Climate and radiative properties of a tidally-locked planet around Proxima Centauri

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Three dimensional General Circulation Models (GCMs) are at the moment the best available tools to investigate and predict the properties of the exo-atmospheres of Earth-like planets orbiting nearby stars. We investigate the detectability of the planet orbiting around Proxima Centauri and its possible climate, in the case an Earth-like atmosphere is present on such planet. We use a 3D GCM of intermediate complexity, the Planet Simulator (PlaSim), and a 1D Radiative Transfer Model (RTM), *uvspec*, to derive the atmosphere circulation along with the radiative properties of the planet with a fixed concentration of carbon dioxide equal to 360 ppm. A circular orbit and a zero obliquity are assumed for the planet which is here considered as an "aquaplanet". The model outputs include the atmospheric dynamics, surface temperature and the presence of liquid water, as well as the high resolution reflection and emission spectra of the planet. In particular, the Planet/Star thermal infrared flux fraction is retrieved during the planet's orbit and is used to evaluate the planet thermal phase curve. The results presented are relative to a simulation of 100 Earth years with a temporal resolution of 1 Earth day and a T42 model grid resolution (64 latitudes and 128 longitudes) with 10 terrain-following vertical levels, postprocessed in 20 pressure levels, from 1000 hPa (ground) to 10 hPa (top of the atmosphere). Our approach can effectively retrieve atmospheric fingerprints of Earth-like planets of nearby systems, giving clues on the habitability of such planets, and can be used to set observational limits for the forthcoming generation of space-born and ground-based telescopes.

STAR

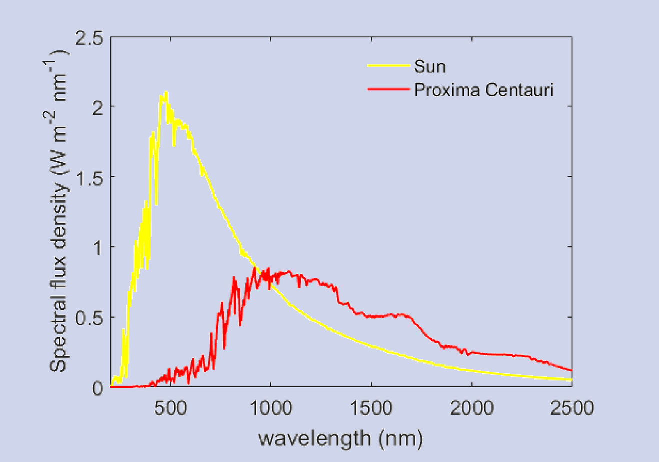


Table 1. Proxima Centauri parameters. Values presented in this table appear without their relative uncertainties, since they are the exact values introduced in PlaSim source code.

Stella property	Symbol	Value
Spectral type	-	M5.5
Mass	$M_\star$	$0.120\ M_\odot$
Radius	$R_\star$	$0.141\ R_\odot$
Bolometric flux	$F_\star^{bol}$	$2.886 \times 10^{-11}\ W\,m^{-2}$
Irradiance at proxima b TOA	$F_\star^{toa}$	$884.650\ W\,m^{-2}$
Effective temperature	$T_\star^{eff}$	$2980\ K$

Anglada-Escudé, G. et al. (2016)
Ribas, I. et al. (2017)

PLANET

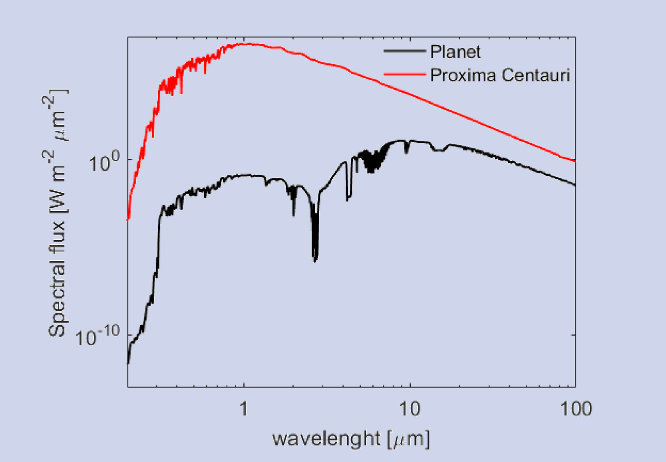


Table 2. Proxima b Keplerian and planetary parameters assumed in PlaSim simulations.

Proxima Centauri b: derived and assumed quantities.

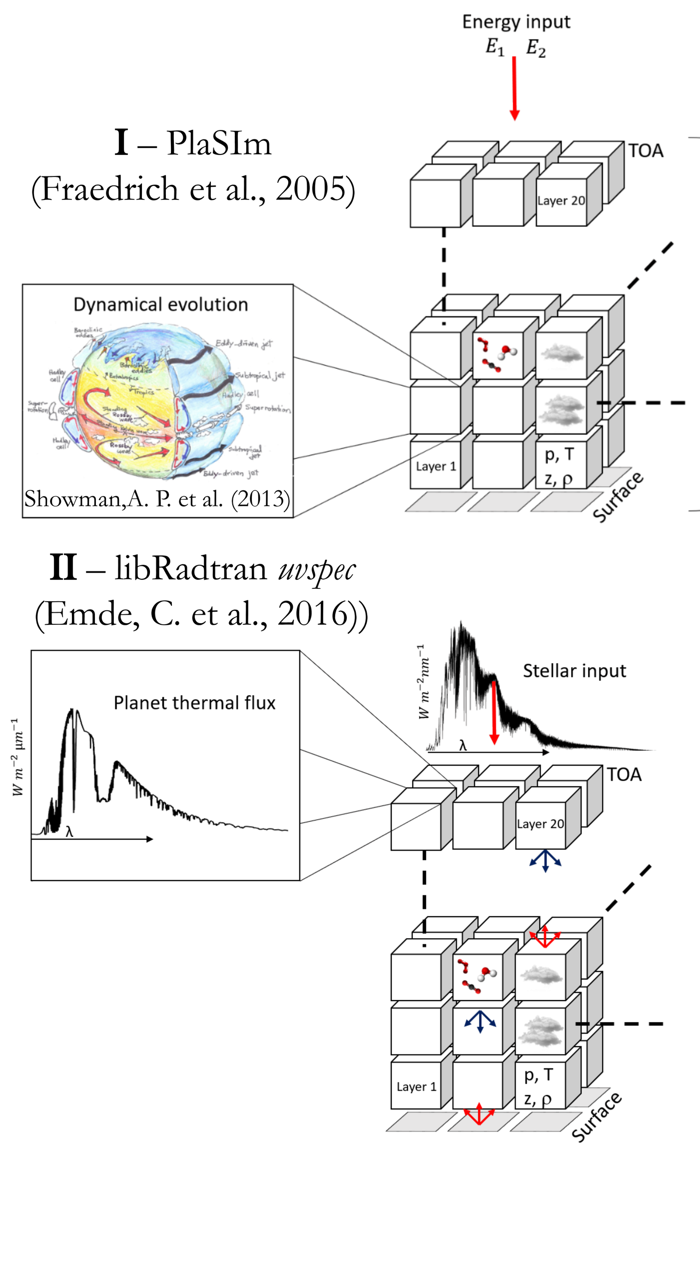
Parameter	Symbol	Value
Orbital period	P	11.186 Earth days †
Orbit eccentricity	e_p	0.0 ‡
Orbit semi-major axis	a	0.0485 AU †
Obliquity	α	0.0 deg ‡
Minimum mass	$m_p \sin(i)$	$1.27\ M_\oplus$ †
Mean density	$\rho_p = \rho_\oplus$	$5514.0\ kg\,m^{-3}$ ‡
Mean radius	r_p	$1.08 R_\oplus$ ‡
Surface gravitational acceleration	g_p	$10.6\ m\,s^{-2}$ ‡
Rotation rate	ω_p	$6.5 \times 10^{-6}\ rad\,s^{-1}$ ‡

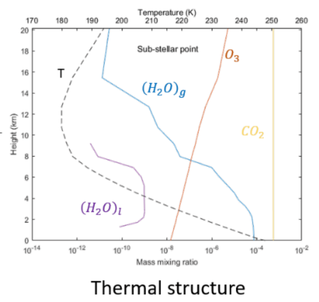
† Measured ‡ Assumed

METHOD: PlaSim + uvspec

I – PlaSIm (Fraedrich et al., 2005)

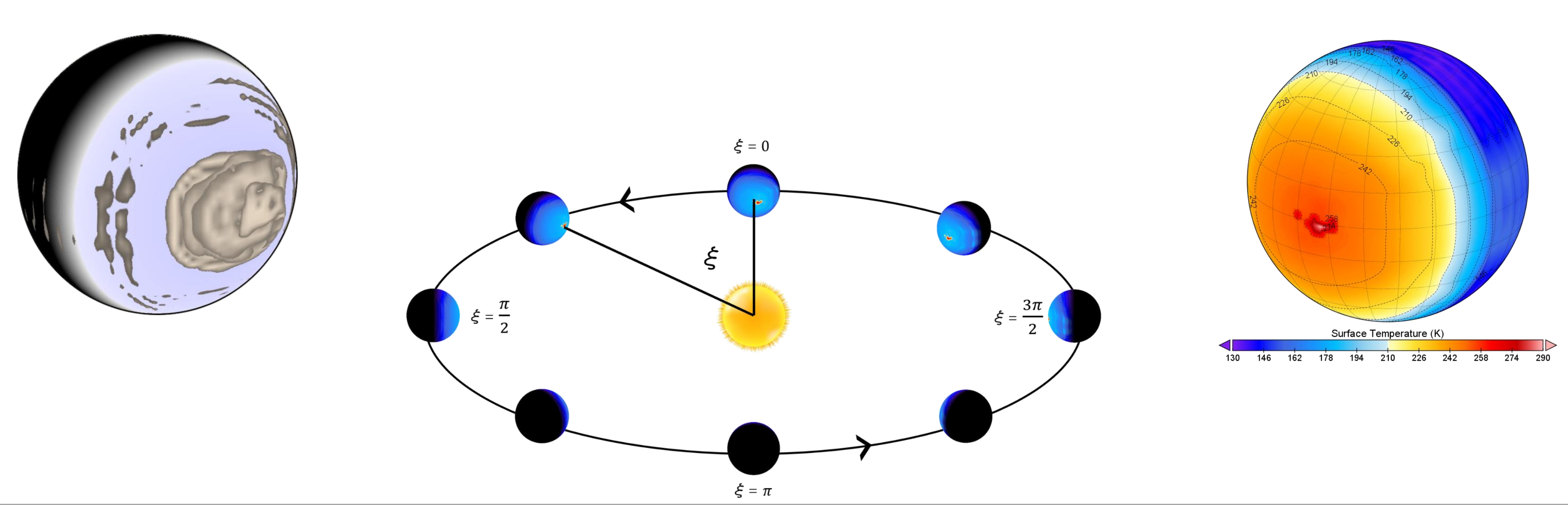
II – libRadtran *uvspec* (Emde, C. et al., 2016))





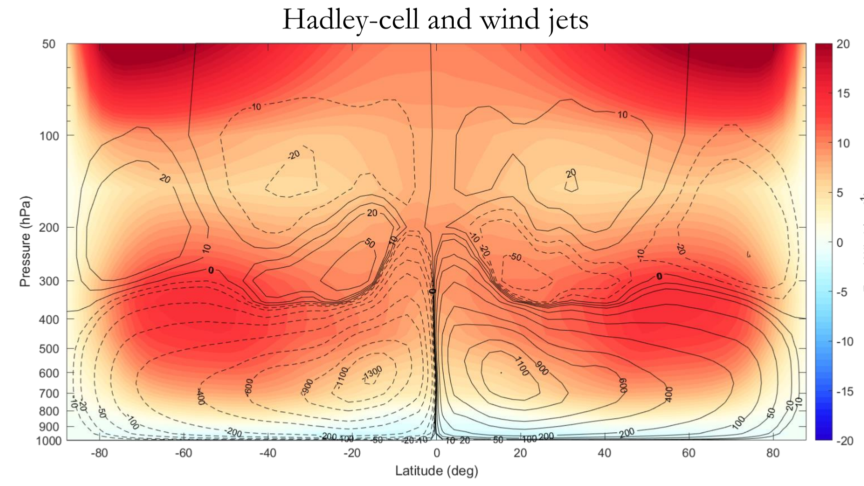
The 3D grid of the PlaSim simulation is here represented. Each rectangular parallelepiped represents an atmospheric vertical column of the planetary atmosphere. Physical properties within each column is given by the PlaSim model run. The vertical profiles of pressure, temperature, air density, carbon dioxide, water vapor, ozone and cloud liquid water content are extracted for each single column to be processed by the radiative transfer model *uvspec*. The input for line-by-line radiative transfer calculation is given by the spectral irradiance of Proxima Centauri at planet TOA. After radiative calculation, the model returns the thermal spectral emission of the planet for each atmospheric column. Integrating the thermal spectral emission on all wave numbers, the Outgoing Longwave Radiation (OLR) for each vertical column top can be obtained. Otherwise, selecting a specific spectral band from λ to λ + Δλ, the thermal broadband emission in the given spectral interval can be also obtained.

CLIMATE



Because of the planet synchronous rotation, the planet receives radiation by the star always in the same region (day-side), while there are regions in permanent night condition (night-side). Since we set the planet with zero obliquity and on a circular orbit, the sub-stellar point falls exactly on the equator and receives always the same amount of energy from the star. For this reason, the resulting mean surface temperature field shows an insolation-symmetric pattern and the temperature is below 273 K on most planet's surface, with the exception of a small region east to the sub-stellar point. This means that the planet is almost completely covered by sea ice, i.e. it is in a peculiar "snowball" equilibrium state. Surface temperature ranges from a minimum value of 130 K to a maximum value of 290 K. This temperature pattern, causes a convective structure at the sub-stellar point which allows the formation of clouds despite the extremely dry atmosphere (clouds liquid water content $\sim 10^{-5} \div 10^{-10}\ kg\ m^{-3}$).

Hadley-cell and wind jets



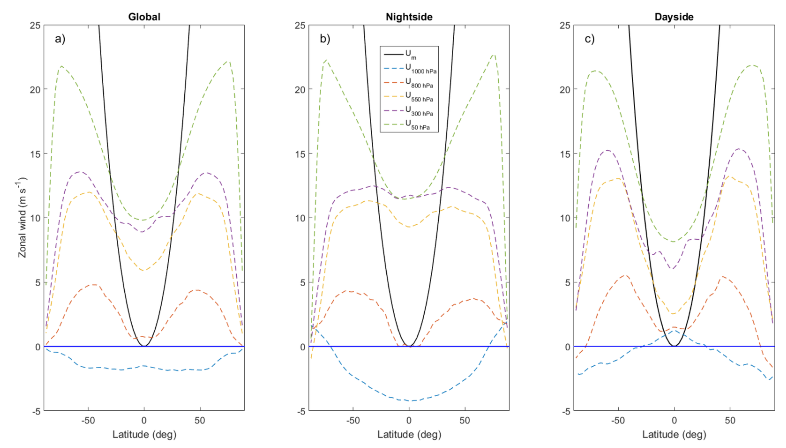
Proxima b mean circulation

Color contours: zonally averaged zonal wind u – warm colors are for westerly winds, cool colors are for easterly winds.

Black contours: mass stream function Ψ – solid lines represent the clockwise branch (Ψ > 0) in the northern hemisphere, dashed lines represent the anticlockwise branch (Ψ < 0) in the southern hemisphere.

$$\Psi(\theta, p) = -\frac{2\pi r_p}{g_P} \int_0^{p'} \bar{v} \cos\theta \, dp$$

θ is the latitude;
p is the pressure level;
$\bar{v}$ is the zonal mean of the meridional wind.



Atmosperic superrotation

Black solid curve: angular momentum conserving wind u_m as a function of latitude θ

$$u_m(\theta) = \frac{\omega_P r_P \sin\theta^2}{\cos\theta}$$

Colored dashed curves: zonal mean zonal wind at different pressure levels for a) planet global mean, b) planet night-side mean and c) planet day-side mean.

Blue solid line: zero mean of the zonal wind.

When a colored curve is above the solid black curve for a given latitude range, the condition $u > u_m$ is satisfied and the relative atmospheric layer is in an equatorial superrotation state.

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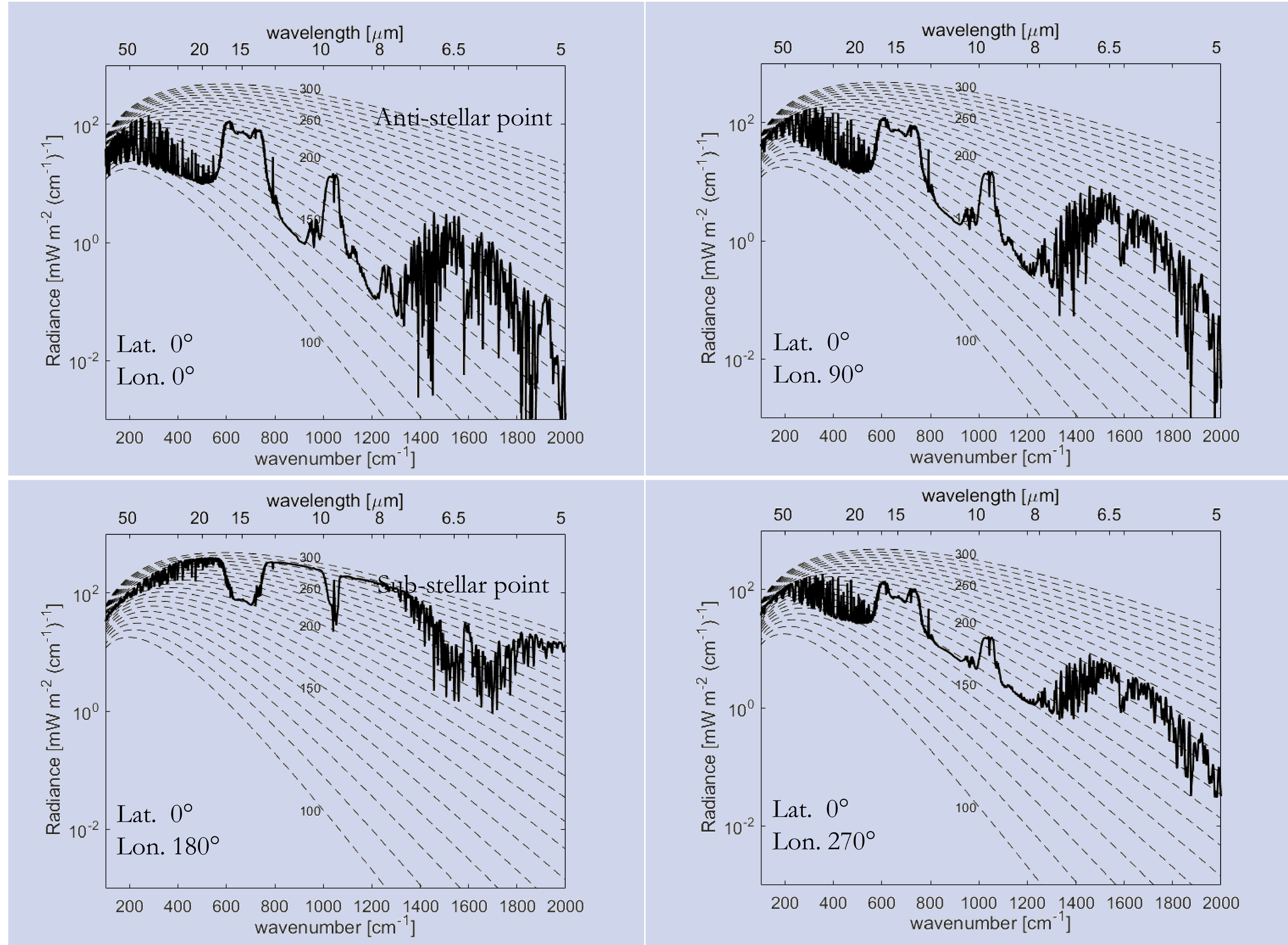
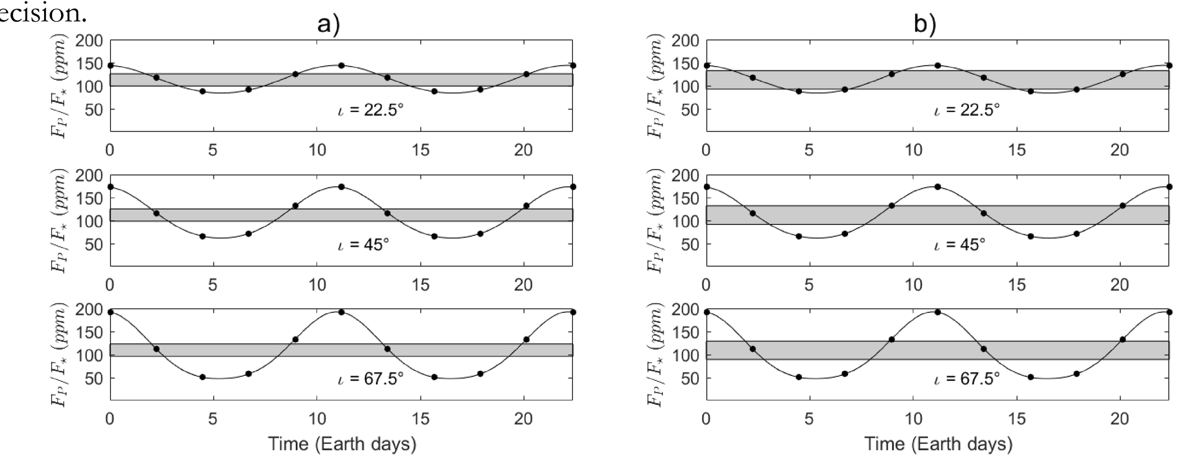
DETECTABILITY

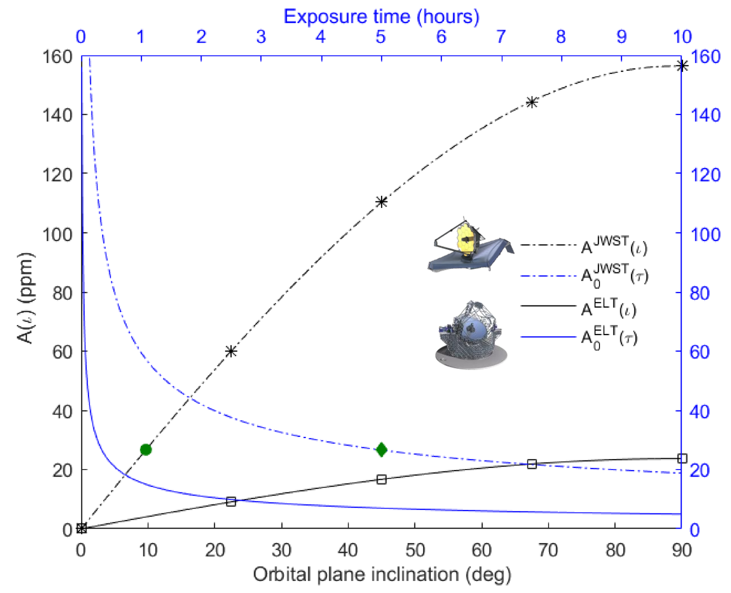


Integrating in the same spectral range (λ_1, λ_2) the planet thermal spectral emission from the visible hemisphere and the stellar spectral irradiance, the planet/star contrast, $F_P/F_\star$, can be evaluated. Below, $F_P/F_\star$ (y-axis) in the spectral band 23.5 ÷ 27.5 μm of the MIRIM instrument on board of the JWST is shown as a function of time (x-axis) for a sample of three possible planet orbital plane inclination angles. The limit of 1σ detection of broadband emission for Proxima b with τ = 5 hours is obtained by **a)** the photon number equation

$$N = \varepsilon \frac{\pi A_T^2}{4} \tau \left(\frac{R_\star}{D}\right)^2 \int_{\lambda_1}^{\lambda_2} \frac{F_\star(\lambda)}{E(\lambda)} d\lambda,$$

(Yang et al., 2013) and **b)** the Exposure Time Calculator (ETC) of JWST, with MIRIM settings. Gray areas represent the instrumental photometric precision for JWST evaluated with the two methods. In the panel **b)**, the more accurate limit evaluated by ETC results in a lower (wide gray area), but comparable, photometric precision.





Comparison between JWST-MIRIM (23.5 ÷ 27.5 μm) and ELT-MIDIR (12.9 ÷13.1 μm) for 1σ detection of Proxima b atmospheric broadband emission. The black curves represent the thermal phase curve amplitude A as a function of the planet orbital plane inclination angle. The blue curves represent the minimum detectable amplitude A_0, as a function of exposure time, evaluated by the photon number equation. Colored axis refer to curves with the same color. Dot-dashed curves refer to the JWST-MIRIM case, whereas solid curves refer to ELT-MIDIR instrument. The solid green diamond indicates the value of A_0 relative to a 5 hours of exposure time with the JWST from which a lower observational limit for the orbital inclination, shown by the solid green circle, can be inferred.