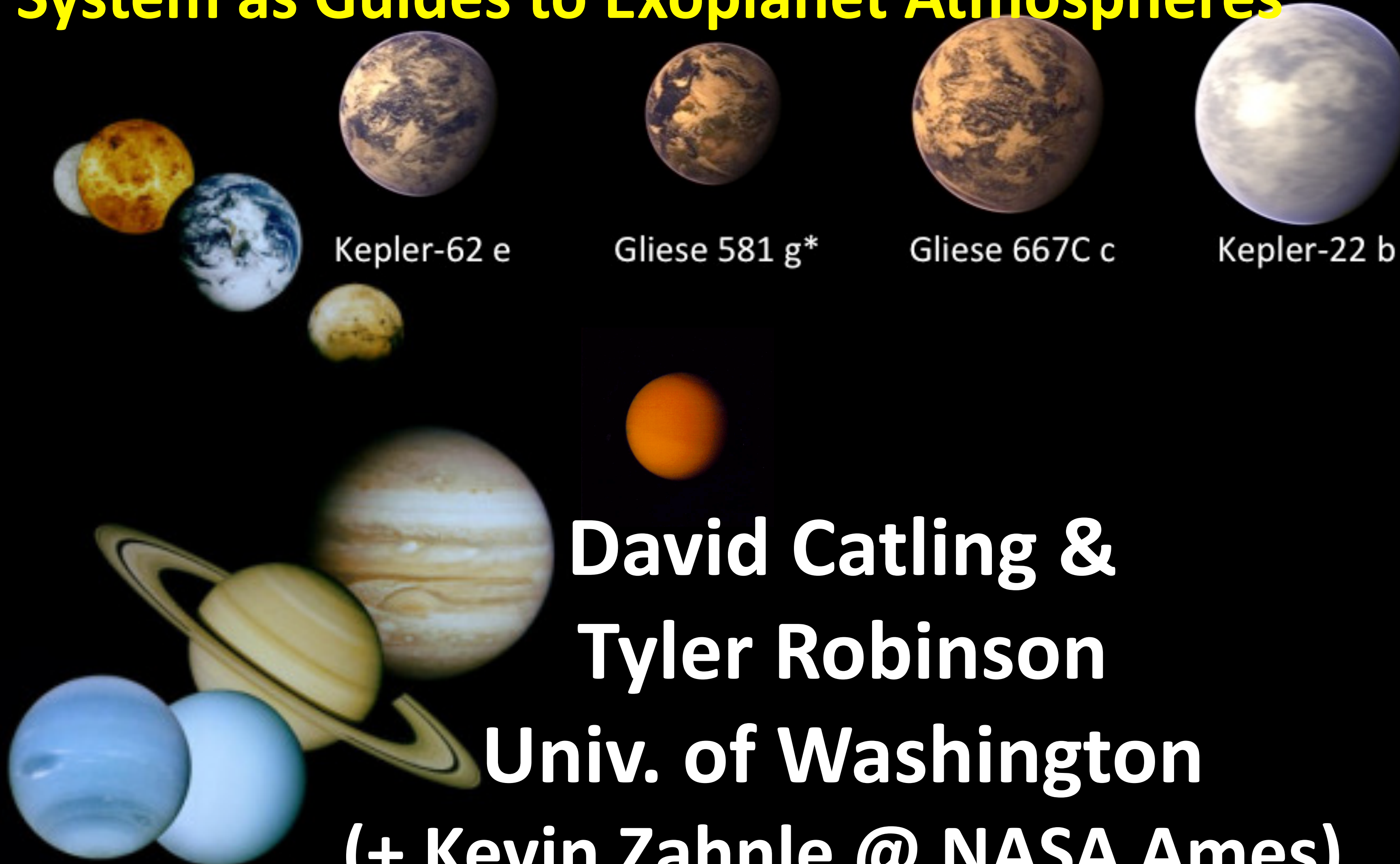
Atmospheric Chemistry and Radiation in the Solar System as Guides to Exoplanet Atmospheres



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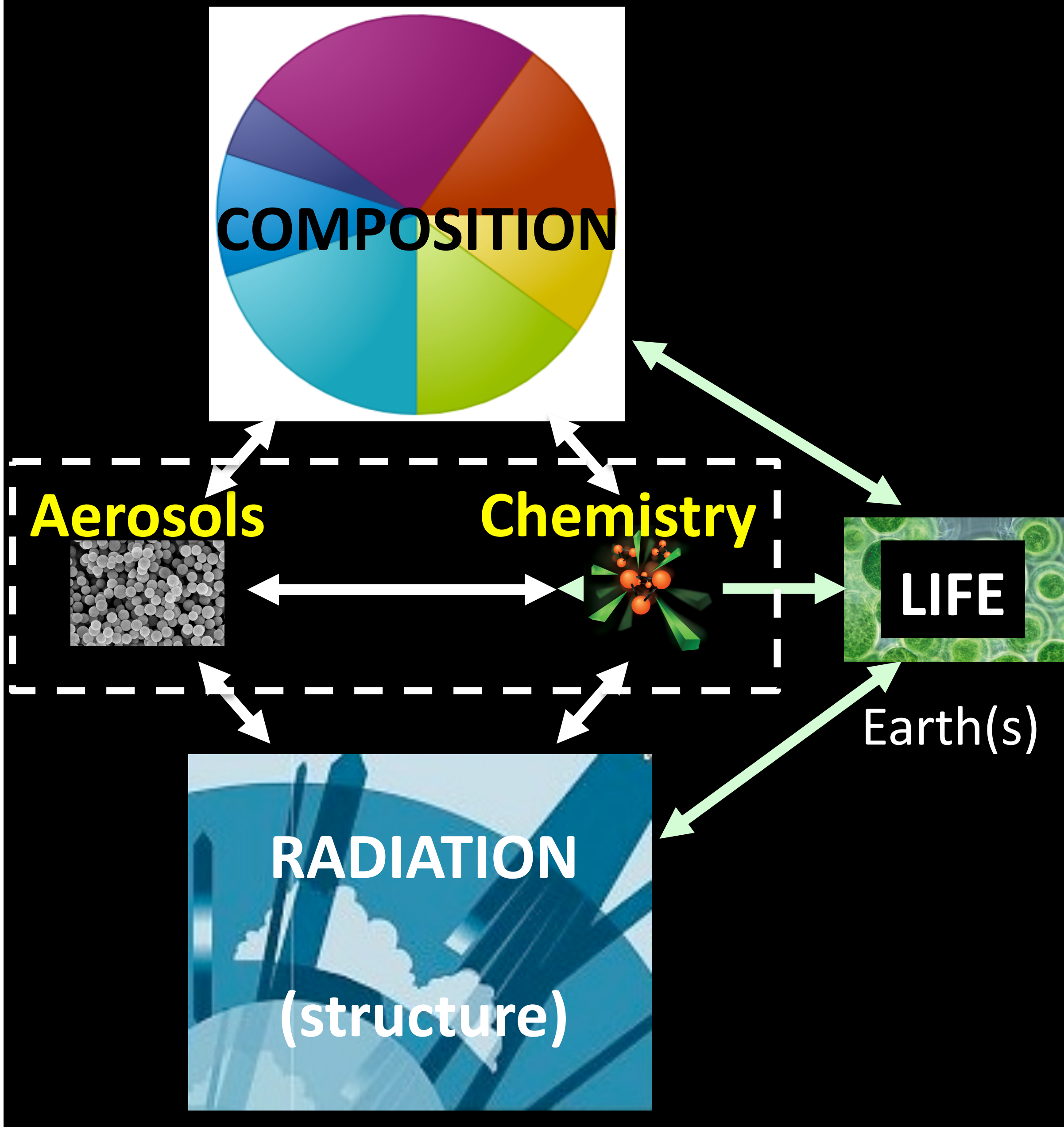
My homework assignment

From: david.crisp@jpl.nasa.gov

Date: February 5, 2013 2:03:37 PM PST

"…overview talk on "Composition/ chemistry/aerosols/radiation"… to identify critical processes that are common to the Earth, other planets in our solar system, and exoplanets, and to discuss their interactions…"

Outline



1) Atmospheric composition:

-Why atmospheres exist (zero-order question of escape and retention)

-The taxonomy of atmospheric composition

-Earth as bio-atmospheric chemistry

2) Radiation and structure:

Chemistry-radiation connection

1st order commonalities

in stratospheres, tropospheres

3) Conclusions

Part 1:
Atmospheric composition

The existence of atmospheres

Nature (volatile-rich origin) vs. nurture (evolution)?

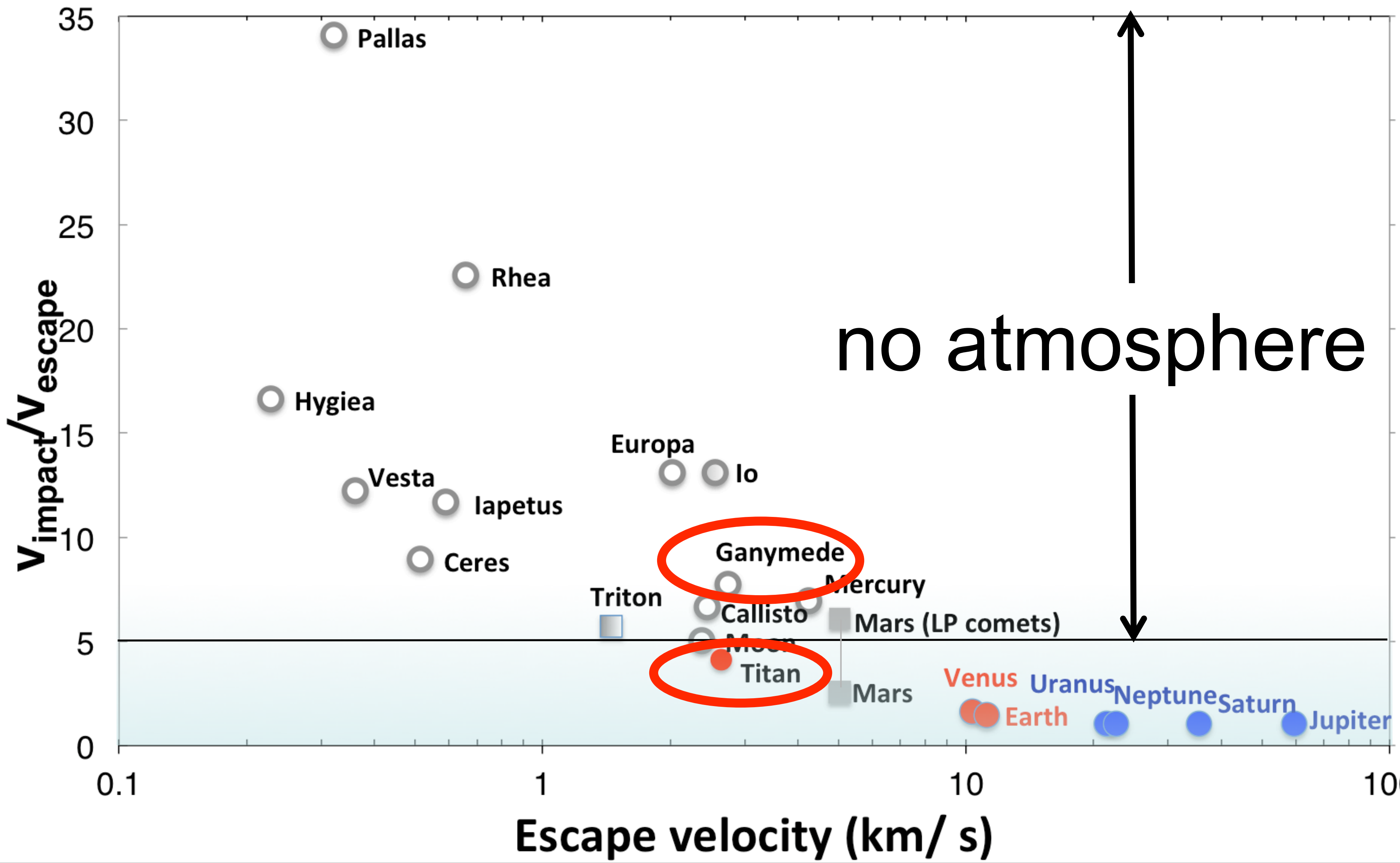
Nurture must ultimately rule because atmospheres must be stable against obliteration by:

1) Impact erosion – loss from large body impacts

2) Irradiation-driven hydrodynamic escape (thermal escape end-member)

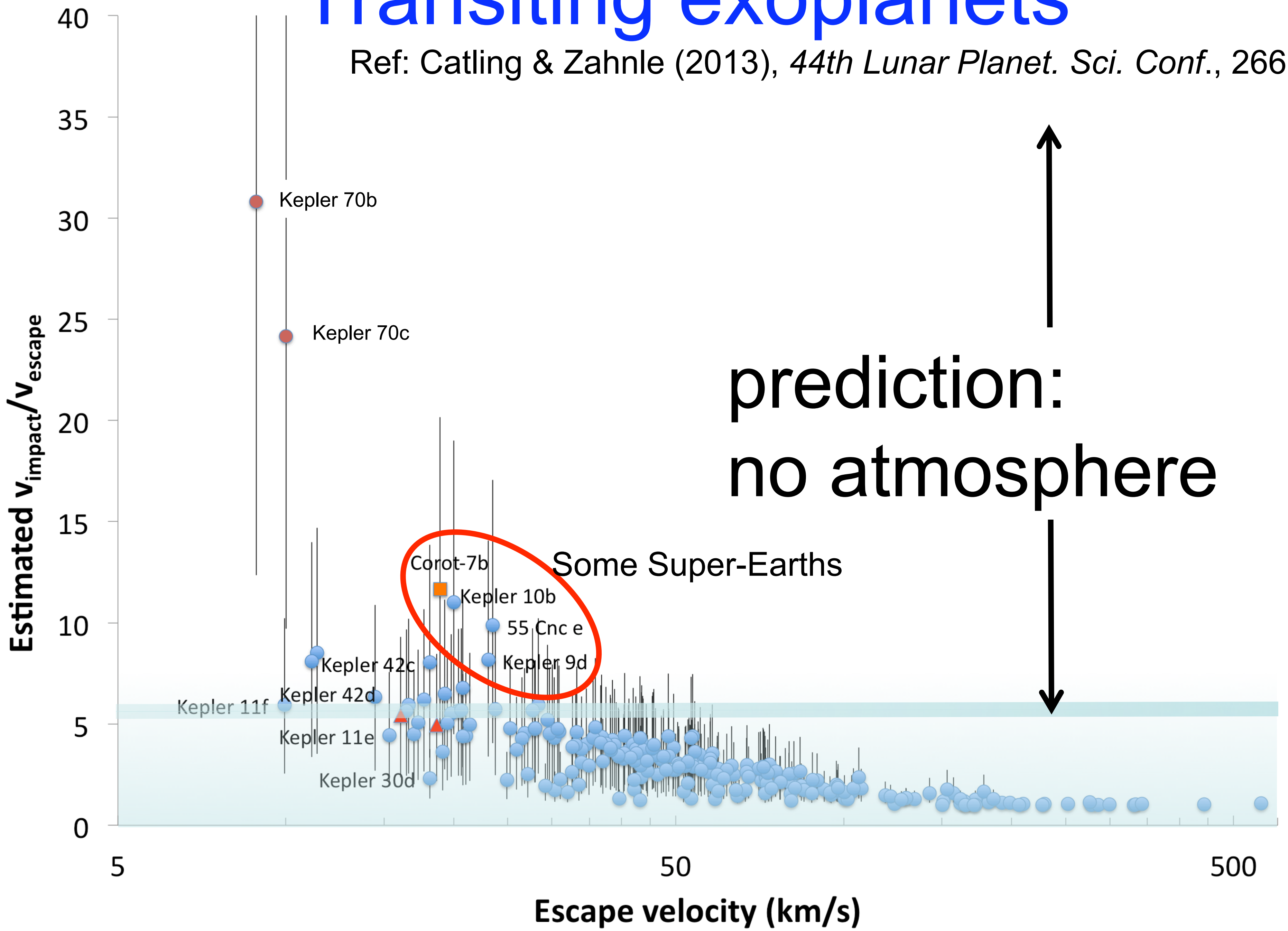
Good versus bad neighborhoods

Ref: Catling & Zahnle (2013), *44th Lunar Planet. Sci. Conf.*, 2665

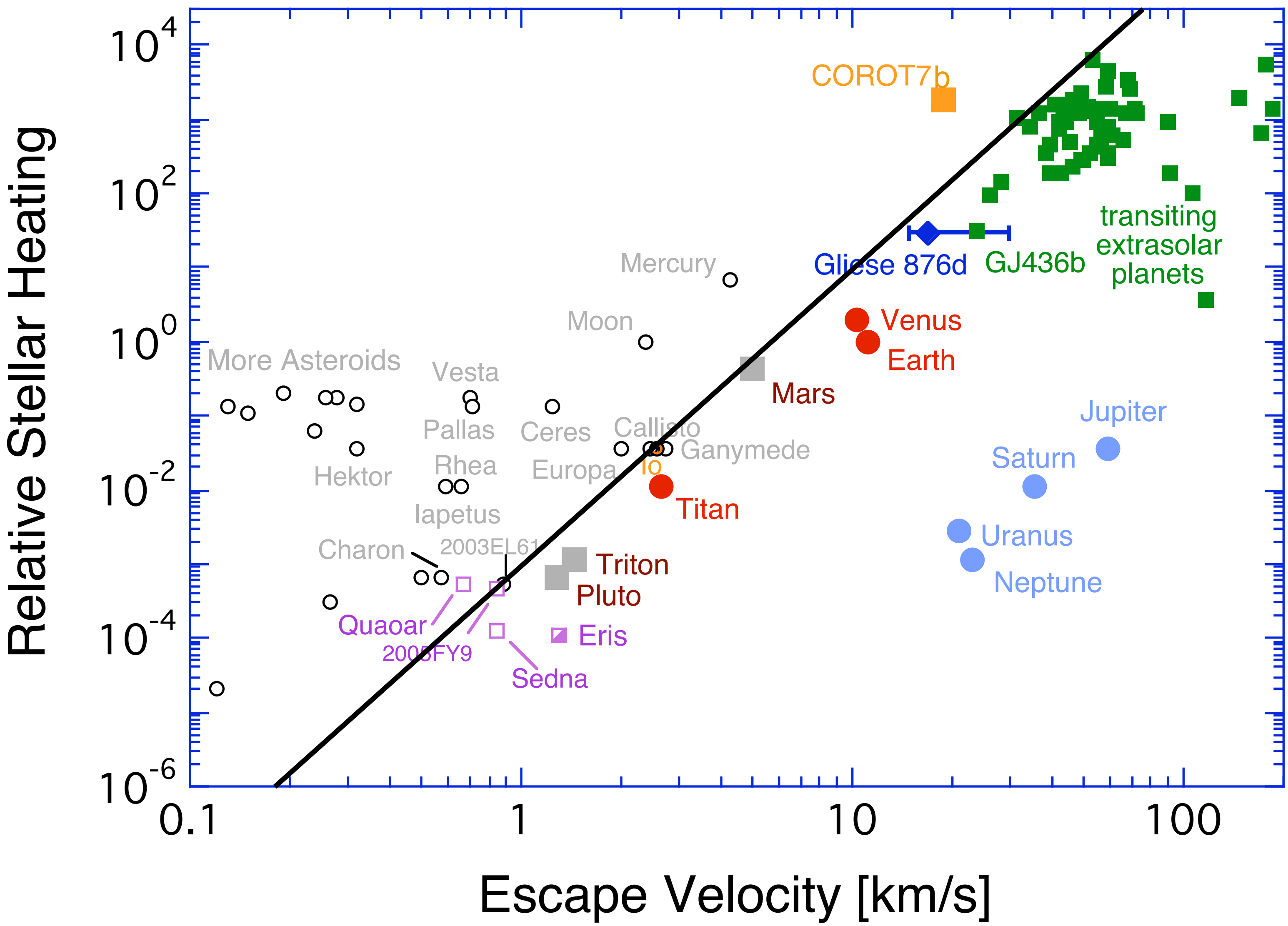


Transiting exoplanets

Ref: Catling & Zahnle (2013), *44th Lunar Planet. Sci. Conf.*, 2665



Thermal (hydrodynamic escape) stability



From Zahnle & Catling (2013), The cosmic shoreline, *44th Lunar Planet. Sci. Conf.*, 2787

So, atmospheres will not exist if:

1) **Bad impact regime** (has received little attention)

- rocky planets in M-star habitable zone are vulnerable
- e.g. Earth @ 1/9AU from 1/3$M_{\odot}$ v_{impact}/v_{esc} ~3 => problem for complex life?
  Mars in same HZ, v_{impact}/v_{esc} ~6 => I predict airless
- M-star planets form 10^5-10^6 yrs => migration is an *unlikely* savior; disk dissipation takes ~10^{6-7} yr from observations, so planet will be in its final orbit while impact regime is bad (Lissauer, 2007, *Ap. J.*).
- Lucky ones? Frozen volatiles on night-side; late slow, volatile-rich impactors

2) **Bad thermal regime** (prone to hydrodynamic escape)

- Pre-main sequence luminosity is under-appreciated
- e.g., a 1/3$M_{\odot}$ M-star is ~10x more luminous during first ~4 Myr than on the main sequence, when planets have formed

Taxonomy of atmospheric compositions

(a Solar System perspective)

Fundamentally, two types:

Atmospheres

- **1. Reducing**
  - Titan
  - giants
  - Pre-2.4 Ga Earth
  - Pre-4.3 Ga? Mars
- **2. Oxidizing**
  - Post-2.4 Ga Earth
  - Venus (at altitude)
  - Mars

I'm ignoring

-very tenuous N_2 (CH_4) ice-vapor equilibria air of KBOs (e.g., Triton, Pluto)

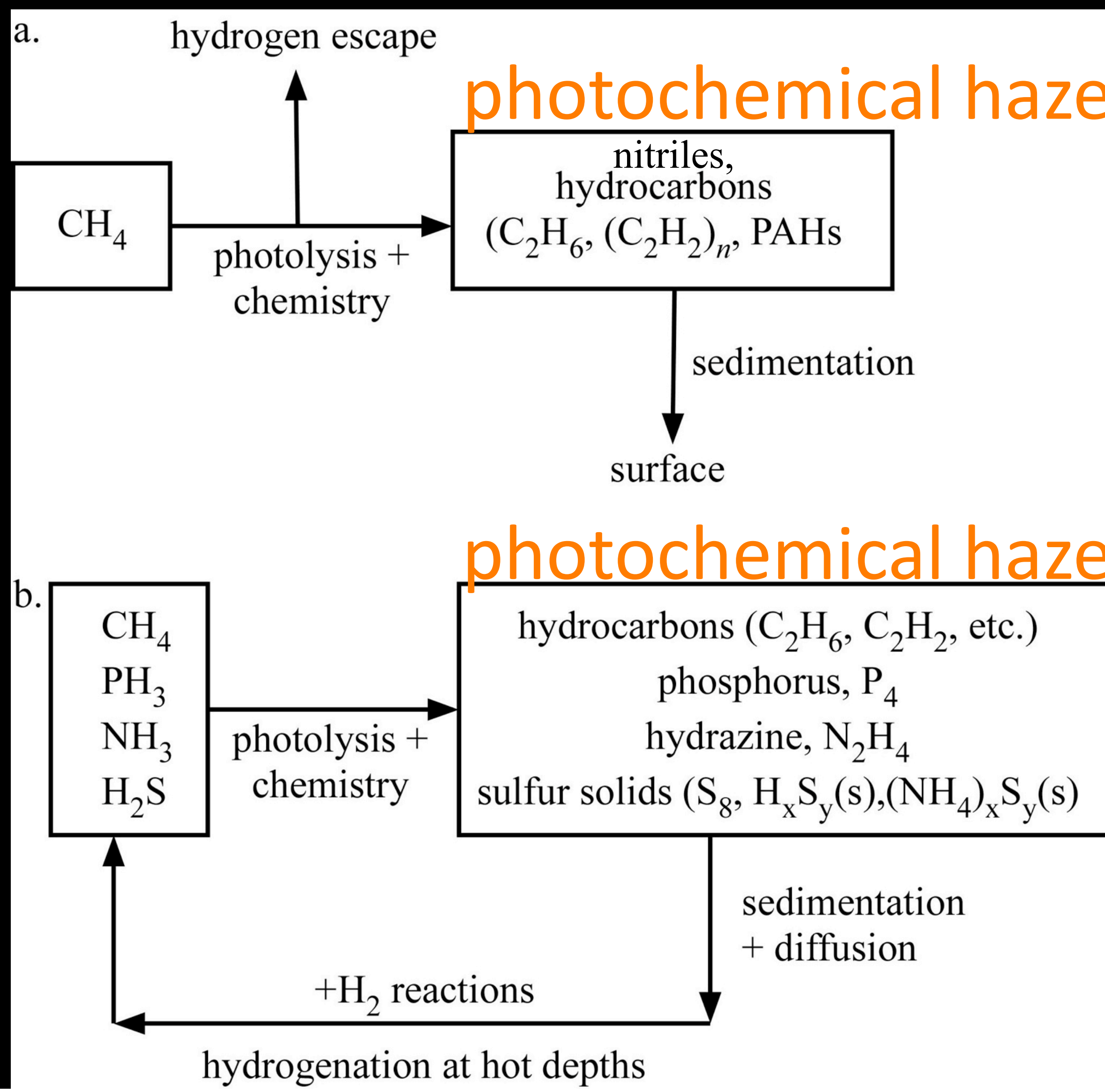
Fate of hydrogen in reducing atmospheres

a key difference in small vs. large bodies

Titan

Reducing

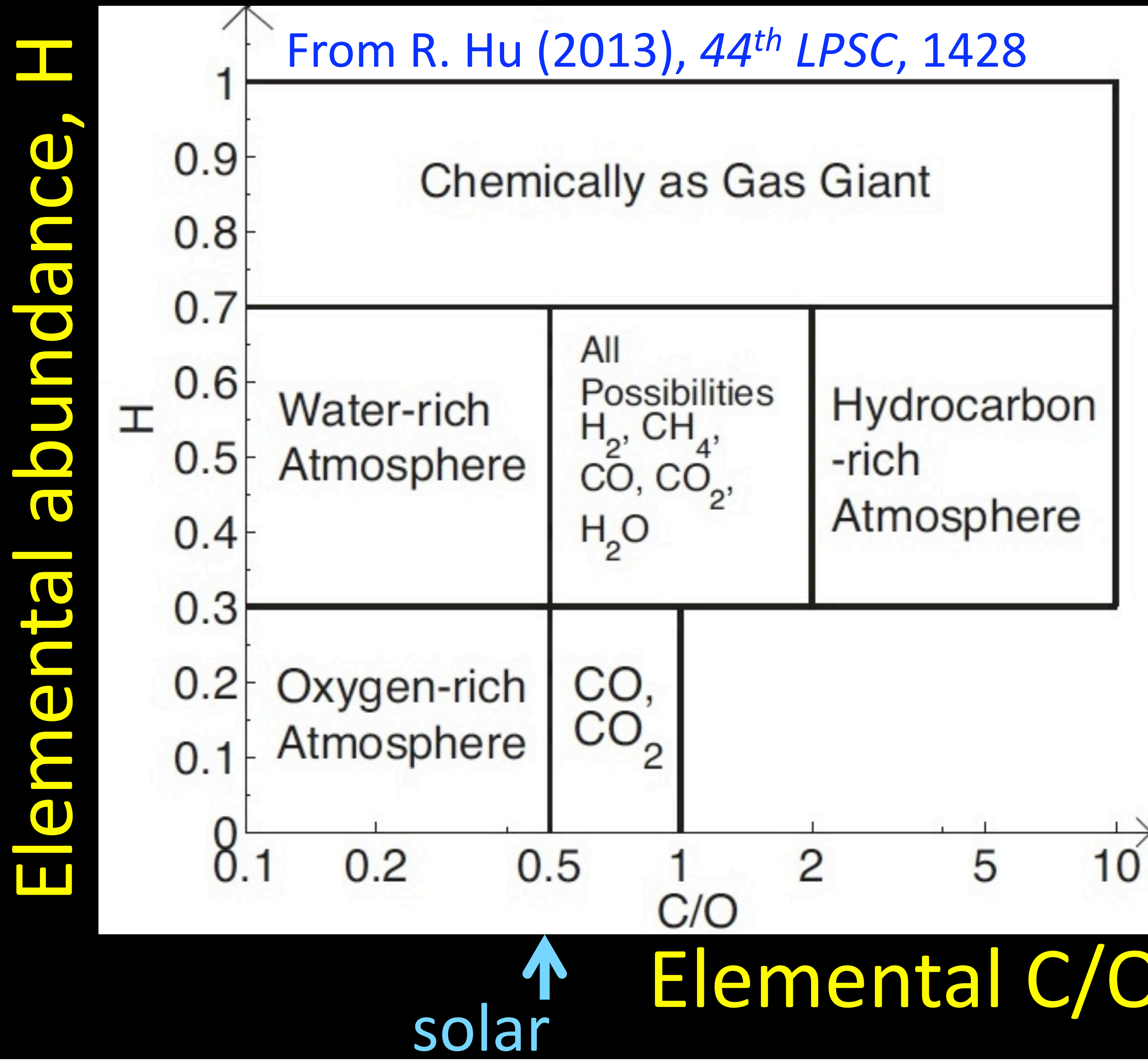
giants



Note: S forms polysulfur

From: Catling & Kasting (2014) *Atmospheric Evolution on Inhabited and Lifeless Worlds*, Cambridge Univ. Press.

Snapshot of taxa: GJ1214b-type atmospheres



Specified:
0.014 AU, M star
470 K top
800 K @1 bar
Fixed C-H-O

hydrocarbon
if O-poor

C-oxide
if O-poor

Sulfur in oxidizing atmospheres

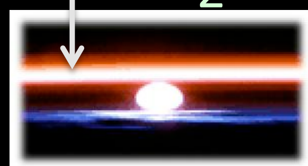
differences in dry vs. wet worlds, cold vs. hot

Oxidizing

Earth

oxidized S in oceanic SO_4(aq)

H_2SO_4 haze (Junge layer @20-25 km)



volcanoes:~1% of ~30% albedo

Venus (>30 km)

Sulfur in air given hot surface

SO_2, 3rd after CO_2, N_2 abundances

H_2SO_4 thick haze, important in IR,

dominates 76% visible albedo

Mars

oxidized S in soil, sedimentary SO_4(s)

H_2SO_4 haze *early* Mars, adds ≥10% albedo (Tian et al., 2010)

Earth: uniquely wet and O_2-rich…

- **2 key consequences for chemistry**: (1) a strong control on trace gases via the hydroxyl radical OH (2) rainfall

1) CLEARS OUT THE MUCK BY OXIDATION; PLUS RAIN OUT

O_3 absorption <340 nm generates $O(^1D)$

$$H_2O + O(^1D) \rightarrow OH + OH$$

Oxidizes H_2S, COS, DMS to sulfate (NH_3 to NH_3-sulfate in troposphere) which rains out.

Oxidizes CO, CH_4 and other hydrocarbons to CO_2 and H_2O

=> air transparent to visible

=> sunniest planet in Solar System with an atmosphere

2) **IF THERE WERE A LACK of 'OH' => HAZE WOULD BUILD UP**

e.g., Archean Earth: CH_4 and associated hydrocarbons + haze

Thick sulfate aerosol haze

Indicates a dry, volcanic planet

Sort of anti-biosignature.

Venus: nailing H_2SO_4 required polarized reflected light as a function of phase angle (Young, 1973; Hansen & Hovenis, 1974).

Exoplanets: ~45 micron sulfate feature, MIR OCS, SO_2 proxies.

(Conversely, S_8 absorption edge@300-400 nm)

Part 2:
Radiation, structure

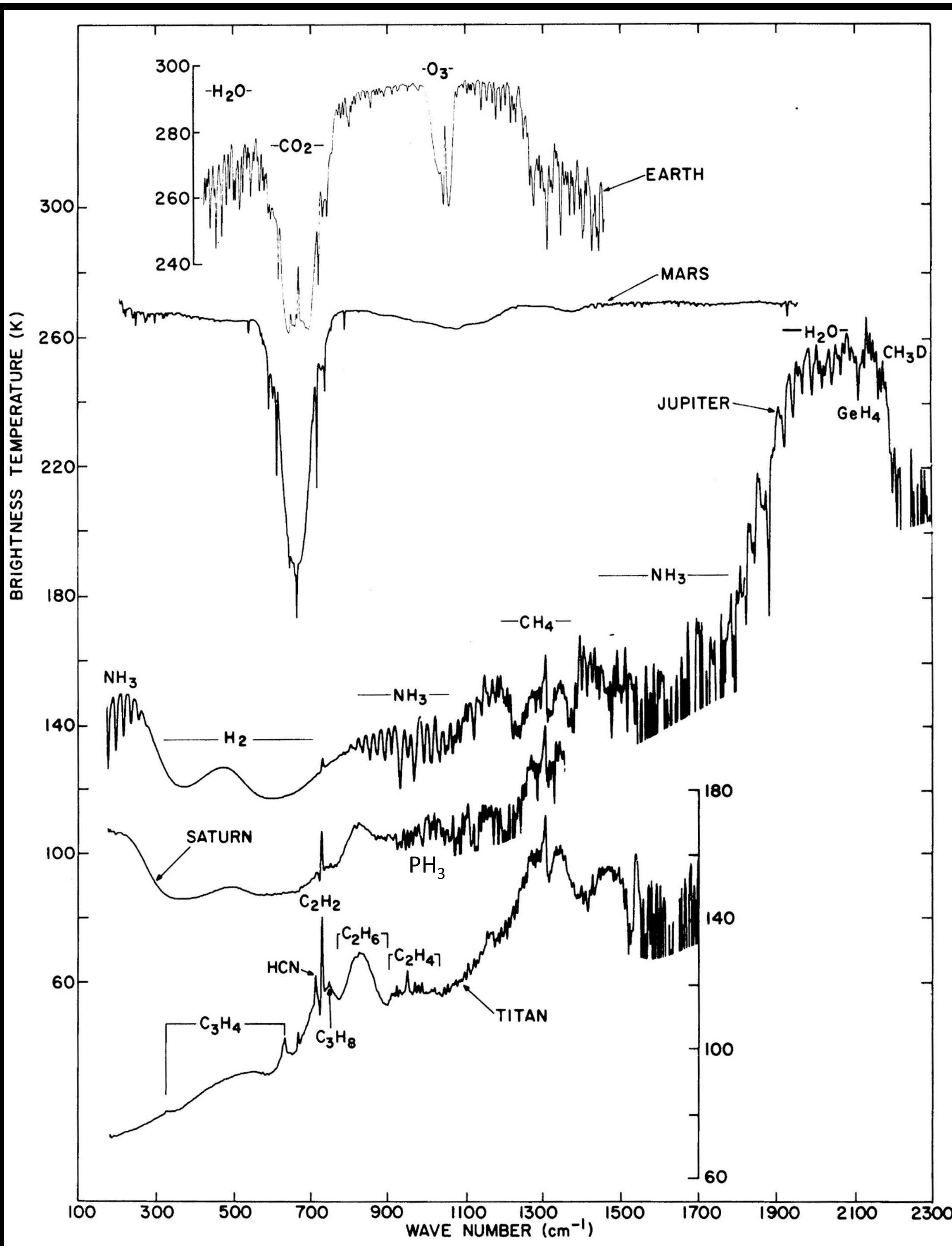
- Chemistry-radiation connection
- 1st order commonalities and differences in stratospheres, tropospheres, tropopauses

STRATOSPHERES: A CHEMISTRY---STRUCTURE CONNECTION

World	Stratospheric Heating	Stratospheric Cooling
Venus	CO_2	CO_2
Earth	ozone (UV)	CO_2
Jupiter	aerosols (UV/vis); methane (NIR)	acetylene (C_2H_2) 13.7 μm ethane (C_2H_6) 12.2 μm
Saturn	aerosols (UV/vis); methane (NIR)	acetylene (C_2H_2); ethane (C_2H_6)
Titan	haze; methane (NIR)	acetylene (C_2H_2); ethane (C_2H_6); haze
Uranus	aerosols (UV/vis); methane (NIR)	acetylene (C_2H_2); ethane (C_2H_6)
Neptune	aerosols (UV/vis); methane (NIR)	acetylene (C_2H_2); ethane (C_2H_6)

TROPOSPHERES: A CHEMISTRY---STRUCTURE CONNECTION

World	Key greenhouse	Cooling factors	Comment
Venus	CO_2 (15 µm)	huge SO_4 haze albedo	
Earth	H_2O (continuum)-CO_2 (15 µm) (CH_4, O_3 N_2O)	H_2O cloud albedo, small SO_4 haze	minor CO_2 control of greenhouse
Jupiter	H_2-H_2, H_2-He CIA; NH_3, CH_4	cloud, haze albedo	Giants: H_2-H_2/-He near Planck peak
Saturn	H_2-H_2, H_2-He CIA; PH_3, CH_4	cloud, haze albedo	
Titan	N_2-N_2, N_2-CH_4, N_2-H_2, CH_4-CH_4 CIA	haze 'anti-greenhouse' absorbs solar in IR optically thin region	minor H_2 affects window (16.5-25 µm) + greenhouse
Uranus	H_2-H_2, H_2-He CIA; CH_4	cloud, haze albedo	
Neptune	H_2-H_2, H_2-He CIA; CH_4	cloud, haze albedo	



Oxidizing

Absorption, oxidized gas: CO_2 (+H_2O +O_3 for Earth)

+band center emission (stratosphere)

Reducing

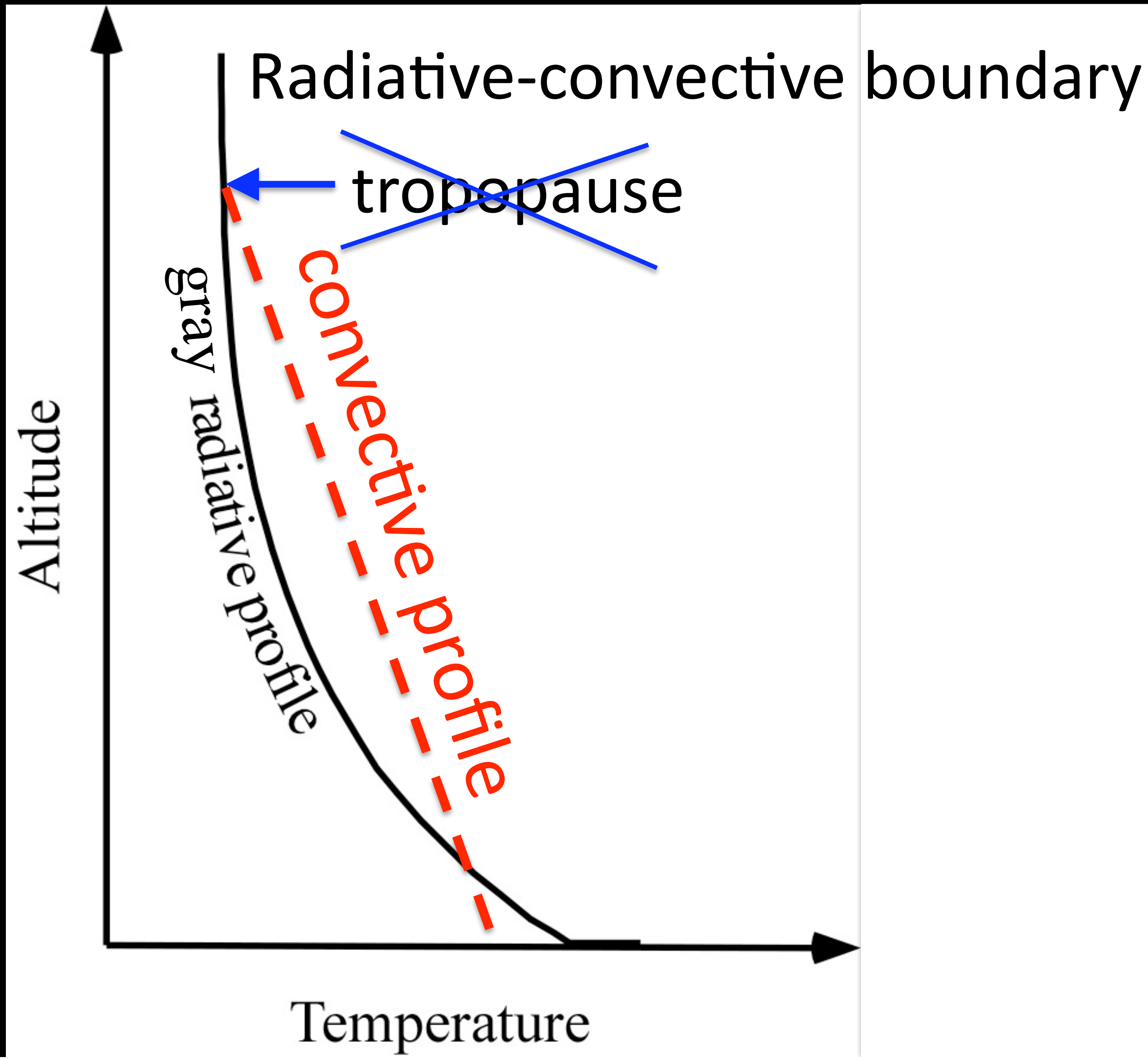
Absorption, reducing gas:

- H_2 on giants
- NH_3, on all giants (1400-1800 cm^{-1}); PH_3 on Saturn
- CH_4, H_2 operating with N_2 on Titan

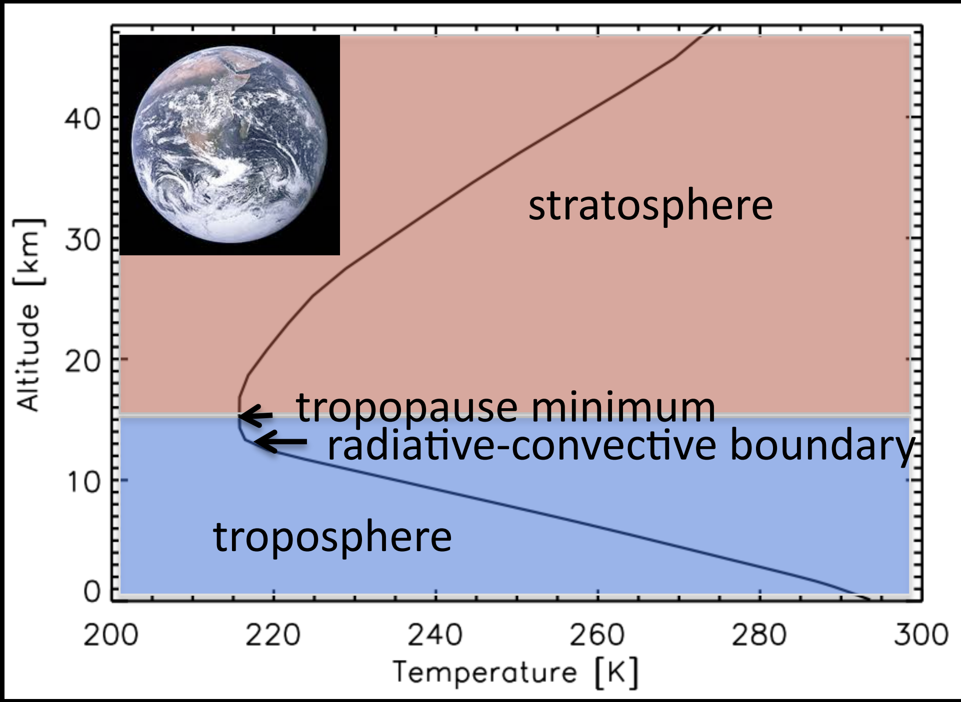
Emission: C_2H_2 (729 = 13.7 μm) C_2H_6 (820 = 12.2 μm), CH_4

Commonalities in atmospheric structure

A note on terminology I'm using



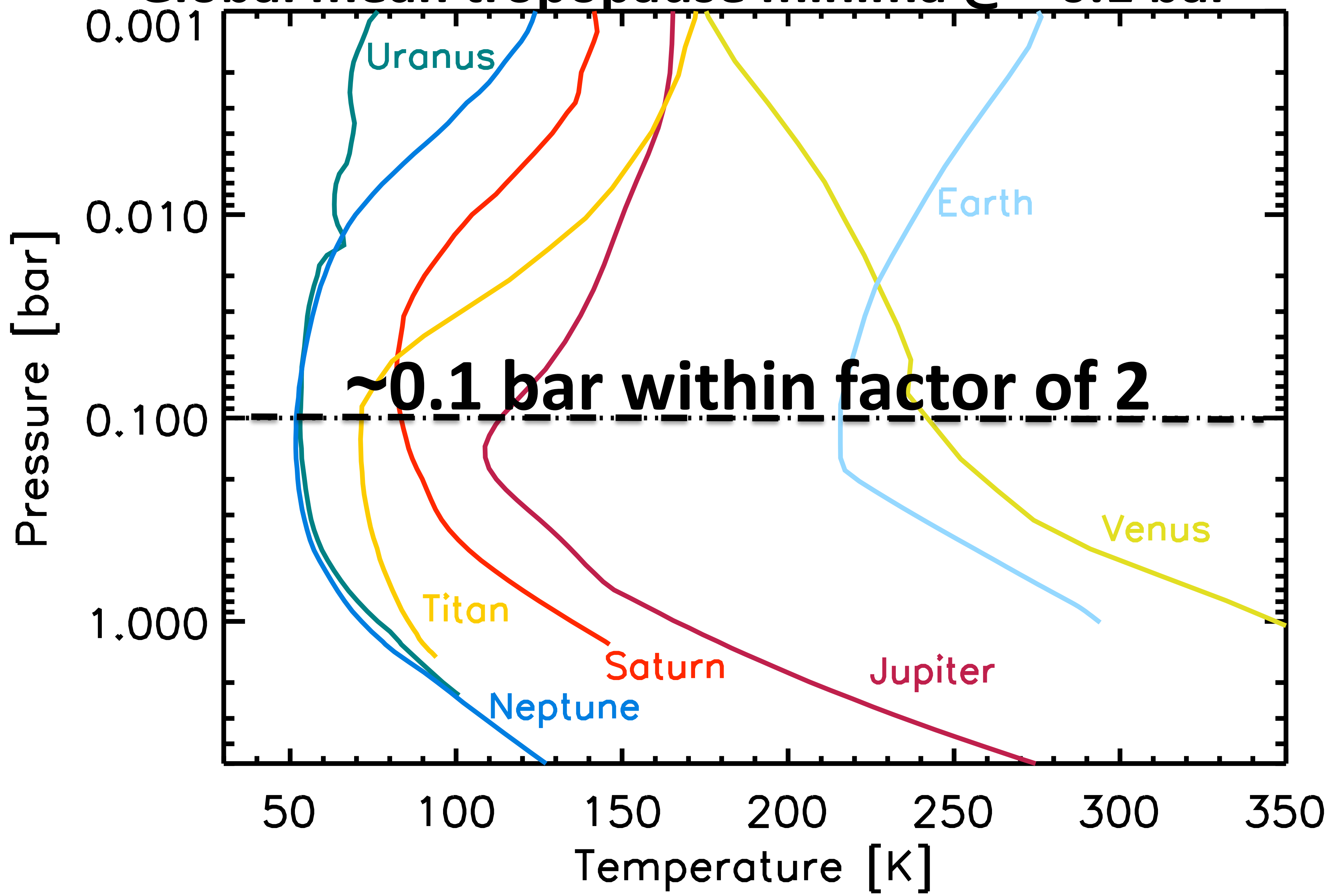
Commonalities in structure: Terminology



1) **temperature minimum** 'tropopause'

2) Shockingly: let's call the
radiative-convective boundary…
the "radiative-convective boundary"

Global mean tropopause minima @ ~0.1 bar



McClatchey+ (1972); Lindal+ (1983); Moroz & Zasova (1997); Moses+ (2005)

I know, I know…

Yes, dynamics modulates the tropopause pressure on Earth by ± x2 and is important for latitudinal differences on Venus

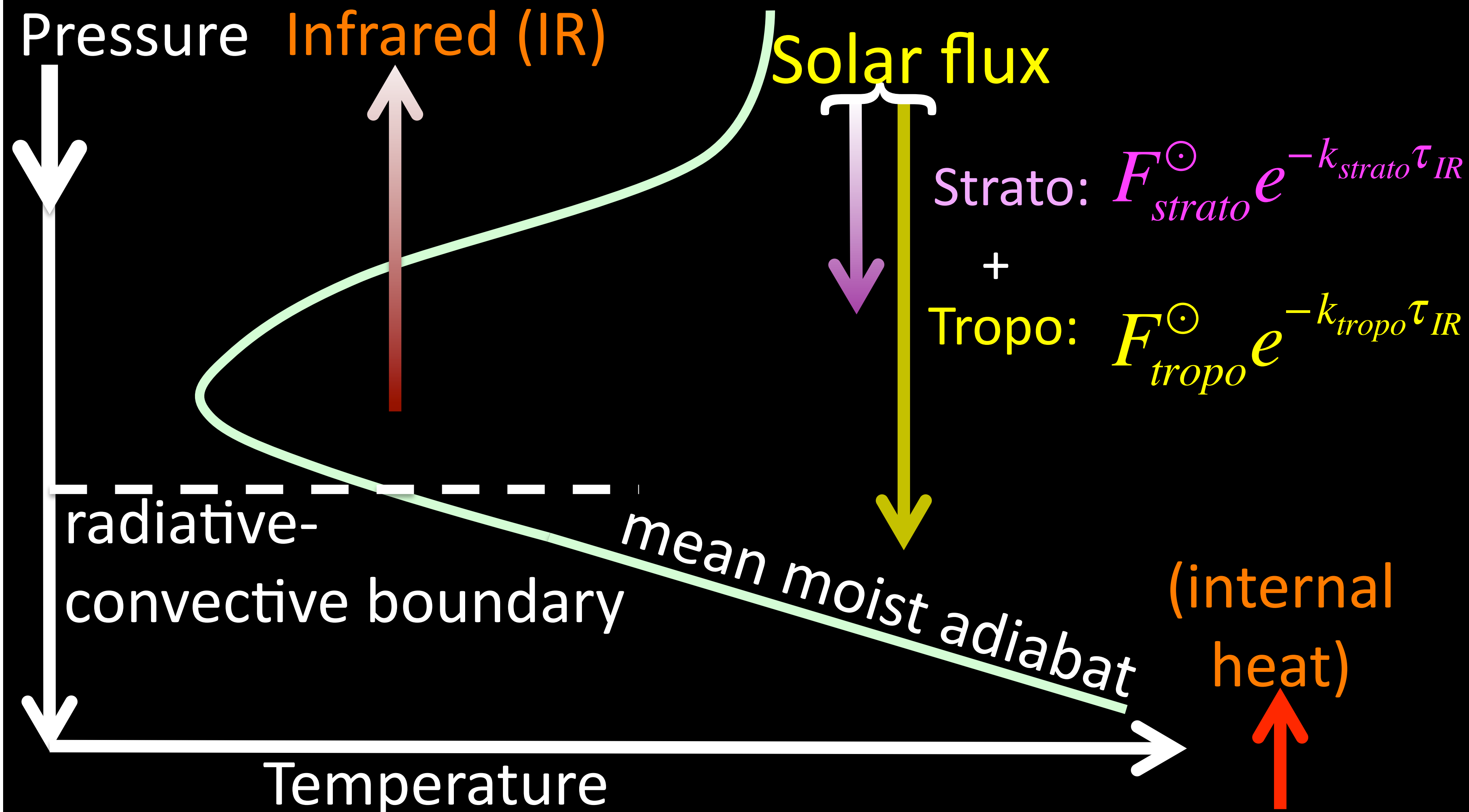
Here I'm concerned with a 1st order global mean state set by radiative-convective equilibrium

Why ~0.1 bar tropopauses?
First, some wrong answers:

1) where the IR absorption by gas changes from pressure to Doppler broadening?

2) Where IR optical depth drops below ~1?
(National Academy atmos. physicist)
(but on the right track)

Analytic radiative-convective: Robinson & Catling (2012) *Ap. J.* 757, 104



1. With T <u>and</u> flux continuity, solve for IR optical depth τ_{IR} at
   (i) radiative-convective boundary (ii) 1 bar
2. Relate optical depth to pressure to get profile

How molecular absorption of IR comes in

IR optical depth at p_0

$$\tau = \tau_0 \left(\frac{p}{p_0} \right)^n$$

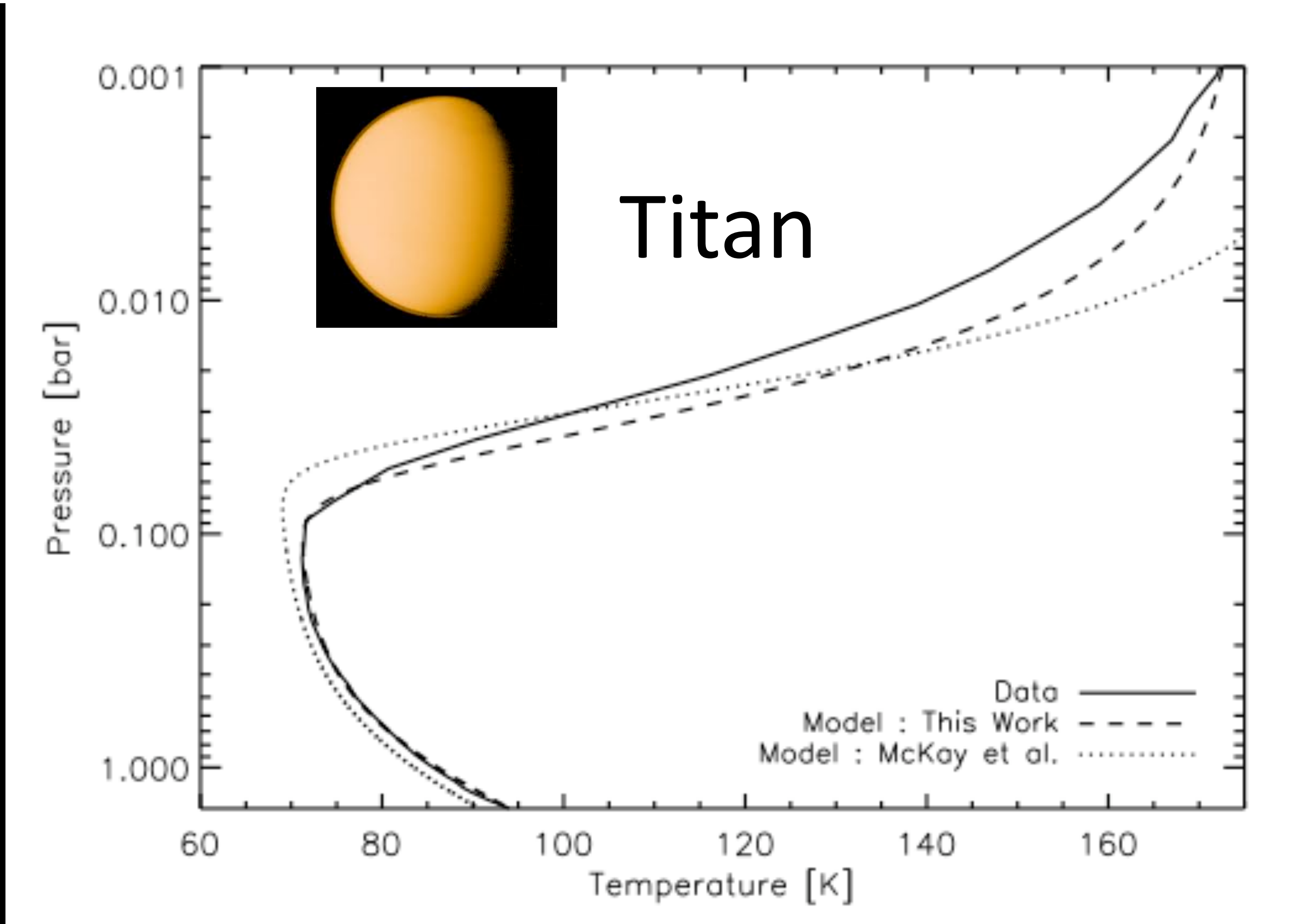
1 bar reference pressure

n = 2 in TROPOSPHERES & LOWER STRATOSPHERES:

pressure broadening (molecules gain or lose energy during collisions so absorption over a wider range of photon energies) or

collision-induced broadening (collision-induced dipoles allow non-polar molecules to be greenhouse gases; also dimers or symmetry-breaking for forbidden transitions)

n = 1 in UPPER STRATOSPHERES (Doppler broadening)



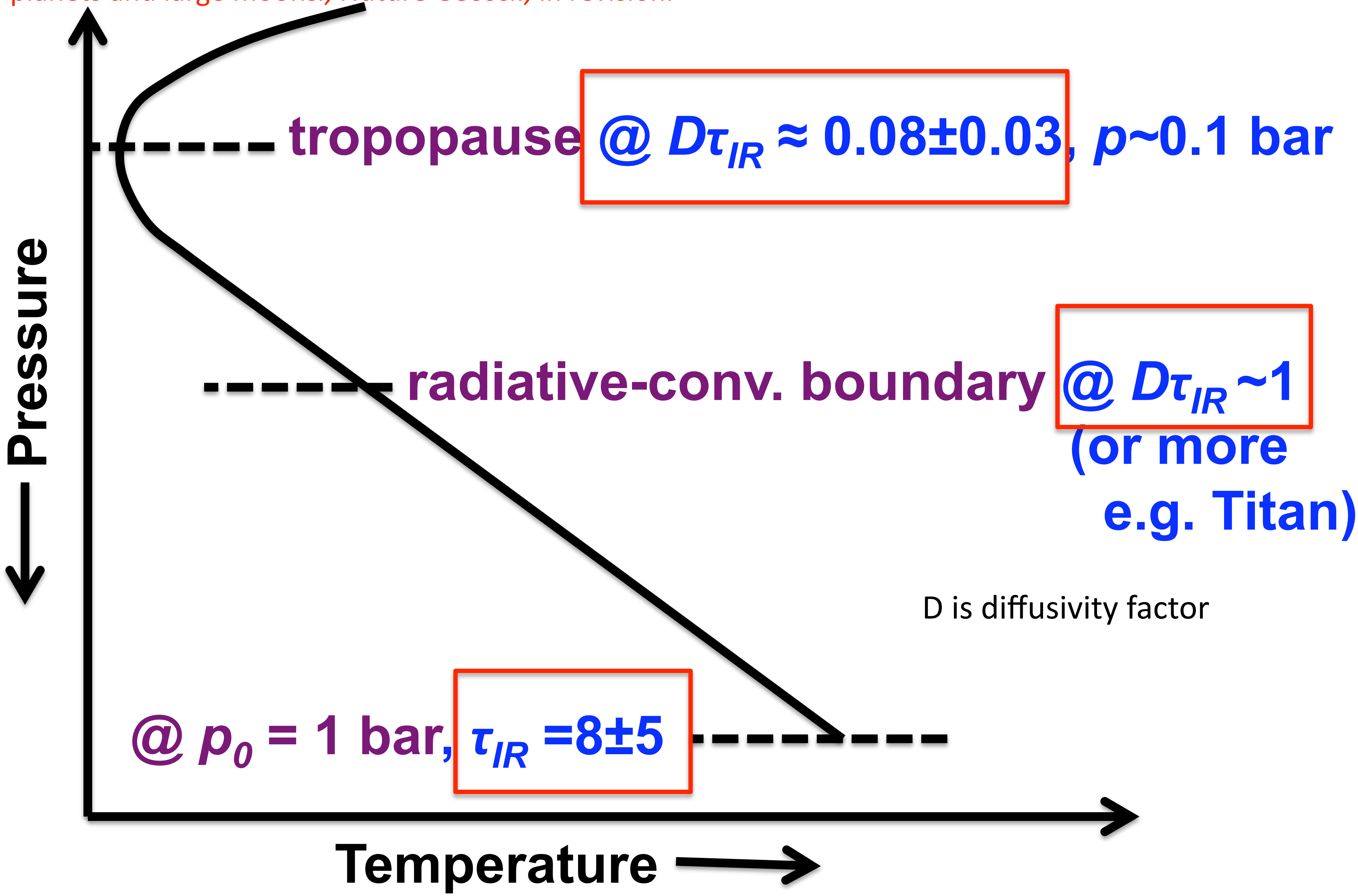
Simple model is decent match to tropospheres and lower stratospheres of Titan, Venus, Earth + 4 giants

Ref: Robinson & Catling (2012) An analytic radiative-convective model for planetary atmospheres, *Ap. J.* 757, 104

Unselfish cooperation in research: IDL source online

Schematic: Solar System *average*

Ref: from Robinson & Catling (2013) Explanation of a common 0.1 bar tropopause in thick atmospheres of planets and large moons., *Nature Geosci., in revision.*



So, why the ~0.1 bar tropopause?

1. minima in T occur at $\boldsymbol{\tau_{IR} \approx 0.05}$ (enough IR transparency for shortwave heating to start dominance)

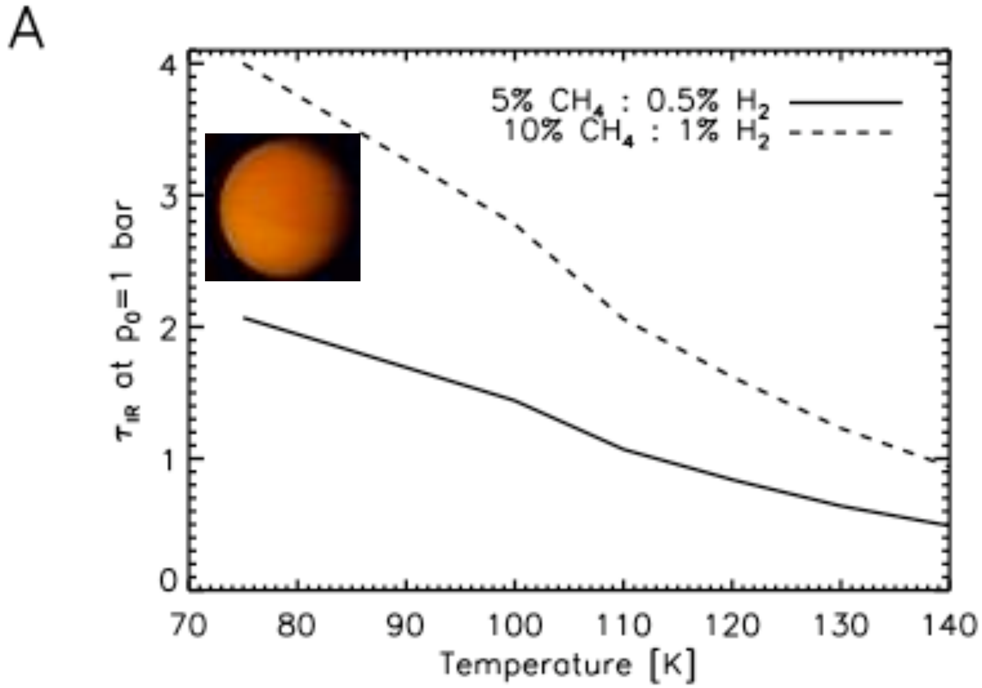
2. pressure broadening and/or collision-induced absorption relate optical depth to pressure

   $\tau \sim p^2 \Rightarrow p \sim \tau^{1/2}$

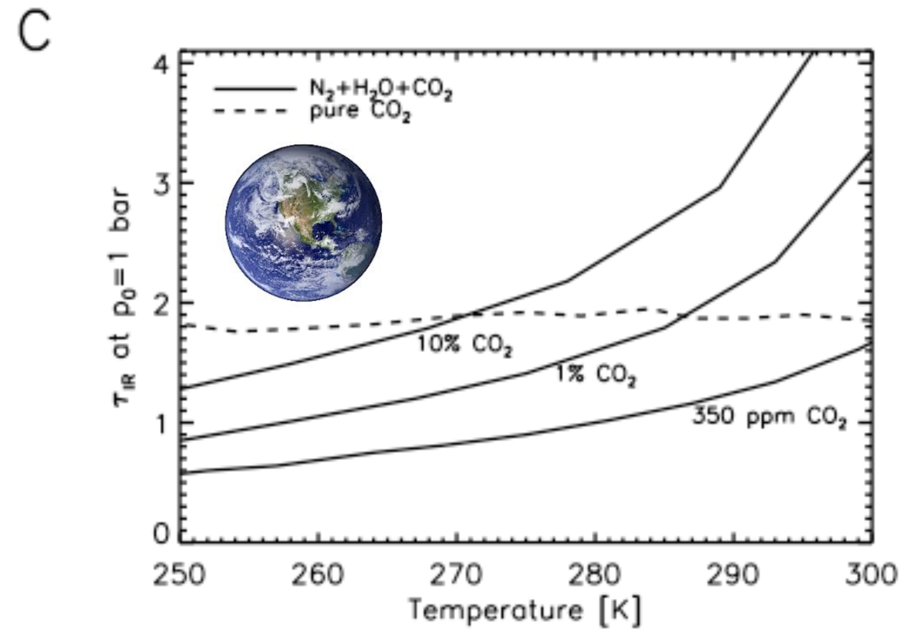
3. atmospheres are IR-optically thick at 1 bar

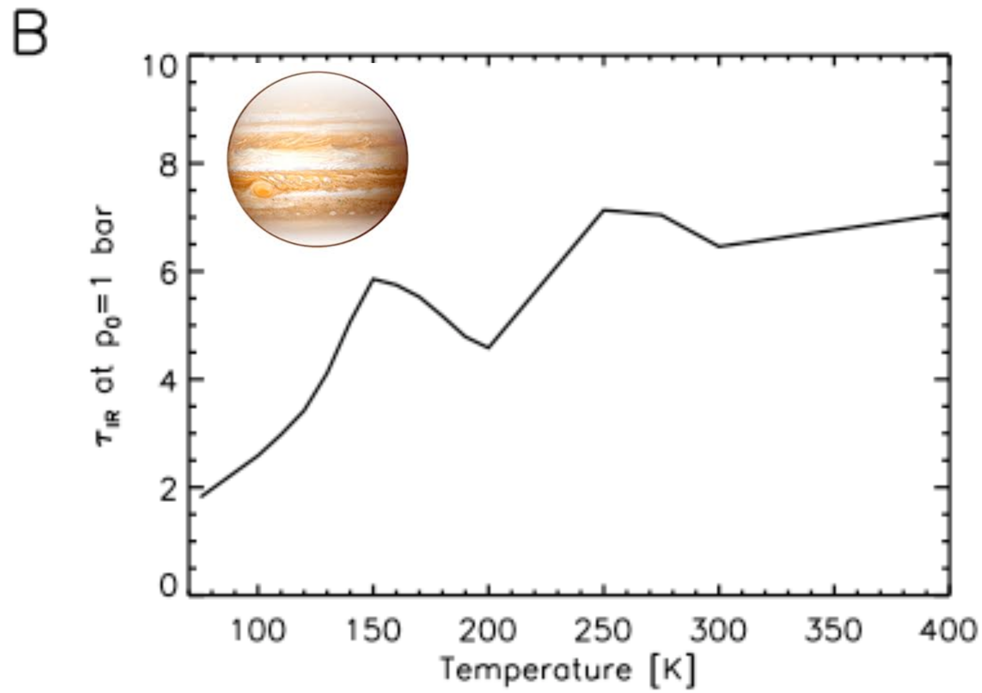
$$\frac{p_{\text{tropo}}}{(p_0 = 1\text{ bar})} \approx \left(\frac{\tau_{\text{tropo}} \sim 0.05}{\tau_0 \sim \text{ a few to several}} \right)^{1/2} \quad \text{is always} \sim 0.1 \text{ bar}$$

Ref: from Robinson & Catling (2013) Explanation of a common 0.1 bar tropopause in thick atmospheres of planets and large moons., *Nature Geosci., in revision.*



Gray optical depths at 1 bar are always ~2-10 for hypothetical Titan-like, Earth-like, and Jupiter-like worlds





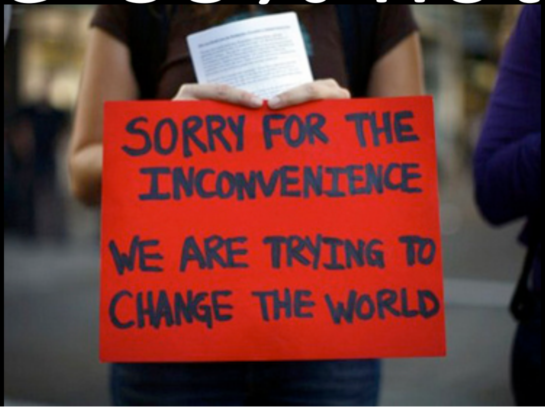
From: Robinson & Catling (2013), *Nature Geosci.*, in revision

Aside: Hot Jupiters are far from the norm

0.5-1% of all planets (Howard, 2013, *Science*)

So, I choose to focus on the other ones.

OCCUPY THE SOLAR SYSTEM :
Favor the 99% not the 1%!



What's the condition for a stratospheric inversion to exist? It's analytic

A tropopause minimum: differentiate and set to 0, gives:

$$\tau_{tp} \approx \underbrace{\frac{1}{k_{strato}}}_{\sim 1/100} \overbrace{\ln\left[\underbrace{\frac{F^{\odot}_{strato}}{F^{\odot}_{tropo} + F_i}}_{\sim 1/10} \underbrace{\left(\frac{k^2_{strato}}{D^2} - 1\right)}_{\sim 10^3}\right]}^{\sim 5} \approx 0.05$$

flux above / flux below

where $k_{strato} = \frac{\text{shortwave optical depth}}{\text{infrared optical depth}}$ of stratosphere

Only has a physical solution if $k_{strato} > D \sim 1.7$, usu. $\sim 10^2$

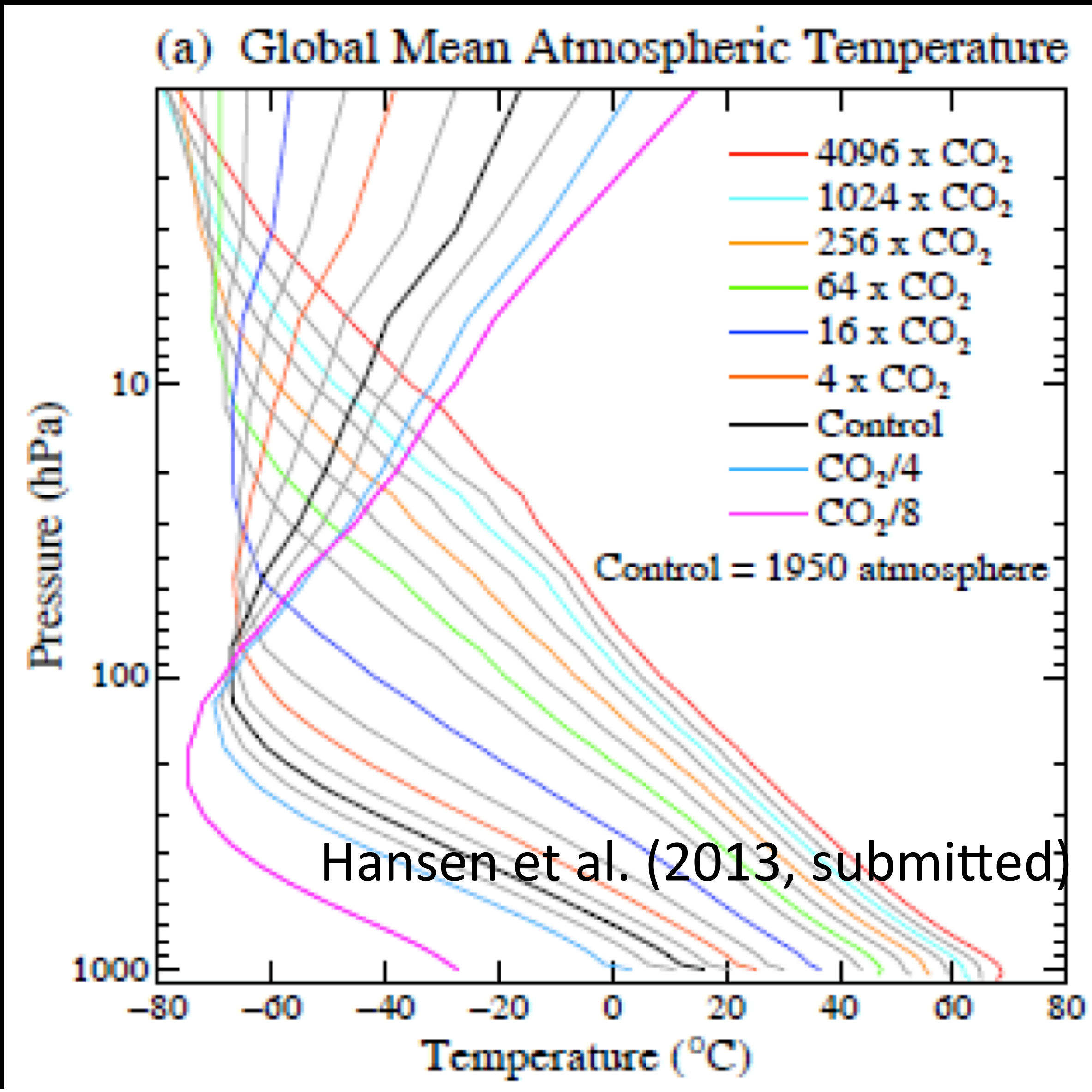
Hence no <u>global mean</u> stratospheric inversion on Venus

THE USER MANUAL:

this "0.1 bar" tropopause ***minimum*** rule does not apply when there's no ***minimum***,

i.e., when the condition for a stratospheric inversion fails

e.g., pump up CO_2 on Earth; make moist stratosphere



Stratospheric inversion and tropopause minimum vanish, consistent with theory: At $64xCO_2$, ~10x H_2O in stratosphere

$k_{strato} = \frac{\text{shortwave optical depth}}{\text{infrared optical depth}}$

goes from ~90 to < 2, the value needed for a tropopause minimum.

Hence no 0.1 bar tropopause minimum at high CO_2 **because THERE IS NO MINIMUM**

Extend to exoplanets?

~0.1 bar tropopause minima of Earth, Titan, giants from
(1) a common IR transparency requirement and
(2) a common pressure dependence on the IR opacity

TESTABLE HYPOTHESIS:

A ~0.1 bar tropopause ***minimum*** is an emergent "rule" arising from common physics that will apply to many exoplanets and exomoons with thick atmospheres

From: Robinson & Catling (2013) Explanation of a common 0.1 bar tropopause in thick atmospheres of planets and large moons., *Nature Geosci., in revision.*

Conclusions

- Atmospheres may not exist in bad impact erosion or thermal escape regimes
  - e.g., double whammy for M-dwarf planets

- No Super-Earth examples in our Solar System (notably present as exoplanets), but the bodies/models at least provide points of reference for exoplanet atmospheres.

- Atmospheres we know are: (1) reducing with **organic hazes** +/- poly-S, poly-P, or (2) oxidizing with **sulfate hazes** of variable radiative significance that can be high vis. albedo
  - Reasonable to expect to such hazes on similar exoplanets – can we see sulfate or S_8?
  - Reasonable to expect corresponding absorption / emission features of common reducing or oxidizing gas suites

- Structure:
  - Reducing atmospheres we know have stratospheric inversions from methane+hazes
  - Oxidizing atmospheres we know do (Earth) or don't (Venus) have strat. inversions

- Stratospheric inversions require IR-optically thin stratospheres and absorbers strong in SW relative to IR. Combined with pressure-broadening or CIA => common ~0.1 bar level for tropopause **minima**. Testable hypothesis: Plausibly true in many exoplanet atmospheres

- Didn't talk about evolution. But observing runaway Venuses (future Earths) states on exoplanets would clearly be an extremely valuable confirmation of theories.

References

ON IMPACT EROSION AND HYDRODYNAMIC ESCAPE OF ATMOSPHERES:

- D. C. Catling & K. J. Zahnle (2013) An impact erosion stability limit controlling the existence of planetary atmospheres on exoplanets and solar system bodies, *44th Lunar Planet. Sci. Conf*., 2665
- K. J. Zahnle & D. C. Catling (2013) The cosmic shoreline *44th Lunar Planet. Sci. Conf*., 2787.

OVERVIEW OF THE CHEMISTRY, RADIATION AND EVOLUTION OF ATMOSPHERES:

- D. C. Catling & J. F. Kasting (2014) *Atmospheric Evolution on Inhabited and Lifeless Worlds*, Cambridge Univ. Press.

RADIATION , ATMOSPHERIC STRUCTURE, and COMMON TROPOPAUSE MINIMUM LEVEL:

- T. D. Robinson & D. C. Catling (2012) An analytic radiative-convective model for planetary atmospheres, *Astrophys. J.* 757, 104 .
- T. D. Robinson & D. C. Catling (2013) Explanation of a common 0.1 bar tropopause in thick atmospheres of planets and large moons., *Nature Geosci.,* in revision.