Greenhouse

Global Warming Science, EPS101

Camille Hankel and Eli Tziperman

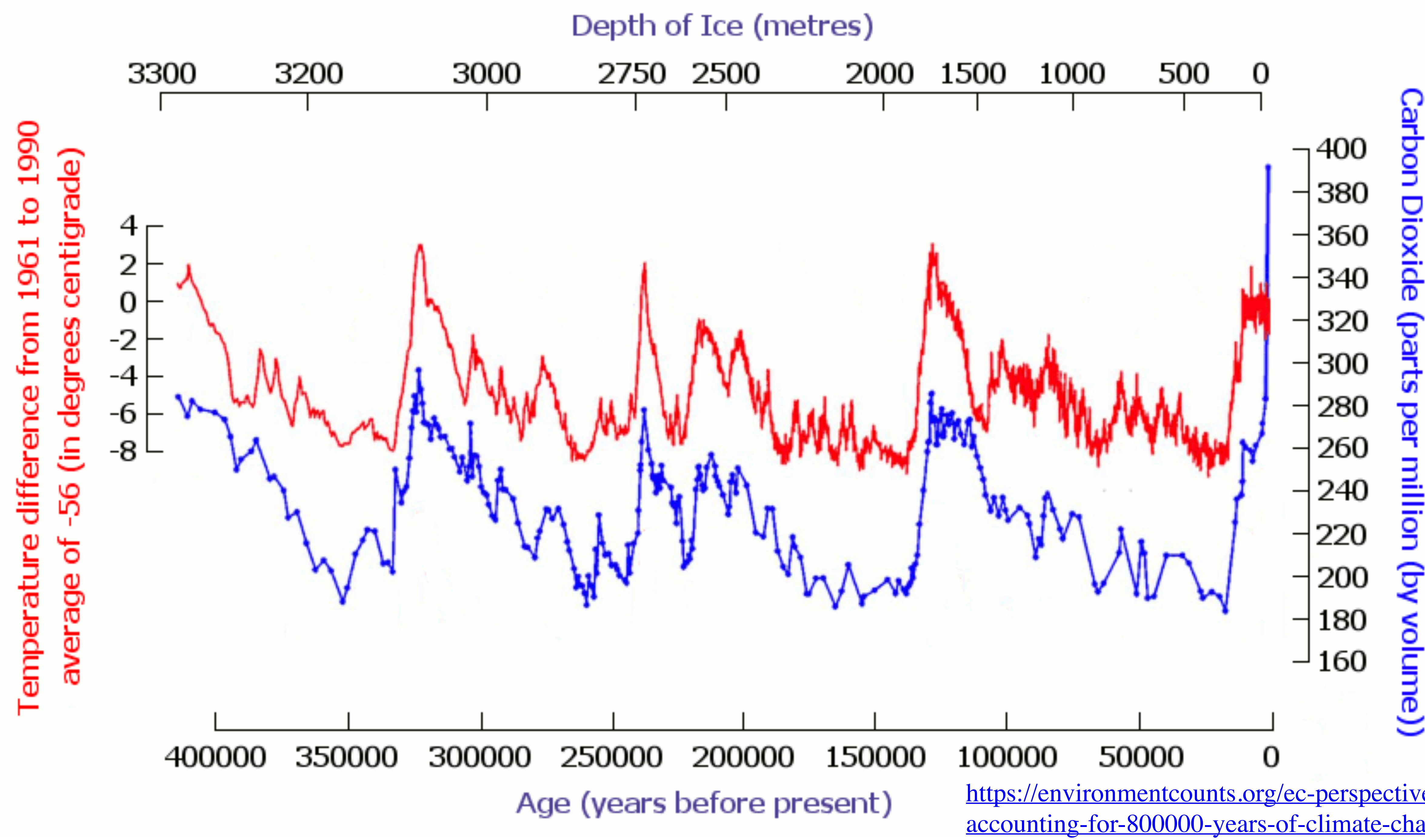
https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/

An inconvenient truth

Start at beginning for ice core collection
Start at 2:10 for intro to temperature/CO2 curve, play until 5:30 or less
https://www.youtube.com/watch?v=-JIuKjaY3r4

Ice ages: CO_2 vs “temperature”

Vostok Antarctica, CO_2 and temperature



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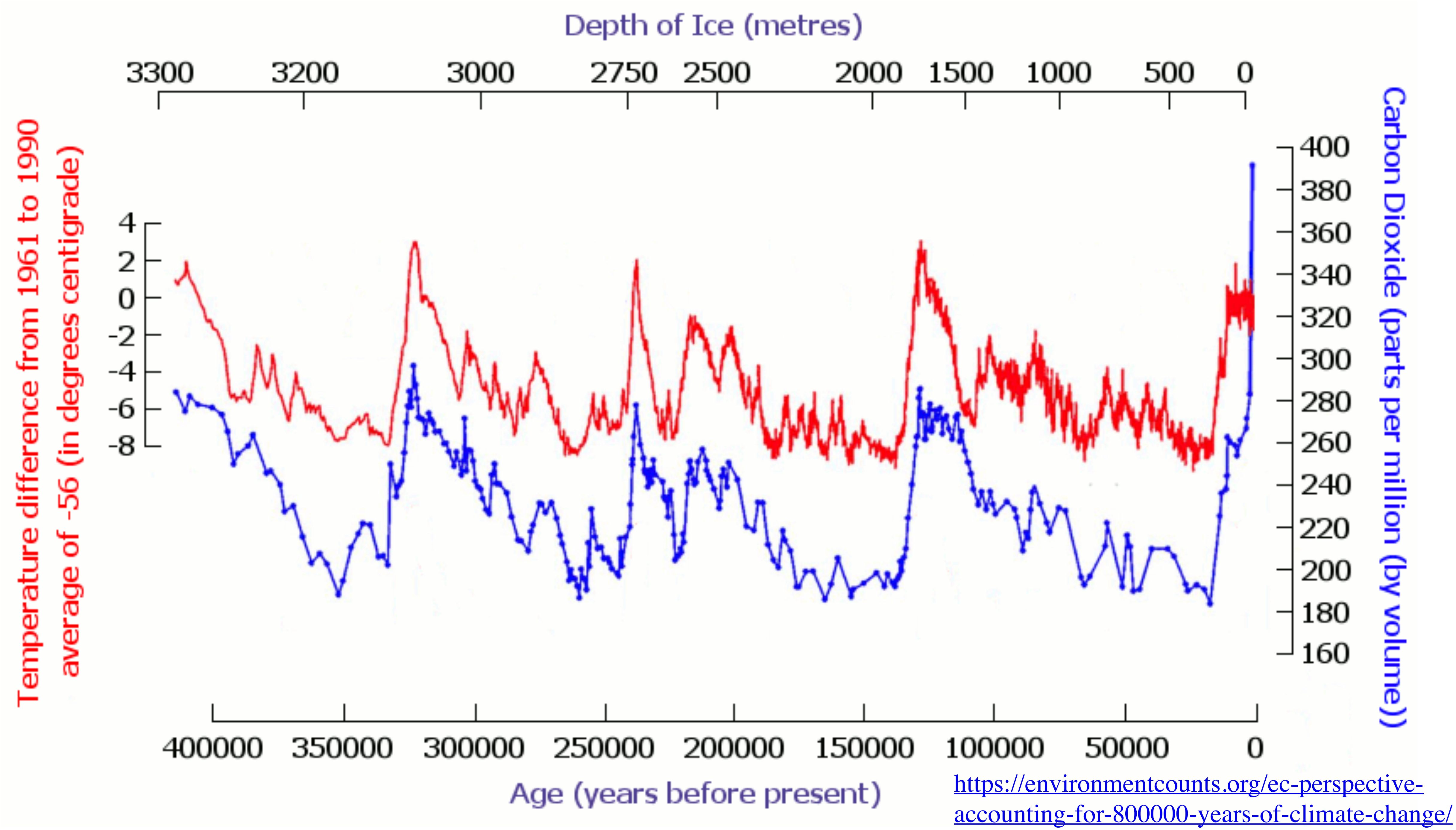

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Why are CO_2 and temperature correlated?

Radiative forcing (RF)

(IPCC AR5, 2013)

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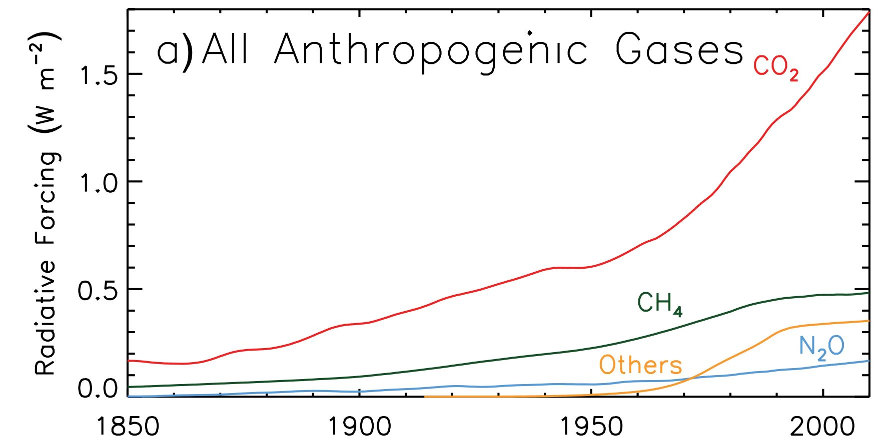

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Figure 8.6 | (a) Radiative forcing (RF) from the major well-mixed greenhouse gases (WMGHGs) and groups of halocarbons, 1850-2011, (b) as (a) but with a log scale, (c) RF from minor WMGHGs, 1850-2011 (log scale). (d) Rate of change in forcing from the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

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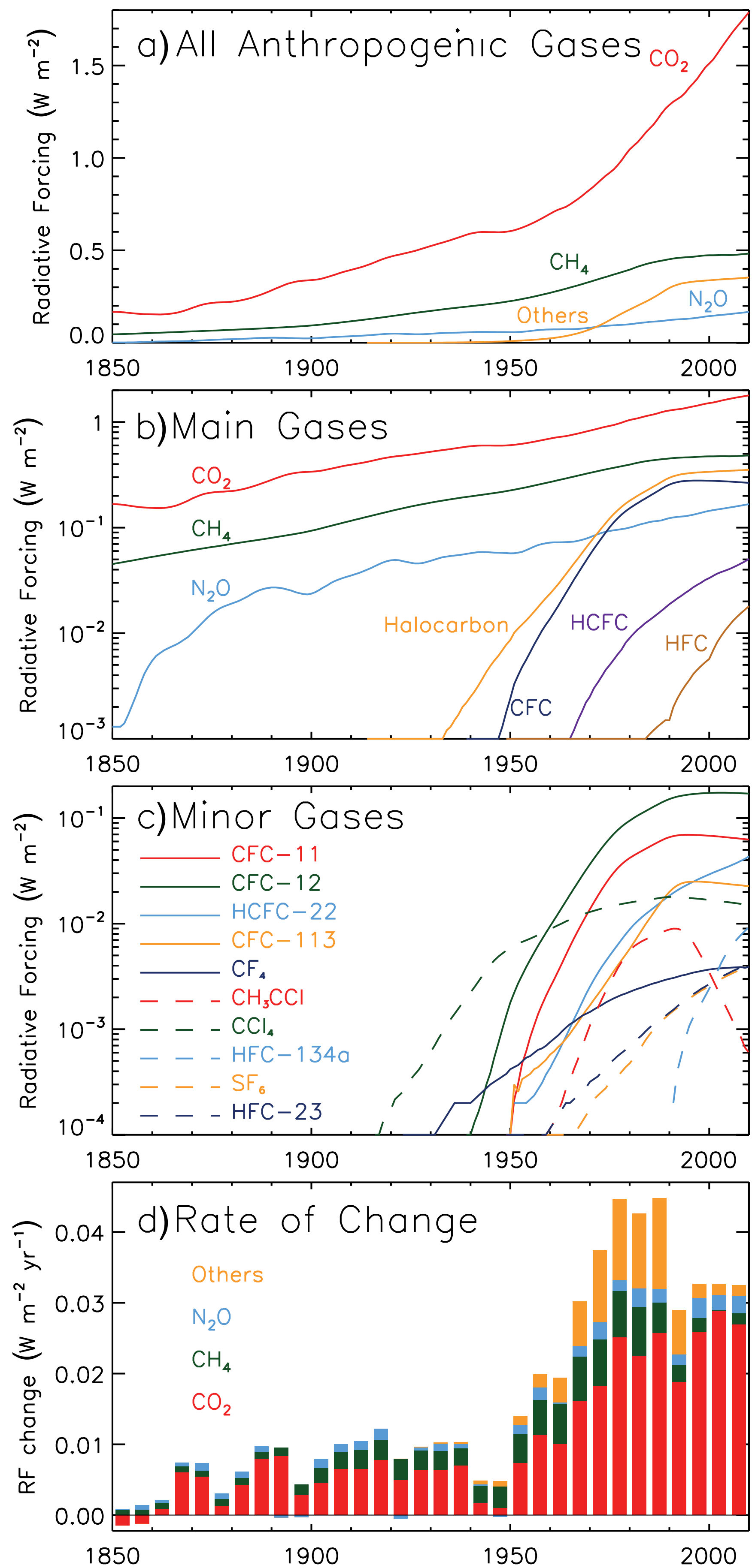

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Representative Concentration Pathway (RCP)

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

(IPCC AR5, 2013)

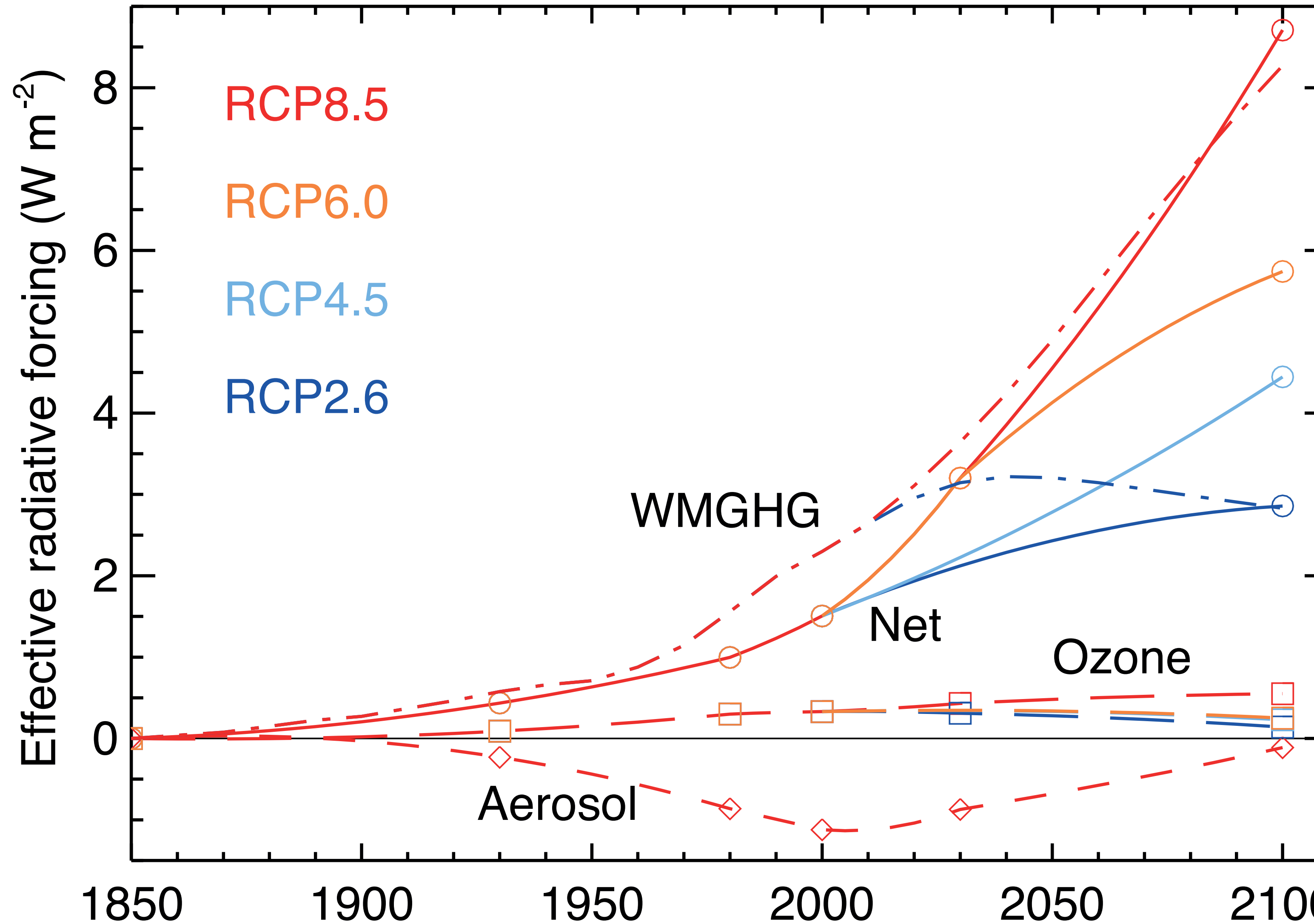

Figure 8.22 | Global mean anthropogenic forcing with symbols indicating the times at which ACCMIP simulations were performed (solid lines with circles are net; long dashes with squares are ozone; short dashes with diamonds are aerosol; dash-dot are WMGHG; colors: RCPs with **red for RCP8.5**, **orange RCP6.0**, **light blue RCP4.5**, **and dark blue RCP2.6**). RCPs 2.6, 4.5 and 6.0 net forcings at 2100 are approximate values using aerosol ERF projected for RCP8.5 (modified from Shindell et al., 2013c). Some individual components are omitted for some RCPs for visual clarity.

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- What is the quantitative relationship between CO_2 and radiative forcing?
- How important are other greenhouse gasses relative to CO_2?
- What is the role of water vapor in the greenhouse effect?

Workshop #1:
Observed and projected increase in greenhouse gasses

Observations & projections of CO_2 concentration

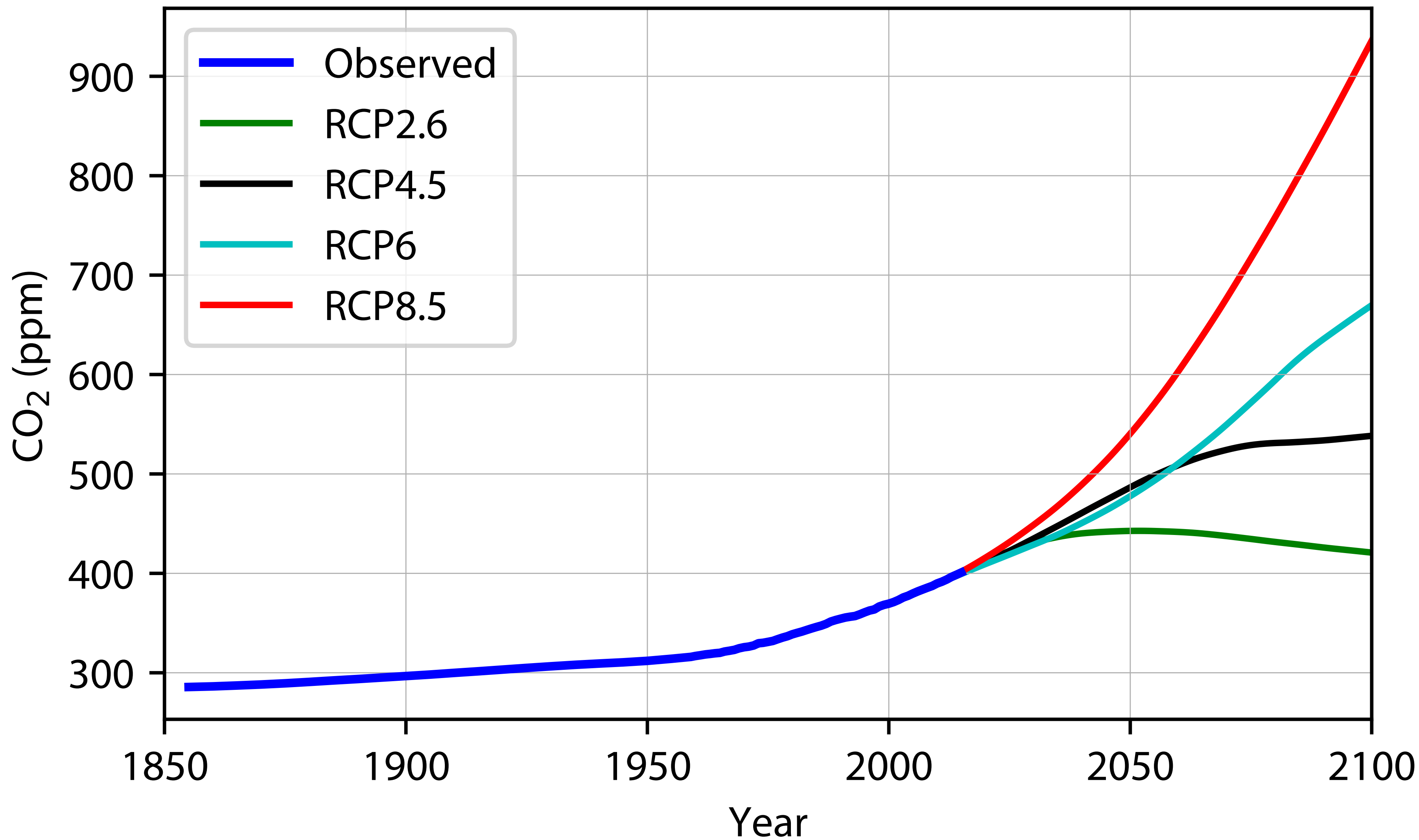

Figure2.1:CO2 time series.
Annually averaged CO2 concentration, observed and projected according to different RCP scenarios.

Historical & projected concentrations

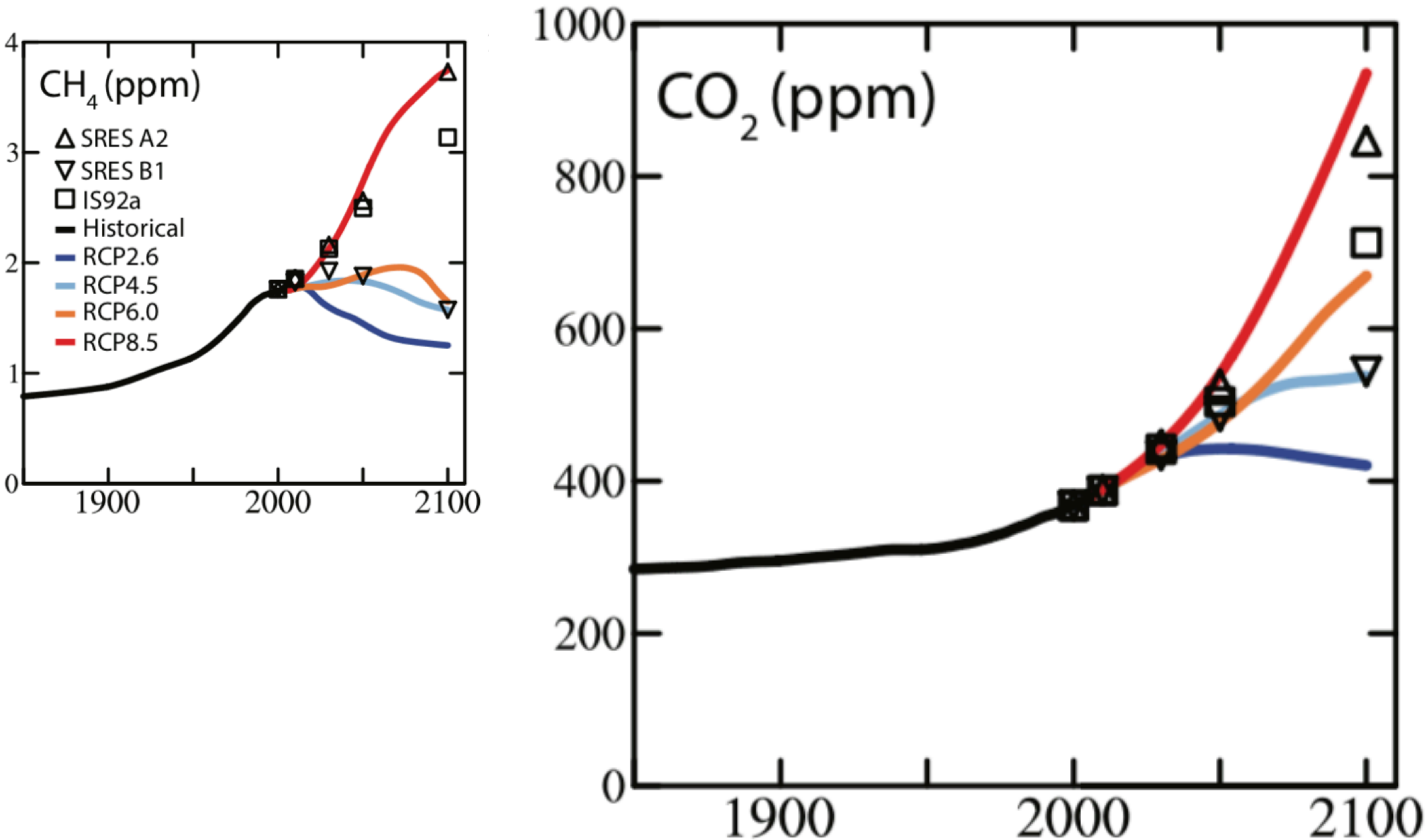

Figure 8.5 (above) Time evolution of global-averaged mixing ratio of long-lived species1850–2100 following each RCP; blue (RCP2.6), light blue (RCP4.5), orange (RCP6.0) and red (RCP8.5). (Meinshausen et al., 2011b)

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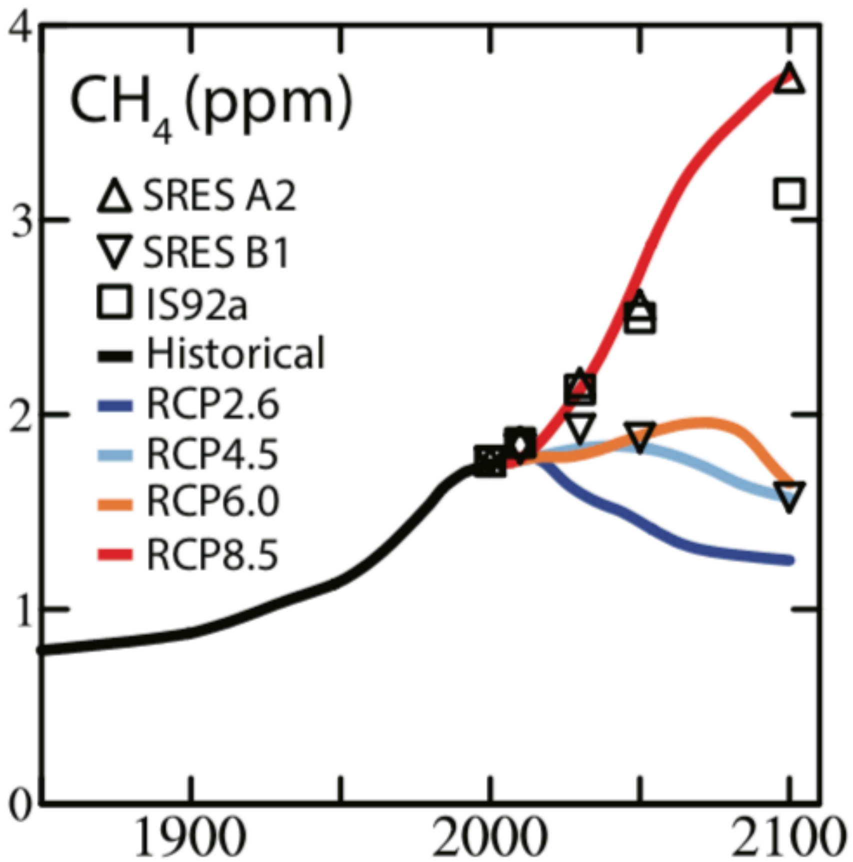
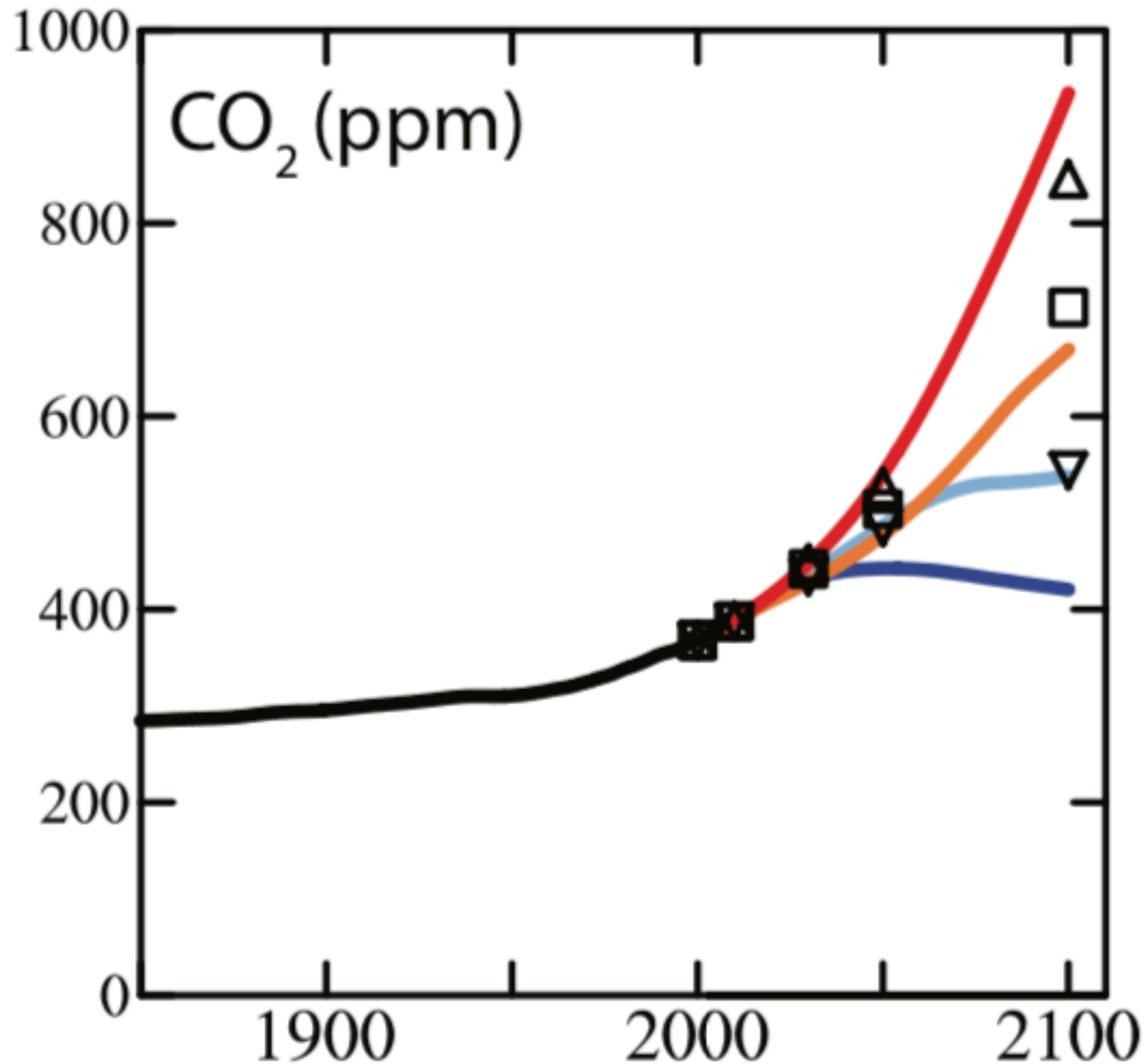


worse than RCP8.5 business as usual considered in 2011



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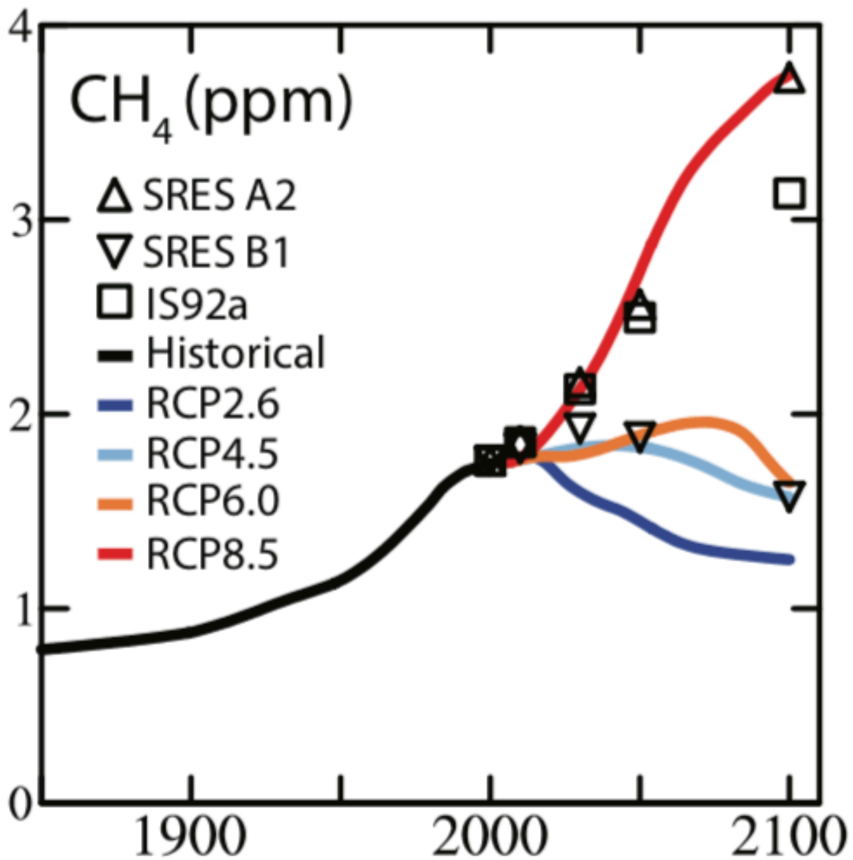

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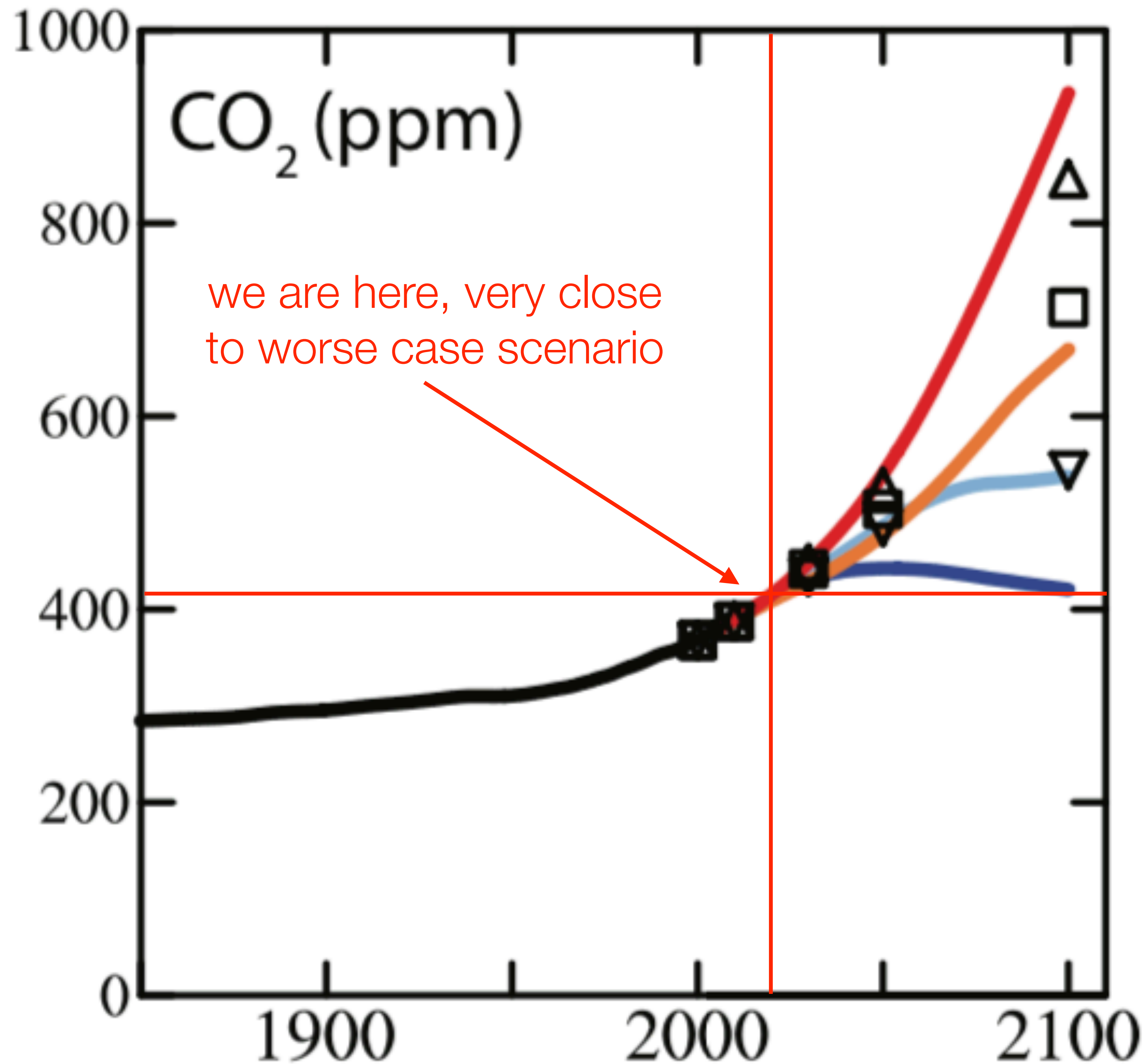

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Energy balance: Albedo, greenhouse

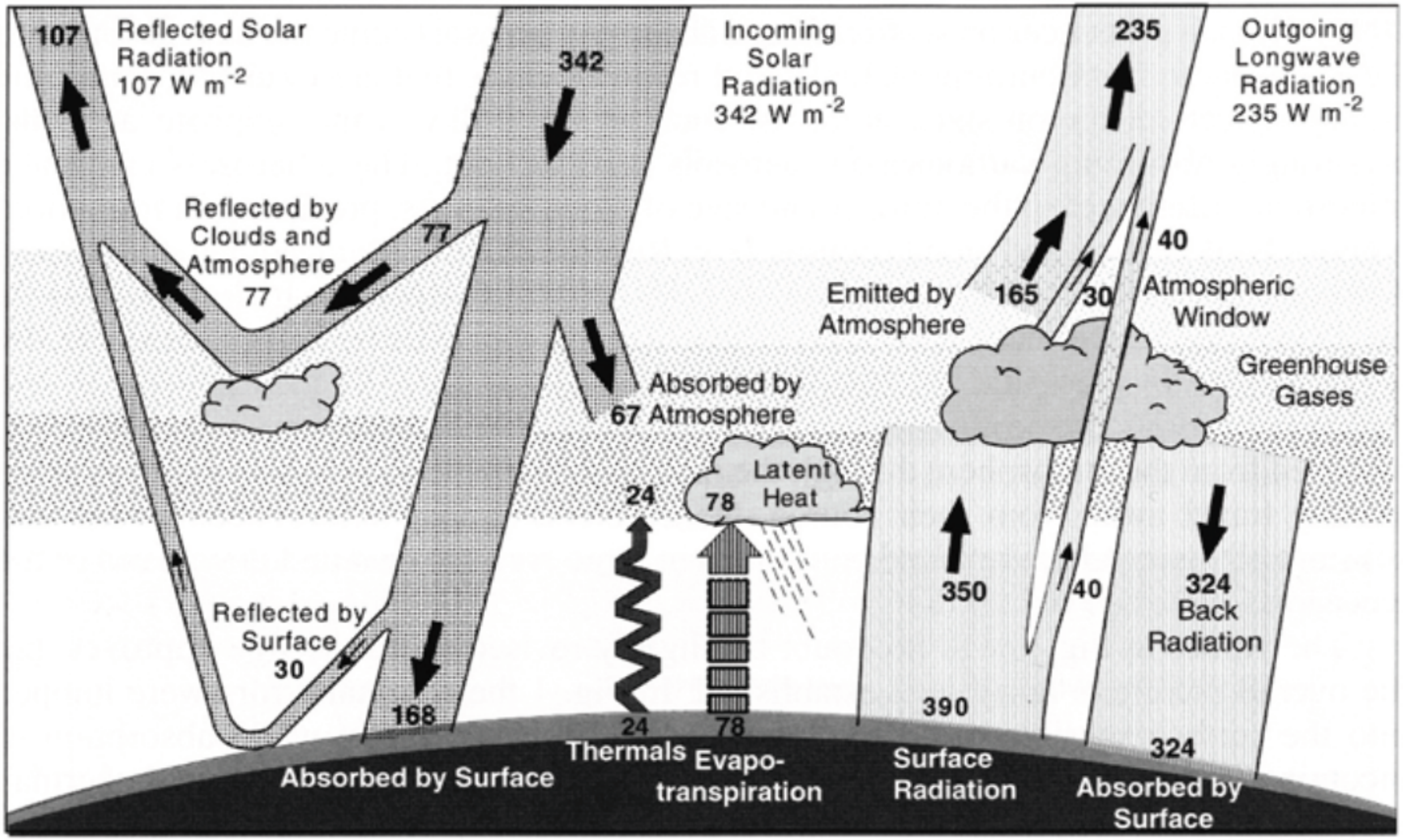


FIGURE 9.4. Earth's energy balance (from Trenberth, K.E., and D.P. Stepaniak, 2004: The flow of energy through the Earth's climate system. **Q.J.R.Meteorol.Soc.**, **130**, 2677-2701).

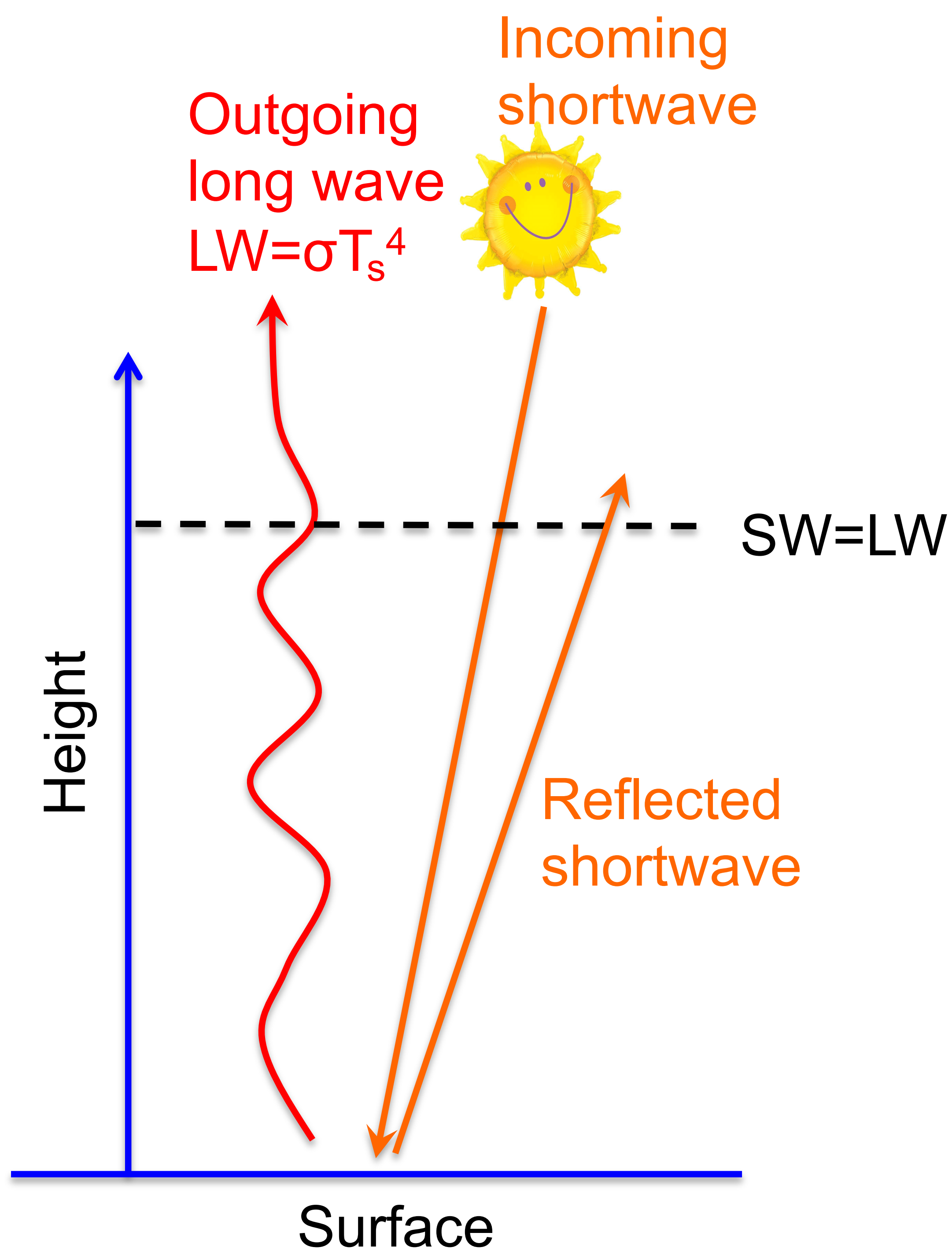
Notes sections 2.1.1, 2.1.2, 2.1.3:
Energy balance, 2-layer model, continuous temperature profile and level of last absorption

(use next three slides)

Energy balance of the Earth

Step 1: no atmosphere!!

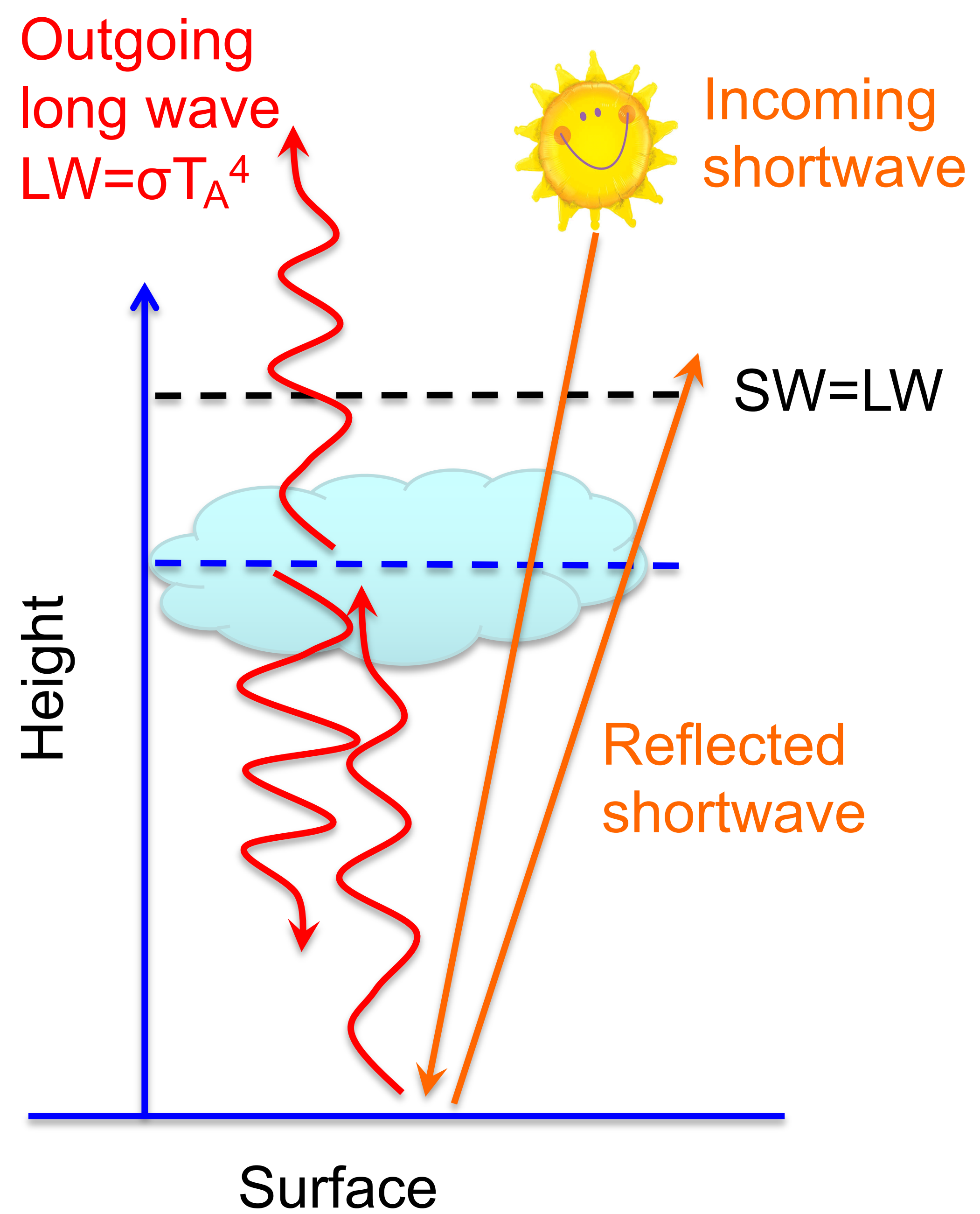
- Energy conservation: incoming **SW** radiation to Earth = outgoing **LW** radiation to space
- Incoming **SW** $= \frac{S_o}{4}(1-\alpha)$
- α = albedo = proportion SW reflected
- Outgoing **LW** $= \sigma T^4$
- Set incoming = outgoing —> solve for T
-



The Greenhouse Effect

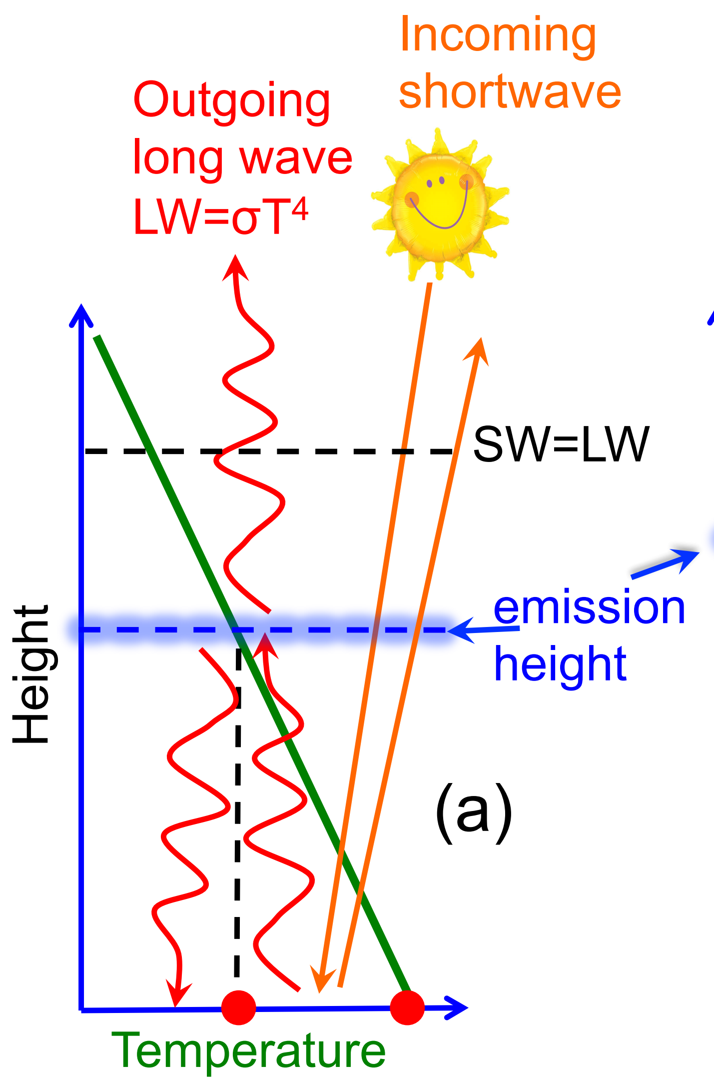
Step 2: add a 1-layer atmosphere

- Add an atmospheric layer (because gases in the real atmosphere absorb radiation): transparent to SW, absorbs/emits LW
- LW radiation emitted from surface is "trapped" (absorbed and re-emitted) by atmosphere
- Two unknowns: surface temperature *T* and (mid) atmospheric temperature θ. Two equations (energy balance at surface, and at mid-atmosphere)
- Do the calculations (see notes) and result: surface temperature increases!
- This is the "greenhouse effect"



The 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 —> raising level of last absorption —> Earth radiates from a colder temperature —> Energy balance is broken: LW < SW —> temperature must adjust

The Greenhouse Effect

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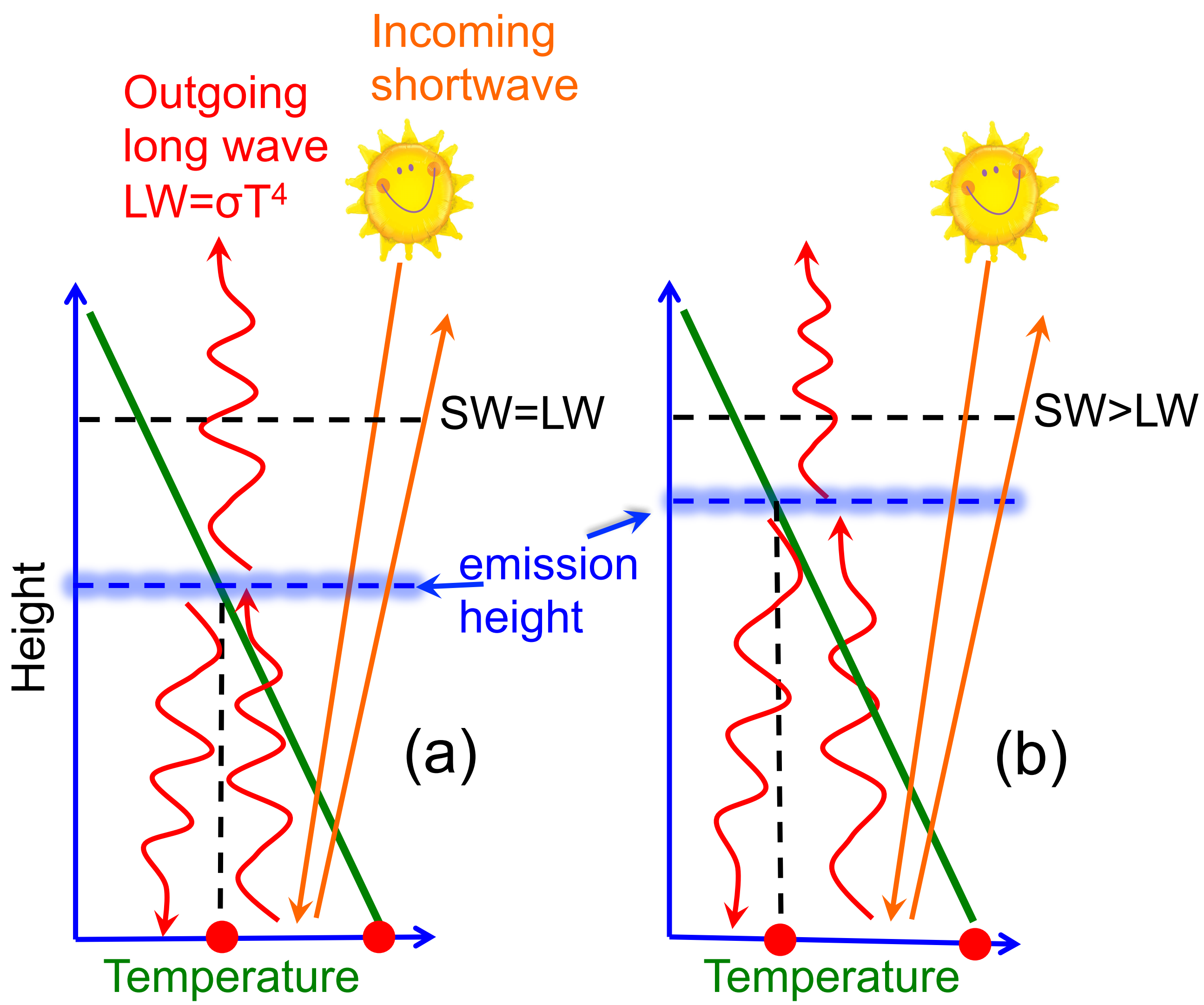

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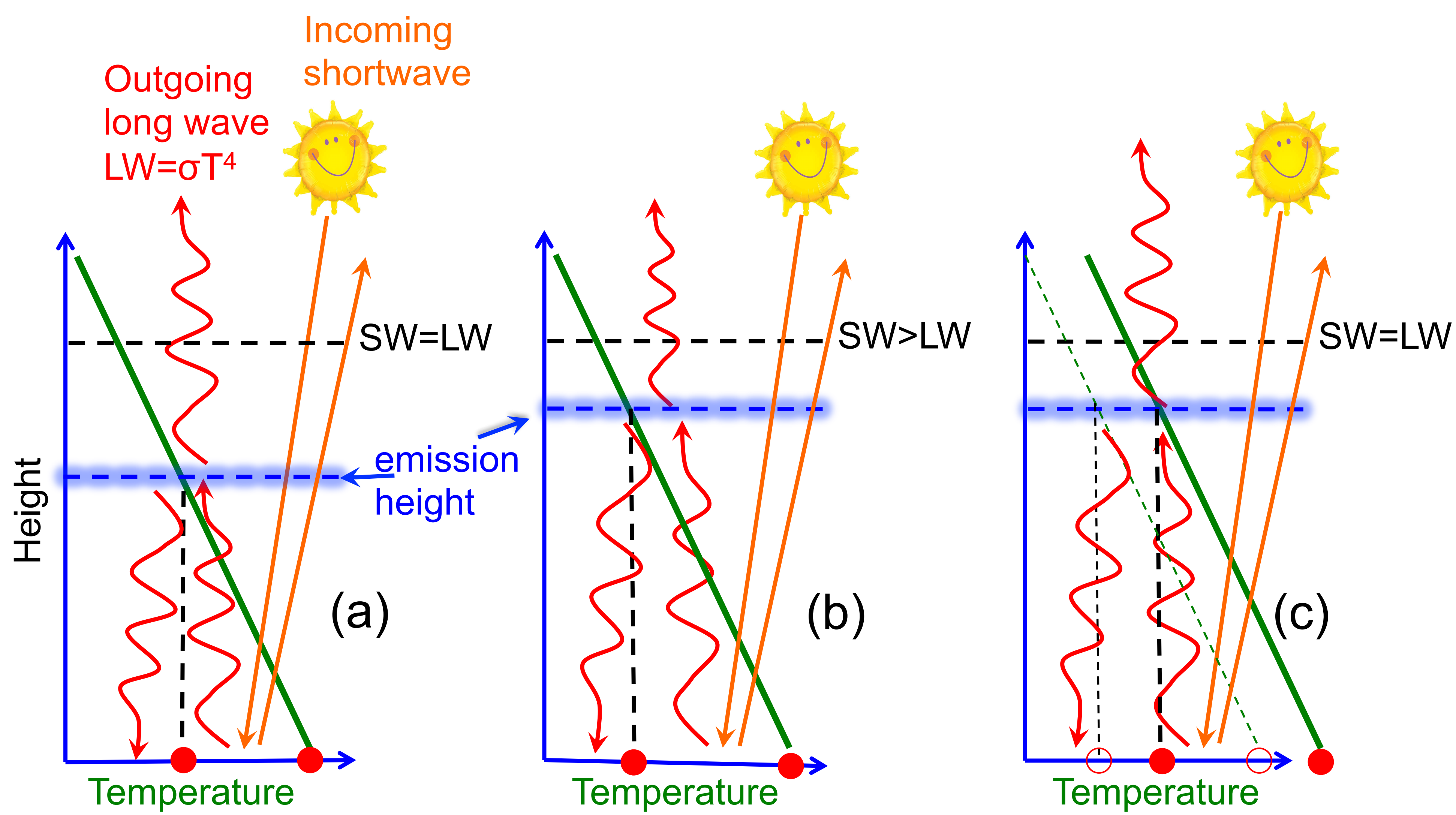

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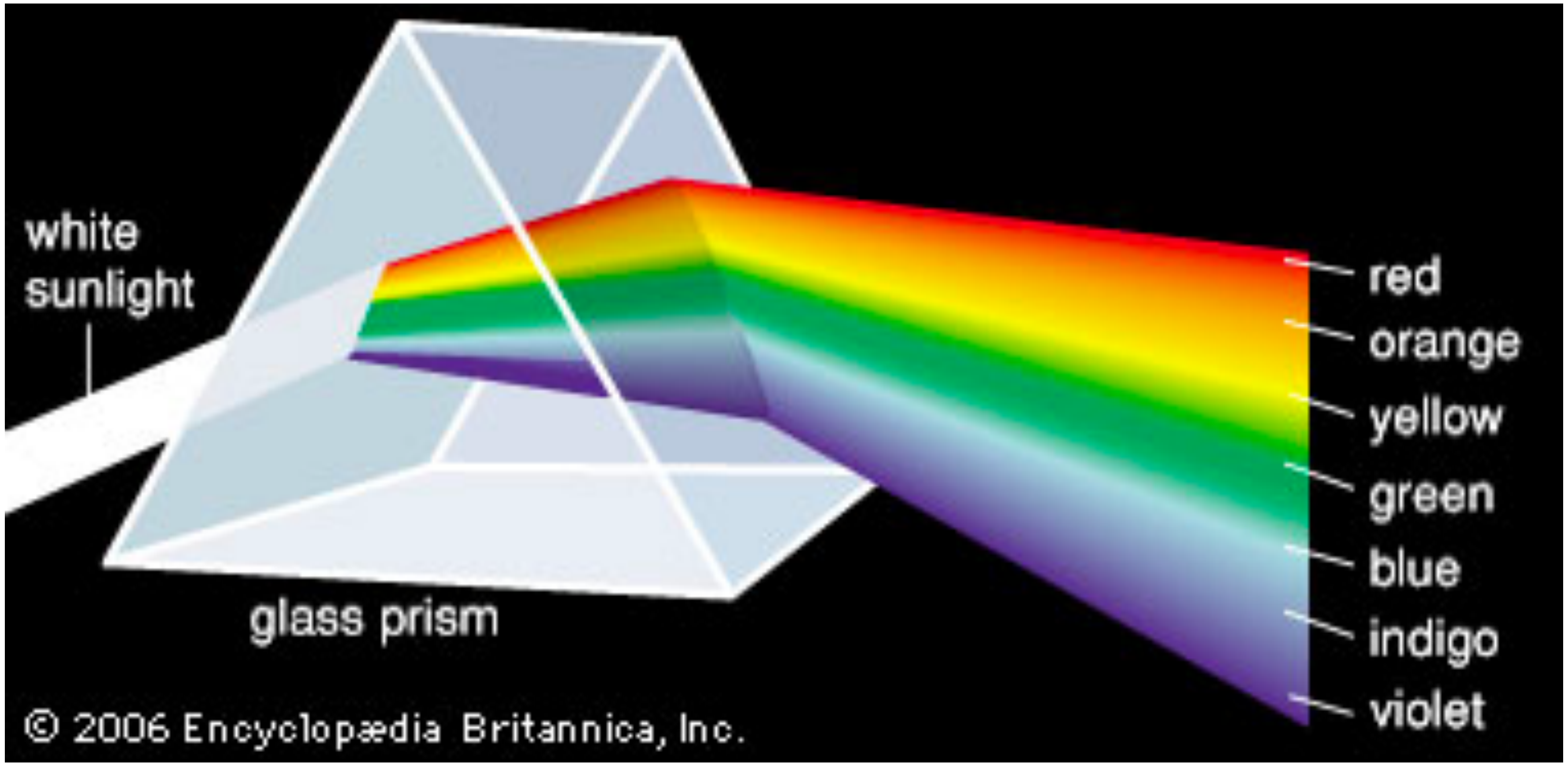
Workshop #2:
2-layer energy balance model

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

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

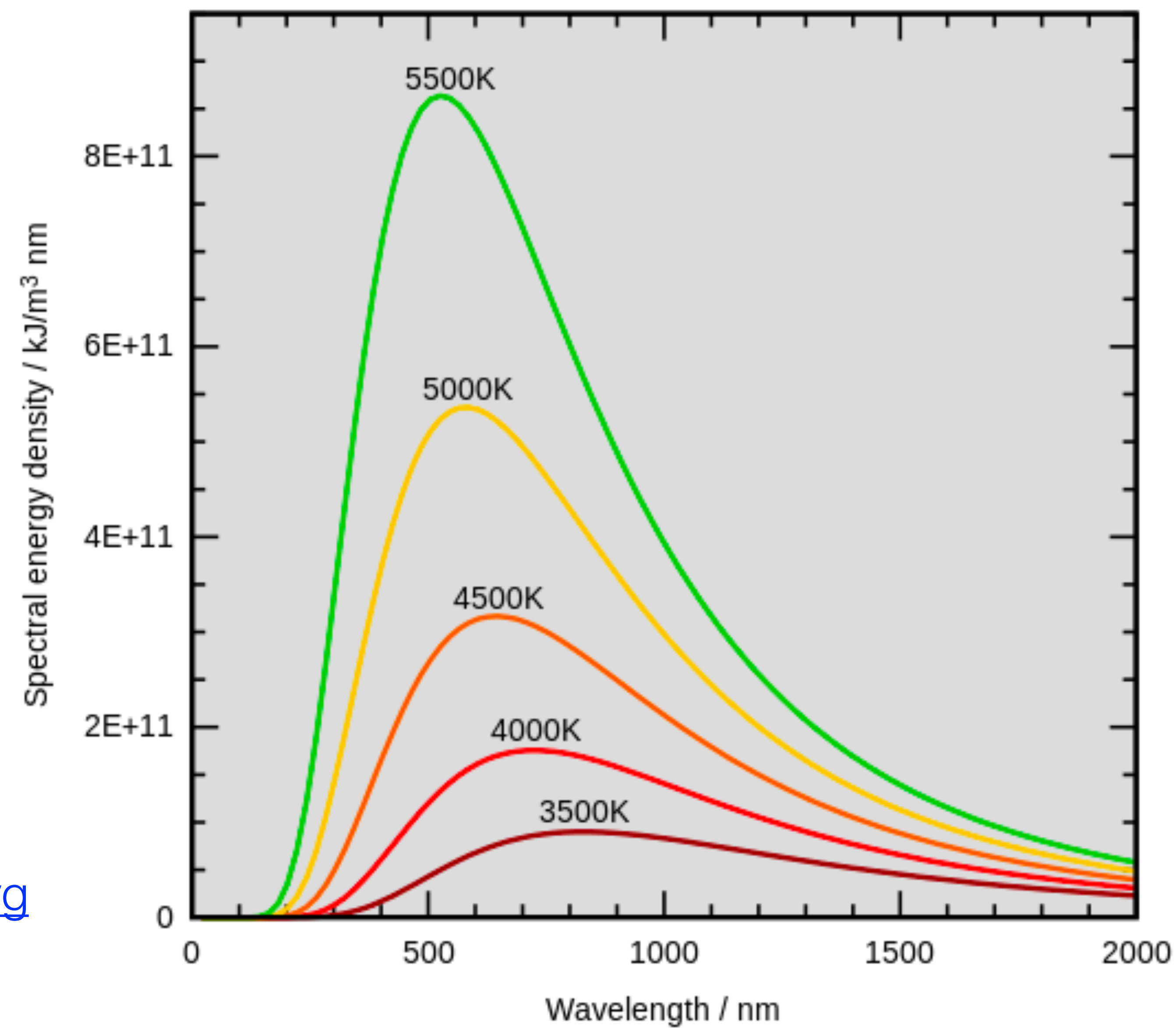


Black body radiation

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.

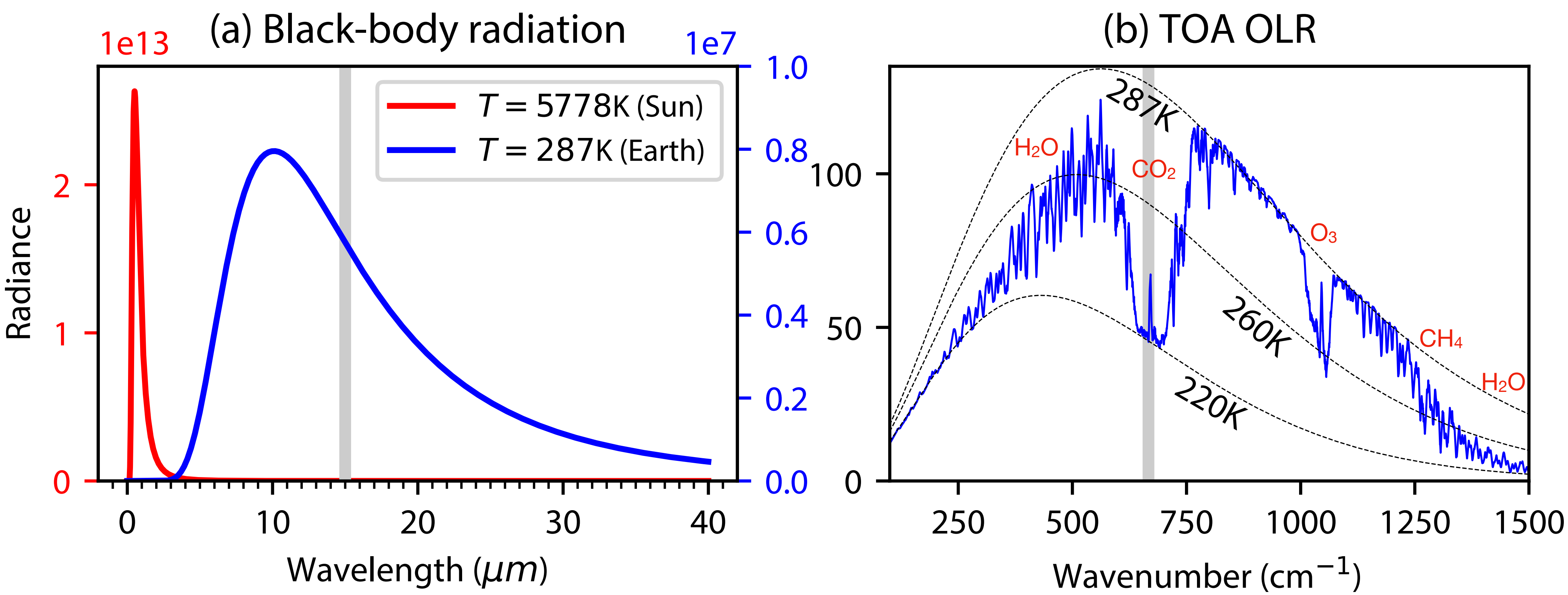
Total emitted radiation per area/ time: σT^4 Stefan–Boltzmann constant: $\sigma = 5.670367\times10^{-8}\ W\cdot m^{-2}\cdot K^{-4}$



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

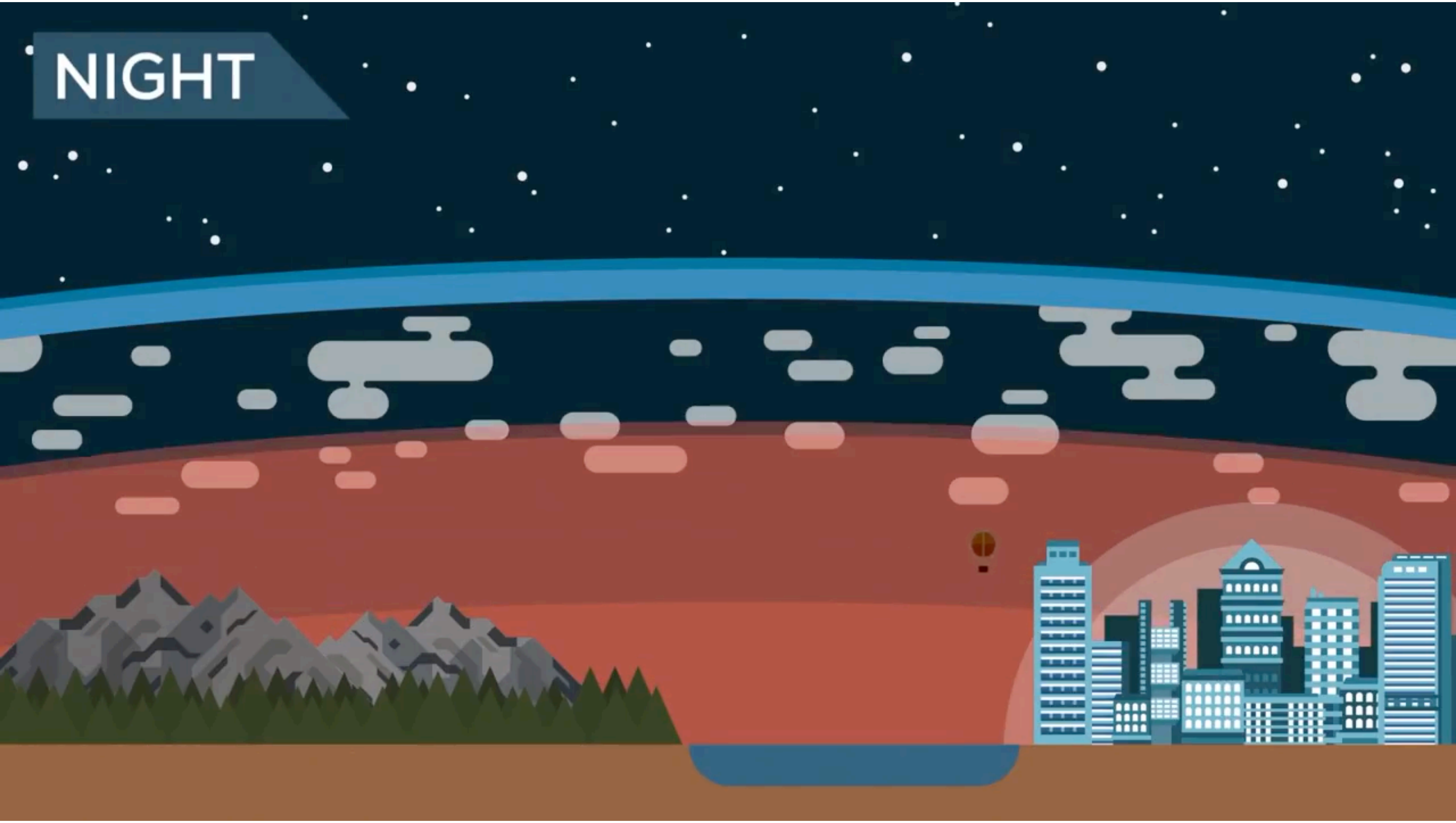


Long wavelength, low frequency, low energy photons

Short wavelength, high frequency, high energy photons

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 CO2, CH4, H2O, and O3; the central CO2 absorption line is shown on both panels as a vertical gray bar.

How do greenhouse gases work?



https://youtu.be/sTvqlijqvTg

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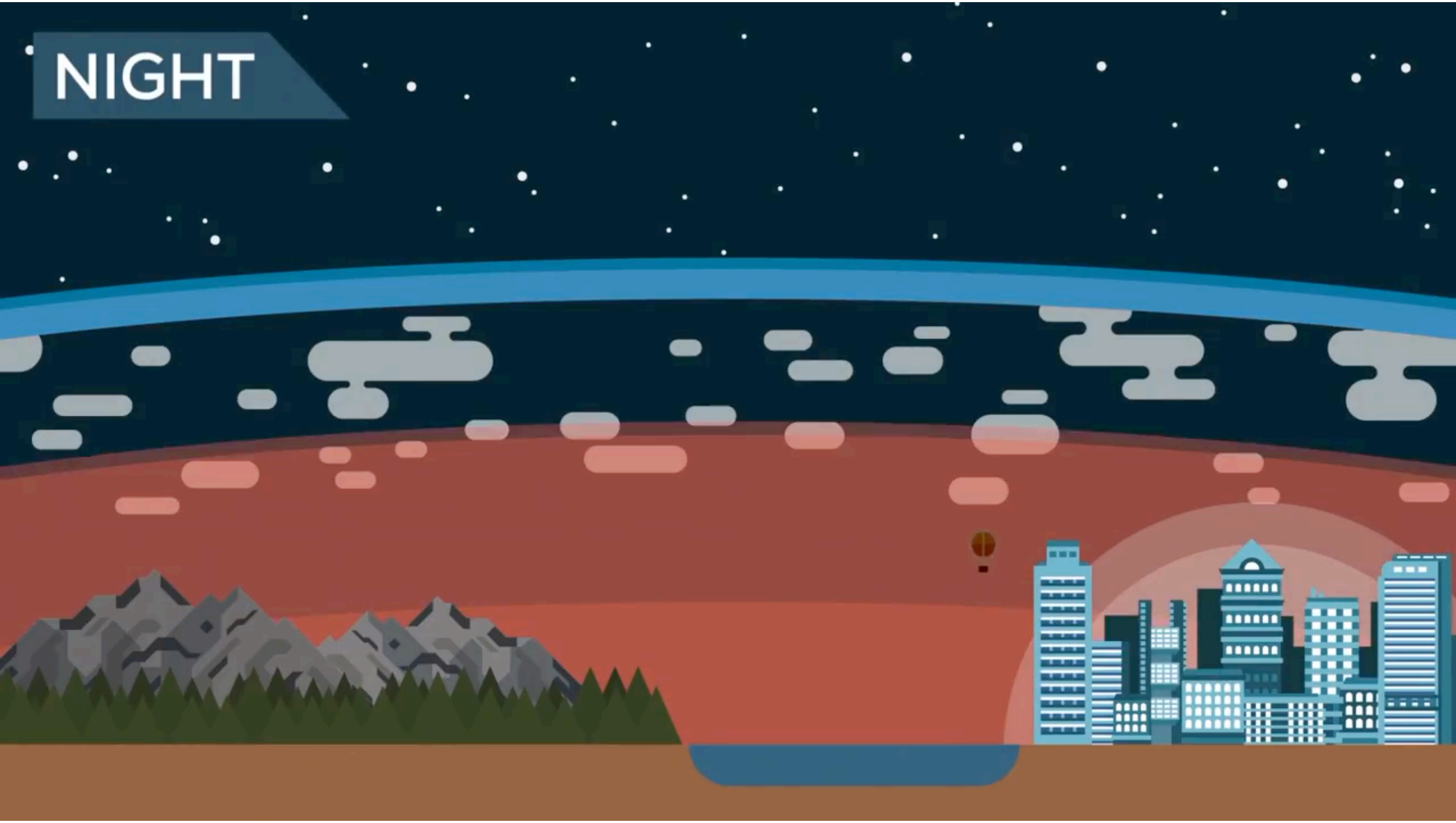

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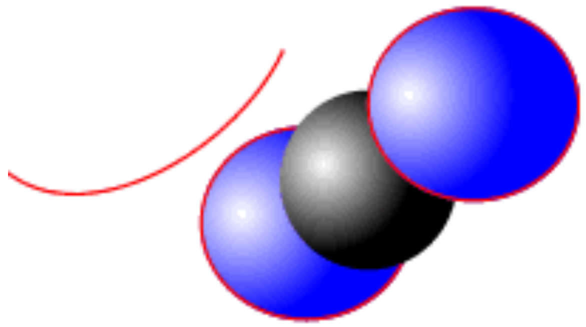
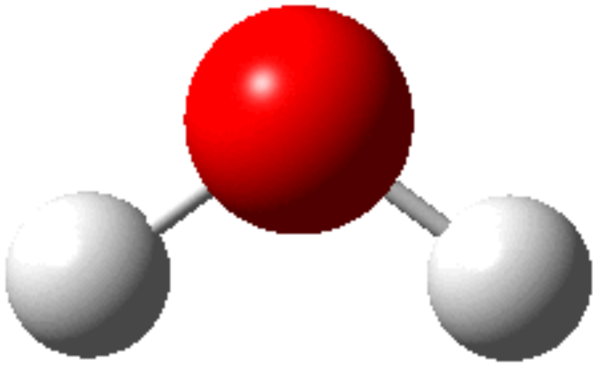
Vibration energy levels of CO_2 & H_2O



CO_2

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



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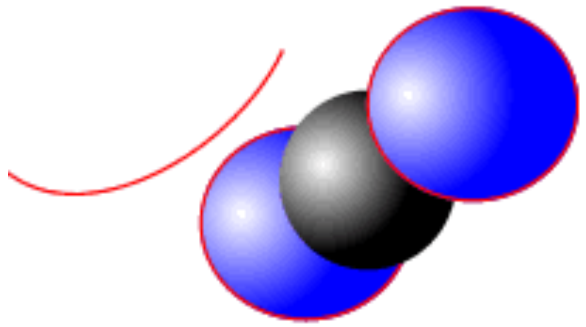
http://davidobru.blogspot.com/2017/01/some-animations.html

The vibration energy levels determine the frequency of absorption

Vibration energy levels of CO_2 & H_2O



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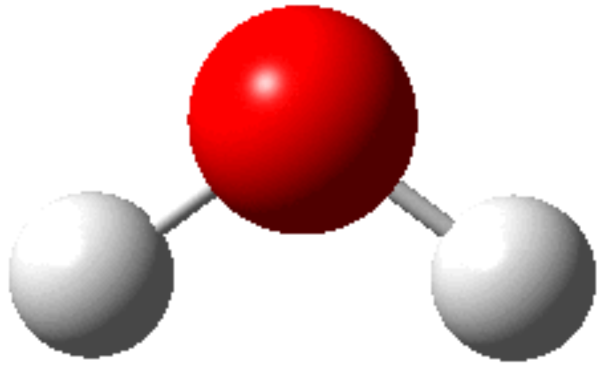

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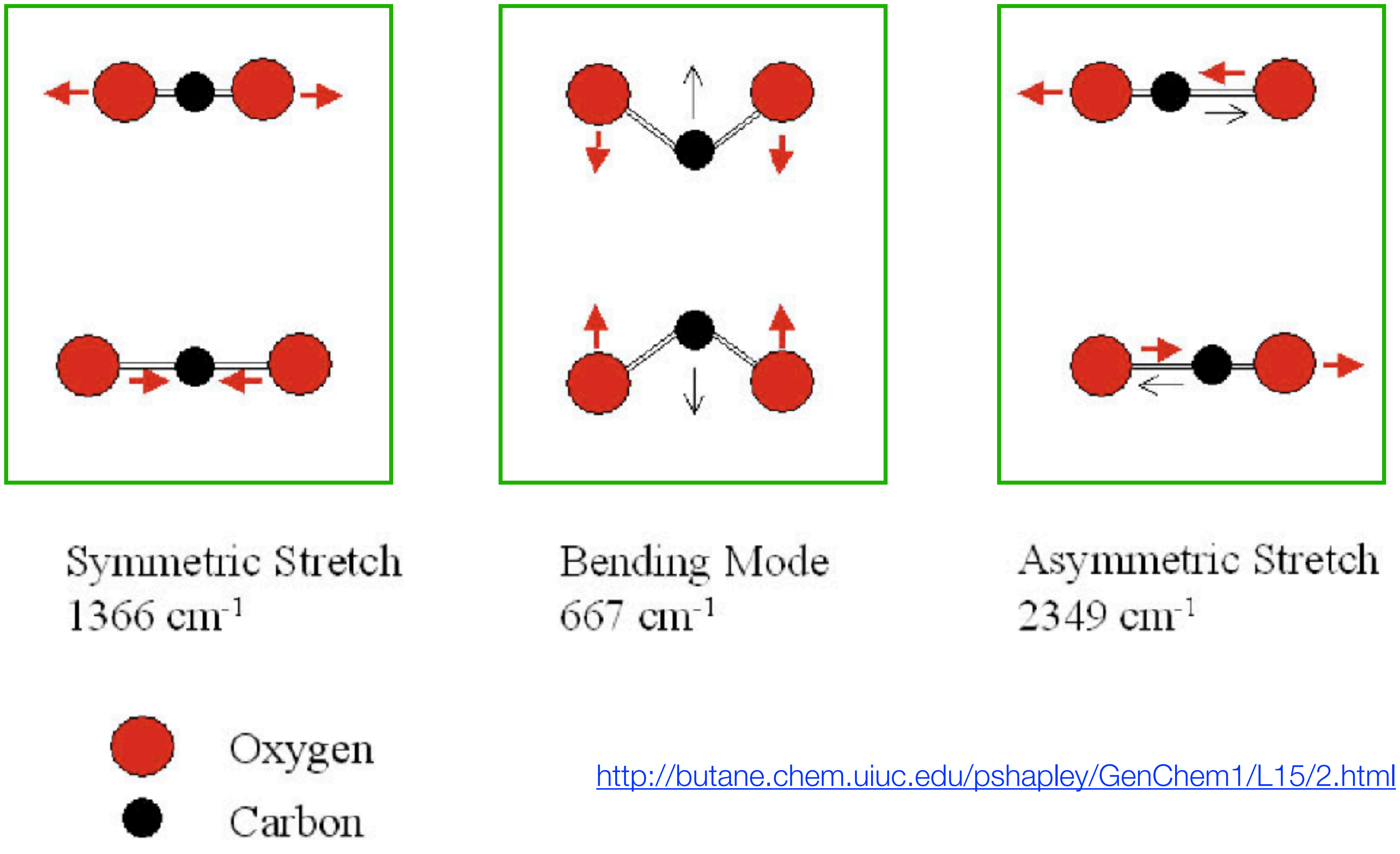
The vibration energy levels determine the frequency of absorption

Greenhouse gasses vibration modes

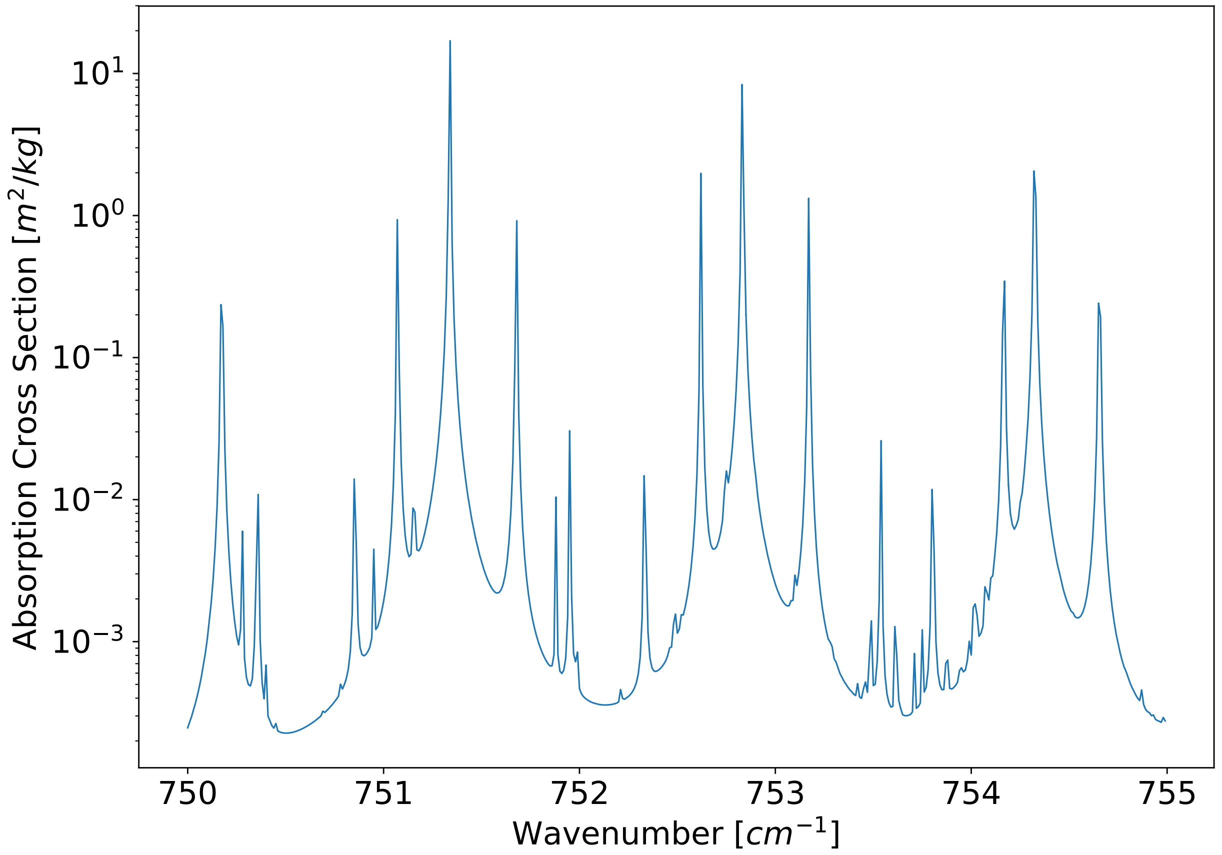
- Discrete wavelengths excite molecular transitions in greenhouse gas molecules
- This results in absorption and re-emission of radiation of that wavelength
- The “transition wavelengths” for various greenhouse gases have been measured in lab experiments



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

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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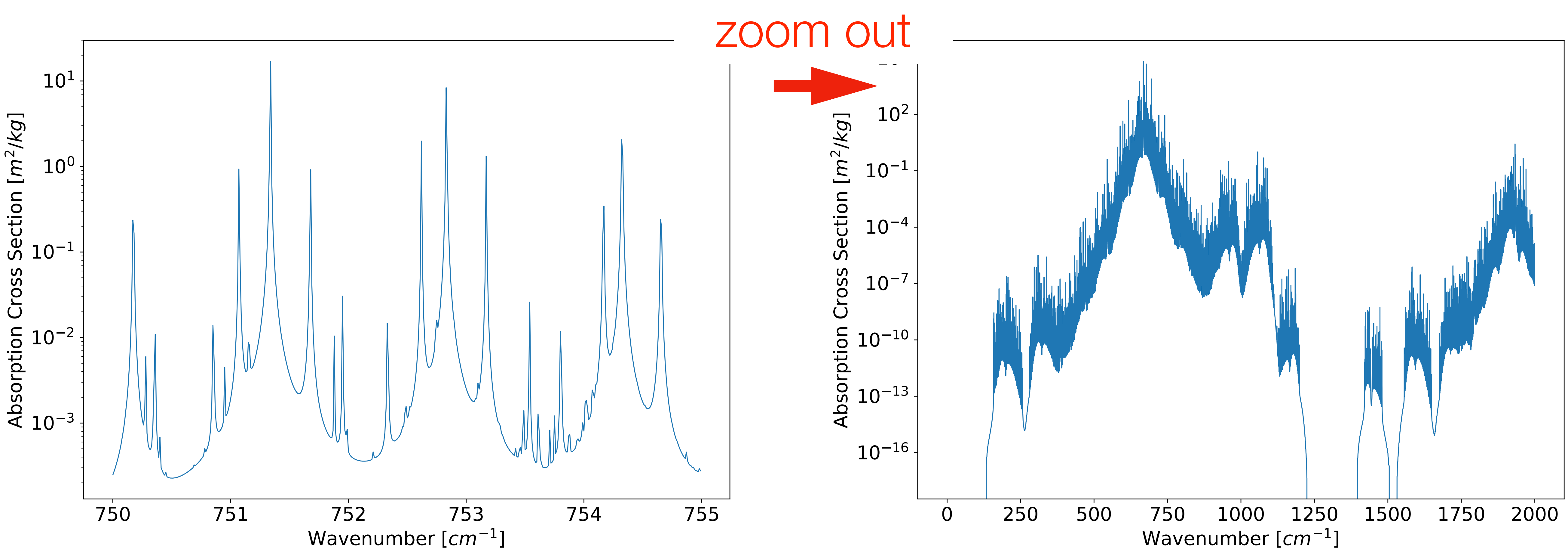
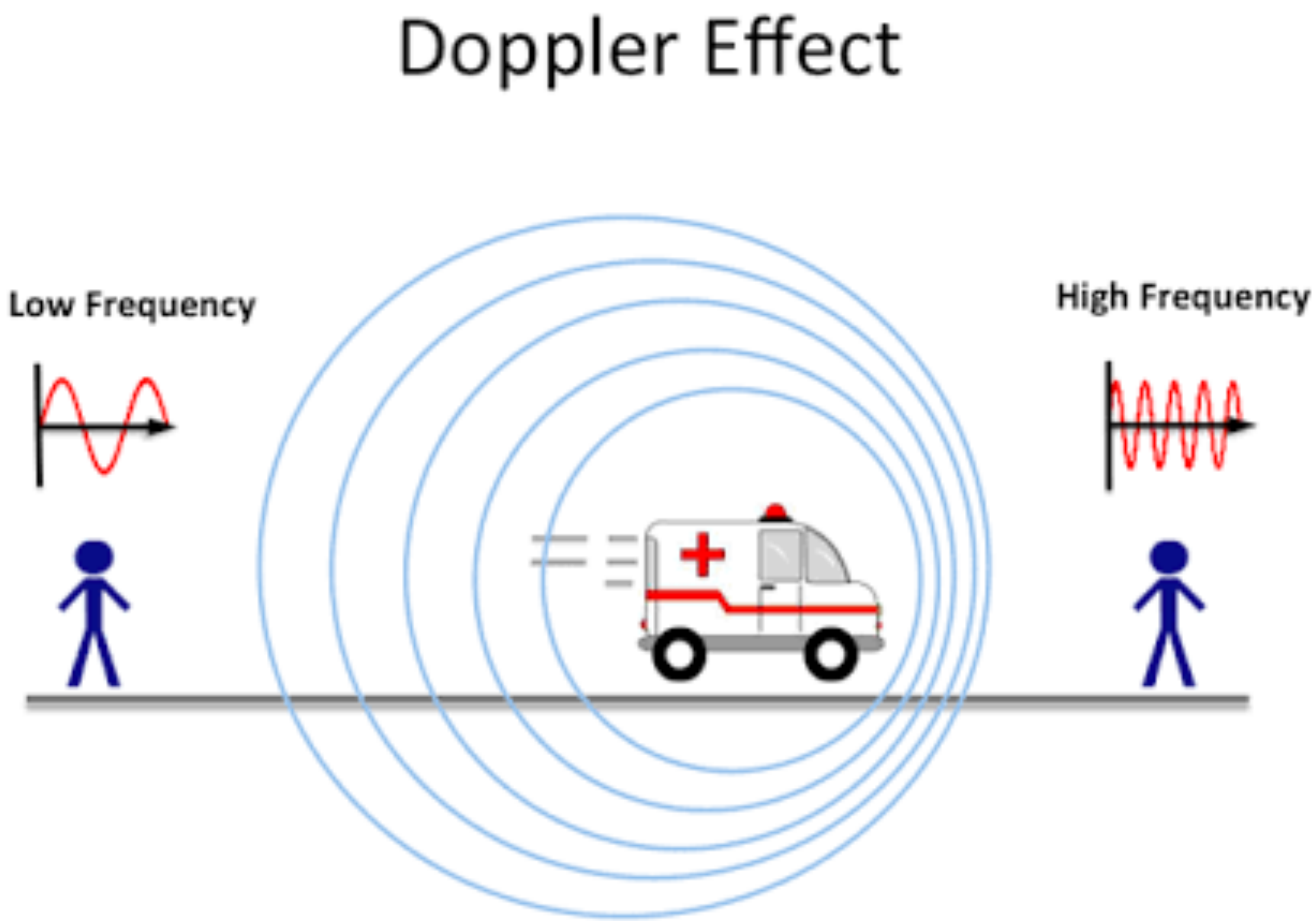


Notes section 2.2.3: Broadening

(use next three slides)

Doppler Broadening



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

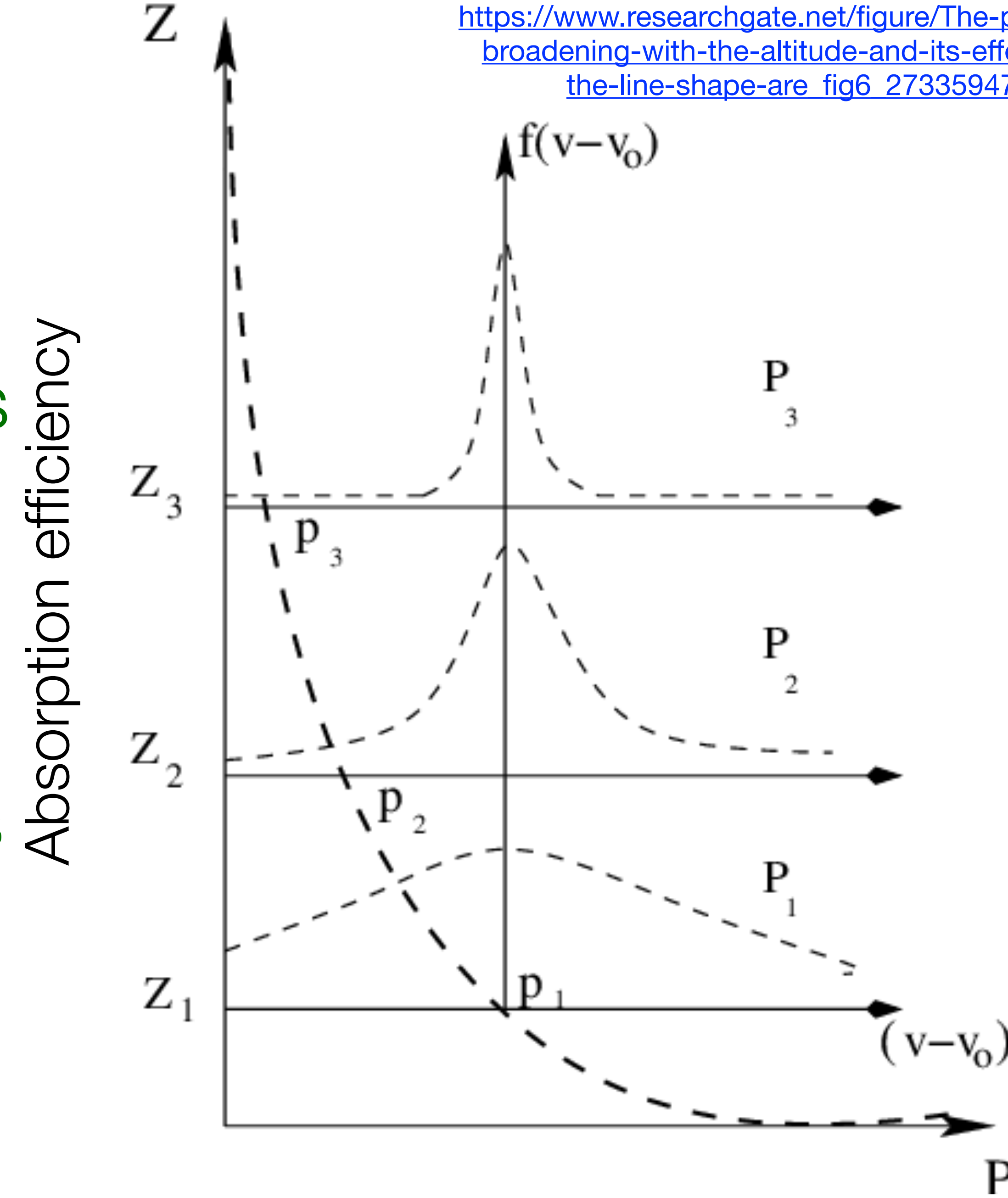
The random motion of the gas molecules causes the widening of absorption lines because molecules that happen to be moving towards/away from the incoming photon will see it at a different frequency/ wavelengths.

Pressure/Collisional Broadening

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

Low pressure,
fewer collisions

High pressure,
more collisions



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

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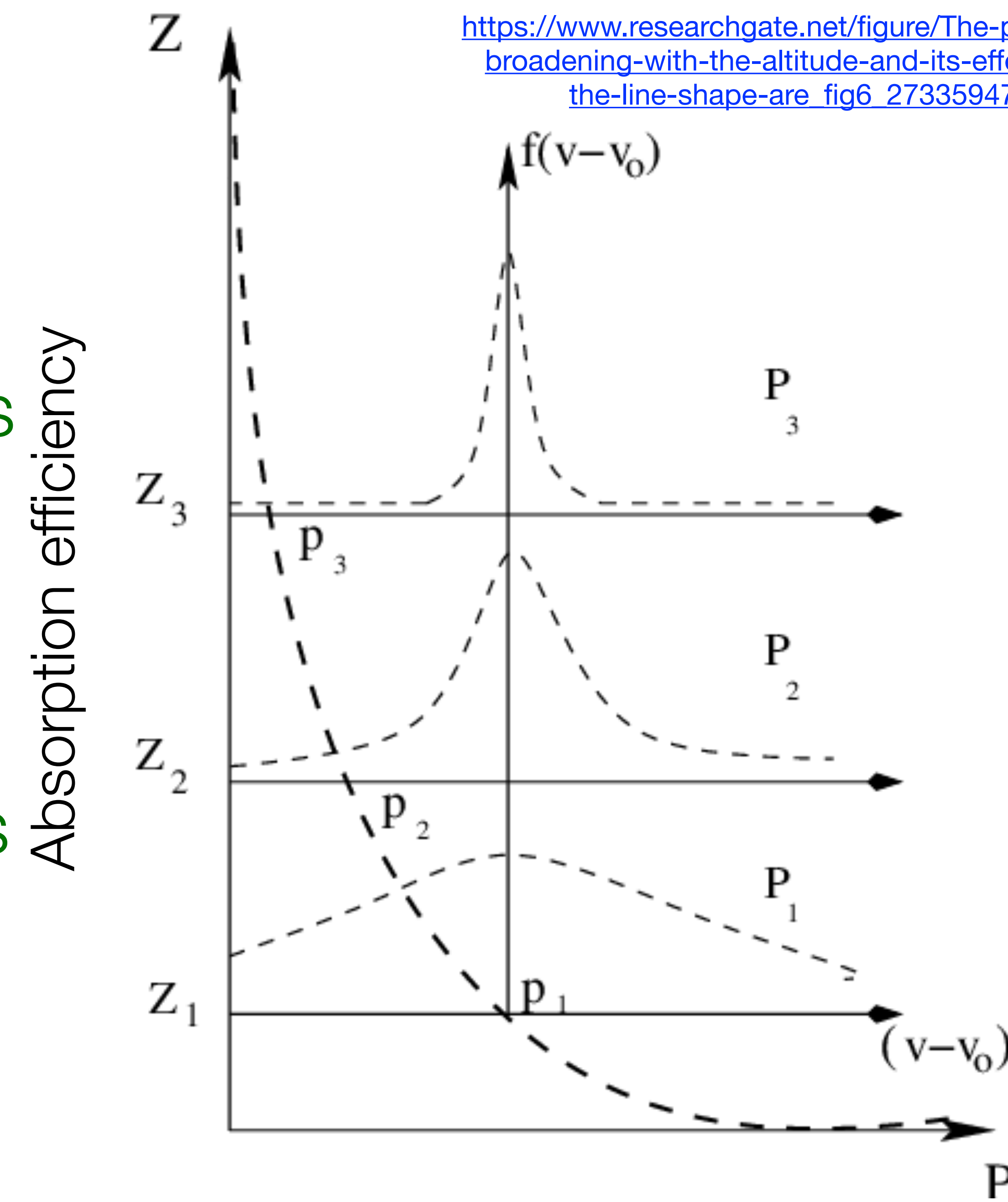

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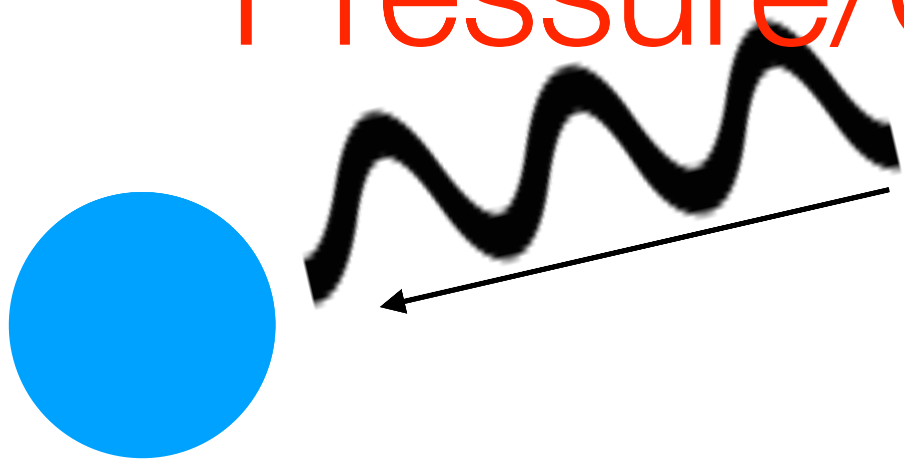

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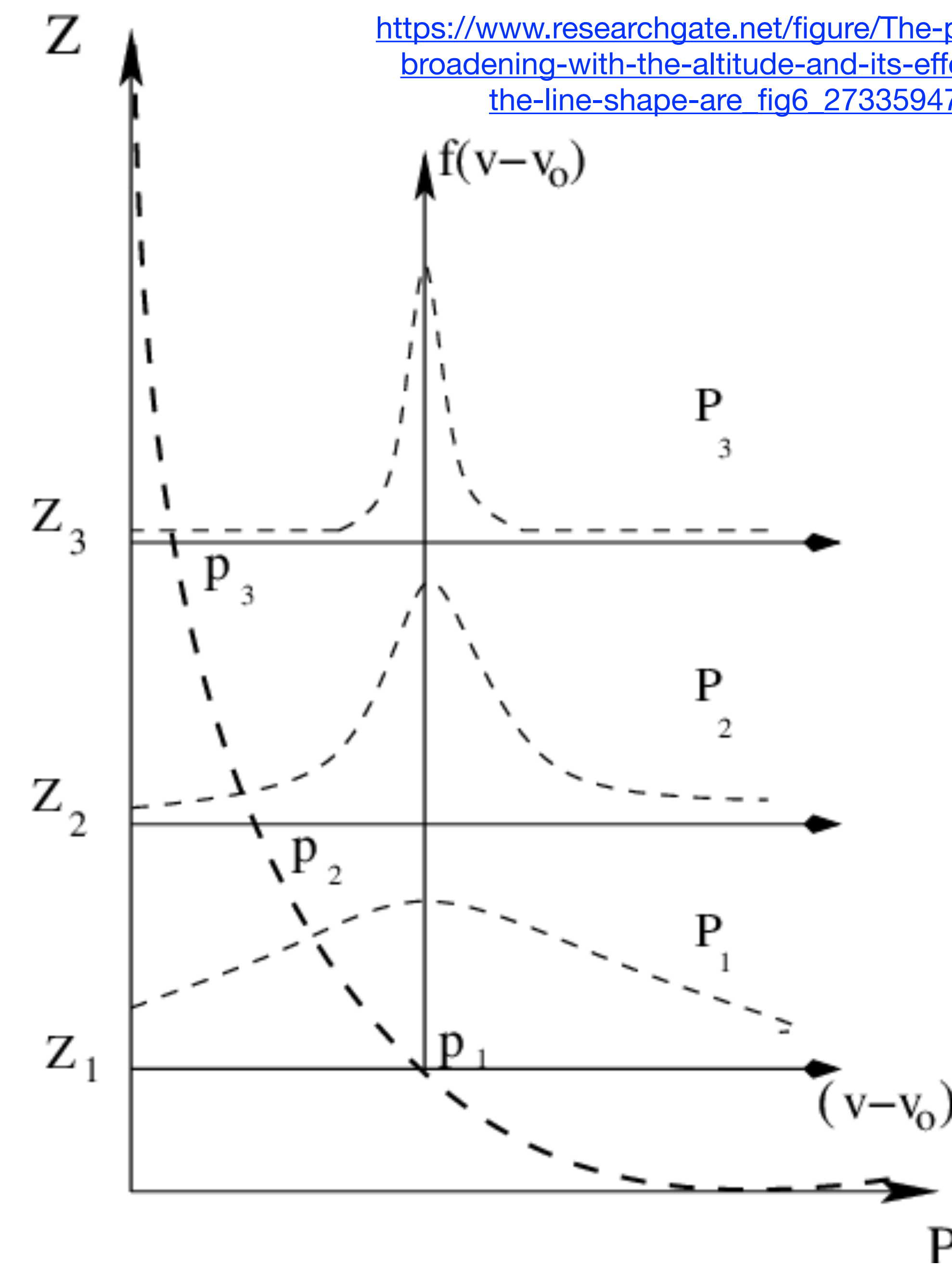
Absorption efficiency



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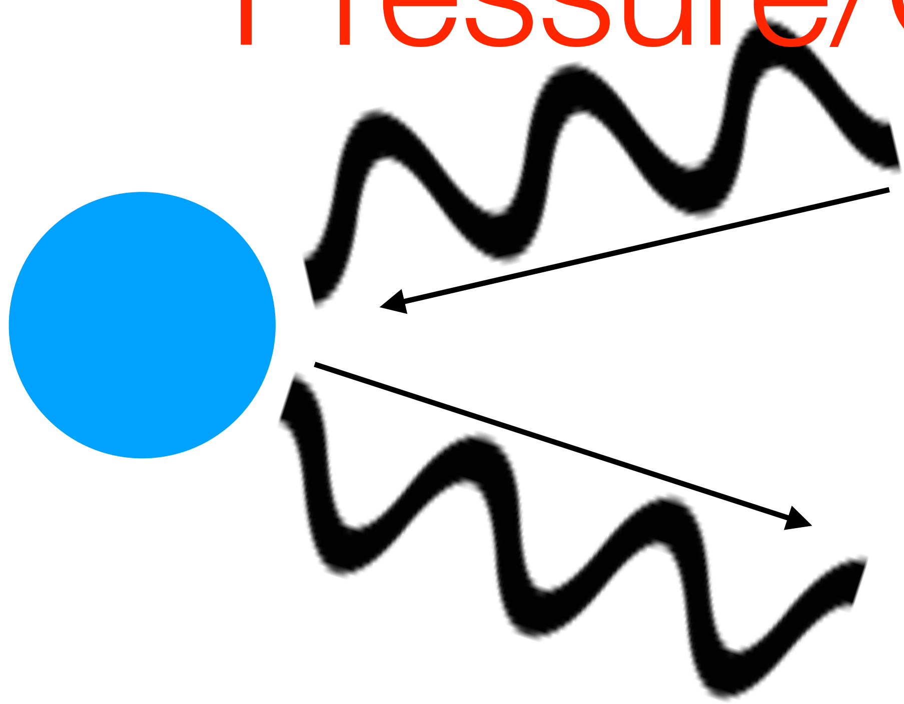

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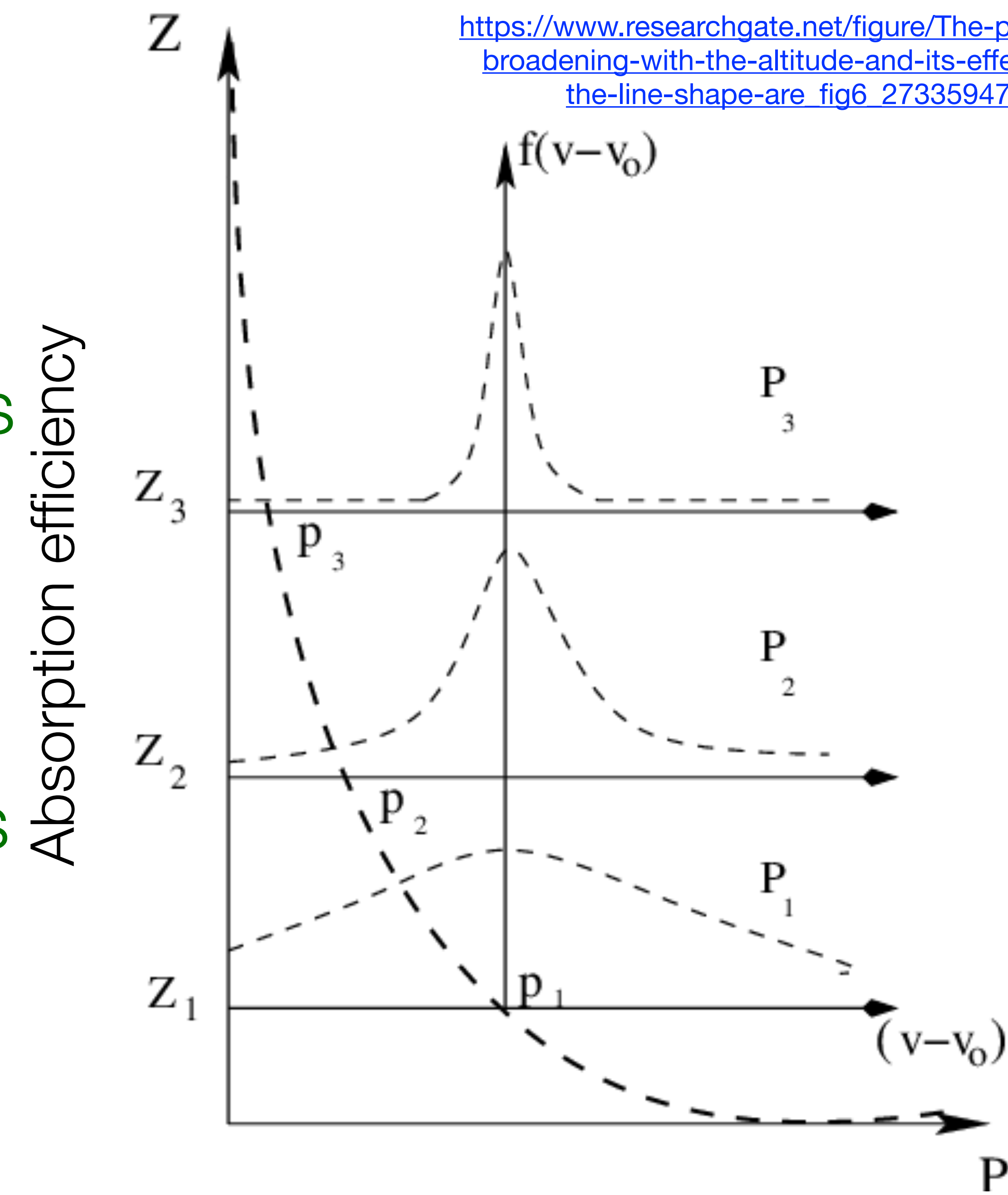

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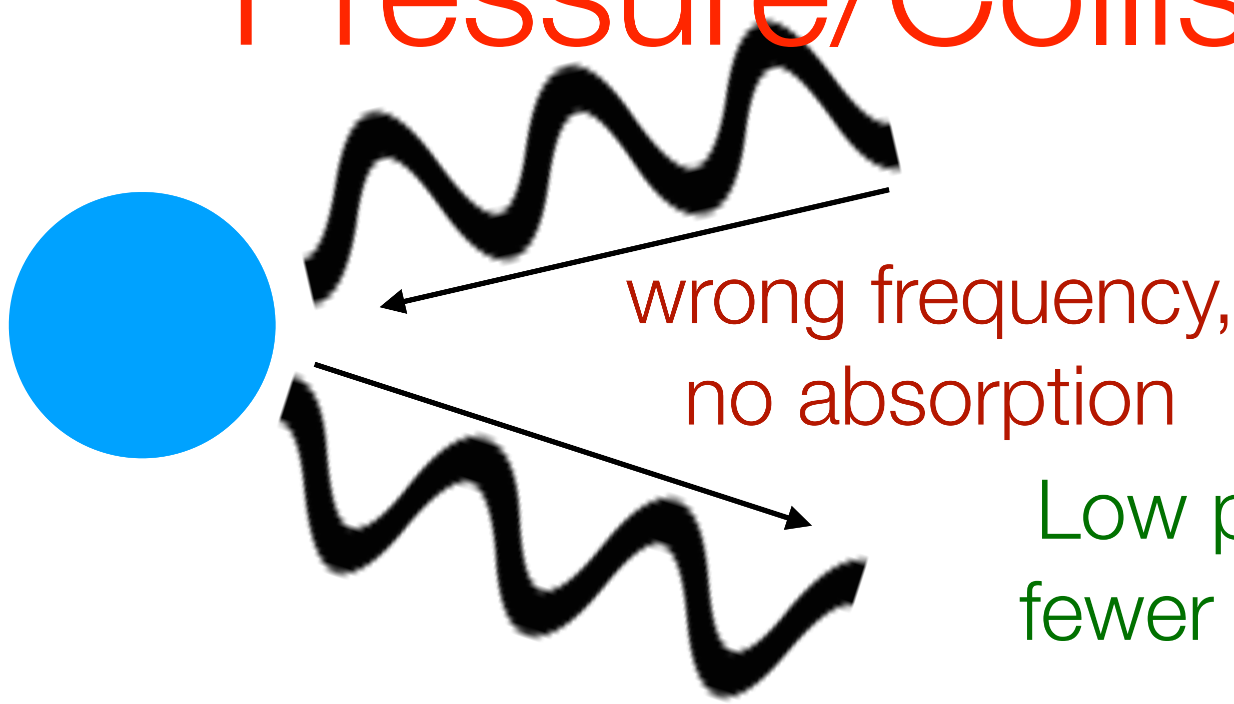

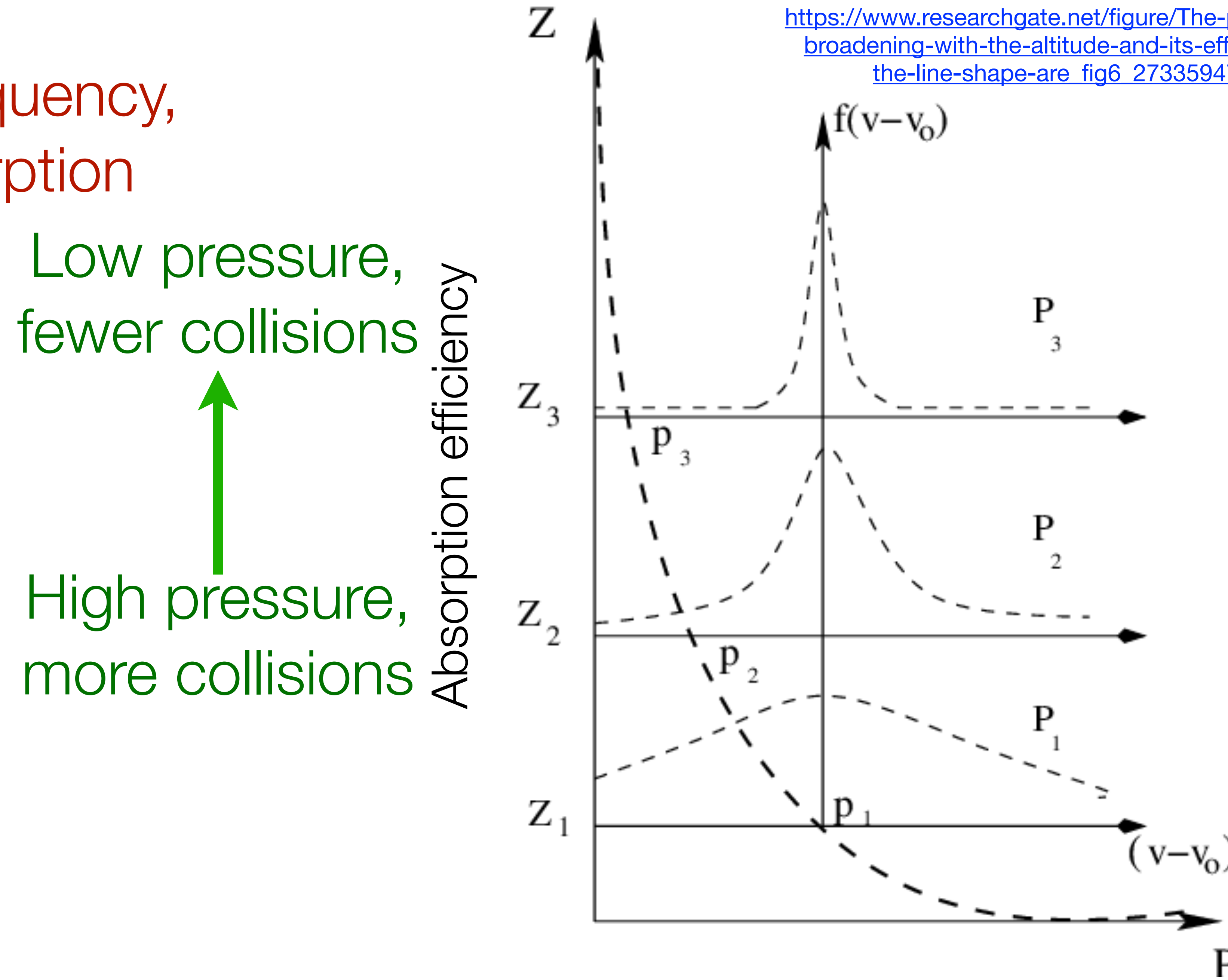

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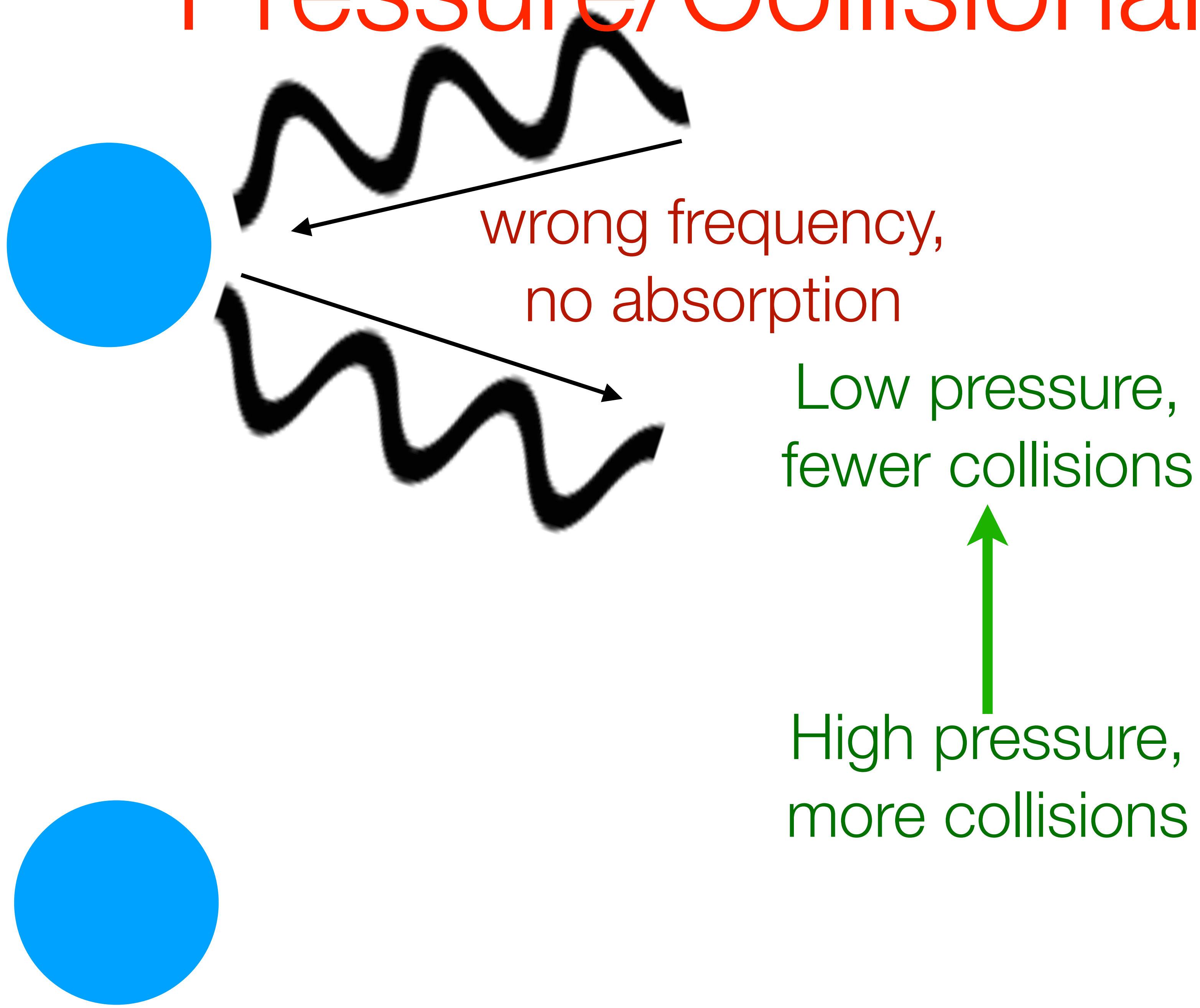

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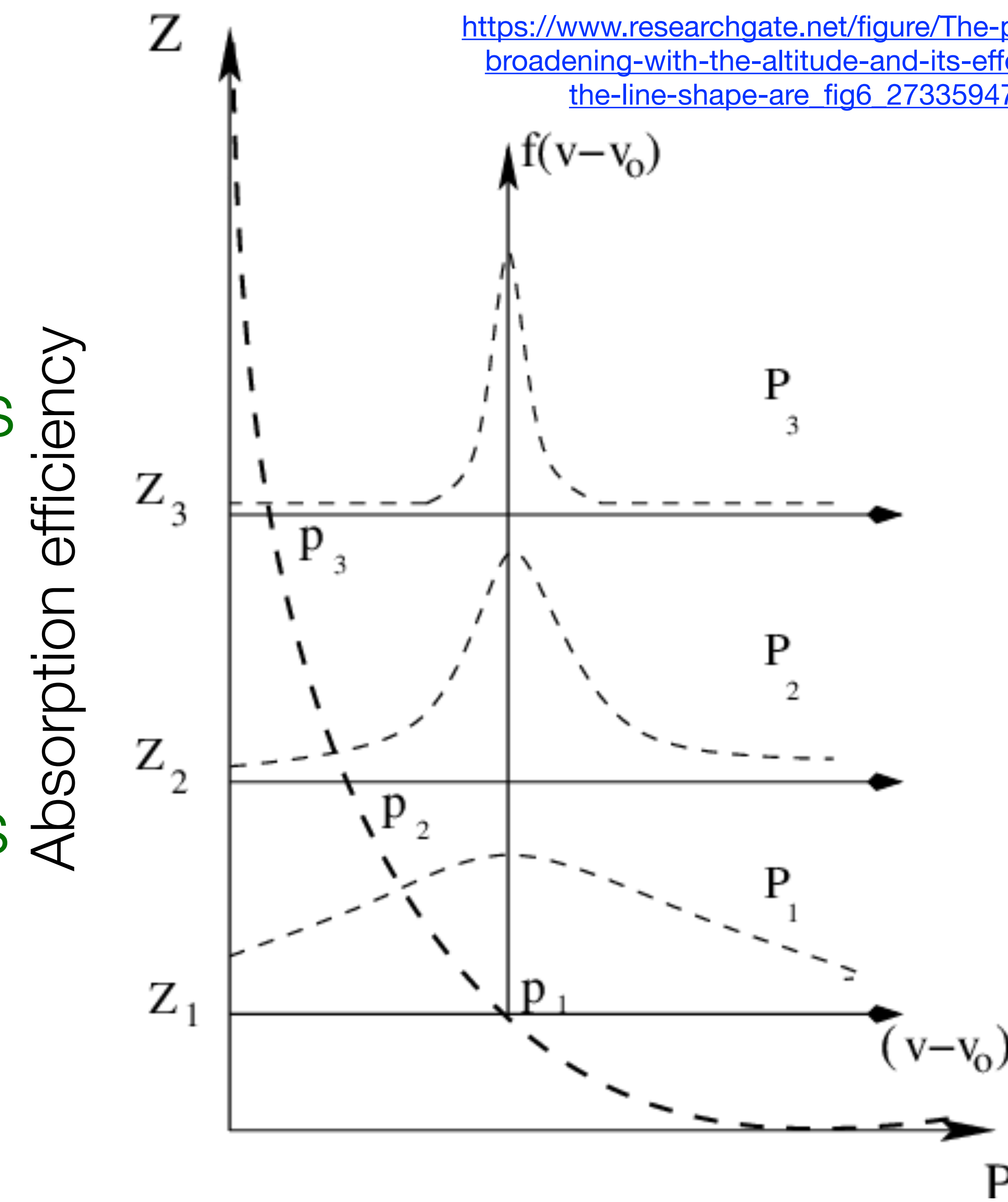
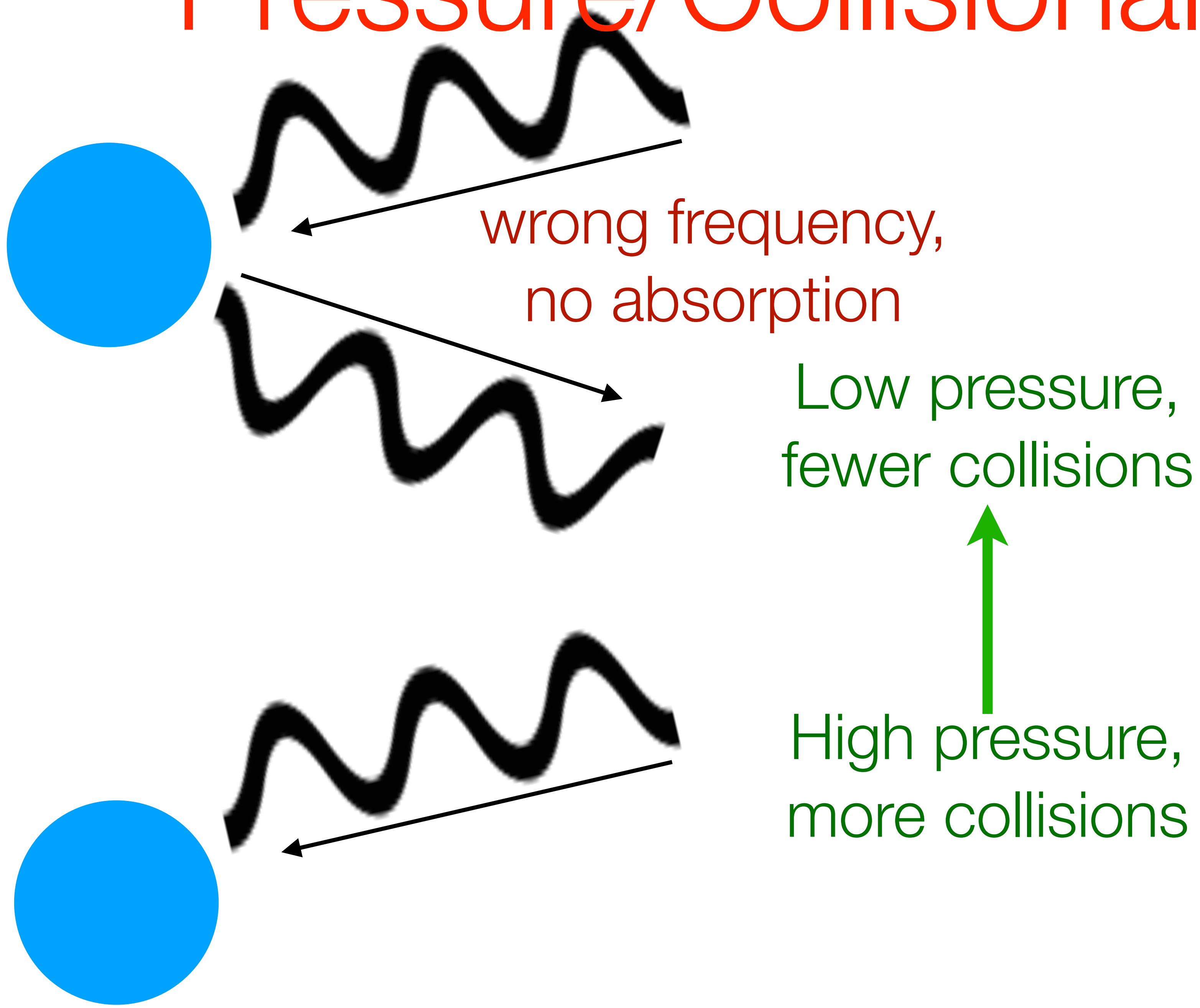
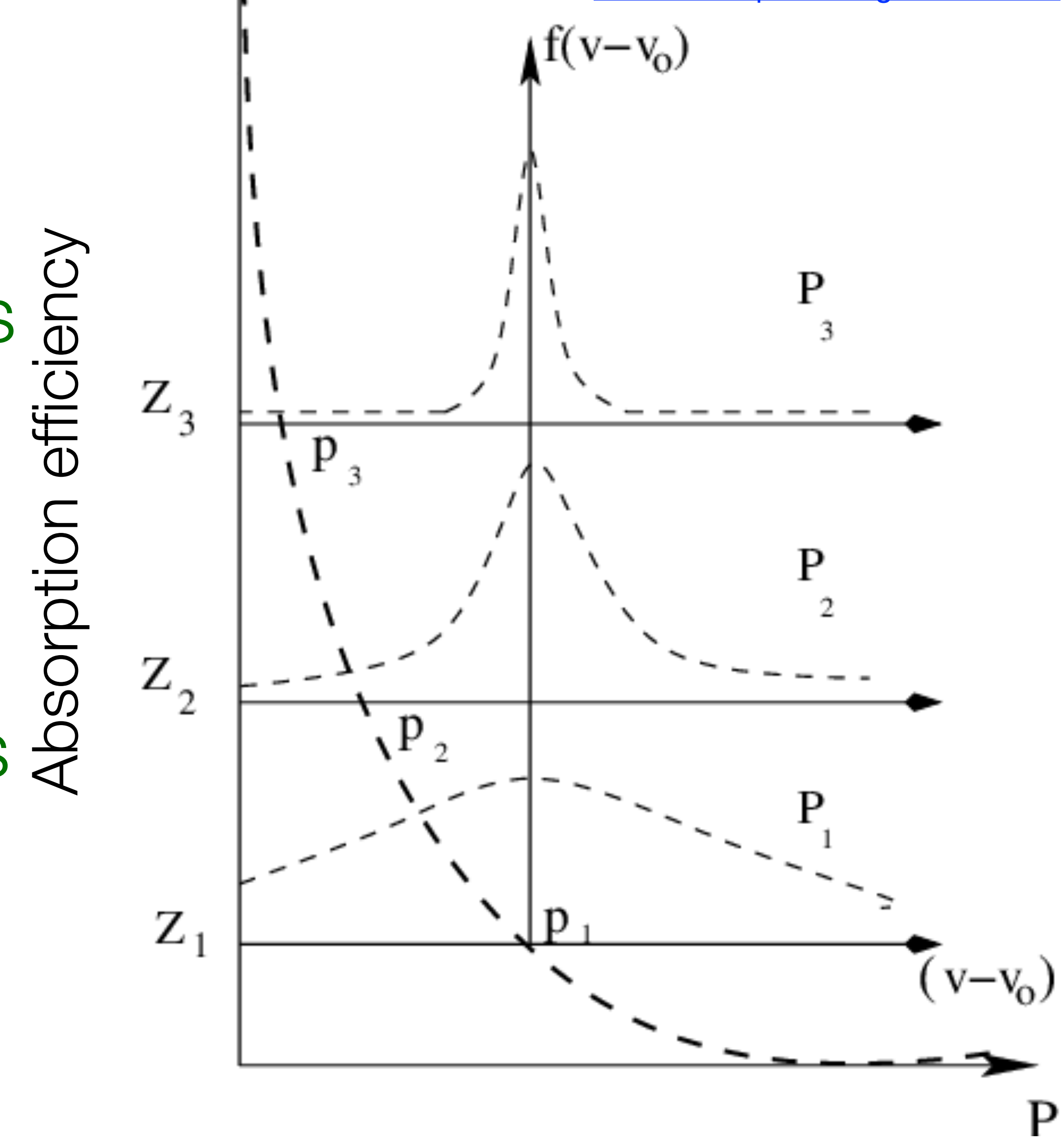


The collisions of gas molecules cause the widening of absorption lines:
If the arriving photon has slightly more energy than needed for energy level transition, the excess energy can be transferred to the colliding molecule, allowing to absorb photons that are not exactly at the right frequency/ energy

Pressure/Collisional Broadening



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



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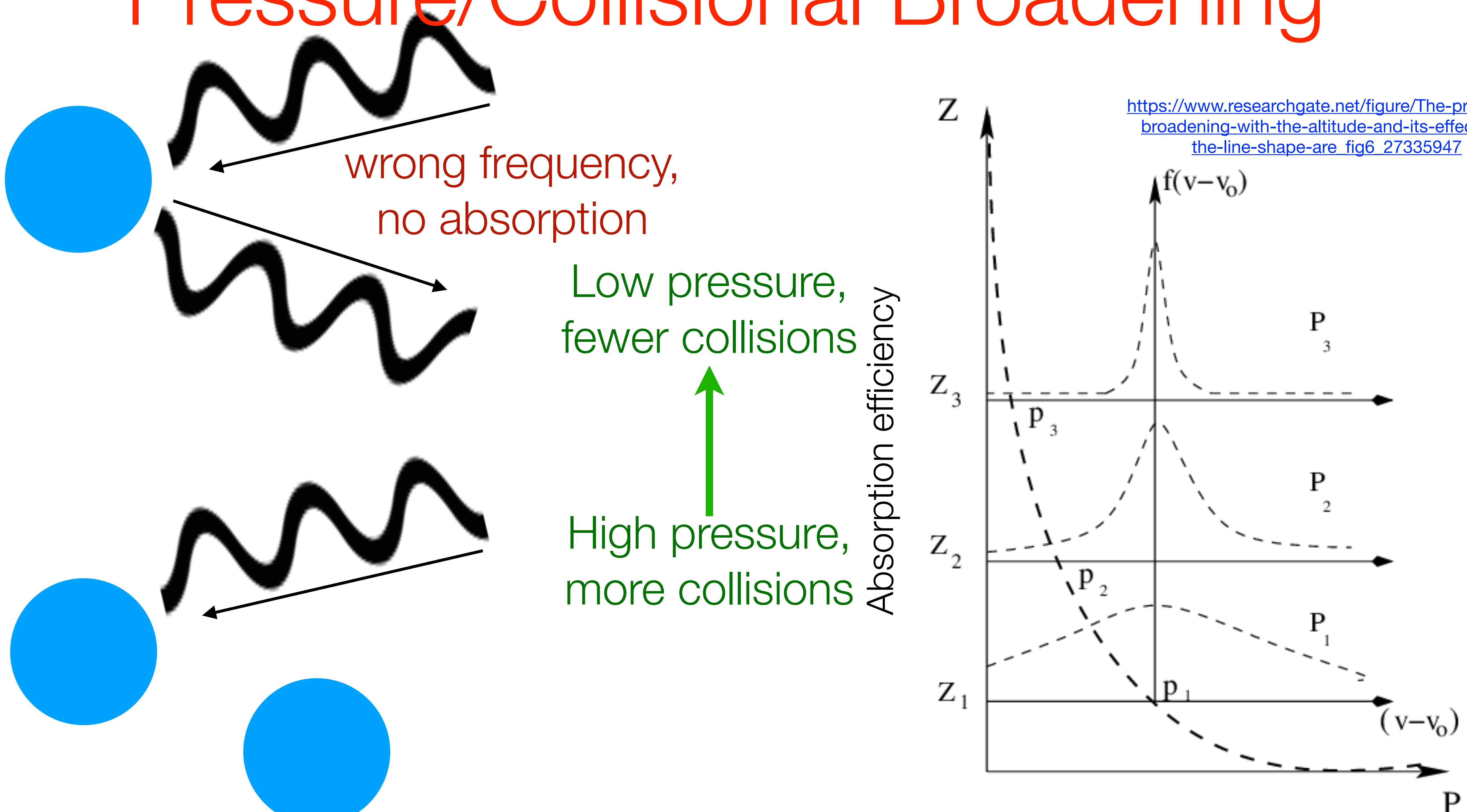

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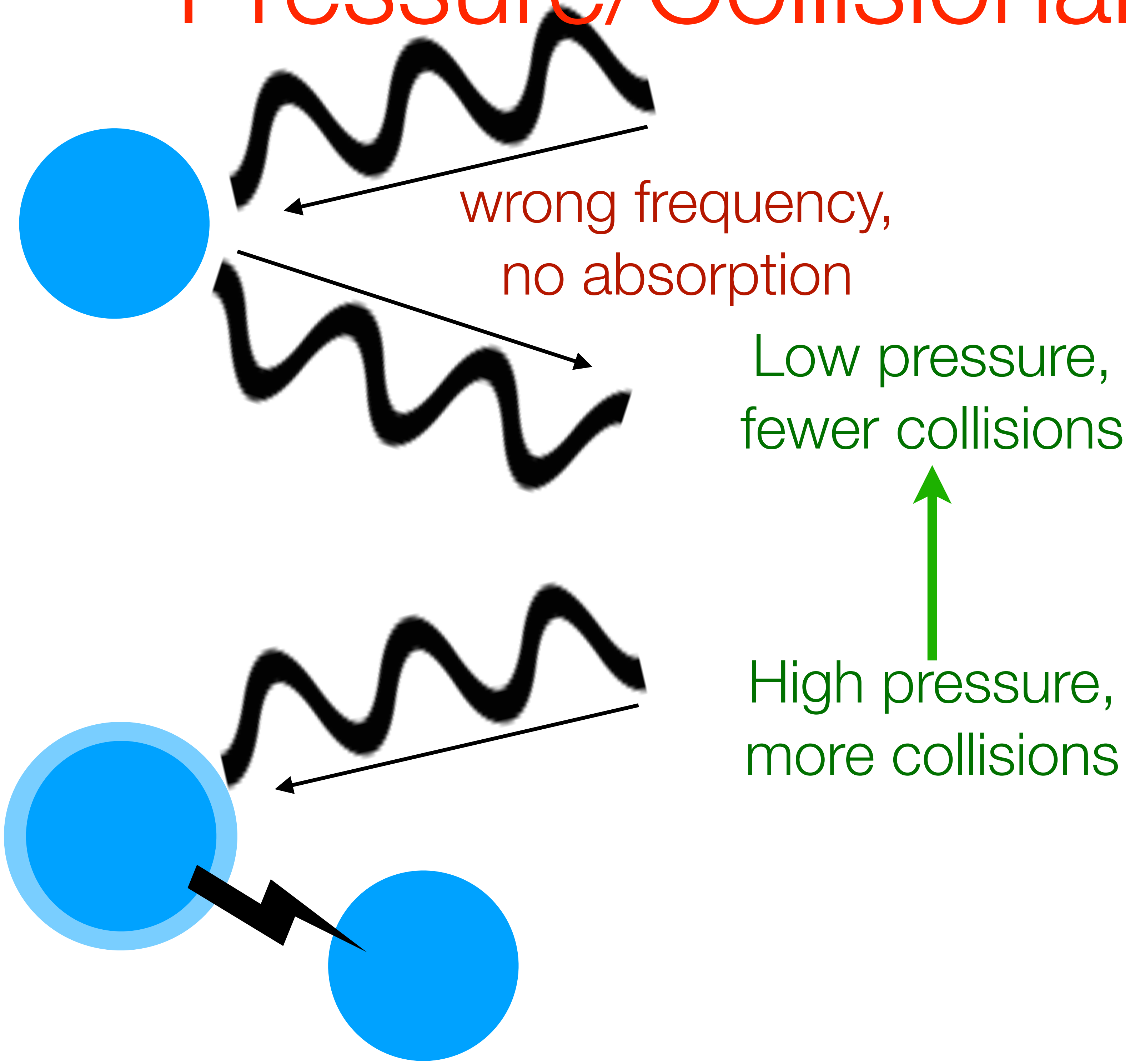

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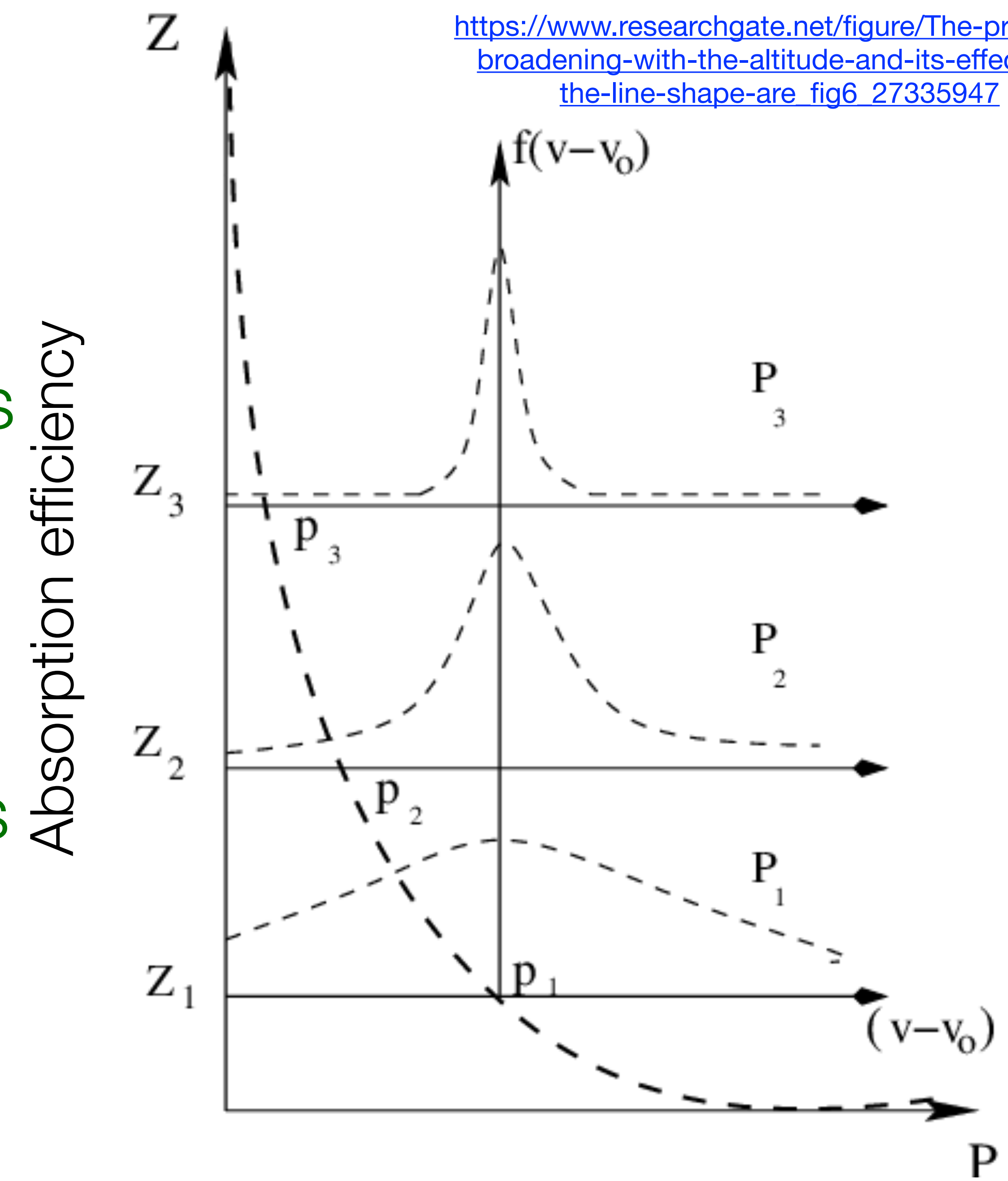

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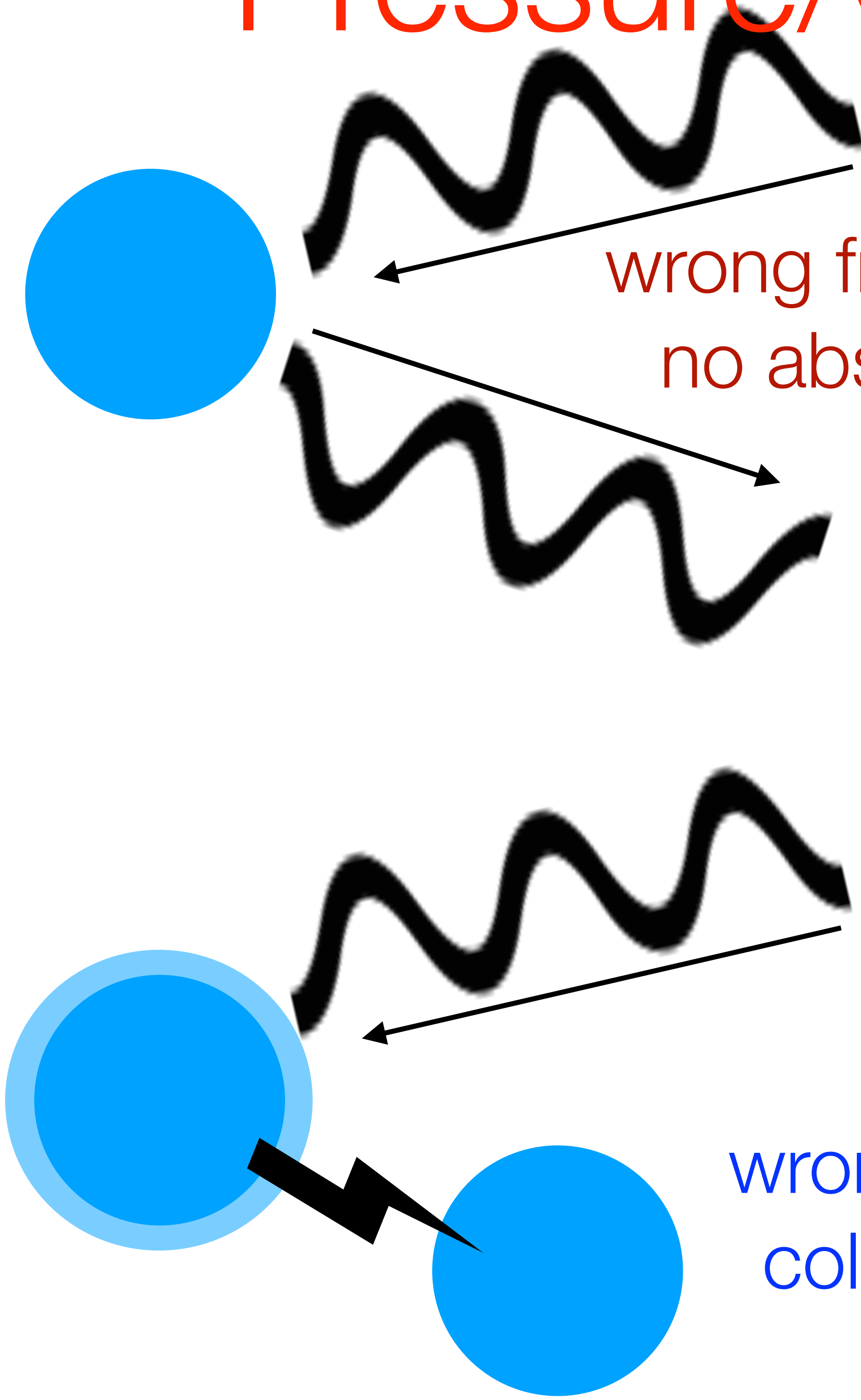
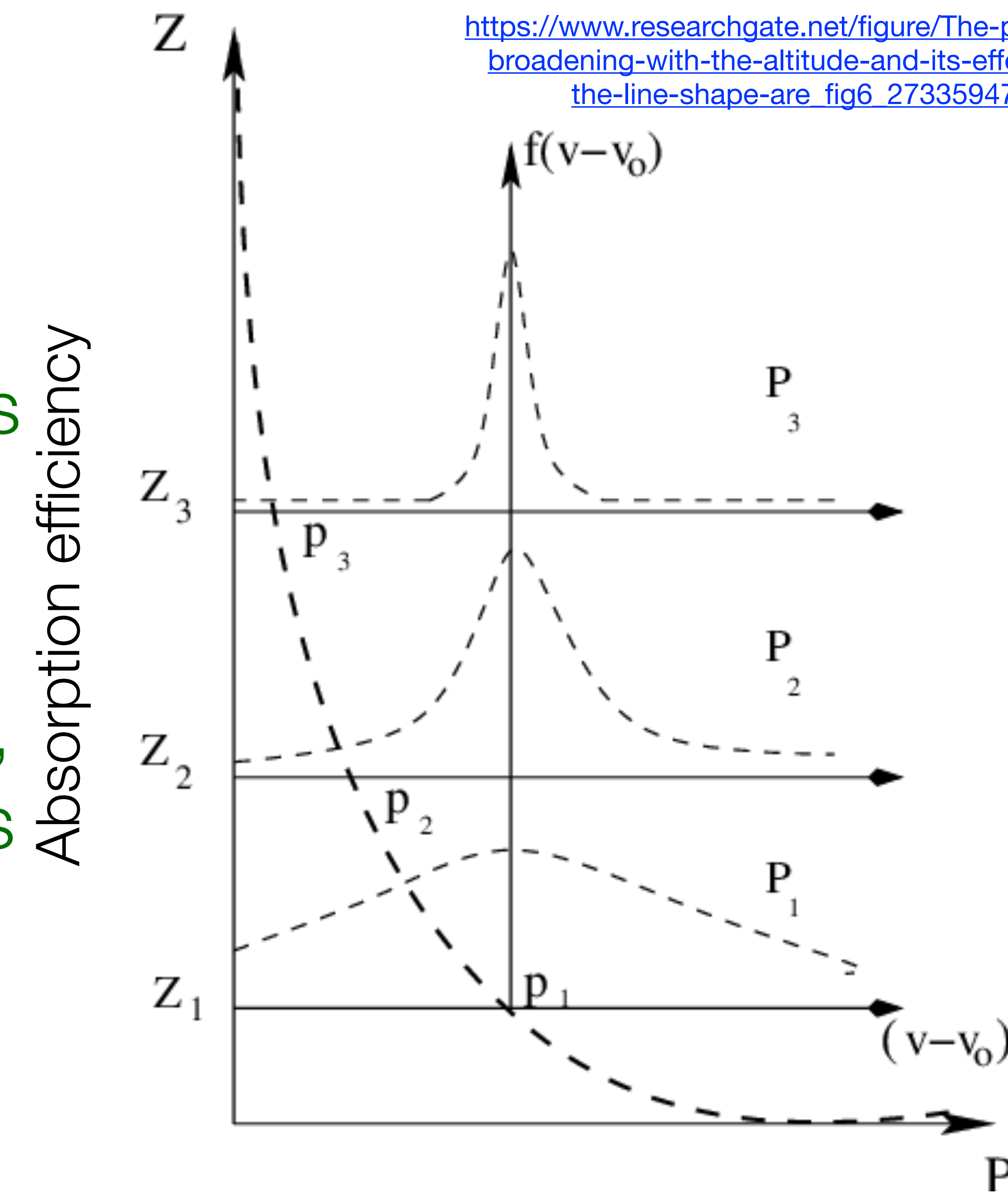


wrong frequency,
no absorption

Low pressure,
fewer collisions

High pressure,
more collisions

wrong frequency, with
collision, absorption
possible



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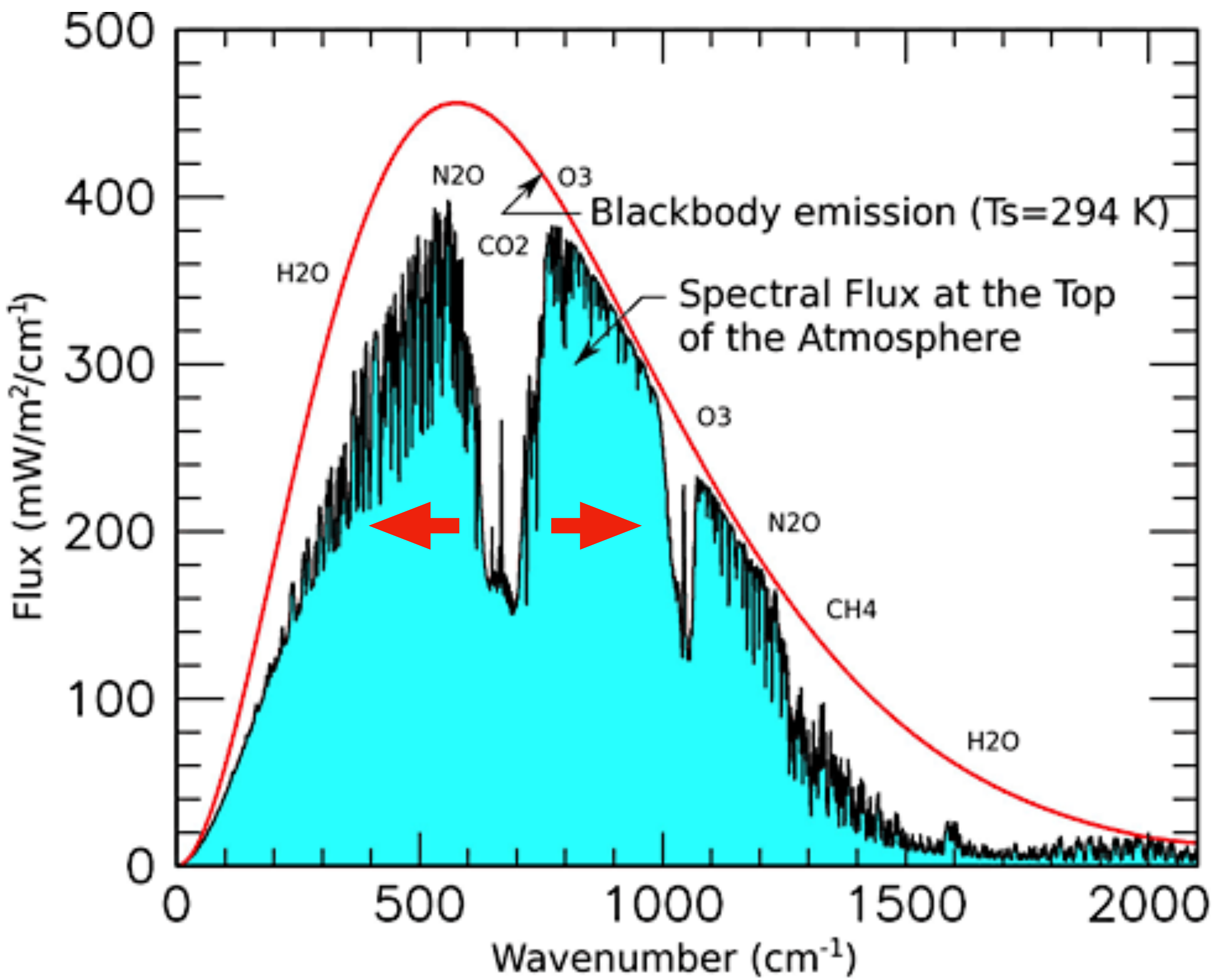
Outgoing Longwave Radiation (OLR)



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

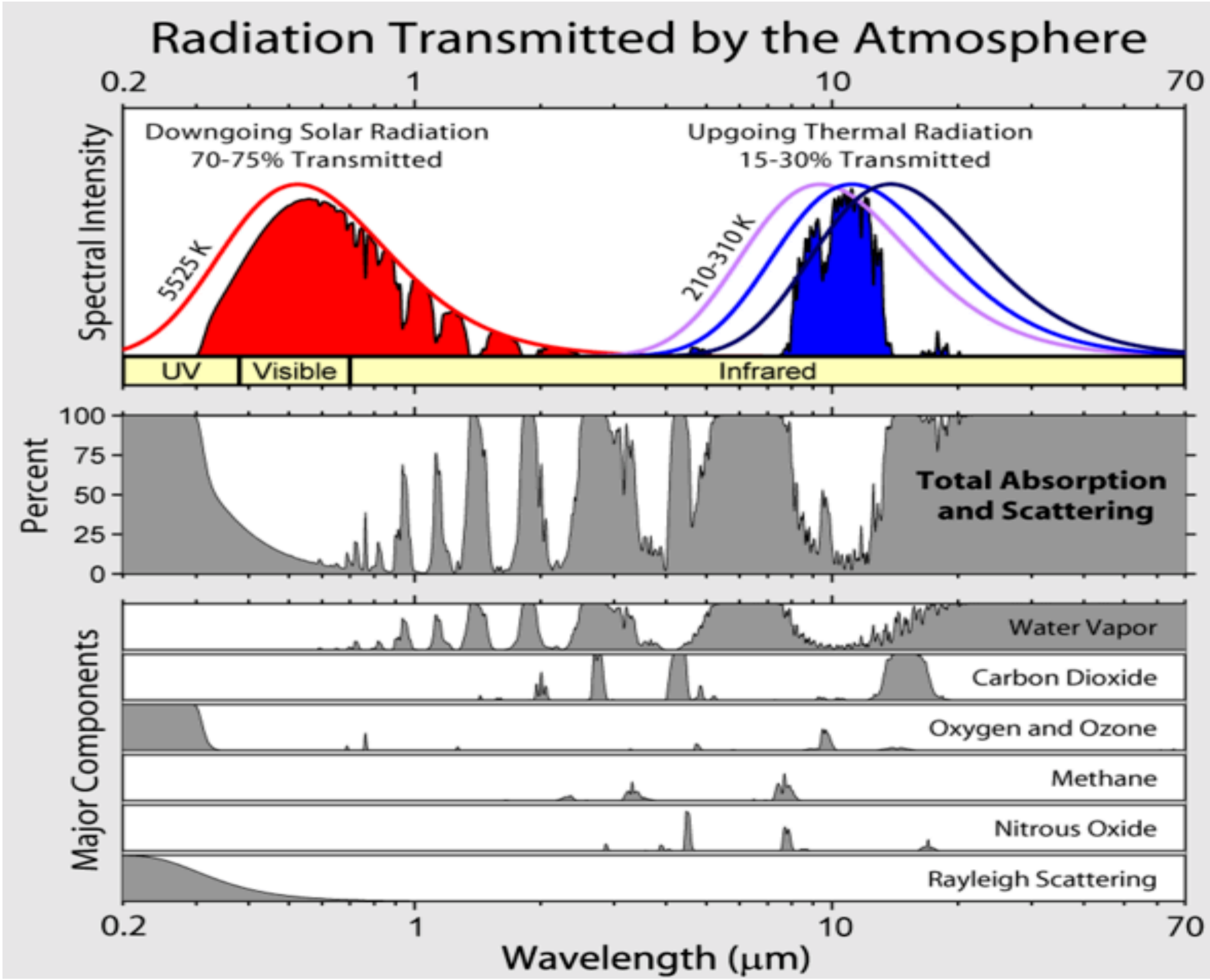
note absorption windows…

Workshop #3
radiative forcing

Notes sections 2.2.4, 2.2.5, 2.2.6: logarithmic dependence, global warming potential, water vapor feedback

(use next 4 slides)

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

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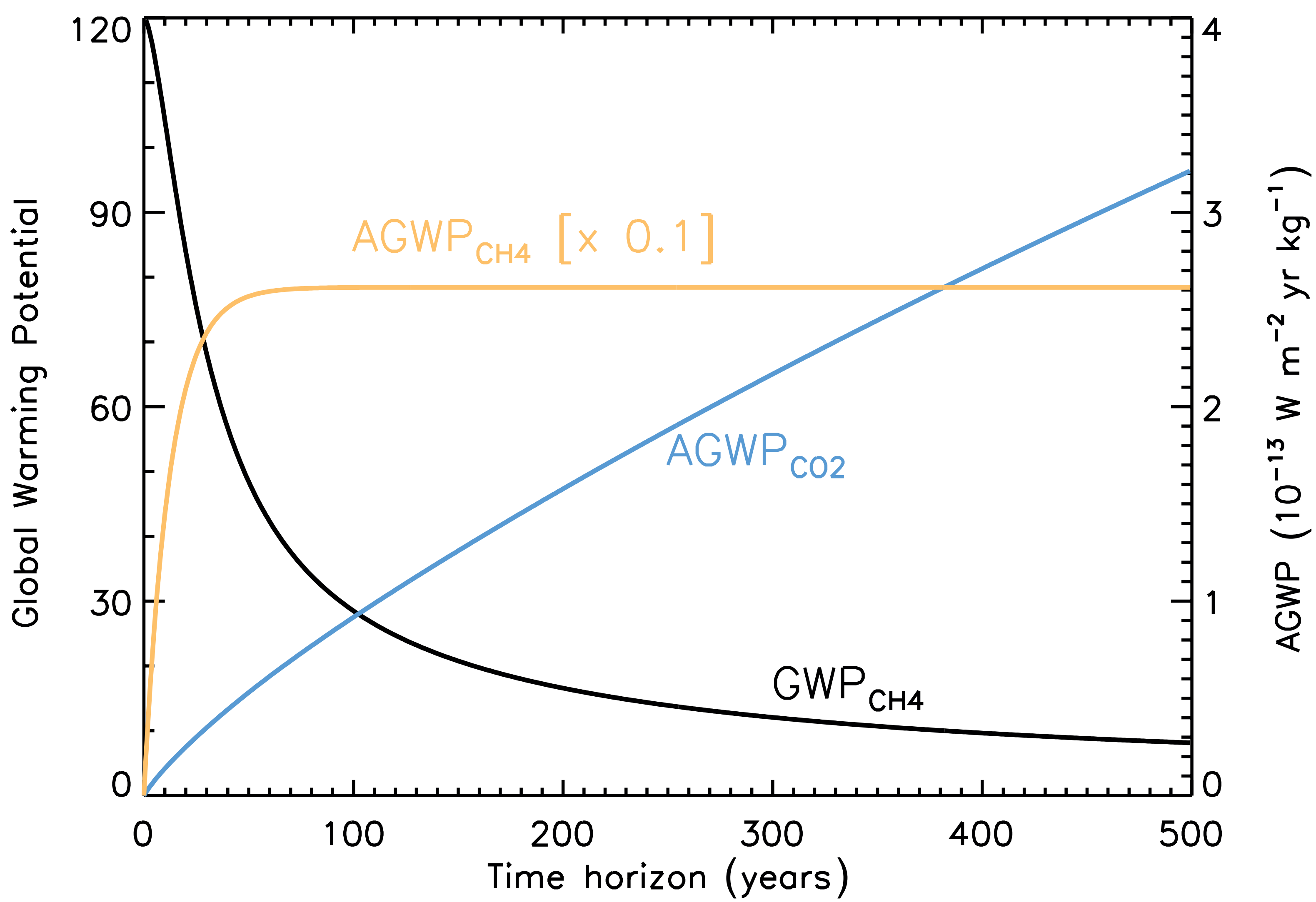

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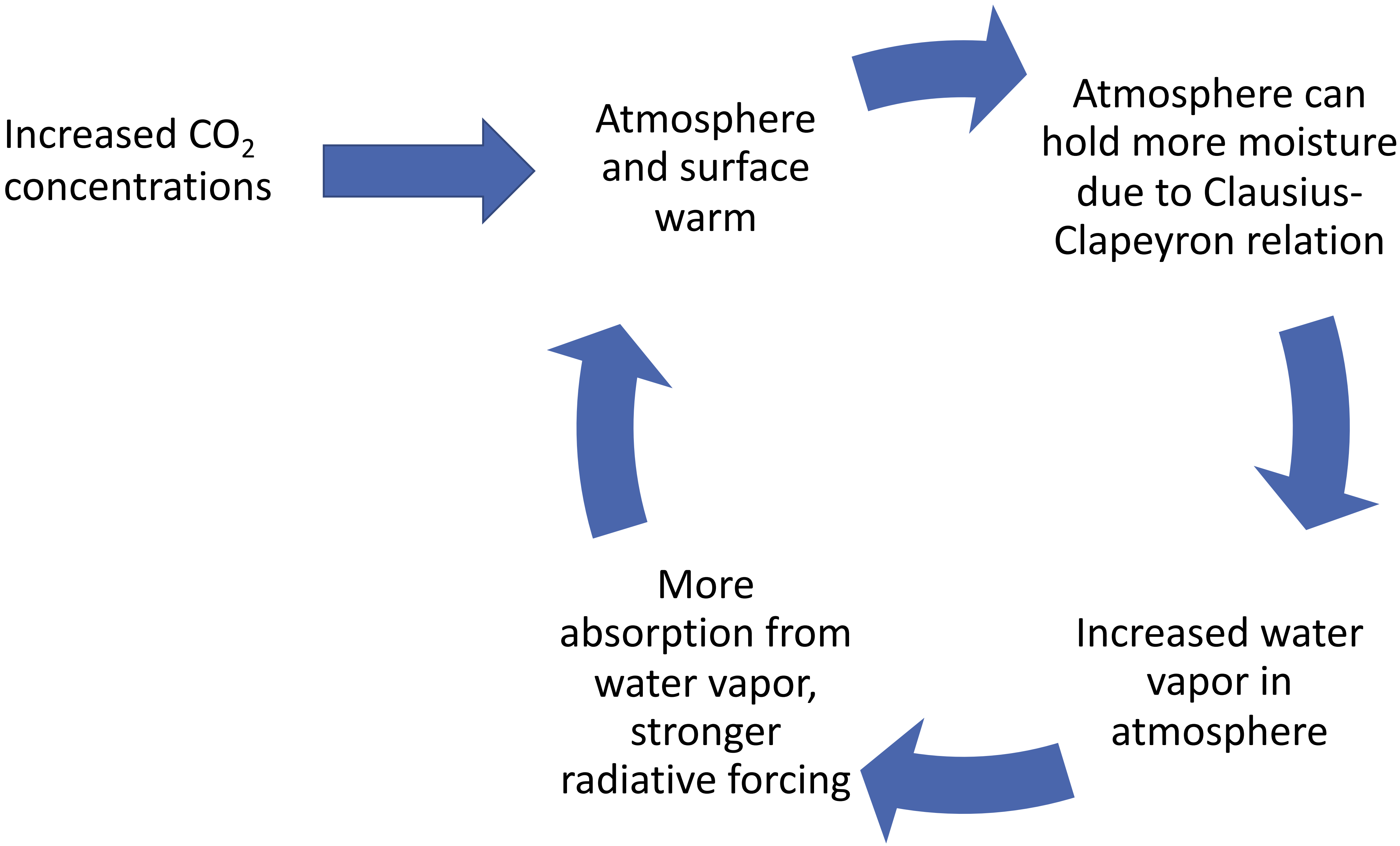
GWP values and lifetimes	Lifetime in years	Global Warming Potential (GWP)		
		20 years	100 years	500 years
Methane	12.4	86	34	
Nitrous oxide (N_2O)	121.0	268	298	
Nitrous oxide (N_2O)	121.0	264	265	
HFC-134a (hydrofluorocarbon)	13.4	3790	1550	

wikipedia

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

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- 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