Towards self-consistent P-T profile modeling in exoplanet atmospheres

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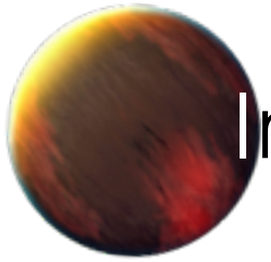
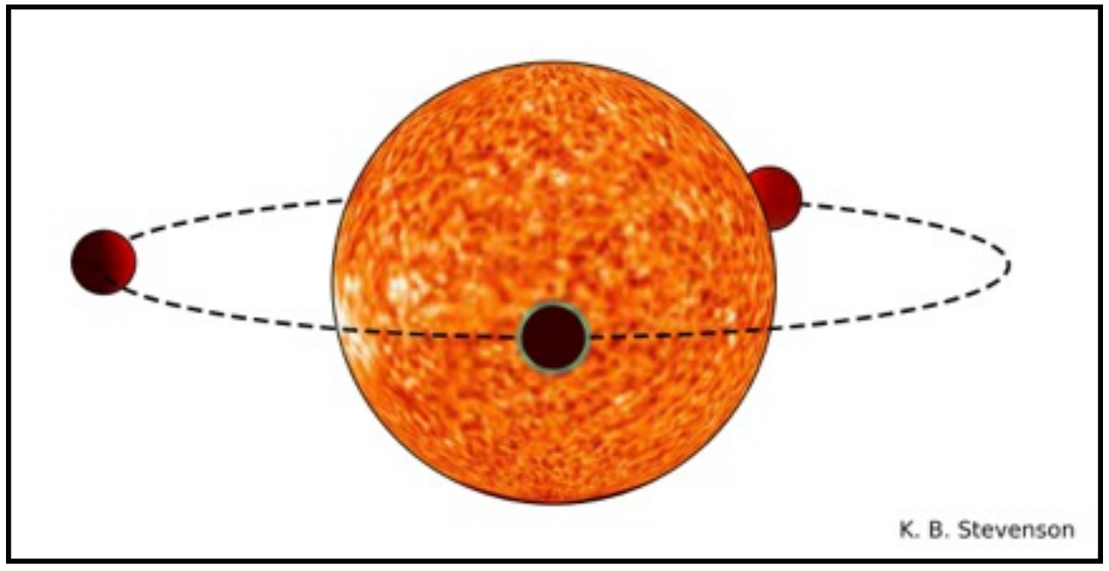
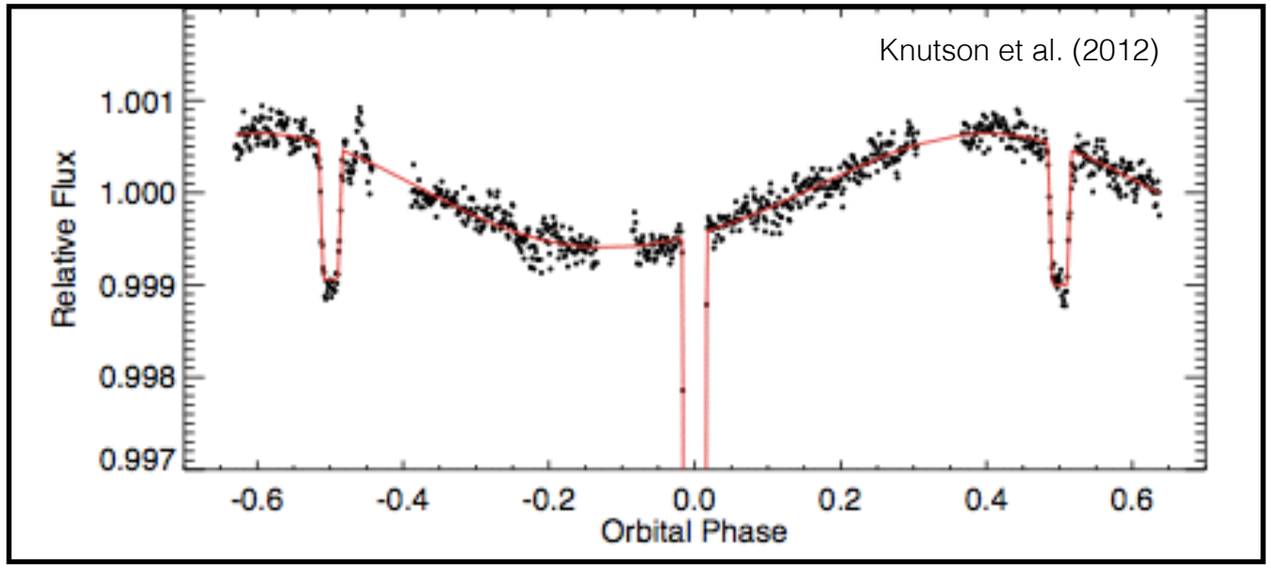


Introduction

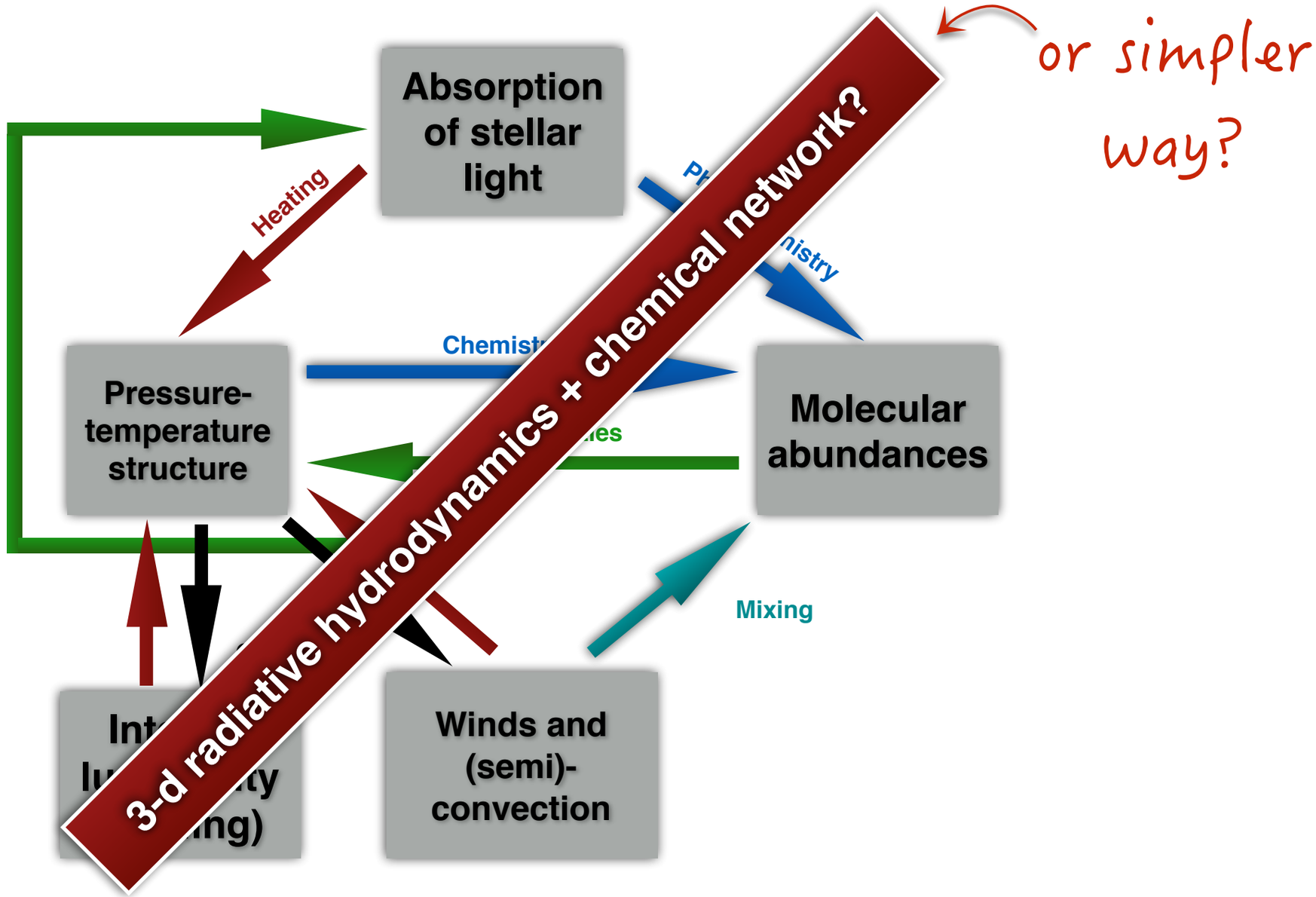
- Atmospheres are our “windows” into giant planets.
- Spectral analysis: Probe atomic composition (hint on formation?) and molecular abundances
- Longitudinal and latitudinal temperature variations: Constraints on energy redistributions by winds.
- Correct description of atmosphere and cooling yields evolution history of planet.

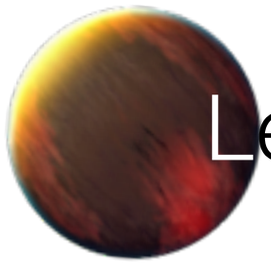




Atmospheric Structure

- Need theoretical atmospheric models to explain observations and processes going on in the atmosphere.
- Many interacting processes shape the actual atmospheric structure:



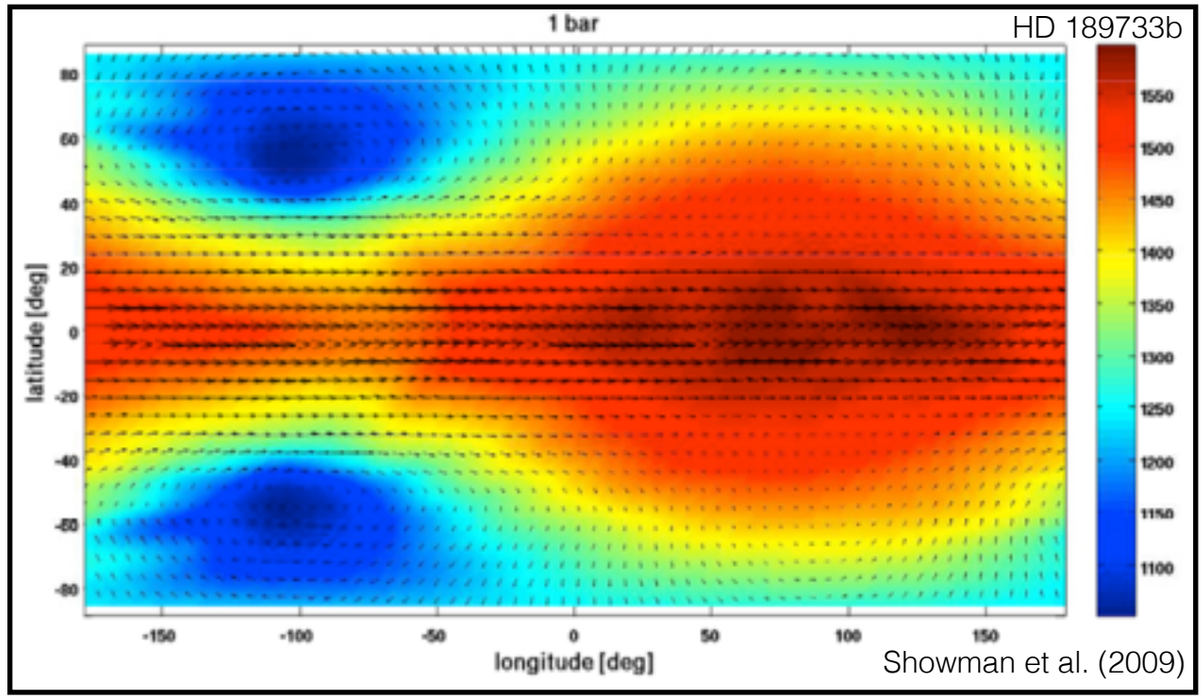


Let's start 1 dimensional…

- 3-d General Circulation Models (GCM) with radiation exist.

- Best approach:
  Mixing and energy transport automatically included.

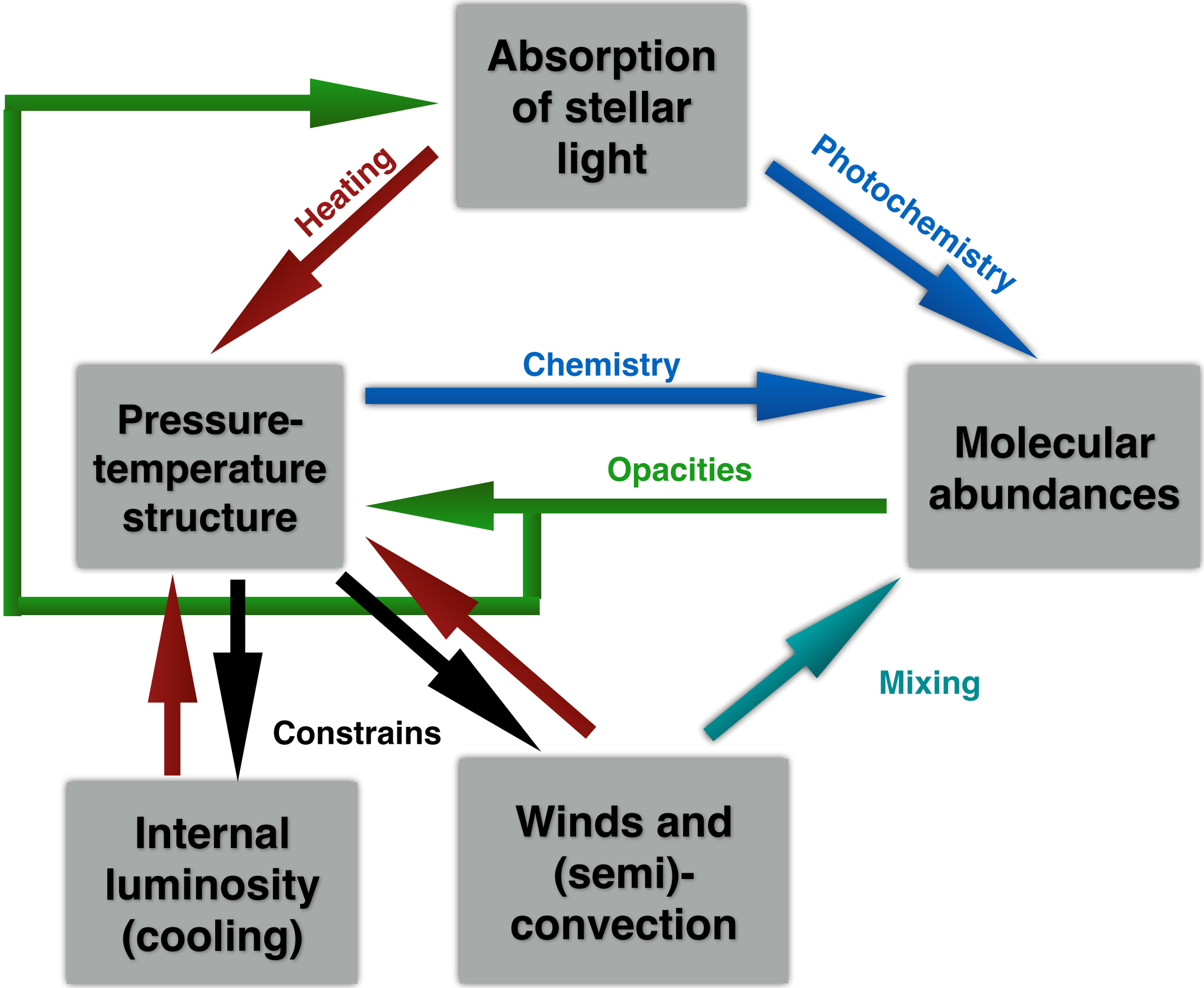
  But: Very expensive!

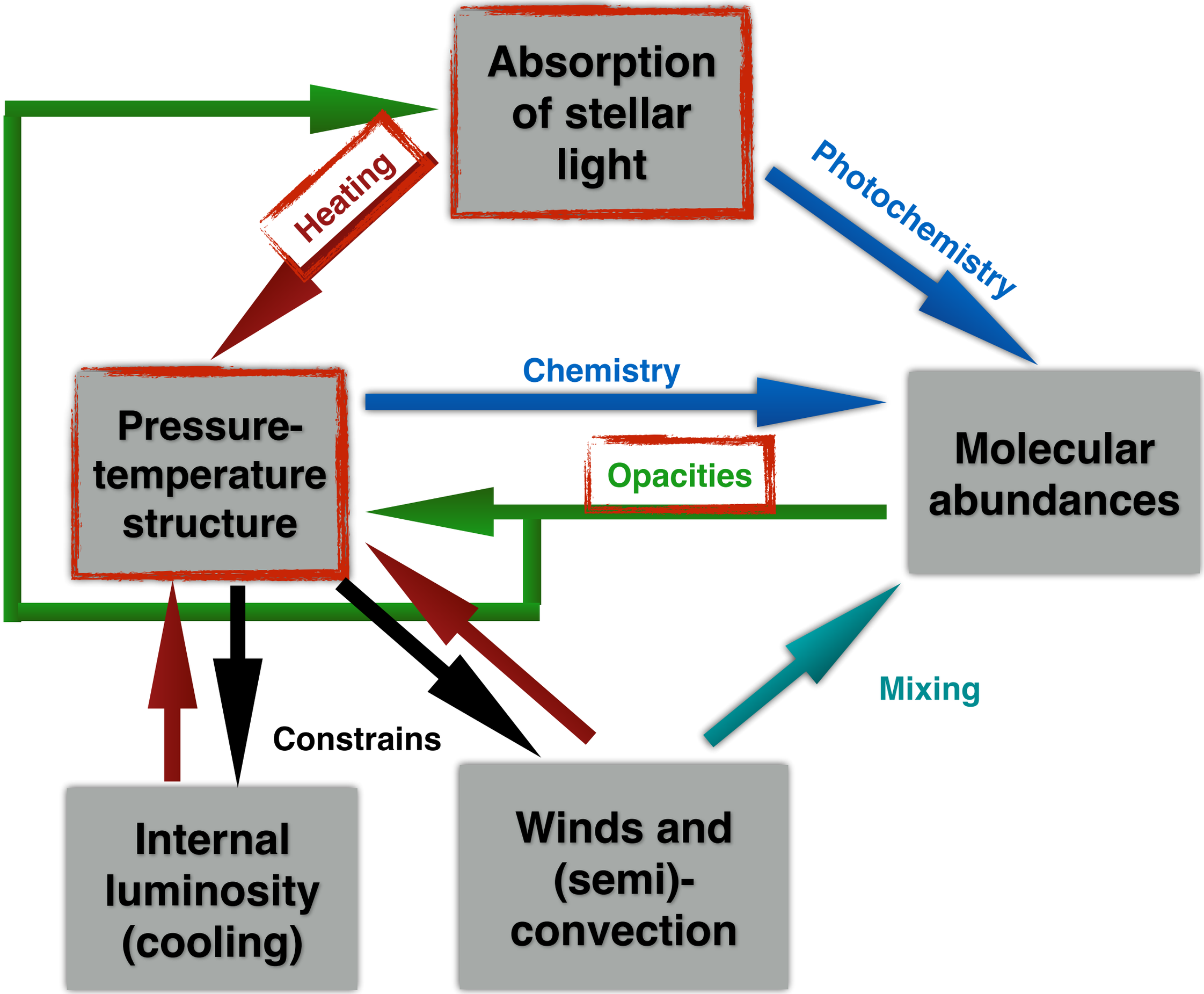


- Too slow for…
  - Coupling to planetary evolution calculations
  - Use in planet population syntheses
  - Molecular abundance retrieval methods

  Which are our goals!

- Let's start from building a 1-d model!


Absorption of stellar light
Heating
Photochemistry
Chemistry
Pressure-temperature structure
Molecular abundances
Opacities
Mixing
Constrains
Internal luminosity (cooling)
Winds and (semi)-convection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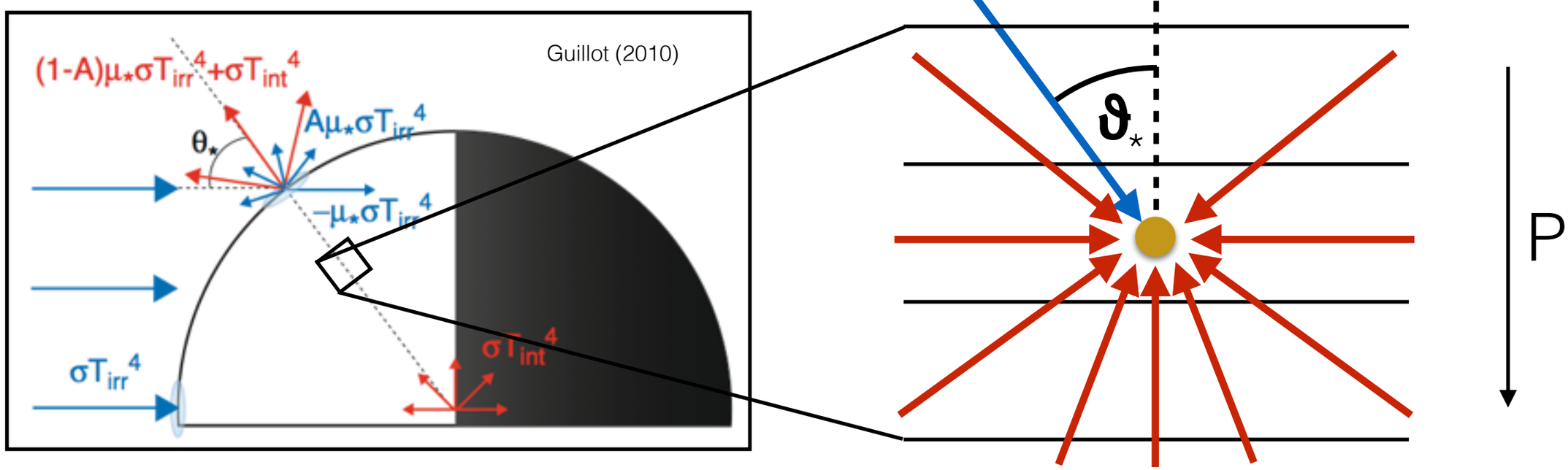
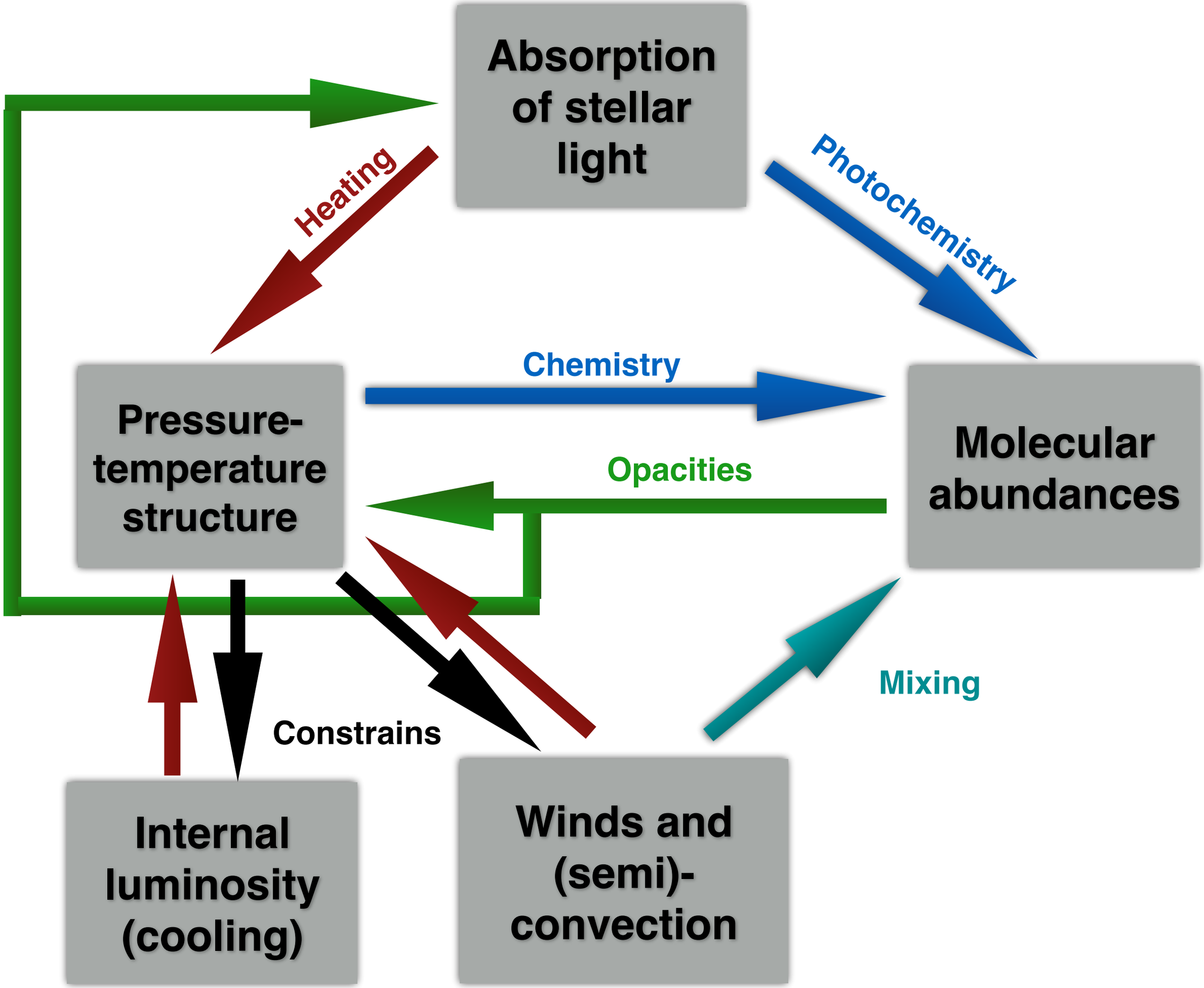
Plane-parallel radiative model



- Plane-parallel approximation good for thin atmospheres not too close to the terminator
- One needs an opacity database as complete as possible ExoMol?!
  - Molecular opacities (e.g. HITRAN / HITEMP database)
  - Collision induced absorption (H_2–H_2, H_2–He, …)
  - Metal oxides (TiO,VO, …), metal hydrides, Alkali metals, …

  See, e.g., Sharp & Burrows (2006)
- Very important: Dust, clouds, hazes…
  Molecules have many lines: Use correlated-k method!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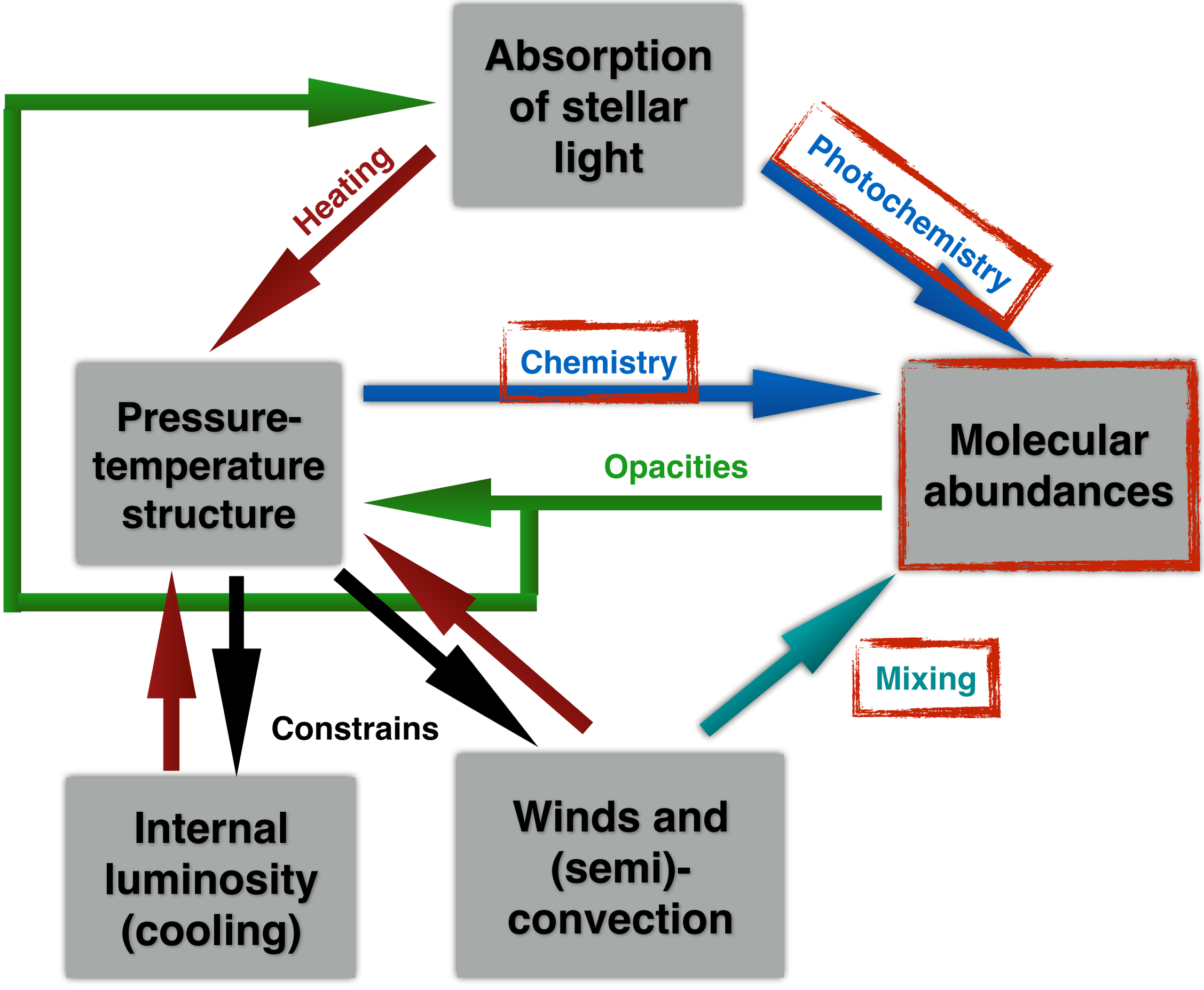
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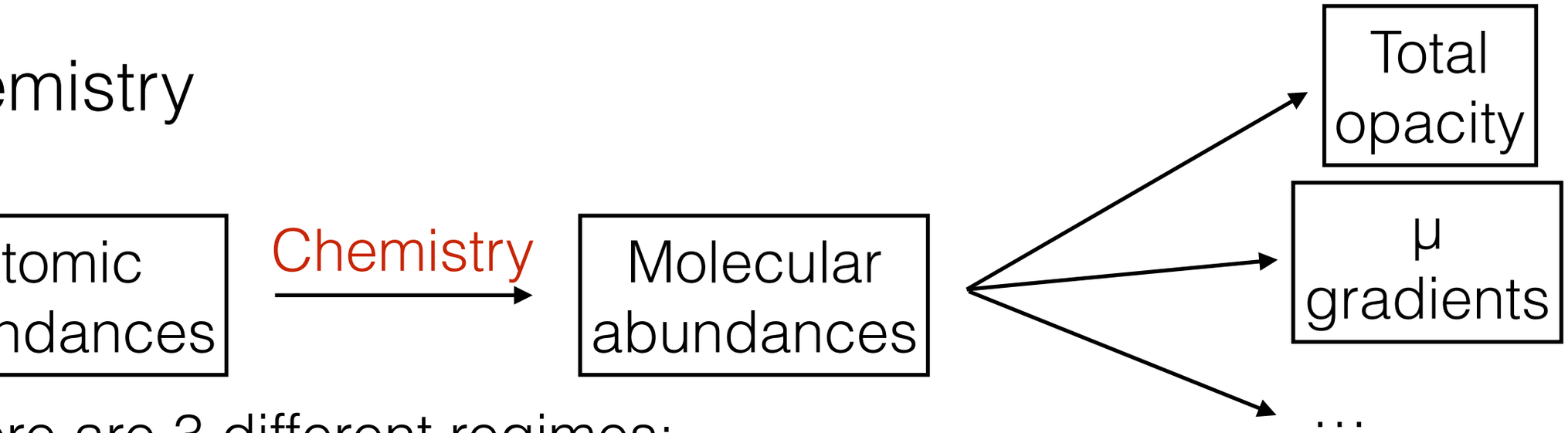
Chemistry



- There are 3 different regimes:

  - Photochemistry:
    Important for cooler close-in exoplanets
    (see, e.g., HD 189733b vs. HD 209458b)

  - Quenched abundances:

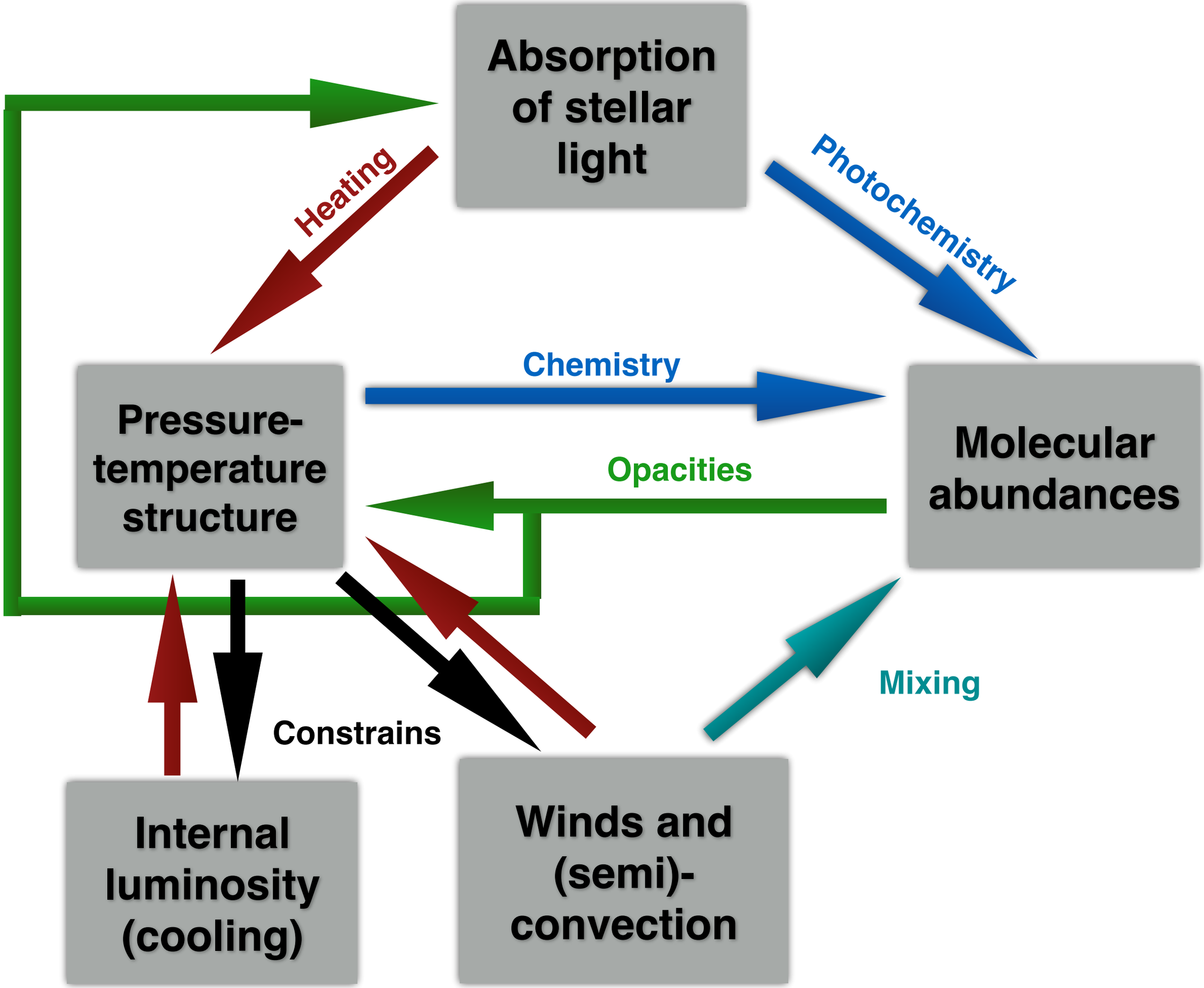
    $\tau_{mix} \lesssim \tau_{chem}$

  - Equilibrium chemistry

    $\tau_{chem} \ll \tau_{mix}$

- In general one needs to solve $\dot{n}_i = P_i - n_i L_i - \nabla \cdot \mathbf{f}_i$.
- Tested non-equilibrium chemical networks exist.

E.g. Venot et al. (2012), for C/O < 1.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Non-radiative transport processes

- Vertical processes affect chemistry and energy transport:
  Vertical eddy diffusion, convection, semi-convection

Diffusion constant from GCM simulations

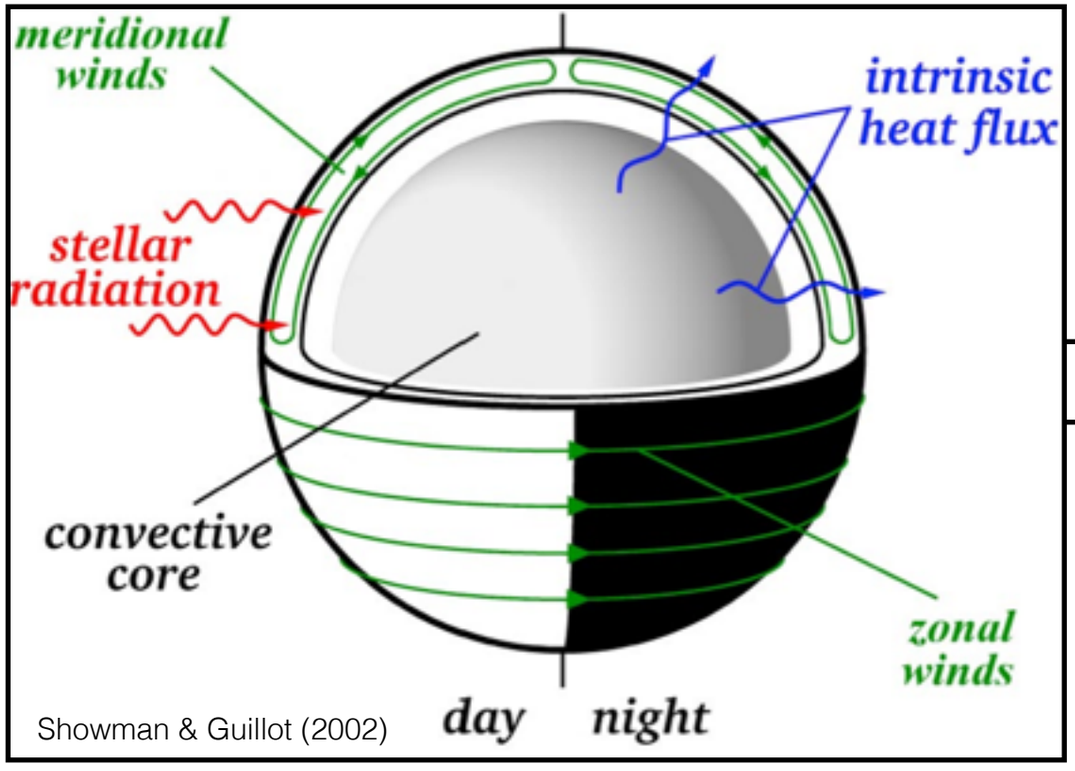
Schwarzschild criterion → adiabatic structure / MLT

Ledoux-stable & Schwarzschild-unstable, analytical models exist

- Horizontal winds are much more difficult to treat…
  Large scale depth-dependent flow patterns

Rotation of atmosphere at v_{wind}.

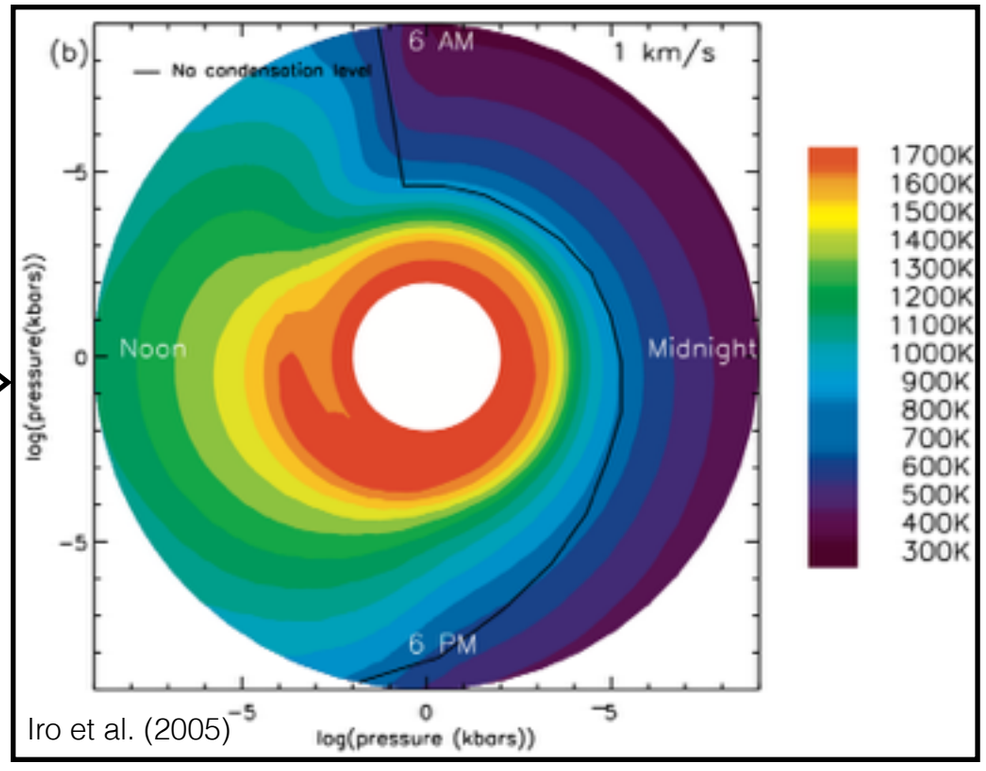
Simple analytic estimation of windspeed magnitudes v_{wind}



Showman & Guillot (2002)

V_{wind}

Latitudinally averaged, time-dependent rad. transfer & cooling



Iro et al. (2005)

Scientific goals I

Couple self-consistent atmospheres with…

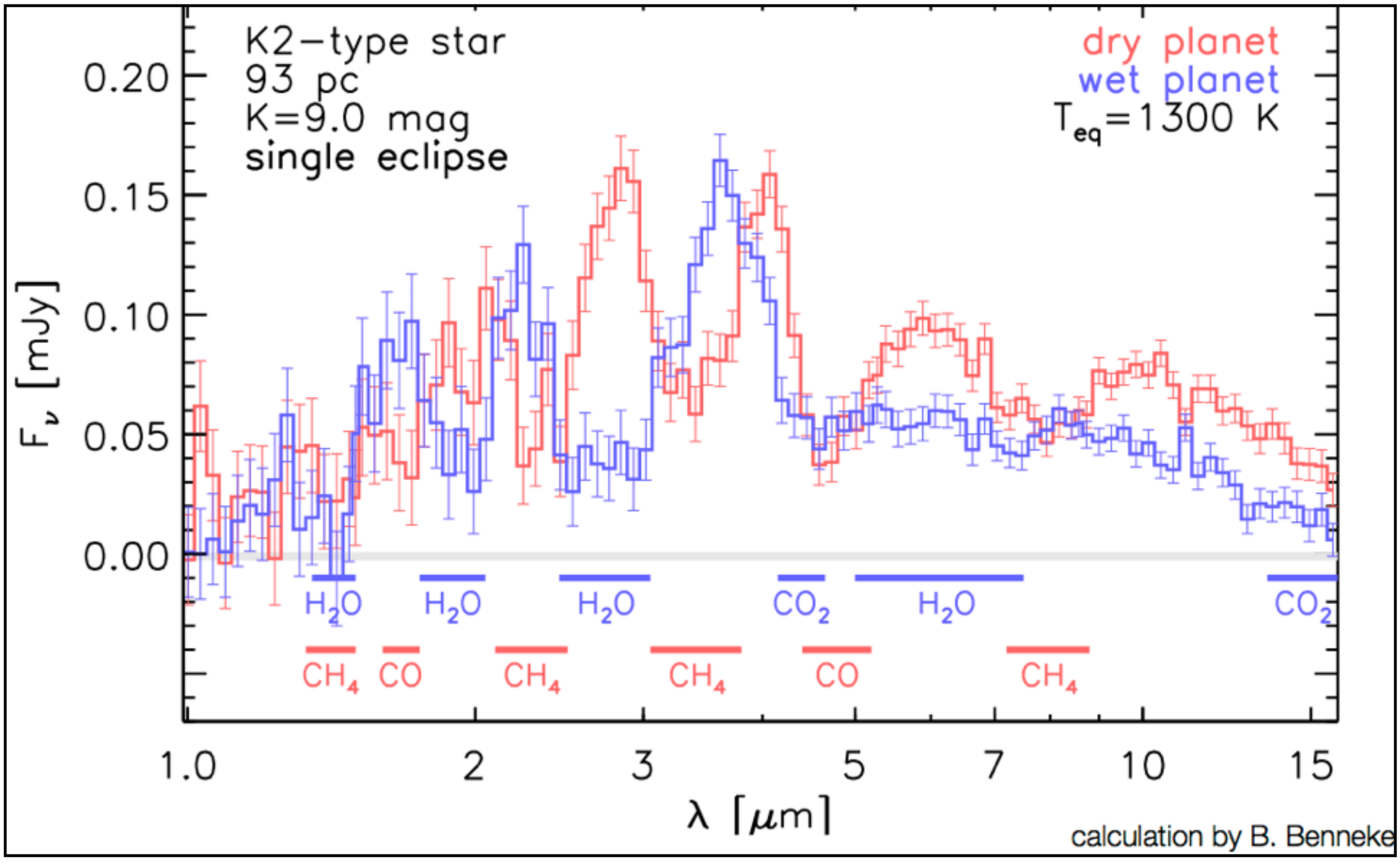
- **Planetary evolution calculations** to get correct cooling.

- (“**Self-consistent retrieval calculations**”, i.e. iterating only on abundances instead of also having to parametrize P-T.)

- **Population syntheses** to see possible implications of the formation history for the spectrum.

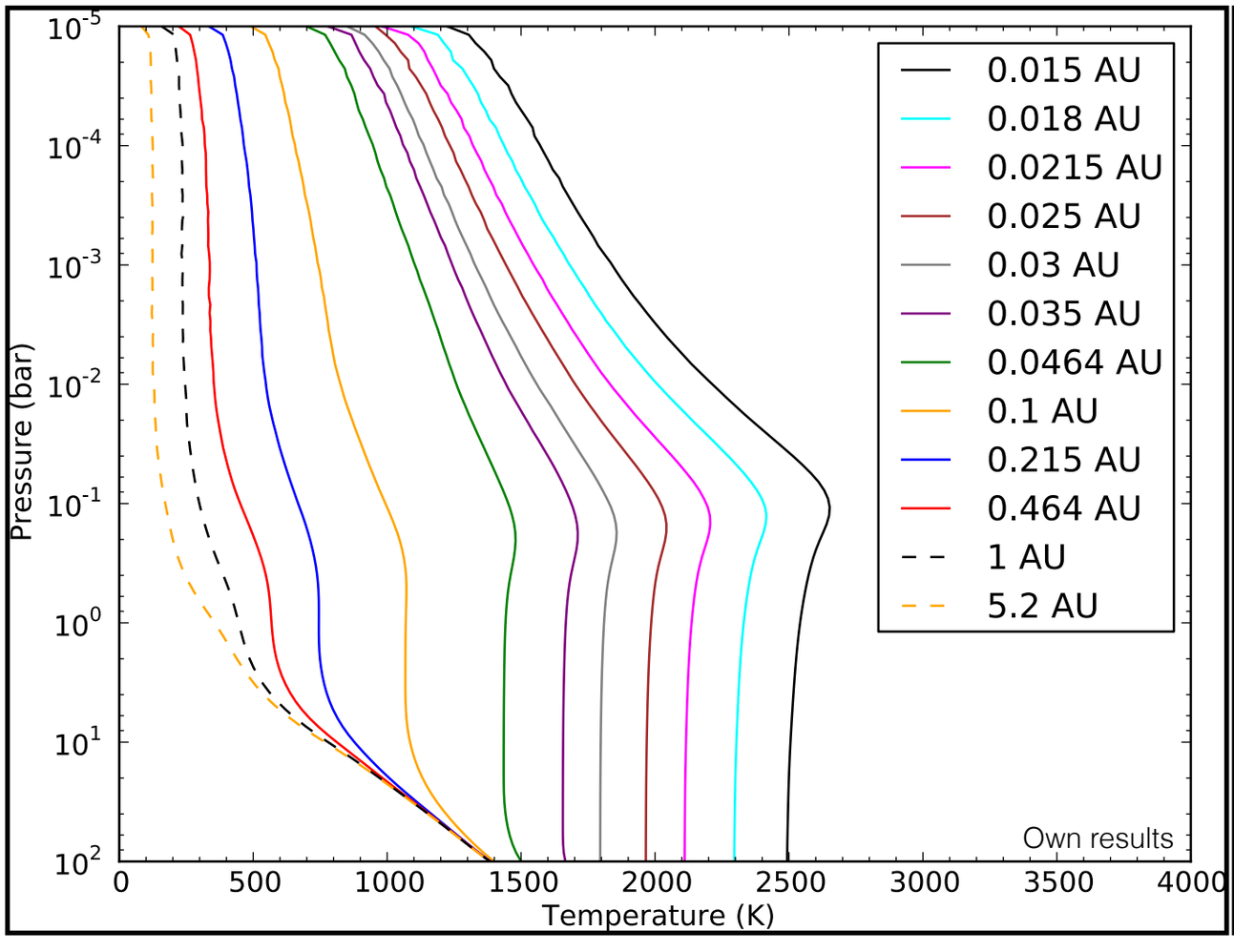
Important for cooling (metal blanketing)
& spectra

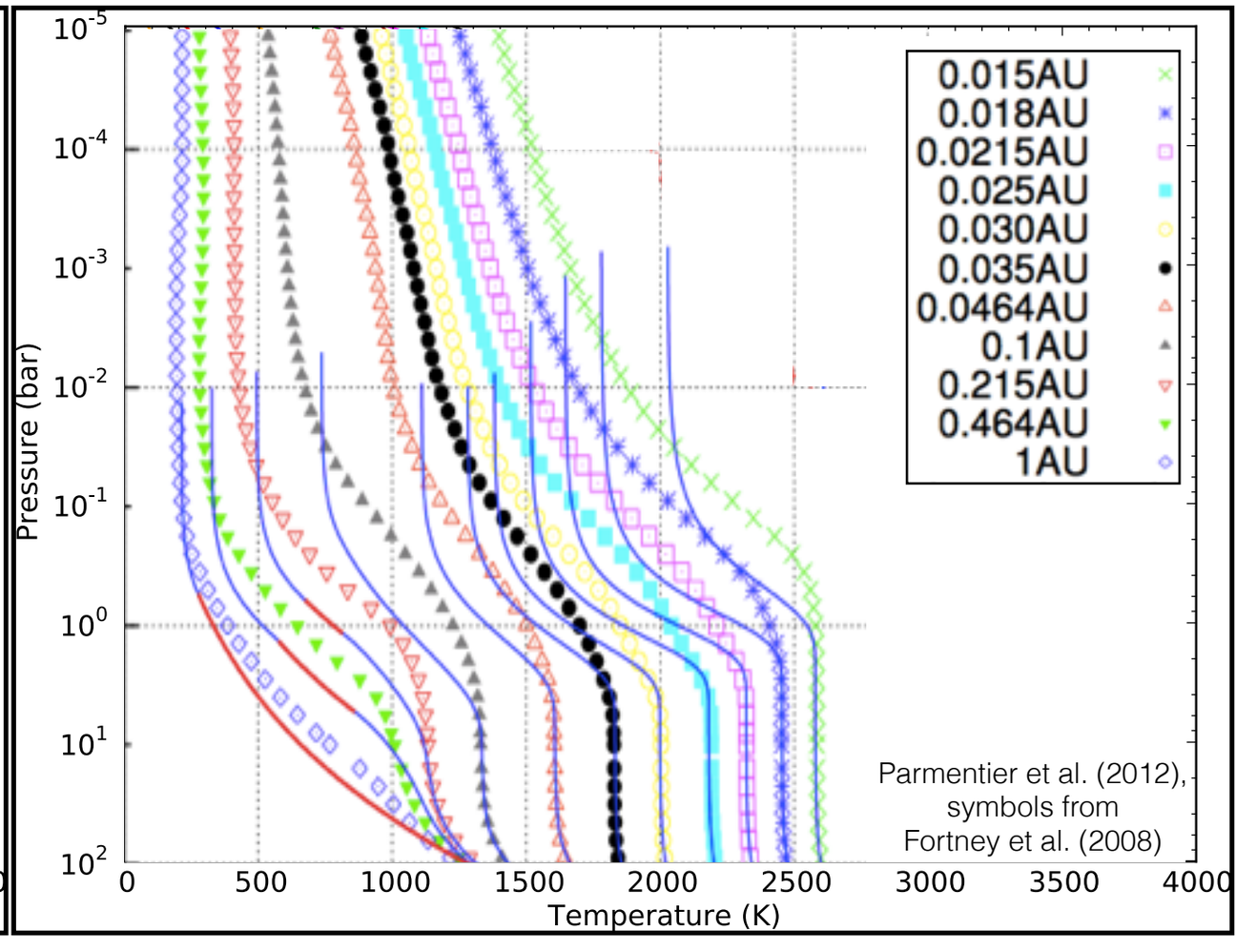
Scientific goals II



Current State I

- 1-d plane parallel corr-k RT + moments iteration temperature model
- HITRAN/HITEMP molecular, CIA & UV/optical dummy opacities
- CEA for abundances
- No Iro et al. (2005) like treatment of winds yet

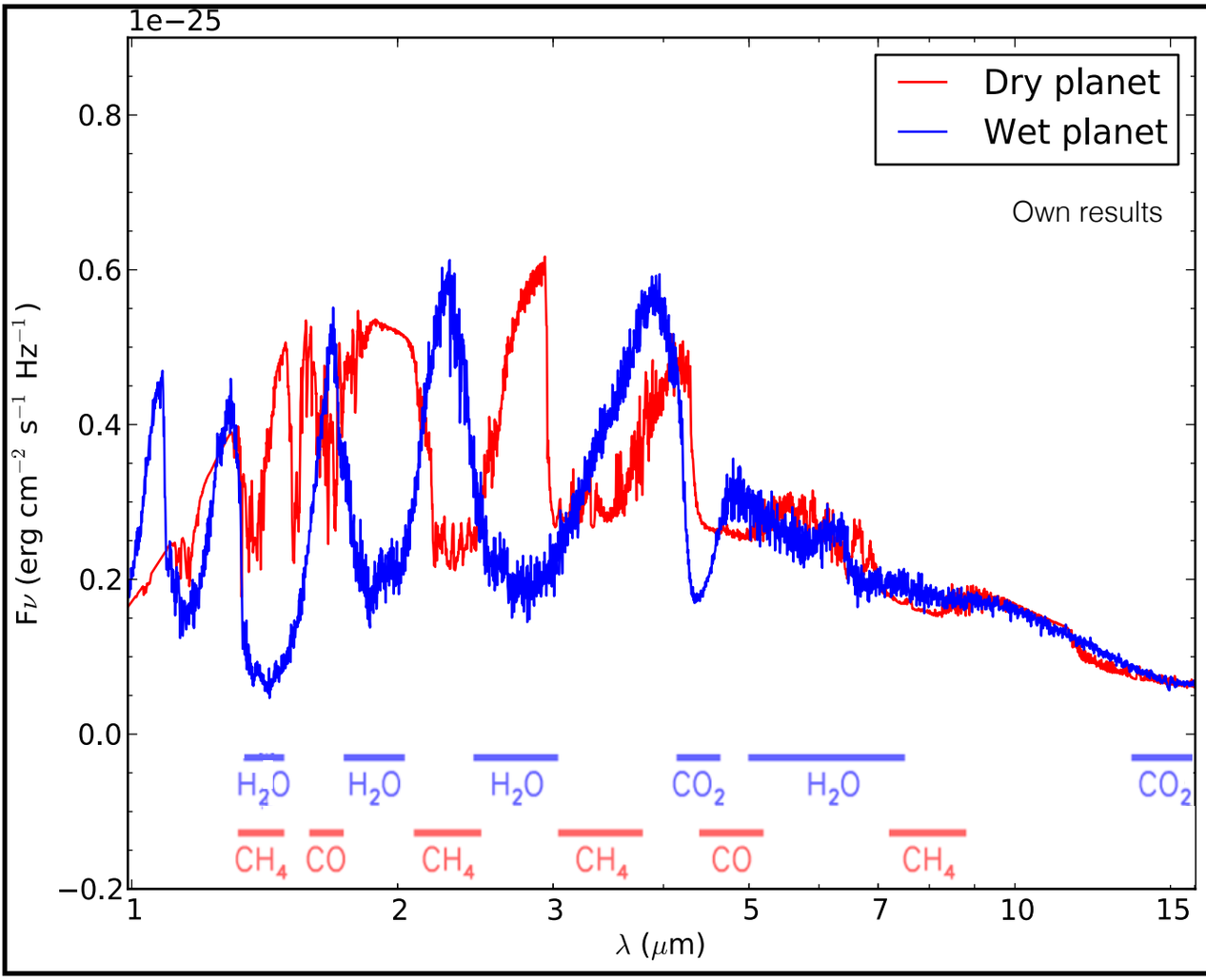


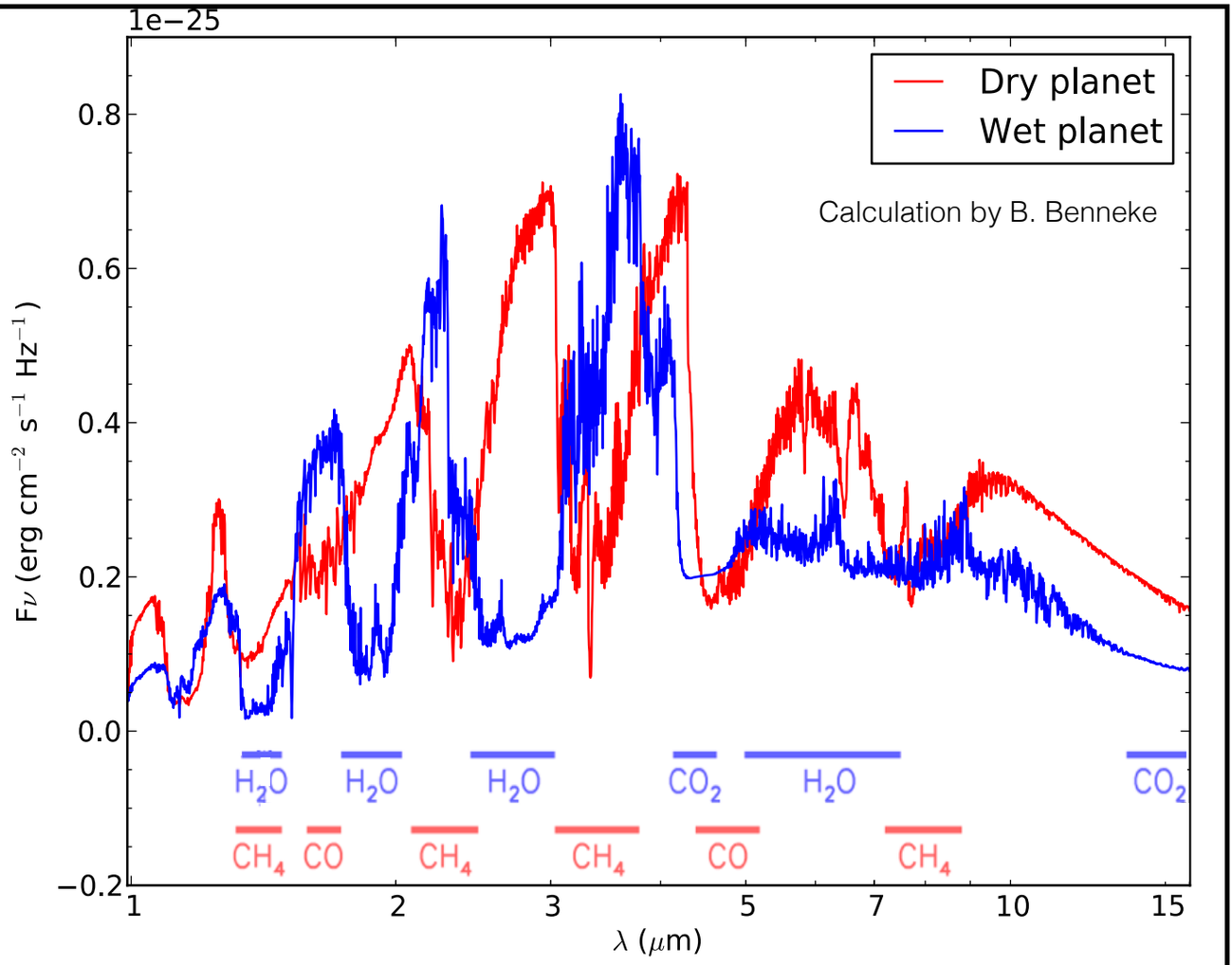


- Convergence time ~ 30 s

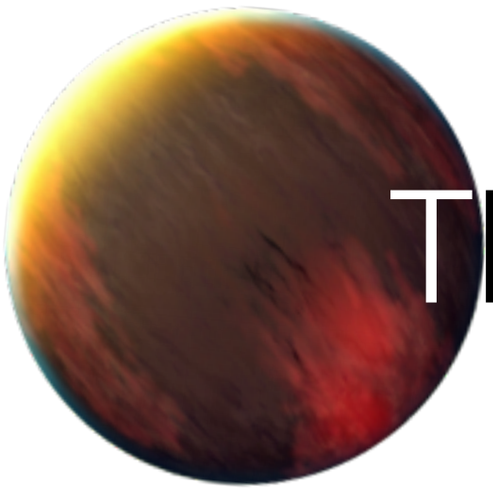
Current State II

- Spectra of planets with different C/O ratios





- Similar absorption features (used different P-T structure)



Thanks for your attention!