Exoplanetary Atmospheres: Theory & Simulation

Kevin Heng

Assistant Professor (Tenure-Track)

University of Bern (Switzerland)

Review Talk at University of Kiel Workshop 2014

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Collaborators:
Brice-Olivier Demory (Cambridge)
Chris Hirata (Caltech/Ohio State)
Antonija Oklopcic (Caltech)
Sid Mishra (ETH Applied Math)
Caroline Dorn (Bern / ETH Geophysics)
Geneva exoplanet group
Cambridge exoplanet group

EEG
EXOPLANETS & EXOCLIMES GROUP

Joao Mendonca, Jaemin Lee,
Simon Grimm, Daniel Kitzmann,
Luc Grosheintz, Matej Malik,
Baptiste Lavie, Shang-Min Tsai

General Questions
(Theory)

What are the processes governing the atmospheric dynamics, chemistry and radiative transfer of exoplanetary atmospheres?

What are the obstacles and degeneracies associated with interpreting transmission (transit) and emission (secondary eclipse) spectra and phase curves of exoplanetary atmospheres?

What lessons can we learn from the Solar System?
(Can the techniques be borrowed without modification?)

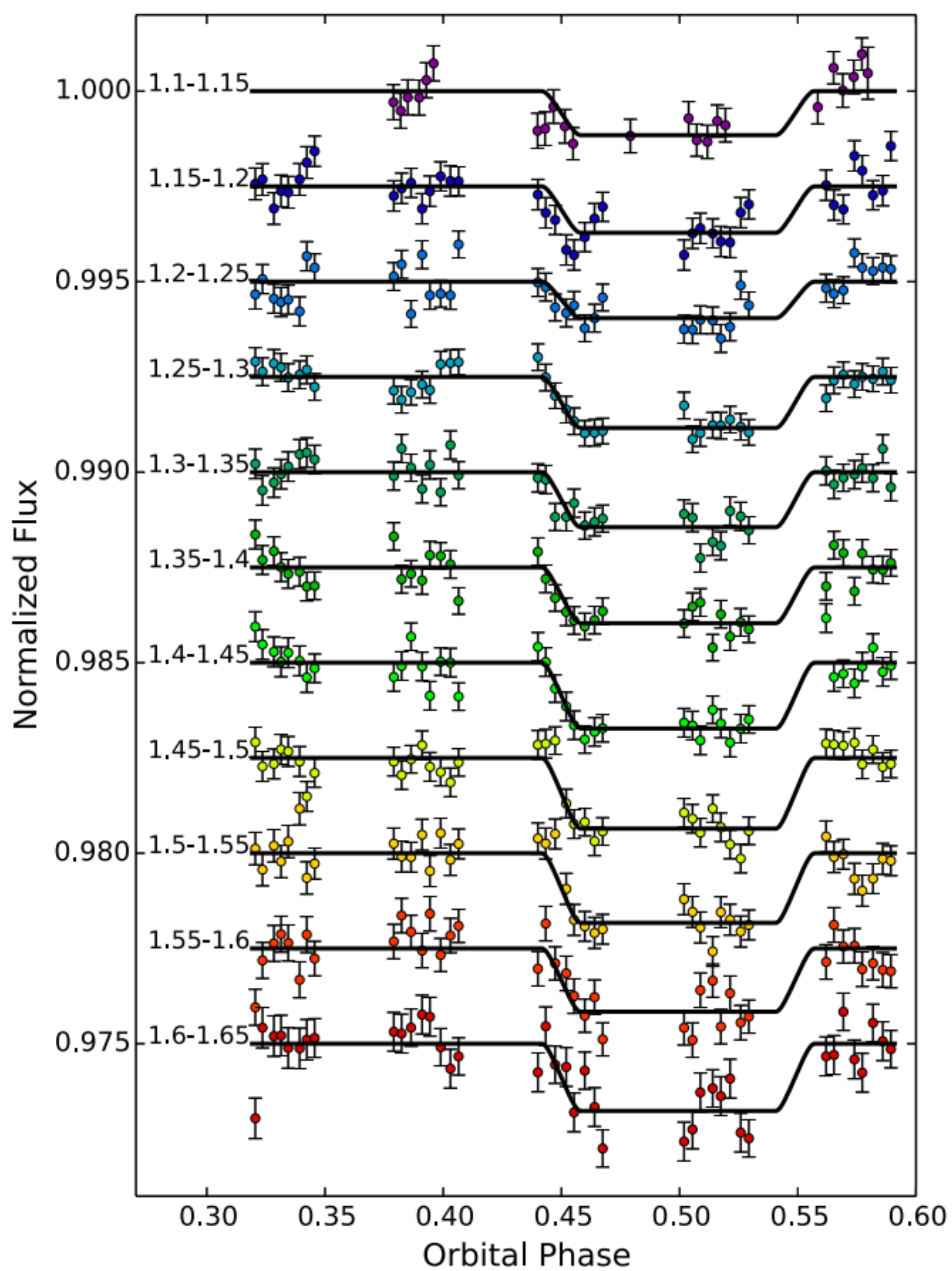
Agenda

I. Brief tour of observations
II. Theory
III. Simulations

I. Brief Tour of Observations

Spectro-photometry: emission spectrum

HST/WFC3



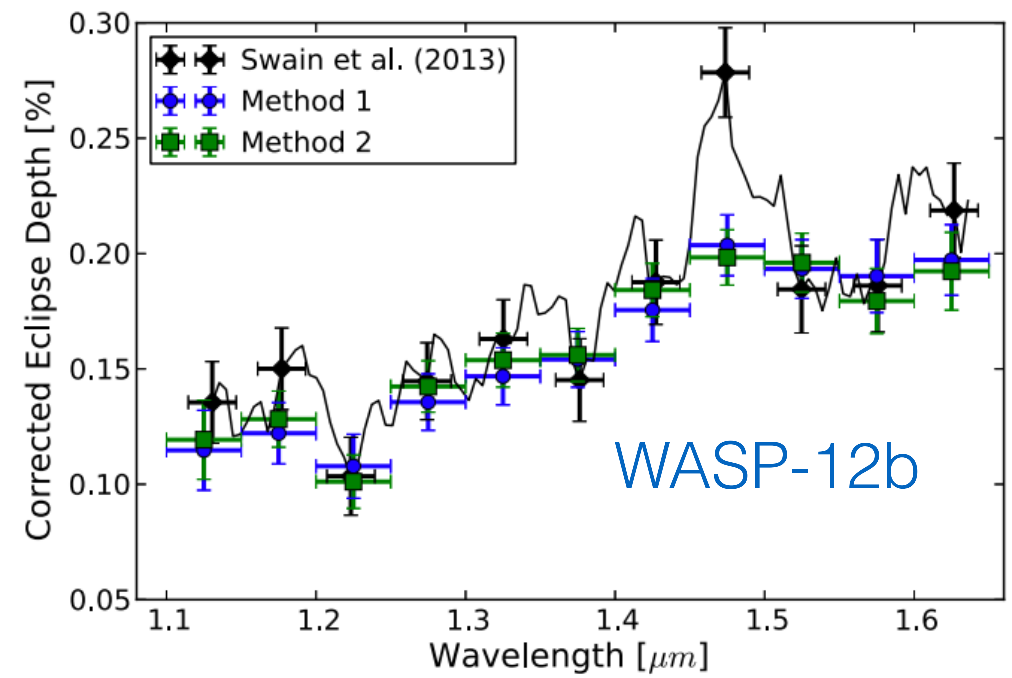


Figure 5. WASP-12b corrected emission spectrum using WFC3's G141 grism. Both methods used in our analyses (blue circles and green squares) agree with the results from Swain et al. (2013, black line with diamonds for comparison) in all but one of the spectroscopic channels.

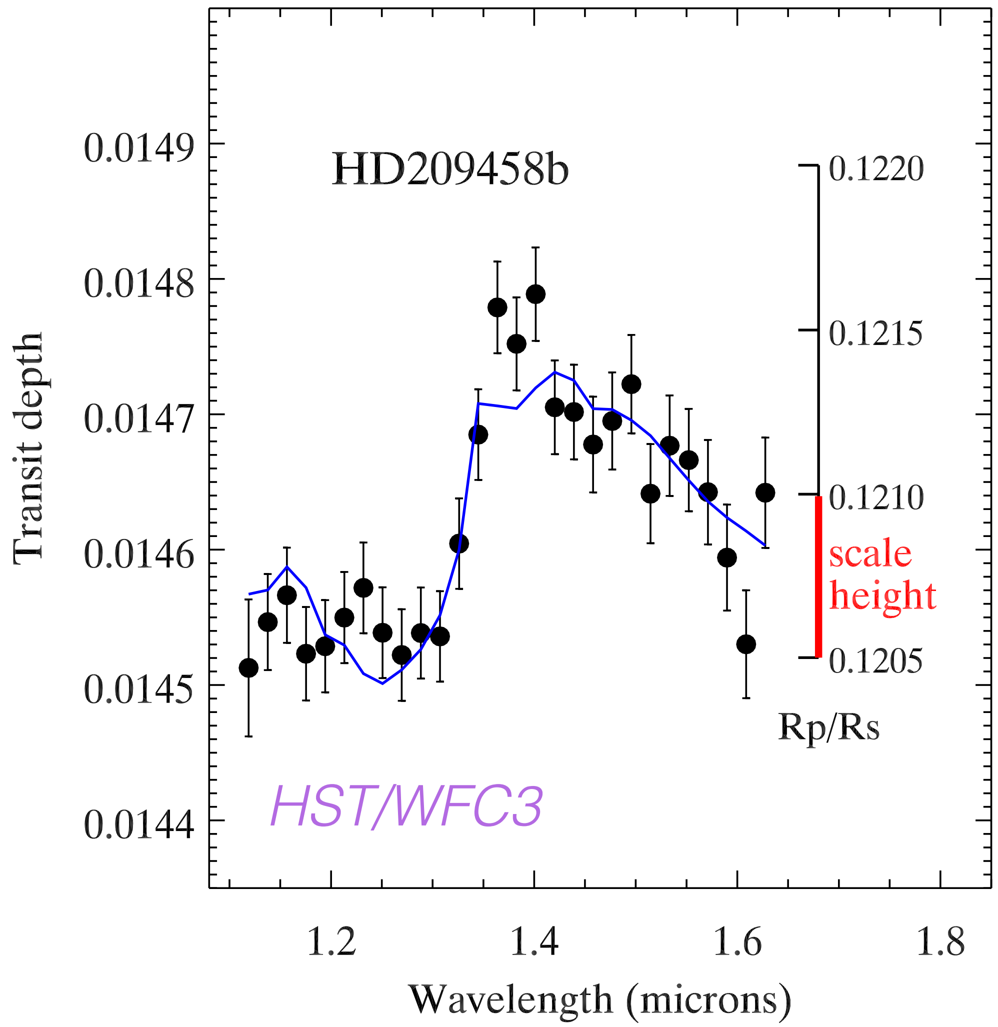
Abundances of major molecules (CO, CH_4, H_2O, CO_2) may be inferred using inversion techniques, albeit currently with some controversy.

Note: these are secondary eclipses (exoplanet's light is obscured by star)

Stevenson et al. (2014, ApJ, 791, 36)

Spectro-photometry: transmission spectra

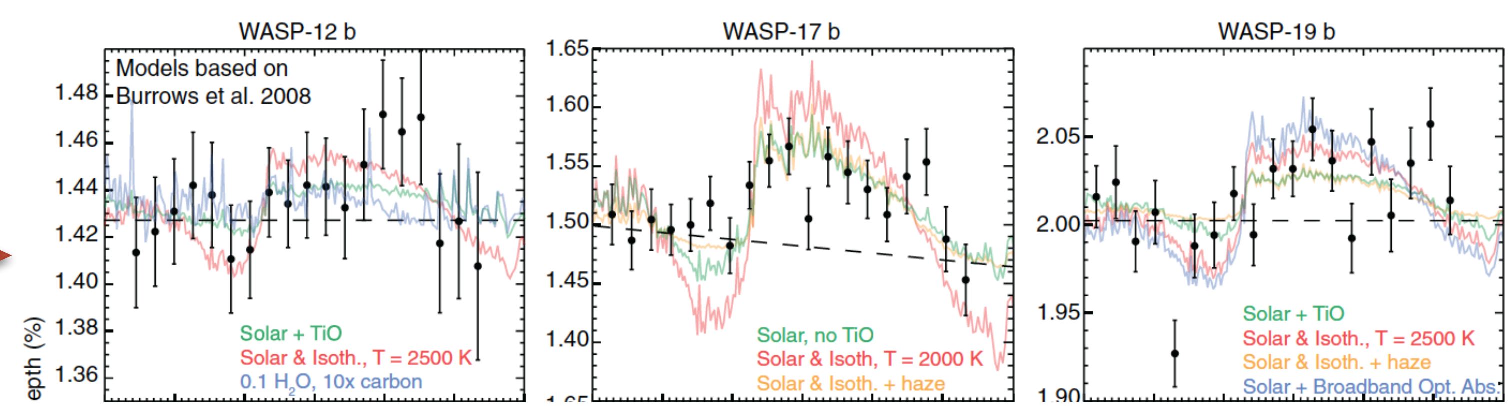
Deming et al. (2013, ApJ, 774, 95)



unambiguous detection of water feature

The observations are consistent with a degenerate range of models (cloud-free, cloudy, different chemistries)

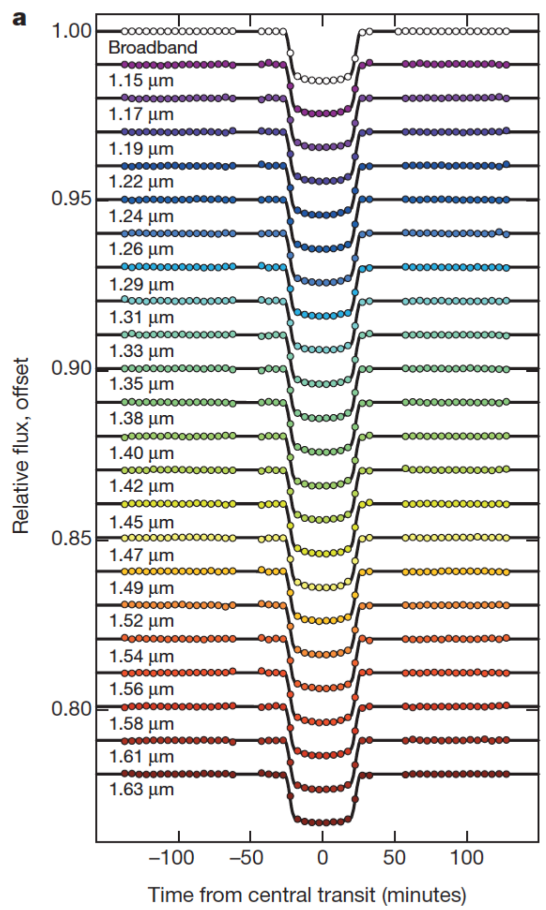
spectra muted by clouds?

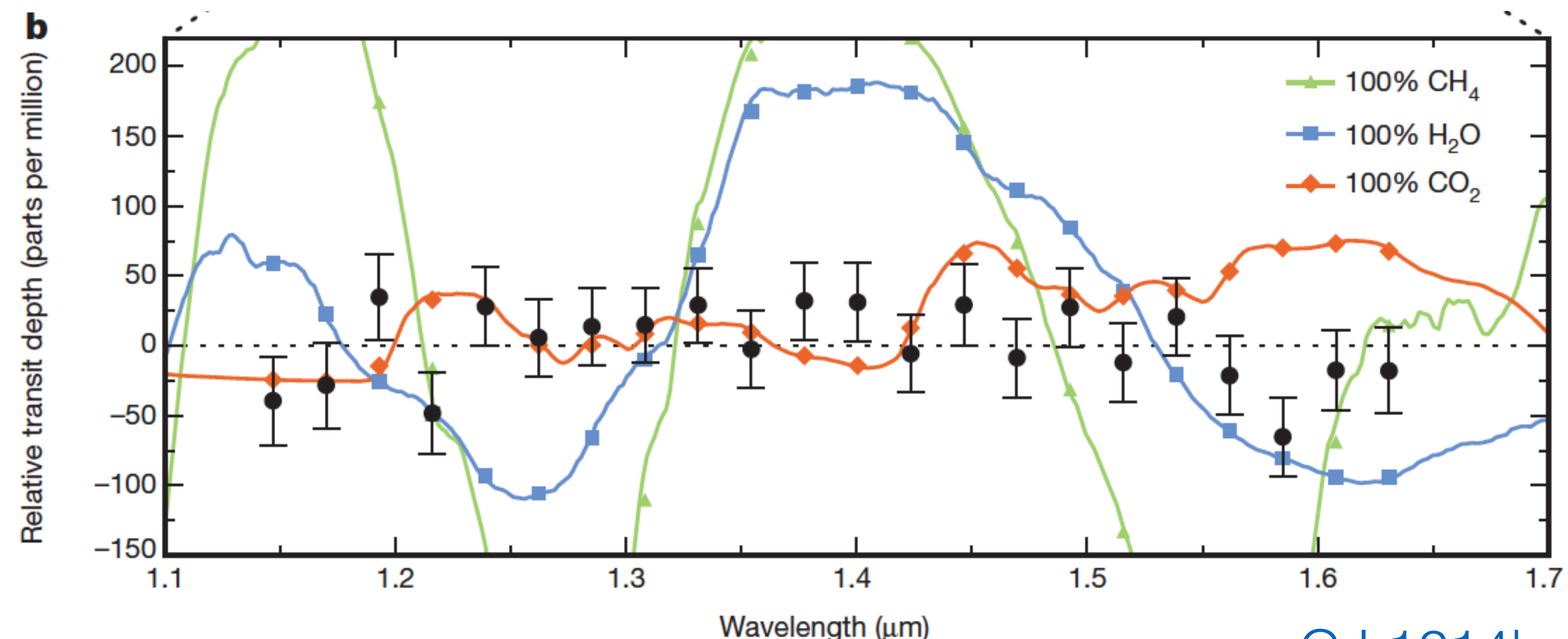


HST/WFC3

Mandell et al. (2013, ApJ, 779, 128)

More transmission spectra: flat lines





GJ 1214b

HST/WFC3

Kreidberg et al. (2014, Nature, 505, 69)

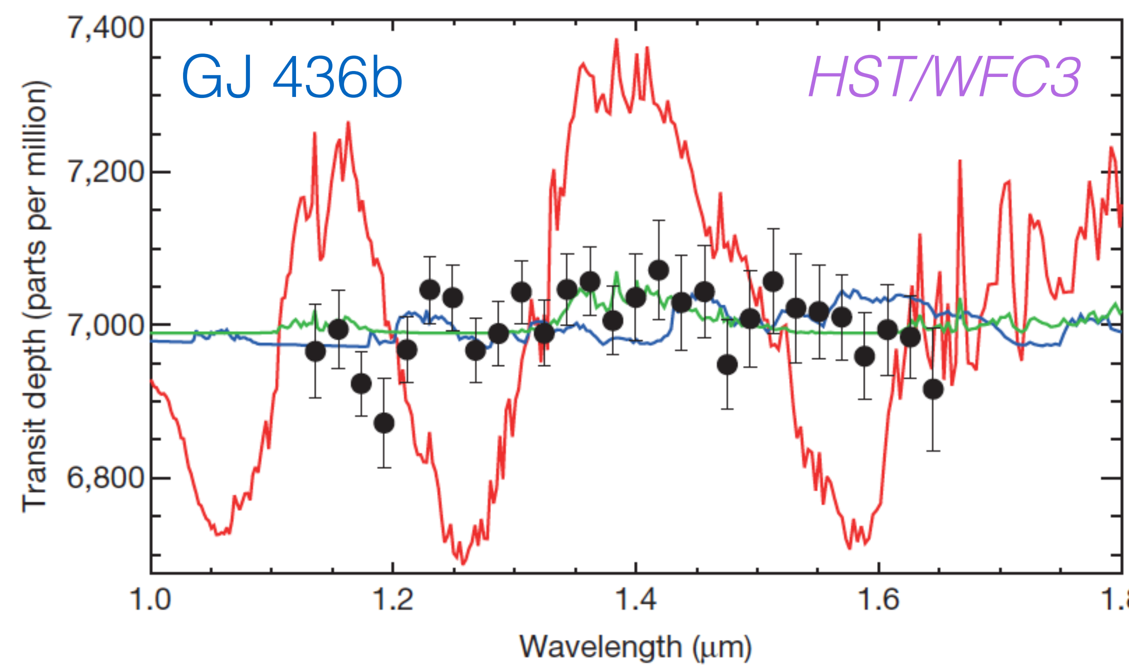
Cloud-free hydrogen-rich atmospheres are ruled out.

Cloudy or metal-rich?

(Or atmosphere-less?)

GJ 436b

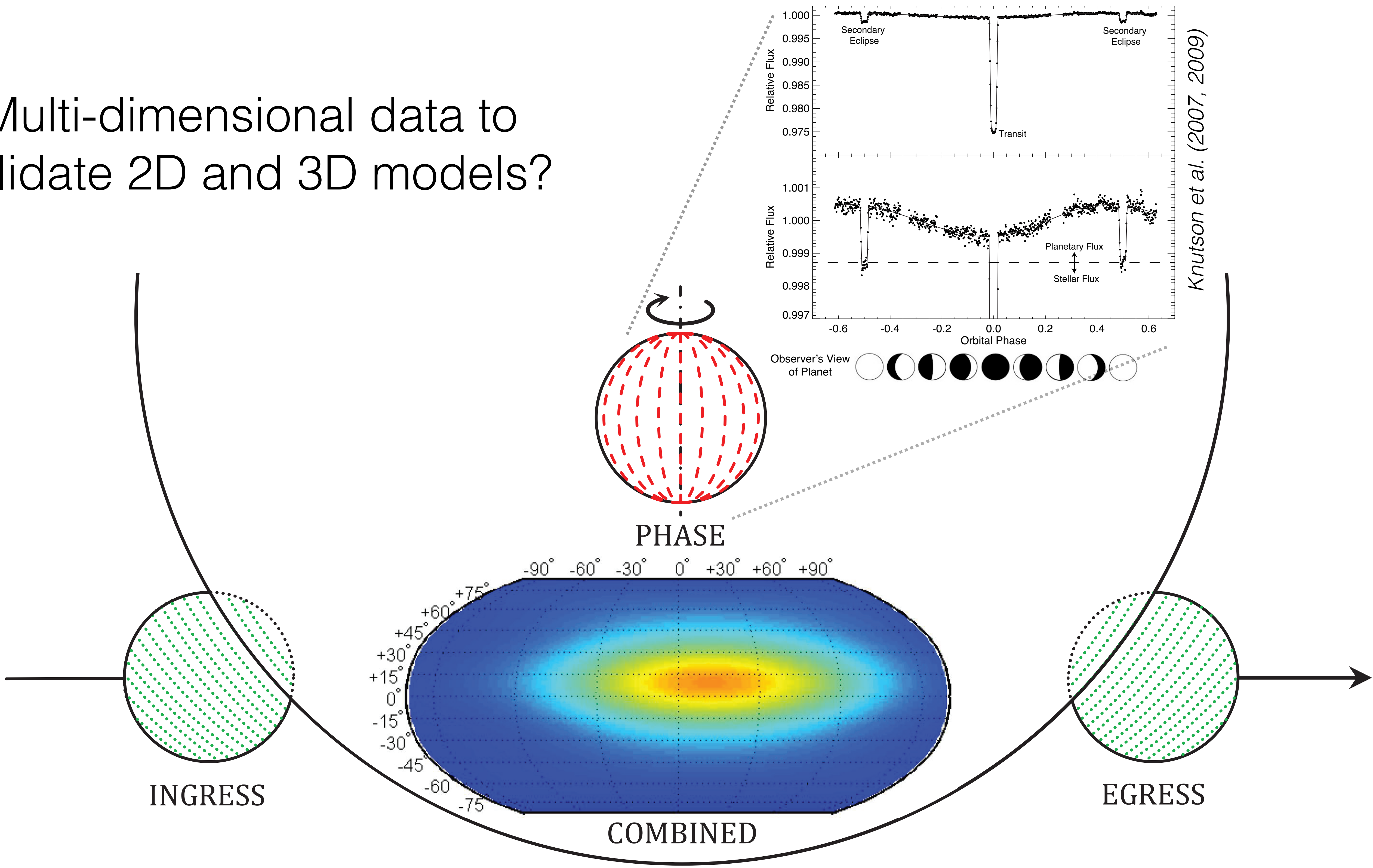
HST/WFC3



Knutson et al. (2014, Nature, 505, 66)

Eclipse mapping

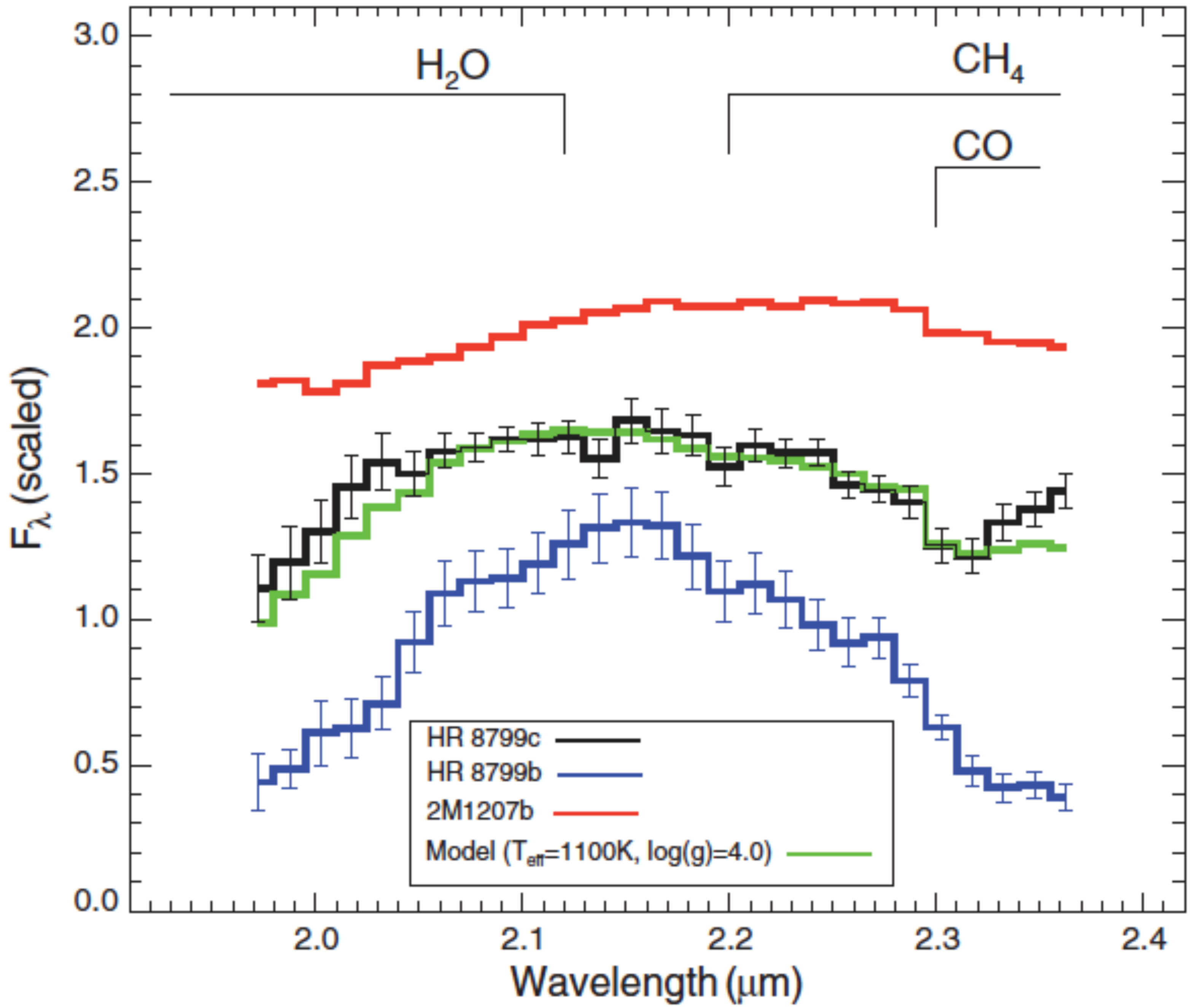
Multi-dimensional data to validate 2D and 3D models?



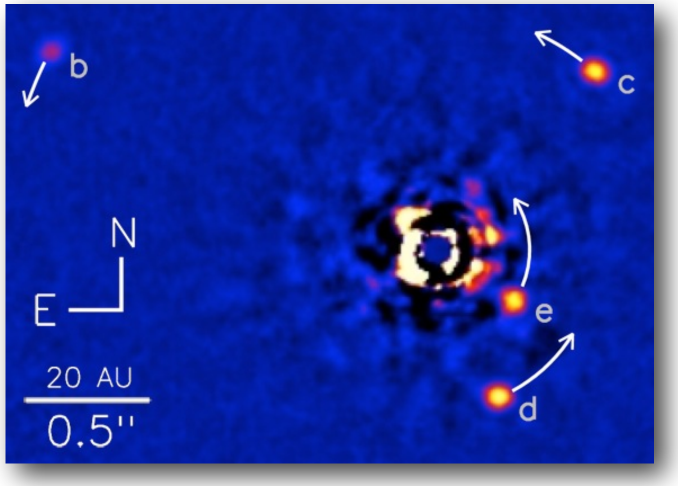
De Wit et al. (2012, A&A, 548, A128)

HD 189733b

Directly imaged exoplanets



HR 8799a,b,c,d



R~100-1000 spectra exist for a small number of objects.

But these objects have no radius or mass measurements.

Konopacky et al. (2013, Science, 339, 1398)

II. Theory

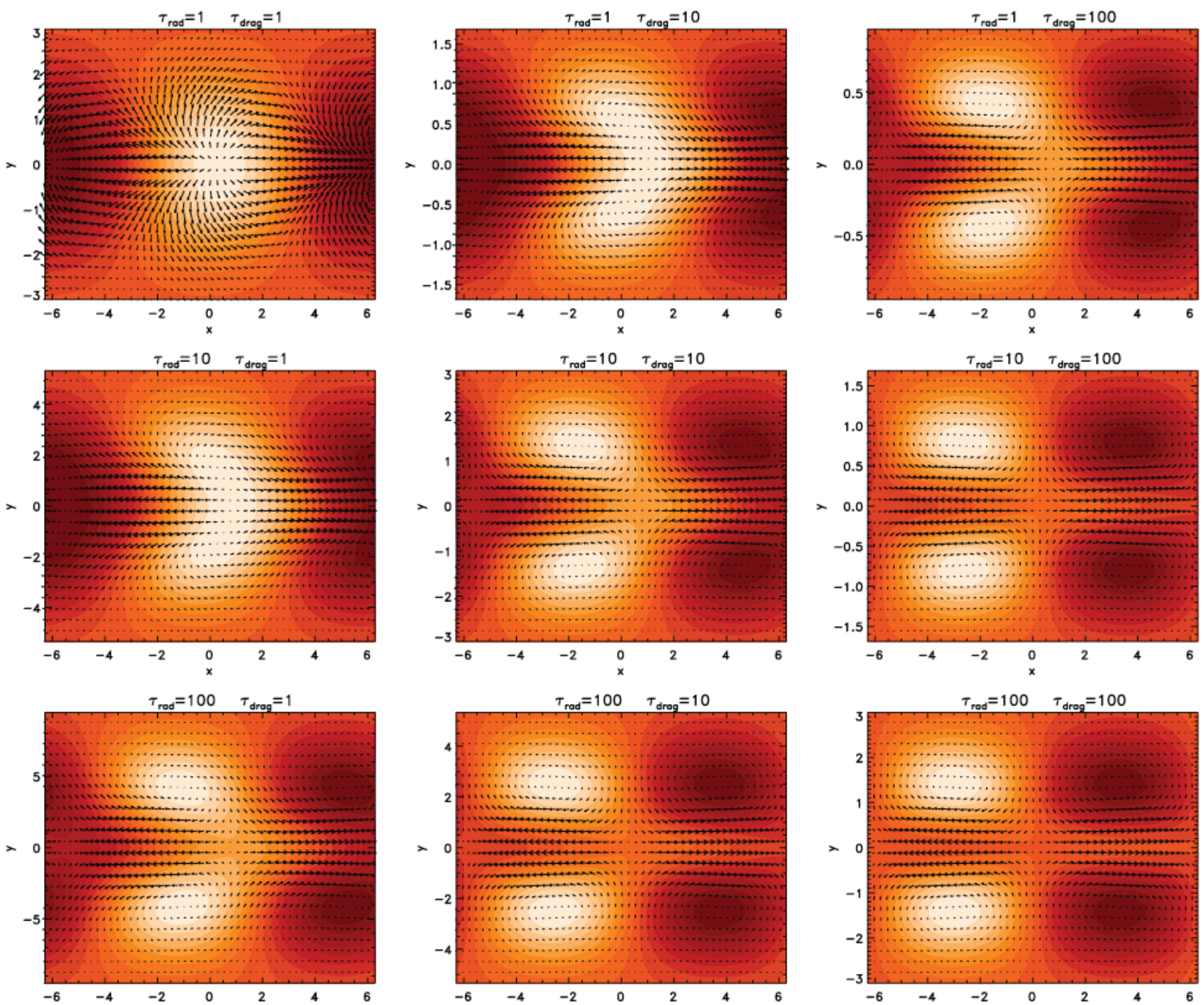
What may we learn from the Solar System?

All of the current characterisable exoplanets
are hot (~800-3000 K).

Solar System	Hot Exoplanets	Implications
stellar and interior flux comparable	stellar flux dominates (by factor ~10,000)	thermal and dynamical structures
fast rotators	slow rotators (indirect arguments)	dynamical structure
small Rossby scale	large Rossby scale	size of vortices
small Rhines scale	large Rhines scale	width of zonal jets
in-situ measurements (some ground truth)	remote sensing (rely on physics)	consider chemical, radiative and dynamical equilibrium carefully

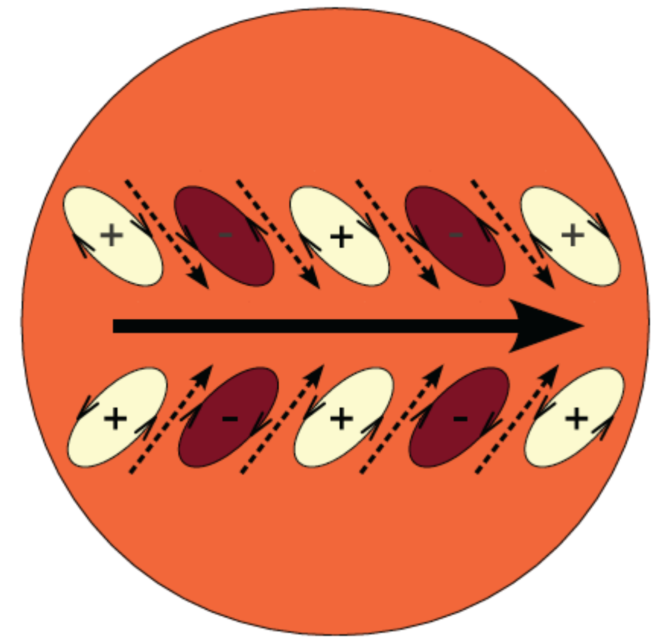
Bottom line: it does not mean we cannot benefit from SS knowledge.
It just means we have to tread carefully…

Atmospheric dynamics: an example where the Earth sciences taught us some physics

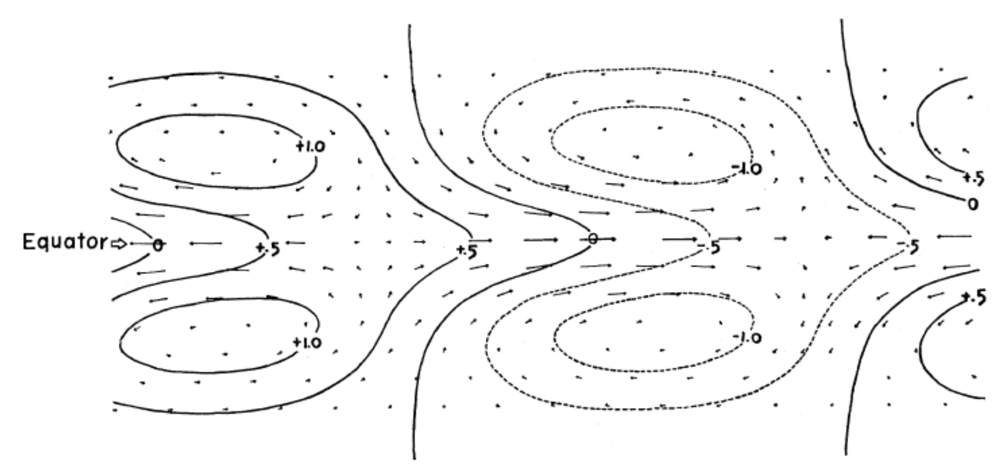


super-rotation appears to be robust
to different applications of friction/drag

Showman & Polvani (2011, ApJ, 738, 71)



Super-rotation:
angular momentum transport
by standing Rossby and Kelvin waves



inspired by Matsuno (1966)
See also: Gill (1980)

And where we could give something back (MHD shallow water waves)

The key governing equation for MHD systems and the quantum harmonic oscillator are identical, even when forcing, sources of friction and magnetic fields are considered.

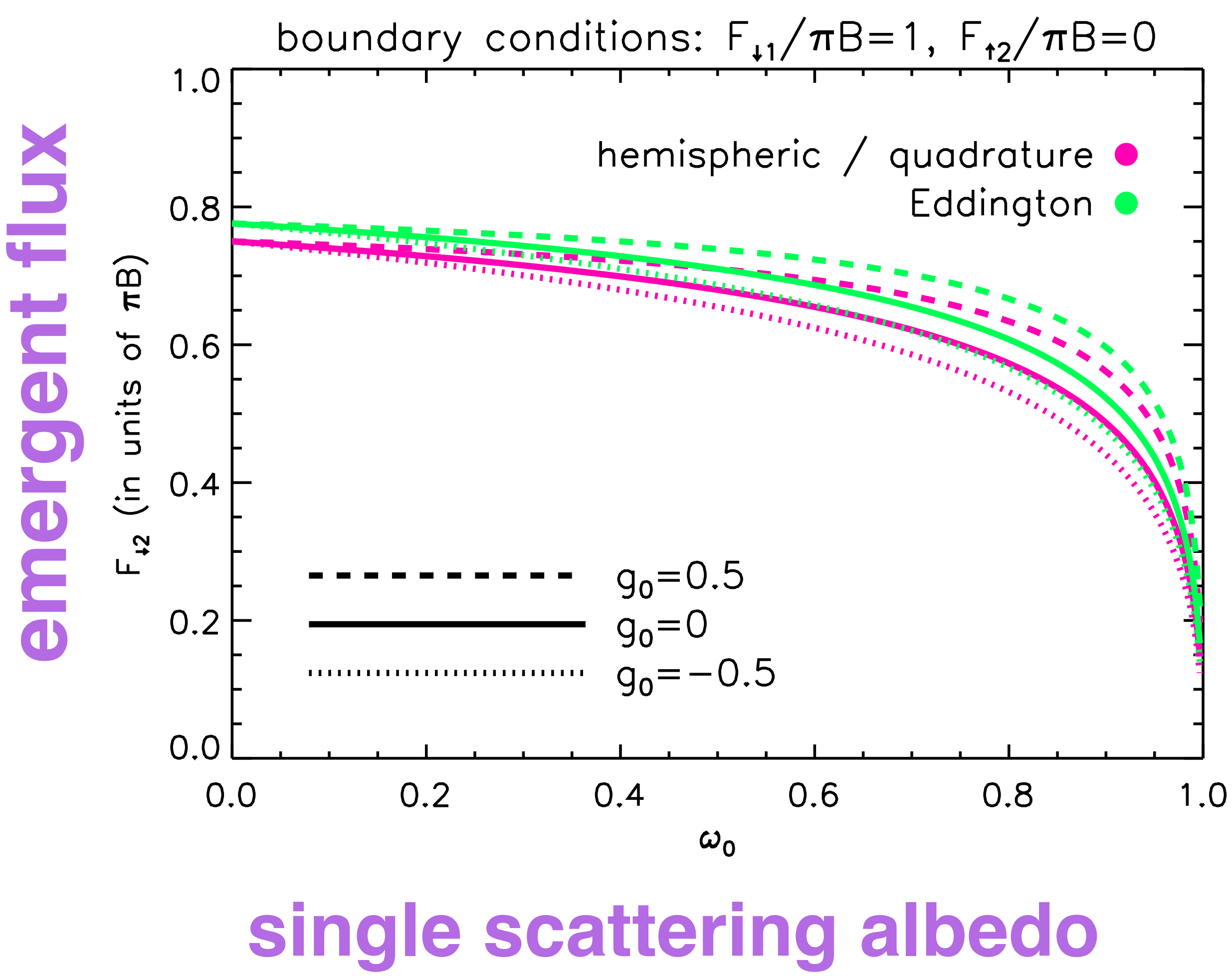
Challenges:

ODEs with complex coefficients raised to fractional powers (double-valued), have to use De Moivre's formula

non-oscillator behaviour (poloidal magnetic field, non-uniform drag)

Heng & Workman (2014, ApJS, 213, 27)

Two-stream radiative transfer: when standard approaches are not so standard



Easier to solve moments of the radiative transfer equation, but there is always one more unknown than number of equations.

Need to "close" the set of equations (Eddington coefficients).

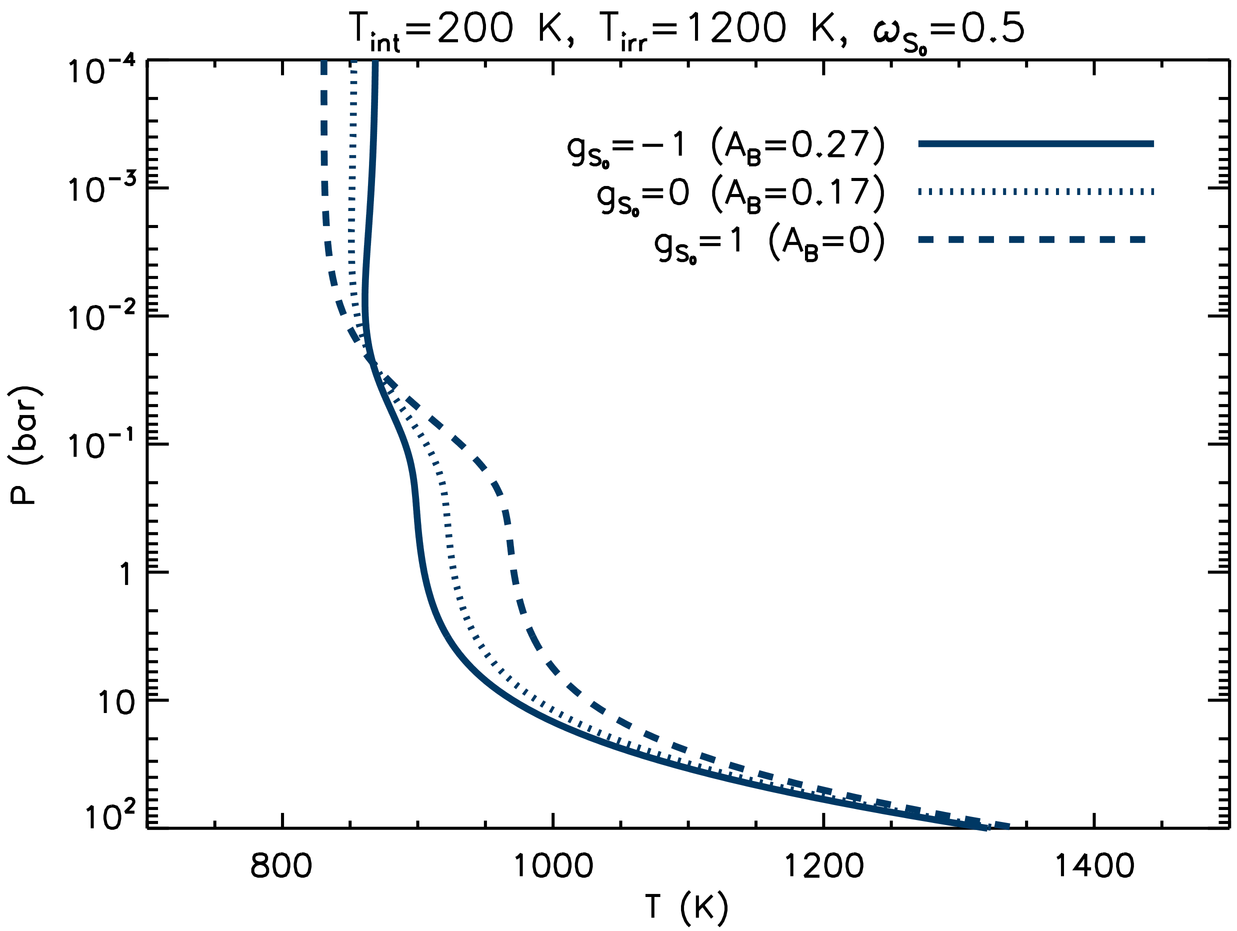
Choice of closure is intimately related to general energy conservation.

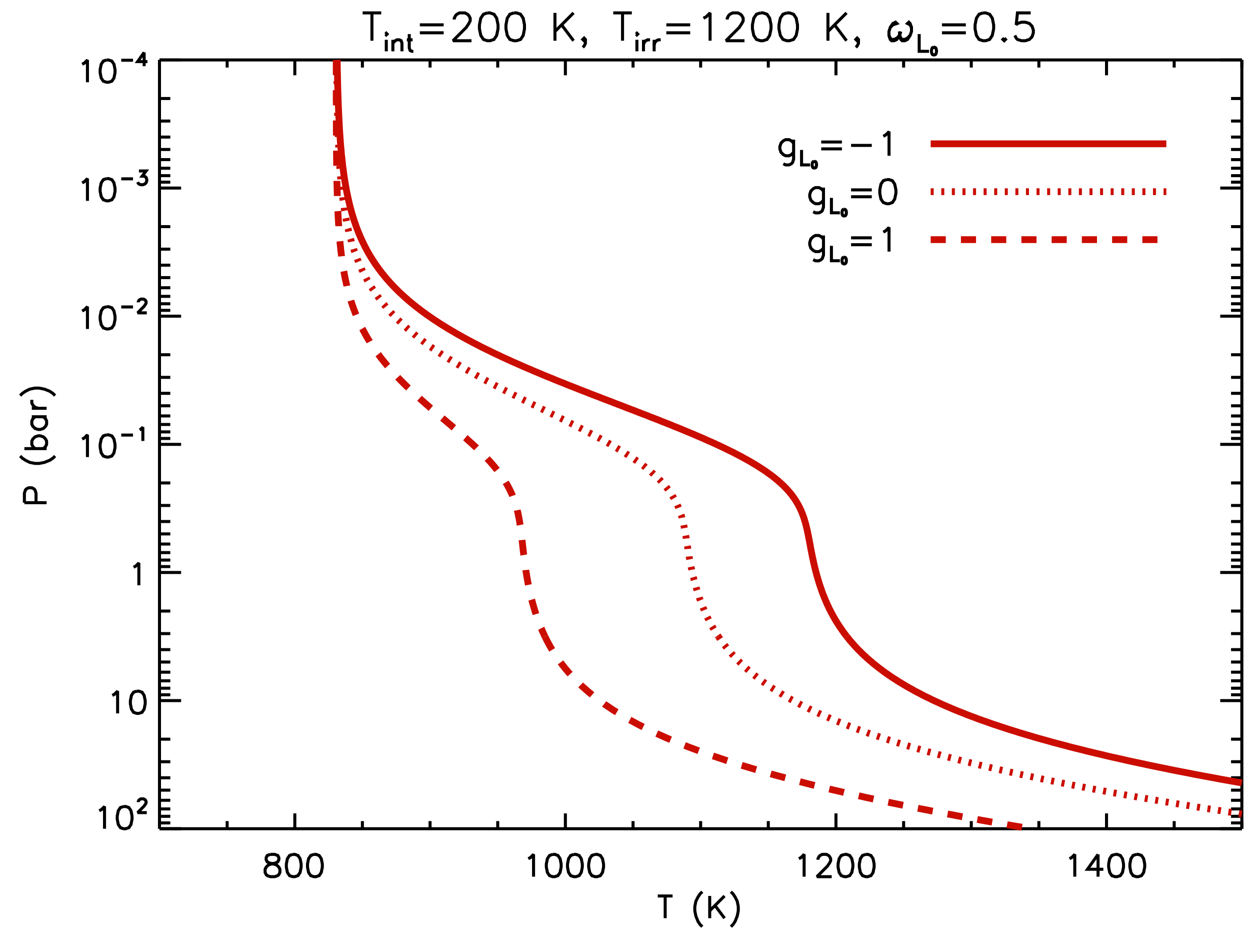
The commonly used **Eddington closure** introduces two types of errors:

1. spurious enhancement of blackbody emission
2. spurious production of reflected flux

Heng, Mendonca & Lee (2014, ApJS, in press)

Building on the work of Chandrasekhar, Mihalas: analytical T-P profiles with irradiation





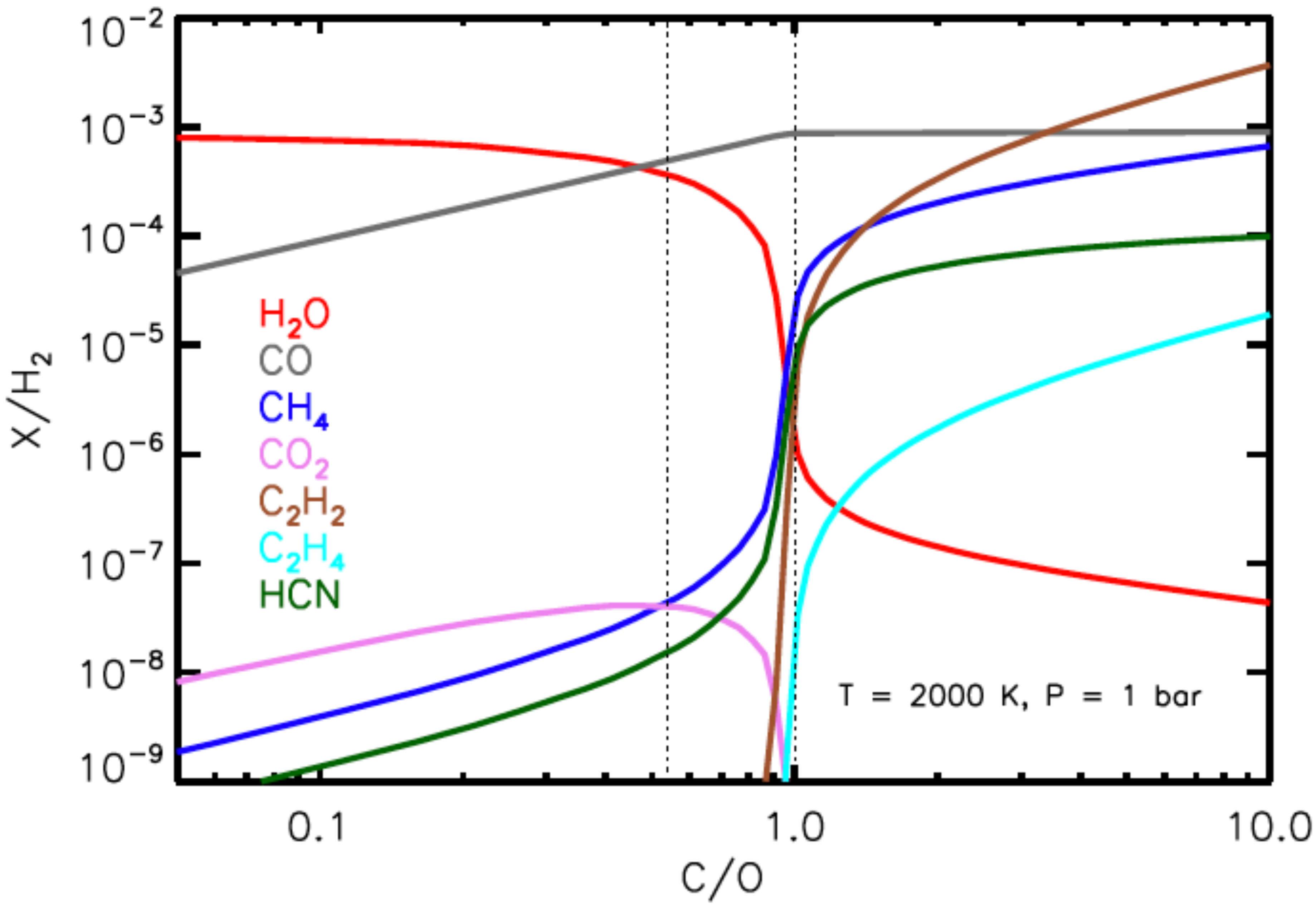
scattering of starlight generally warms the upper atmosphere and cools the lower atmosphere **(anti-greenhouse effect)**

scattering of thermal emission generally warms the atmosphere, unless it is purely forward scattering **(scattering greenhouse effect)**

Heng, Mendonca & Lee (2014, ApJS, in press)

See also: Hubeny et al. (2003), Hansen (2008), Guillot (2010), Heng et al. (2012), Parmentier & Guillot (2014)

Do hot exoplanets display chemical diversity?



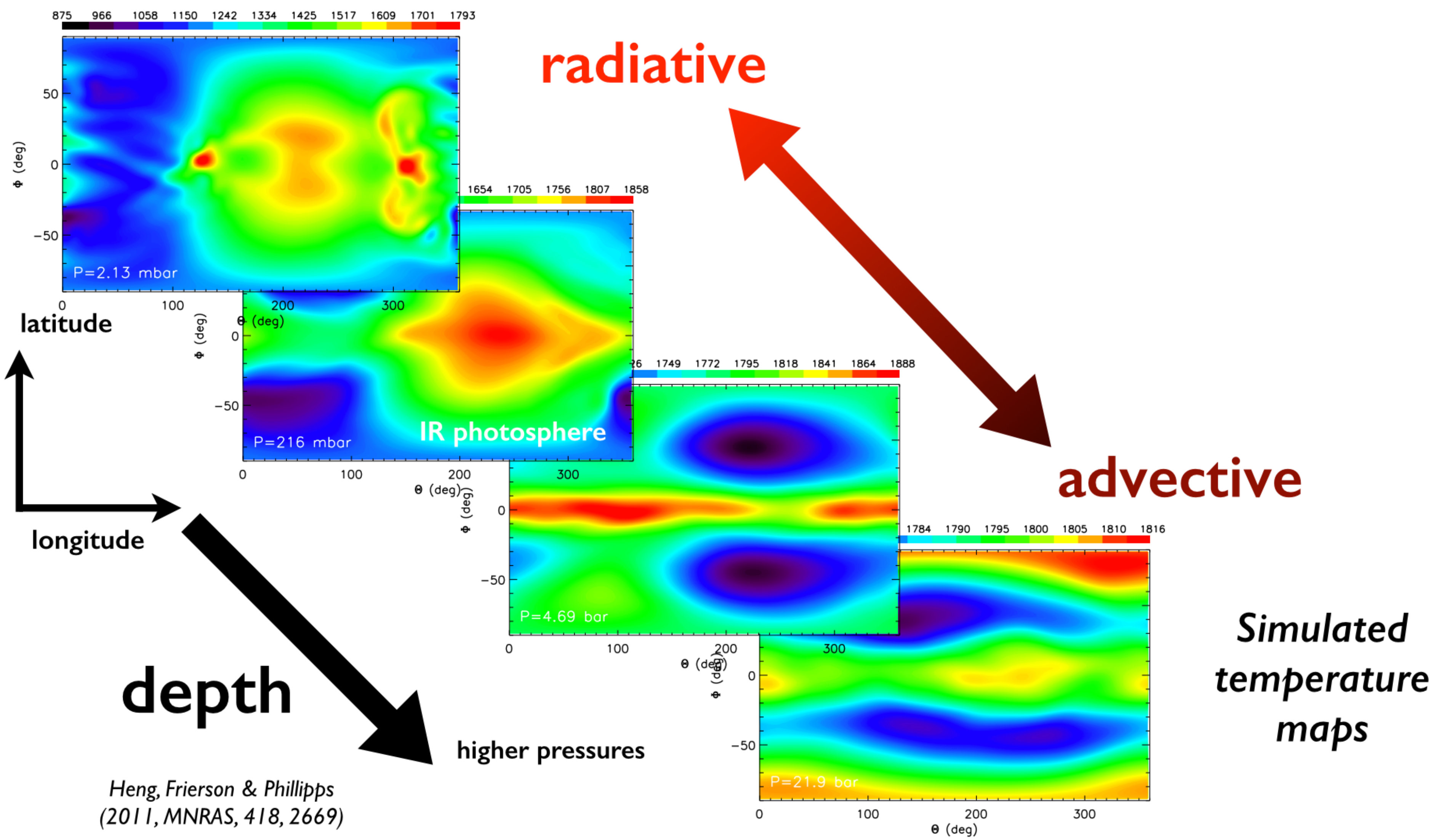
As C/O ratio varies, abundances of molecules generally vary by orders of magnitude (except for CO). VO and TiO formation are inhibited in carbon-rich environments.

See also: Helling & Lucas (2009), Moses et al. (2011)

Madhusudhan (2012, ApJ, 758, 36)

III. Simulations

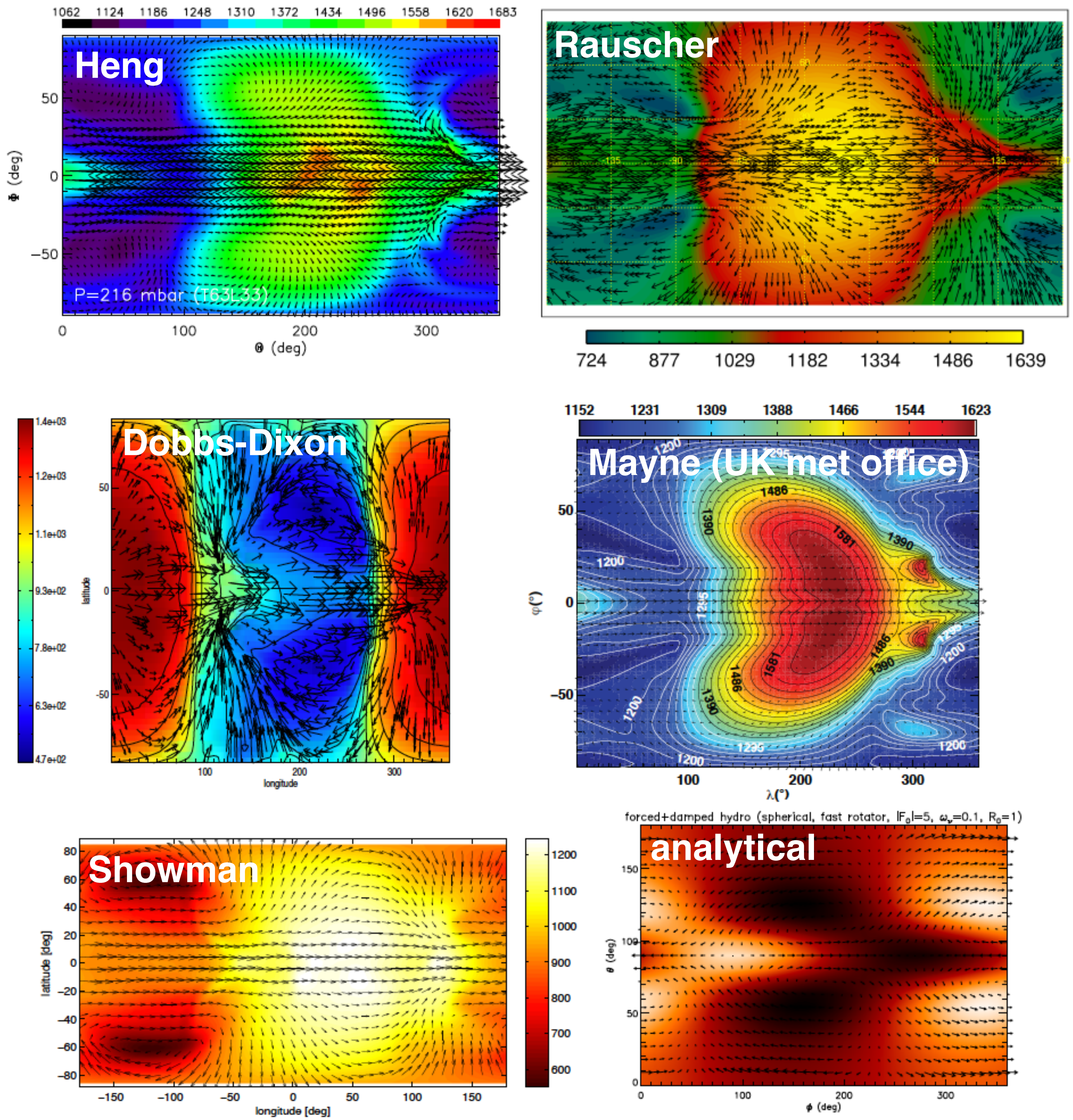
Why do we even need 3D simulations in the first place?



We are interested in the infrared photosphere, but to simulate it properly we need to simulate the different interacting atmospheric layers.

GCMs (general circulation models) have had some success explaining basic trends and observed spectra (Showman et al. 2009).

Published simulations show consensus on global structure of hot Jupiters



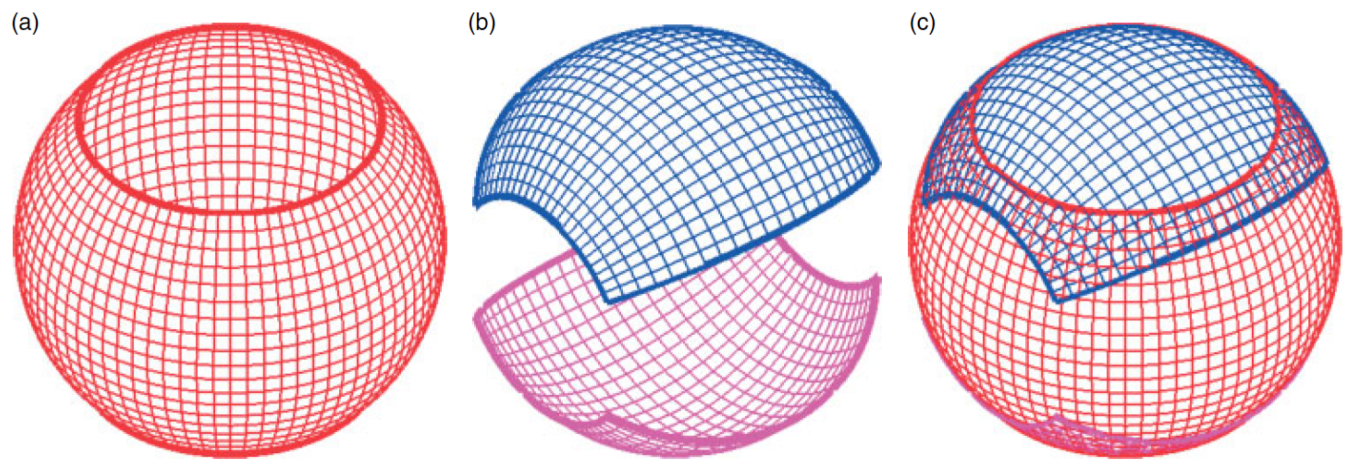
Heng & Showman (2015, Annual Review of Earth & Planetary Science)

Quantitative differences exist between results from different groups, but the qualitative trends agree.

Nevertheless, several formidable technical challenges remain (see upcoming slides).

Challenge #1: the pole problem

regular spherical grids have singularities
at the poles (zero time step)



multiple spherical grids

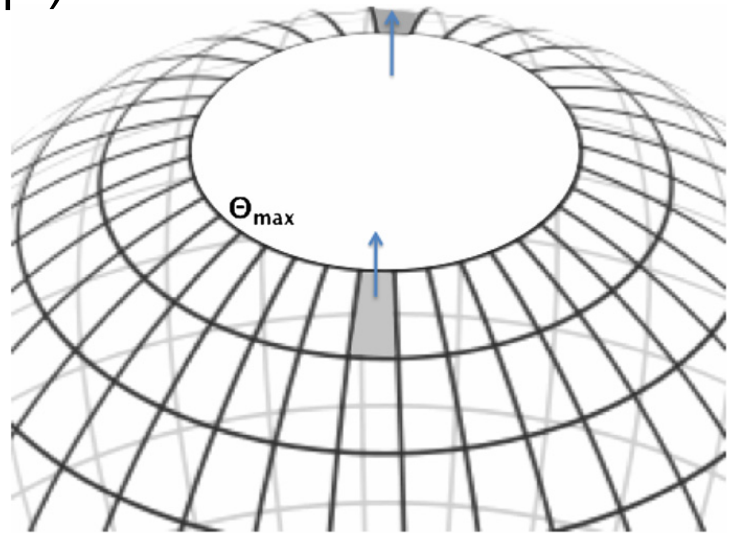
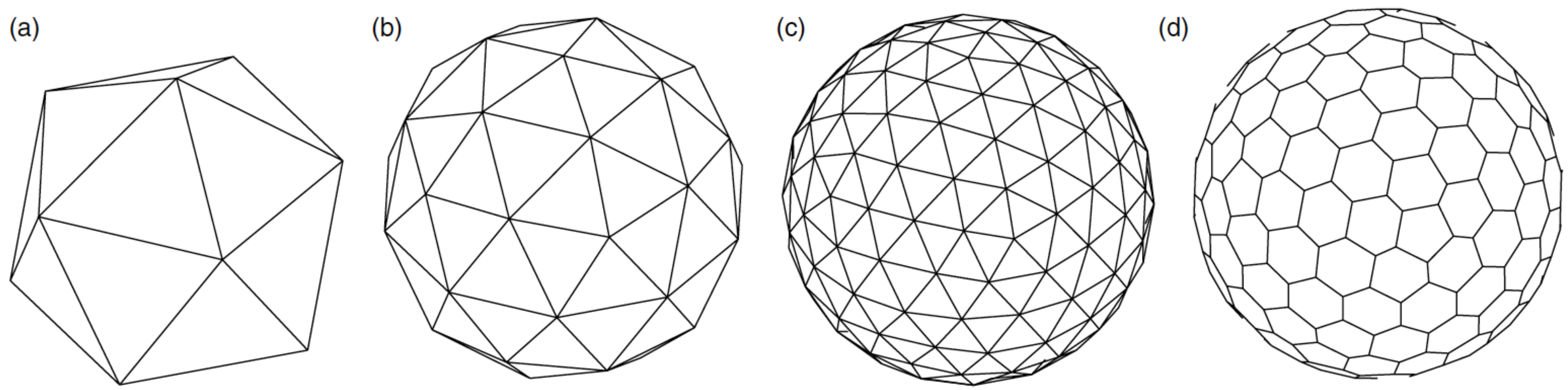


Figure 1. Illustration of the staggered grid setup near the north pole. Scalars are defined at grid centers while velocities and fluxes are defined along appropriate grid edges. Cells along the polar circle $((\phi, \theta) = (\phi, \theta_{max}))$ utilize the cell at $(\phi + \pi, \theta_{max})$ as a neighboring cell. For instance, the two shaded cells communicate directly and the velocities (blue arrows) across the cell edges are identical.

truncation (ignore the problem)
cf. Dobbs-Dixon



icosahedral grid

Stanisforth & Thuburn (2012, QJRMS, 138, 1)

Challenge #2: atmospheres are nearly hydrostatic

Common belief:
hydrostatic balance (pressure vs. gravity)
implies zero vertical/radial flow

True only in 1D!
It really means that adjustment back to
hydrostatic equilibrium is very fast.

Computational challenge:
bottlenecks time step in the
vertical/radial direction

Possible solutions include using
hybrid explicit-implicit schemes (e.g., HEVI).

Challenge #3: ~1000 K flows form shocks

supersonic flow

“wall”
(zero-velocity
boundary condition)

Traditional astrophysical situation

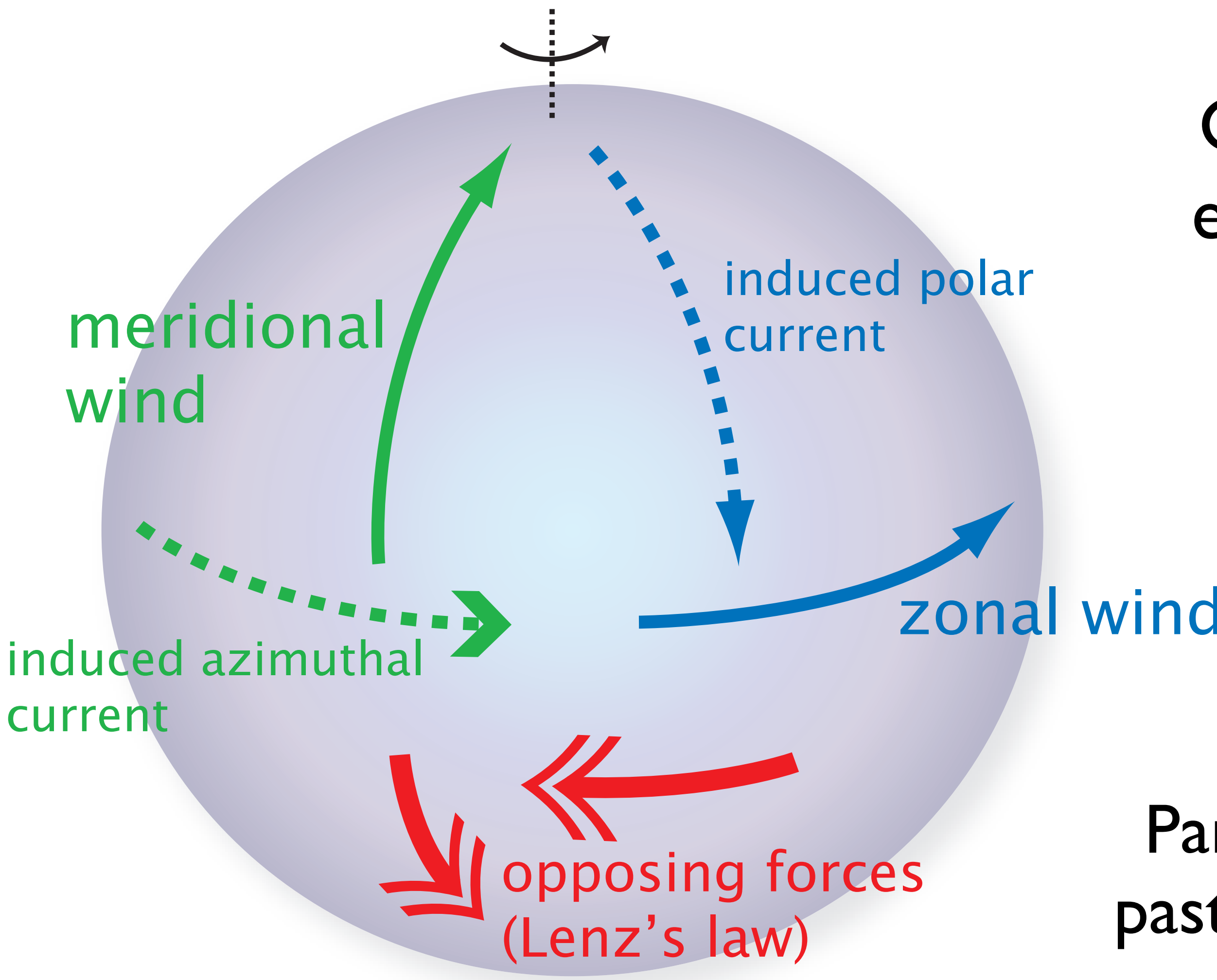
e.g., supernova explosion into ISM

In an exoplanetary atmosphere, the “wall” is created naturally by the night-to-day transition of the flow (re-compression). Shocks convert ~25% of kinetic energy into heat.

The situation is similar to a **wind tunnel**.
The Mach number needs to exceed unity and decrease locally for a shock to form.

Heng (2012a, ApJL, 761, L1)

Challenge #4: ~1000 K flows are partially ionised



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

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

An exoplanet-scale manifestation of Lenz's law

Perna, Menou & Rauscher (2010a,b); Batygin & Stevenson (2010); Batygin et al. (2011); Menou (2012); Heng (2012b); Rauscher & Menou (2013); Rogers & Showman (2014); Batygin & Stanley (2014)

Study (Alphabetical)	Approx. Used	Global Grid?	Irradiated† Atmosphere?	Radiative† Transfer?	Treats Shocks?	Magnetic Fields?	Passes Earth‡ Benchmark?	Ref.
Batygin et al. (2013)♣	BQ (3D)	Y	Y	N	N	Y	N	[6]
Bending et al. (2012)	PE (3D)	Y	Y	N	N	N	Y	[7]
Burkert et al. (2005)♣⋄	EE (2D)	N	Y	Y	N	N	N	[15]
Burrows et al. (2010)	PE (3D)	Y	Y	N	N	N	Y	[18]
Cho et al. (2003)	EB (2D)	Y	N	N	N	N	N	[23]
Cho et al. (2008)	EB (2D)	Y	N	N	N	N	N	[24]
Cooper & Showman (2005)	PE (3D)	Y	Y	N	N	N	Y	[25]
Cooper & Showman (2006)	PE (3D)	Y	Y	N	N	N	Y	[26]
Dobbs-Dixon & Lin (2008)♣	EE (3D)	N	Y	Y	N	N	N	[41]
Dobbs-Dixon et al. (2010)♣	NS (3D)	N	Y	Y	Y	N	N	[42]
Dobbs-Dixon et al. (2012)♣	NS (3D)	N	Y	Y	Y	N	N	[43]
Dobbs-Dixon & Agol (2013)	NS (3D)	N	Y	Y	Y	N	N	[44]
Heng et al. (2011a)	PE (3D)	Y	Y	N	N	N	Y	[57]
Heng et al. (2011b)	PE (3D)	Y	Y	Y	N	N	Y	[58]
Kataria et al. (2013)	PE (3D)	Y	Y	Y	N	N	Y	[68]
Langton & Laughlin (2008)	EE (2D)	Y	Y	Y	N	N	N	[82]
Lewis et al. (2010)	PE (3D)	Y	Y	Y	N	N	Y	[85]
Li & Goodman (2010)	NS (2D)	N	Y	N	Y	N	N	[87]
Liu & Showman (2013)	PE (3D)	Y	Y	N	N	N	Y	[88]
Mayne et al. (2013)	EE (3D)	Y	Y	N	N	N	Y	[96]
Mayne et al. (2014)♡	EE (3D)	Y	Y	N	N	N	Y	[97]
Menou & Rauscher (2009)	PE (3D)	Y	Y	N	N	N	Y	[99]
Menou (2012)	PE (3D)	Y	Y	Y	N	N	Y	[101]
Merlis & Schneider (2010)♠	PE (3D)	Y	Y	Y	N	N	Y	[103]
Parmentier et al. (2013)	PE (3D)	Y	Y	Y	N	N	Y	[107]
Perna et al. (2010a)	PE (3D)	Y	Y	N	N	N	Y	[111]
Perna et al. (2010b)	PE (3D)	Y	Y	N	N	N	Y	[112]
Perna et al. (2012)	PE (3D)	Y	Y	Y	N	N	Y	[113]
Polichtchouk & Cho (2012)	PE (3D)	Y	N	N	N	N	Y	[117]
Rauscher & Menou (2010)	PE (3D)	Y	Y	N	N	N	Y	[119]
Rauscher & Menou (2012a)	PE (3D)	Y	Y	N	N	N	Y	[120]
Rauscher & Menou (2012b)	PE (3D)	Y	Y	Y	N	N	Y	[121]
Rauscher & Menou (2013)	PE (3D)	Y	Y	Y	N	N	Y	[122]
Rogers & Showman (2014)	AN (3D)	Y	Y	N	N	Y	N	[127]
Showman & Guillot (2002)	PE (3D)	Y	Y	N	N	N	Y	[132]
Showman et al. (2008)	PE (3D)	Y	Y	N	N	N	Y	[134]
Showman et al. (2009)	PE (3D)	Y	Y	Y	N	N	Y	[135]
Thrastarson & Cho (2010)	PE (3D)	Y	Y	N	N	N	Y	[151]
Thrastarson & Cho (2011)	PE (3D)	Y	Y	N	N	N	Y	[152]

†: "Irradiated" refers specifically to whether the model atmosphere is being forced by stellar irradiation, i.e., whether the irradiation is doing work on the atmosphere. Simulations that are unforced by irradiation are sometimes termed "adiabatic". It is possible for the effects of radiation in irradiated atmospheres to be mimicked without explicitly performing radiative transfer, by adopting a Newtonian relaxation or cooling term in the thermodynamic equation.

‡: only marked "Y" if there is either an explicit demonstration in the publication or a clear citation to previous publications describing that the simulation code used is able to reproduce the Held-Suarez benchmark test for Earth [56]. Since it is a 3D test, 2D simulations, by definition, are unable to reproduce it.

♣: Employs flux-limited diffusion in the region encompassing the photosphere, an approximation that is strictly valid only in optically thin or thick situations.

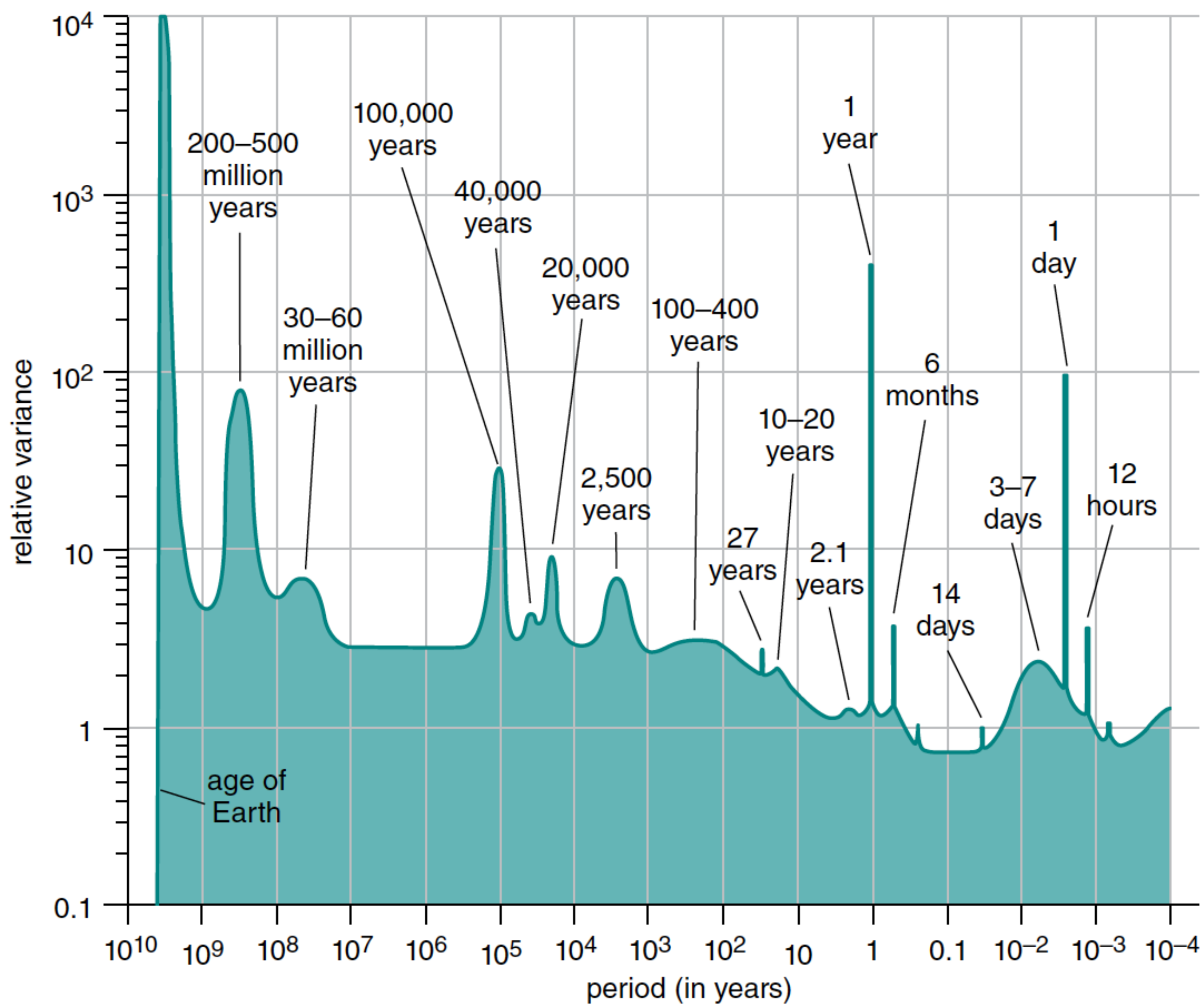
⋄: Rotation of the exoplanet is not included. ♠: Effects of hydrological cycle included. ♡: Non-hydrostatic.

Acronyms: Boussinesq (BQ), anelastic (AN), equivalent barotropic (EB), primitive equations (PE), Euler equation (EE), Navier-Stokes equation (NS).

Table 1: Summary table of atmospheric circulation studies of exoplanets using GCMs

Heng & Showman (2015, Annual Review of Earth & Planetary Science)

A futuristic thought: power spectrum of an exoplanet?



Mitchell (1976, Quaternary Research, 6, 481)

If Earth was an exoplanet……

Summary

- The theory and simulation of exoplanetary atmospheres is a nascent, interdisciplinary field that builds upon the work of astronomy/astrophysics, atmospheric/climate science, high-performance computing and computer science, etc.

- It is ultimately aimed at developing a deeper understanding of the processes governing atmospheric dynamics, radiative transfer and chemistry, so as to aid in the interpretation of observations.

- Expect order-of-magnitude leaps in both observational and simulational techniques in the coming decade.

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www.exoclime.org

Heng & Showman (2015, Annual Review of Earth & Planetary Science)

The Landscape of Things

(biased towards transits)

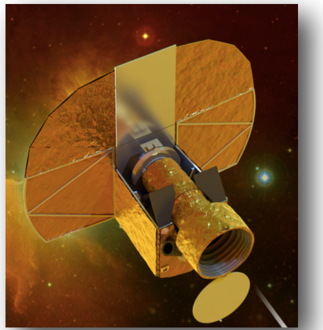
Also: transition from 1D radiative transfer models to hierarchy of models including 3D GCMs

Spitzer/Hubble era: "spectro-photometry"

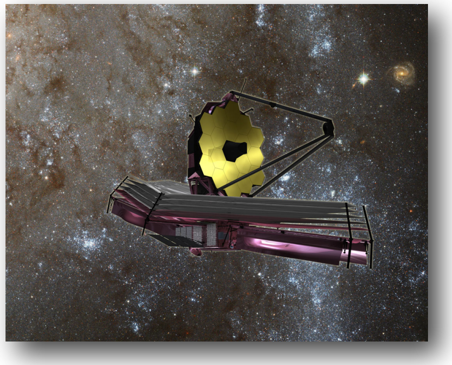
JWST spectroscopy (and E-ELT, GMT, TMT)

Kepler (2009): discovery, statistics

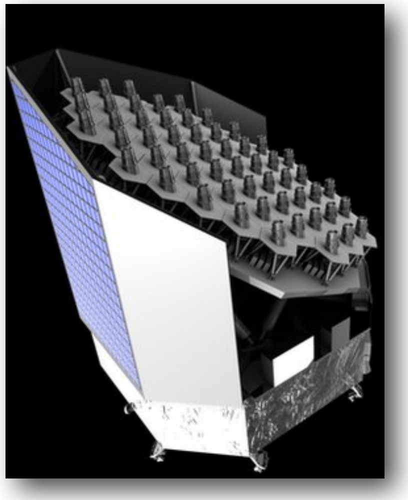
TESS (2017): discovery



CHEOPS (2017): follow-up

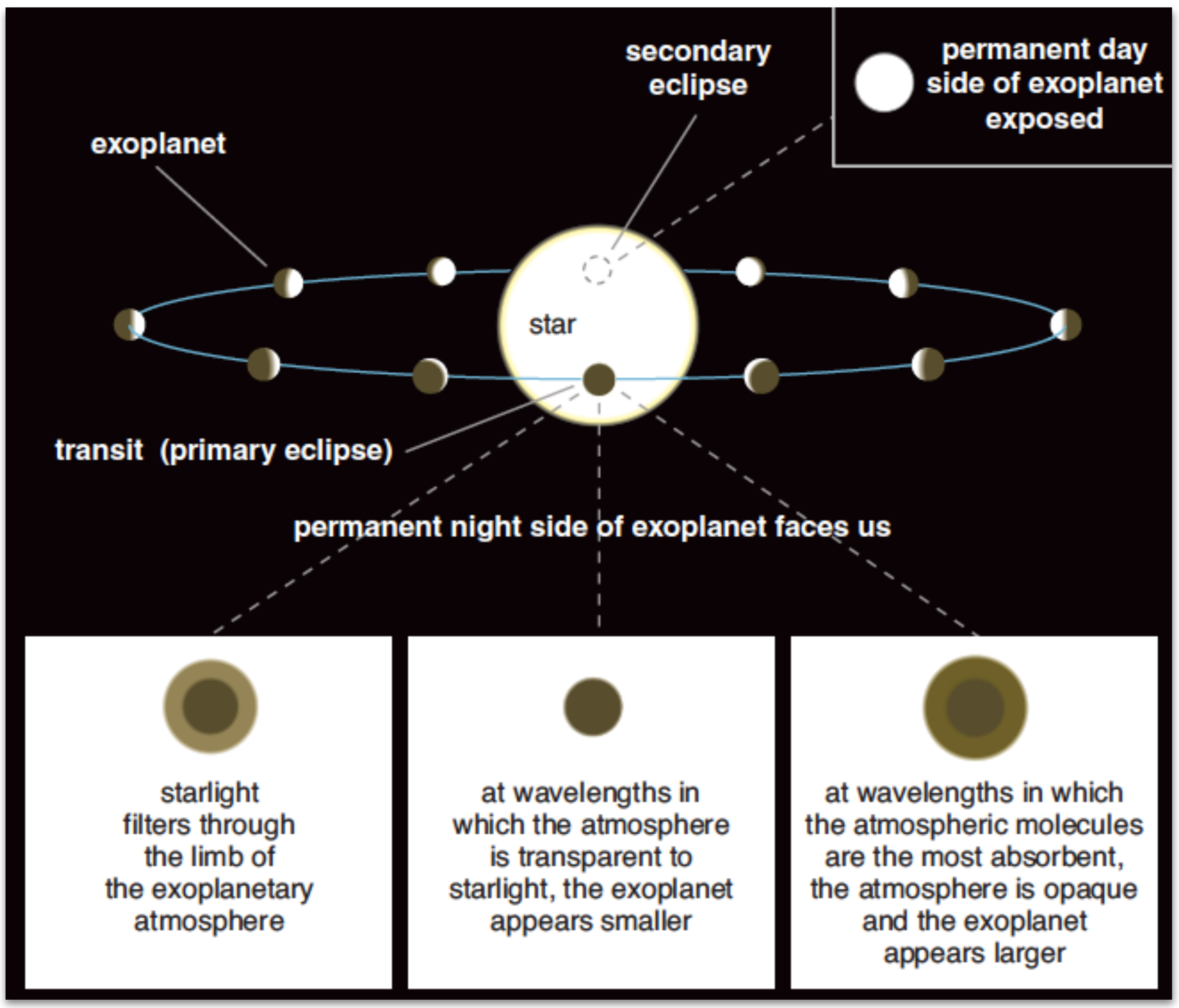


JWST (2018): spectroscopy



PLATO (2024): discovery, statistics

Why do we even need 3D simulations in the first place?



Heng & Showman (2015, Annual Review of Earth & Planetary Science)

To understand the connection between transmission (limb) and emission (dayside) spectra.

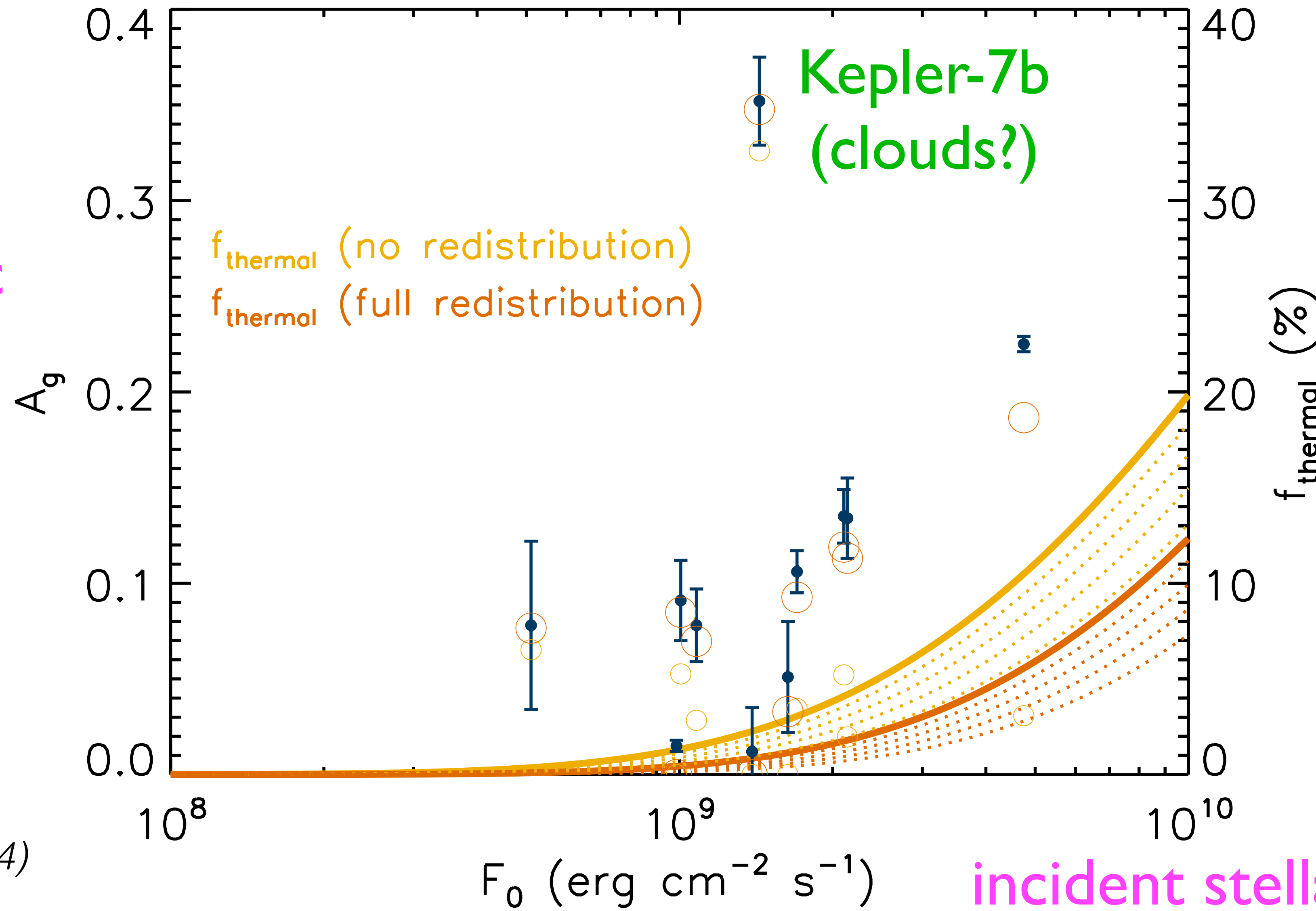
To simulate phase curves, eclipse maps, day-night flux contrasts.

Future: to predict temporal variability

The cutting-edge data (and an anticipated flood with the next-generation instruments) will provide 2D and even 3D information.

Optical secondary eclipses yield the geometric albedo of the atmosphere

geometric albedo
(Kepler bandpass)



incident stellar flux

Heng & Demory (2013, ApJ, 777, 100)

See also: Angerhausen et al. (2014)

No obvious trend with stellar irradiation

Corrected for contamination by thermal emission (for the hottest objects).