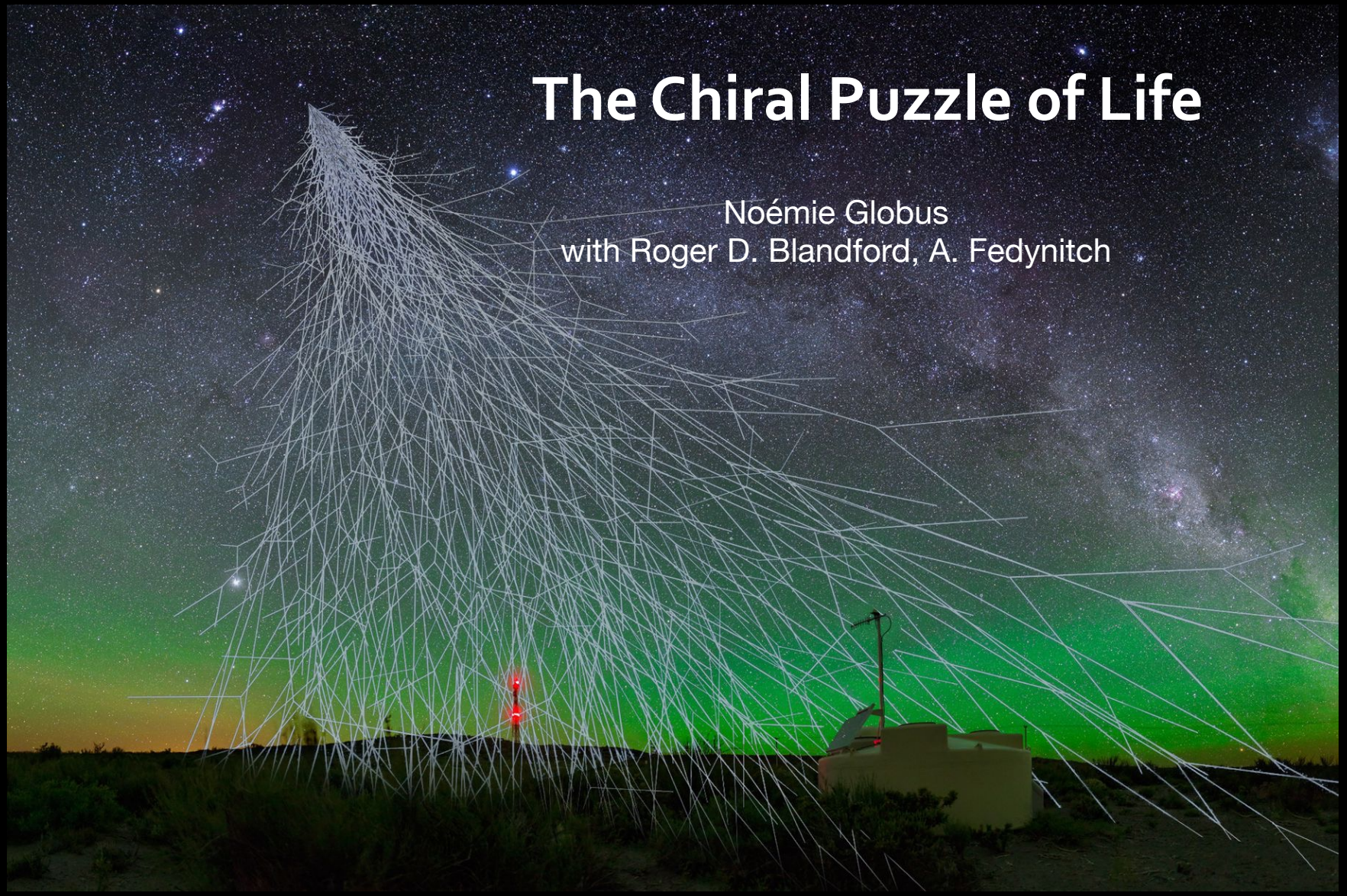
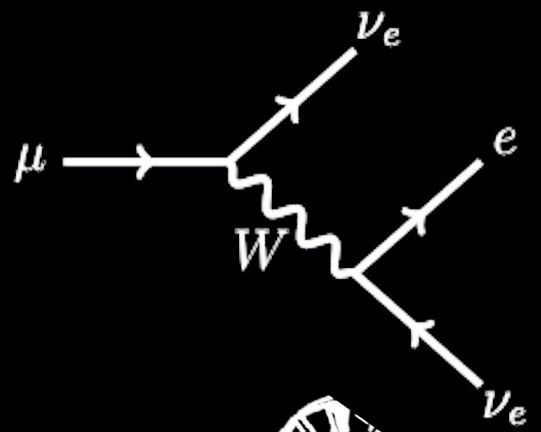
The Chiral Puzzle of Life

Noémie Globus
with Roger D. Blandford, A. Fedynitch





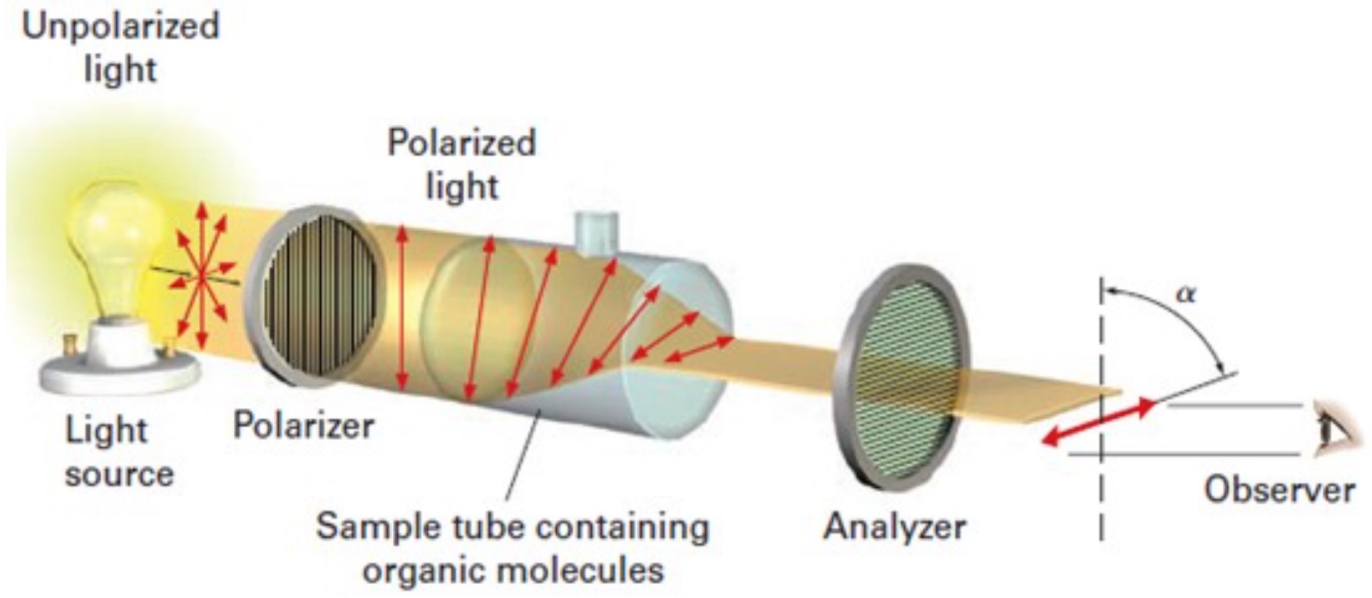
FLATIRON INSTITUTE

eli beamlines

On the contribution of wine to scientific knowledge

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.



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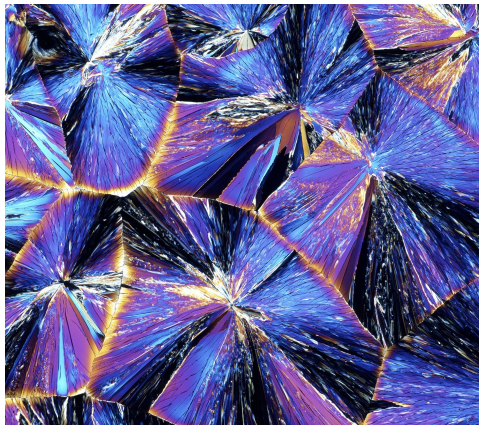
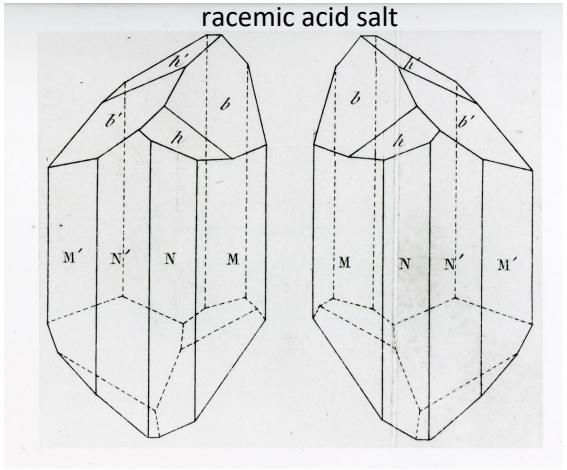
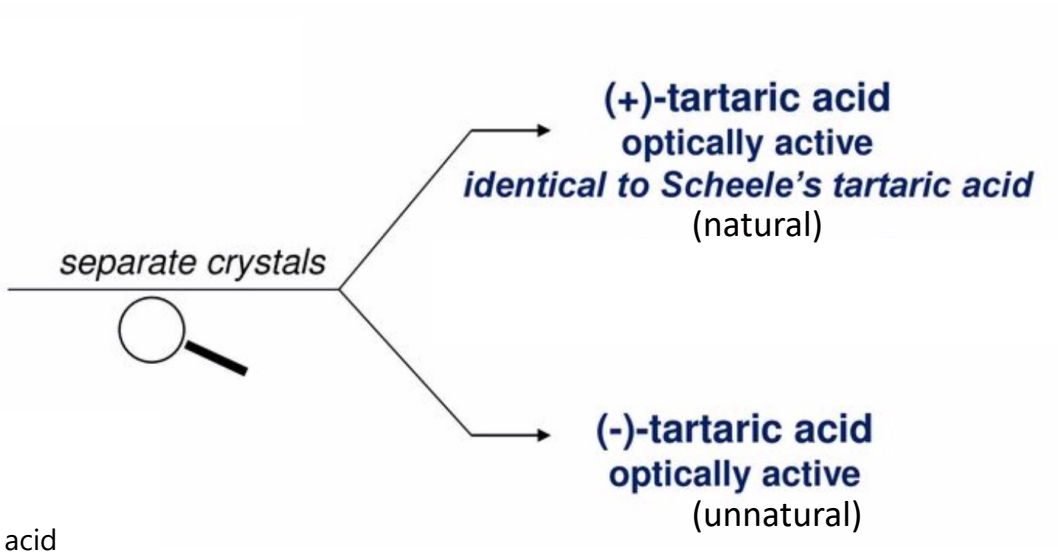


1848: Experiments by Pasteur on optical activity of tartaric acid

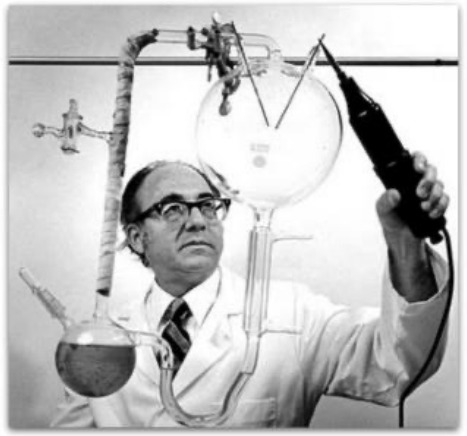


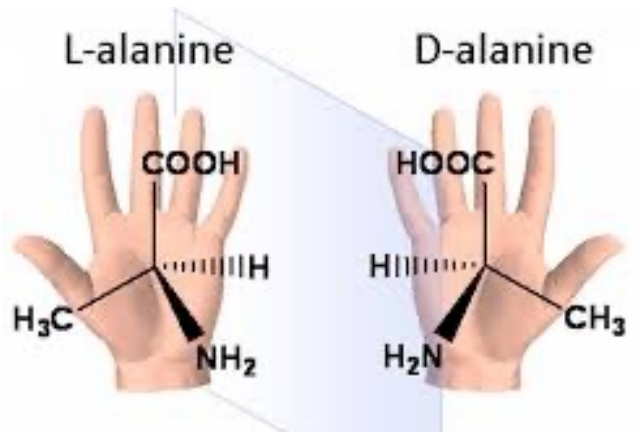
Drawing by Louis Pasteur of a pair of tartaric acid crystals. From the collections of the Chemical Heritage Foundation.

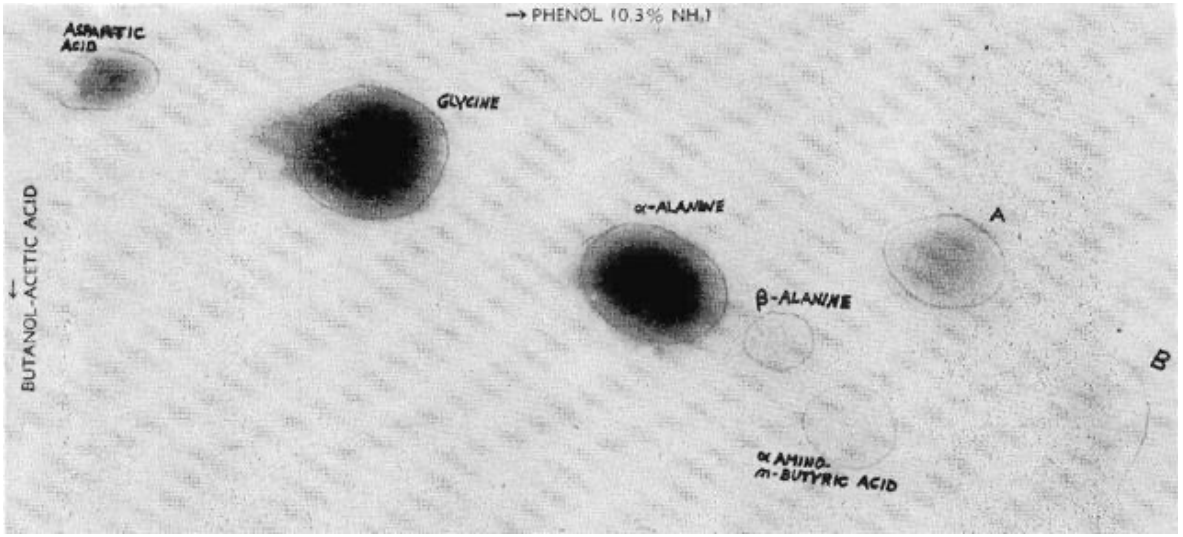


Life building blocks: amino acids

The Miller-Urey experiment (1952) in some sense is a realization of Charles Darwin's 1871 warm pond model

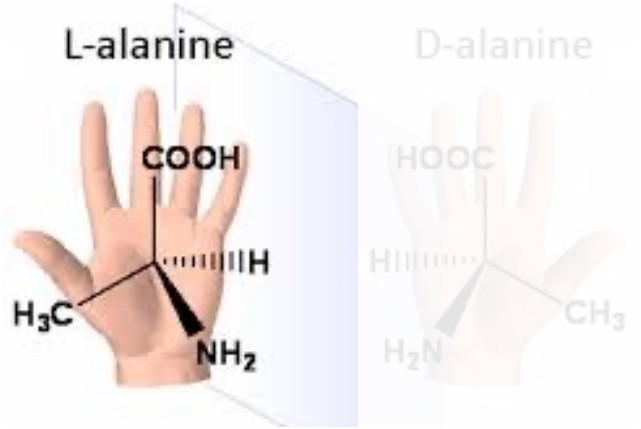




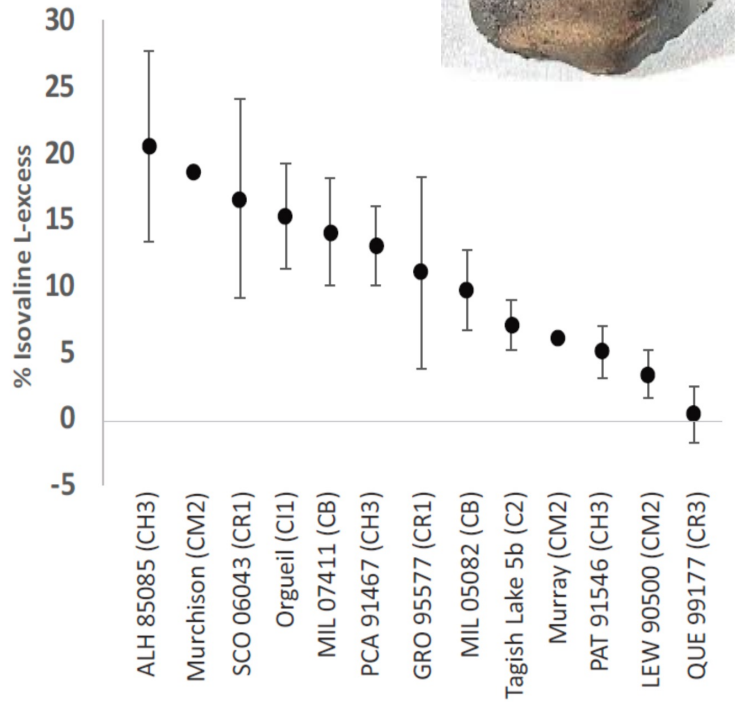


products of Miller's experiment: amino acids!
But equal quantities of both right- and left-handed

Life building blocks: amino acids



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

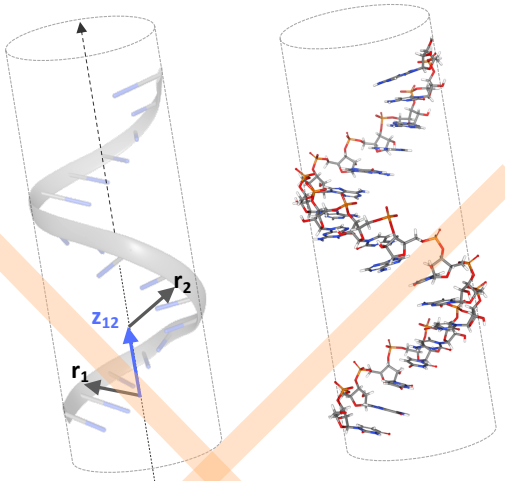


Enantiomeric excesses in meteorites

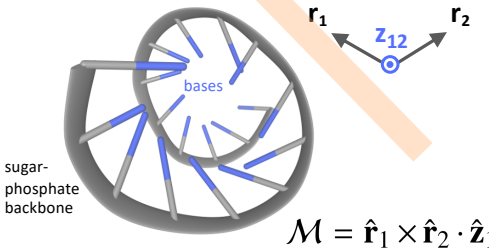
More left-handed than right-handed!

Life building blocks: nucleic acids

L-RNA (evil system)

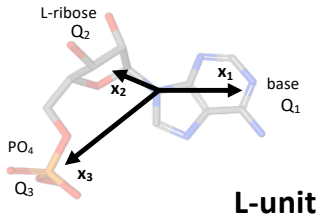


Left-handed helix
(side view)



(top view)

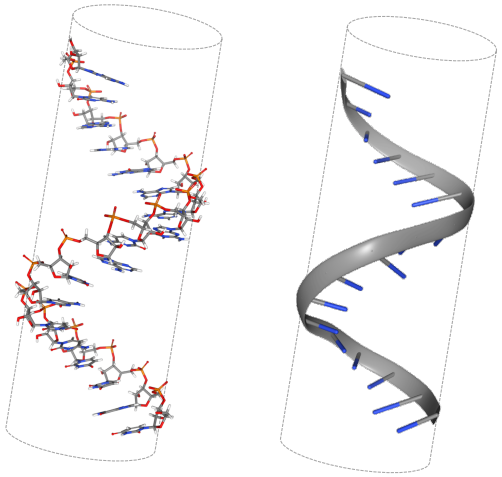
$$\mathcal{M} = \hat{\mathbf{r}}_1 \times \hat{\mathbf{r}}_2 \cdot \hat{\mathbf{z}}_{12}$$



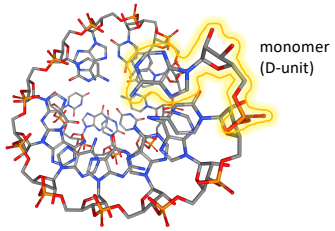
$$\mathcal{M} = \hat{\mathbf{x}}_1 \times \hat{\mathbf{x}}_2 \cdot \hat{\mathbf{x}}_3$$

L-unit

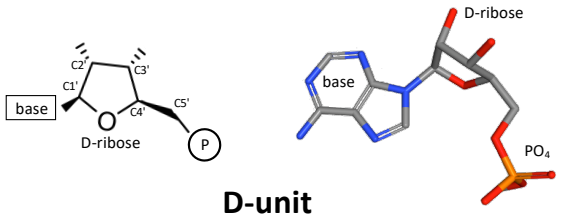
D-RNA (live system)



Right-handed helix
(side view)



(top view)



D-unit

What broke the biological mirror ?

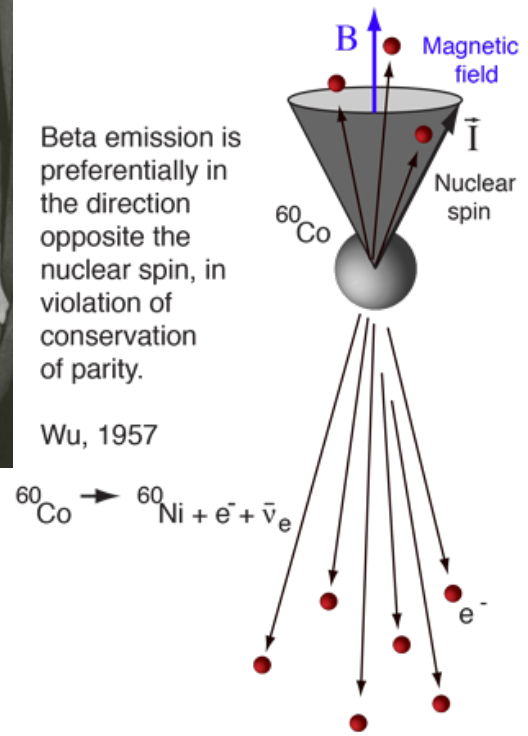
Pasteur anticipation: asymmetric cosmic laws

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

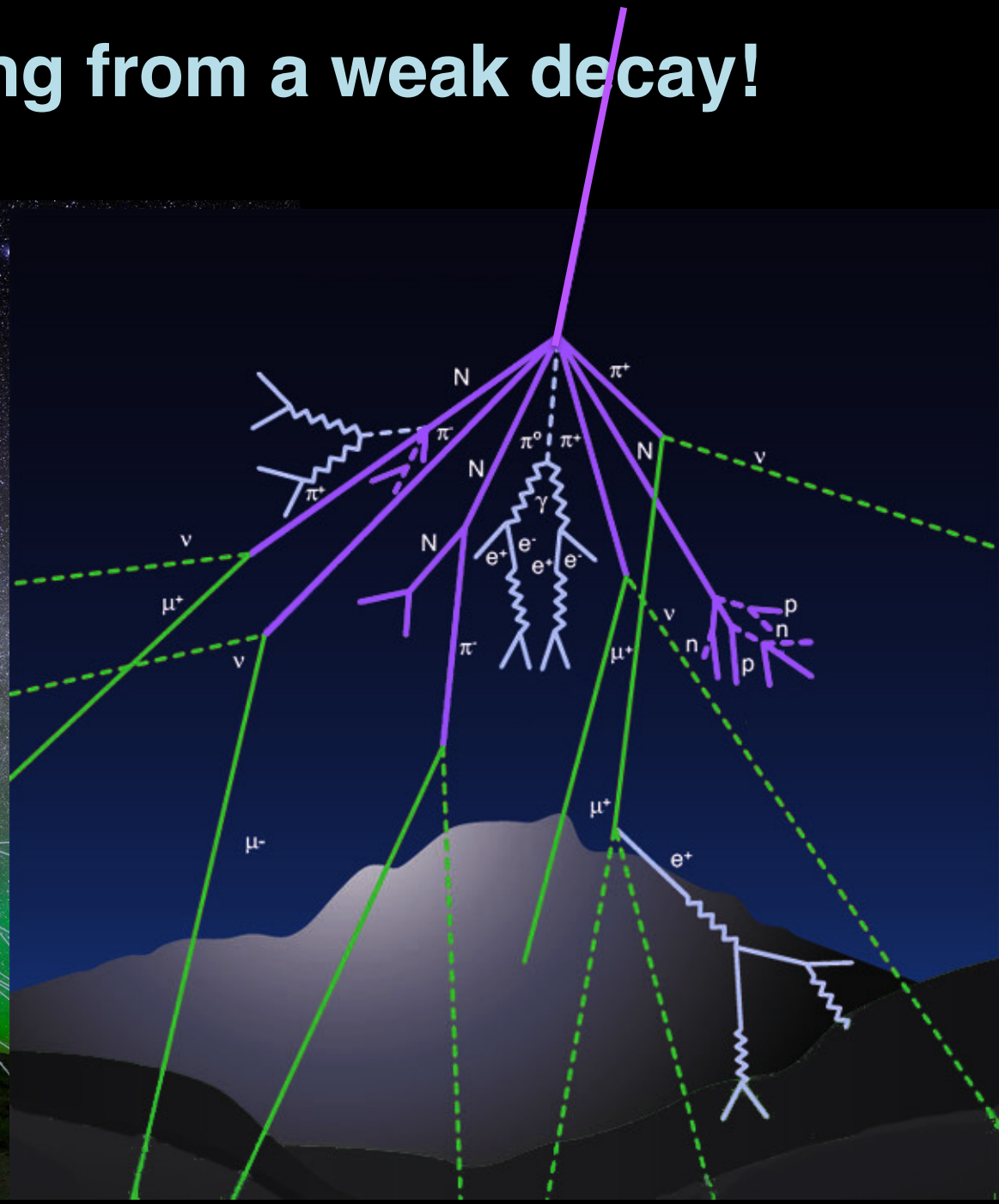


Possible (experimental) paths to homochirality

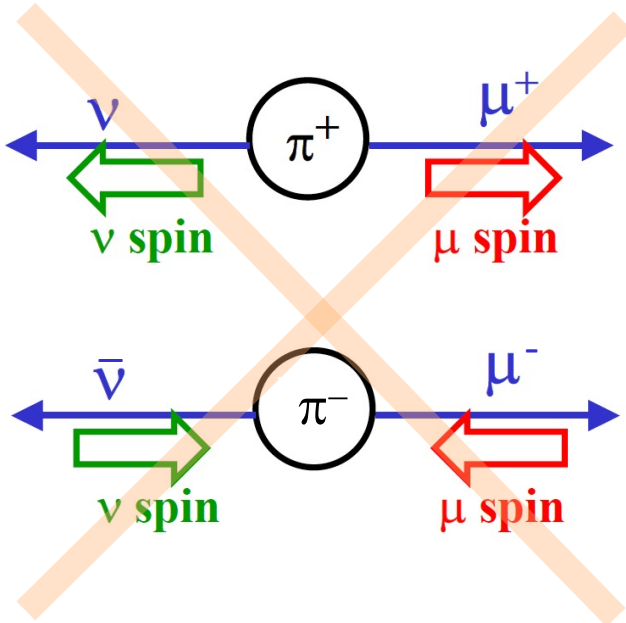
	Actor	Effect	Chiral preference	Magnitude	Involves W?	Authors
Pre-Biotic	Parity Violating Energy Differences (PVED)	PVED-induced phase transition	Left-handed amino acids (in water)	$e.e.=\frac{D-L}{D+L}.100$ Not reported (theory only : 10^{-17})	yes	Salam, Quack …
	Ultra-violet circularly polarized light (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. << 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/mu	Not reported (theory only : 10^{-7}- 10^{-8})	yes	Globus-Blandford

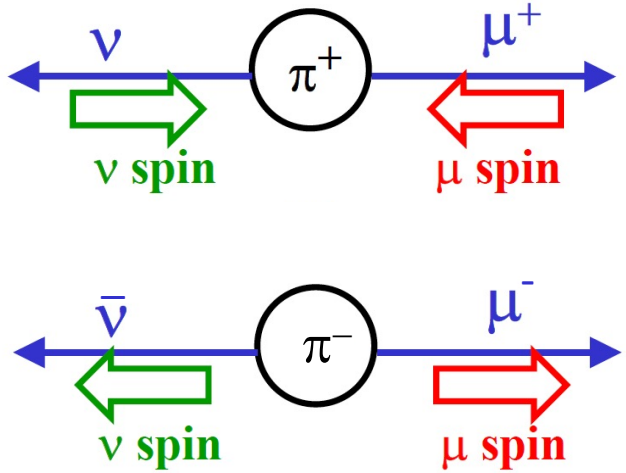
Cosmic muons are coming from a weak decay!

Cosmic Ray shower on Earth



Weak interactions violate parity





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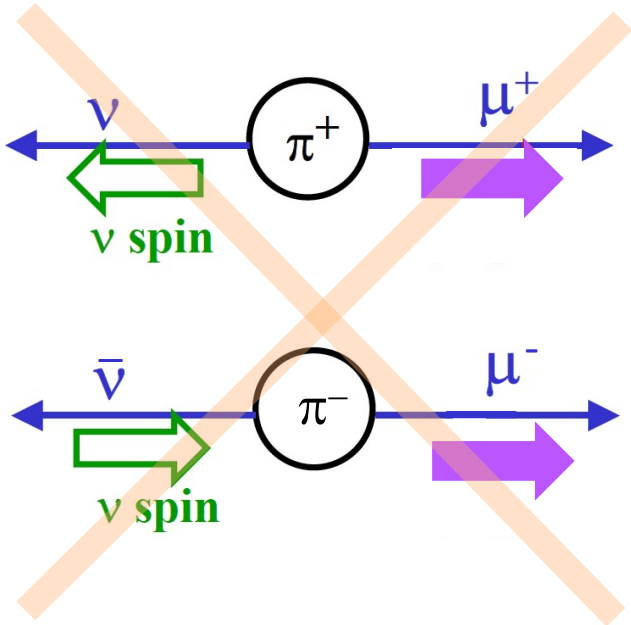

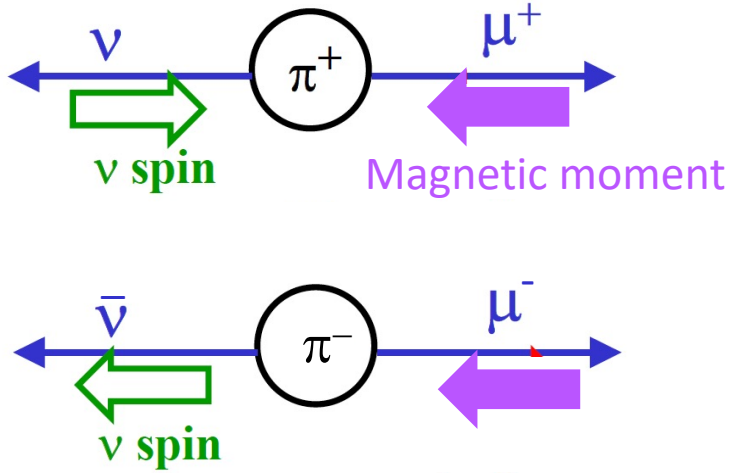

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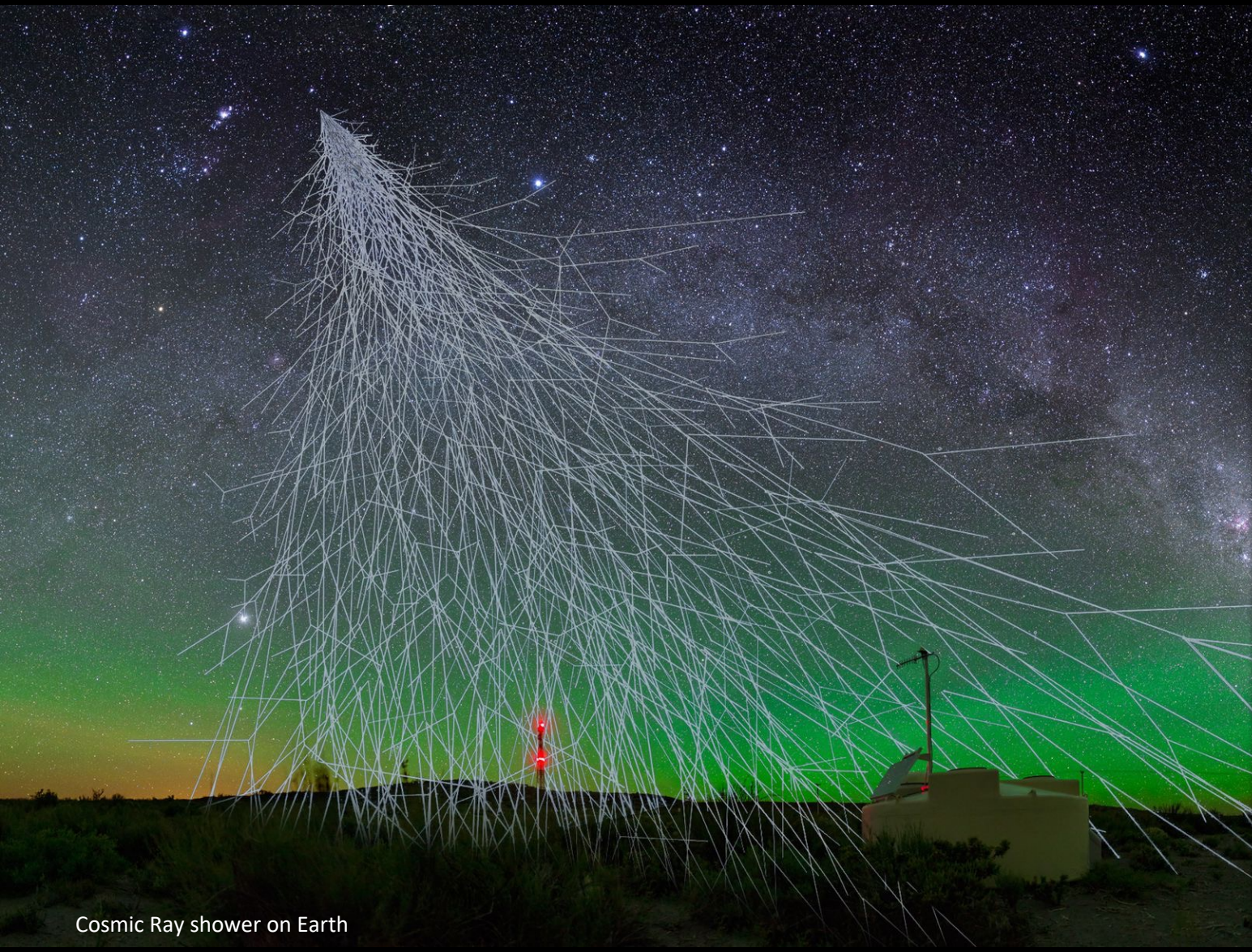
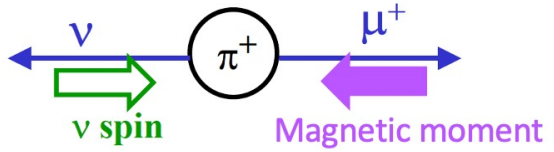
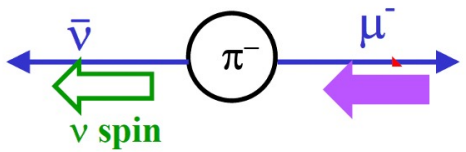
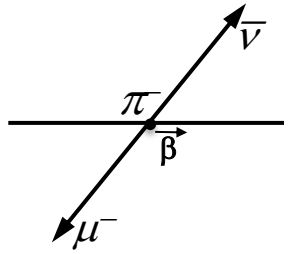


Cosmic Ray shower on Earth

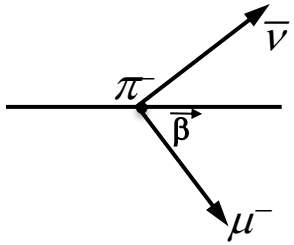
Pion decay (two body decay involving W)







π rest frame



lab frame

The product of the magnetic moment and the velocity vectors is **always of the same sign** $< \vec{\mu} \cdot \vec{v} > < 0$

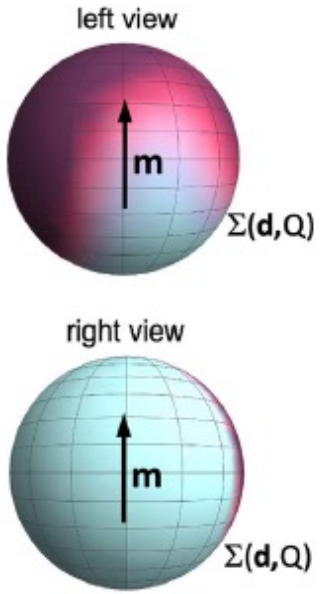
Call this pseudoscalar quantity the **Iodacity** $\mathcal{L}$

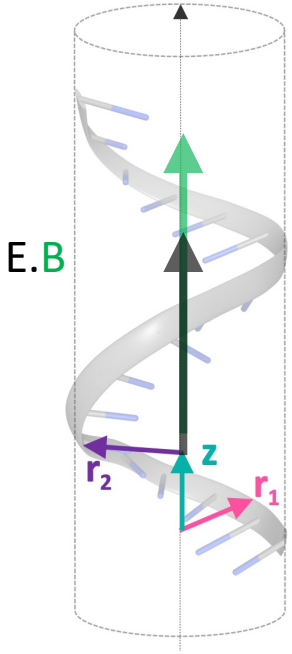
(Trans-)biotic scenario

Globus & Blandford 2020 ApJL 895 L11

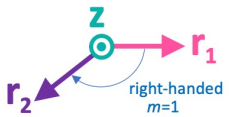
Molecular chirality $\mathcal{M}$

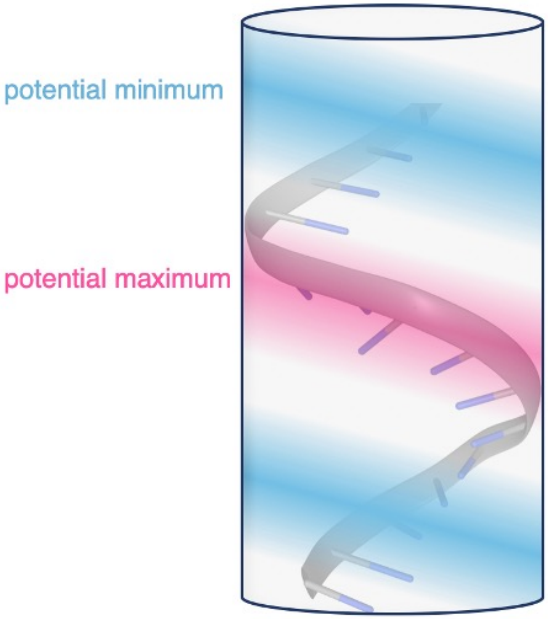
$\mathcal{M}$ involves charge distribution, magnetic moments (E.B)





z x r_1.r_2

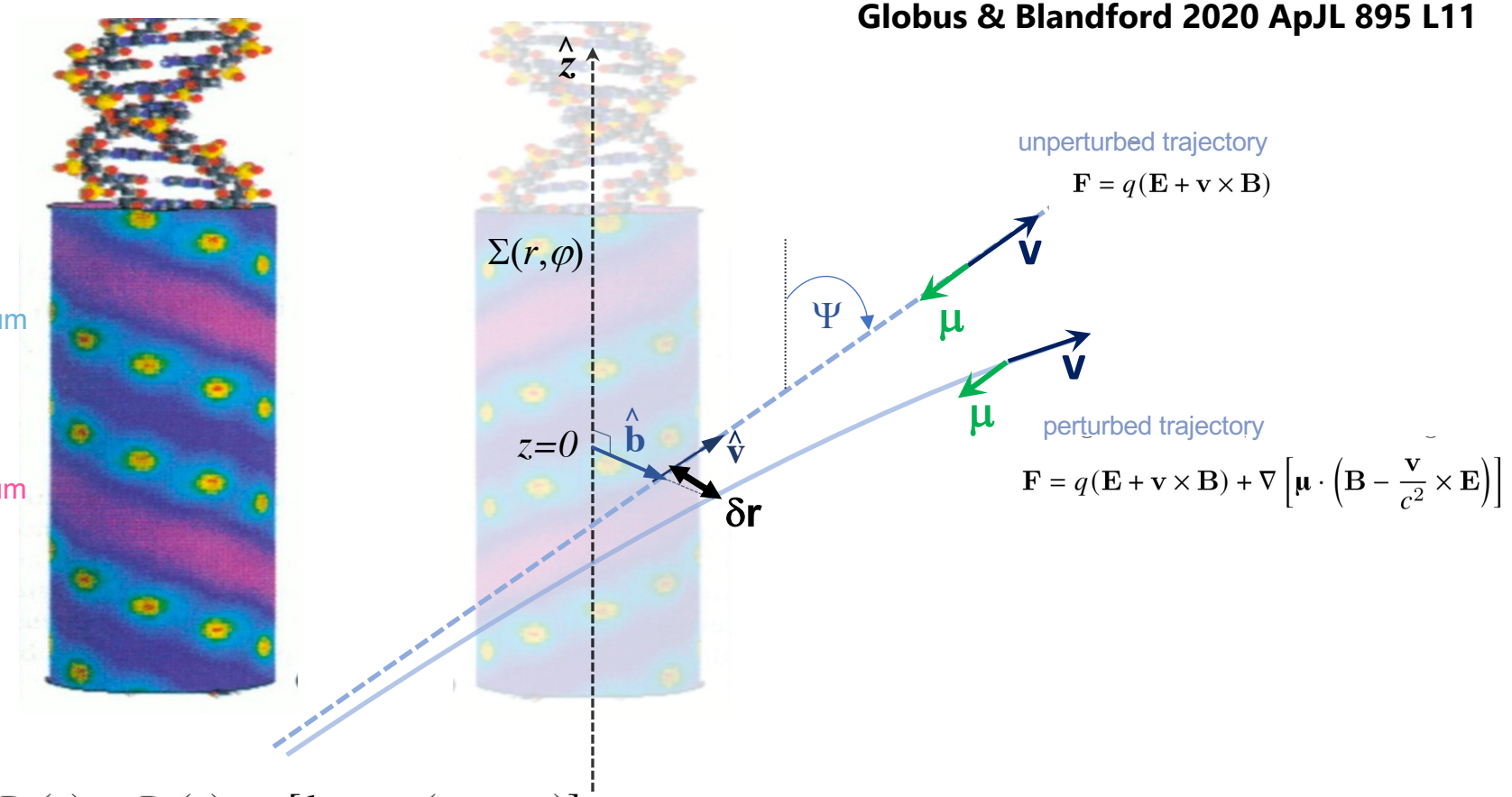




Enantioselective biology?

Globus & Blandford 2020 ApJL 895 L11

- Follow cosmic ray trajectory perturbatively
- Treat ionization as proxy for mutation
- Effects finite but small
- Need to consider quantum mechanically



Electrostatic potential $\Phi = R_0(r) + R_1(r)\cos[kz - m(\varphi - \varphi_0)]$

Mutability $\kappa = K_0(r) + K_1(r)\cos[kz - m(\varphi - \varphi_0)]$

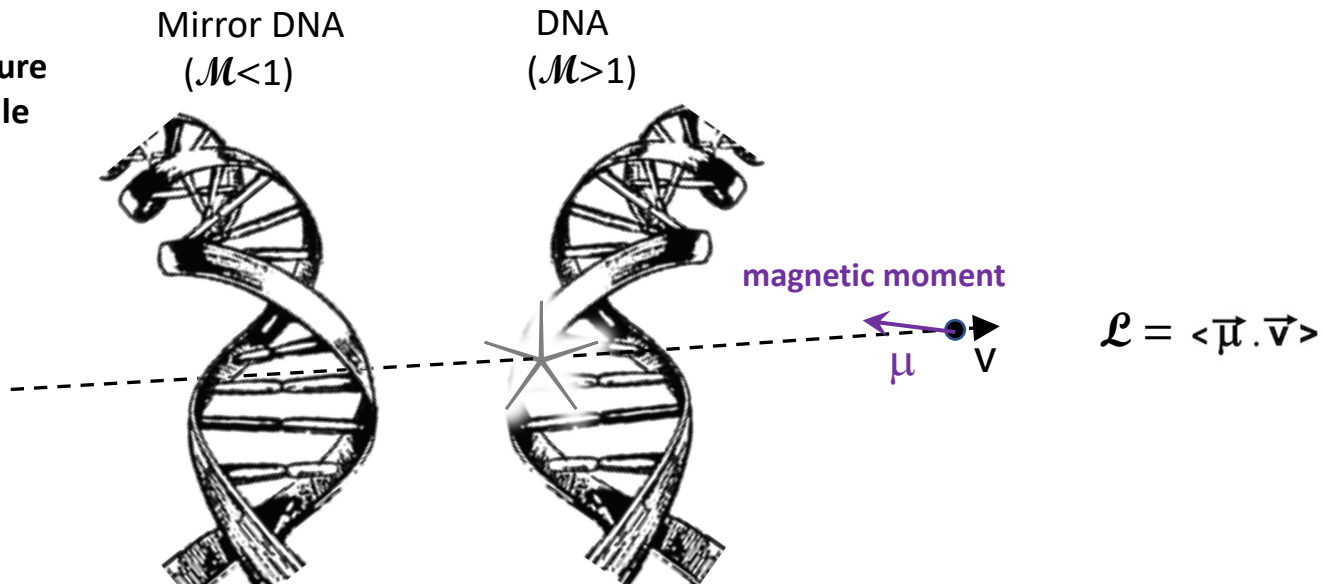
Mutability : probability per unit length to act on the mutation
= number density of electrons times the mutation cross section
= probability per unit length of CR trajectory that we get a mutation

$$\delta P = \int_{-\infty}^{\infty} dz\, \overline{\delta \mathbf{r}_\perp}(z) \cdot \nabla\kappa(z) = -\frac{q\alpha^5 \mathcal{L}}{2(Mv\cos\Psi)^3} \int_{-\infty}^{\infty} dz \int_{-\infty}^{z} dz' \int_{-\infty}^{z'} dz''(z - z'')\hat{\mathbf{v}} \cdot \nabla\Phi(z') \times \nabla\nabla\Phi(z'') \cdot \nabla\kappa(z)$$

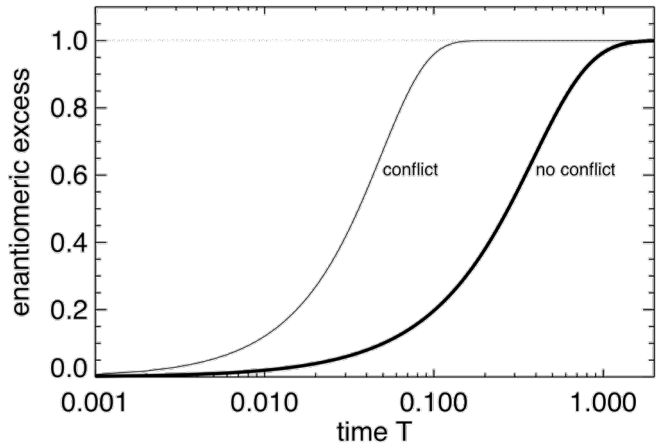
(Trans-)biotic scenario

Globus & Blandford 2020 ApJL 895 L11

- **Polarized cosmic rays acts as an evolutionary pressure**
- **Homochirality emerges on an evolutionary timescale**
- **Testable idea (laboratory experiments)**



Chiral preference is expressed as the product $\mathcal{M}.\mathcal{L}$

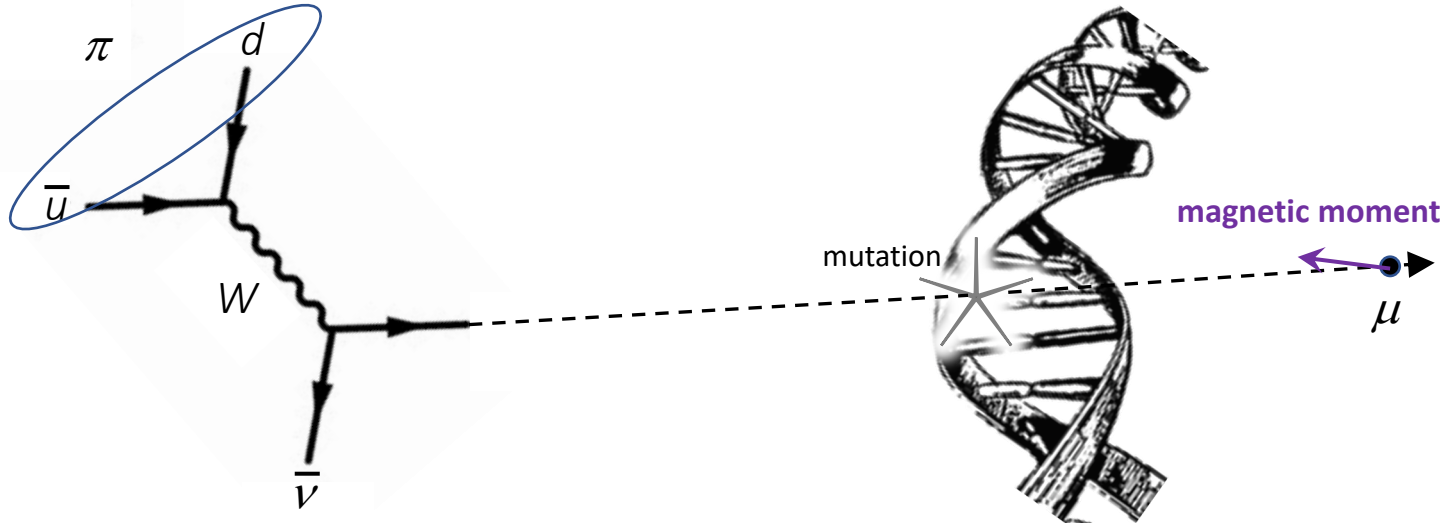


Our scenario: summary

Globus & Blandford 2020 ApJL 895 L11

Trans-biotic: involves helical molecules

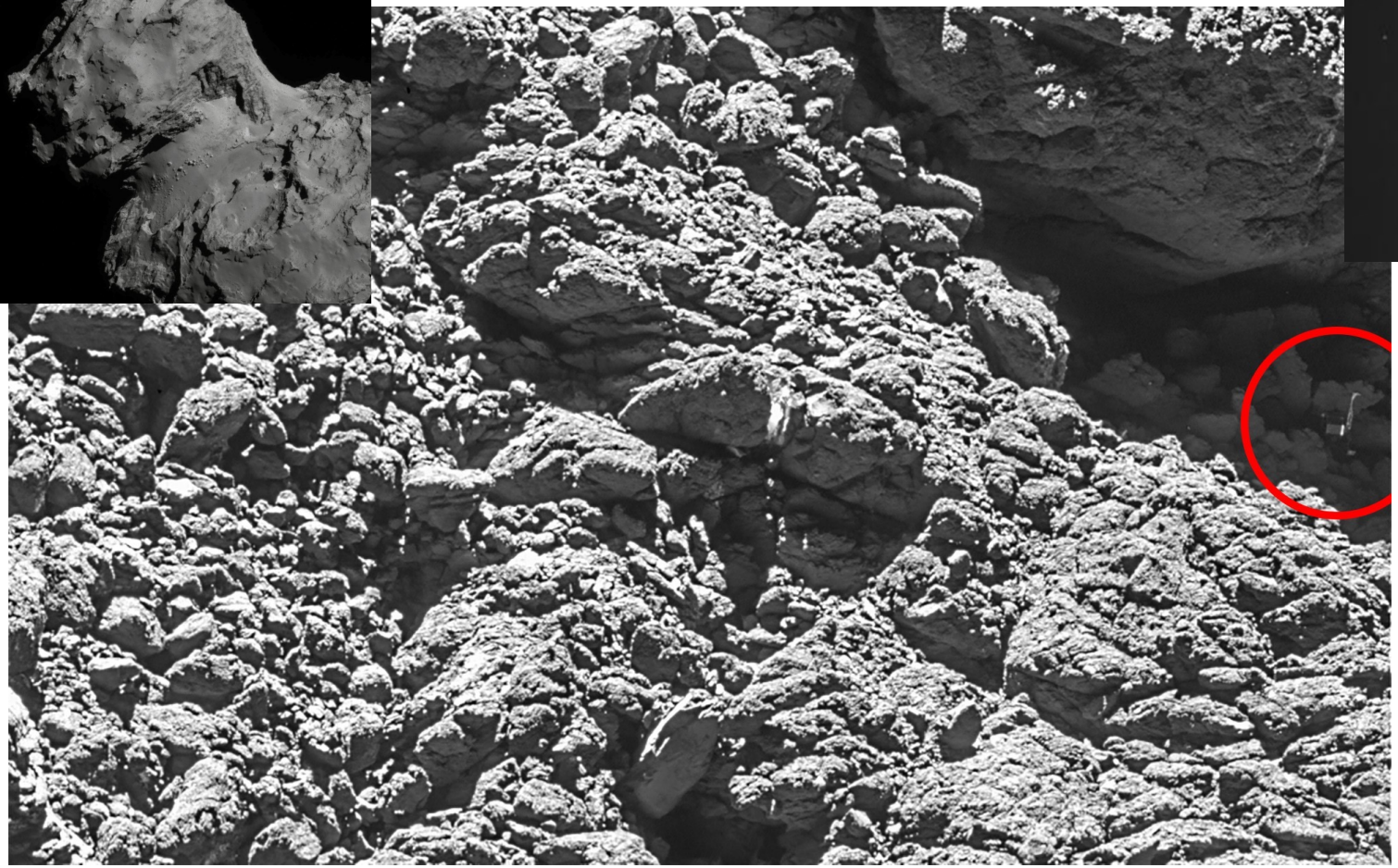
- Helical conformation *necessary* for life evolution (stability required for transmission of genetic material)
- Spin-polarized cosmic muons can induce a chiral imbalance in the mutation rate
- Even a 10^{-8} difference in the mutation rate would be amplified by self-replication processes
- Cosmic radiation is a small bias, but *persistent* (evolutionary pressure role)



- **Depends on the environment (biosignatures? e.e. measured *in situ* by space missions?)**

Rosetta mission (2004-2016)

67P/Churyumov-Gerasimenko

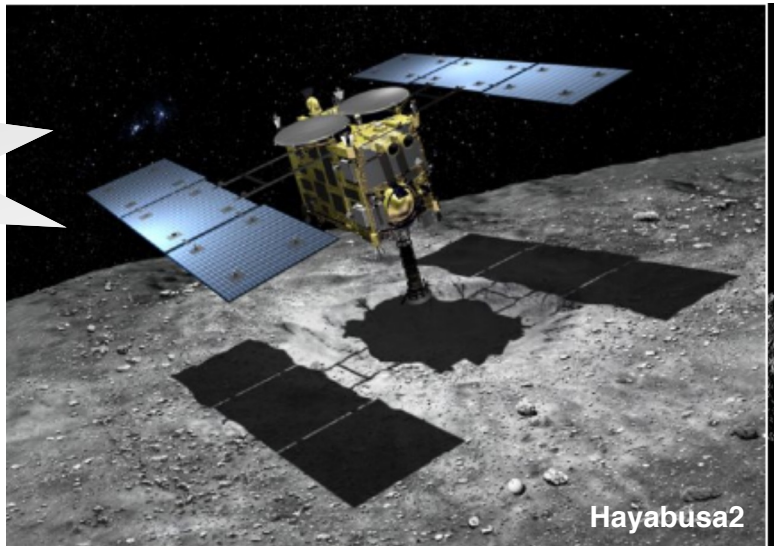


To the far right of a high-resolution observation of the comet's surface taken on Sept. 2, the Philae lander can be seen, jammed in a dark ditch, on its side (ESA)

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.

December 6,2020
Hayabusa2 return
2023: OSIRIS-Rex



Sample return can tell us about chirality of molecules in extraterrestrial environments

Hayabusa2 mission ends with recovery of capsule containing asteroid samples in Australian outback

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

Life on Mars?

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

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

May 10, 2017 by News Staff / Source

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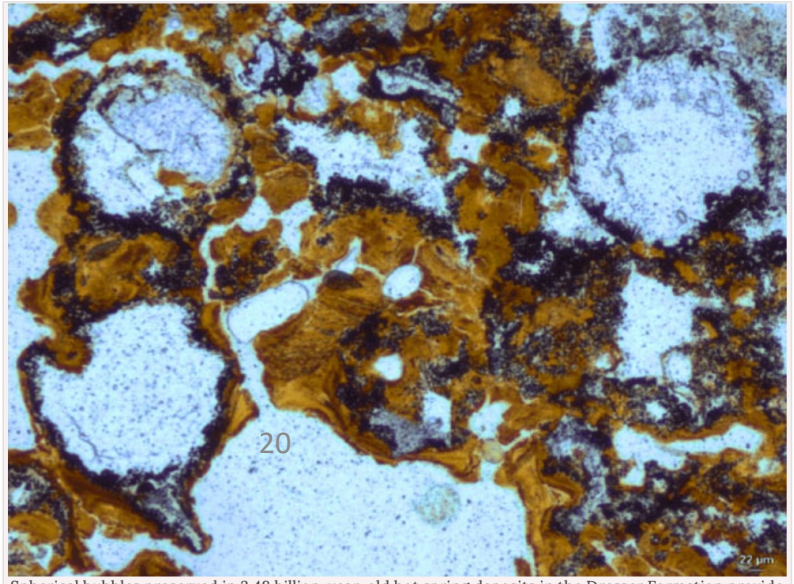
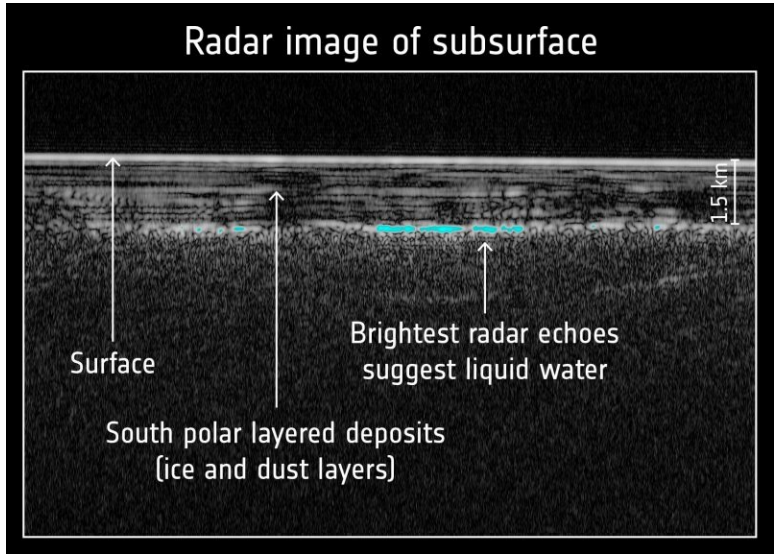
Fossil evidence of early microbial life has been found in ancient hot spring deposits in the Dresser Formation in the Pilbara Craton, Western Australia, that date back approximately 3.48 billion years. A paper reporting this discovery is published in the journal *Nature Communications*.



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.

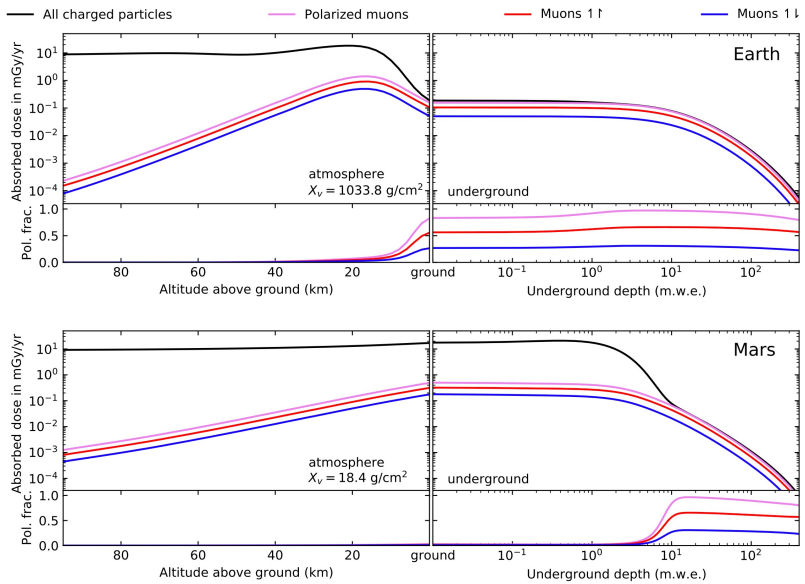
Cosmic-ray spin-polarized radiation doses

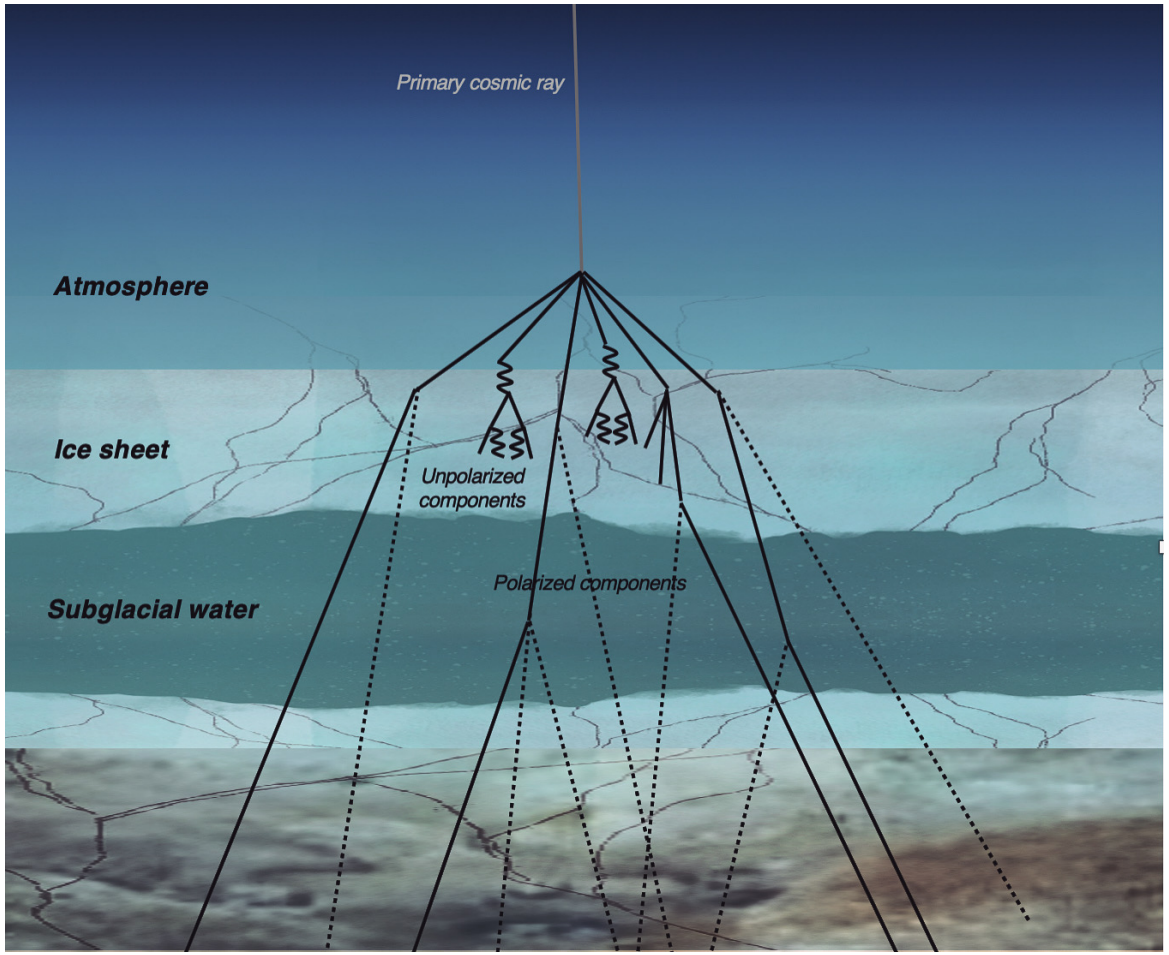


ESA's Mars Express

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.

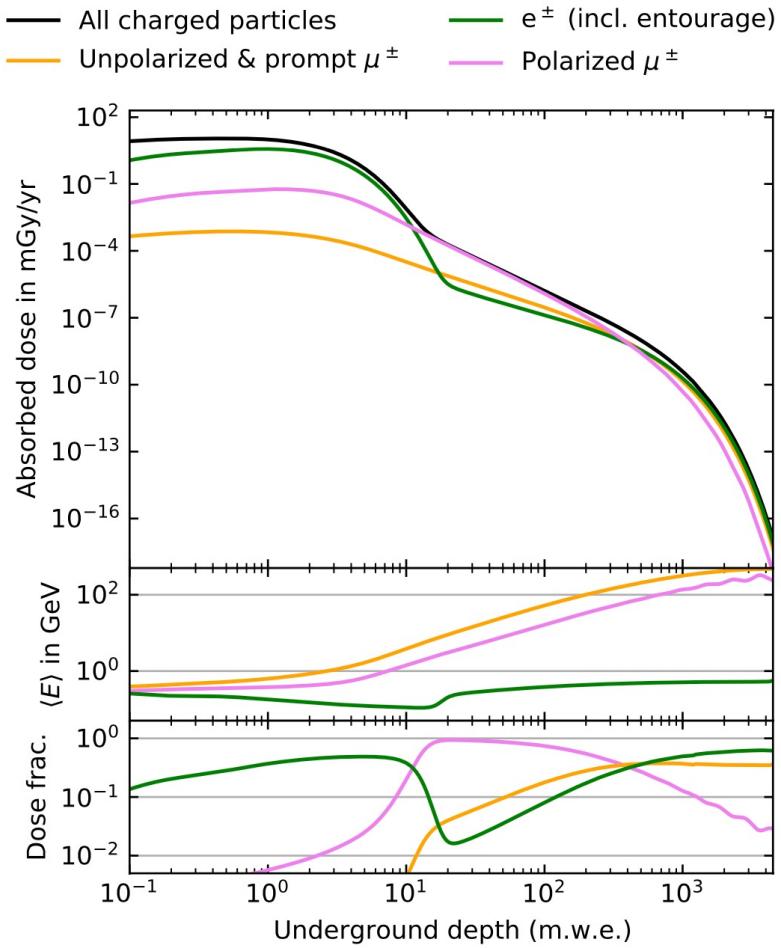


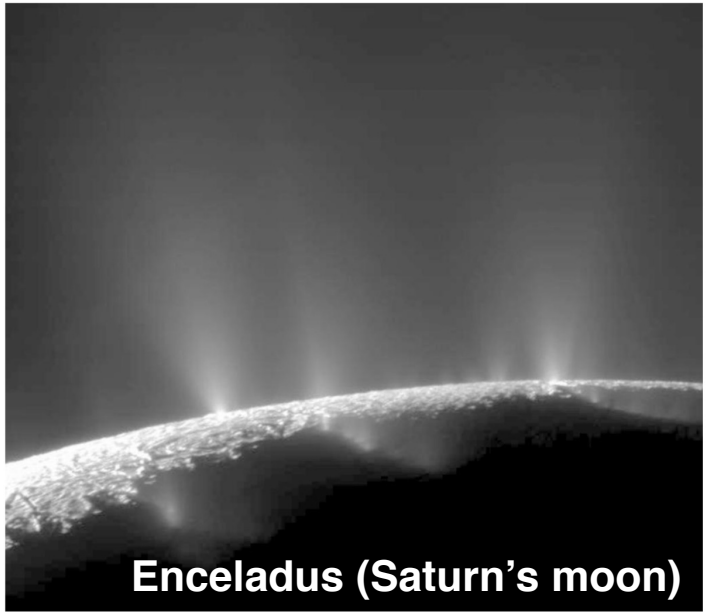


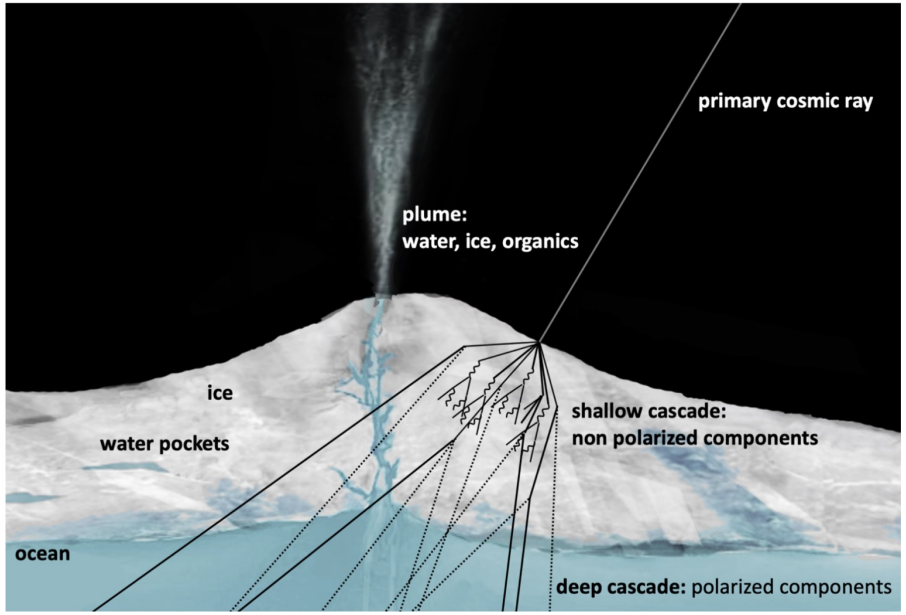
Globus, Fedynitch, Blandford (accepted in ApJ, arXiv:2101.00530)

Spin-polarized radiation doses: icy moons, asteroids

Globus, Fedynitch, Blandford
(accepted in ApJ, arXiv:2101.00530)

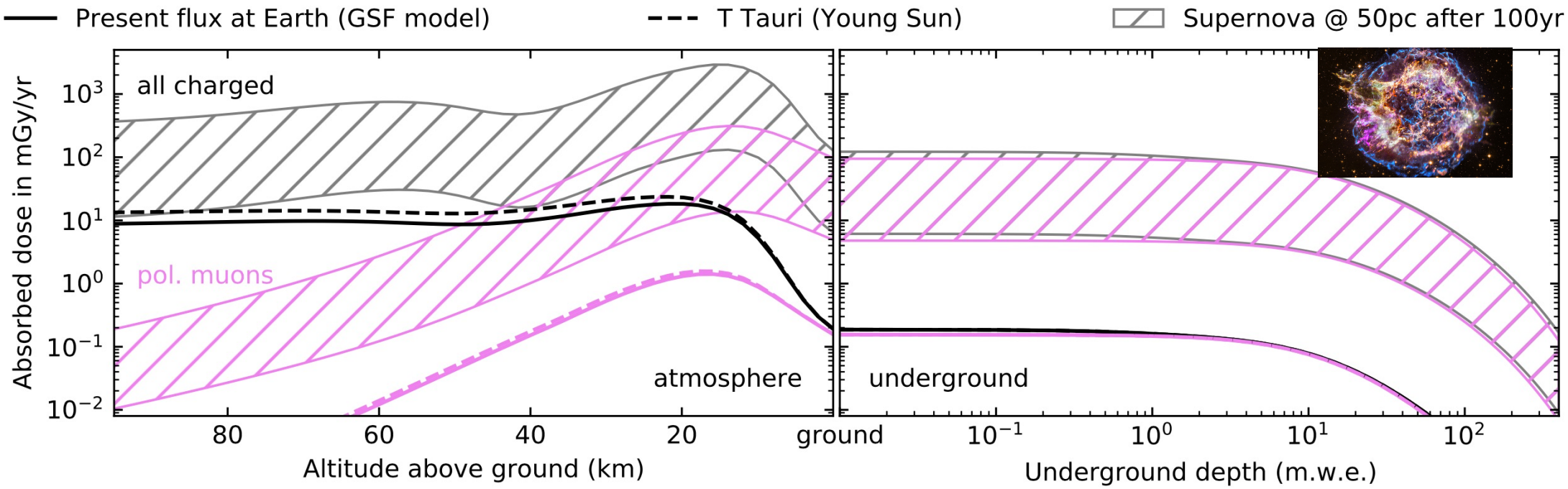




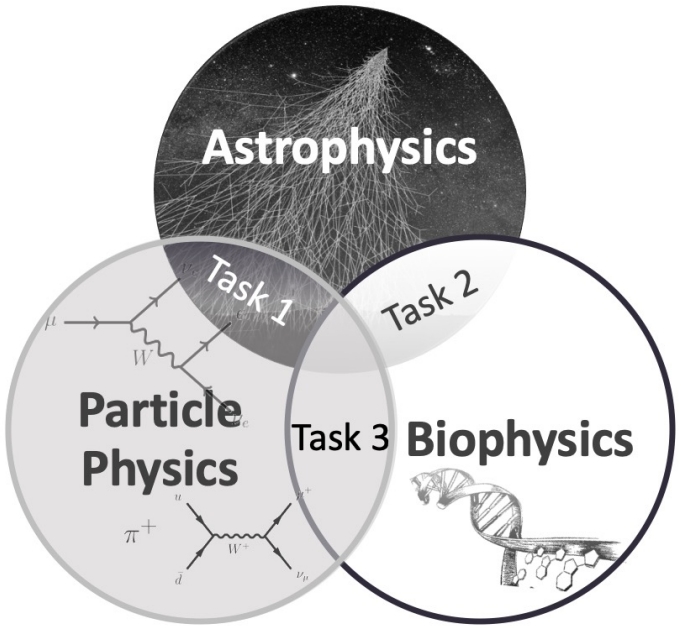


Variations of cosmic ray flux

Globus, Fedynitch, Blandford
(accepted in ApJ, arXiv:2101.00530)



Interdisciplinary research on cosmic rays and astrobiology



2020

Task 1: Studying cosmic ray radiation in different astrophysical environments

- Modern computing/machine learning is being introduced into cosmic ray codes
- Better understanding of the cosmic-ray shower physics
- Better understanding of cosmic-ray accelerators

Task 2: Studying theoretically and numerically the changes in helical biopolymers (proteins, DNA) caused by spin polarized radiation

- Multidisciplinary research involving biology and quantum mechanics (e.g., CISS)
- Collaboration with biologists and experts in biomolecular engineering

Task 3: Conducting radiation biology experiments to determine the biological response of simple microorganisms to spin polarized radiation

- Collaboration with Stanford University, SLAC and UC Santa Cruz
- Collaboration with J-PARC (muon beam) in Japan (proposal accepted)
- Prospects to use laser beams as muon sources (ELI Beamlines)
- Prospects to use UV-CPL to understand enantioselective mutagenesis (ELI Beamlines,IBT/ BIOCEV)

Summary

- **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 ?
    - Lodacity 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?)