



Mapping 3D climates in the habitable zone of M dwarfs

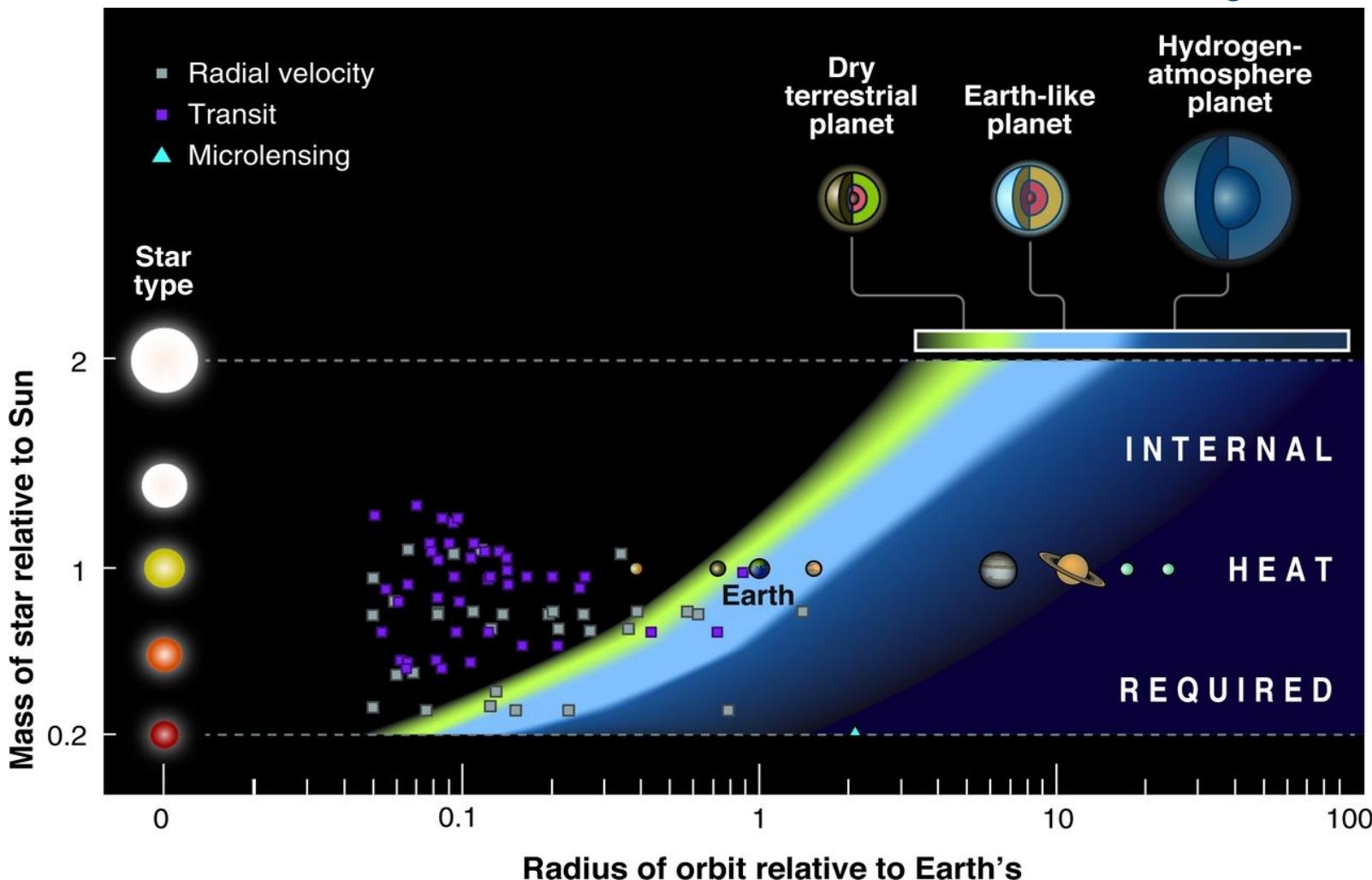
Ludmila Carone(1), Rony Keppens(1), Leen Decin (2)

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



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

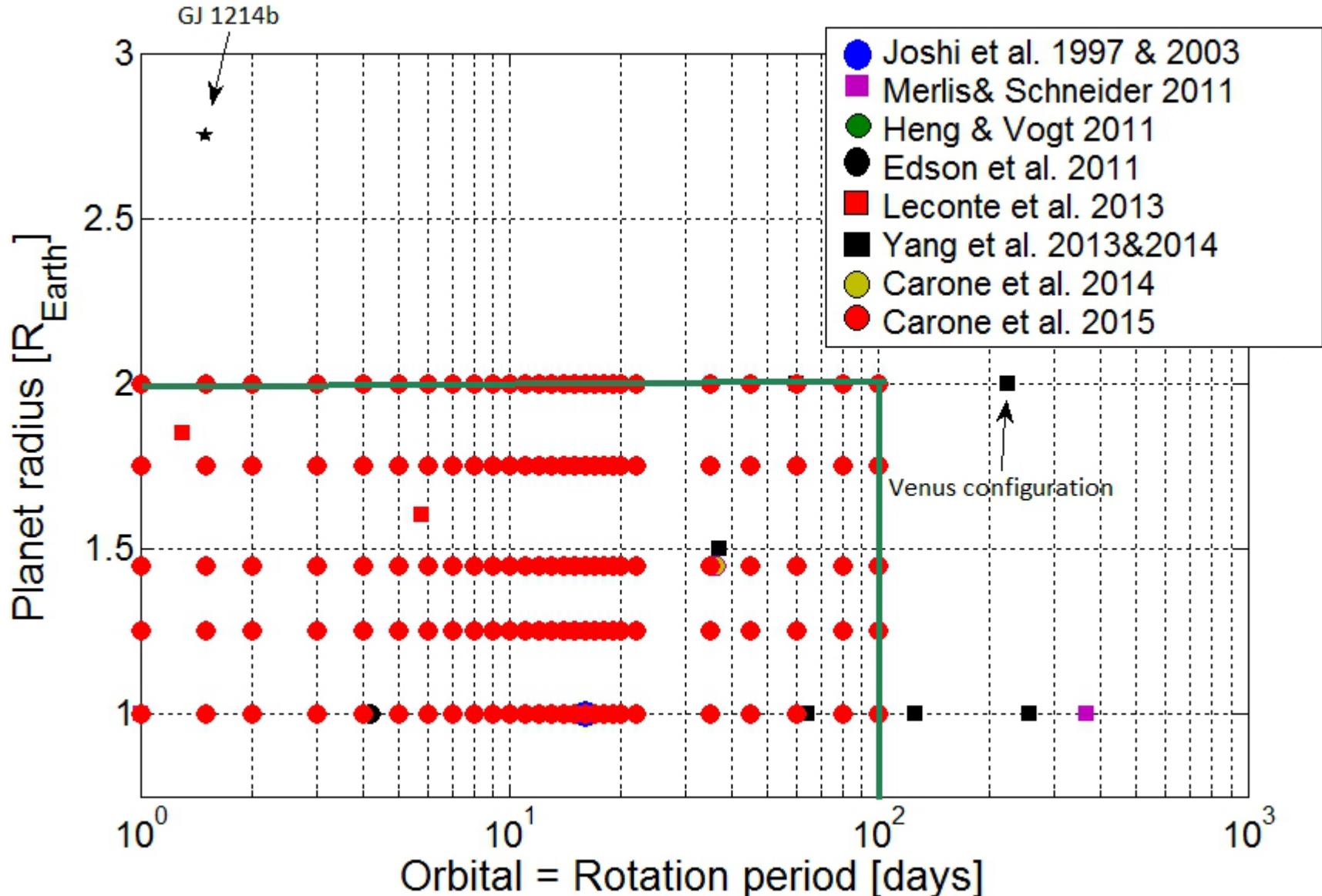
Seager 2013, Science



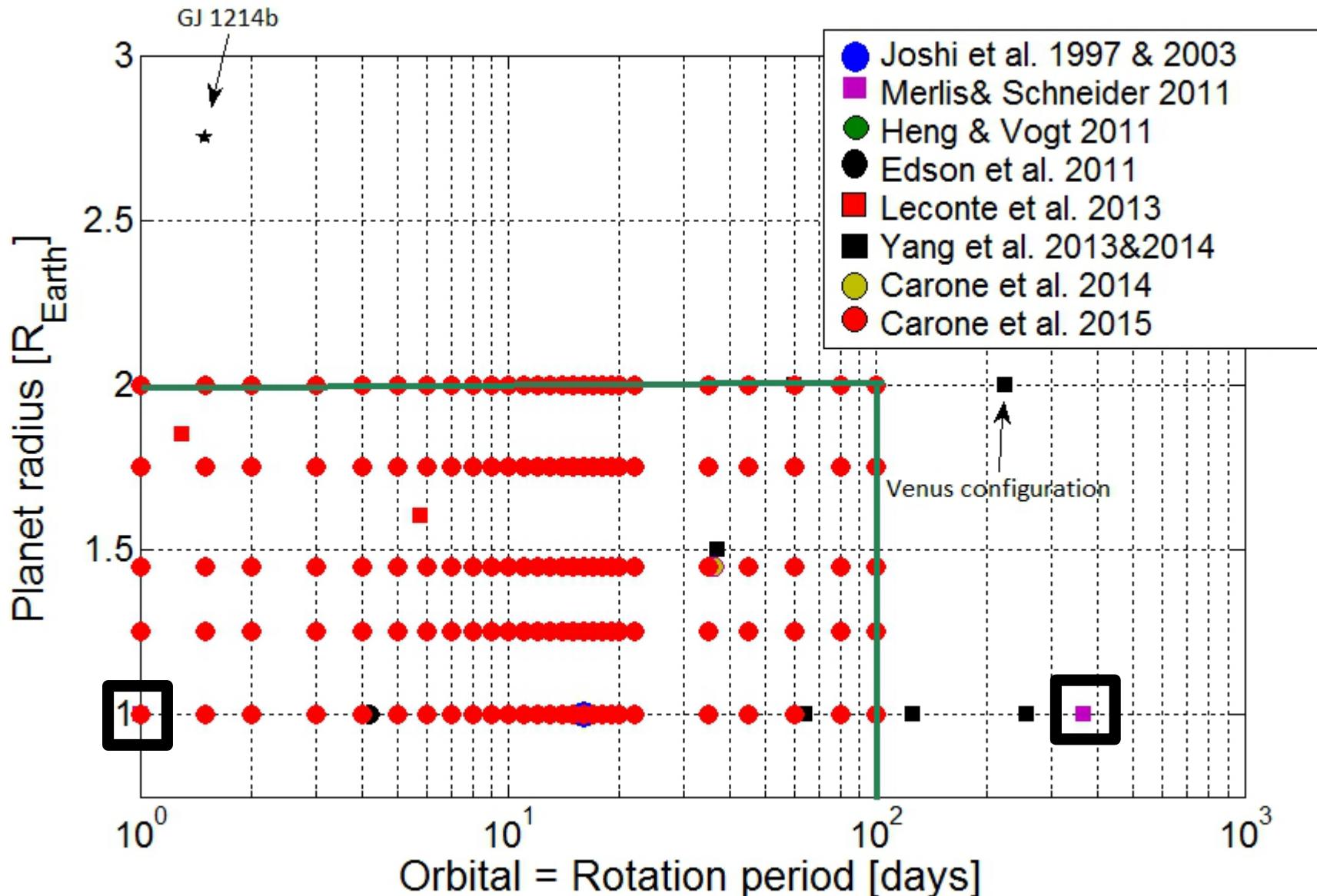
Large scale parameter study I :
(Carone et al., 2015, MNRAS, 453,pp 2412)
with

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

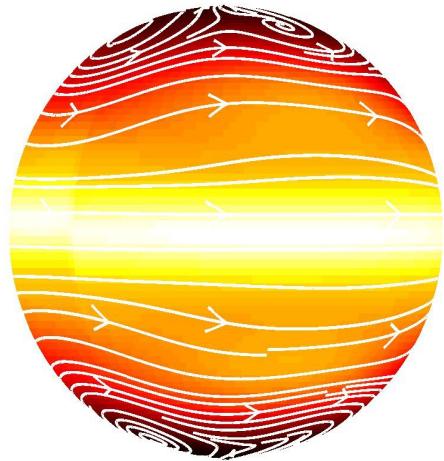


Example cases

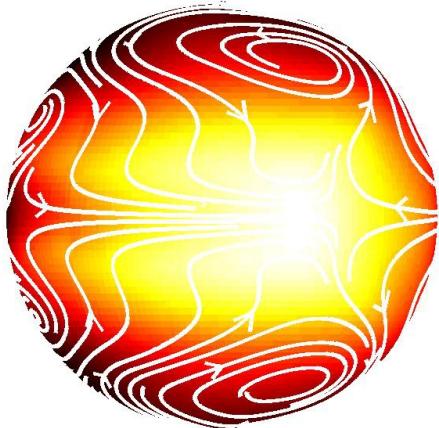


Rossby wave jets vs Direct circulation (fast rotation, 1d) (slow rotation, 100d)

Upper atmosphere



Surface



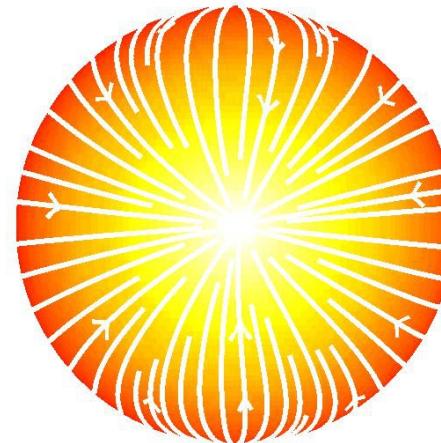
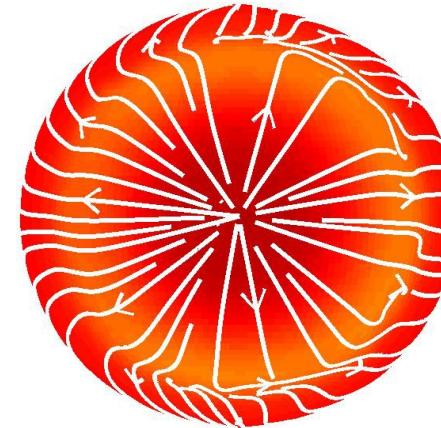
[K]

285
280
275
270
265
260
255
250
245
240
235

[K]

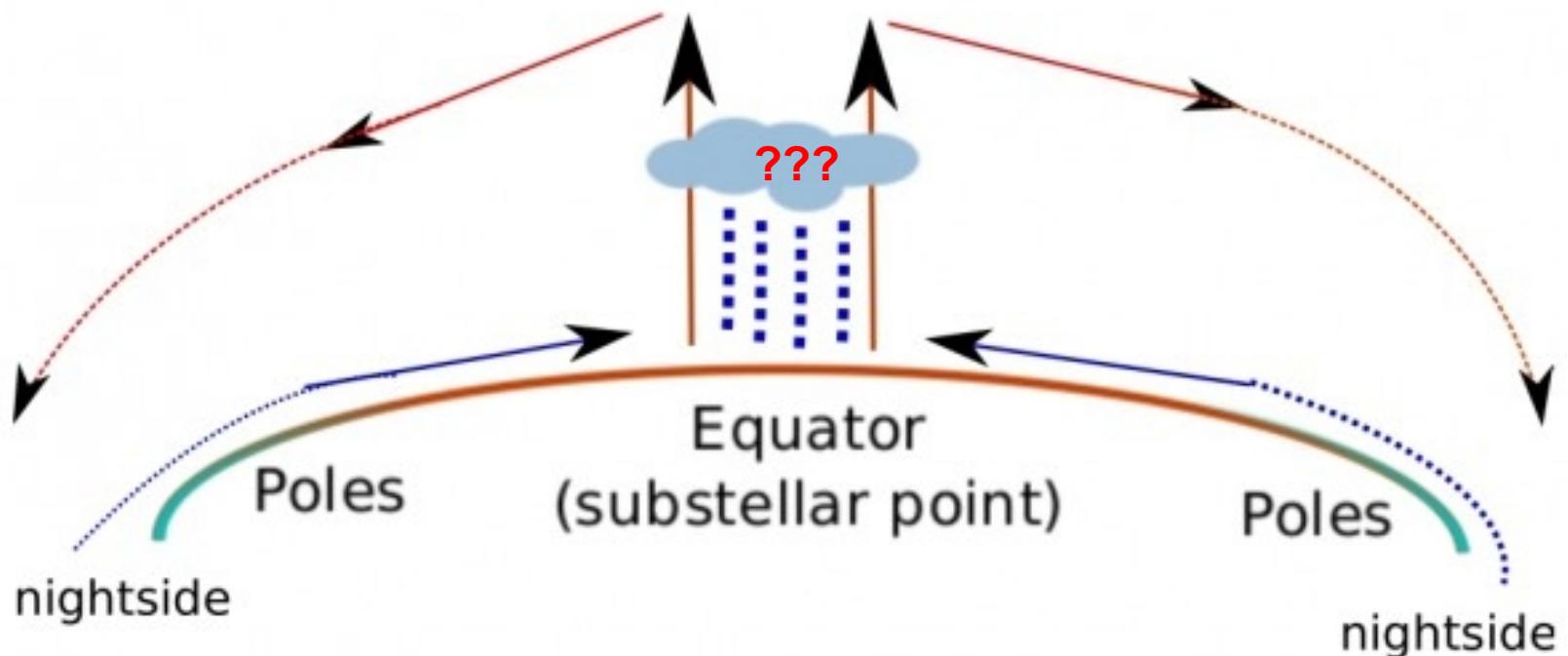
350
340
330
320
310
300
290

(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

The diagram illustrates the decomposition of the meridional Rossby wave number λ_R into tropical and extra-tropical components. The total Rossby wave number is given by:

$$\lambda_R = \sqrt{\frac{NH}{2\beta}}$$

This equation is derived from the following components:

- Buoyancy frequency equiv. Vertical thermal stability (top left)
- Scale height (top right)
- tropical component (left side)
- extra-tropical component (right side)

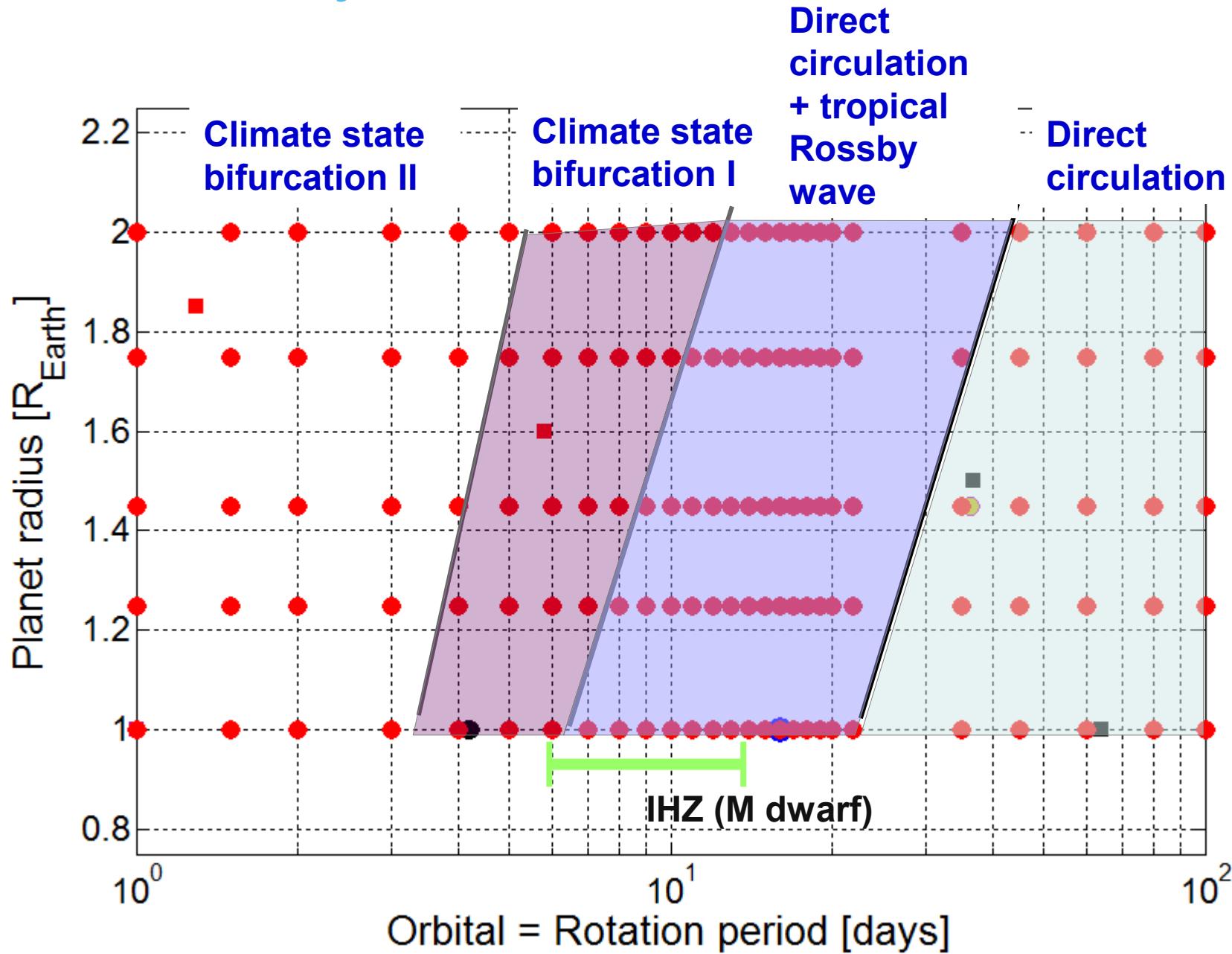
The extra-tropical component is defined as:

$$L_R = \frac{NH}{f}$$

This component is influenced by:

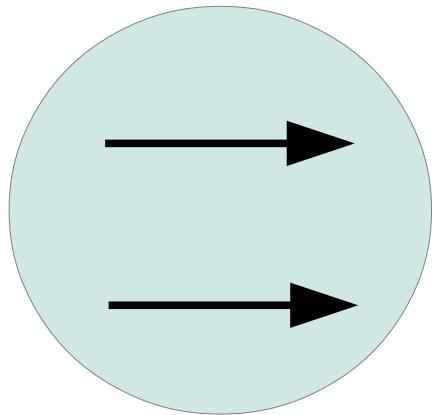
- Meridional change in Coriolis force at equator (top right)
- Coriolis force at mid-latitude (bottom right)

Climate dynamic state maps

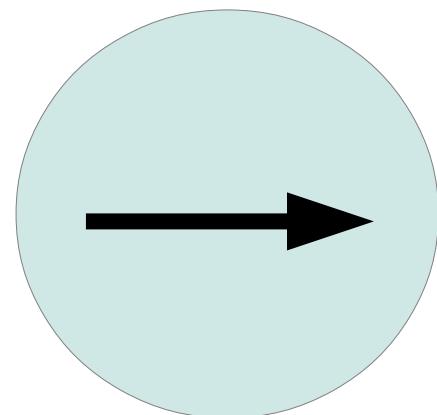
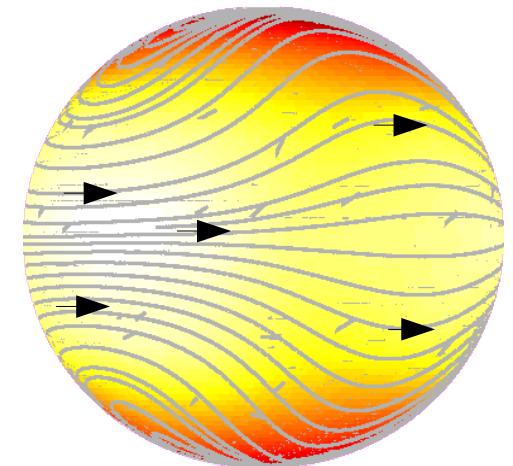


Rossby wave driven climate state bifurcation I

$P_{rot} < 12\ days$



$P_{rot} > 12\ days$



extra tropical
Rossby wave

strong tropical
Rossby wave

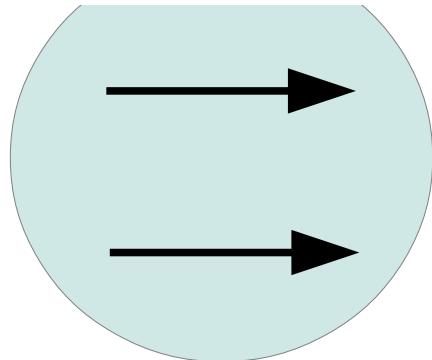
$P_{rot} \approx 12\ days$

Weak tropical Rossby wave
+
Direct circulation

First indication by Edson et al. 2011

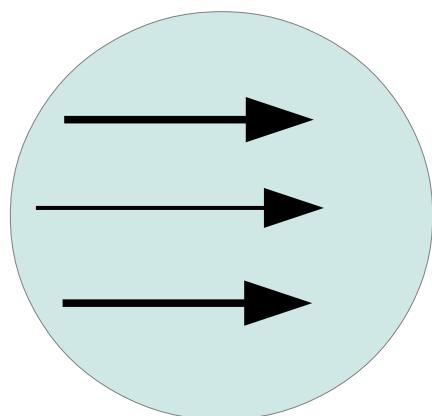
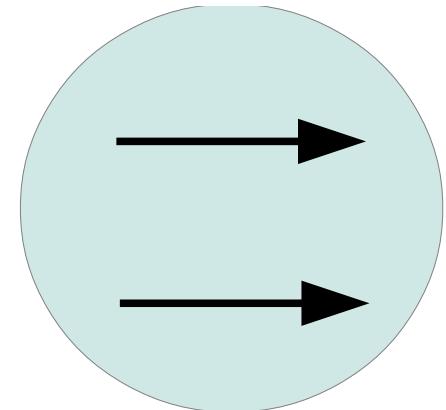
Rossby wave driven

$P_{rot} < 6 \text{ days}$



climate state bifurcation II

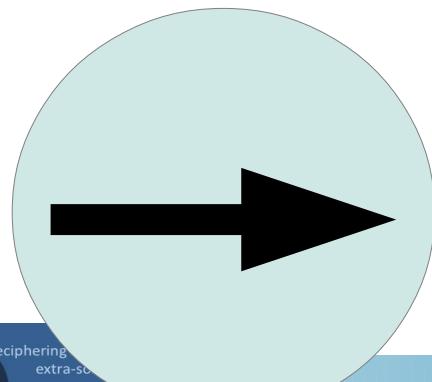
$P_{rot} > 6 \text{ days}$



Climate III

Mixed
Rossby waves

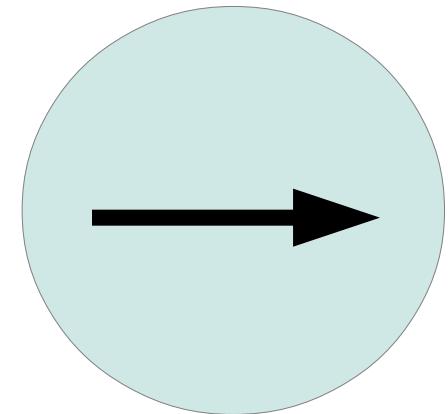
$P_{rot} \approx 6 \text{ days}$



Climate I

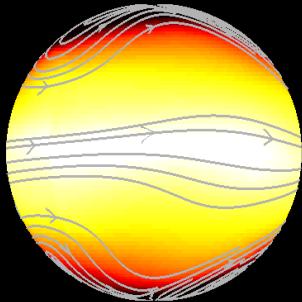
Even stronger tropical
Rossby wave

extra tropical
Rossby wave



View on eternal day side (upper atmosphere)

$P_{\text{rot}} = 3$ days



$R_{\text{Pl}} = 2 R_{\text{Earth}}$

Climate I

$R_{\text{Pl}} = 1.25 R_{\text{Earth}}$

Climate III

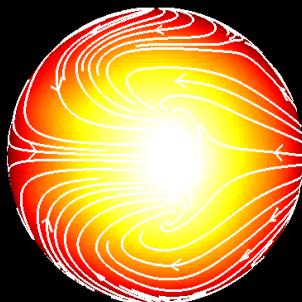
$R_{\text{Pl}} = 1 R_{\text{Earth}}$

Climate II

10° C
-35° C
95° C

View on eternal day side (surface)

$P_{\text{rot}} = 3$ days



$R_{\text{Pl}} = 2 R_{\text{Earth}}$

Climate I

$R_{\text{Pl}} = 1.25 R_{\text{Earth}}$

Climate III

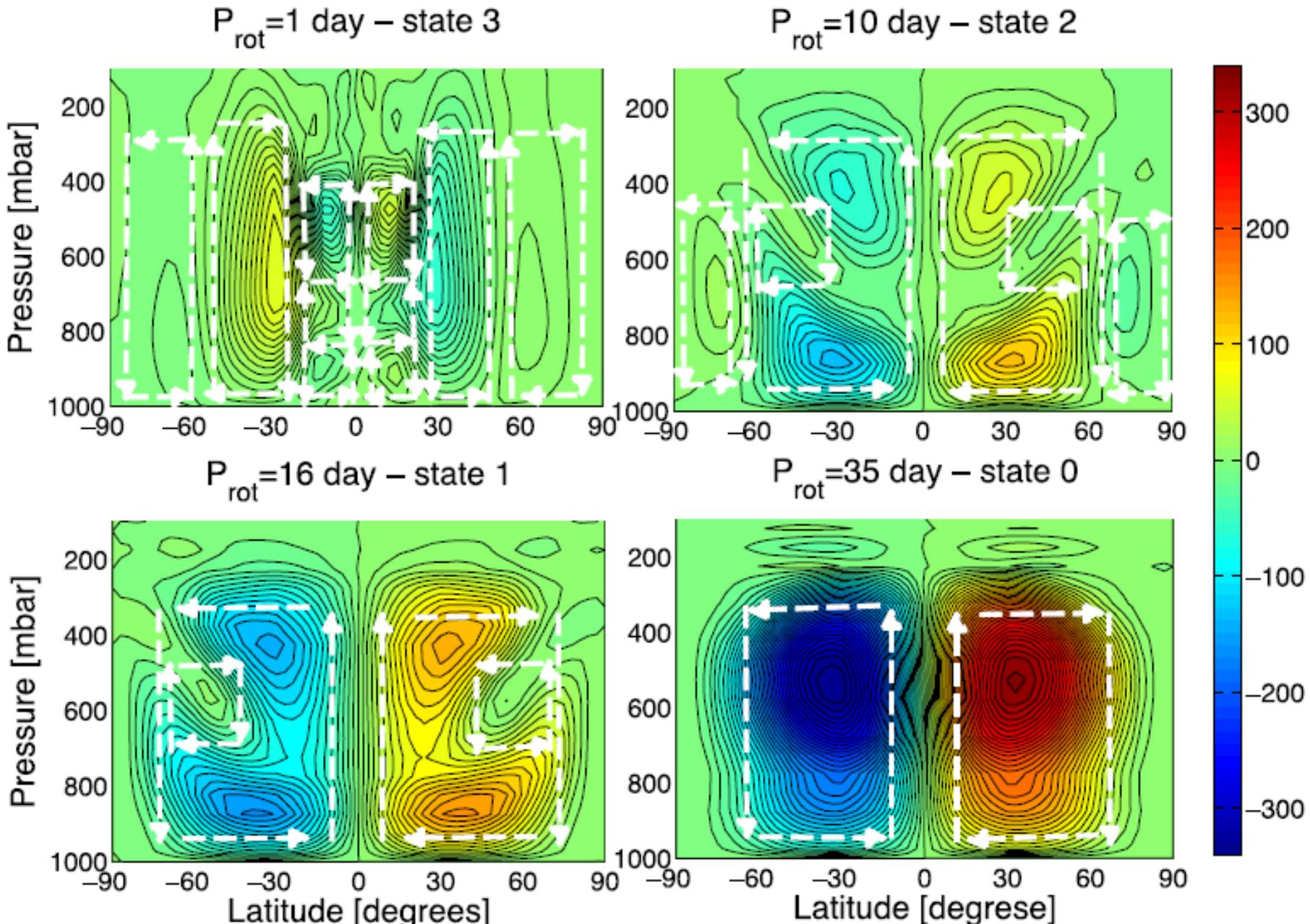
$R_{\text{Pl}} = 1 R_{\text{Earth}}$

Climate II

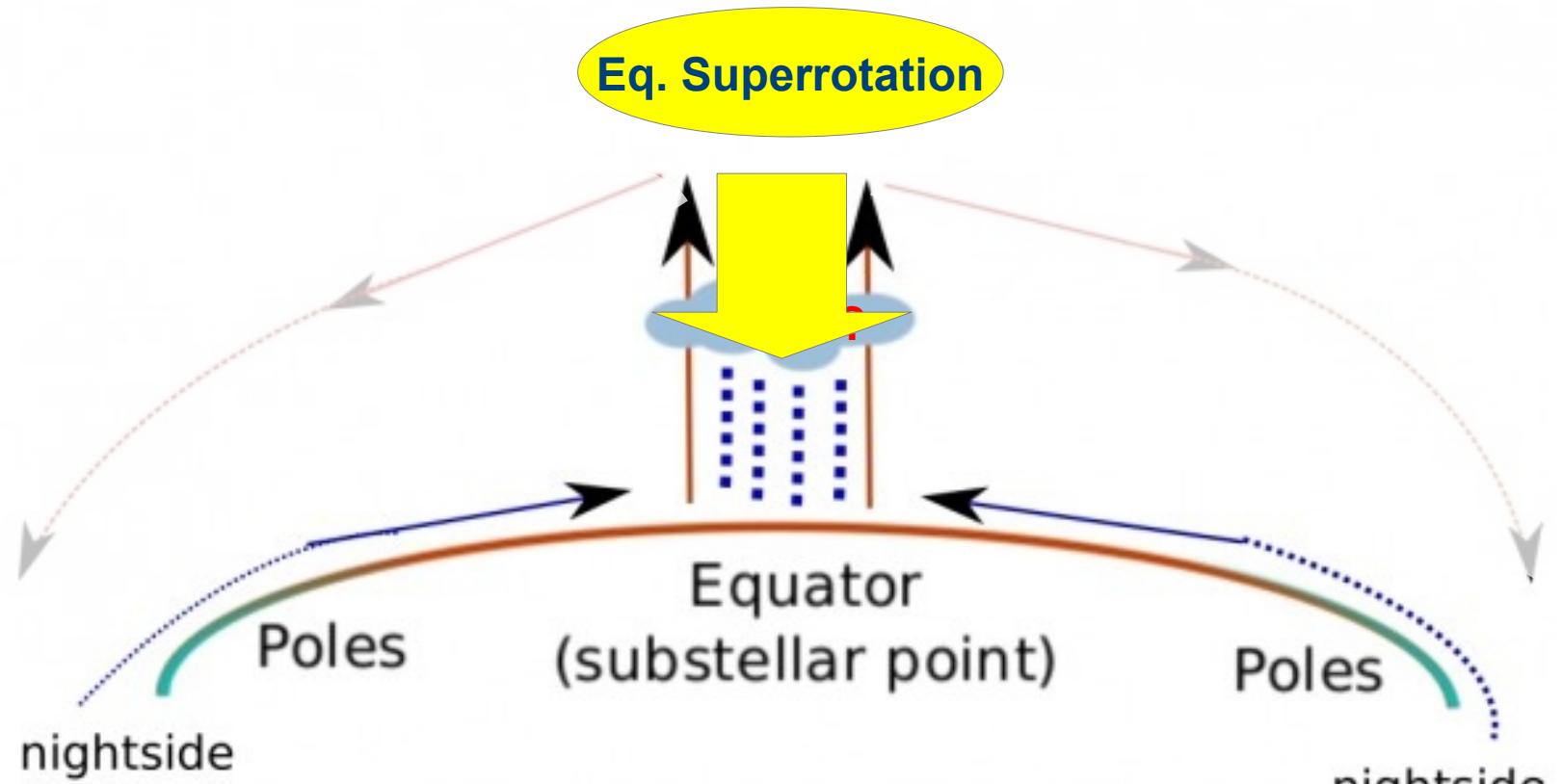
-35° C

LEUVEN

Evolution of circulation cells ($R_p = 1 R_{\text{Earth}}$)



Direct circulation disrupted by strong equatorial superrotation (Climate)



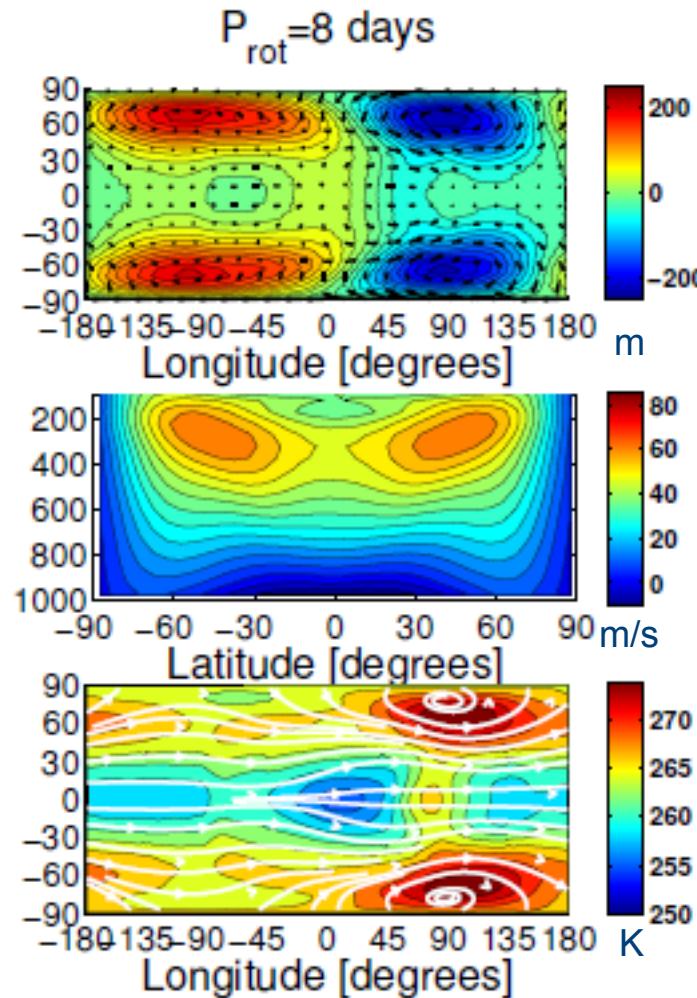
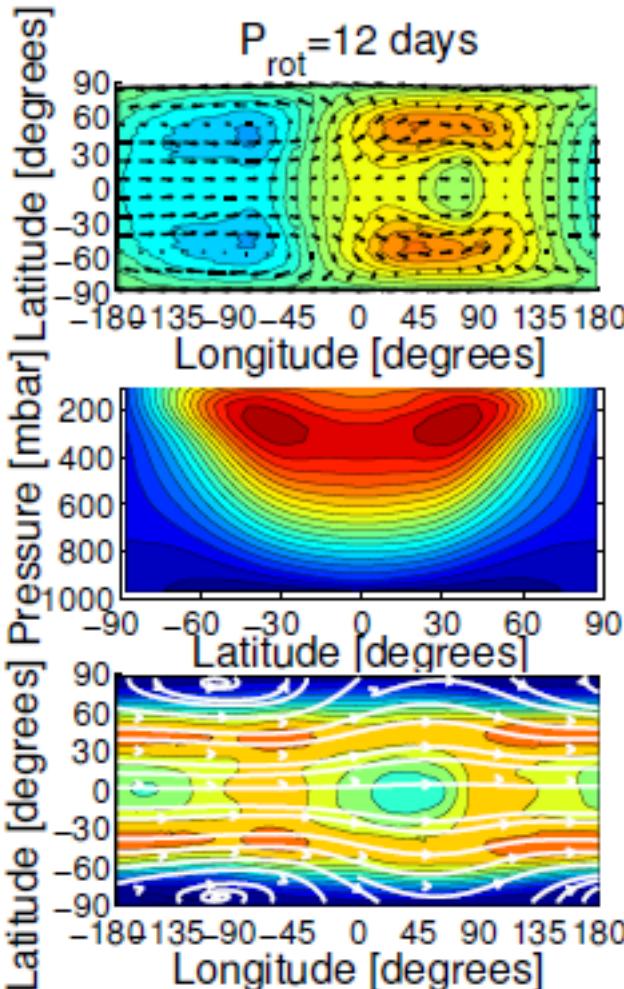
Shielding by clouds over substellar point
Yang, Y. et al. 2014, 2013
also suppressed

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

528 3D climate simulations

- Change surface friction time scale
(nominal $\tau_{fric} = 1 \text{ days}$)

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