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

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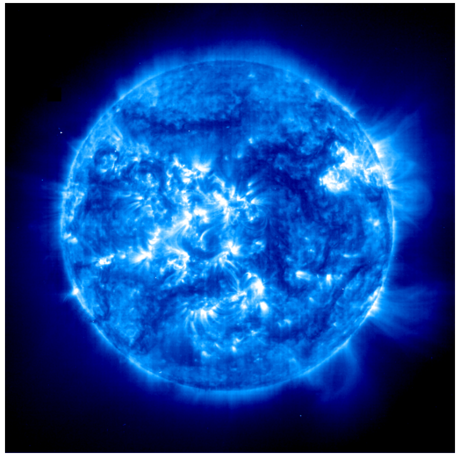
SOLAR PHYSICS UTOV

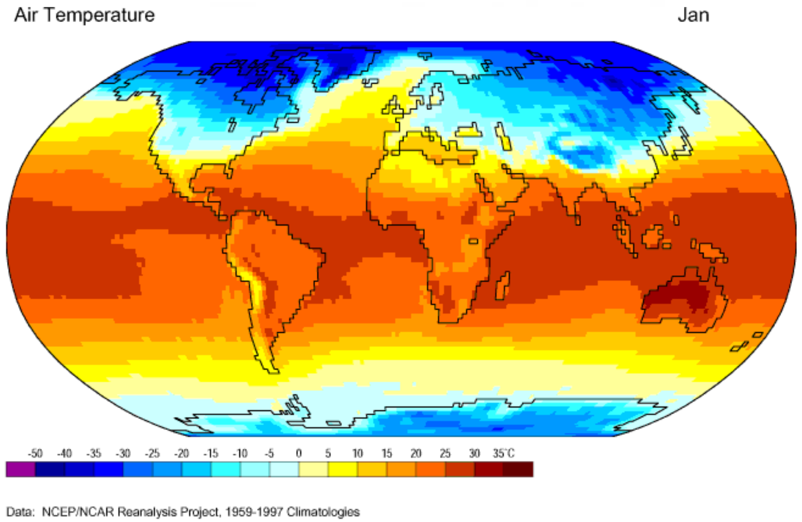
Università di Roma Tor Vergata

Consiglio Nazionale delle Ricerche

ISAC Istituto di Scienze della Atmosfera e del Clima



Bordi, Berrilli & Pietropaolo, Ann. Geo., 2015



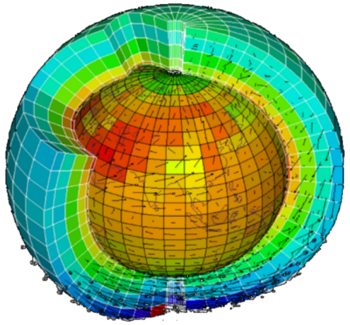
UV new proxies suitable for Str. O_3

Climate and possible role of stratospheric ozone

UV Color, Mg II, UV recons., O_3 (ML)

UV Color and fluxes in 3D GCM (DG)

Earth's thermosphere



UV Color Stellar Application

3D GCM + 1D RTM (exoplanets)

Lovric+, *J. Space Weather Space Climate*, 2017
Criscuoli+, *ApJ*, 2018

(Exo)planetary-Stellar Connection

Galuzzo+, *ApJ submitted*, 2018
Galuzzo+, *J. Climate in preparation*, 2018

Goals

1. From solar and atmospheric physics to exoplanet climate and star/planet interactions;

2. Explore a wide range of parameters for habitability conditions;

3. Develop a procedure to assess space and ground based detection limits for exoplanets;

4. Supply a method to evaluate the required performances of future detectors.

Why the atmosphere?

Habitability → Liquid environment (*Bains, W., 2004*) → Water / ?

Water → Atmosphere → known habitable planets: 1

Water → No atmosphere → known habitable planets: 0

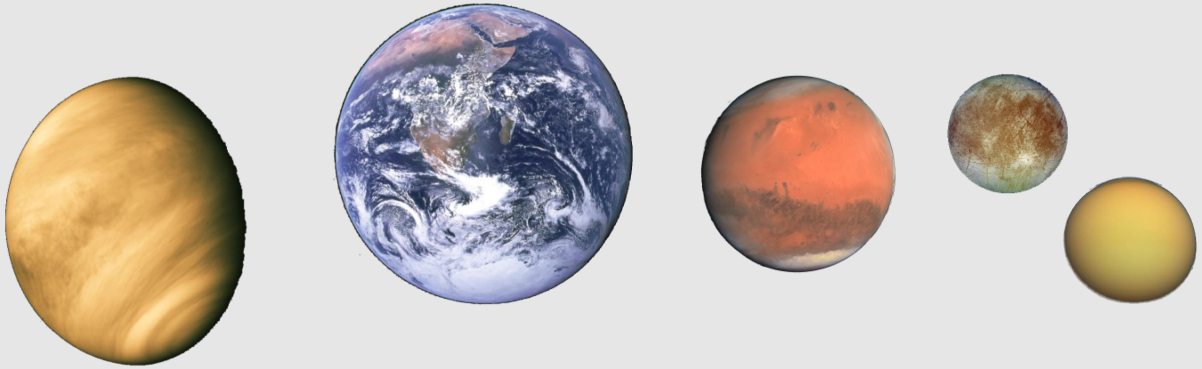
Other **fundamental** requirements:

- Characterization of the central star: activity and variability

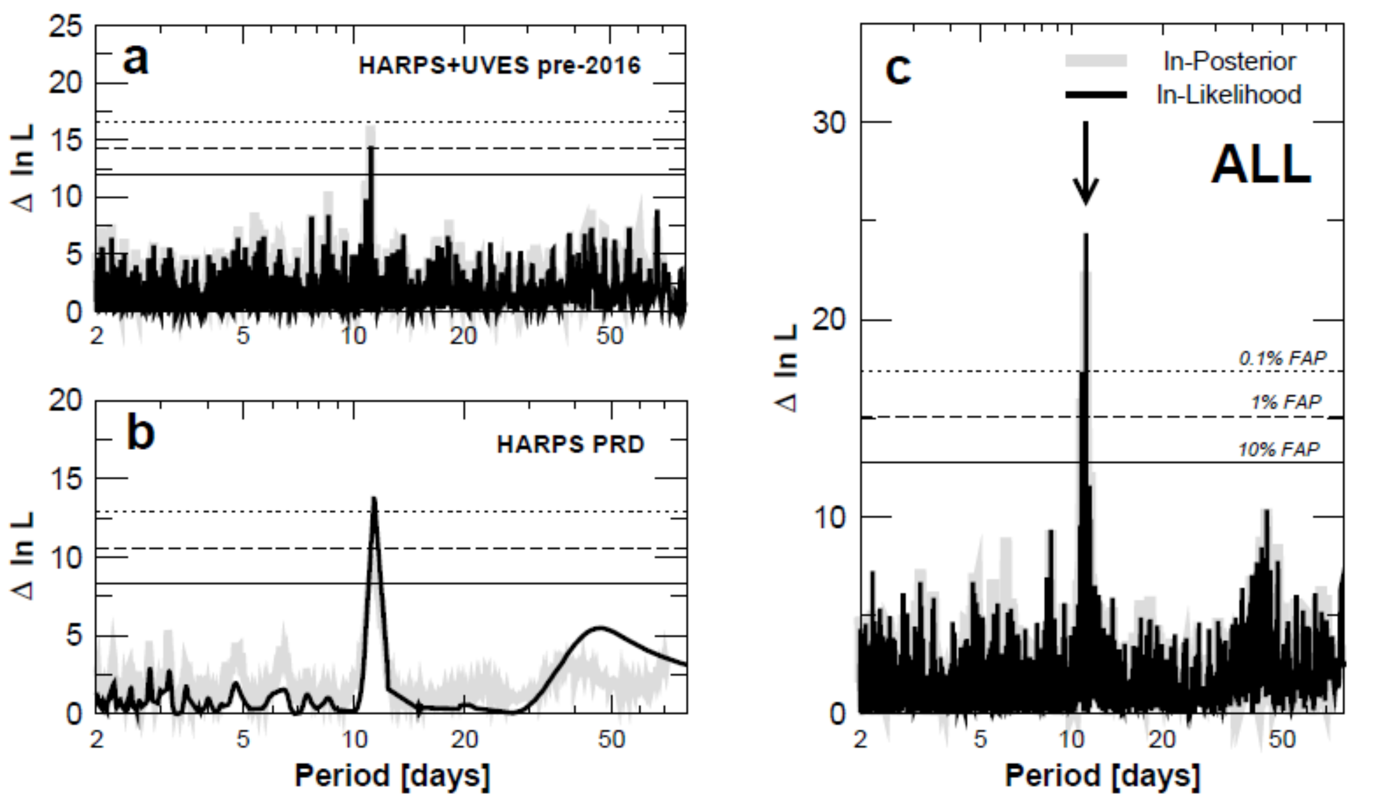
  Use what we learned from Sun and Solar System

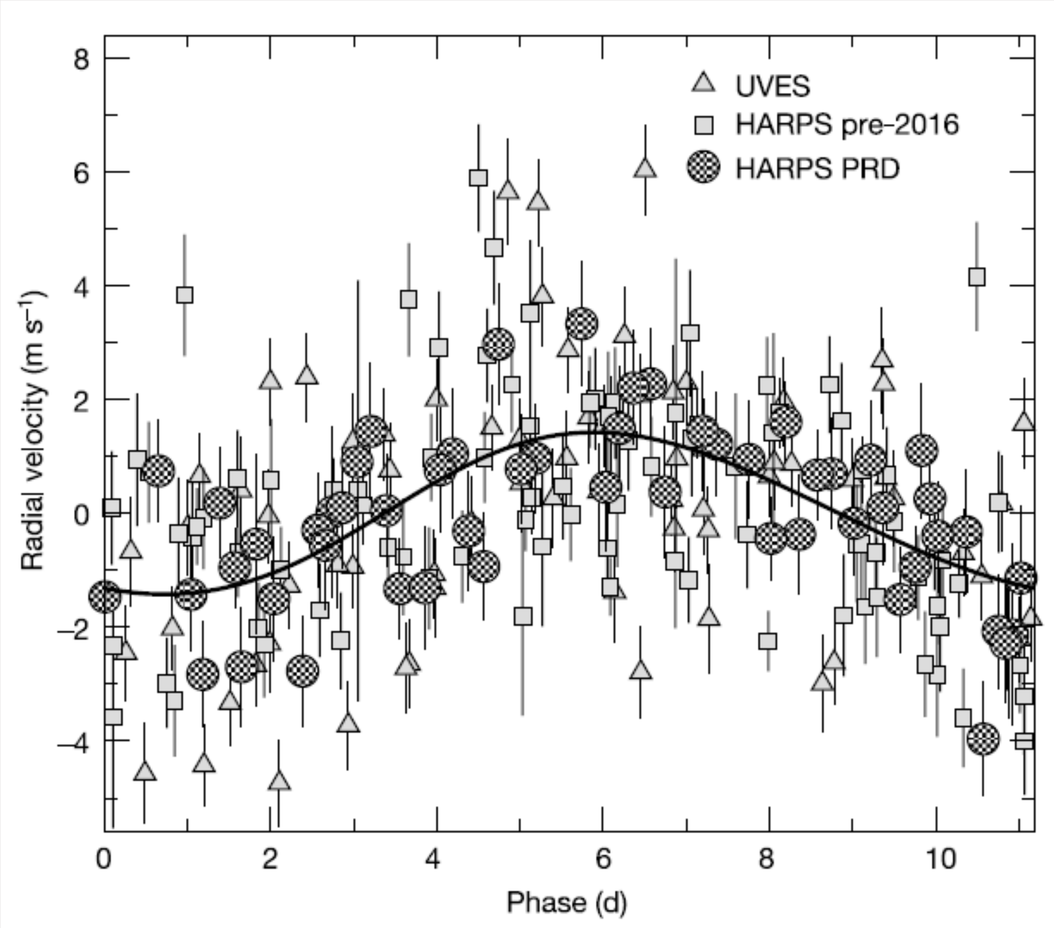
- Planetary magnetic fields

- Orbital stability conditions



A case study: Proxima b





Anglada-Escudé, G. et al., 2016

European Southern Observatory
High Accuracy Radial velocity Planet Searcher and
Ultraviolet and Visual Echelle Spectrograph Intruments

Planet properties

Proxima b: derived parameters from radial velocity
(*Anglada-Escudé, G. et al., 2016*)

Parameter	Symbol	Value
Orbital period	T	11.186 Earth days
Orbital semi-major axis	a	0.0485 AU
Orbit eccentricity	e	< 0.35
Planet minimum mass	m_P	$1.27\ M_\oplus$
Eq. blackbody temperature	T_{eq}	$234\ K$

Proxima b: Unknown planetary parameters
(extrapolated for the simulation)

Parameter	Symbol	Value
Mean density	ρ_P	$\rho_\oplus$
Radius	r_P	$1.08\ R_\oplus$
Surface gravity acceleration	g_P	$10.64\ m/s^2$
Axial tilt	α	0 deg
Rotation rate	ω_P	$6.50\times10^{-6}\ rad/s$

$$m_P = M_P \sin \iota$$

$$\rho_\oplus = 5514\ \frac{kg}{m^3}$$

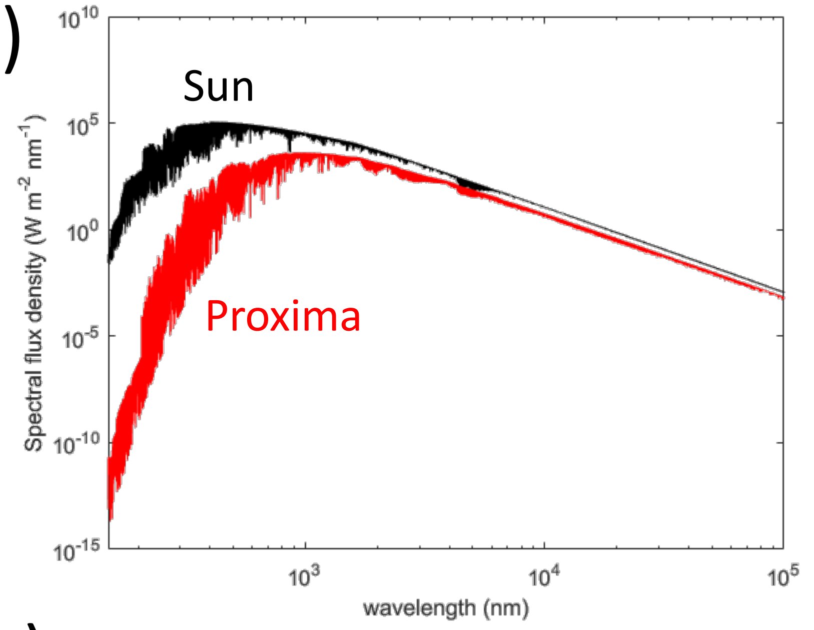
Rotation period = Orbital period
(*Ribas, I. et al., 2016*)

Host star properties

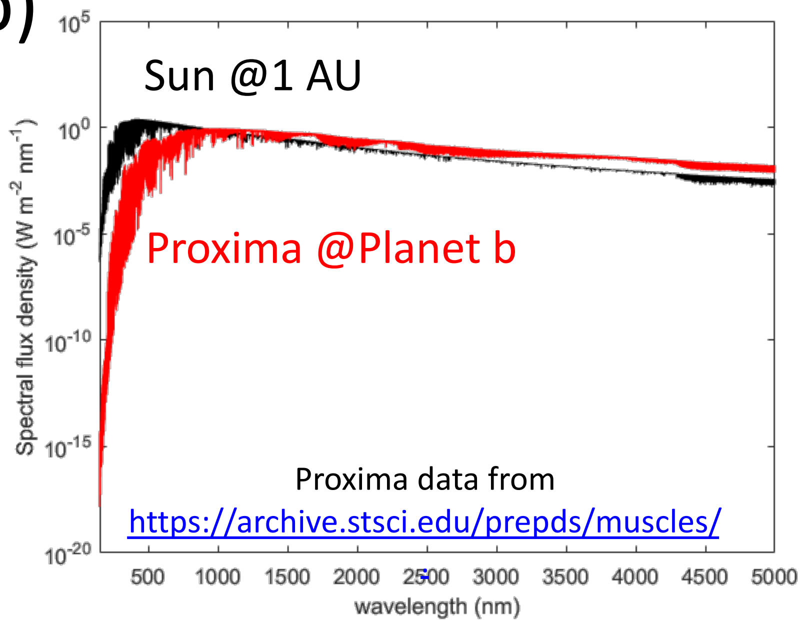
Stellar property	Symbol	Value
Spectral type	-	M5.5
Mass	$M_\star$	$0.120\ M_\odot$
Radius	$R_\star$	$0.154\ R_\odot$
Bolometric flux	$F_\star^{bol}$	$2.186{\times}10^{-11}\ W\ m^{-2}$
Irradiance at Planet b TOA	$F_\star^{toa}$	$884.650\ W\ m^{-2}$
Effective temperature	$T_\star^{eff}$	$3050\ K$

Ribas, I. et al., 2017

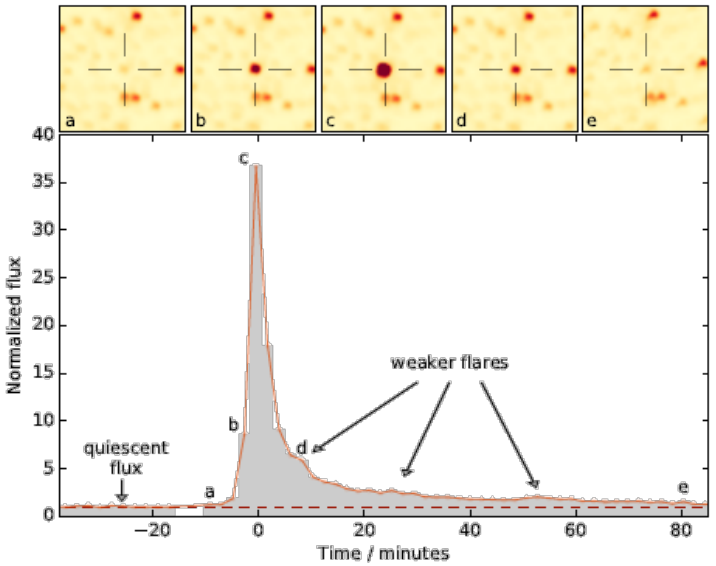
a)



b)



c)



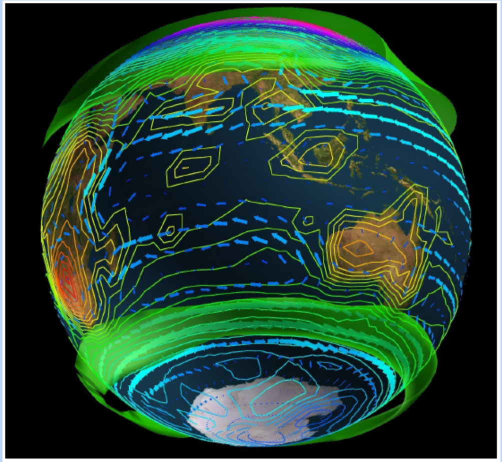
Howard, W. S. et al., 2018

Simulating an exoplanetary atmosphere

3D Intermediate Complexity GCM

Planet Simulator (PlaSim)

(*Fraedrich, K. et al., 2005*)



Keplerian parameters

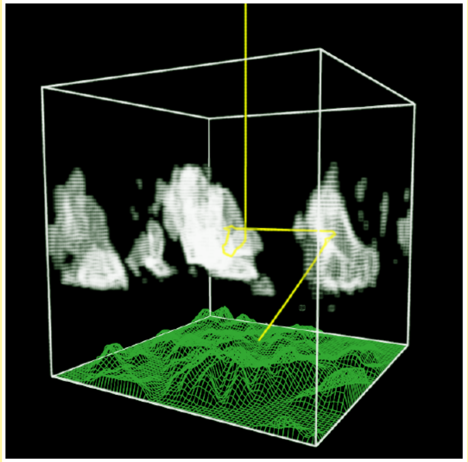
atmospheric composition

surface properties

1D RTM

Library for radiative transfer (libRadtran)

(*Emde, C. et al., 2016*)



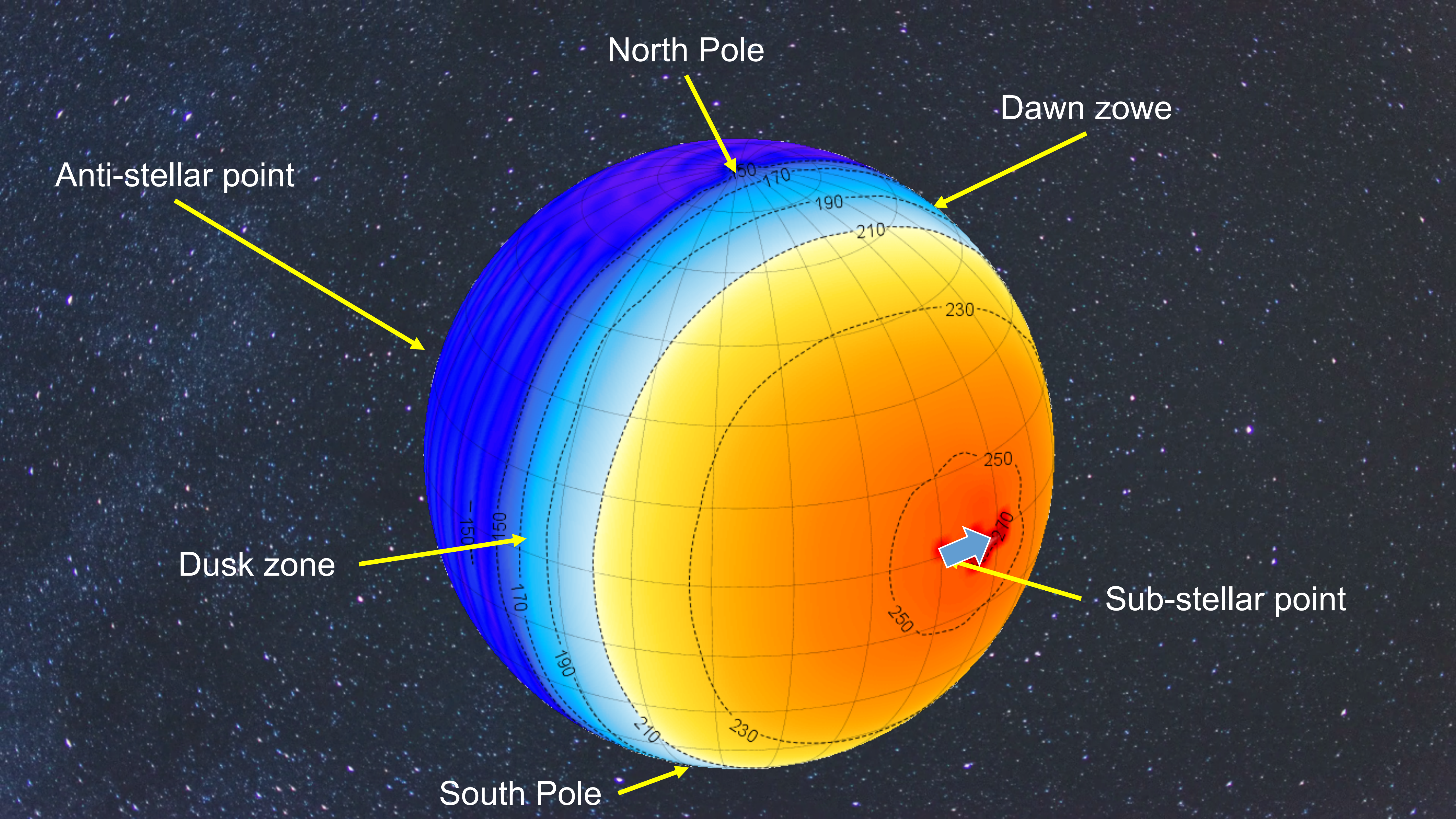
Host star

Geometry of incident radiation

Clouds properties

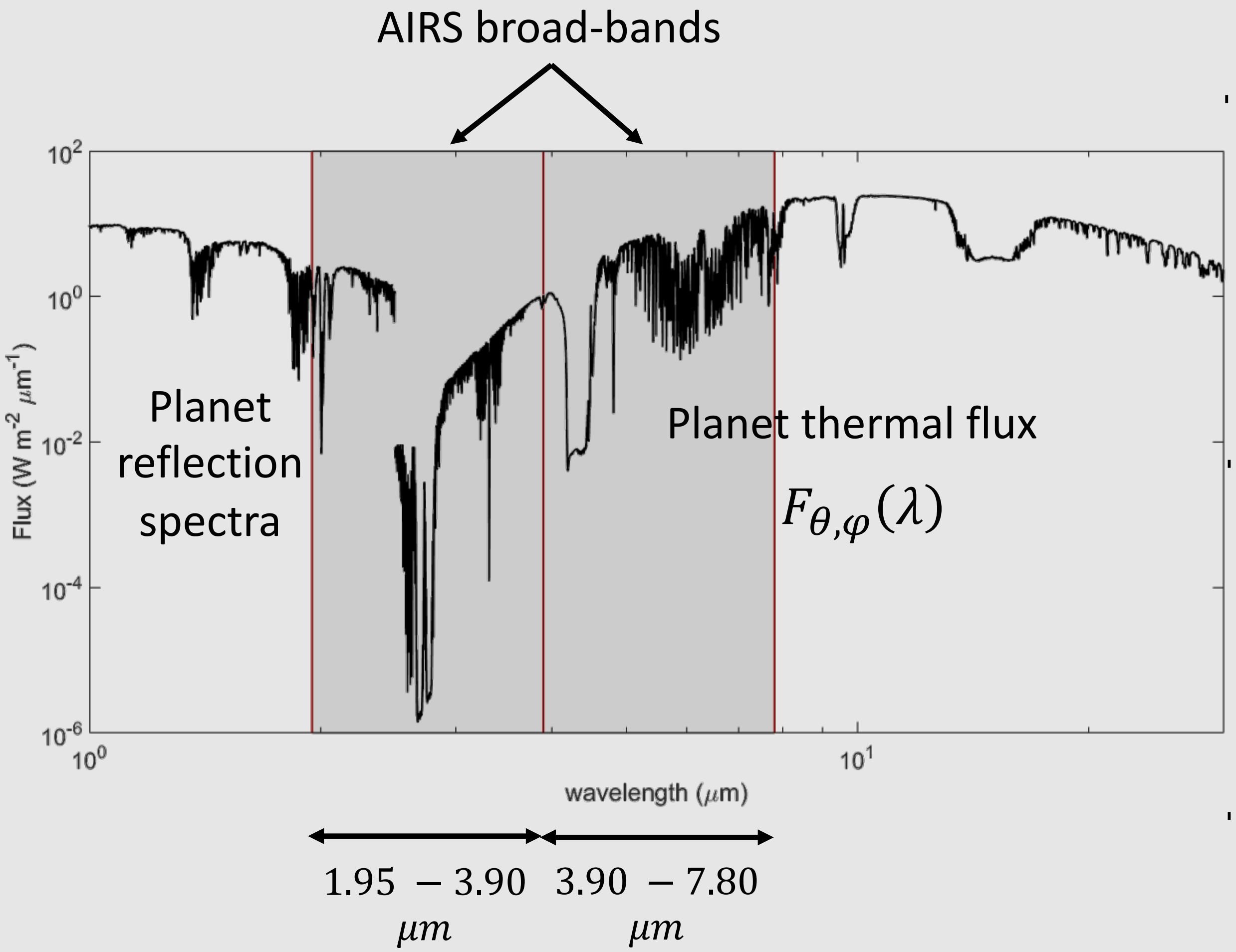
Simulation initial conditions

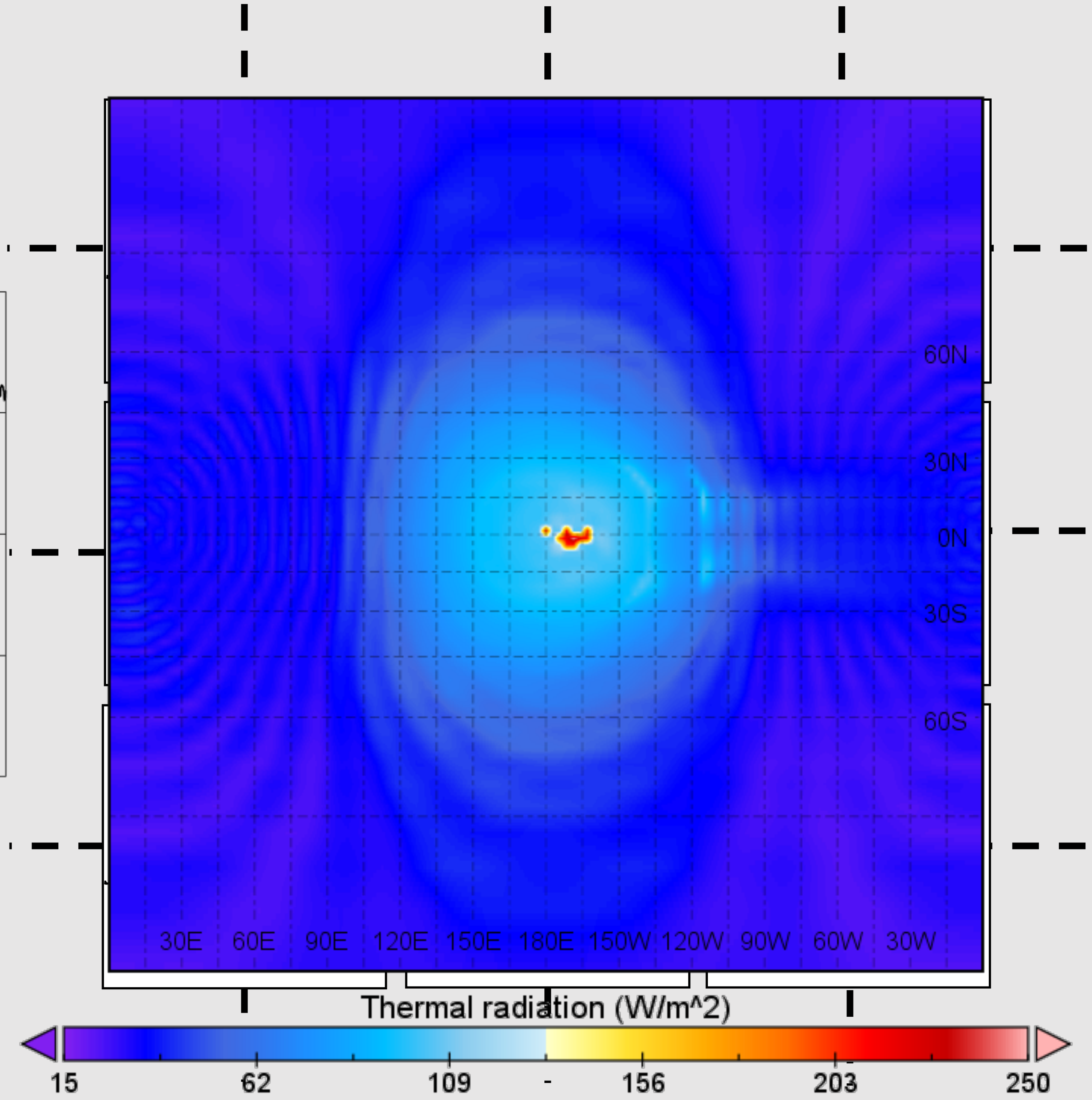
- Earth-like preindustrial atmosphere with 360 ppm of CO_2;
- Stationary vertical profiles for gasses (no seasonal changes), parameterized O_3 profile, taken from Green (1980);
- Aquaplanet with a slab thermodynamic ocean of 50 meters depth;
- Surface pressure of 1000 hPa (1000 millibars) and top of the atmosphere (TOA) fixed at 50 hPa.



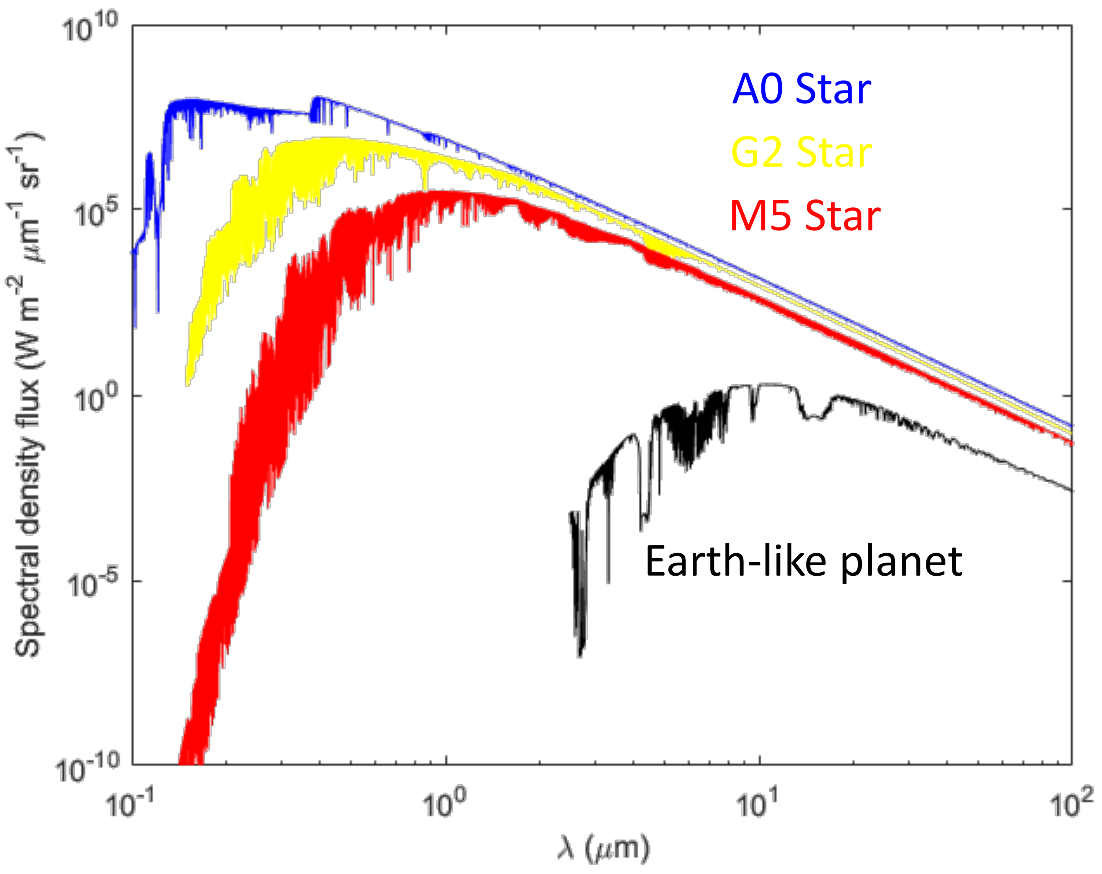
North Pole
Dawn zowe
Anti-stellar point
Dusk zone
Sub-stellar point
South Pole
150
170
190
210
230
250
270

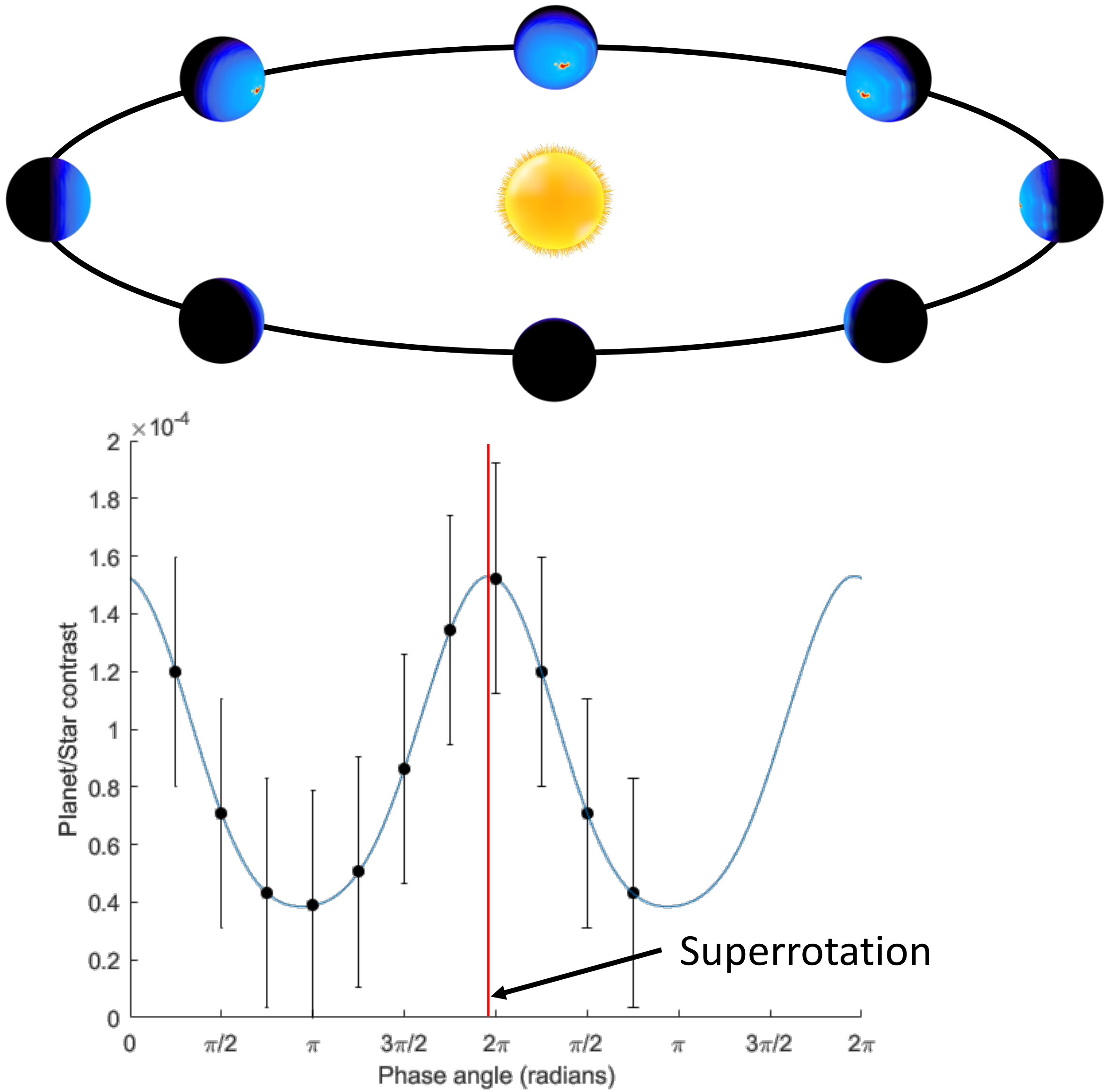
Results: Synthetic spectra



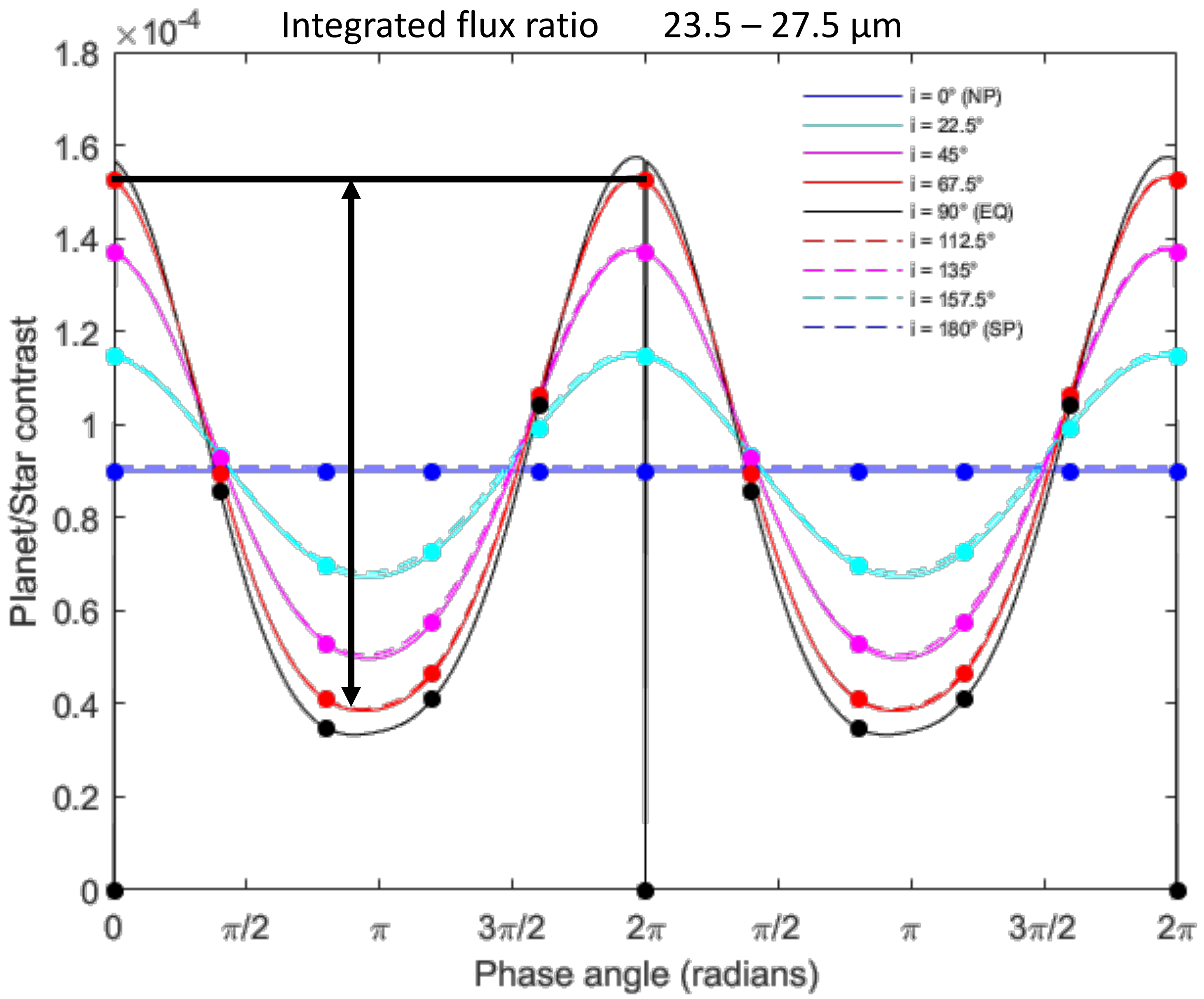


Results: Atmosphere/climate detectability





Results: PlaSim + libRadtran output

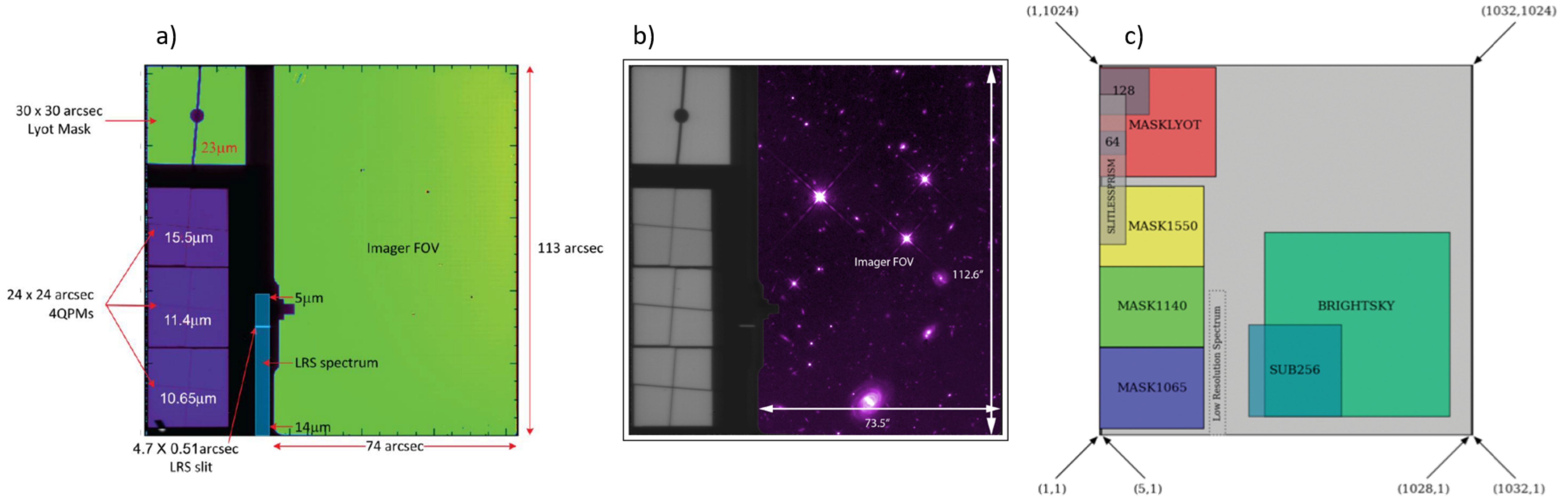


Simulate an observation:

- From space with the Mid-Infrared Imager on the James Webb Space Telescope

- From ground based instruments by photometry in the Earth's atmospheric windows

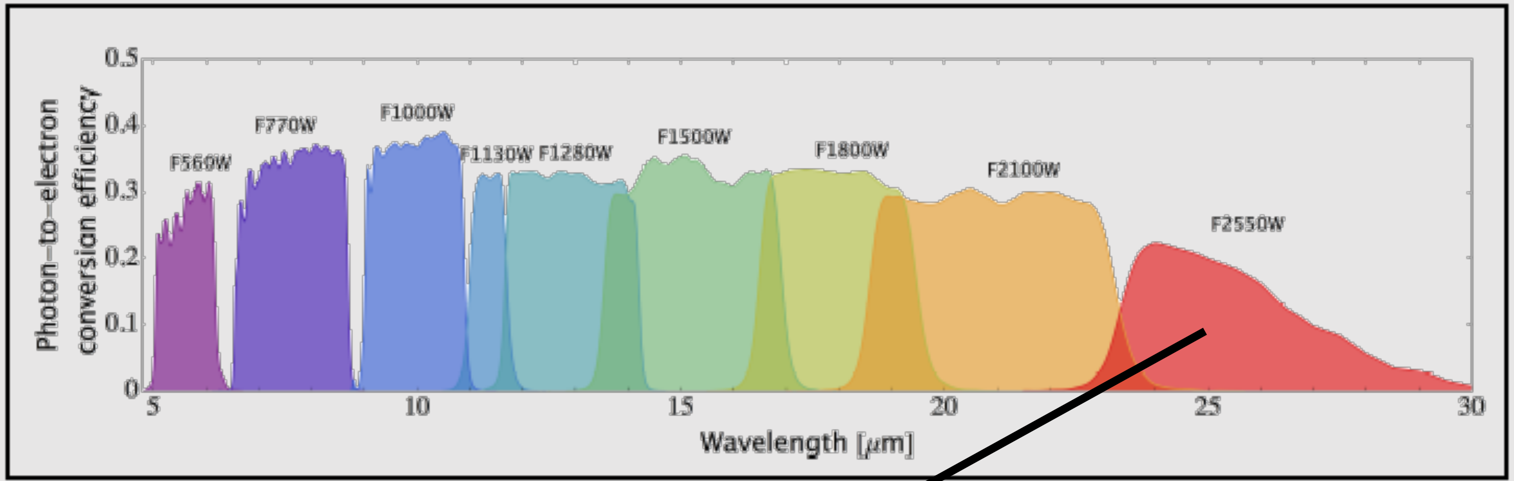
James Webb Space Telescope – Medium Infrared Instrument Imager (MIRIM)



MIRIM input field of view

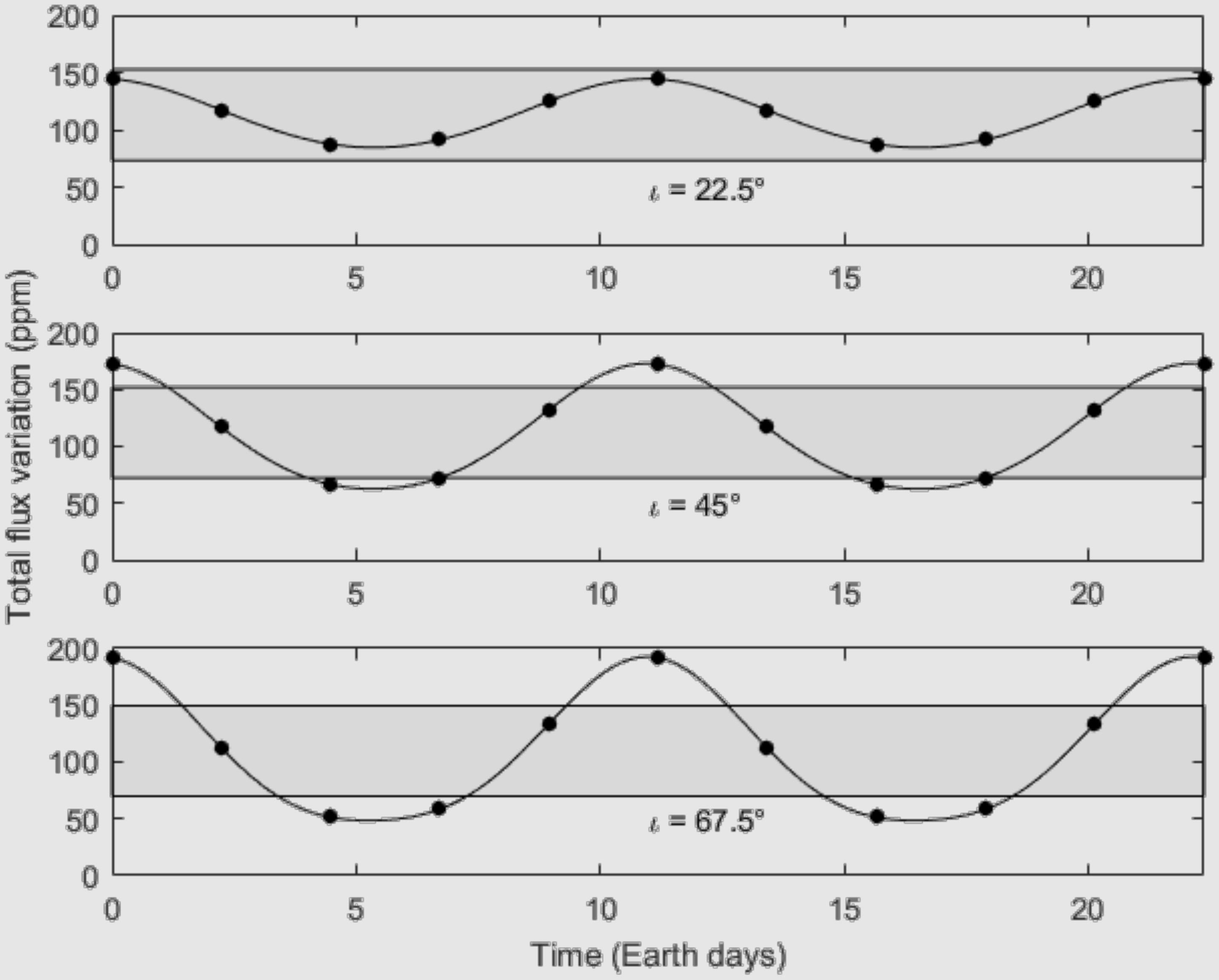
FULL = 1024 × 1024;
BRIGHTSKY = 512 × 512;
SUB256 = 256 × 256;
SUB128 = 128 × 136;
SUB64 = 64 × 72

JWST MIRIM – Filters and relative signal amplitude



System inclination	Maximum contrast	Maximum modulation amplitude	
~~$\iota = 0^\circ$~~	~~[illegible] $\times 10^{-5}$~~	~~[illegible] $\times 10^{-11}$~~	Not face-on
$\iota = 22.5^\circ$	1.15×10^{-4}	4.76×10^{-5}	
$\iota = 45^\circ$	1.37×10^{-4}	8.77×10^{-5}	
$\iota = 67.5^\circ$	1.53×10^{-4}	1.16×10^{-4}	
~~$\iota = 90^\circ$~~	~~[illegible] $\times 10^{-4}$~~	~~[illegible] $\times 10^{-4}$~~	Non-transiting
$\iota = 112.5^\circ$	1.53×10^{-4}	1.14×10^{-4}	
$\iota = 135^\circ$	1.38×10^{-4}	8.74×10^{-5}	
$\iota = 157.5^\circ$	1.15×10^{-4}	4.72×10^{-5}	
~~$\iota = 180^\circ$~~	~~[illegible] $\times 10^{-5}$~~	~~[illegible] $\times 10^{-11}$~~	Not face-on

Specular by symmetry



James Webb Space Telescope Exposure Time Calculator

https://jwst.etc.stsci.edu/

Orbital period

11.186 Earth's days

Exposure Time

5 hours

Color variation – Ground based observation simulation

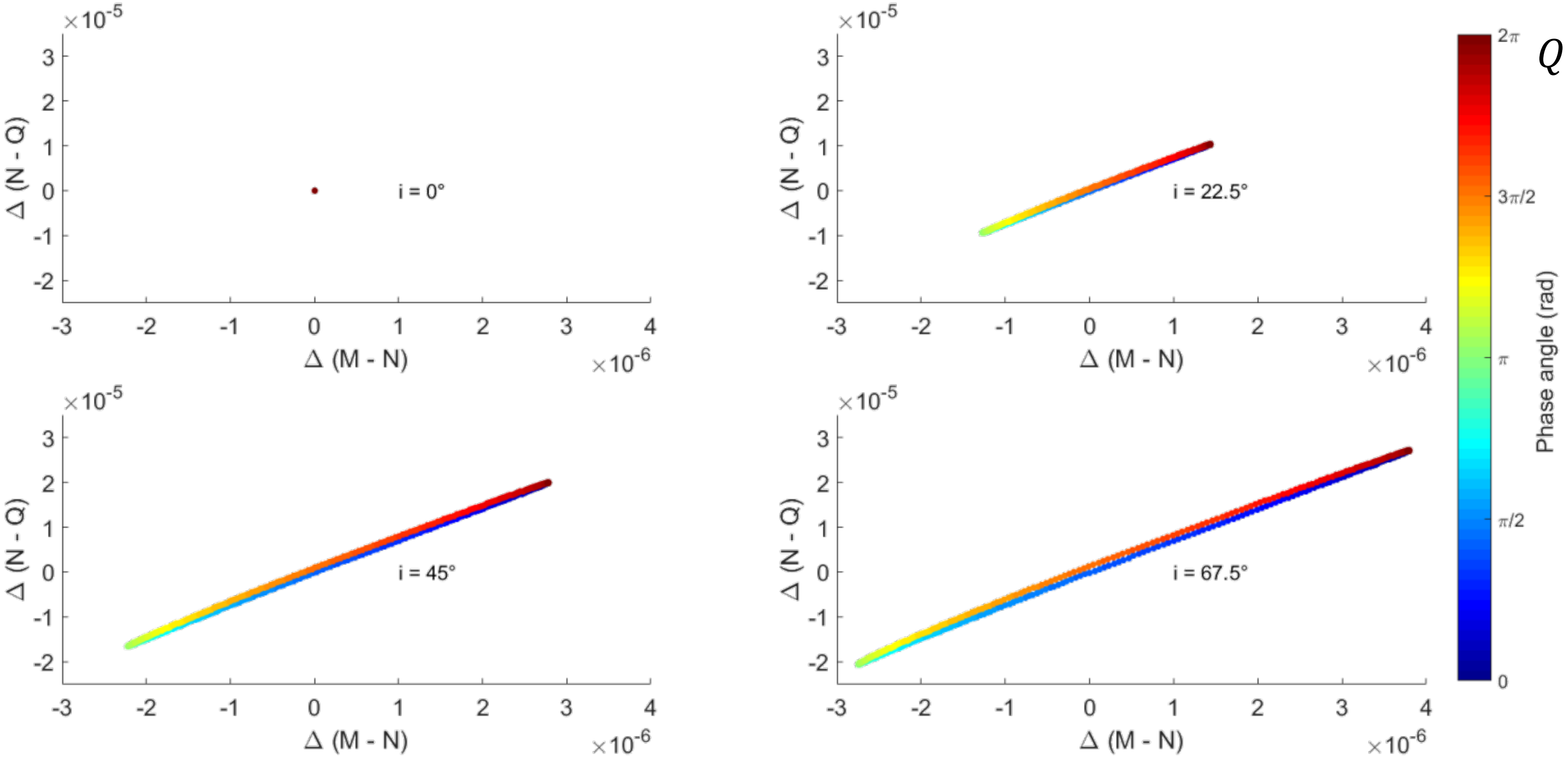
$$M - N = 2.5\log_{10}\left(\frac{F_\lambda^N}{F_\lambda^M}\cdot\frac{F_0^M}{F_0^N}\right) \qquad N - Q = 2.5\log_{10}\left(\frac{F_\lambda^Q}{F_\lambda^N}\cdot\frac{F_0^N}{F_0^Q}\right)$$

ESO IR photometric passbands

$$M = 4.58 \div 4.96\ \mu m$$

$$N = 8.32 \div 13.79\ \mu m$$

$$Q = 17.05 \div 20.28\ \mu m$$



CONCLUSIONS AND PERSPECTIVES

- 3D GCM can be used to evaluate the instrumental observation limits for exoplanets;
- Exoplanet climatic conditions can be inferred by fitting model results to observational data;
- Habitability can be studied under a wide range of conditions;
- Ongoing collaboration between UniToV, ISAC-CNR, UniCal and INAF-IAPS to develop a 3D radiative, magnetic and particles model for planet/star interaction;
- We are able to simulate atmospheric spectra in the observing range of ARIEL.

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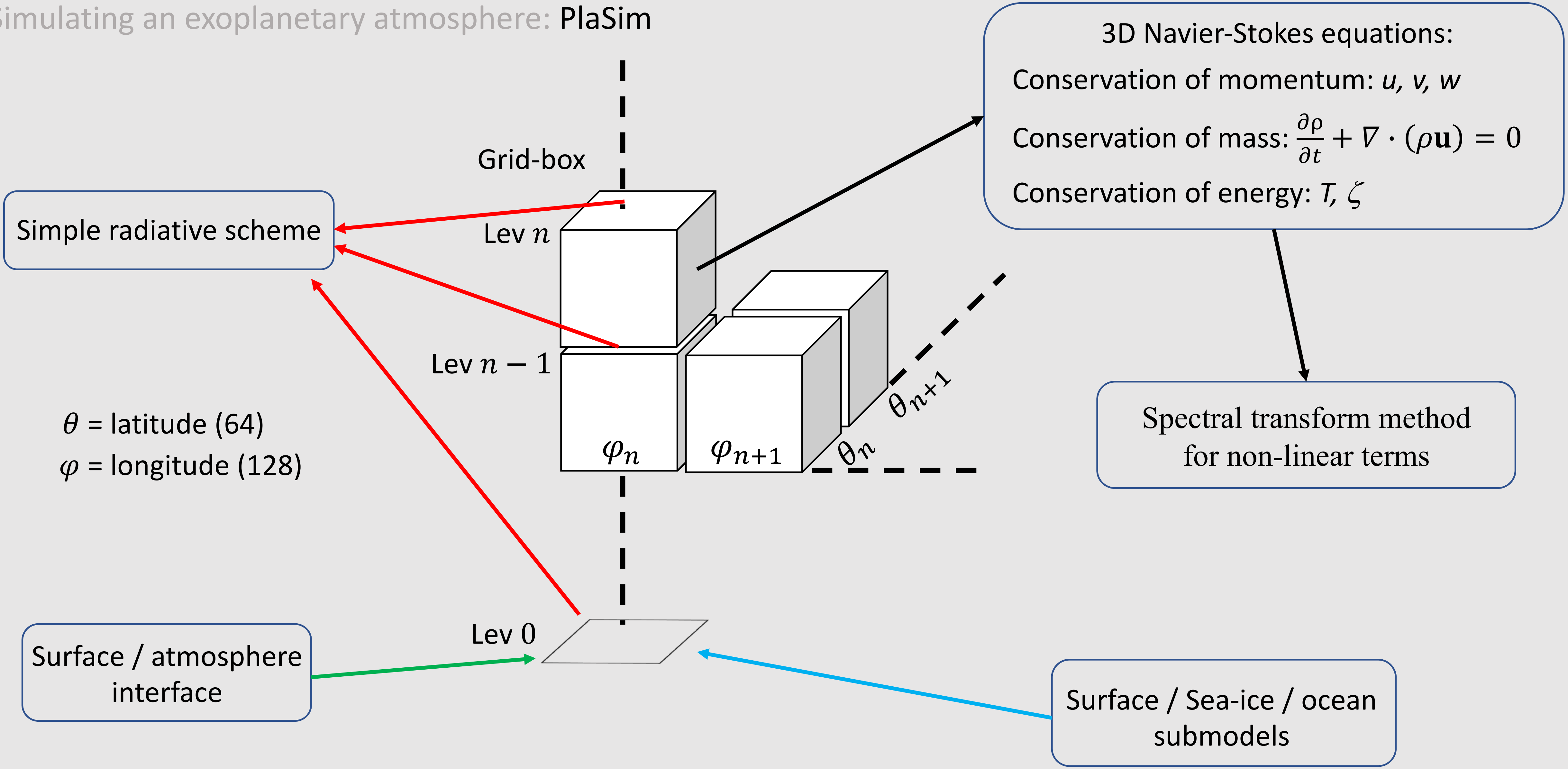
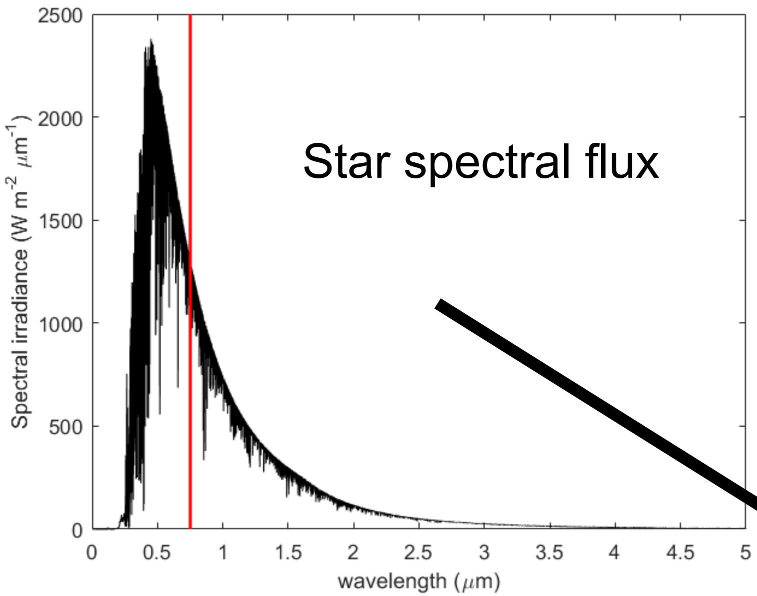
Presentation Overview

- Work’s aims and motivations
- A case study: Proxima b
- Simulating an exoplanetary atmosphere: models
- Method for line-by-line planetary emission spectrum
- Proxima b atmosphere: photometric and spectral features
- Conclusions

Simulating an exoplanetary atmosphere: PlaSim





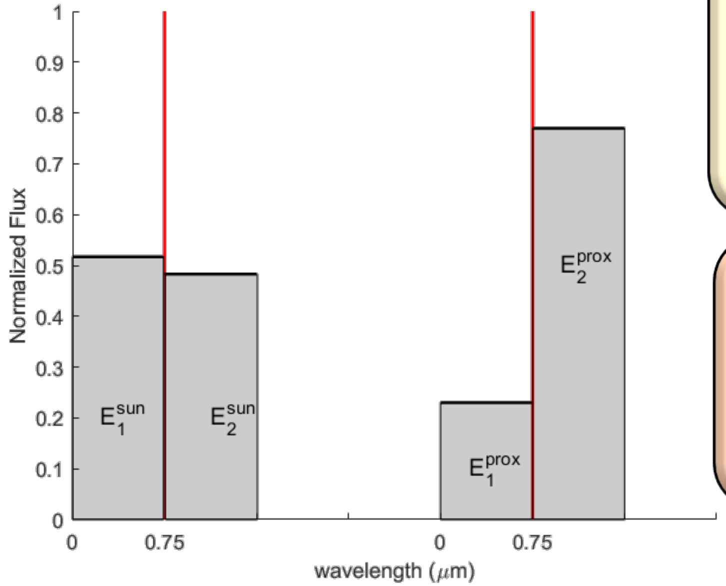
The stellar spectral range is divided into two regions:

- UV / VIS spectrum, for λ < 0.75 μm: pure clouds scattering, O_3 absorption and Rayleigh scattering;
- NIR spectrum, for λ > 0.75 μm: clouds scattering and absorption, H_2O absorption.

Energy flux fractions:

$$E_0 = \int_0^{\infty} F_\lambda d\lambda$$

$$E_1 = \frac{\int_0^{\lambda_1} F_\lambda d\lambda}{E_0} \qquad E_2 = 1 - E_1$$



Sun

$E_1 = 0.51$

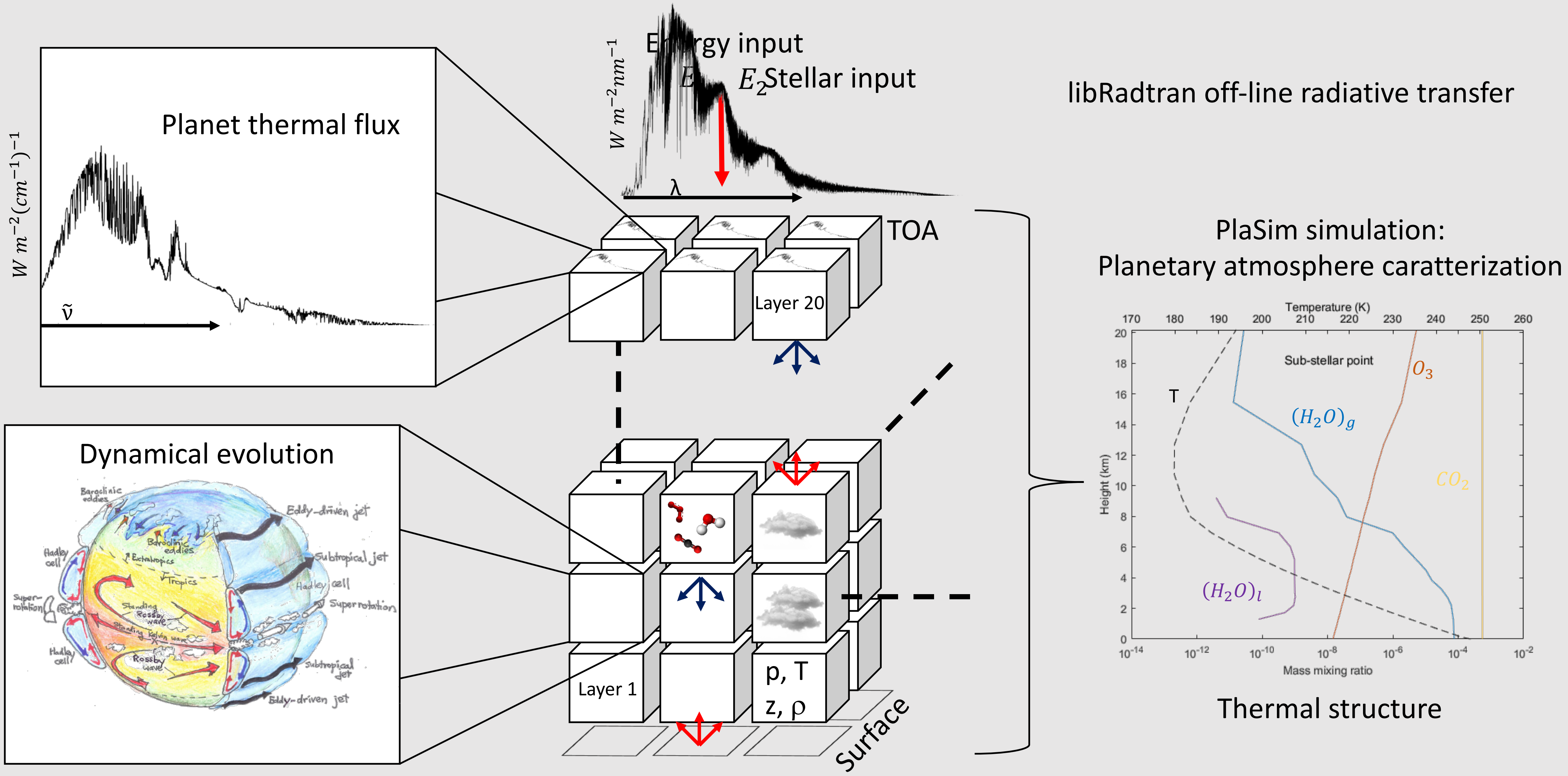
$E_2 = 0.49$

Proxima

$E_1 = 0.23$

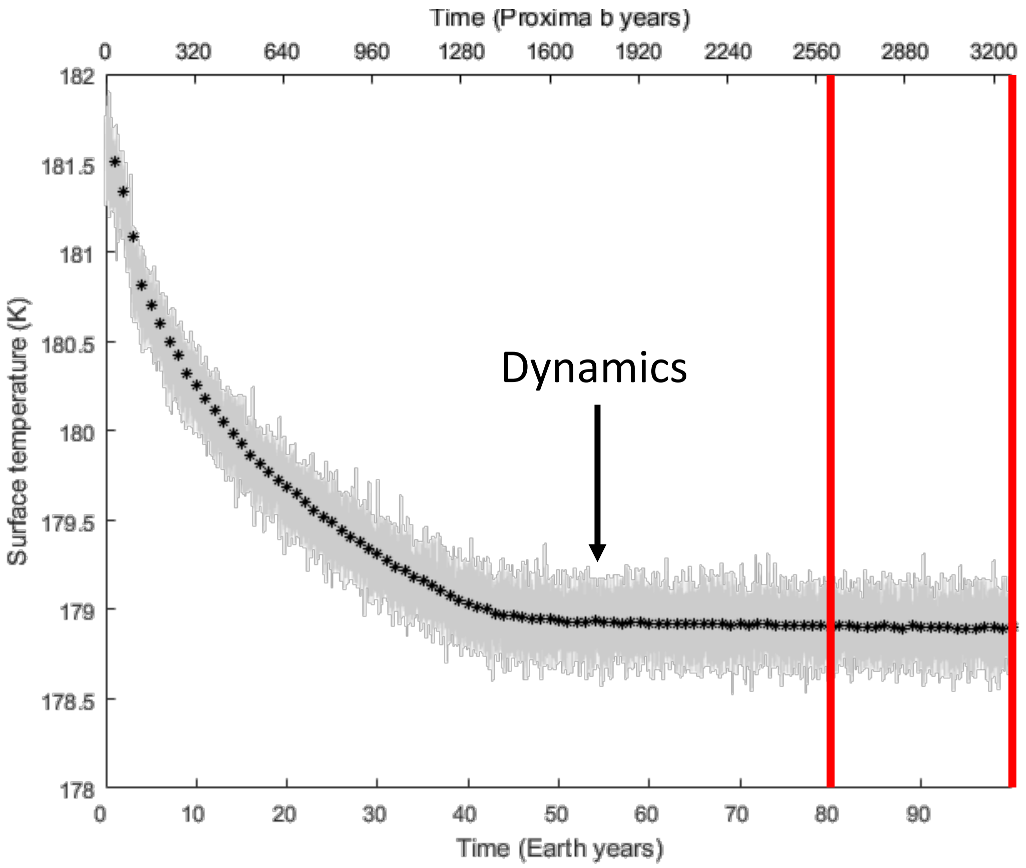
$E_2 = 0.77$

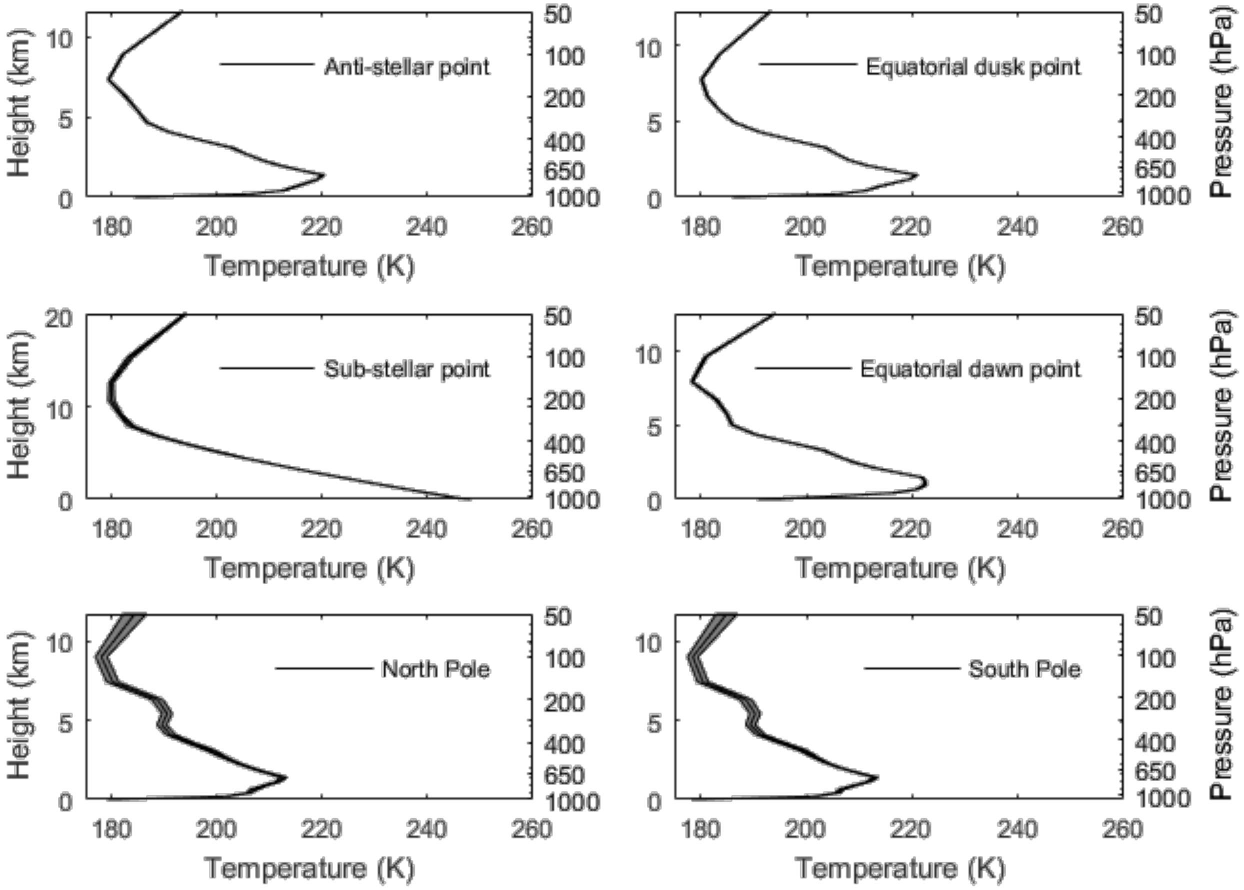
Method for line-by-line planetary emission spectrum



RESULTS

Check for system steady state





$$R_o = \frac{U}{fL}$$

- ~~$\ll 1$ rotationally dominated atmosphere~~
- $\gtrsim 1$ Hadley-cell dominated atmosphere

Mass streamfunction:

$$\psi = \frac{2\pi r_P}{g_P} \int_0^p [\bar{v}] \cos\theta \, dp'$$

[#] Showmann, A. P. et al., ArXive 2010

[#] Showmann, A. P. and Polvani, L. M., ApJ 2011

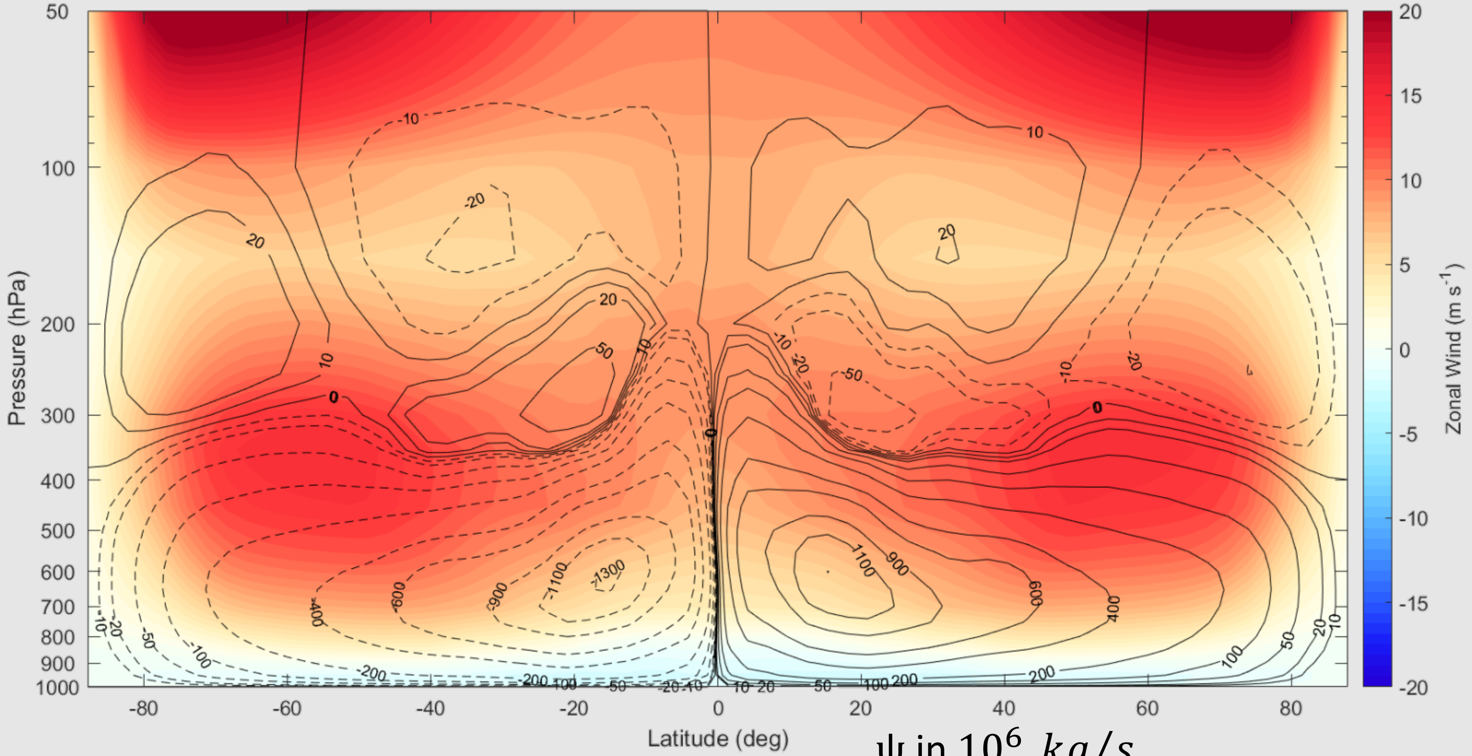
[#] Showmann, A. P. et al., book 2013

$\psi < 0$ anticlockwise circulation $\psi > 0$ clockwise circulation

$$U \sim 10 \ m/s$$

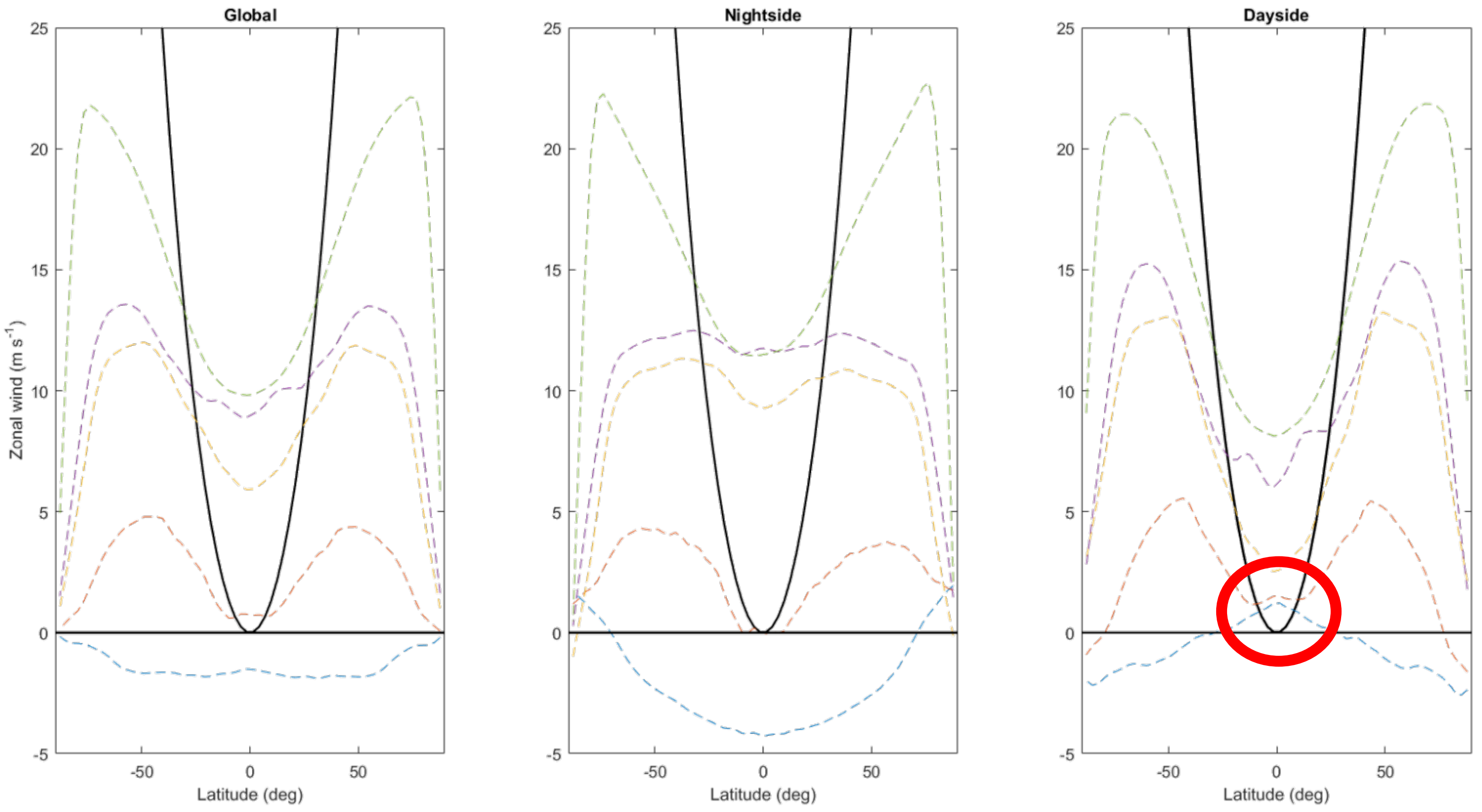
$$L \sim 10^6 \ m$$

$$f = 2\omega_P \sin\theta$$
$$\sim 10^{-7} \sin\theta$$



ψ in $10^6 \ kg/s$

Results: Dynamics - Superrotation



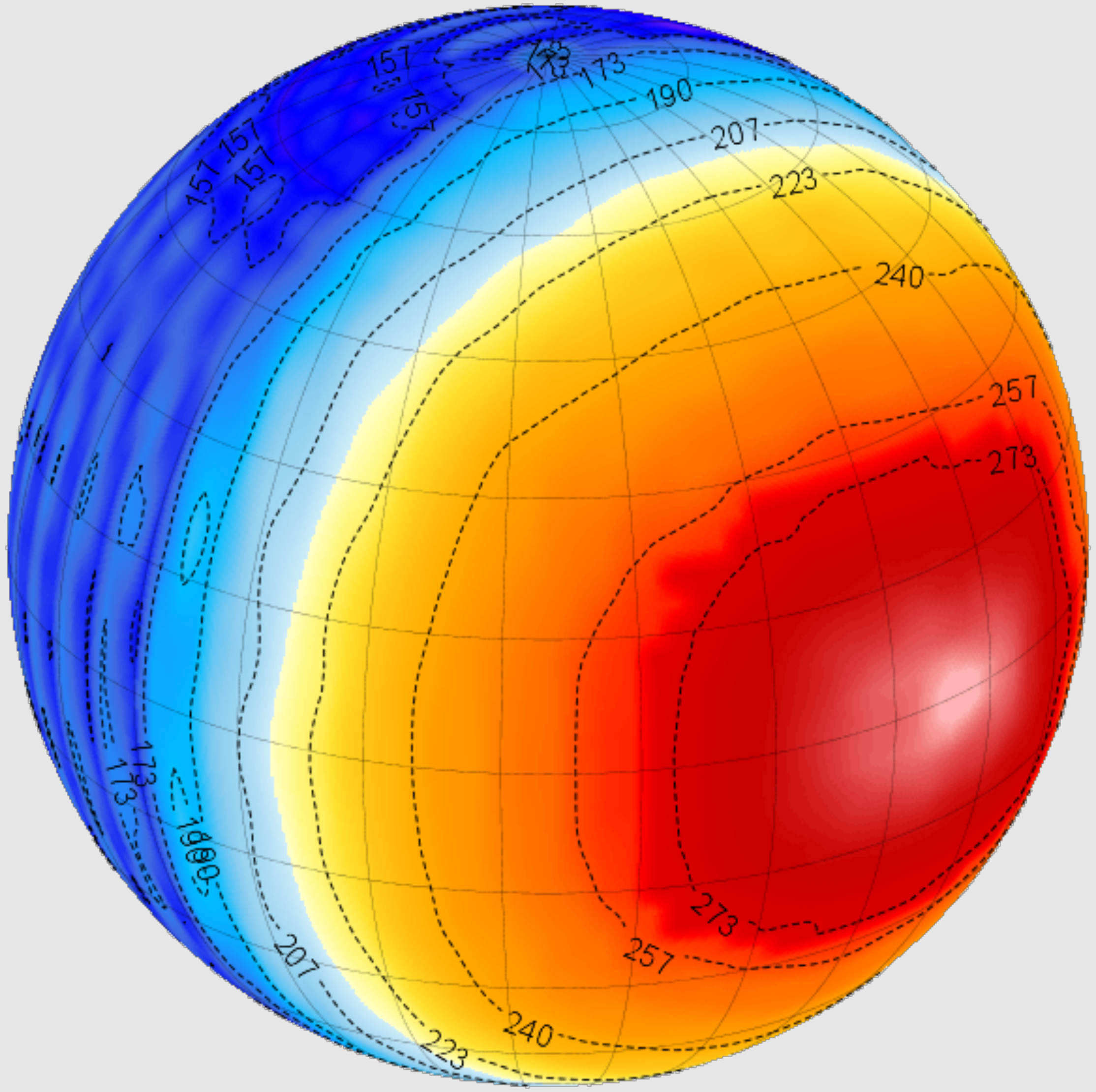
$$M_a > M_0$$

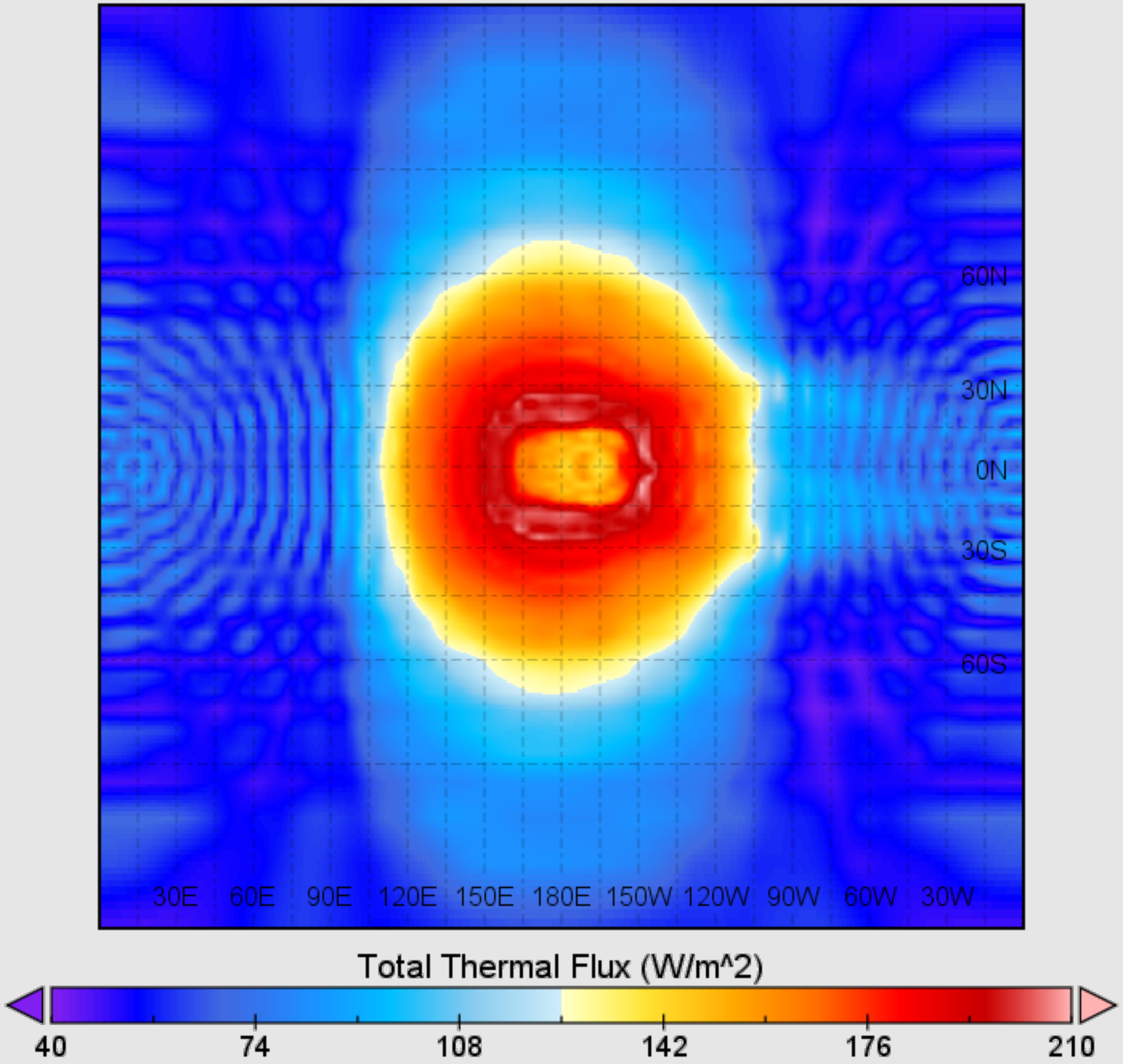
$$r_P \cos\theta(\omega_P r_P \cos\theta + u) > \omega_P r_P^2$$

$$u > u_m$$

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

Showman, A. P., et al., 2010 & 2013


157
173
190
207
223
240
257
273


60N
30N
0N
30S
60S
30E 60E 90E 120E 150E 180E 150W 120W 90W 60W 30W
Total Thermal Flux (W/m^2)
40
74
108
142
176
210