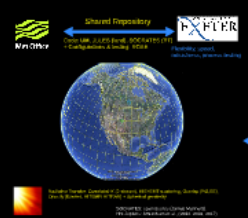
Exoplanetary Atmospheres in 3D: multidimensional processes and opportunities

James Manners,
Ian Boutle.

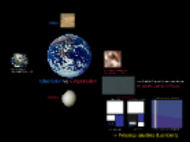
Nathan Mayne
exoclimatology.com

Observations

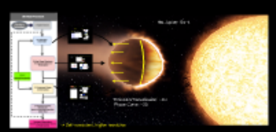
Model Framework



Terrestrial Planets



Gas giant planets



Conclusions & Future

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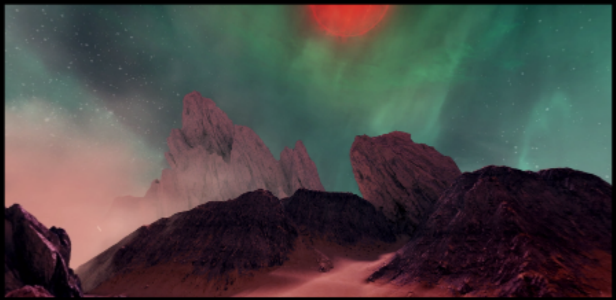

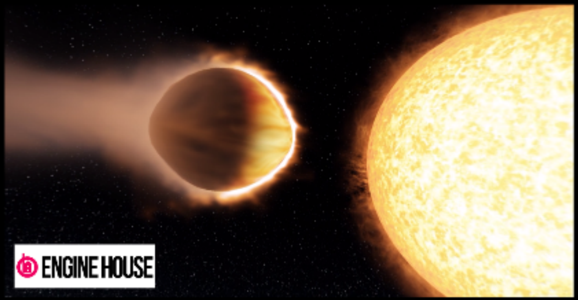

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Stefan Lines (postdoc),
Benjamin Drummond (postdoc),
Jayesh Goyal (PhD),
Florian Debras (PhD, Univ. Lyon).
David Amundsen.

Met Office

LEVERHULME TRUST

UNIVERSITY OF EXETER

Collaborators:
Pascal Tremblin (CEA-ATMO Lead), Hugo Lambert, Eric Hebrard, David Sing, Isabelle Baraffe, Christiane Helling (St Andrews), Graham Lee (Oxford/Bern), Daniel Apai (Arizona)

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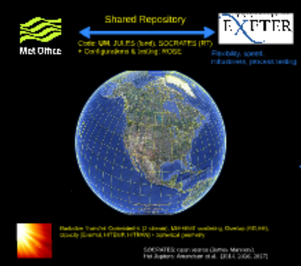

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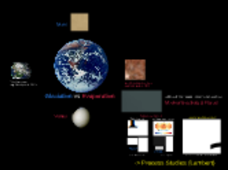

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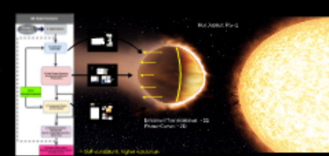


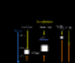
Conclusions & Future

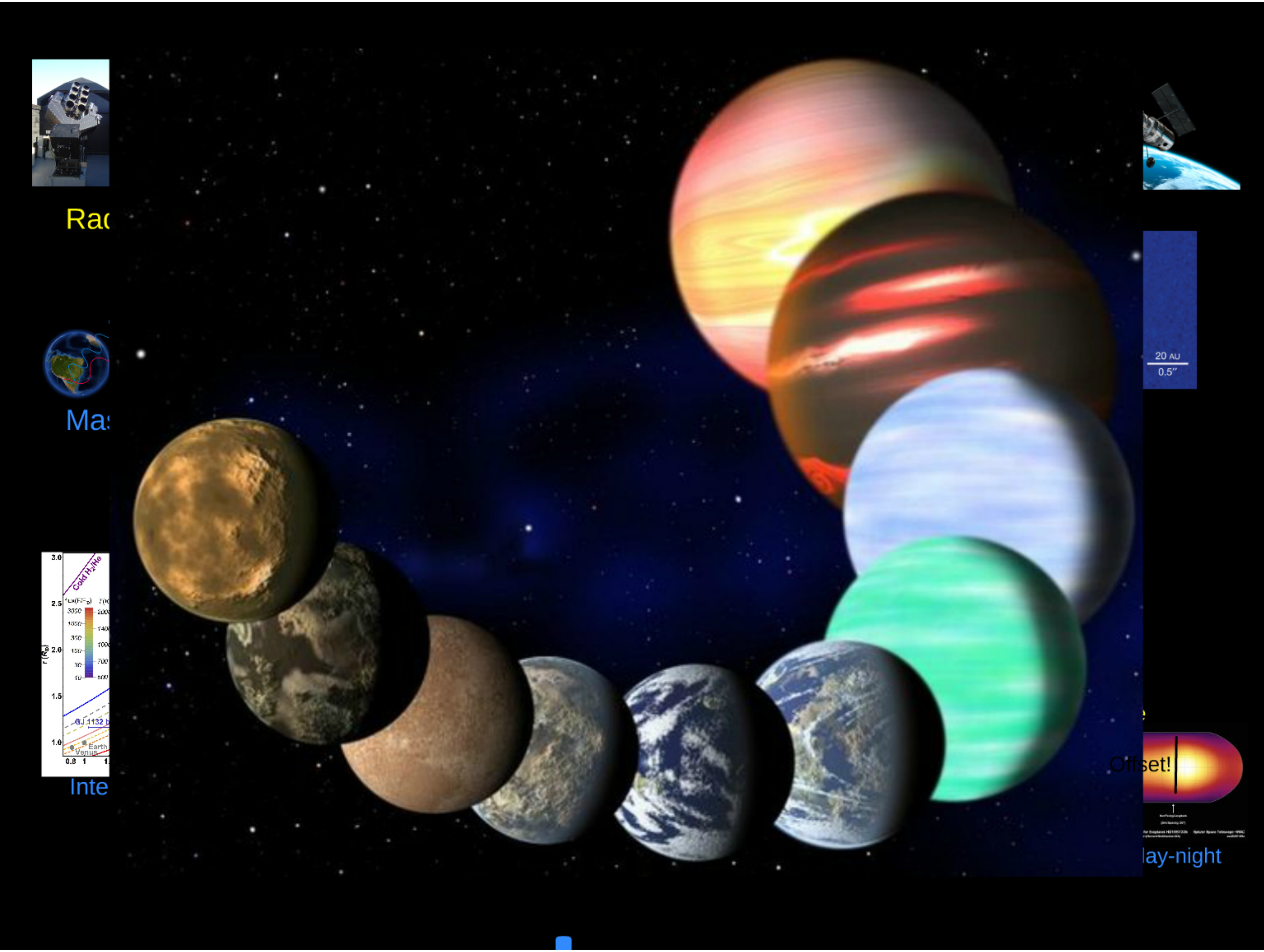
Hot Jupiters [Dynamics connect deep -> Observable + Control Structure]:
- Radius inflation: advection & deep profile (1)
- Chemistry: 2D mixing+RT (2)
- Clouds: scattering cools -> toward (3)
  - Too cloudy, and no visual offset (dampened ?)

Future:
1) Chemistry: full chemical kinetics
2) Clouds: gas phase consistency, particles(?), more species (Mxs, Fe)
3) Eddy-Sed vs DIHRT
4) Simulated HRes spectra -> Dynamical constraints

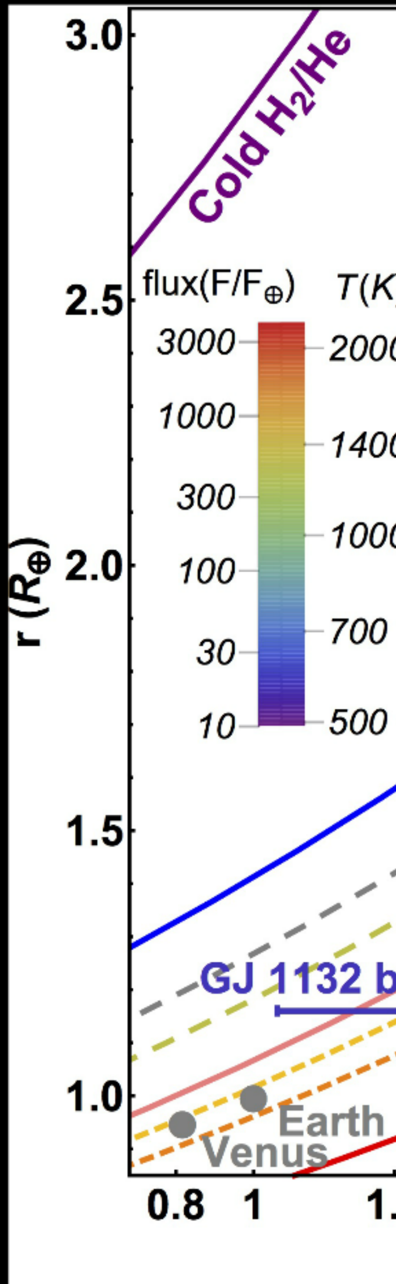
Terrestrial Planets-M-Dwarf, temperate planets:
- Tidally-Locked: Convection, clouds + rain -> hot spot (1)
- Resonant, Eccentric: Hydro cycle -> Phase curve (2)
- Continent alters circulation (3)

Future:
1) Condensible CO2, Ocean, CIA CO2 etc., Fluxes(...)
2) High-res process studies.





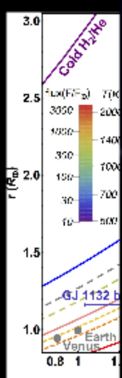
Rac
Mas
Inte
20 AU
0.5″
Offset!
lay-night


Cold H2/He
flux(F/F⊕)
3000
1000
300
100
30
10
r (R⊕)
3.0
2.5
2.0
1.5
1.0
GJ 1132 b
Earth
Venus
0.8
1

Inte

Rac

Ma



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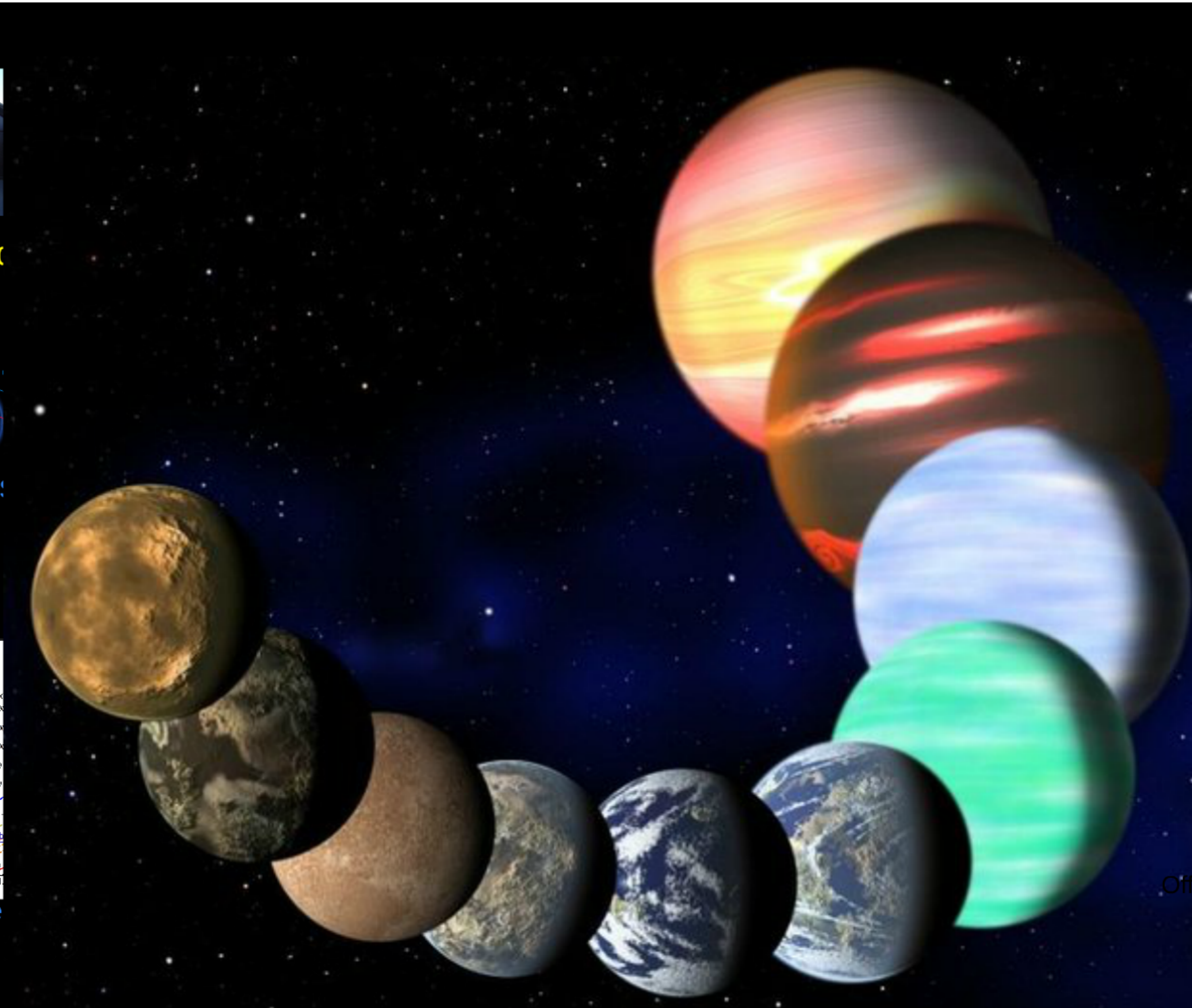
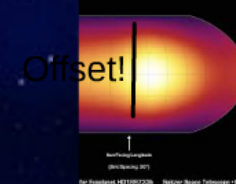
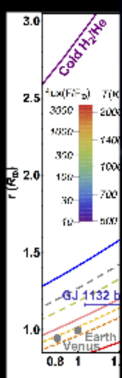




lay-night

Rac

Mas



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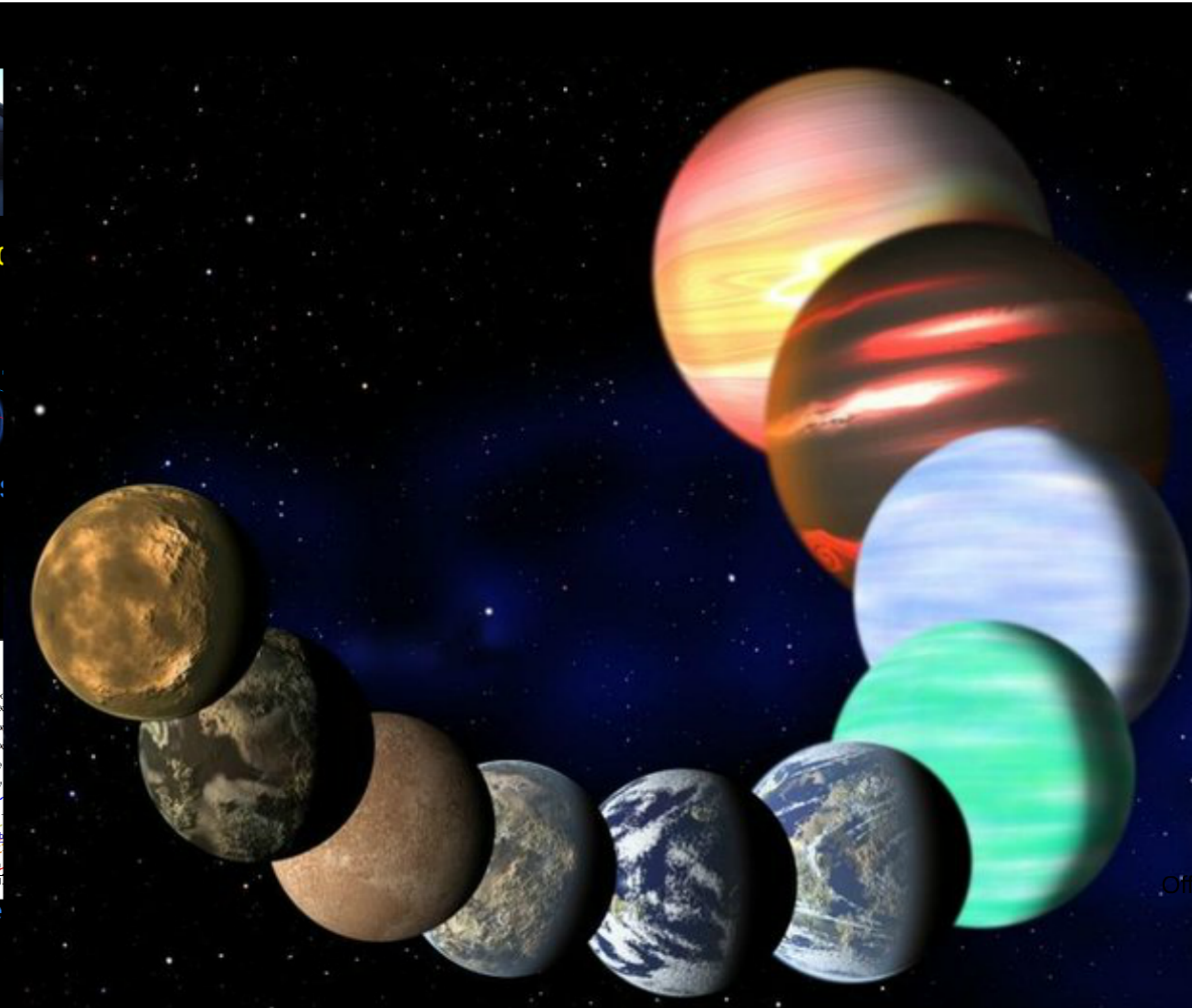
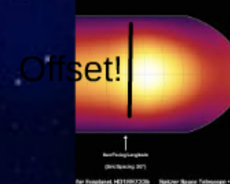


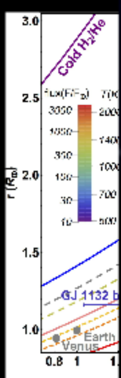
e



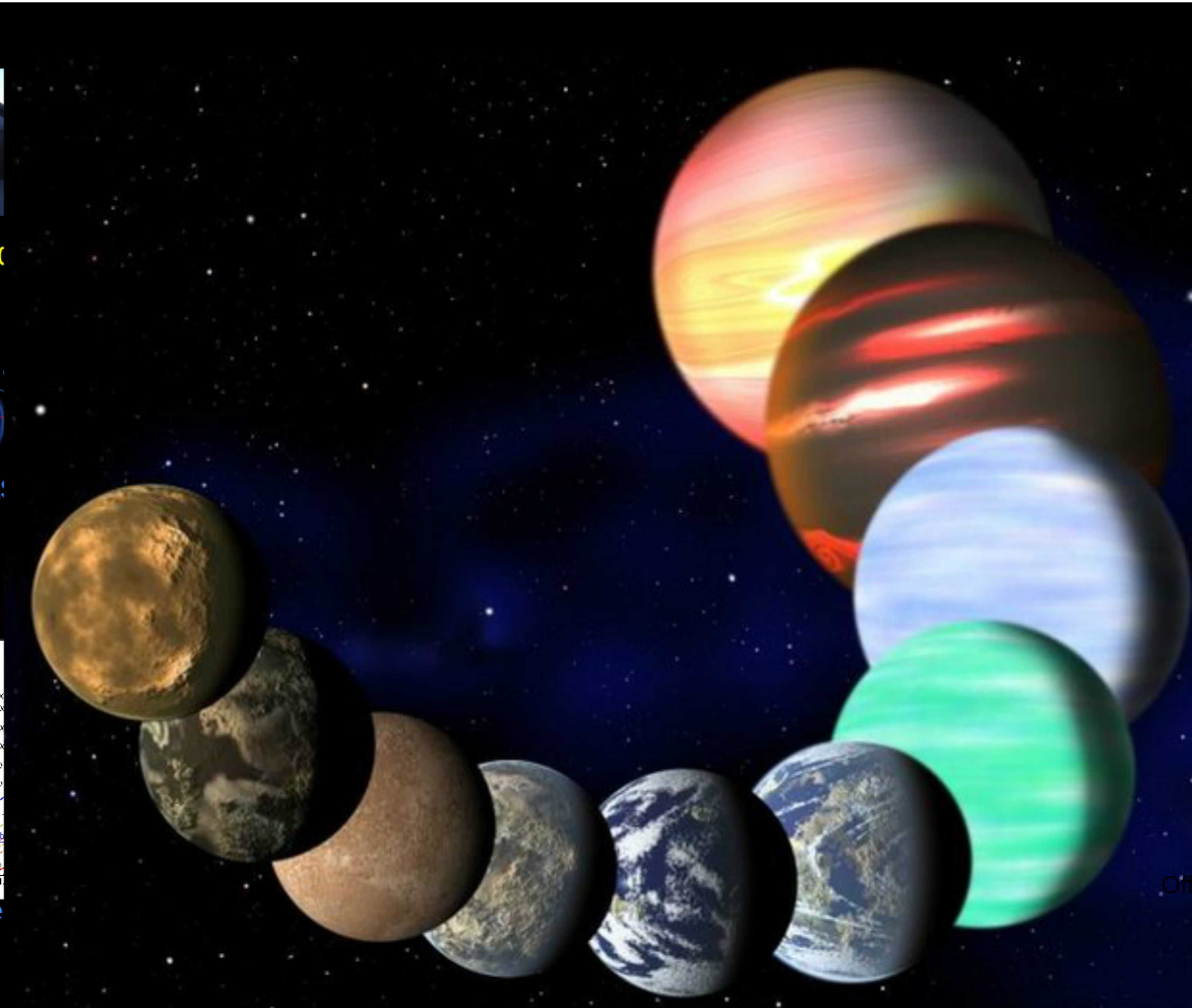
lay-night

Rad

Mas



Inte



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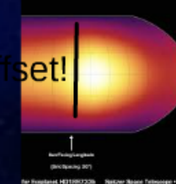
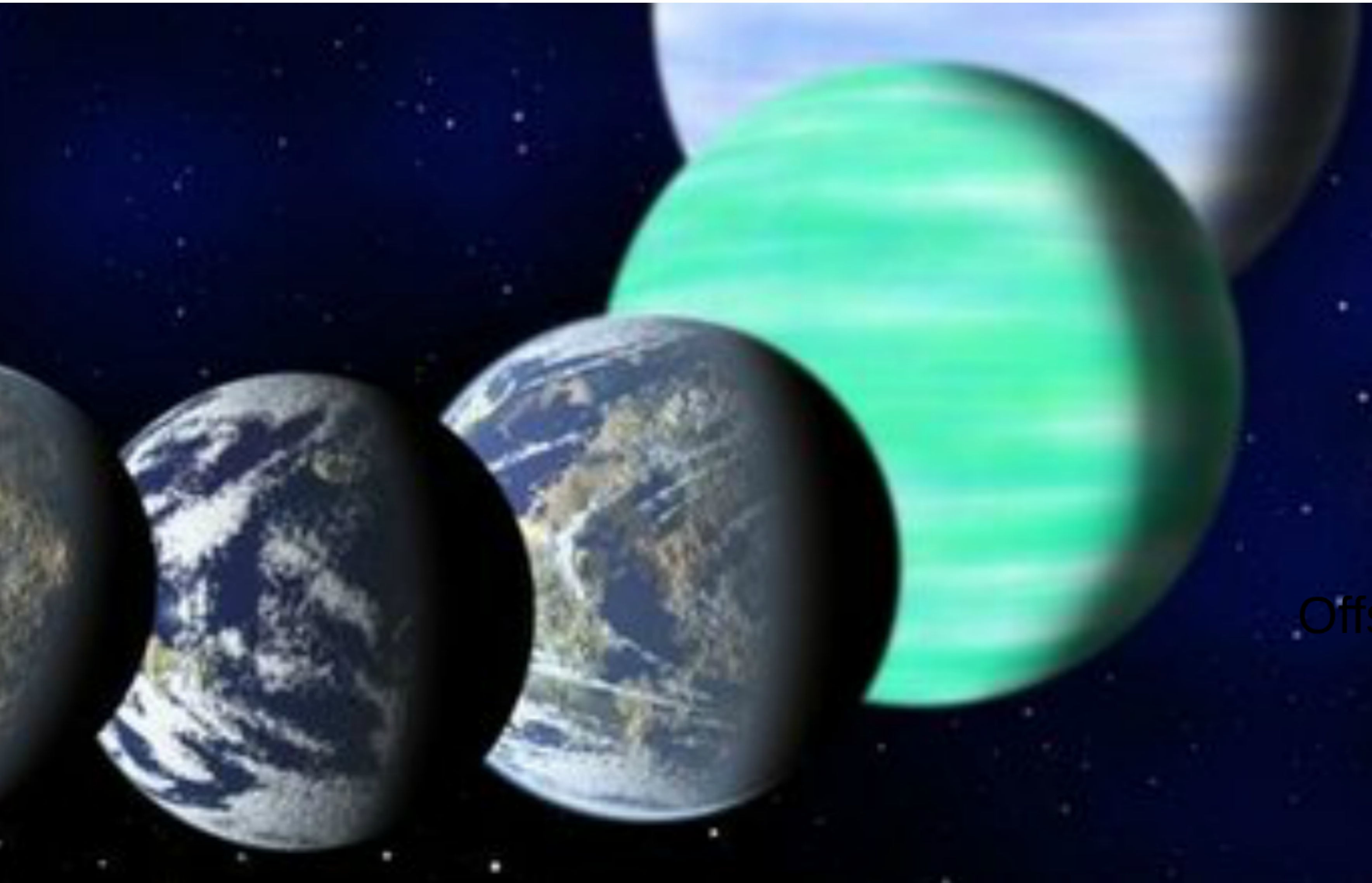
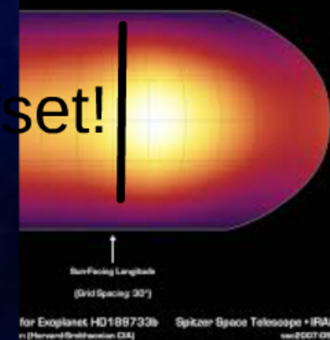


lay-night



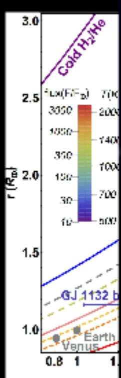


Offset!
(Grid Spacing: 30°)
for Exoplanet HD189733b
Spitzer Space Telescope • IRAC

lay-night

Ra

Ma



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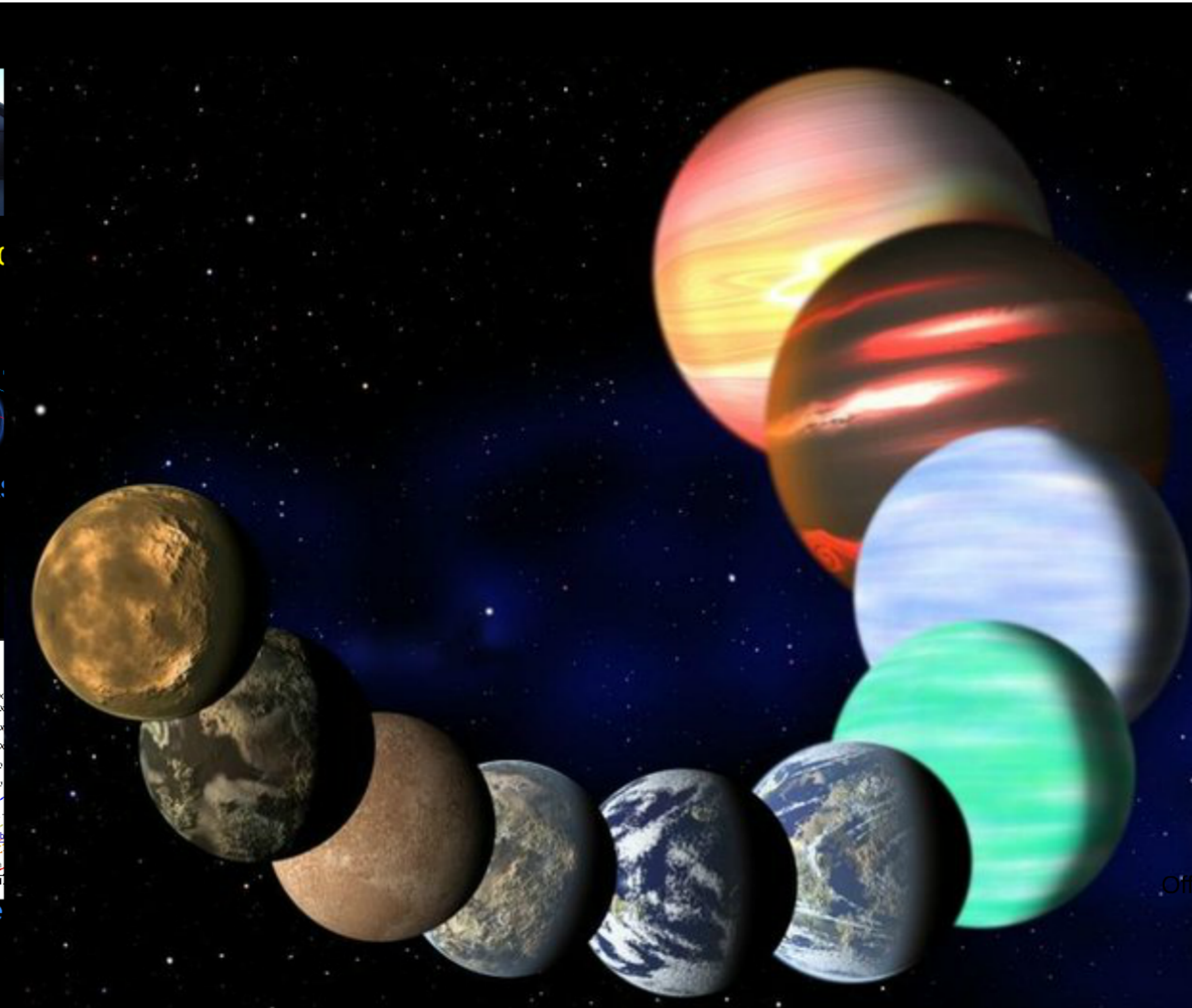

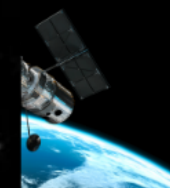

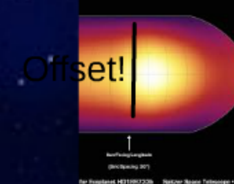

lay-night

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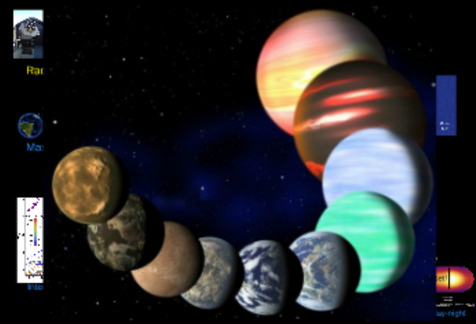


Model Framework

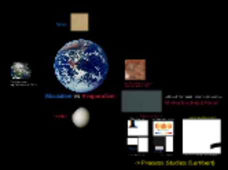
Shared Repository

Code: UM, JULES (land), SOCRATES (RT)
+ Configurations & testing: ROSE

Flexibility, speed, robustness, process testing

SOCRATES: open source (Dehn; Manners).
Hot Jupiters: Amundsen et al. (2014, 2016, 2017)

Terrestrial Planets



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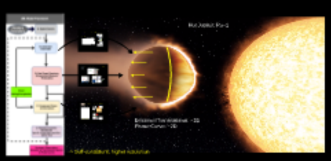

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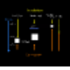

Model Framework

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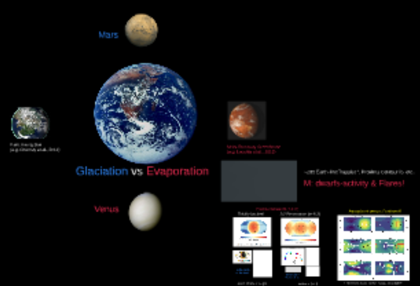

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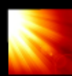

Radiative Transfer: Correlated-K (2-stream), MIE+EMT scattering, Overlap (RO,EE),
Opacity [Exomol, HITEMP, HITRAN] + Spherical geometry

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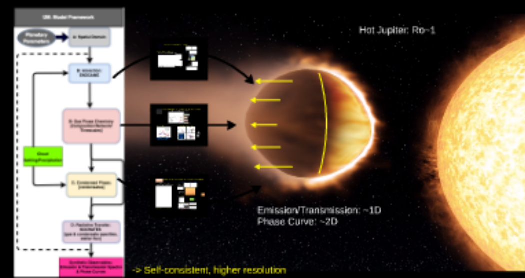

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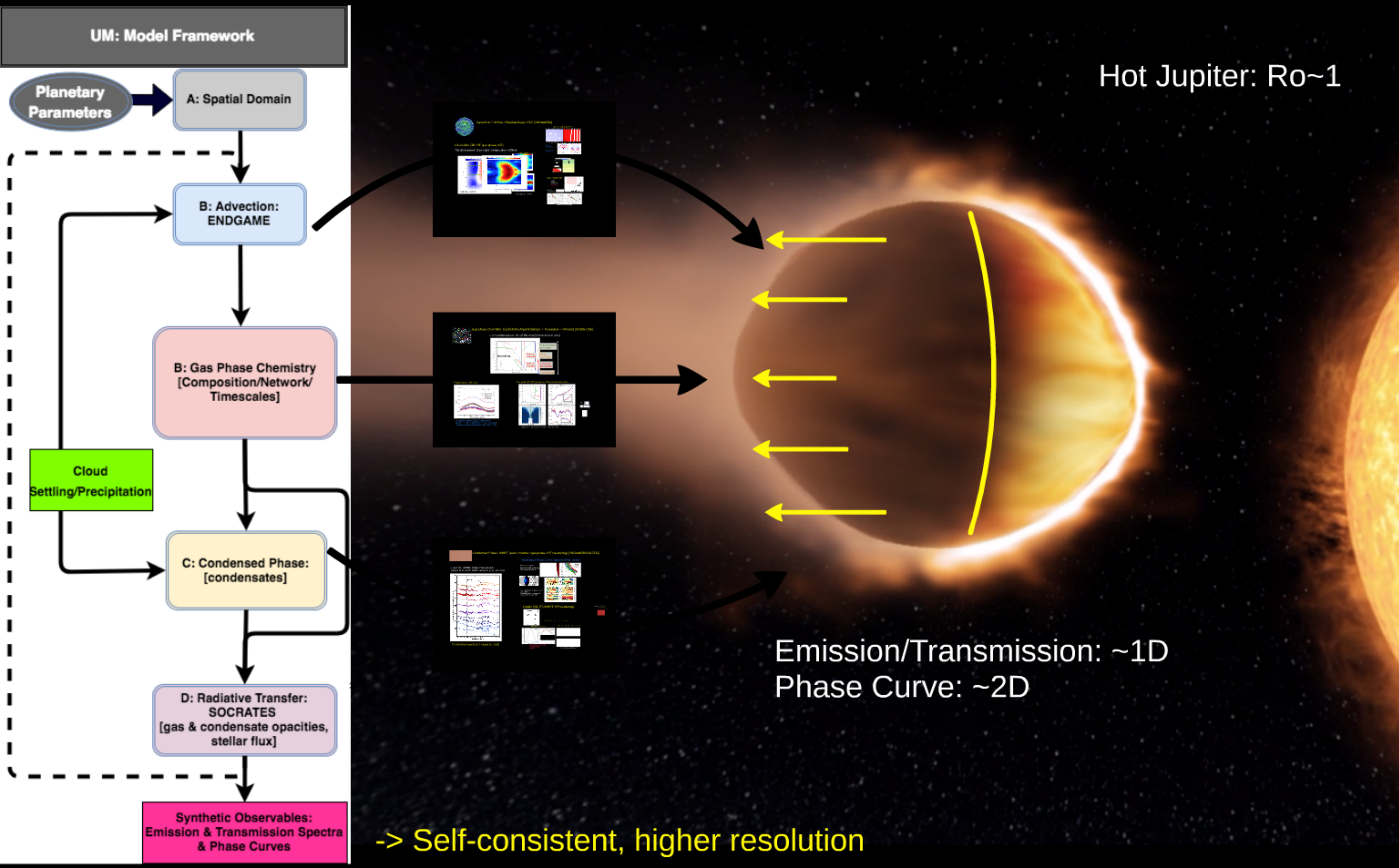
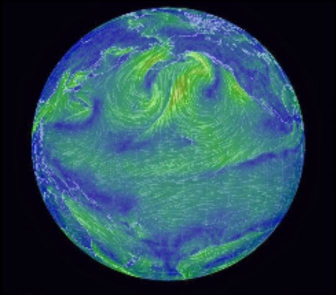
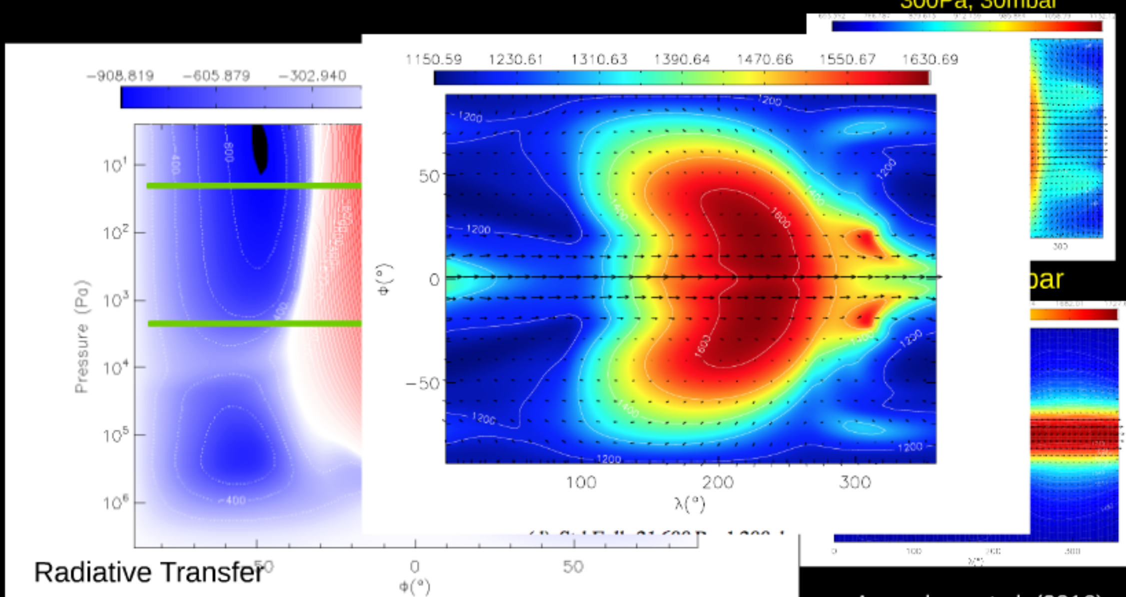

UM: Model Framework
Planetary Parameters
A: Spatial Domain
B: Advection: ENDGAME
B: Gas Phase Chemistry [Composition/Network/ Timescales]
Cloud Settling/Precipitation
C: Condensed Phase: [condensates]
D: Radiative Transfer: SOCRATES [gas & condensate opacities, stellar flux]
Synthetic Observables: Emission & Transmission Spectra & Phase Curves
Hot Jupiter: Ro~1
Emission/Transmission: ~1D
Phase Curve: ~2D
-> Self-consistent, higher resolution



Dynamics: Primitive->Shallow-Deep->Full [HD209458b]

Circulation (3D: RT, gas phase, CE)

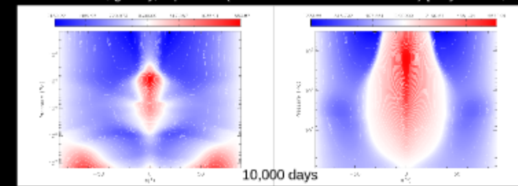
Tidally-Locked: Day-night->Advection->Offset



Amundsen et al. (2016)

Jet: Pumping & Sensitivity

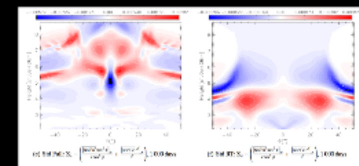
Jet robust: time, gravity, equations (narrows+weakens: Prim-> Full) [Mayne et al, 2014]

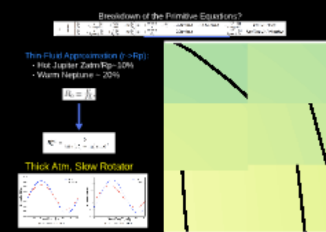


P > 10bar, Equator-Pole +500K.....10,000 days.... [Mayne et al., 2017]

Pumping:
t~1day: Matsuno-Gill
t~100+days: V' ~ w'
[Showman & Polvani, 2011]

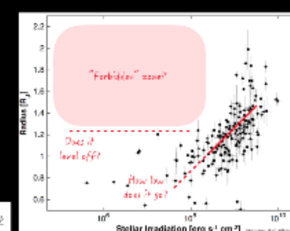
Analysis of dominant modes
[Debras et al., in prep*2]
t>1 < 100 days?





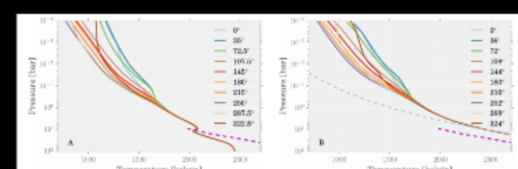
Radius Inflation (F(irr))

- -Tidal
- -Magnetic
- -Circulation



2D ATMO:
Steady, UM:v/w

$$\frac{1}{r^2}\frac{\partial r^2 \rho v_r}{\partial r} = \frac{1}{r\alpha}\frac{\partial \rho u_\phi}{\partial \phi}$$

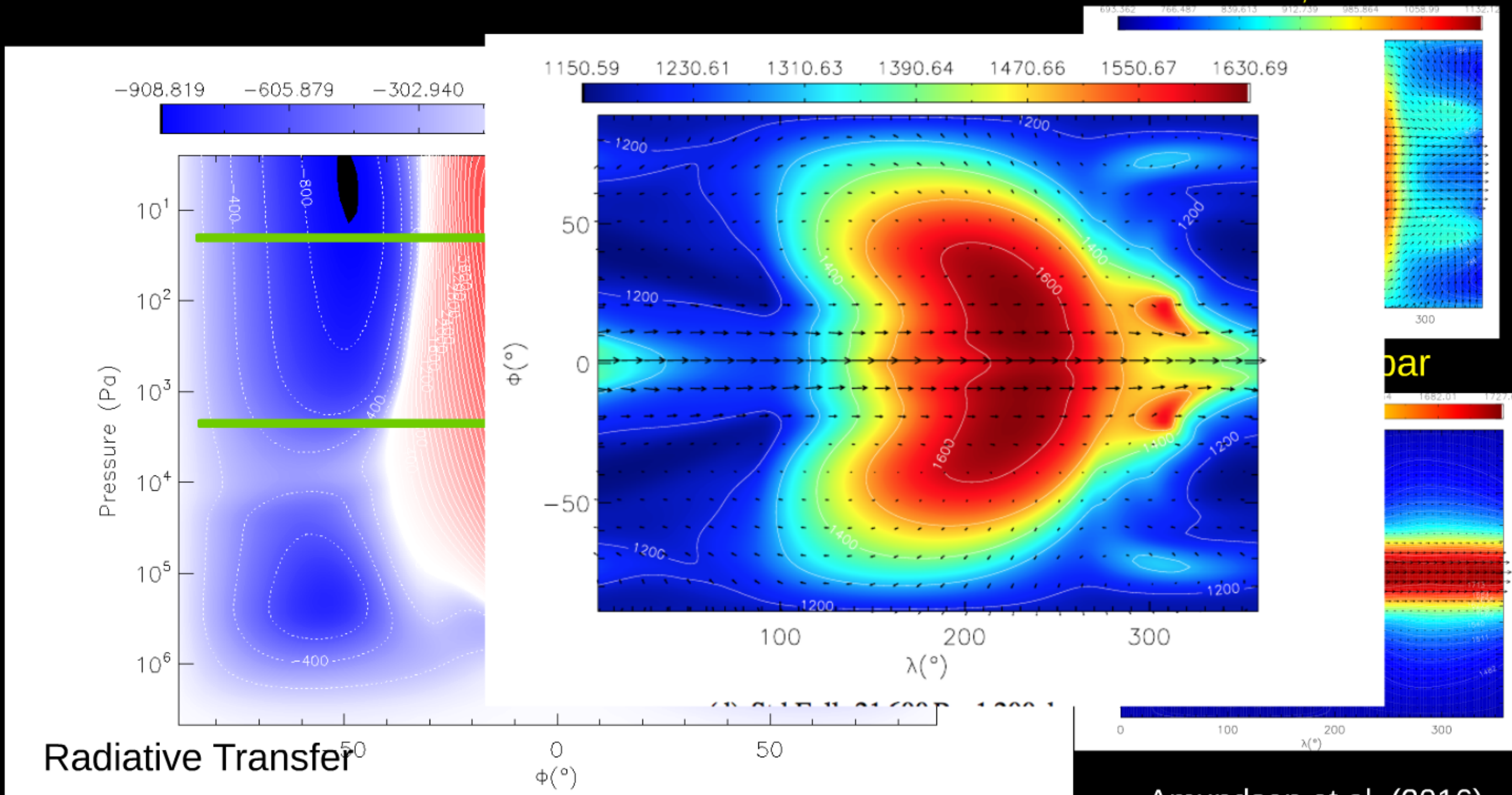


Advection of Theta=Inflation

Circulation (3D: RT, gas phase, CE)

Tidally-Locked: Day-night->Advection->Offset

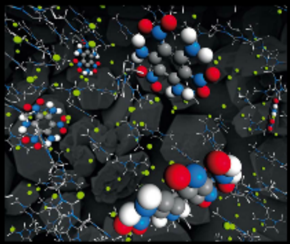
300Pa, 30mbar



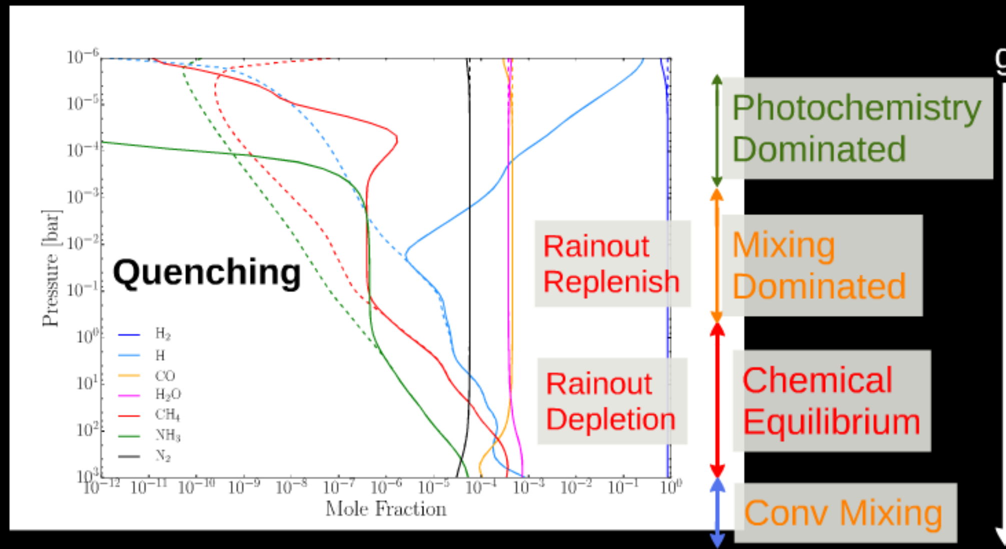
Radiative Transfer

Amundsen et al. (2016)

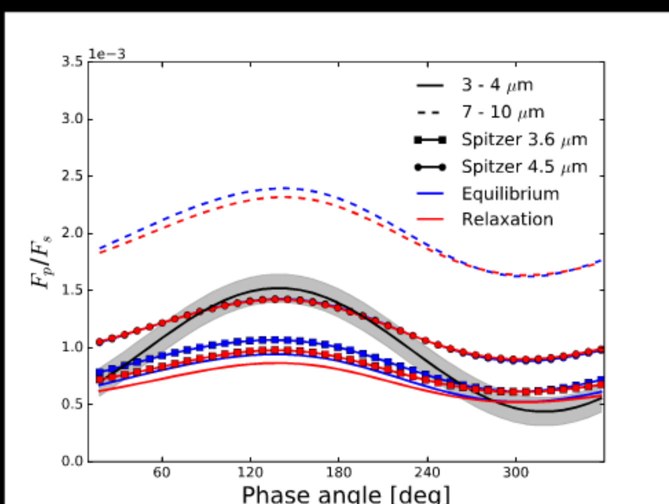
Gas phase Chemistry: Equilibrium (Analytic/Gibbs) -> Relaxation -> Kinetics [HD209+189]



Chemical Abundances: 1D (ATMO, Kzz) [Drummond et al, 2016]

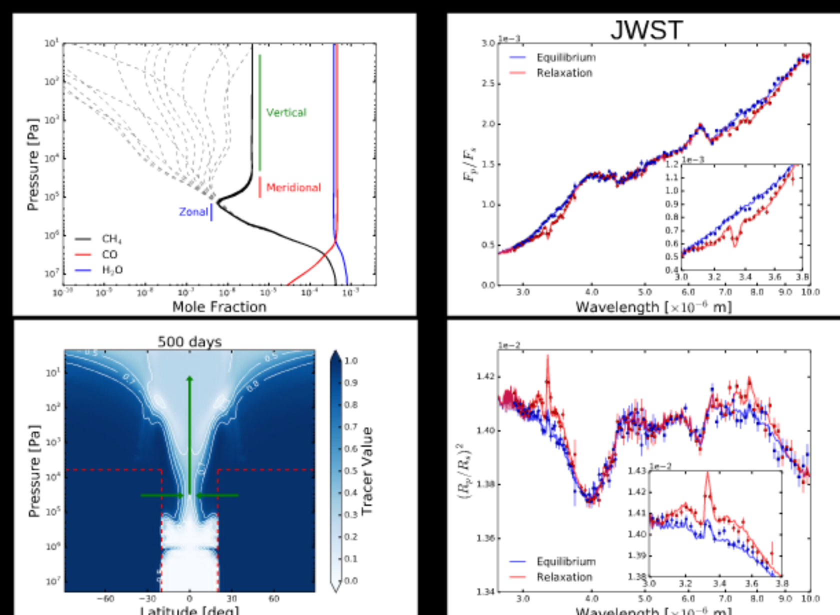


Phase Curve: CH4/CO?

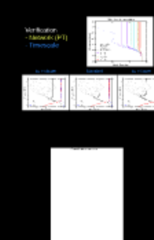


Cooper & Showman (2006): Vertical (3d*)
Agundez et al (2014): Horizontal (2d: chemistry*)
Drummond et al (2018, inprep): BOTH (3d*, RT*)

Chemistry (3D: RT, gas phase, CE+CO/CH4 relaxation)



3D flow sets CH4 abundance (Drummond et al, 2018)



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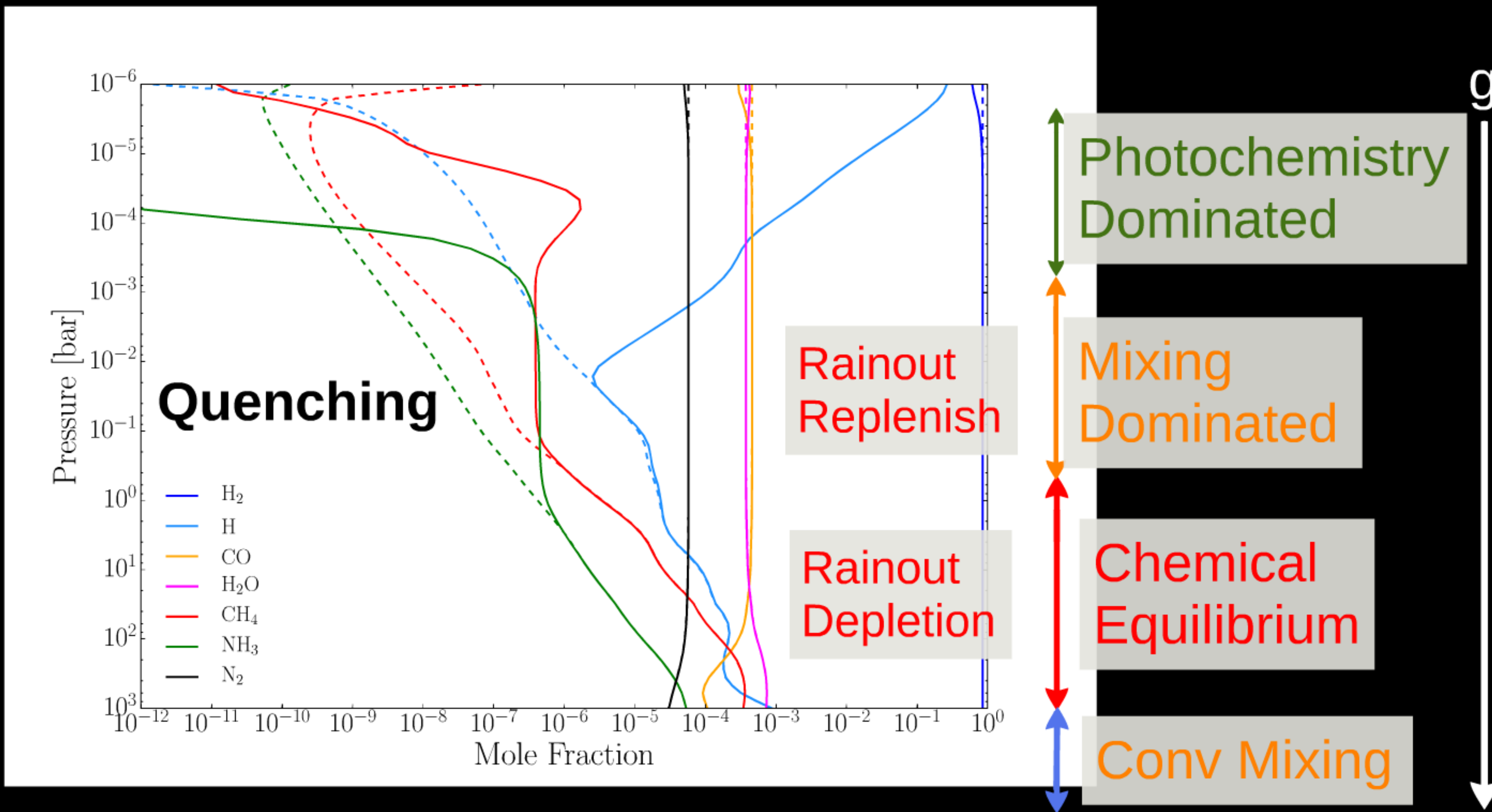

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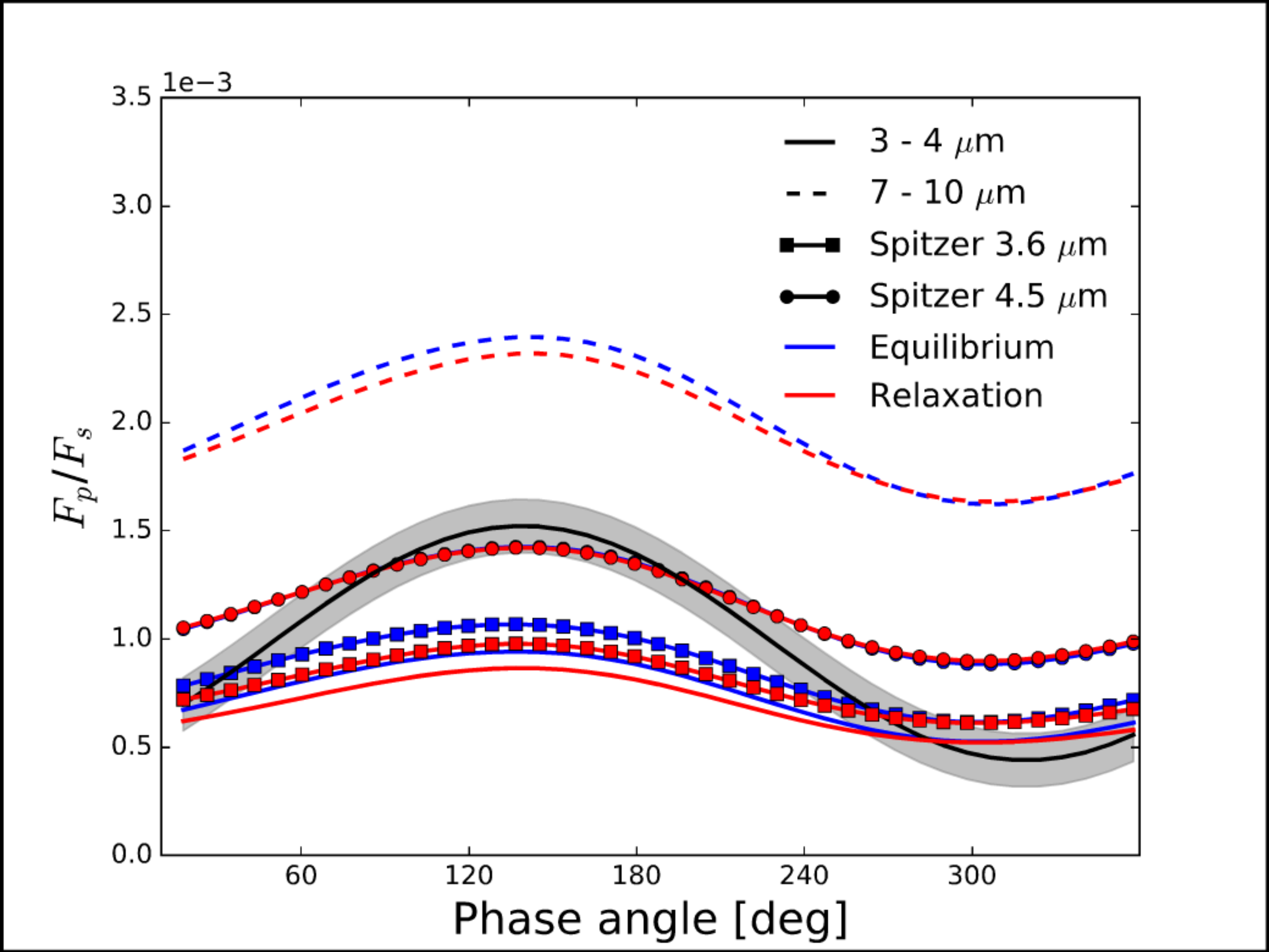

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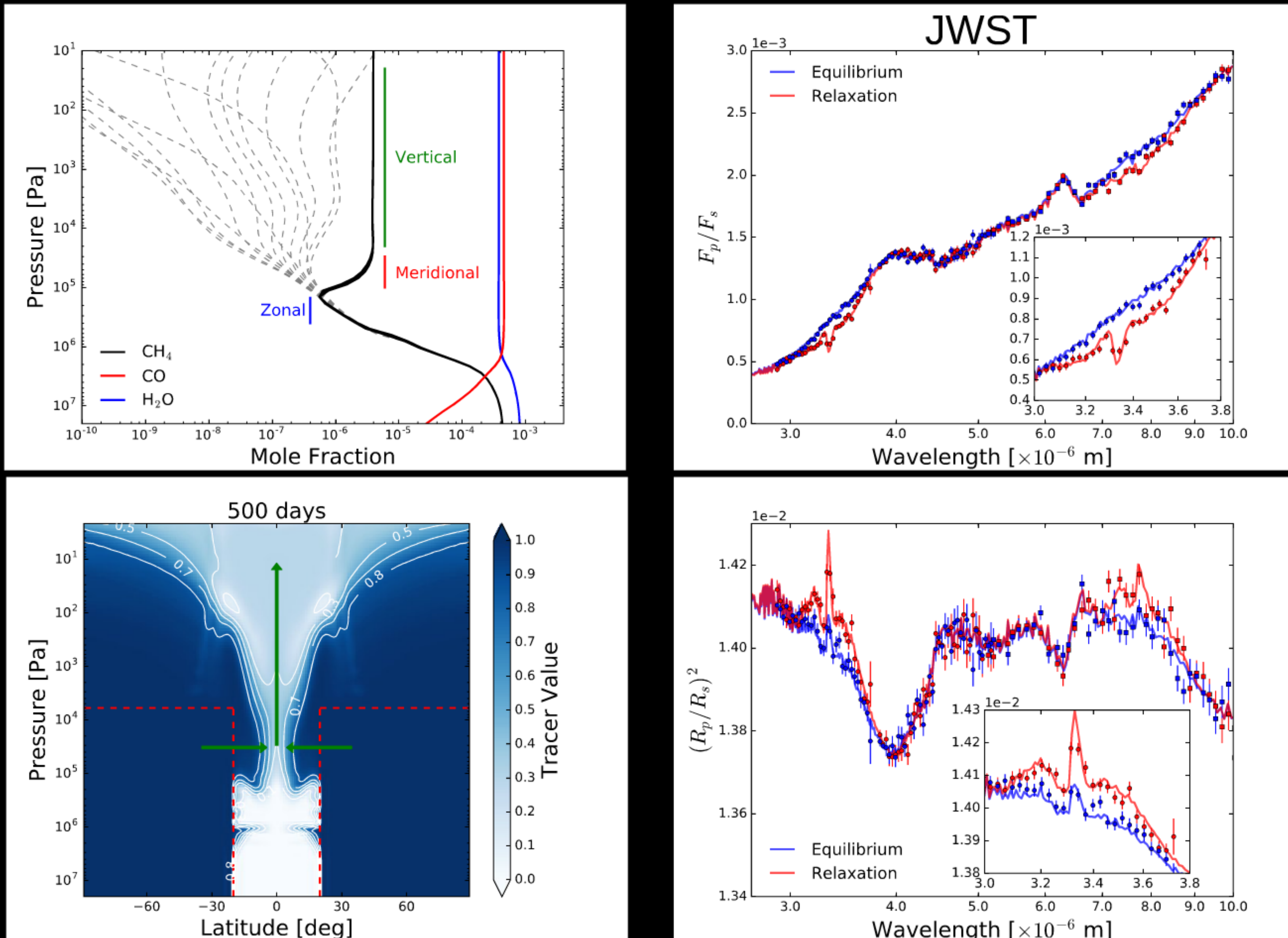

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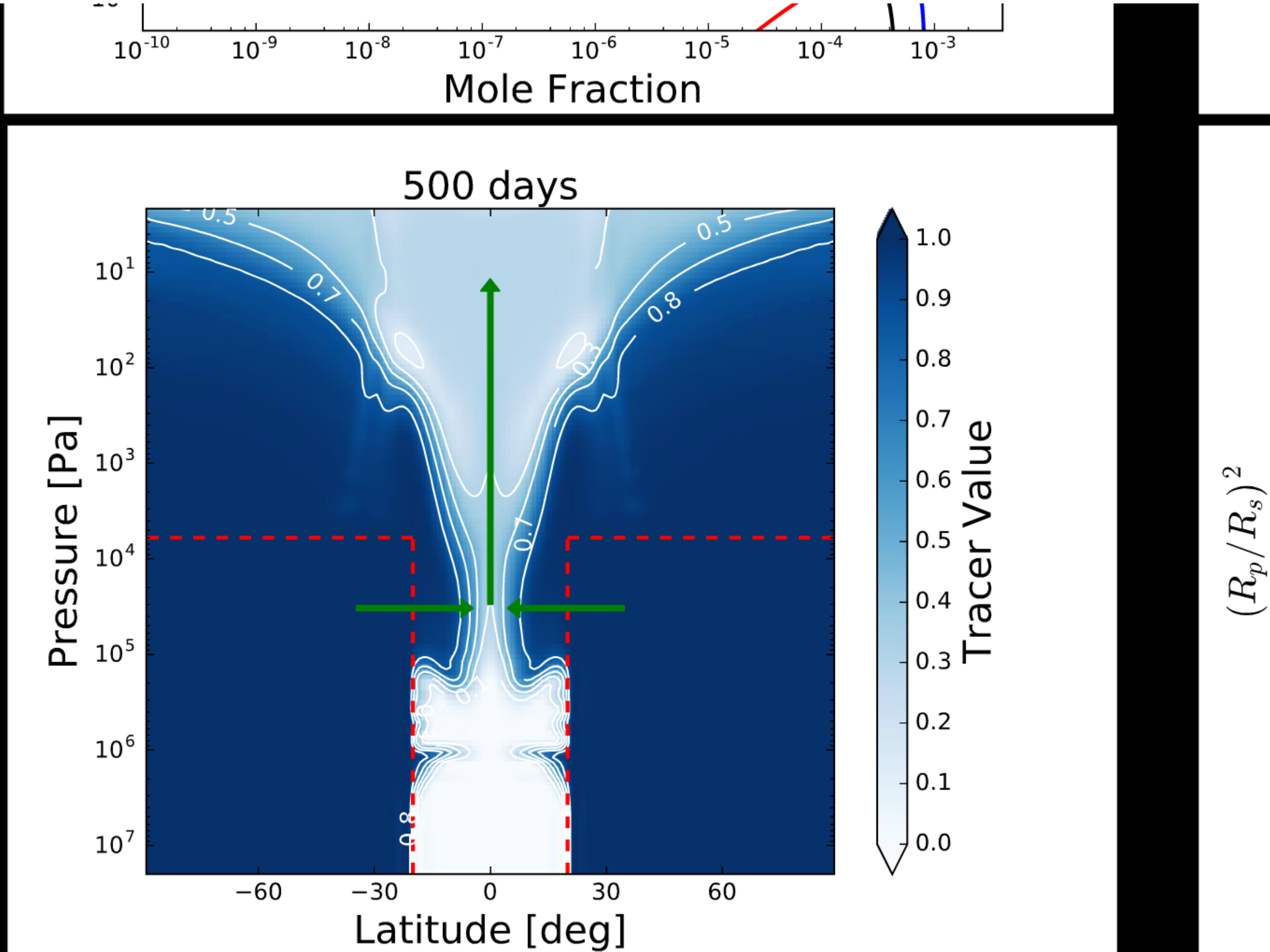

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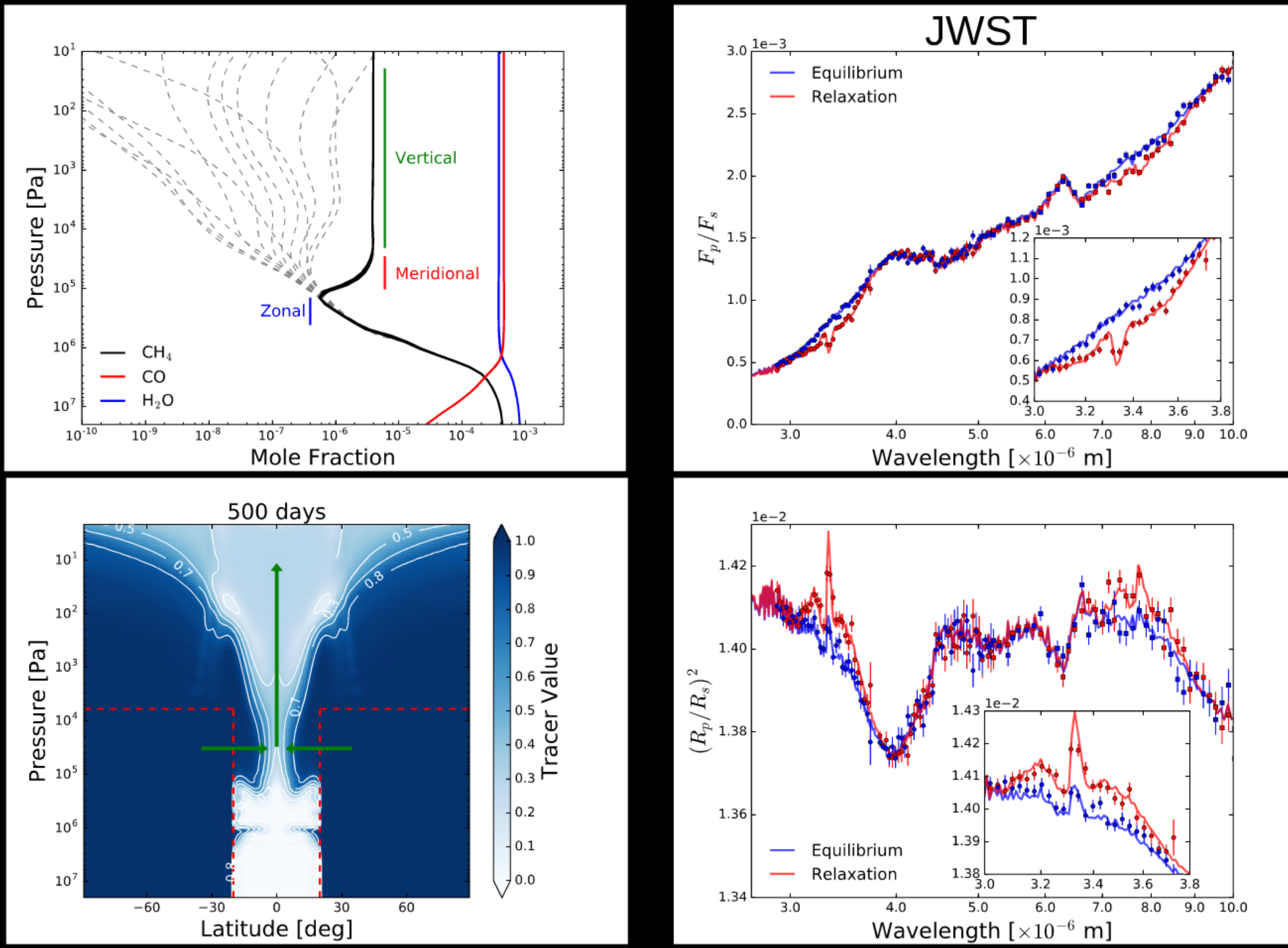

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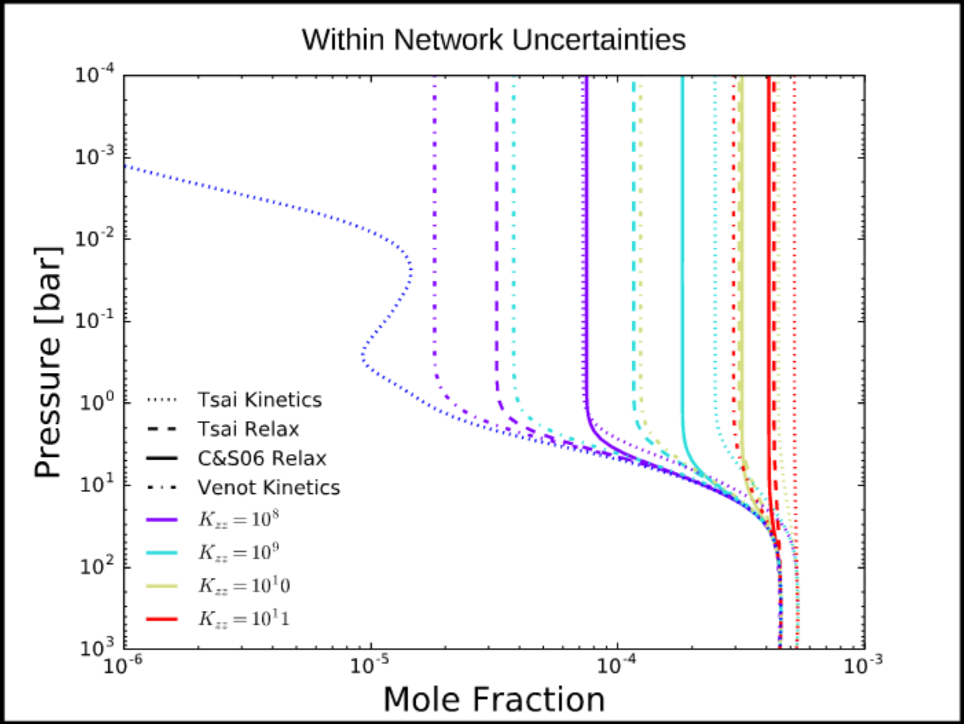
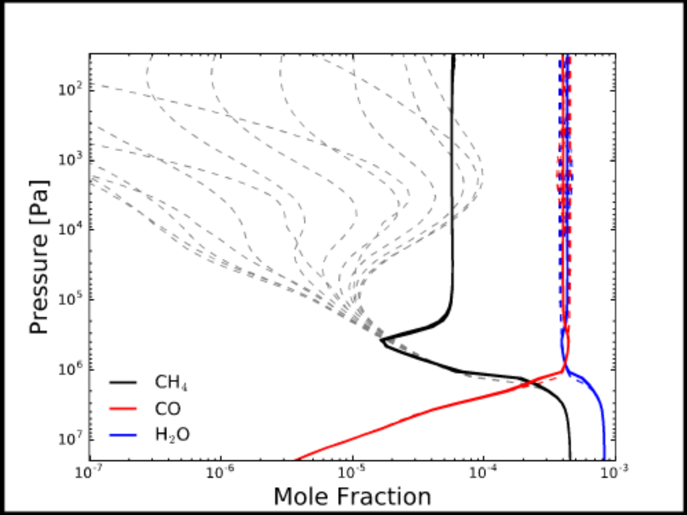
Verification

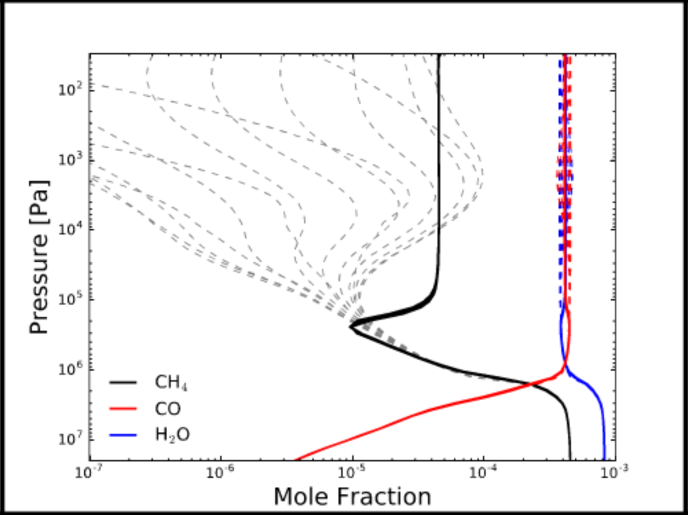
- Network (PT)
- Timescale



10 x slower



Standard



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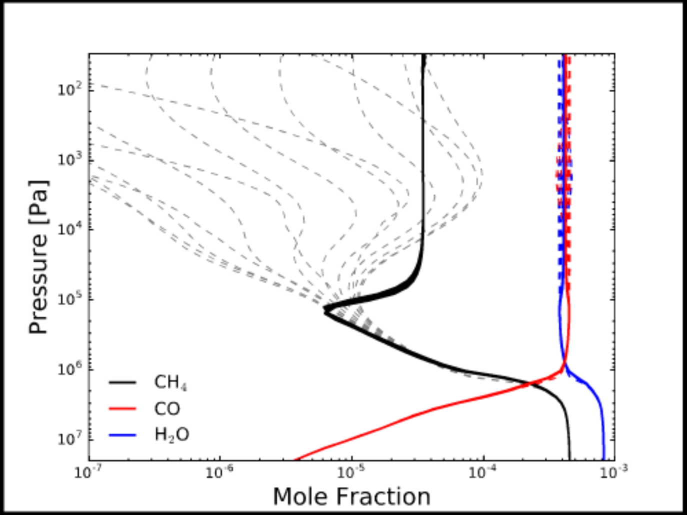
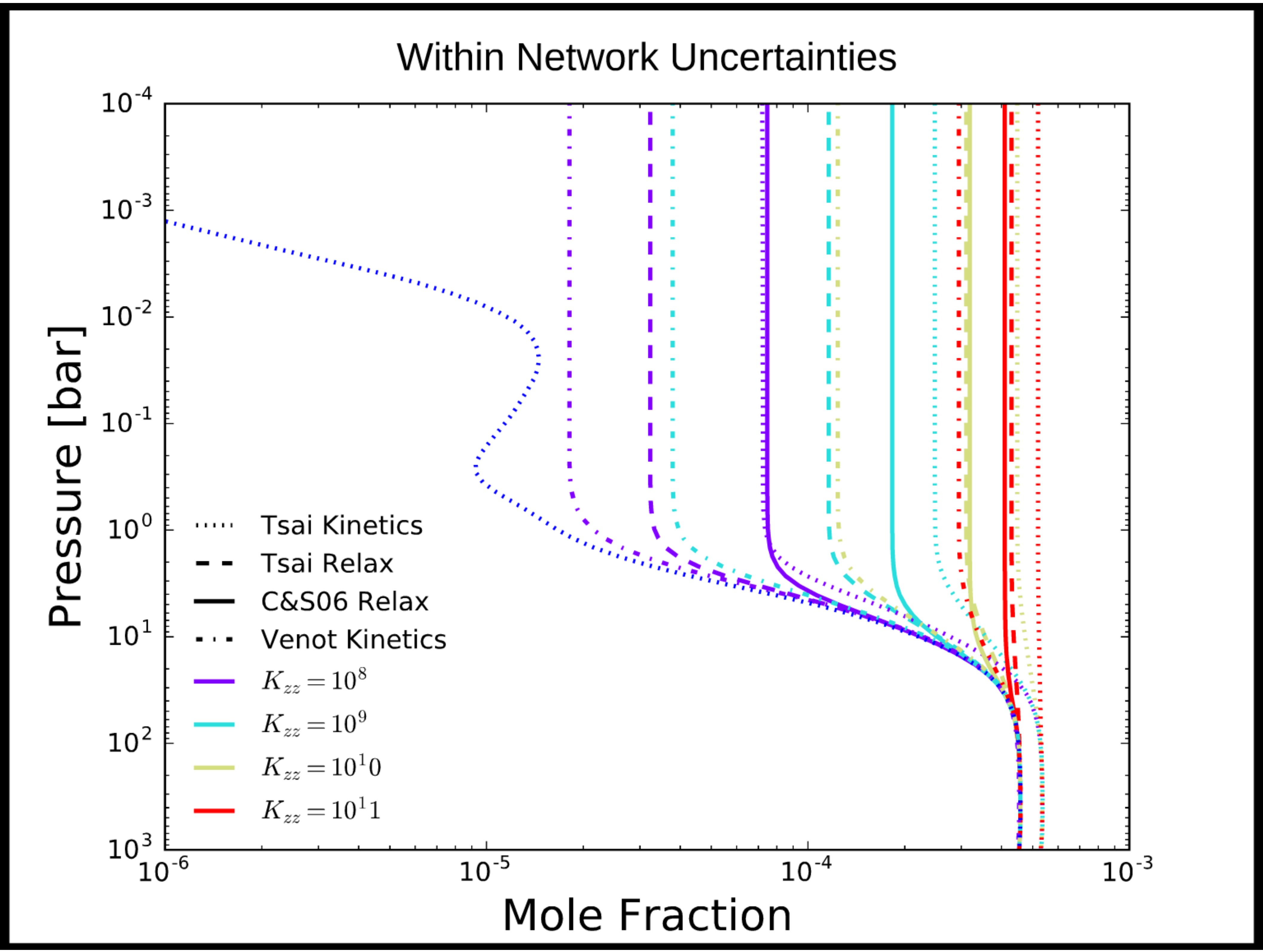
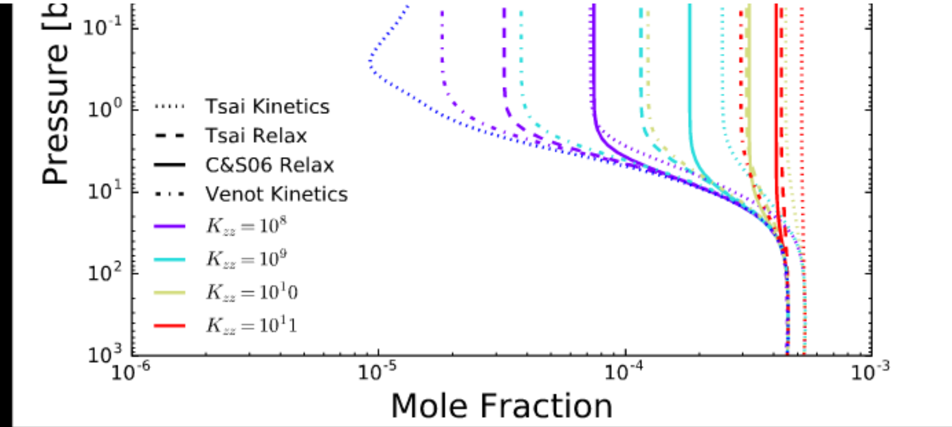


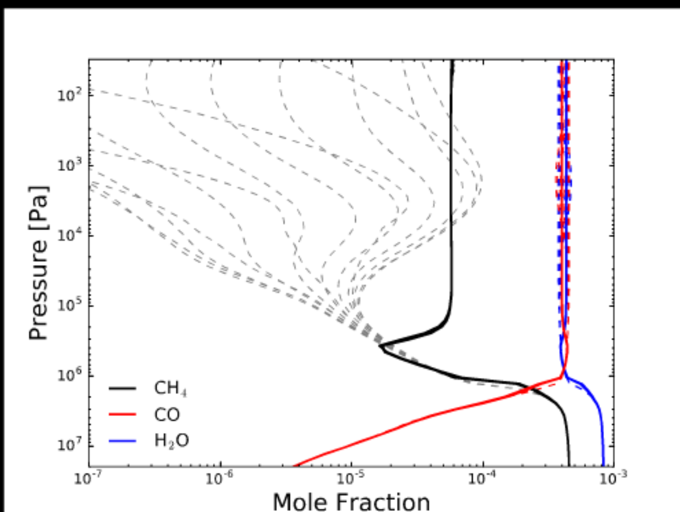


Within Network Uncertainties
Pressure [bar]
Mole Fraction
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
Tsai Kinetics
Tsai Relax
C&S06 Relax
Venot Kinetics
$K_{zz} = 10^8$
$K_{zz} = 10^9$
$K_{zz} = 10^10$
$K_{zz} = 10^11$

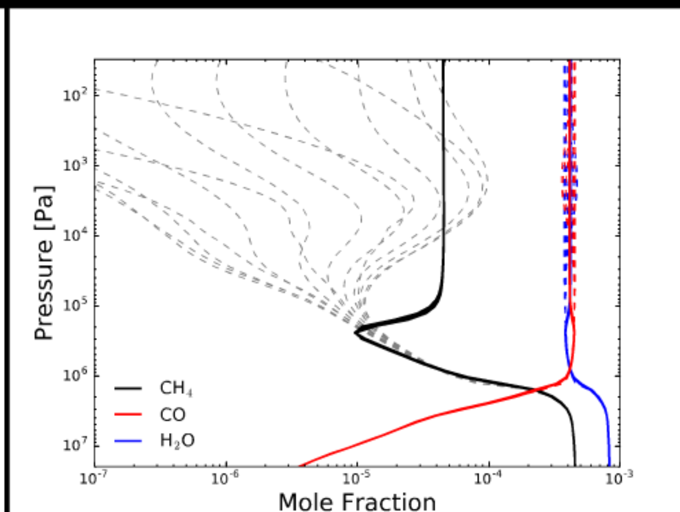
- Network (PT)
- Timescale



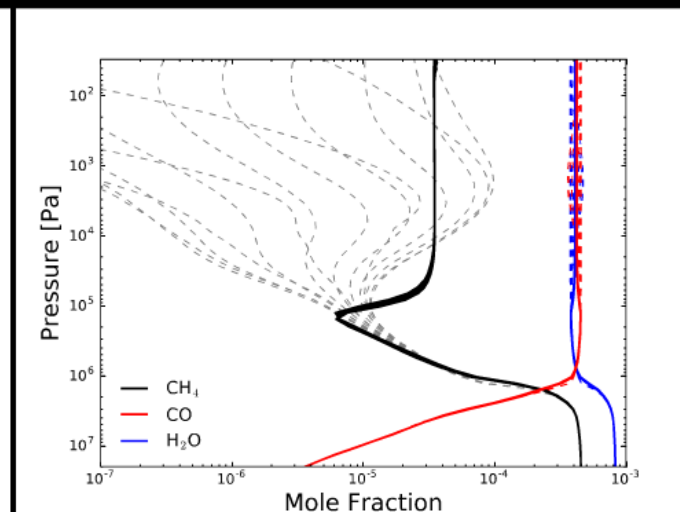
10 x slower

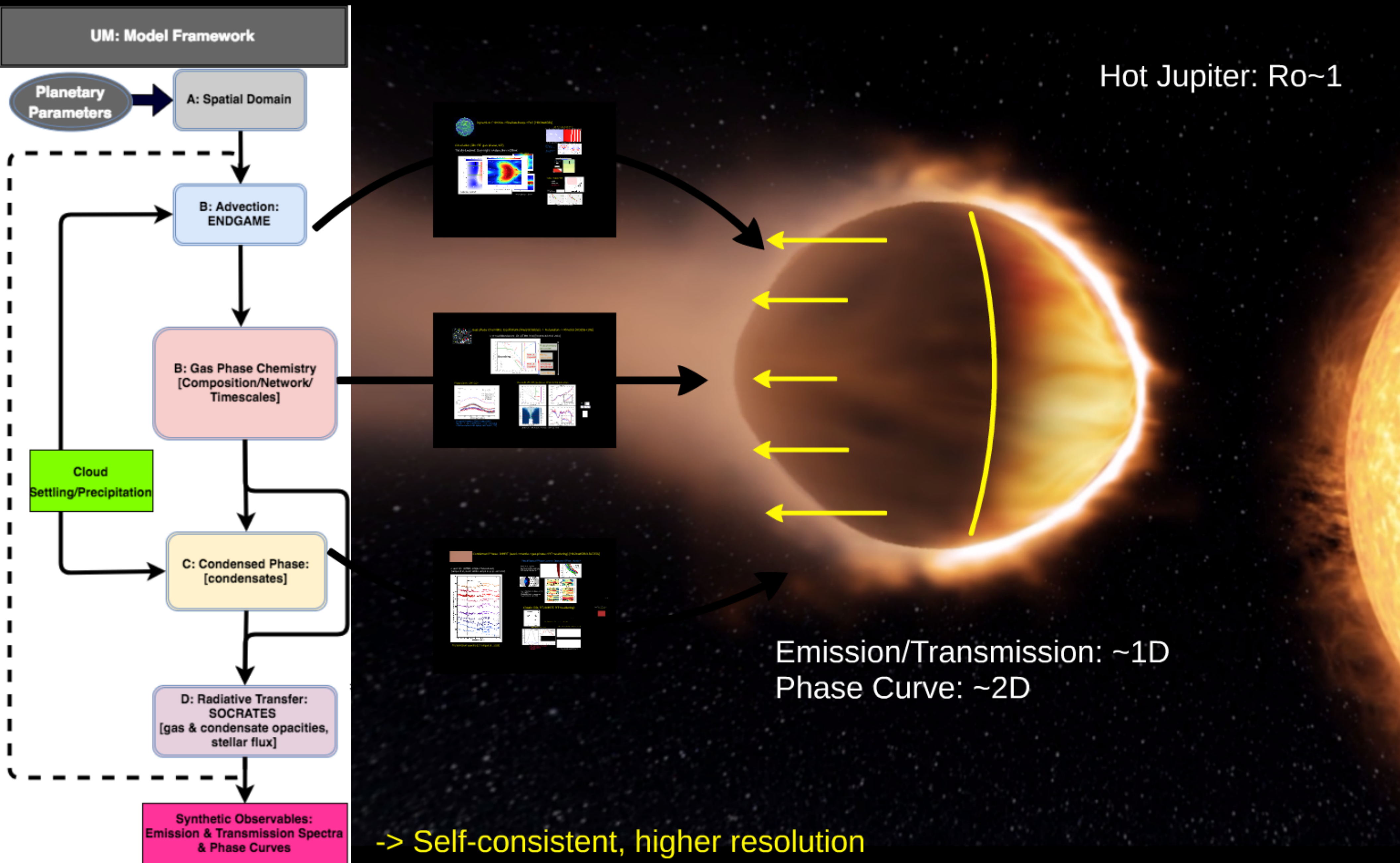


Standard



10 x faster




UM: Model Framework
Planetary Parameters
A: Spatial Domain
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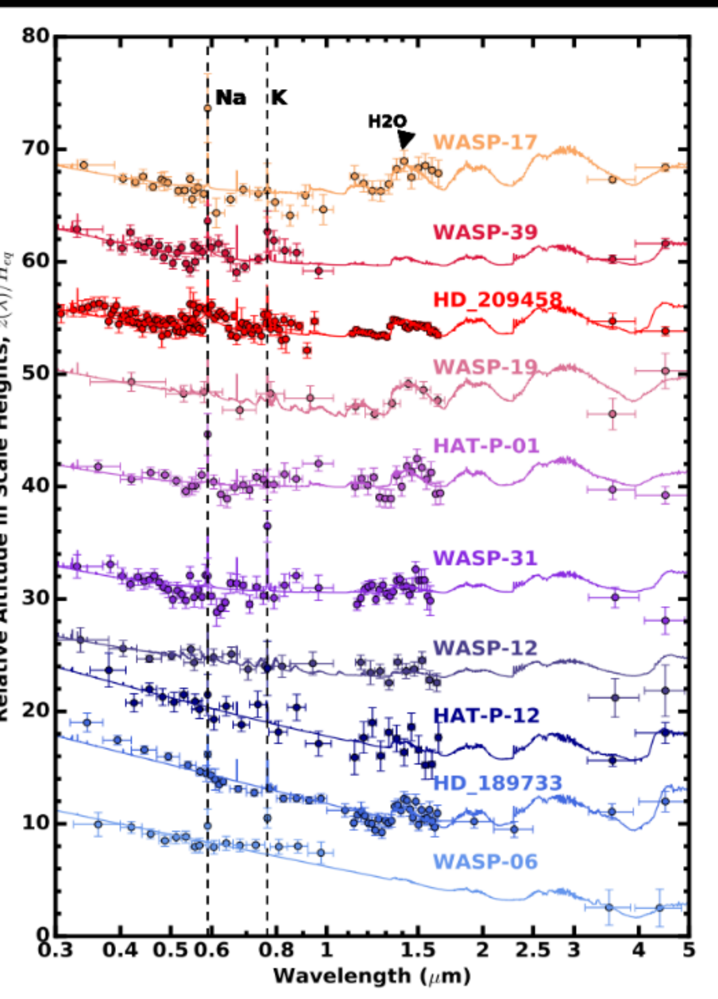
Cloud Settling/Precipitation
C: Condensed Phase: [condensates]
D: Radiative Transfer: SOCRATES [gas & condensate opacities, stellar flux]
Synthetic Observables: Emission & Transmission Spectra & Phase Curves
Hot Jupiter: Ro~1
Emission/Transmission: ~1D
Phase Curve: ~2D
-> Self-consistent, higher resolution

Condensed Phase: DIHRT (seed->mantle->gas phase->RT+scattering) [HD209458b/18973

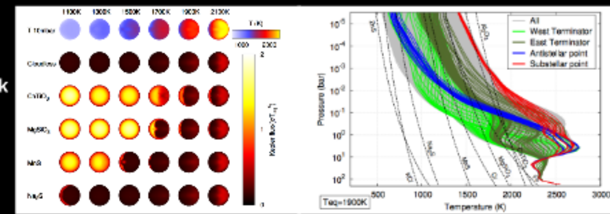
oud: 1D (ATMO, simple Haze+cloud)
Goyal et al, 2018: GRID, Goyal in prep, Generic]

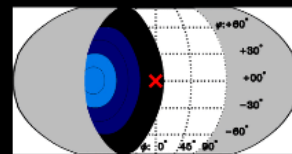


Transmission Spectra (c.f. Sing et al., 2016)

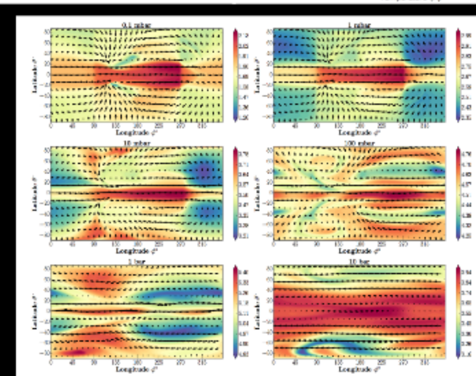
Visual/Optical Phase Curves: Opposite Offset, clouds?

Parmentier et al. (2016):
3D: Gas phase, CE, no cloud->
Diagnostic clouds: no feedback
Assumed Size distribution

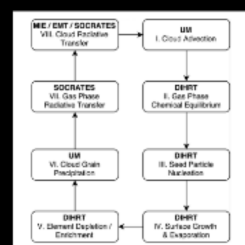


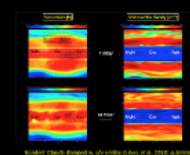


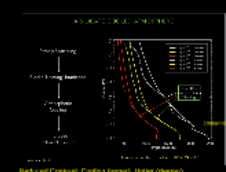
Lee, Dobbs-Dixon, Helling et al. (2016)
3D+(DIHRT):
Prognostic cloud: no scattering
Mean Particle size (=F(T,P))



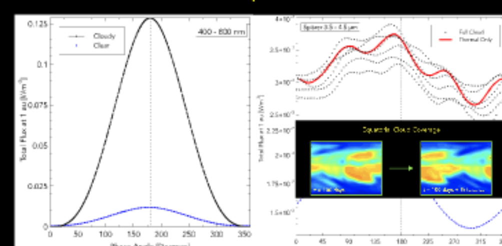
Clouds (3D, RT, DIHRT, RT+scattering)





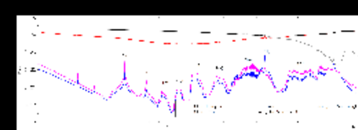


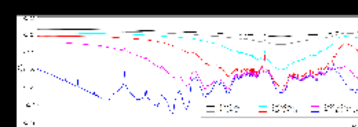
Visual & IR phase curves



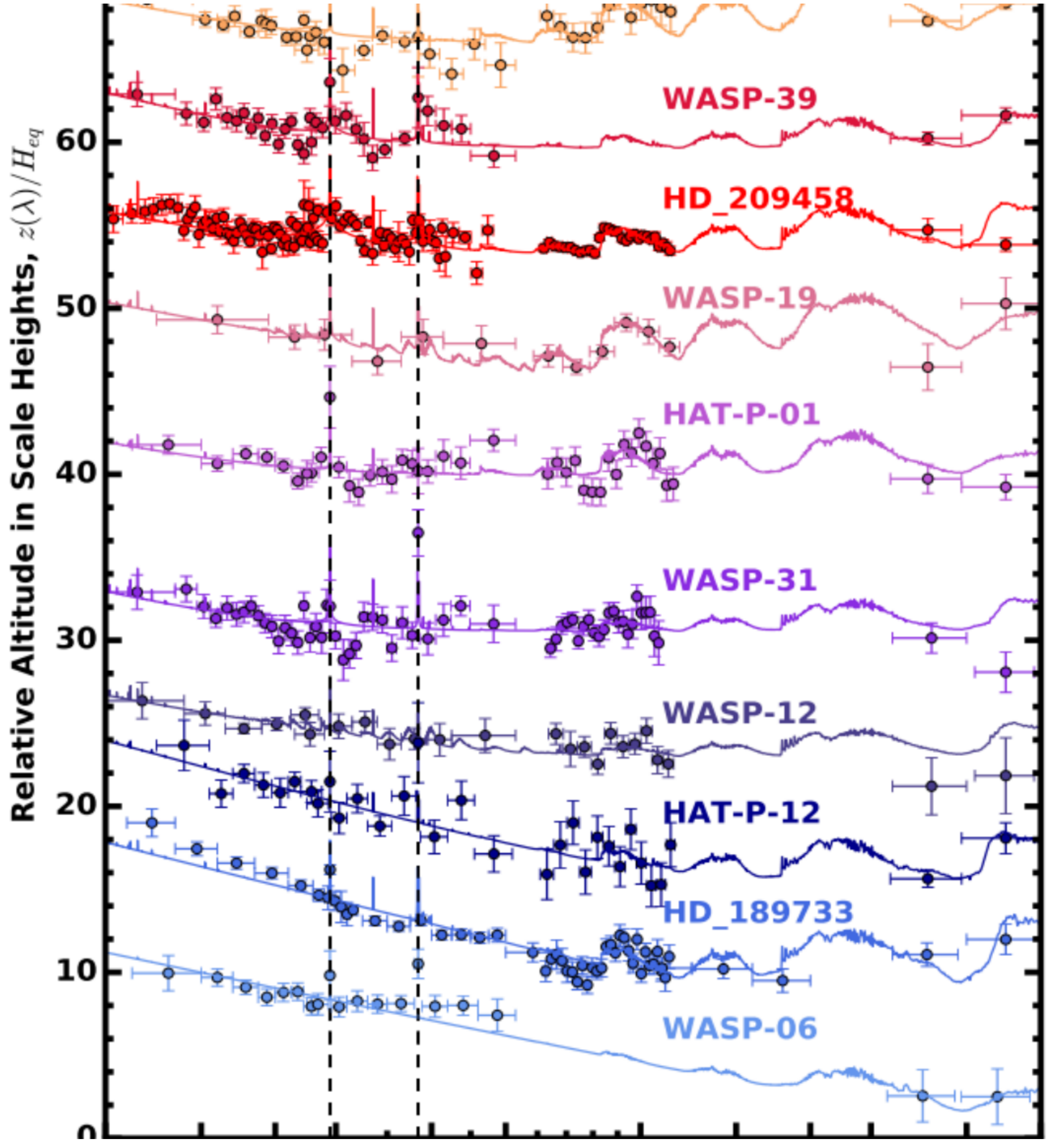
-> RT: gas phase CE analytic
-> Limited species
-> Shocks

Transmission Spectra: Physical Insight + JWST [Lines et al., submitted]





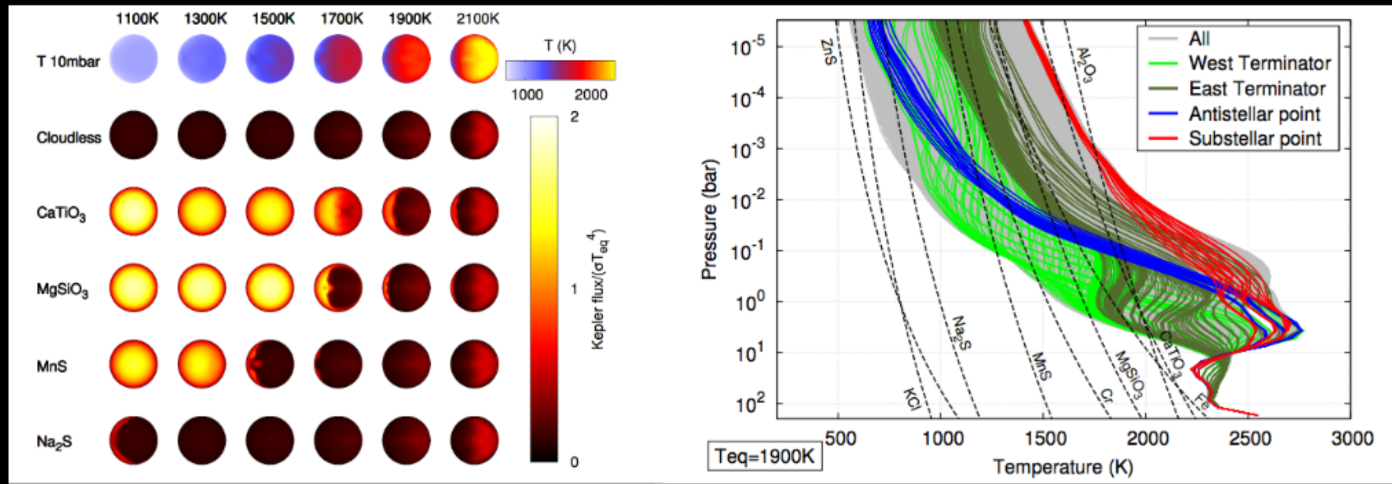
Too cloudy, everywhere!!!!

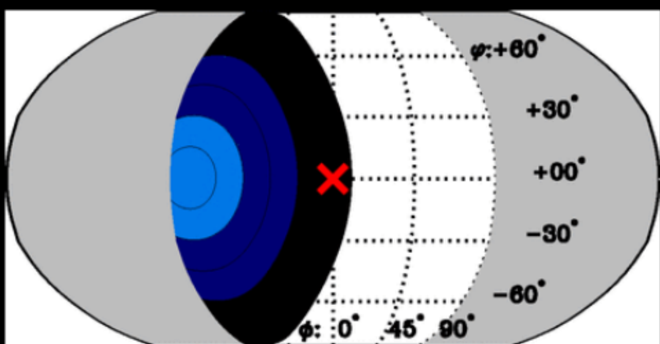


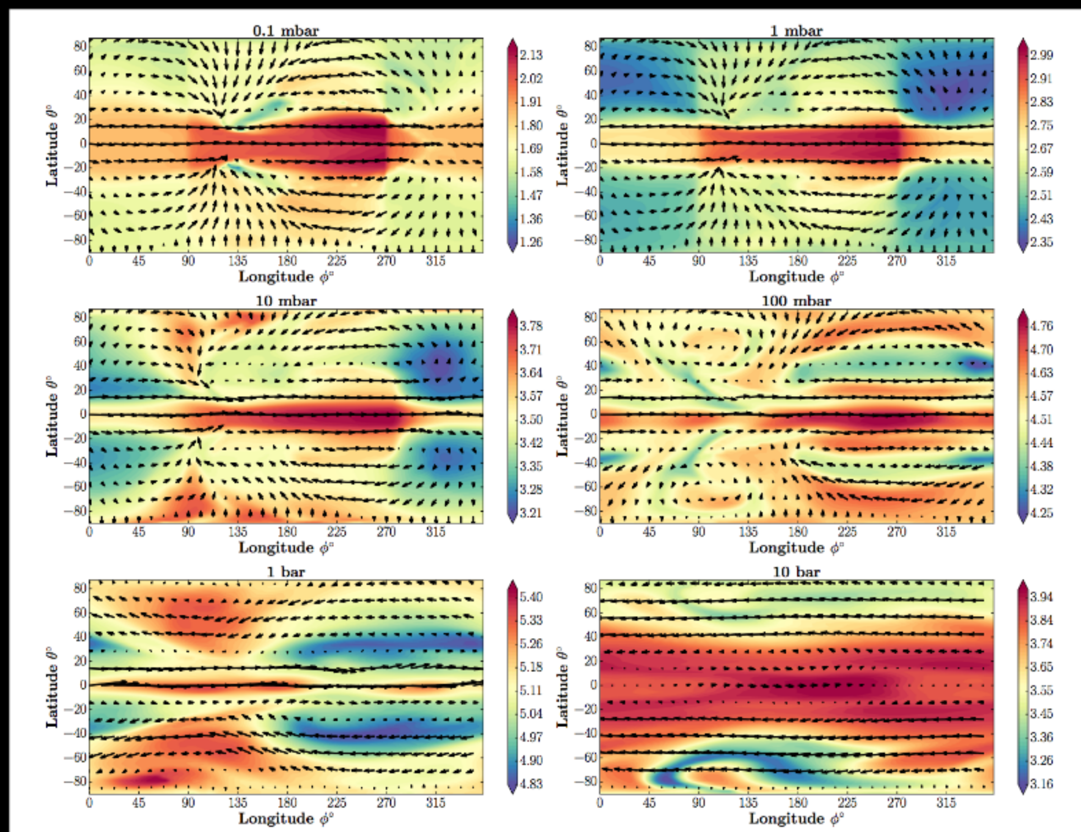
WASP-39
HD_209458
WASP-19
HAT-P-01
WASP-31
WASP-12
HAT-P-12
HD_189733
WASP-06
Relative Altitude in Scale Heights, $z(\lambda)/H_{eq}$
0
10
20
30
40
50
60

Visual/Optical Phase Curves: Opposite Offset, clouds?

Parmentier et al. (2016):
3D: Gas phase, CE, no cloud->
Diagnostic clouds: no feedback
Assumed Size distribution







Lee, Dobbs-Dixon, Helling et al. (2016)
3D+(DIHRT):
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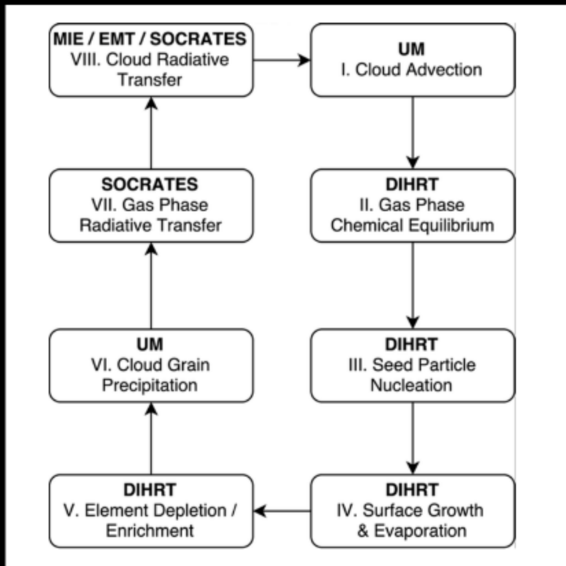
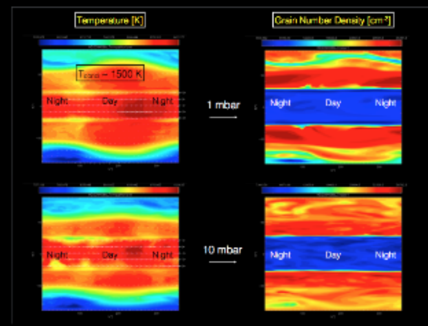
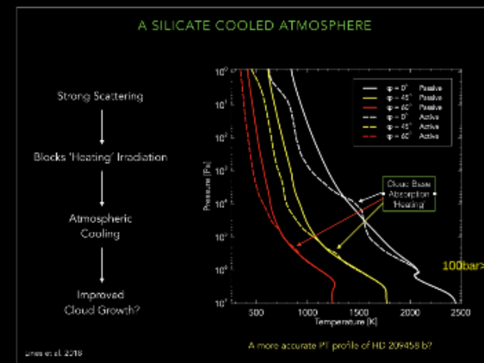
Mean Particle size (=F(T,P))

Clouds (3D, RT, DIHRT, RT+scattering)





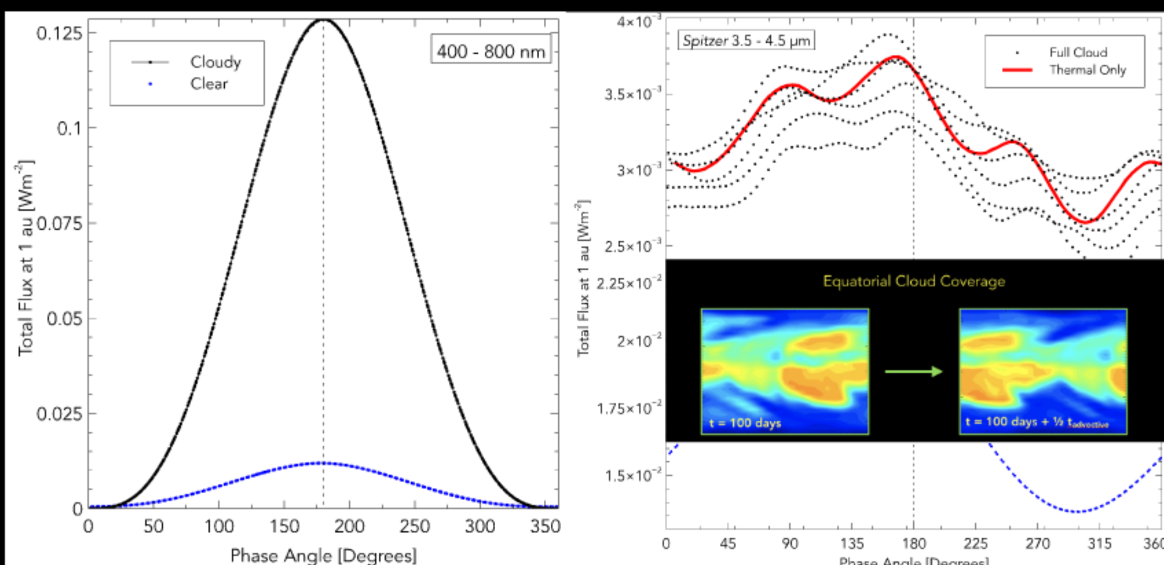
'Banded' Clouds damped w, u/v similar (Lines et al, 2018; submitted)

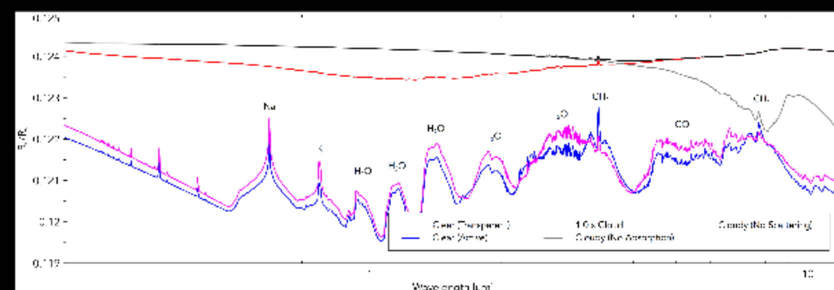


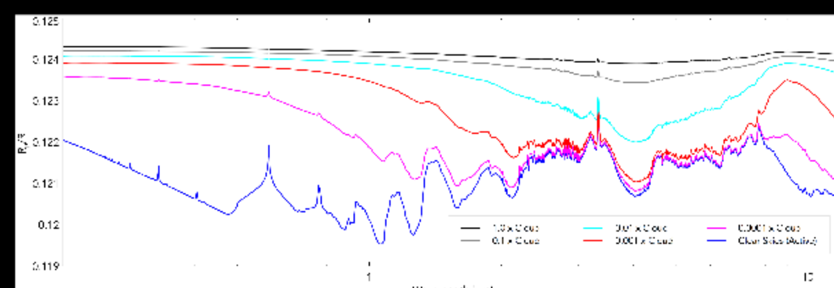
Reduced Contrast: Cooling (upper), Hotter (deeper)

Transmission Spectra: Physical Insight + JWST [Lines et al., submitted]

Visual & IR phase curves

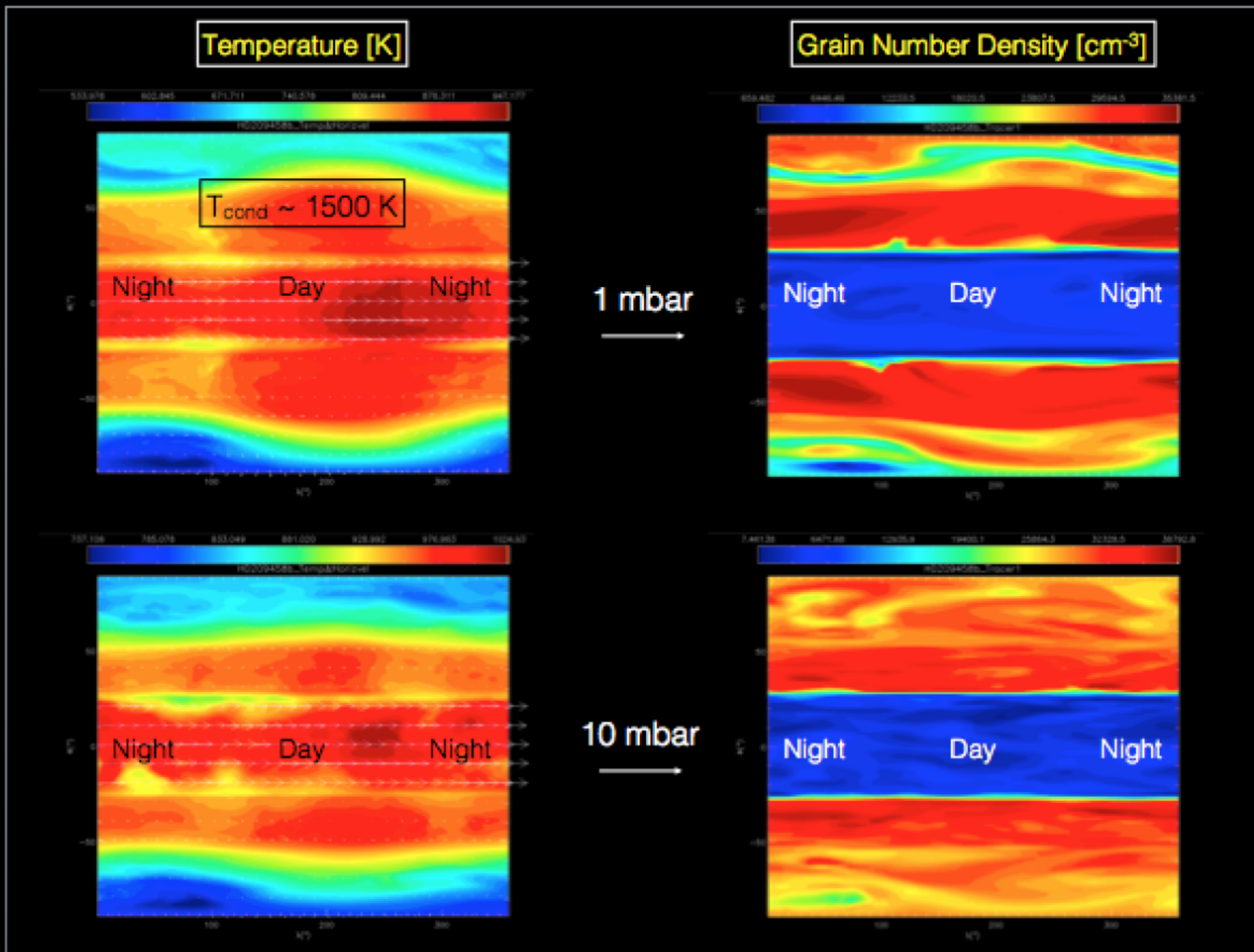






-> RT: gas phase CE analytic
-> Limited species
-> Shocks

Too cloudy, everywhere!!!!



'Banded' Clouds damped w, u/v similar (Lines et al, 2018; submitted)

A SILICATE COOLED ATMOSPHERE

Strong Scattering

↓

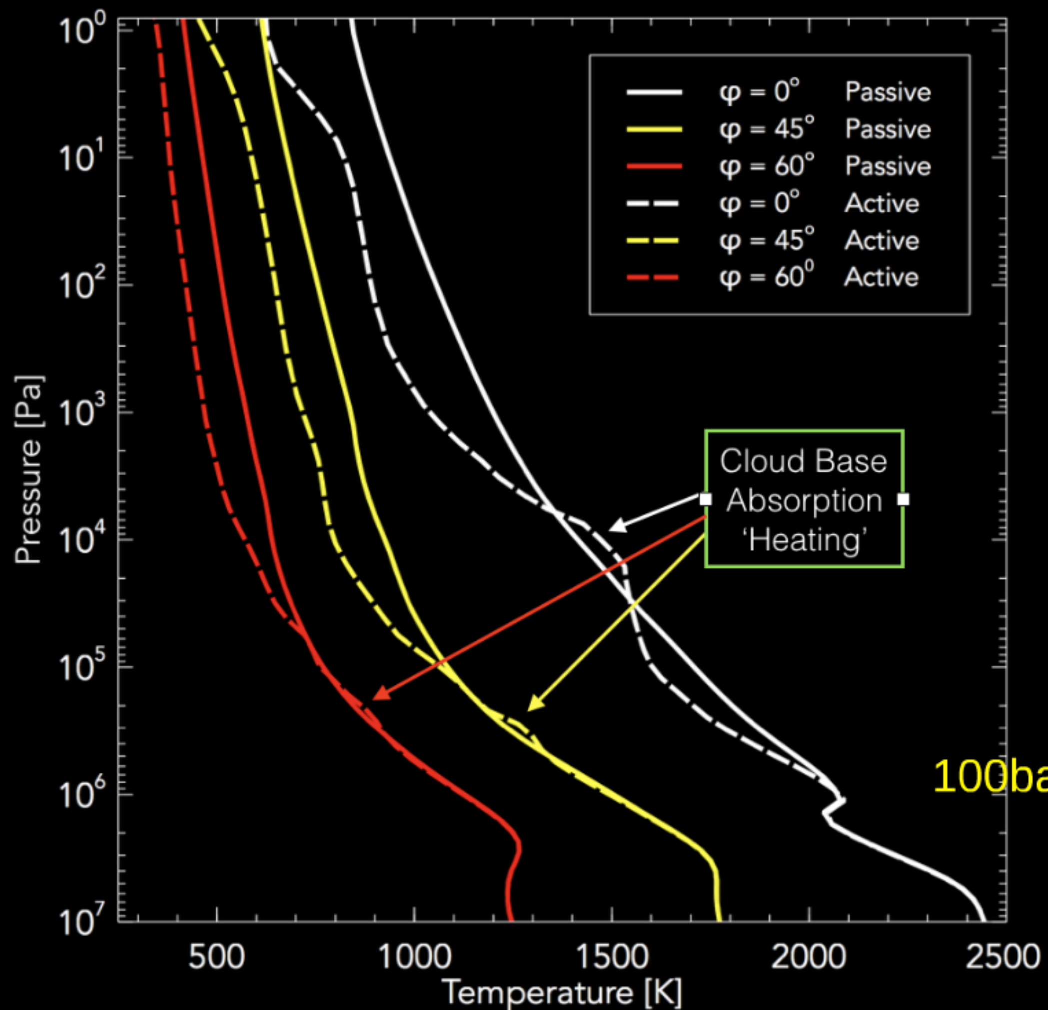
Blocks 'Heating' Irradiation

↓

Atmospheric Cooling

↓

Improved Cloud Growth?



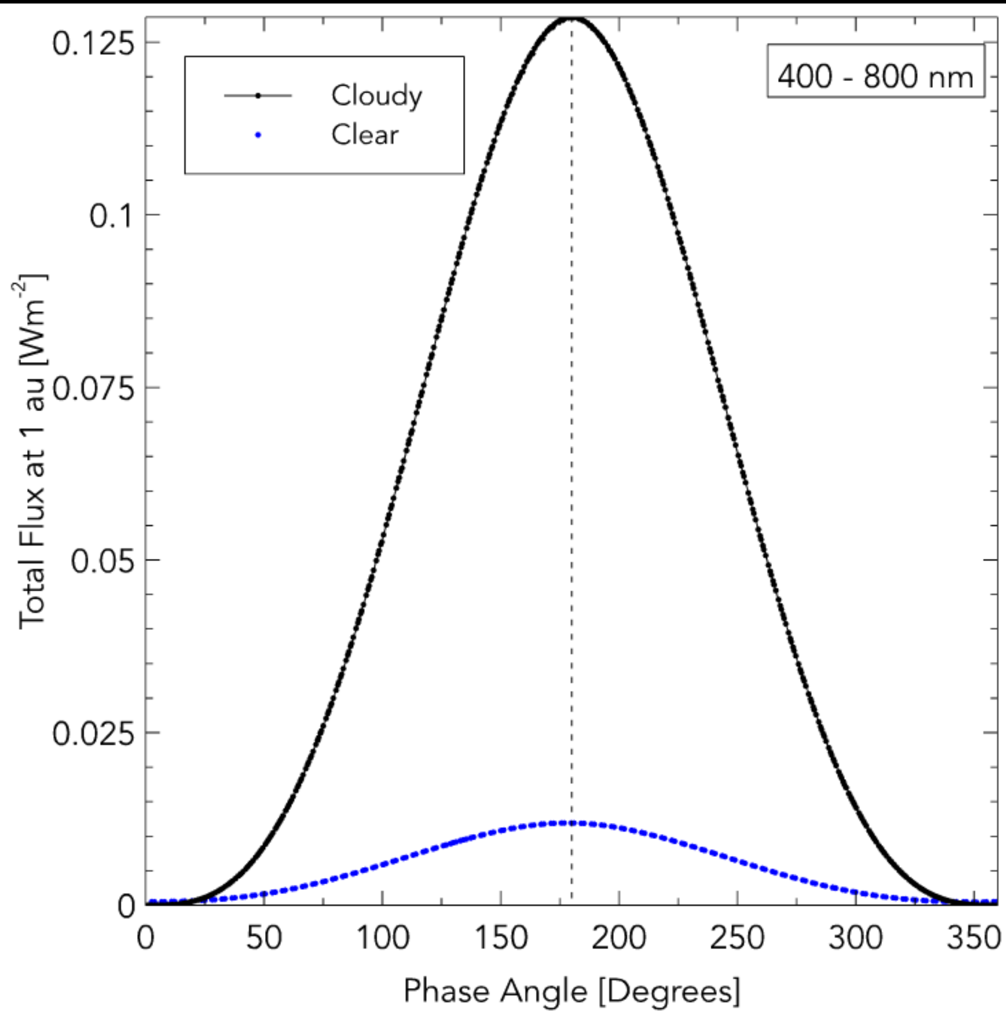
100bar>2500K

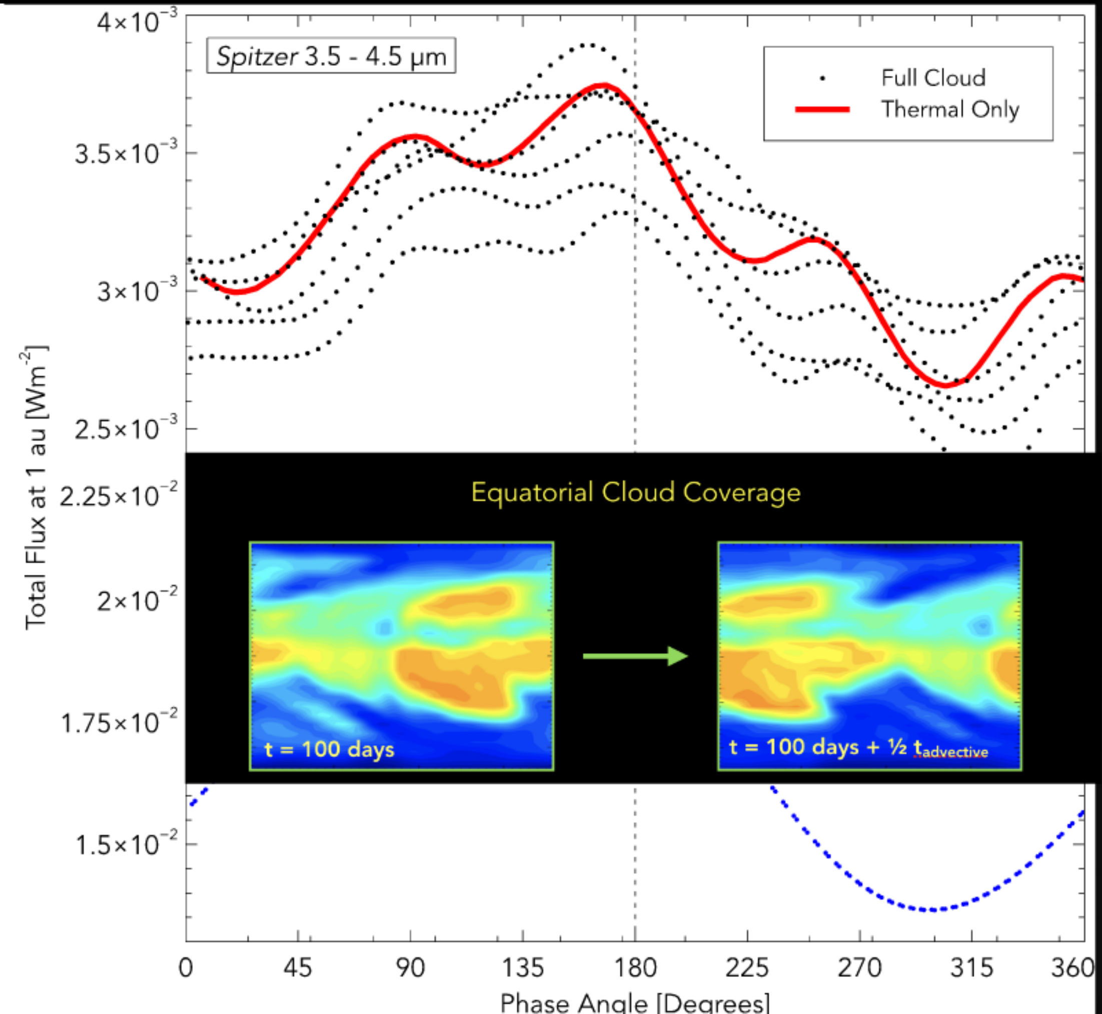
A more accurate PT profile of HD 209458 b?

Lines et al. 2018

Reduced Contrast: Cooling (upper), Hotter (deeper)

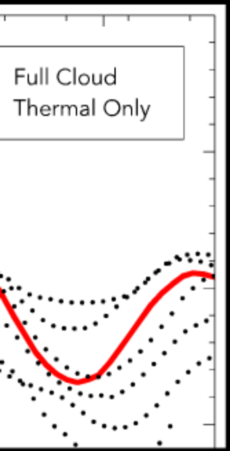
Visual & IR phase curves

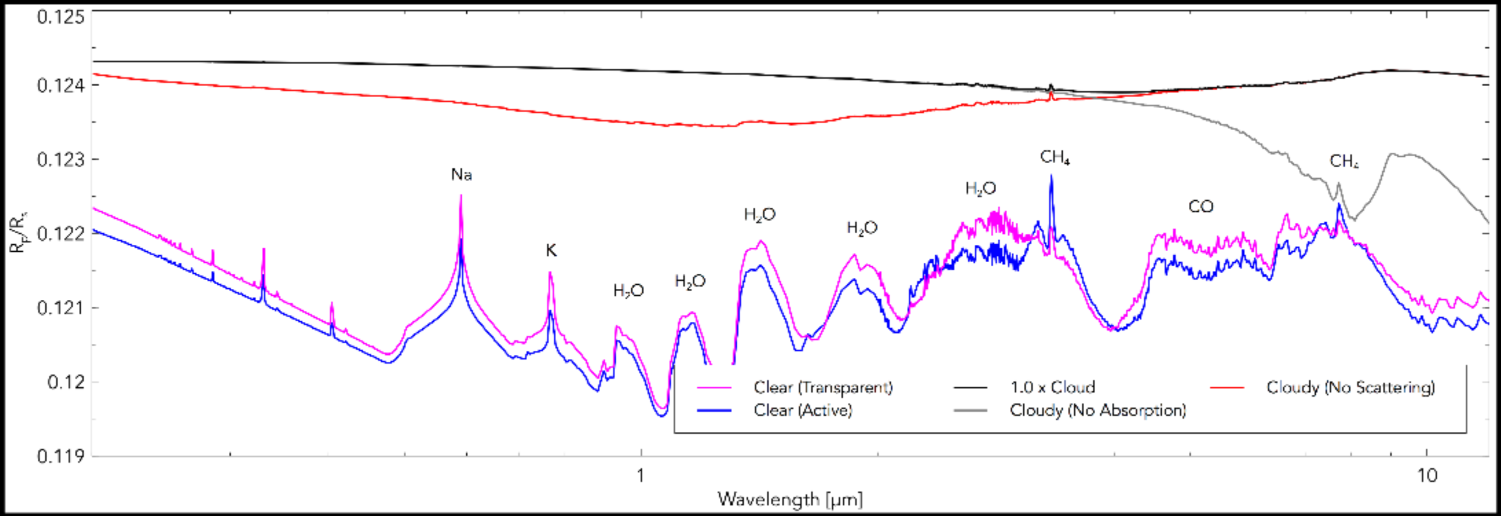


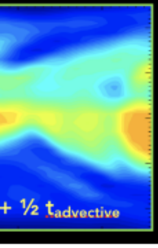


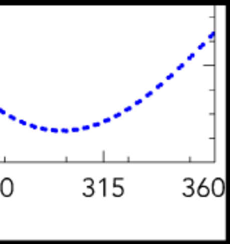
-> RT: gas phase CE analytic
-> Limited species
-> Shocks

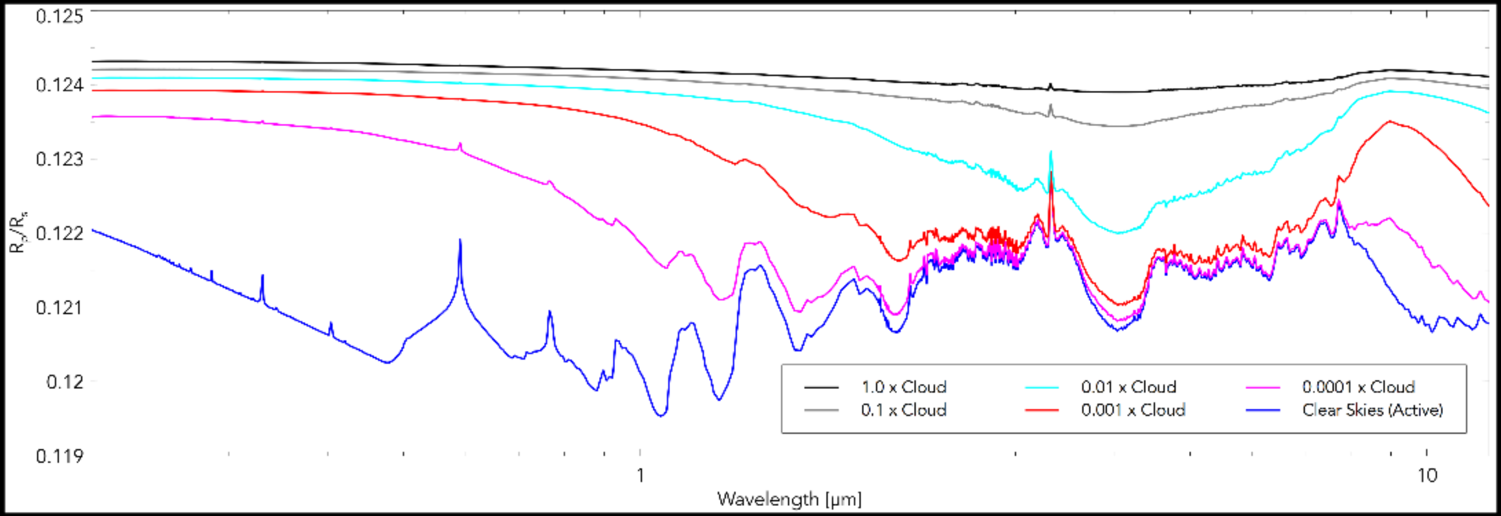
Transmission Spectra: Physical Insight + JWST [Lines et al., submitted]







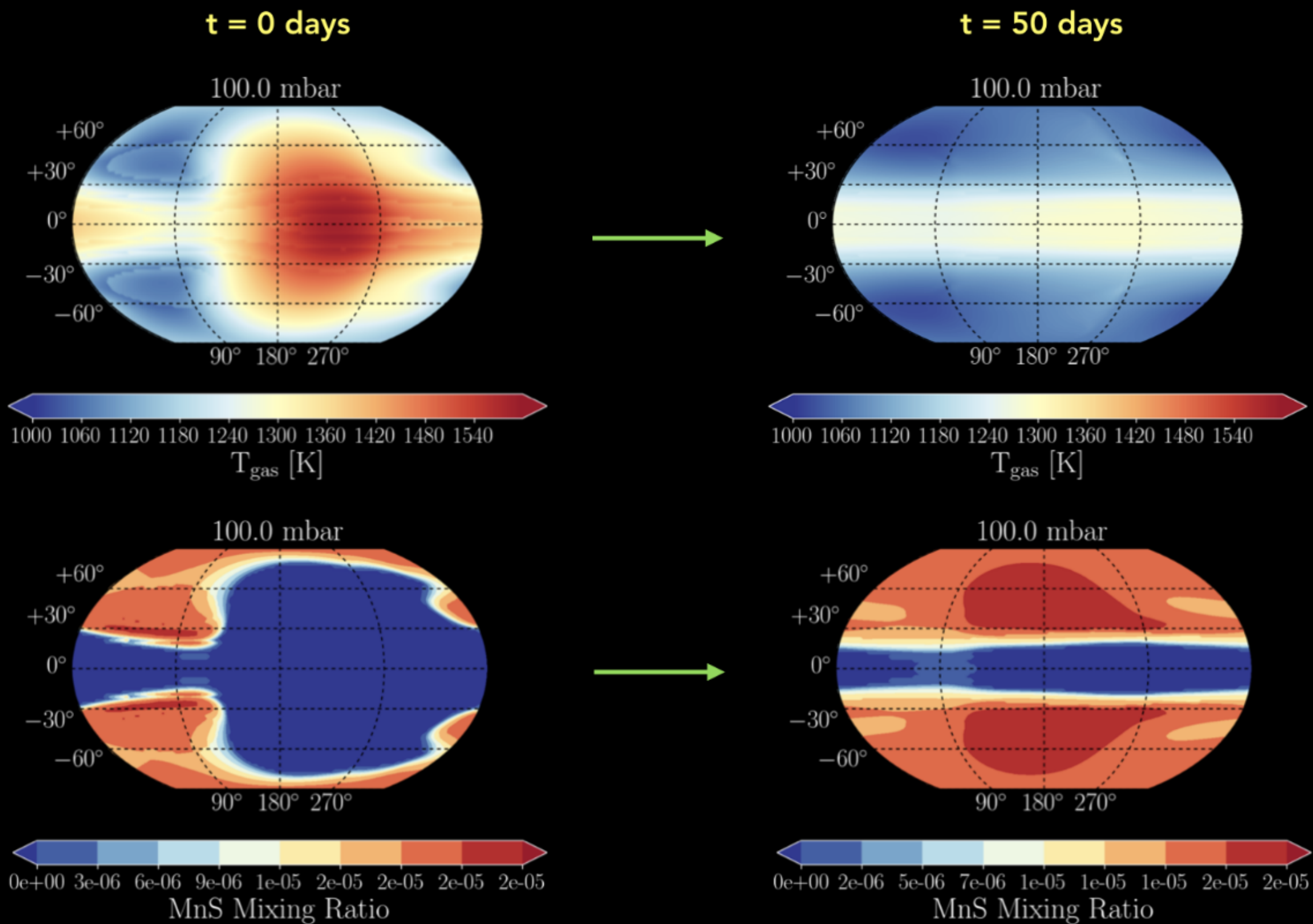




Too cloudy, everywhere!!!!

EVOLUTION OF MNS DUE TO ΔT_{3D}

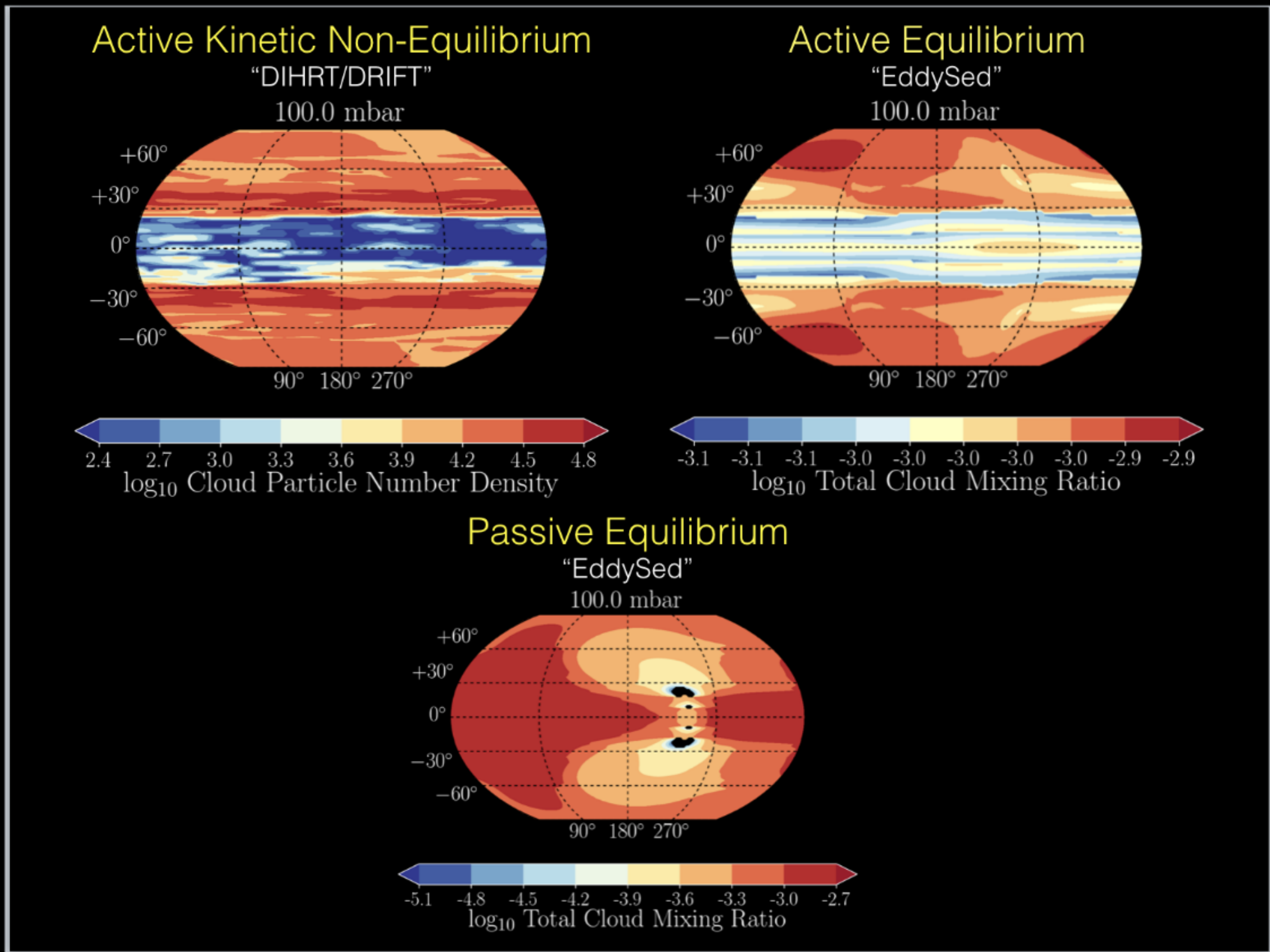
Lines et al (in prep)



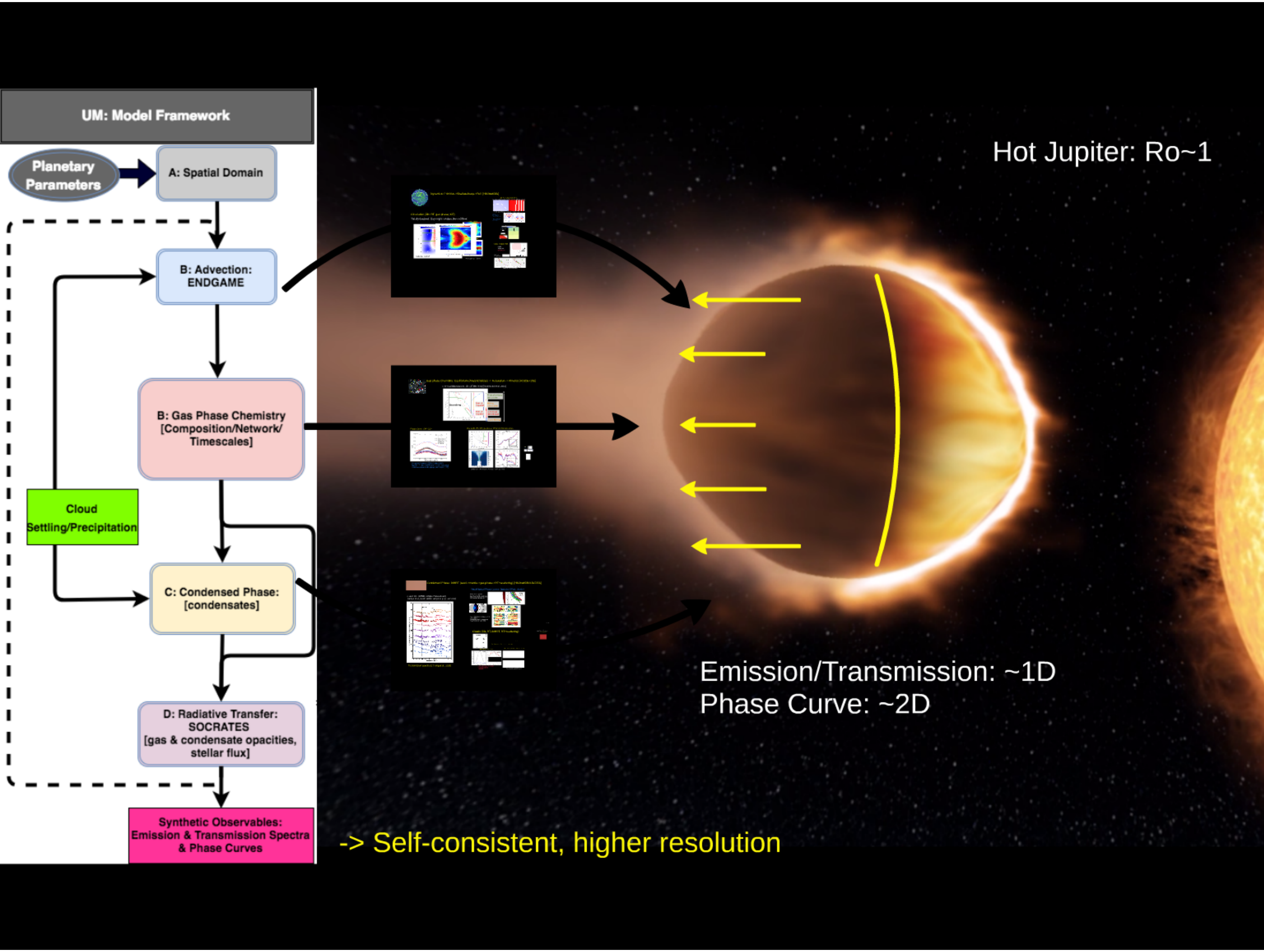
Eddy-Sed: Fast (!), Assumed Particle Size Distribution, Diagnostic Condensates

Equator: lower pressure cloud base (hotter) -> mixing to lower pressures

Particle Size? -> CARMA (OWL ESP)



Active Kinetic Non-Equilibrium
"DIHRT/DRIFT"
100.0 mbar
+60°
+30°
0°
−30°
−60°
90° 180° 270°
2.4 2.7 3.0 3.3 3.6 3.9 4.2 4.5 4.8
log10 Cloud Particle Number Density
Active Equilibrium
"EddySed"
100.0 mbar
+60°
+30°
0°
−30°
−60°
90° 180° 270°
-3.1 -3.1 -3.1 -3.0 -3.0 -3.0 -3.0 -3.0 -2.9 -2.9
log10 Total Cloud Mixing Ratio
Passive Equilibrium
"EddySed"
100.0 mbar
+60°
+30°
0°
−30°
−60°
90° 180° 270°
-5.1 -4.8 -4.5 -4.2 -3.9 -3.6 -3.3 -3.0 -2.7
log10 Total Cloud Mixing Ratio


UM: Model Framework
Planetary Parameters
A: Spatial Domain
B: Advection: ENDGAME
B: Gas Phase Chemistry [Composition/Network/ Timescales]
Cloud Settling/Precipitation
C: Condensed Phase: [condensates]
D: Radiative Transfer: SOCRATES [gas & condensate opacities, stellar flux]
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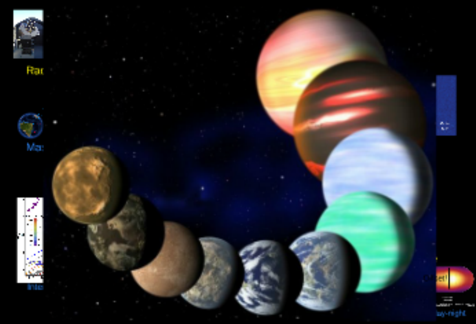
Hot Jupiter: Ro~1
Emission/Transmission: ~1D
Phase Curve: ~2D
-> Self-consistent, higher resolution

Observations



Model Framework

Met Office

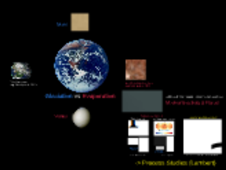
Shared Repository

Code: UM, JULES (land), SOCRATES (RT)
+ Configurations & testing: ROSE

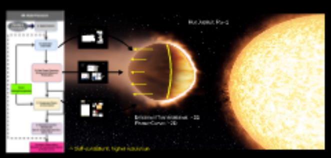
EXETER

Flexibility, speed, robustness, process testing

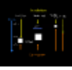
Terrestrial Planets



Gas giant planets



Conclusions & Future



Hot Jupiters **[Dynamics connect deep -> Observable + Control Structure]**:

- *Radius inflation: advection & deep profile (1)*
- Chemistry: 3D mixing+RT (2)
- Clouds: scattering cools -> banded (3)
  - Too cloudy, and no visual offset (dampened w).

Future:

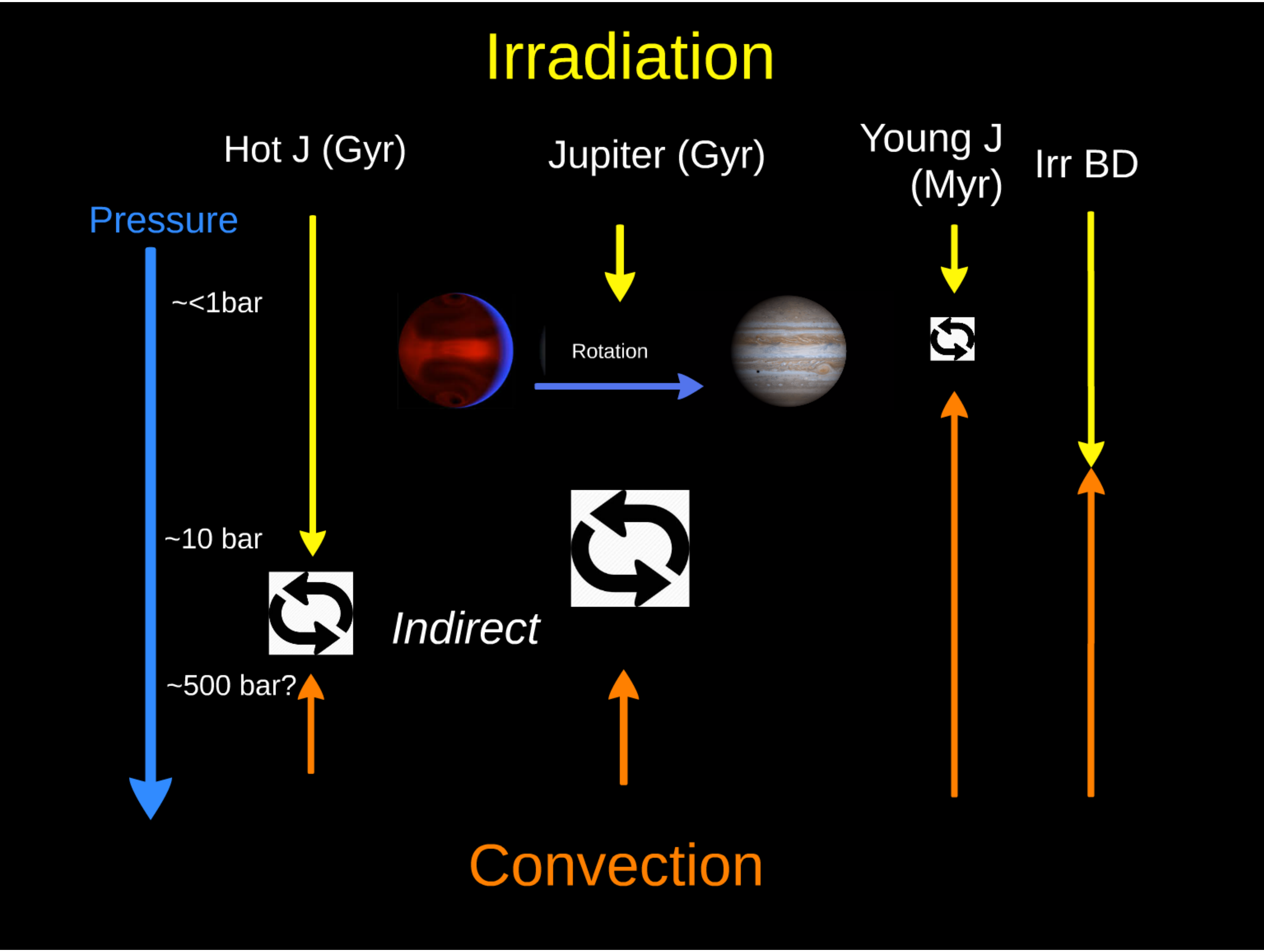
1) Chemistry: full chemical kinetics
2) Clouds: gas phase consistency, particles(?), more species (MnS, Fe)
3) Eddy-Sed vs DIHRT
4) Simulated Hires spectra -> Dynamical constraints

Terrestrial Planets-M-Dwarf, temperate planets:

- Tidally-Locked: Convection, clouds + rain = hot spot (1)
- Resonant, Eccentric: Hydro cycle -> Phase curve (2)
- Continent alters circulation (3)

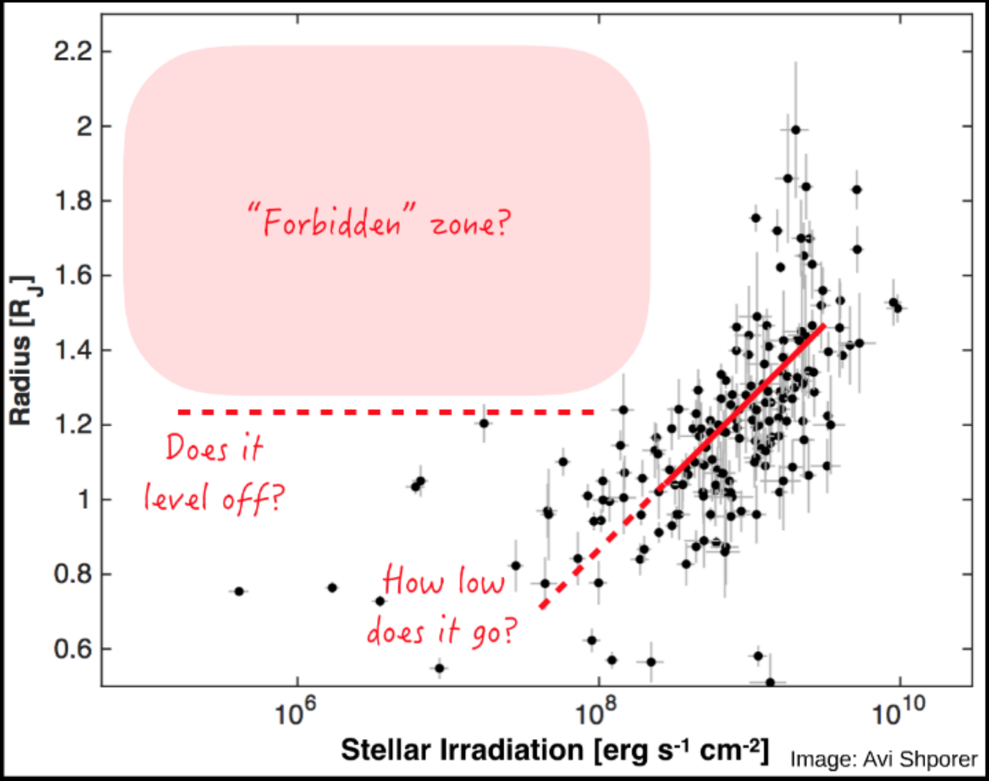
Future:

1) Condensible CO_2, Ocean, CIA CO_2 etc, Flares!....
2) High-res process studies.


Irradiation
Hot J (Gyr)
Jupiter (Gyr)
Young J (Myr)
Irr BD
Pressure
~<1bar
Rotation
~10 bar
Indirect
~500 bar?
Convection

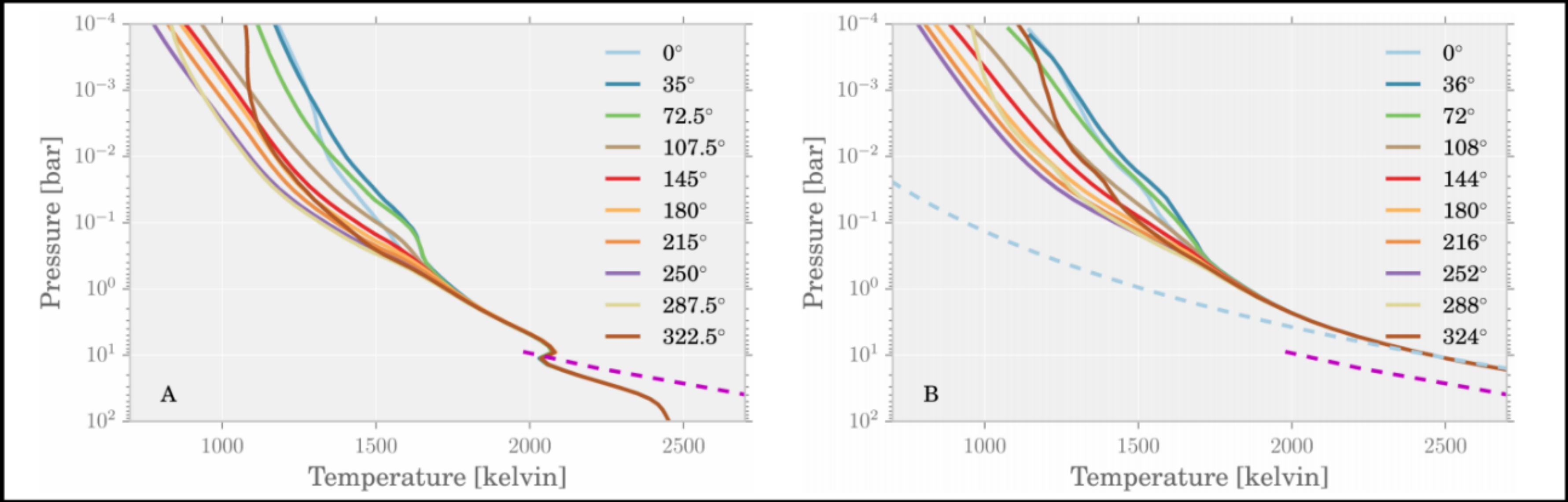
Radius Inflation (F(irr))

-Tidal
-Magnetic
-Circulation



2D ATMO:
Steady, UM:v/w

$$\frac{1}{r^2}\frac{\partial r^2 \rho u_r}{\partial r} = \frac{1}{r\alpha}\frac{\partial \rho u_\phi}{\partial \phi}$$



Advection of Theta=Inflation

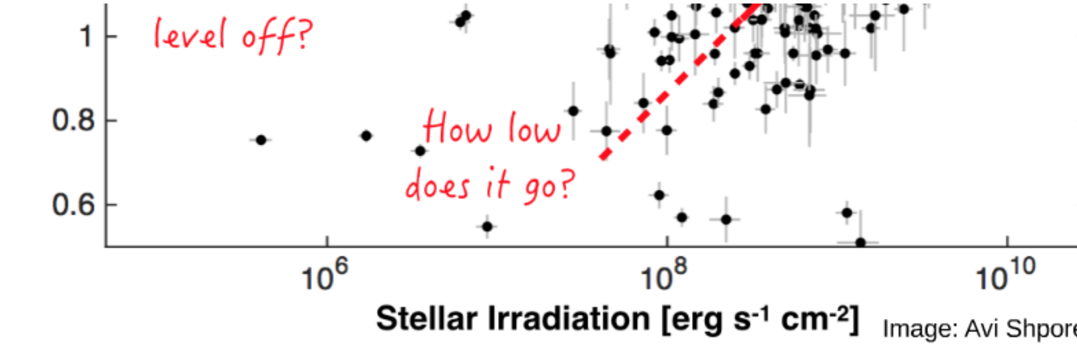
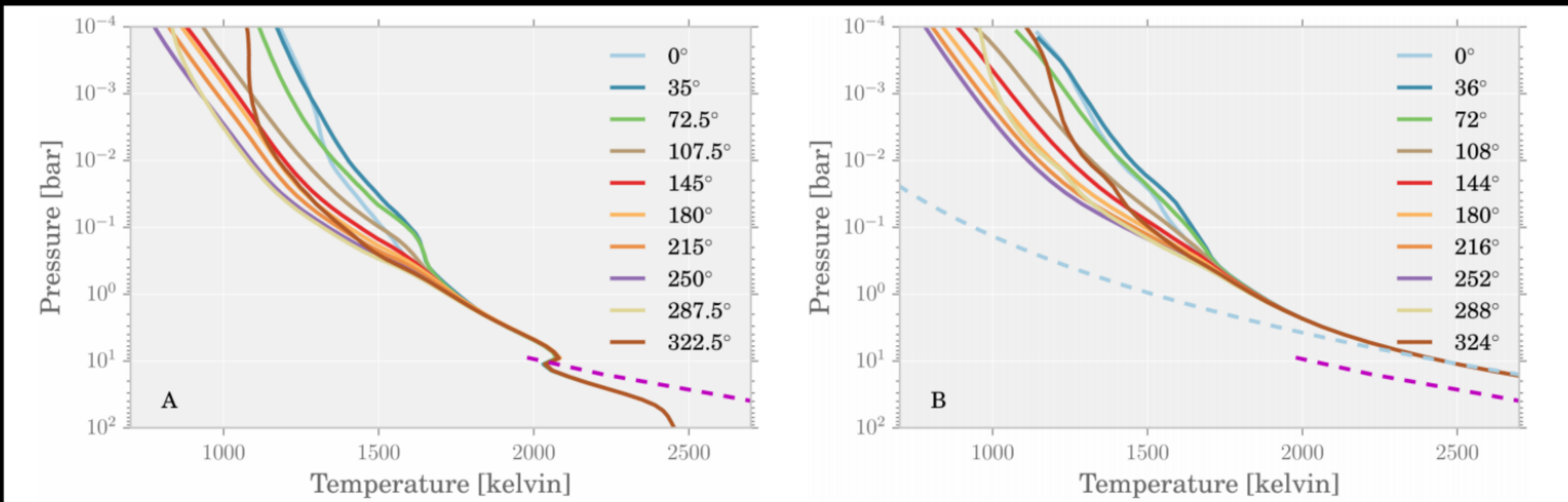


Image: Avi Shpore

2D ATMO:
Steady, UM:v/w

$$\frac{1}{r^2}\frac{\partial r^2 \rho u_r}{\partial r} = \frac{1}{r\alpha}\frac{\partial \rho u_\phi}{\partial \phi}$$



Advection of Theta=Inflation

Contribution Function

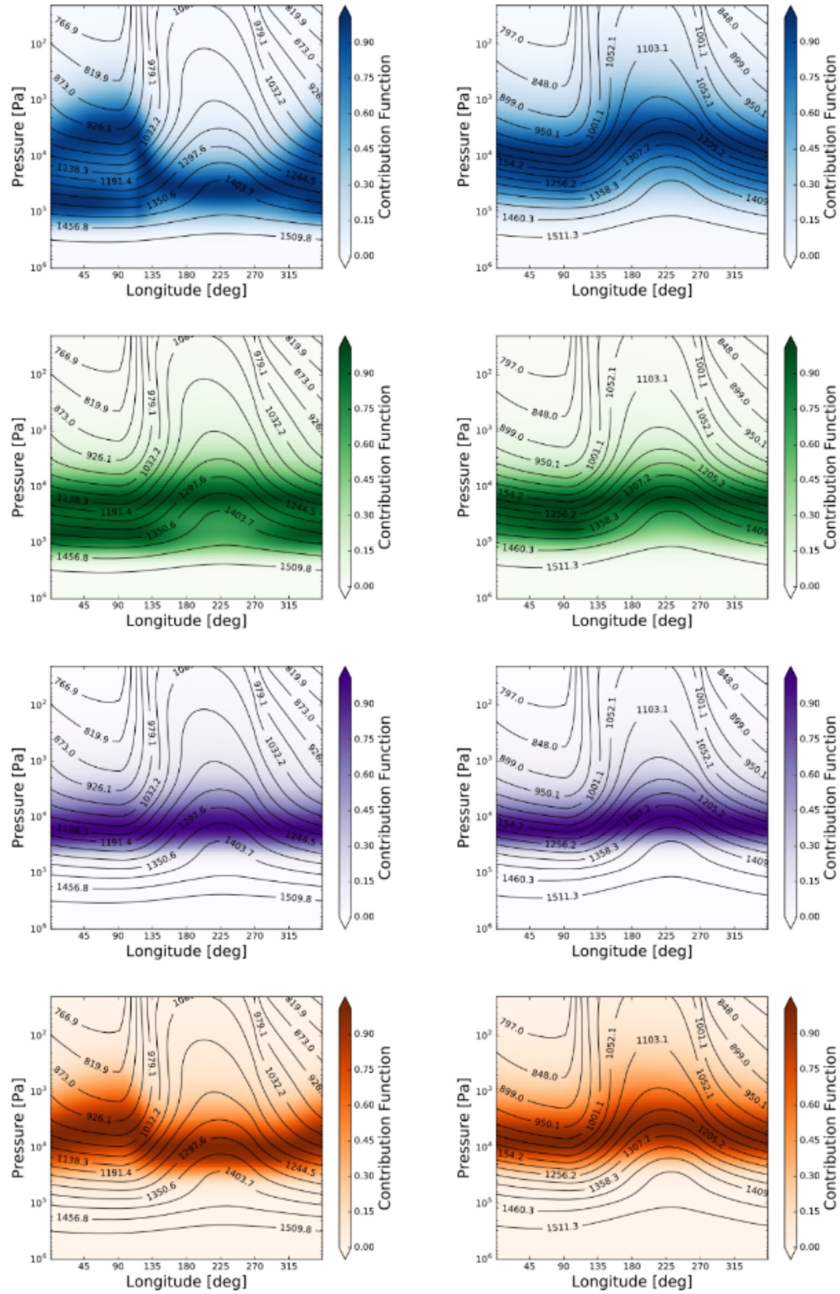


Figure 9. Normalised ontribution functions (colour scale) and atmospheric temperature (black contours) meridionally averaged between ±20° latitude for different Spitzer/IRAC channels: 3.6 µm (top), 4.5 µm (second from top), 5.8 µm (second from bottom) and 8.0 µm (bottom).

Drummond et al. (submitted)

Met Office

Shared Repository

UNIVERSITY OF EXETER

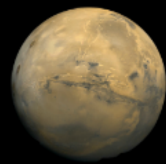
Code: **UM**, JULES (land), SOCRATES (RT)
+ Configurations & testing: ROSE

Flexibility, speed,
robustness, process testing

Radiative Transfer: Correlated-K (2-stream), MIE+EMT scattering, Overlap (RO,EE),
Opacity [Exomol, HITEMP, HITRAN] + Spherical geometry

SOCRATES: open source (James Manners).
Hot Jupiters: Amundsen et al., (2014, 2016, 2017)

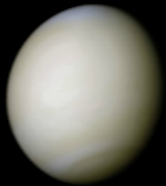
Mars

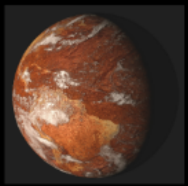


Faint Young Sun
(e.g. Charney et al., 2014)

Glaciation vs Evaporation

Venus





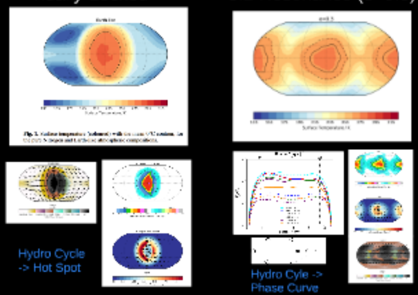
Moist Runaway Greenhouse
(e.g. Leconte et al., 2013)

~200 Earth-like:Trappist *, Proxima Centauri b, etc..

M: dwarfs-activity & Flares!

Proxima Centauri B (if, if, if)

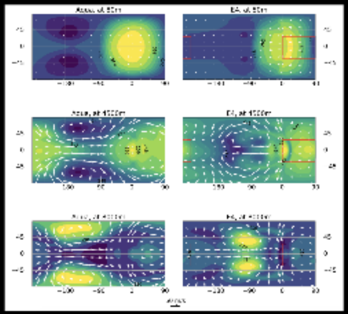
Tidally-Locked | 3:2 Resonance (e~0.3)



e>0.1 Warm enough!

Boutle et al (2017)

Aquaplanet versus Continent?



E4: 16.6% land, east-offset from hot spot: **Circulation!!**

-> Process Studies (Lambert)

~200 Earth-like:Trappist *, Proxima Centauri b, etc..

M: dwarfs-activity & Flares!

Proxima Centauri B (if, if, if)

Tidally-Locked

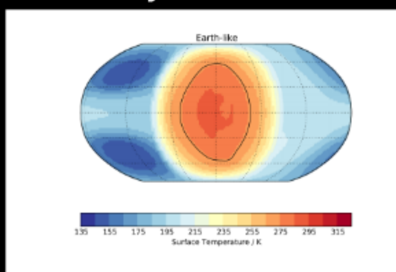
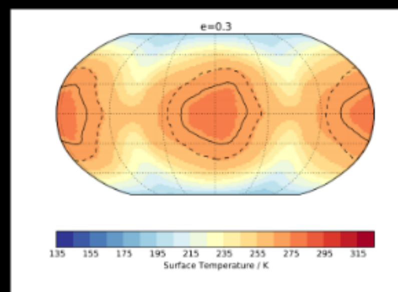
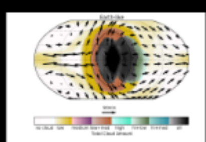
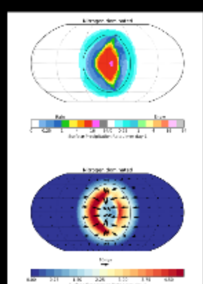


Fig. 1. Surface temperature (coloured) with the mean 0°C contour, for the pure Nitrogen and Earth-like atmospheric compositions.

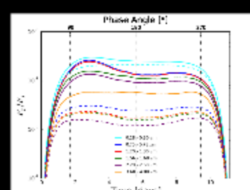
3:2 Resonance (e~0.3)

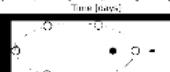




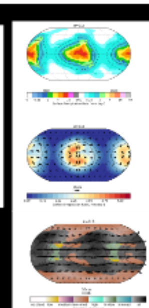


Hydro Cycle
-> Hot Spot





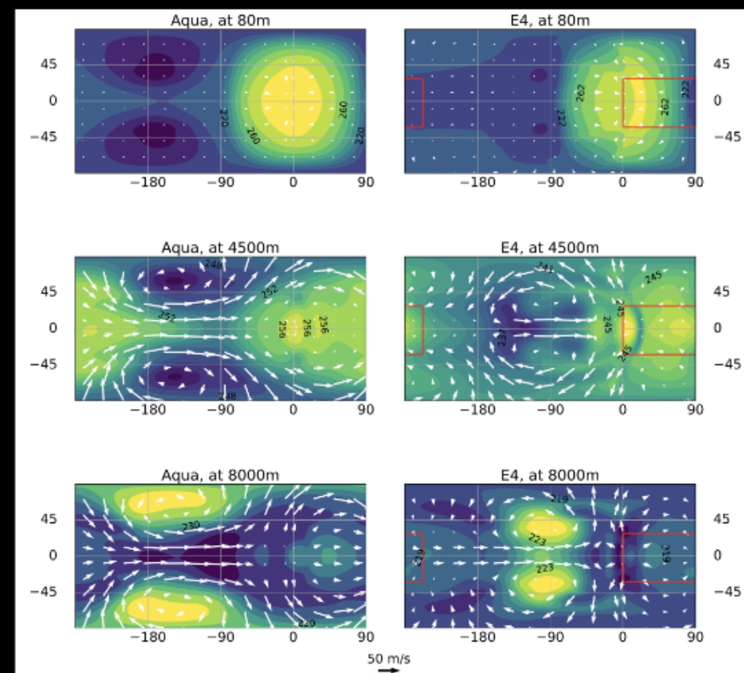
Hydro Cyle ->
Phase Curve



e>0.1 Warm enough!

Boutle et al (2017)

Aquaplanet versus Continent?

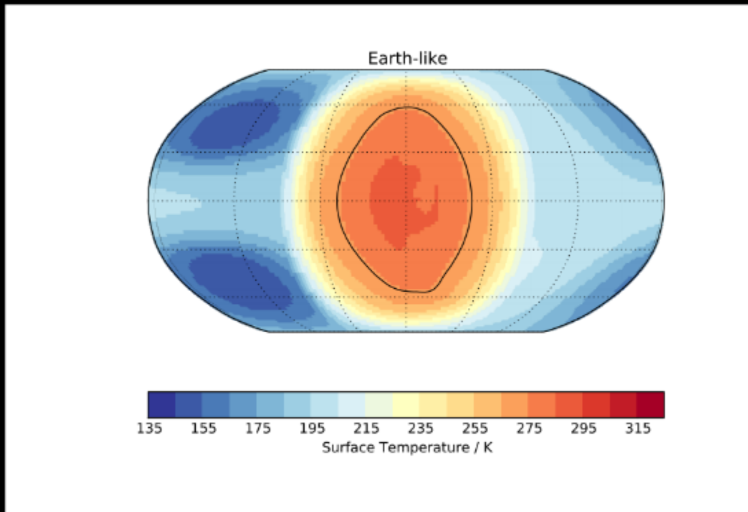


E4: 16.6% land, east-offset from hot spot: **Circulation!!**

-> Process Studies (Lambert)

Proxima Centauri B (if, if, if)

Tidally-Locked



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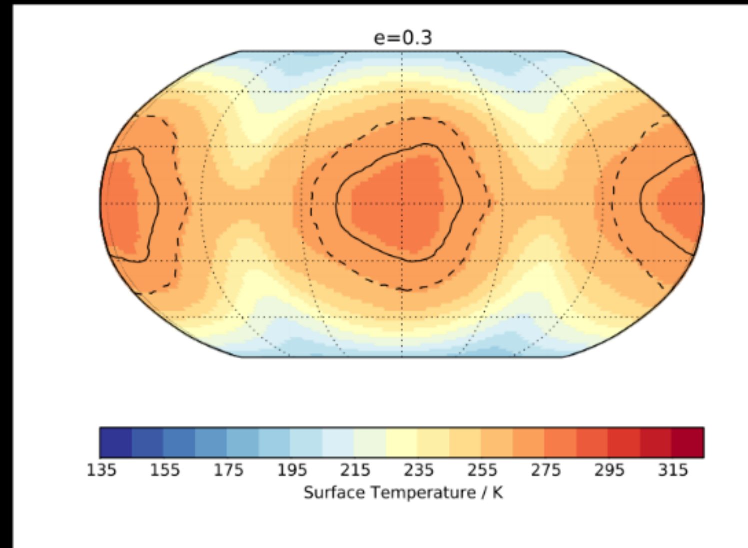

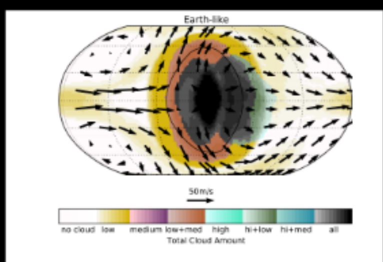

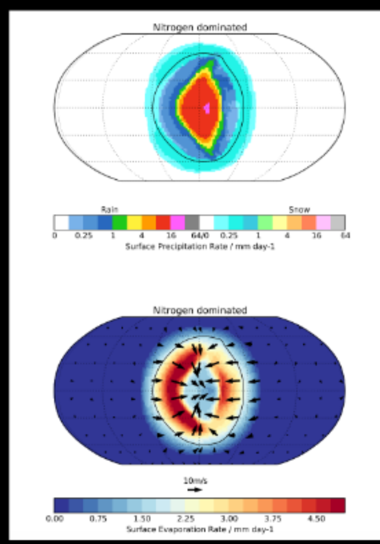

Hydro Cycle
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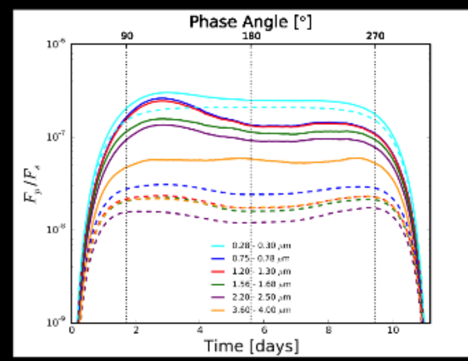

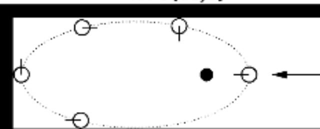

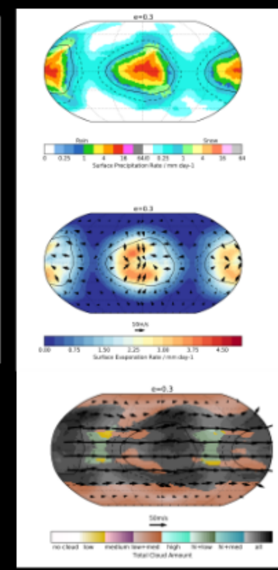

Hydro Cyle ->
Phase Curve

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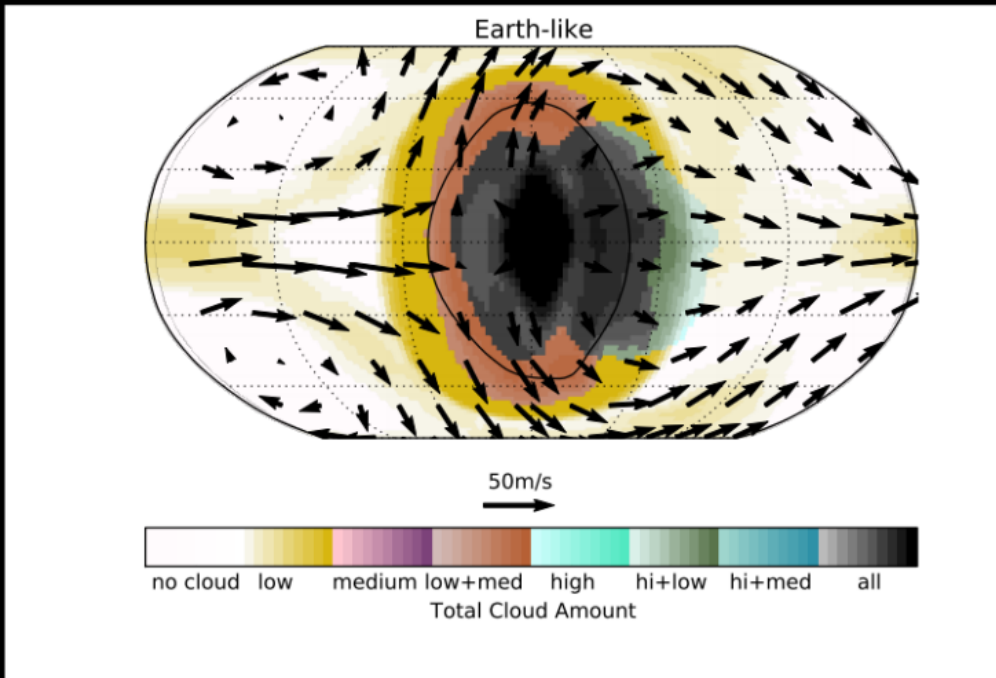
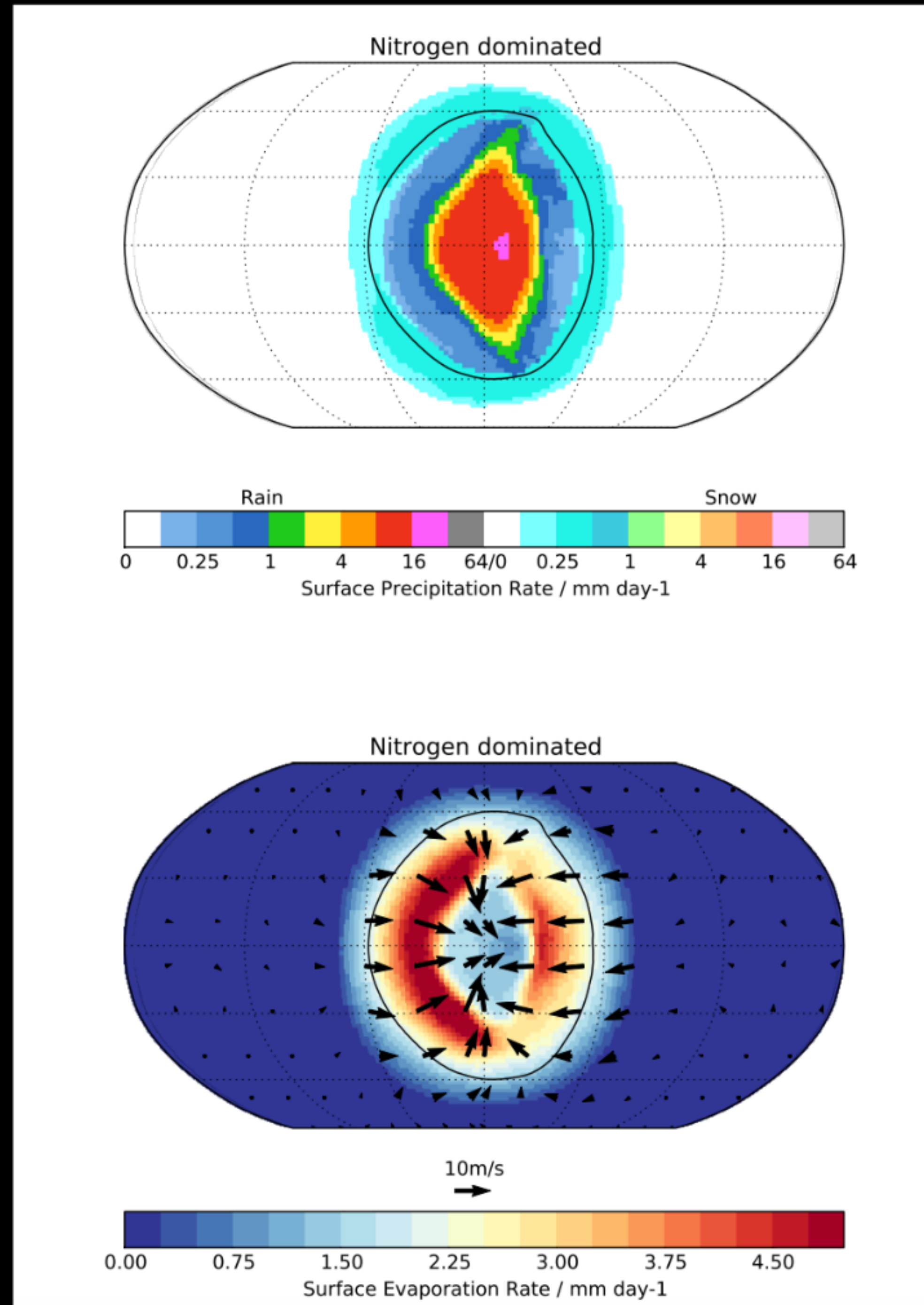
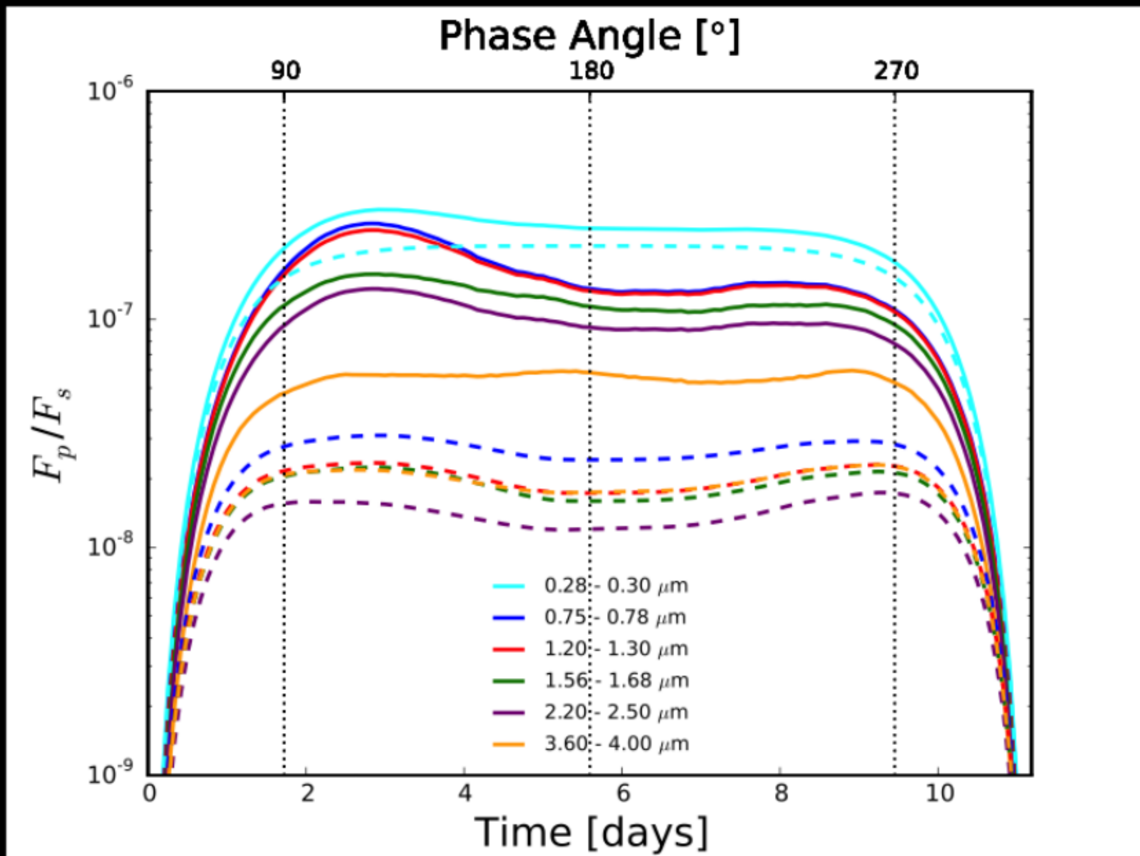
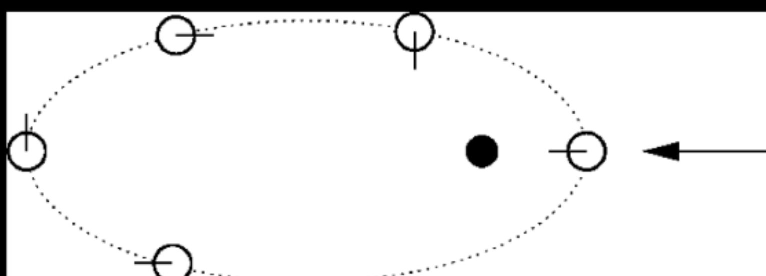
Boutle et al (2017)

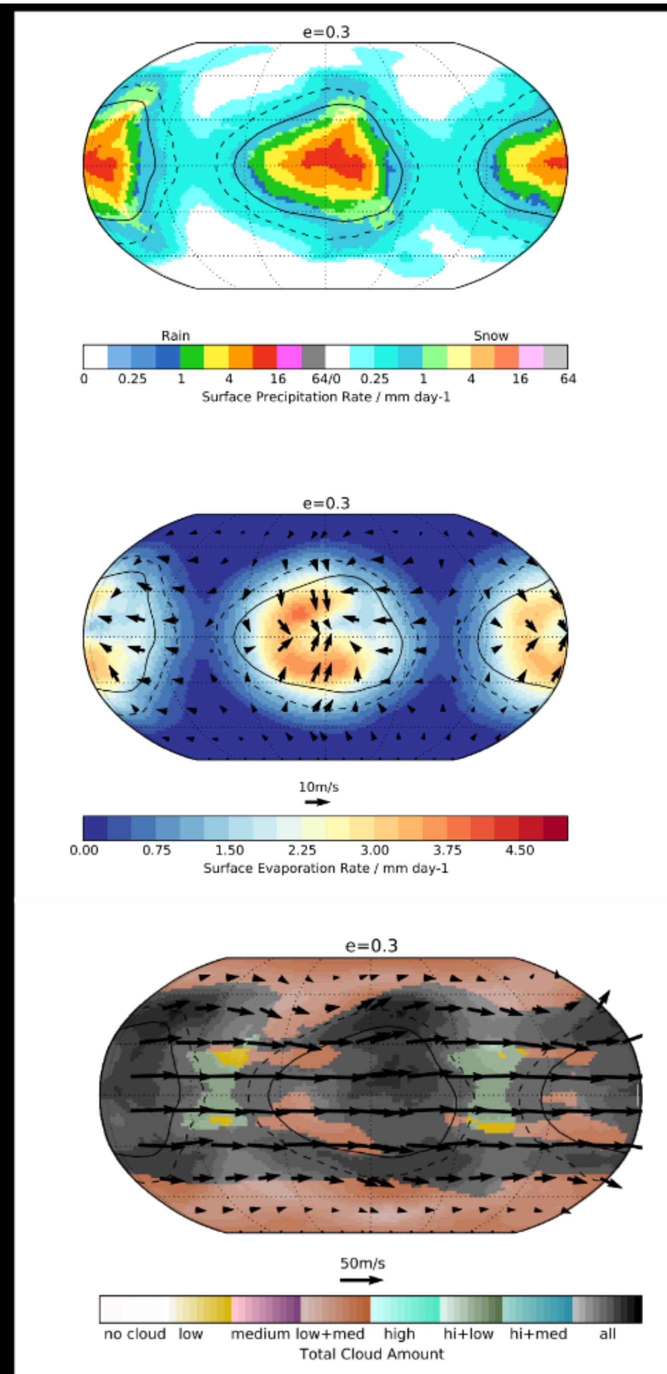




Hydro Cycle -> Hot Spot

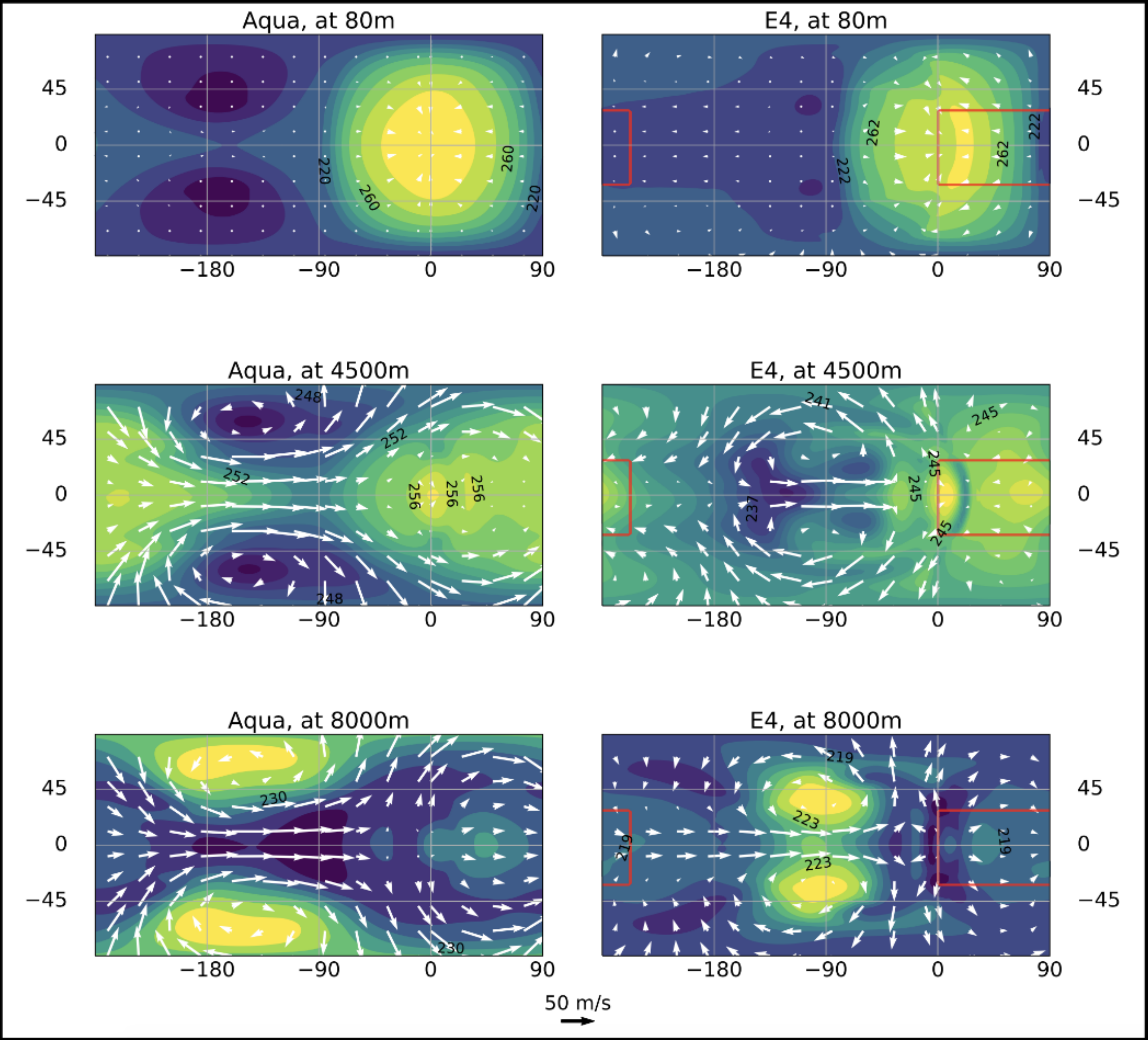






Hydro Cyle -> Phase Curve

Aquaplanet versus Continent?



E4: 16.6% land, east-offset from hot spot: **Circulation!!**

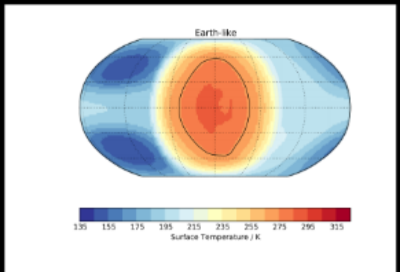
~200 Earth-like:Trappist *, Proxima Centauri b, etc..

M: dwarfs-activity & Flares!

Proxima Centauri B (if, if, if)

Tidally-Locked

3:2 Resonance (e~0.3)



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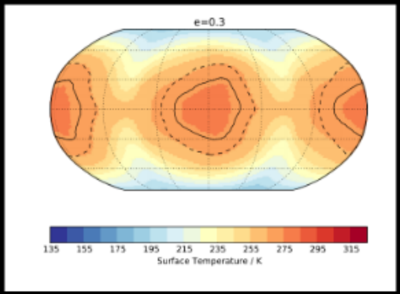

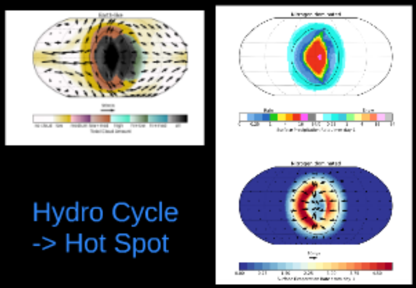

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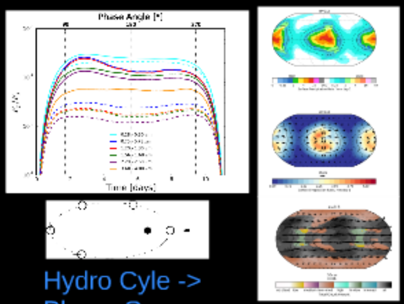

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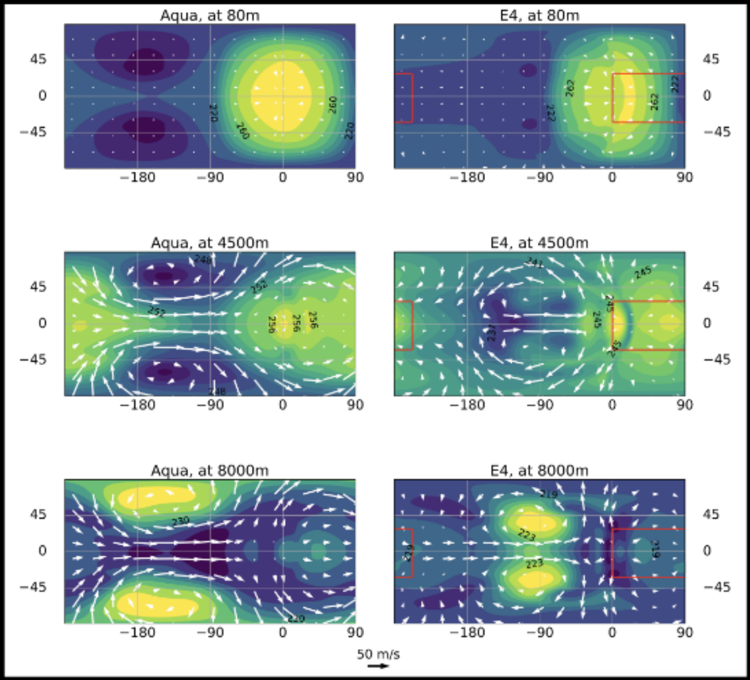


E4: 16.6% land, east-offset from hot spot: **Circulation!!**

-> Process Studies (Lambert)

Hot Jupiters **[Dynamics connect deep -> Observable + Control Structure]**:

- *Radius inflation: advection & deep profile (1)*
- Chemistry: 3D mixing+RT (2)
- Clouds: scattering cools -> banded (3)
  - Too cloudy, and no visual offset (dampened w).

Future:

1) Chemistry: full chemical kinetics
2) Clouds: gas phase consistency, particles(?), more species (MnS, Fe)
3) Eddy-Sed vs DIHRT
4) Simulated Hires spectra -> Dynamical constraints

Terrestrial Planets-M-Dwarf, temperate planets:

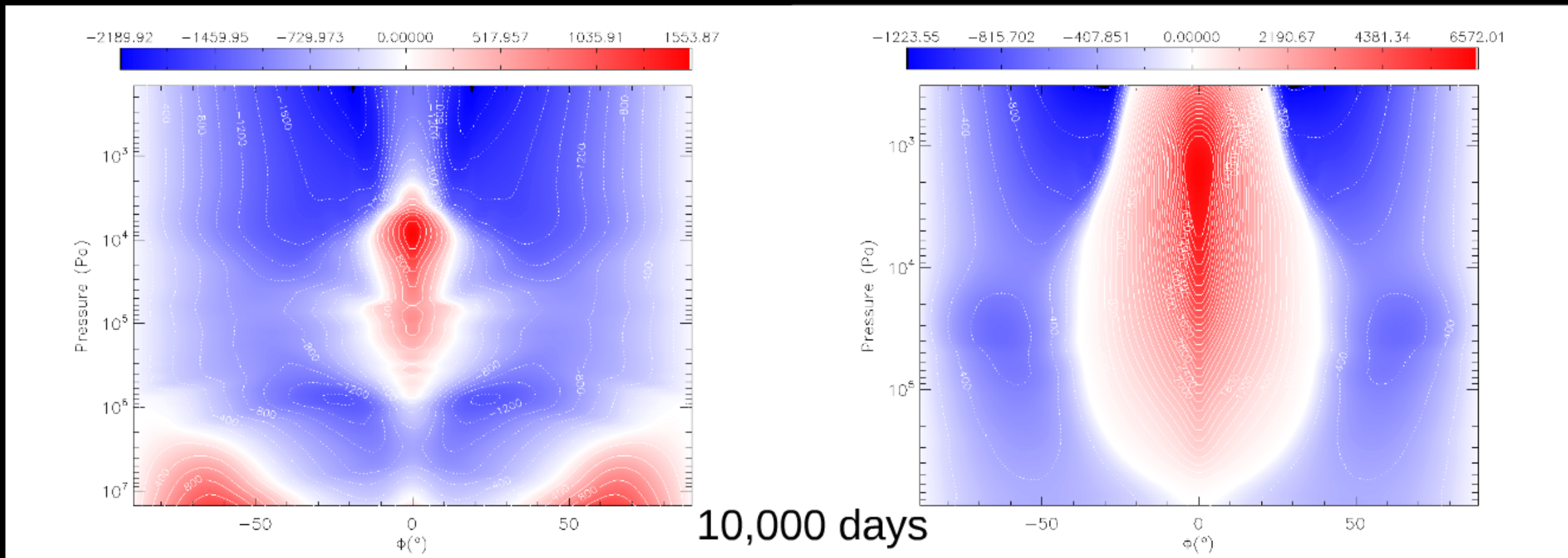
- Tidally-Locked: Convection, clouds + rain = hot spot (1)
- Resonant, Eccentric: Hydro cycle -> Phase curve (2)
- Continent alters circulation (3)

Future:

1) Condensible CO_2, Ocean, CIA CO_2 etc, Flares!....
2) High-res process studies.

Jet: Pumping & Sensitivity

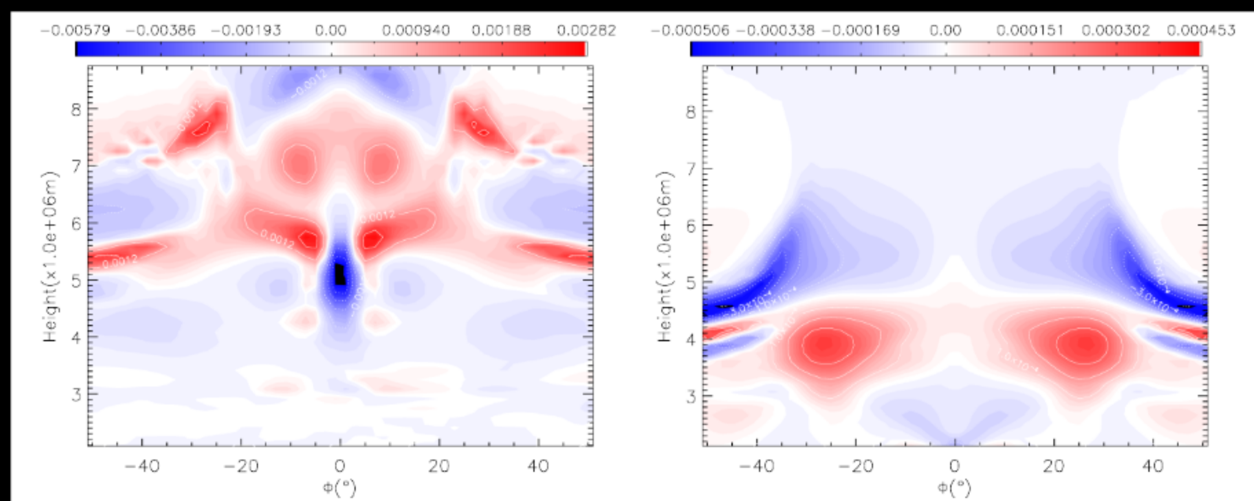
Jet robust: time, gravity, equations (narrows+weakens: Prim-> Full) [Mayne et al, 2014]



P > 10bar, Equator-Pole +500K.....10,000 days.... [Mayne et al., 2017]

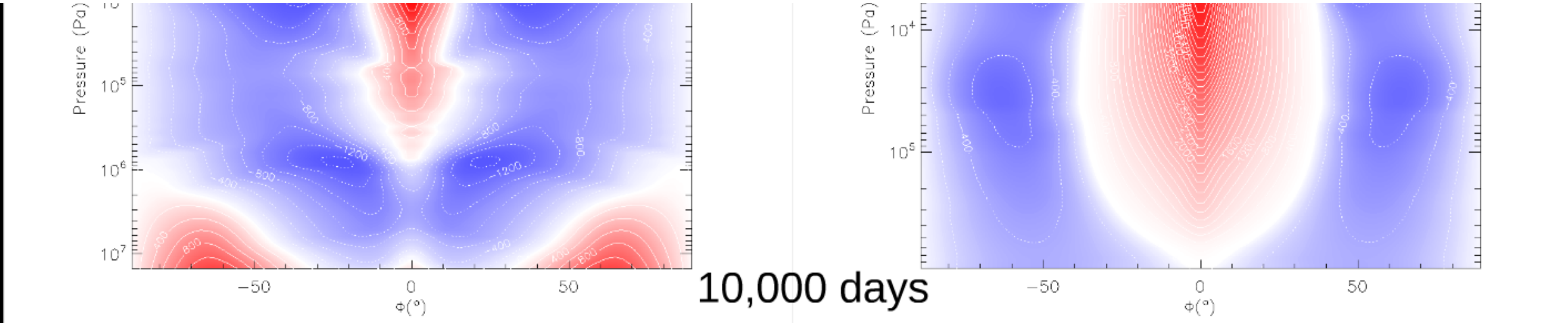
Pumping:
t~1day: Matsuno-Gill
t~100+days: v' ~ w'
[Showman & Polvani, 2011]

Analysis of dominant modes
[Debras et al., in prep*2]
t>1 < 100 days?



(e) Std Full: $\Sigma_\lambda - \left(\frac{\left[\overline{(\rho v)'u'}\cos^2\phi\right]_{,\phi}}{r\cos^2\phi} + \frac{\left[\overline{(\rho w)'u'}r^3\right]_{,r}}{r^3}\right)$, 1 000 days

(f) Std RT: $\Sigma_\lambda - \left(\frac{\left[\overline{(\rho v)'u'}\cos^2\phi\right]_{,\phi}}{r\cos^2\phi} + \frac{\left[\overline{(\rho w)'u'}r^3\right]_{,r}}{r^3}\right)$, 1 000 days



10,000 days

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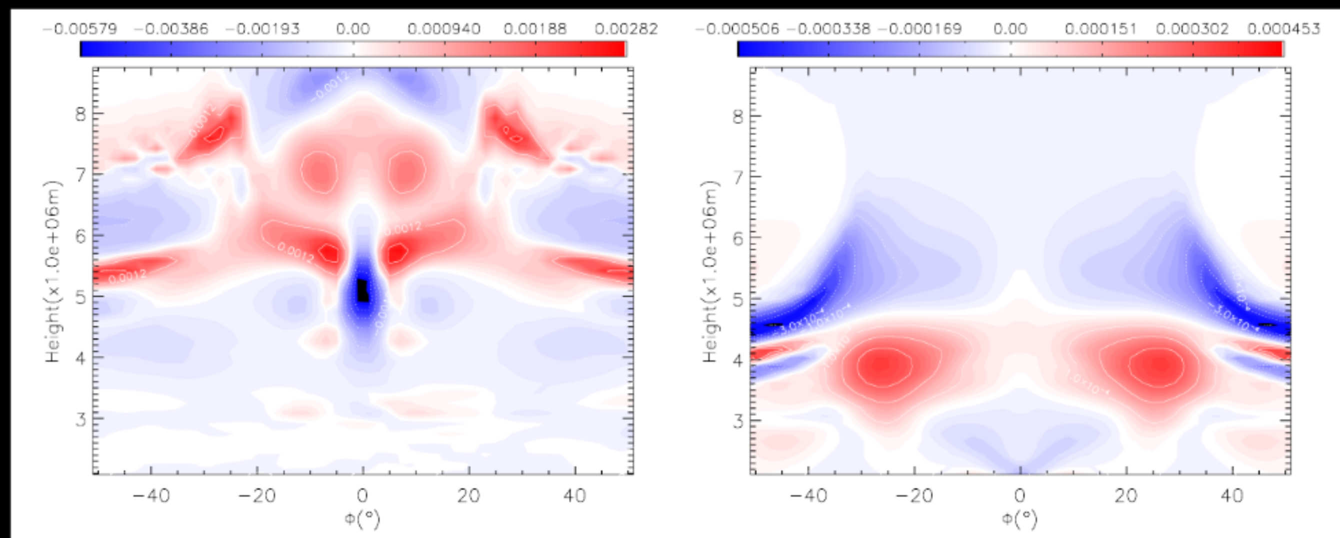

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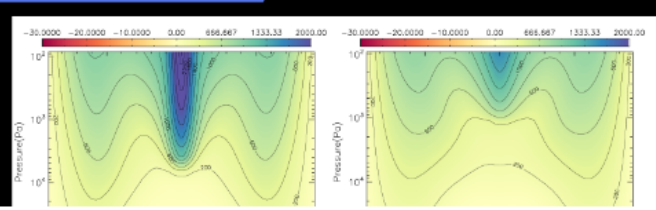
Breakdown of the Primitive Equations?

$$u \left\{ \begin{array}{ll} \left[\frac{\partial u}{\partial t} + \frac{u}{r\cos\phi}\frac{\partial u}{\partial \lambda} + \frac{v}{r}\frac{\partial u}{\partial \phi} + w\frac{\partial u}{\partial r}\right] = + \frac{uv\tan\phi}{r} - \frac{uw}{r} + 2\Omega v\sin\phi - 2\Omega w\cos\phi - \frac{c_p\theta}{r\cos\phi}\frac{\partial \Pi}{\partial \lambda} & \textit{Full \& Deep} \\ \left[\frac{\partial u}{\partial t} + \frac{u}{R_p\cos\phi}\frac{\partial u}{\partial \lambda} + \frac{v}{R_p}\frac{\partial u}{\partial \phi} + w\frac{\partial u}{\partial z}\right] = + \frac{uv\tan\phi}{R_p} + 2\Omega v\sin\phi - \frac{c_p\theta}{R_p\cos\phi}\frac{\partial \Pi}{\partial \lambda} & \textit{Shallow \& Primitive} \end{array}\right.$$

Thin-Fluid Approximation (r->Rp):
- Hot Jupiter Zatm/Rp~10%
- Warm Neptune ~ 20%



Breakdown of the Primitive Equations?

$$u\left\{\begin{array}{llllllllll}
\left[\frac{\partial u}{\partial t}\right. & +\frac{u}{r\cos\phi}\frac{\partial u}{\partial\lambda} & +\frac{v}{r}\frac{\partial u}{\partial\phi} & \left.+w\frac{\partial u}{\partial r}\right] = & +\frac{uv\tan\phi}{r} & -\frac{uw}{r} & +2\Omega v\sin\phi & -2\Omega w\cos\phi & -\frac{c_p\theta}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} & \textit{Full \& Deep}\\
\left[\frac{\partial u}{\partial t}\right. & +\frac{u}{R_p\cos\phi}\frac{\partial u}{\partial\lambda} & +\frac{v}{R_p}\frac{\partial u}{\partial\phi} & \left.+w\frac{\partial u}{\partial z}\right] = & +\frac{uv\tan\phi}{R_p} & & +2\Omega v\sin\phi & & -\frac{c_p\theta}{R_p\cos\phi}\frac{\partial\Pi}{\partial\lambda} & \textit{Shallow \& Primitive}
\end{array}\right.$$

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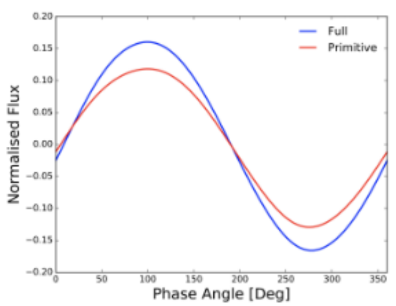
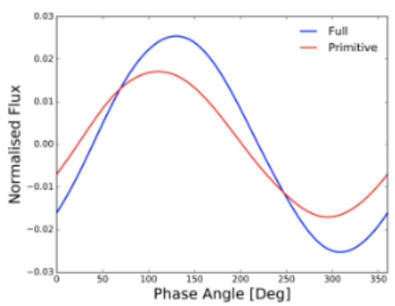
$$R_o \equiv \frac{U}{fL},$$

$$R_o^{\rm full} = \frac{U}{4\Omega\pi(R_p + z_U)\sin\phi},$$

Thick Atm, Slow Rotator



(e) Std Prim/Full: 100 Pa



(f) Std Prim/Full: 3000 Pa