Dynamic Mineral Clouds on HD 189733b

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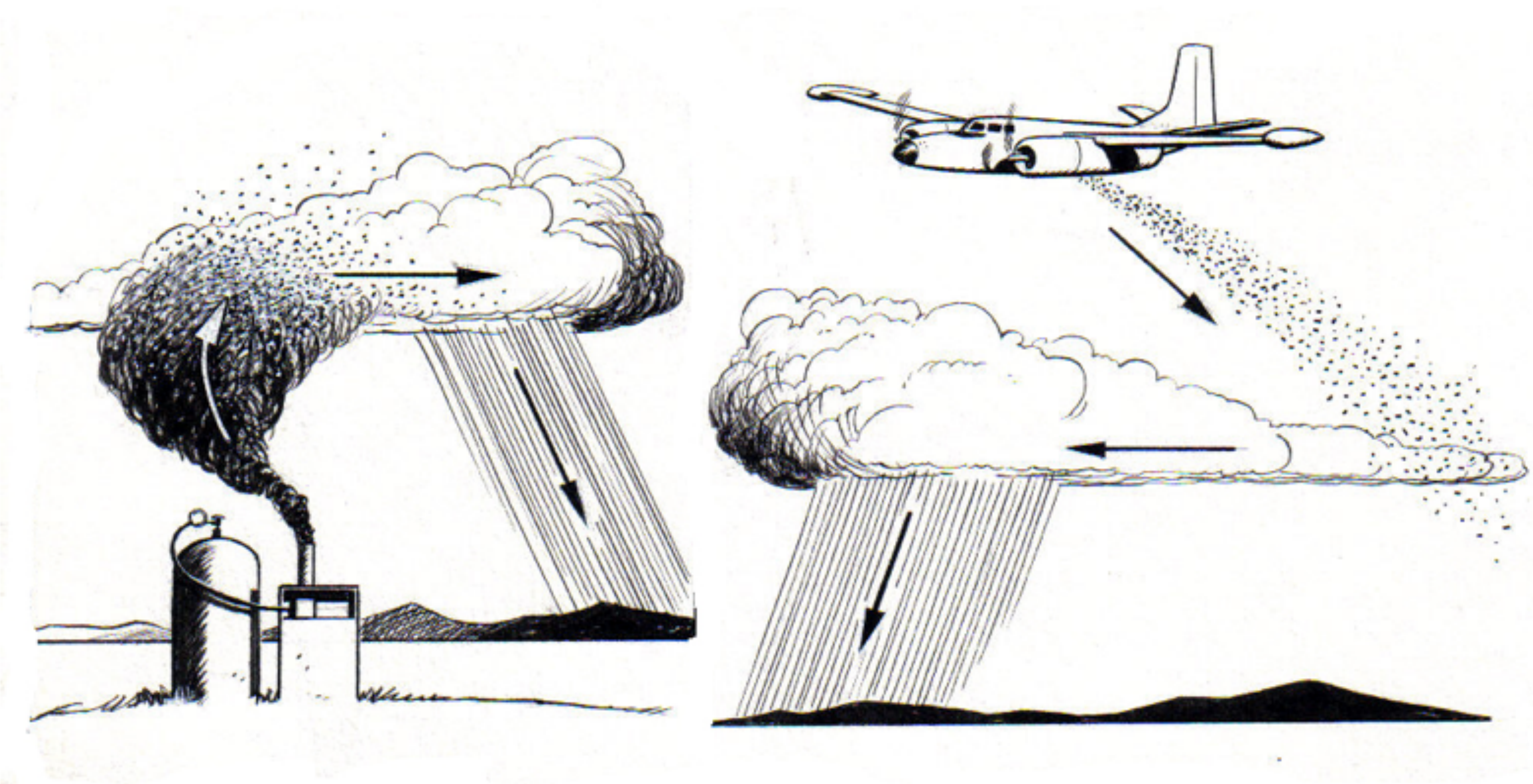
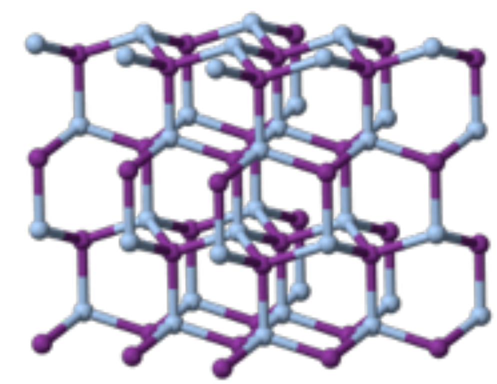
Lee et al. (A&A submitted)
arXiv:1603.09098

I. Dobbs-Dixon[2], Ch. Helling[1], K. Bognar[3] & P. Woitke[1]

1. St Andrews
2. NYU Abu Dhabi
3. Toronto

Why does it never rain on the Moscow parade?





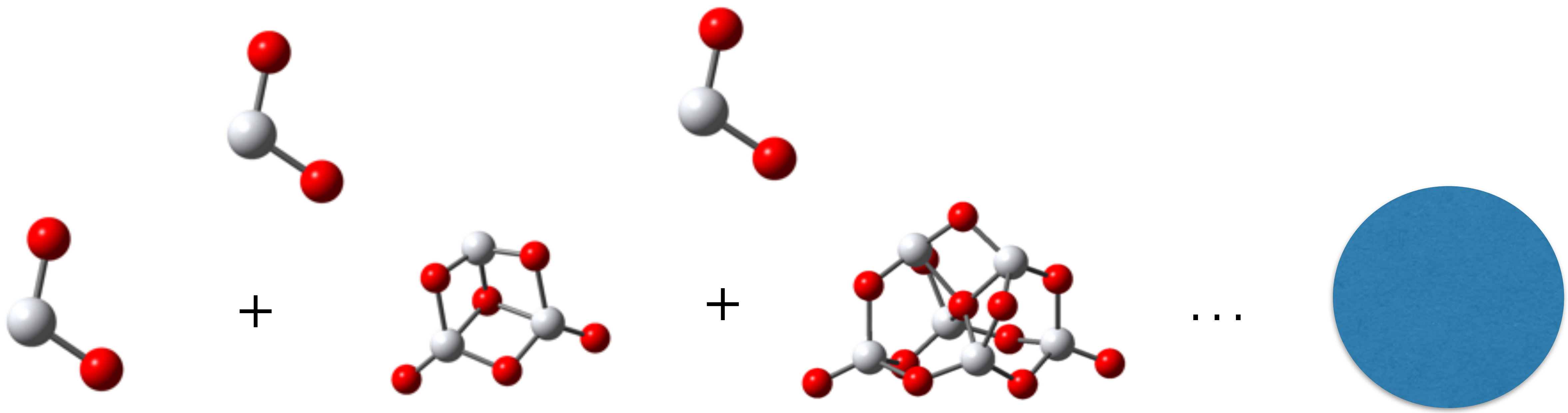
Silver Iodide

DooFi - “Cloud Seeding”

See also:
C.W. McCall - “Silver Iodide Blues”

Seed particles on hot Jupiters?

Cloud Particle Nucleation



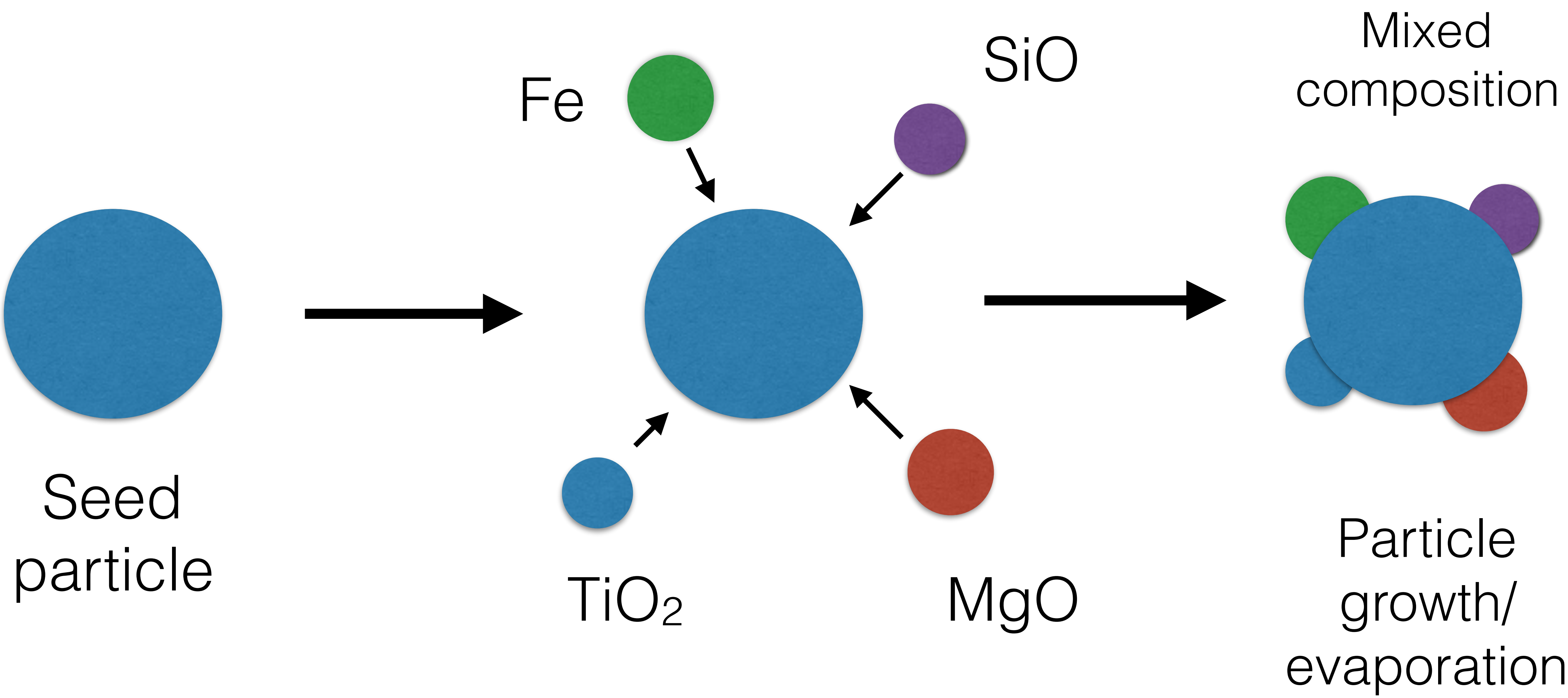
Gas molecules → Seed particle (~1 nm)

J_* [cm^{-3} s^{-1}]

Depends on - Local gas temperature | Molecular abundance | Material properties

Woitke & Helling (2003)

Cloud Particle Growth



Growth velocity $$\sum_s \chi_s = \chi^{\mathrm{net}} \quad [\mathrm{cm\ s^{-1}}]$$

Woitke & Helling (2003)

Dust Moment Definition

$$\rho_{\rm gas} L_j(\vec{r},t) = \int_{V_l}^{\infty} f(V,\vec{r},t) V^{j/3} \mathrm{d}V$$

j = 0,1,2,3

$j^{\rm th}$ Volume integrated moment

Grain volume distribution · $j^{\rm th}$ Weighting in volume

Moment Conservation Equations

$$\frac{\partial\left(\rho_{\rm gas} L_j\right)}{\partial t} + \nabla\cdot\left(\rho_{\rm gas} L_j \mathbf{u}_{\rm d}\right) = V_l^{j/3} J_* + \frac{j}{3}\chi^{\rm net}\rho_{\rm gas} L_{j-1}$$

Dust moment time dependence

Advective flux

Nucleation

Surface growth/evaporation

Dust hydrodynamic velocity: $\mathbf{u}_{\rm d}$

Woitke & Helling (2003), Helling, Woitke & Thi (2008)

Element Conservation Equations

Local element abundance | Advection of un-condensed elements | Depletion from nucleation

$$\frac{\partial\left(n_{\langle H\rangle}\varepsilon_i\right)}{\partial t} + \nabla\cdot\left(n_{\langle H\rangle}\varepsilon_i\mathbf{u}_{\rm gas}\right) = -\nu_{x,0}N_l J(V_l)$$

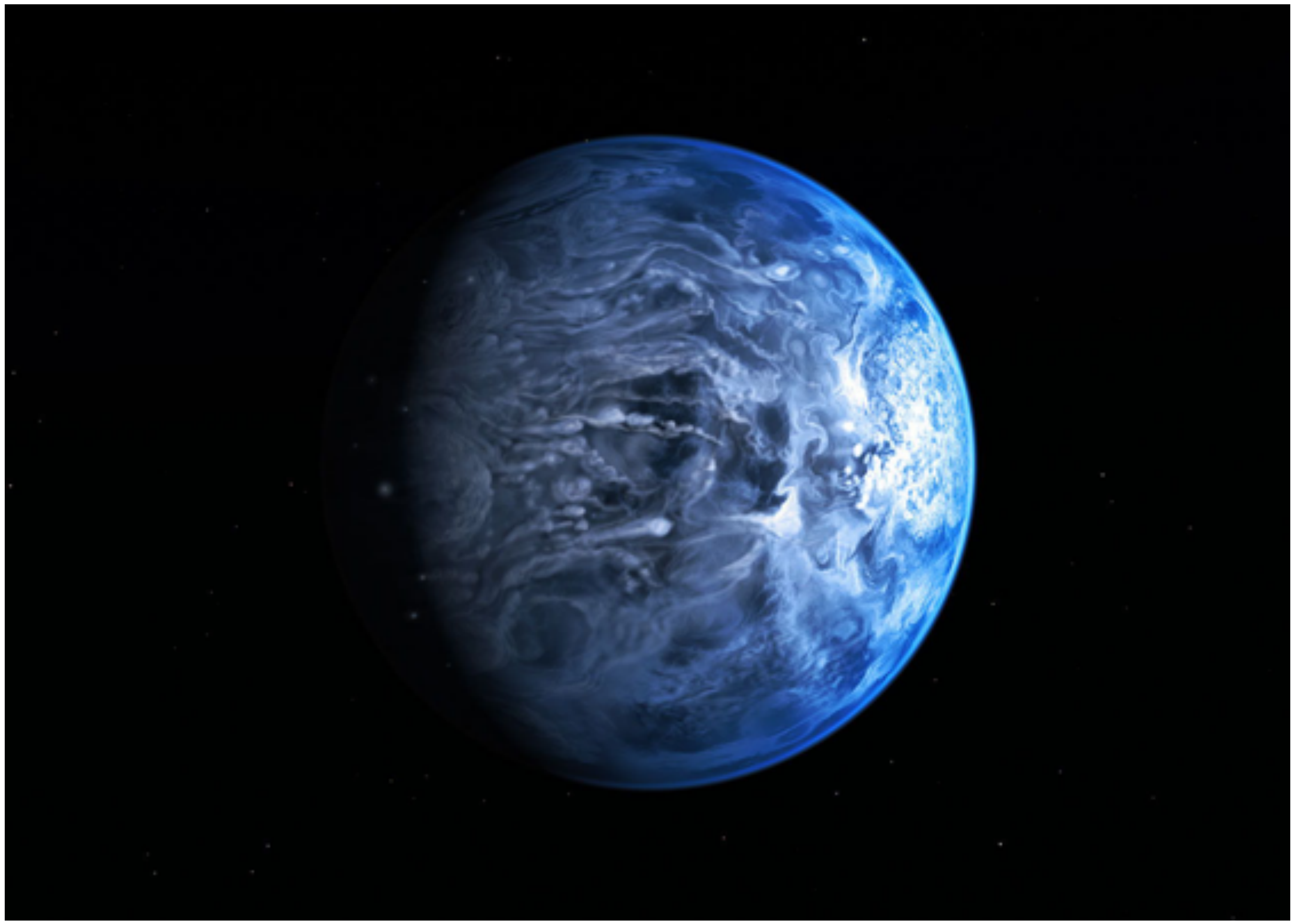
$$-\sqrt[3]{36\pi}\rho L_2\sum_{r=1}^{R}\frac{\nu_{x,s}n_r^{\rm key}v_r^{\rm rel}\alpha_r}{\nu_r^{\rm key}}\left(1-\frac{1}{S_r}\frac{1}{b_{\rm surf}^s}\right)$$

$S_r > 1$ Growth of material = element depletion

$S_r < 1$ Evaporation of material = element replenishment

Woitke & Helling (2003)

RHD + clouds test case: HD 189733b



Nasa/ESA
- "HD 189733b deep blue dot"

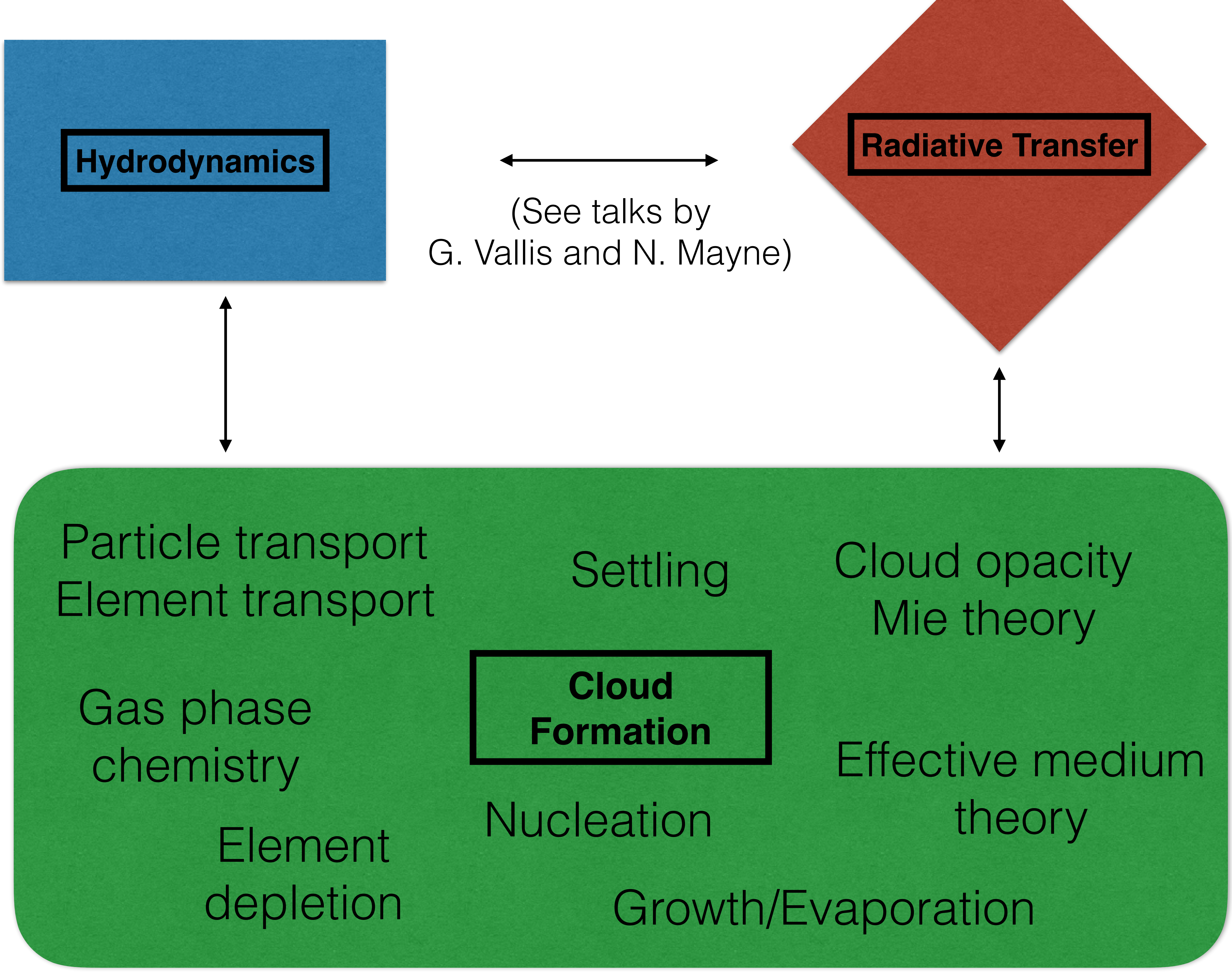
Hot Jupiter -
Mass: 1.138 M_J
Radius: 1.138 R_J
Semi-major axis: 0.03142 AU

Most observed exoplanet to date from radio to X-ray

Use **Dobbs-Dixon & Agol (2013)** RHD model framework

Add 3D cloud formation modules

Evolve conservation equations in time


Hydrodynamics
Radiative Transfer
(See talks by
G. Vallis and N. Mayne)
Particle transport
Element transport
Settling
Cloud opacity
Mie theory
Gas phase
chemistry
Cloud
Formation
Effective medium
theory
Nucleation
Element
depletion
Growth/Evaporation

Seed particles

TiO_2

Cloud formation species

TiO_2[s], SiO[s], SiO_2[s], $MgSiO_3$[s], Mg_2SiO_4[s]

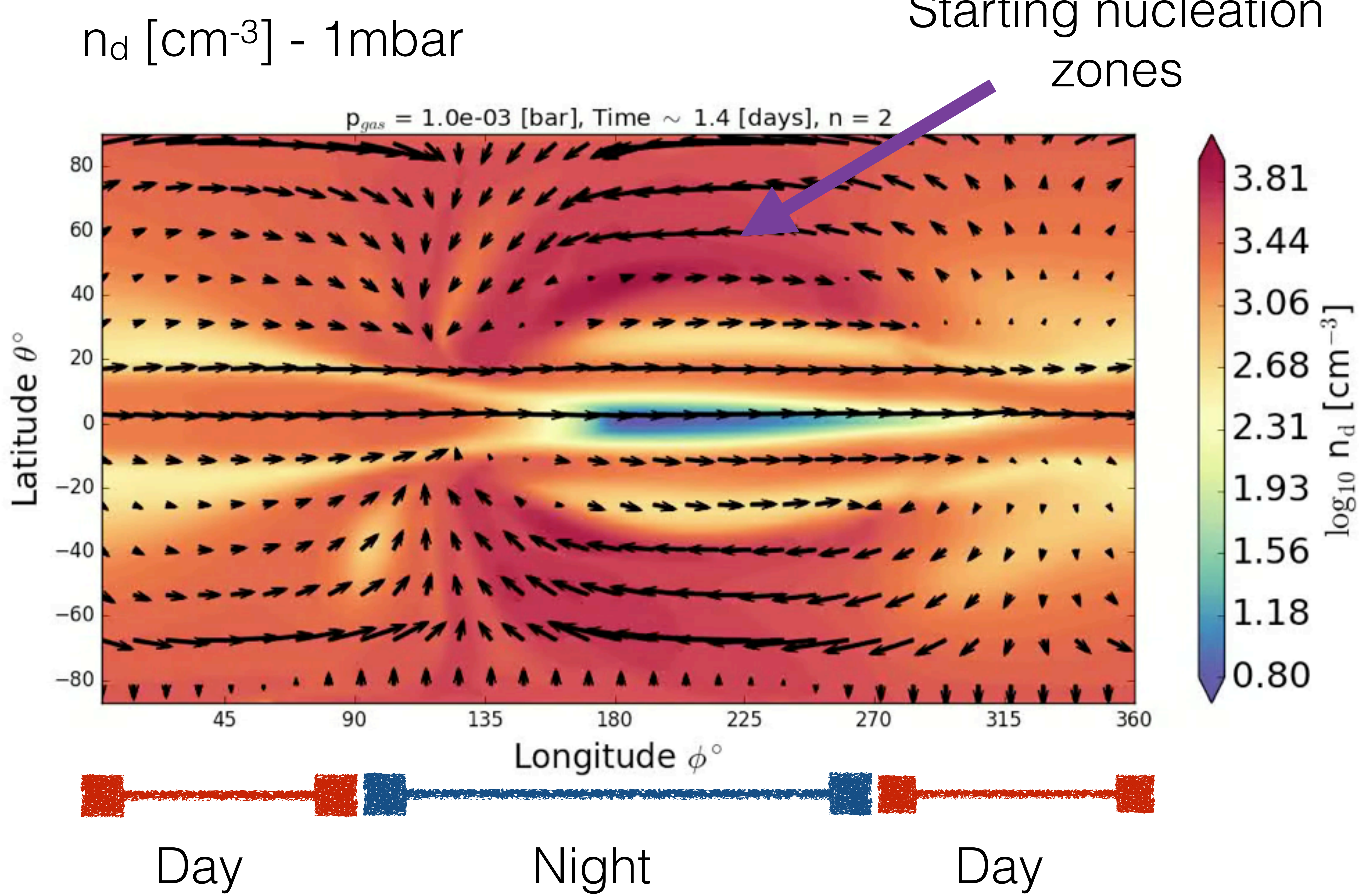
Element depletion

Ti, O, Si, Mg

Conservation equations

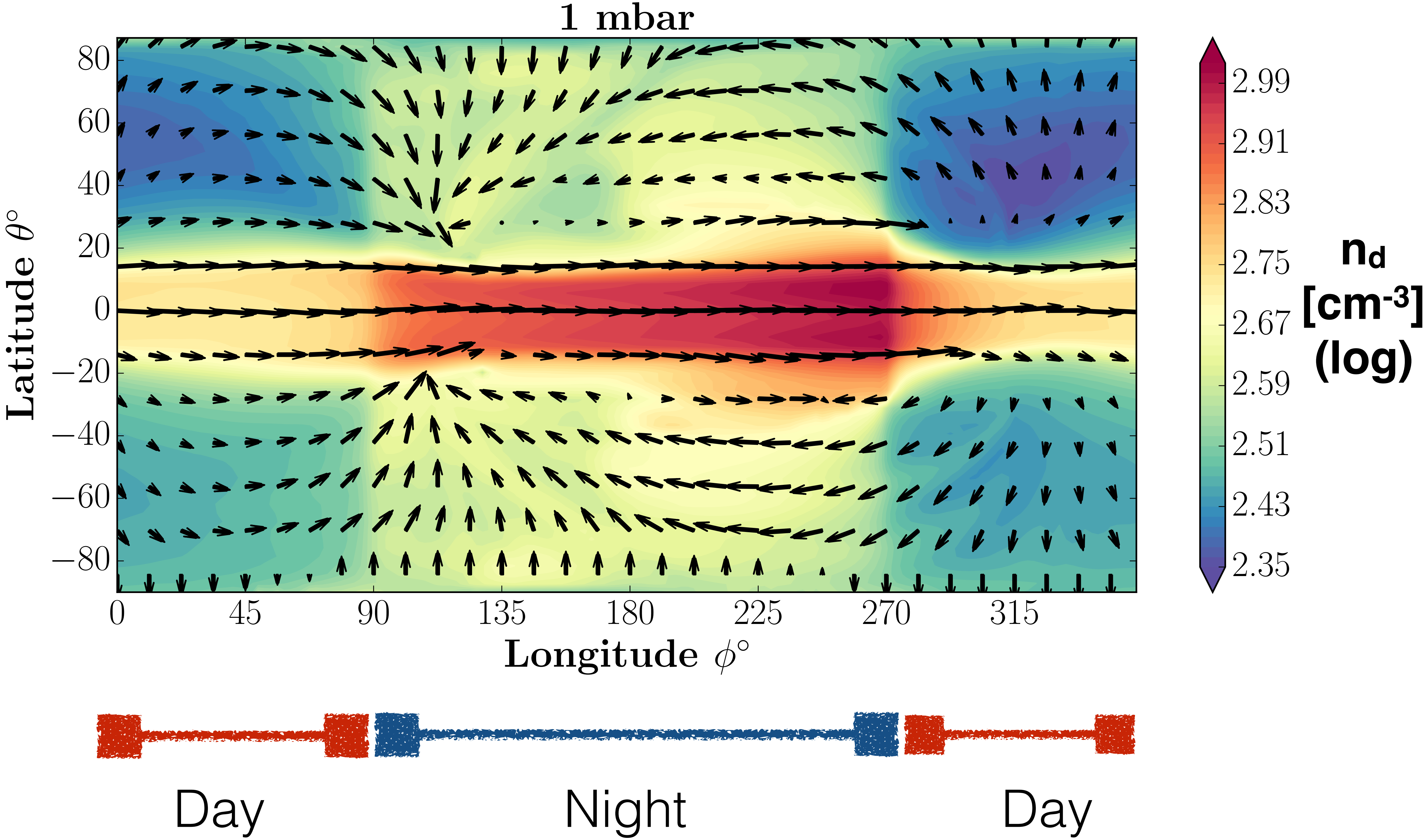
4 moments, 5 volume fractions, 4 element

Dynamic transport of cloud



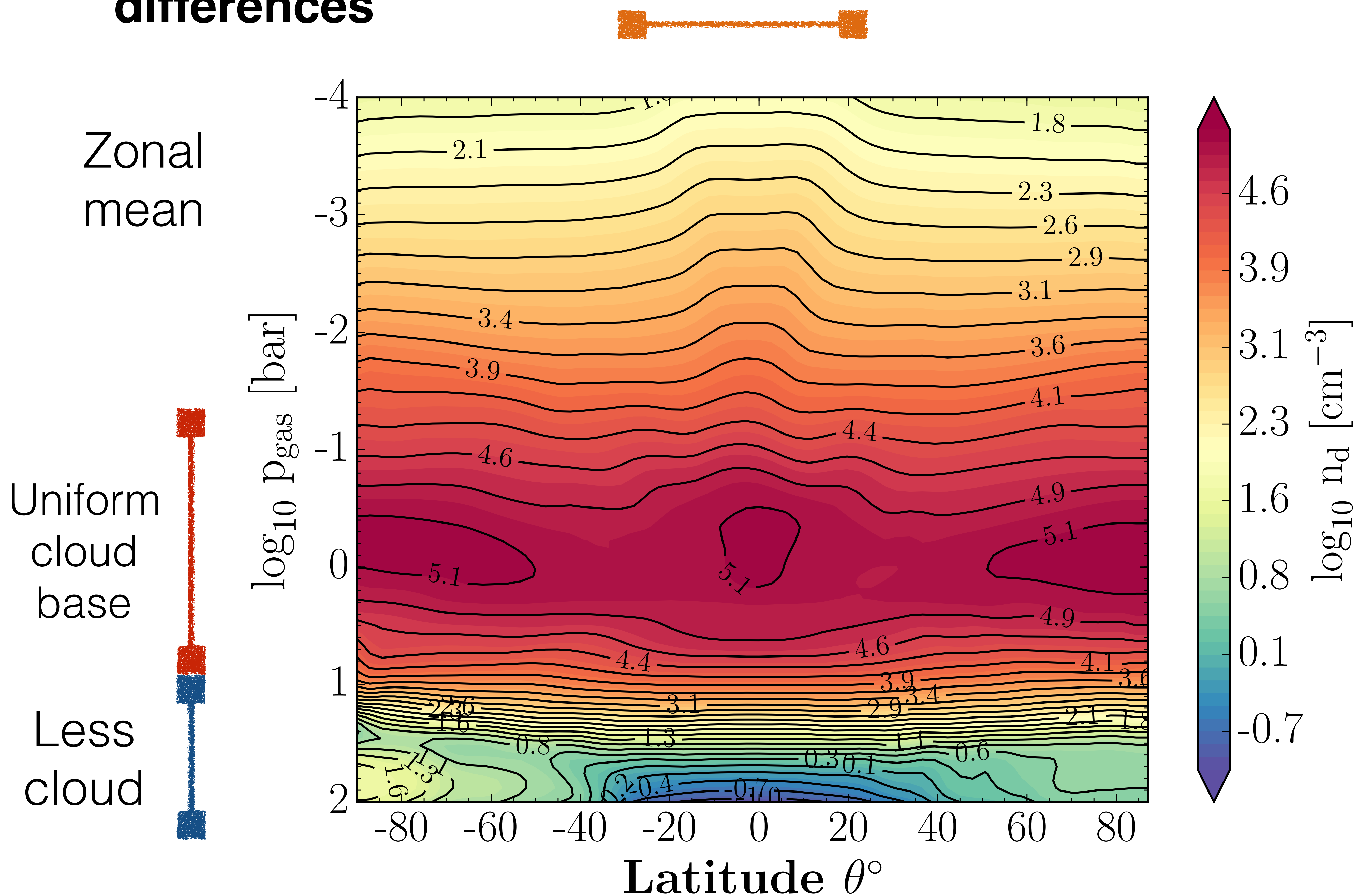
Global distribution of cloud particles

n_d [cm^{-3}] - 1mbar



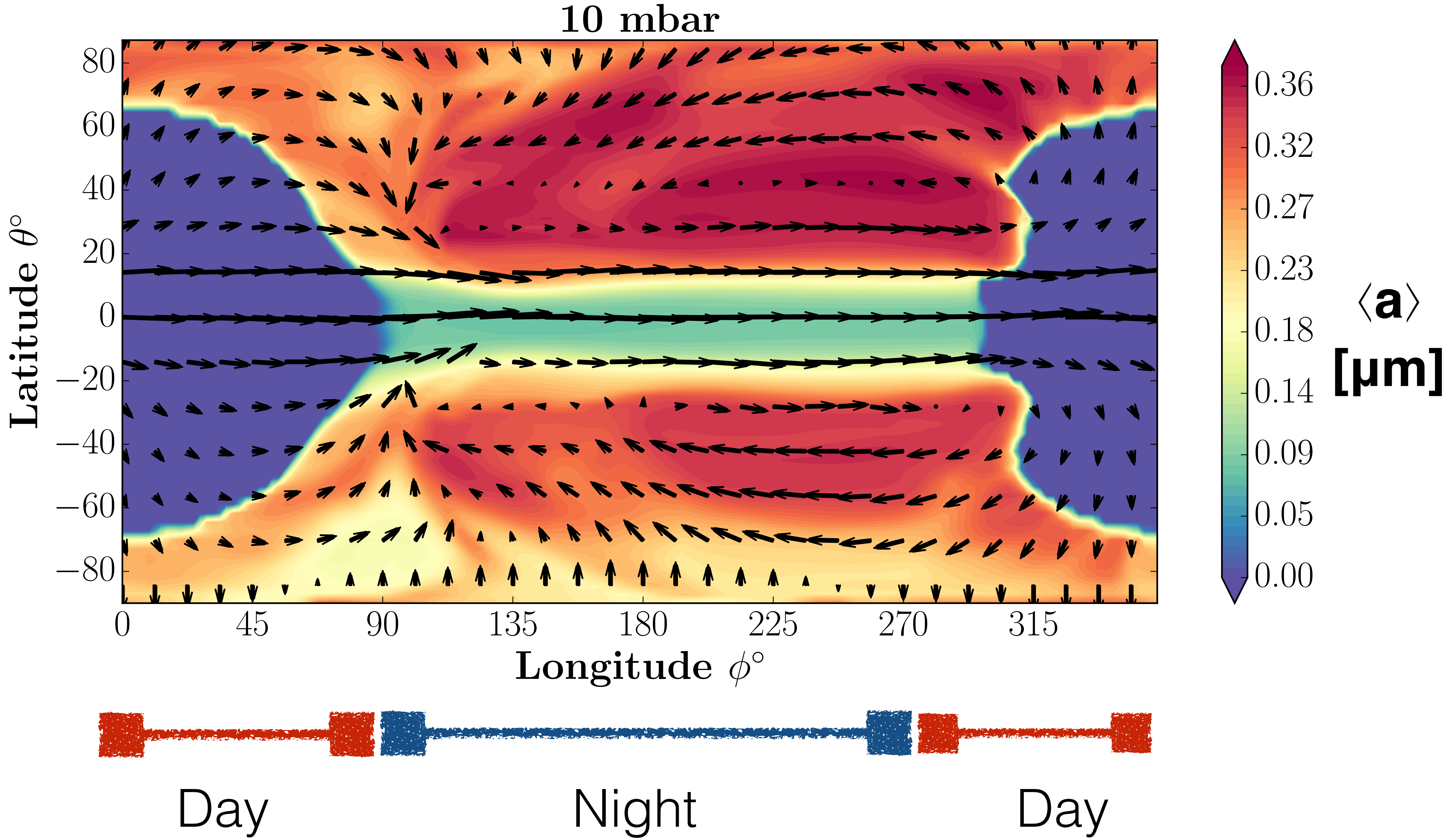
Latitude and depth differences

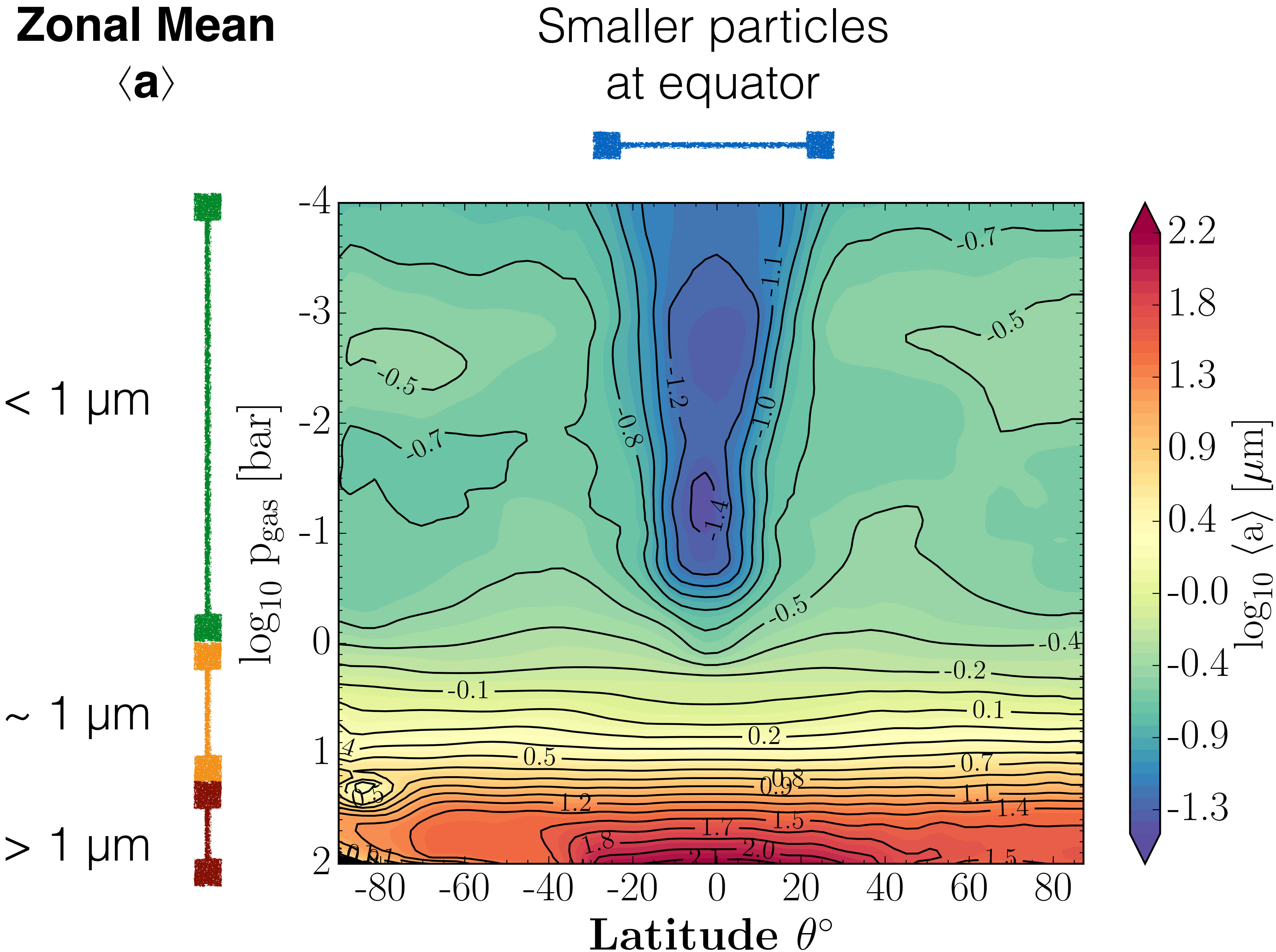
Equator more dense



Diversity of cloud particle sizes

⟨a⟩ - 10mbar





Zonal Mean
⟨a⟩
Smaller particles
at equator
< 1 µm
~ 1 µm
> 1 µm
log10 pgas [bar]
Latitude θ°
log10 ⟨a⟩ [µm]
2.2
1.8
1.3
0.9
0.4
-0.0
-0.4
-0.9
-1.3

Meridional Polar Slice

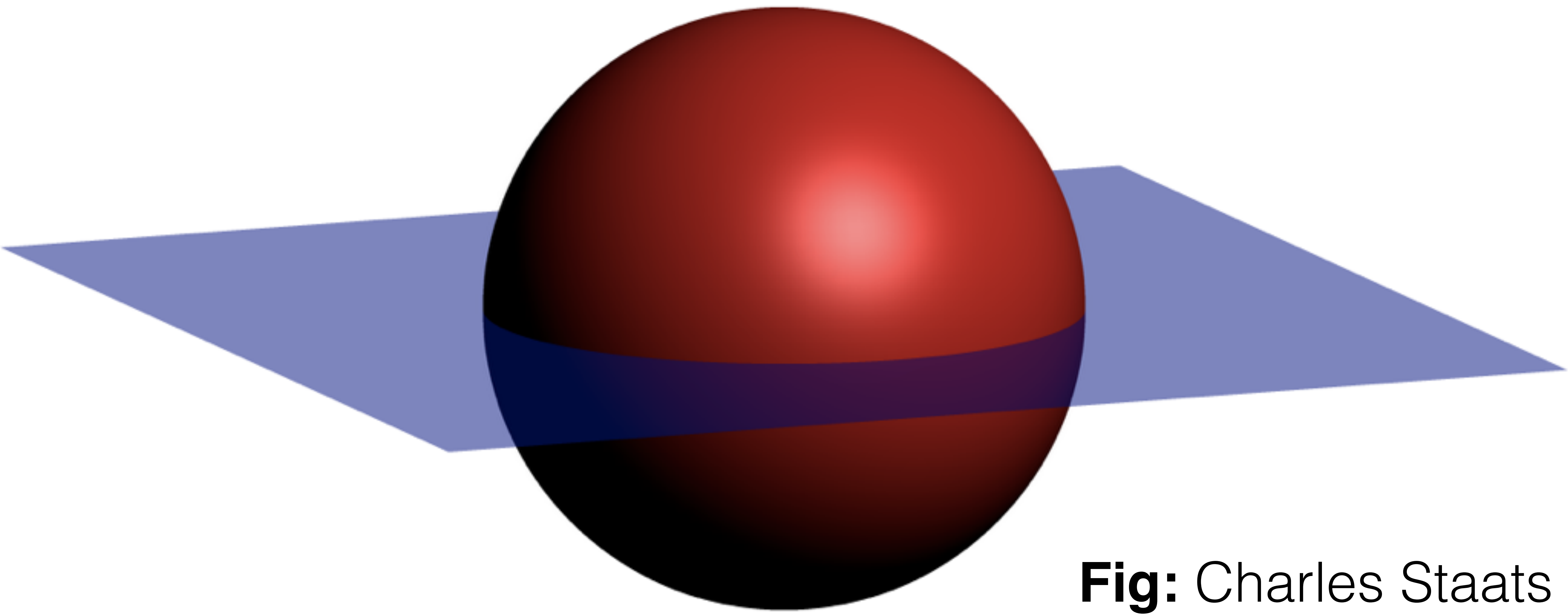
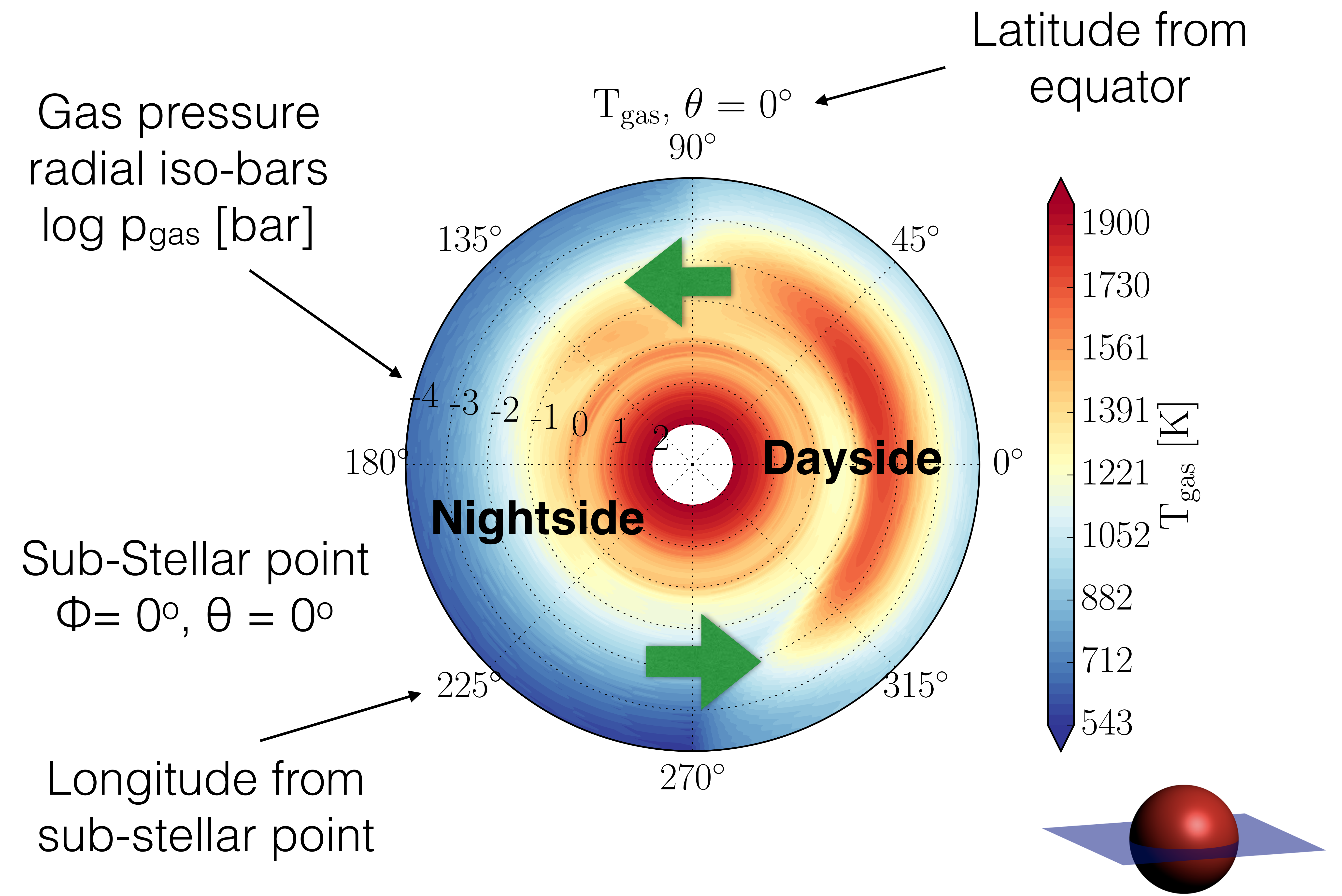


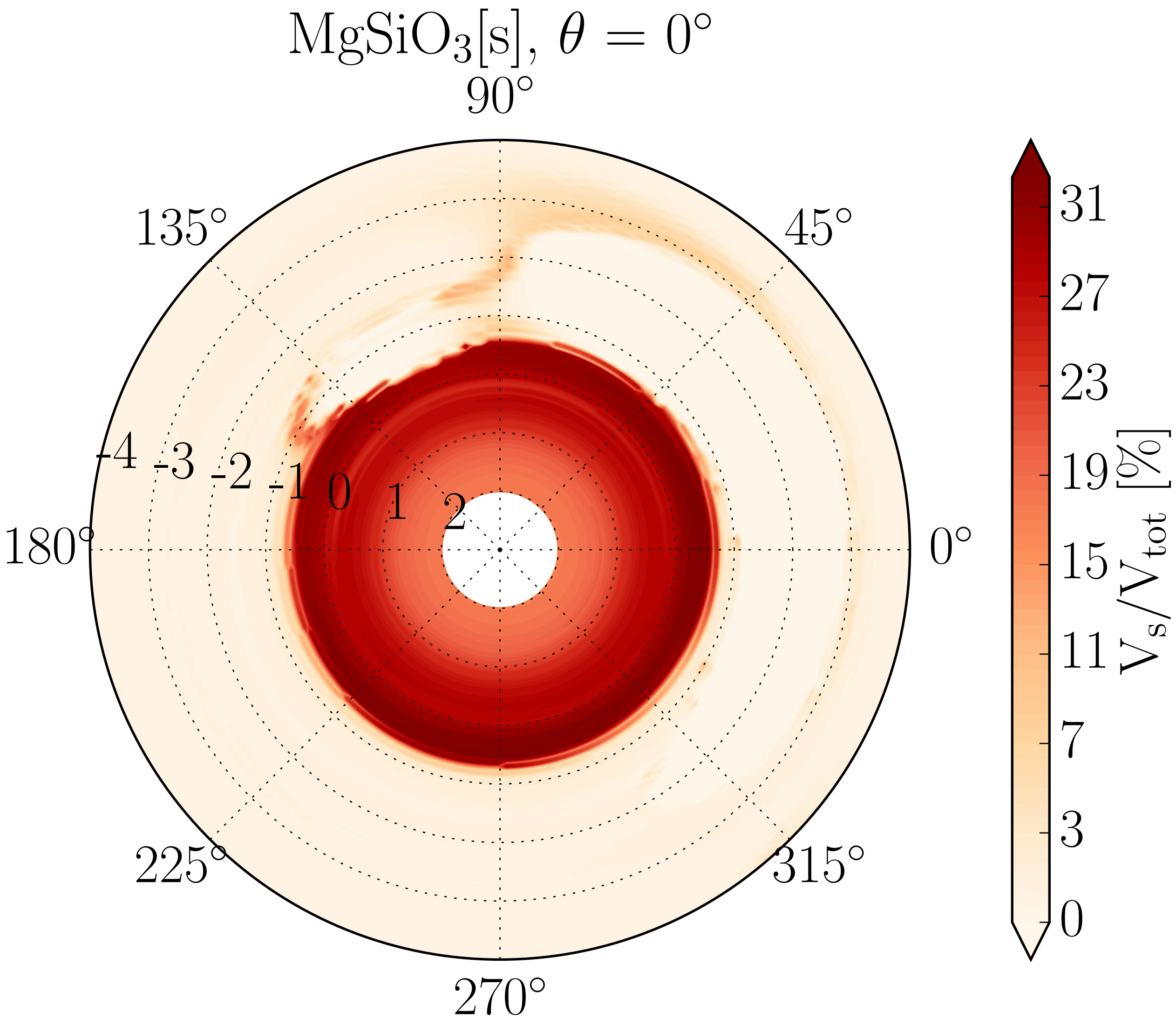
Fig: Charles Staats

Slice RHD spherical grid at a latitude
View results from a polar perspective

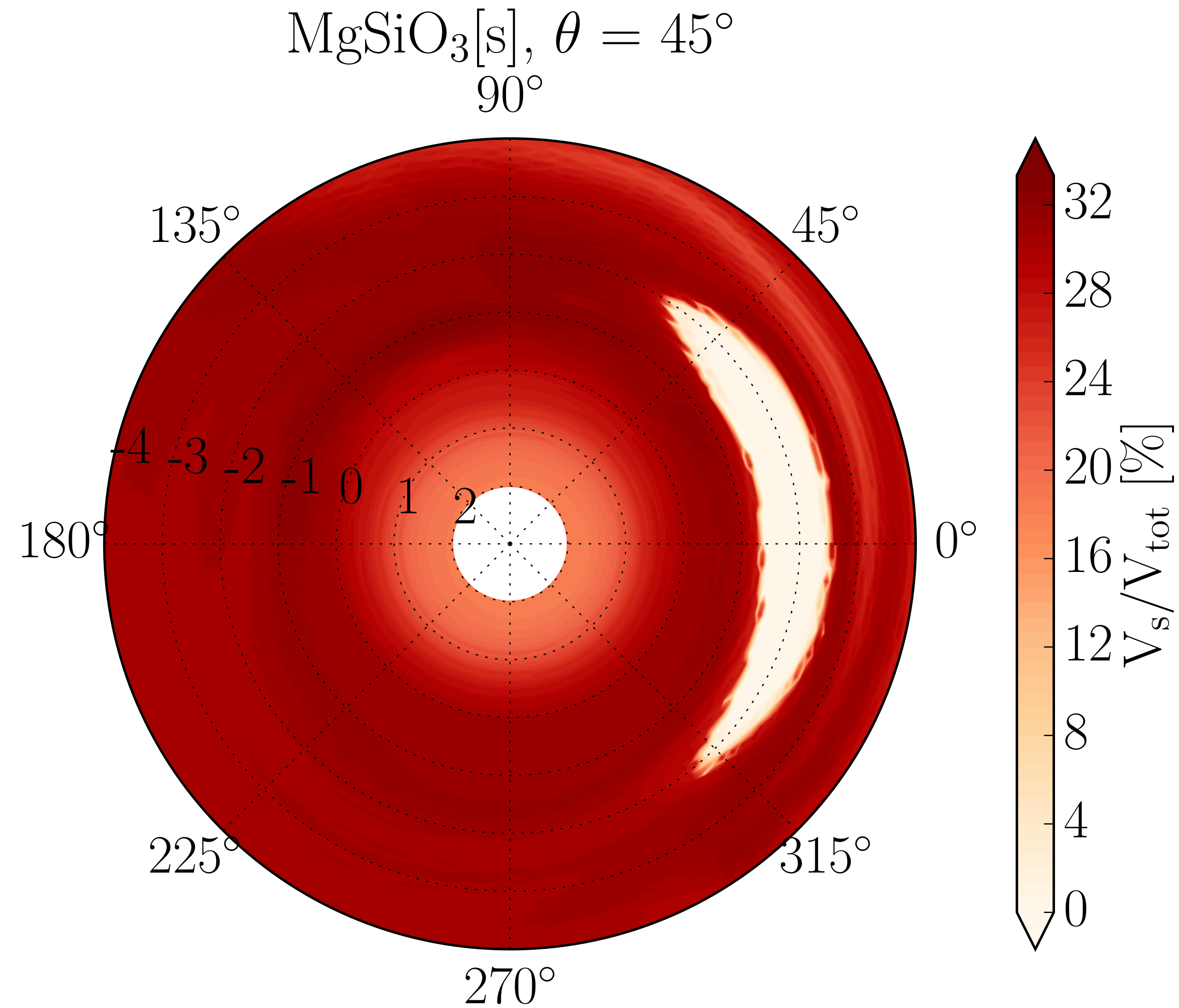


Latitude from equator
T_{gas}, $\theta = 0°$
Gas pressure radial iso-bars log p_{gas} [bar]
90°
135°
45°
180°
0°
225°
315°
270°
-4 -3 -2 -1 0 1 2
Dayside
Nightside
Sub-Stellar point
Φ= 0°, θ = 0°
Longitude from sub-stellar point
1900
1730
1561
1391
1221
1052
882
712
543
T_{gas} [K]

$MgSiO_3[s]$ Volume Fractions



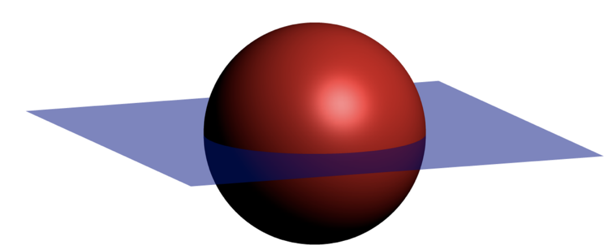
Equator



Mid-Latitude

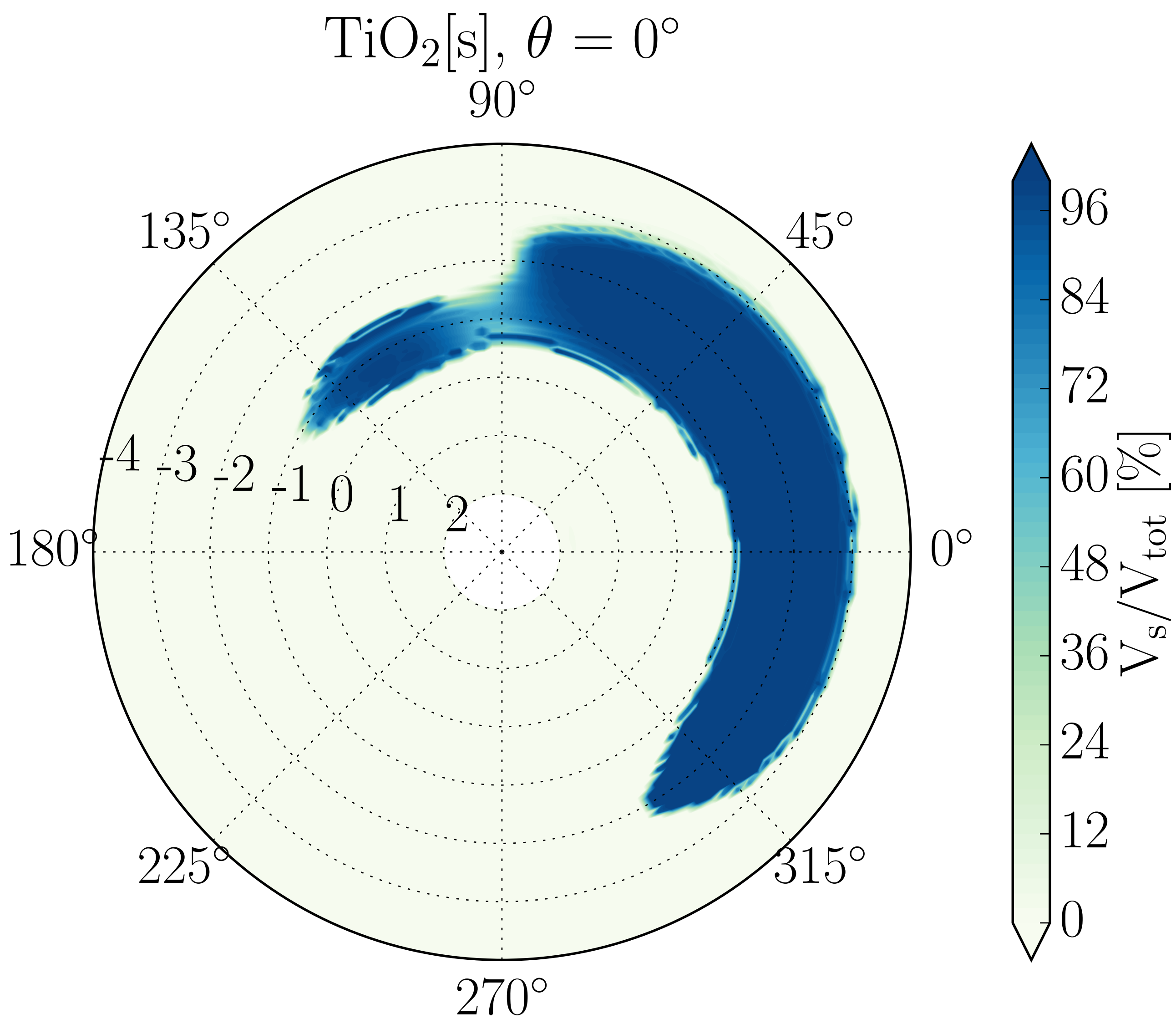
Dominant at mid-high latitudes

$MgSiO_3[s]$ + $Mg_2SiO_4[s]$ = 90+%

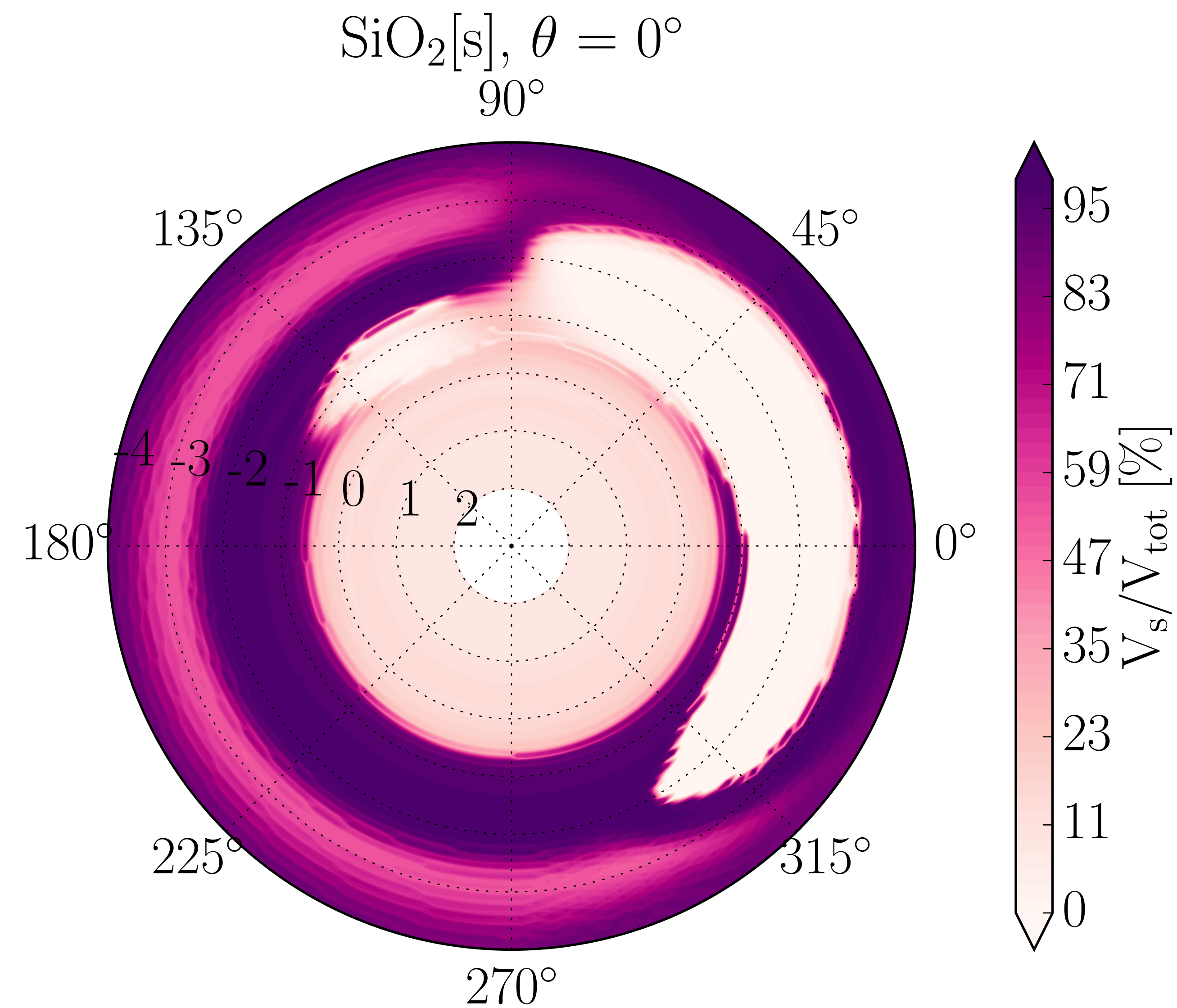


Equatorial Cloud Composition

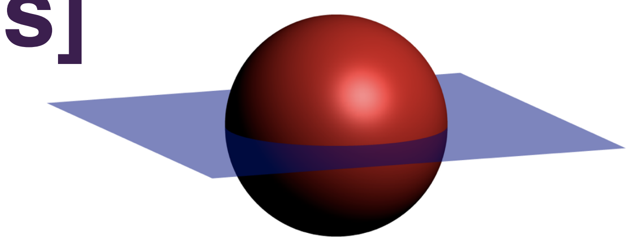
Equator, θ = 0°



Dayside **TiO_2[s]** seed particles

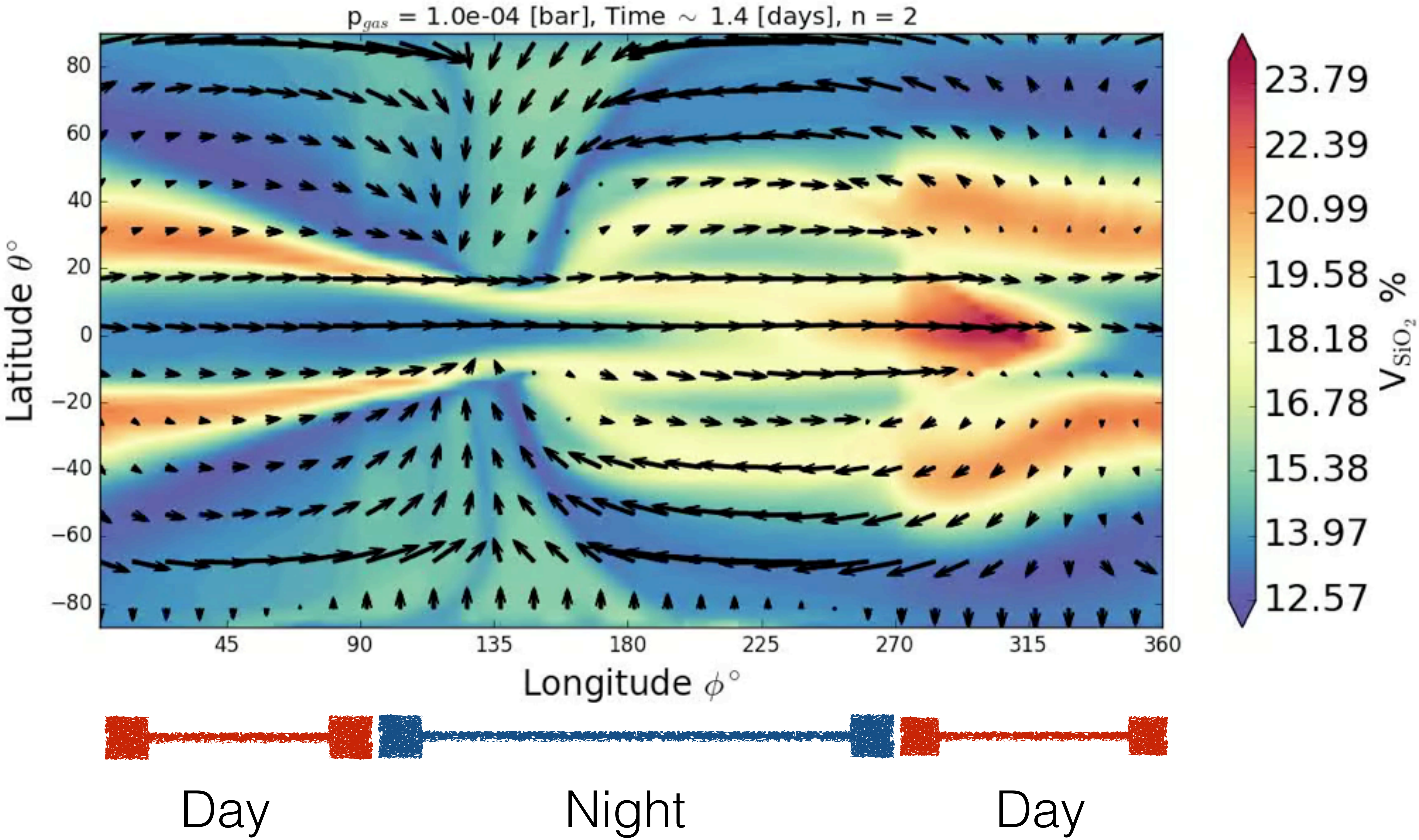


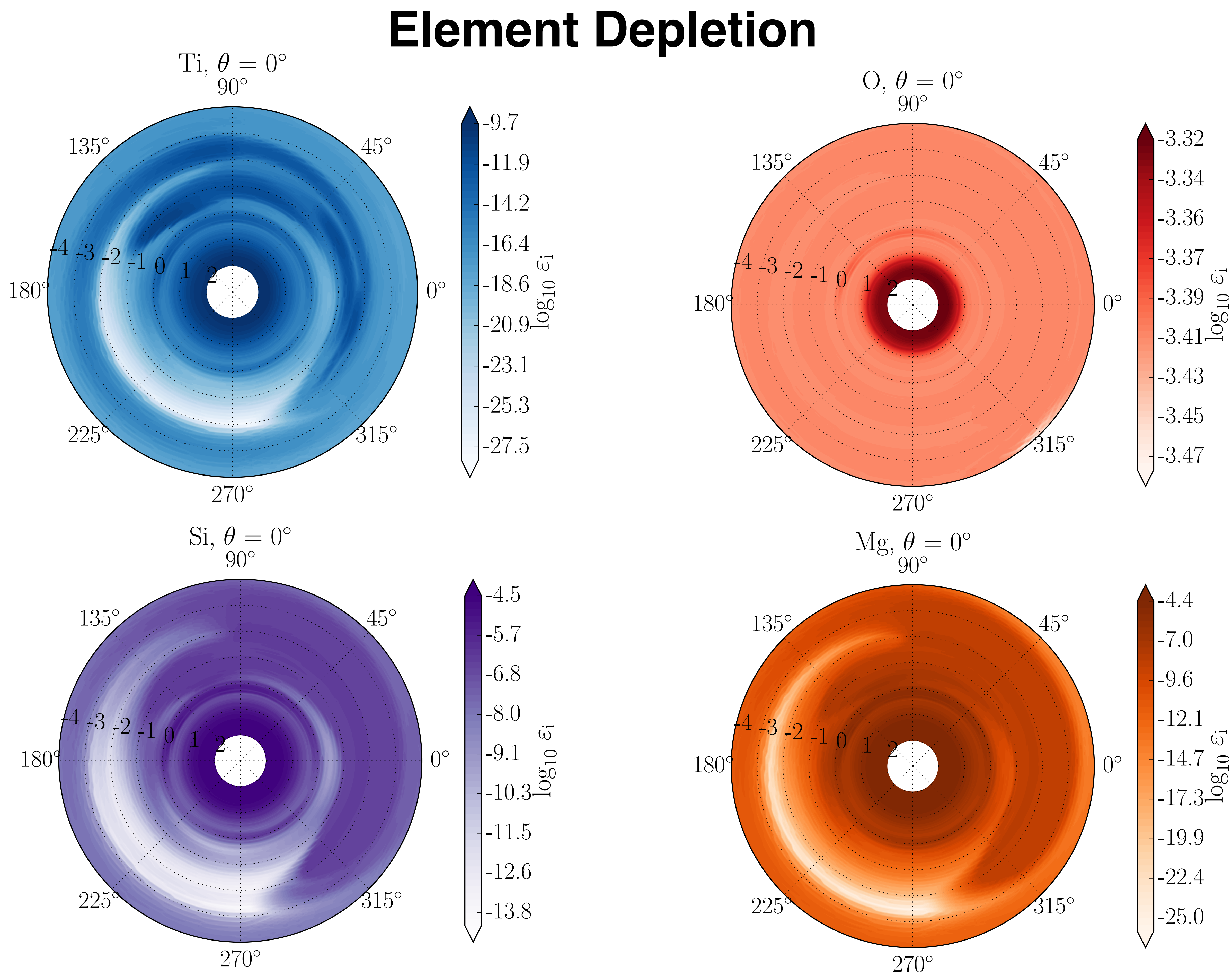
Equator dominated by **SiO_2[s]**



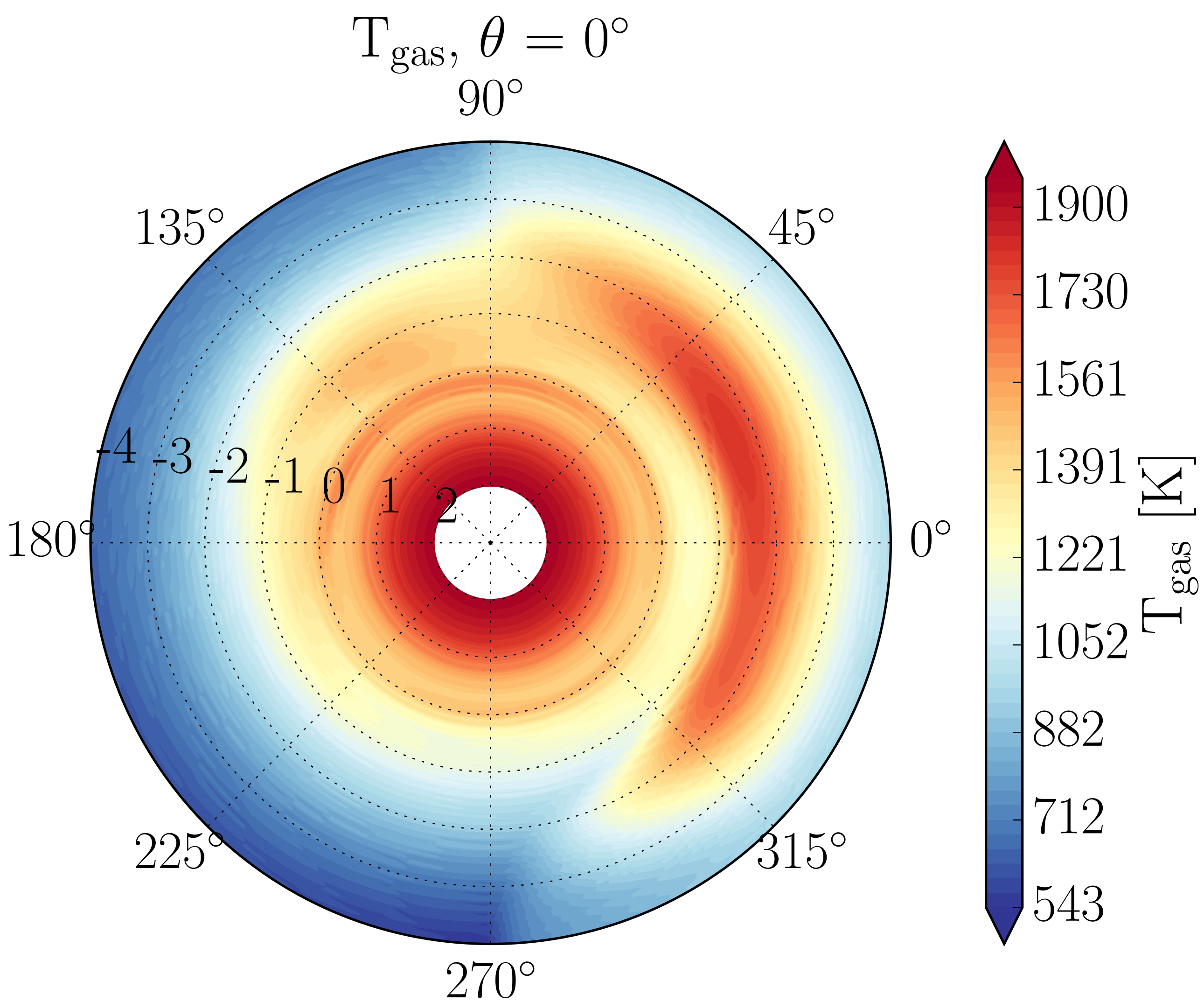
Formation of SiO_2[s] equatorial belt

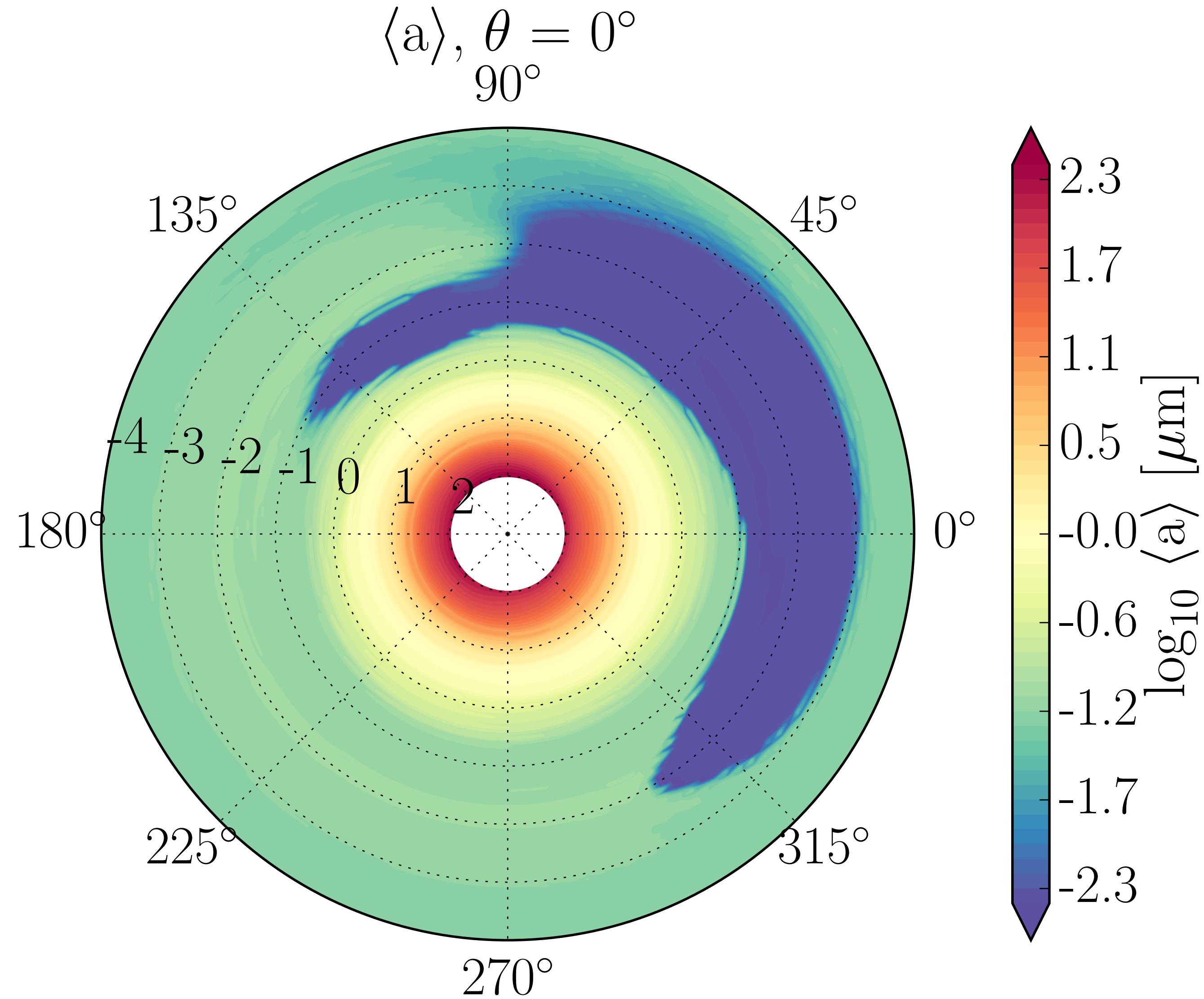
$V_{SiO2[s]}$ [%] - 0.1 mbar




Element Depletion
Ti, $\theta = 0°$
O, $\theta = 0°$
Si, $\theta = 0°$
Mg, $\theta = 0°$
90°
45°
135°
0°
180°
225°
315°
270°
-4
-3
-2
-1
0
1
2
$\log_{10} \varepsilon_i$
-9.7
-11.9
-14.2
-16.4
-18.6
-20.9
-23.1
-25.3
-27.5
-3.32
-3.34
-3.36
-3.37
-3.39
-3.41
-3.43
-3.45
-3.47
-4.5
-5.7
-6.8
-8.0
-9.1
-10.3
-11.5
-12.6
-13.8
-4.4
-7.0
-9.6
-12.1
-14.7
-17.3
-19.9
-22.4
-25.0

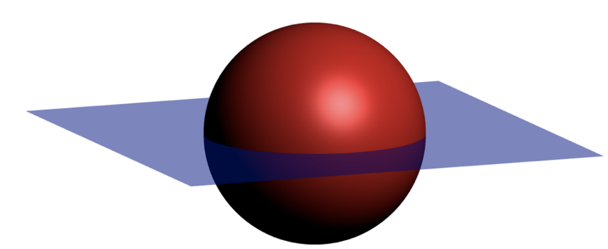
Cloud Formation Cycle



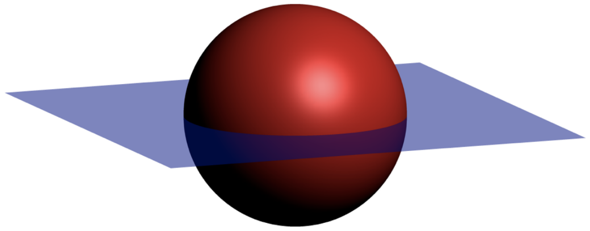


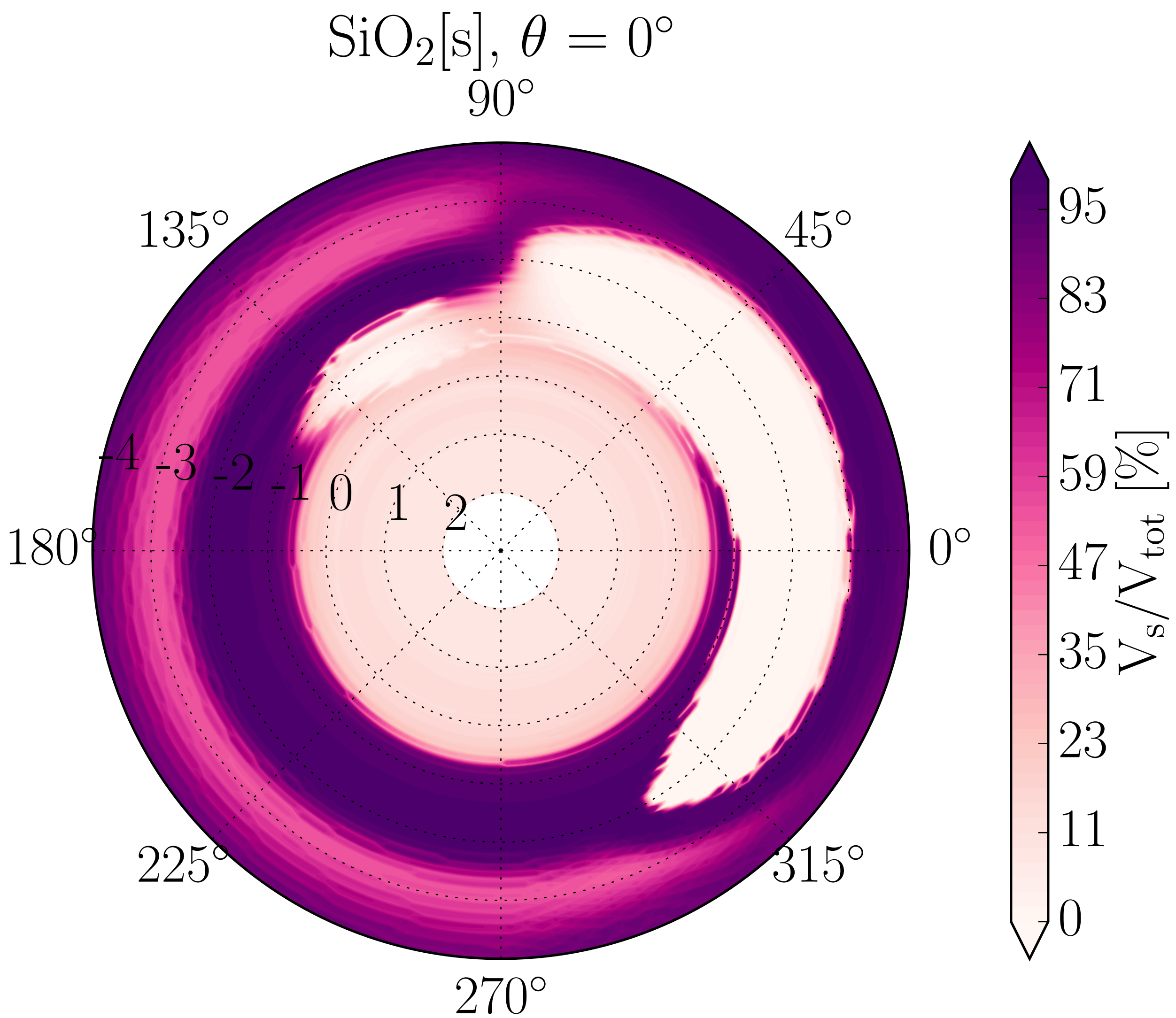
Hot gas transported to nightside

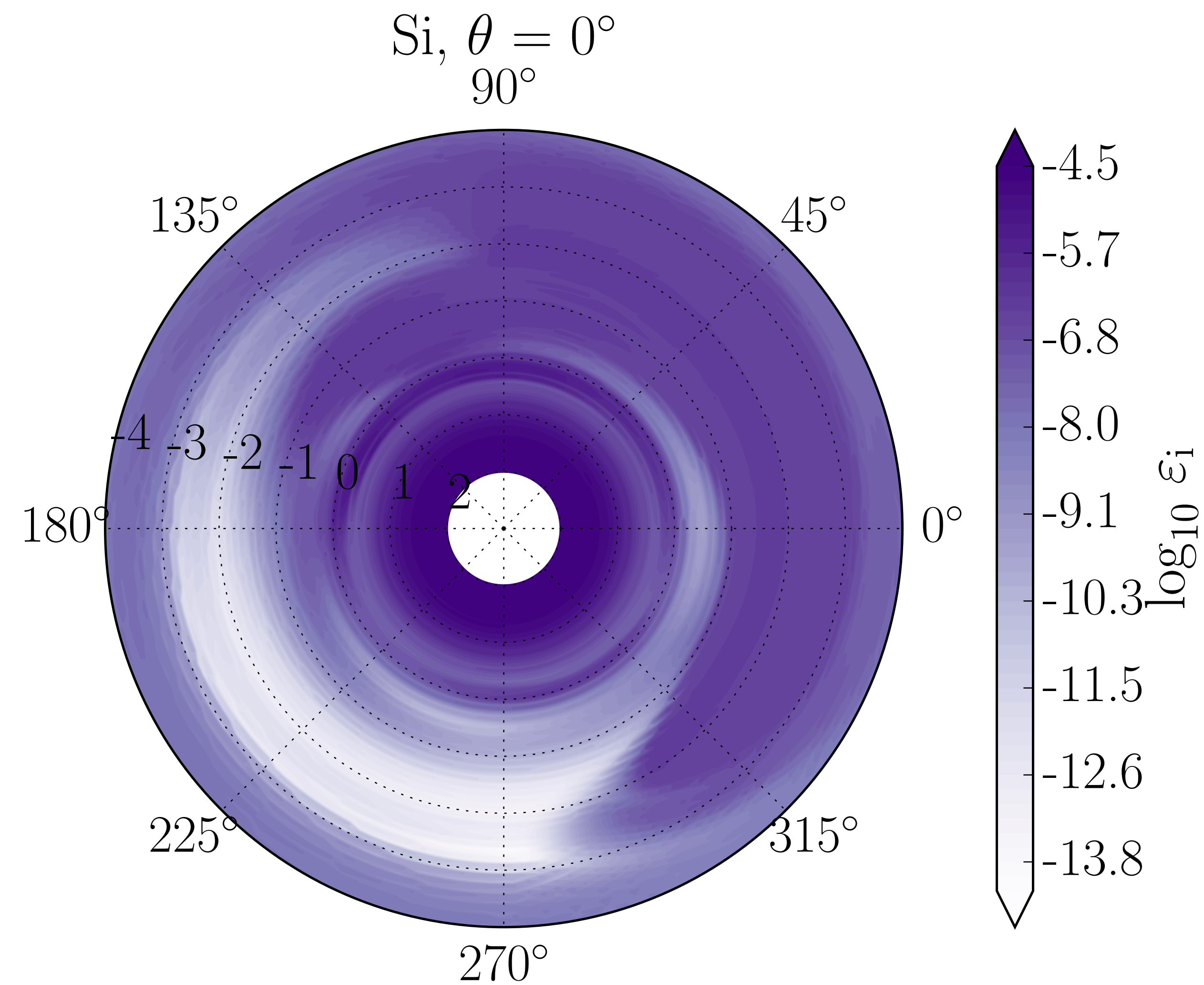
Smaller particles at dayside and terminator



Cloud Formation Cycle







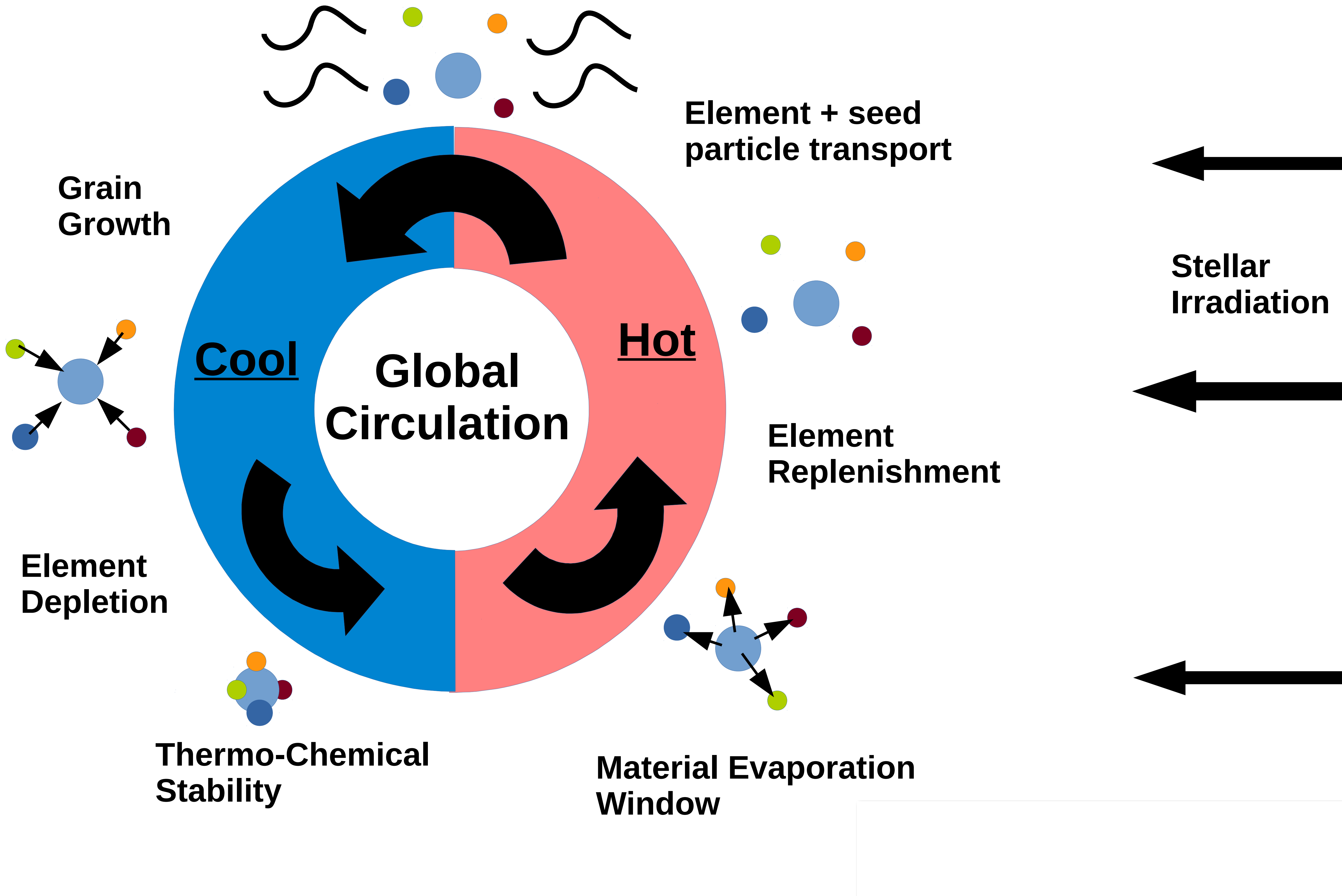
Evaporation of material
Φ ~ 270°-315°

Growth of material
Φ ~ 90°-180°

Nightside replenished by winds

Severe depletion nightside & Φ ~ 270° terminator

“Reduce *(gaseous elements)* - Reuse *(seed particles)* - Recycle *(regrow grains)*”



More results:

Velocity structure

Temperature bumps - cloud backwarming

Gas vs Cloud opacity - radiative effects

Near future results:

Transit spectra, phase curves, dayside luminosities

(Preliminary results look promising)

Optical scattering of cloud particles: Kepler-7b?

Summary & Conclusions

Interplay between hydrodynamics and cloud formation leads to a complicated inhomogeneous cloud structure

A cycle of element depletion and replenishment from particle growth and evaporation is present, driven by the equatorial jet

Clear differences between night and day cloud properties

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Charge processes in planetary atmospheres LEAP

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