*A two-band theoretical radiative physical model for predicting the *Greenhouse (GH) Effect on Earth-like planets*

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**Greenhouse Effect*
is the response of the atmospheric P(z)-T(z) profile to its radiative properties as determined by its chemical composition and by the astronomical configuration

Plan of the talk

The scope: *Our Full-Line (FL) radiative transfer model* ***(Shaviv et al, 2011)***

The basis: *Imposing energy conservation*

The model: *Multi-Wavelengths Two Band (TBMW)*

The representation: *A* $T_{surf}\{Log(^*\tau_{vis}) / Log(^*\tau_{fir})\}$ *plane*

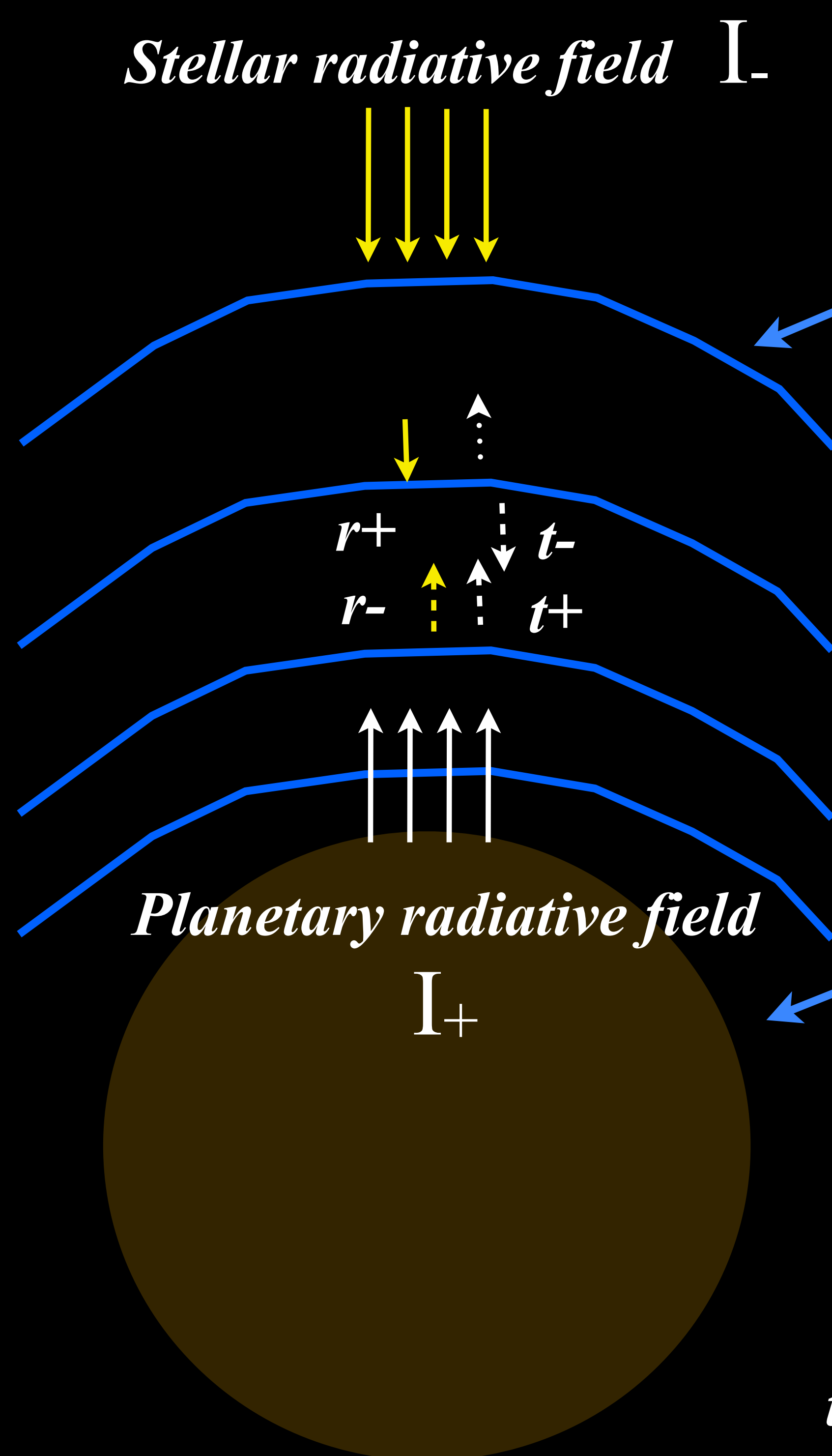
$^*\tau_{vis}$ and τ_{fir} are the optical depth averages κdz, in the short-wave and far infrared

The results: *Estimation of the GH/anti-GH effects for different atmospheric gaseous species*

The scope: *Our Full-Line (FL) model for GH calculations*

The geometry of the system and the Boundary conditions

transmission and reflection coefficients in every layer



****TOA - top boundary***

$$I^{-}(\lambda, Z) = \frac{1}{4}\frac{R_*^2}{d^2} I_*(\lambda)$$

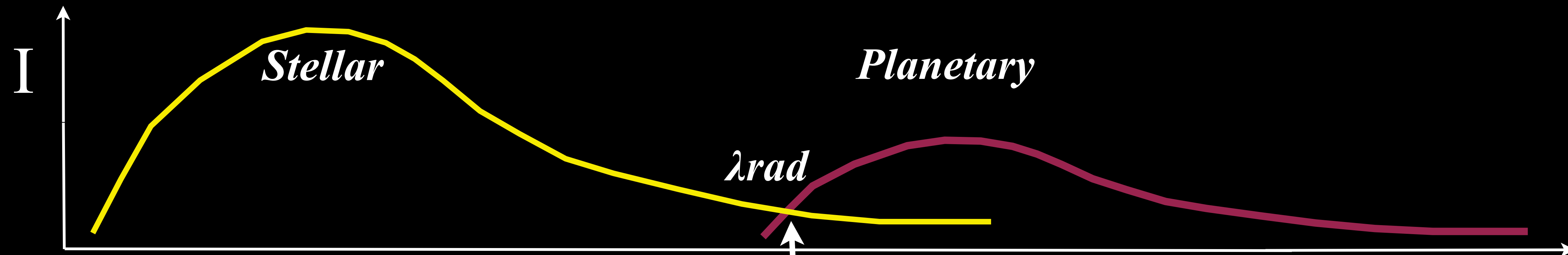
**TOA - Top Of the Atmosphere*

Surface boundary

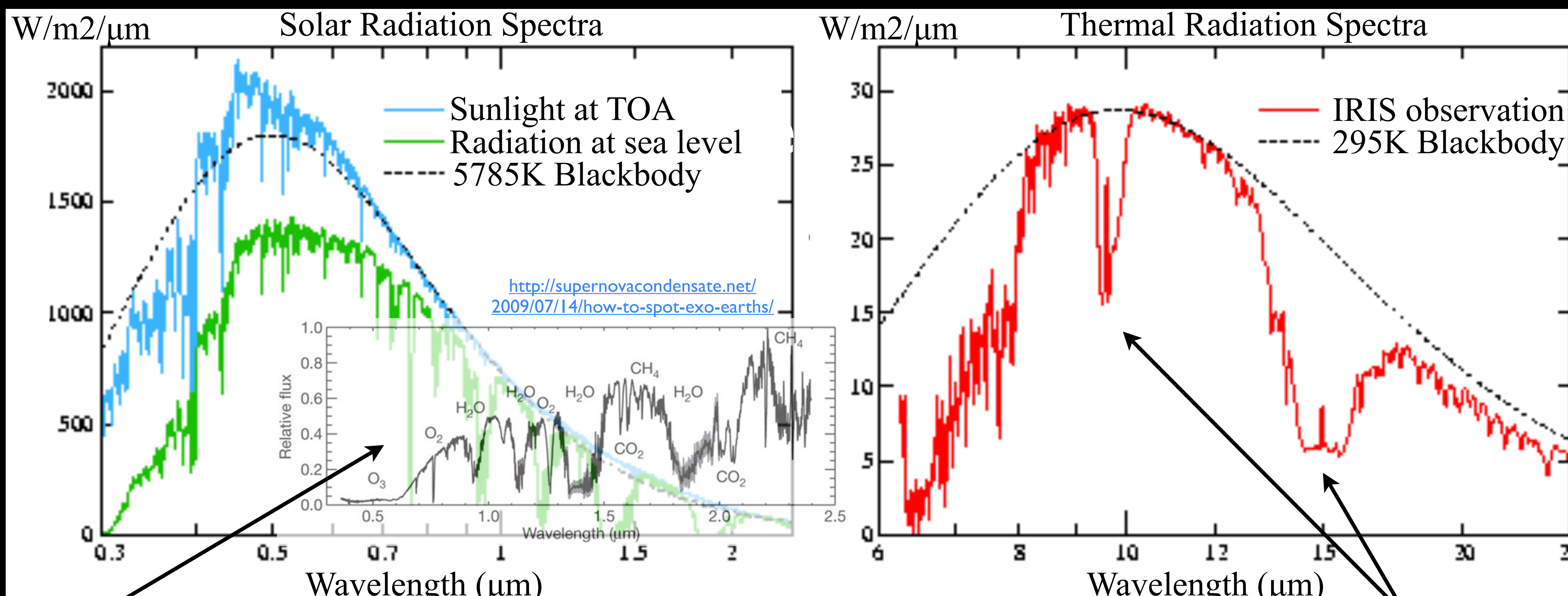
$$\int_0^\infty (1 - a(\lambda)) I_-(0, \lambda) d\lambda = \sigma T_{\text{surf}}^4$$

t- transmission in the downward direction
t+ transmission in the upward direction
r- reflection of the downward radiation
r+ reflection of the upward radiation

The radiative fields and spectral details



$$\frac{(1-\langle a(\lambda)\rangle)}{4}\frac{R_*^2}{d^2}I_*(\lambda_{rad}) = I_p(\lambda_{rad})$$



http://www.columbia.edu/~mhs119/Storms/

Shortwave absorption

Atmospheric windows

The key to analyzing the GHE in detail!

The two-stream radiative equation

$$\pm \frac{dI^{\pm}}{dz} = -\left[\kappa(z,\lambda) + \sigma(z,\lambda)\right] I^{\pm} + \sigma(z,\lambda) J(z,\lambda) + \kappa(z,\lambda) B(T(z),\lambda)$$

z - height; λ - wavelength; κ -absorption coeff; σ - scattering coeff; B - the Planck function

Where:

$$I = \begin{pmatrix} I^{+} \\ I^{-} \end{pmatrix}$$

I - specific intensity

and

$$J(z,\lambda) = \frac{I^{+}(z,\lambda) + I^{-}(z,\lambda)}{2}$$

J - mean intensity

At first Approximation we assume:

Isotropic scattering only

No convection

No diurnal changes - sun is at zenith

No clouds or ocean feedback

The basis: *Imposing Energy conservation*

The steady state approximation: Energy conservation in every layer

Energy conservation over flux

$$0 = \frac{\partial F_{\text{net}}}{\partial \tau} = (\gamma_1 - \gamma_2)F^{+} + (\gamma_1 - \gamma_2)F^{-} - (S^{+} + S^{-}) + \pi F_s \exp(-\tau/\mu_0)$$

Numeric model
Integrated fluxes - total downward and total upward

$$F_{\text{net}} = \int I\mu \, d\Omega = F^{+} - F^{-}$$

Toon et al, 1989

Energy conservation over heat

$$\int_0^\infty k_e(z,\lambda)[J(z,\lambda) - S(z,\lambda)]\,\mathrm{d}\lambda = 0$$

Analytic model
Integrated specific intensities - each wavelength contributes
Neglecting the 'vis' range

Rutily et al, 2008
Parmentier & Guillot, 2014

Our steady state condition

Shaviv, Shaviv & Wehrse, 2010

$$\int_{z_i}^{z_{i+1}} \frac{dQ(z)}{dt} dz = \sum_{j=1}^{N_{tot}} \tau(z, \lambda_j) \left[J_i(\lambda_j) - B(T_i, \lambda_j) \right] \Delta\lambda_j = 0$$

Numeric model

Multi-Wavelengths integration

Over Full-Lines or Two-Bands

Calculating P-T and T_{surf} by the double-iteration scheme

The steepest descent method, to $\Delta T<10^{-7}$

RTE - Radiative Transfer Equation
HBE - Heat Balance Equation

First iteration

- fixed Tsurf
- Release of lower Boundary Condition
- Solution of RTE when HBE=0 at all layers

Convergence
$\Delta T(z)<10^{-7}$

Second iteration

- Release fixed T_{surf}
- Insert lower Boundary Condition
- Solution of RTE and HBE to obtain T_{surf}

Convergence
Equal fluxes at surface

Unique features of our model

1. The TOA boundary condition ***Flux in = Flux out***

$$\frac{1}{4}\frac{R_*^2}{d^2}\int_0^\infty I*(\lambda)d\lambda = \int_0^\infty I^+(Z,\lambda)d\lambda$$

is an outcome of the model and not an assumption

2. Tsurf and the P-T profile are free parameters

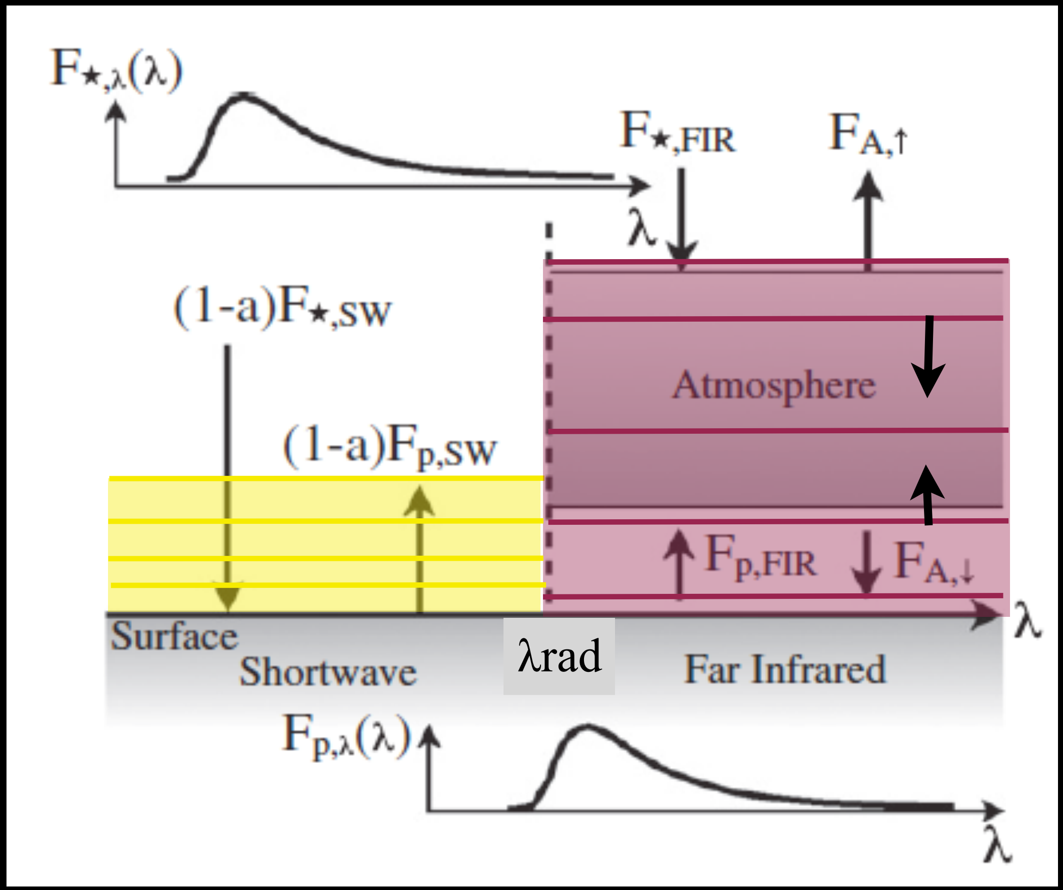
3. The double iteration scheme & the steady state energy condition are used

Thus, the calculation of the complete feedback of the atmospheric radiative field is obtained for changes in the absorption coefficients

The model: Multi-Wavelength Two Band (TBMW)

The bands and fluxes in a semi-grey atmosphere

The fluxes



$(1\text{-}a)F_{p,SW}$

Notice that this flux may not be neglected

Shaviv et al , 2011

The Two-Band lower boundary condition

$$(1-a)I_{\star,\mathrm{SW}} + I_{A,\downarrow} = (1-a)I_{p,\mathrm{SW}} + I_{p,\mathrm{FIR}}$$

Shaviv et al , 2011

The TBMW steady-state equation

$$\int_{z_i}^{z_{i+1}} C_V \frac{dT(z)}{dt} dz = \langle\tau_{vis,i,j}\rangle \Delta\lambda_{vis} \sum_{j=1}^{N_{vis}} [J_{vis,i,j} - B(T_i)] + \langle\tau_{fir,ij}\rangle \Delta\lambda_{fir} \sum_{j=1}^{N_{fir}} [J_{fir,i,j} - B(T_i)] = 0$$

Bressler et al, 2016, in press

'vis' (H1) **'fir' (H2)**

The short-wave'vis' range - non-*LTE

$$\ln\langle\tau_{\mathrm{vis,S}}\rangle_i = -\frac{\int_{z_i}^{z_{i+1}} dz \int_{\nu_1}^{\nu_2} B(T_*,\nu) e^{-\tau_{\mathrm{tot}}(\nu, T_{\mathrm{atm}}(z))} d\nu}{\int_{z_i}^{z_{i+1}} dz \int_{\nu_1}^{\nu_2} B(T_*,\nu) d\nu} \quad \textit{with } 0 < \nu_1 < \nu_2 \leq \lambda_{\mathrm{rad}}$$

LTE - Local Thermodynamic Equilibrium

Bressler et al, 2013

The long-wave'fir' range - *LTE

$$\langle\tau_{\mathrm{fir,S}}\rangle_i = \frac{4}{3}\left[\frac{\int_{z_i}^{z_{i+1}} dz \int_{\nu_1}^{\nu_2} B(T_{\mathrm{atm}}(z),\nu) d\nu}{\int_{z_i}^{z_{i+1}} dz \int_{\nu_1}^{\nu_2} \frac{B(T_{\mathrm{atm}}(z),\nu)d\nu}{1+3\tau_{\mathrm{tot}}(T_{\mathrm{atm}}(z),\nu)/4}} - 1\right] \quad \textit{with } \lambda_{\mathrm{rad}} \leq \nu_1 < \nu_2$$

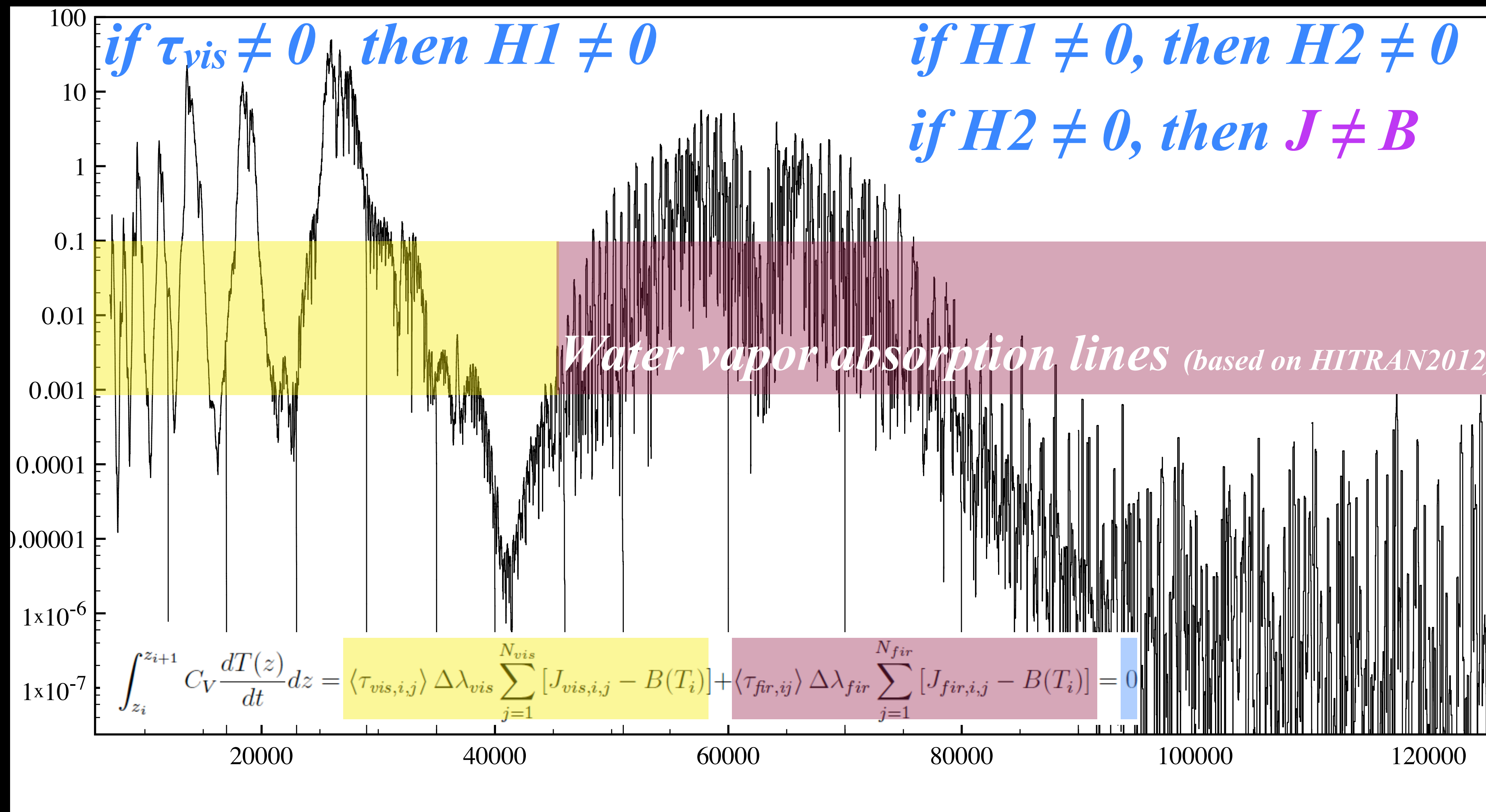
Shaviv et al 2011

The Simpson solution

$$T_p \approx \left[\left(1 + \frac{3\tau_{\mathrm{tot}}}{4}\right)\frac{(1-a)}{4}\left(\frac{R_\star}{d}\right)^2\right]^{1/4} T_\star$$

The LTE assumption

Absorption Coefficient



Bressler et al, 2016, unpublished results

Wavelength, Å

*If $J \neq B$, the assumption of LTE is violated

*The diffusion approximation cannot be applied for the 'fir'

*The 'vis' absorption cannot be neglected

*Radiative transfer can be calculated only numerically

The deviation from LTE is accounted for by iterating over the specific intensities used in the weight functions

*Initial results of our FL and TBMW models and other band averages**

Model	T_{surf} in K
FL model	294.29
κ_{eff} (2 band model)	301.9
κ_{Planck}	332.00
κ arithmetic	74.55
Simpson	401.73

Bressler et al , 2016 in press

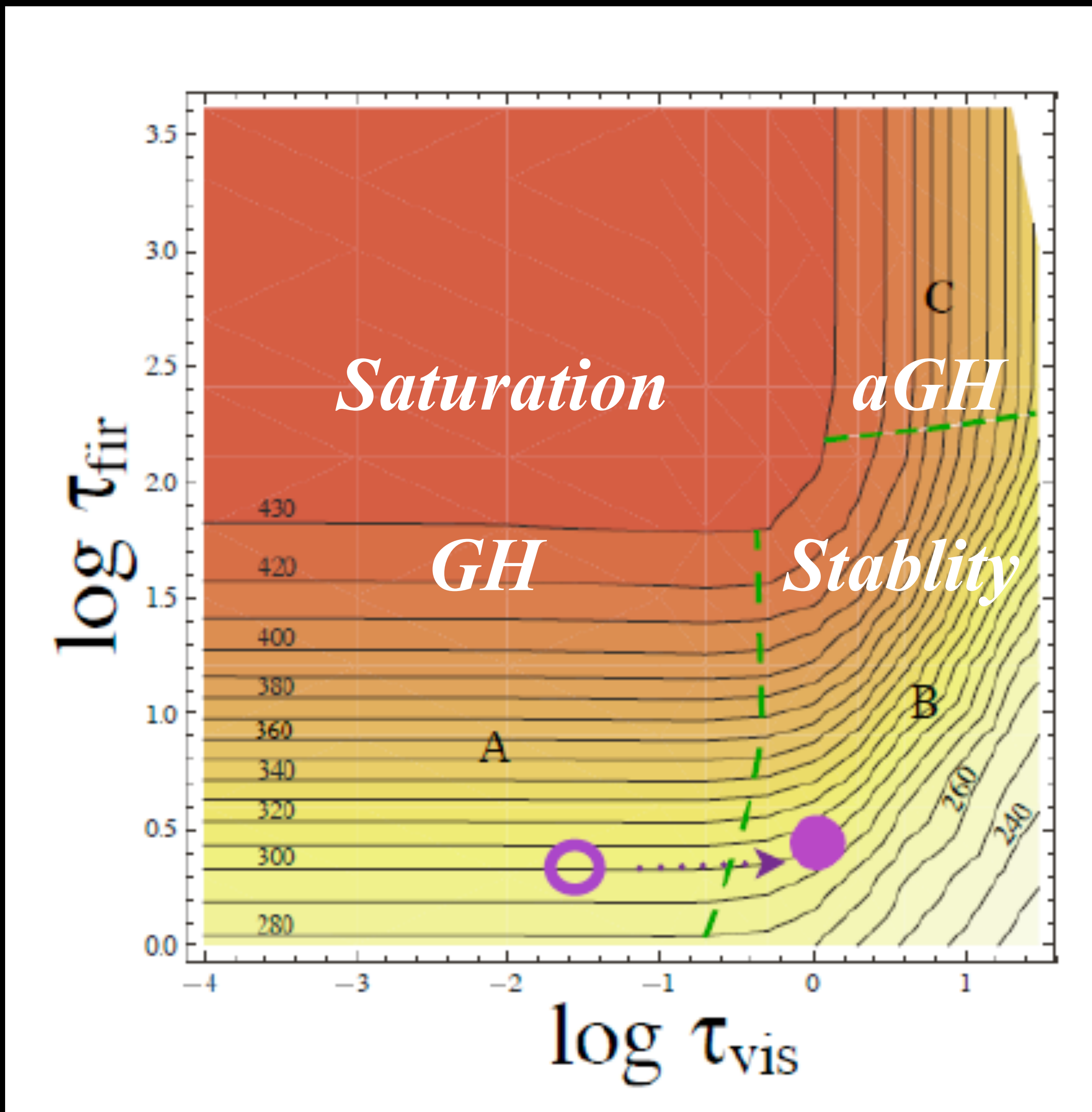
****The Rosseland mean breaks down in atmosperic windows***

****97.5% correspondence between models***

****We are now calculating additional cases***

The representation: *A* T_{surf} *{Log(*τ_{vis}*) / Log(*τ_{fir}*)} plane*

The $T_{surf}\{Log(\tau_{vis})/Log(\tau_{fir})\}$ plane



Bressler et al , 2016
in press

* *T_{surf} is calculated for arbitrary τ_{vis}/τ_{fir} pairs*

* *GH and a-GH on the same plane*

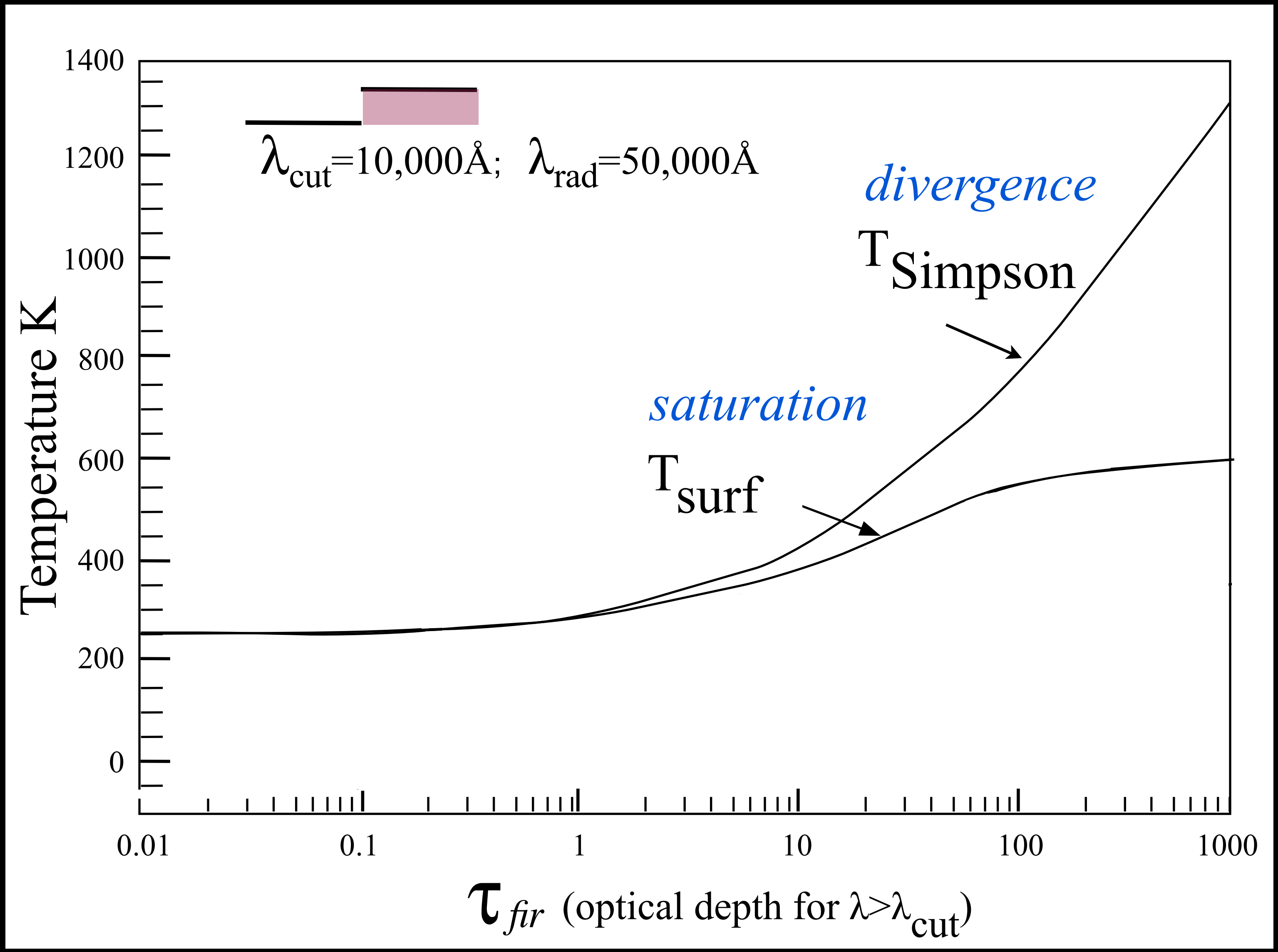
**The purple dots represent real spectral band averages*

Pure LTE (J=B) two bands

A non-LTE 'vis' band & LTE 'fir' band averages

Is the Earth in the stability region?

An illustration for saturation



Non - Thermodynamic solution

T_{surf} diverges with τ_{fir}

Thermodynamic solution

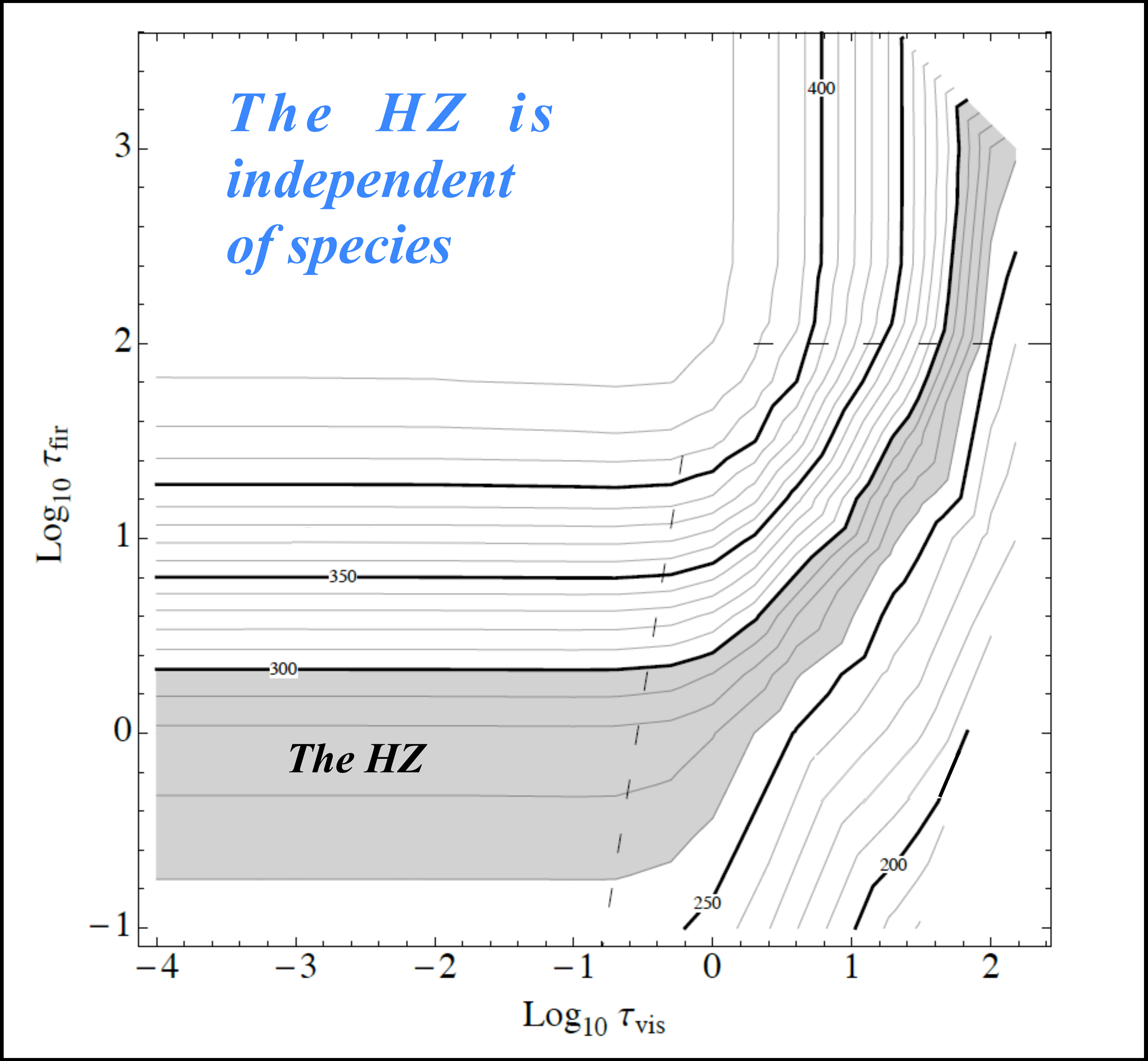
T_{surf} saturates with τ_{fir}

Bressler et al , 2016 in press

****The integration over the entire spectrum allows for radiation escape from the 'vis'***

****This leads to saturation - a thermodynamic solution for T_{surf}***

Determination of the Habitable Zone (HZ)

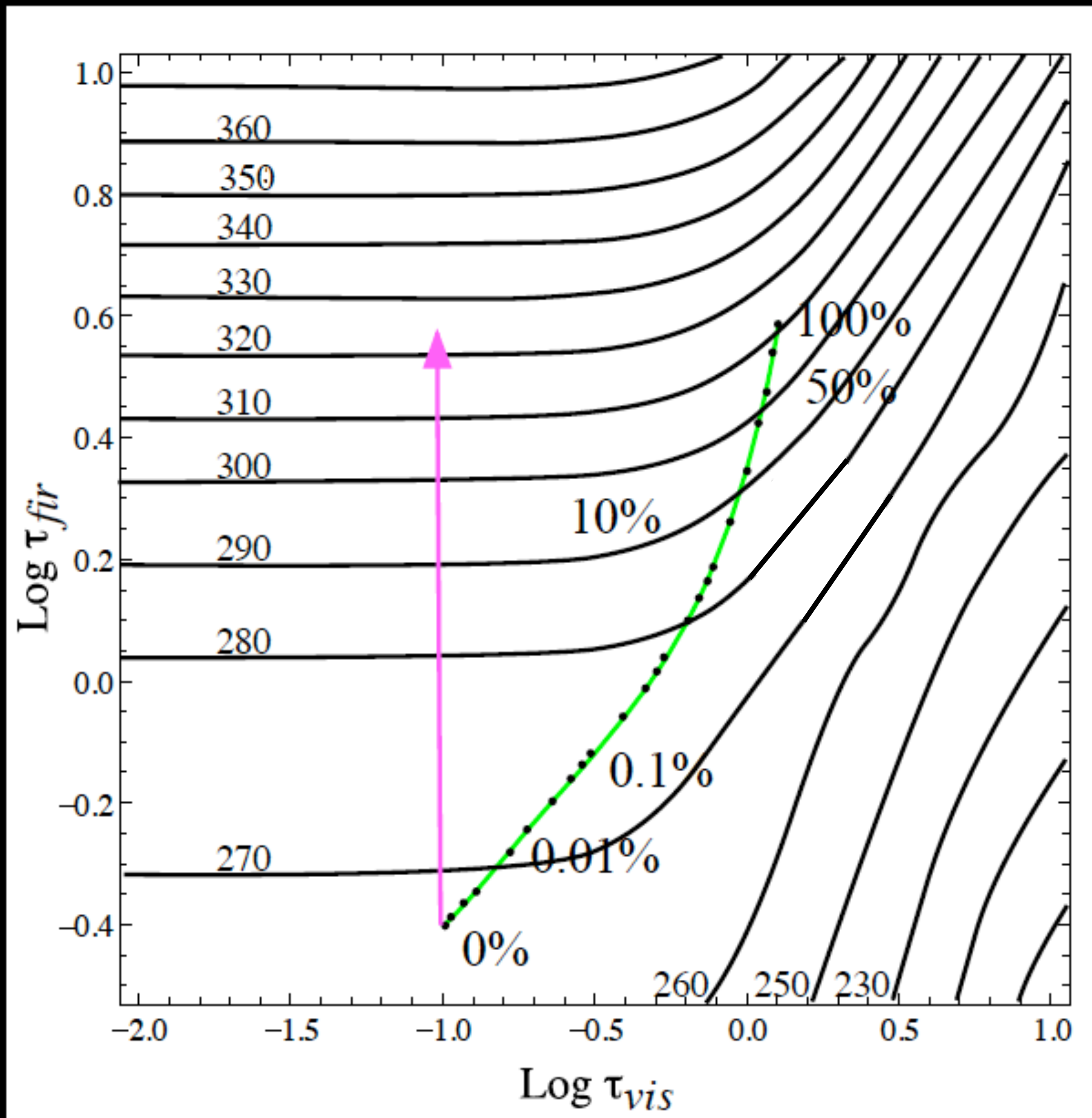


Distance = 1AU
Albedo=0.36
λrad=50,000Å

The results: *Estimation of the GH/anti-GH effect for different atmospheric species*

GHE dependence on Relative Humidity (RH) of water vapor

Standard Atmosphere composition

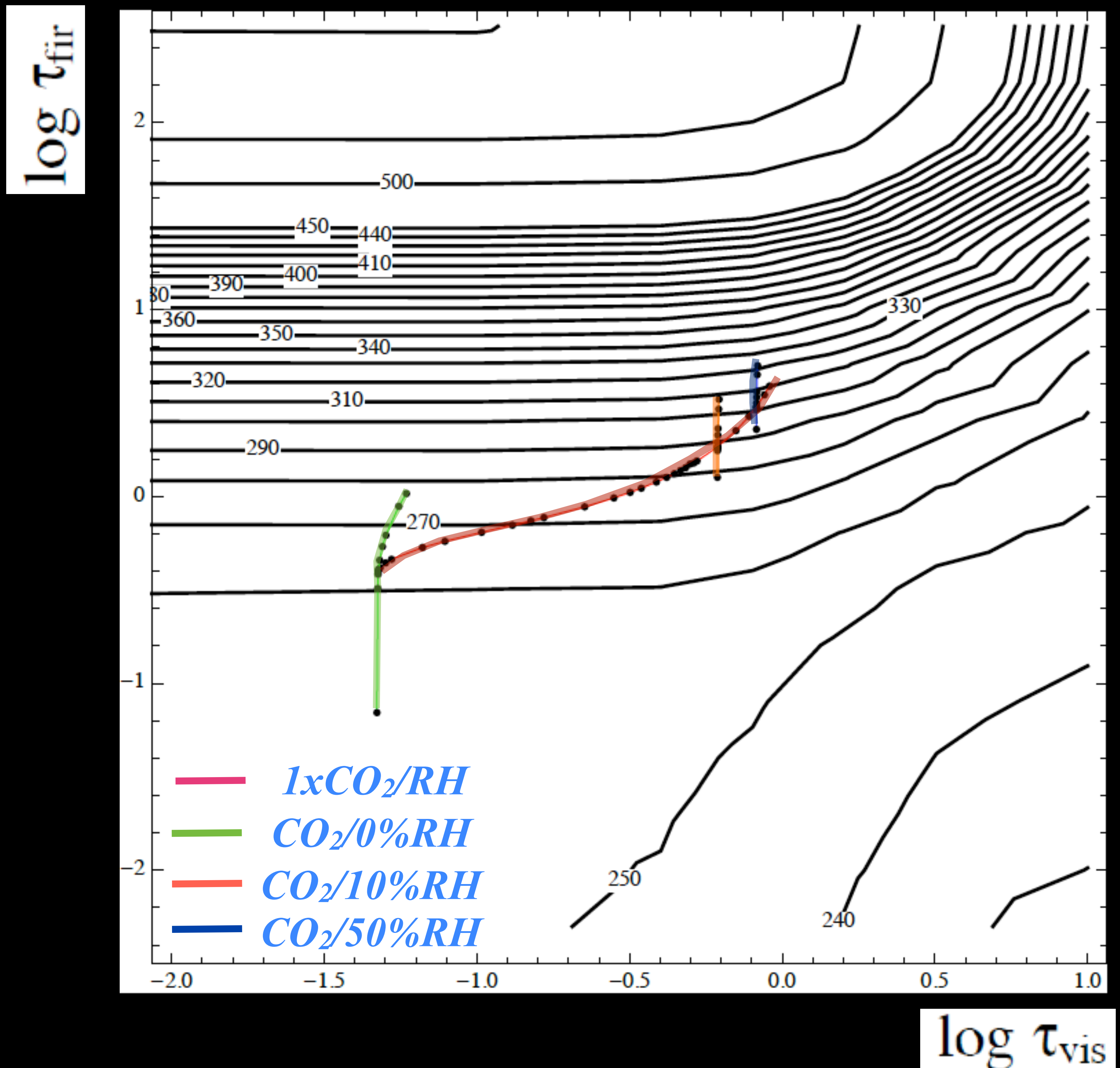


* *The 'vis' range moderates the GHE*

* *Increase of RH blocks incoming radiation at higher layers in the 'vis' wavelengths*

Bressler et al , 2016 in press

The contribution of CO_2 and water vapors to the GHE



***CO_2 is a stronger GH agent than water vapor**

***Combinations of atmospheric species yield different GHE**

Bressler et al , 2016 in press

Doubling the CO_2

RH	xCO_2	$\log_{10} \tau_{vis}$	$\log_{10} \tau_{fir}$	T_{surf} (K)
0%	1	-1.03589	-0.400832	262.154
	2	-1.00533	-0.349574	263.577
		diff.		+1.423
10%	1	-0.0960	0.2615	288.869
	2	-0.0940	0.2855	290.716
		diff.		+1.847
50%	1	0.02223	0.47682	304.156
	2	0.02324	0.49588	305.965
		diff.		+1.809

Earth RH ~ 13%

Bressler et al , 2016 in press

* *T_{surf} rise is of the same order of magnitude of radiative forcing ~3K (IPCC Report, 2013)*

* *This is an upper limit to the GHE T_{surf} change*

* *Scattering, clouds, diurnal changes, etc. will reduce it further*

Thank you!