Venus: looking for PH_3 with ALMA

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Phosphine on Venus **P.I. Jane Greaves**, Cardiff University, Wales

ALMA is a partnership of ESO, NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile.

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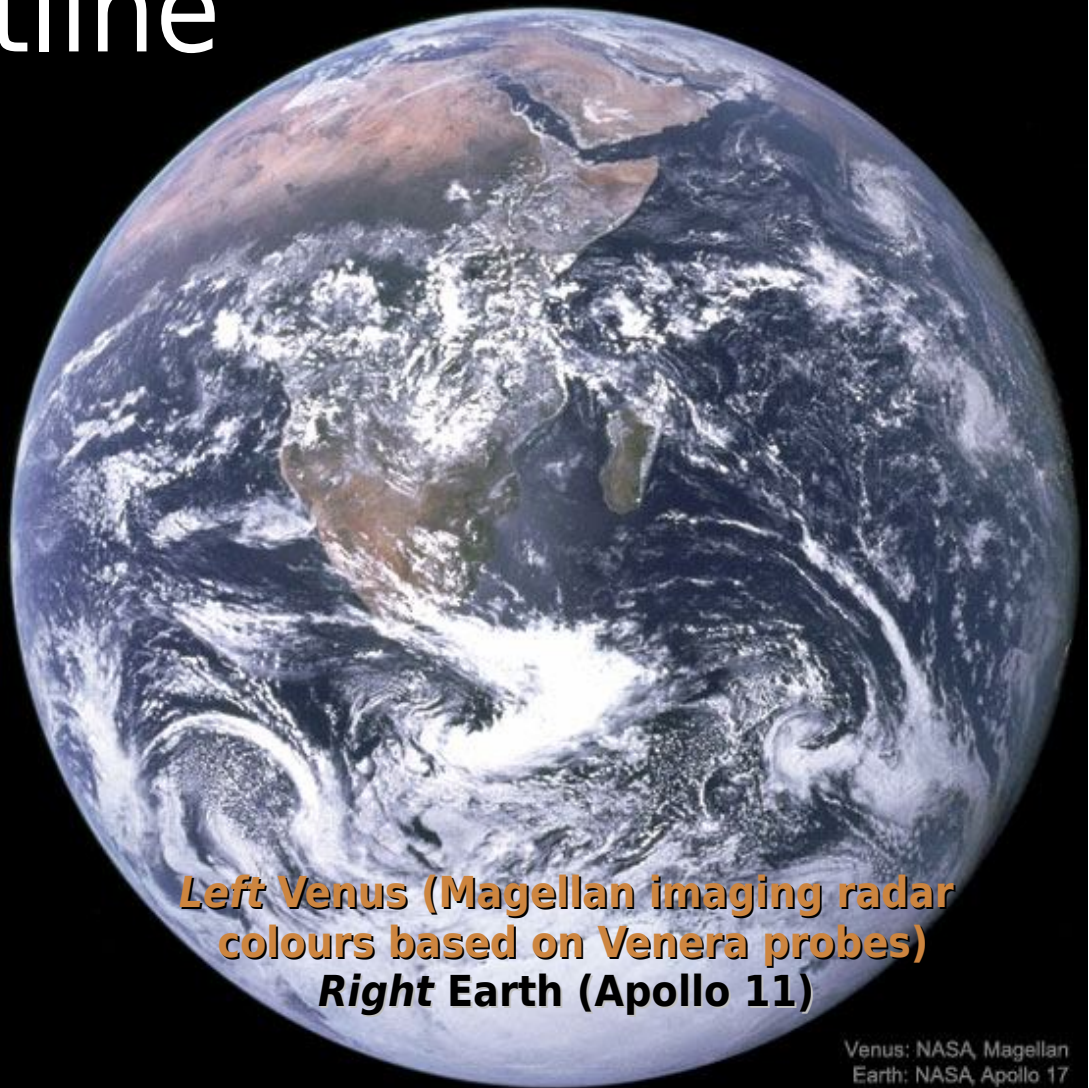
Co-authors, collaborators, and thanks

- **Greaves et al.** 2020NatAs.tmp..234G**,** 2020arXiv201108176G, 2020arXiv201205844G
  - https://arxiv.org/abs/2104.09285 *Nature astronomy 2021 accepted Apr 20*
    - original authors and more: J S Greaves, A M S Richards, W Bains, P B Rimmer, H Sagawa, D L Clements, S Seager, J J Petkowski, C Sousa-Silva, S Ranjan, E Drabek-Maunder, H J Fraser, A Cartwright, I Mueller-Wodarg, Z Zhar, P Friberg, I Coulson , E Lee, J Hoge, W Dent, R Simon

- Astrochemistry/astrobiology Seager et al. 2020arXiv200906474S, 2020NatAs...4..802S, Rimmer et al. 2021arXiv210108582R, Bains et al. 2020arXiv200906499B
  - Further analysis ApJ In Prep.
  - JCMT, ESO and JAO staff for help in observations and data processing
  - Journal editors for facilitating a lively discussion!
  - Additional images: NASA, National Geographic, Wikipedia, Sky & Telescope
  - Gianni and all INAF colloquium organisers

Outline

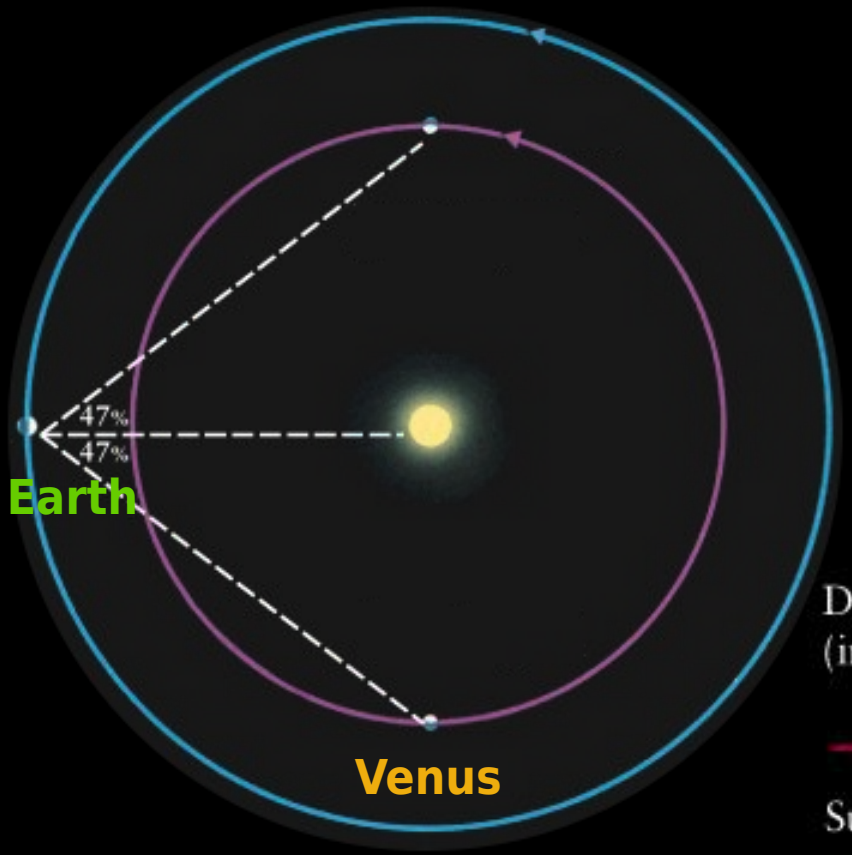
- Venus
- Why phosphine?
  - JCMT detection of 1.1 mm PH_3 line
- ALMA observations
- Other evidence
- Atmosphere of Venus and phosphorous chemistry
- History of Venus v. life on Earth
- Next?

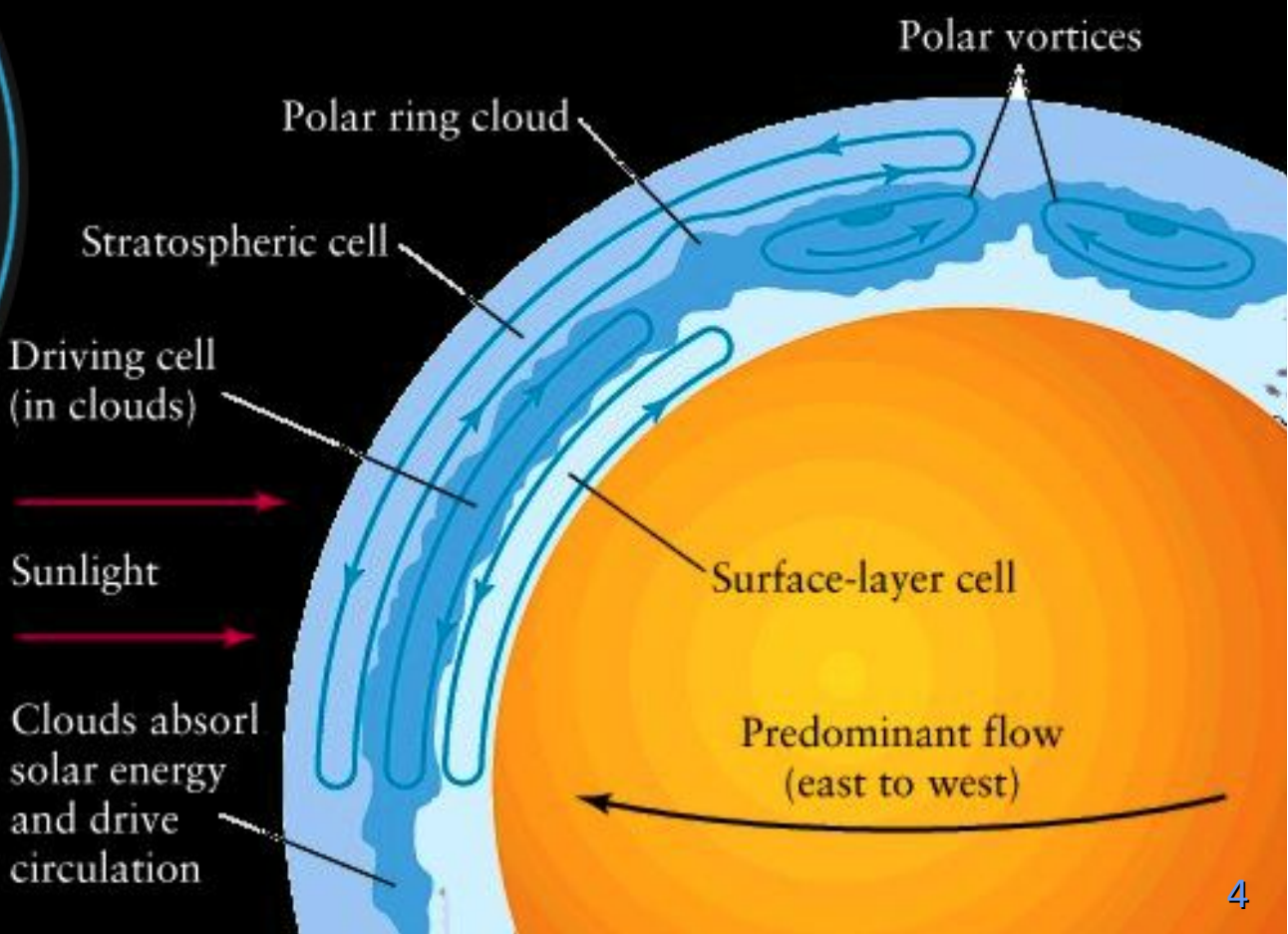


Left **Venus (Magellan imaging radar colours based on Venera probes)**
Right **Earth (Apollo 11)**

Venus: NASA, Magellan
Earth: NASA, Apollo 17

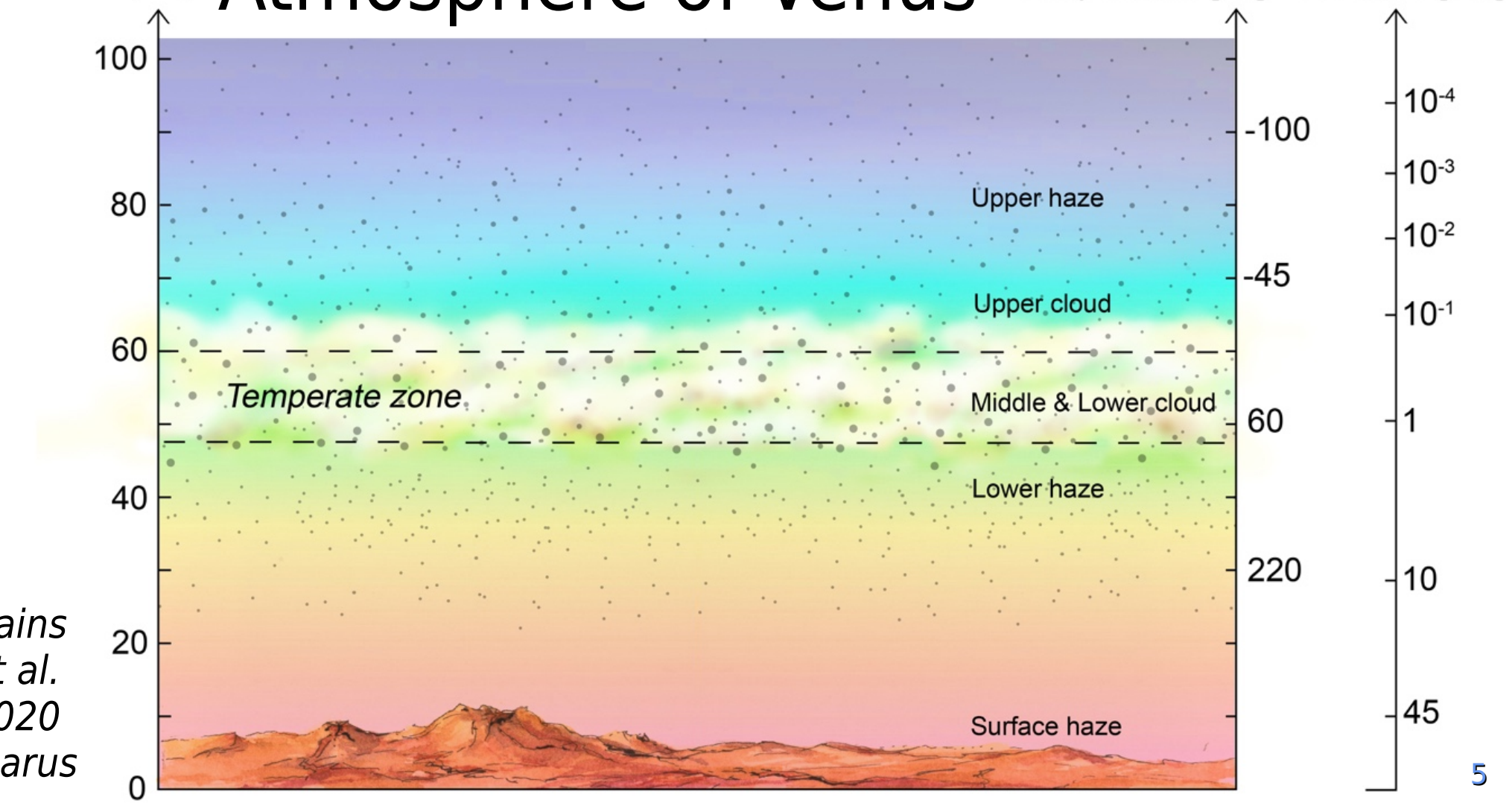
Venus





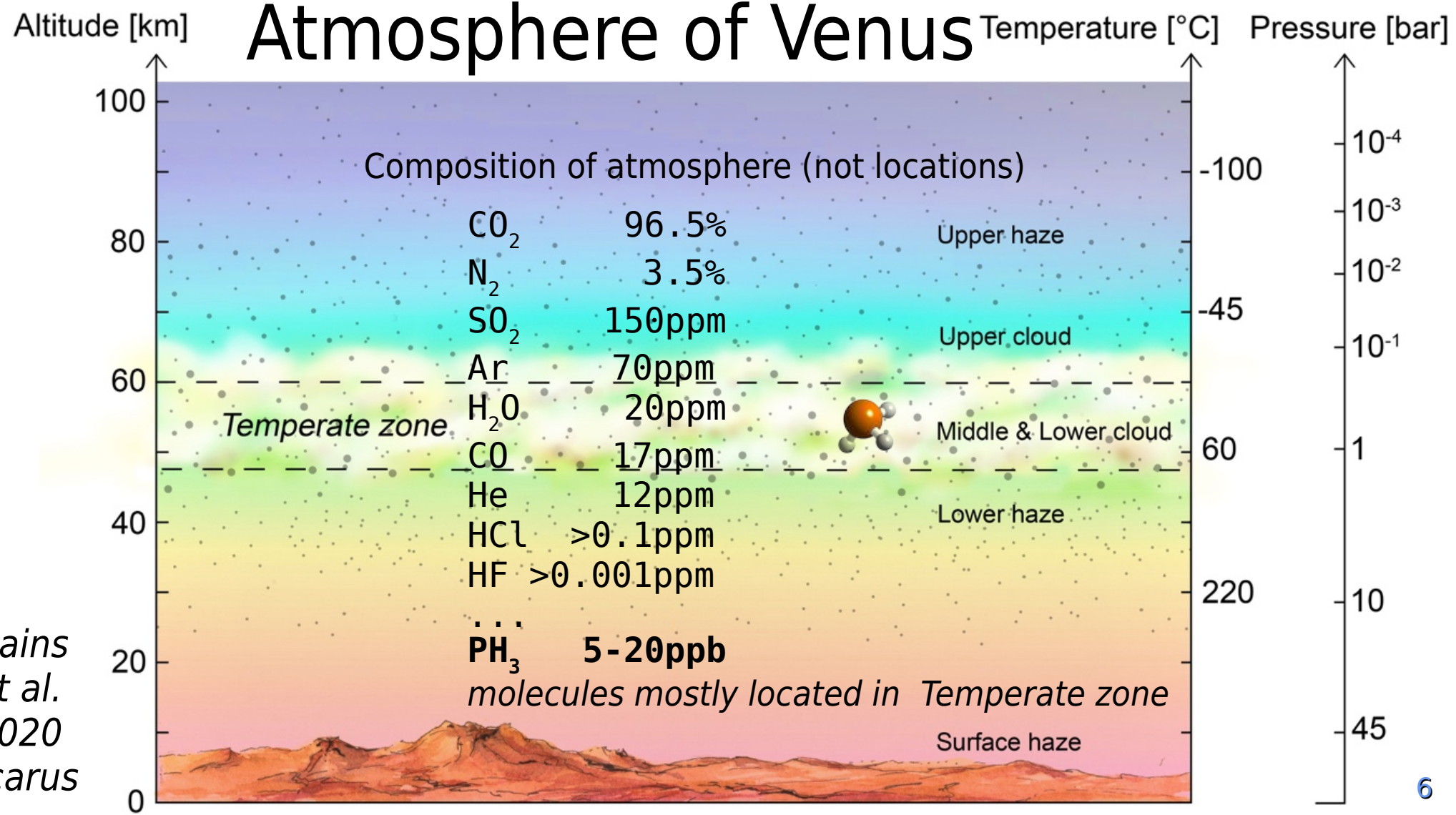
https://wisp.physics.wisc.edu/astro104/lecture16

Atmosphere of Venus

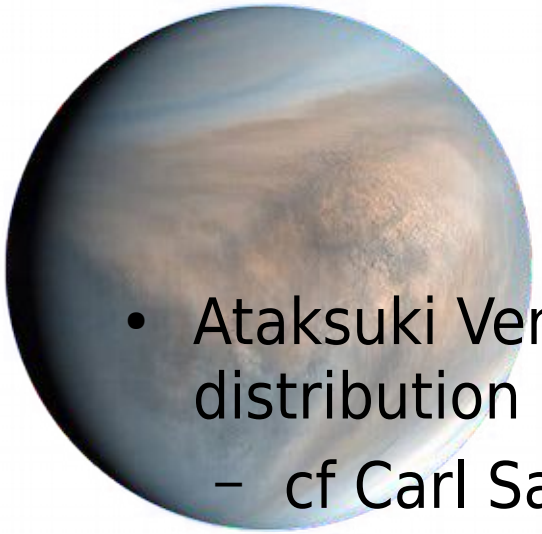


Bains et al. 2020 Icarus

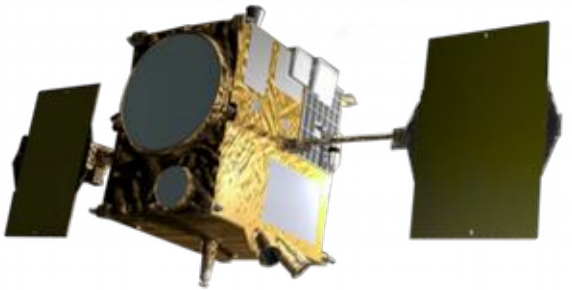
Atmosphere of Venus



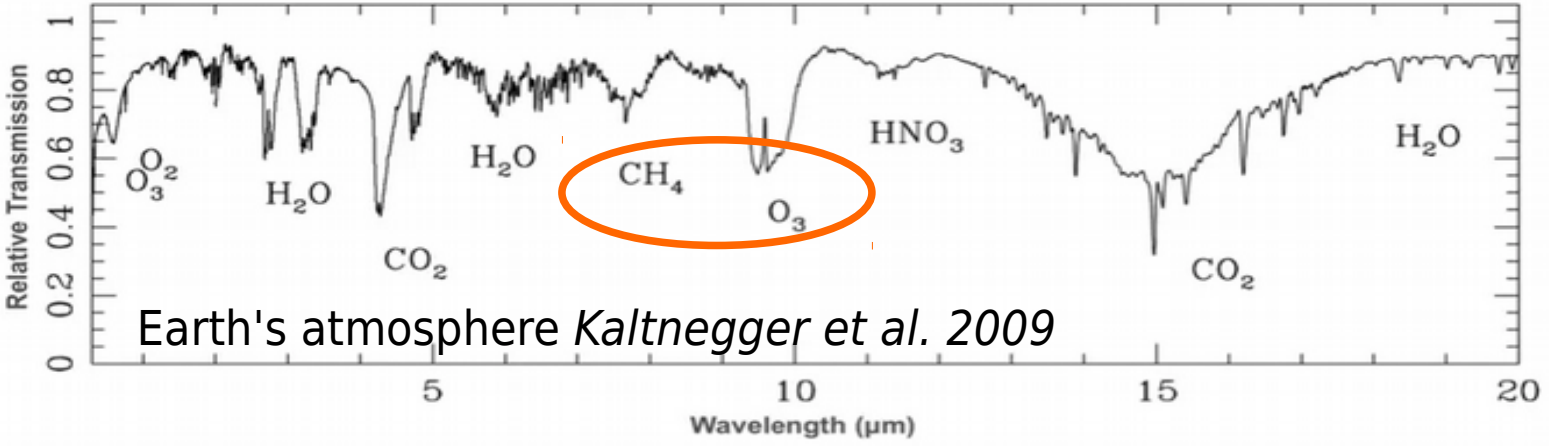
Bains et al. 2020 Icarus



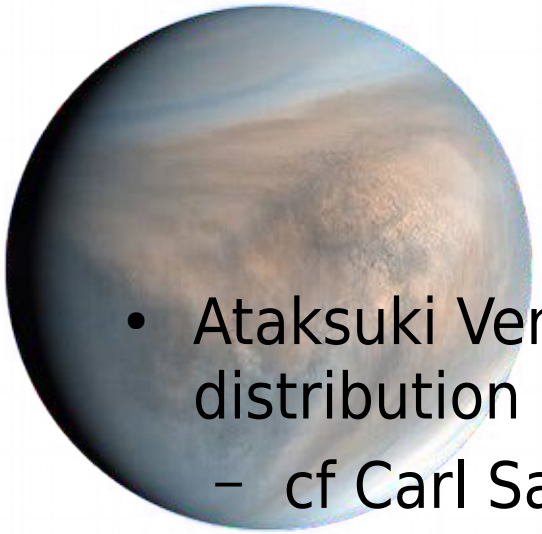
Venus and phosphine



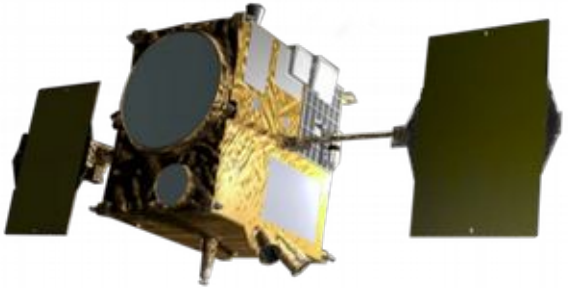
- Ataksuki Venus climate orbiter found unexpected, irregular distribution of particles (*Limaye+'17*)
  - cf Carl Sagan's “unexplained UV absorber”
    - Reminiscent of Terrestrial cloud bacteria
- Classic search for life is to look for non-equillibrium gas mixture



Earth's atmosphere *Kaltnegger et al. 2009*



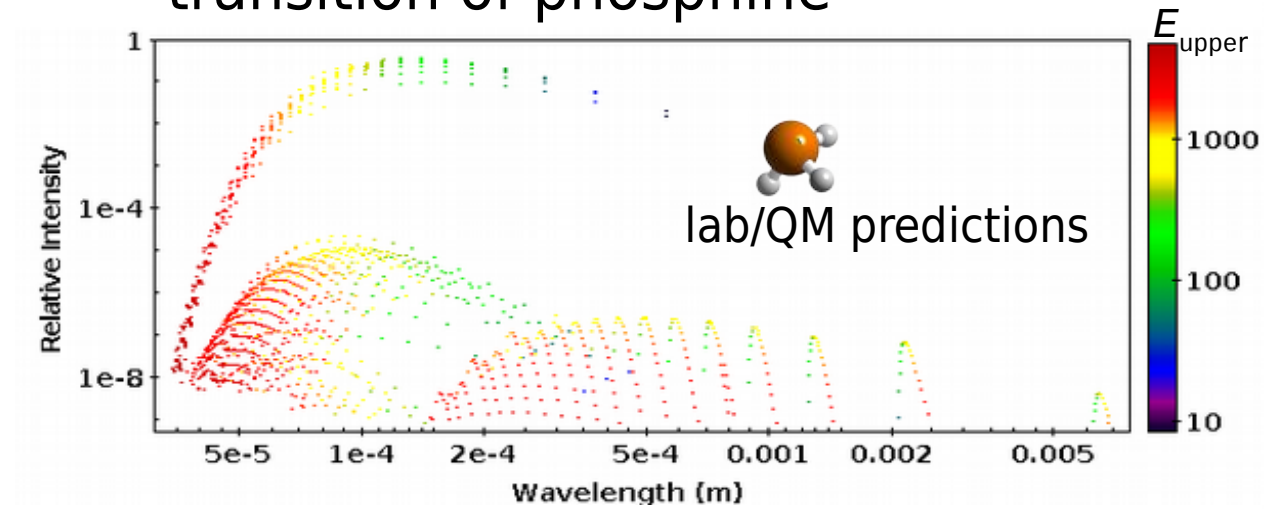
Venus and phosphine

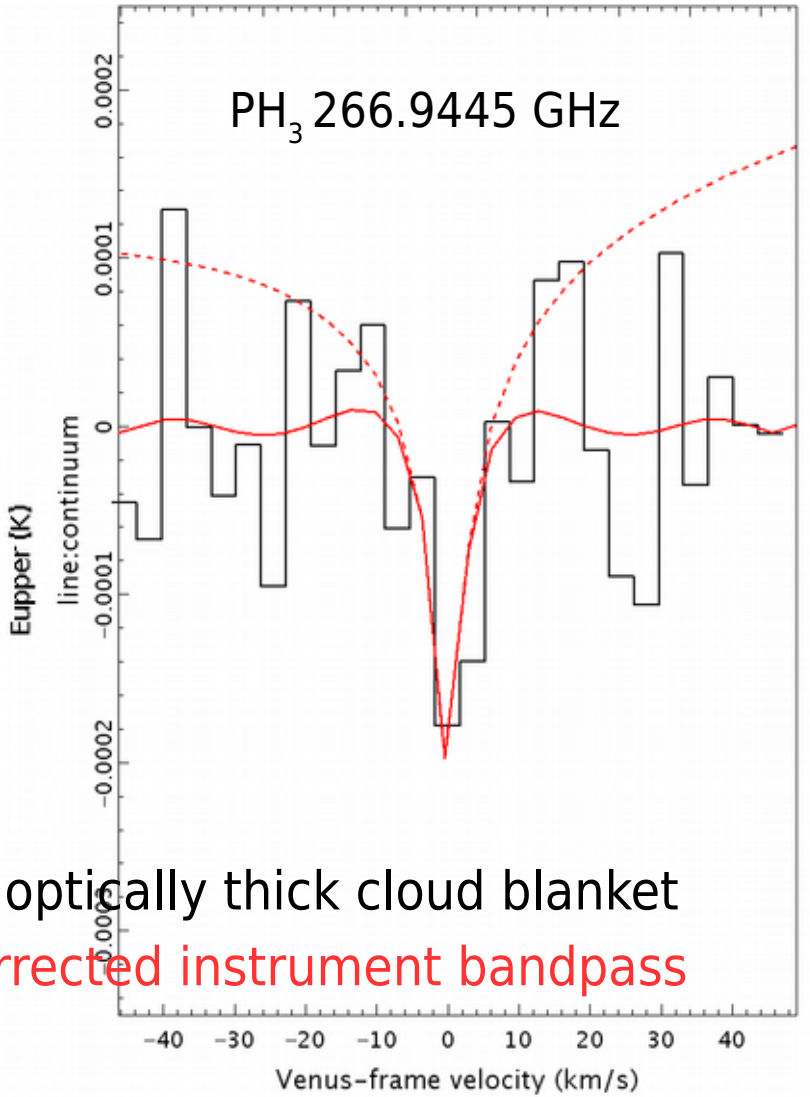


- Ataksuki Venus climate orbiter found unexpected, irregular distribution of particles (*Limaye+'17*)
  - cf Carl Sagan's “unexplained UV absorber”
  - Reminiscent of Terrestrial cloud bacteria
- Classic search for life is to look for non-equillibrium gas mixture
  - Phosphine, PH_3 reacts rapidly with oxidising agents like CO_2, SO_2
    - Uniquely associated with life on Earth
      - Not expected to occur on other rocky planets
    - Greaves used JCMT to benchmark upper limits
      - Amazed to detect PH_3 towards Venus

JCMT 2017

- Observe strongest longer-wavelength transition of phosphine



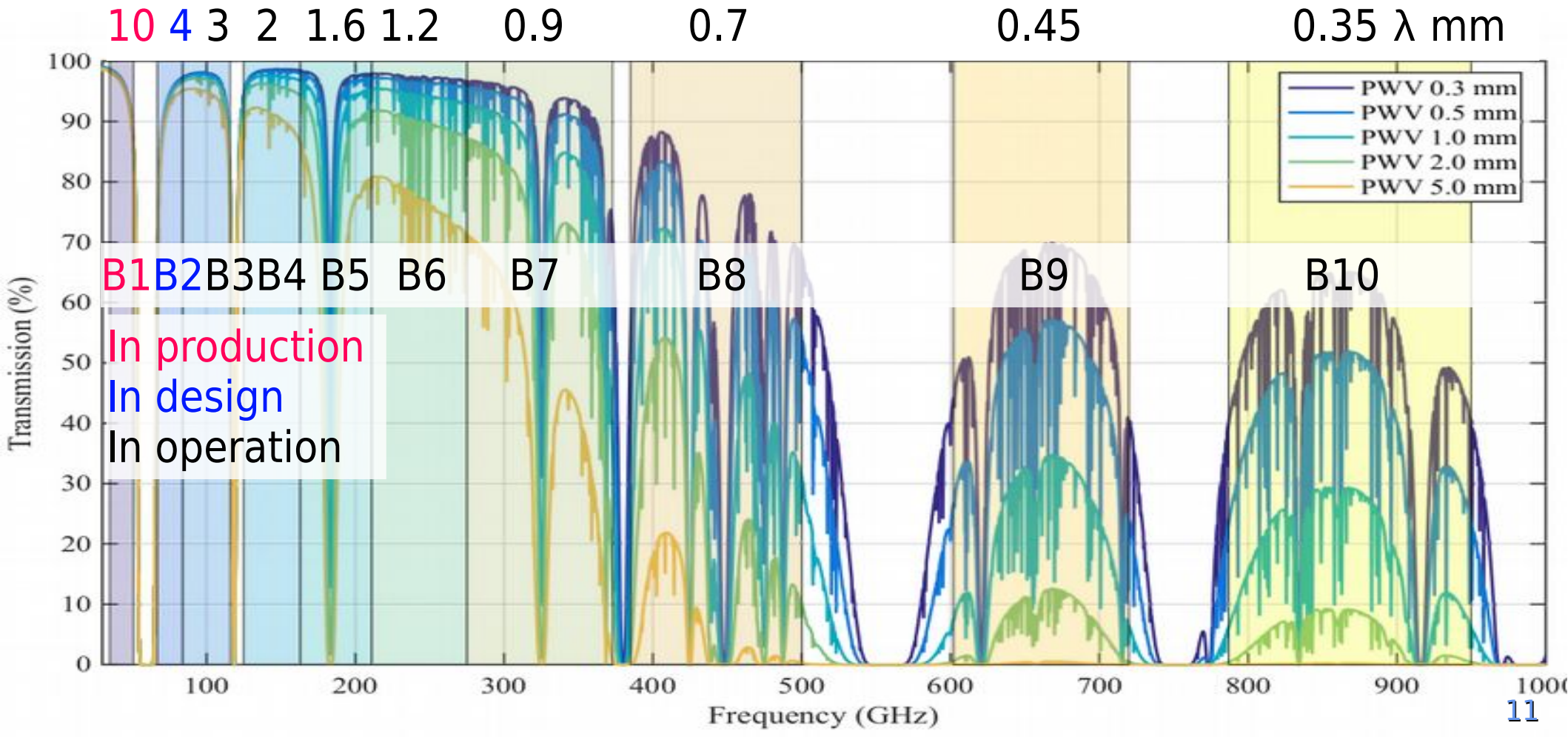


- λ 1.123 mm absorption against optically thick cloud blanket
- ---- model — convolved with corrected instrument bandpass
- ~20 parts per billion (ppb) PH_3
- Pressure, hence altitude, estimated roughly from line width

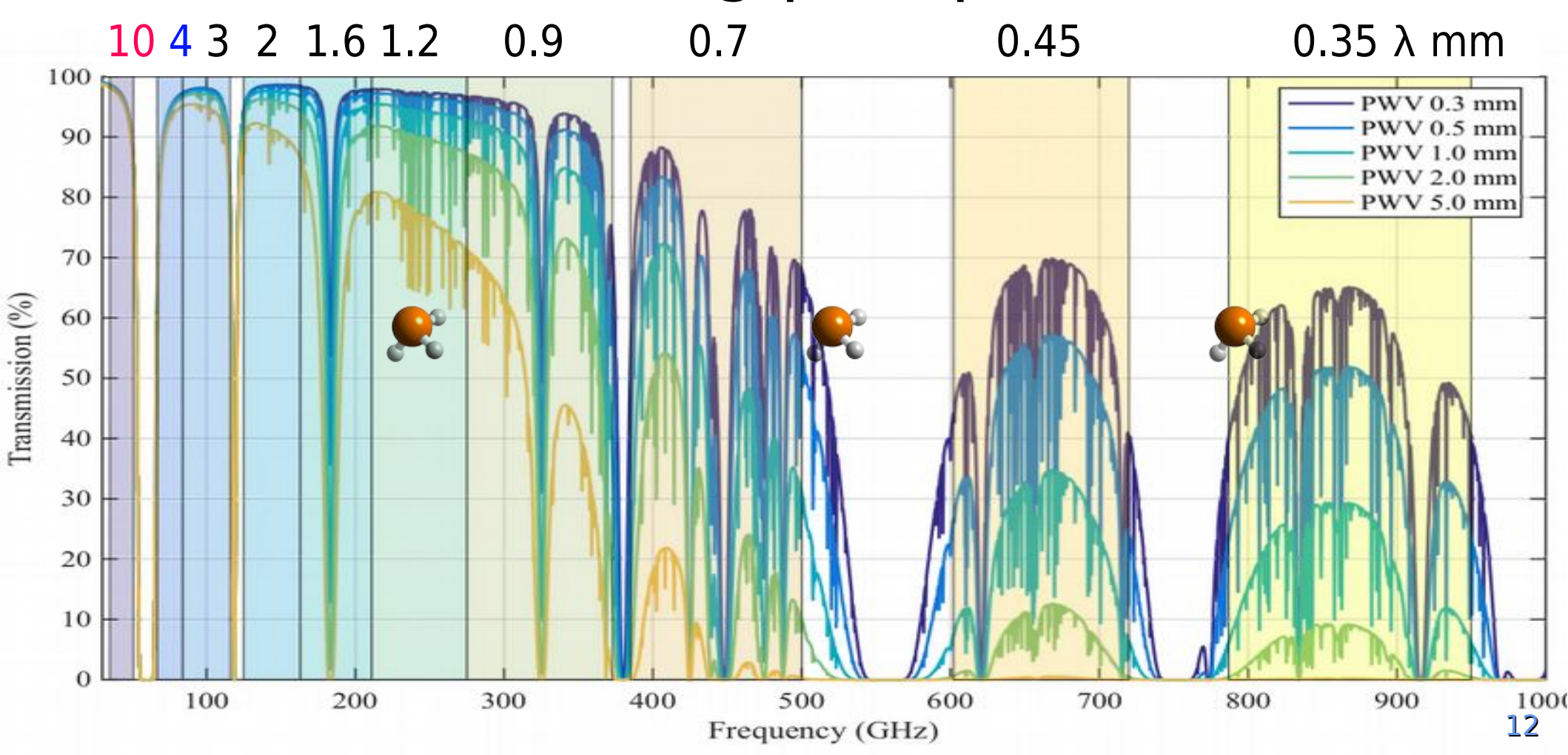
ALMA: 5000 m up in the Andes

- Chajnantor plateau of the Atacama Desert
  - 5000 m altitude
  - Precipitable water vapour (PWV) ≥0.1 mm
- 50 12-m antennas in main array
  - Baselines up to 16 km
- 12 7-m antennas short spacing array
- 4 more 12-m for total power

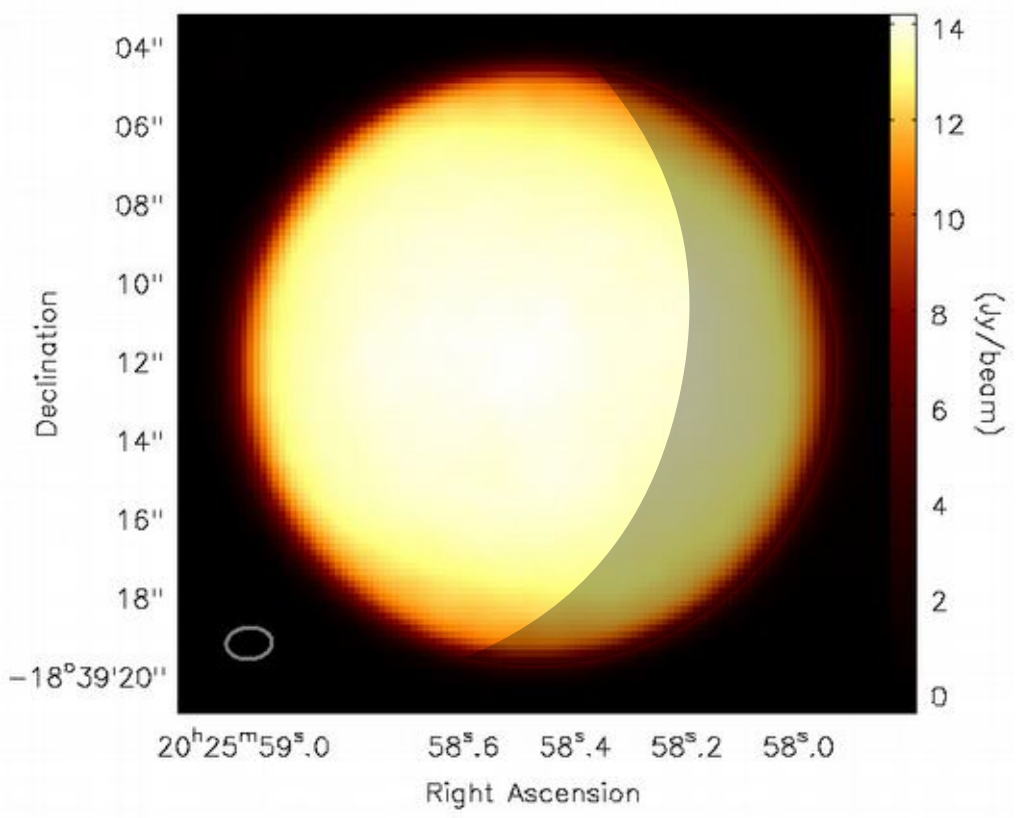
ALMA observing bands transmission



Observing phosphine



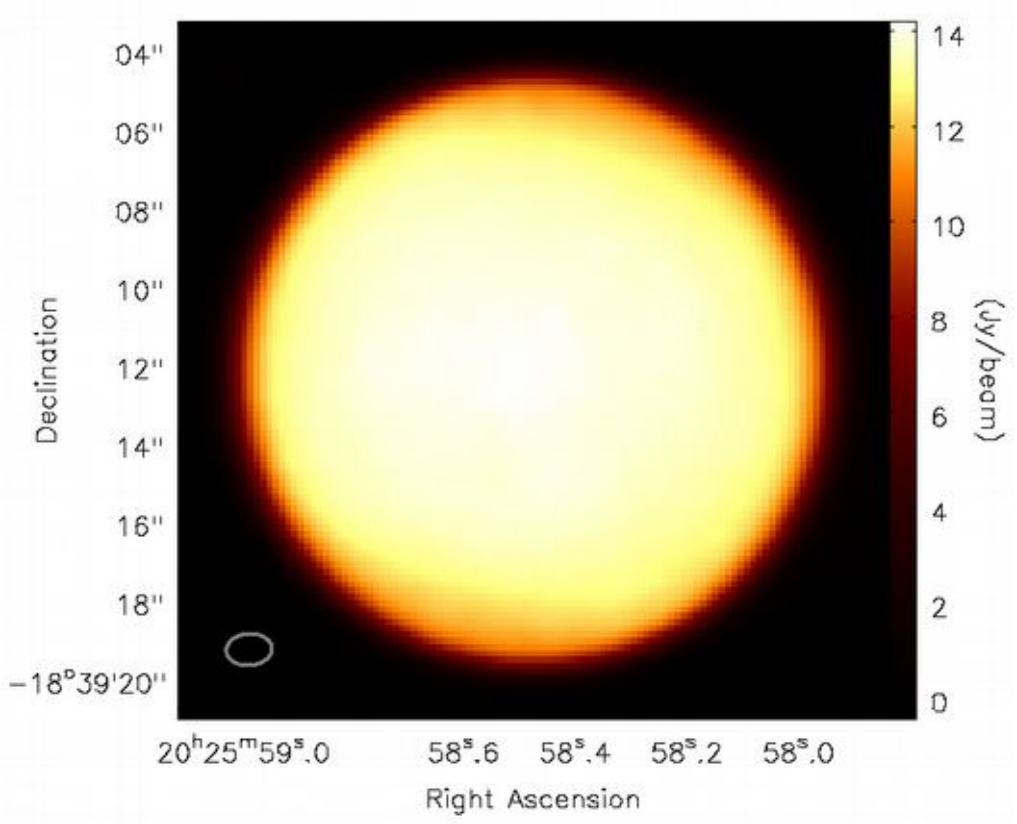
Observing Venus



ALMA observations March 2019 DDT

- Orbital radius 0.72 au
- Year 224.7 Earth days
  - <2 Venus days!
- Some cloud layers blow round the planet in a few Earth days
- mm-wave 'continuum' is blanket of optically thick cloud lines
  - Flux density ~independent of insolation
- Any bugs may be active in sunlight?

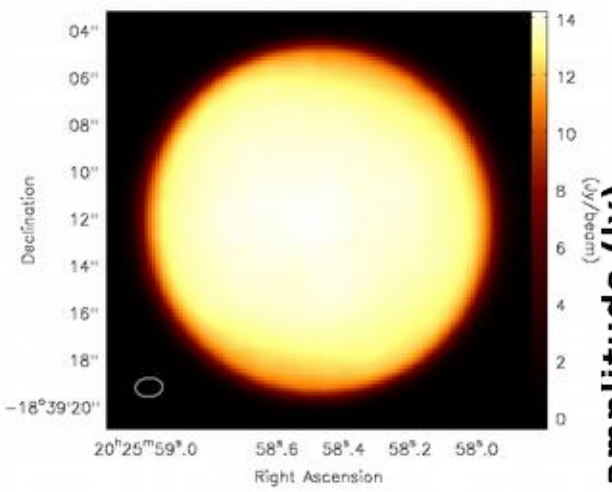
Venus with ALMA



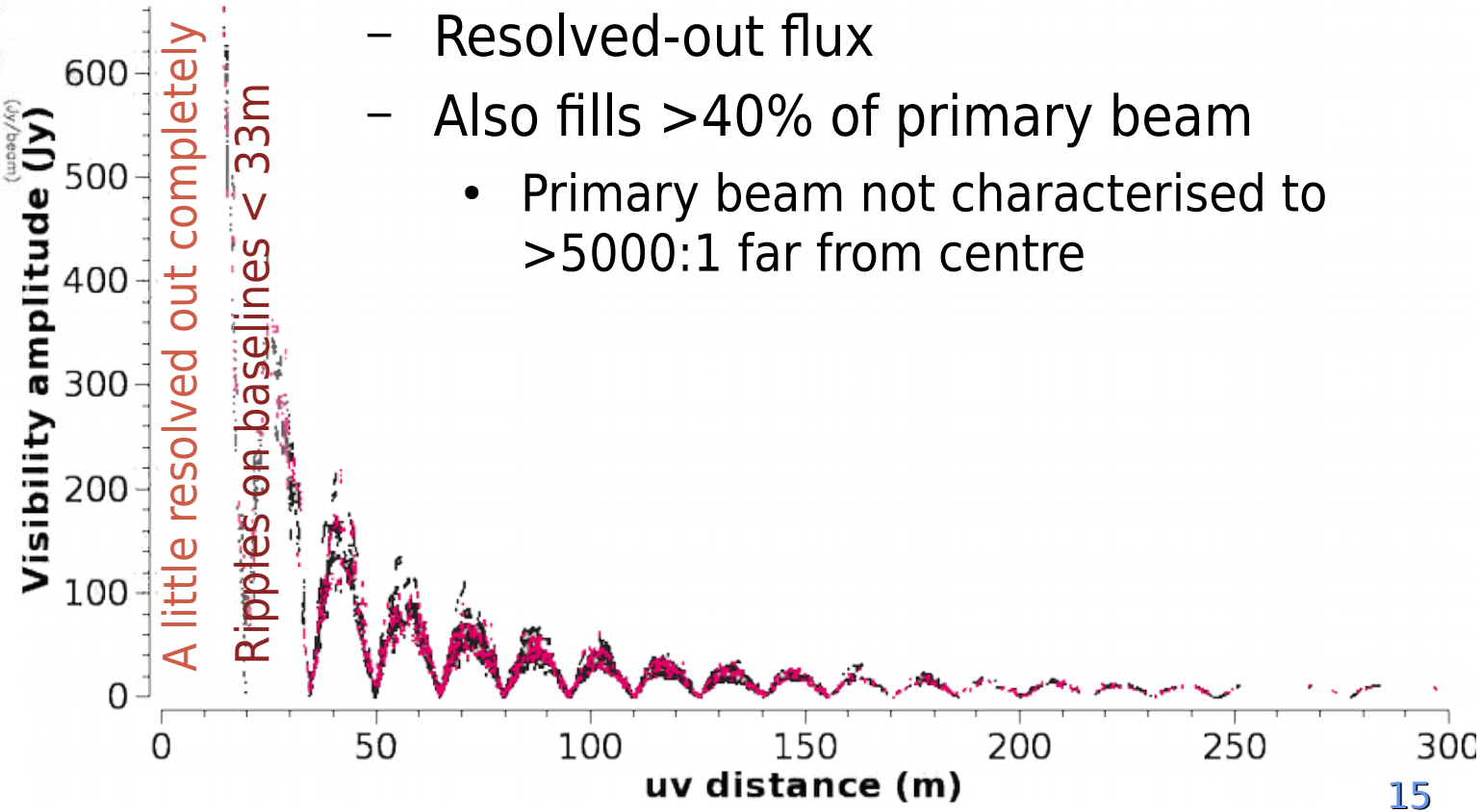
Greaves et al. 2020

- Great care with observing and calibrating bandpass
- Total continuum flux 2291 Jy
  - Large uncertainty
  - ~14 Jy per 1”.16 x 0”.80 beam
  - Need ~5000:1 spectral dynamic range
- Angular size ~16”
  - Continuum almost smooth
    - Slightly limb-darkened

Imaging Venus

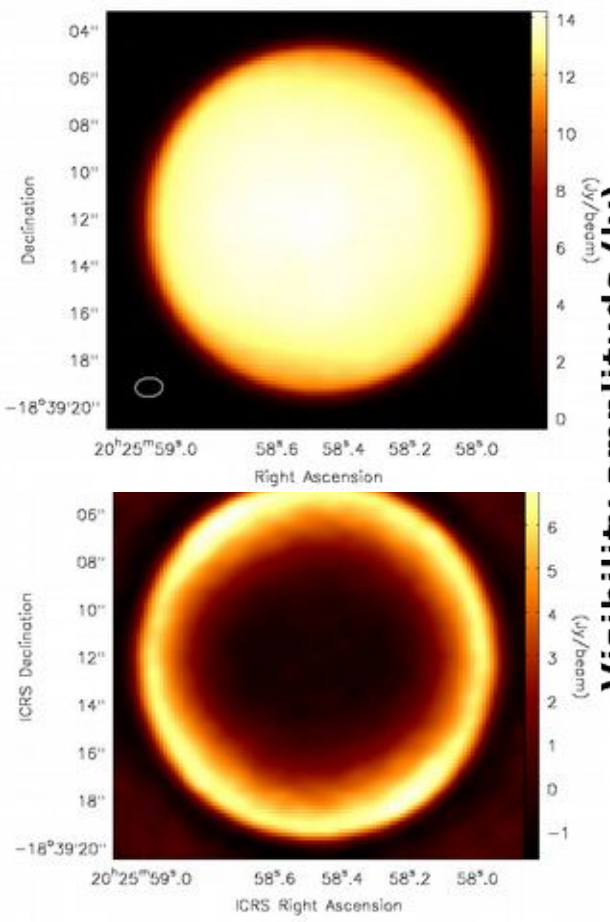


- All-data cube bandpass ripples
  - Resolved-out flux
  - Also fills >40% of primary beam
    - Primary beam not characterised to >5000:1 far from centre

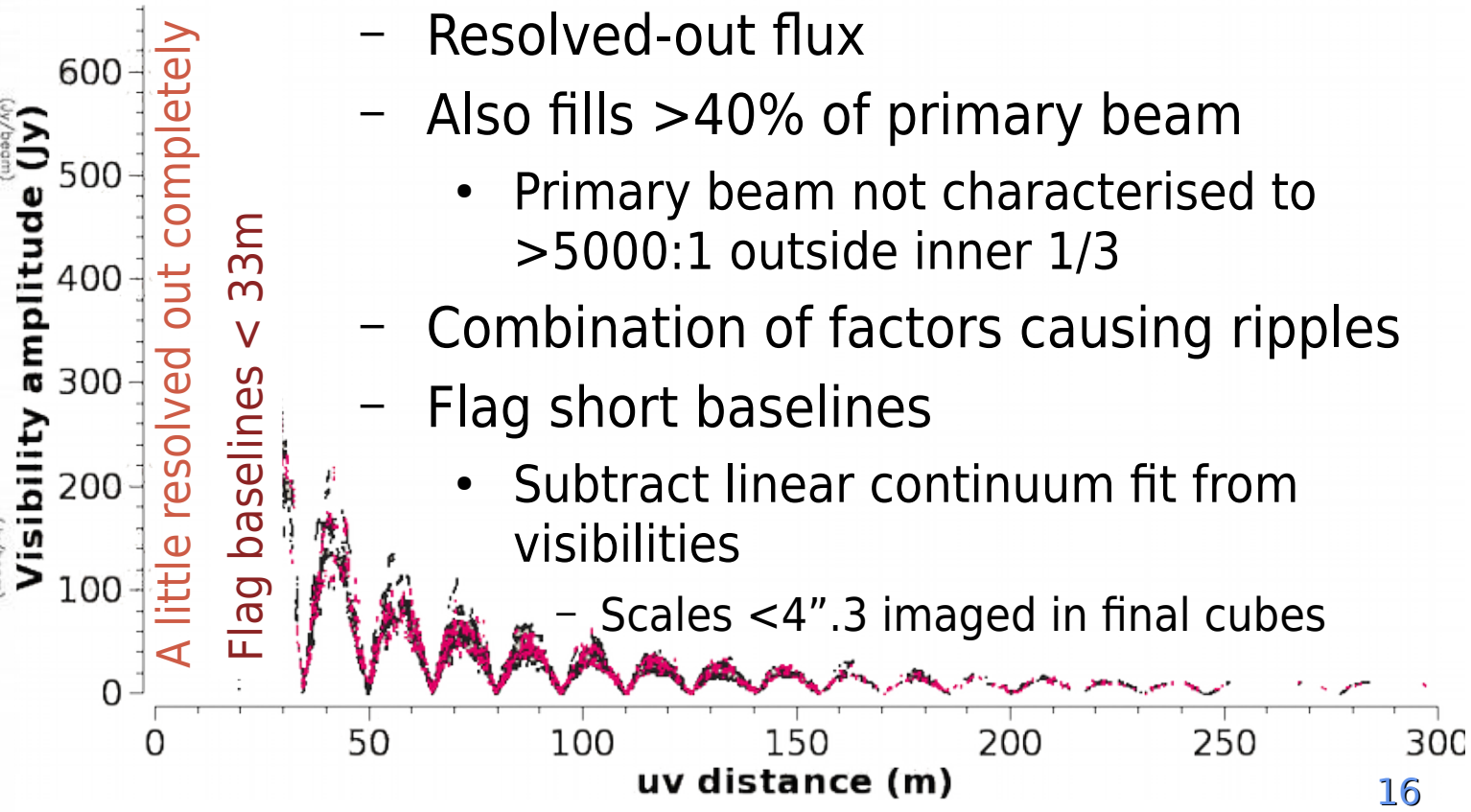


Greaves et al. 2020

Imaging Venus

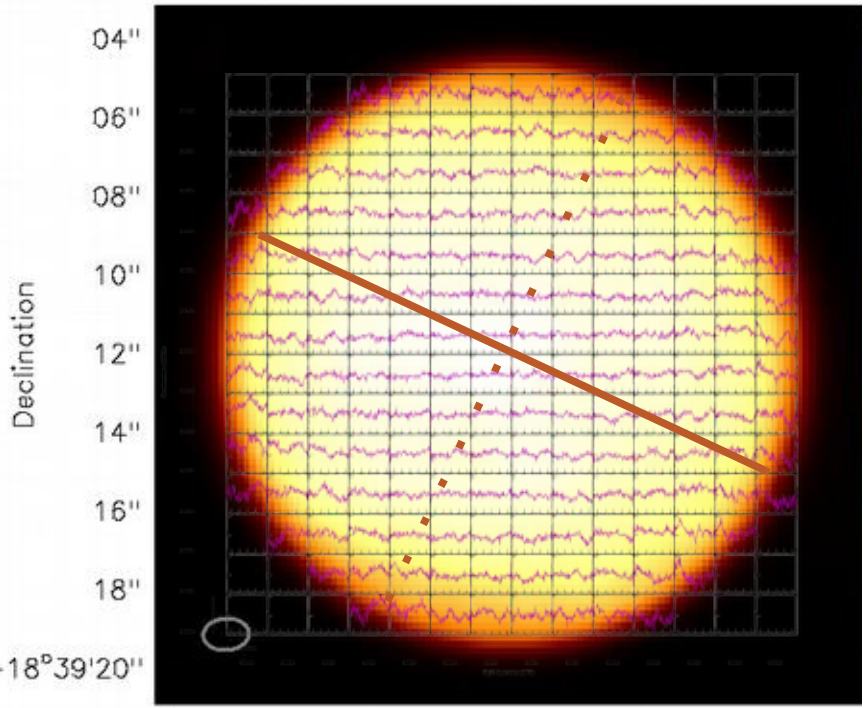


- All-data cube bandpass ripples
  - Resolved-out flux
  - Also fills >40% of primary beam
    - Primary beam not characterised to >5000:1 outside inner 1/3
  - Combination of factors causing ripples
  - Flag short baselines
    - Subtract linear continuum fit from visibilities
      - Scales <4”.3 imaged in final cubes

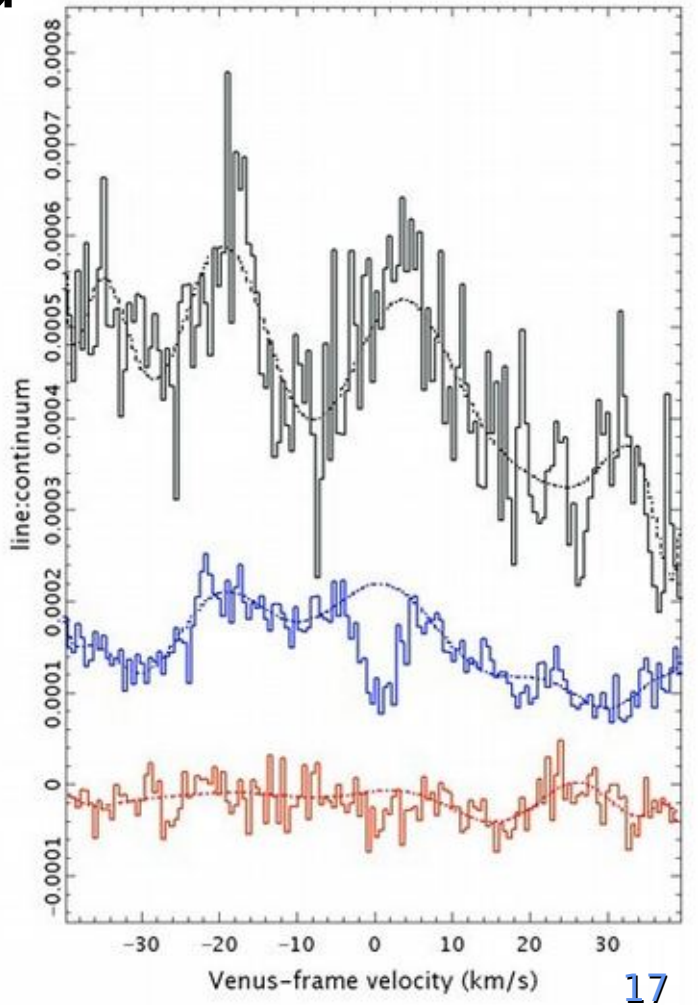


Extracting spectra

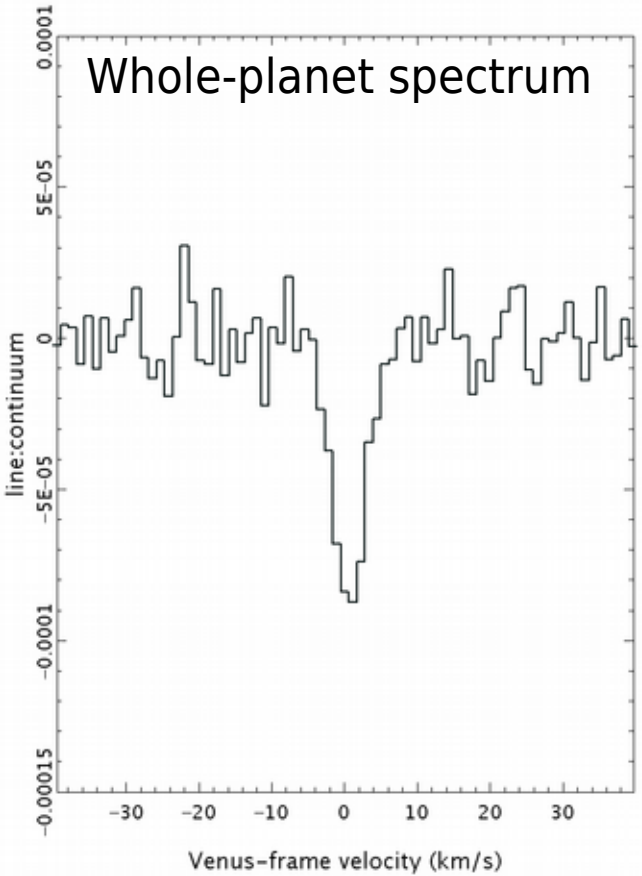
- Spectra per synthesised beam dominated by noise
  - Sum across polar regions, mid latitudes and equator



- Fit polynomial baseline to co-added spectra

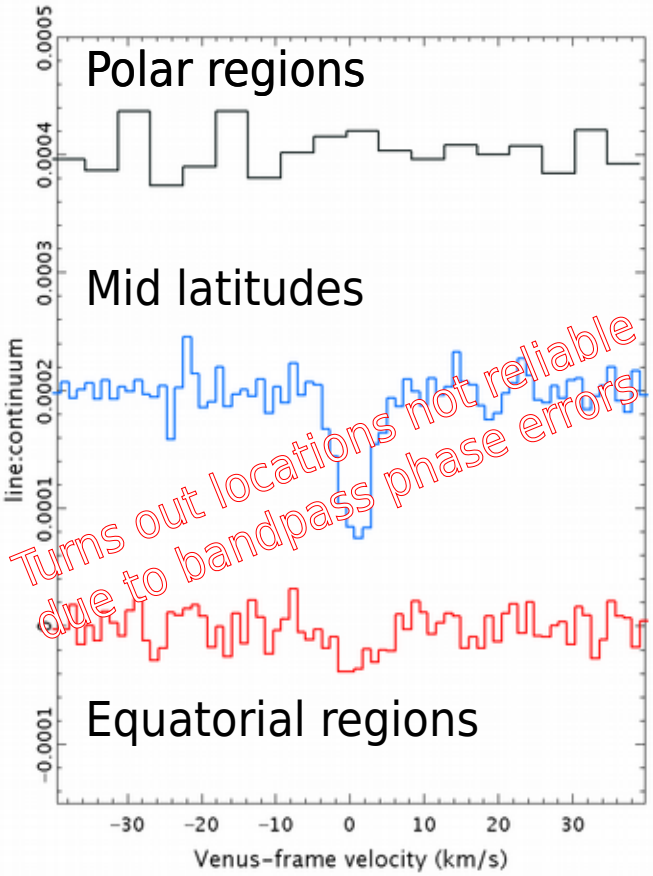


ALMA phosphine absorption (2019 processing)



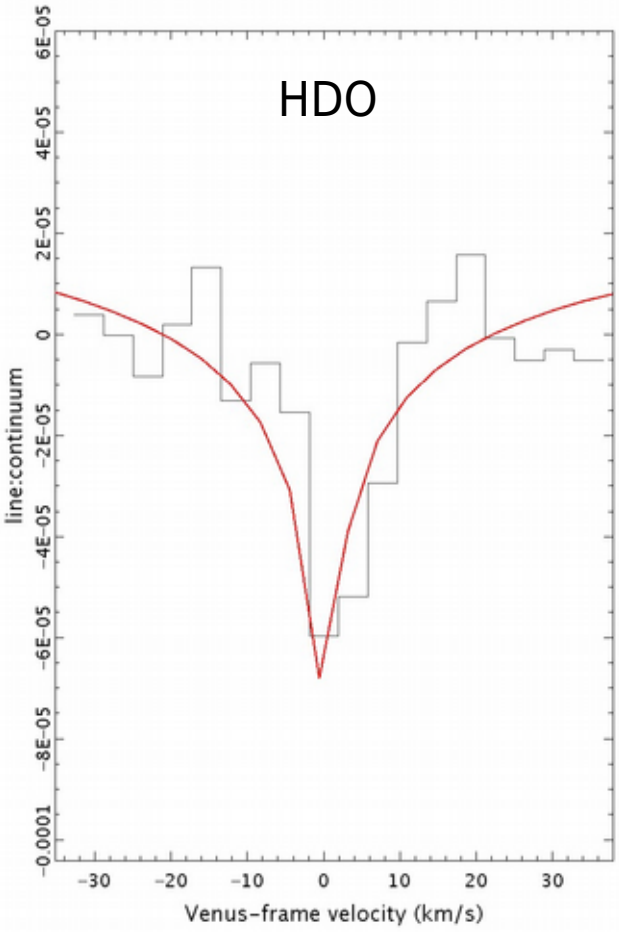
Greaves et al. 2020

- Compare with full-disc continuum
- Line:continuum ratio
  - JCMT -250±80 ×10^{-6}
  - ALMA -87±11 ×10^{-6}
  - Mid -126±14 ×10^{-6}
- ALMA < JCMT
  - Structures >4” not imaged
- Line centre within 0.7 km/s of Venus velocity



Checking

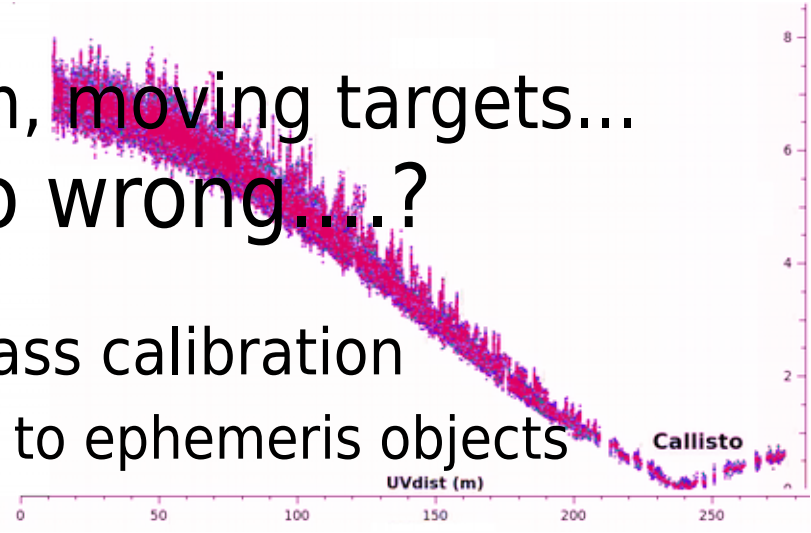
- Various checks that PH_3 detection not an artifact:
- No line at 1.123 mm in calibration sources
- Try baseline fitting around different parts of spectrum
  - No line appears
- HDO (heavy water) line at 1.126 mm also observed
  - And detected at expected strength



Greaves et al. 2020

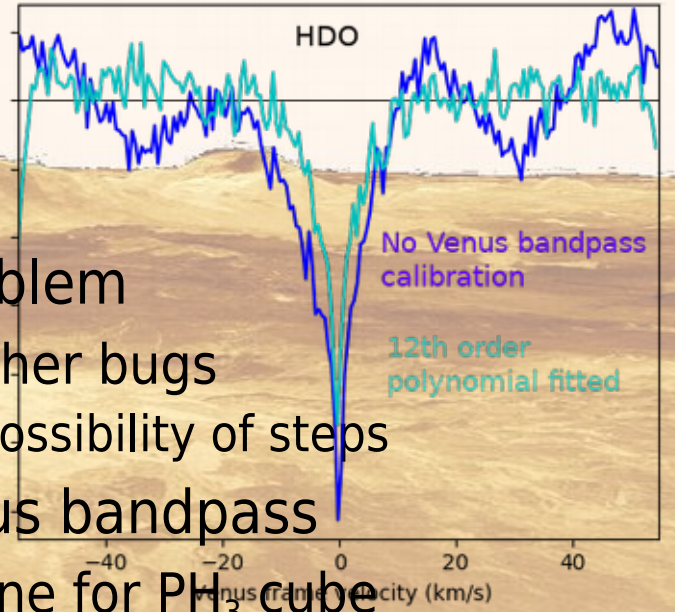
5000:1 dynamic range, fills beam, moving targets...

What could possibly go wrong...?



- Jupiter's moon Callisto used for bandpass calibration
  - 2019 ALMA BP calibration not adapted to ephemeris objects
    - Flux overestimated, bandpass ripples
  - Standard procedure averages narrow channels to increase S/N
    - Can introduce 'steps' at very high dynamic range
- Venus' contribution to Tsys not allowed for
  - Underestimates flux - coincidentally hiding bandpass problem!
- Venus tracked perfectly but primary beam correction lopsided
  - Bug in CASA 5.4

Reprocessing of data

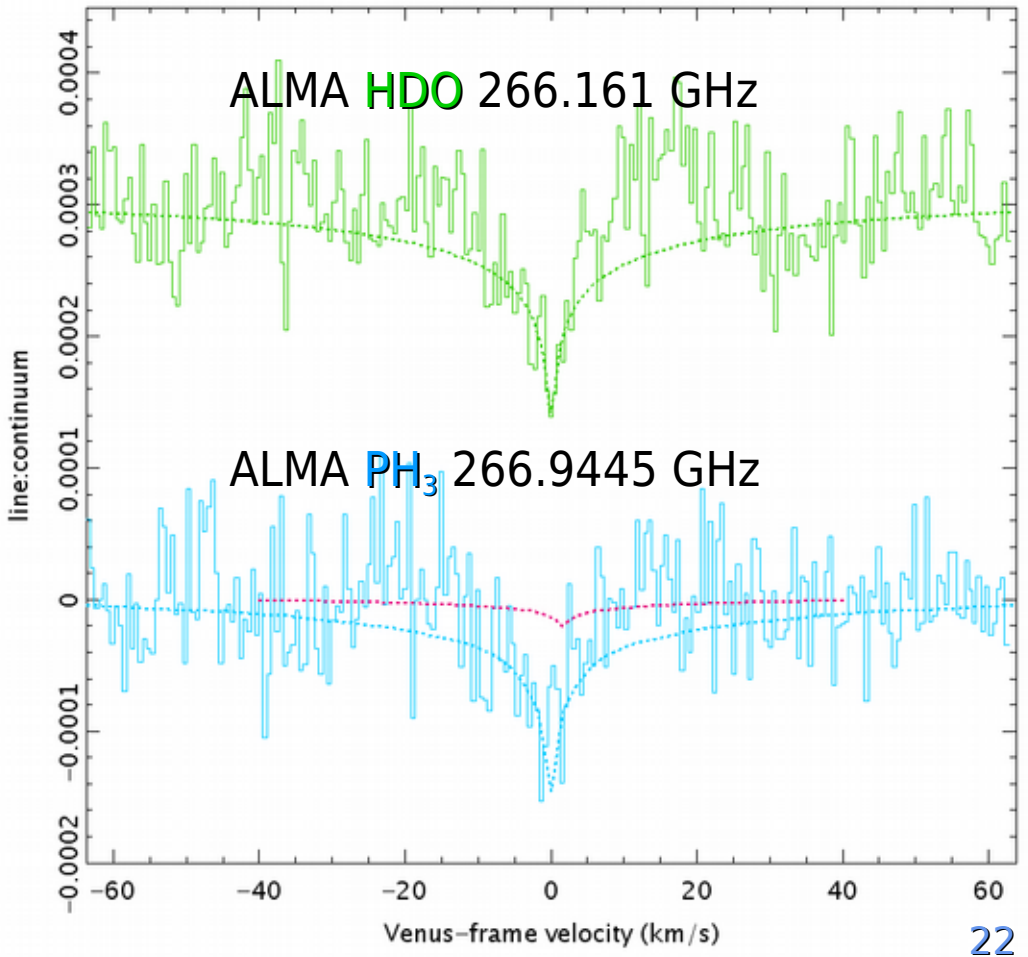


- Villanueva's team informed JAO of Callisto problem
  - Data reprocessed ('QA3') by ESO, also fixing other bugs
    - Fit polynomial to bandpass calibrator to avoid possibility of steps
- Post-standard calibration, tried flattening Venus bandpass
  - Prefer image plane removal of 6th-order baseline for PH_3 cube
    - Cannot remove phase errors but more intelligible to non-experts
- Remaining strengths and weaknesses:
  - Minimised IF chain systematics by cycling 3 LO settings ✔
  - Residual direction-dependent bandpass ripples
    - Reduced by removing baselines <33 m
      - Due to uncertainties in characterising primary beam outer regions?
      - Try small mosaic next time

buried under red-hot data

Reprocessed Venus PH_3 detection

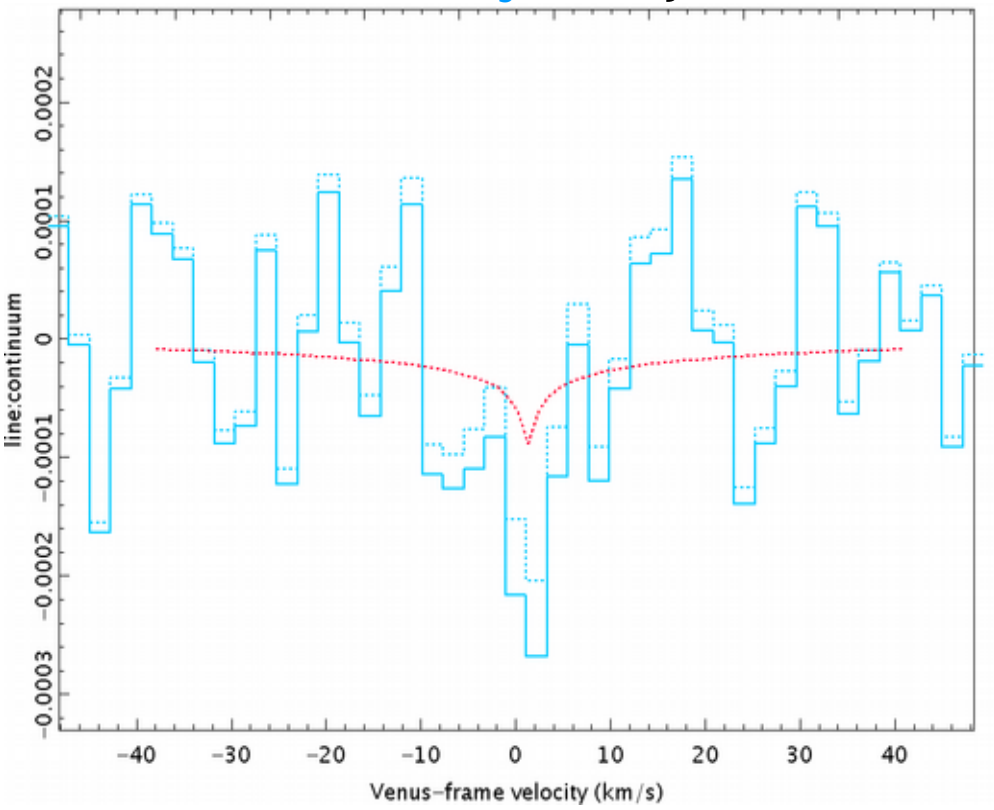
- Spectra from ~equatorial region symmetric about Venus centre
  - Localisation unreliable due to BP phase residual errors
- Dotted blue line 5 ppb PH_3 abundance model
  - Reduced but significant detection
- Any large-scale PH_3 and line wings lost in processing



Line contamination? Unlikely

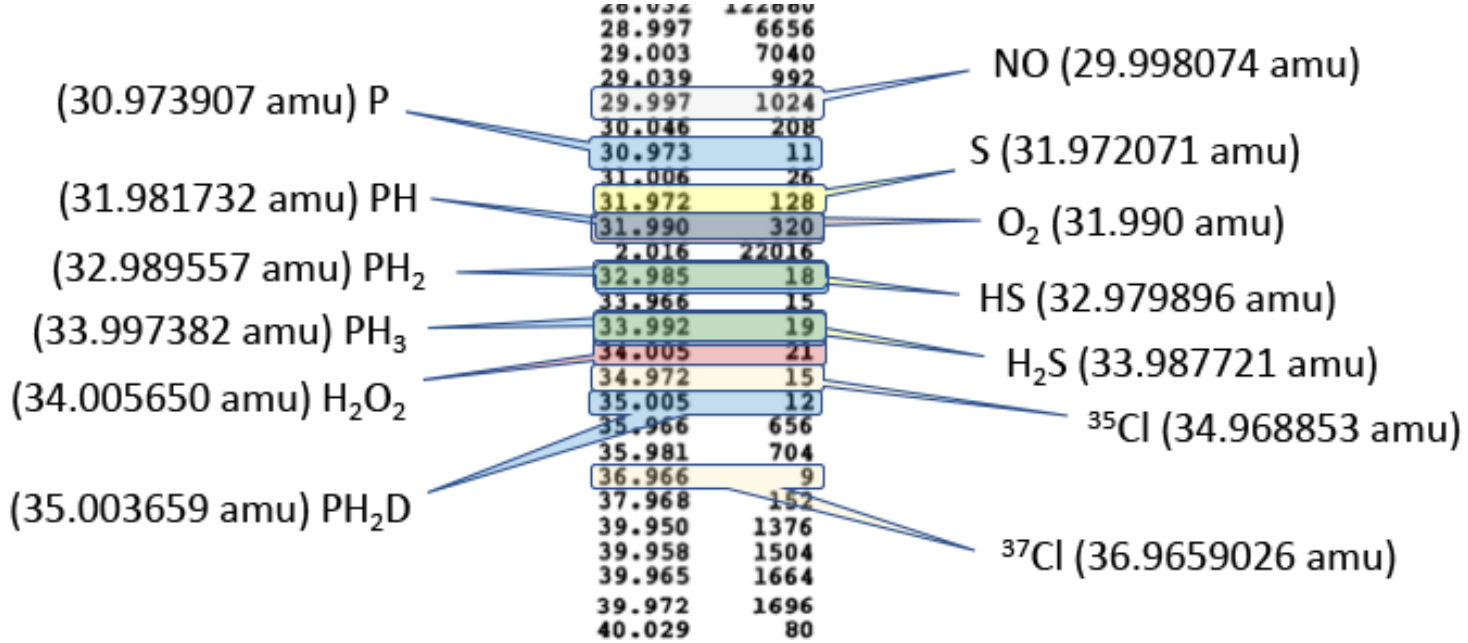
- SO_2 266.943 GHz
  - Offset +1.3 km/s from PH_3 line
    - >2 ALMA channels
- SO_2 267.537 GHz not detected by ALMA
  - Limits 266.943 GHz to <20% PH_3
- SO_2 346.652 GHz JCMT detection
  - 2017 June 06 (3 days before PH_3)
  - Predict 266.943 GHz line strength
    - <10% of observed PH_3 line

JCMT SO_2 model
PH_3 2017 June 09-16



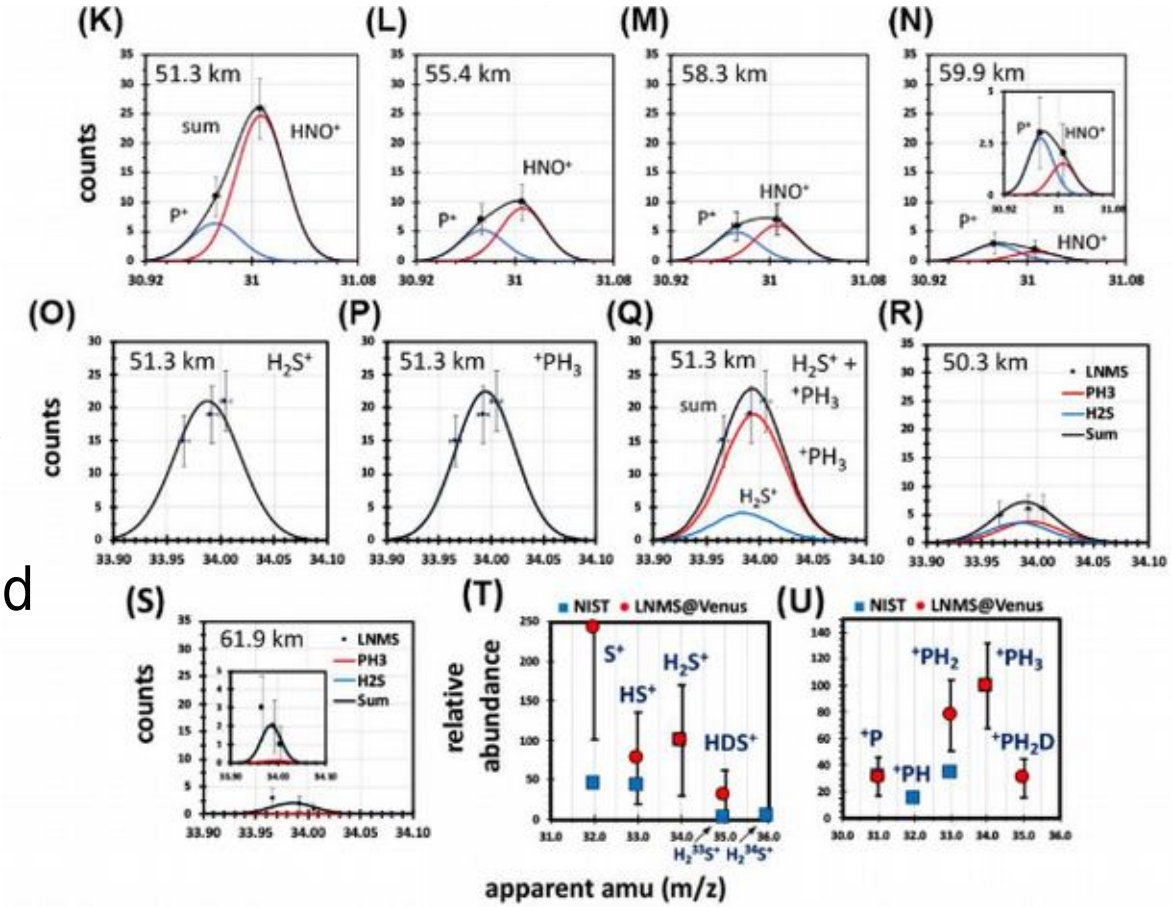
PH_3 suggested by direct sampling!

- Re-examine Pioneer-Venus 1978 mass spectrometer
  - Sampled ~50 - 60 km altitudes
  - P compounds not previously considered

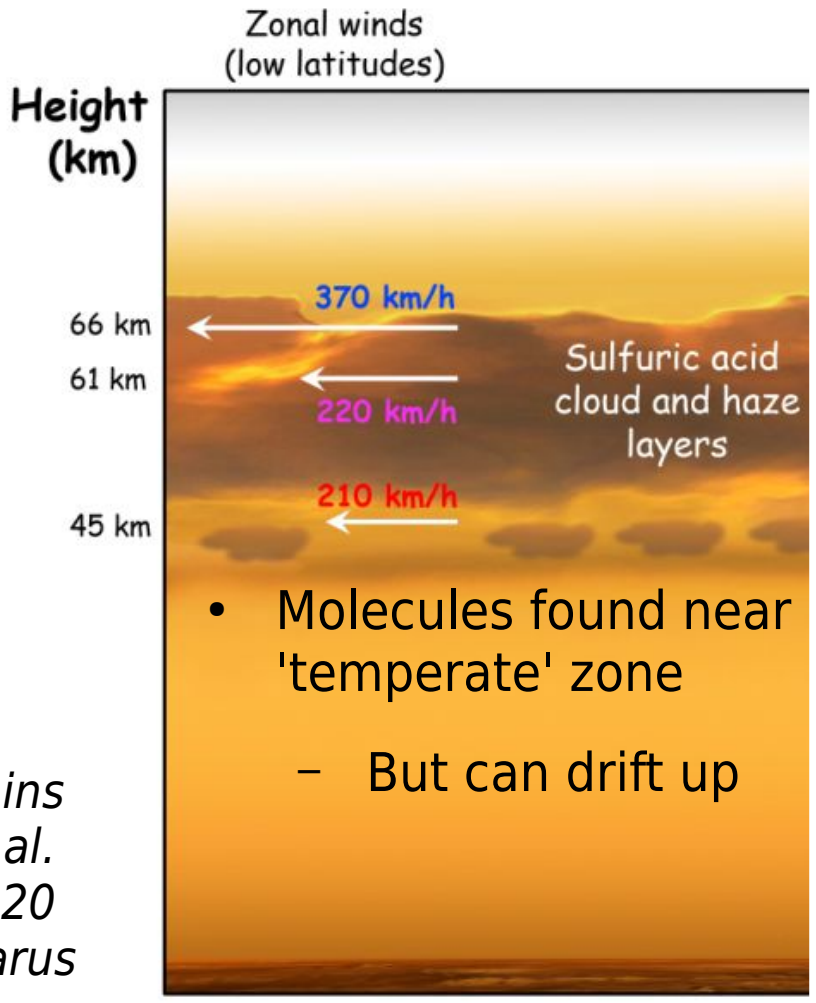


Pioneer-Venus reanalysis

- Mass signals blended but parent molecules identified by comparing potential fragments, isotopes, ions
  - 33.992 amu signal likely to be more PH_3 (33.997) than previously-assigned H_2S (33.988)
  - *Mogul et al. 2020, 2021*

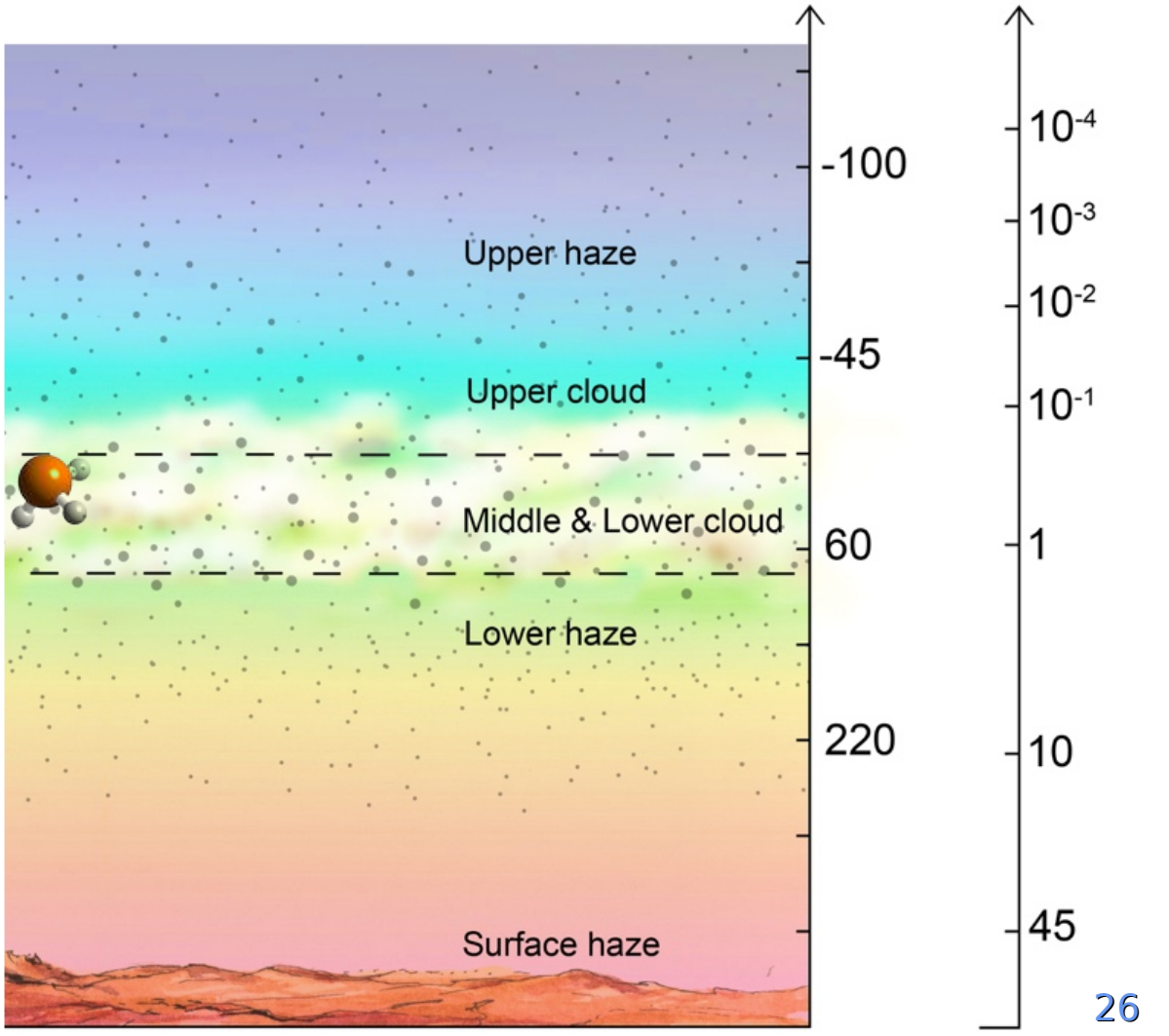


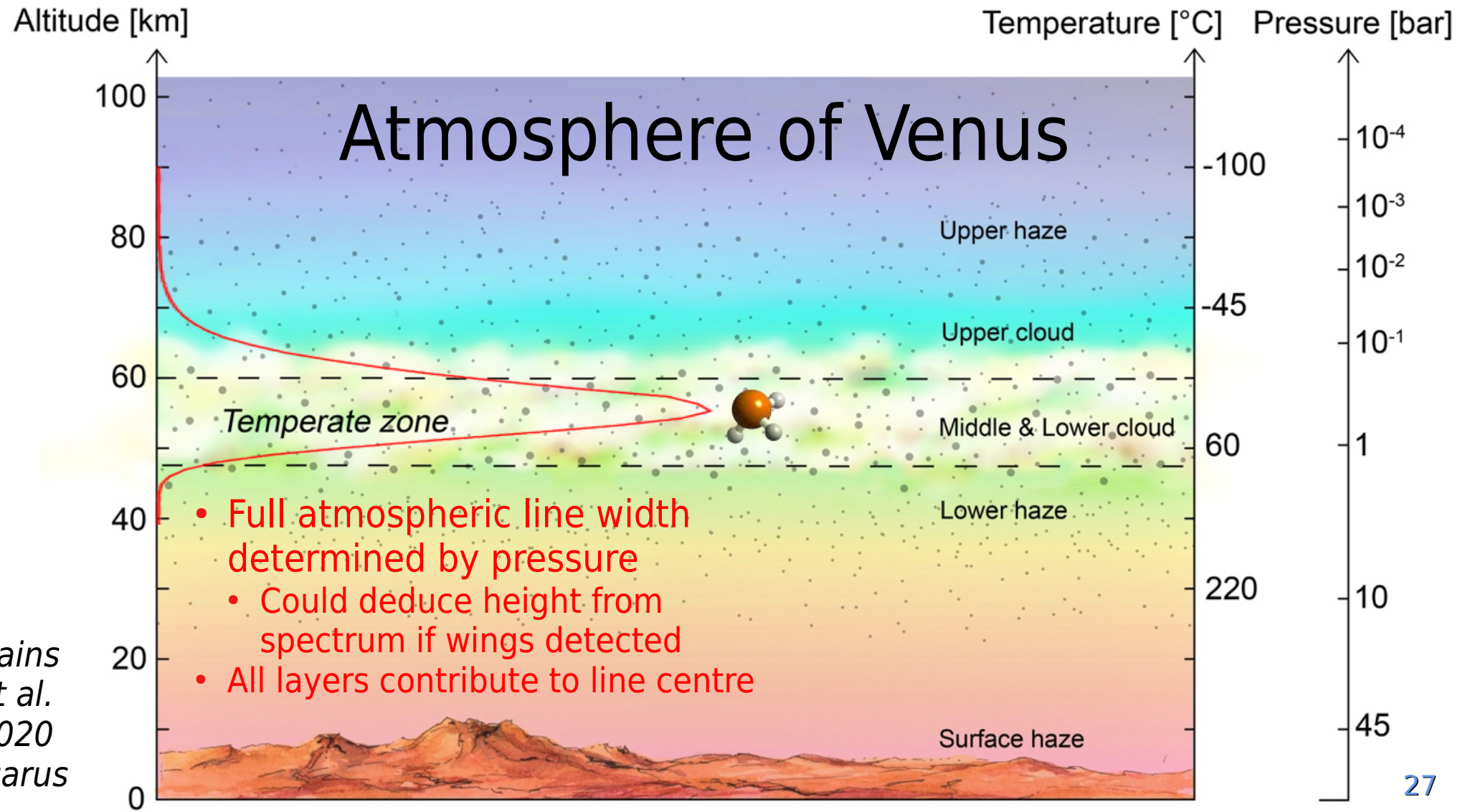
Atmosphere of Venus



- Molecules found near 'temperate' zone
  - But can drift up

Bains et al. 2020 Icarus



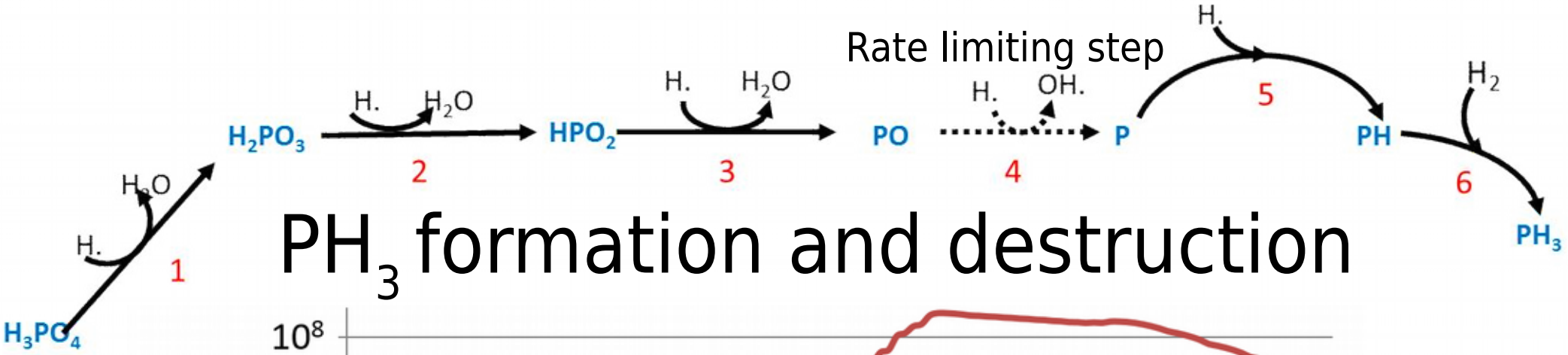


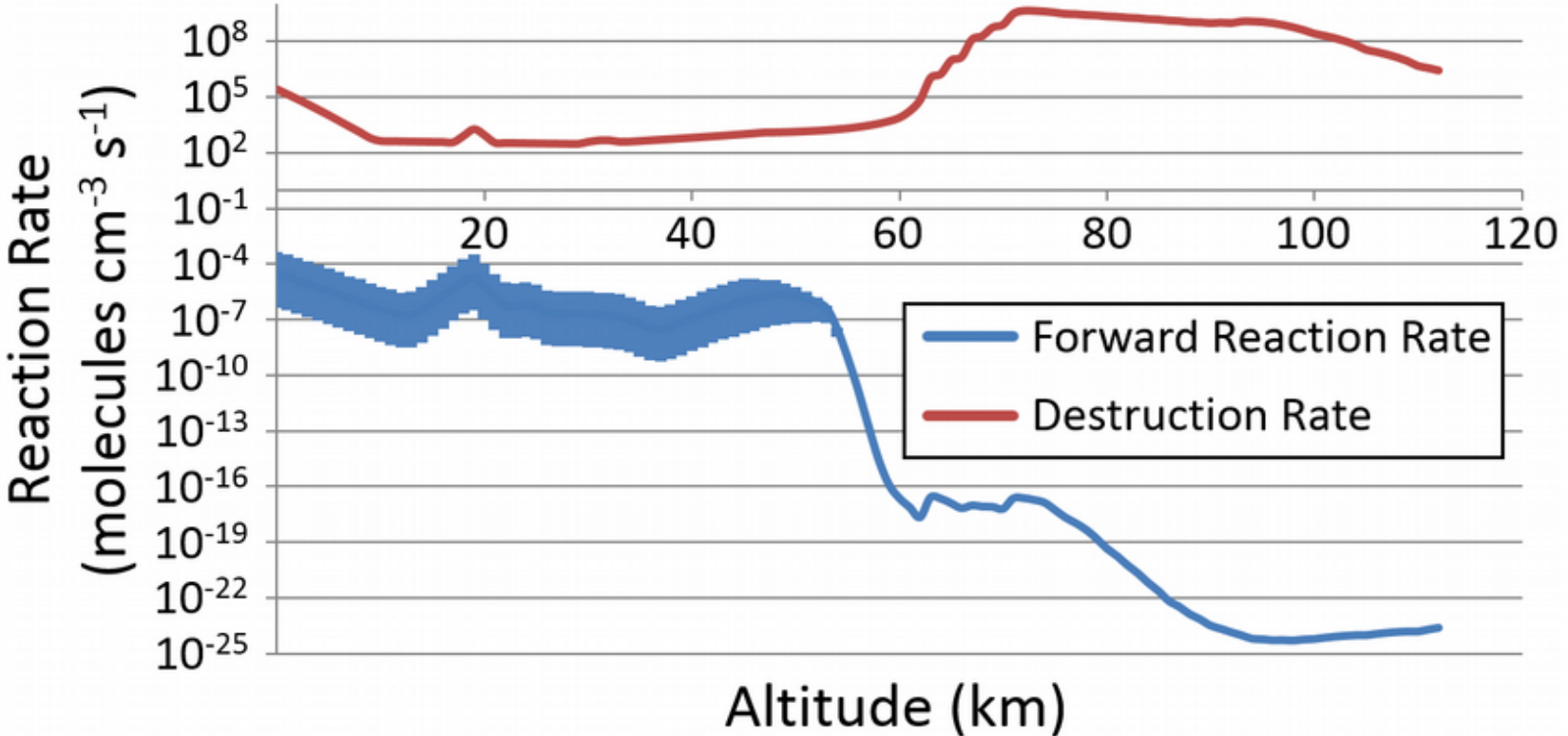
Bains et al. 2020 Icarus

Formation of Phosphine

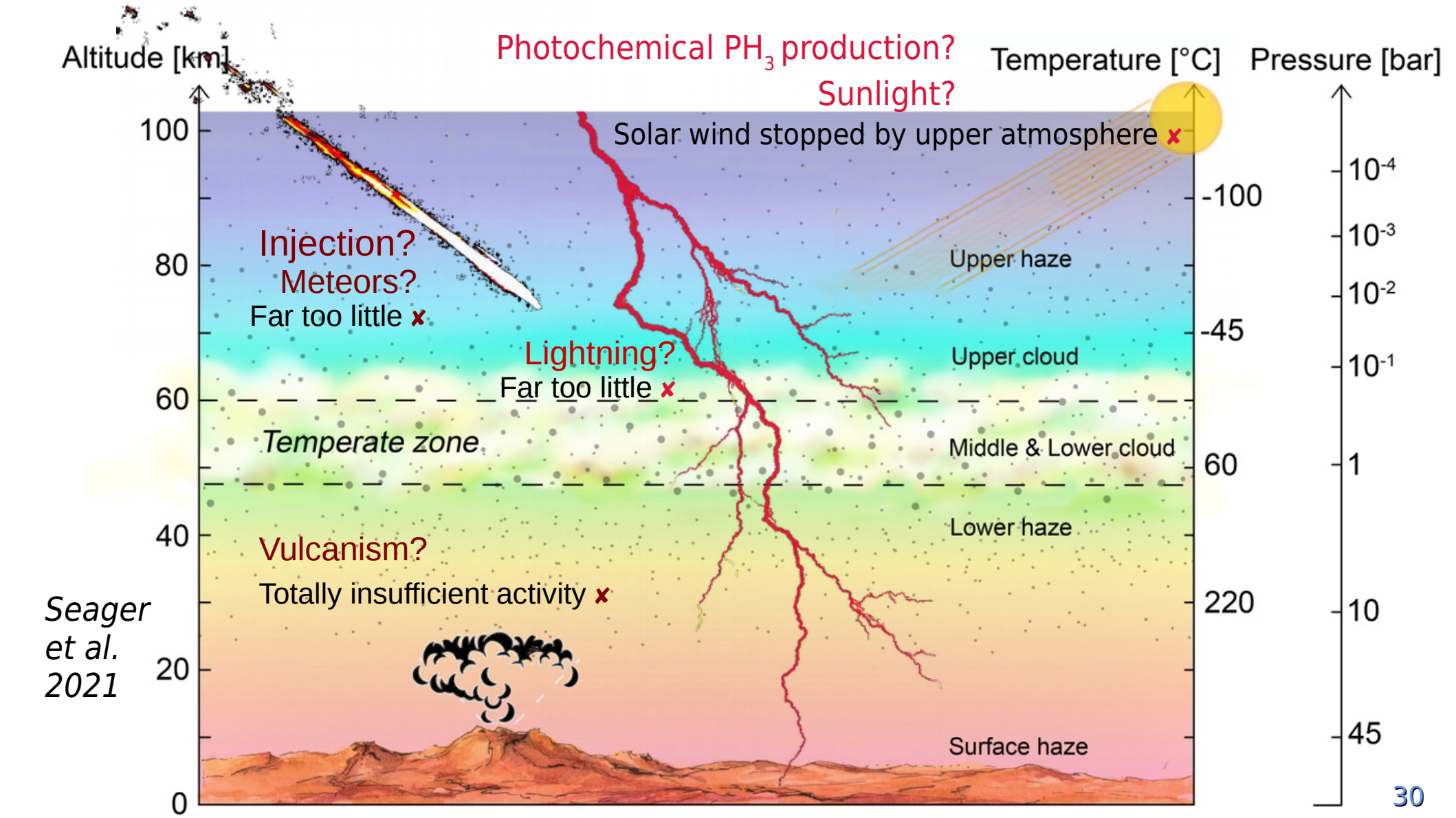
- Formed deep in H-rich gas giants (Jupiter etc.) at high pressures
- <0.001 ppm PH_3 in terrestrial atmosphere
  - Formed by anaerobic bacteria & industry
    - Not found in terrestrial volcanic gases but theoretically possible
- Photochemical model for Venus (*Bains et al.*)
  - PH_3 destruction by O, Cl in atmosphere, heat at surface
  - H_3PO_4 likely to be most abundant P species
  - Abiological reduction with O, H, H_2 to PH_3
    - At 10^{-9} of destruction rate

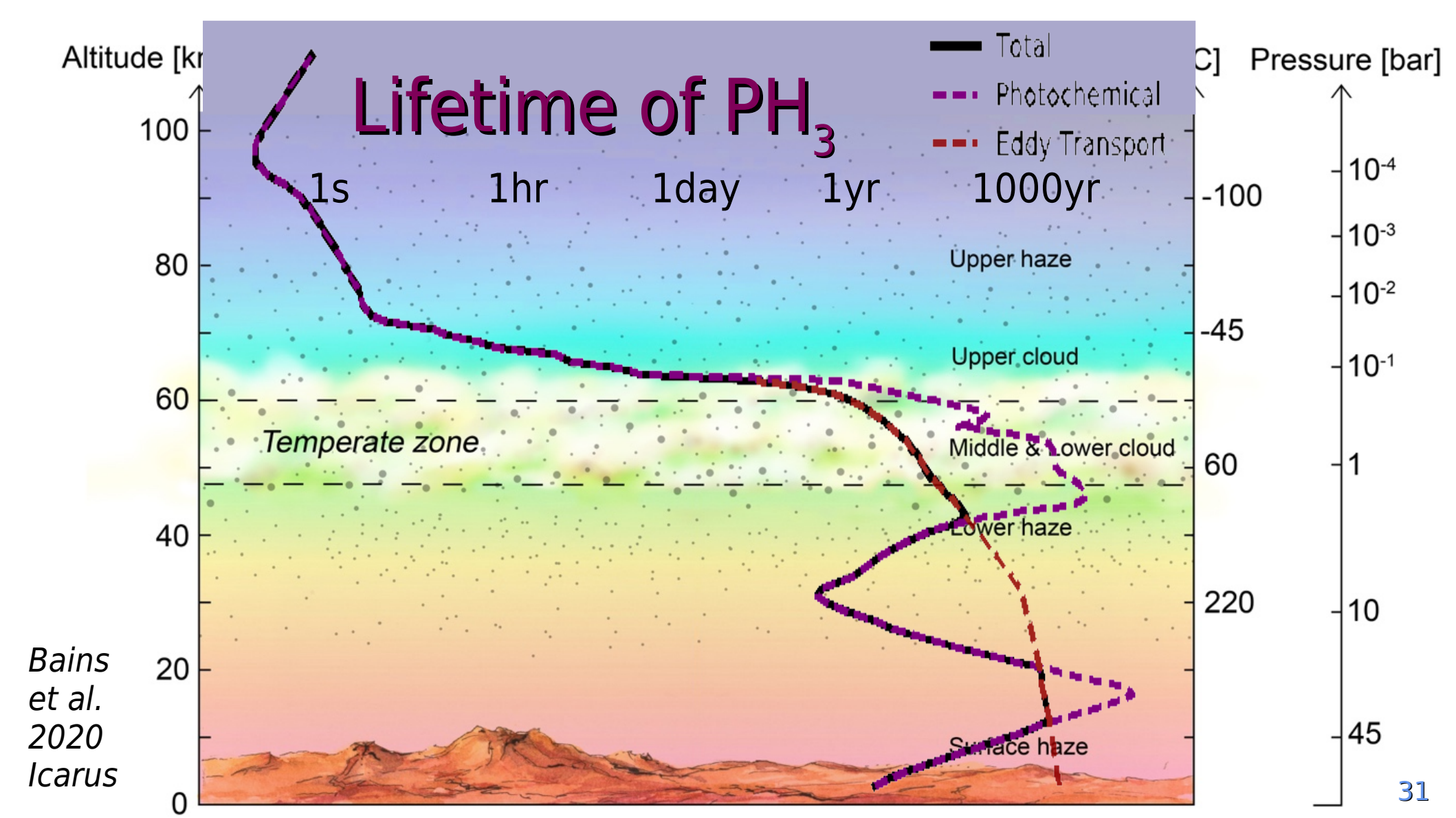
PH_3 formation and destruction





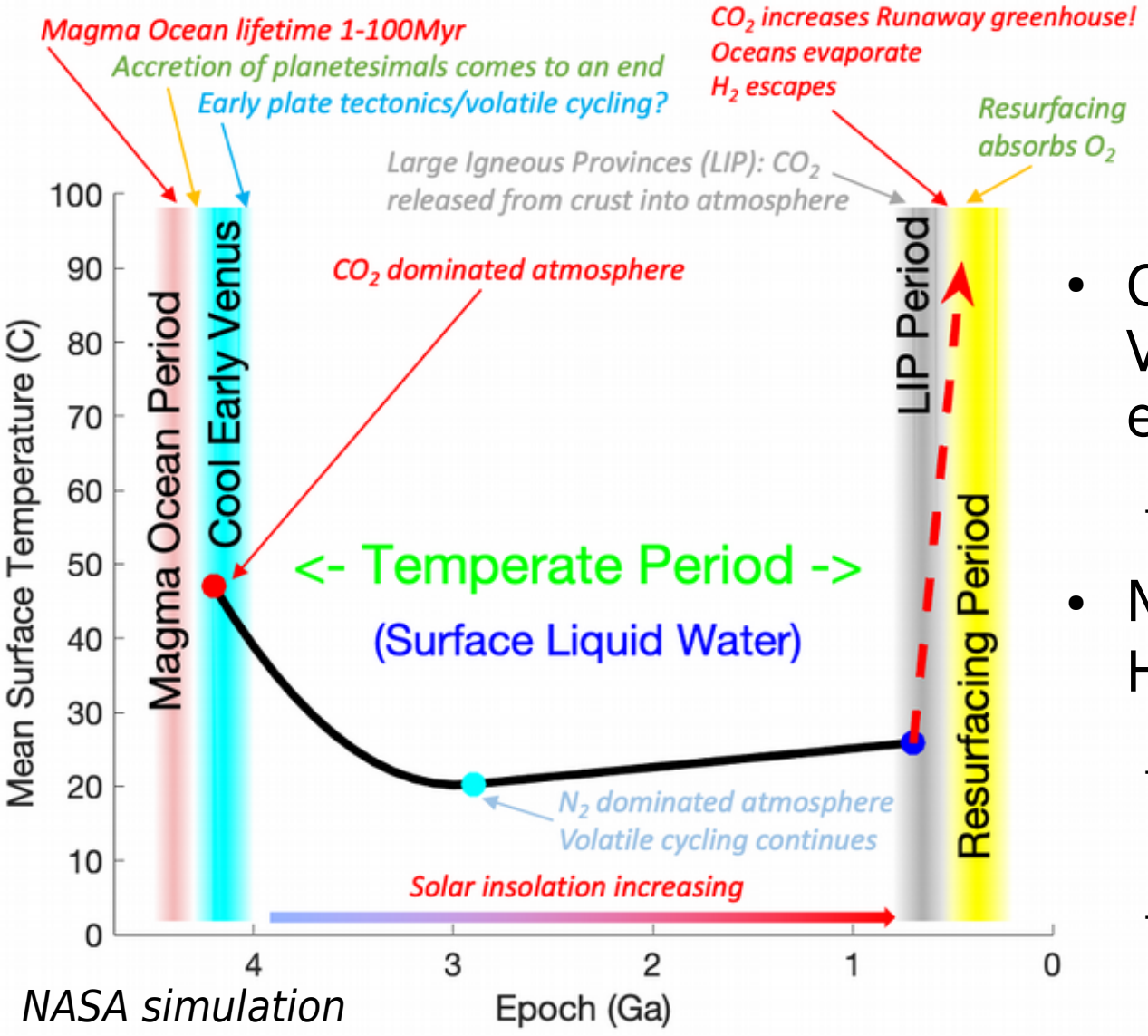
Bains et al. 2020 Icarus


Altitude [km]
Photochemical PH_3 production?
Sunlight?
Temperature [°C]
Pressure [bar]
Solar wind stopped by upper atmosphere ✘
Injection?
Meteors?
Far too little ✘
Lightning?
Far too little ✘
Vulcanism?
Totally insufficient activity ✘
Upper haze
Upper cloud
Middle & Lower cloud
Lower haze
Surface haze
Temperate zone
100
80
60
40
20
0
-100
-45
60
220
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
45
Seager et al. 2021



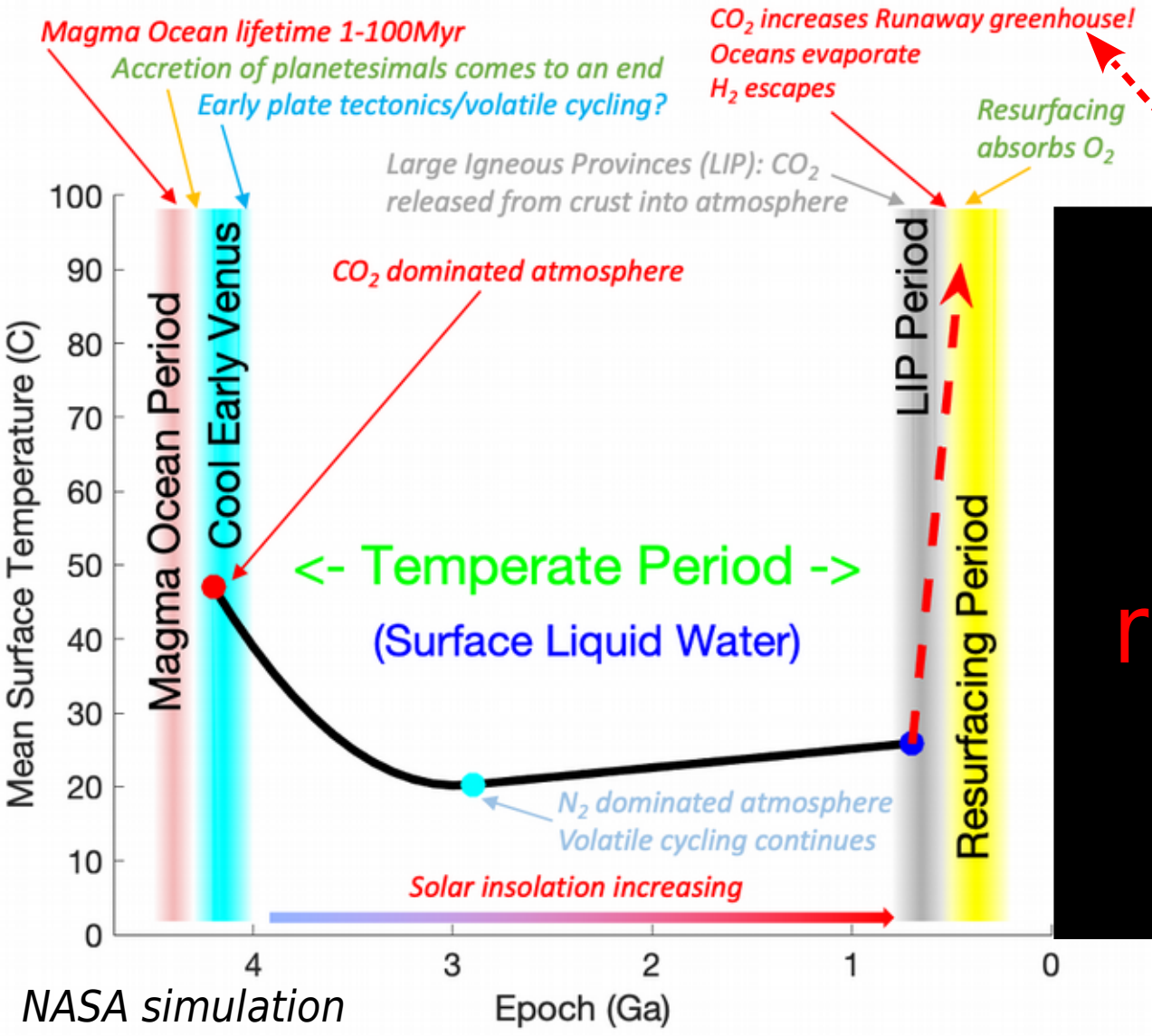
Bains et al. 2020 Icarus

History of Venus



NASA simulation

- Could life have evolved when Venus surface was cool enough for liquid water?
  - Up to 800 million yr ago
- Now, CO_2 atmosphere with H_2SO_4 droplets
  - Ascend, form cloud layer, droplets grow, rain out
  - Liquid-based life could only thrive inside droplets

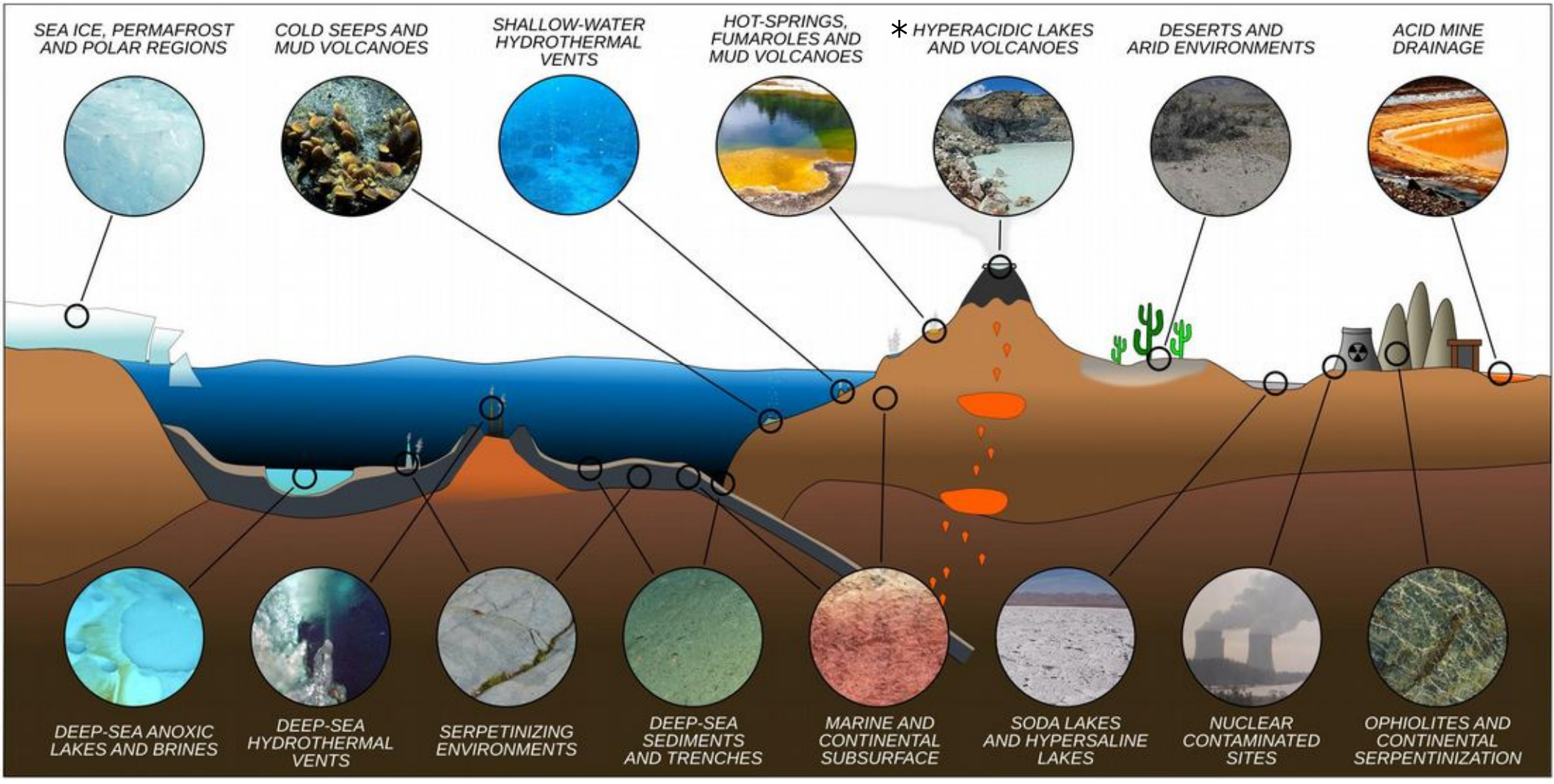


The awful warning of runaway global heating

NASA simulation

Extremophiles on Earth

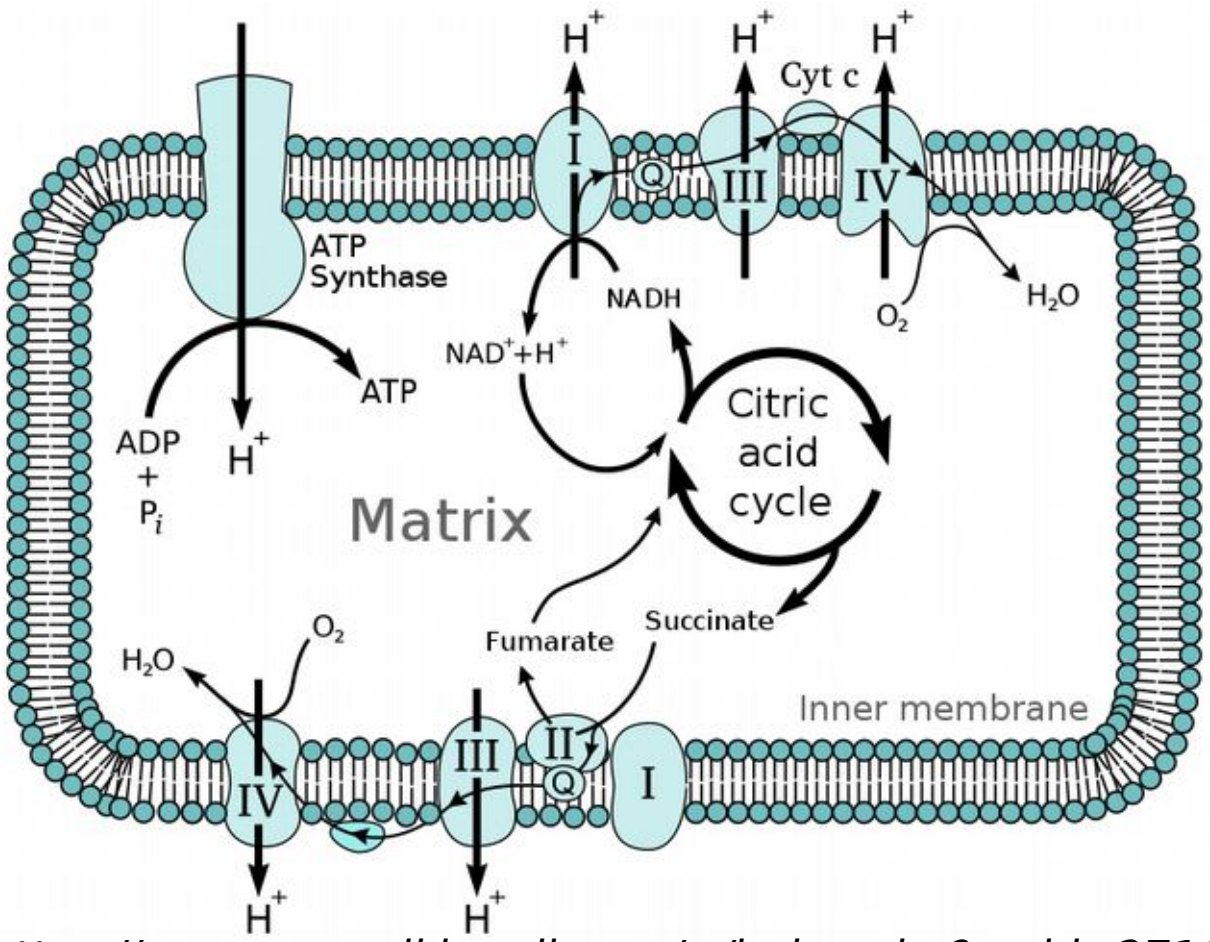
Algae at Tatio hot springs (near ALMA) -20 to 80 C every morning



Merino et al. 2019 Frontiers in Microbiology

* but not nearly as acid as Venus

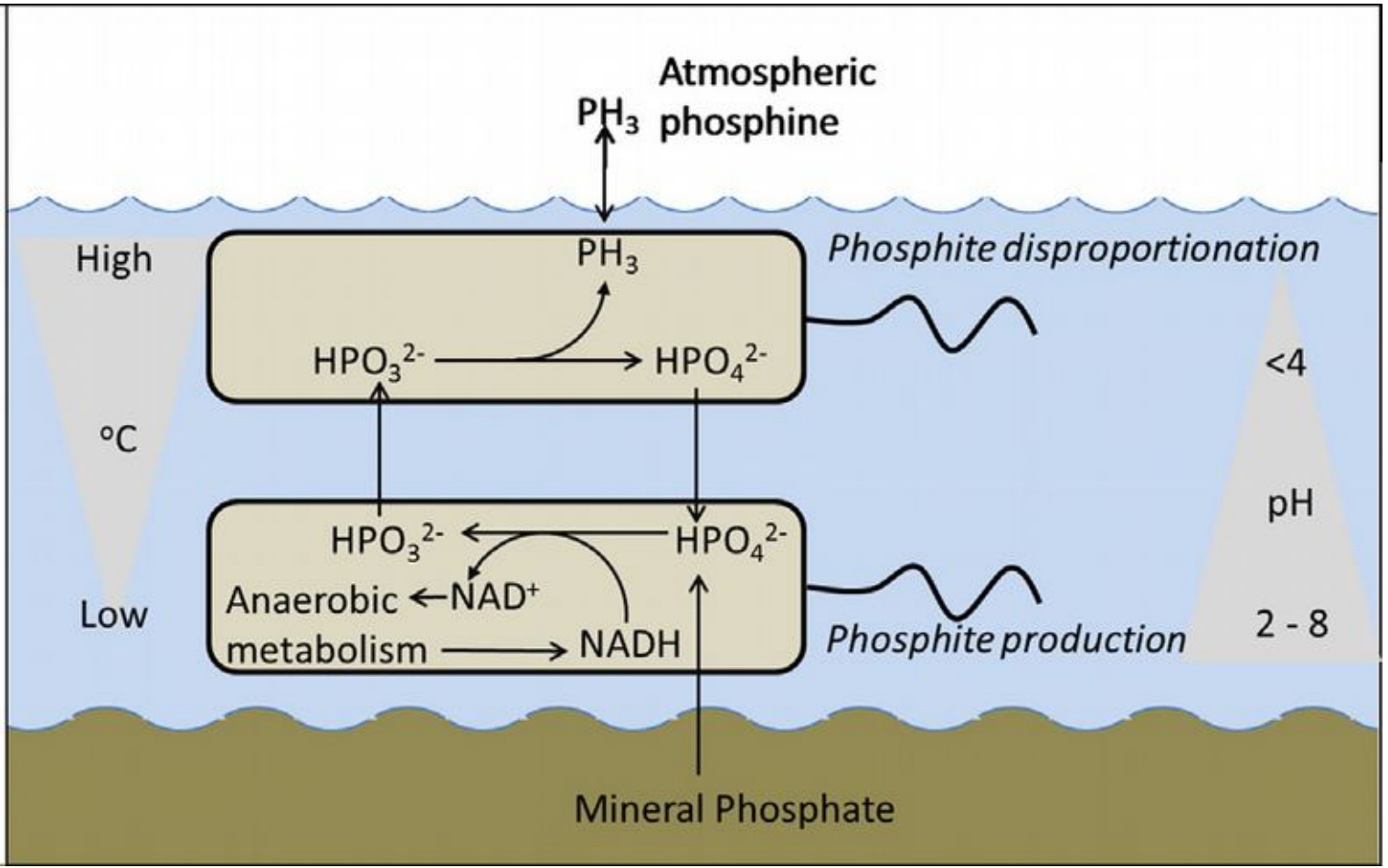
P vital for terrestrial cell energy transport



https://commons.wikimedia.org/w/index.php?curid=2716553

- Adenosine Di-Phosphide ⇌ A Tri-Phosphide
  - Metabolism of NADH
  - Form/store energy-rich molecules
- NADH: 2 nucleiotides joined by phosphate
  - Powerful redox agent
    - H^+ / *e* transport

Possible terrestrial PH_3 pathway



- Anaerobic bacteria
  - Swamps, gut…
  - Acidic environment
- (hypo-)phosphite electron donor
- Energy storage/ use cycle

Bains et al. 2019 Science of the Total Environment

Speculative cloudy Venusians

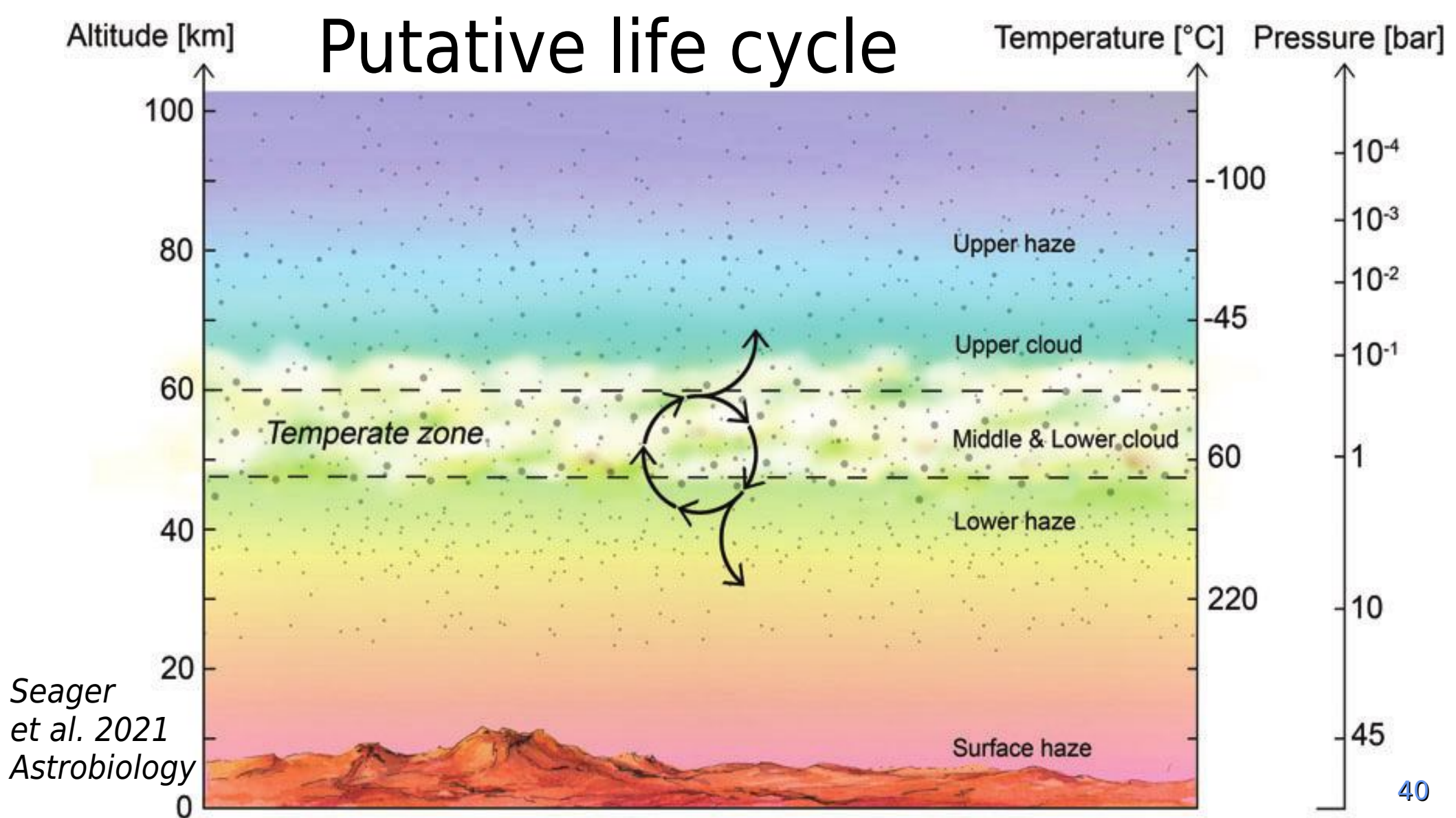
- Water based? Atmosphere 50x more arid than Atacama desert (relative humidity)
  - Droplets are ~15% H_2O ... but bound to sulphuric acid
  - CHONPS available (similar P and S abundances, Venera) but <1% of H_2 relative to Earth
  - Low atmospheric metal abundance (cell ion transport)
- Plenty of energy for photosynthesis - O or S based?
  - And enough insolation to maintain H_2O gradient
- Cell walls - protective sulphur + hydrophilic filaments?

Hypothetical life cycle

- Desiccated spores 'float' in lower haze (few 100 C)
  - Terrestrial spores 0.2~1.2 μm, similar to observed particles
    - Survival & sedimentation timescales >century
- Gravity waves/convection transport upwards
  - Spores act as rapid cloud droplet condensation nuclei
  - Droplets grow to 2-3 μm, spores rehydrate in temperate zone
    - Micro-organisms (≳0.5 μm) reproduce
- Large droplets rain down, evaporate
  - Cycle repeats

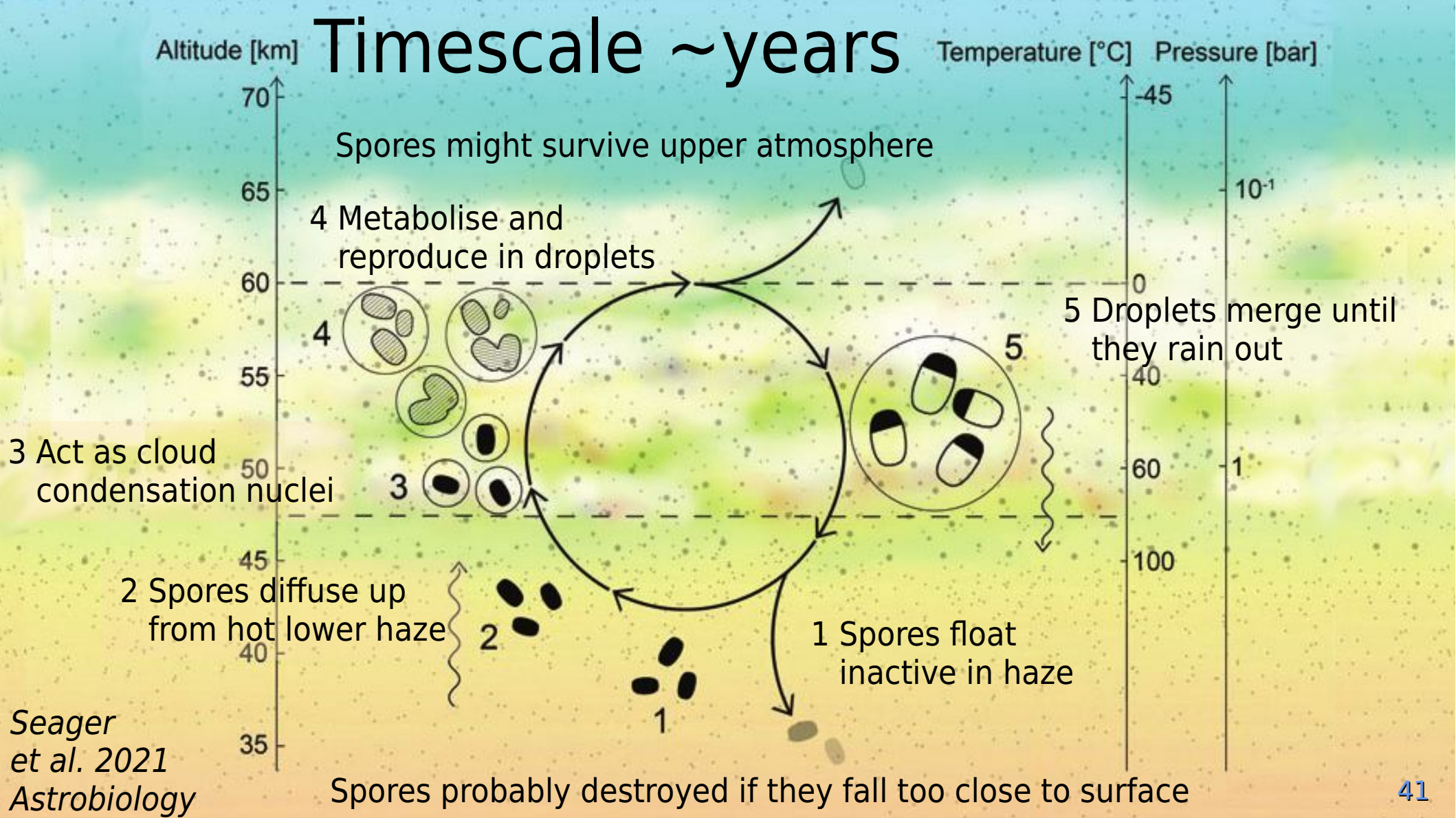
Seager et al. 2021 Astrobiology

Putative life cycle



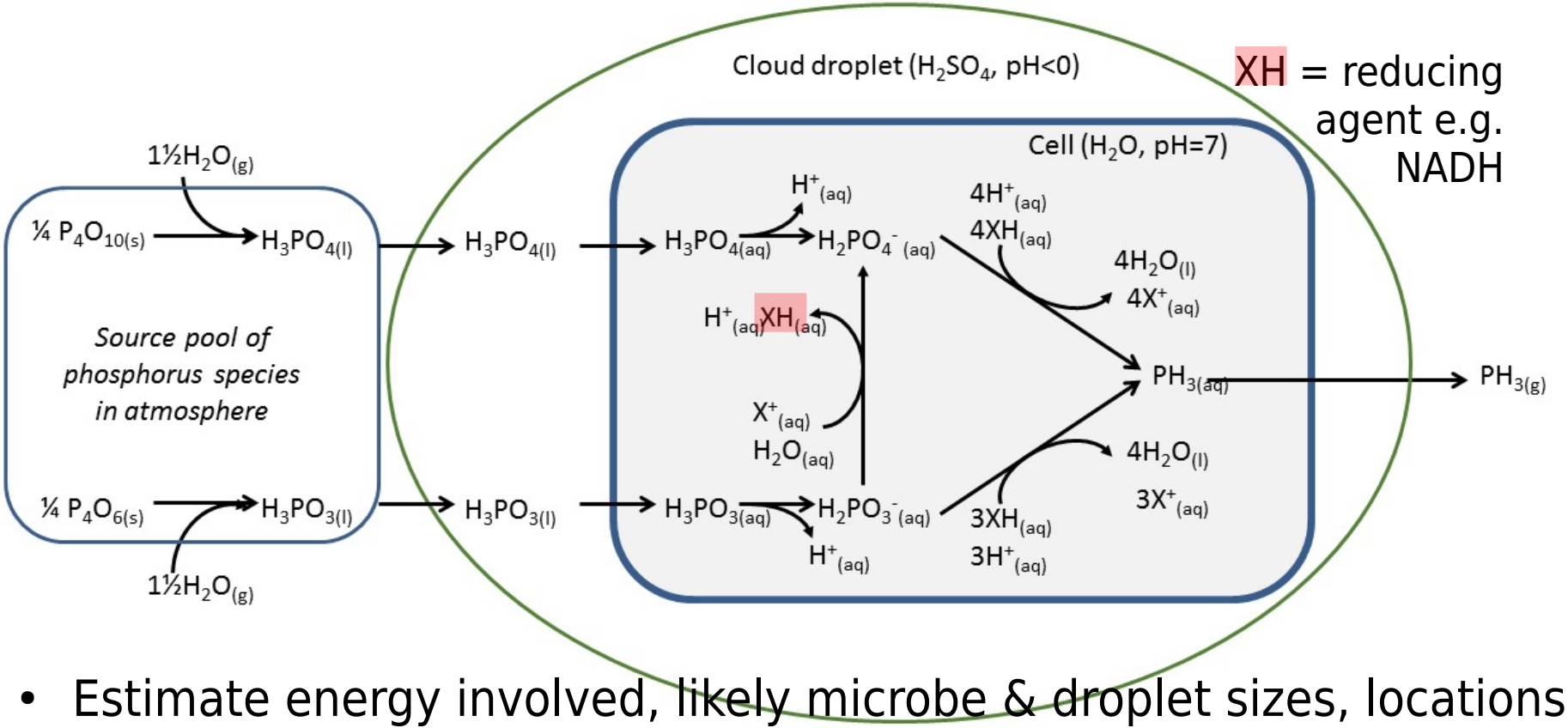
Seager et al. 2021 Astrobiology

Timescale ~years



Seager et al. 2021 Astrobiology

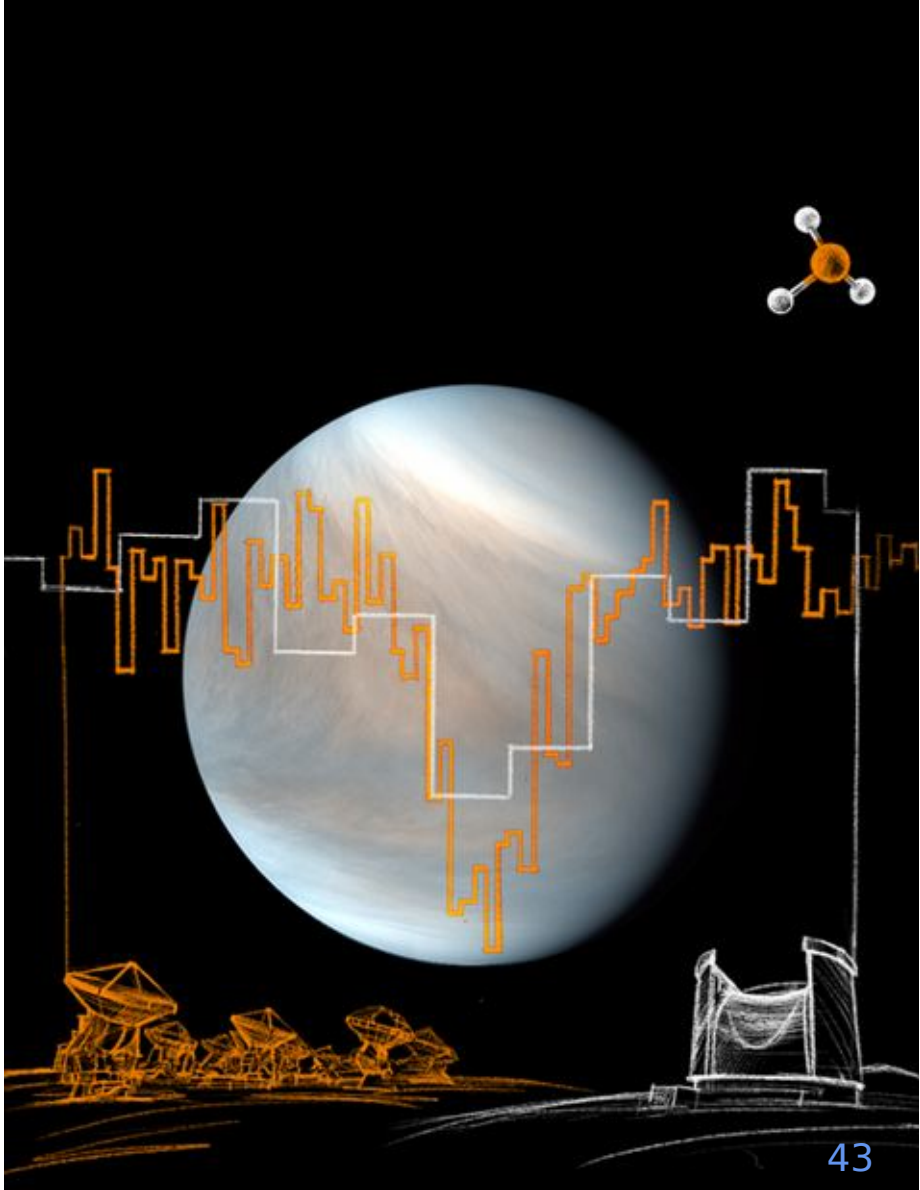
Hypothetical Venusian production

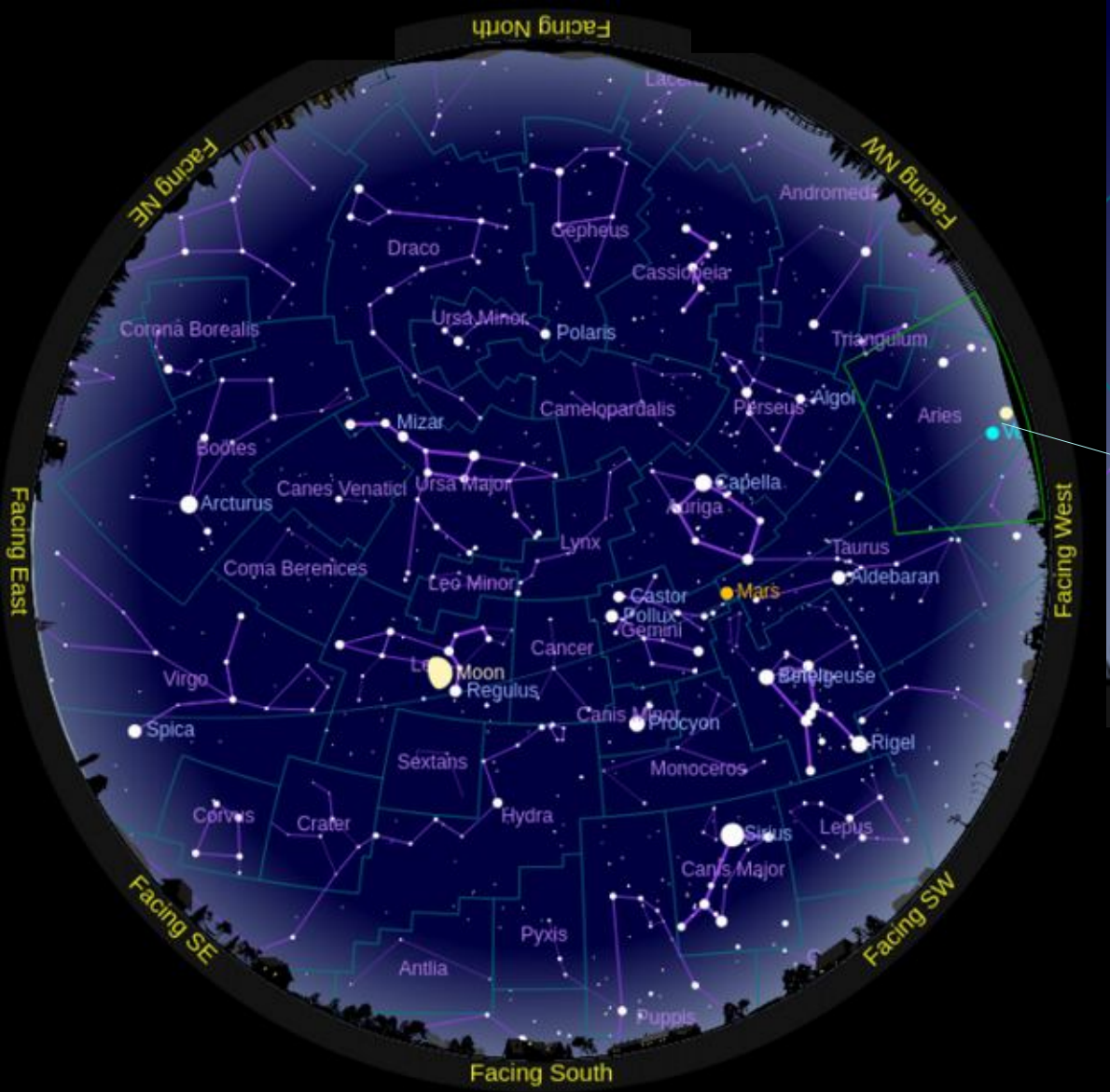


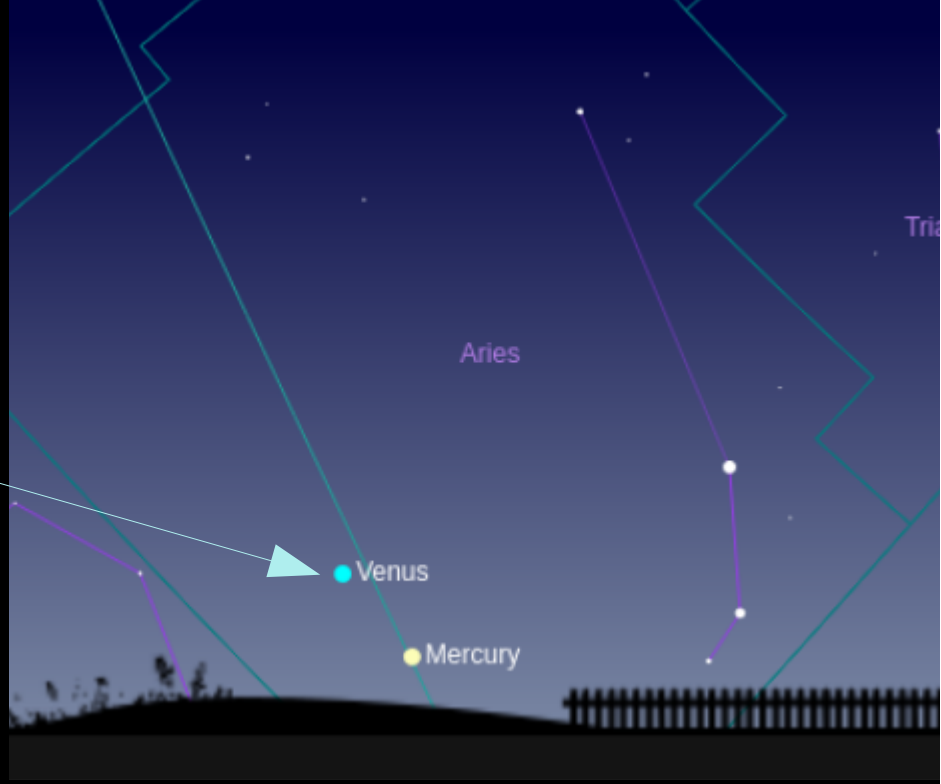
- Estimate energy involved, likely microbe & droplet sizes, locations
- 20 ppb PH_3 needs bio mass ~4x10^7 kg ~10^{-4} mg m^{-3} (v. Earth 44 mg m^{-3})
  Lingham & Loeb 2020

Follow-up

- ALMA C8 proposal, observing strategy 'lessons learned'
- JWST IR lines? Venus bright...
- Candidate missions:
  - ESA EnVision
    - Geology & atmospheric evolution, D:H
  - NASA VERITAS
    - Tectonics, vulcanism
  - NASA DAVINCI+
    - Atmosphere, evidence for past ocean







Venus just visible at sunset tonight from Bologna looking West