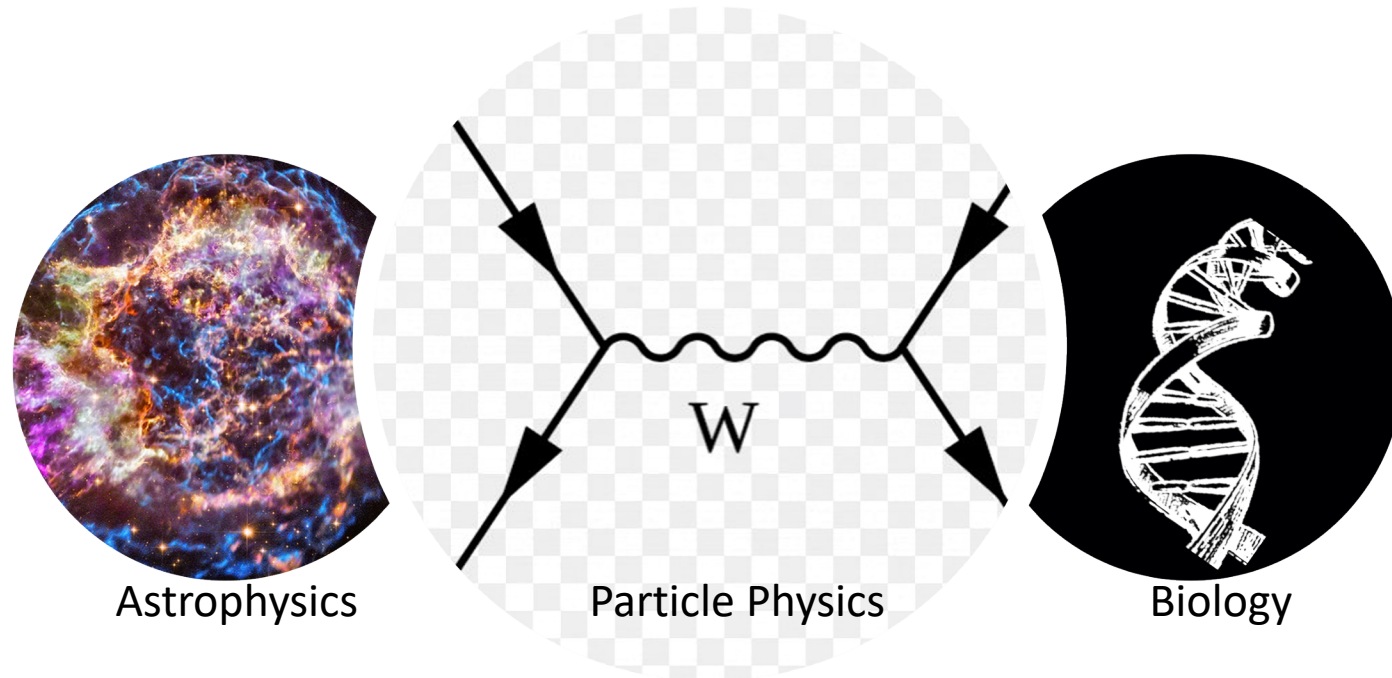


Cosmic Rays and The Chiral Puzzle of Life

Noémie Globus

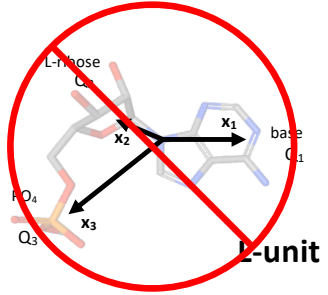
Collaborators: Roger Blandford, Eefei Chen, David Deamer, Anatoli Fedynitch, David Kliger



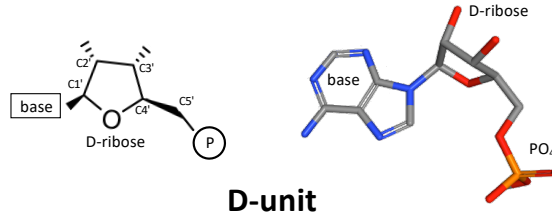
APC colloquium

Life's building blocks

Nucleic acids

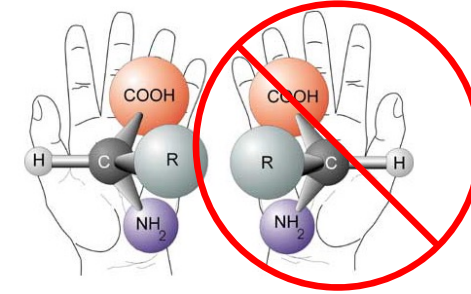


$$\mathcal{M} = \hat{x}_1 \times \hat{x}_2 \cdot \hat{x}_3$$

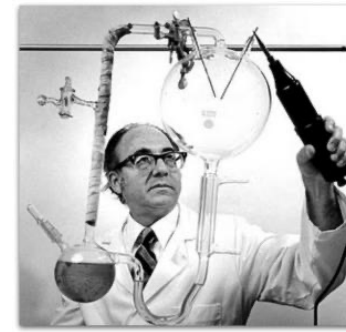
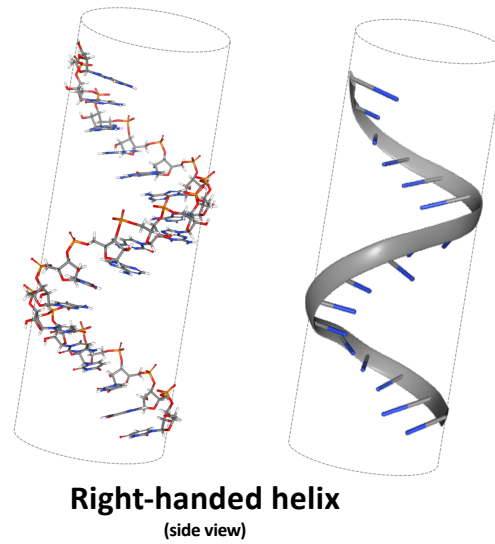
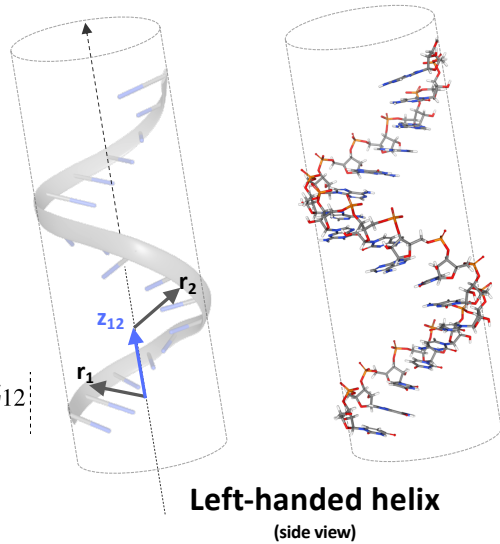


Mirror

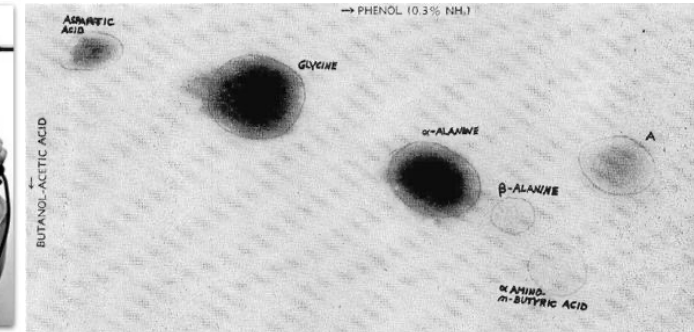
Amino acids



- **Amino acids** synthesized in laboratory always appear always in 50-50 proportions
- **For living organisms, the two mirror images are NOT equivalent: biological homochirality**



The Miller-Urey experiment (1952)



In Vino Veritas?



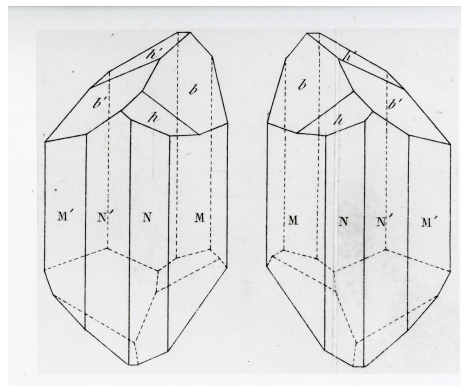
1769: Carl Wilhelm Scheele examines tartar (deposited in casks during wine fermentation); isolates tartaric acid



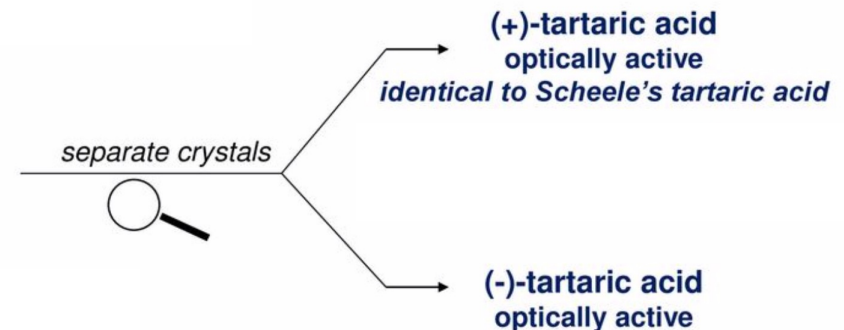
1815: Optical activity was first observed by Jean-Baptiste Biot. The direction of plane-polarized light changes when it passed through certain natural substances (->**molecular basis**)



1848: Experiments by Louis Pasteur on optical activity of tartaric acid



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



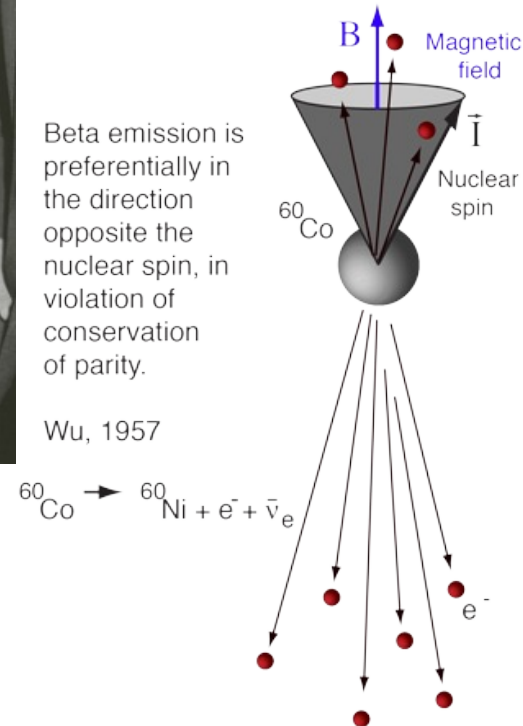
Ces actions dissymétriques, placées peut-être sous des influences cosmiques, résident-elles dans la lumière, dans l'électricité, dans le magnétisme, dans la chaleur? Seraient-elles en relation avec le mouvement de la terre, avec les courants électriques par lesquels les physiciens expliquent les pôles 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 (the world is different from the mirror world!)



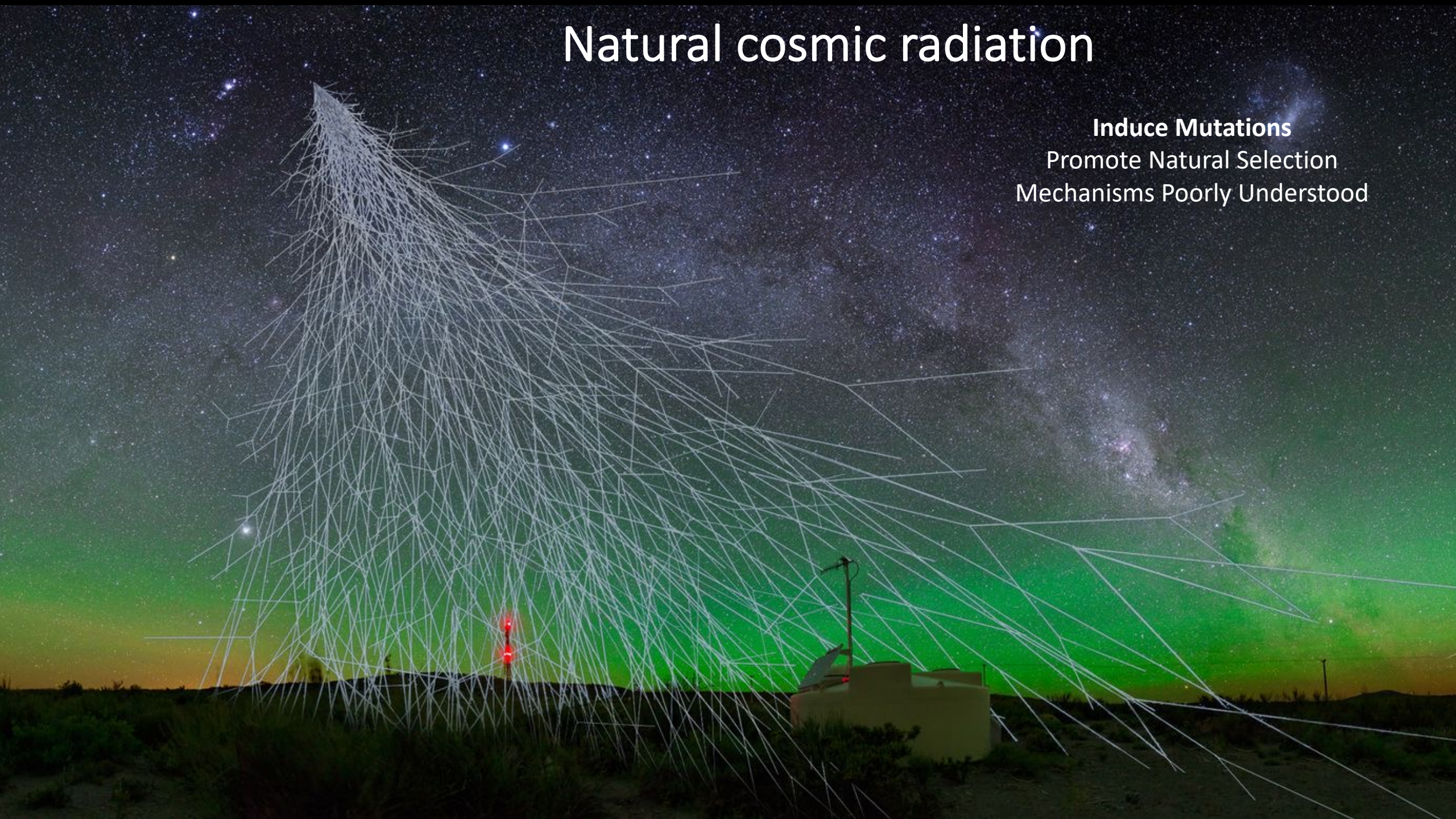
Chien-Shiung Wu in 1958



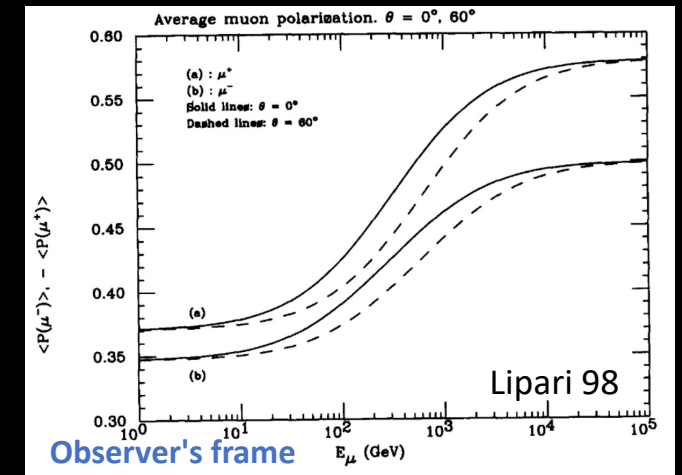
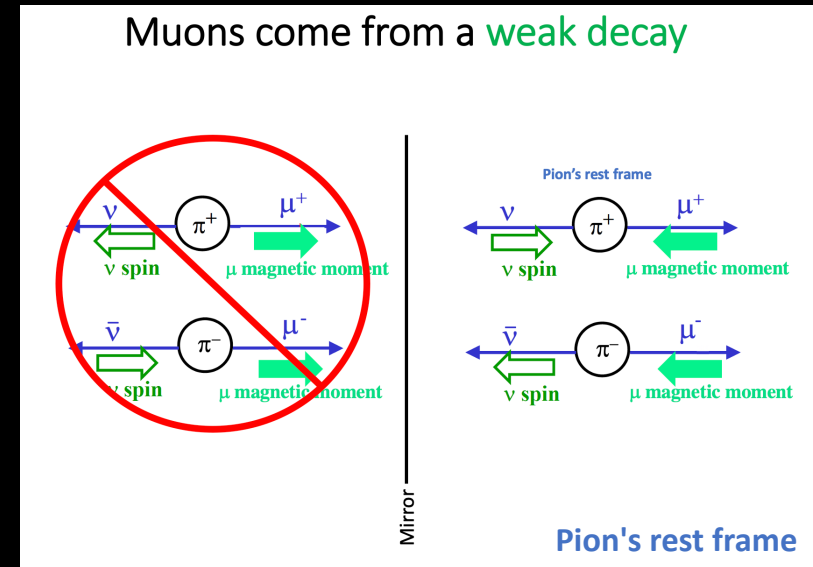
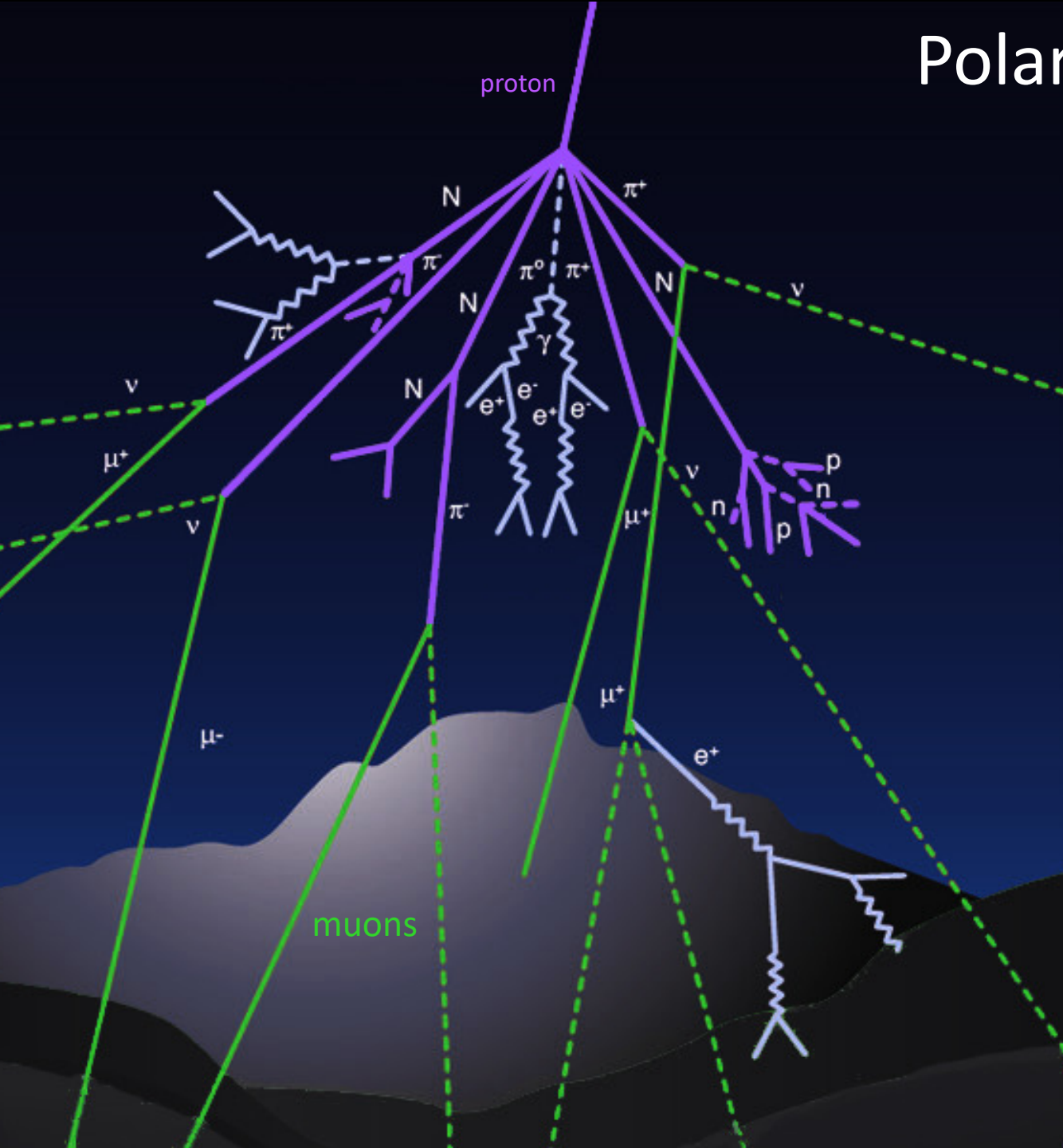
Wu, 1957

Natural cosmic radiation

Induce Mutations
Promote Natural Selection
Mechanisms Poorly Understood

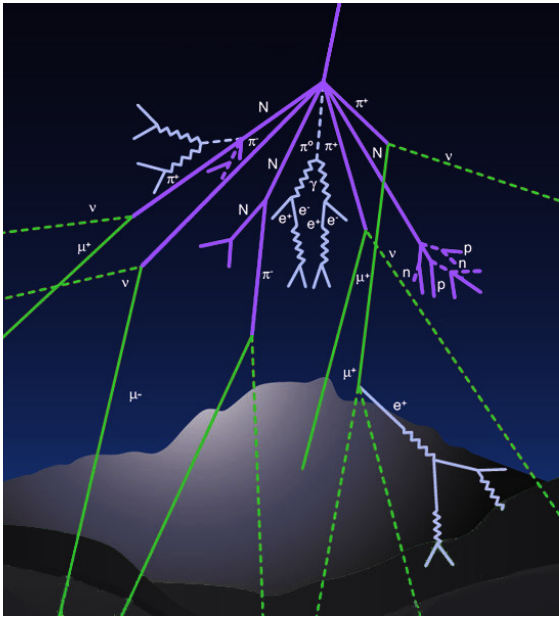


Polarization of the muon flux



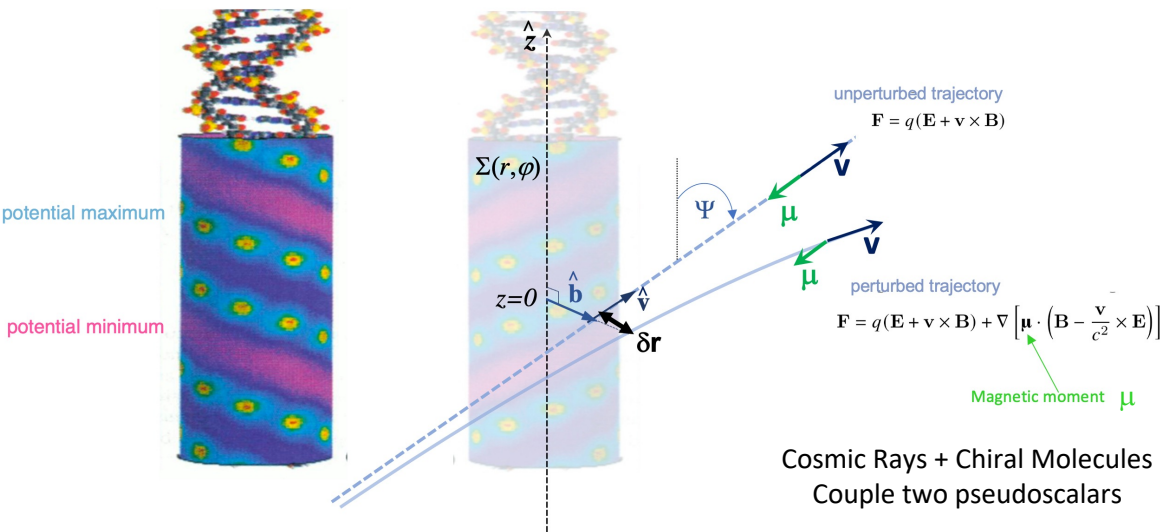
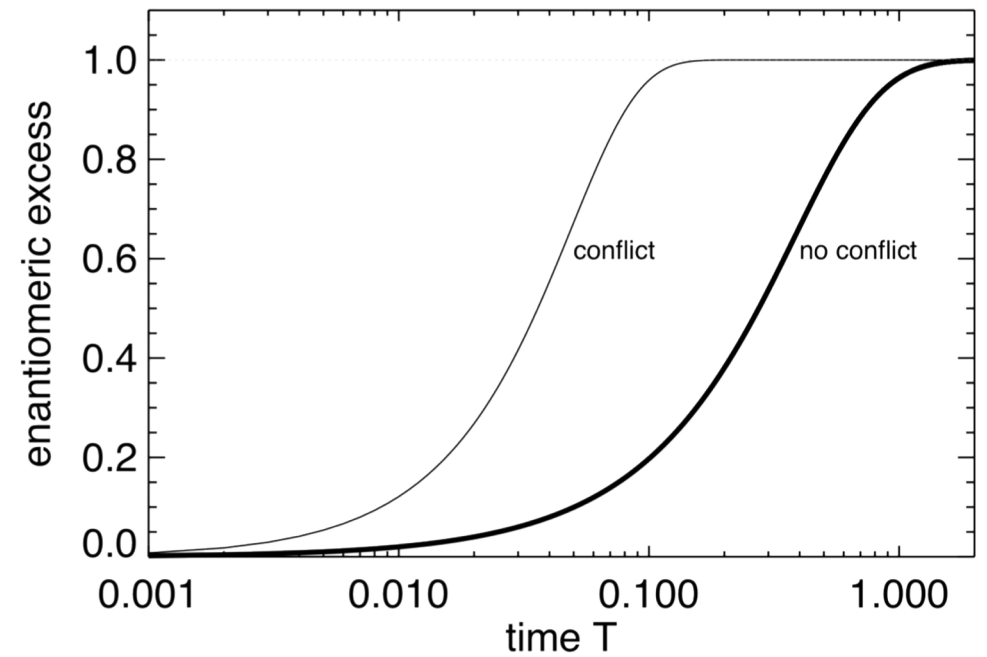
A cosmic ray origin for biological homochirality

Globus & Blandford
2020 ApJL 895 L11



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

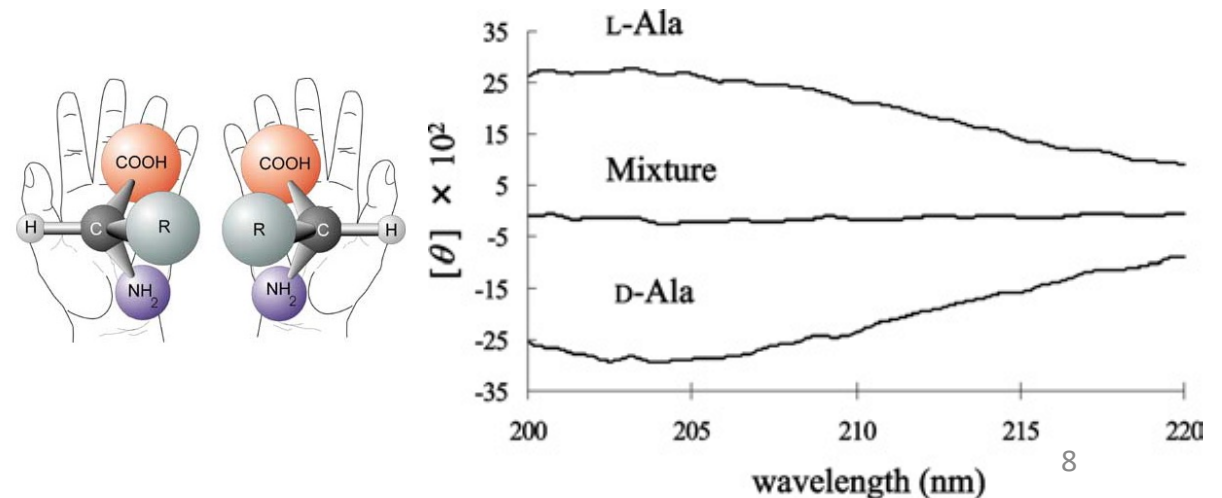
homochiralization timescale



Approaches to homochirality (prebiotic)

	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)	$e.e. = \frac{D-L}{D+L} \cdot 100$ (theory only : 10^{-17})	yes	Salam, Quack ...
	Ultra-violet circularly polarized light (UV CPL)	Differential destruction	Depends on chirality of light and photon energy	e.e. ~ 2.5 %	no	Vester & Ulbricht processes; De Marcellus, D'Hendecourt...
	Irradiation with β -decay products	Differential destruction	Depends on spin-polarization of radiation	e.e. \ll 1%	yes	Bonner...
	Low-energy (<10 eV) spin-polarized electrons	Enantioselective chemistry	Depends on spin-polarization of and electron energy	e.e. ~ 1%	no	Vester-Ulbricht processes; Rosenberg, Kessler,...

*need amplification mechanism: Autocatalytic models (Soai,...), non-enzymatic synthesis of nucleic acids from racemic mononucleotides inevitably tends toward homochiral structures (Ross & Deamer)



Approaches to homochirality (biological)

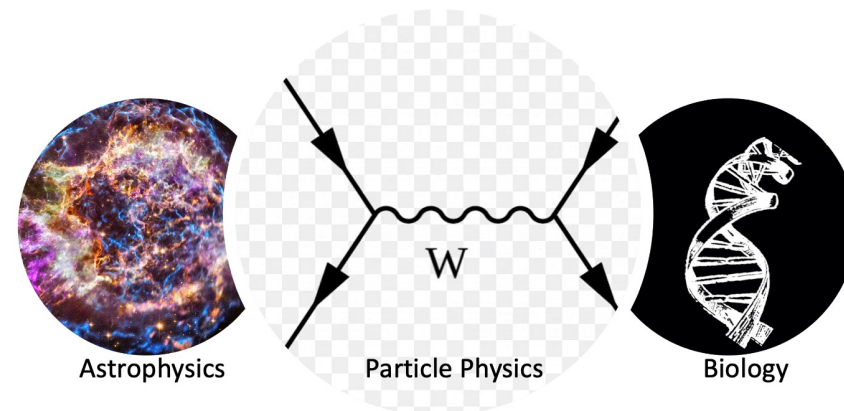
	Actor	Effect	Chiral preference	Magnitude	Involves W?	Authors
Pre-Biotic*	Parity Violating Energy Differences (PVED)	PVED-induced phase transition	Left-handed amino acids (in water)	$e.e. = \frac{D-L}{D+L} \cdot 100$ (theory only : 10^{-17})	yes	Salam, Quack ...
	Ultra-violet circularly polarized light (UV CPL)	Differential destruction	Depends on chirality of light and photon energy	e.e. ~ 2.5 %	no	Vester & Ulbricht processes; De Marcellus, D'Hendecourt...
	Irradiation with β -decay products	Differential destruction	Depends on spin-polarization of radiation	e.e. << 1%	yes	Bonner...
	Low-energy (<10 eV) spin-polarized electrons	Enantioselective chemistry	Depends on spin-polarization of and electron energy	e.e. ~ 1%	no	Vester-Ulbricht processes; Rosenberg, Kessler,...
*need amplification mechanism: Autocatalytic models (Soai,...), non-enzymatic synthesis of nucleic acids from racemic mononucleotides inevitably tends toward homochiral structures (Ross & Deamer)						
Biological	Low-energy (~eV) spin-polarized electrons	Chiral Induced Spin Selectivity (CISS)	Depends 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 ...
	Ultra-violet circularly polarized light (UV CPL)	Denaturing of biopolymers	Depends on chirality of light and photon energy	Not reported	no	Michaelian
	High-energy polarized muons or electrons	Enantioselective Mutagenesis	Depends on spin-polarization or "lodacity" (magnetic moment)	Not reported (theory only : $< 10^{-6}$)	yes	Globus & Blandford

Goal of this research

Goal: Understand if polarized radiation could act as a **chiral evolutionary pressure**

Two questions:

- How polarized radiation interacts with molecules ? (laboratory experiments/biophysics)
- What are the astrophysical sources of polarized radiation ? (astrophysics/ particle physics)

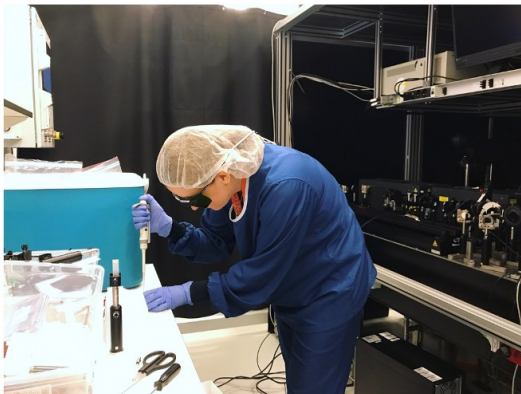
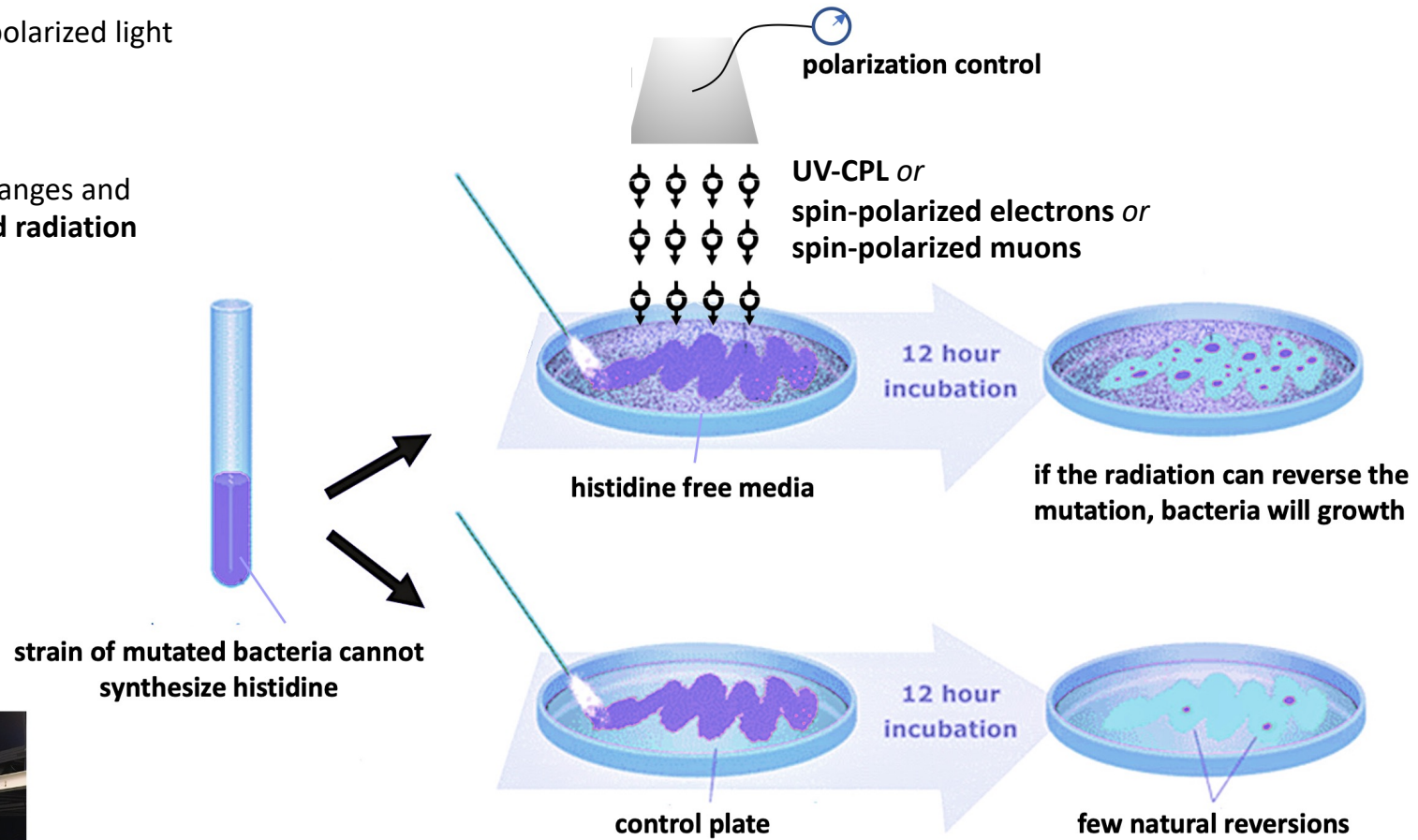


Experiments

Proposed tests: irradiate with polarized light

- single stranded DNA,
- double stranded DNA,
- bacteria,...

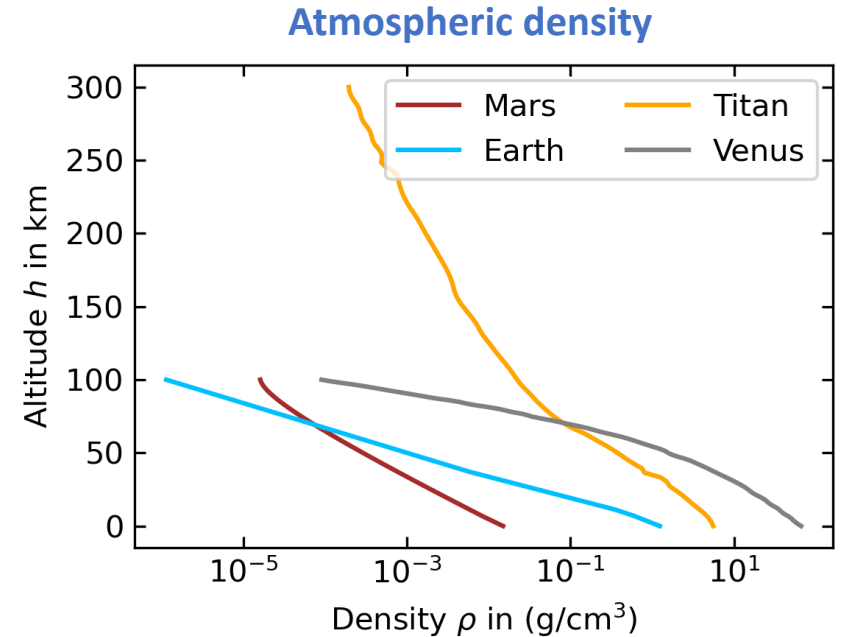
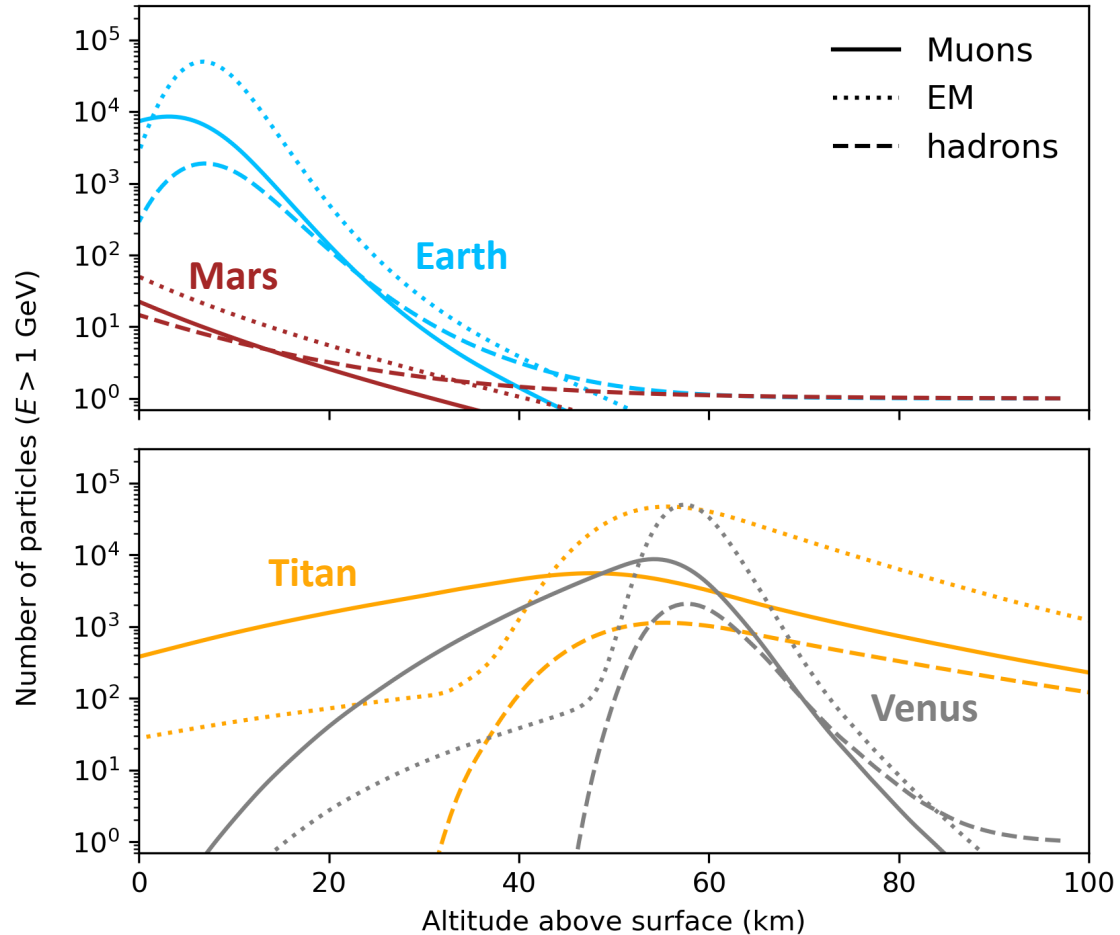
to understand the molecular changes and **biological response to polarized radiation**



Calculations of polarized doses: extraterrestrial cosmic showers

Globus, Fedynitch, Blandford
2021 ApJ 910 85

Extraterrestrial cosmic ray showers (1 PeV proton, $\sim 10 \text{ m}^{-2}\text{yr}^{-1}$)



- Some facts:
 - Earth: $\sim 78\% \text{ N}_2 + \sim 21\% \text{ O}_2$, $\langle A \rangle \sim 14.5$, $R \sim 6371 \text{ km}$
 - Mars: $> 95\% \text{ CO}_2$, $\langle A \rangle \sim 15.1$, $R \sim 3389 \text{ km}$
 - Titan: $> 98\% \text{ N}_2$, $\langle A \rangle \sim 14.4$, $R \sim 2574 \text{ km}$
 - Venus: $> 96\% \text{ CO}_2$, $\langle A \rangle \sim 14.1$, $R \sim 6050 \text{ km}$

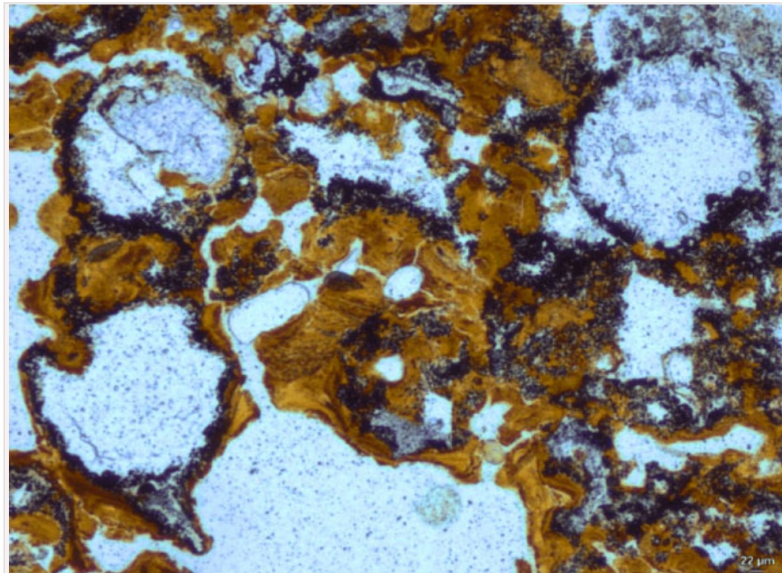
Common origin of life on Earth and Mars?

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*.



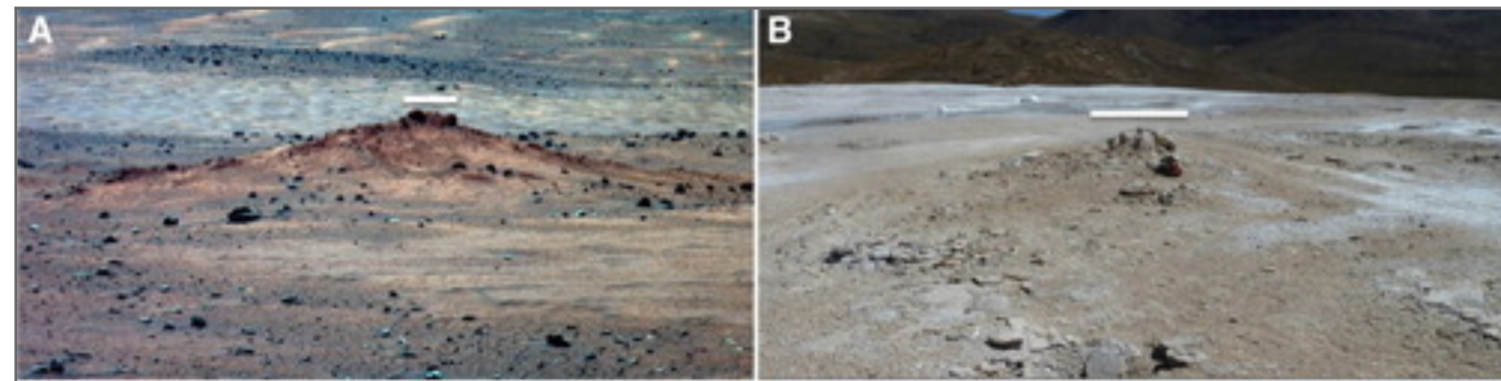
Spherical bubbles preserved in 3.48 billion-year-old hot spring deposits in the Dresser Formation provide evidence for early microbial life having lived on land. Image credit: University of New South Wales.

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

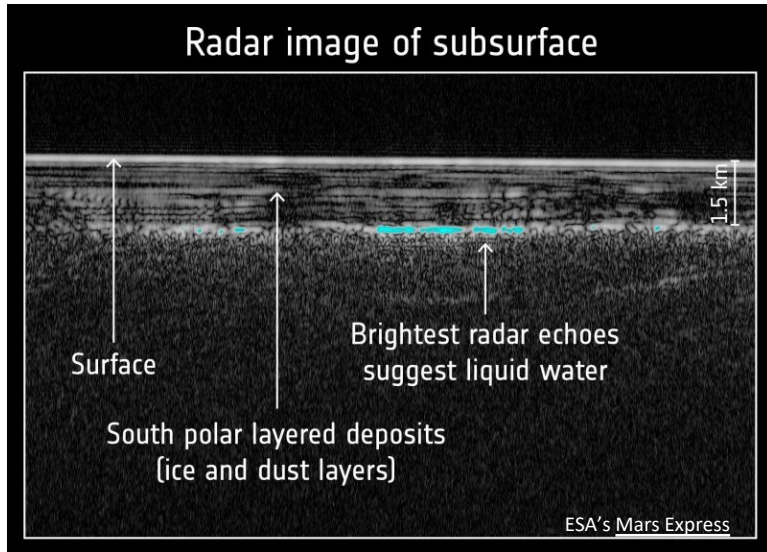


Hot spring hypothesis
Deamer & Damer, 2020

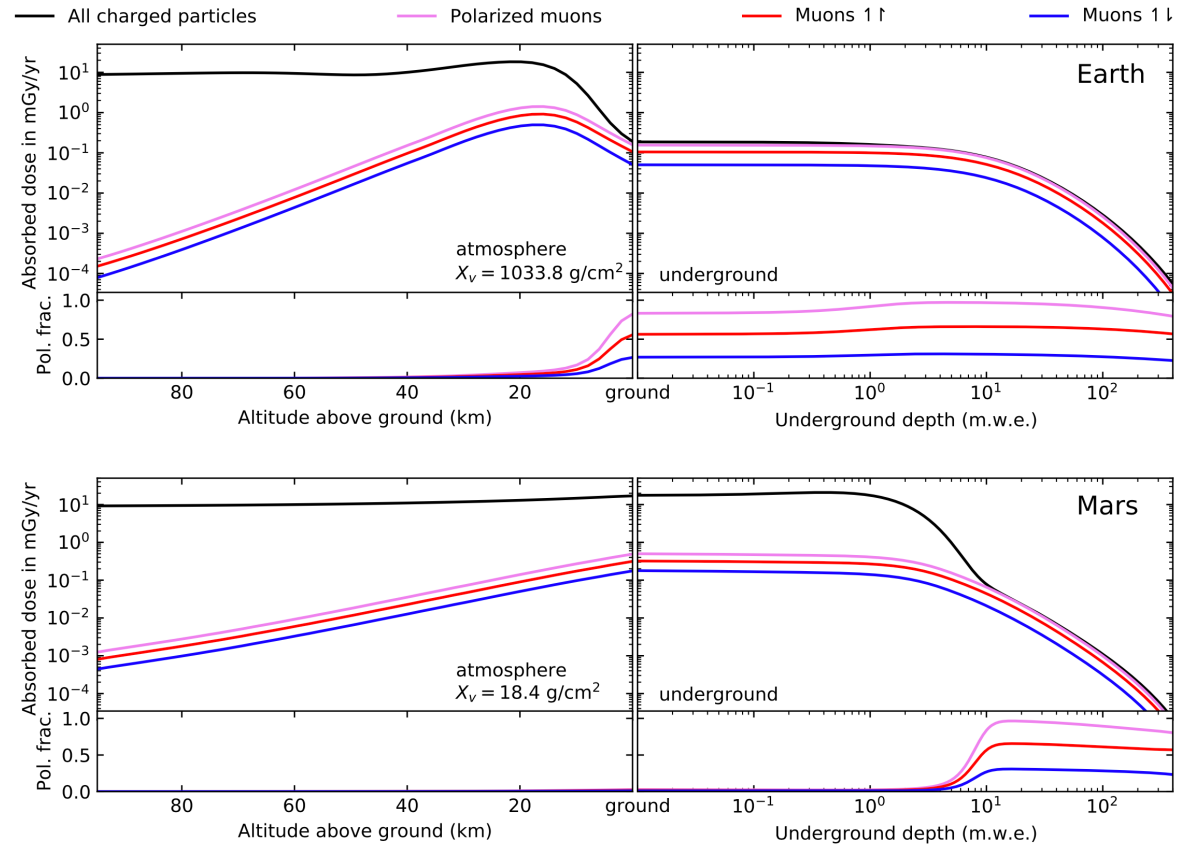
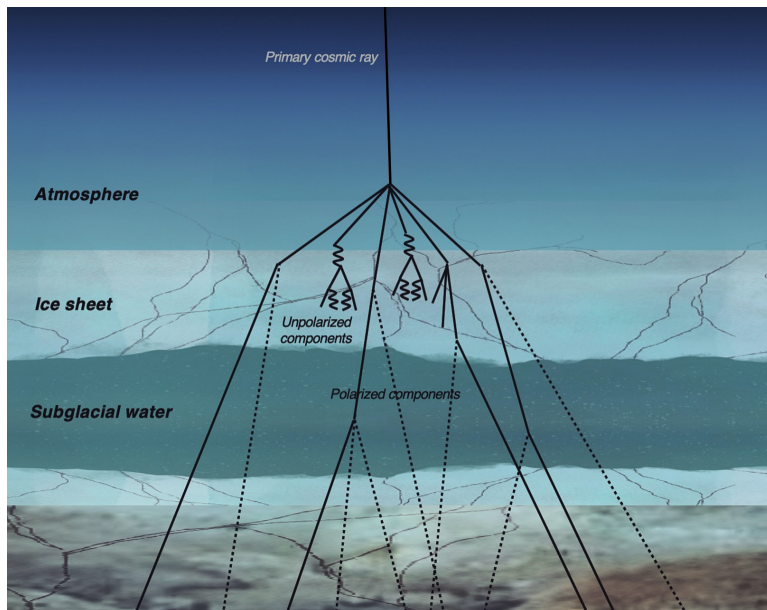


Pioneer Mound resembles hot spring vent mounds of comparable size on Earth. White bar in each image represents ~2 m.
(A) Pioneer Mound shown in Pancam false color image from sol 1860 (P2561).
(B) Extinct hot spring mound at Puchuldiza, Chile.

Spin-polarized radiation doses: Earth-Mars comparison

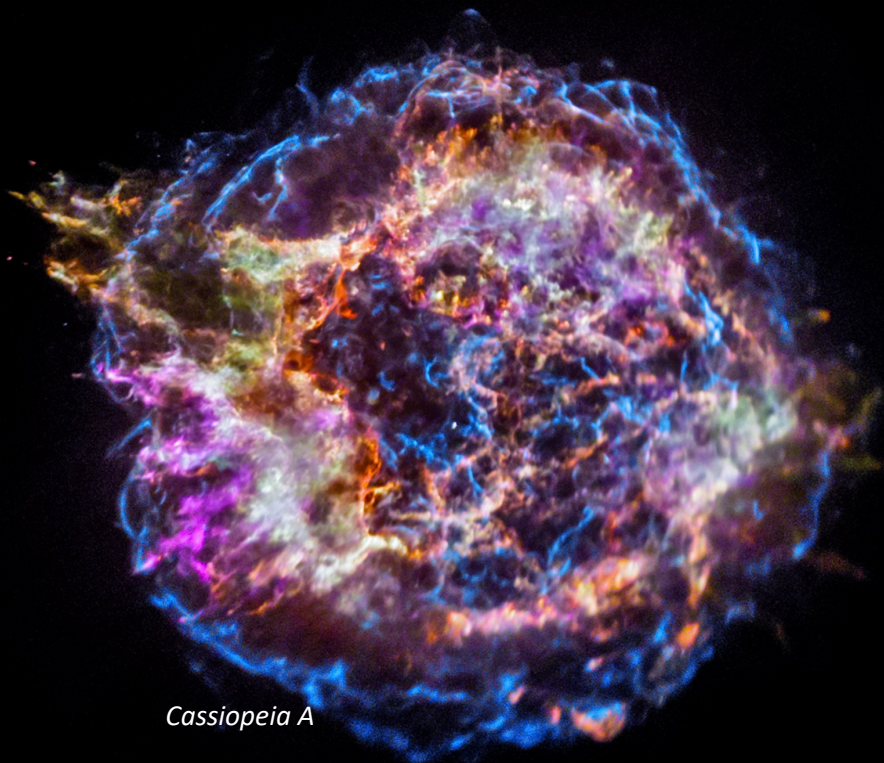


July 25, 2018
 1st evidence for a subsurface liquid lake on Mars. If it exists, this lake is likely salty and cold, but possibly habitable for some microorganisms.



Globus, Fedynitch, Blandford
 2021 ApJ 910 85

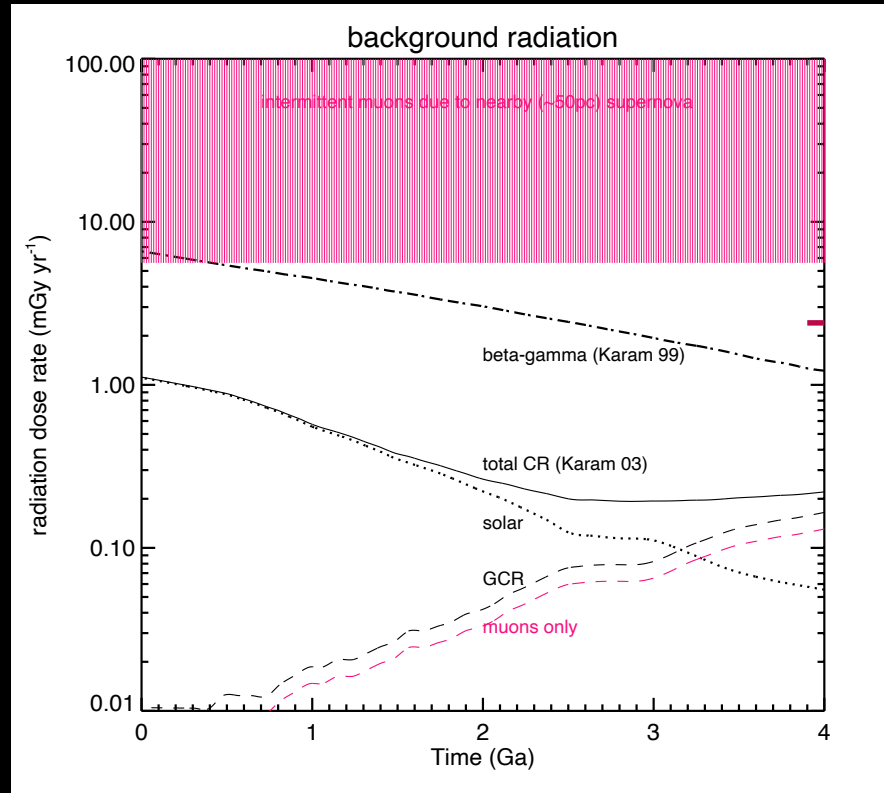
Calculations of polarized doses: elevated doses due to nearby supernovae



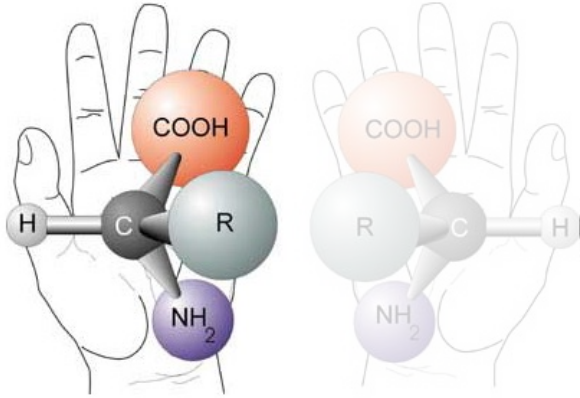
Cassiopeia A

Globus, Fedynitch, Blandford
(ApJ 910 85, arXiv:2101.00530)
and ICRC 2021 Proceeding

- 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



Meteoritic puzzle



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

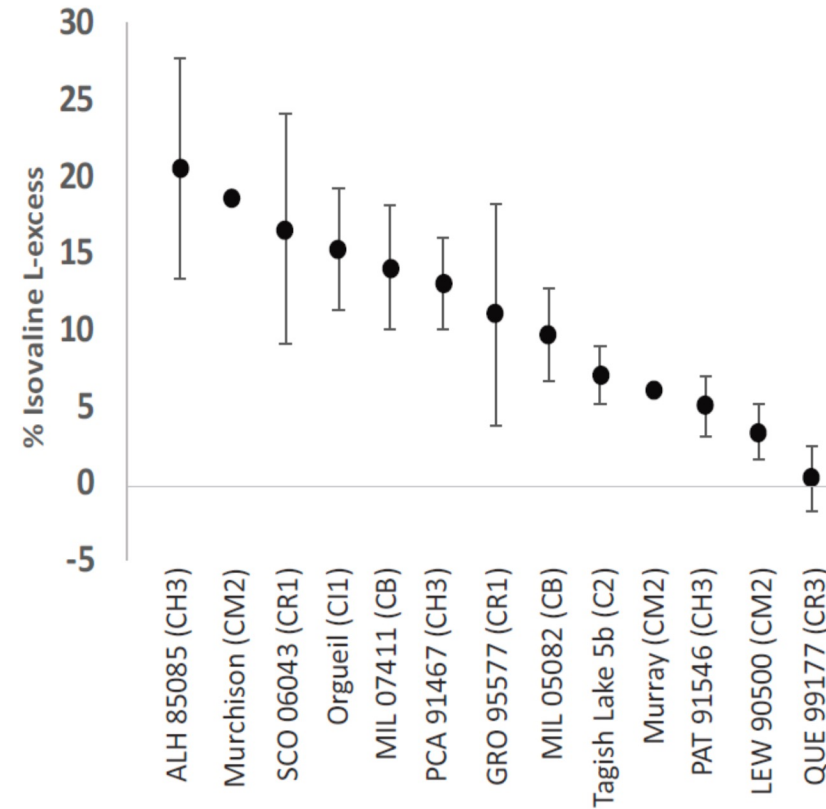


photo by - Tim Heitz

Burton & Berger, 2018

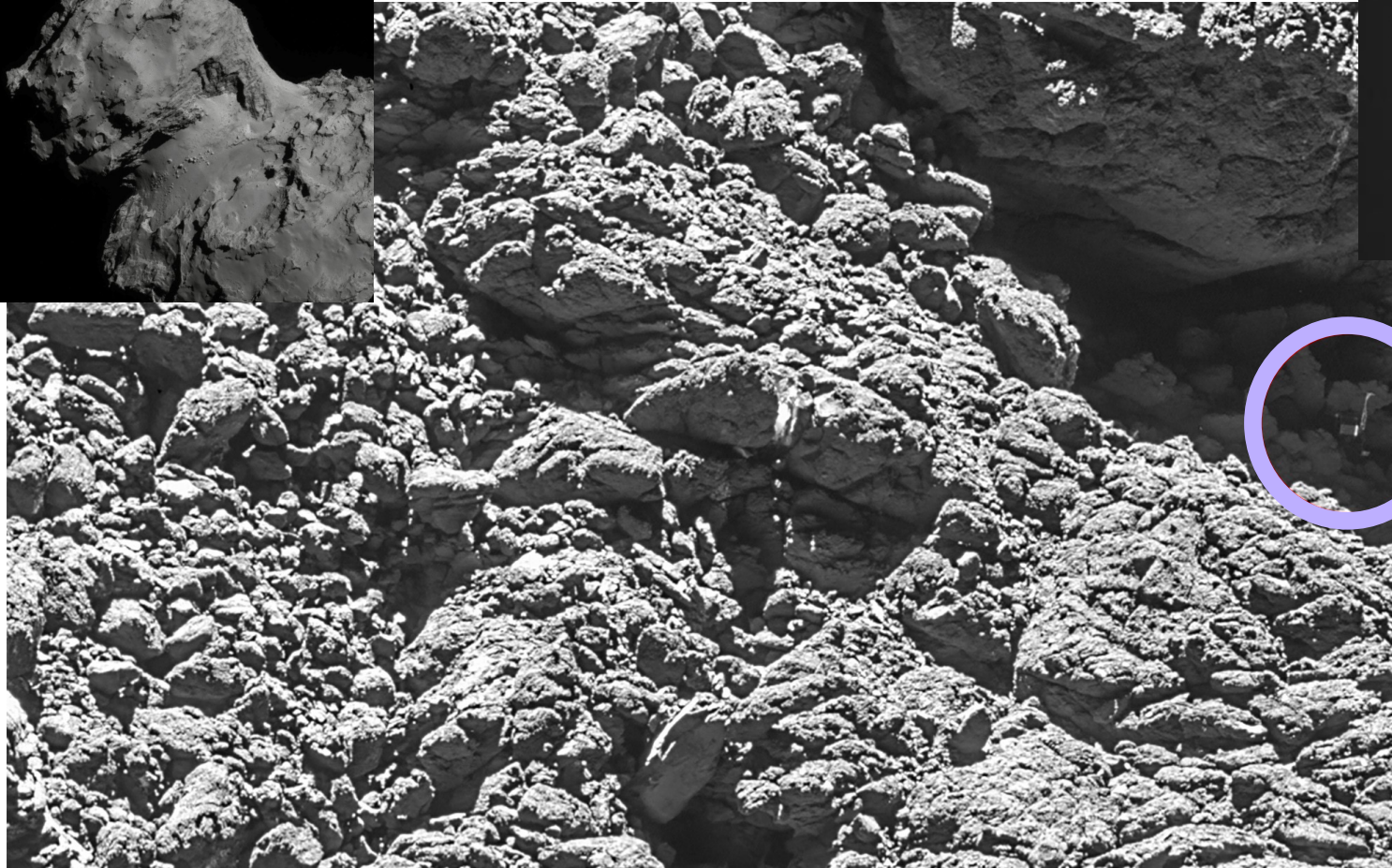
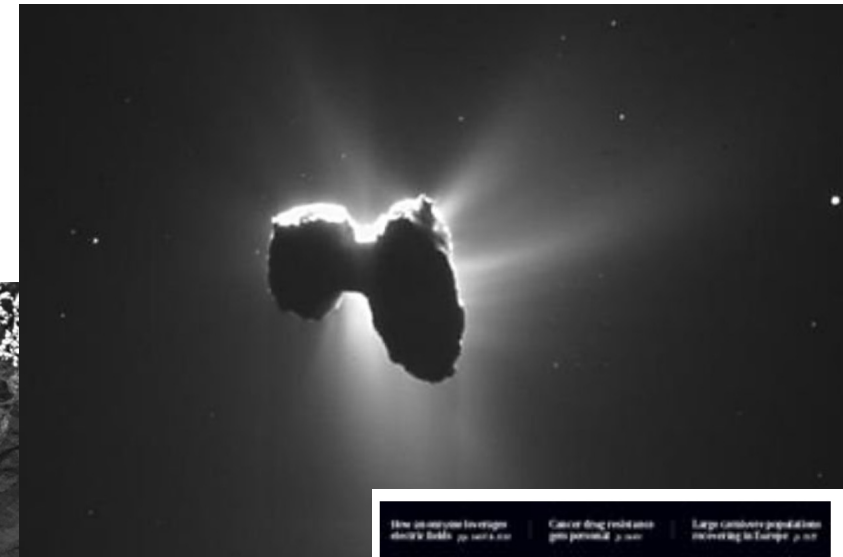
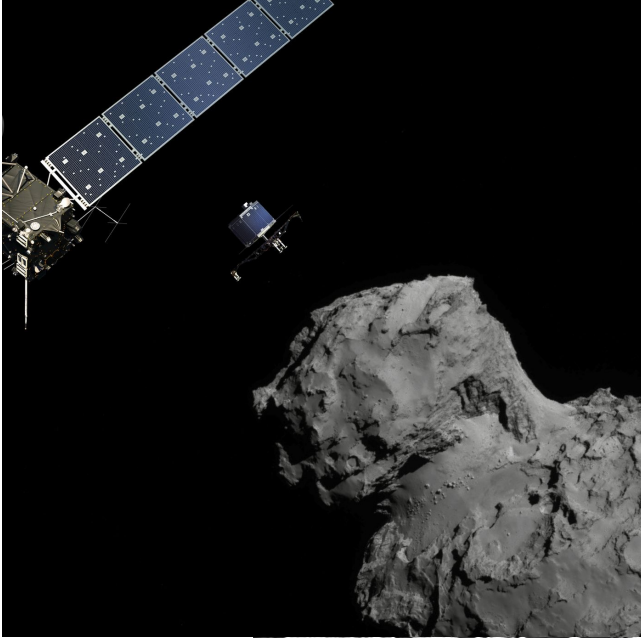
Evidence for asymmetry!

... may have bias by contamination at Earth?

space missions tell us about chirality of molecules in extraterrestrial environments

In Situ

67P/Churyumov-Gerasimenko



lost and found



This week's Science includes a **special section** on the Breakthrough of the Year: The Rosetta mission. Rosetta captured headlines when its lander touched down for the first time on the surface of a comet.

To the far right of a high-resolution observation of the comet's surface taken on Sept. 2, the Philae lander can be seen, jammed in a dark ditch, on its side (ESA)

Rosetta mission (2004-2016)

Sample return



A team member carries the capsule, which contains samples from an asteroid

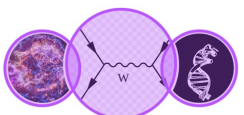


A rover deployed by Hayabusa-2 sent back this image from the surface of Ryugu

Summary

- **The origin of biological homochirality is a fundamental problem connecting astronomy, biology, chemistry and physics**
 - Chance or necessity ?
 - Prebiotic or biotic ?
 - In which environments?
- **Role of cosmic muons ?**
 - Ionization or capture?
 - Lodacity or charge ratio ?
- **Enantioselective biology**
 - Proof of principle for mechanisms that allow cosmic rays to bias evolution towards one chirality
 - Homochiralization timescale ?
 - Conflict necessary ?
- **Testable idea**
 - Sample return from surfaces and subsurfaces (Hayabusa2, OSIRIS-REx)
 - Experiments (irradiate biological samples with polarized particles and light)
 - Interstellar chirality (c.f. propylene oxide)
- **Homochirality as a biosignature**
 - The homochirality of organic molecules is **a phenomenon only produced by life**
 - Is homochirality universal? If so, **its presence on an extraterrestrial body will be a powerful indicator of life**
 - Instruments capabilities to detect chiral molecules in Venusian clouds ? Martian underground? In exoplanets?

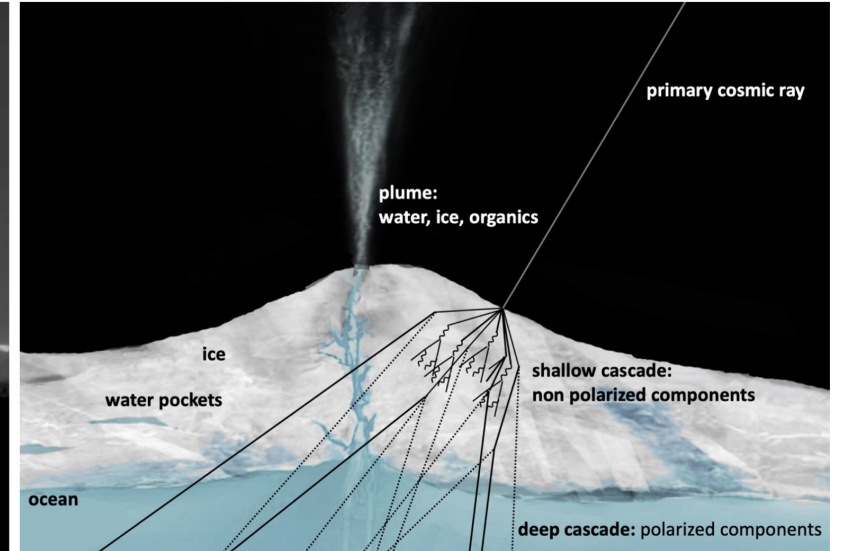
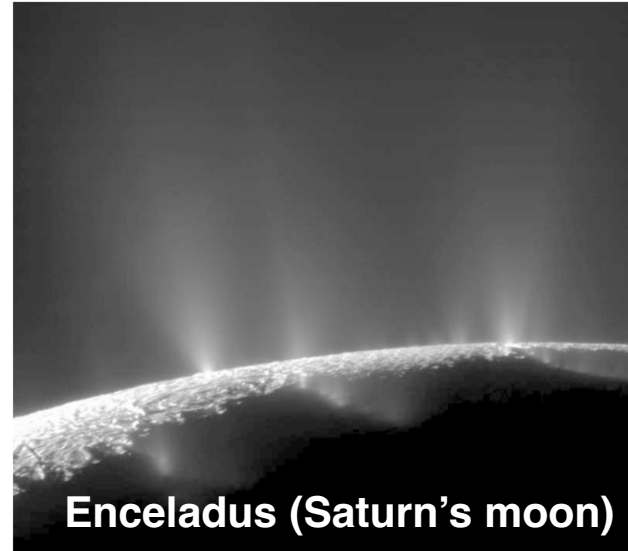
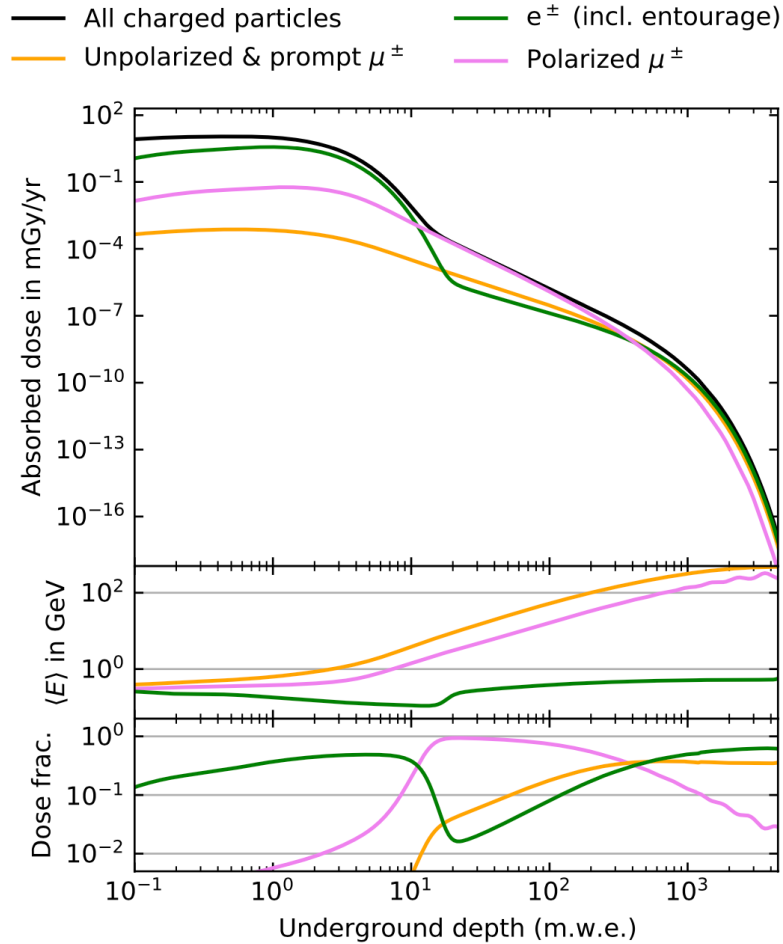
Astro-bio-physics !



Back-up

Cosmic-ray spin-polarized radiation doses - icy moons or asteroids

Globus, Fedynitch, Blandford
ApJ 910 85

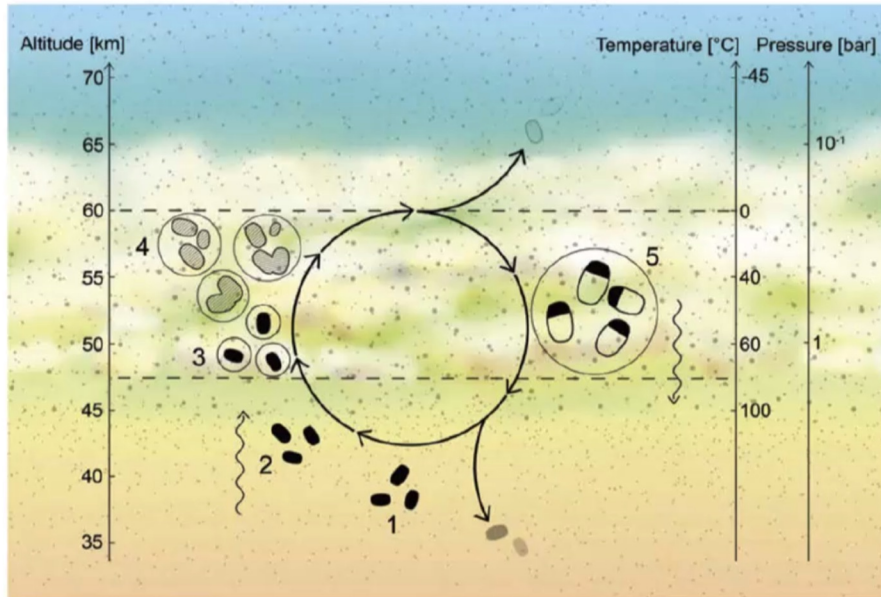


- On icy moons, like Enceladus, life may have emerged in the sub-surface oceans
- Environment close to surface cold
- However, polarized doses deep-underground are low
- Polarization is screened electromagnetically
- Salty water is a source of stronger natural radiation, such as ^{40}K

Common origin of life on Earth and Venus?

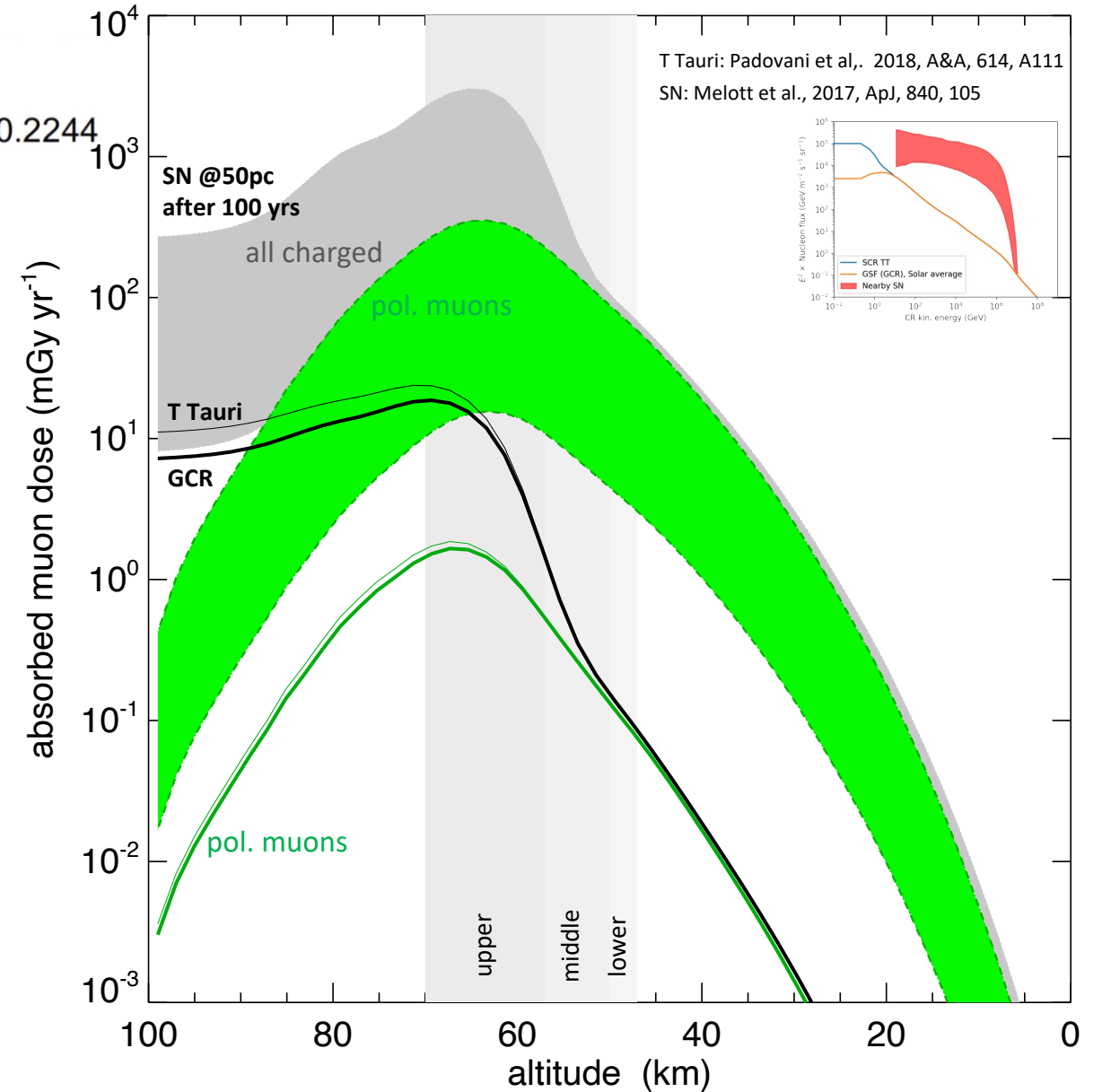
Potential Venusian Life Cycle

Proposed by Seager et al, 2020, Astrobiology 21, DOI: 10.1089/ast. 2020.2244



Size of organisms vary with altitude. Dessicated spores at depth. Larger metabolically active organisms at higher altitudes.

- Polarized muons start to dominate in the middle cloud layer (50-57 km)
- During nearby SN explosions, the rate can be boosted for 10,000 of years



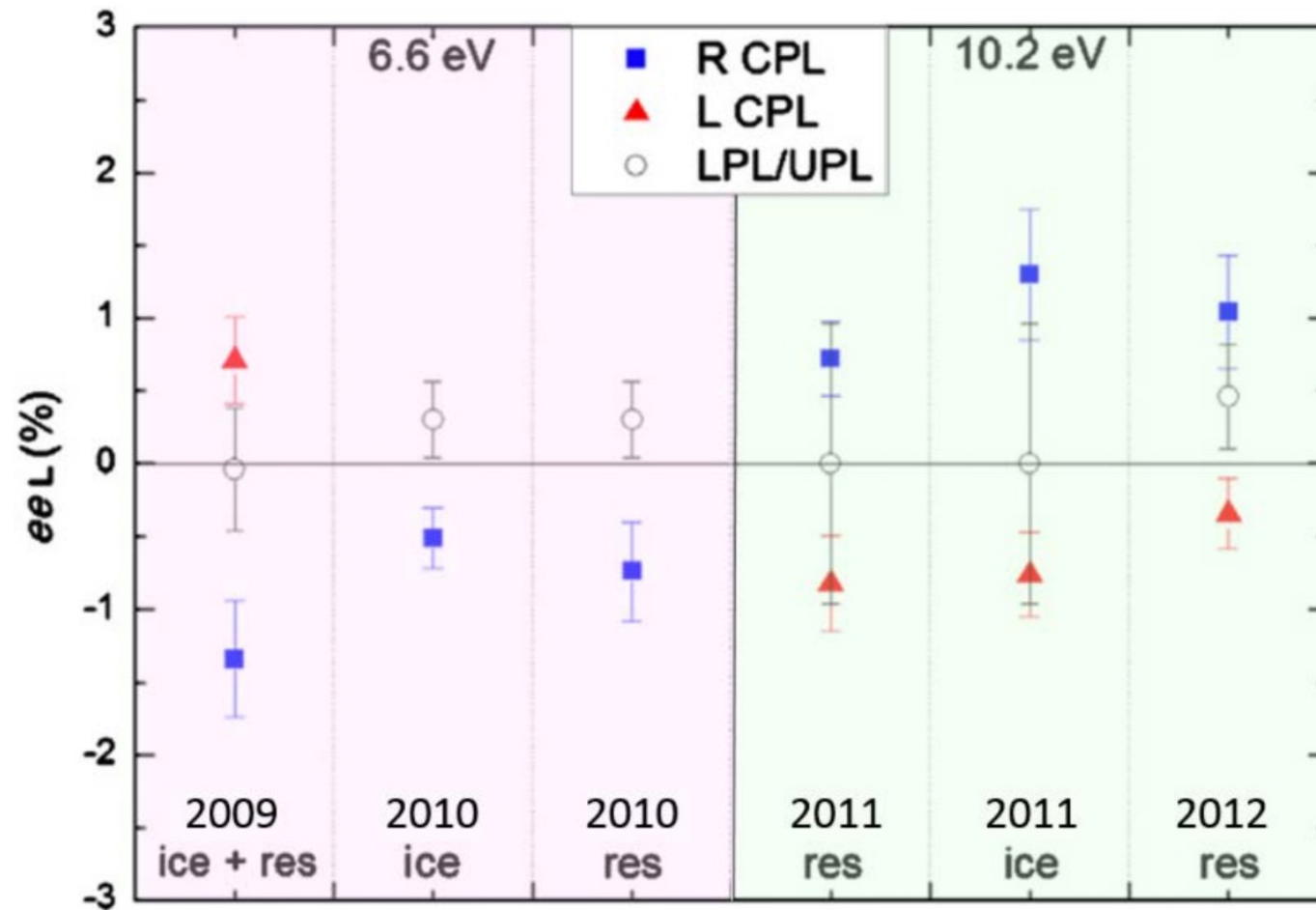


Figure 4: Measured eeL in ^{13}C alanine for the different synchrotron sessions over four years. The pink panel includes experiments conducted at 6.6 eV, the green panel those at 10.2 eV. Blue squares represent eeL induced by R CPL, red triangles those by L CPL, and white circles those after LPL or UPL. Note that the sign of the eeL depends on the helicity and the energy of CPL and do not depend on the stage of the sample (residue or ice). Figure adapted from Modica et al (2014).