The Venusian Chronicles

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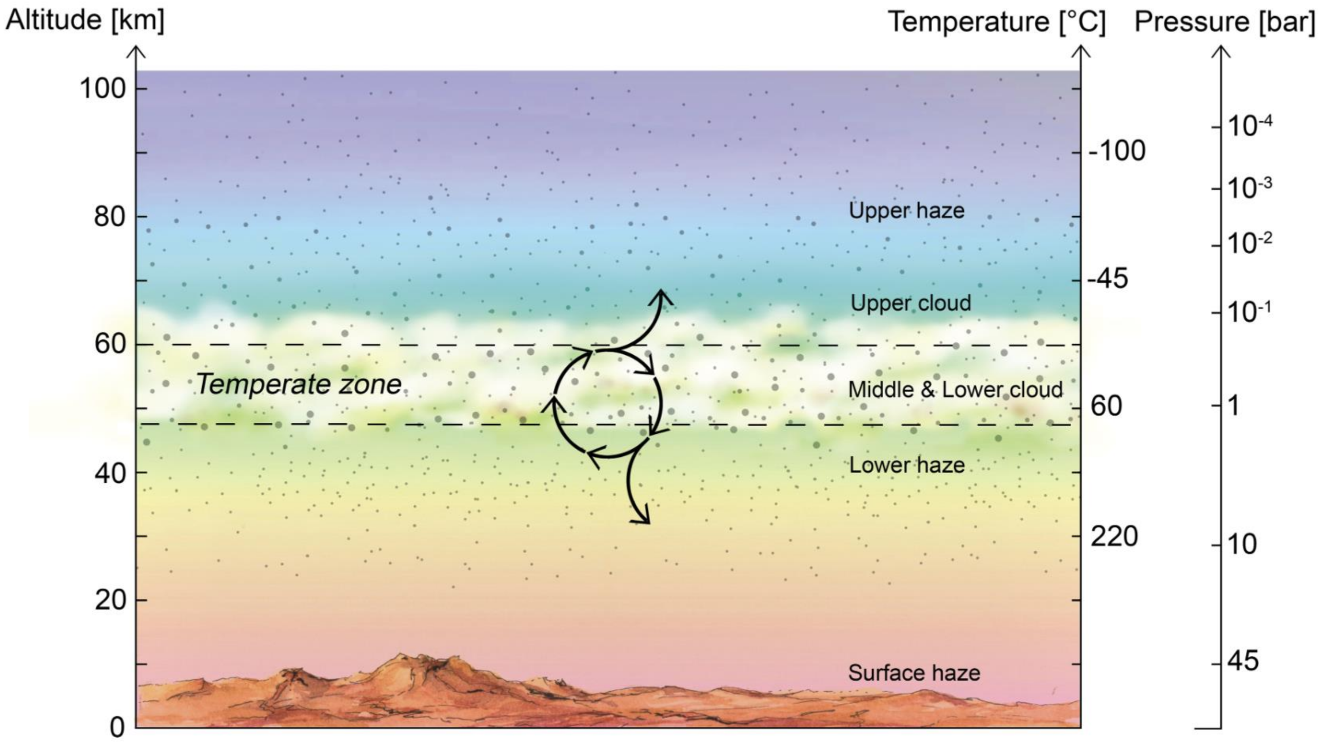
Motivation

Various observations of millimeter-waveband spectra of Venus atmosphere provide evidence (signal-to-noise ratio of about 15σ) of a **phosphine absorption-line profile** from deep layers of that atmosphere[1]. The phosphine signal has also been observed in historical data collected by the Pioneer Venus Large Probe Neutral Mass Spectrometer[2]. **Phosphine (PH_3)** is a **biosignature gas** associated with anaerobic ecosystems[3].

1. J. S. Greaves *et al.*, *Nature Astronomy*, **5**, 655 (2021).
2. R. Mogul, *et al.*, *Geophys. Res. Lett.*, **48**, e91327 (2021).
3. C. Sousa-Silva, *et al.*, *Astrobiology*, **20**, 235 (2020).

Life in Venus? Where? How?



- Main composition of venusian atmosphere: 96.5% carbon dioxide (CO_2), 3.5% nitrogen (N_2).
- Clouds of (mostly) sulphuric acid (SO_4H_2) from **~45 km up to ~70 km**.
- **Same region characterized for moderate temperatures and pressures (Earth-like).**
- **A proposed life cycle involves microbial life inside cloud droplets**, drying out as liquid droplets enlarge and enter the stagnant lower haze layer (33–48 km altitude), and consequently desiccating. The produced spores eventually return to the cloud layer by upward diffusion, act as cloud condensation nuclei, and rehydrate for a continued life cycle.

S. Seager *et al.*, *Astrobiology*, **21**, 1206 (2021).

Can cosmic rays affect Venus microbial life?

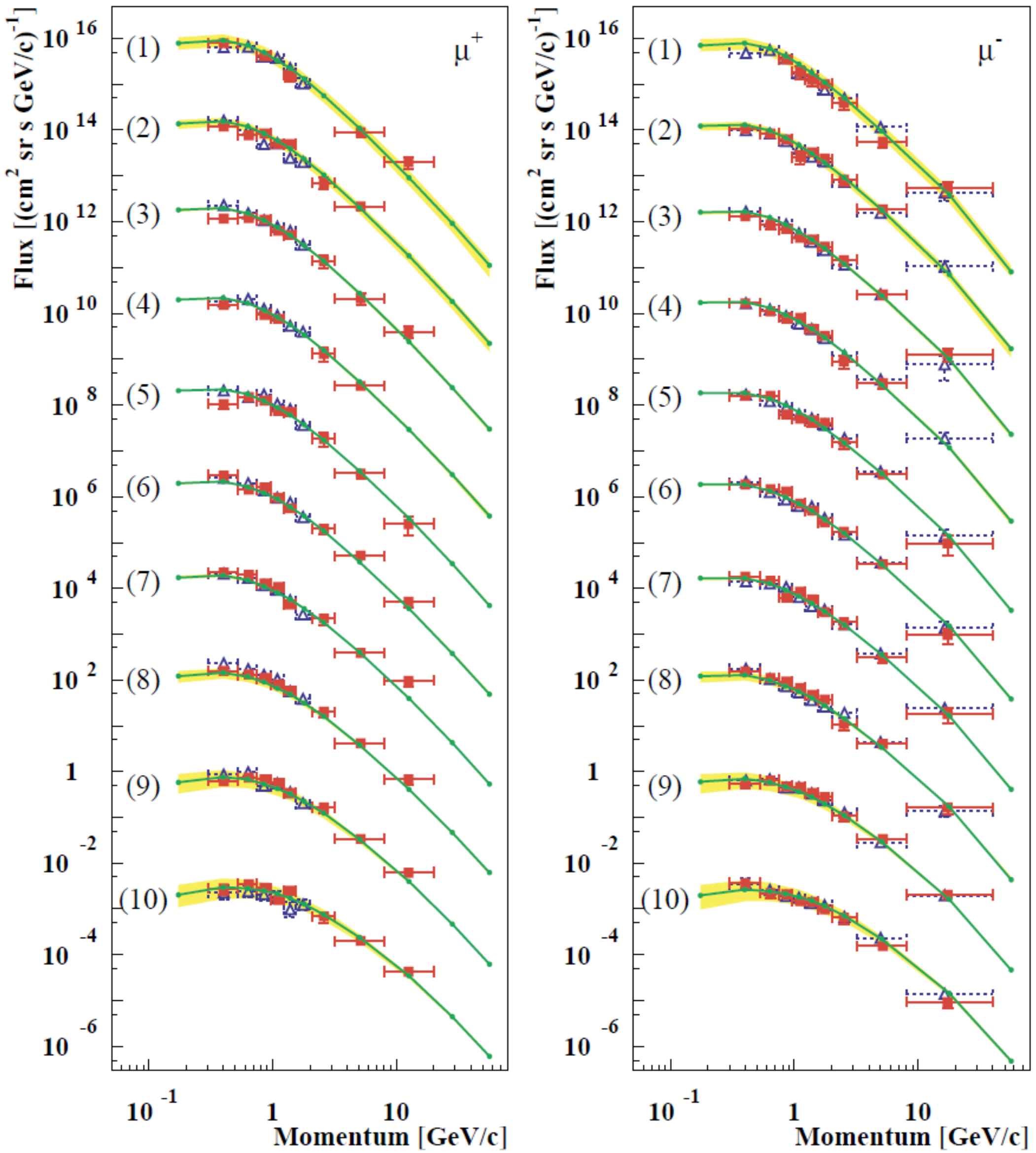
(the grain of sand we contribute to this intriguing topic)

Venus, like Earth, is subject to the action of cosmic rays.

It is well known that cosmic radiation in high doses can prevent the development of life as we know it on our planet. Since the atmospheric and magnetic conditions on Venus and Earth are different, we considered it important to make a comparative study of the level of cosmic radiation on both planets, towards establishing whether the level of radiation on Venus can prevent or not the development of microscopic life.

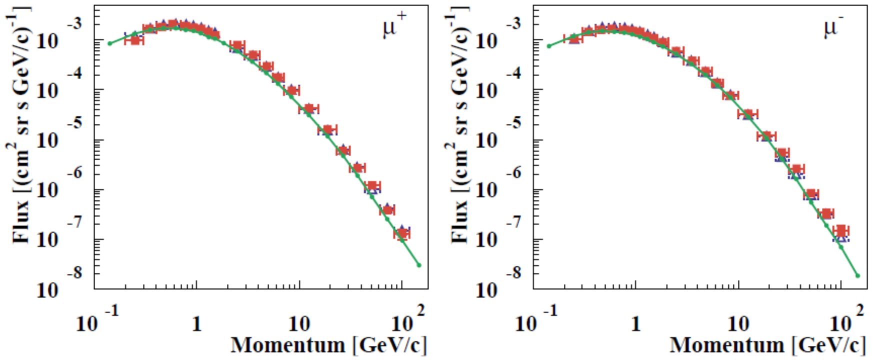
We report here the first results of our investigations on this issue, carried out by means of simulations using **AIRES** (http://aires.fisica.unlp.edu.ar).

Antecedent: AIRES simulations and comparison with atmospheric muon flux measurements.



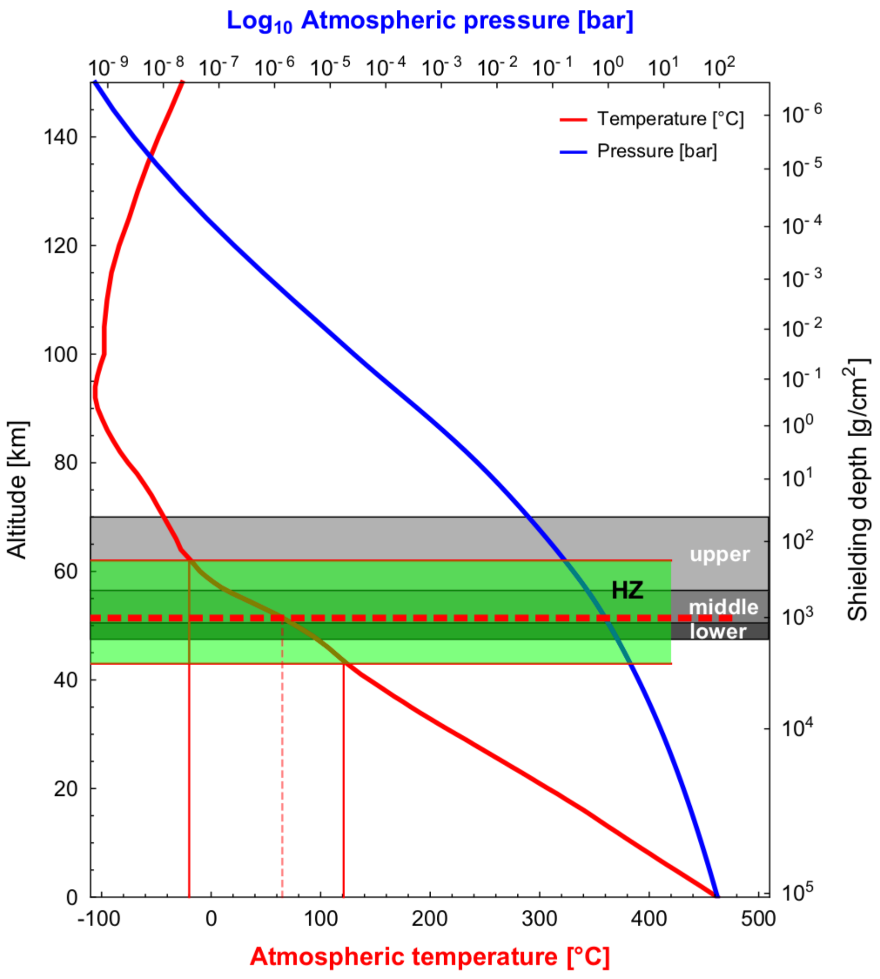
At different altitudes

At ground level



For details see: *Flux of atmospheric muons: Comparison between AIRES simulations and CAPRICE98 data*, P. Hansen, P. Carlson, E. Mocchiutti, SJS, M. Boezio, *Phys. Rev. D*, **68**, 103001 (2003).

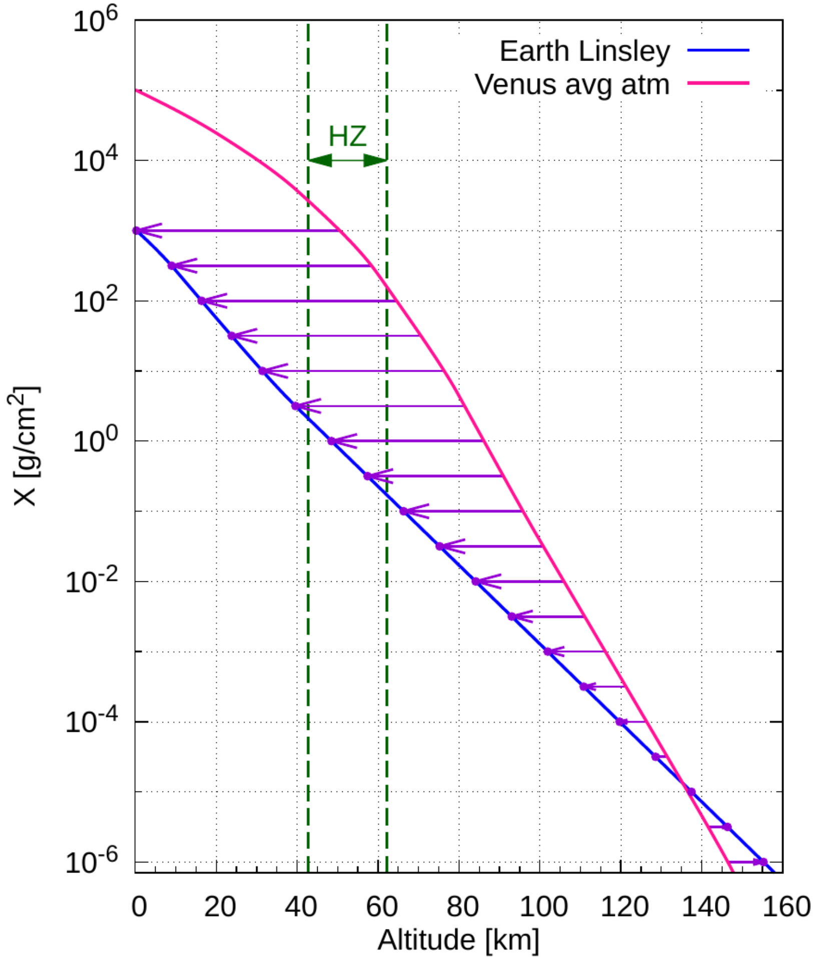
Venus atmosphere



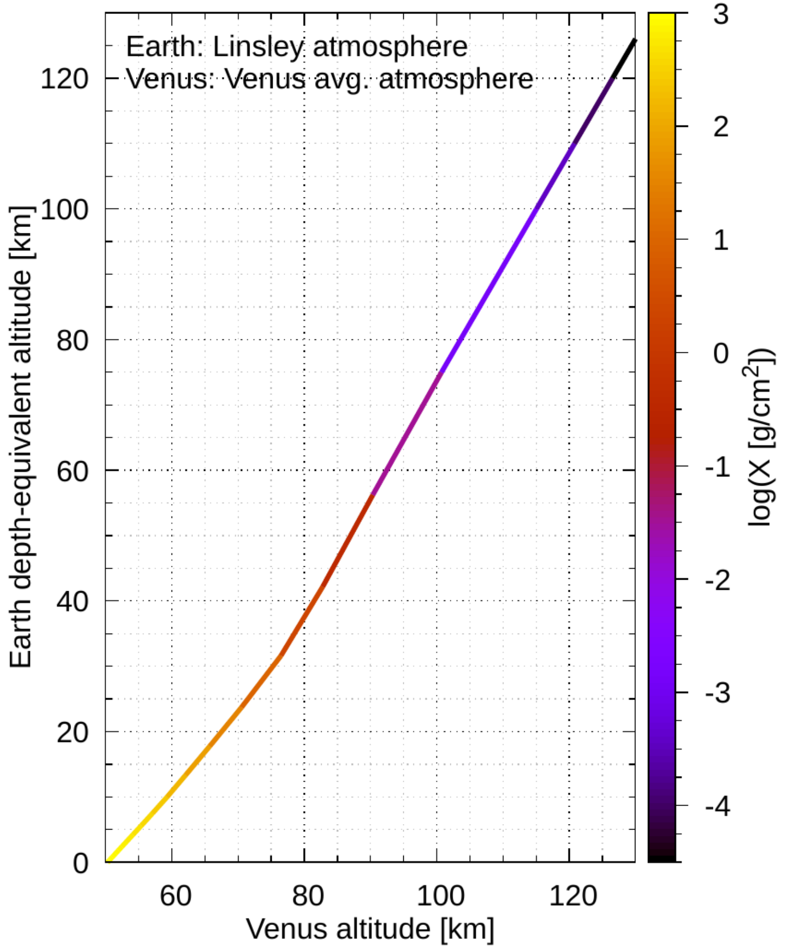
L. R. Dartnell *et al.*, *Icarus*, **257**, 396 (2015).

- **Main molecular composition of venusian atmosphere:** 96.5% carbon dioxide (CO_2), 3.5% nitrogen (N_2).
- **Clouds** of (mostly) sulphuric acid (SO_4H_2) from **48 km up to 70 km**.
- **Habitable zone (HZ) characterized for moderate temperatures and pressures (Earth-like).**
- Multilayer model developed to reproduce in **AIRES** the Venus average atmospheric depth profile, based in reported density measurements.
- **Also adjusted:** atomic atmospheric composition (65% O, 33% C, 2% N); mean atomic number and charge; radiation length; planet radius.

Venus and Earth atmospheres

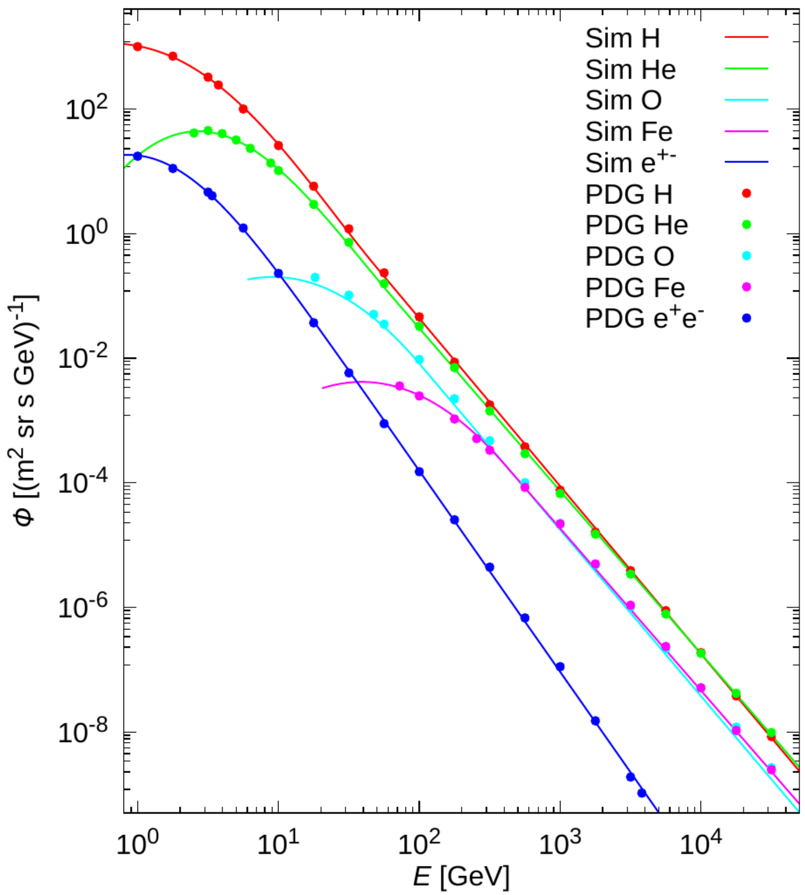


- Venus atmosphere is significantly more dense than the Earth atmosphere for altitudes up to ~130 km.
- Depth at Venus ground level ~10^5 g/cm^2.
- Depth at Venus altitude of h_{V0} = 50.5 km: 1000 g/cm^2.
- For venusian altitudes $h_V > h_{V0}$, an **Earth depth-equivalent altitude**, h_E, can be defined that verifies $X_E(h_E) = X_V(h_V)$.



Venus atmosphere data from: A. Seiff, *et al.*, *Adv. Space Res.*, **5**, 3 (1985).

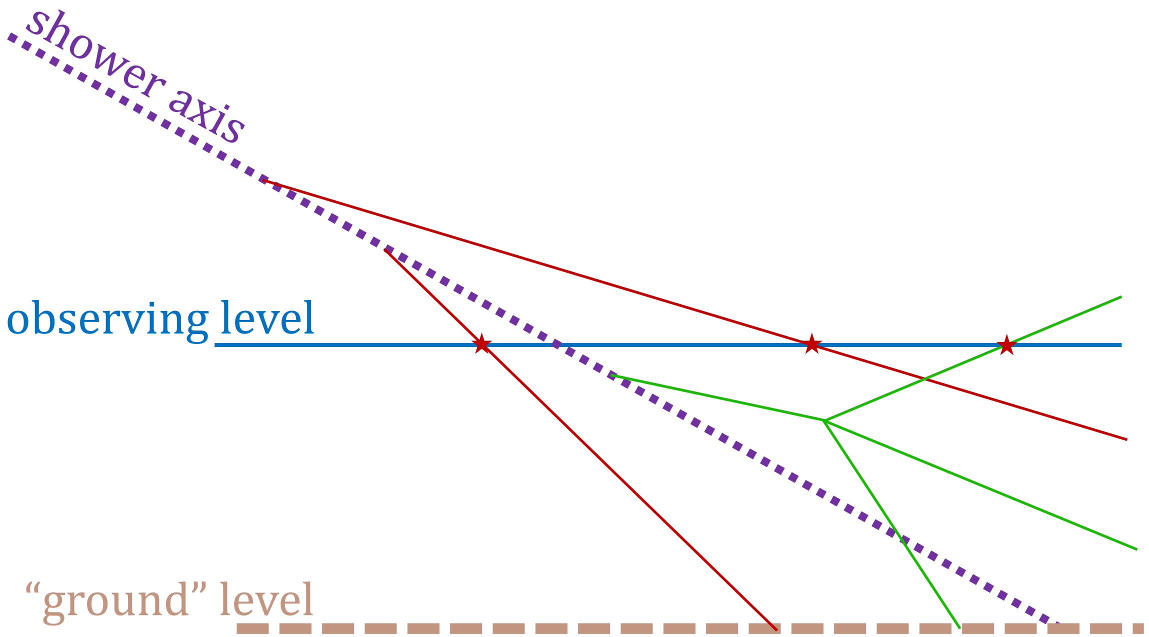
Simulations with AIRES – TOA primary flux



TOA fluxes data from: S. Navas *et al.* (Particle Data Group), *Phys. Rev. D*, **110**, 030001 (2024).

- **Cosmic ray flux is assumed to be equal in both Venus and Earth TOA.**
- **Primary particles.** Nuclei (^{1}H, ^{2}H, ^{3}He, ^{4}He, ..., ^{56}Fe), and e^+e^-. For both Venus and Earth simulations, abundances taken accordingly with the respective fluxes at the top of the Earth's atmosphere.
- **Primary energy range.** From 1 GeV up to 50 TeV.
- **Zenith angles.** From 0 to 90 deg (isotropic distribution).
- **Earth magnetic field.** F = 32 μT.
- **Venus magnetic field.** Venus has negligible intrinsic magnetic field.

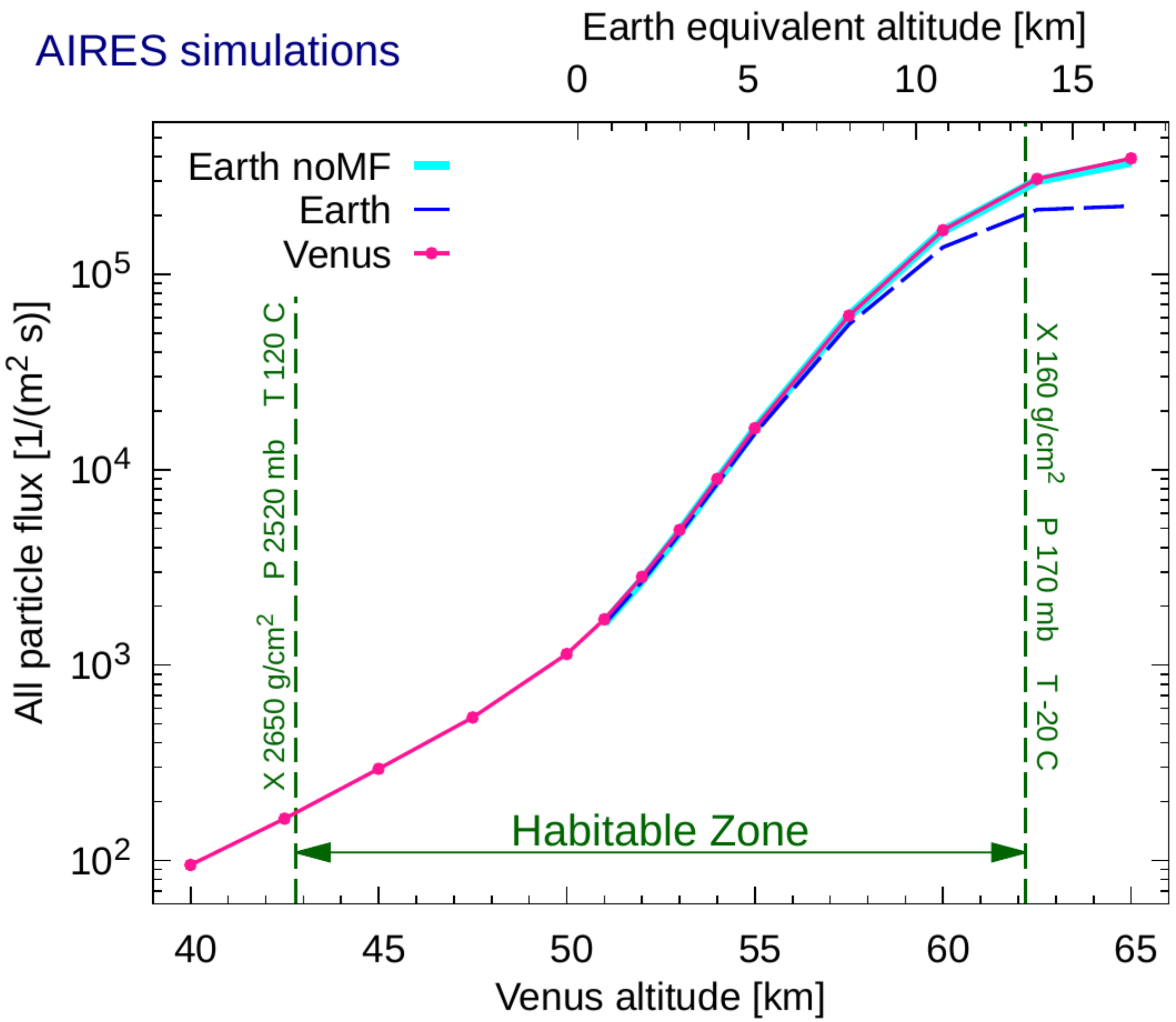
Simulations with AIRES – Particle counting



AIRES propagates both downgoing and upgoing particles. This is **essential** to properly simulate **total fluxes** of particles at points immersed within the atmosphere.

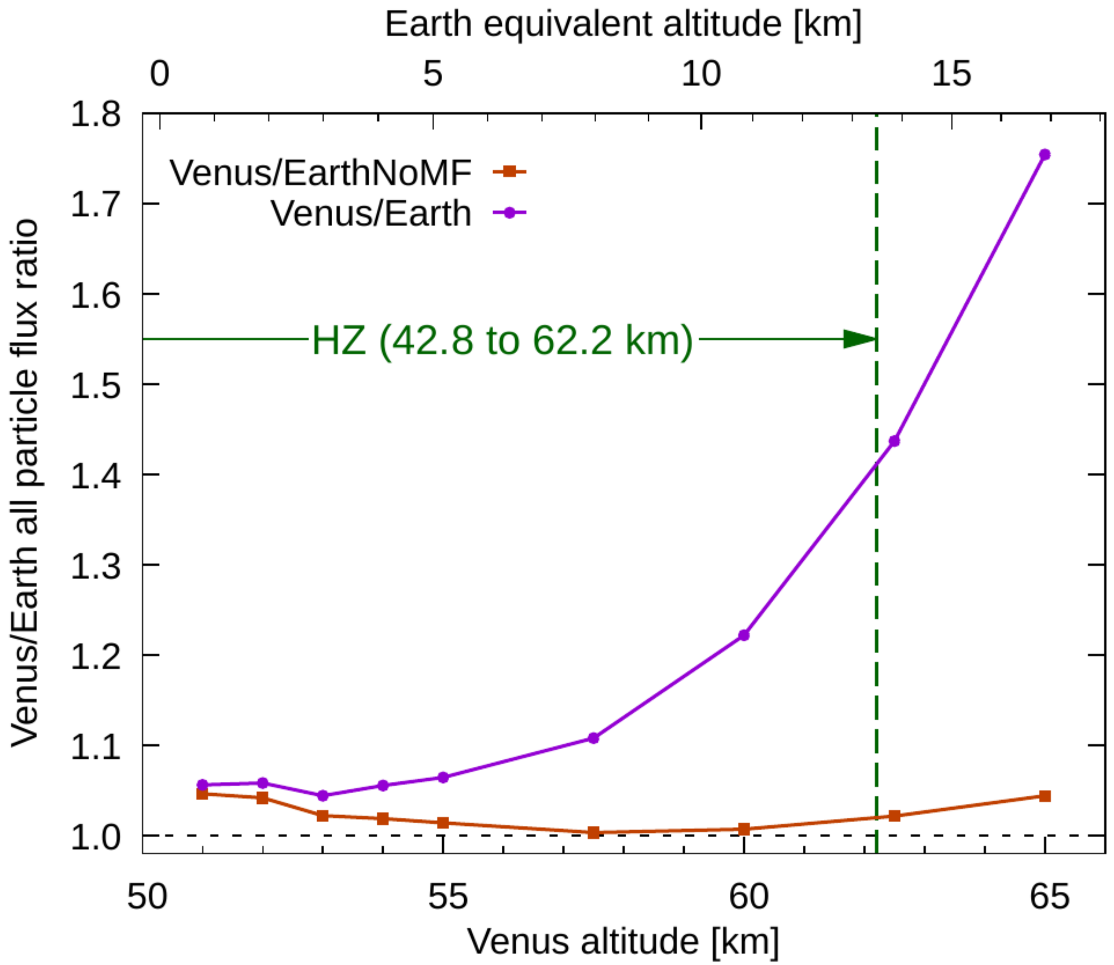
- **Observing levels.** Generously covering the Venus “habitable zone”, at altitudes 40, 42.5, 45, 47.5, 50, 51, 52, 53, 54, 55, 57.5, 60, 62.5, and 65 km, corresponding to atmospheric depths from 3710 g/cm^2 down to 93 g/cm^2.
- **“ground” levels.** Technically needed, placed about 1 km below the corresponding observing level.
- Additional runs at Earth (with and without magnetic field) were included for all the levels with $X \leq 1000$ g/cm^2 (Venus altitude > 50 km).
- **Statistics.** More than 7×10^6 simulated showers per observing level.
- **Total statistics.** About 290 million showers simulated for the entire task.

Simulation results – All particle flux



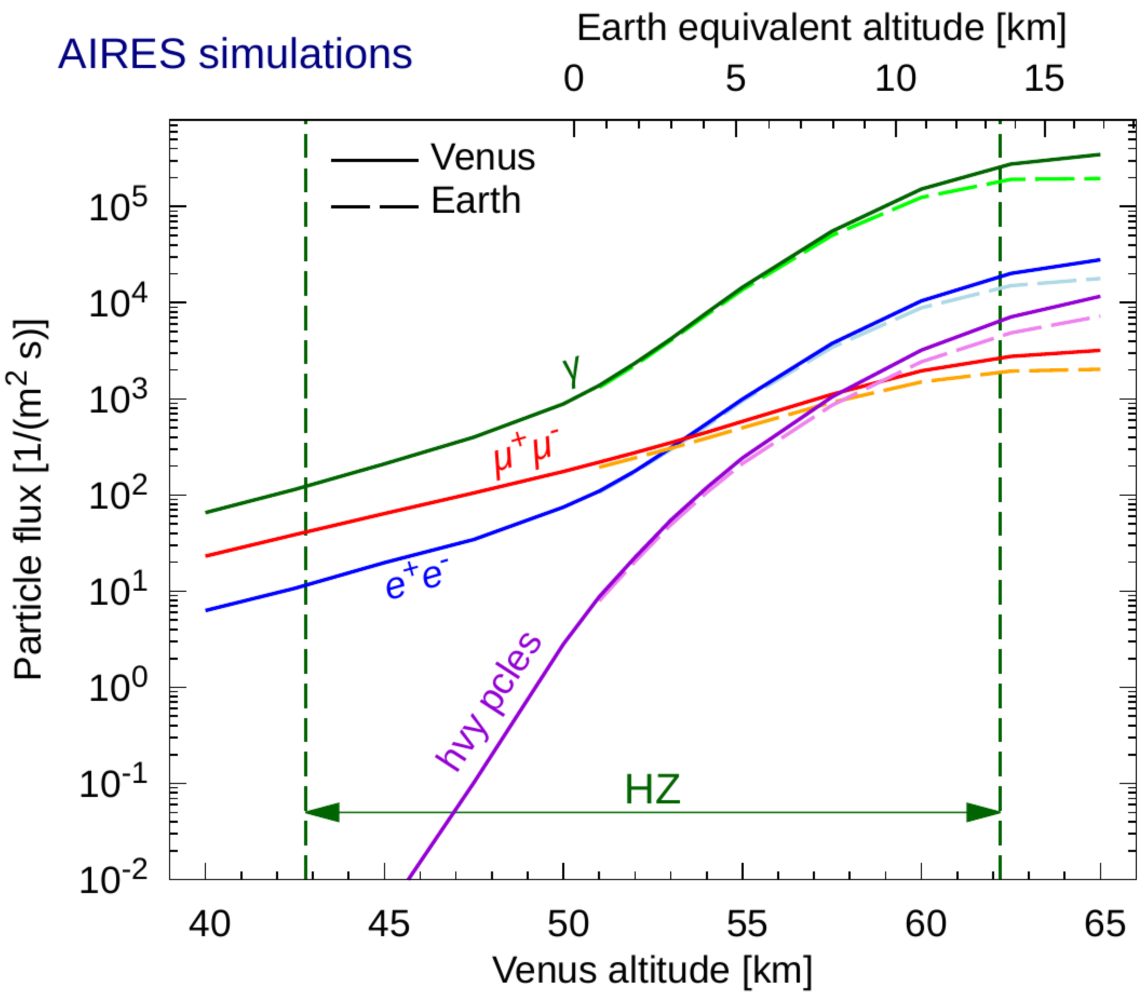
- Very similar integrated flux obtained in both Venus and Earth cases.
- Simulations with disabled magnetic deflections show almost perfect matching.
- Small but non negligible differences between Venus and Earth fluxes show up for $h_V > 57$ km.

Simulation results – All particle flux ratios



- Relative differences between Venus and Earth simulated fluxes remain less than 10% for Venusian altitudes less than 57 km, rising up to ~ 40% at the upper end of the habitable zone ($h_V \simeq 60$ km).
- Relative differences with respect to no geomagnetic field simulations remain well below 10% for all the altitudes that were considered.

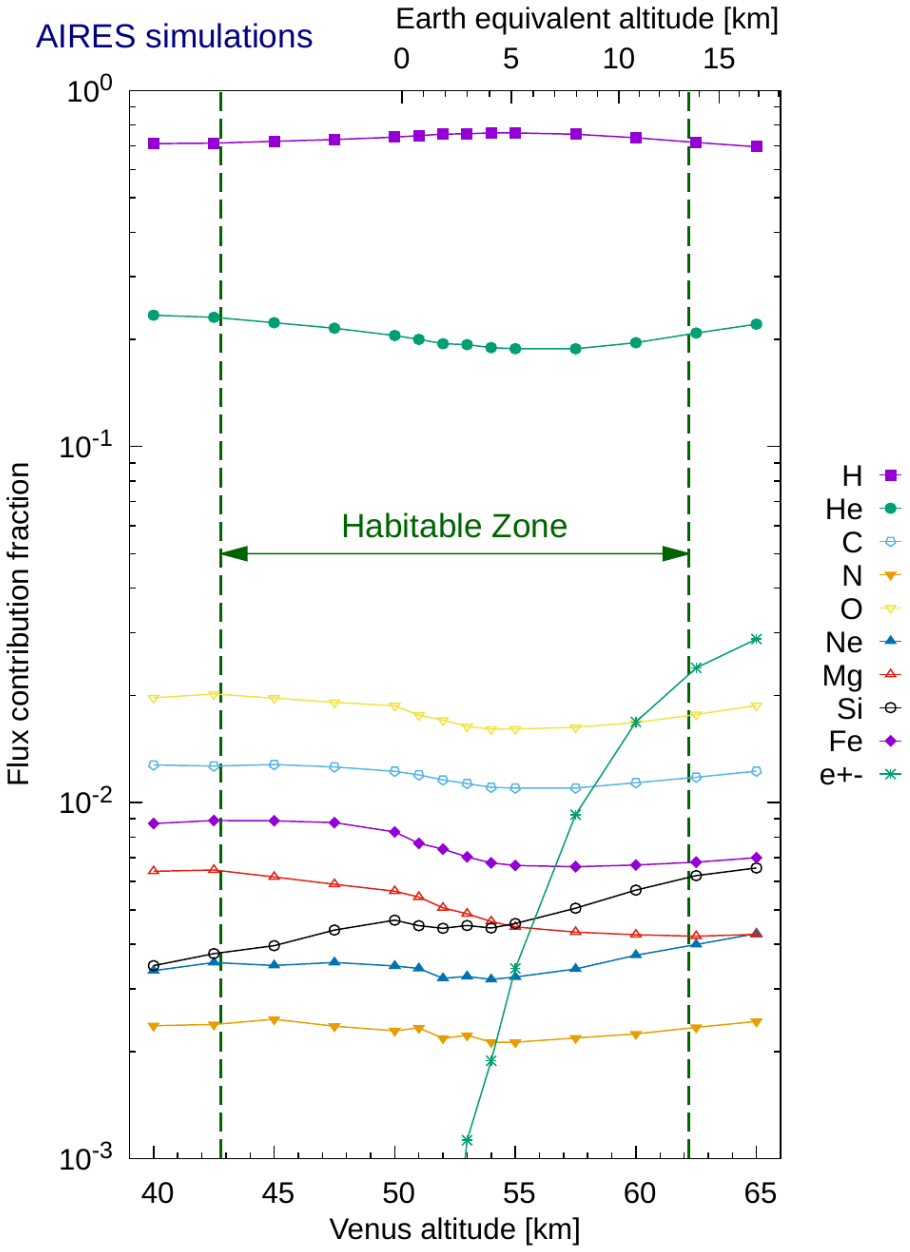
Simulation results – Flux of different particles



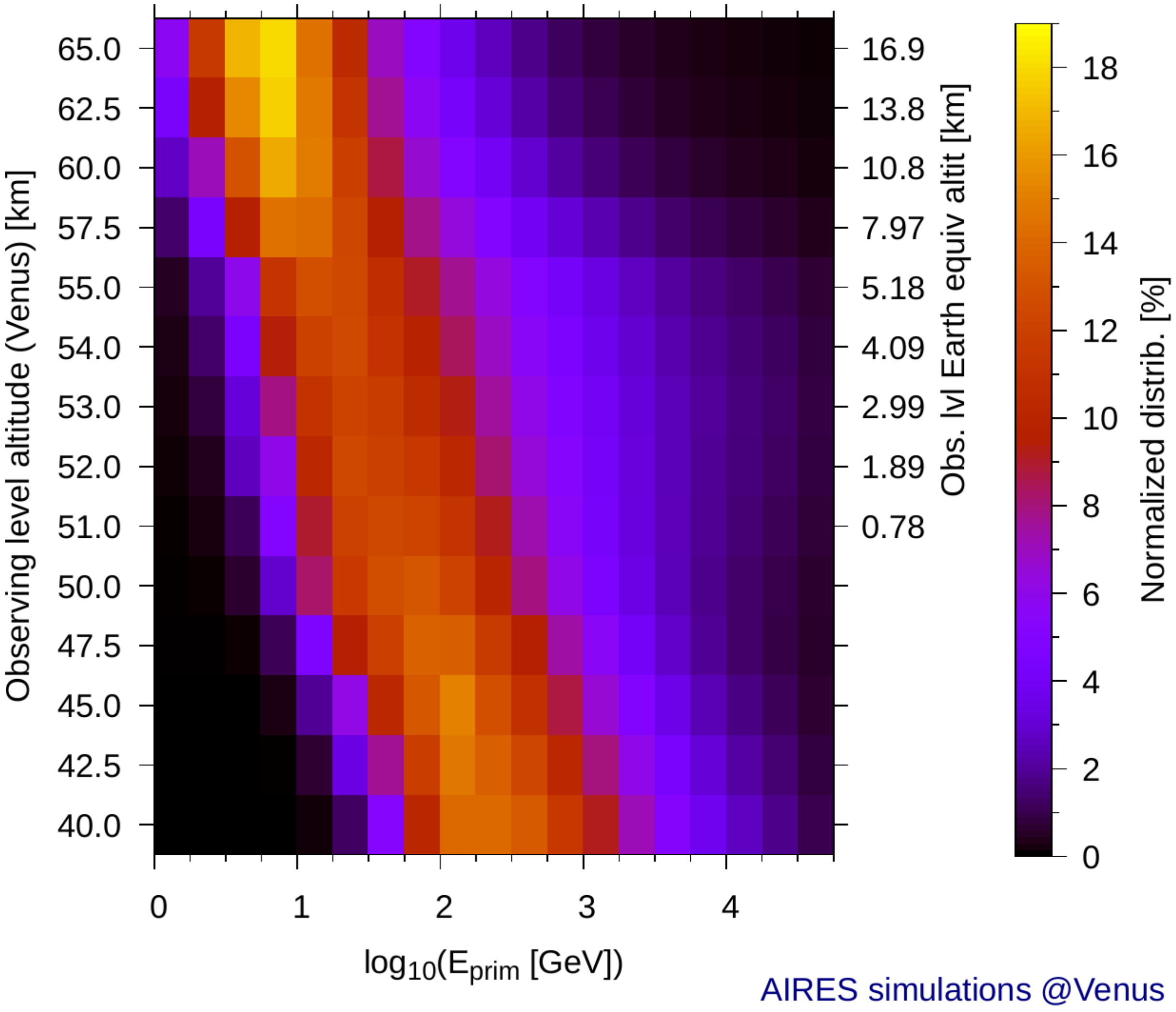
For all particle kinds, the relative differences between Venus and Earth fluxes are qualitatively similar for all the studied observing levels.

Contributions of different primaries to the total flux

- **Proton and helium** primaries account for more than 95% of the flux at all the studied observing levels.
- Follow O (~ 2%) and C (~ 1%)
- All the remaining nuclei provide less than 1% of the flux.
- The contribution of primary **electrons and positrons** are always below 3%, and overpasses 1% only for Venusian altitudes larger than 57 km.
- CAVEAT: The actual e^+e^- flux at the top of the Venusian atmosphere is, to our best, currently unknown; and it could be larger than the corresponding flux at the Earth used in our calculations. But even if the actual e^+e^- TOA flux results appreciably greater than the one used at this work (a factor of 2, say), its contribution will remain in the few percent level, and only for the highest observing levels.



Contribution of different primary energies



- Range of primary energies: [1 GeV, 50 TeV] (for all altitudes).
- Primary energies with largest contribution to the total flux:

$$
\begin{aligned}
\sim 250\ \text{GeV} \quad & \text{at } h_V = 40\ \text{km} \\
\sim 75\ \text{GeV} \quad & \text{at } h_V = 50\ \text{km} \\
\sim 7.5\ \text{GeV} \quad & \text{at } h_V = 60\ \text{km}
\end{aligned}
$$

- Contributions from primaries outside the selected energy range are always small.

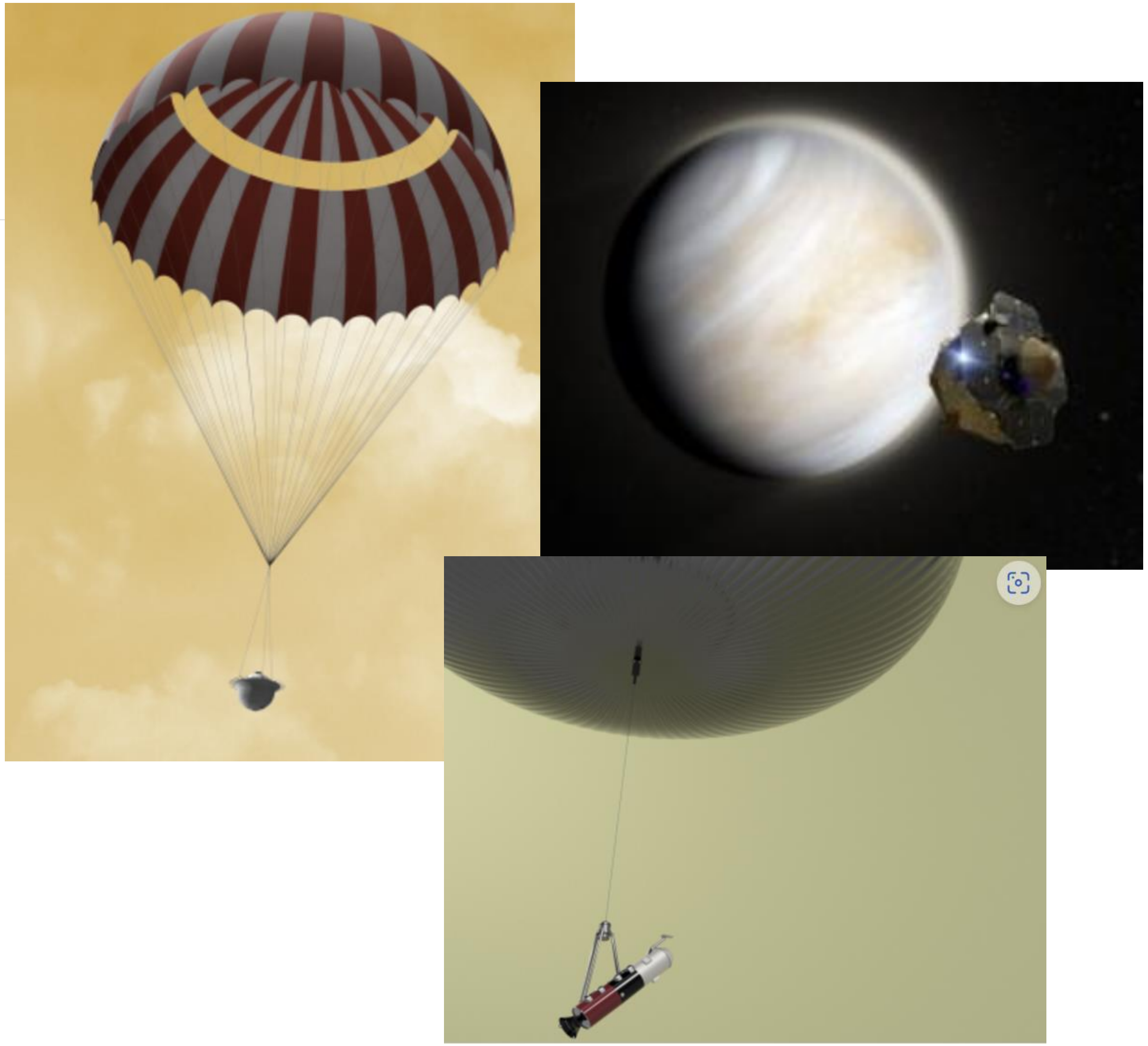
Conclusions and final remarks

- Extensive study of cosmic ray fluxes at different atmospheric altitudes, for the cases of Venus and Earth atmospheres, focusing on altitudes corresponding to the potentially habitable zone. For the Earth atmosphere, the case of simulations disabling the geomagnetic deflections was also considered.
- The Venus-Earth comparisons have always been done using, for both planets, observing levels located at the same atmospheric depth.
- We observe that both Venus and Earth fluxes are very similar in all the cases considered. There exist some small differences in the fluxes at the highest altitudes (they virtually disappear when comparing with the Earth with disabled magnetic field).
- Consequently, our study leads to the conclusion that within al the so-called “habitable zone” of Venus, the level of radiation exposure should be like that registered in Earth, at the corresponding equivalent altitude. And for those Venus altitudes located below 50 km, the radiation intensity is less than the Earth radiation intensity at sea level. Thus, the biological effects of cosmic radiation on the “habitable zone” of Venus atmosphere should be not larger than those on Earth’s atmosphere (at depth-equivalent altitudes), which are well known.

And more for the future!...

Simulating atmospheric fluxes of secondary particles generated by cosmic rays is an excellent exercise for testing air shower simulation programs. We plan to go ahead in this direction and make comparative analysis of simulations with AIRES linked to various low and high energy hadronic packages.

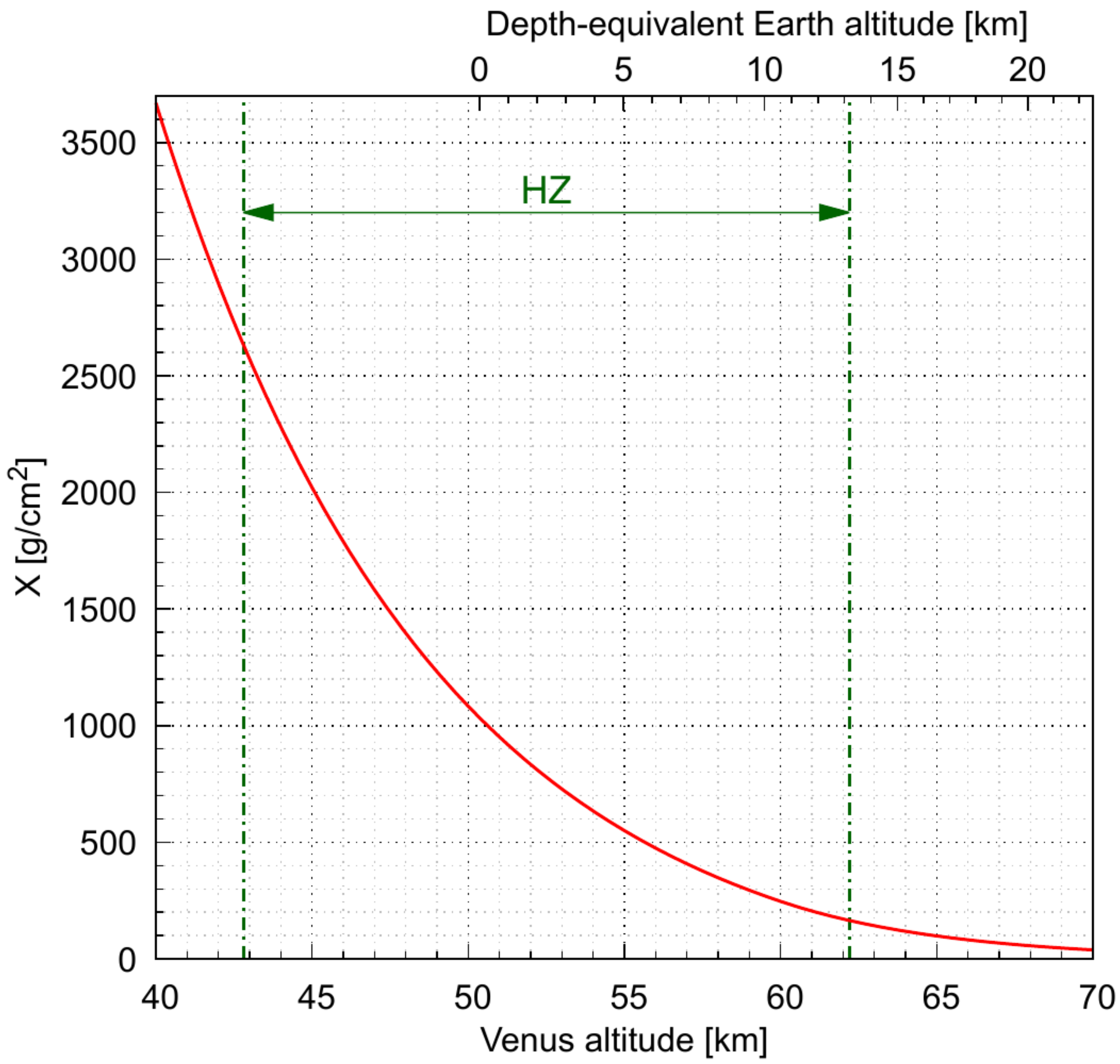
Keep connected with projected missions to Venus that will try to recover new data from the Venusian atmosphere (see for example: *venuscloudlife.com*).



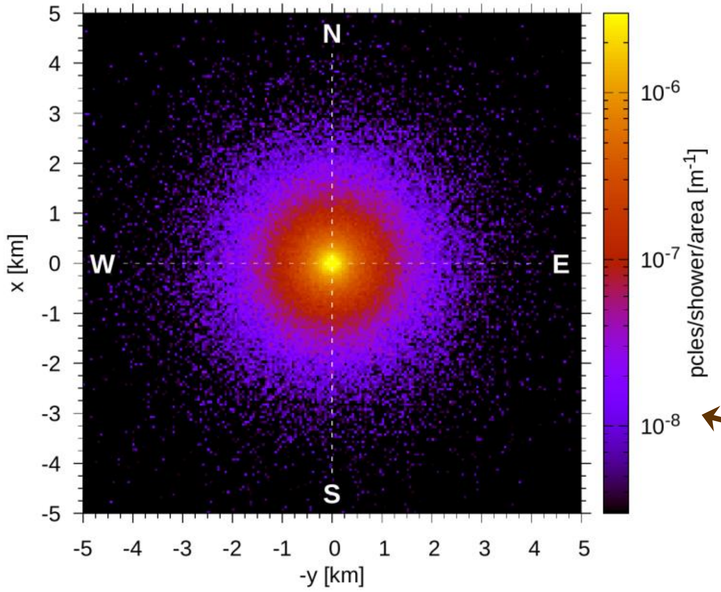
THANK YOU!

Backup slides

Venus atmospheric profile at the habitable zone



Influence of the Earth's magnetic field.



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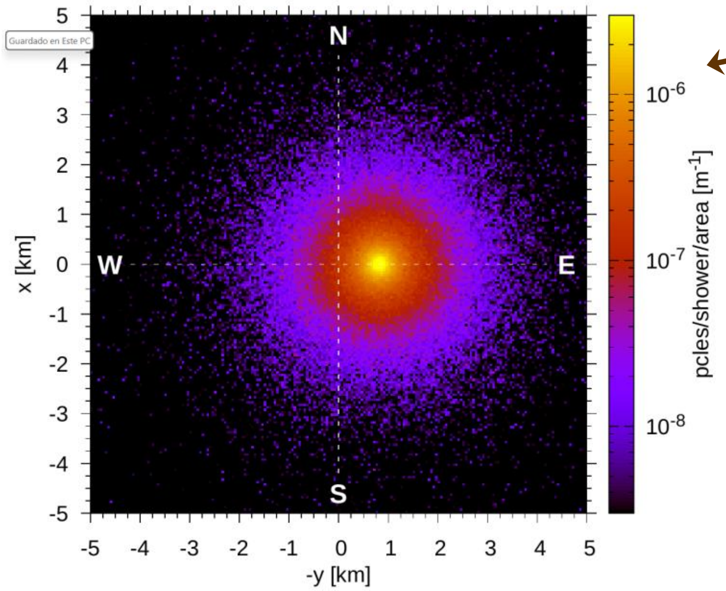
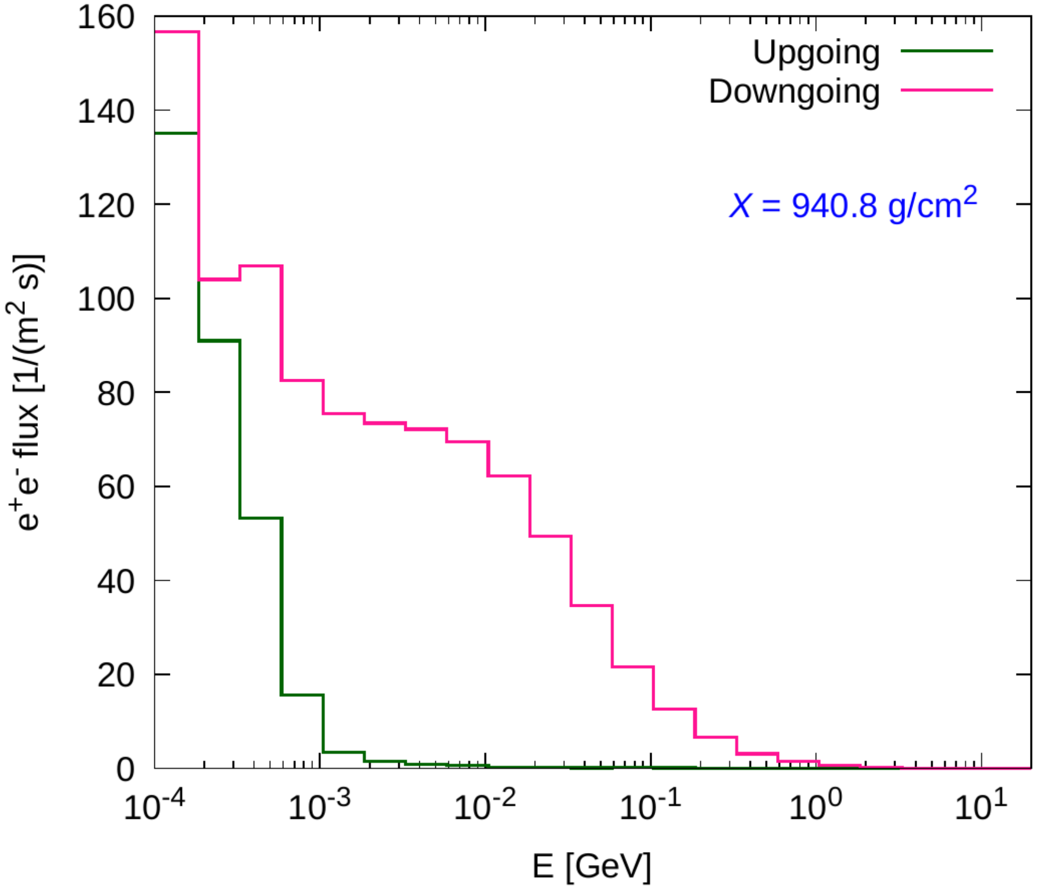
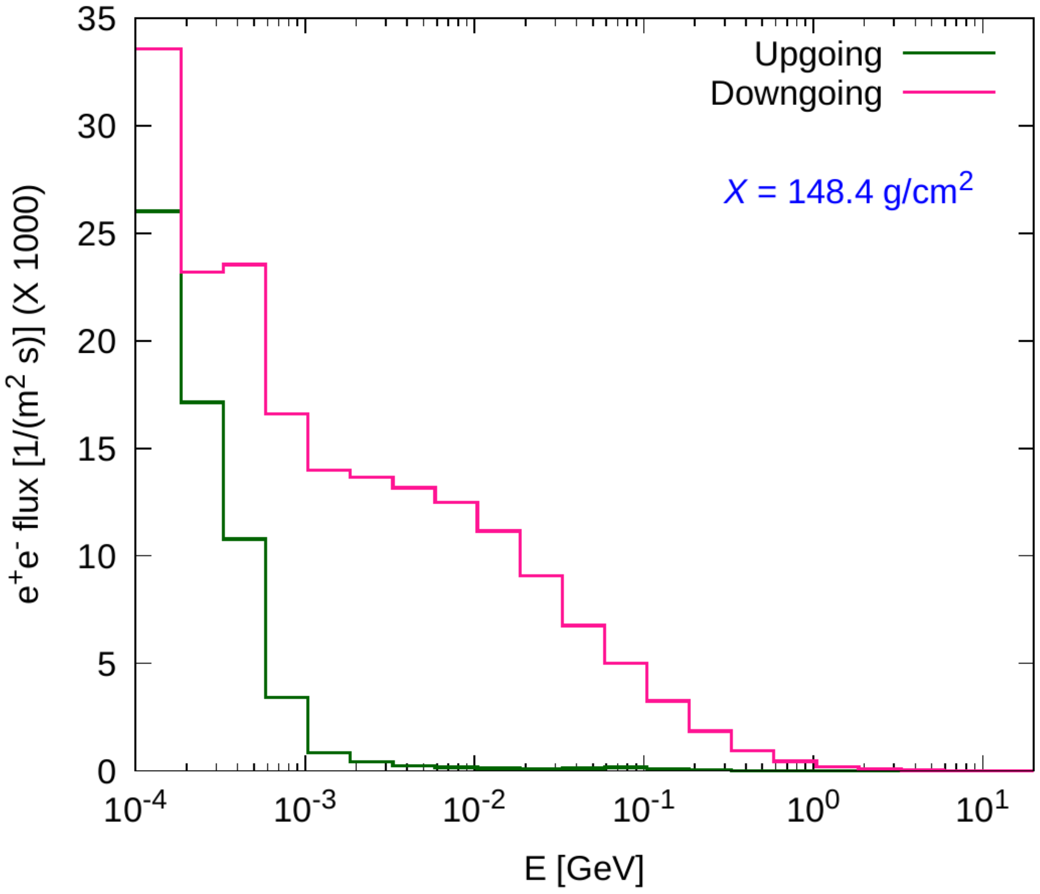


MF ENABLED

- Vertical 100 GeV proton primaries.
- 2D Lateral distribution of e+e- at 1000 m.a.s.l (916 g/cm2)

Simulation results – down/upgoing particles





AIRES simulations @Venus

On the detection of PH_3 in the Venusian atmosphere.

Some publications that questioned the experimental results about the detection of PH_3 absorption lines in Venus atmosphere:

- G. L. Villanueva et al., *No evidence of phosphine in the atmosphere of Venus from independent analyses. Nature Astron.*, **5**, 636 (2021) [arXiv:2010.14305].
- M. A. Thompson, *The statistical reliability of 267-GHz JCMT observations of Venus: no significant evidence for phosphine absorption. Mon. Not. Roy. Astron. Soc.*, **501**, L18 (2021) [arXiv:2010.15188].
- *A. B. Akins, A. P. Lincowski, V. S. Meadows, and P. G. Steffes, Complications in the ALMA detection of phosphine at Venus*. *Astrophys. J.*, **907**, L27 (2021) [arXiv:2101.09831].
- A. P. Lincowski *et al.*, *Claimed detection of PH_3 in the clouds of Venus is consistent with mesospheric SO2*. *Astrophys. J.*, **908** , L44 (2021) [arXiv:2101.09837].

Have been addressed, reaffirming the positivity of the originally reported phosphine signals:

- J. S. Greaves *et al.*, *Adendum: Phosphine gas in the cloud decks of Venus*. *Nature Astron.*, **5**, 726 (2021) [arXiv:2012.05844].
- J. S. Greaves *et al.*, *Reply to: No evidence of phosphine in the atmosphere of Venus from independent analyses.* . *Nature Astron.*, **5**, 636 (2021) [arXiv:2011.08176].
- J. S. Greaves *et al.*, *Low levels of sulphur dioxide contamination of venusian phosphine spectra*. *Mon. Not. Roy. Astron. Soc.*, **514**, 2994 (2022) [arXiv:2108.08393].

With the conclusion that the observed excess is still statistically significant. For an up-to-date review. See:

- D L. Clements, *Venus Phosphine: Updates and lessons learned*, [arXiv:2409.13438].

On the sustainability of life in the Venusian atmosphere

Very recent studies showed that single-chain saturated lipids with sulfate, alcohol, trimethylamine, and phosphonate head groups are resistant to sulfuric acid degradation at room temperature:

- Daniel Duzdevich *et al., Simple lipids form stable higher-order structures in concentrated sulfuric acid*, [arXiv:2409.12982].
- S. Seager *et al., Stability of Nucleic Acid Bases in Concentrated Sulfuric Acid: Implications for the Habitability of Venus' Clouds*, [arXiv:2306.17182].