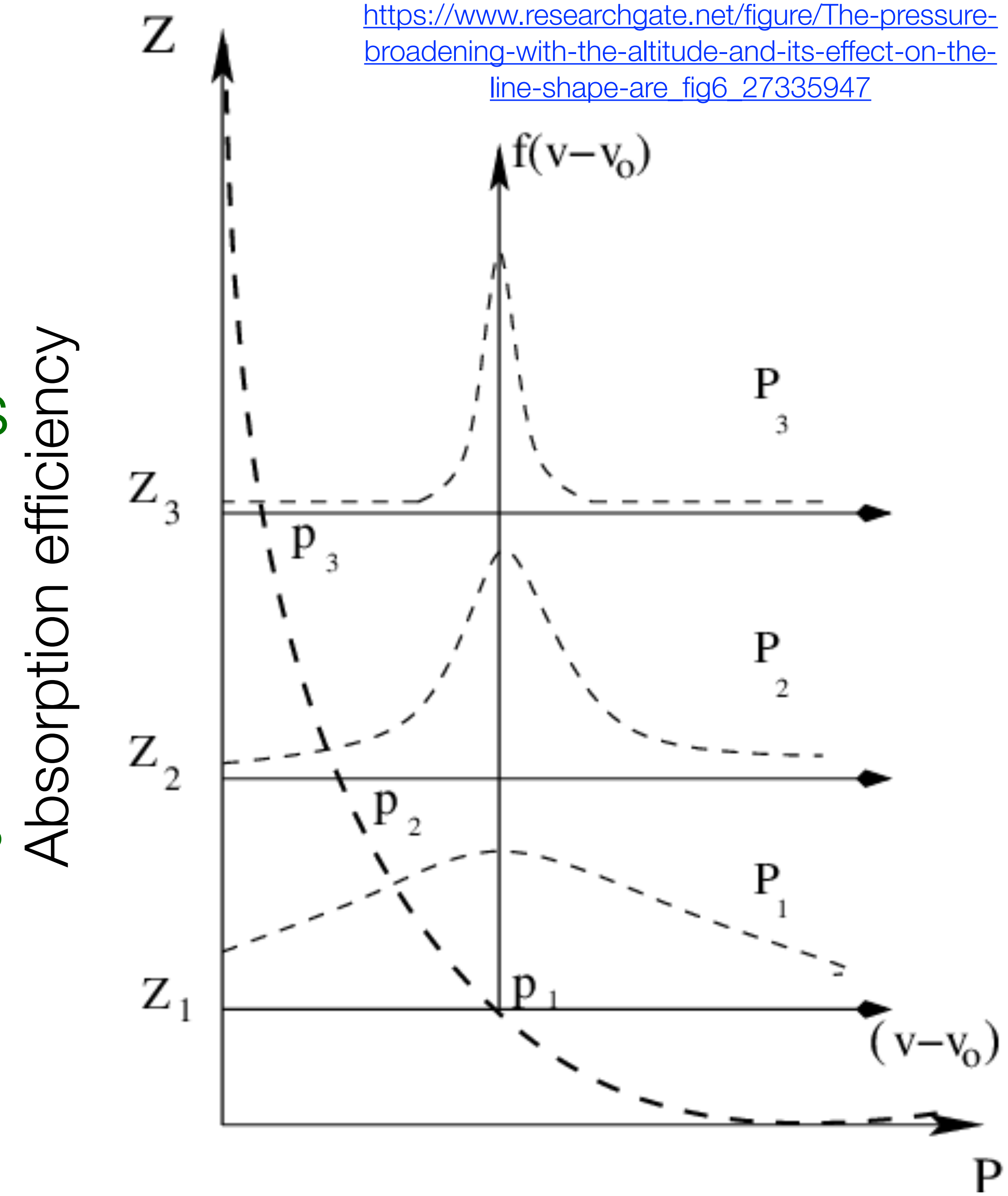

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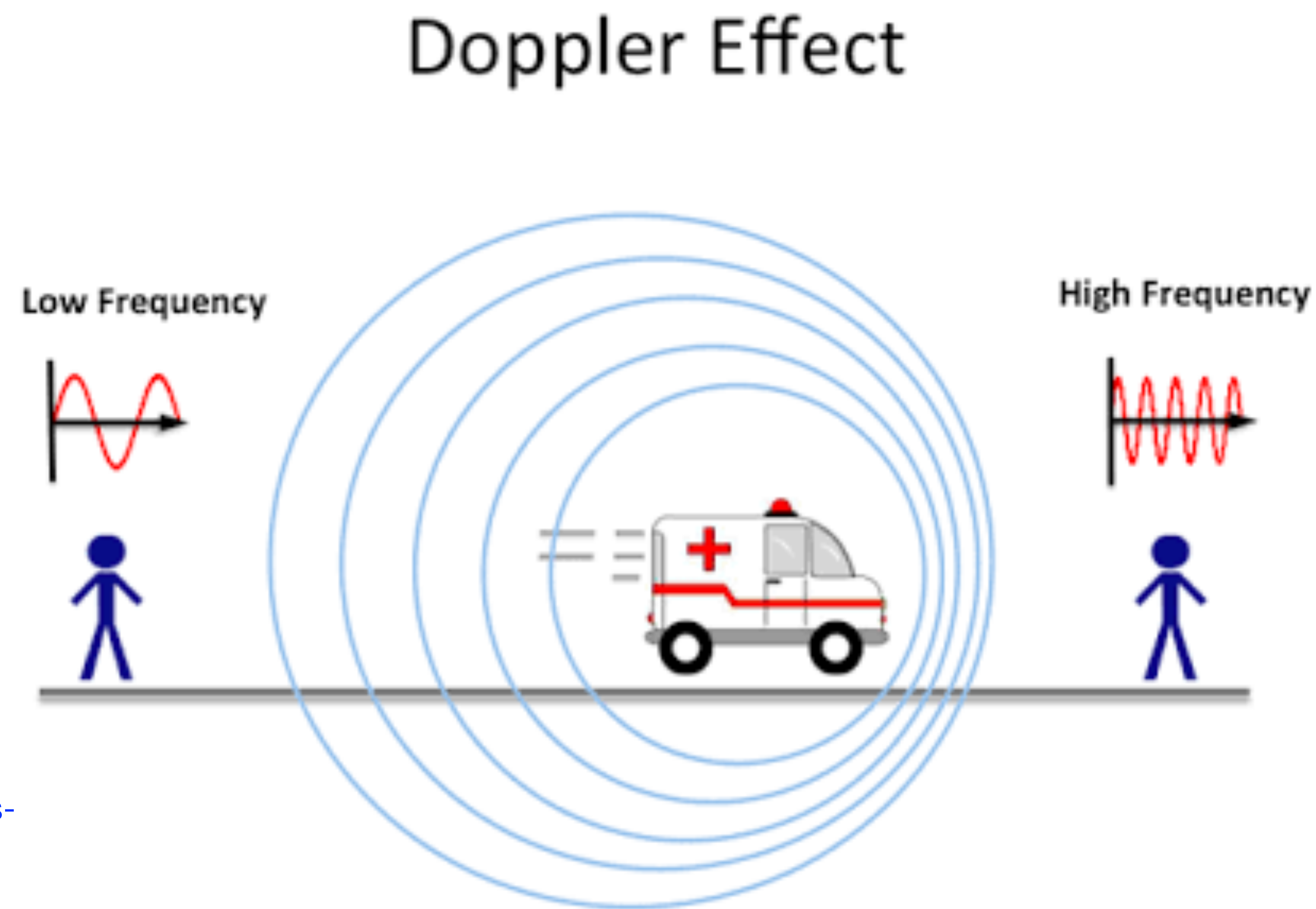
Doppler Broadening (significantly weaker in Earth's atmosphere)

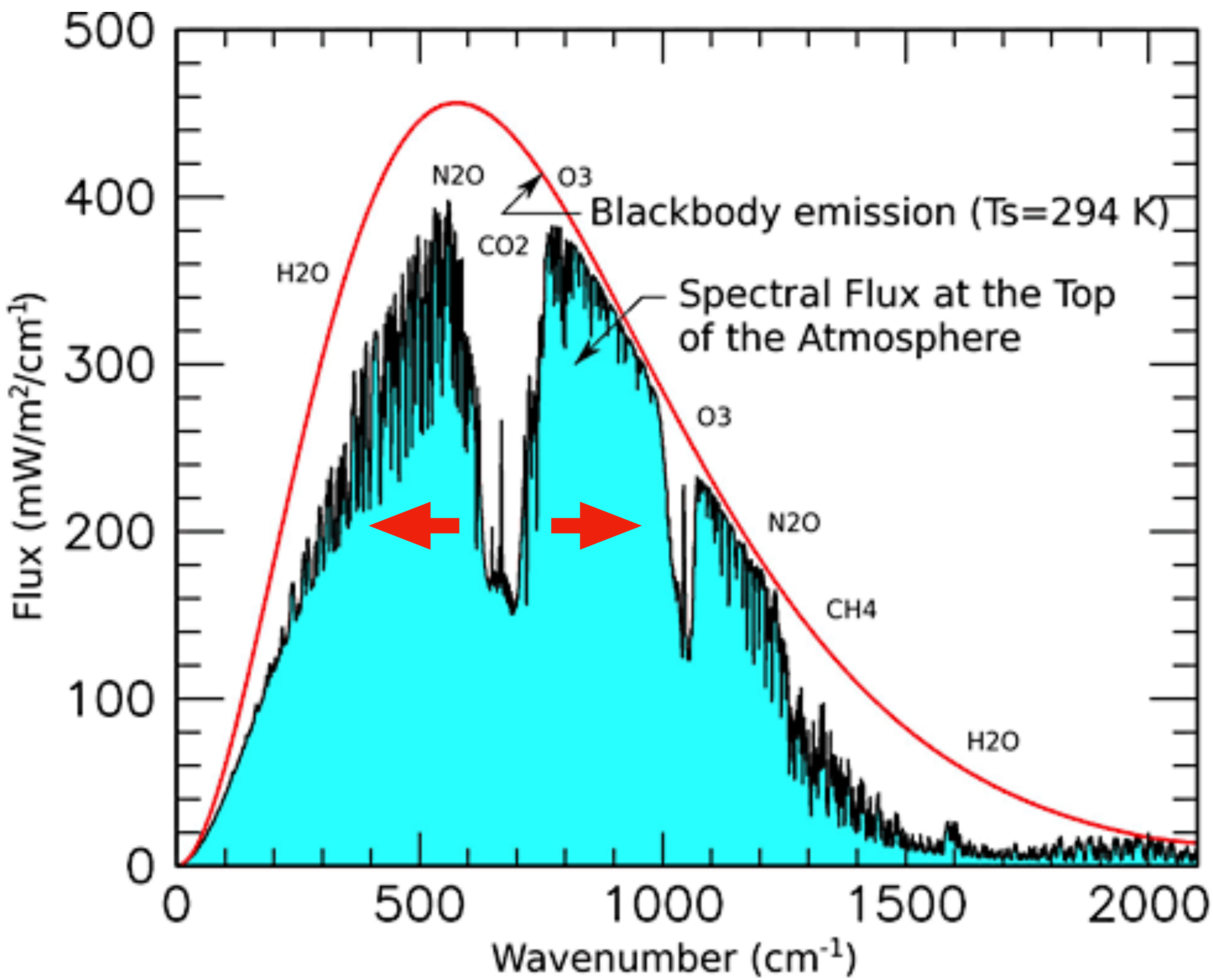


https://forum.huawei.com/enterprise/en/what-is-the-doppler-effect/thread/510221-100305

CO_2 molecule moves toward photon ➨ photon seems at higher frequency ➨ molecule absorbs a photon of lower frequency than that of absorption line.
CO_2 molecule moves away from photon ➨ opposite

The random motion of the gas molecules causes the widening of absorption lines because molecules that happen to be moving towards/away from the incoming photon will see it at a different frequency/ wavelengths.

Outgoing Longwave Radiation (OLR)



https://www.giss.nasa.gov/research/briefs/schmidt_05/

note absorption windows…

Workshop #3
radiative forcing

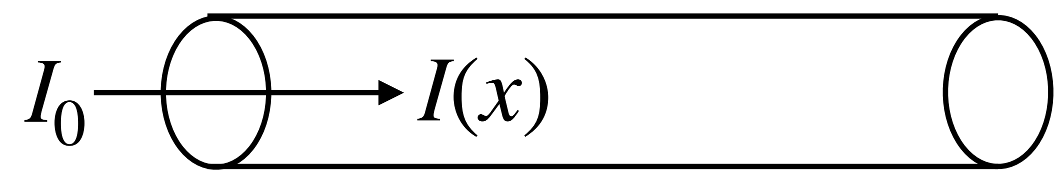
Notes sections 2.2.4, 2.2.5:
logarithmic dependence, global warming potential

(use next 5 slides)

Logarithmic dependence of RF on CO_2

The absorption is typically proportional to the radiation intensity at any given location, and therefore the equation for the transmitted radiation, I(x), may be written as $dI/dx = -\mu I$, where μ depends on the absorbing medium. The solution for the radiation intensity along the pipe is, therefore,

$$I(x) = I_0 e^{-\mu x}$$



For CO_2, the RF varies logarithmically with concentration. We showed in section 3.2 that the warming and radiative forcing are approximately linearly related. This implies that the temperature response also depends logarithmically on the CO_2 concentration. We, therefore, write, schematically,

$$T = T_0 + A \log_2(CO_2/280)$$

which implies:

$$T_{\times 2} - T_{\times 1} = A \log_2(2CO_2/280) - A \log_2(CO_2/280) = A \log_2 2 = A,$$

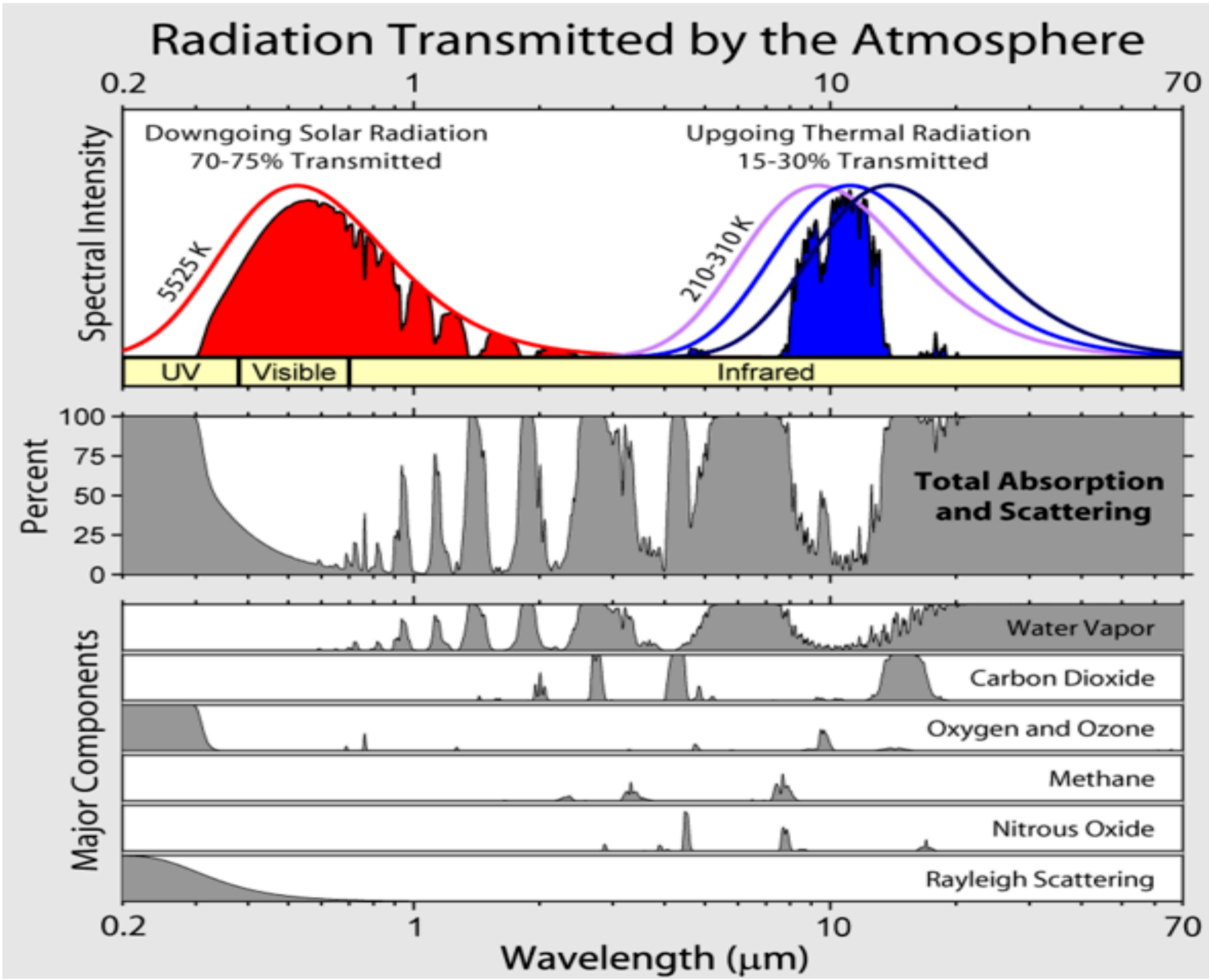
$$T_{\times 4} - T_{\times 2} = A \log_2(4CO_2/280) - A \log_2(2CO_2/280) = A \log_2 2 = A.$$

That is, each doubling of CO_2 leads to the same increase in temperature!

What about other greenhouse gases?

How do we quantify their effect relative to that of CO_2?

IR absorption of the major greenhouse gases



https://en.wikipedia.org/wiki/Absorption_band

CO_2 & water vapor absorbs the most IR, at different wavelengths

Other GHG: Global Warming Potential (GWP)

GWP: the time-integrated RF due to a pulse emission of a GHG, relative to a pulse emission of an equal mass of CO_2

IPCC, Climate Change 2013, Chapter 8

Other GHG: Global Warming Potential (GWP)

GWP: the time-integrated RF due to a pulse emission of a GHG, relative to a pulse emission of an equal mass of CO_2

The GWP of a greenhouse gas is its radiative forcing effect relative to CO_2, given its lifetime and strength as an absorber over a specified time horizon (TH).

IPCC, Climate Change 2013, Chapter 8

Other GHG: Global Warming Potential (GWP)

GWP: the time-integrated RF due to a pulse emission of a GHG, relative to a pulse emission of an equal mass of CO_2

$$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)]\, dt}{\int_0^{TH} a_r \cdot [r(t)]\, dt}.$$

The GWP of a greenhouse gas is its radiative forcing effect relative to CO_2, given its lifetime and strength as an absorber over a specified time horizon (TH).

$x(t)$: time-dependent decay of a GHG; $r(t)$: that of CO_2; $a_{x,r}$: RF per 1 kg ($W/m^2/kg$).

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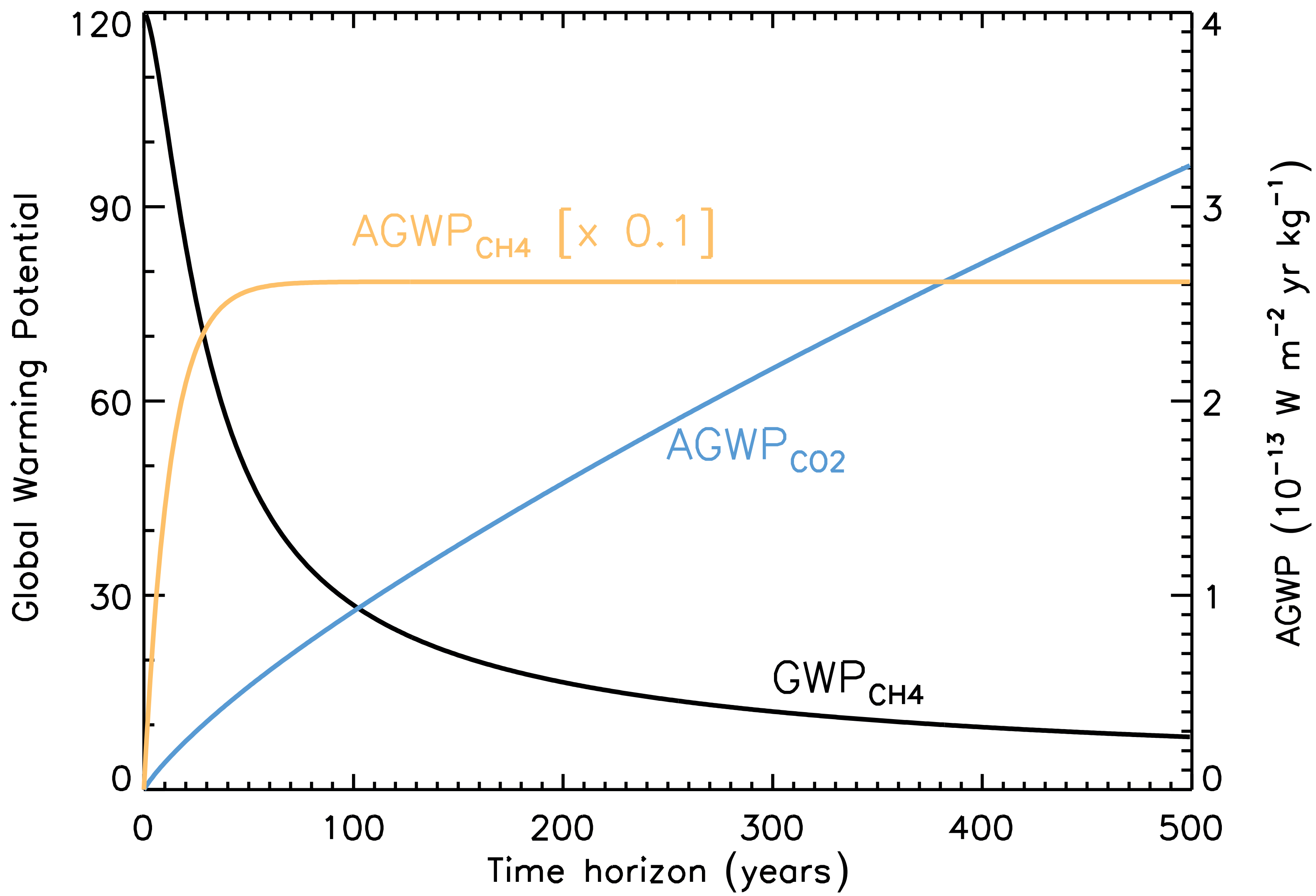

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GWP values and lifetimes	Lifetime in years	Global Warming Potential (GWP)		
		20 years	100 years	500 years
Methane	12.4	86	34	
Nitrous oxide (N_2O)	121.0	268	298	
Nitrous oxide (N_2O)	121.0	264	265	
HFC-134a (hydrofluorocarbon)	13.4	3790	1550	

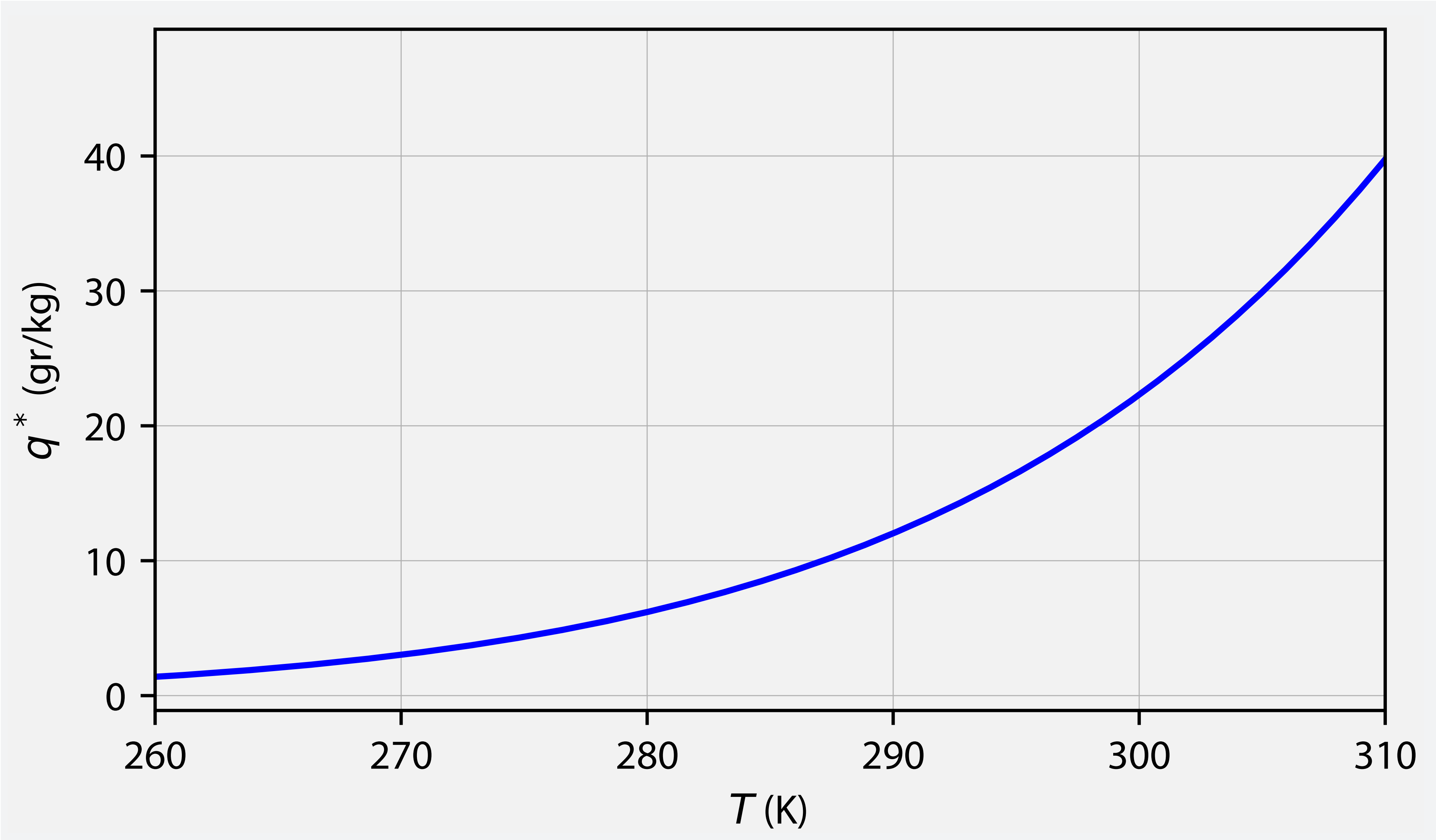
wikipedia

Notes sections 2.2.6:
water vapor feedback

(use next 2 slides)

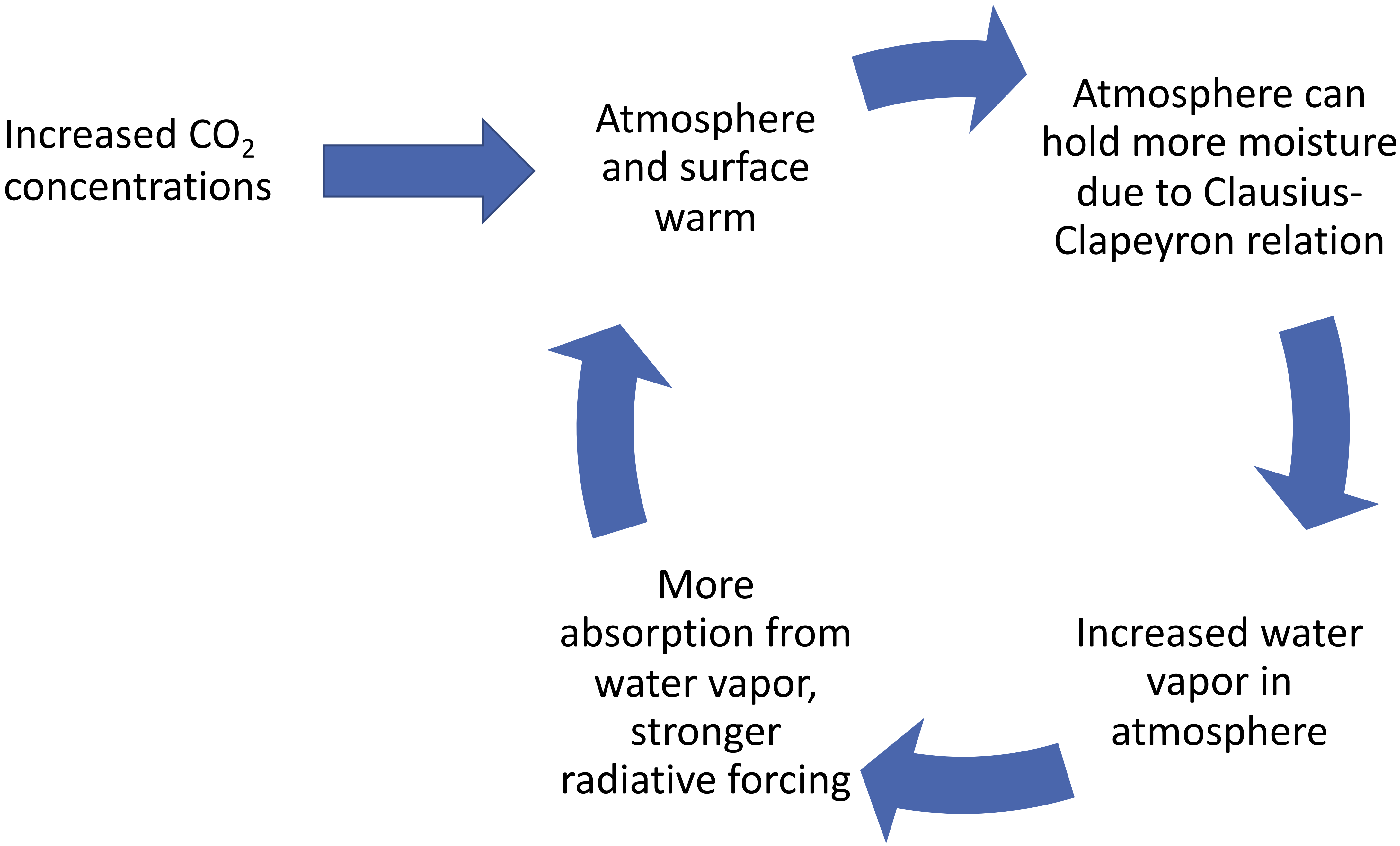
The water vapor feedback

First, a reminder: the Clausius-Clapeyron relation



The saturation water vapor increases exponentially with temperature, at about 6%/ °C

The water vapor feedback



Direct radiative forcing of absorption by water vapor molecules reinforces that by CO_2 via the water vapor feedback

Workshops #4,5:
logarithmic dependence
global warming potential

Conclusions

- Climate cools/warms to reach radiative equilibrium: incoming SW = outgoing LW

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- Greenhouse effect of water vapor leads to a positive feedback on CO_2 increase
- The Global warming potential of other GHGs depends on both their efficiency and life time, CO_2 has an especially long life time in the atmosphere

The End