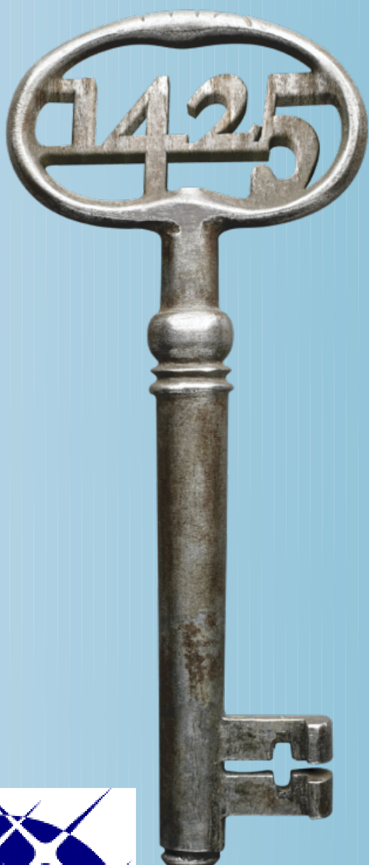
KU LEUVEN



Mapping 3D climates in the habitable zone of M dwarfs

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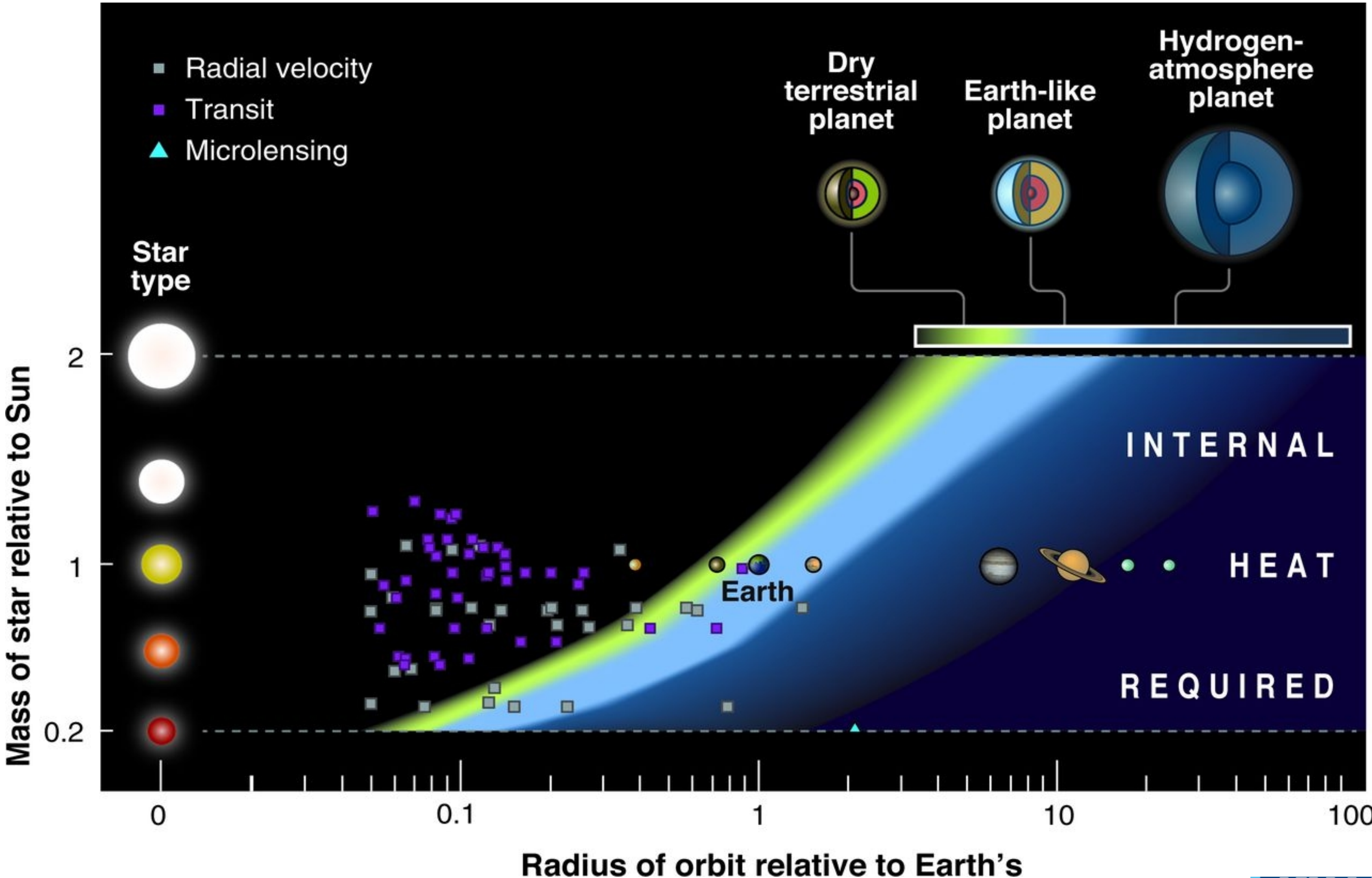
KU Leuven,
(1) Centre for mathematical Plasma-Astrophysics
(2) Institute of Astronomy

The inner edge of the HZ – When is hot too hot?

Seager 2013, Science



Light blue: Kasting et al. 1993, Kopparapu et al. 2013
Yellow: Zsom et al. 2013

Large scale parameter study I :

(Carone et al., 2015, MNRAS, 453,pp 2412)

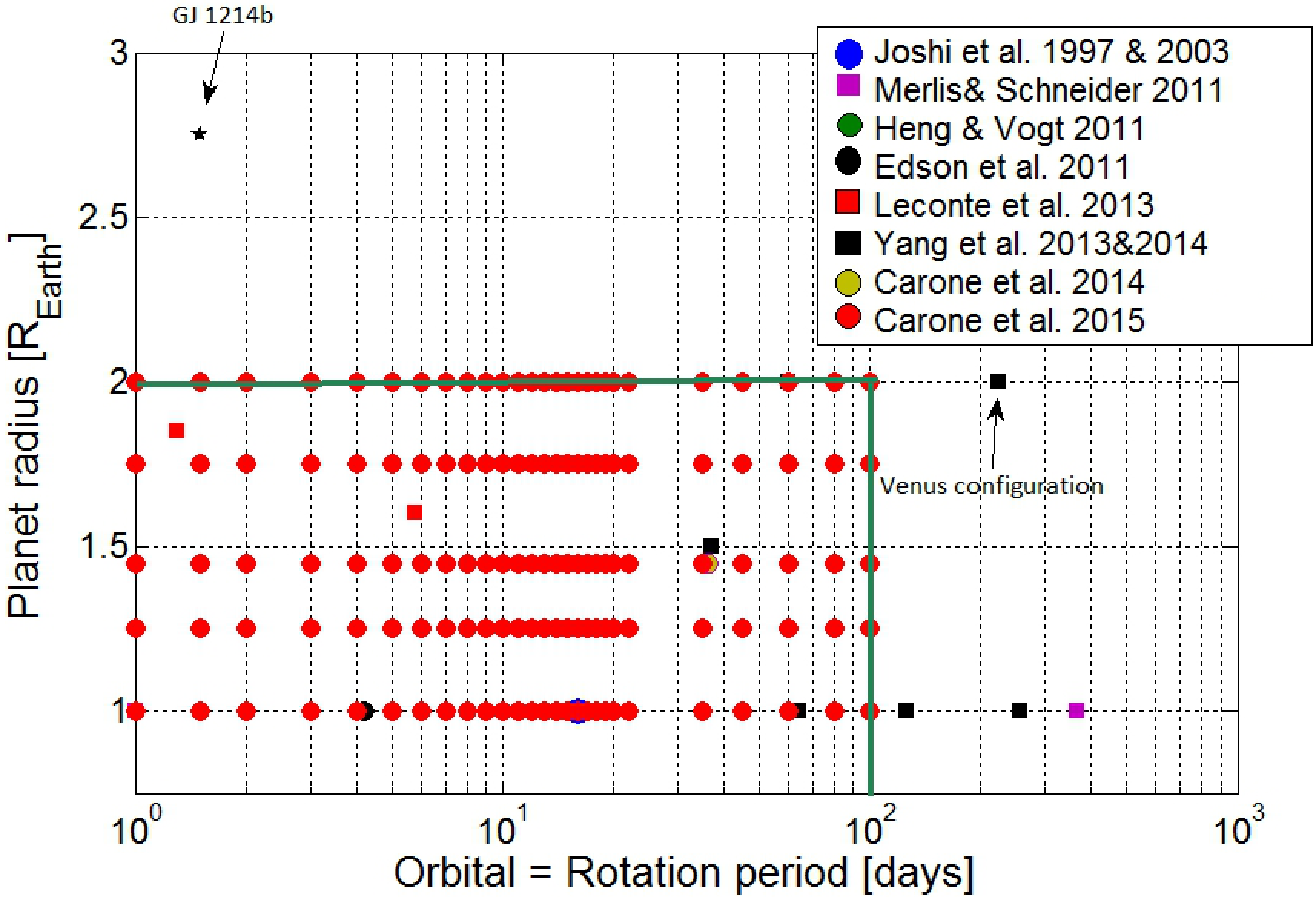
with

Tidally locked Earth-like atmosphere scenario:

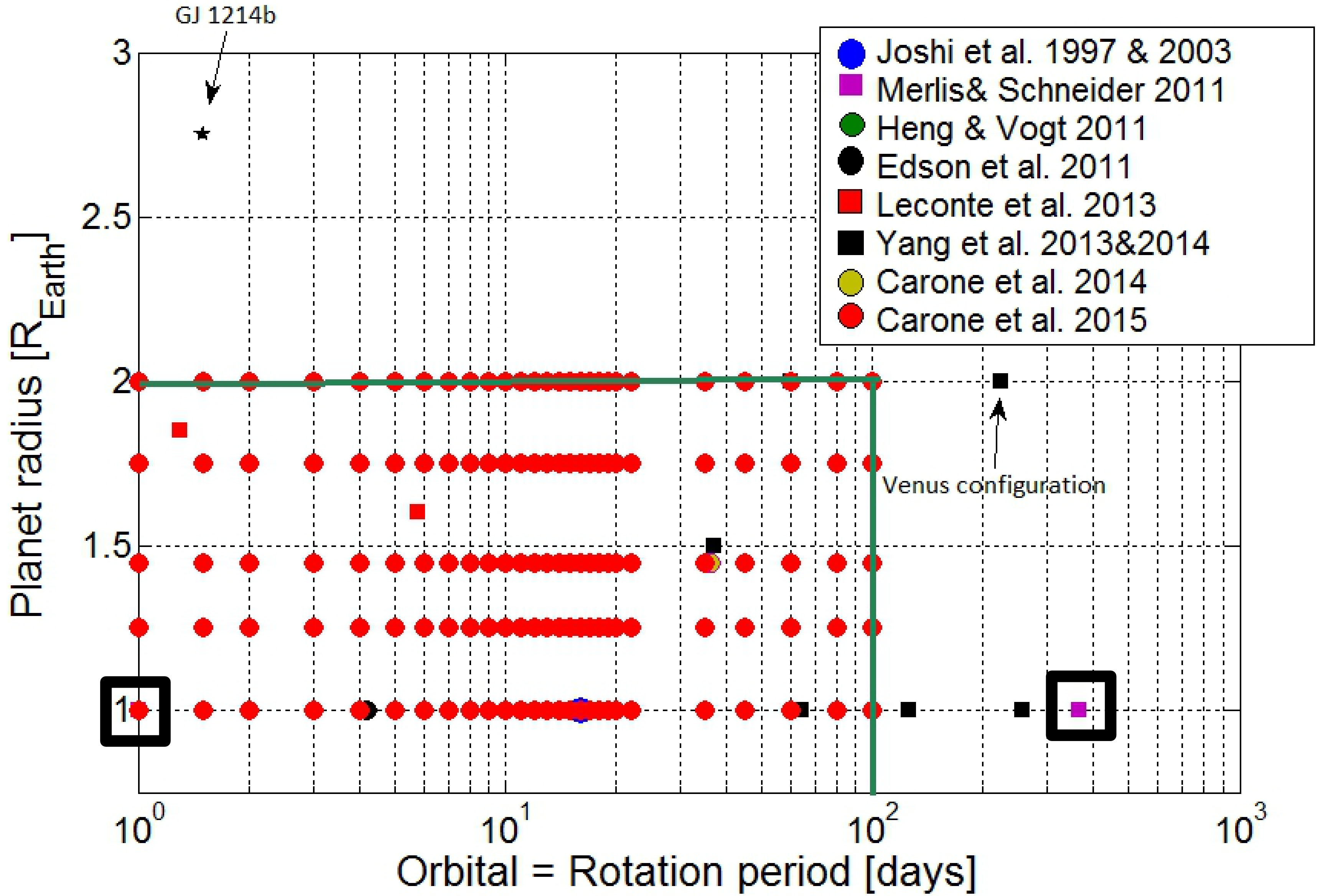
1 bar, N2 dominated greenhouse atmosphere and effective Earth-like stellar irradiation

(Carone et al. 2014, MNRAS,445,pp 930)

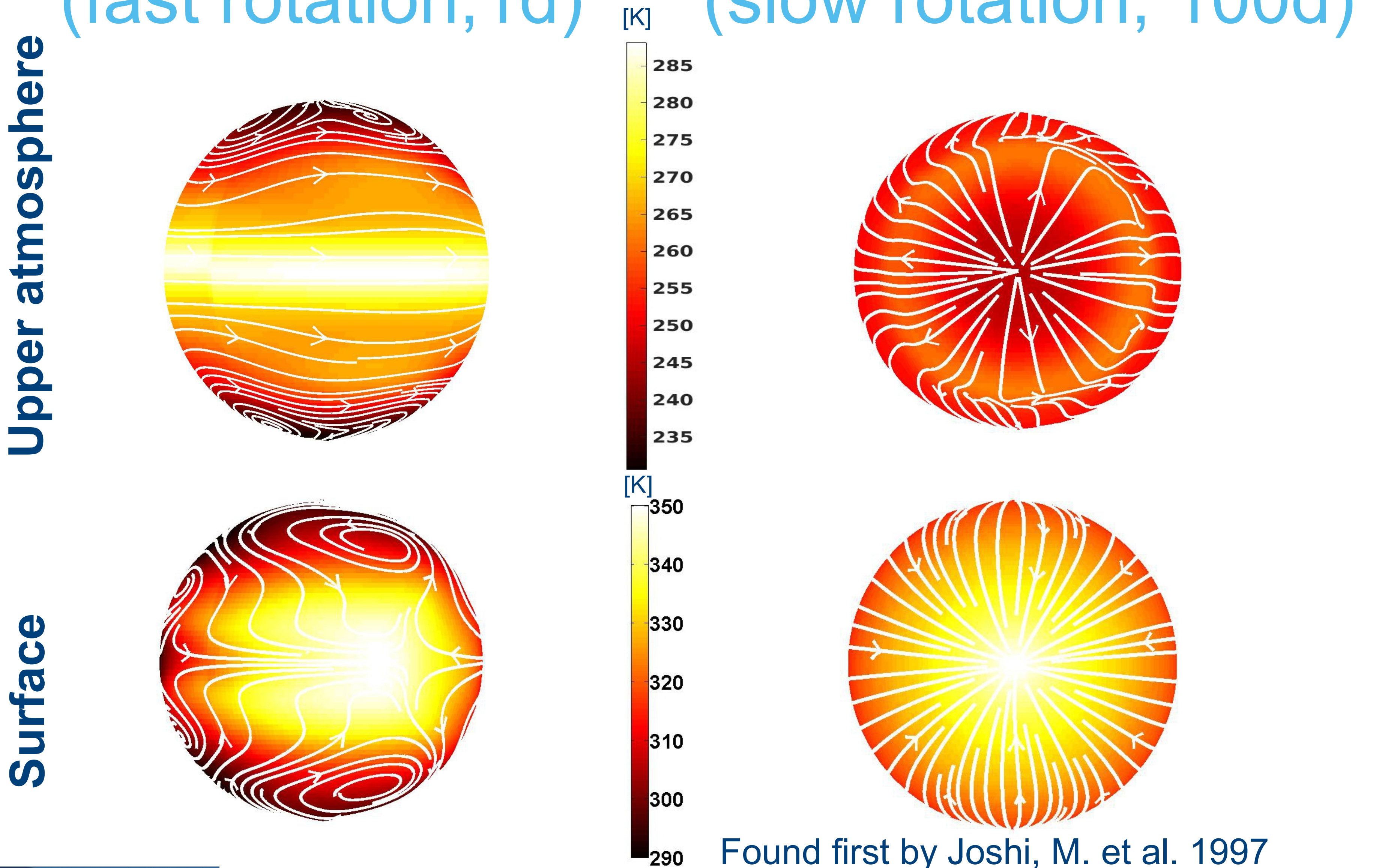
165 full 3D climate simulations



Example cases

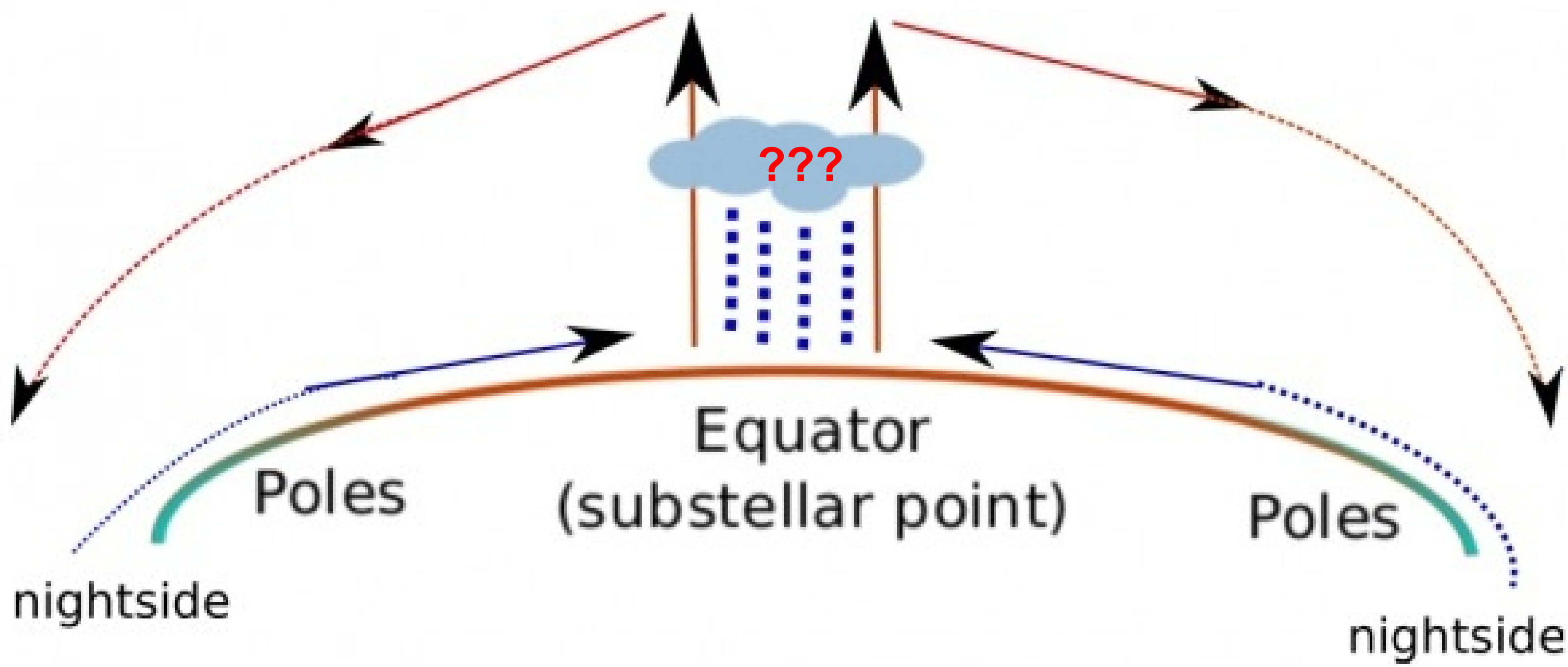


Rossby wave jets vs Direct circulation
(fast rotation, 1d) (slow rotation, 100d)



Found first by Joshi, M. et al. 1997

Substellar point surface cooling via direct circulation



Shielding by clouds over substellar point
Yang, Y. et al. 2014, 2013

Meridional Rossby wave numbers

- Amplitude of Rossby wave

Buoyancy frequency equiv. Vertical thermal stability

Scale height

tropical

$$\lambda_R = \sqrt{\frac{N H}{2 \beta}}$$

$$\beta = \frac{df}{dy} = \frac{2 \Omega}{R_P}$$

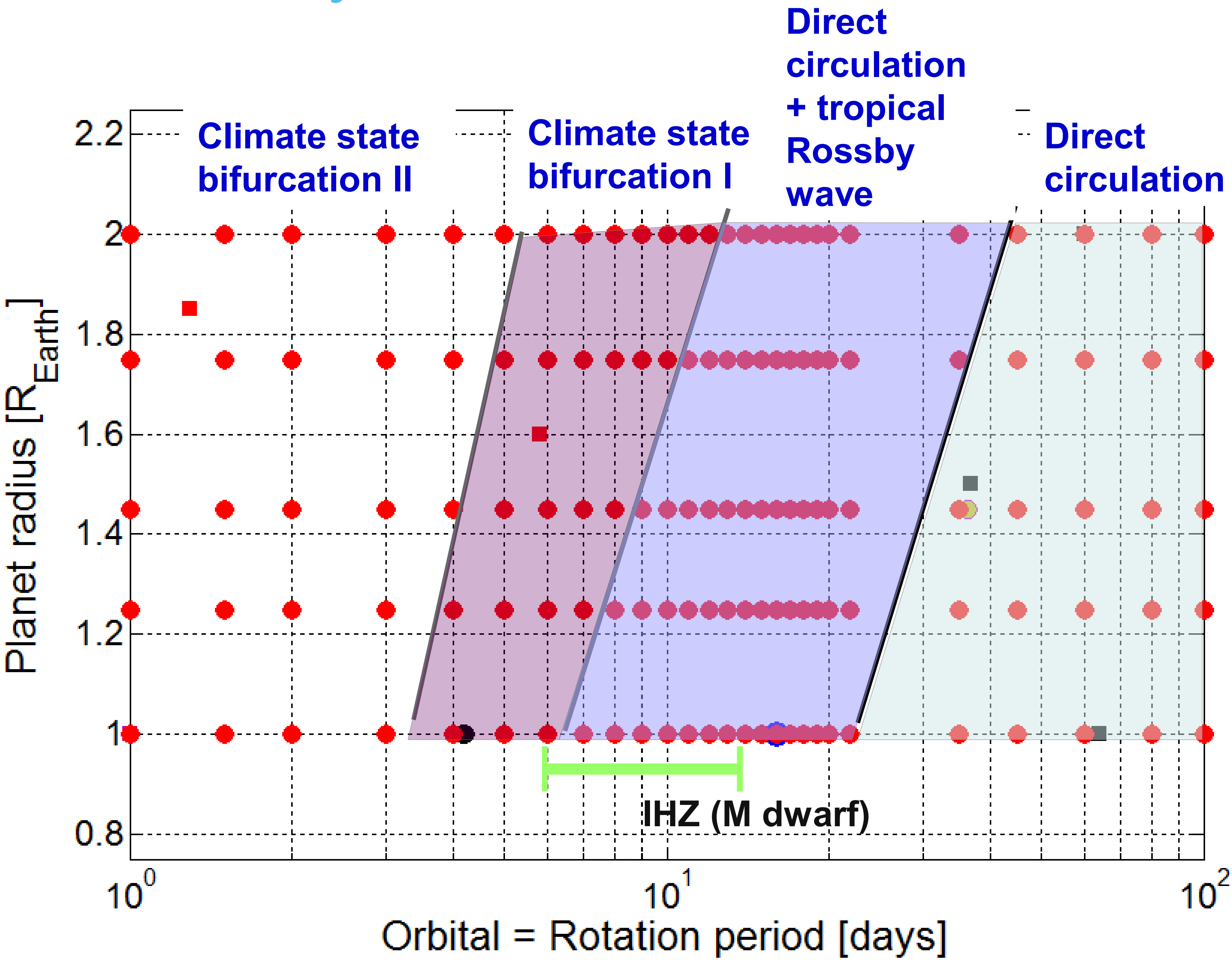
Meridional change in
Coriolis force at equator

Extra tropical

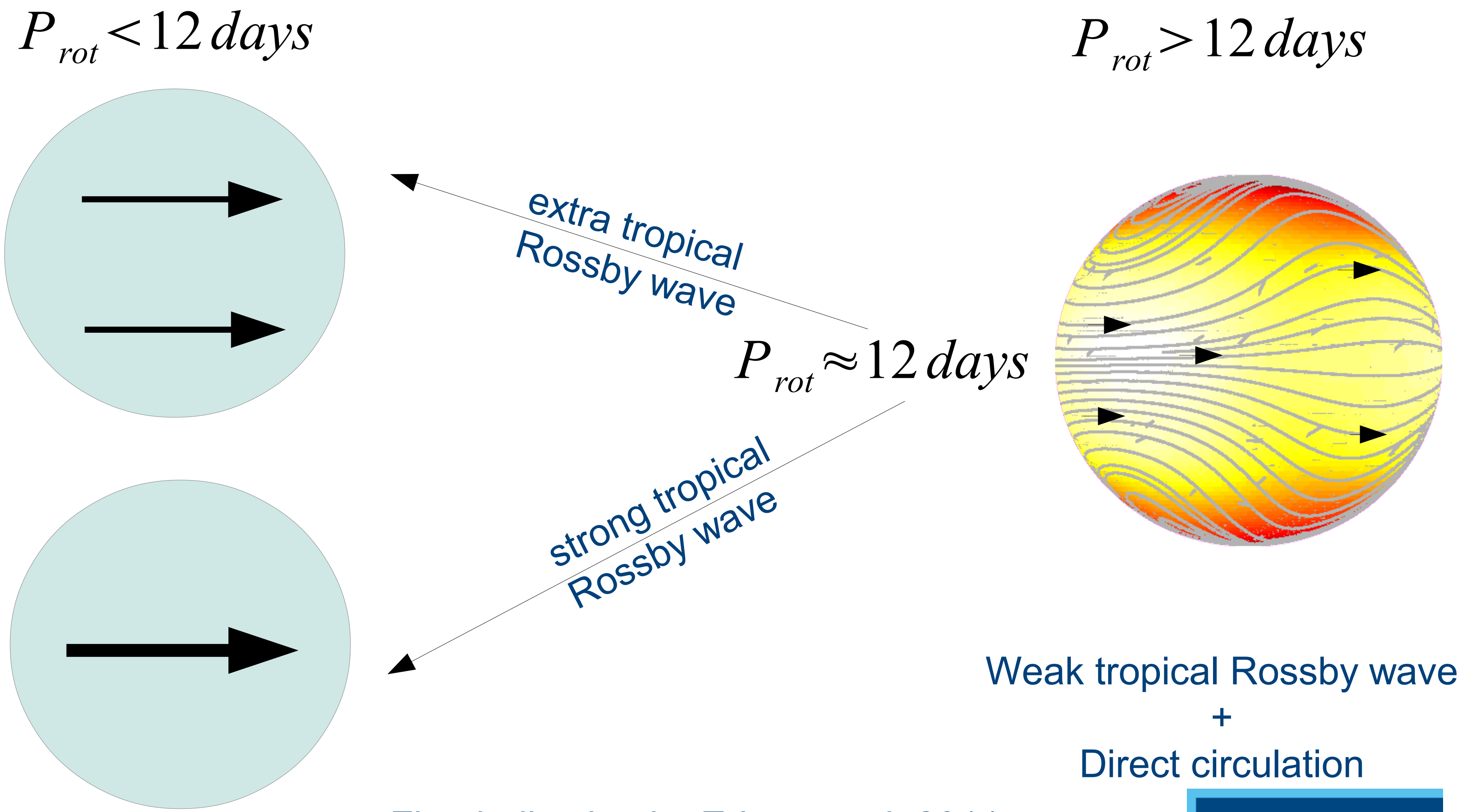
$$L_R = \frac{N H}{f}$$

Coriolis force at mid-latitude

Climate dynamic state maps

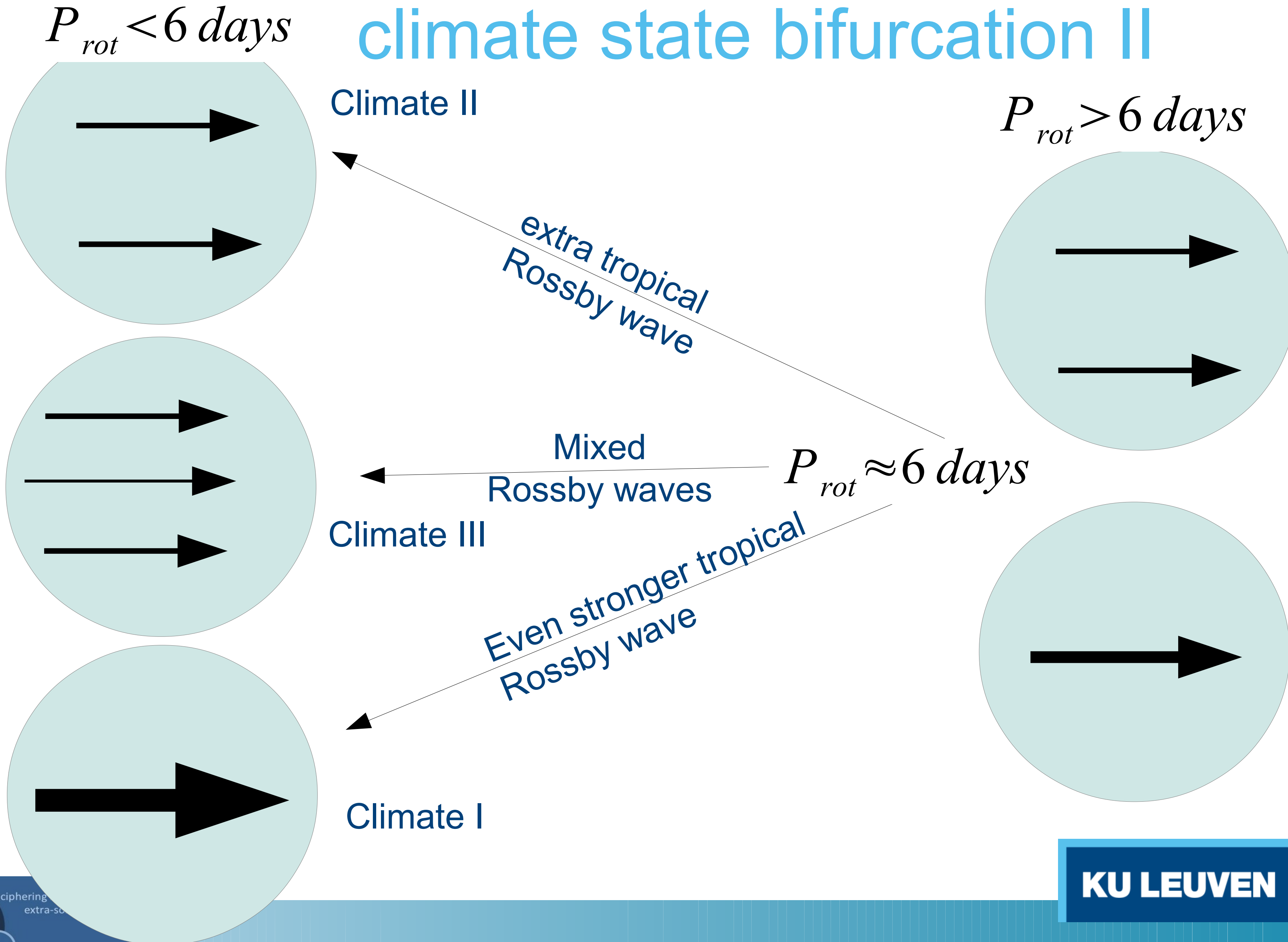


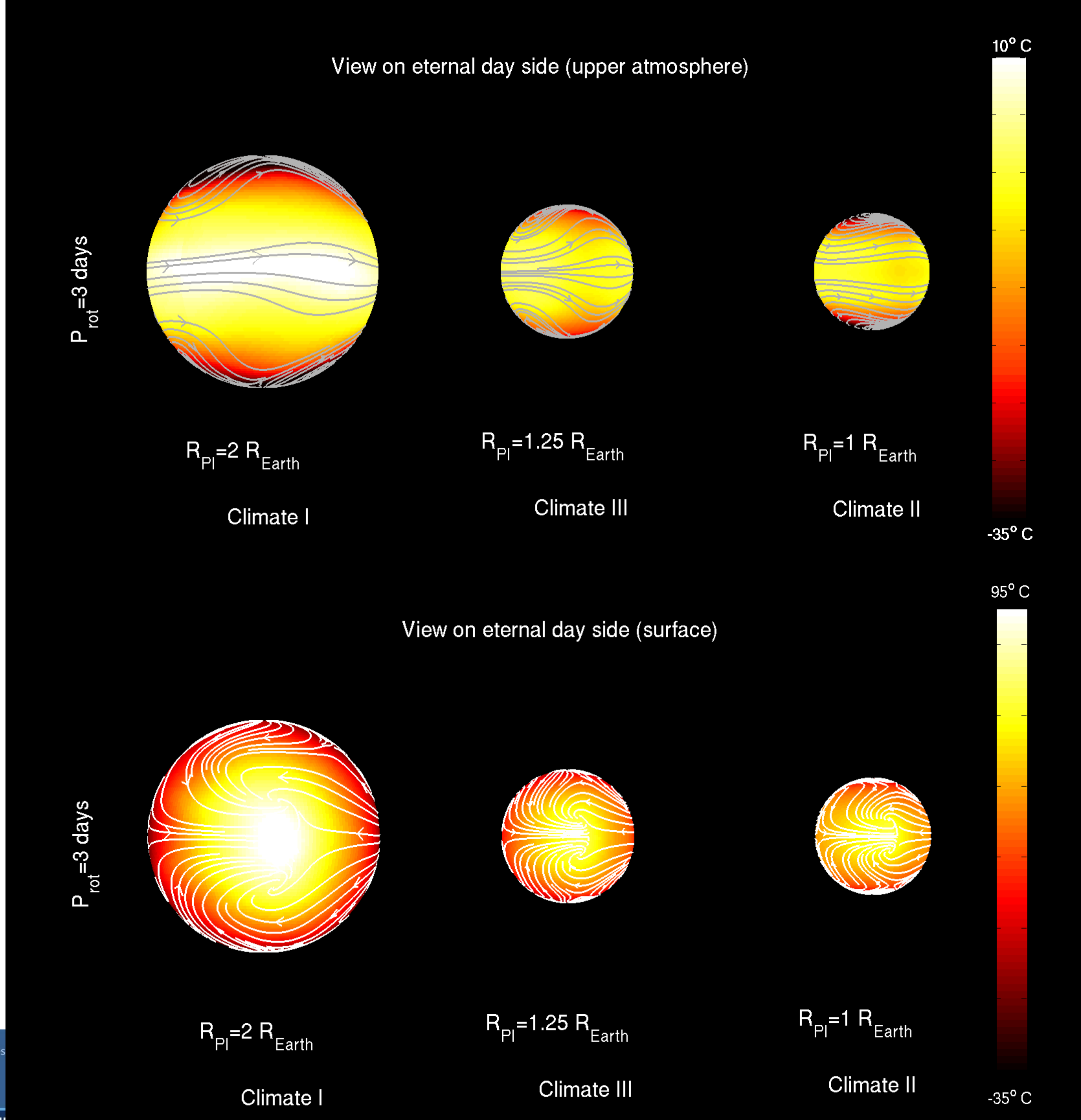
Rossby wave driven climate state bifurcation I



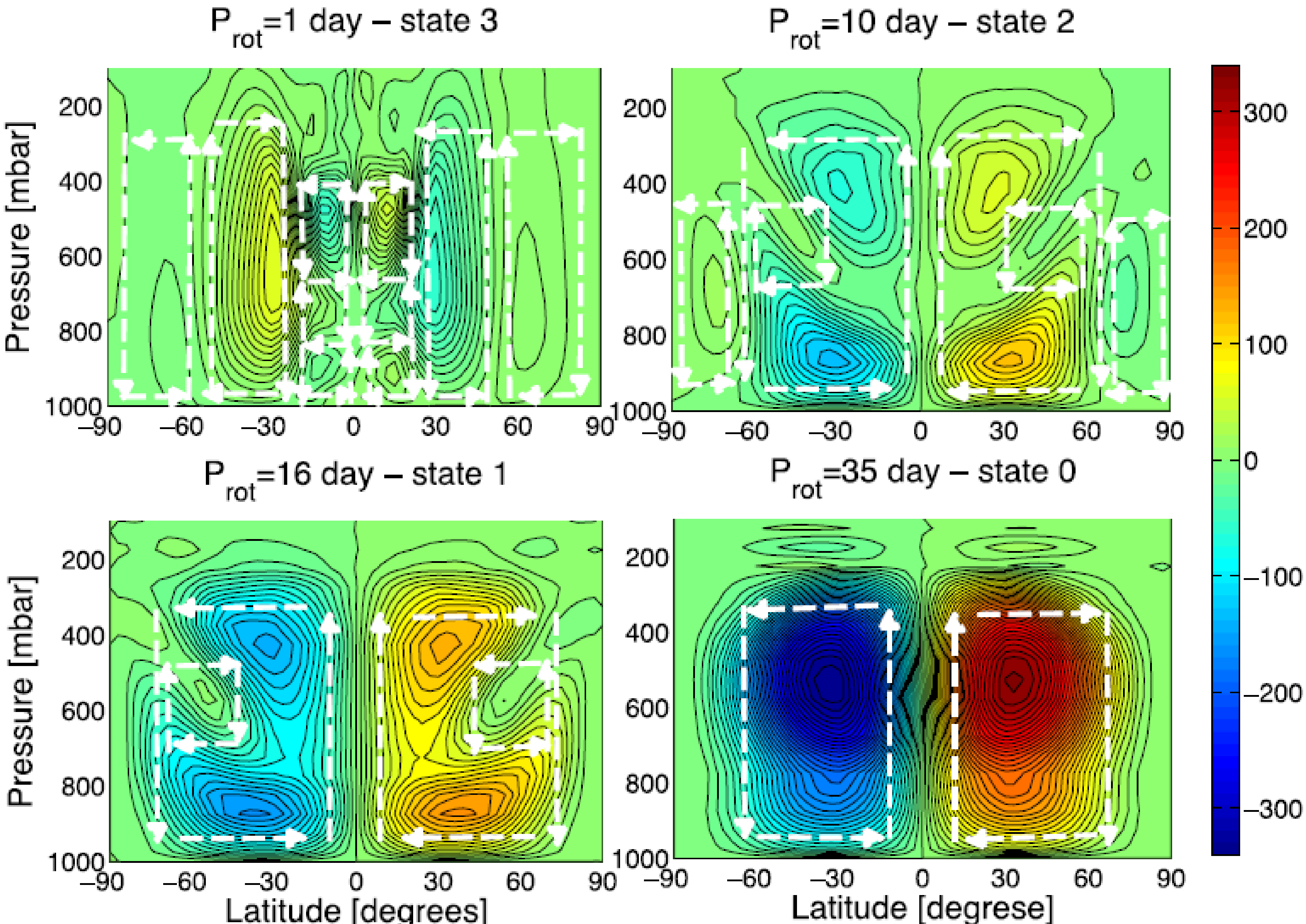
First indication by Edson et al. 2011

Rossby wave driven climate state bifurcation II

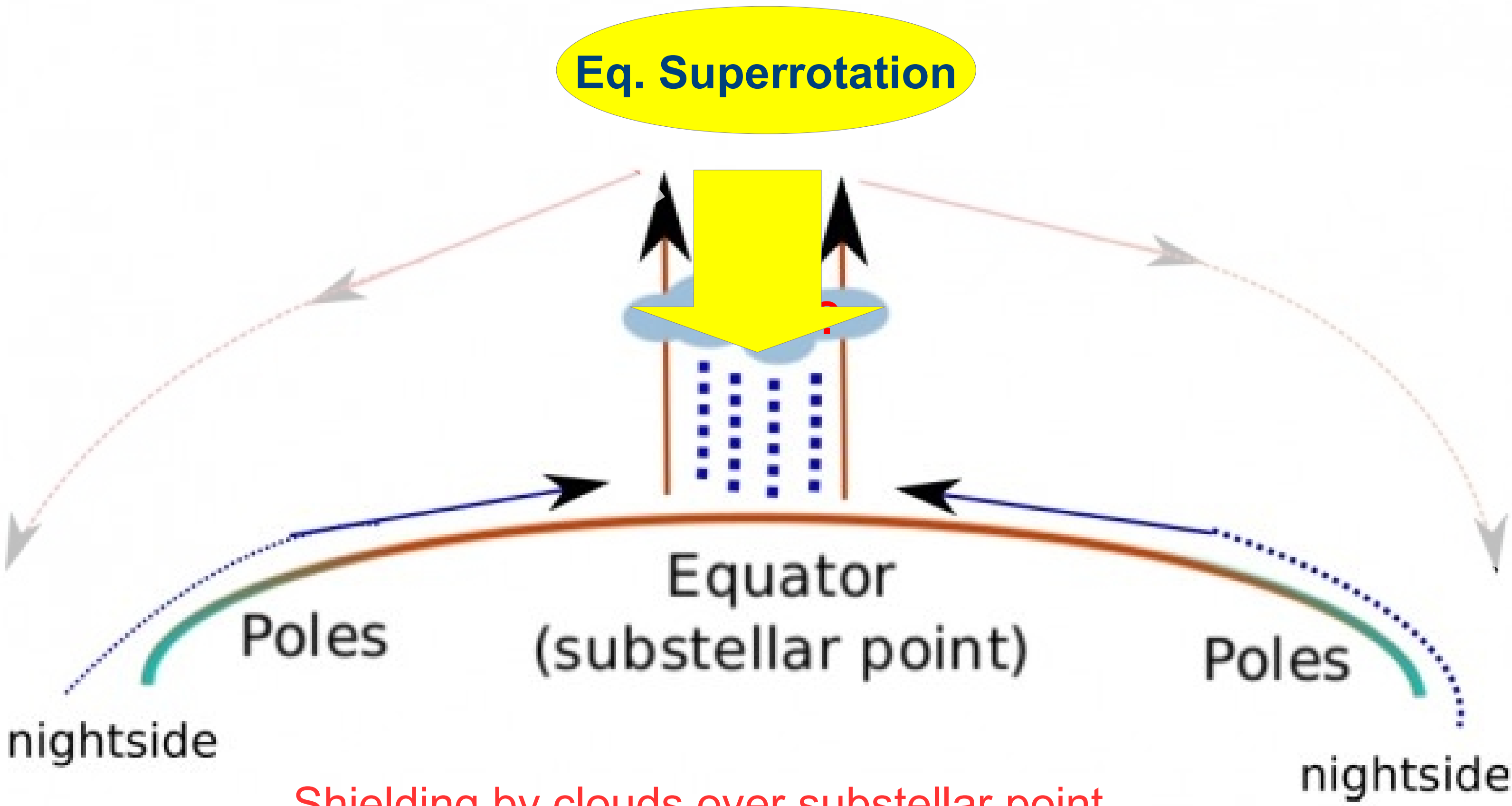



View on eternal day side (upper atmosphere)
10° C
-35° C
P_{rot}=3 days
R_{Pl}=2 R_{Earth}
Climate I
R_{Pl}=1.25 R_{Earth}
Climate III
R_{Pl}=1 R_{Earth}
Climate II
View on eternal day side (surface)
95° C
-35° C
P_{rot}=3 days
R_{Pl}=2 R_{Earth}
Climate I
R_{Pl}=1.25 R_{Earth}
Climate III
R_{Pl}=1 R_{Earth}
Climate II

Evolution of circulation cells (R_P=1 R_{Earth})



Direct circulation disrupted by strong equatorial superrotation (Climatel)



Shielding by clouds over substellar point
Yang, Y. et al. 2014, 2013
also suppressed

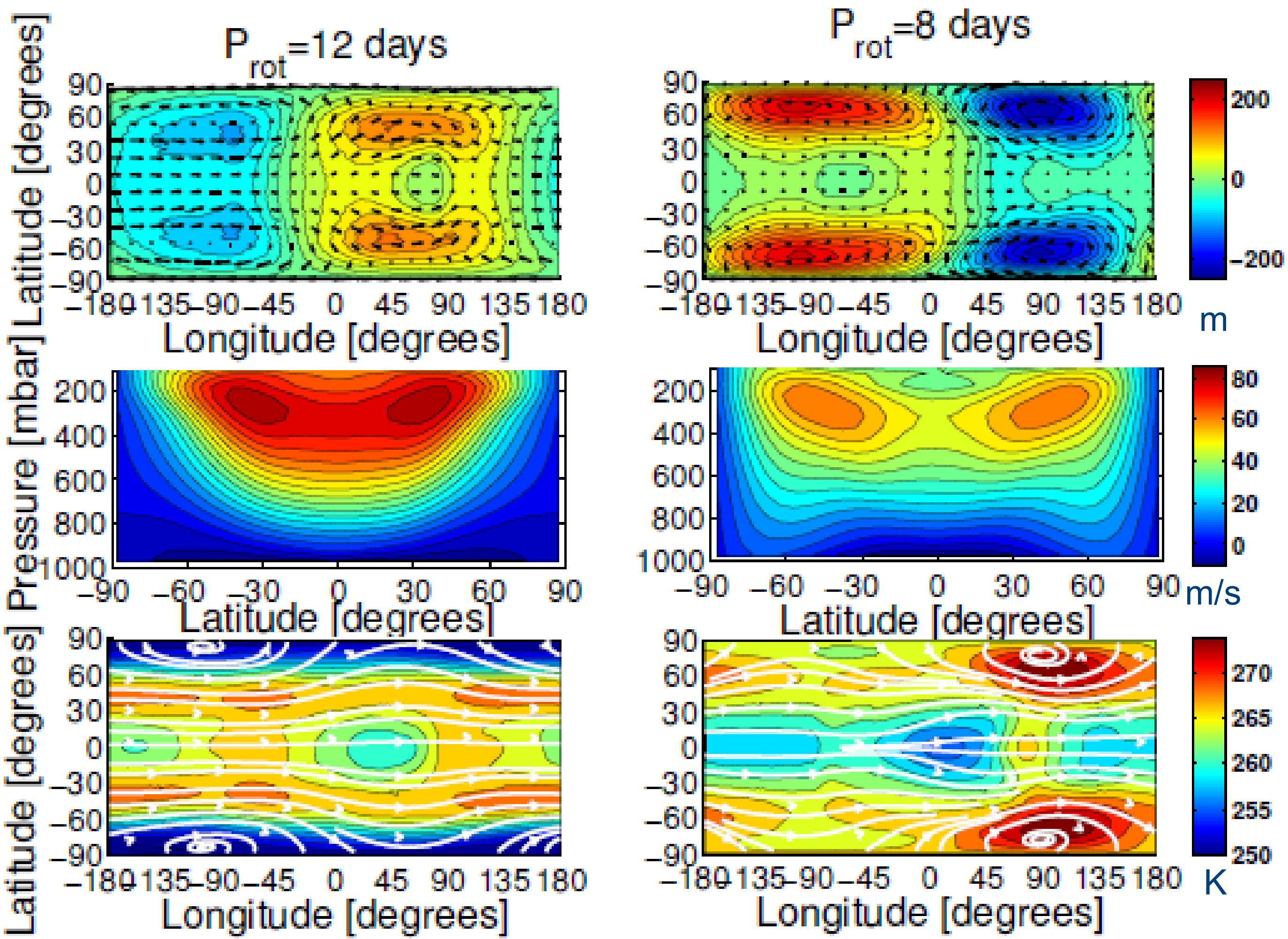
Large scale parameter study II:
Carone et al., 2016,MNRAS, in review

528 3D climate simulations

- Change surface friction time scale

(nominal $\tau_{fric} = 1\, days$)

Efficient surface friction ($\tau_{fric} = 0.1\, days$)



Atmosphere 'height' anomalies (color)

Vertical cross section of average zonal wind

Upper atmosphere flow & temperature (color)

Abrupt transition from weak tropical → extra tropical Rossby wave

Conclusions

- Climate states of tidally locked planets at IHZ of M stars can be dominated by Rossby waves
- Short rotation periods: <12 days
    - 2 Climate states possible:
        - Equatorial Superrotation
        - High latitudes westerly jets
- Ultra short rotation period < 6 days
    - 3 Climate states possible
        - Two as above
        - + mixed states
- Eq. superrotation 'kills' direct circulation cells and thus efficient cooling of dayside
- Efficient surface friction =>High latitude jets state favored