Exoplanetary Atmospheres: Theory and Simulation

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UNIVERSITÄT BERN

CSH CENTER FOR SPACE AND HABITABILITY

Collaborators:

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Chris Hirata (Caltech/Ohio State)

Sid Mishra (ETH)

Geneva exoplanet group

Cambridge exoplanet group

Exeter exoplanet group

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Fact:

exoplanet discovery is an established enterprise

Frontier:

exoplanet characterization (atmospheres)

Why do we study atmospheres?

1. Component of the climate system
2. Target for remote sensing
3. Sanctuary for and signature of life

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We need to understand #1 and #2
as we attempt to detect #3

Does the Solar System provide good templates for atmospheres in general?

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- **Super Earths**: novel architectures, some fraction probably have hydrogen-dominated envelopes.
- **Highly-irradiated exoplanets**: different dynamical, chemical regimes of atmospheres.
- **Directly-imaged exoplanets**: young gas giants, self-luminous from their remnant heat of formation.

It certainly depends on the question one is asking, but for the current inventory of exoplanets, the Solar System is not a good guide.

I. Observational Motivation

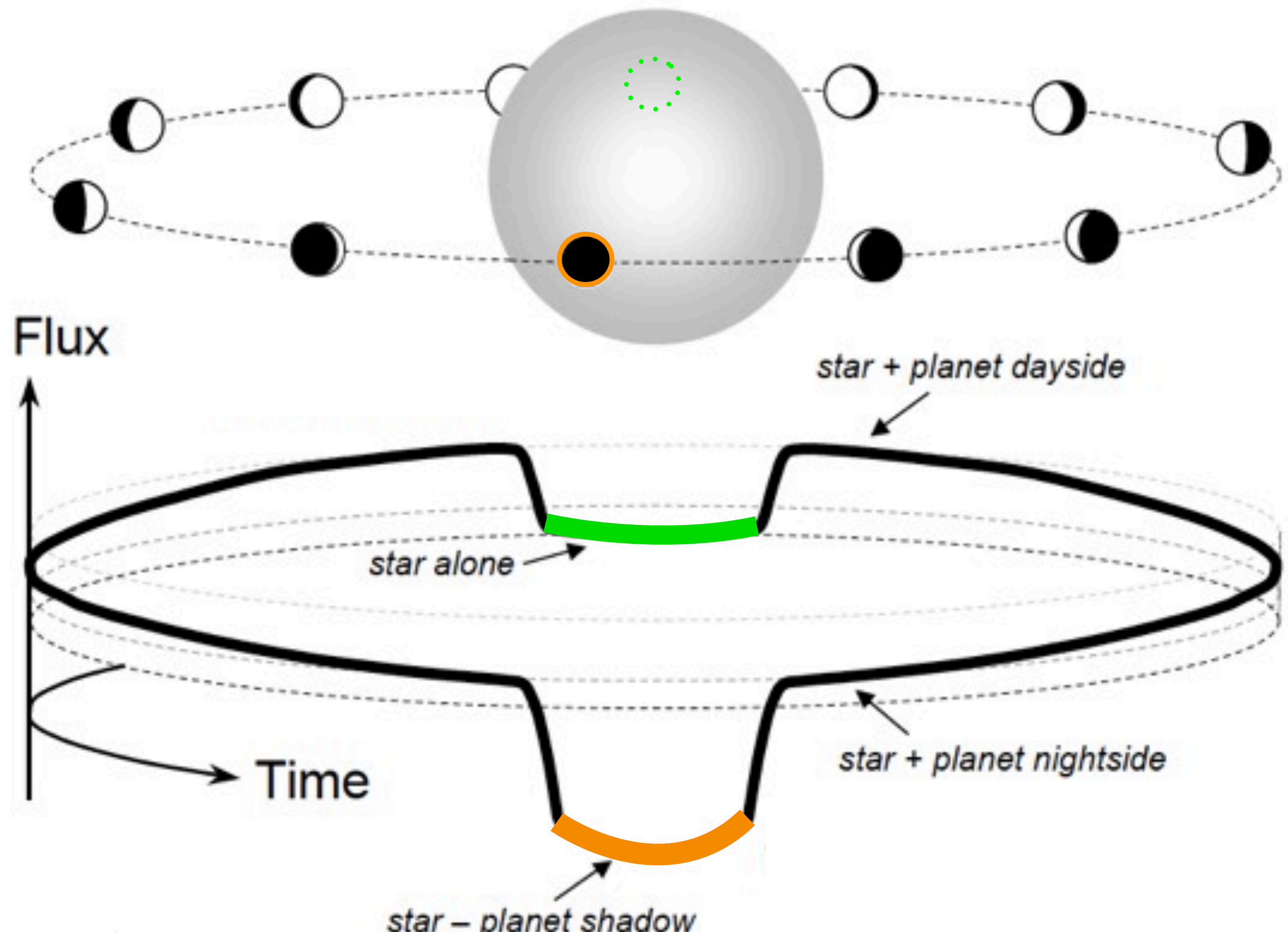
II. Theory

III. Simulation

IV. Future Perspectives

I. Observational Motivation

Transits and eclipses



Transit:
exoplanet obscures star
(absorption spectrum)

Eclipse:
star blocks out exoplanet
(emission spectrum)

Original schematic from Winn (2010)

Observational motivation: transit spectra

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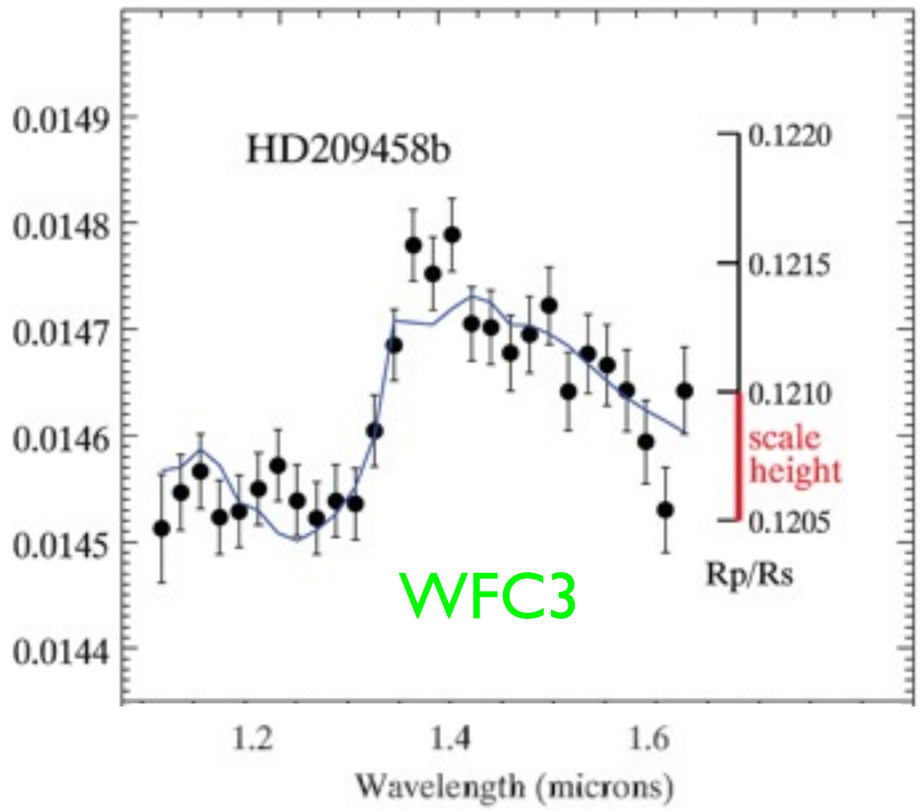
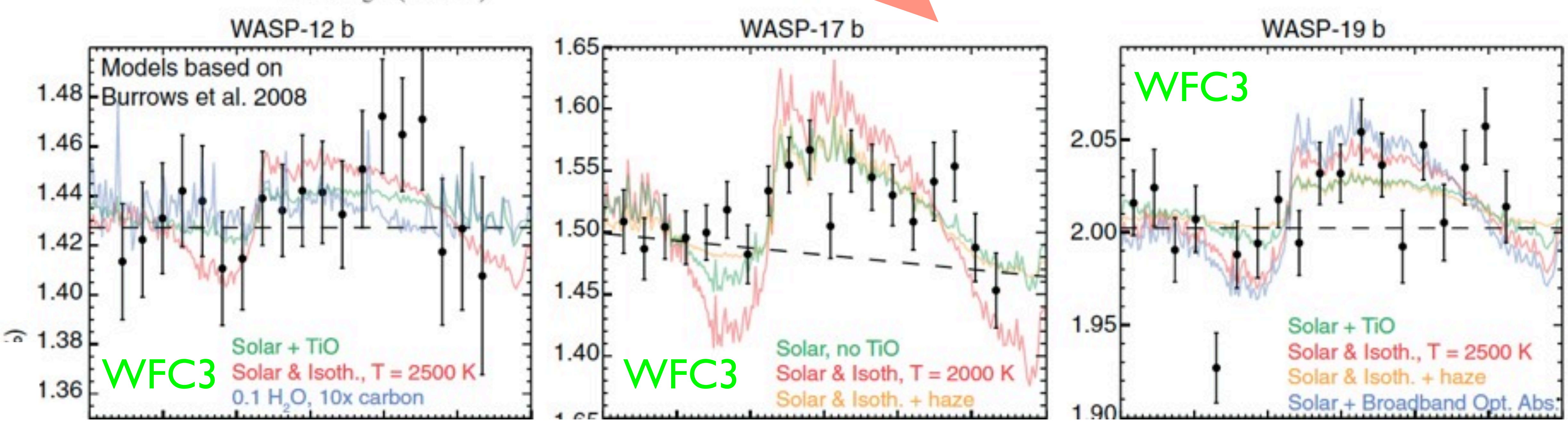


Model-independent detection of water?
(Deming et al. 2013)

Water signals diluted by clouds?
(Mandell et al. 2013)



See also Beaulieu et al. (2010)

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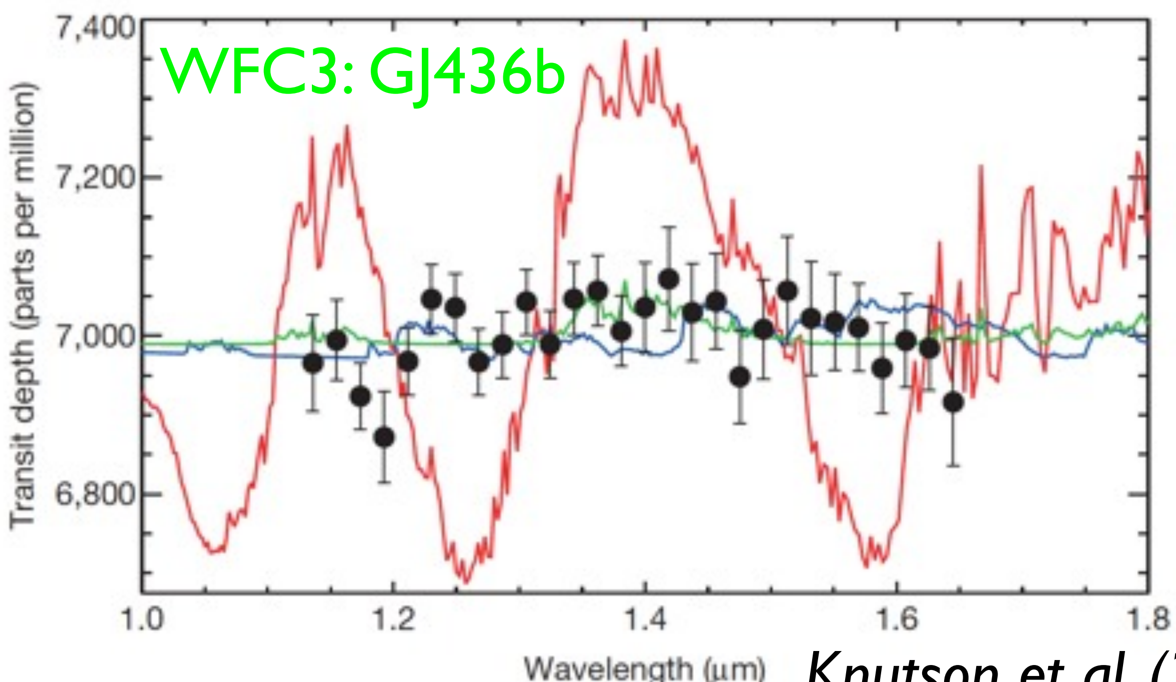
Observational motivation: transit spectra

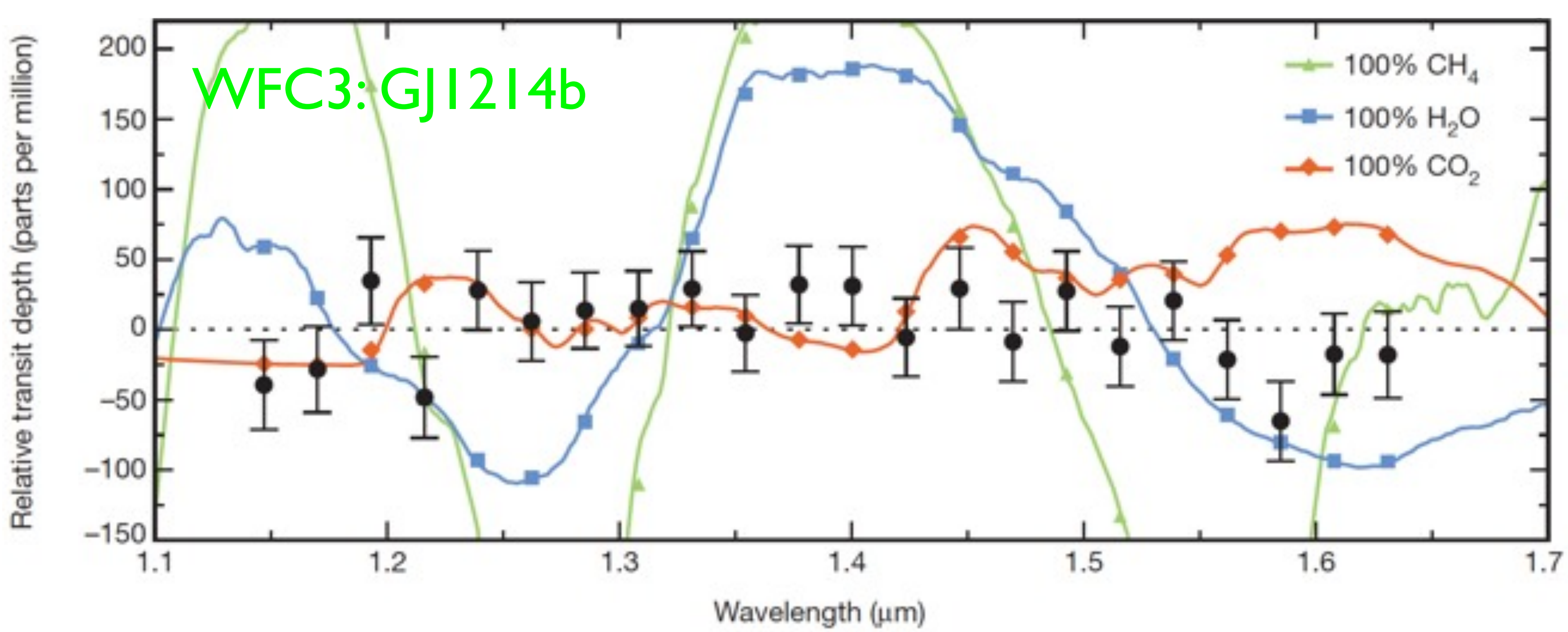


Knutson et al. (2014)

Cloudy atmospheres?

(Very expensive flat lines from HST)

Interpretation becomes very degenerate!

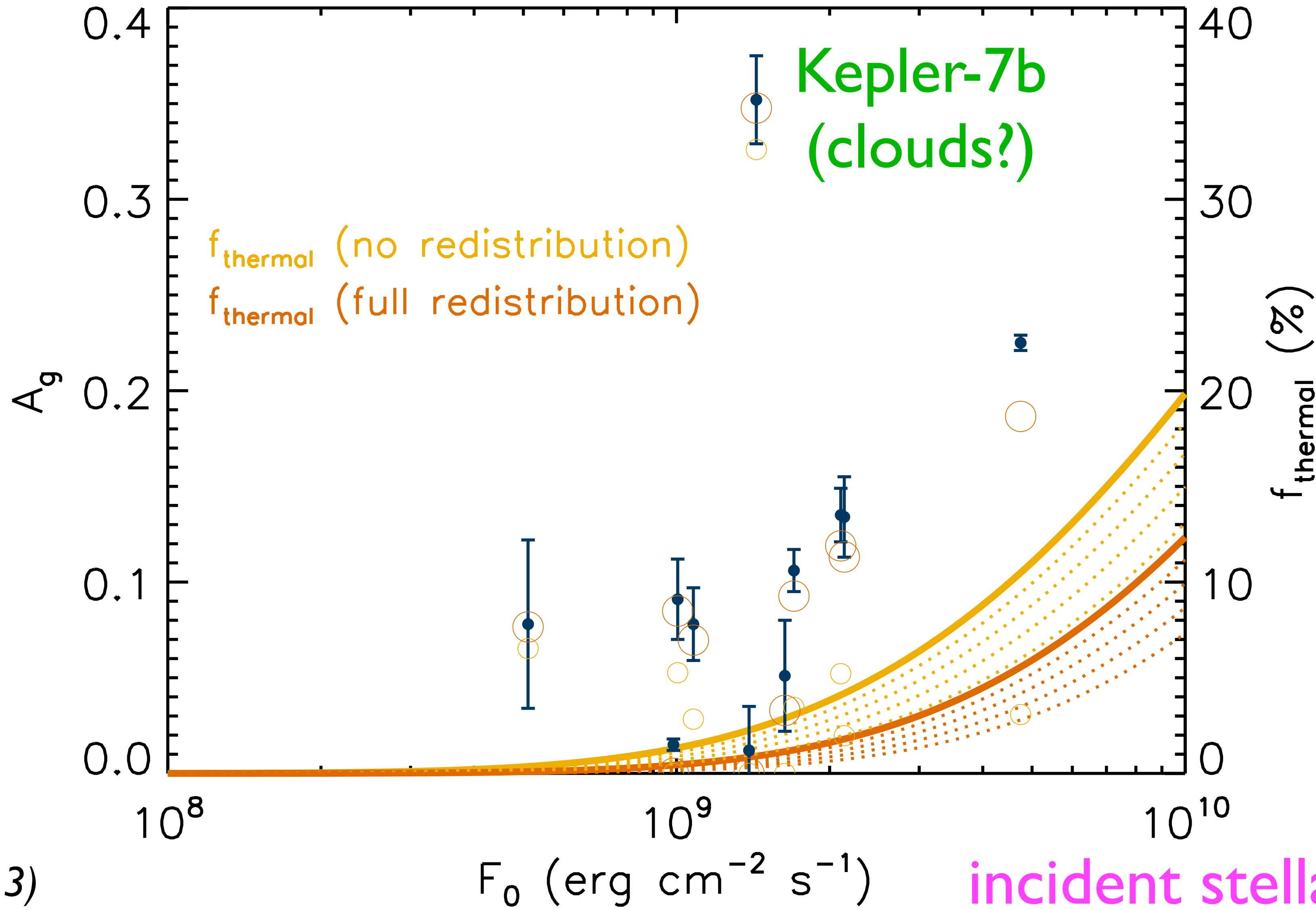


Kreidberg et al. (2014)

Observational motivation: albedos

geometric albedo

(Kepler bandpass)

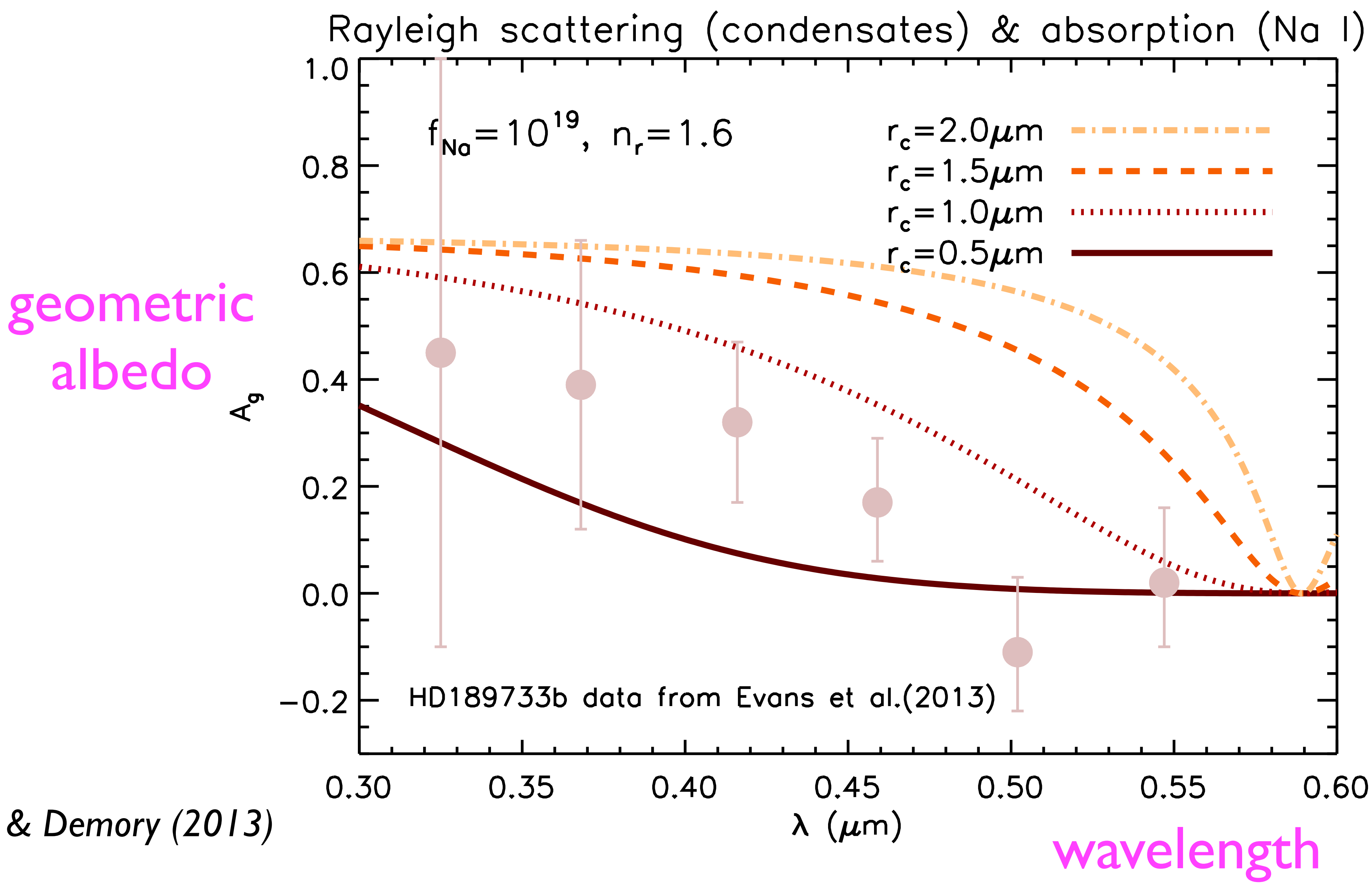


Heng & Demory (2013)

incident stellar flux

The albedo of an exoplanet determines the energy budget available to its atmosphere, hence its thermal structure, dynamics, chemistry, etc.

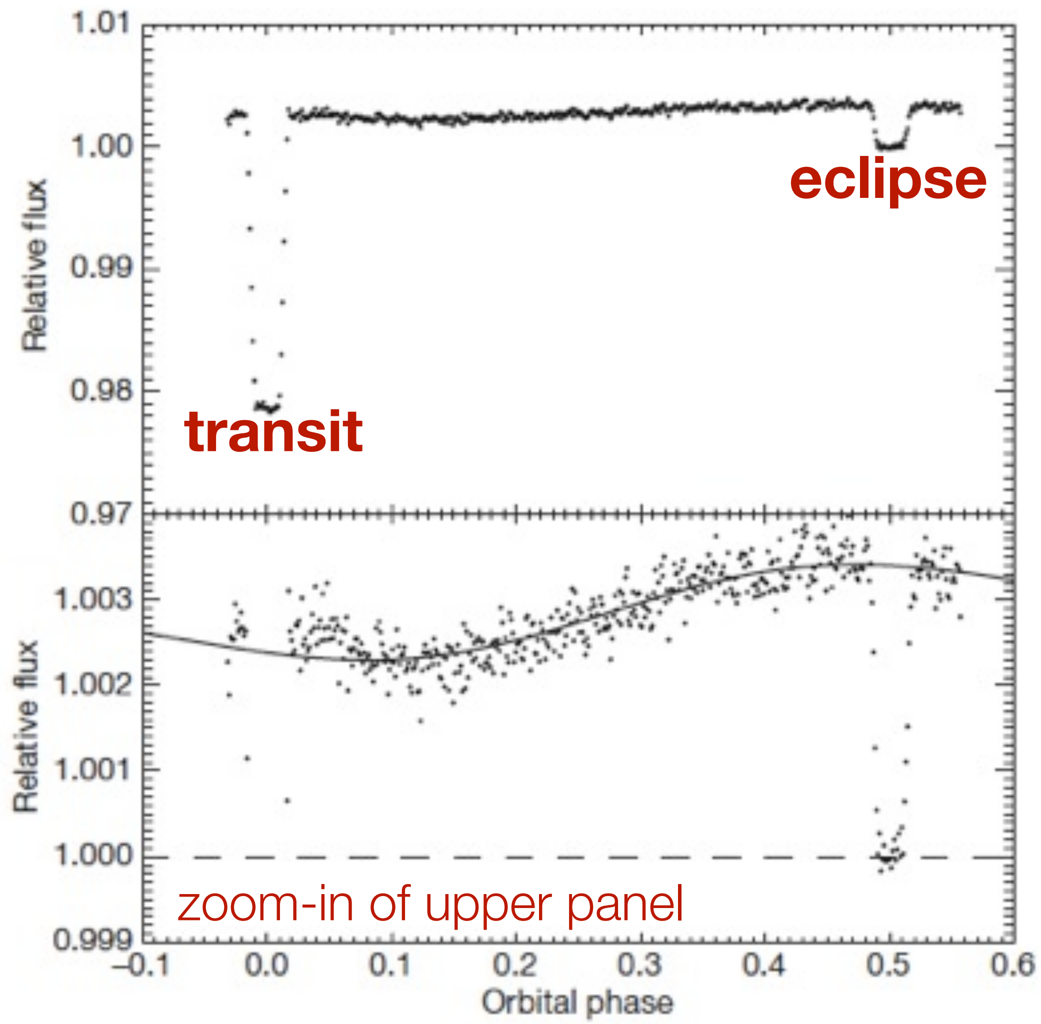
Observational motivation: albedo spectrum

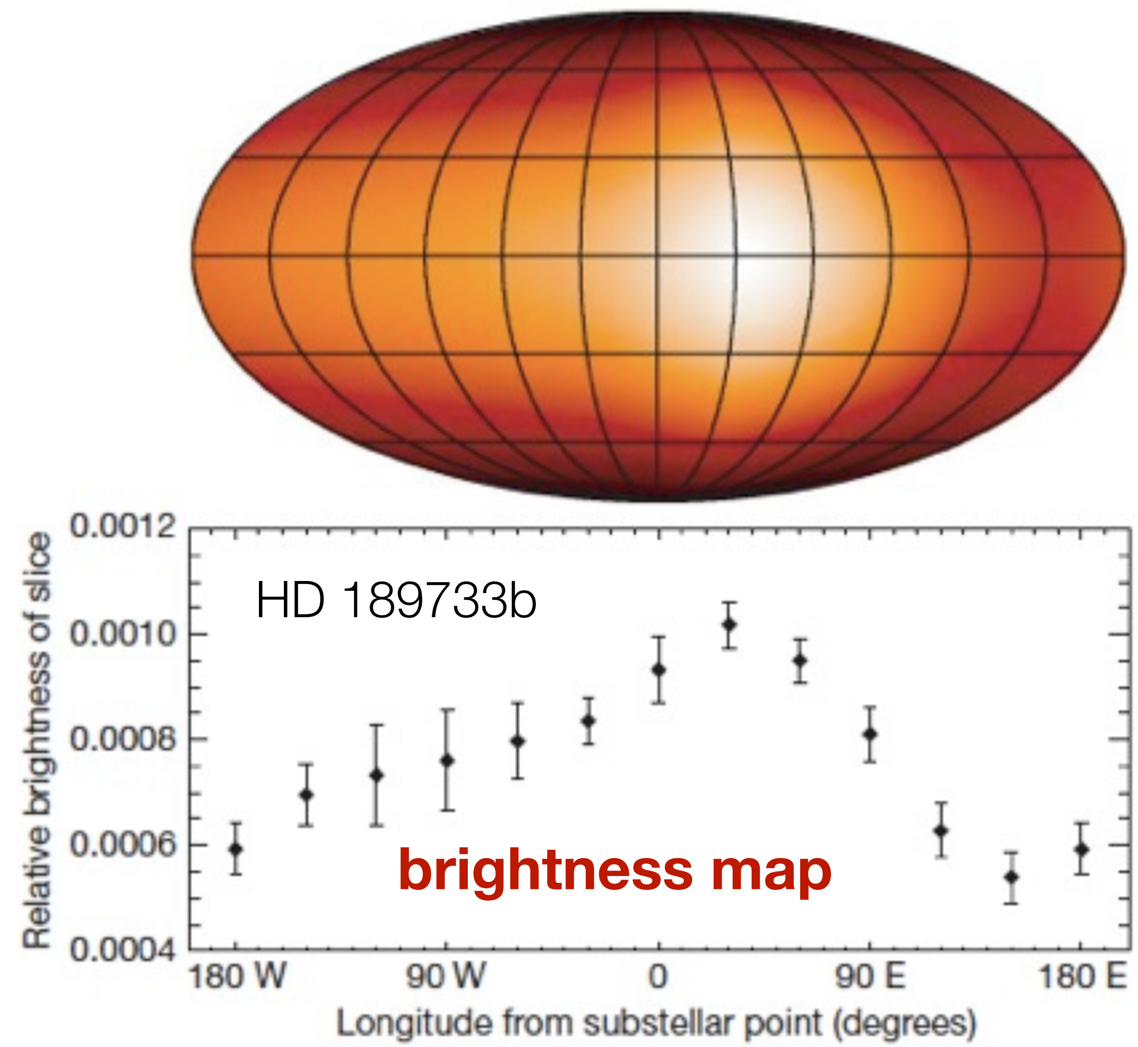


Heng & Demory (2013)

Albedo spectrum is determined by a degenerate combination of relative abundance of scatterers vs. absorbers and size of scatterers.

Observational motivation: infrared phase curves

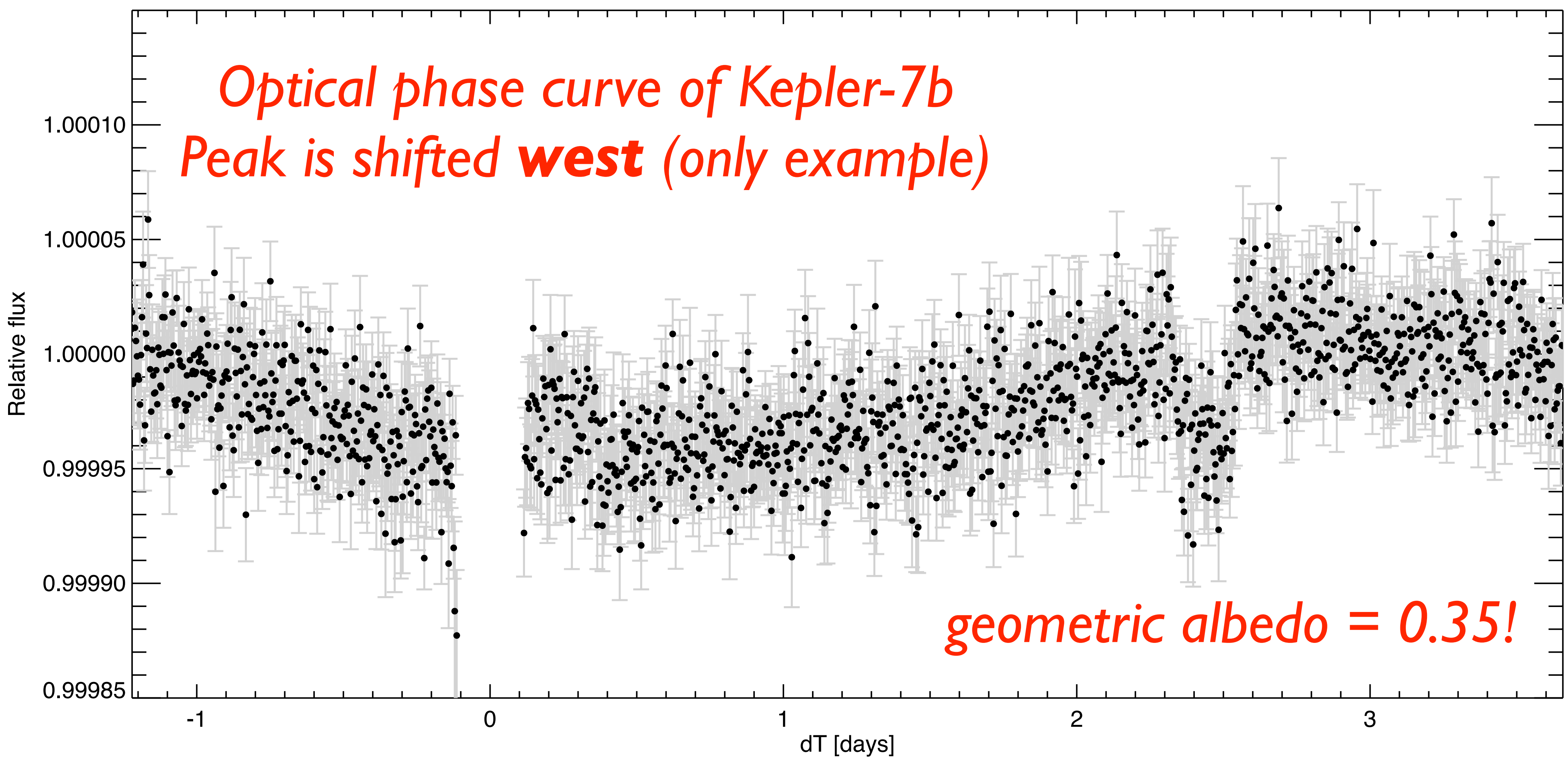




Claim: direct evidence for existence of atmospheric winds

From Knutson et al. (2007) for the hot Jupiter HD 189733b

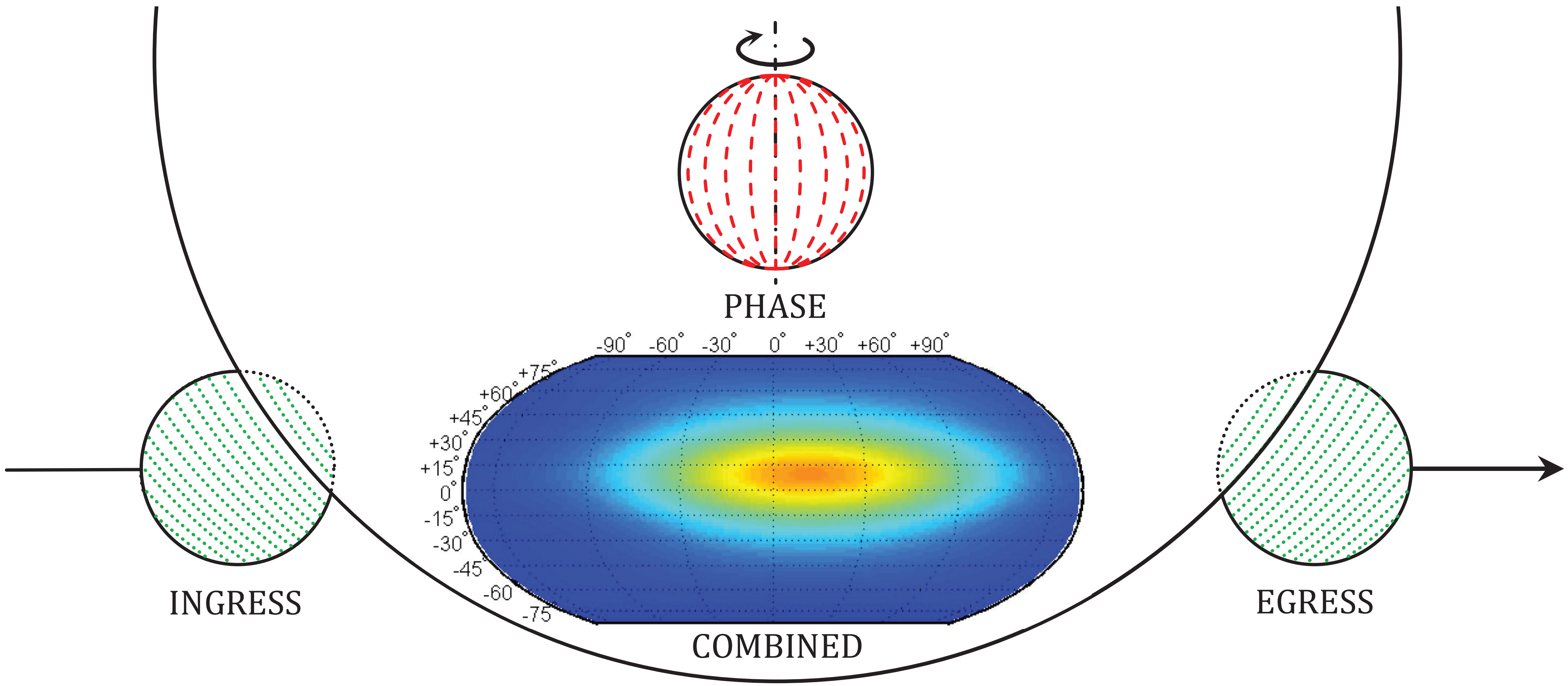
Observational motivation: optical phase curves (reflected light)



Demory et al. (2013)

Albedo across longitude (east-west) indicates relative abundance of clouds, which are modulated by atmospheric dynamics.

Observational motivation: phase + eclipse maps



de Wit et al. (2012)
HD 189733b

A future wealth of data for validation of 3D simulations?

The puzzle of inflated hot Jupiters: an effect driven by stellar irradiation

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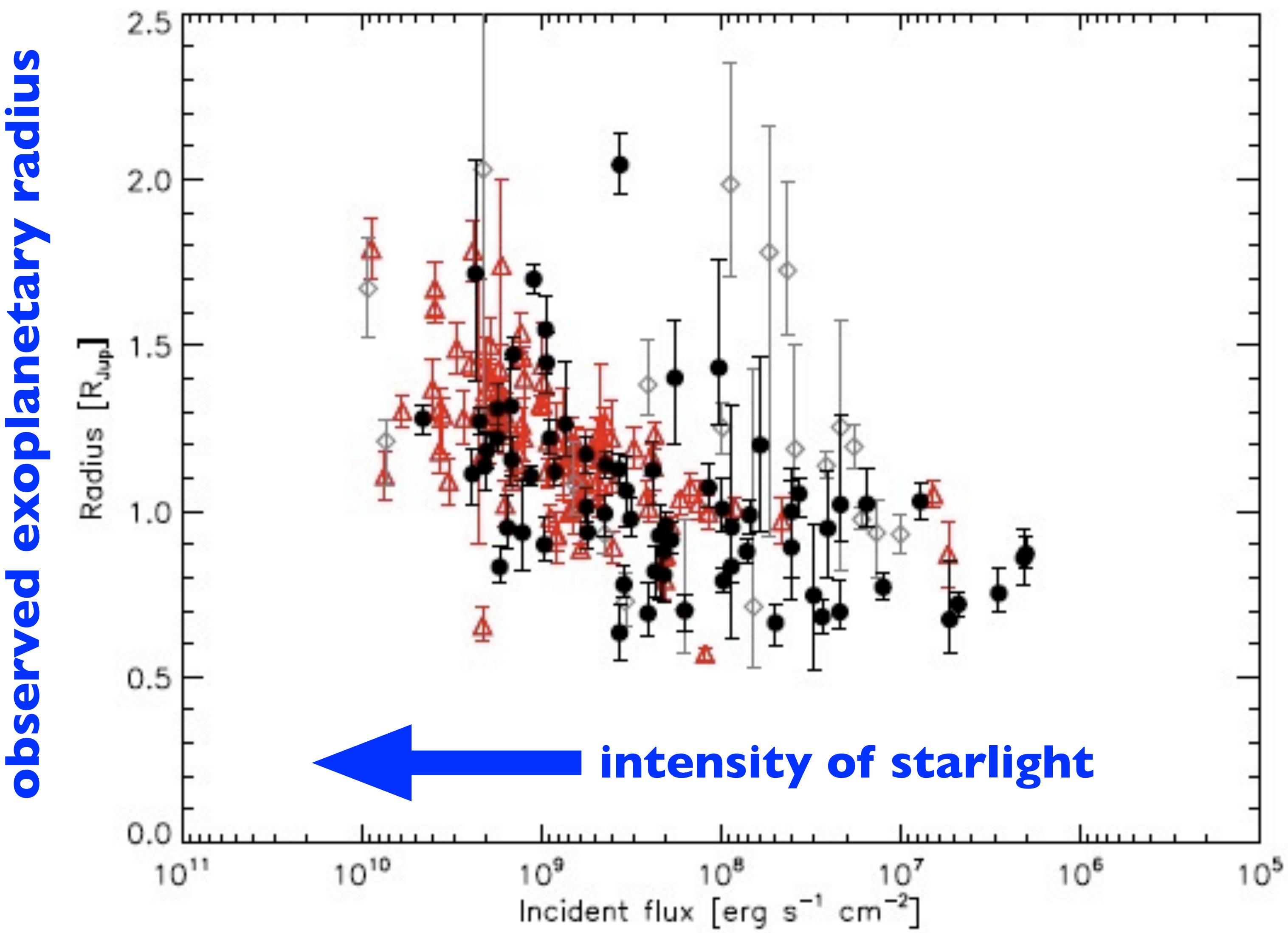


FIG. 1.— Planetary radii as a function of incident flux. Black filled circles are KOI ranked as planetary candidates in the frame of this work while gray diamonds represent KOI whose origin is ambiguous (see Sect. 3). Transiting giant planets previously published, and mostly from ground-based surveys, are shown as red triangles. The relevant parameters R_p, R_s, T_{eff} and a have been drawn from http://www.inscience.ch/transits on August 29, 2011.

The observations tell us that the mechanism is related to or driven by the intensity of starlight, but they do not tell us *what* the mechanism is.

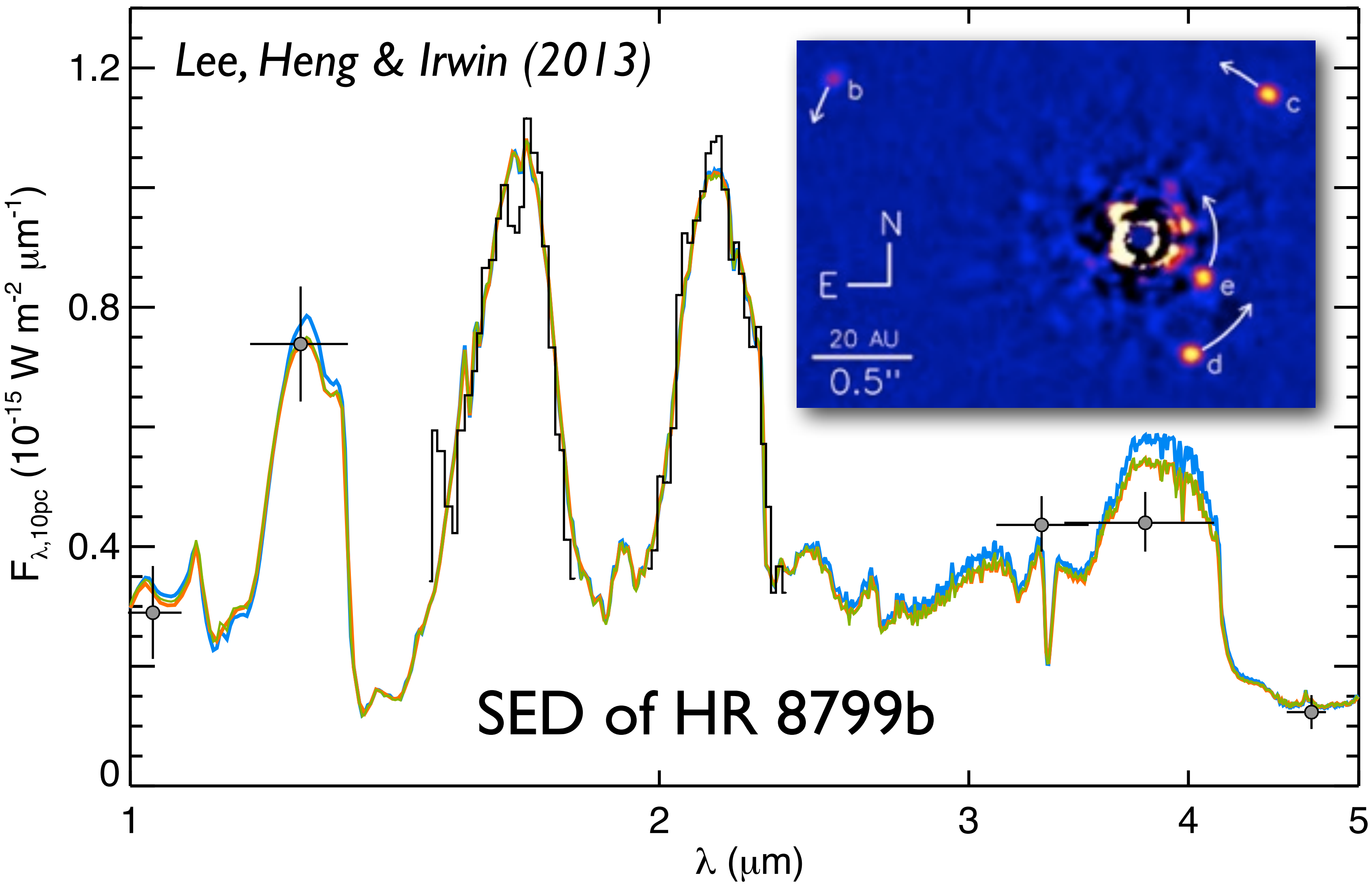
Demory & Seager (2011)

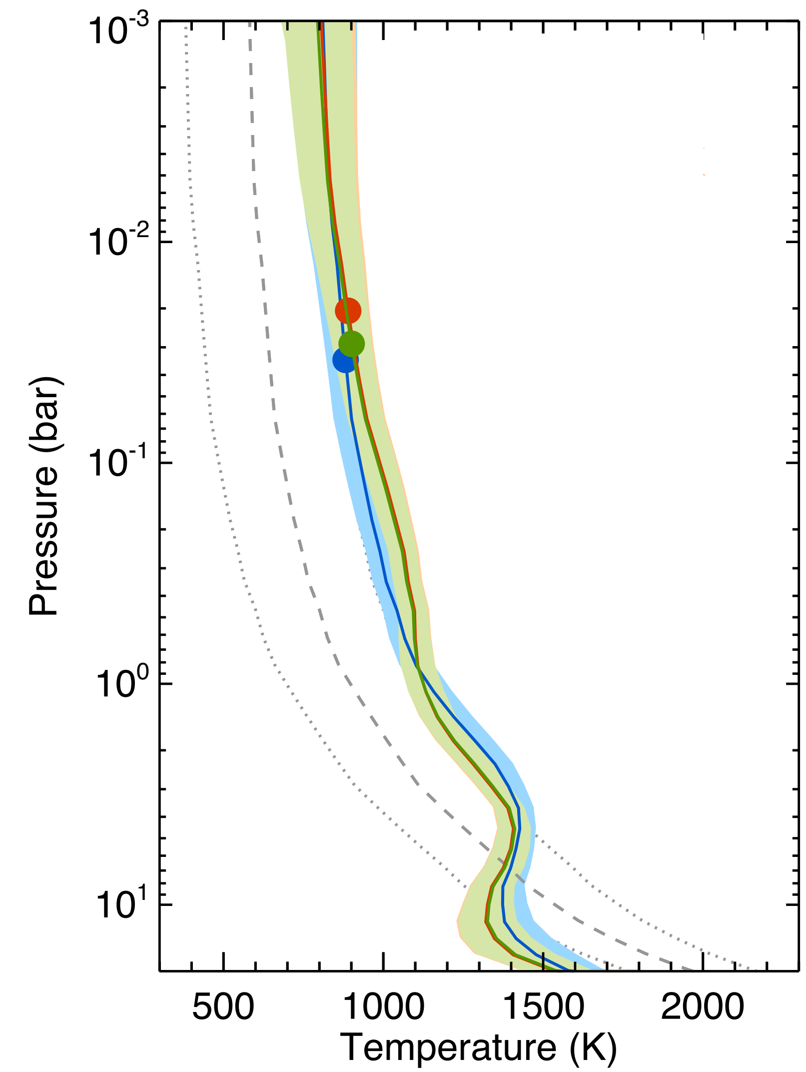
Black points: Kepler candidates
Red points: others
grey: ambiguous origin

See also: Burrows et al. (2007), Enoch et al. (2011), Laughlin et al. (2011), Miller & Fortney (2011), Perna et al. (2012)

II. Theory

Atmospheric retrieval: directly imaged exoplanets





Retrieval: data ⟶ chemistry + thermal structure

Can you tell between the models: cloudfree, fully cloudy, intermediate?
(models are indistinguishable via chi-square comparison)

Atmospheric retrieval: hot Jupiters

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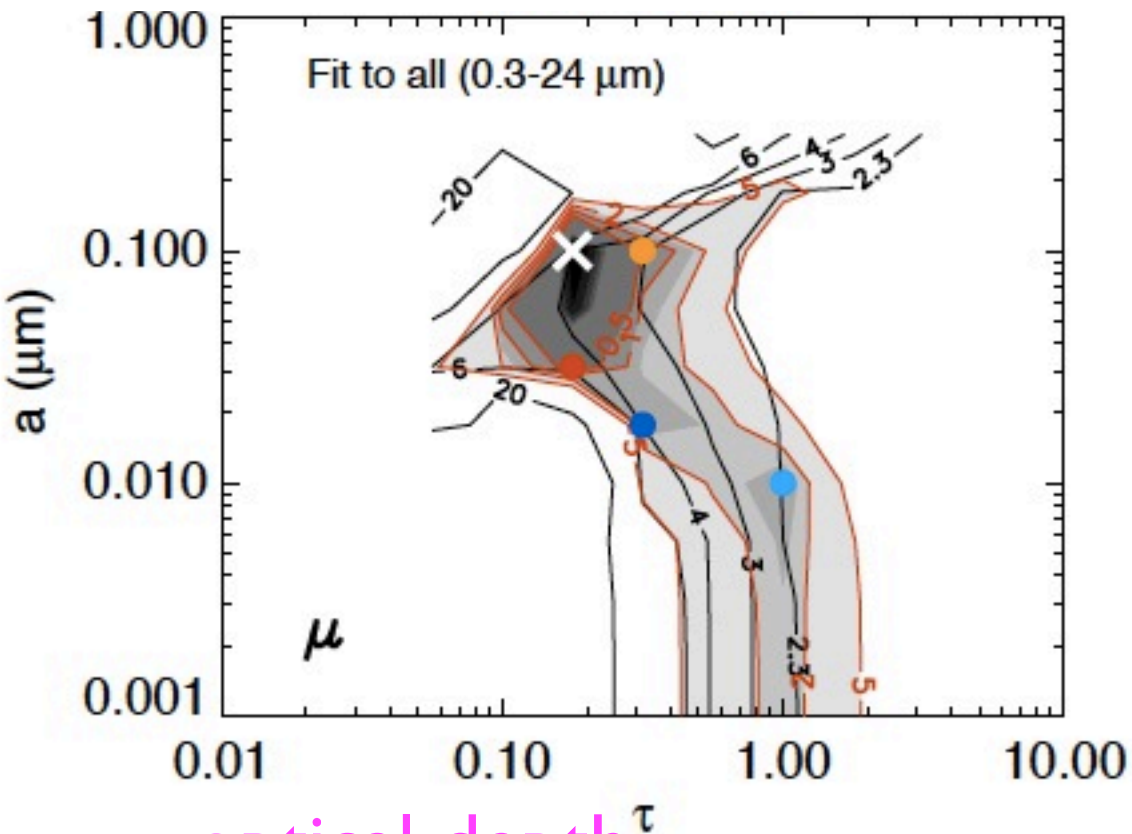
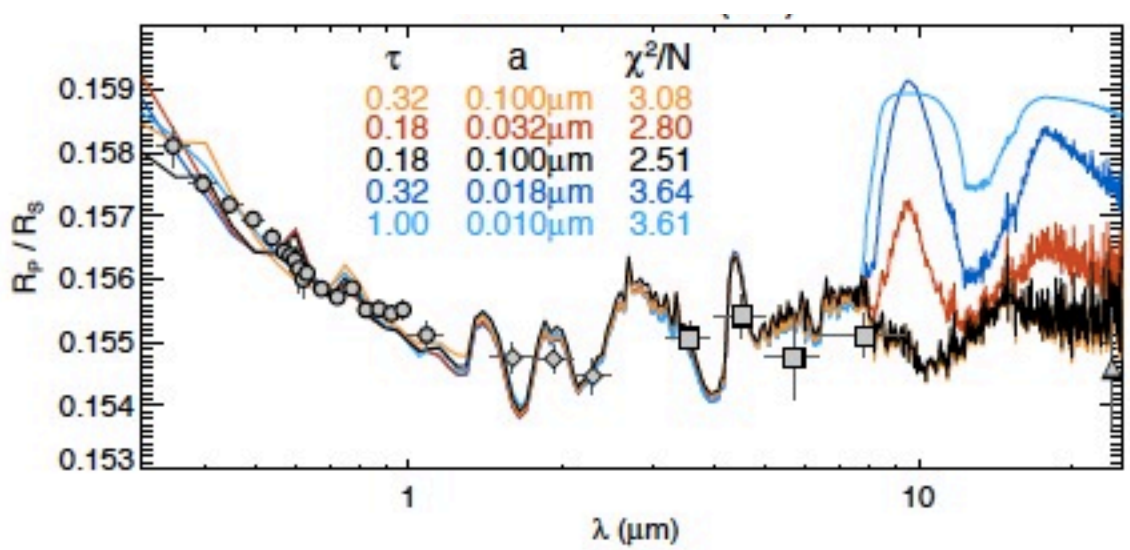
particle size



optical depth

With knowledge of mass and radius, one may infer the cloud particle size and optical depth.

transit spectrum



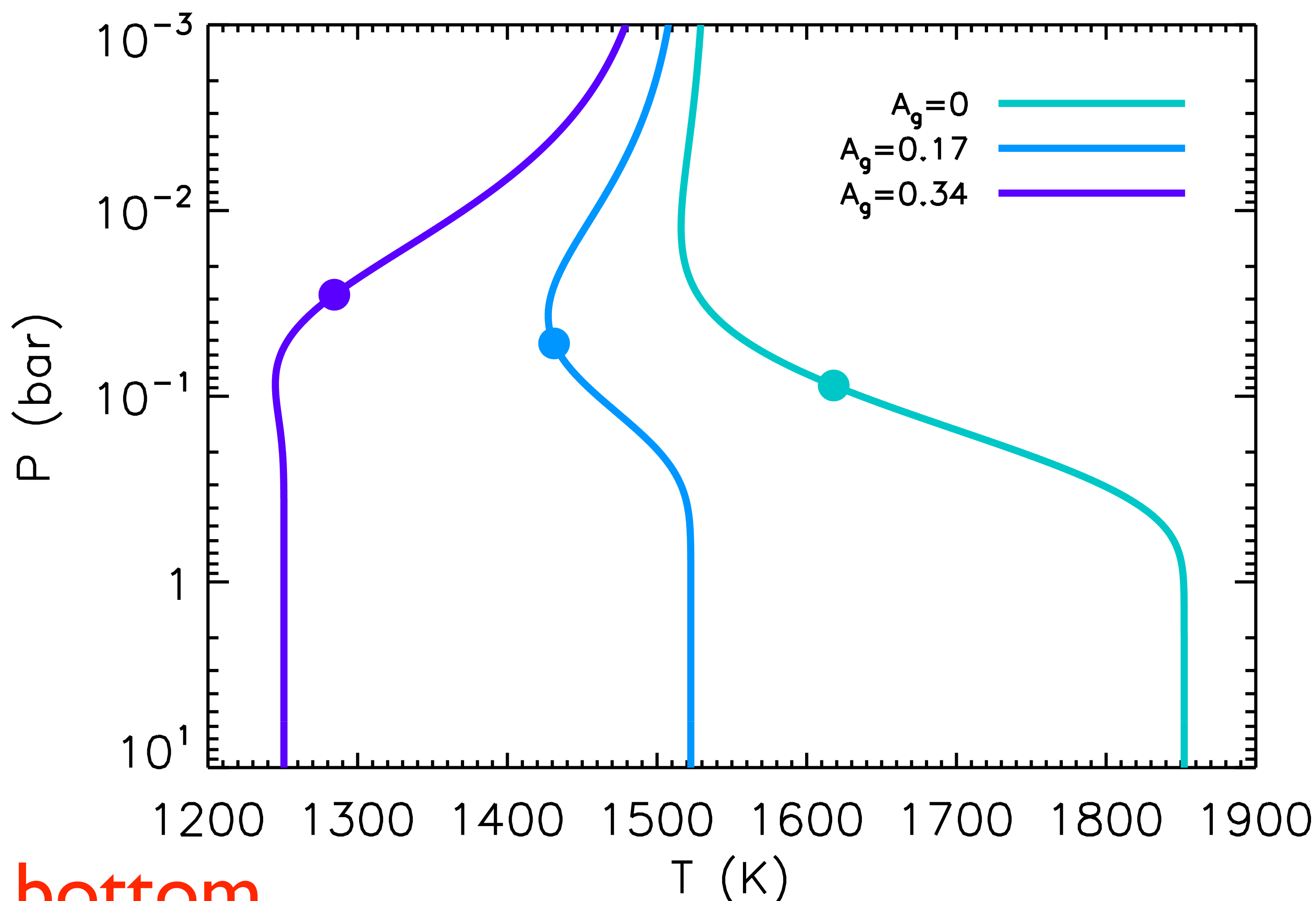
Single Spitzer data point at 24 microns is more constraining than all of the data points at <1 micron!

(Important for space mission design.)

Lee et al. (2013)

How do clouds alter the structure of an atmosphere?

top



bottom

Examples of ***temperature-pressure profiles*** *in model atmospheres*

Guillot (2010), Heng et al. (2012)

Two effects:

1. the amount of starlight penetrating the atmosphere

2. the depth of the penetration

thermal structure of atmosphere

See also: Sudarsky et al. (2000), Fortney et al. (2008), Dobbs-Dixon et al. (2012)

Atmospheric dynamics using analytical models

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As a prelude to 3D simulations, one may study the 2D "shallow water" system.

Key insight:

governing equation for atmospheres and quantum harmonic oscillators are identical across a broad range of conditions (forcing, friction, magnetic fields).

Heng & Workman (2014)

Atmospheric dynamics using analytical models

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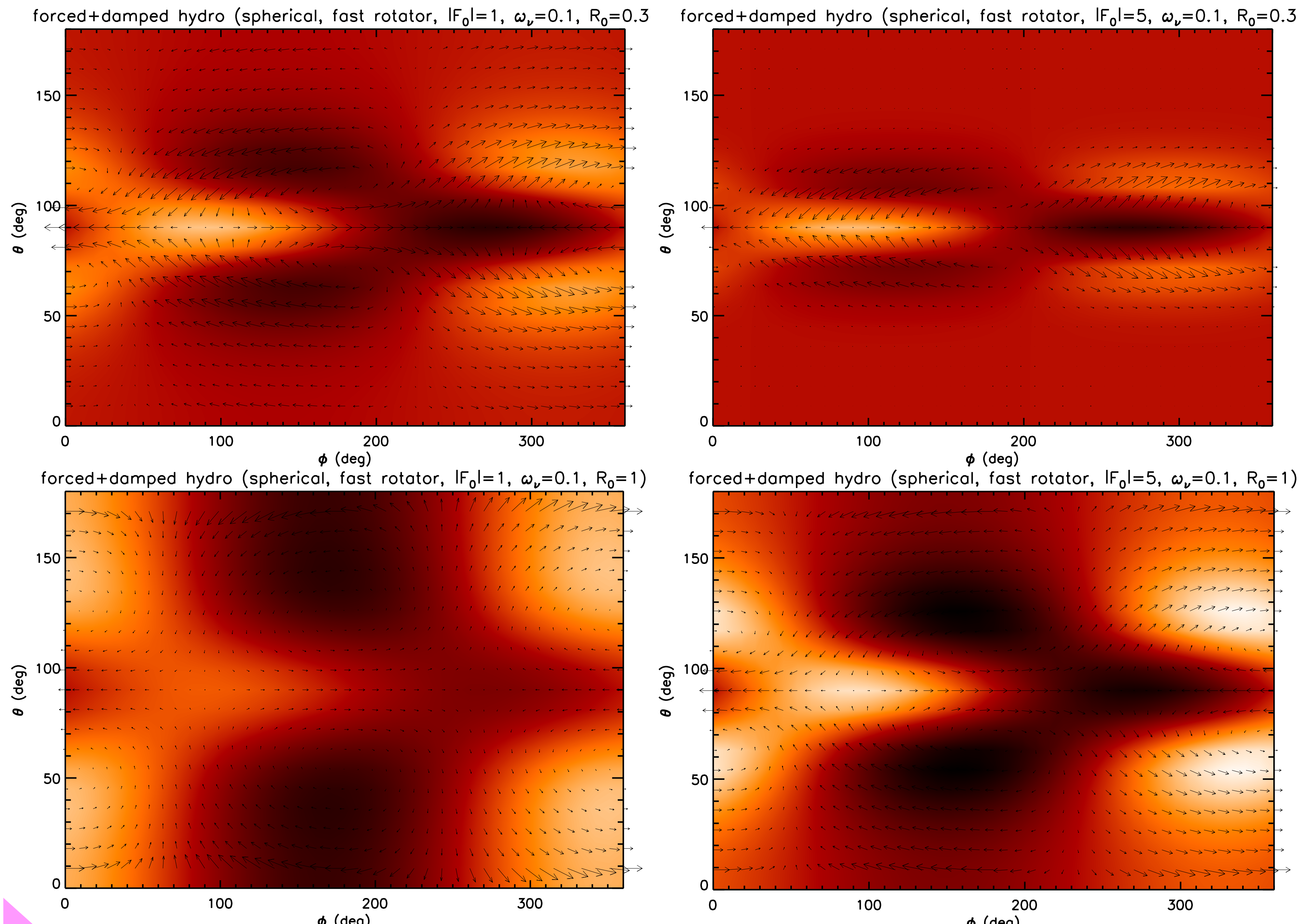

faster rotation

more intense starlight (or weaker friction)

Heng & Workman (2014)

Atmospheric radiative transfer using analytical models

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- Atmospheric researchers often use an approach known as the "two-stream approximation".
- I am in the process of re-examining this approach.
- To solve the equations, one needs to define a series of "closures" (Eddington coefficients).
- I find that some choices are at conflict with basic astrophysical principles (conservation of energy).

III. Simulation

The use of adapted climate simulators as atmospheric laboratories

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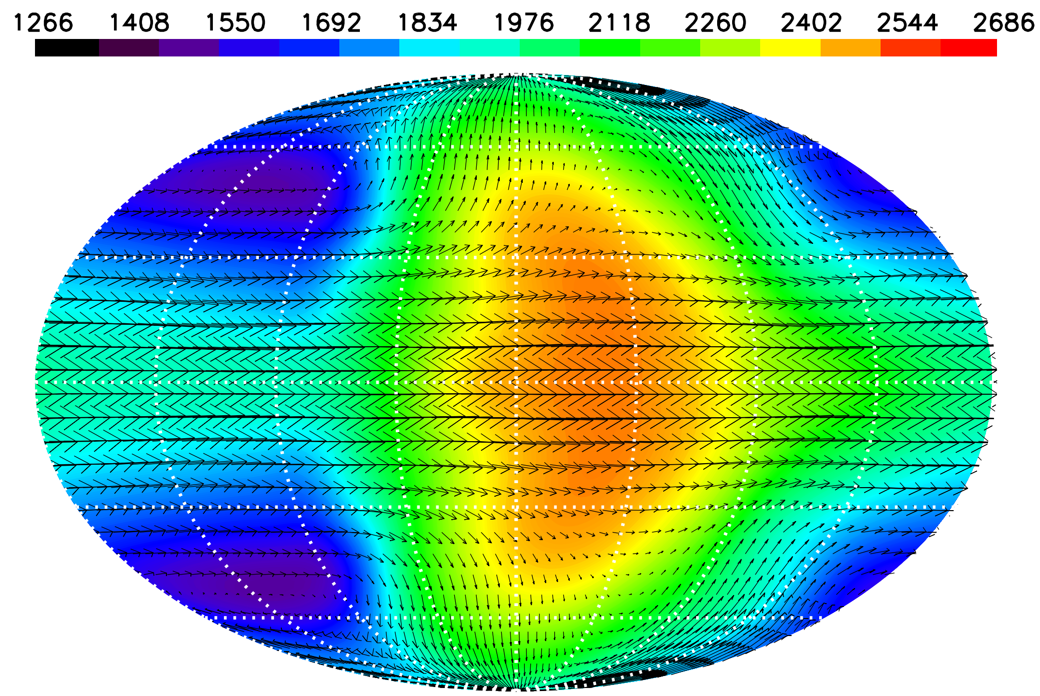
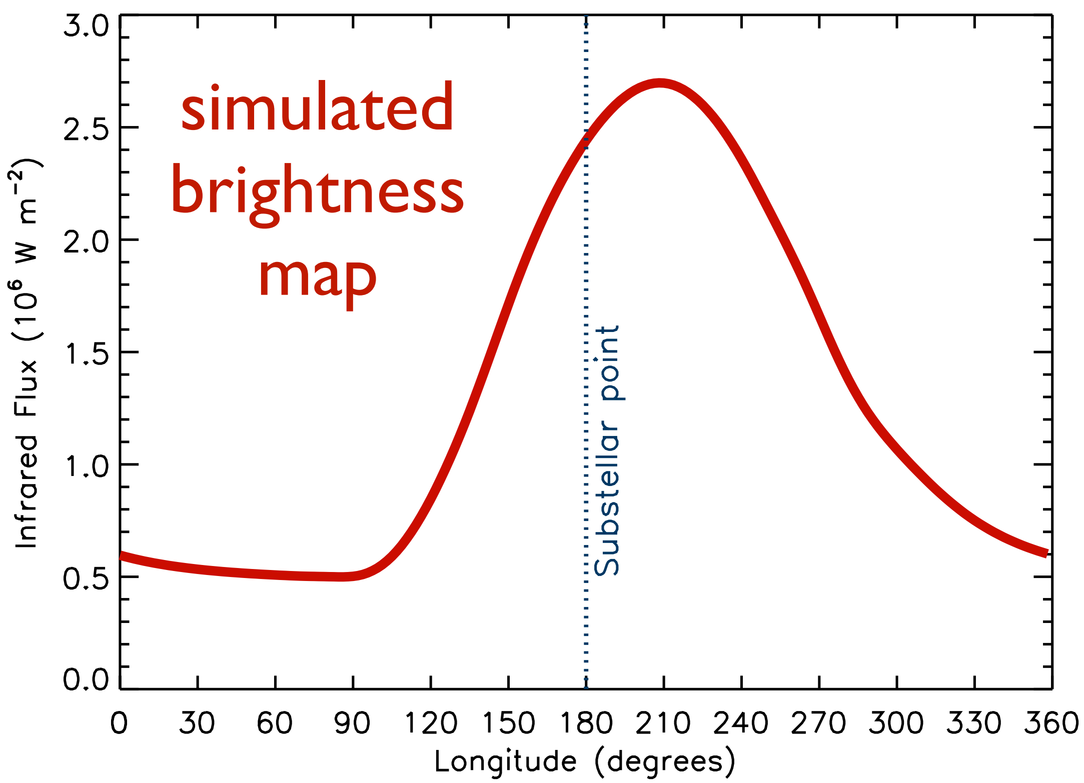
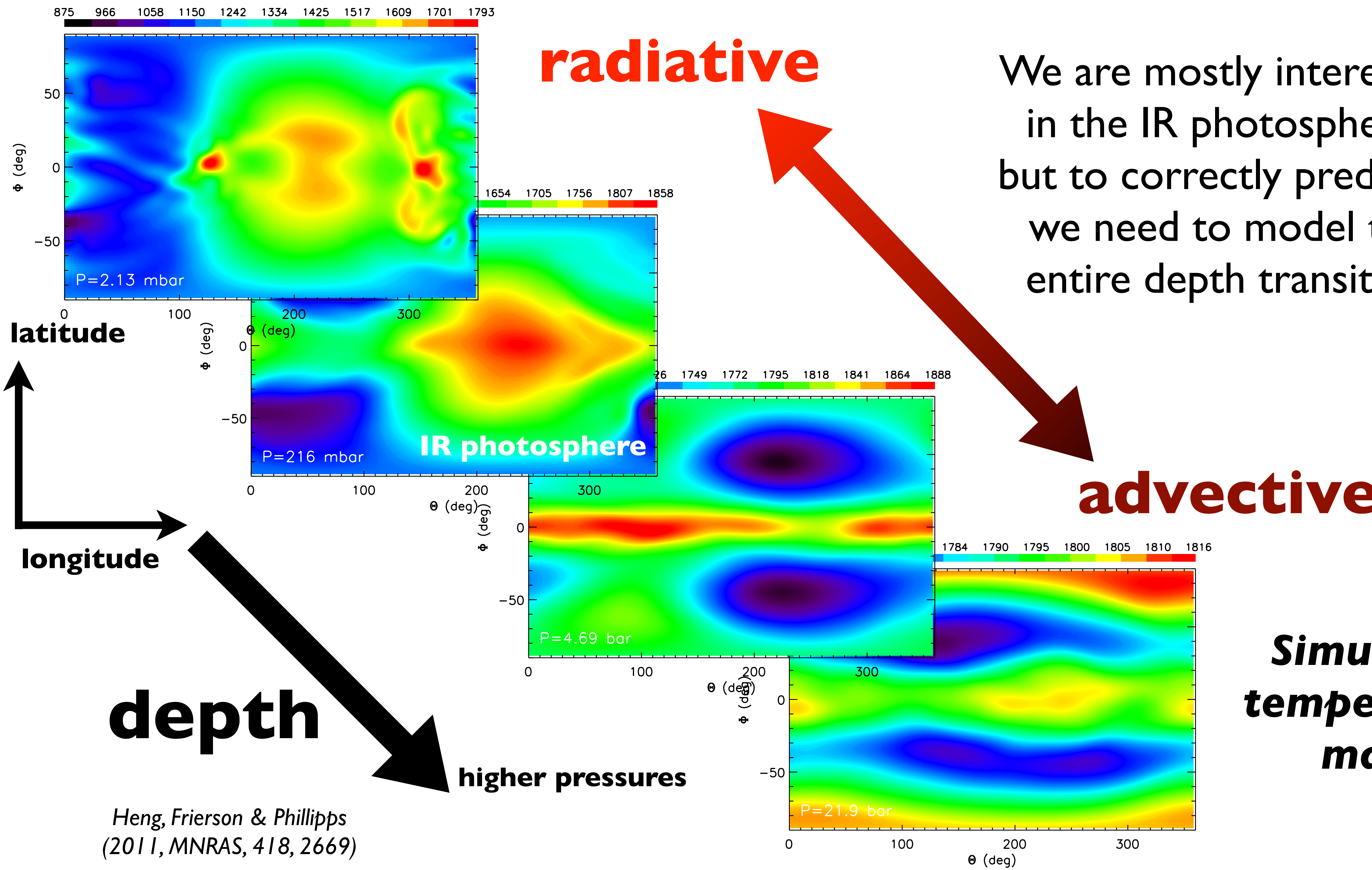




Exercise:
dismantle a climate simulator for Earth, reassemble with relevant parts (desired physics).

Used to predict the global temperature, velocity, density, pressure distribution, which affects temporal and spectral appearance.

The challenge of simulating an exoplanetary atmosphere



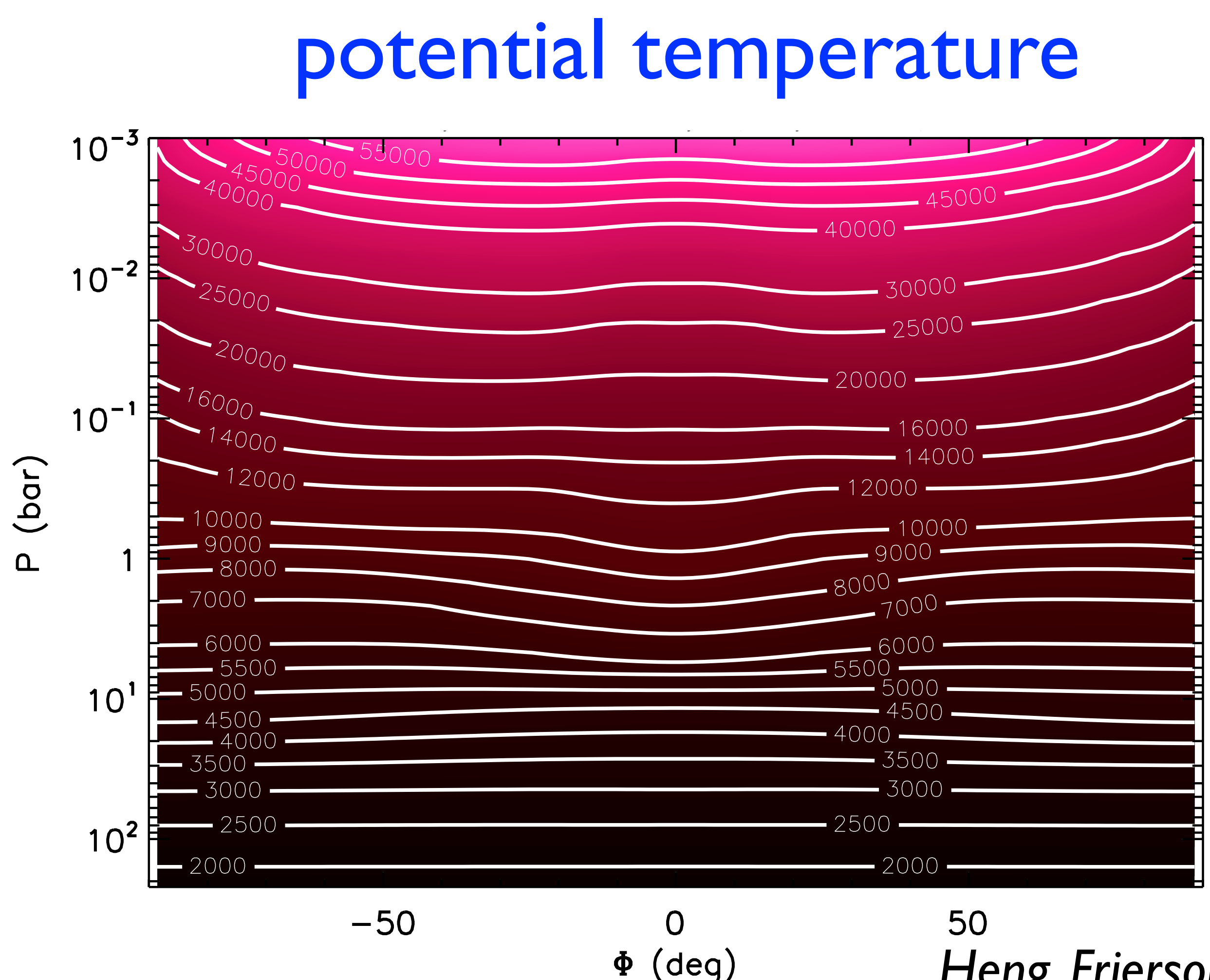
We are mostly interested in the IR photosphere, but to correctly predict it we need to model the entire depth transition

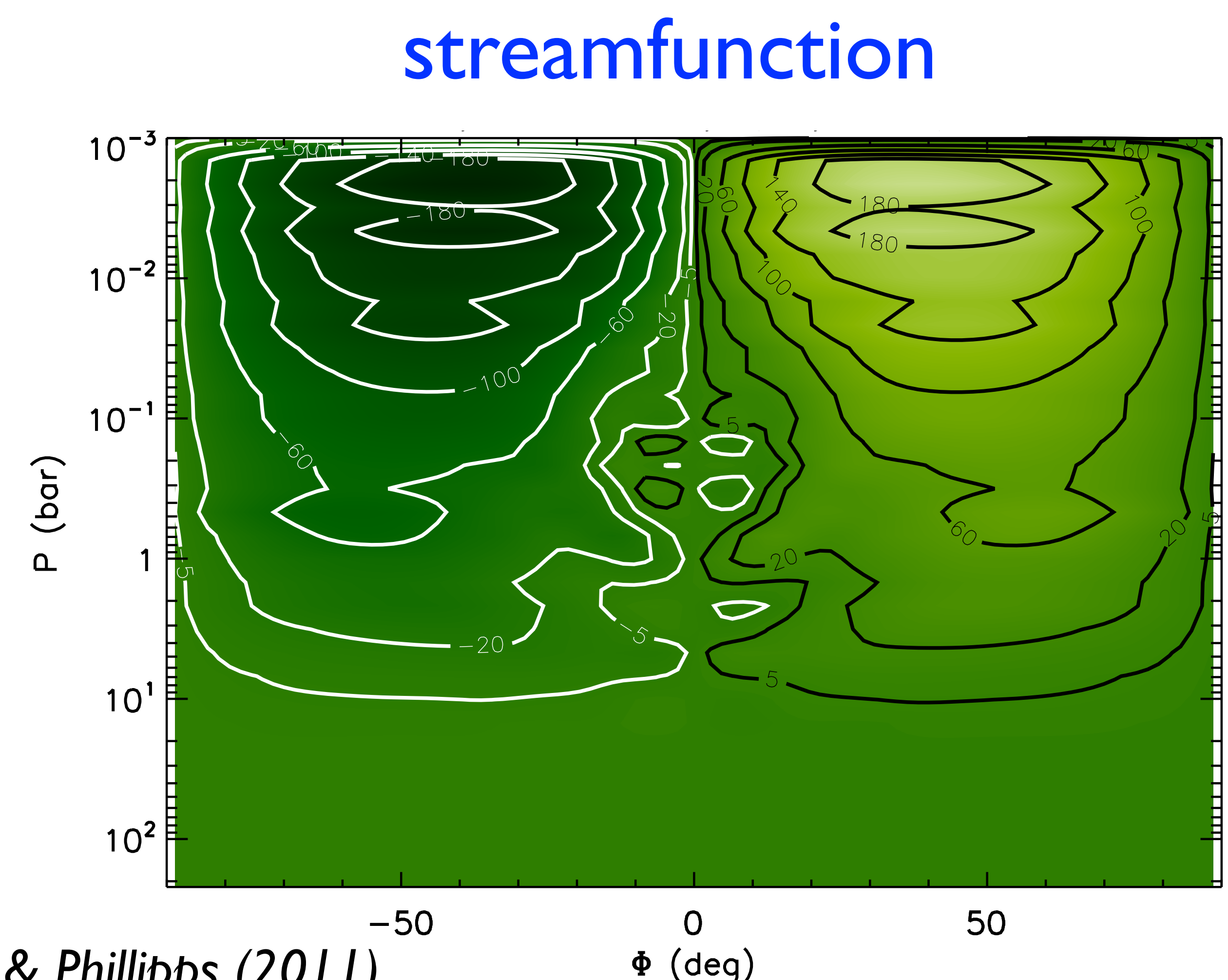
Simulated temperature maps

Heng, Frierson & Phillipps (2011, MNRAS, 418, 2669)

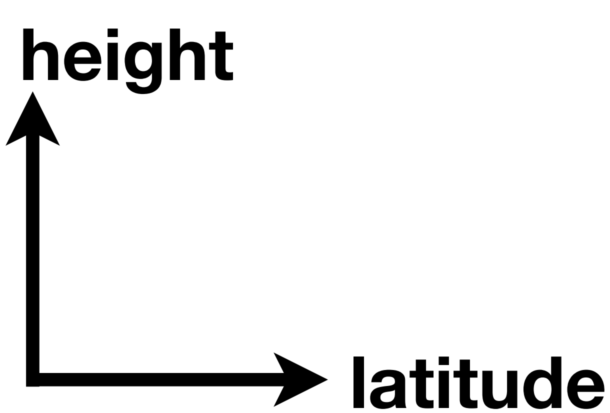
See also work by Burrows, Cho, Dobbs-Dixon, Fortney, Guillot, Langton, Laughlin, Menou, Polichtchouk, Rauscher, Showman, Thrastarson.

Why irradiated gas giants may be simpler beasts than Jupiter





Heng, Frierson & Phillipps (2011)



Depth and strength of atmospheric circulation depends sensitively on the strength of stellar irradiation.

On hot Jupiters, circulation is strong and deep, suggesting that mixing is global.

Irradiated atmospheres as wind tunnels: shocks?

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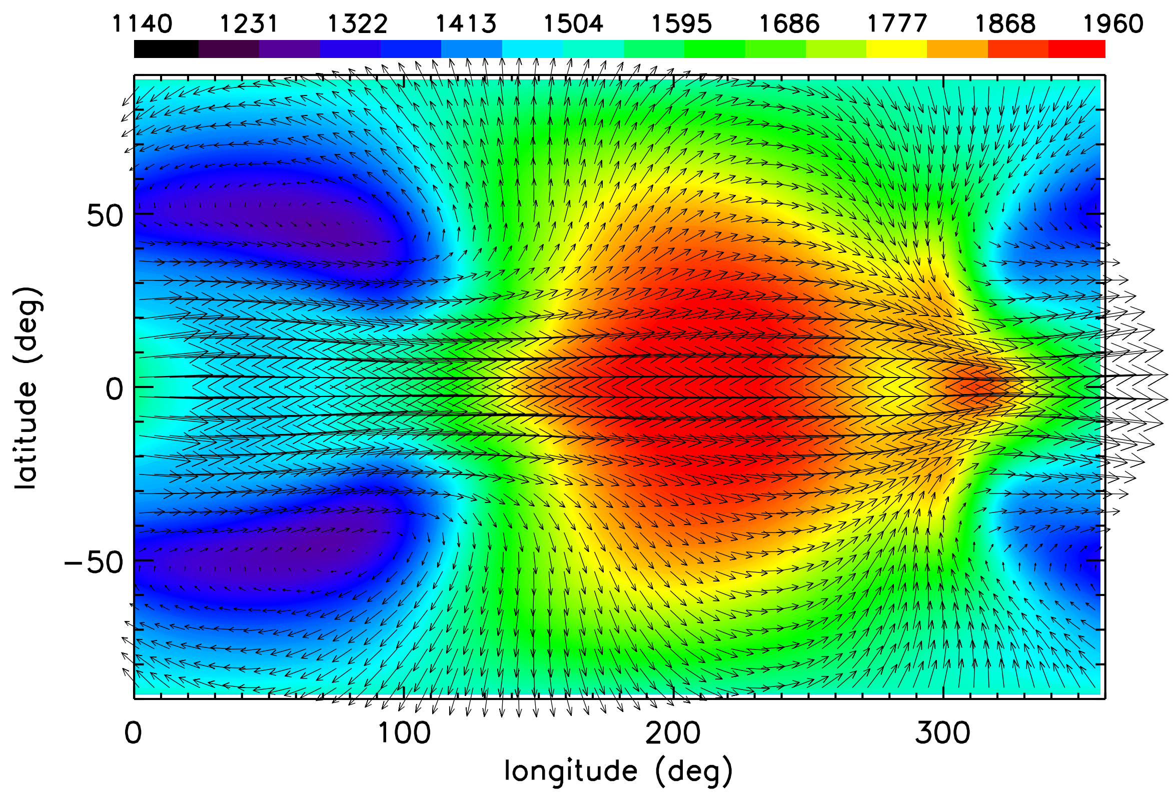
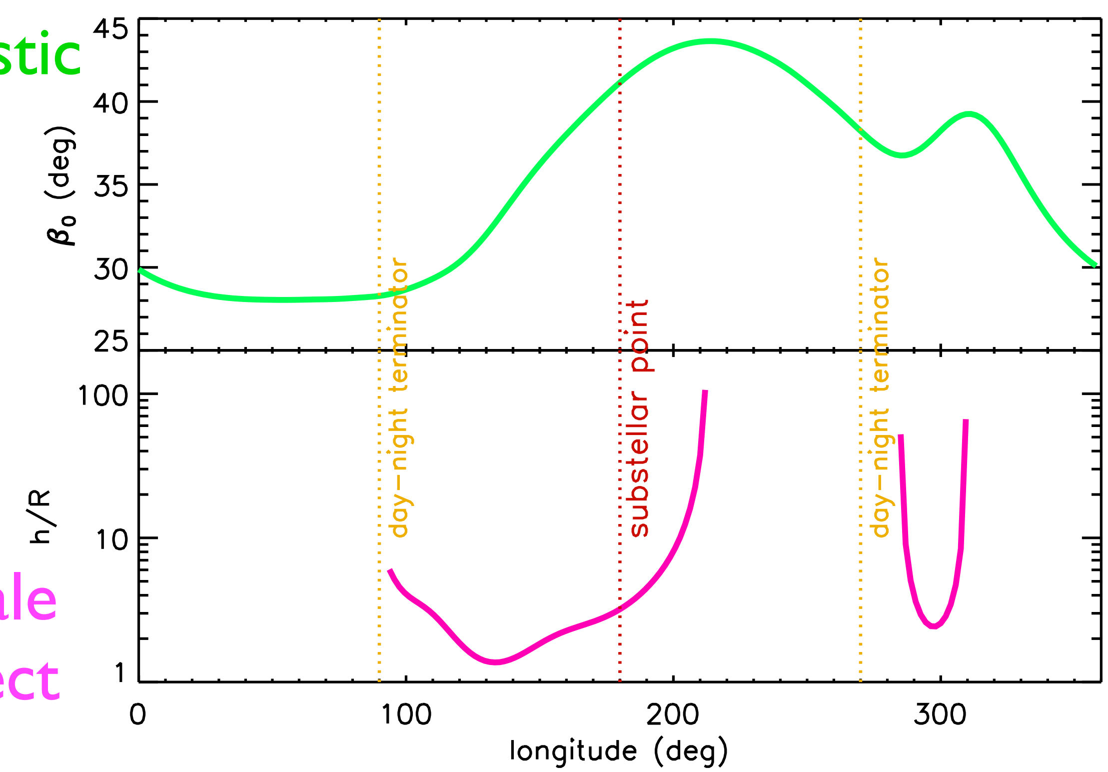


characteristic angle

length scale to intersect



Flows are expected to become supersonic.

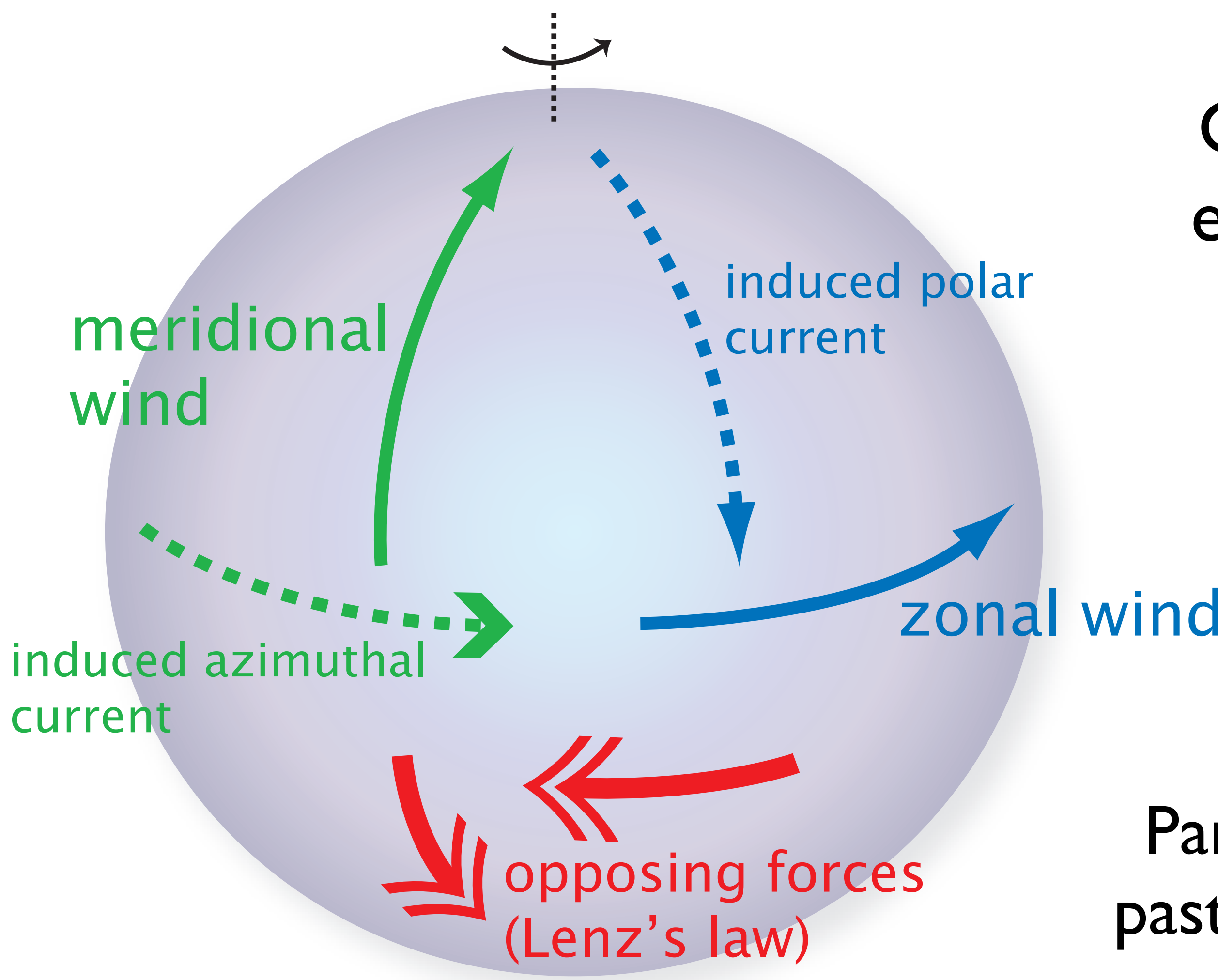
Shocks convert ~25% of kinetic energy into heat.

Supersonic flow is an insufficient condition. Requires also Mach number to locally decrease.

Tidally-locked, irradiated exoplanets create their own pressure barrier for the returning flow (from nightside to dayside) to crash into!

Heng (2012, ApJ, 761, L1)

Irradiated atmospheres as giant electric circuits: Ohmic heating?



Collisional ionization liberates electrons from Group I metals (Na, K)

Partially ionized atmosphere advected past magnetic field induces currents and opposing forces

In progress with Sebastien Fromang

A global, exoplanetary-scale manifestation of Lenz's law

Perna, Menou & Rauscher (2010a,b); Batygin & Stevenson (2010); Batygin et al. (2011), Rogers & Showman (2014)

Why adapted climate simulators are not entirely up to the task

- Dynamical cores (fluid solvers) may not conserve mass, momentum and energy simultaneously.
- Implemented chemistry and cloud schemes are often Earth-centric.
- Shocks are not captured.
- Magnetic fields are not included in dynamical cores.
- Current attempts to use hydrodynamic friction to mimic magnetic drag are fundamentally flawed (cf. Heng & Workman 2014).
- Climate simulators are not designed for constructing large ensembles of models to explore trends across parameter.

Our long-term solution

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ESP
EXOCLIMES SIMULATION PLATFORM

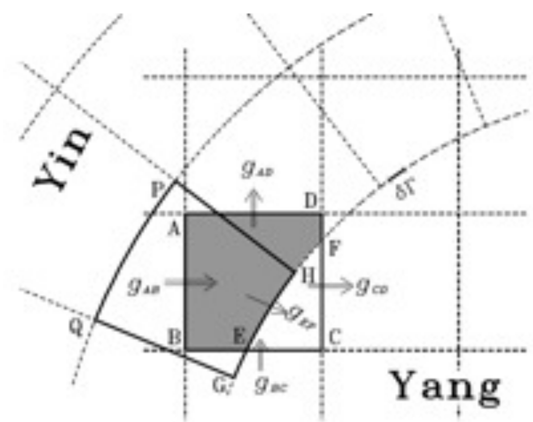
Our dream and vision:
a set of freely available simulational tools,
designed from the "ground up",
GPU-accelerated (~10-100 times faster),
supported by a full-time research team
with astro, comp sci, atmos/climate backgrounds

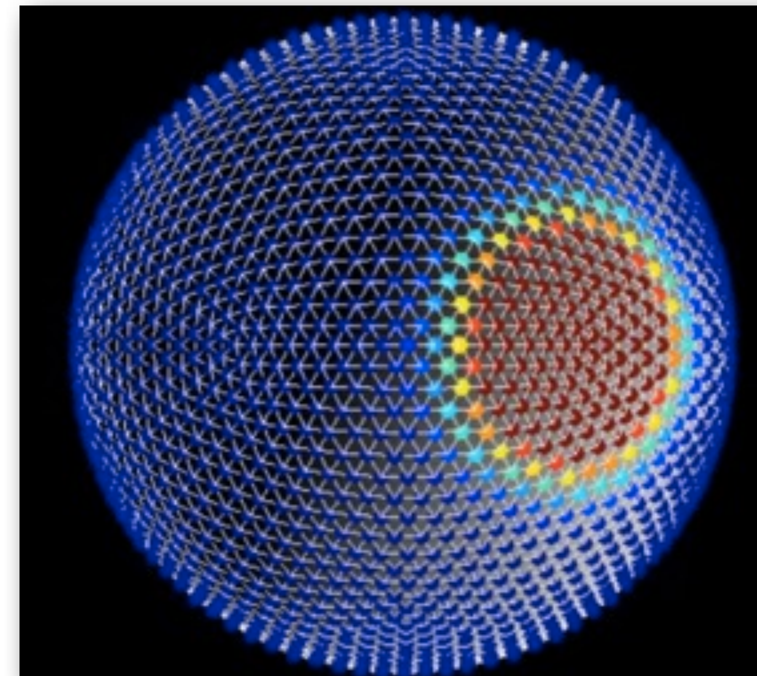
Team: Heng (general), Lee (radiation), Mendonca (dynamics, cloud physics), Grimm (dynamics, HPC), Grosheintz (dynamics, HPC), Malik (radiation, chemistry)

Some technical challenges we face

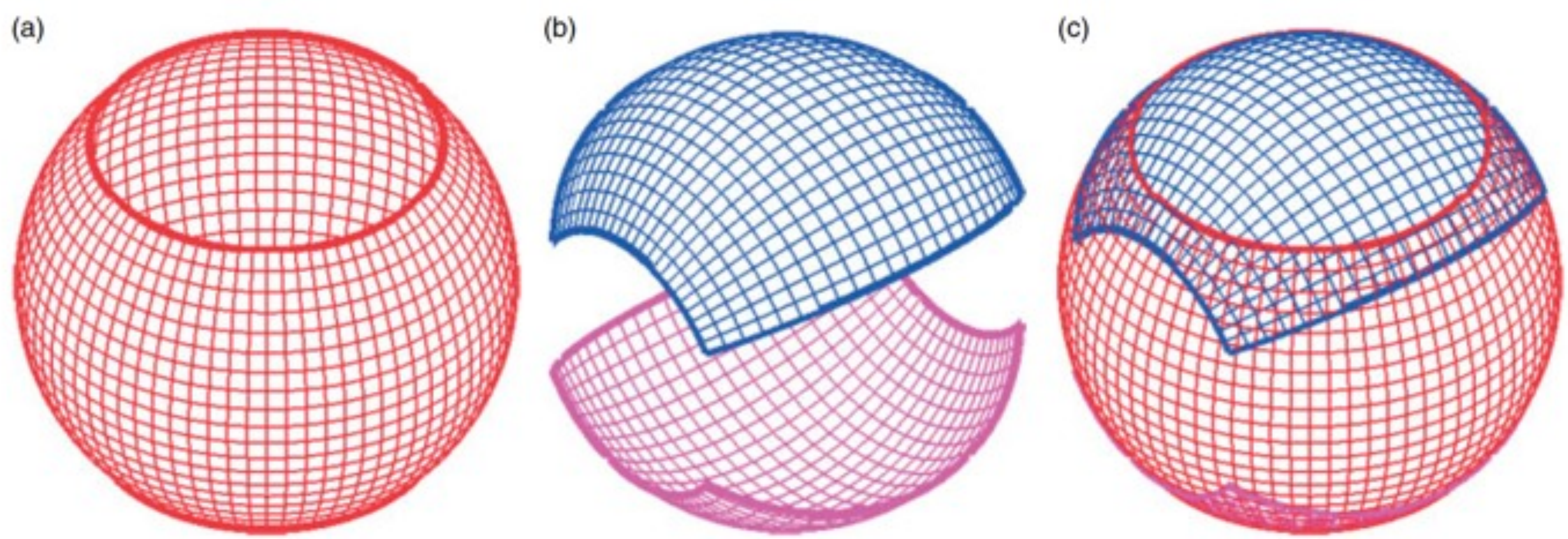
Example: the "pole problem"

Modified Yin-Yang grid.
Issue of mass conservation across grids.

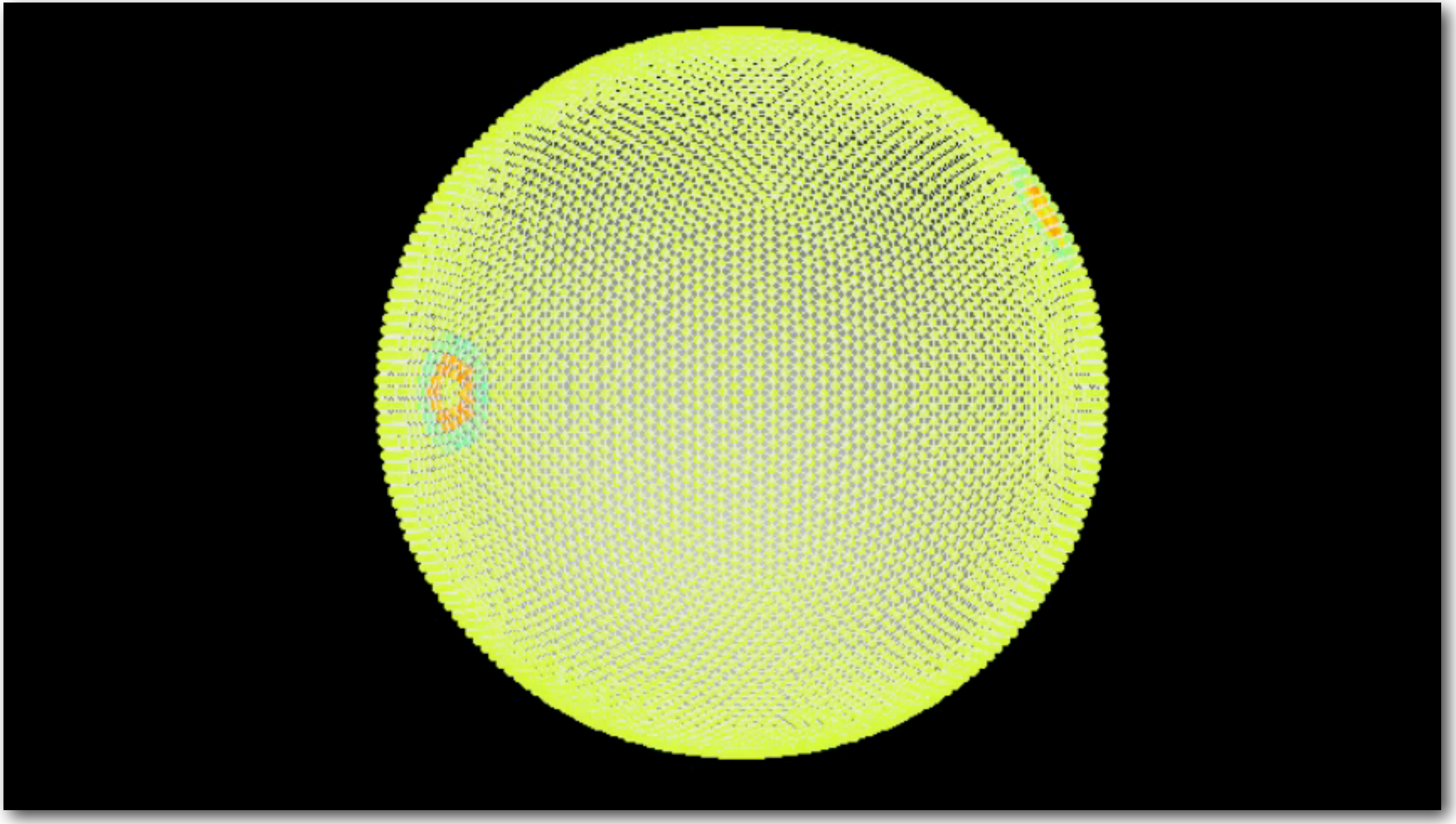




Using Platonic solids (icosahedral grid)



Test of our icosahedral grid (from Joao Mendonca)



IV. Future Perspectives

We need targets around bright stars

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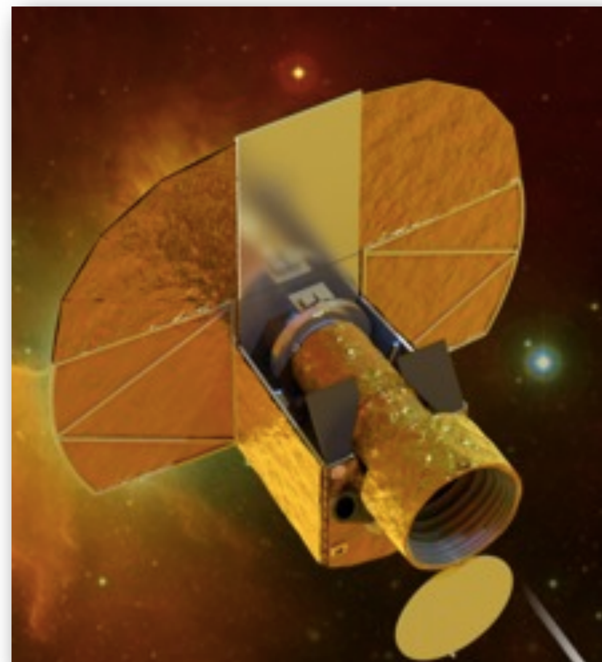
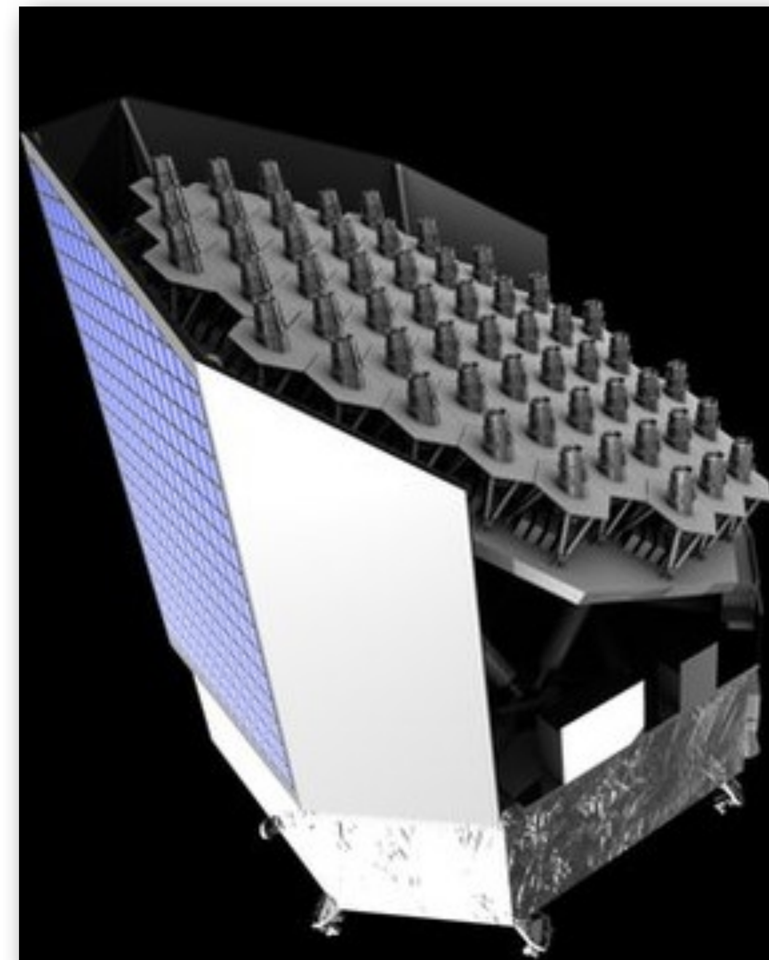
TESS
(2017)



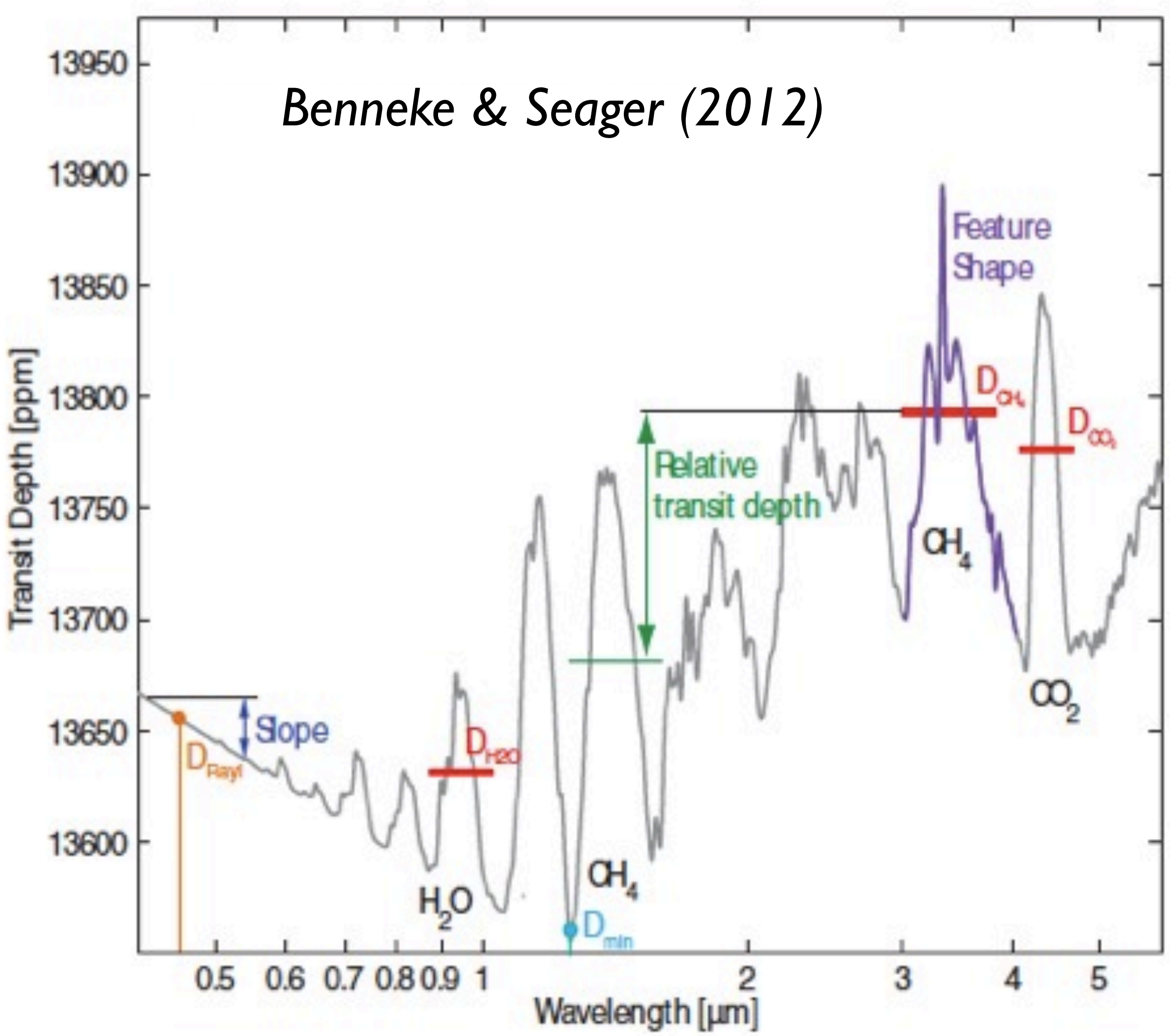
CHEOPS
(2017)

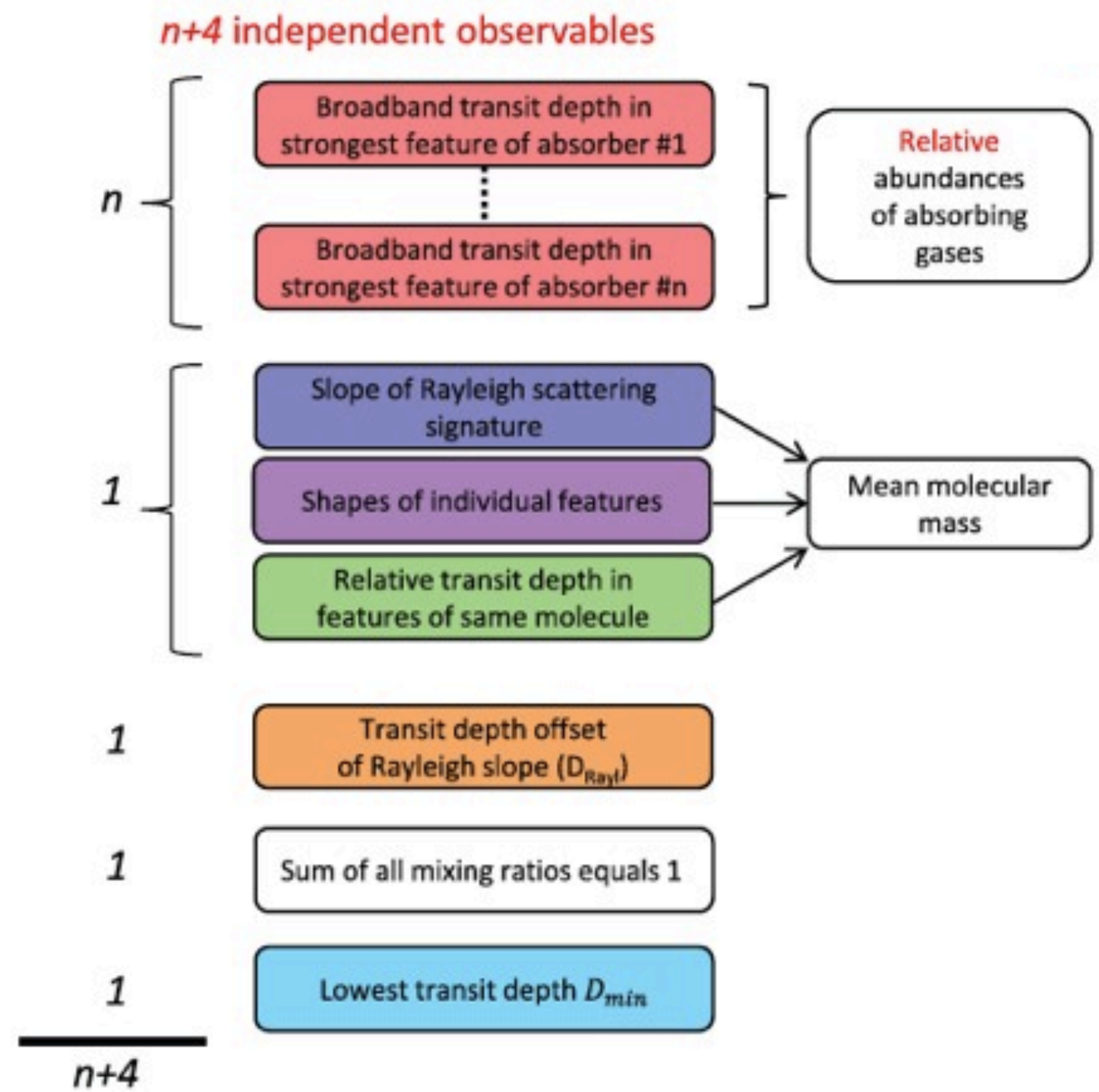


PLATO
(2024)

We need more HD189s and GJ1214s.

Preparing for JWST: decoding high-resolution spectra





Measuring either the **Rayleigh slope** in the optical or the **shape of the molecular features** in the infrared constrains the **mean molecular mass**.

An abused term: the "habitable zone"

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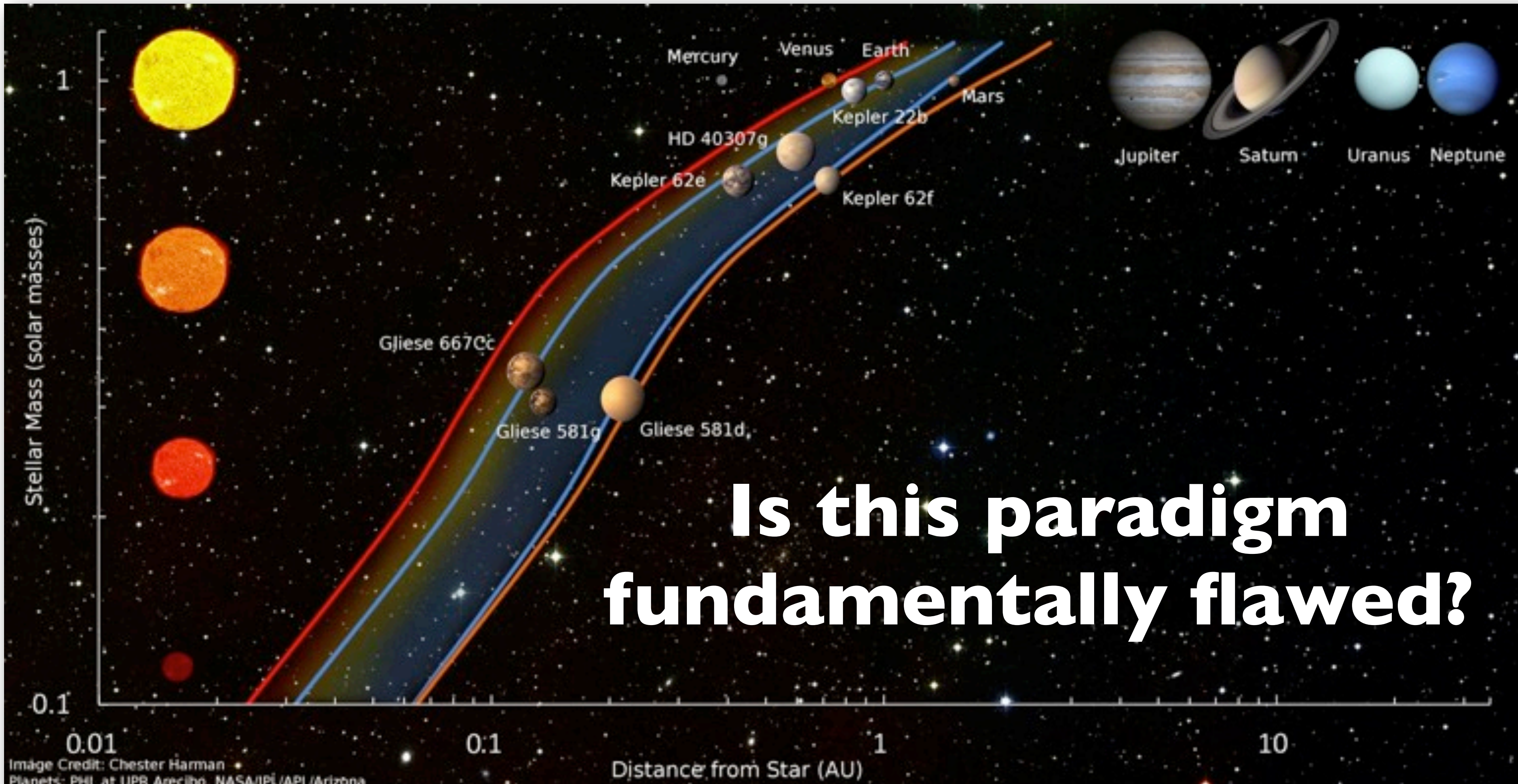

Three gases needed:
inert, condensible greenhouse, incondensible greenhouse

Hydrogen-dominated atmospheres: outer boundary may be much farther away (Pierrehumbert & Gaidos 2011)

The Gap between Simulation and Understanding in Climate Modeling

BY ISAAC M. HELD

Should we strive to construct climate models of lasting value? Or should we accept as inevitable the obsolescence of our models as computer power increases?

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E-mail: isaac.held@noaa.gov
DOI:10.1175/BAMS-86-11-1609

In final form 22 June 2005

We need an interdisciplinary framework

Astrophysical flamboyance

vs.

Solar System: data-rich

vs.

Earth: precision

Not constructive! Need mechanisms for "cross talk".

(e.g., PlanetS national framework in Switzerland, Exoclimes III)

Summary

- Exoplanet atmospheres are now accessible to astronomical scrutiny.
- Theory and simulation play key roles in data interpretation, but there is a need to rethink our assumptions and rebuild our tools.
- Clouds are a major obstacle in our interpretations of exoplanet atmospheres.

Coming:

"Exoplanetary Atmospheres"

Heng & Showman (2014), Annual Reviews of Earth & Planetary Science