

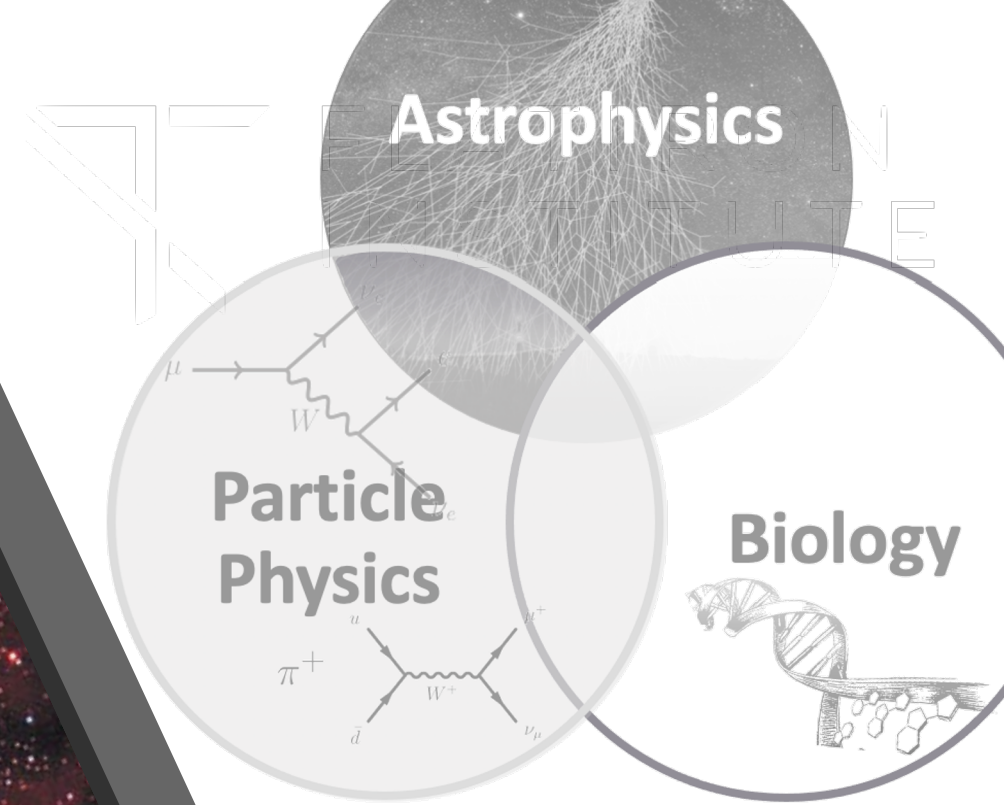
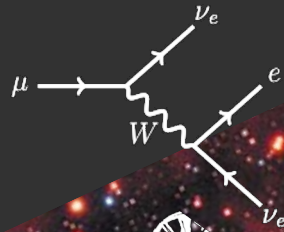
Polarized muons and the origin of biological homochirality

Noémie Globus^{1,2,3}

¹ELI beamlines (Czech Republic),

²Flatiron Institute (USA)

³ABBL, RIKEN (Japan)



ICRC 2021

THE ASTROPARTICLE PHYSICS CONFERENCE

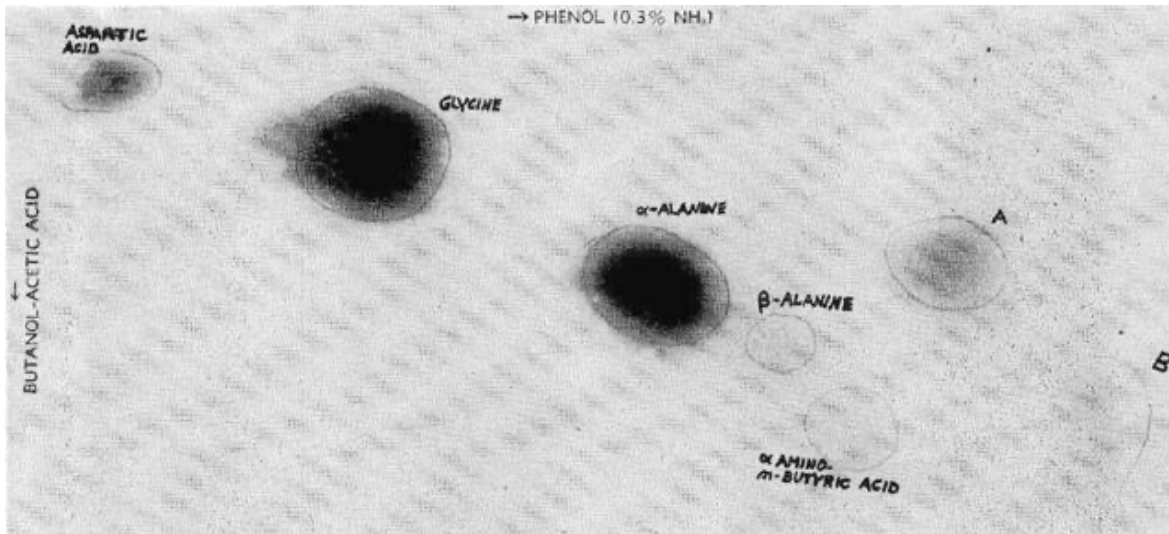
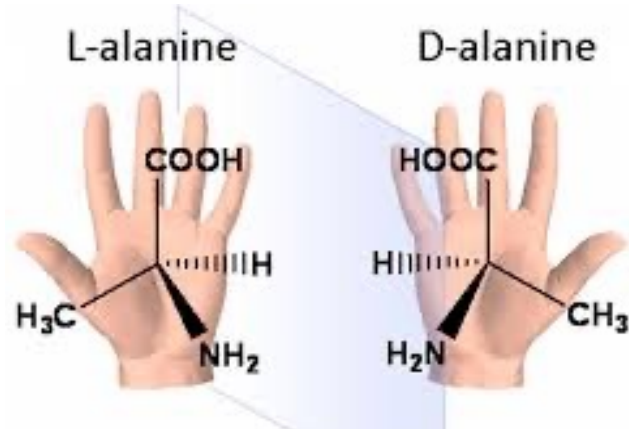
Berlin | Germany

Astrobiology – the search for life beyond Earth

- The search for life beyond Earth **requires an understanding of life, and the nature of the environments that support it.**
- We still do not know what are **all** the necessary conditions for life to emerge.
- But we can study what are the signatures of life *as we know it* and search for these signatures in the universe.
- The **homochirality** of organic molecules is a phenomenon **only produced by life.**
- Homochirality is thus a very unambiguous **biosignature** and its presence on an extraterrestrial body will be a **powerful indicator of life.**

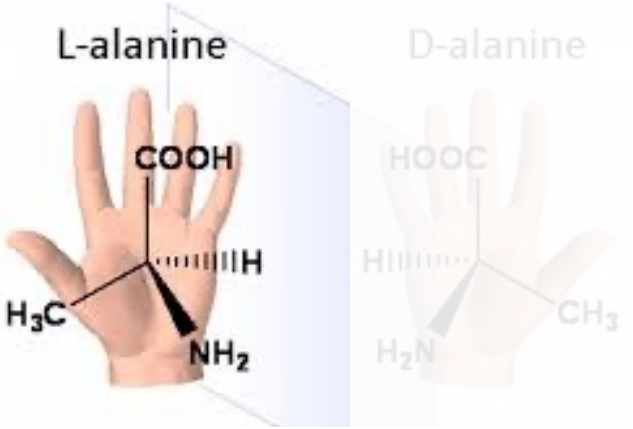
Amino acids – building blocks of life

The Miller-Urey experiment (1952) aimed to probe Charles Darwin's 1871 warm pond model



products of Miller's experiment: amino acids!
But equal quantities of both right- and left-handed

Asymmetry in amino acids found in meteorites



$$e.e. = \frac{D-L}{D+L} \cdot 100$$

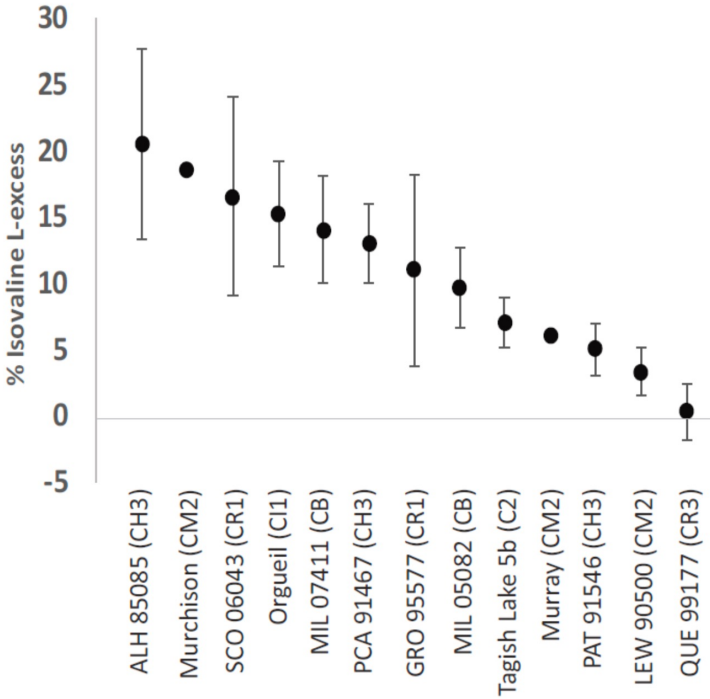


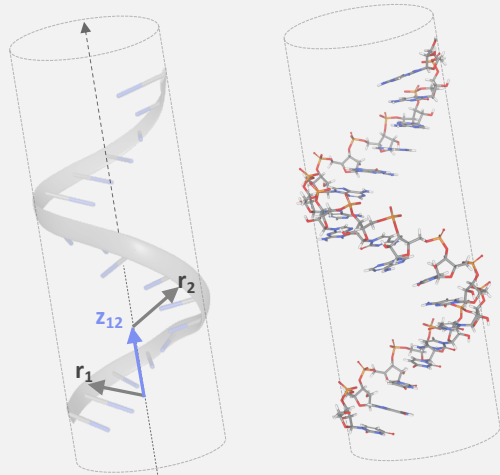
photo by : Tim Heitz

Burton & Berger, 2018

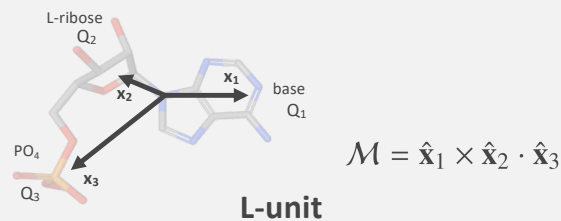
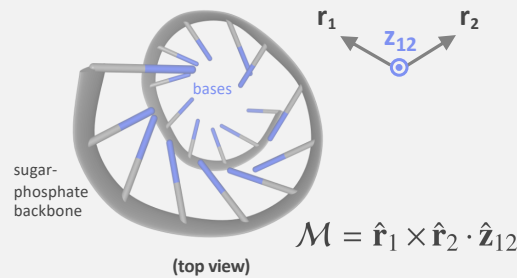
Evidence for asymmetry!
 ... may have bias by contamination at Earth

Nucleic acids – building blocks of life

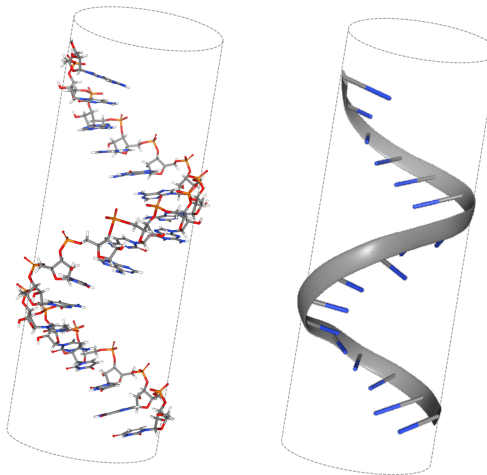
L-RNA (evil system)



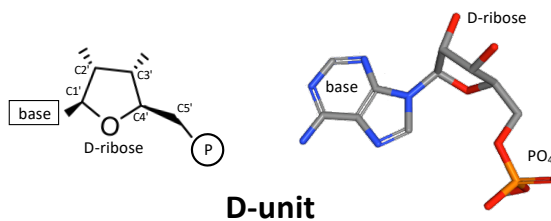
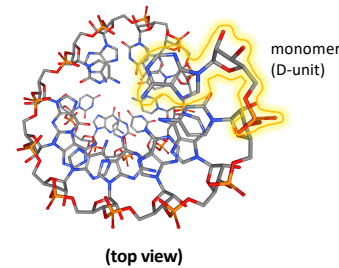
Left-handed helix
(side view)



D-RNA (live system)



Right-handed helix
(side view)



- We define:
 - **Live system:** the handedness of the present-day DNA in lifeforms
 - **Evil system:** the mirrored system not found on Earth
- “Evil” blocks can be synthesized in laboratory
- Origin of this choice?

Globus & Blandford
2020 ApJL 895 L11

The discovery of homochirality

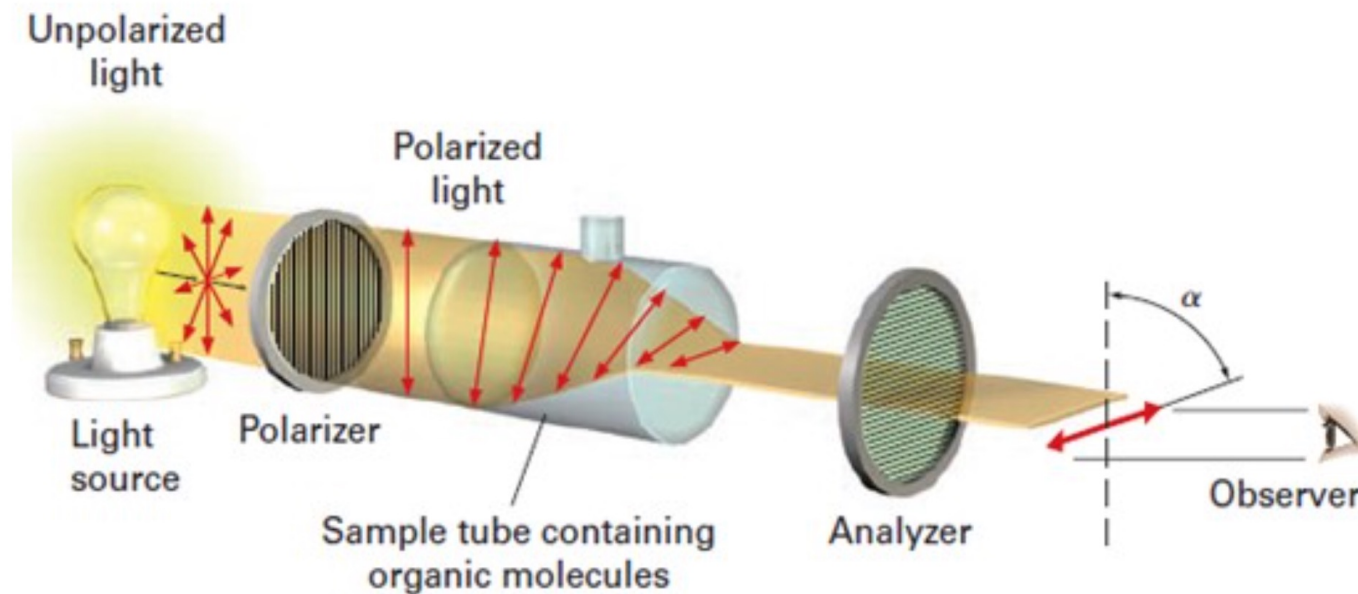


Tartaric acid crystals on cork. Wikipedia

1769: Carl Wilhelm Scheele examines tartar (deposited in casks during wine fermentation); isolates tartaric acid



1815: Optical activity was first observed by Jean-Baptiste Biot. He concluded that the change in direction of plane-polarized light when it passed through certain substances had a molecular basis.



The discovery of homochirality

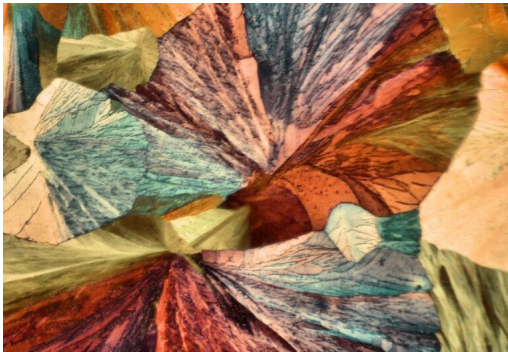


Tartaric acid crystals on cork. Wikipedia

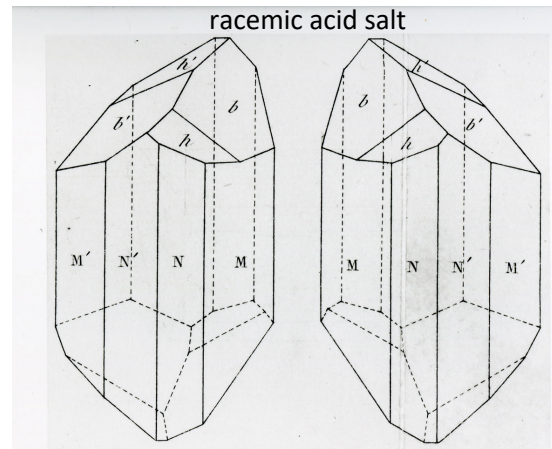
1769: Carl Wilhelm Scheele examines tartar (deposited in casks during wine fermentation); isolates tartaric acid



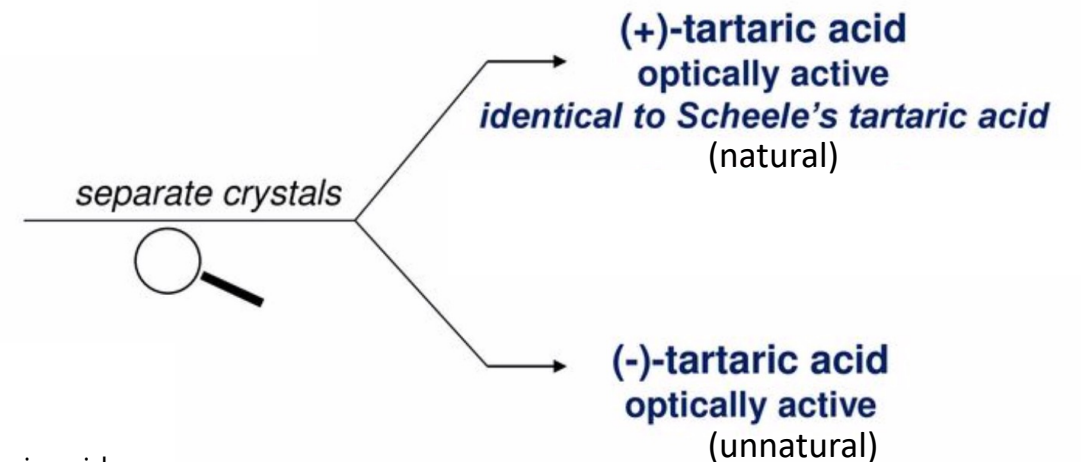
1848: Experiments by Pasteur on optical activity of tartaric acid



Tartaric acid crystals. [Gwyneth Thurgood](#)



Drawing by Louis Pasteur of a pair of tartaric acid crystals. From the collections of the Chemical Heritage Foundation.



What broke the biological mirror?

Pasteur anticipation: asymmetric cosmic laws



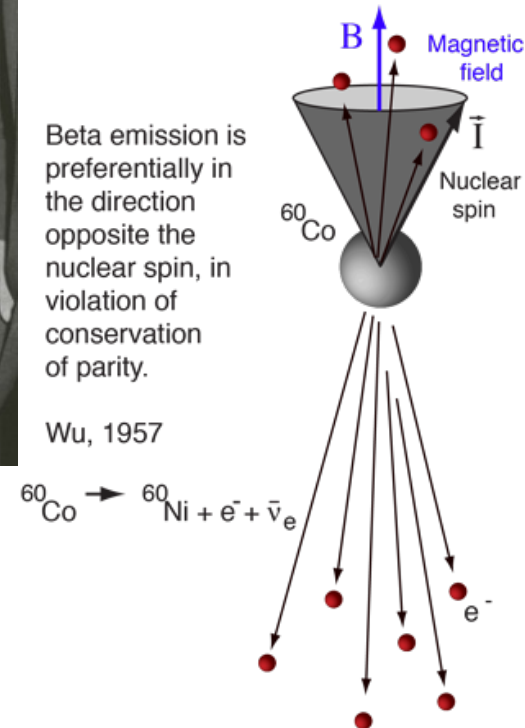
Ces actions dissymétriques, placées peut-être sous des influences cosmiques, résident-elles dans la lumière, dans l'électricité, dans le magnétisme, dans la chaleur? Seraient-elles en relation avec le mouvement de la terre, avec les courants électriques par lesquels les physiciens expliquent les pôles magnétiques terrestres? Il n'est pas même possible aujourd'hui d'émettre à cet égard les moindres conjectures.

Mais je regarde comme nécessaire la conclusion de l'existence de forces dissymétriques au moment de l'élaboration des produits organiques naturels, forces qui seraient absentes ou sans effet dans les réactions de nos laboratoires, soit à cause de la brusque action de ces phénomènes, soit pour toute autre circonstance inconnue.

1957: discovery of the parity violation in the weak interaction



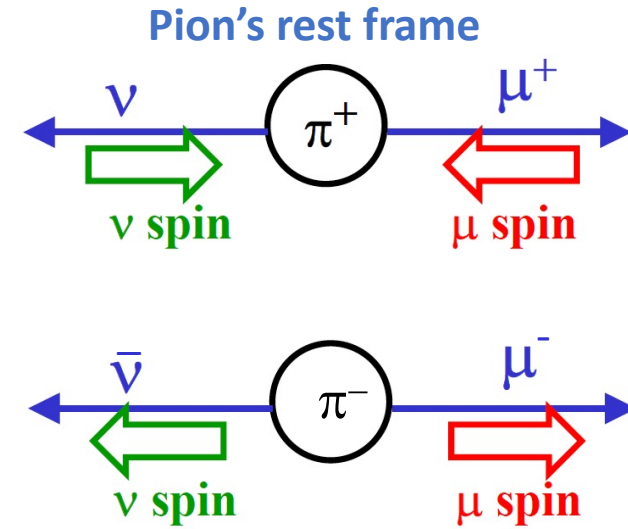
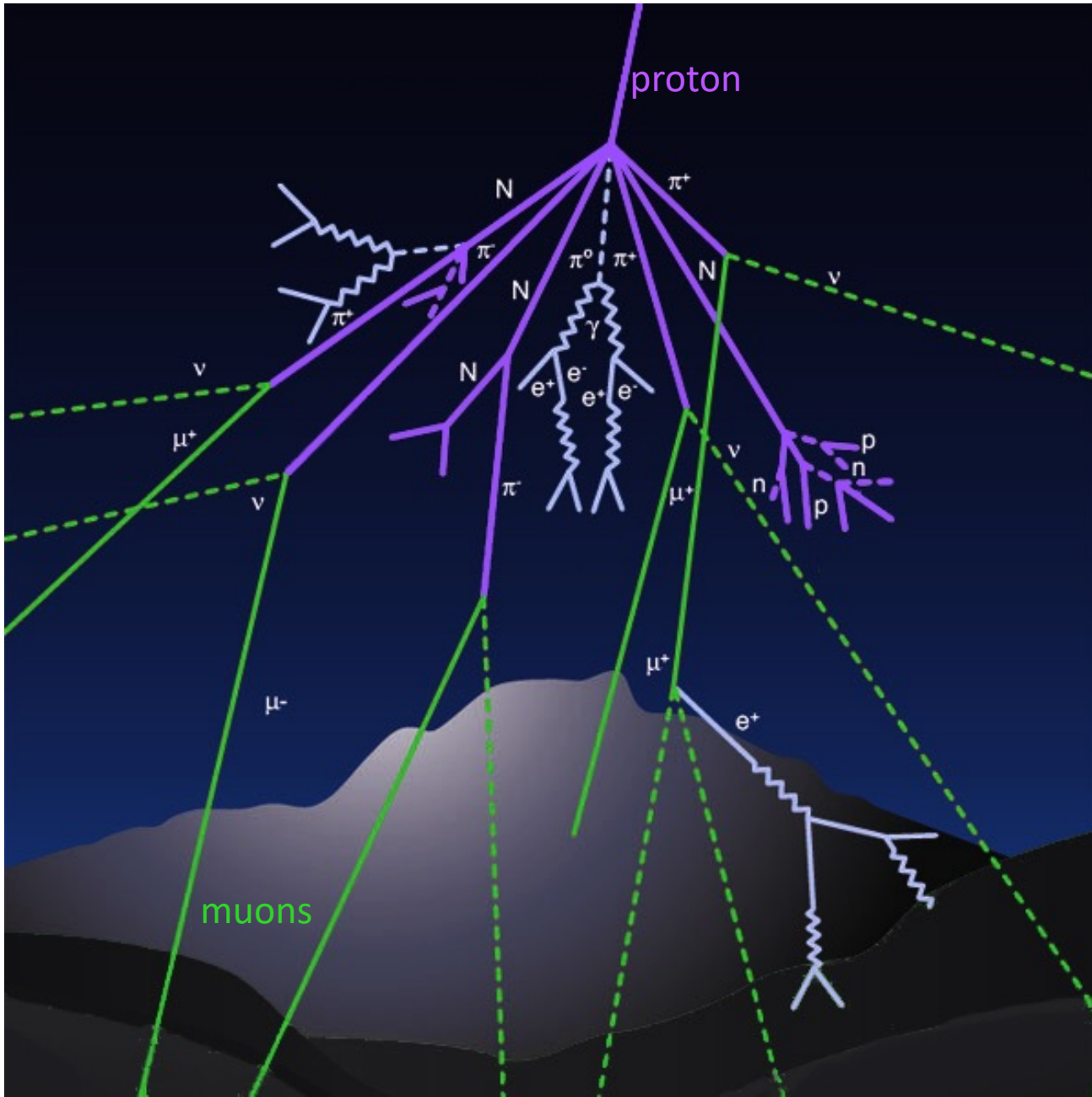
Chien-Shiung Wu in 1958



Previous studies on homochirality

	Actor	Effect	Chiral preference	Magnitude	Involves W?	Authors
Pre-Biotic	Parity Violating Energy Differences (PVED)	PVED-induced phase transition	Left-handed amino acids (in water)	$e.e. = \frac{D-L}{D+L} \cdot 100$ Not reported (theory only : 10^{-17})	yes	Salam, Quack ...
	Ultra-violet circularly polarized light (UV CPL)	Differential destruction	Depend on chirality of light and photon energy	e.e. ~ 2.5 %	no	Vester & Ulbricht processes; De Marcellus, D'Hendecourt, Modica...
	Irradiation with β -decay products	Differential destruction	Depend on spin-polarization of radiation	e.e. \ll 1%	yes	Bonner...
	Low-energy (<10 eV) spin-polarized electrons	Enantioselective chemistry	Depend on spin-polarization of and electron energy	e.e. ~ 1%	no	Vester-Ulbricht processes; Rosenberg, Kessler,...
Trans-Biotic	Low-energy (~ eV) spin-polarized electrons	Chiral Induced Spin Selectivity (CISS)	Depend on spin-polarization of electron	$SP = \left[\frac{I_{up} - I_{down}}{I_{up} + I_{down}} \right] \cdot 100$ SP ~ 85 – 90%	no	Naaman, Vardeny ...
	High-energy (polarized) muons and electrons	Enantioselective Mutagenesis	Depend on magnetic-polarization of e/ μ	Not reported (theory only : 10^{-7} - 10^{-8})	yes	Globus & Blandford

Muons come from weak decays that violate parity



208

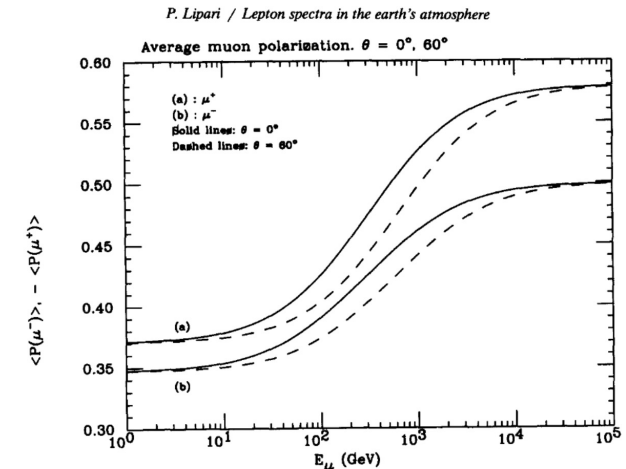
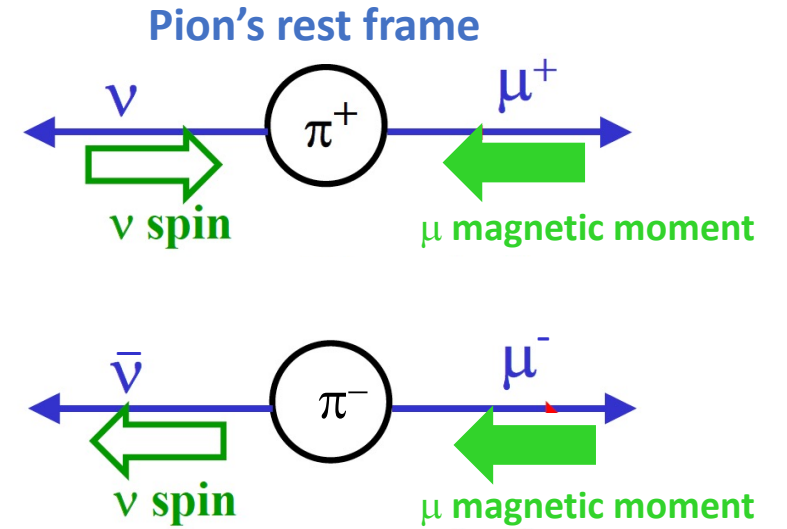
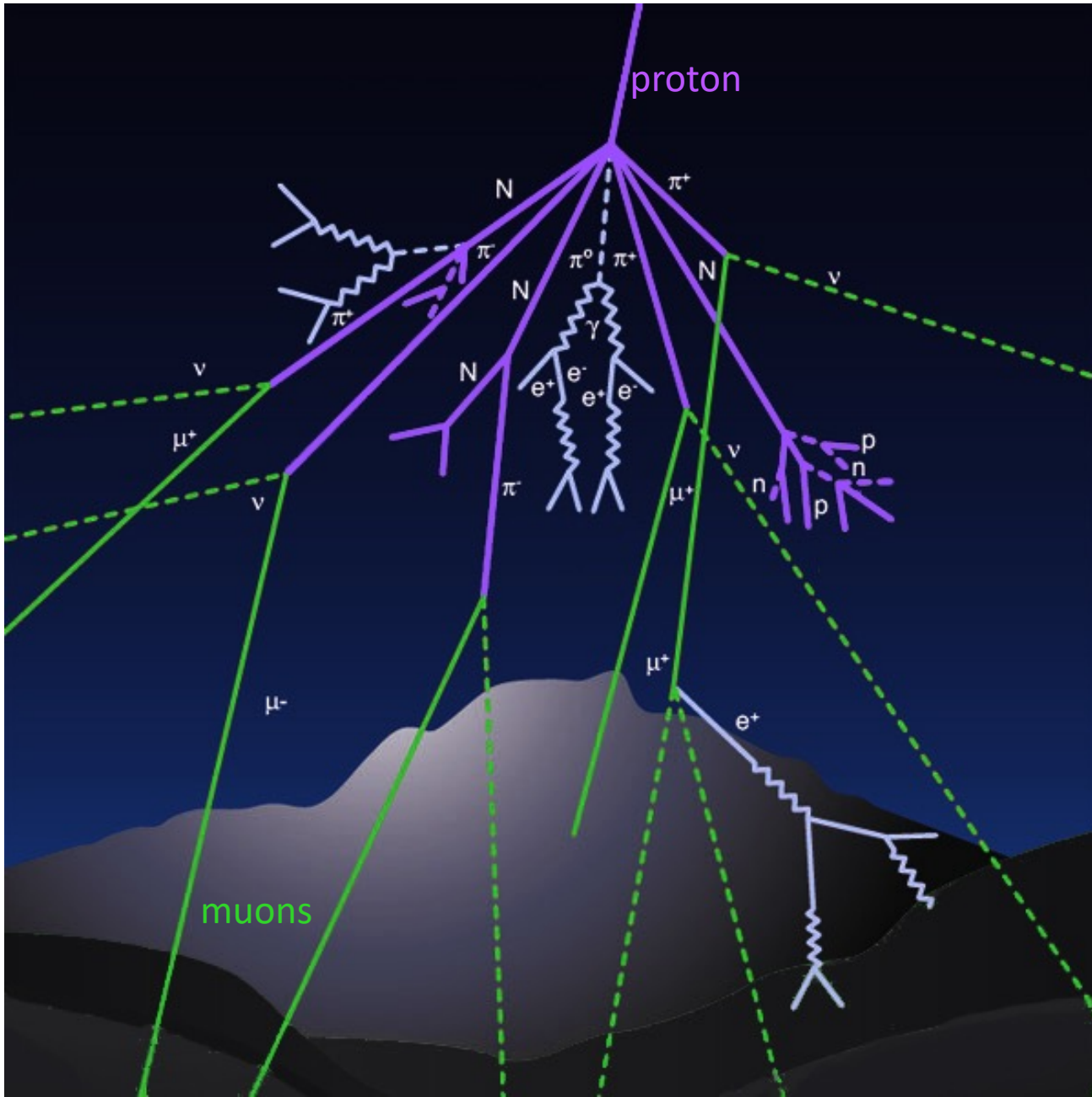


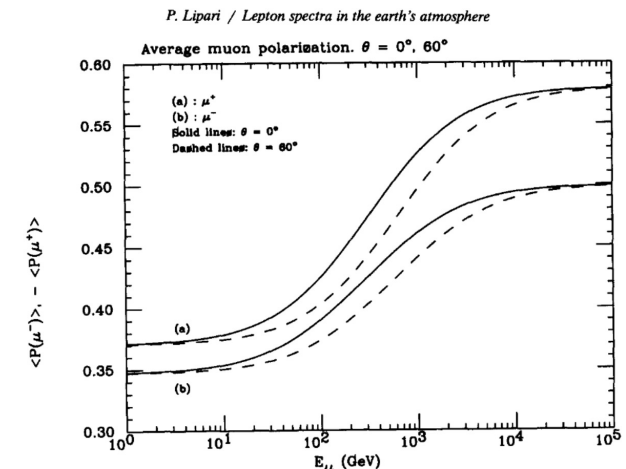
Fig. 1. Polarization of the muon fluxes at sea level. The 4 curves refer to μ^+ and μ^- , at two values of the zenith angle: $\theta = 0^\circ$ and $\theta = 60^\circ$.

Muons come from weak decays that violate parity



Magnetic moment anti-oriented in the direction of muons velocity

208



“lodacity”
 $\langle \vec{\mu} \cdot \vec{v} \rangle < 0$

Fig. 1. Polarization of the muon fluxes at sea level. The 4 curves refer to μ^+ and μ^- , at two values of the zenith angle: $\theta = 0^\circ$ and $\theta = 60^\circ$.

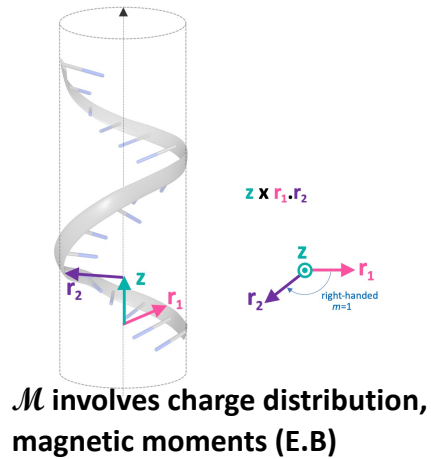
Connection between mutability and the magnetic moment

Globus & Blandford
(ApJL 895 L11, [arXiv:2002.12138](https://arxiv.org/abs/2002.12138))

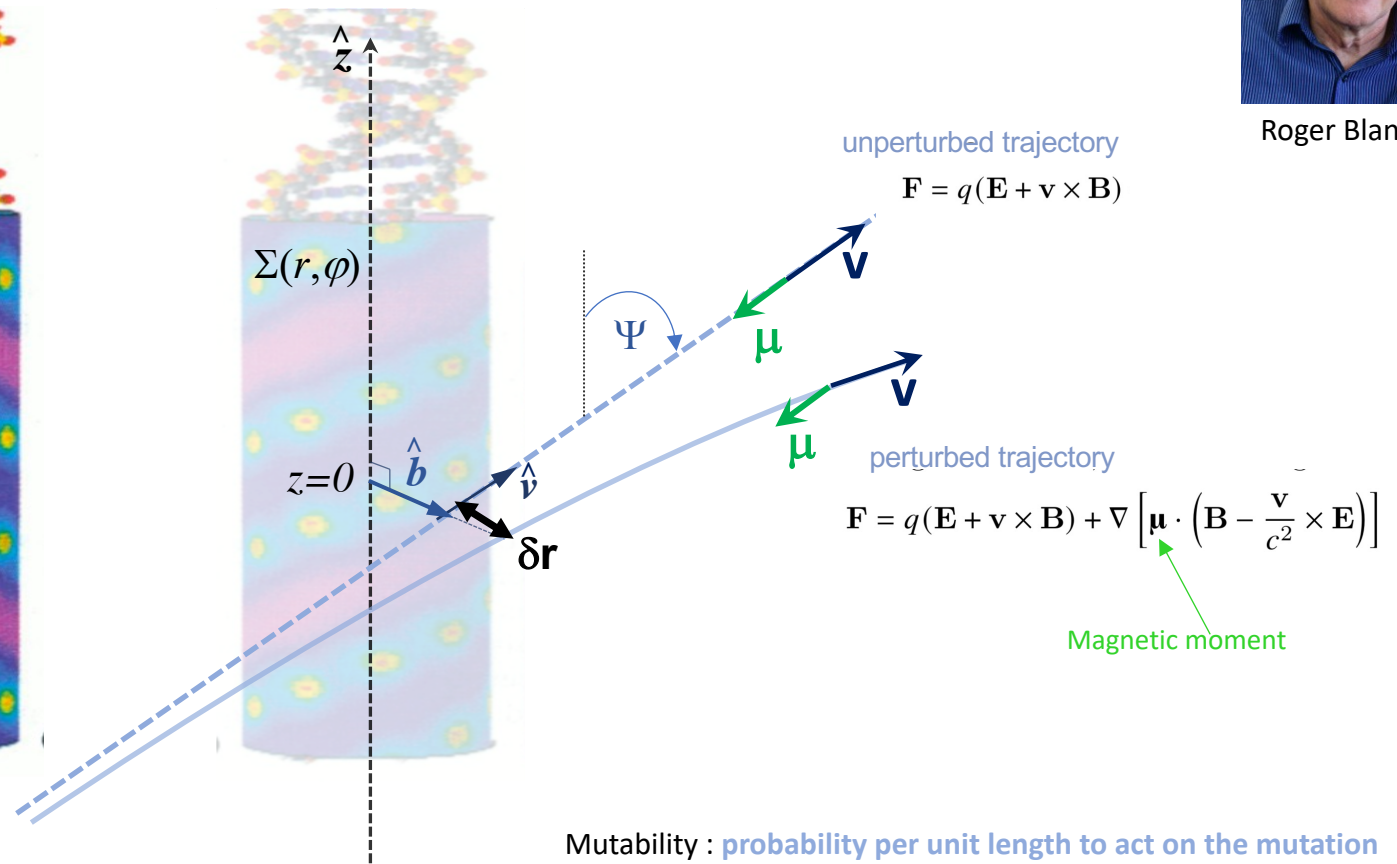
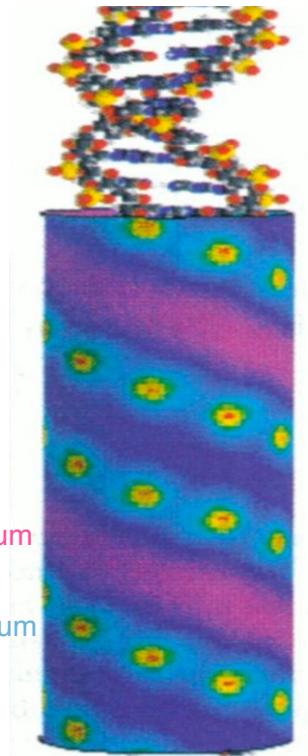


Roger Blandford

\mathcal{M} Molecular chirality



potential minimum
potential maximum

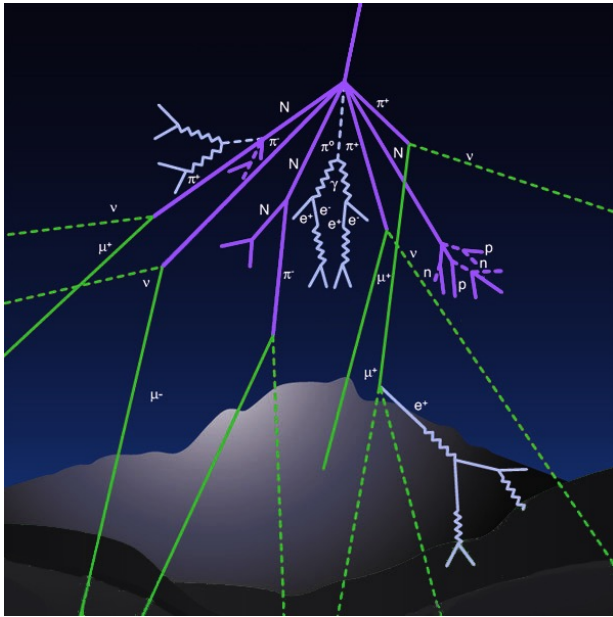


- Follow cosmic ray trajectory perturbatively
- Treat ionization as proxy for mutation
- Effect finite but small, remains after averaging over all directions
- Present calculation is classical, needs to be treated quantum mechanically
- Trajectories that remain longer within the DNA potential have higher mutation probability

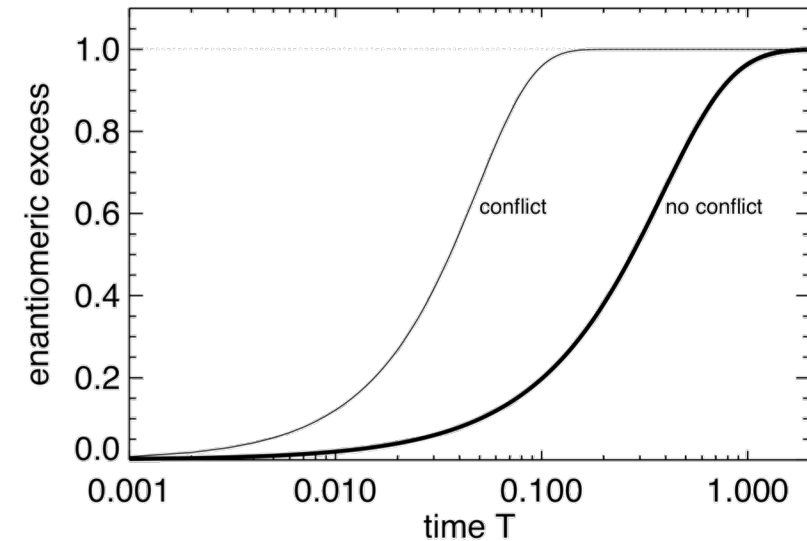
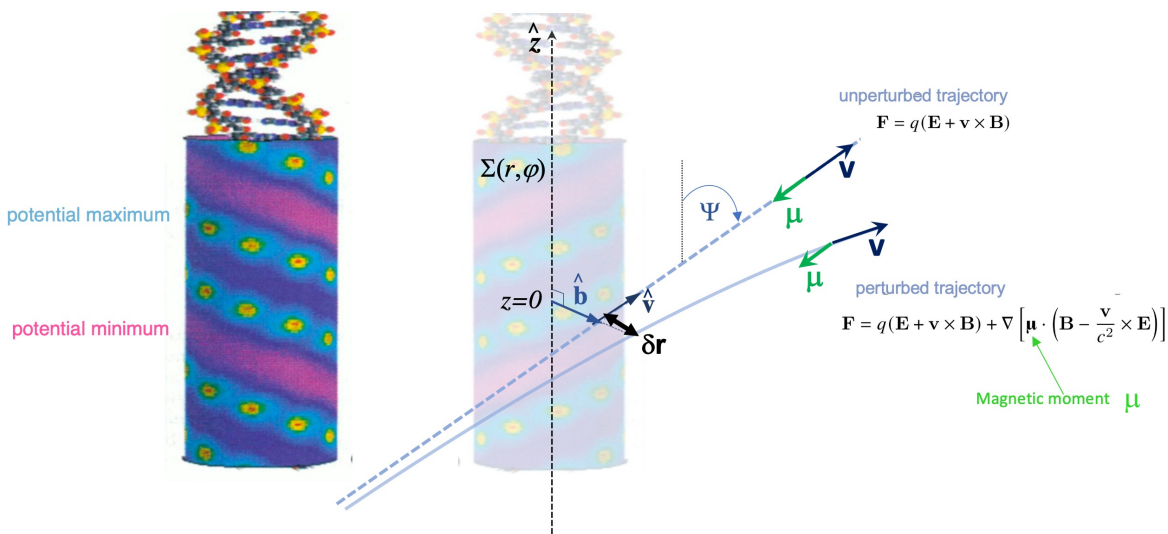
Mutability : **probability per unit length to act on the mutation**
= number density of electrons times the mutation cross section
= probability per unit length of CR trajectory that we get a mutation

The trans-biotic path to homochirality

Globus & Blandford
(ApJL 895 L11, [arXiv:2002.12138](https://arxiv.org/abs/2002.12138))



- Polarized cosmic rays (**muons**) acts as an evolutionary pressure
- Homochirality emerges on an evolutionary timescale
- Amplification of the small difference over many generations : trans-biotic
- Testable idea (laboratory experiments)
- Depends on the environment



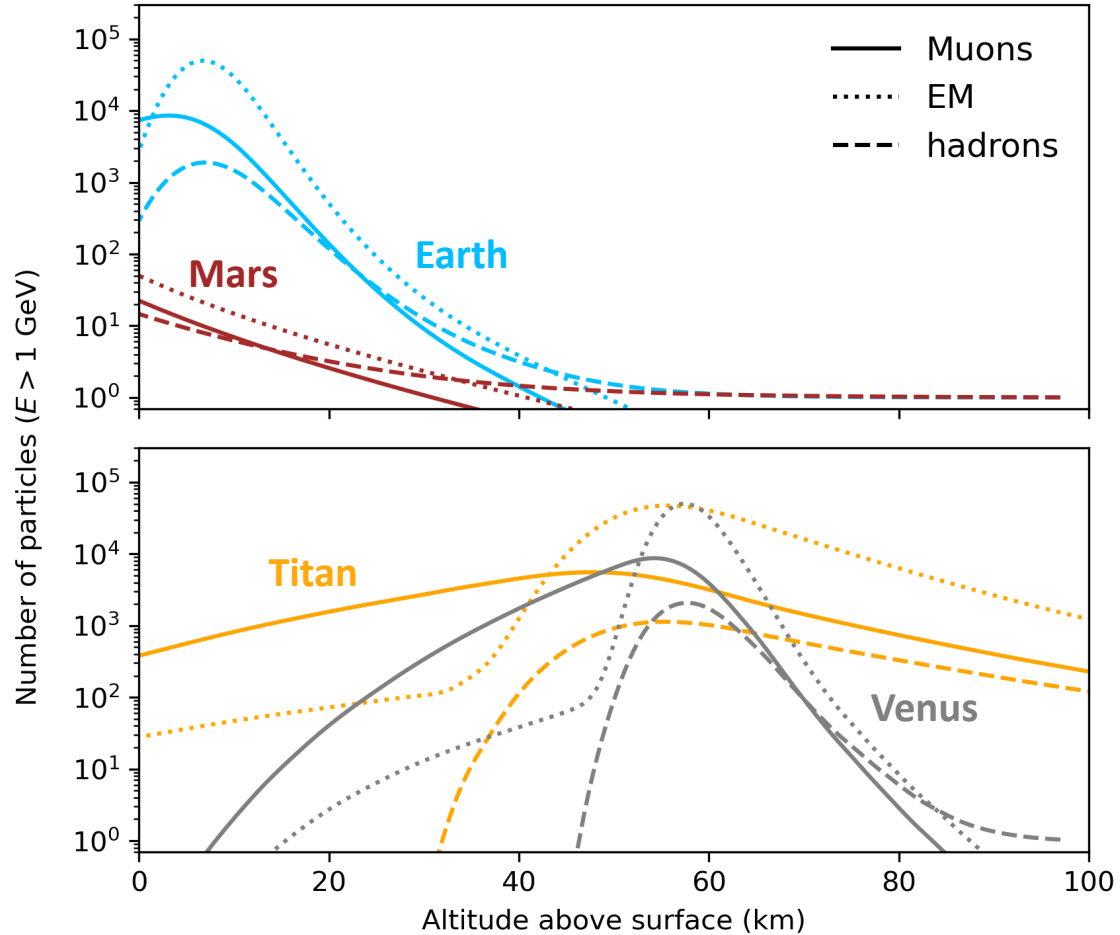
Extraterrestrial cosmic showers

Globus, Fedynitch, Blandford
(ApJ 910 85, [arXiv:2101.00530](https://arxiv.org/abs/2101.00530))



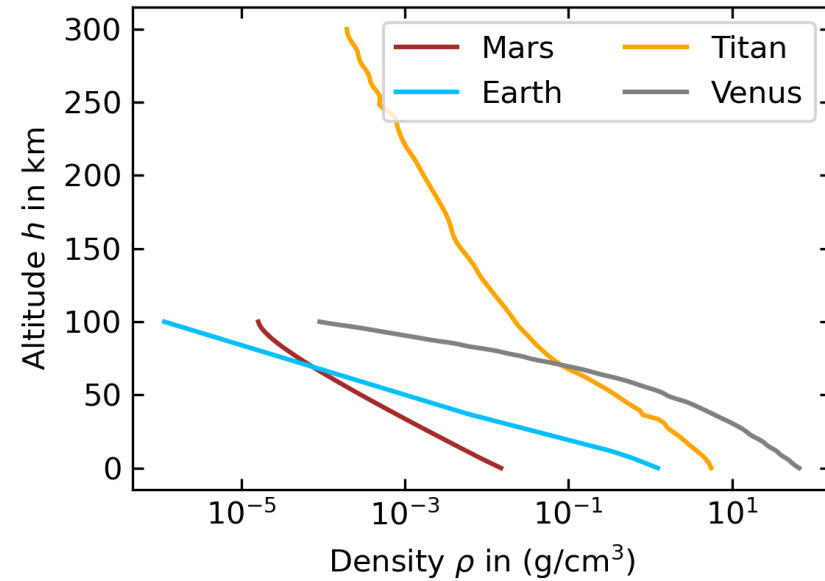
Anatoli Fedynitch

Extraterrestrial cosmic ray showers (1 PeV proton)



Particle rate: $\sim 10 \text{ m}^{-2}\text{yr}^{-1}$

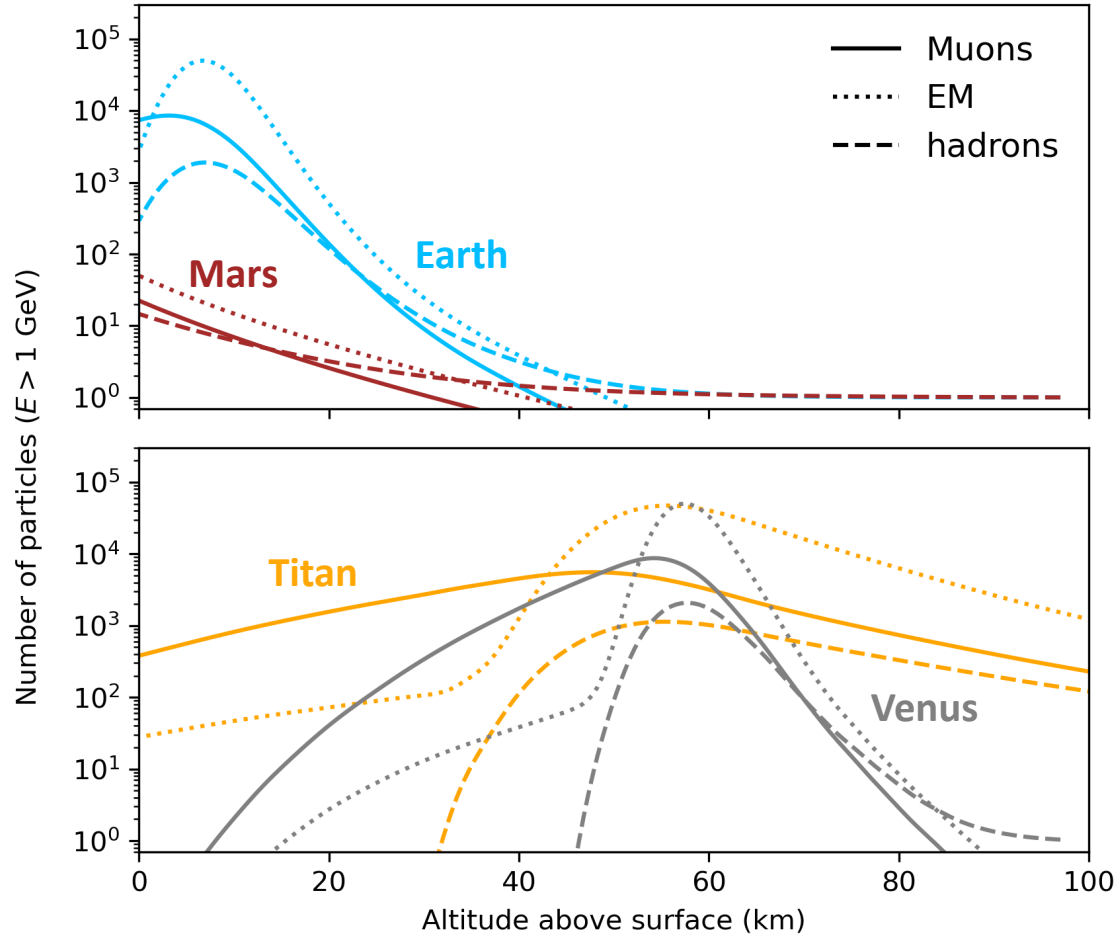
Atmospheric density



- Some facts:
 - **Earth**: $\sim 78\%$ N_2 + $\sim 21\%$ O_2 , $\langle A \rangle \sim 14.5$, $R \sim 6371$ km
 - **Mars**: $> 95\%$ CO_2 , $\langle A \rangle \sim 15.1$, $R \sim 3389$ km
 - **Titan**: $> 98\%$ N_2 , $\langle A \rangle \sim 14.4$, $R \sim 2574$ km
 - **Venus**: $> 96\%$ CO_2 , $\langle A \rangle \sim 14.1$, $R \sim 6050$ km

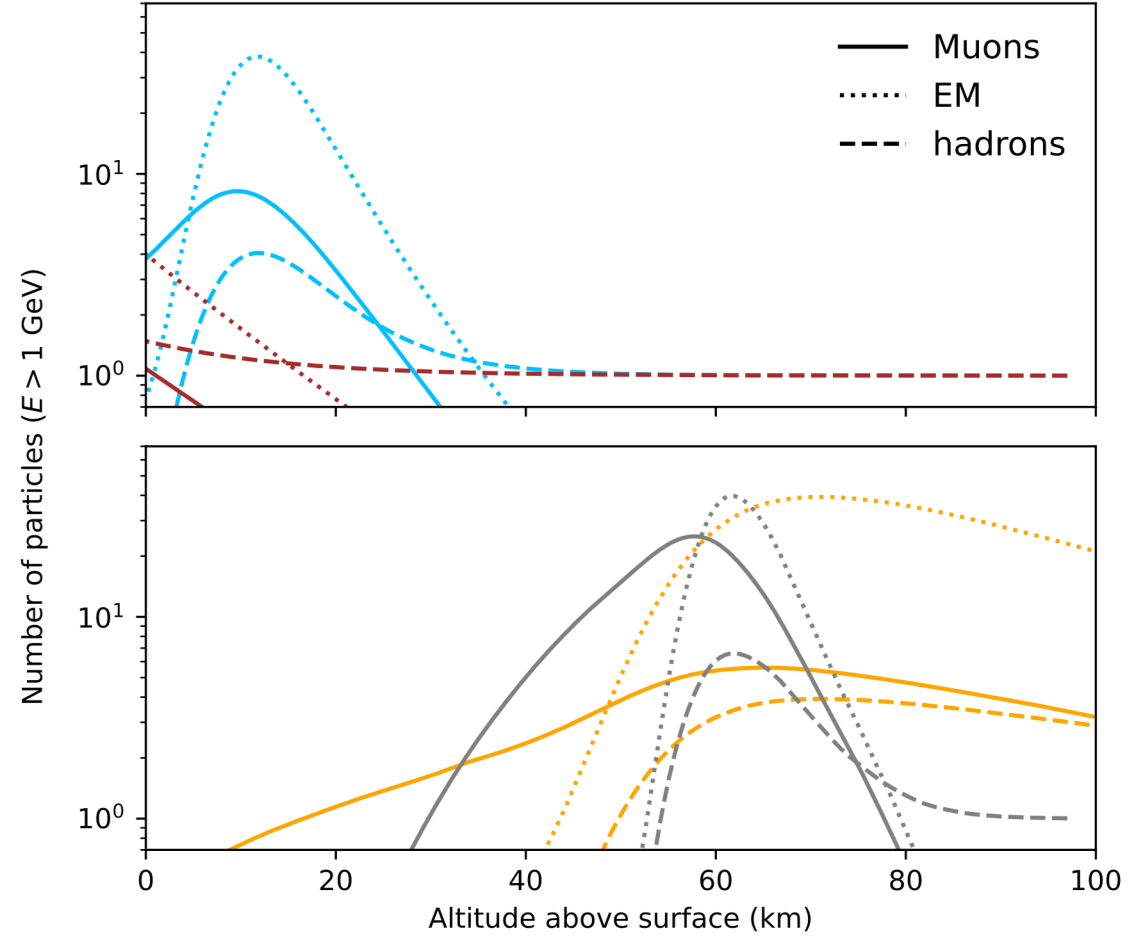
PeV (SNe) vs. TeV (T Tauri)

Extraterrestrial cosmic ray showers (10^{15} eV proton)



Particle rate: $\sim 10 \text{ m}^{-2}\text{yr}^{-1}$

Extraterrestrial cosmic ray showers (10^{12} eV proton)



Particle rate: $1 \text{ m}^{-2}\text{s}^{-1}$

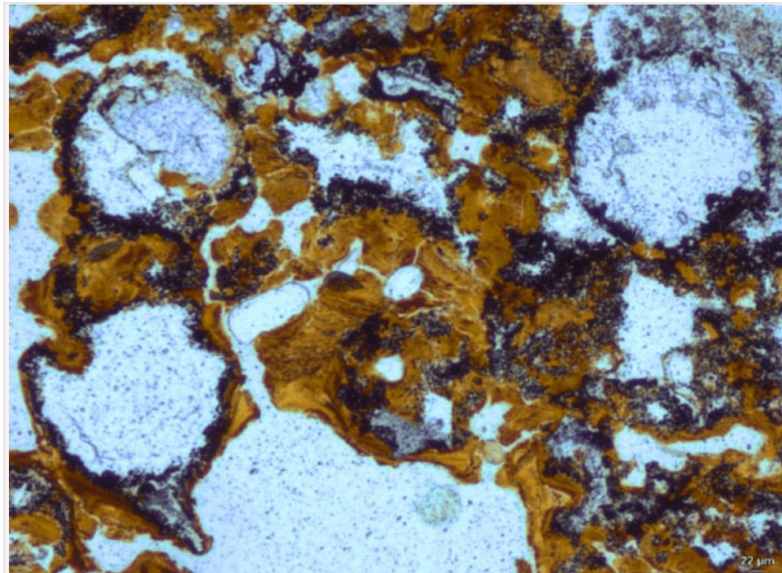
Common origin of life on Earth and Mars?

Earliest Signs of Microbial Life on Land Found in 3.48-Billion-Year-Old Hot Spring Deposits

May 10, 2017 by News Staff / Source

« Previous | Next »

Fossil evidence of early microbial life has been found in ancient hot spring deposits in the Dresser Formation in the Pilbara Craton, Western Australia, that date back approximately 3.48 billion years. A [paper](#) reporting this discovery is published in the journal *Nature Communications*.



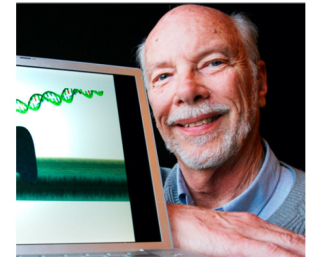
Spherical bubbles preserved in 3.48 billion-year-old hot spring deposits in the Dresser Formation provide evidence for early microbial life having lived on land. Image credit: University of New South Wales.

gun on the Red Planet. But if life on Earth originated in terrestrial hot springs, it could have also begun on Mars, which had the hot spring ingredients of widespread volcanism and water. Indeed, in 2008 the Spirit rover discovered 3.65-billion-year-old hot spring deposits in the Columbia Hills on Mars, about the same age as our Dresser hot springs, which did a great job of preserving early evidence for life on Earth.

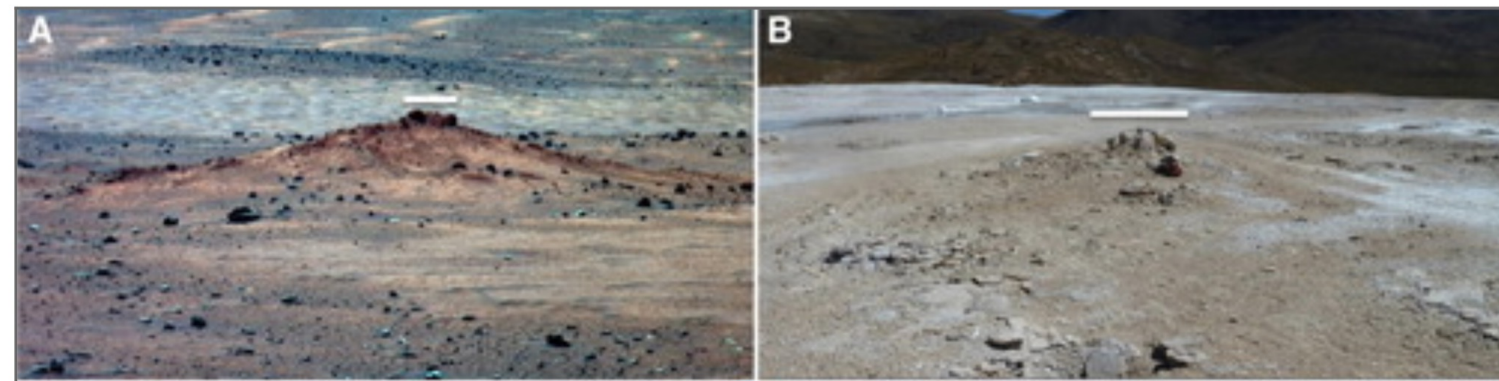
Van Kranendonk, Deamer, Djokic, 2020



Hot spring hypothesis
Deamer & Damer, 2020

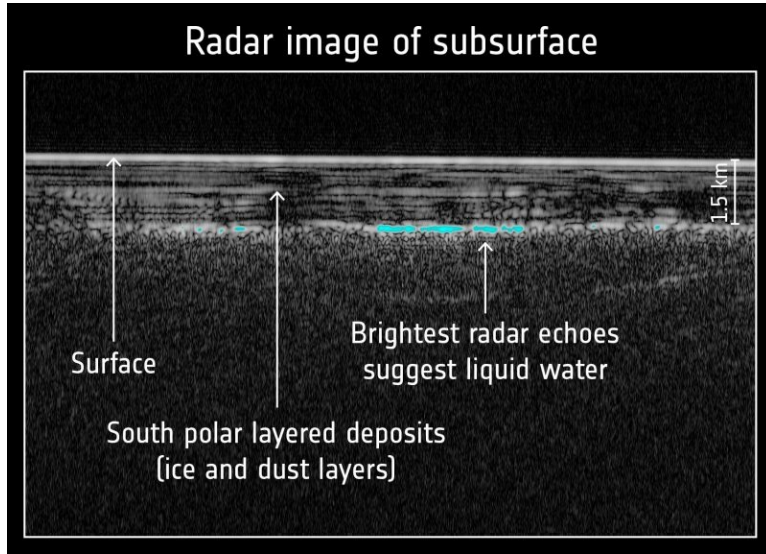


David Deamer



Pioneer Mound resembles hot spring vent mounds of comparable size on Earth. White bar in each image represents ~2 m.
(A) Pioneer Mound shown in Pancam false color image from sol 1860 (P2561).
(B) Extinct hot spring mound at Puchuldiza, Chile.

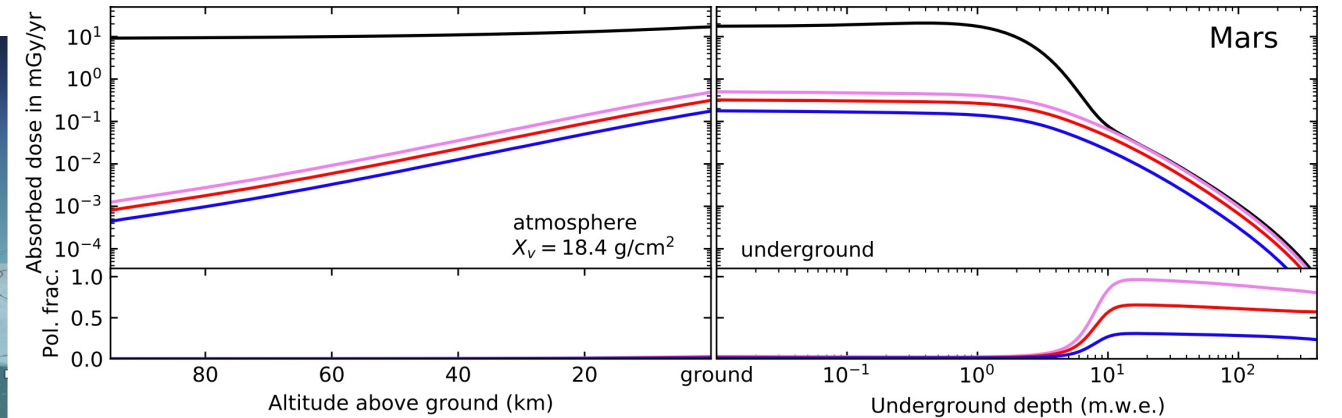
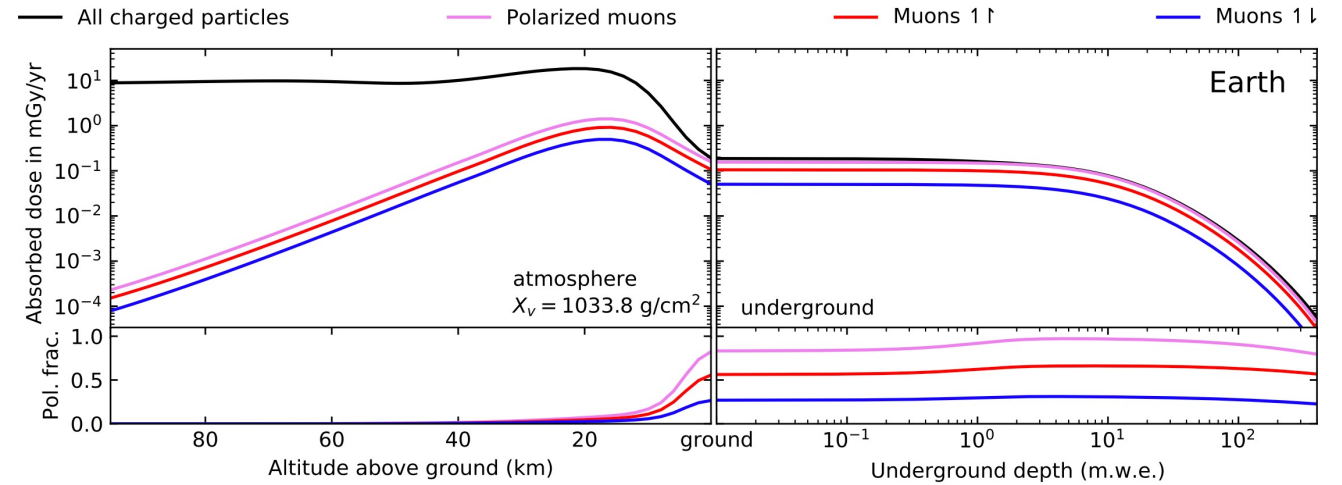
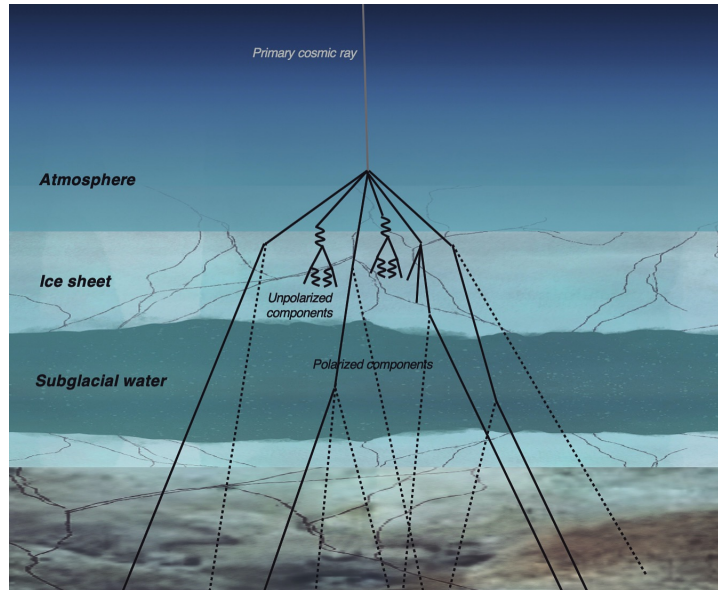
Cosmic-ray spin-polarized radiation doses - Mars



ESA's [Mars Express](#)

July 25, 2018

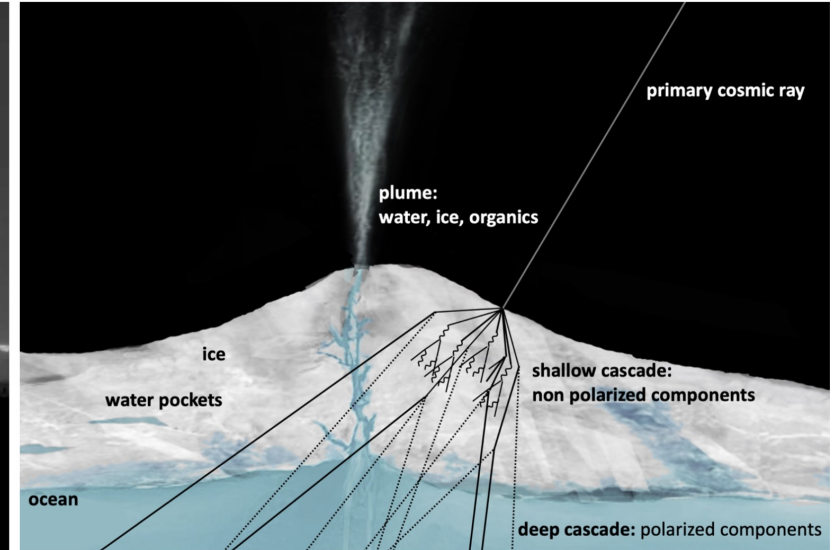
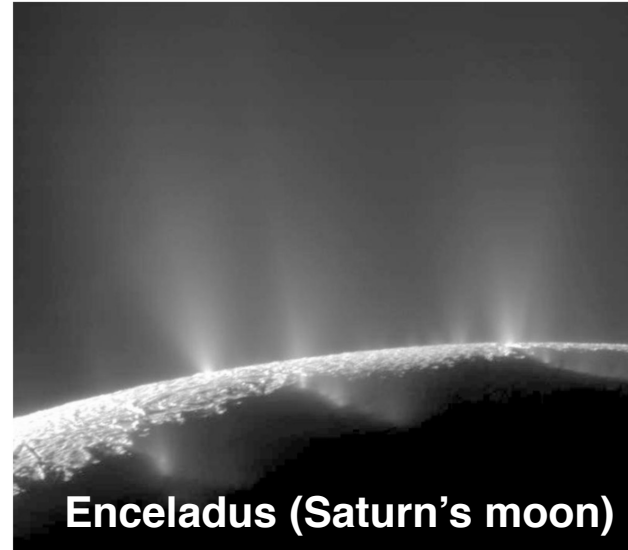
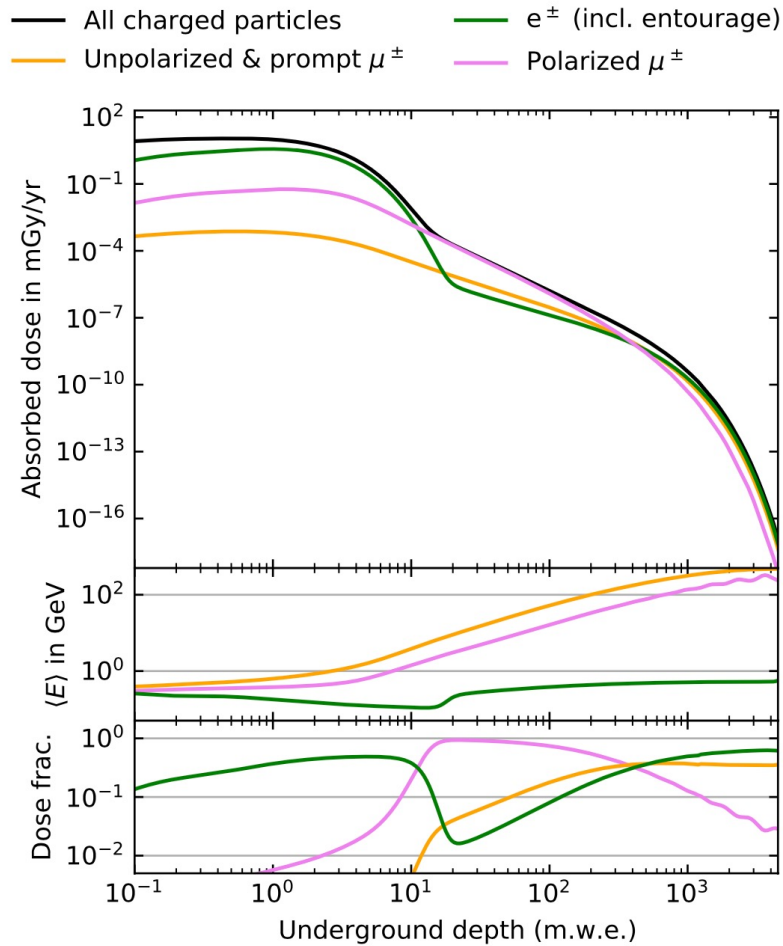
1st evidence for a subsurface liquid lake on Mars. If it exists, this lake is likely salty and cold, but possibly habitable for some microorganisms.



Globus, Fedynitch, Blandford
(ApJ 910 85, [arXiv:2101.00530](#))

Life on icy moons or asteroids

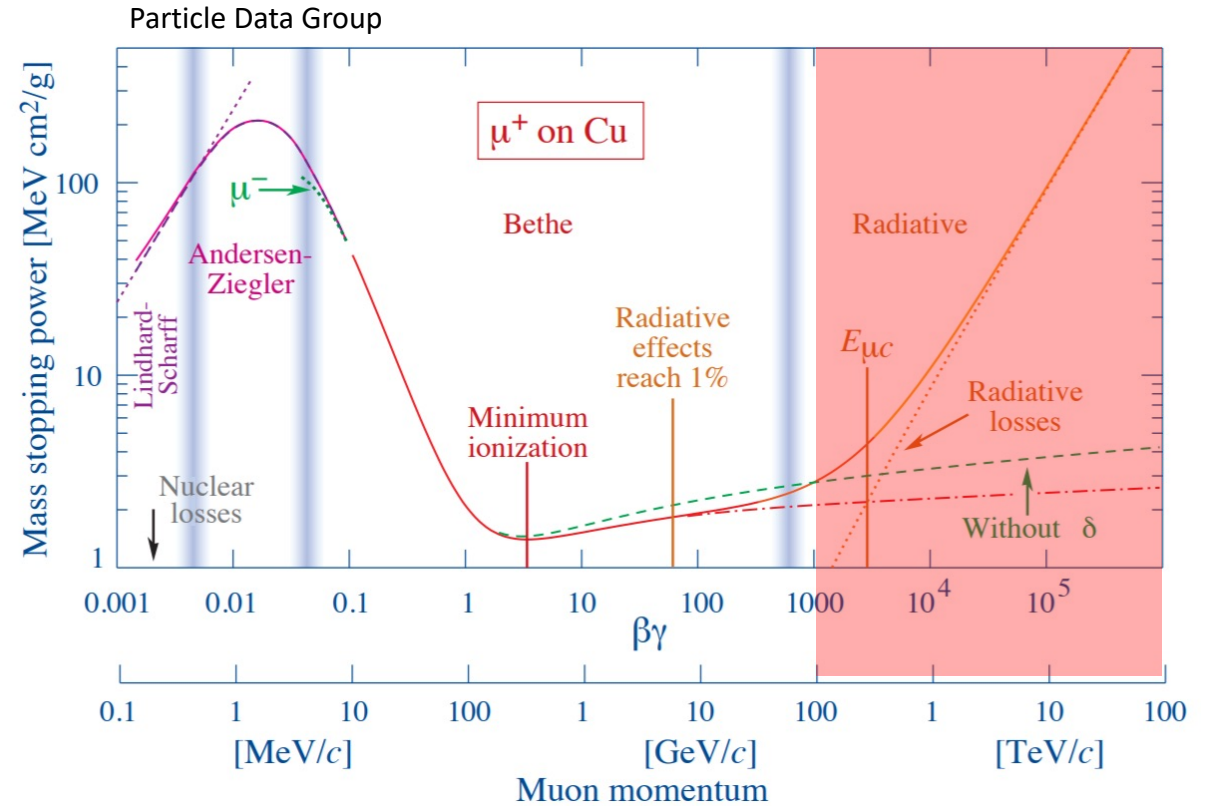
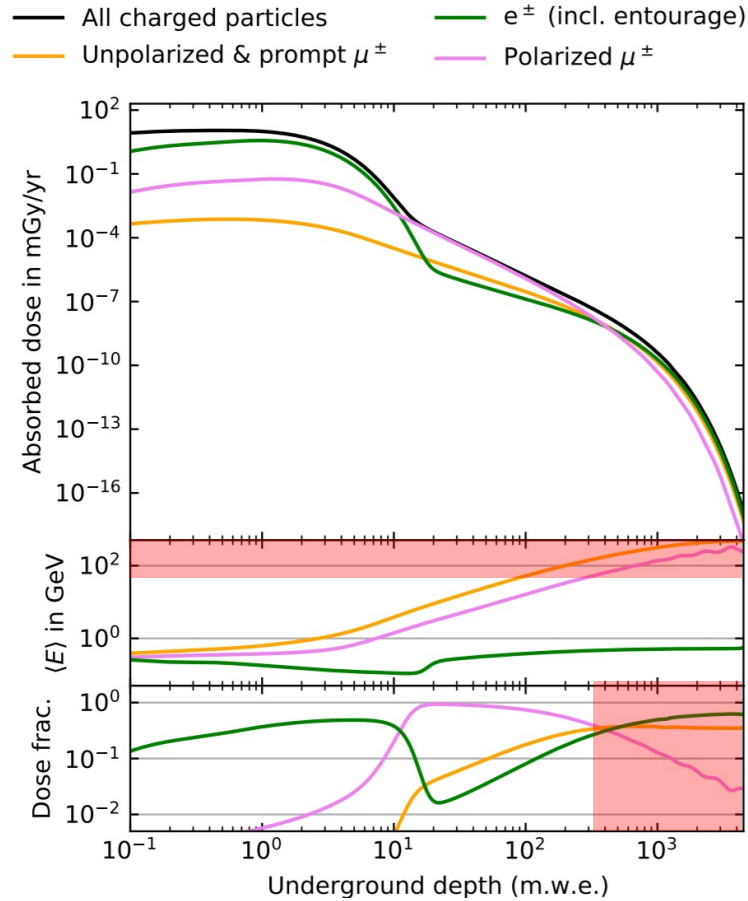
Globus, Fedynitch, Blandford
(ApJ 910 85, [arXiv:2101.00530](https://arxiv.org/abs/2101.00530))



- On icy moons, like Enceladus, life may have emerged in the sub-surface oceans
- Environment close to surface cold
- However, polarized doses deep-underground are low
- Polarization is screened electromagnetically
- Salty water is a source of stronger natural radiation, such as ^{40}K

Deep underground: screening by bremsstrahlung

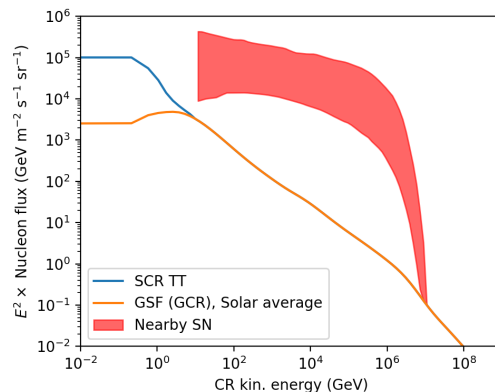
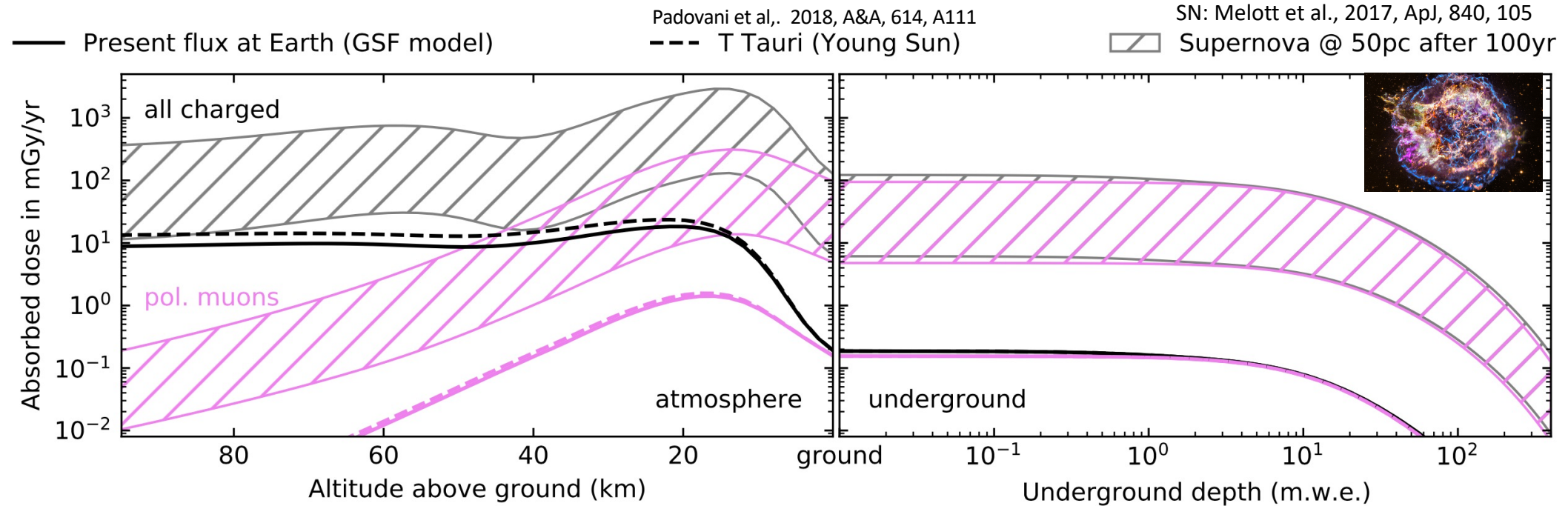
Globus, Fedynitch, Blandford
(ApJ 910 85, [arXiv:2101.00530](https://arxiv.org/abs/2101.00530))



Very deep underground, $\langle E_\mu \rangle \sim 100$ GeV
 \rightarrow unpolarized electromagnetic entourage

Phases of boosted “polarized” radiation

Globus, Fedynitch, Blandford
(ApJ 910 85, [arXiv:2101.00530](https://arxiv.org/abs/2101.00530))



- Compared to other natural radiation sources, muon doses may appear weak
- Solar activity, even in the most extreme phases, has no impact on this scenario
- During nearby SN explosions, the rate can be boosted for 100 to 10,000 of years

“Conclusions”

- **The origin of homochirality is a fundamental problem connecting biology, chemistry and physics**
 - Chance or necessity ?
 - Prebiotic or biotic ?
 - In which environments?
- **Cosmic rays ?**
 - Muons or electrons ?
 - Ionization or charge ratio ?
 - Different environments ?
- **Mutation and evolution ?**
 - Homochiralization timescale ?
 - Conflict necessary ?
- **Testable idea**
 - Sample return from surfaces and subsurfaces
 - Experiments (irradiate biological samples with polarized beams)
 - Interstellar chirality? (c.f. propylene oxide?)

ONLINE

ICRC 2021

THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany

Thank you

