The effect of cosmic rays on planetary atmospheres

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“Cosmic Rays 3: The Salt of the Star Formation Recipe”
Arcetri Observatory, Florence, 22nd October 2024

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DIAS
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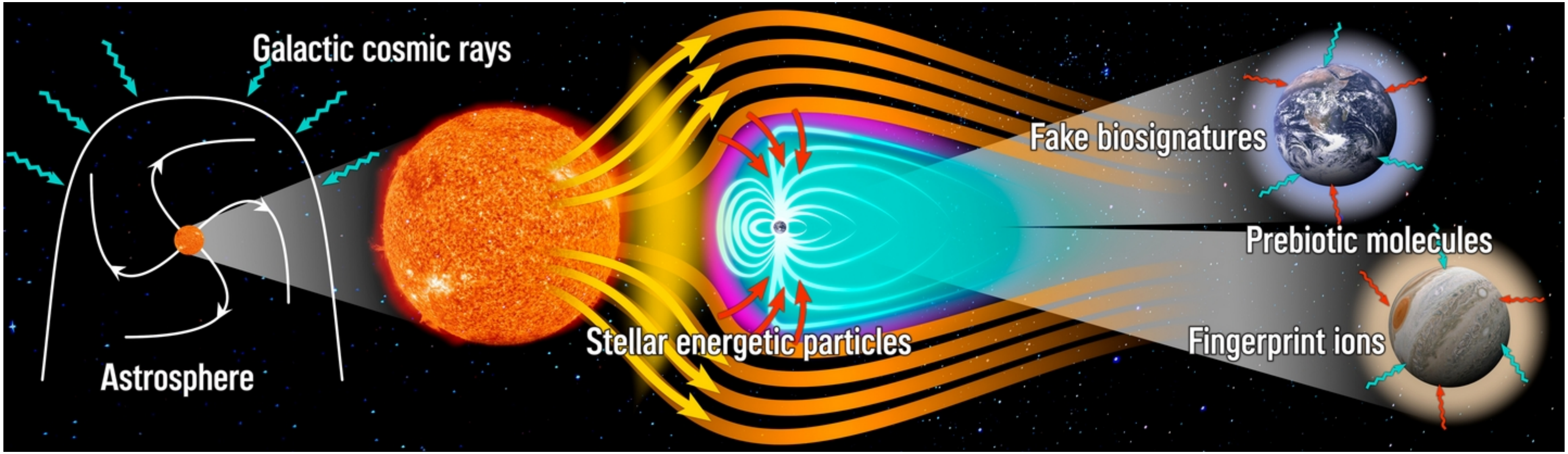
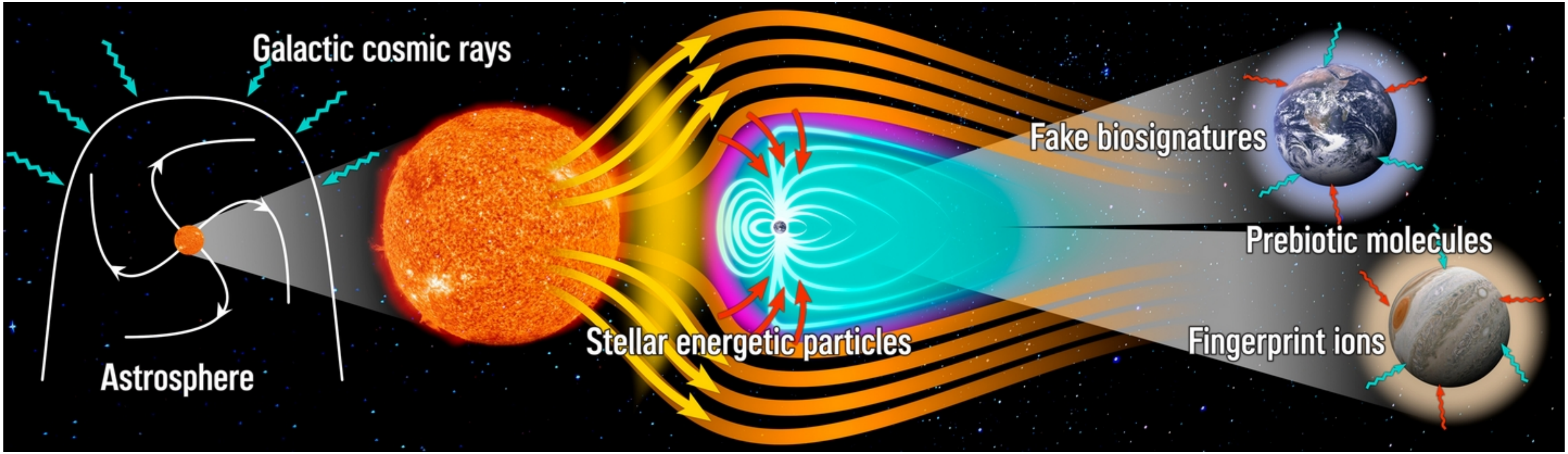
Two types of cosmic rays



- Galactic cosmic rays – from the interstellar medium
- Stellar energetic particles – from flares and coronal mass ejections

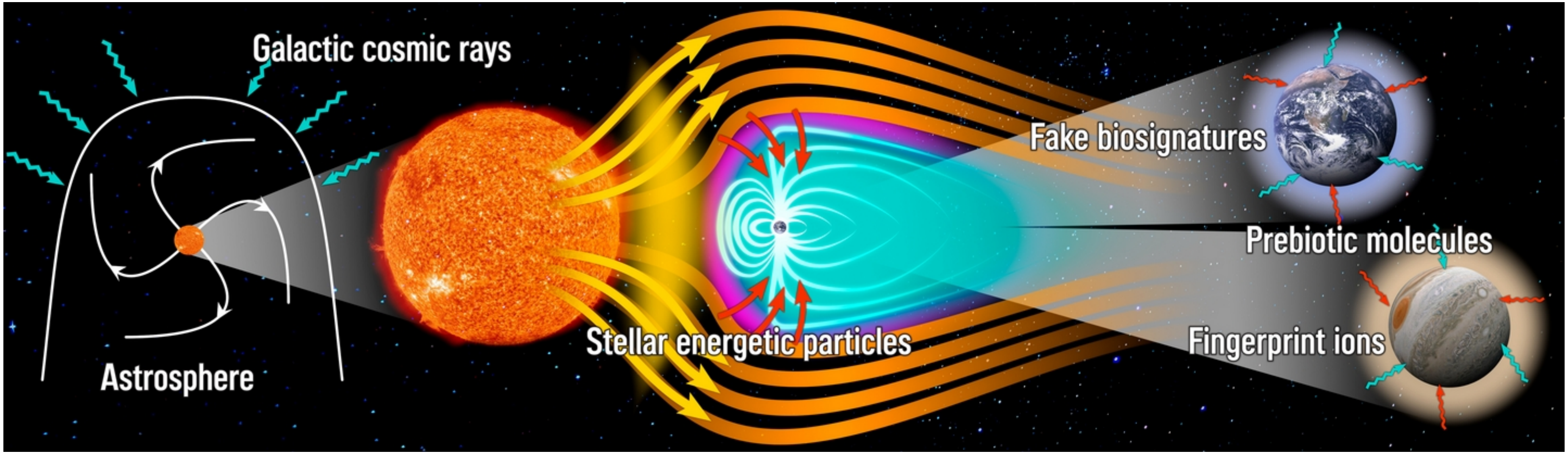
→ see V. Brunn & A. Marcowith's talks

Impact of cosmic rays on exoplanets



- affect life-forms by damaging DNA (e.g. Herbst et al 2019; Atri 2020)
- indirectly left an imprint on the helicity of DNA (Globus & Blandford 2020)
- lead to prebiotic molecule formation (e.g. Airapetian et al 2016; Dong et al 2019)

Impact of cosmic rays on Earth-like exoplanets



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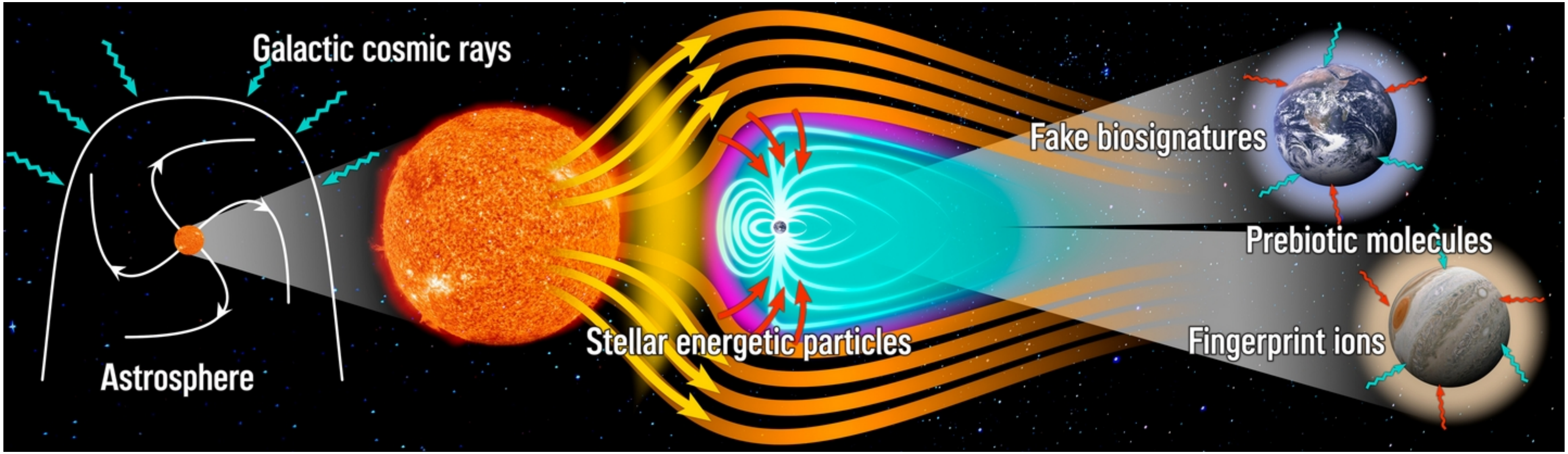
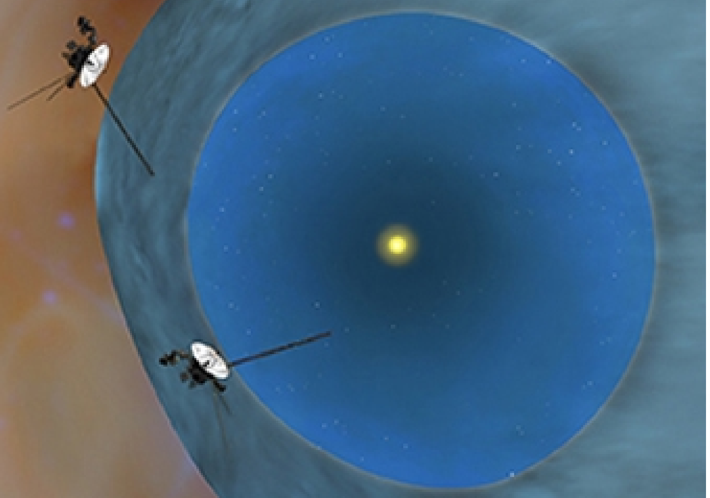
Impact of cosmic rays on exoplanets

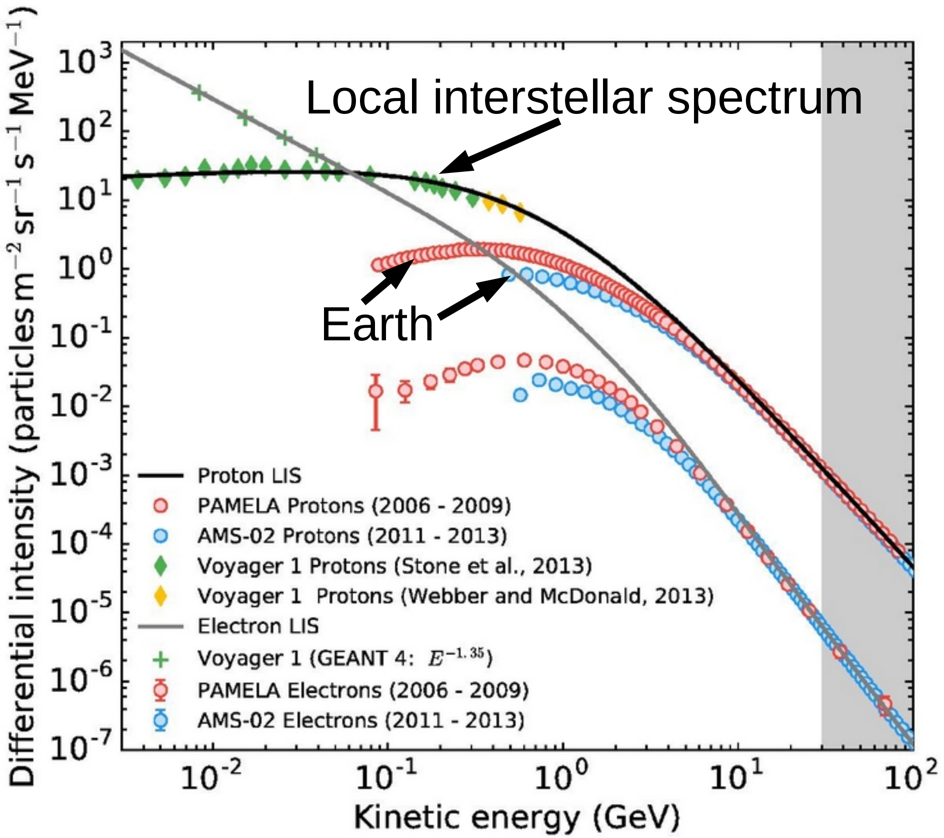


- affect life-forms by damaging DNA (e.g. Herbst et al 2019; Atri 2020)
- indirectly left an imprint on the helicity of DNA (Globus & Blandford 2020)
- lead to prebiotic molecules <u>and fingerprint ions</u> (e.g. Airapetian et al 2016; Dong et al 2019; Helling & Rimmer 2019; Barth et al 2021)

Galactic cosmic rays and Voyager

(see D. Long & N. Indriolo’s talks!)

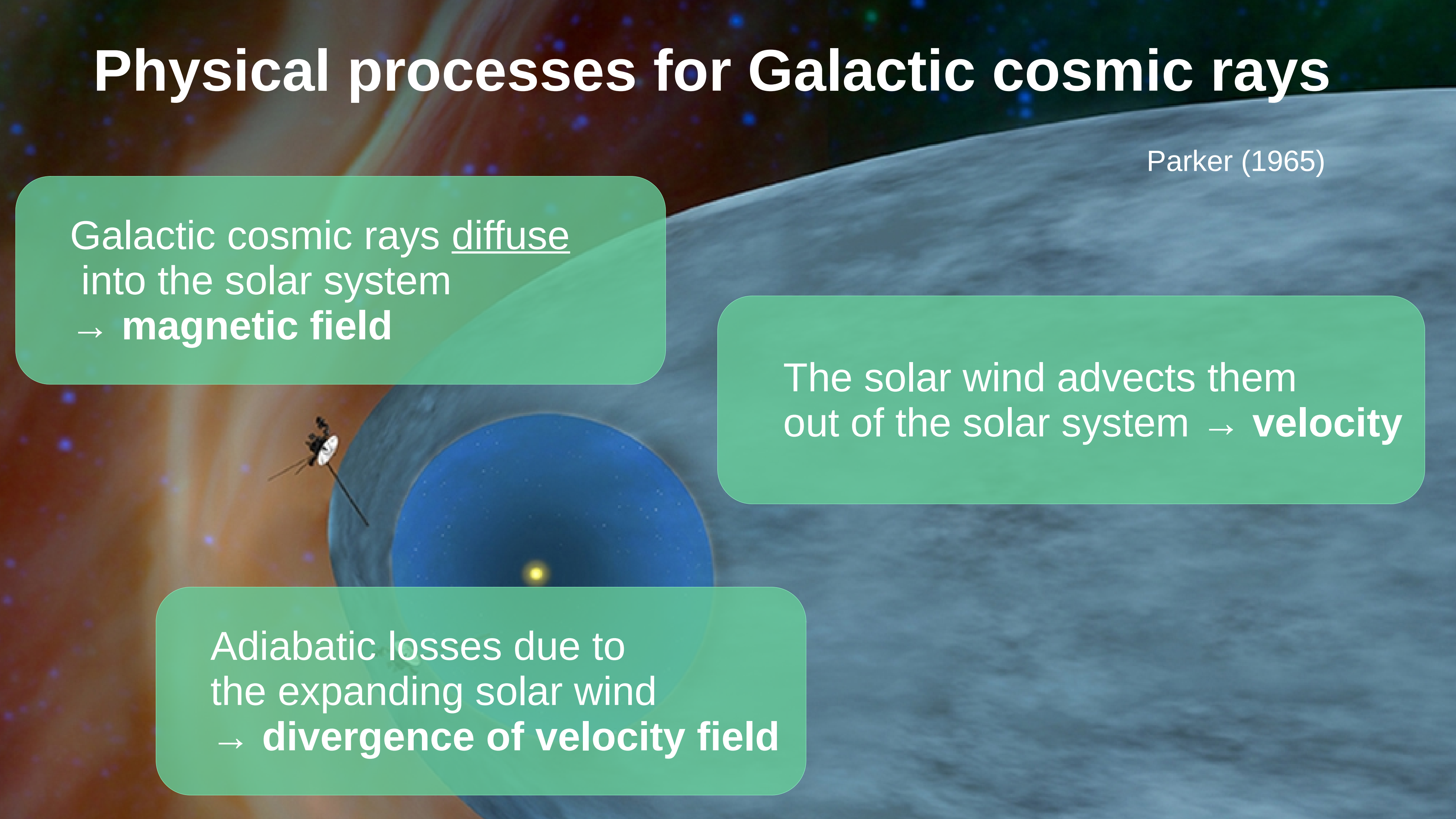




Potgieter & Vos (2017)

Physical processes for Galactic cosmic rays

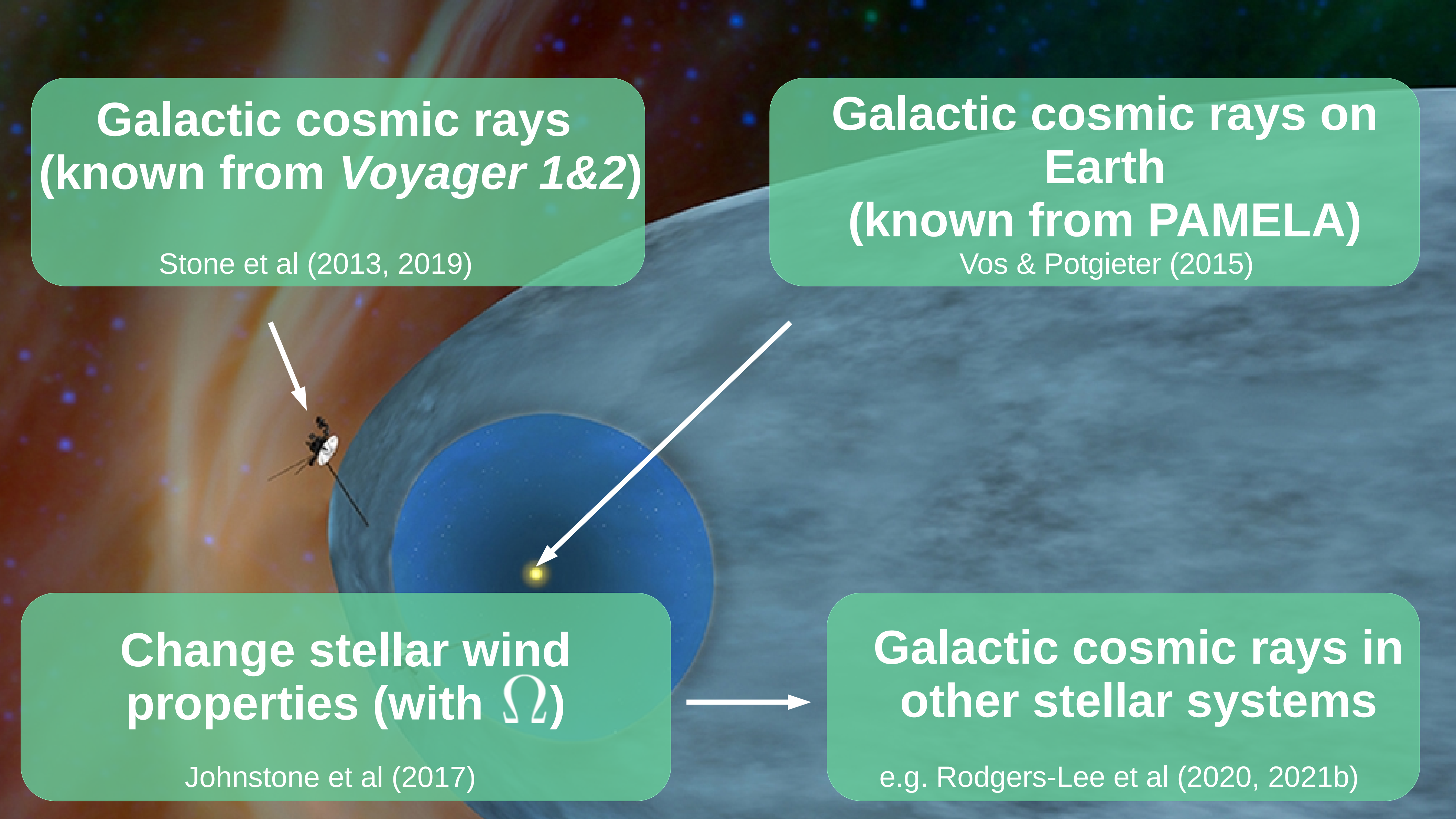
Parker (1965)



Galactic cosmic rays <u>diffuse</u> into the solar system
→ **magnetic field**

The solar wind advects them out of the solar system → **velocity**

Adiabatic losses due to the expanding solar wind
→ **divergence of velocity field**


Galactic cosmic rays
(known from *Voyager 1&2*)
Stone et al (2013, 2019)
Galactic cosmic rays on Earth
(known from PAMELA)
Vos & Potgieter (2015)
Change stellar wind properties (with Ω)
Johnstone et al (2017)
Galactic cosmic rays in other stellar systems
e.g. Rodgers-Lee et al (2020, 2021b)

We often extrapolate from the Sun...

Difficult to measure:

- $B_\star$ for known planet-hosting stars
- $\dot{M}$

Difficult to constrain:

- Stellar energetic particle spectrum
- Turbulence properties of stellar winds

What do we need?

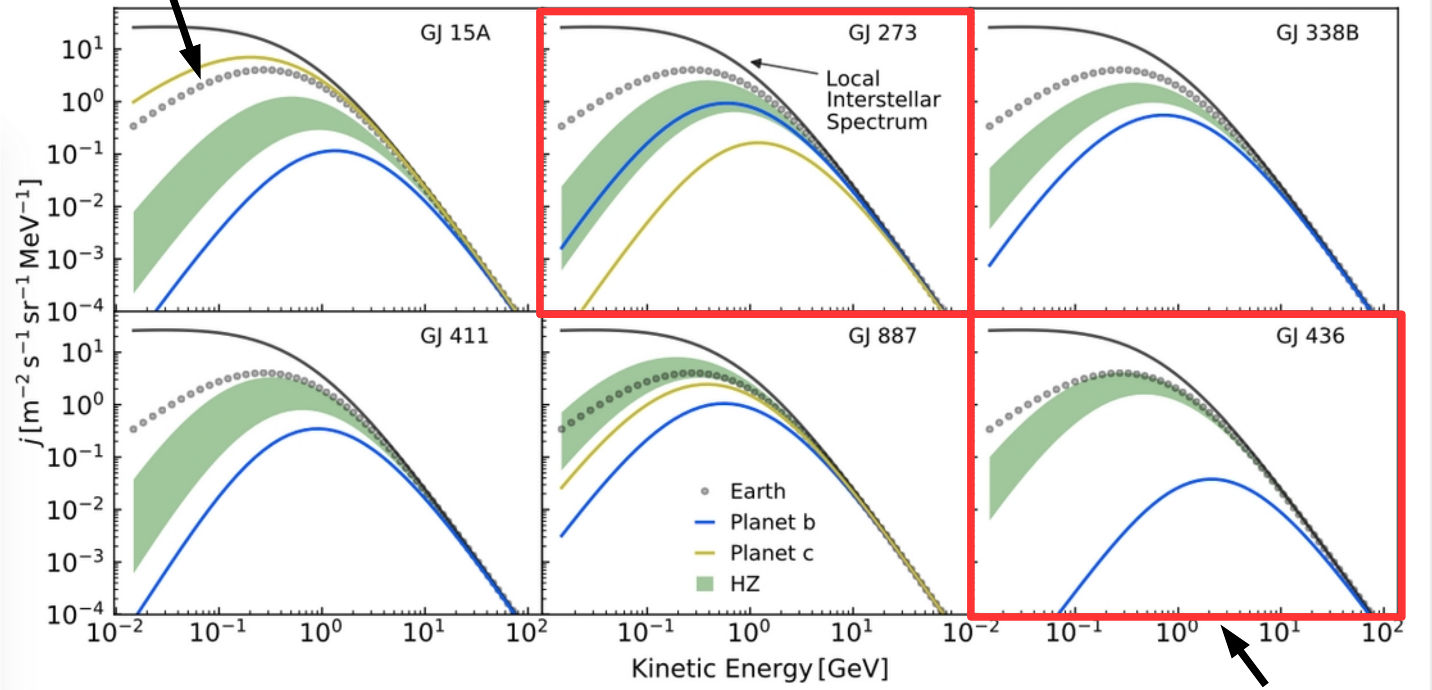
- Chemical modelling of H_2 atmospheres

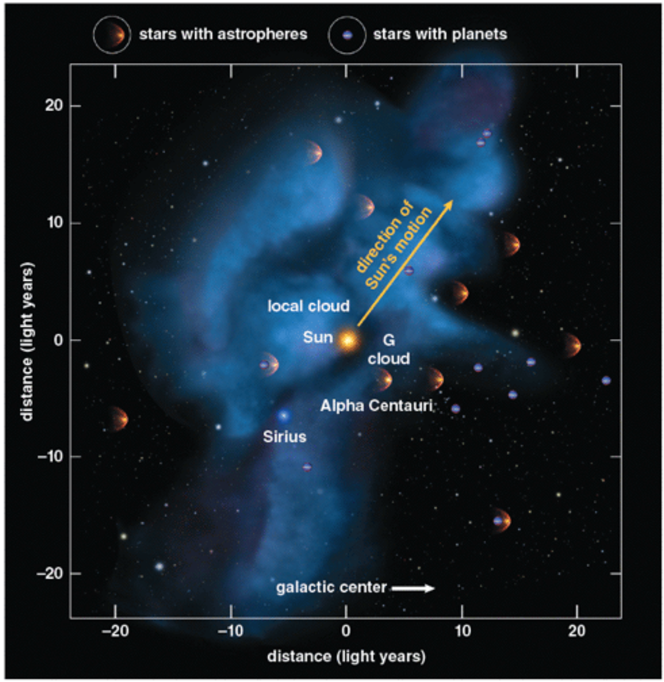
Credit: JPL

Conditions for life on exoplanets orbiting M dwarf stars

values at Earth

Radiation dose





Mesquita, **DRL** et al (2021; 2022a)

JWST and Ariel target

See also Herbst et al (2020), Scheucher et al (2020)

Transport of cosmic rays through a GJ 436b-like atmosphere

- M dwarf with a warm Neptune exoplanet with 0.03au orbit
- Relatively inactive star
- Comet-like tail behind the planet detected with Hubble (Ehrenreich et al 2015)

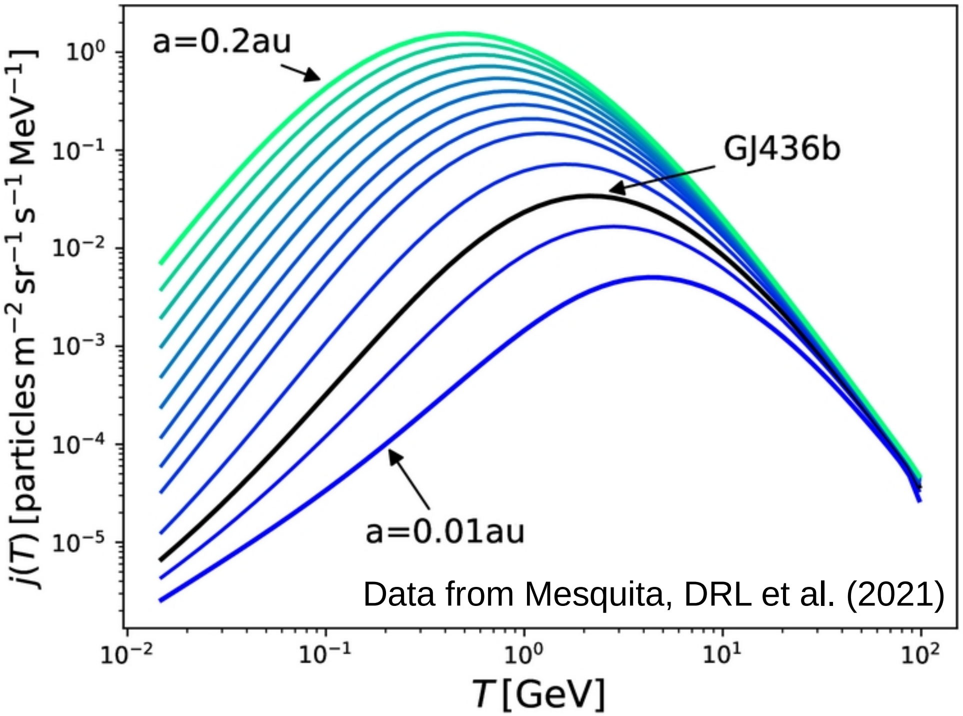
Transport of cosmic rays through a GJ 436b-like atmosphere

- Atmospheric composition and temperature-pressure profile (250-1300K)

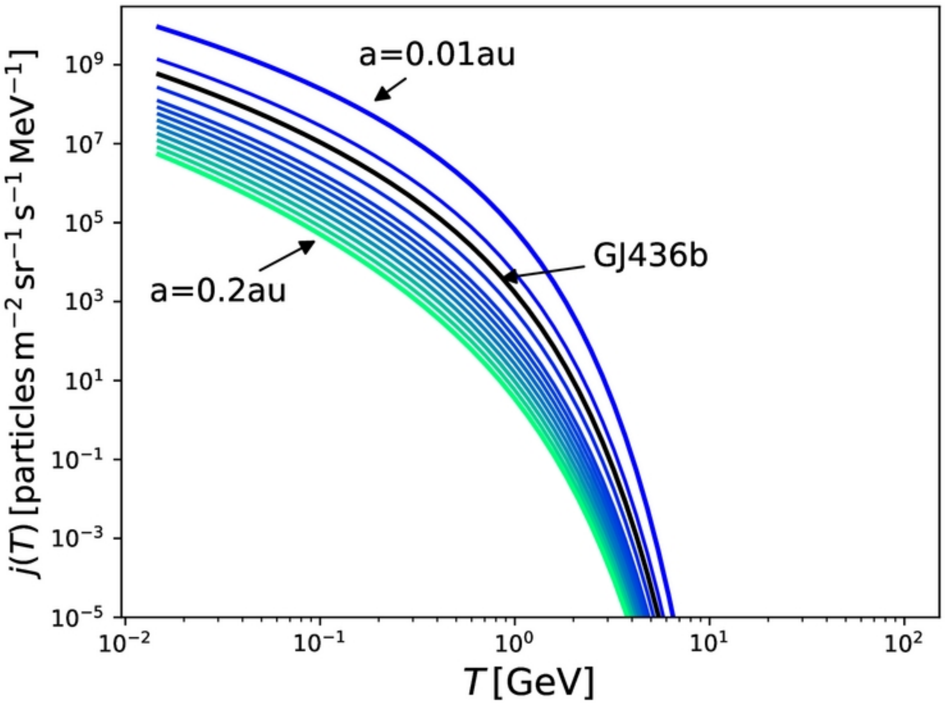
  → density of the atmosphere

- Stellar wind properties $(v, B, \dot{M})$
  → cosmic ray fluxes

Cosmic ray fluxes for GJ436 system



Galactic cosmic rays

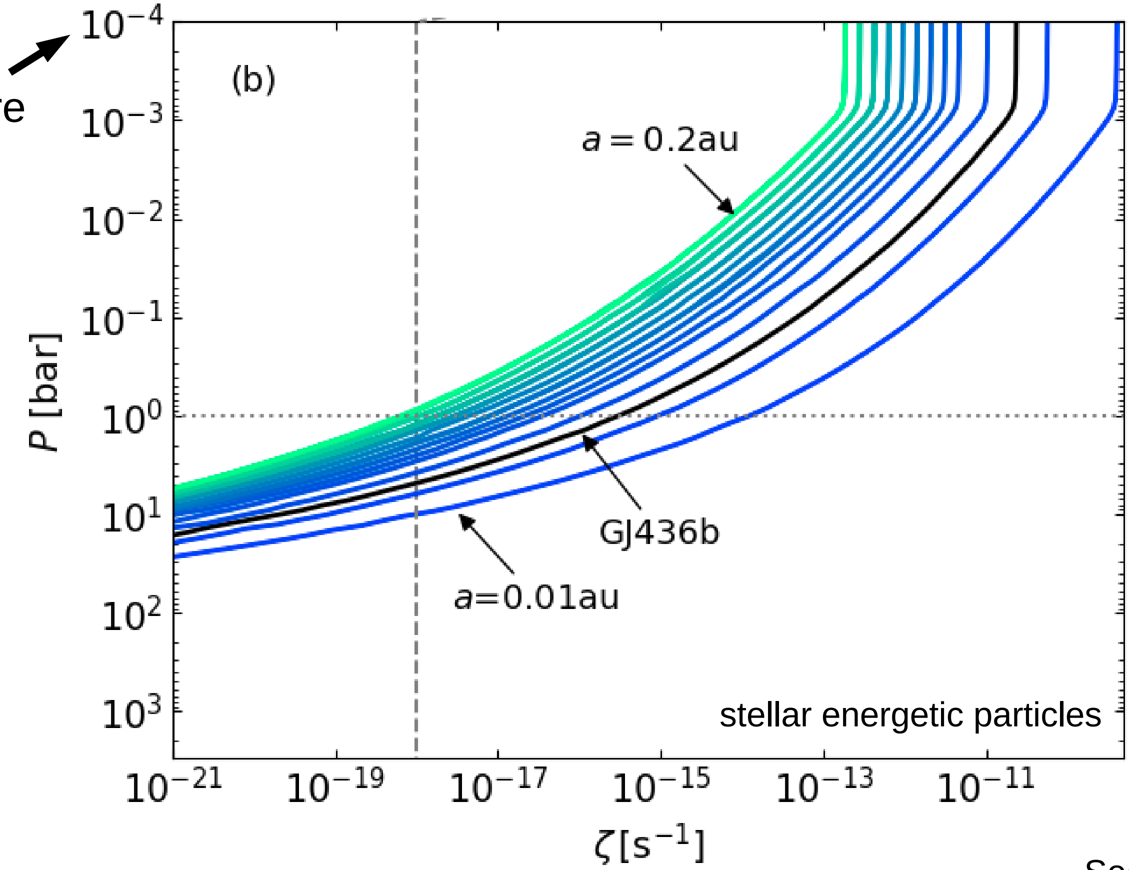


Stellar energetic particles

→ <u>Stellar energetic particle spectra & transport model:</u> Rodgers-Lee et al (2020b, 2021b)

High ionisation rate due to stellar energetic particles for GJ436 system

Top of the atmosphere



Rodgers-Lee et al. (2023)

$$\zeta_{H_2} \sim \int j(E)\sigma(E)\,dE$$

→ See also Herbst et al (2018), Barth et al (2021), Hu et al (2022)

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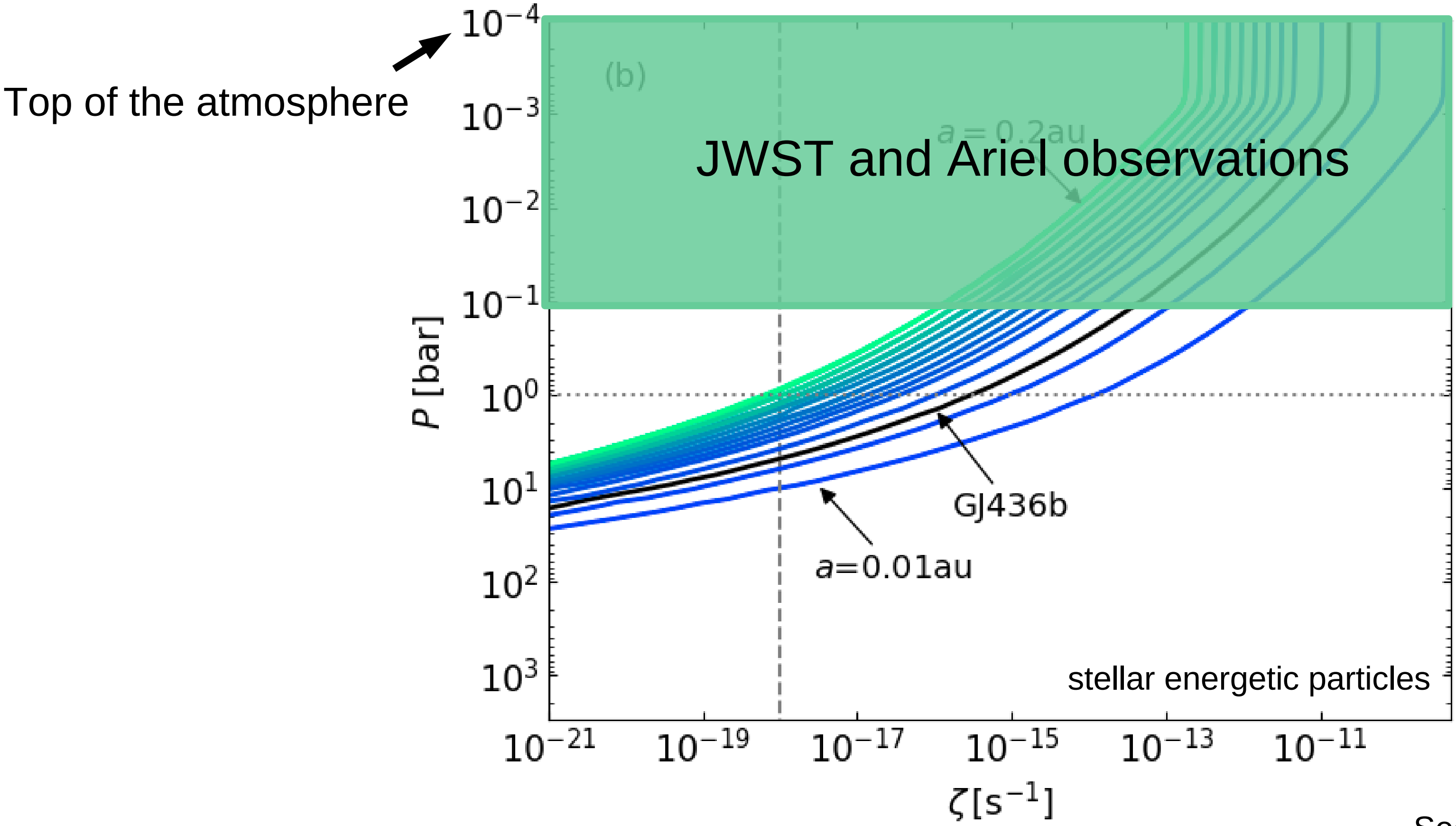

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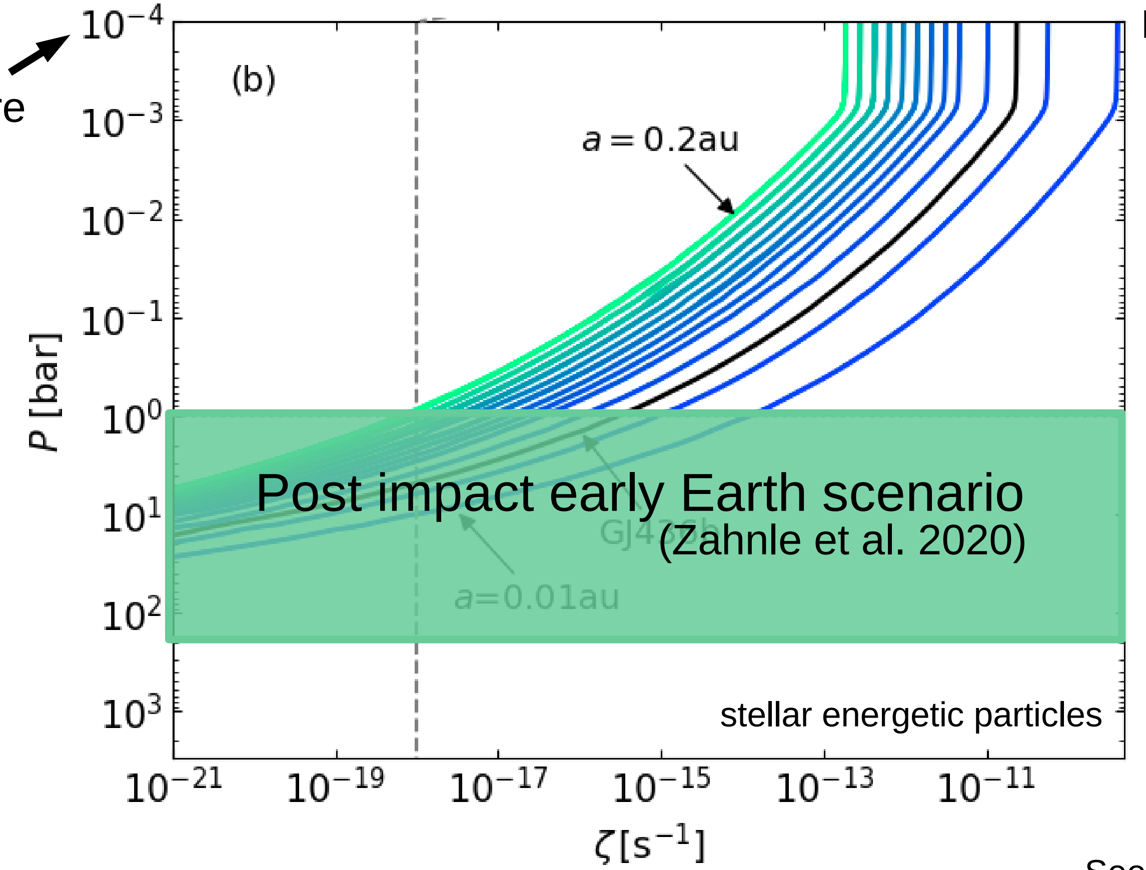

Rodgers-Lee et al. (2023)

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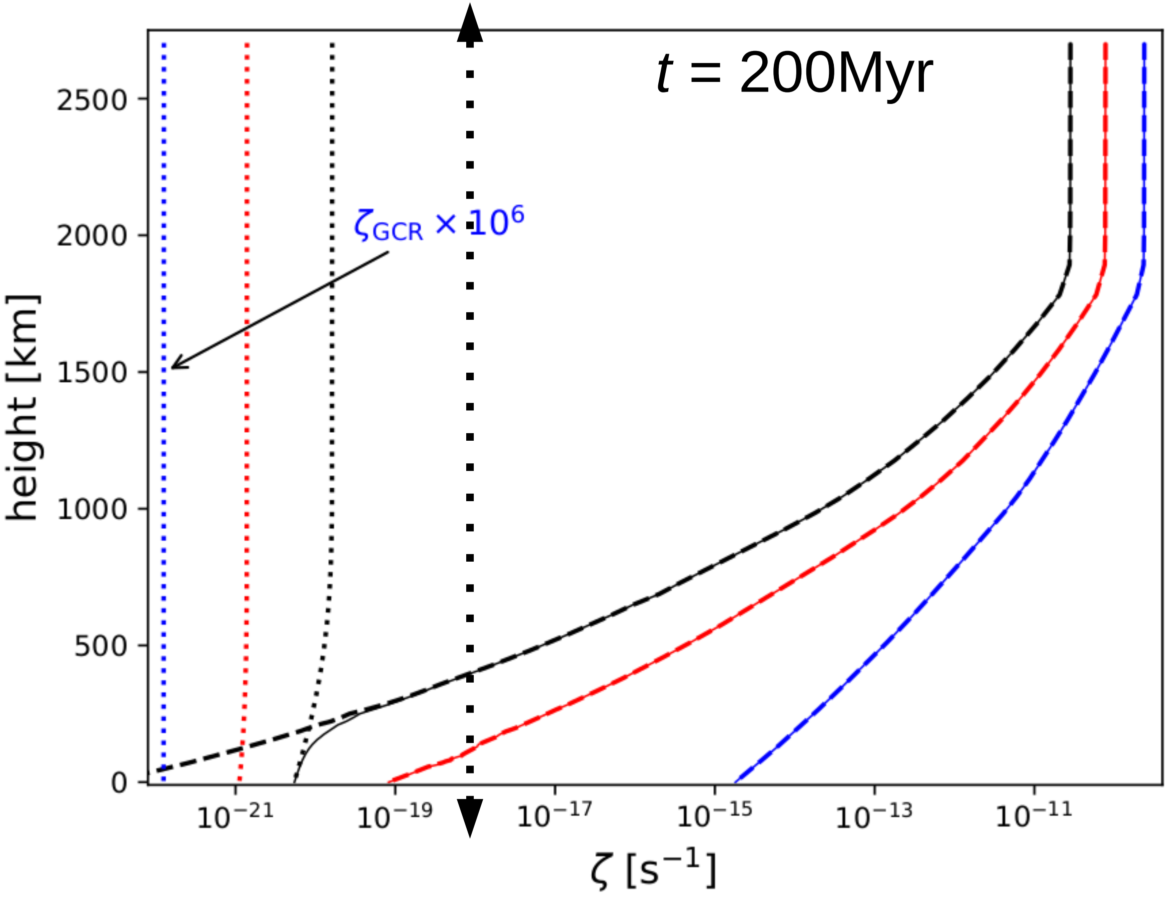
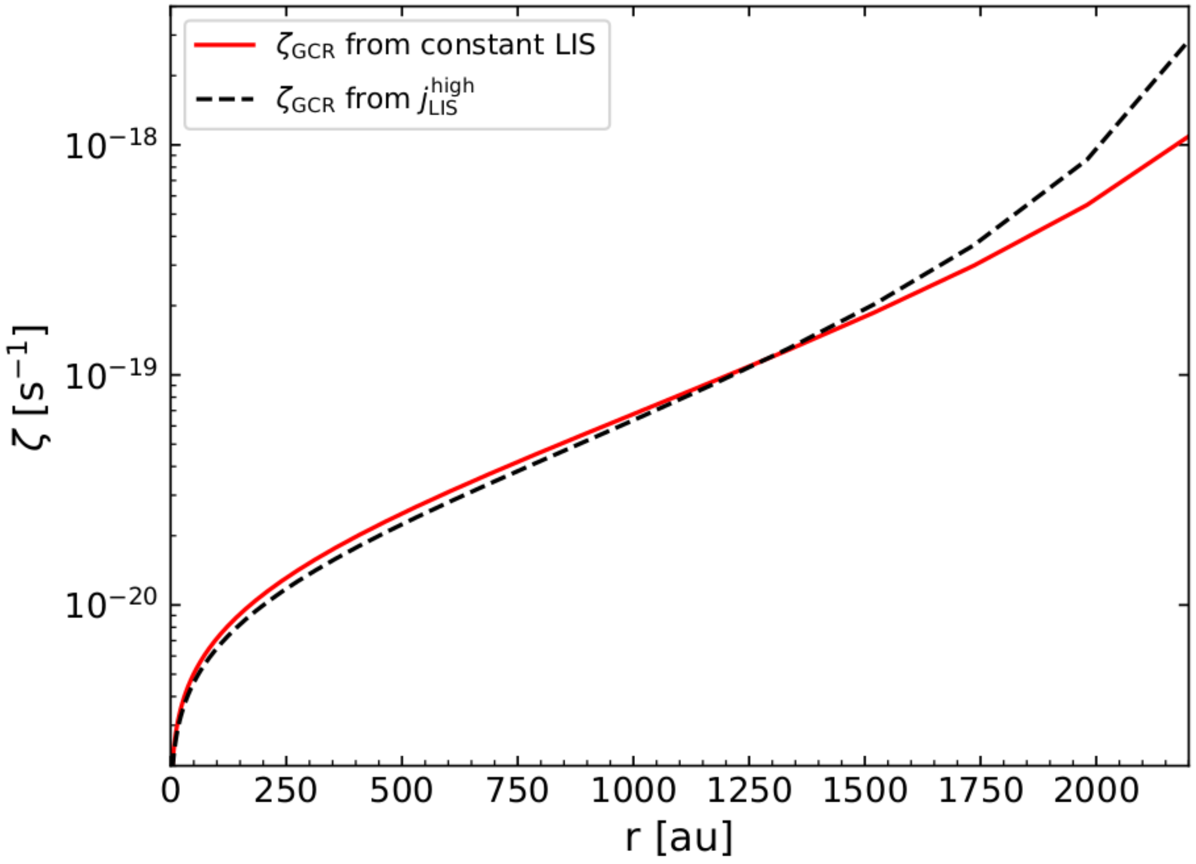
Earth's surface: stellar energetic particle ionisation rate high if Sun was a fast rotator

→ High pressure H_2 dominated atmosphere



Raeside, **DRL** et al (in prep.)

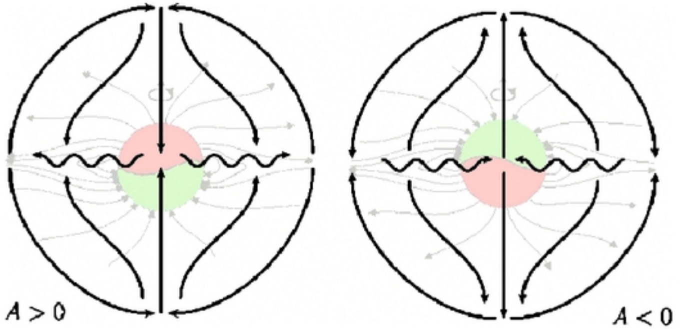
Changing the low-energy Galactic cosmic ray spectrum has no effect at 1au at 200 Myr

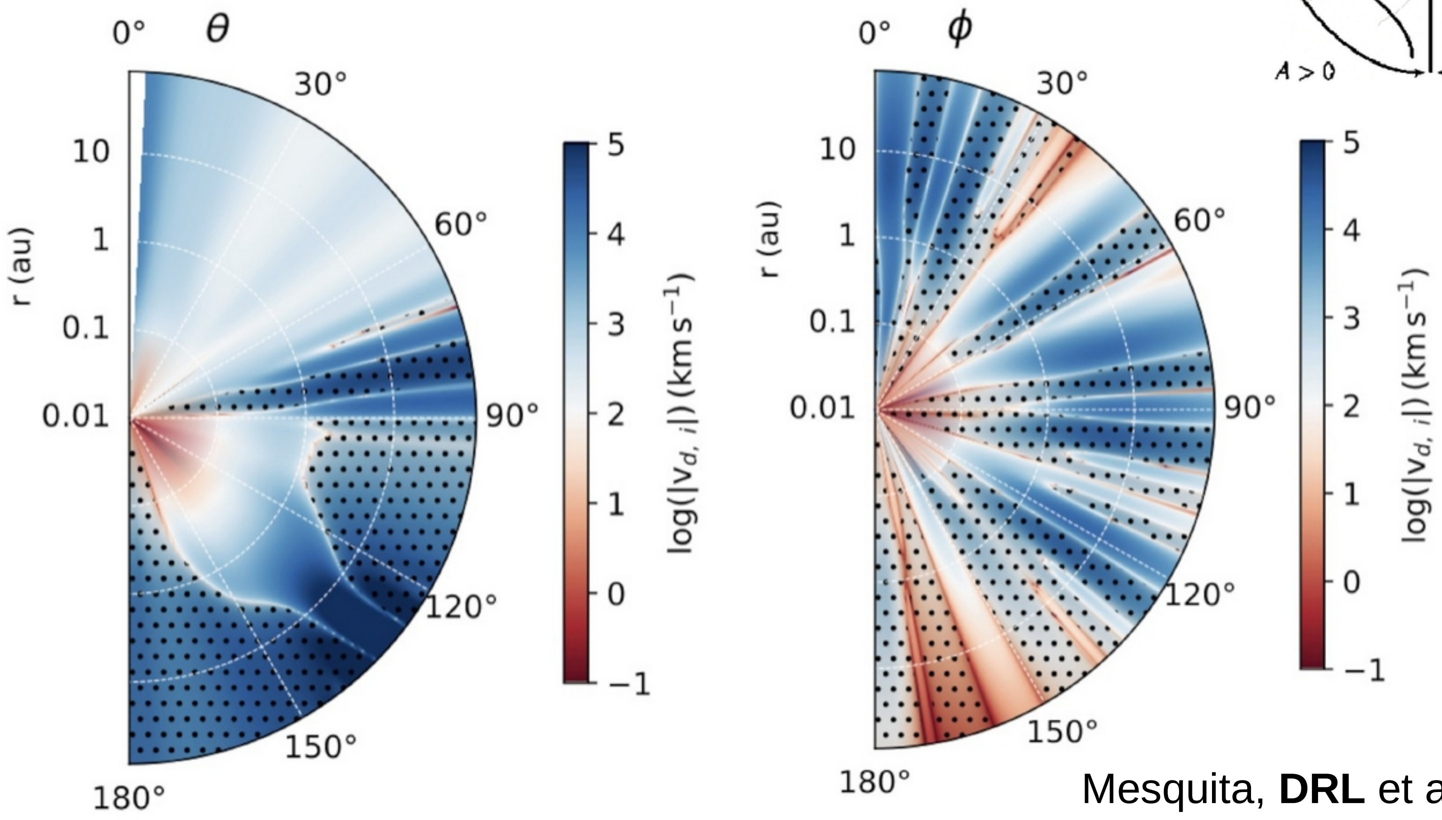


j_{LIS}^{high} from Padovani et al (2018)

Raeside, **DRL** et al (in prep.)

Prox Cen: drift velocities

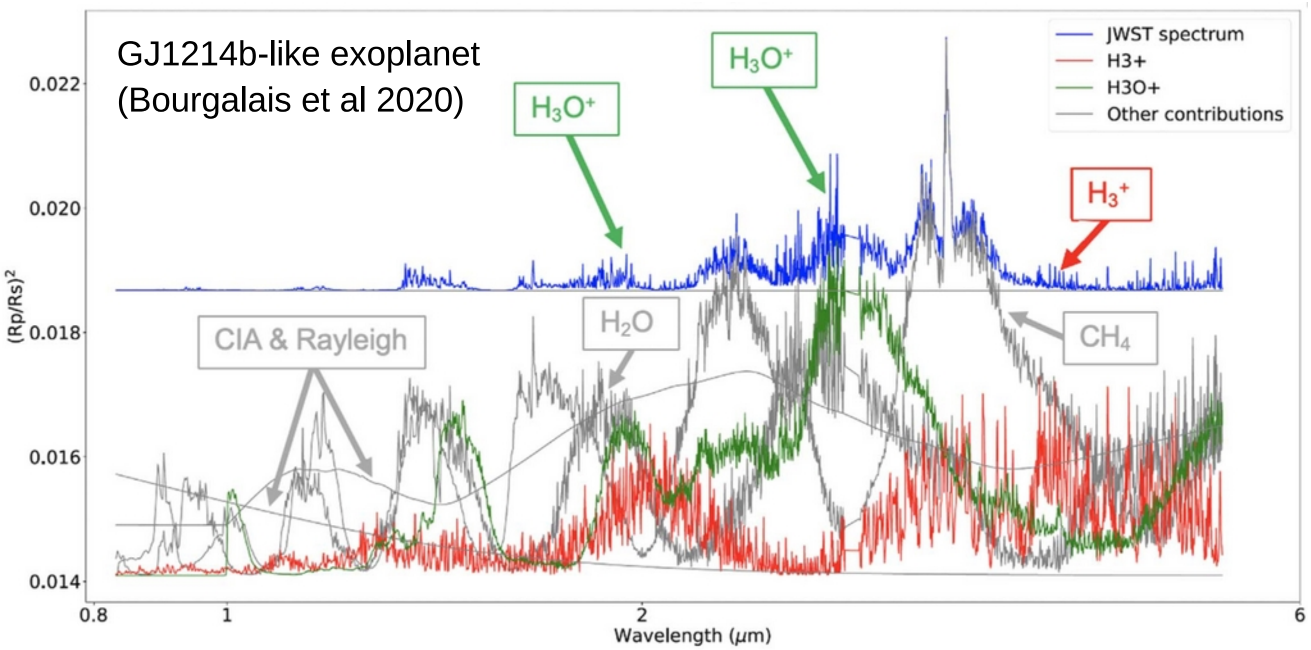




Mesquita, **DRL** et al (2022b)

→ see also Engelbrecht et al (2024)

Chemical effect of cosmic rays on hydrogen-dominated atmospheres



Fingerprint ions:

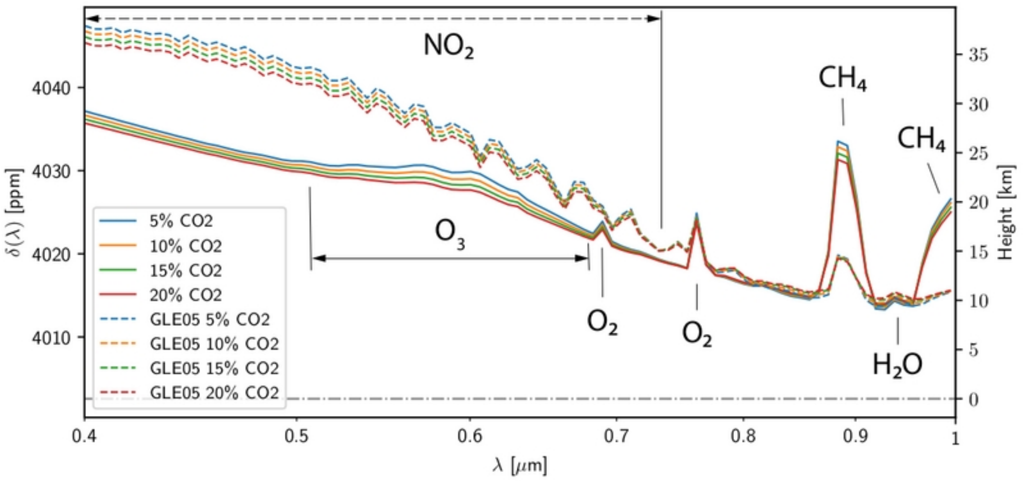
(Helling & Rimmer 2019)

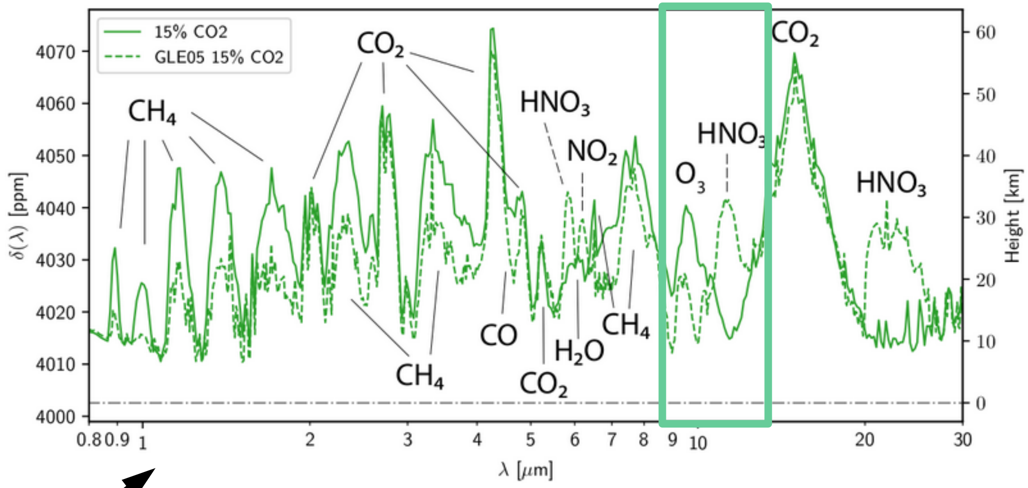
$$H_2 + CR \rightarrow H_2^+ + e^- + CR$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

$$H_3^+ + H_2O \rightarrow H_3O^+ + H_2$$

Cosmic ray effects in Earth-like atmospheres





Scheucher et al (2020)

Ozone depletion

→See also Herbst et al (2018), Grenfell et al (2012)

Conclusions & next steps

Stellar wind properties, composition and density of exoplanet atmospheres determine the cosmic ray fluxes in exoplanet atmospheres

Stellar energetic particles lead to high ionisation rates in a GJ 436b-like exoplanet atmosphere

Create model JWST/Ariel spectra including the chemical effect of Galactic cosmic rays and stellar energetic particles

Effect of planetary magnetospheres, air shower models, 3D models….

Postdoc position coming soon!

Thank you!