Atmospheric Biomarkers

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HELMHOLTZ ALLIANCE
PLANETARY EVOLUTION AND LIFE

Atmospheric Biomarkers Overview of Talk

- The Diversity of Life on Earth
- Historical Context – the Many Worlds and Life Debate
- Methods for finding Biomarkers (life-indicators)
- Atmospheric Biomarkers
- Learning from the Solar System
- Going beyond the Solar System
- Summary and Conclusions

Diversity of Life on Earth

Plurality (Many) Worlds Debate in Ancient Greece

Atomist School
… the atom being infinite in number, forms an infinite number of worlds (Democritus, Epicurus)

Aristotlean School
… a unique creator implies unique creation

Democritus of Abdera c. 400 BC

Famous Astronomers’ views on plurality

Nikolaus Copernicus (1473-1543)

…never mentions the question of plurality

Galileo Galilei (1564-1642)

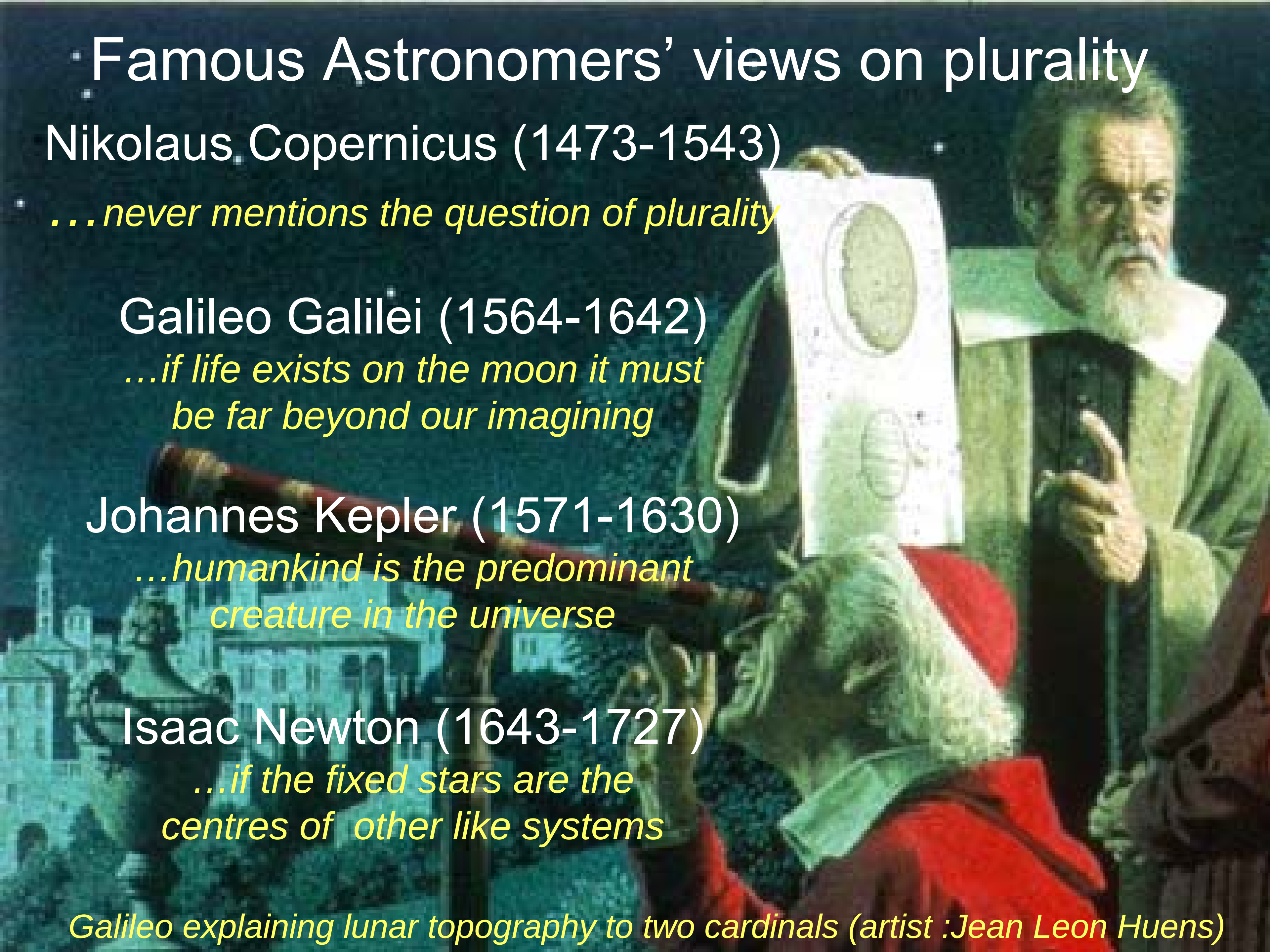
…if life exists on the moon it must be far beyond our imagining

Johannes Kepler (1571-1630)

…humankind is the predominant creature in the universe

Isaac Newton (1643-1727)

…if the fixed stars are the centres of other like systems



Galileo explaining lunar topography to two cardinals (artist :Jean Leon Huens)

Defining life

Classical Definition:

Homeostasis
Organisation
Metabolism
Growth
Adaption
Reproduction
Response to Stimuli

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Defining life … is not easy

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Classical Definition:

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Modern Definition:

Genetics and Evolution

Some definitions

Biomarker

In Astrobiology: evidence of life

(In Medicine: tracer to examine health)

(In Geology: biology involved in petroleum formation)

Biosignature

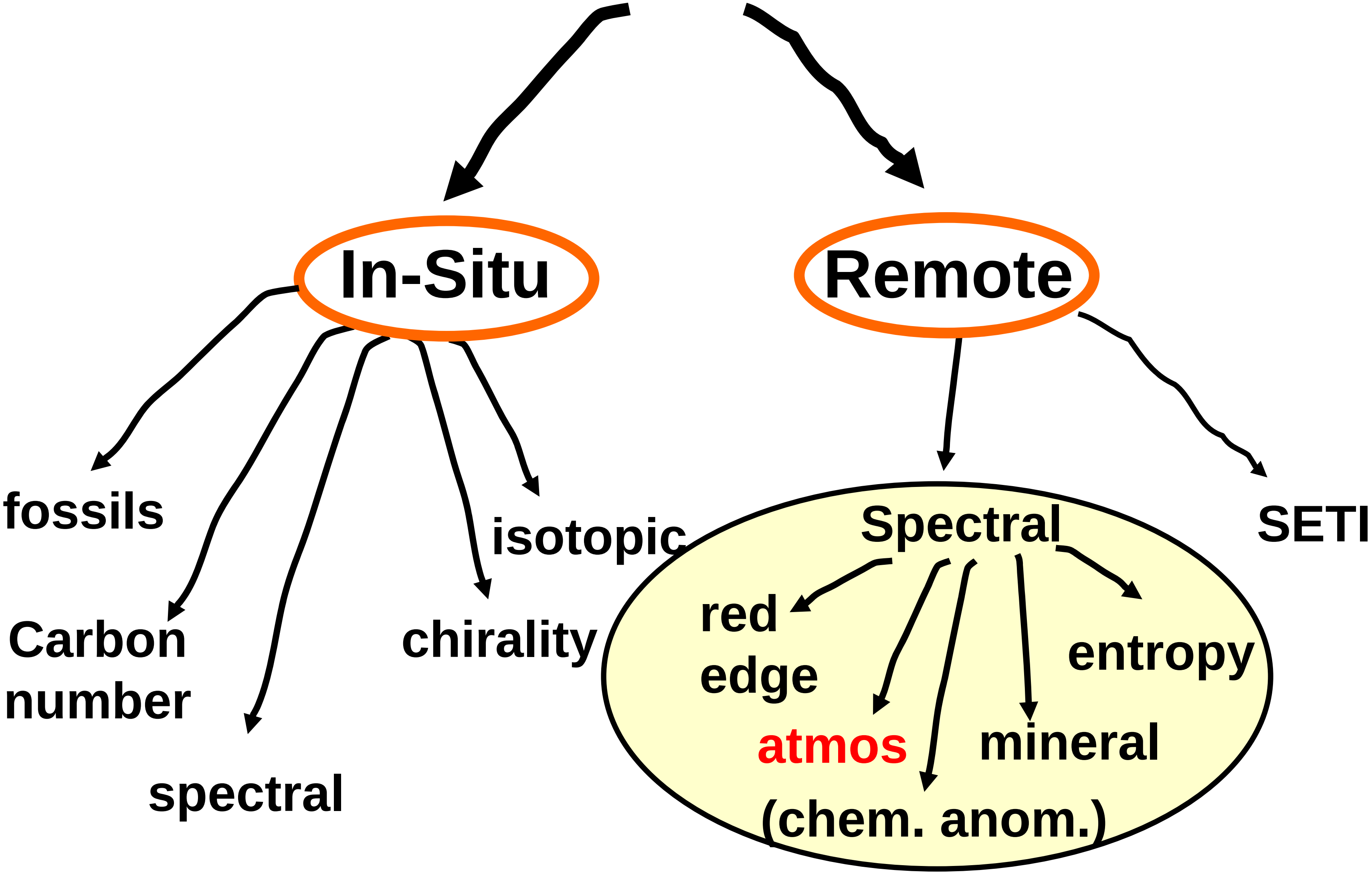
Usually synonymous with biomarker

Bioindicator

In Astrobiology: could be life but probably need more info

(e.g. large O_2 alone does not neccesarily mean life)

Methods to Find Biomarkers



In-Situ

Remote

fossils

isotopic

Carbon number

chirality

spectral

Spectral

SETI

red edge

entropy

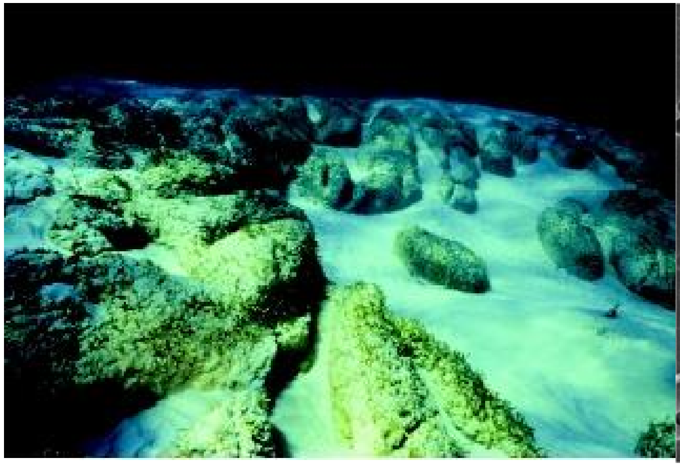
atmos

mineral

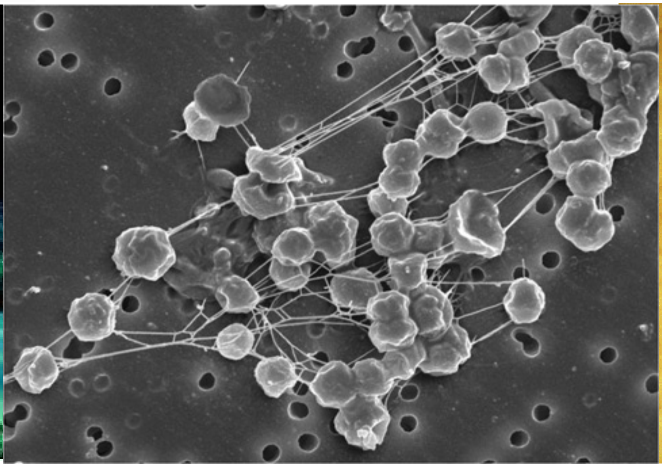
(chem. anom.)

Lovelock (1965), Lederberg (1965)

In-Situ Biomarkers:
Ancient Fossils



stromatolites



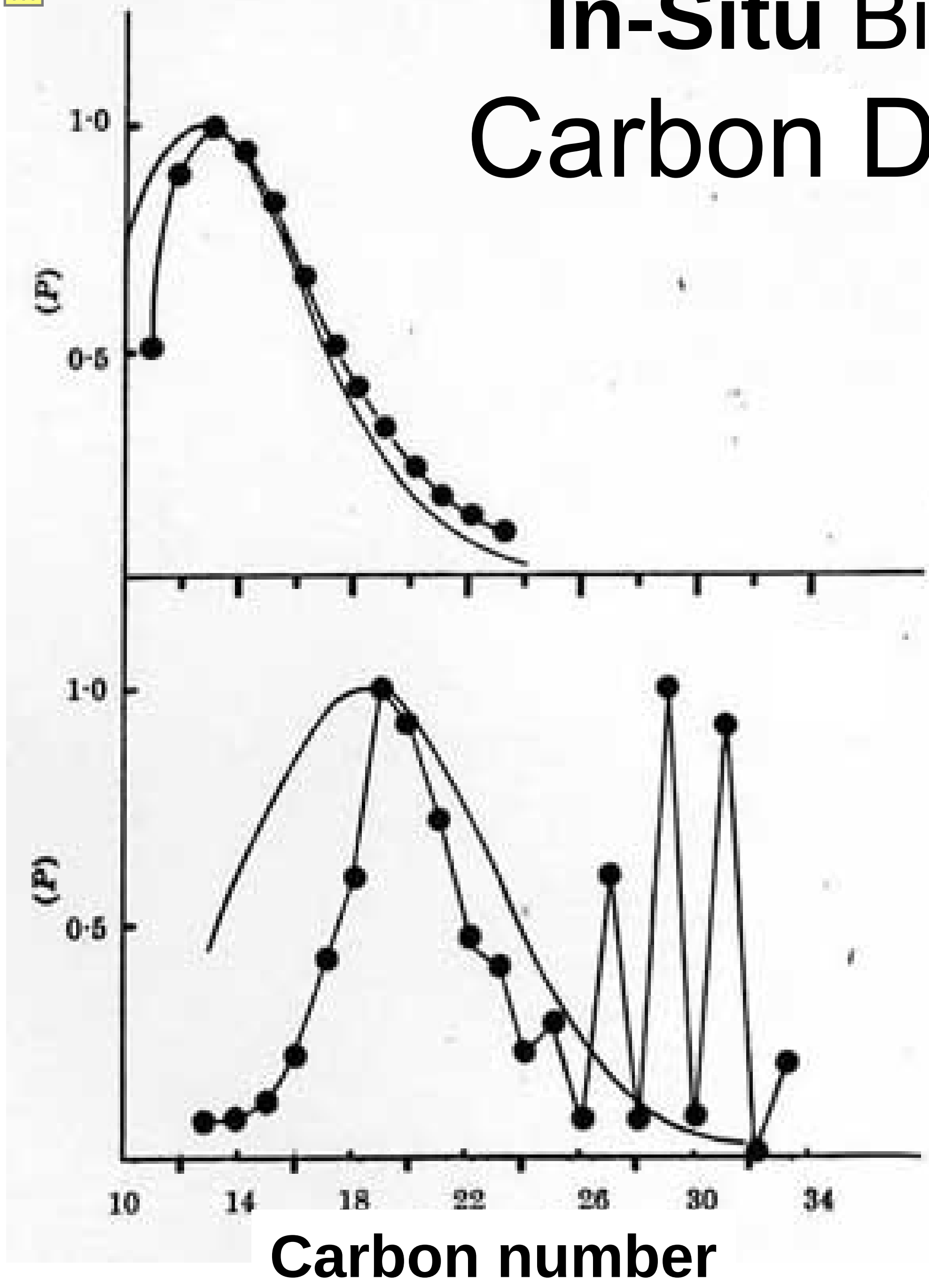
methanogens

cyanobacteria

e.g. Westall et al. (2001)

source: softpedia, course gG100, geology.wisc.edu, cosmology.net

In-Situ Biomarkers:
Carbon Distribution



Non-life

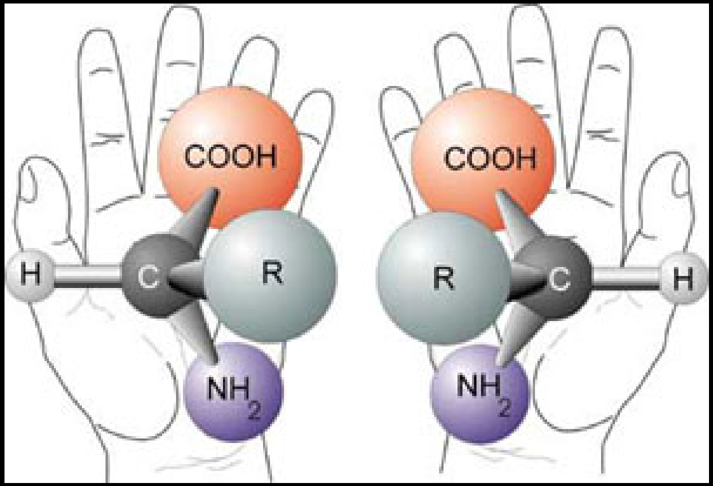
SMOOTH CURVE

Life (protein)

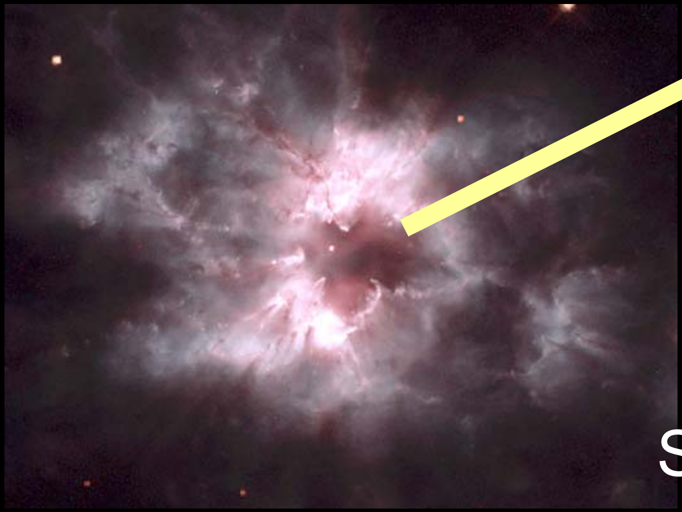
SPIKES

Lovelock (1965)

In-Situ Biomarkers:
Chirality



Pasteur found that life
is *chiral-specific*
Why?



One theory:
magnetised dust grains
induce chirality in life
precursors (amino acids)

CHIRALITY AS REMOTE BIOMARKER
Polarisation signal of Earthshine
Sterzik (2009) ASP 420, need 10^{-5} accura

Review: Keszthelyi (2001)

In-Situ Biomarkers:
Isotope Ratios

-life (mostly) favours the lighter isotopes of H,C,N,S

-enzyme kinetic isotope effect influences transition state

-isotopic biofractionation signal results

Schidlowski (1999) Adv. Spa. Res. 15,441

Kohen et al. (2010)

"Remote" Biomarkers:
Entropy Production

Life produces *high entropy* to maintain its order, so

ΔG^o (= $\Delta H^o - T\Delta S^o$) is lowered

But, since, $\Delta G_o = - RT\ln(K)$

Atmosphere with life moves *away* from chemical equilibrium

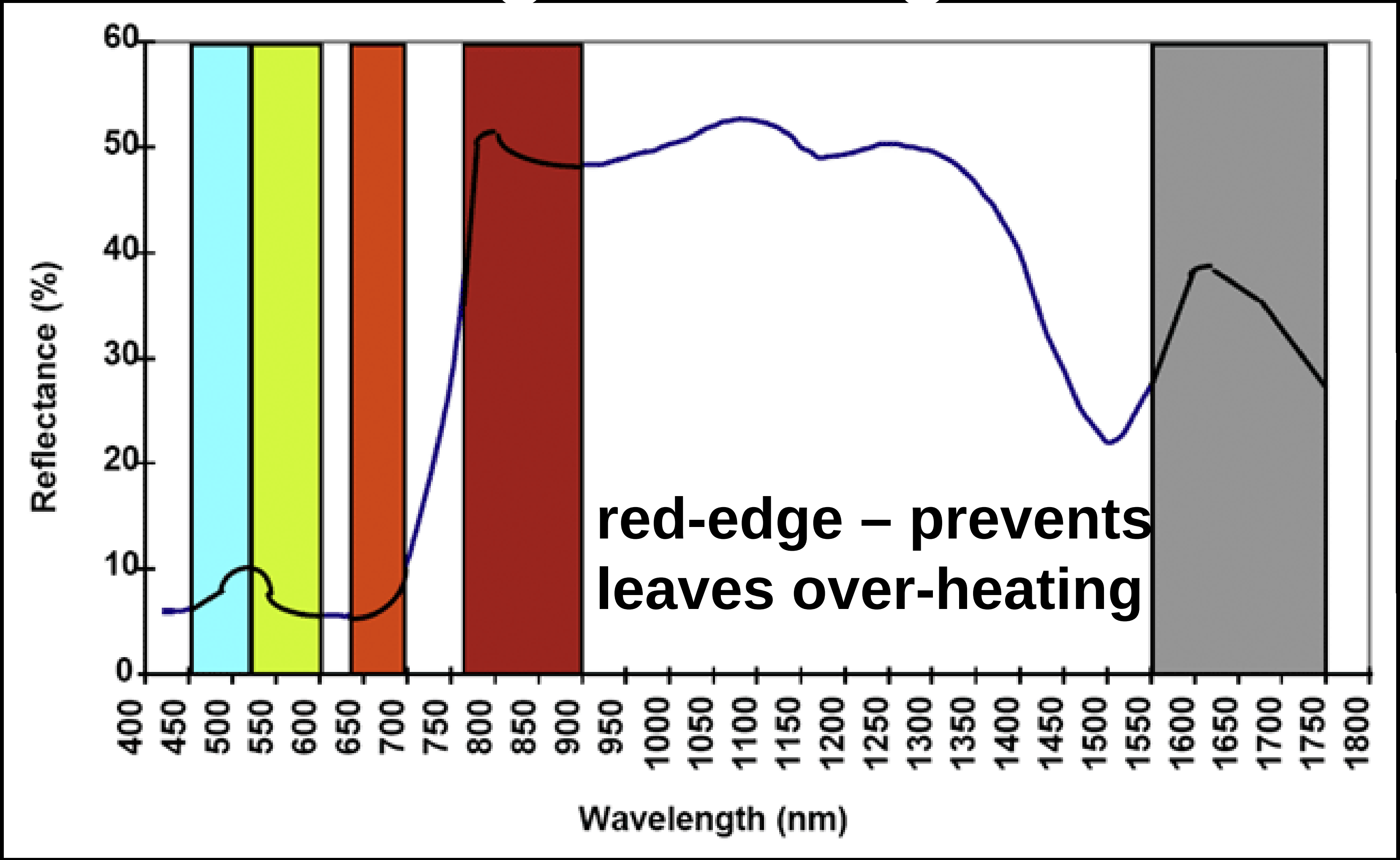
Kleidon (2011) Phil. Trans. Theory: Earth

Simoncini (2010) EPSC

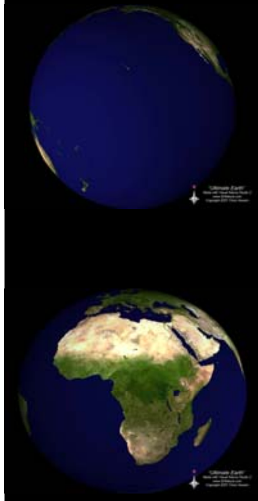
Catling (2011) (in preparation) for Solar System

Caution: however, all atmospheres are out of chemical equil. to some degree (photochemistry, cool temperatures)

Remote Biomarkers:
Red Edge for Vegetation

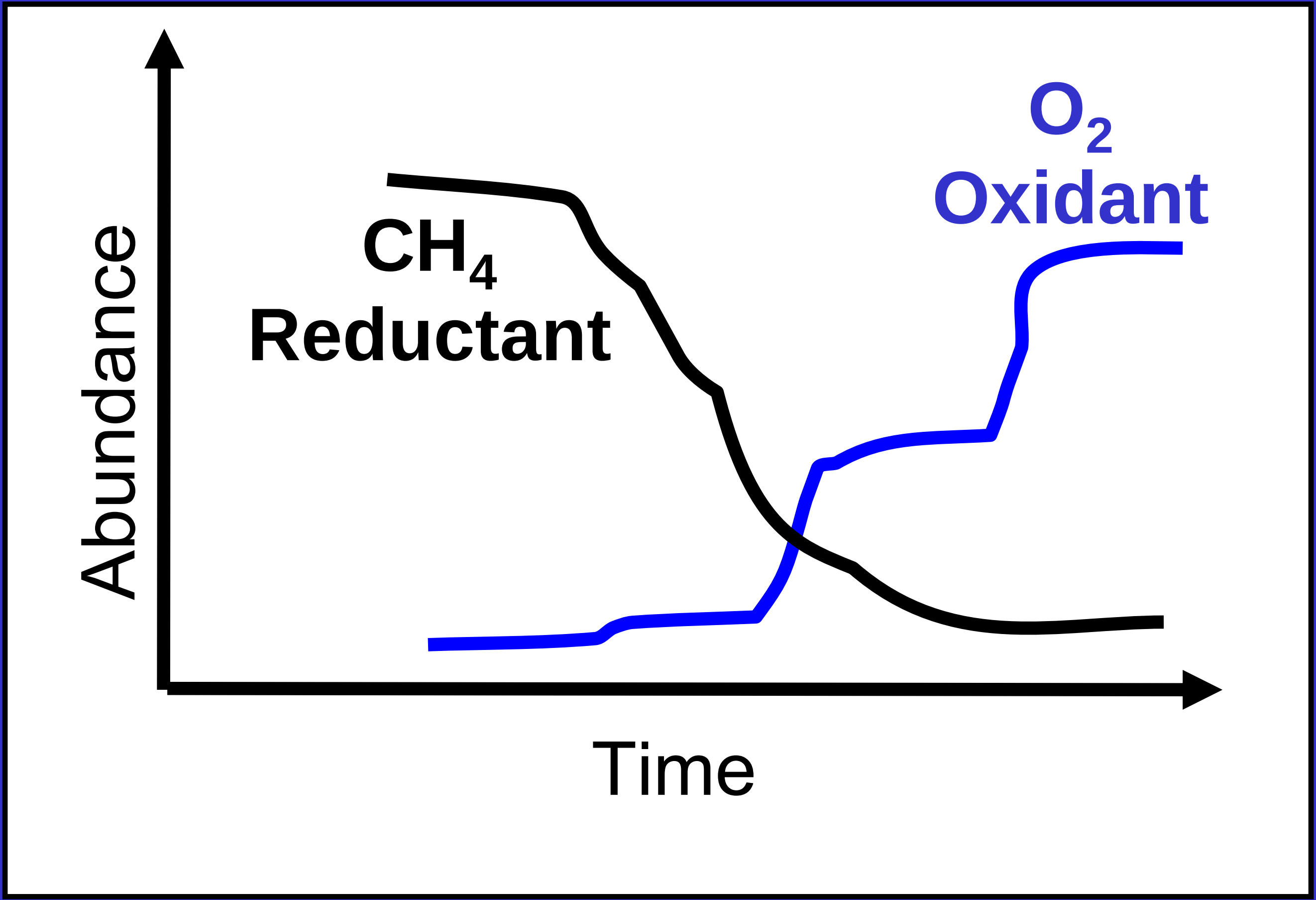


red-edge – prevents leaves over-heating



Arnold et al. (2002) *Woolf et al. (2002)* *Seager et al. (2005)*

Remote Atmospheric Biomarkers: Chemical Anomalies

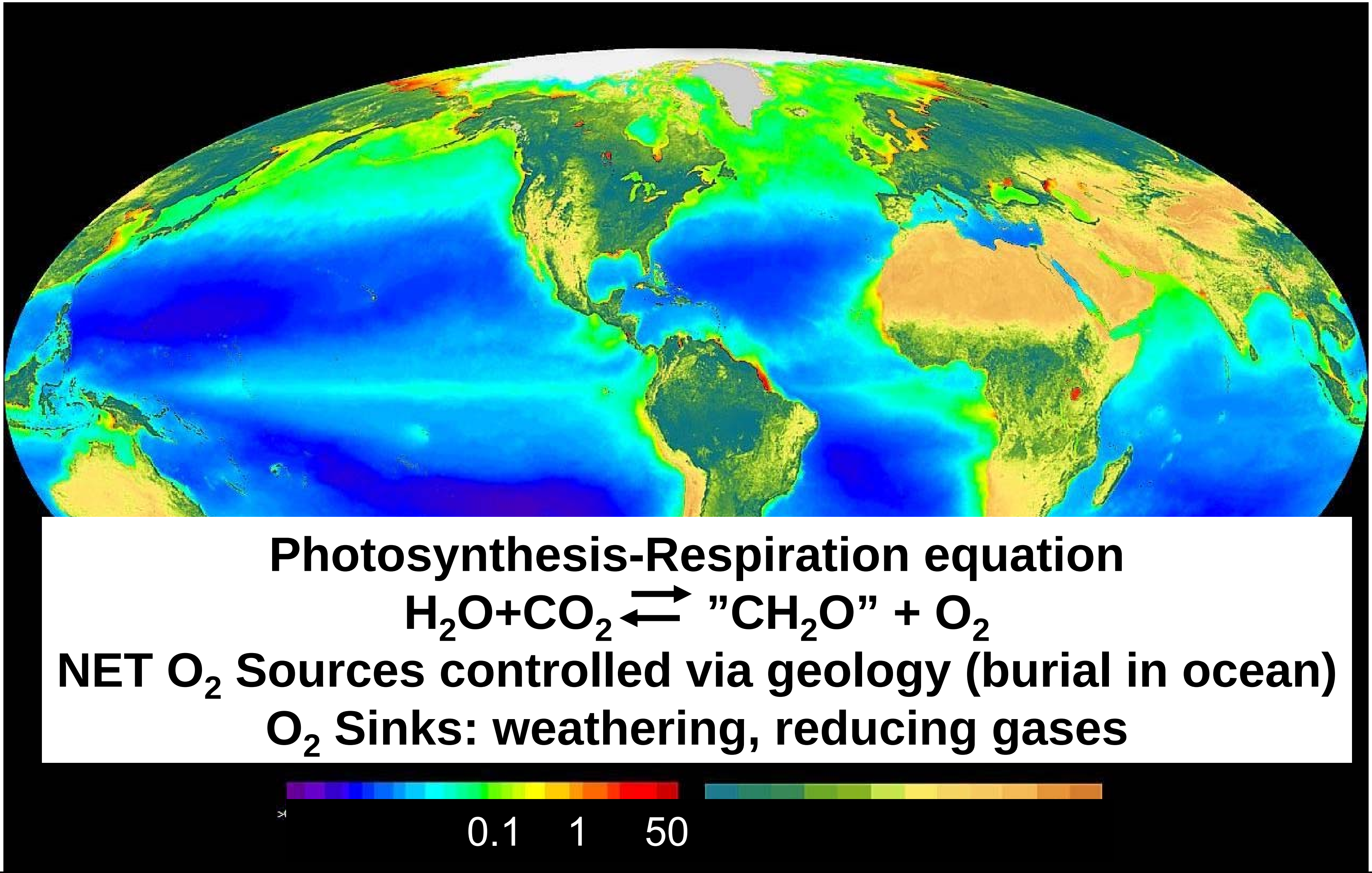


Sagan et al. (1993) *Lovelock (1965)*

Remote Biomarkers:
Atmospheric Species

Biomarker/Bioindicator	**Source**
Oxygen (O_2) (hence O_3)	**Photosynthesis**
Nitrous oxide (N_2O)	**Denitrifying bacteria**
Chloromethane (CH_3Cl)	**Vegetation (Yokouchi et al.)**
Carbonyl Sulphide (COS)	**Vegetation (Andraea et al.)**
Methane CH_4 (possibly)	**Methanogenic bacteria**

Biological activity influencing O_2 in Earth's atmosphere



Photosynthesis-Respiration equation

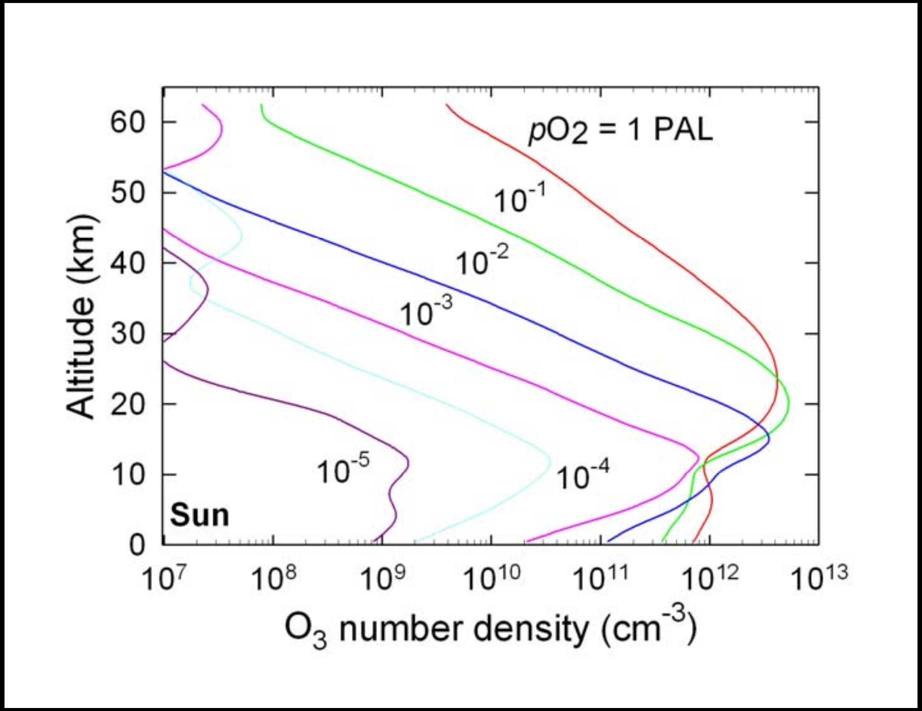
$$H_2O+CO_2 \rightleftarrows \text{"}CH_2O\text{"} + O_2$$

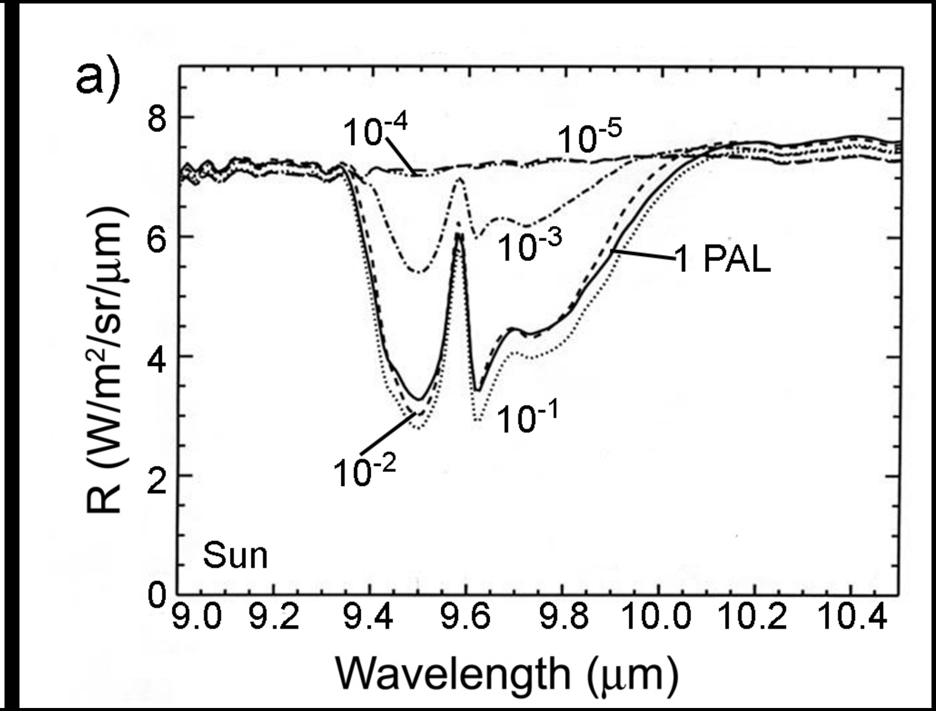
NET O_2 Sources controlled via geology (burial in ocean)

O_2 Sinks: weathering, reducing gases

Ocean: Chlorophyll production (mg/m^3) Land: Vegetation index (NASA)

Oxygen or Ozone as Spectral Biomarkers?



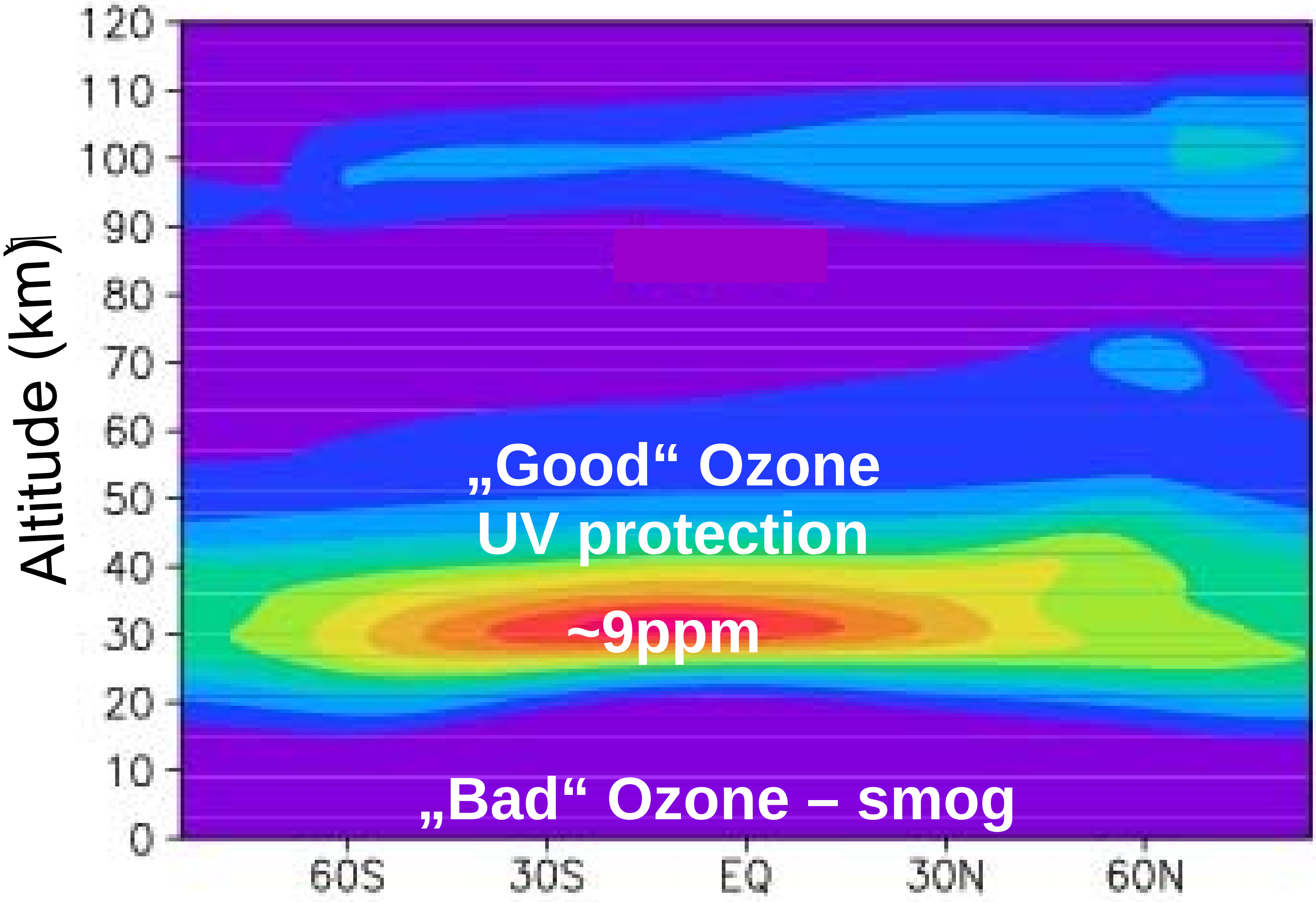


- 'PAL' = 'times the Present Atmospheric Level'
- O_3 signal remains strong down to at least 10^{-2} PAL of O_2 due to nonlinear chemistry and stratosphere cooling

Ozone is the better spectral biomarker

A. Segura et al. *Astrobiology* (2003)

Atmospheric Biomarkers: Earth's Ozone Layer



„Good“ Ozone
UV protection

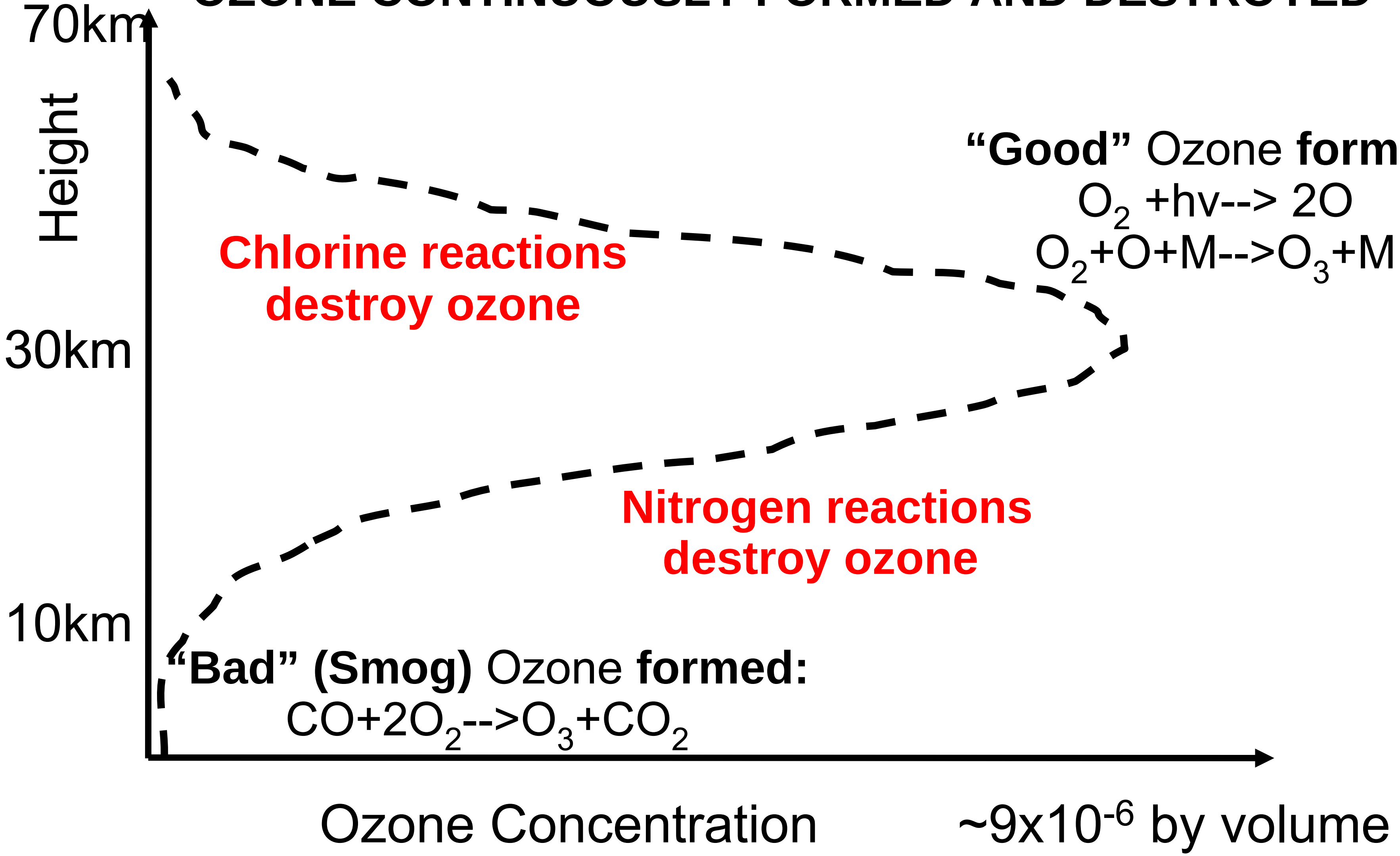
~9ppm

„Bad“ Ozone – smog

Source: 2D Model SOCRATES

Ozone in Earth's Atmosphere

OZONE CONTINUOUSLY FORMED AND DESTROYED



"Good" Ozone **formed**:
O_2 +hv--> 2O
O_2+O+M-->O_3+M

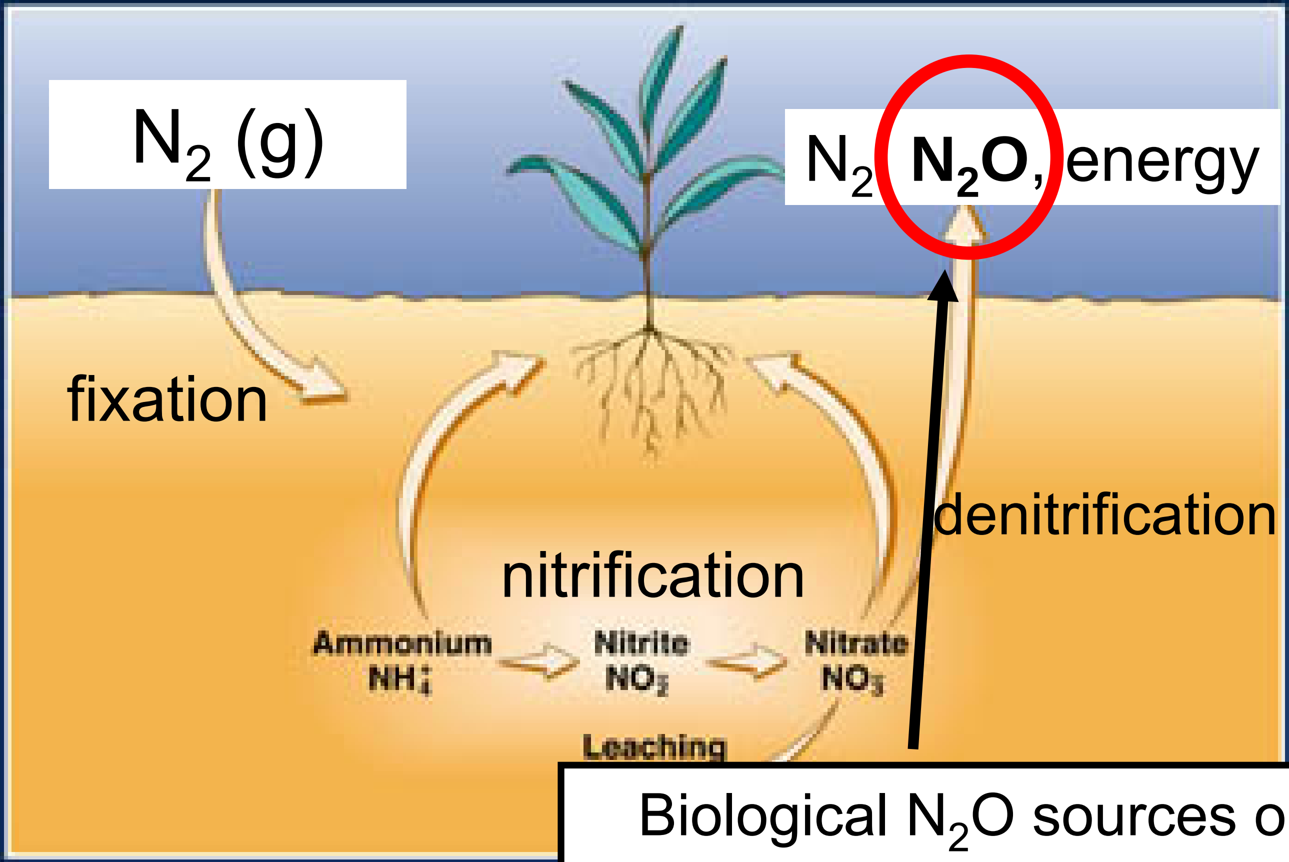
Chlorine reactions destroy ozone

Nitrogen reactions destroy ozone

"Bad" (Smog) Ozone **formed:**
$CO+2O_2 \text{-->} O_3+CO_2$

Nitrous Oxide (N_2O) in Earth's Atmosphere

Nitrogen Cycle



N_2 (g)

fixation

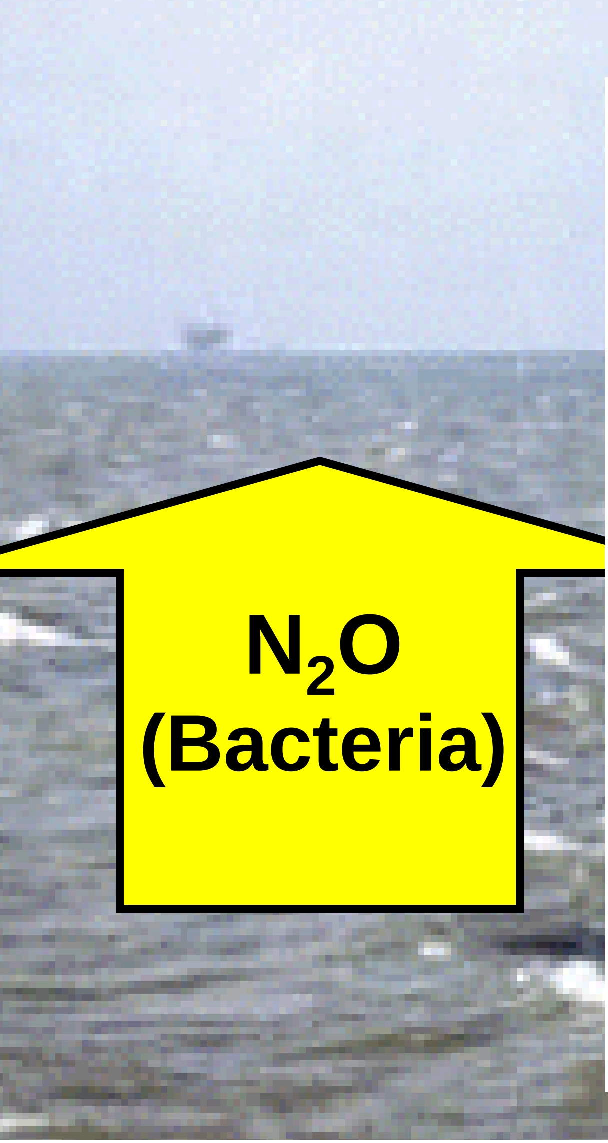
nitrification

N_2, **N_2O**, energy

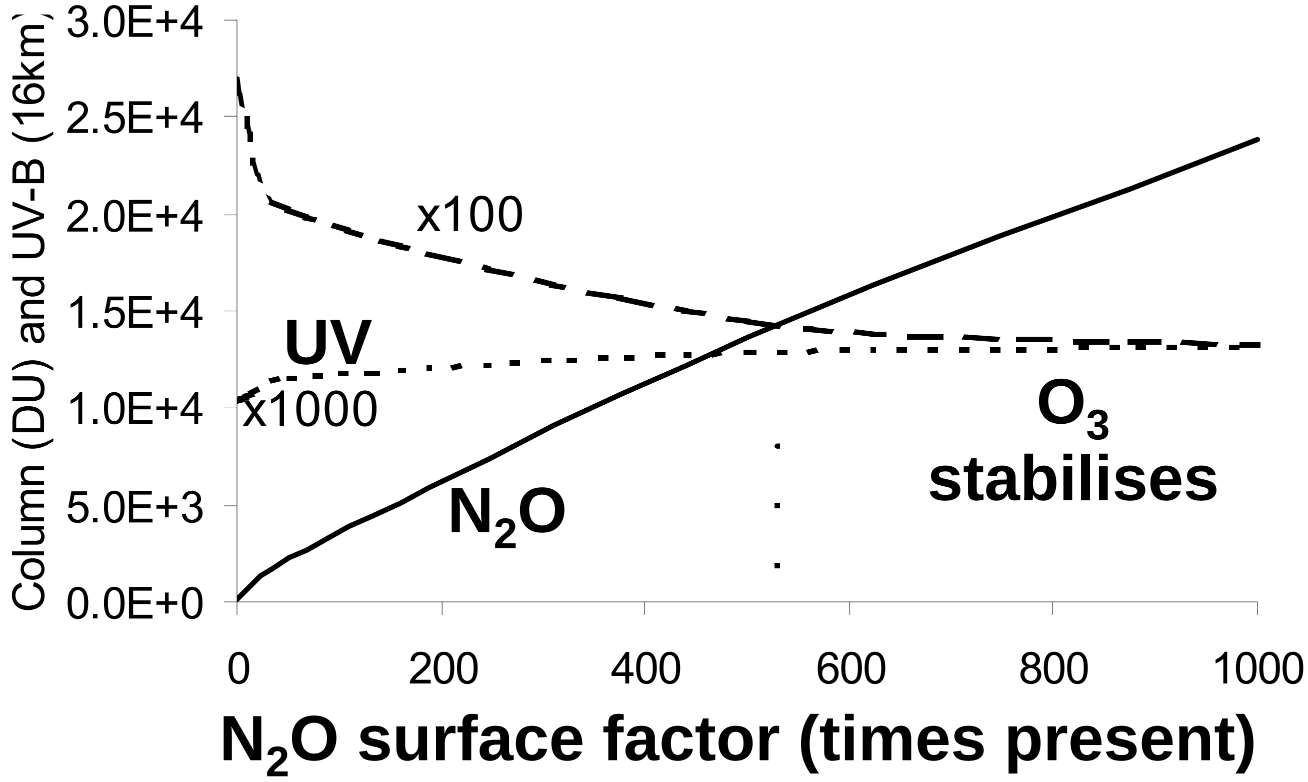
denitrification

Biological N_2O sources on Earth about one billion times stronger than non-biological (photochemistry)

Were Early Earth Oceans a strong Source of N_2O



Resulting N_2O and O_3 feedbacks



Canfield Ocean: Buick (2007)

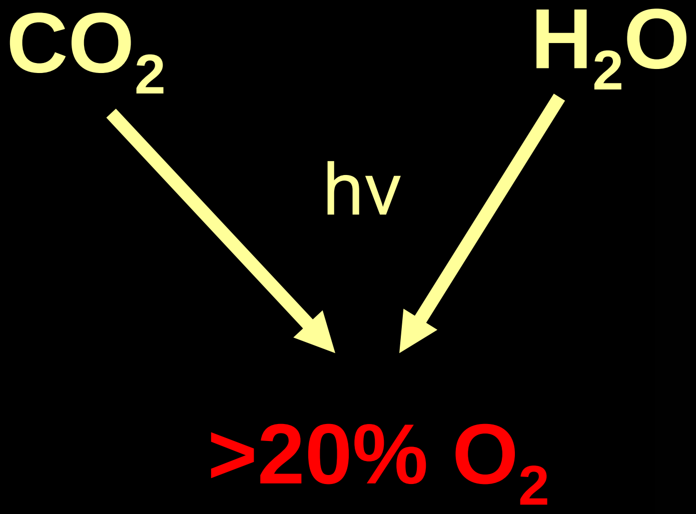
Grenfell et al. Icarus 211, 81-88, (2011)

Biomarker Caveats (“Red Herrings”)

False Positives

i.e. conclude FALSELY that life is present. Why?
Consider some simple atmospheres:

Pure CO_2 atmospheres



CO_2

H_2O

hv

>20% O_2

Pure Steam atmospheres

-would trigger false positive in O_2 for life

Selsis et al. (2002) A&A triple signature

False Positives (cont.)

Nitrous oxide (N_2O) non-life sources:

$N_2 + O^* + M \rightarrow N_2O + M$ (JPL Report, 2006)

$NO_3 + N_2 \rightarrow N_2O + NO_2$

$O_3^* + N_2 \rightarrow N_2O + O_2$ (Prasad 2008)

Probably very slow cf biology but need improved kinetic data

Chloromethane (CH_3Cl) source(s):

$(CH_4 + Cl_2 \rightarrow CH_3Cl + Cl)$

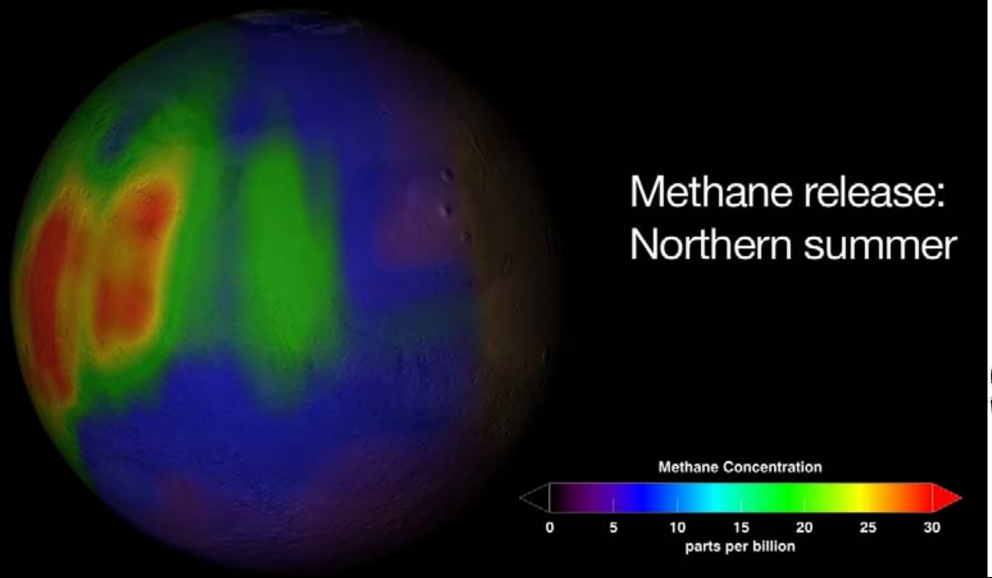
false positive if CH_4, Cl_2 from outgassing

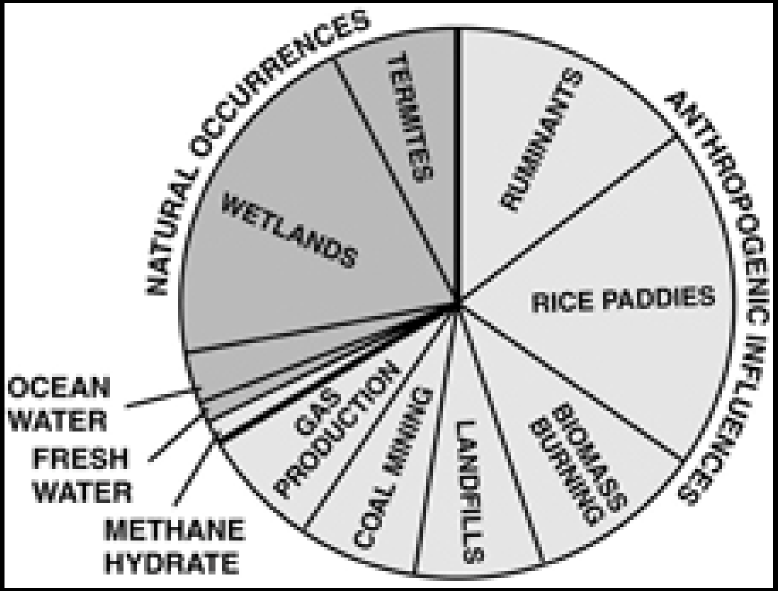
CH_3Cl loss via OH and hv, >x10 faster than methane

Methane – Biomarker or false positive?

Methane on Mars (?)

Methane Sources on Earth





source: NASA (Keck, M. Mumma)

Review (Mars): Zahnle et al. (2011) - remove telluric lines

Problems understanding CH_4 photochem. lifetime on Mars

False Negative

Life is there but we don’t see it because it is hidden e.g. by thick clouds or by interfering absorption bands (or it doesn’t want to be found…)

Biomarkers: Learning from the Solar System

Mars and Mars-like Atmospheres

Oxygen: (1×10^{-3}) (Barker, 1972)

Ozone: ($1\text{-}80\times10^{-8}$) (Barth and Hord, 1971)

Methane (a few tens of ppbv?)

Hydrogen Peroxide: $\sim10^{-8}$ (Encrenaz et al. 2004) Anti-biomaker

CASE 1: Pure CO_2 atmosphere

$$CO_2 \xrightleftharpoons[\text{slow}]{h\nu} CO + O \longrightarrow (O_2)$$

False Positive

CASE 2: Mars with catalytic chemistry (HOx, NOx)

$$CO_2 \xrightleftharpoons[\text{Cycles}]{} CO + O$$

Mars

TO DISTINGUISH CASES (1) AND (2)

Need more information (e.g. H_2O to estimate HOx cycles)

Biomarkers: Learning from the Solar System

Venus and Venus-like Atmospheres

Oxygen: ($1x10^{-3}$) (Barker, 1972)

Ozone: Thin, 100km O_3 layer (Montmessin, AAS 442)

Large [COS] abundance in troposphere ~few ppm (Svedhem et al. (2007)

-Probably volcanic BUT on Earth it is a biomarker

CASE 1: Pure CO_2 atmosphere

$$CO_2 \underset{\text{slow}}{\overset{h\nu}{\rightleftarrows}} CO + O \longrightarrow (O_2)$$

False Positive

CASE 2: Pure H_2O atmosphere

$$H_2O \xrightarrow{h\nu} OH + O \longrightarrow (O_2)$$

False Positive

CASE 3: Venus with catalytic chemistry (**ClOx**, NOx, HOx)

$$CO_2 \underset{\text{Cycles}}{\overset{h\nu}{\rightleftarrows}} CO + O$$

Venus

Biomarkers: Learning from the Solar System
Earth and Earth-like Atmospheres

- Earthshine (e.g. Palle 2002)
- Basis for chemical disequilibrium and entropy biomarkers
- Model studies: "moving the Earth"

(Segura et al., 2003; Grenfell et al. 2007; Rauer et al. 2011)

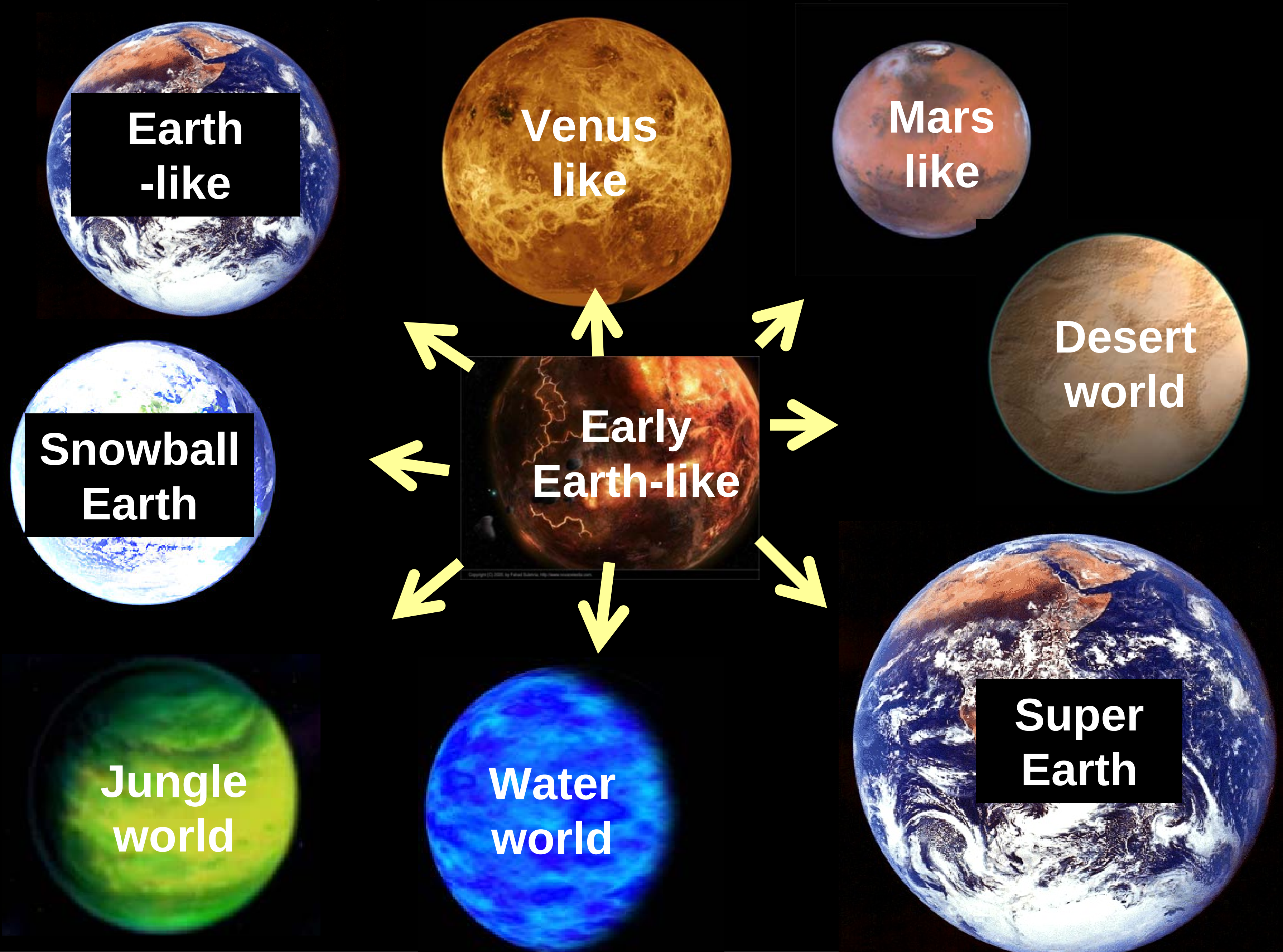
- Early Earth

e.g. Earth in time (Kaltenegger et al. (2007)

Titan – Reducing Atmospheres

- Low C_2H_2, H_2 abundances *could* be interpreted as biomarkers (bugs eating them) (but, difficult to establish this)

Beyond the Solar System



Early Earth-like

Earth -like

Venus like

Mars like

Desert world

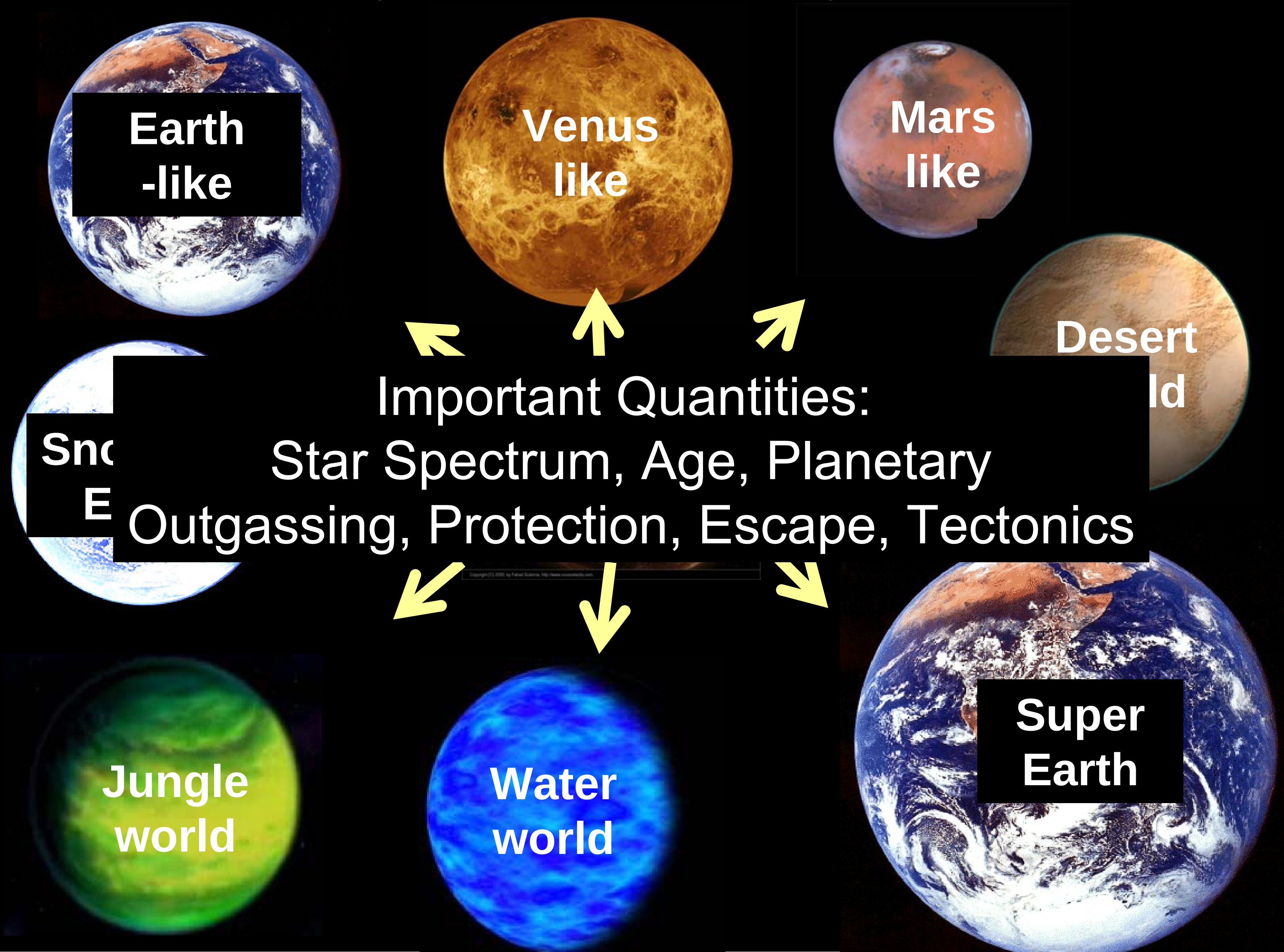
Super Earth

Water world

Jungle world

Snowball Earth

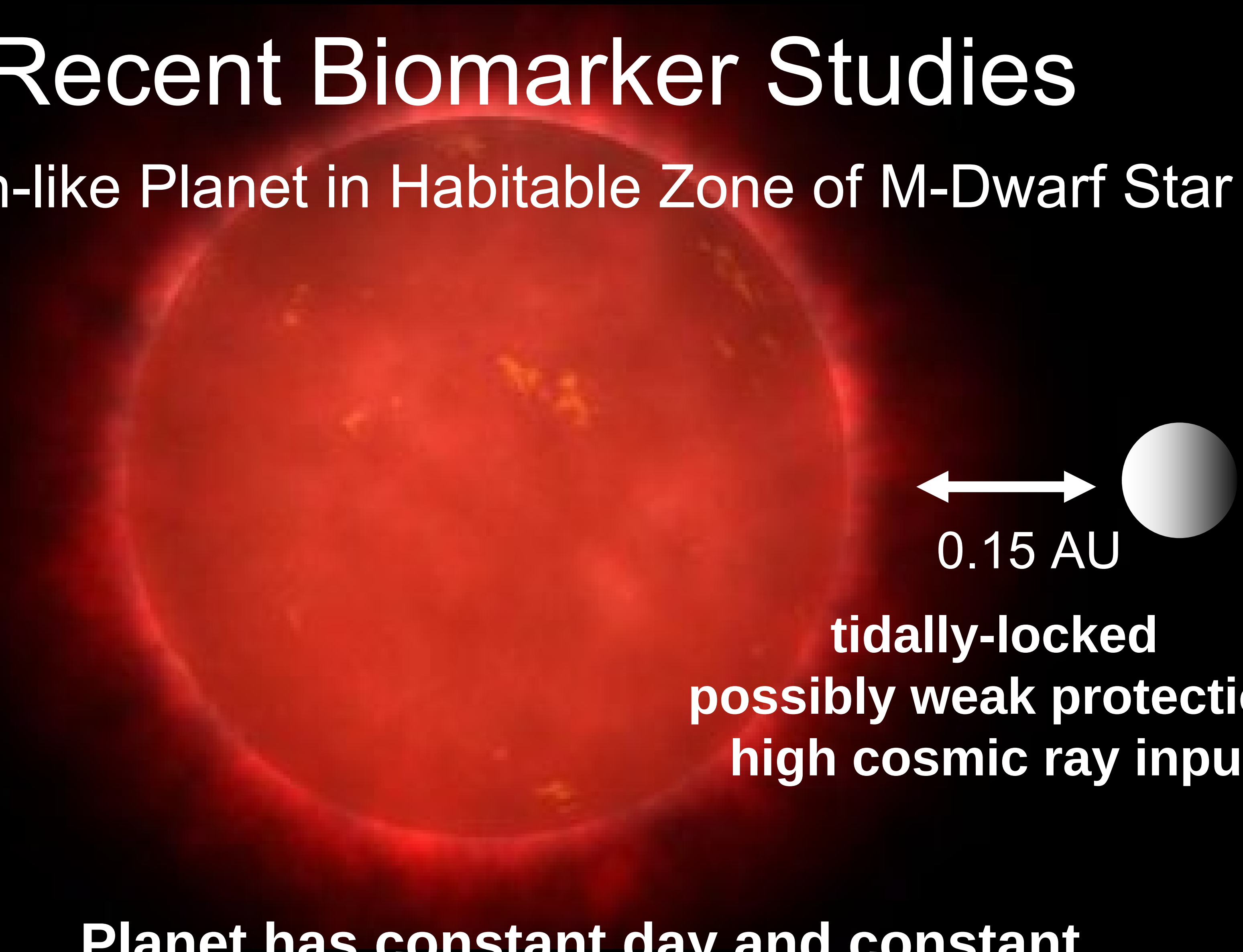
Beyond the Solar System



Important Quantities:
Star Spectrum, Age, Planetary Outgassing, Protection, Escape, Tectonics

Recent Biomarker Studies

Earth-like Planet in Habitable Zone of M-Dwarf Star

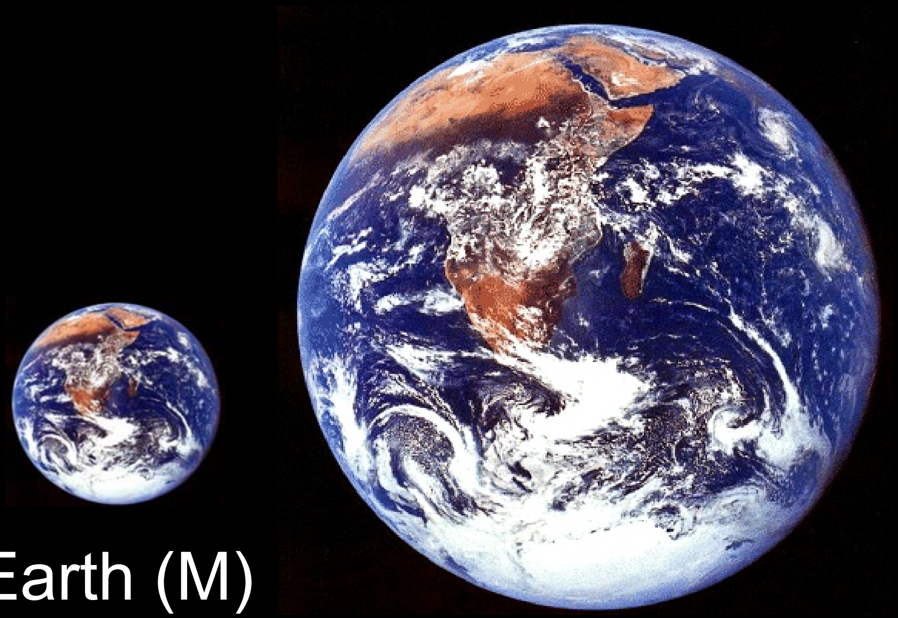


tidally-locked
possibly weak protection
high cosmic ray input

Planet has constant day and constant night hemispheres. Can atmosphere survive? What about Cosmic Rays/Transport/Biomarkers?

Potential biosignatures in Superearth atmospheres

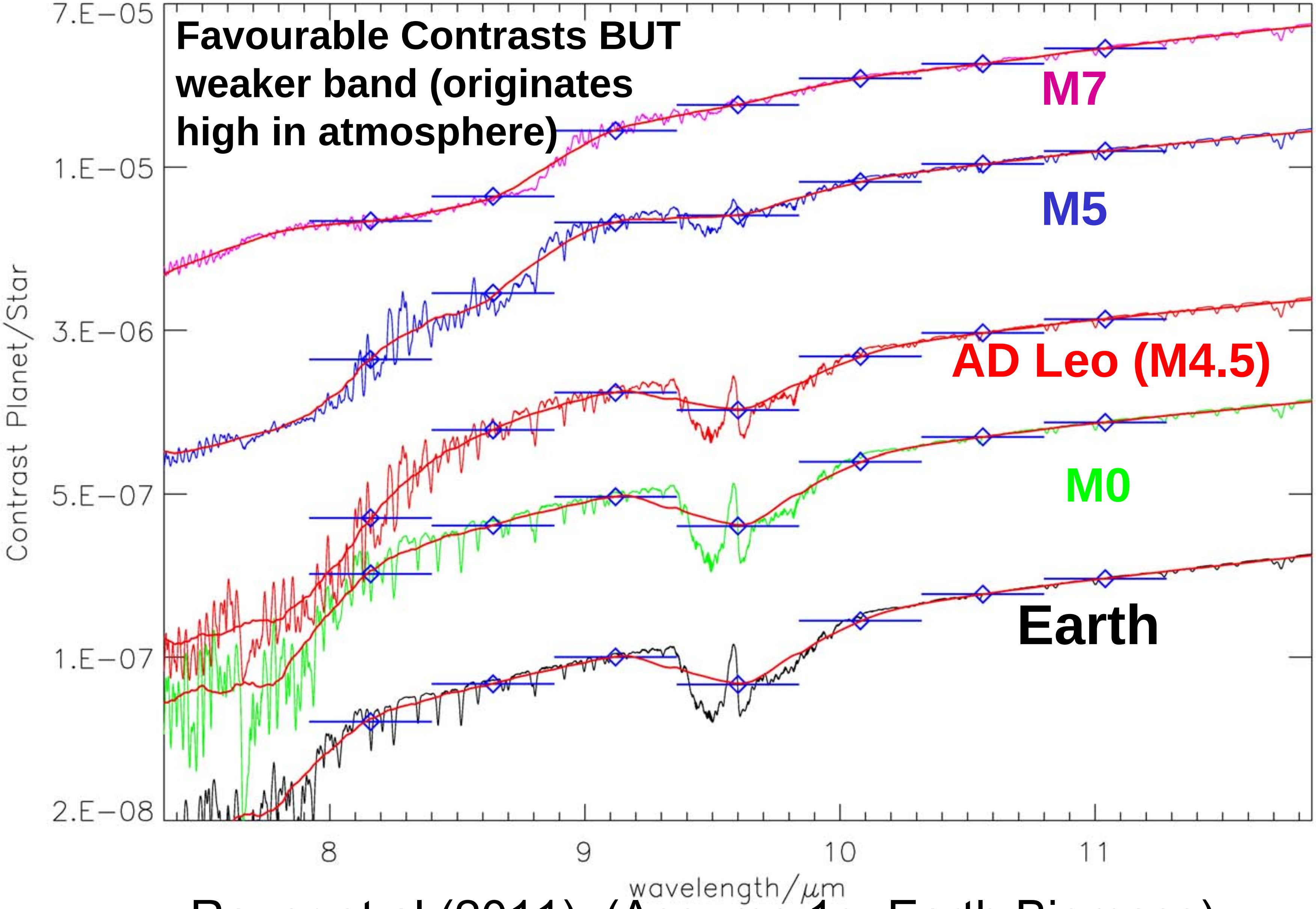
Rauer et al. (2011) A&A 529 A8



Assume an Earthlike development
(1bar at surface, Earth biomass)

see Grenfell et al. (2011) in preparation
for photochemical responses

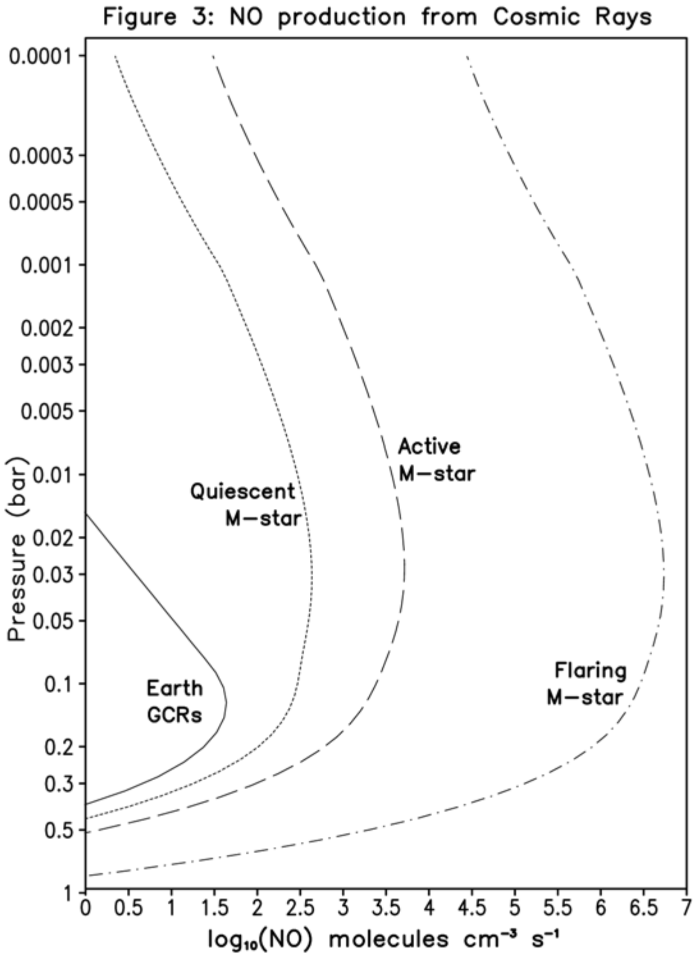
Contrast Ratios for Ozone (9.6μm) Band

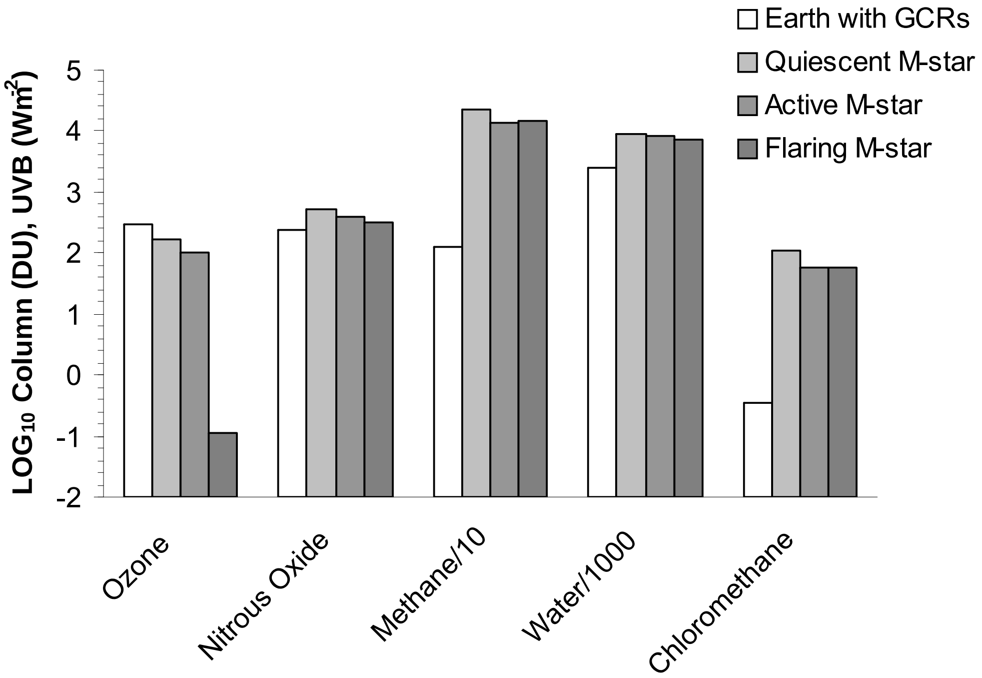


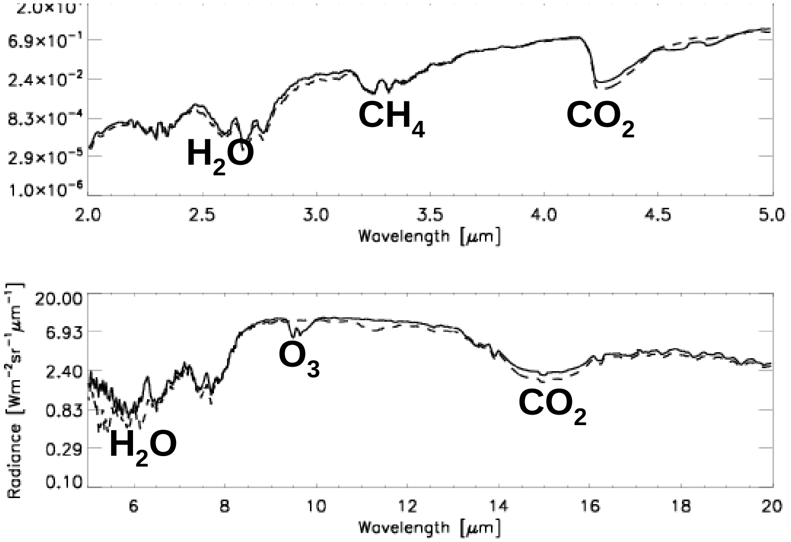
Favourable Contrasts BUT weaker band (originates high in atmosphere)

Rauer et al.(2011) (Assume 1g, Earth Biomass)

Effect of M-Dwarf Stellar Cosmic Rays on Biomarkers







Grenfell et al. (2011) submitted

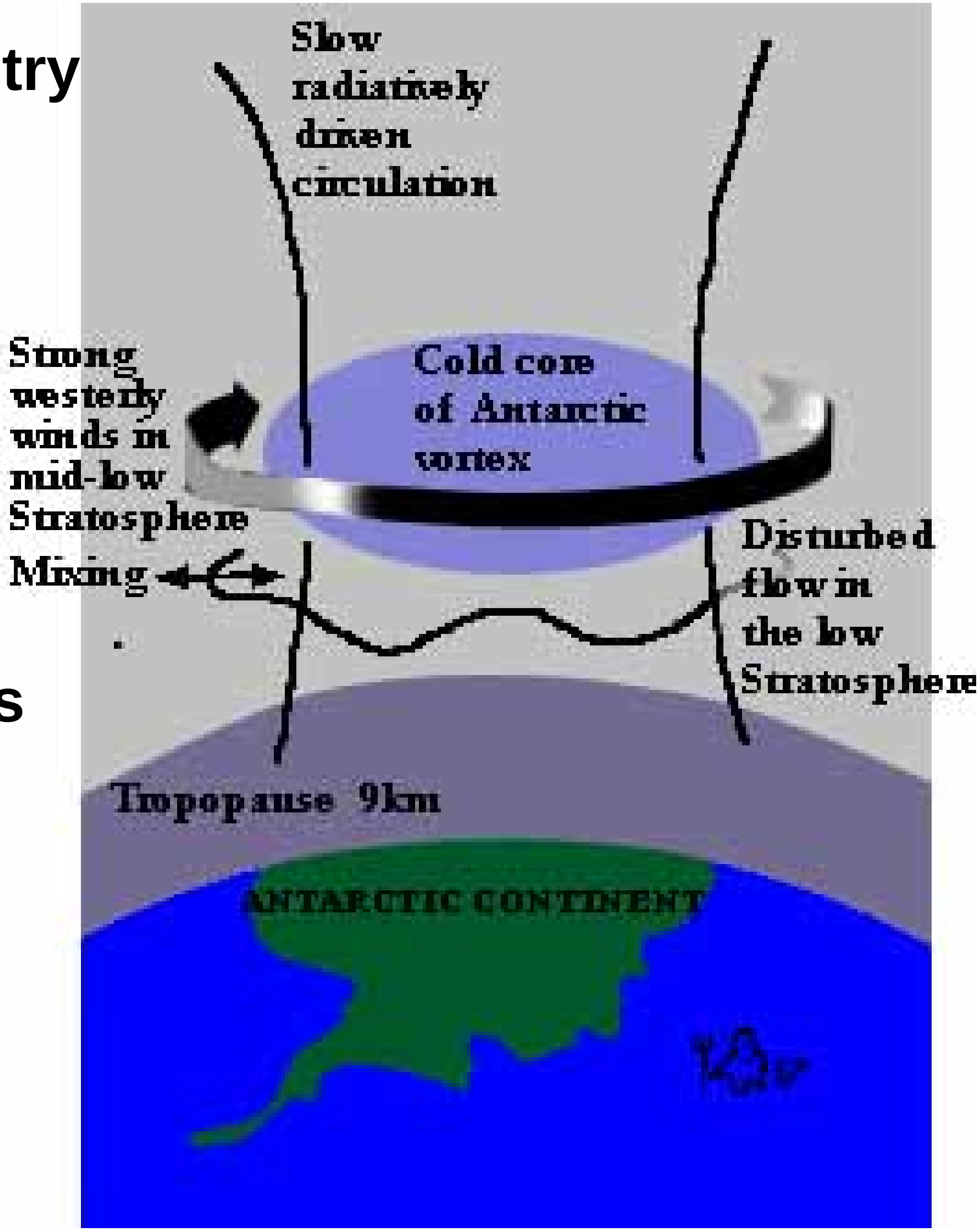
Effect of Cosmic Rays on O_3 in Earth's Atmosphere

Fast Cosmic Ray chemistry
NO (etc) production

Downward transport
NO survives in dark

3D mixing to mid latitudes
Biomarker chemistry

Exoplanet Case
3D circulation
of e.g. Earth-like
planet around M-dwarf
not well-known



Summary and Conclusions

- There are a wide range of biomarker criteria which should be applied together for best results
- Desirable to improve atmospheric models with e.g. more accurate stellar spectra and ages, developmental scenarios, photochemical kinetics, radiation transfer, outgassing, escape etc.
- In future – couple with interior (outgassing) models, escape models etc (HGF alliance)

Diversity of Life on Earth