The PHOENIX + CO5BOLD models at the 2018 Horizon

Centre de Recherche Astrophysique de Lyon

5 Mai 2016

Vendredi 15h35

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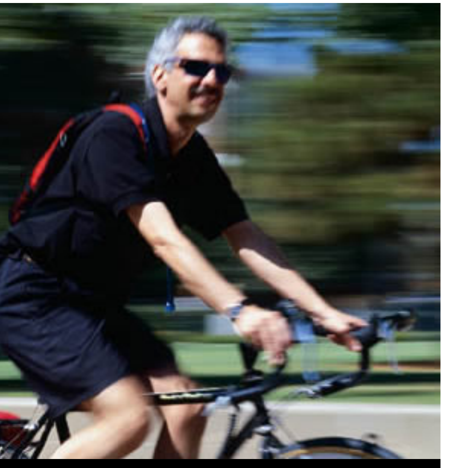
Directrice de Recherche (DR2), CNRS
Centre de Recherche Astrophysique de Lyon
Site ENS-Lyon

PHOENIX

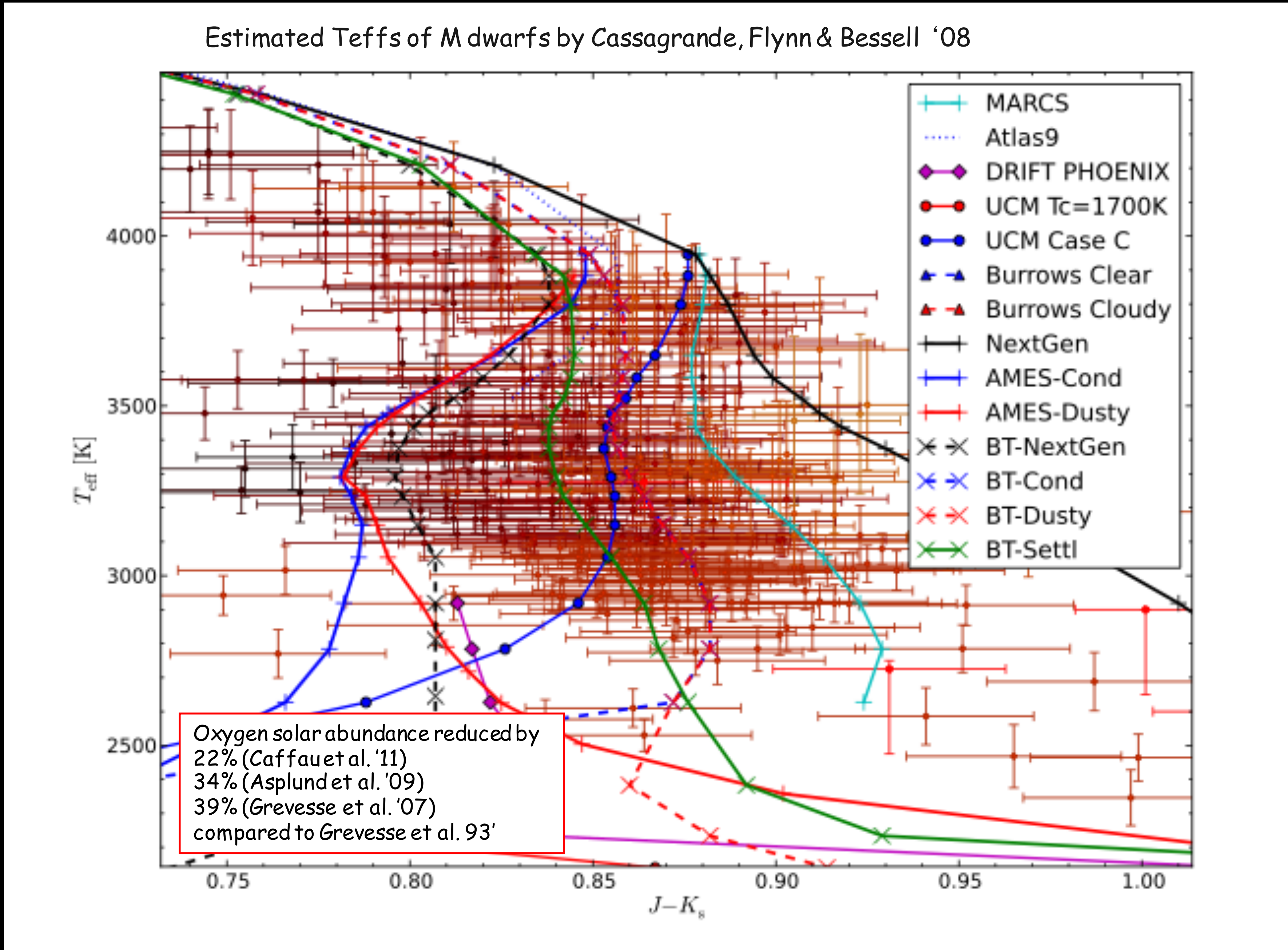


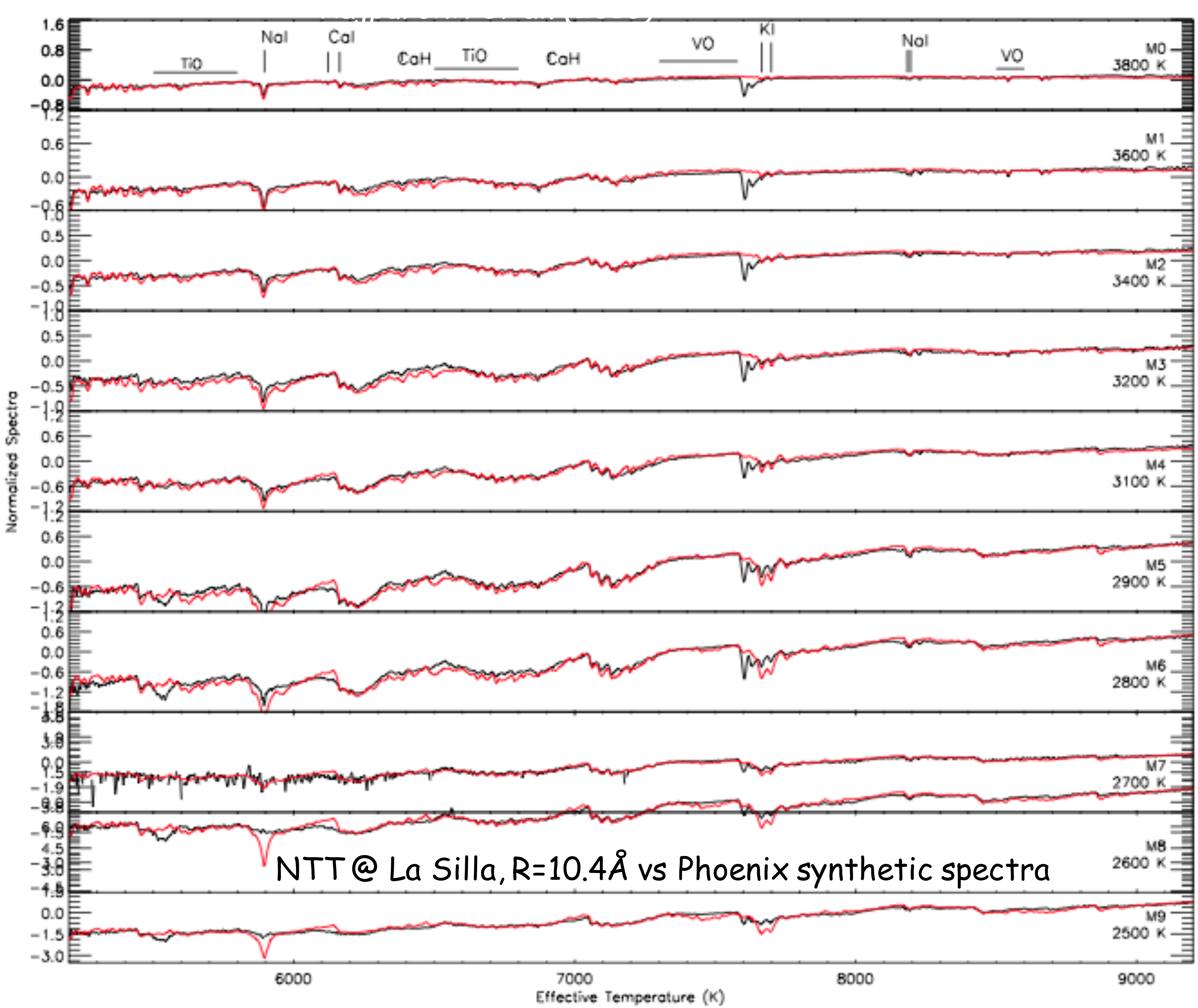
Created in 1994 in Phoenix, AZ
Peter Hauschildt, France Allard & Eddie Baron

Allard & Hauschildt, ApJ 445, 443 (1995)

- 1D, static, Radiative Transfer OS/ALI :
  - spherical symmetry with adaptive angular resolution
  - restraint relativity effects (solution in comoving frame)
  - 3D
- Hydrostatic Equilibrium (stars, brown dwarfs, planets), or
- Velocity field in relativistic expansion (novae, supernovae)
- Layer-dependant velocity up to speed of light (novae, supernovae)
- Convection: Mixing Length Theory
- Atomic diffusion
- Non-LTE (rate-operator splitting) for atoms and CO
- Chemical Equilibrium whit NLCE for certain species (CO, CH_4, NH_3)
- 26 ionization levels, 85 elements (Th, U), 600 molecules, >1000 grain types
- Dynamical (no pre-tabulation) Opacity Sampling
- Database of atomic and molecular transitions
- Extinction cross-sections for 56 types of grains
- Cloud Model based upon Rossow (1978) timescales (sedimentation, condensation)
- Supersaturation computed from chemical equilibrium precomputations.
- Mixing from Radiative HydroDynamic (RHD)

M-L transition: Comparing models from different authors




NTT @ La Silla, R=10.4Å vs Phoenix synthetic spectra
TiO
NaI
CaI
CaH
TiO
CaH
VO
KI
NaI
VO
M0 3800 K
M1 3600 K
M2 3400 K
M3 3200 K
M4 3100 K
M5 2900 K
M6 2800 K
M7 2700 K
M8 2600 K
M9 2500 K
Normalized Spectra
Effective Temperature (K)
6000
7000
8000
9000

Rajpurohit et al. (2016): sdK7 -sdM2

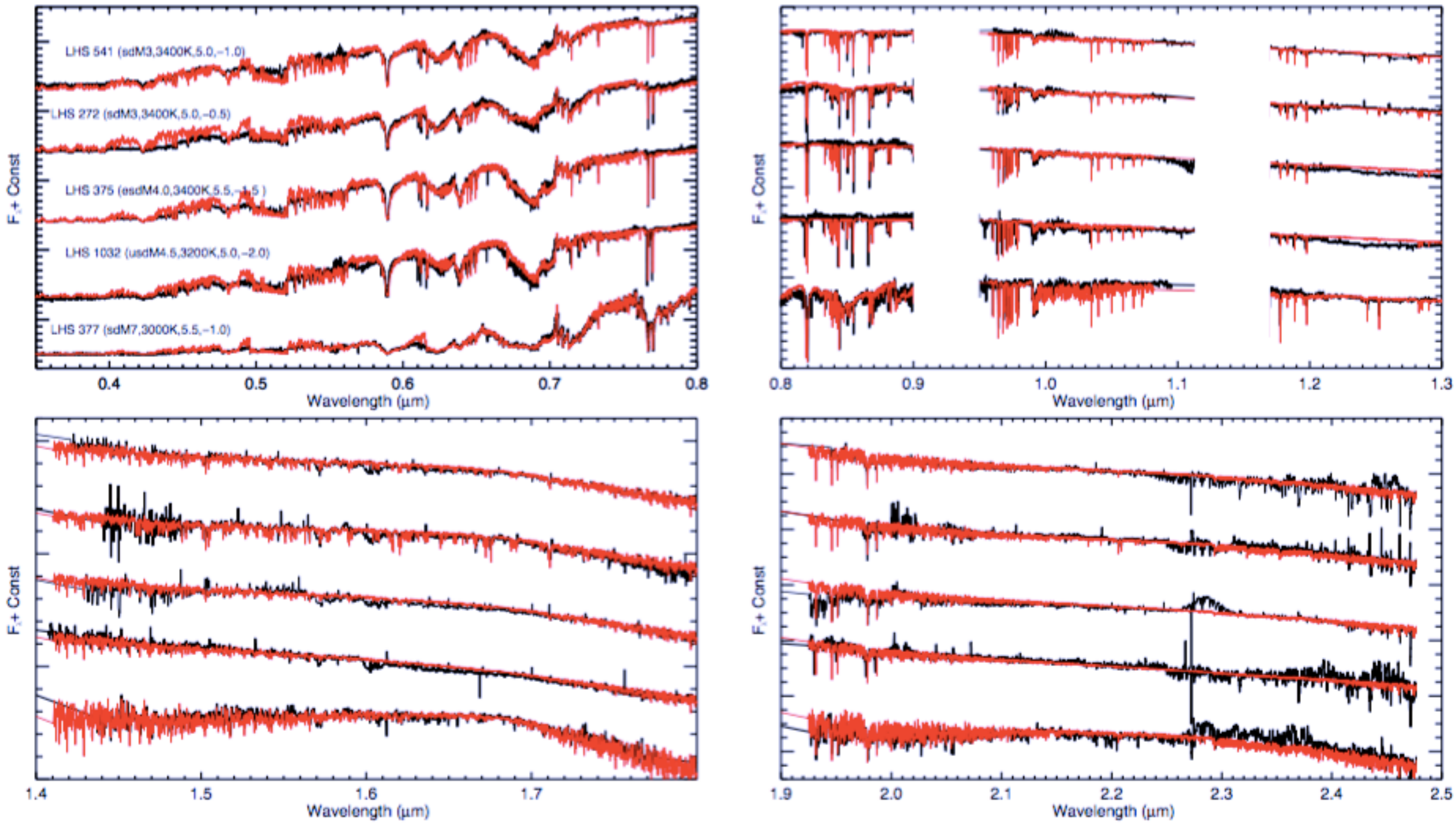


Fig. 6: X-SHOOTER spectra (black) compared with the best-fit BT-Settl synthetic spectra (red) from spectral sequence of sdK7 to sdM2.

Rajpurohit et al. (2016): sdM3-sdM7

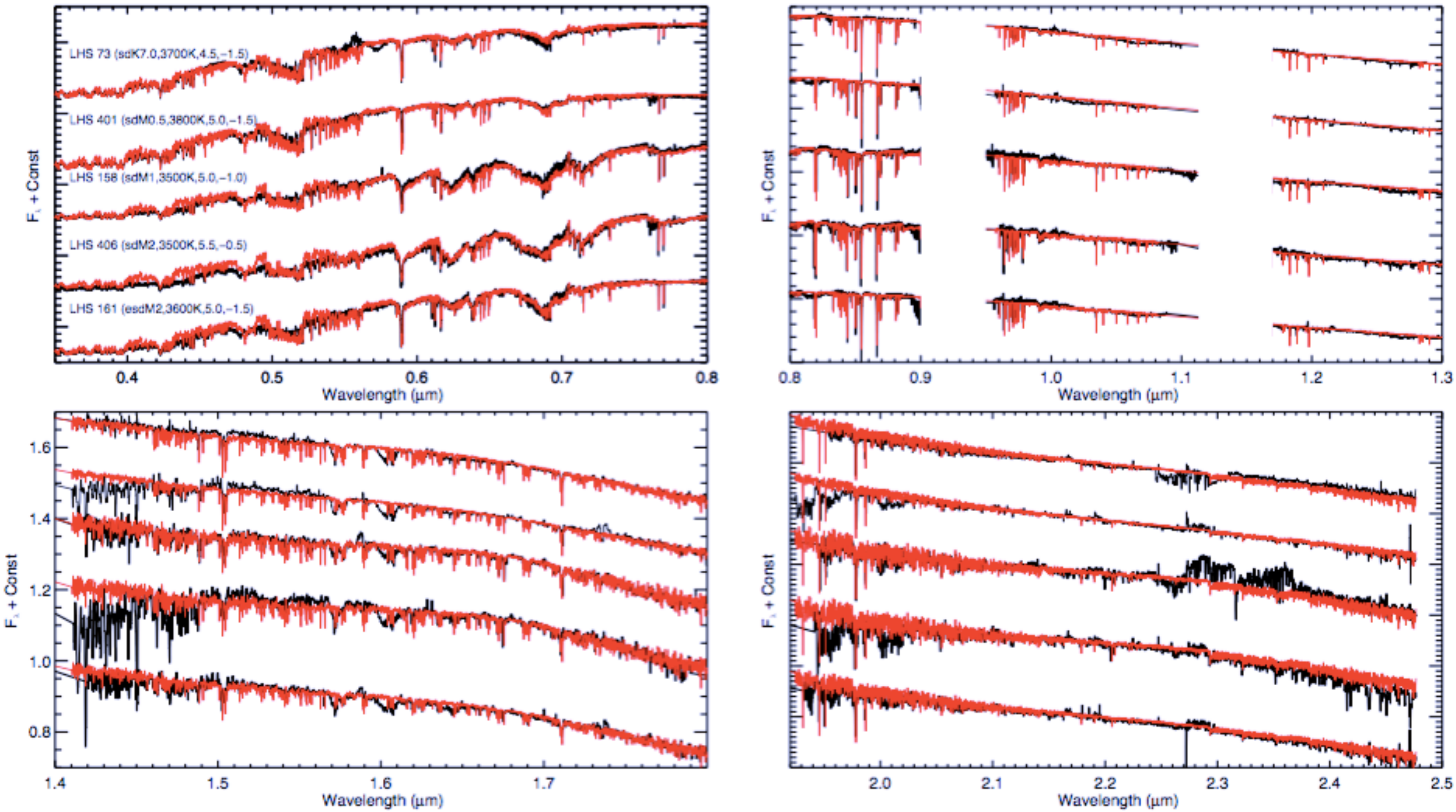
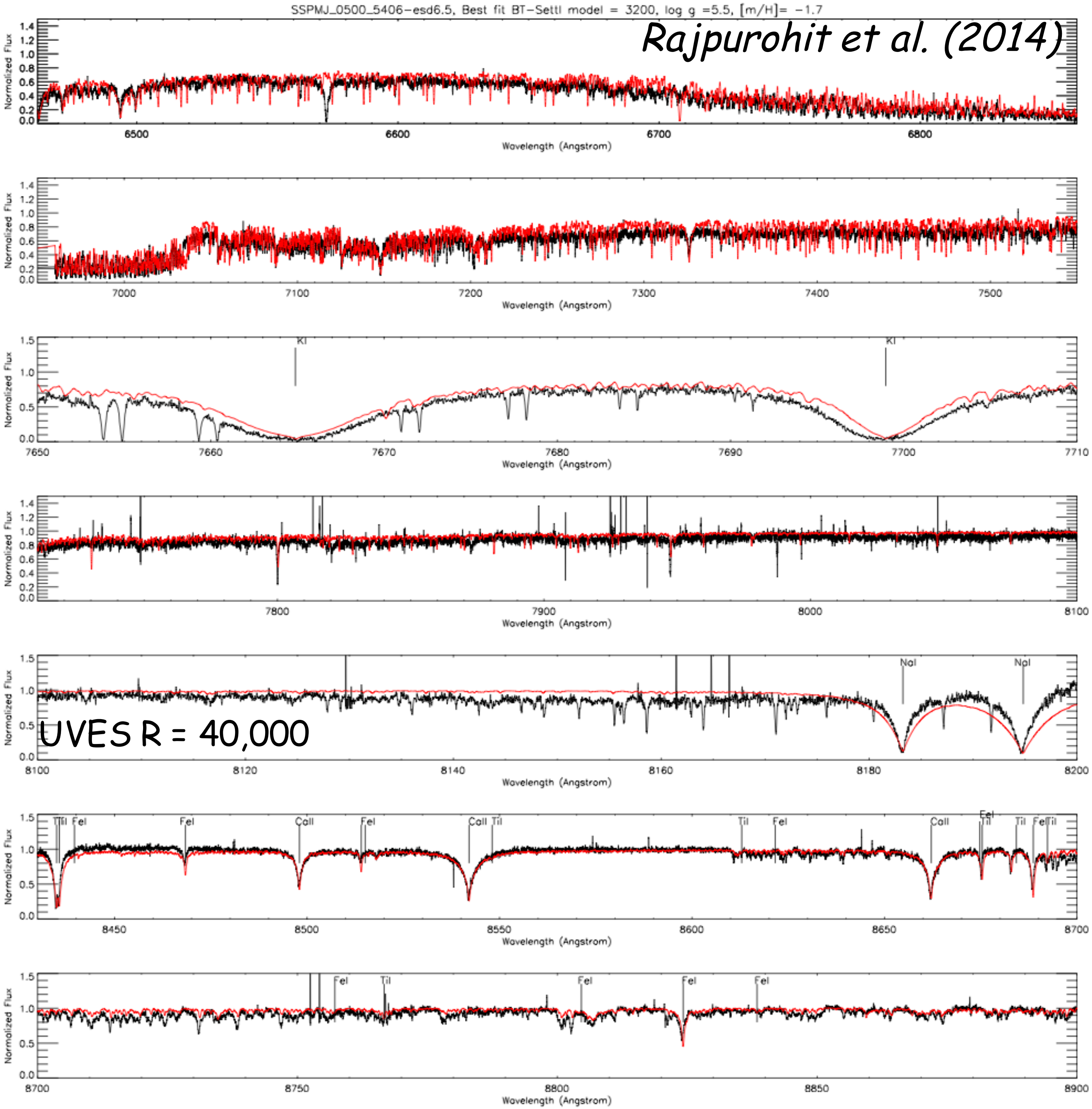


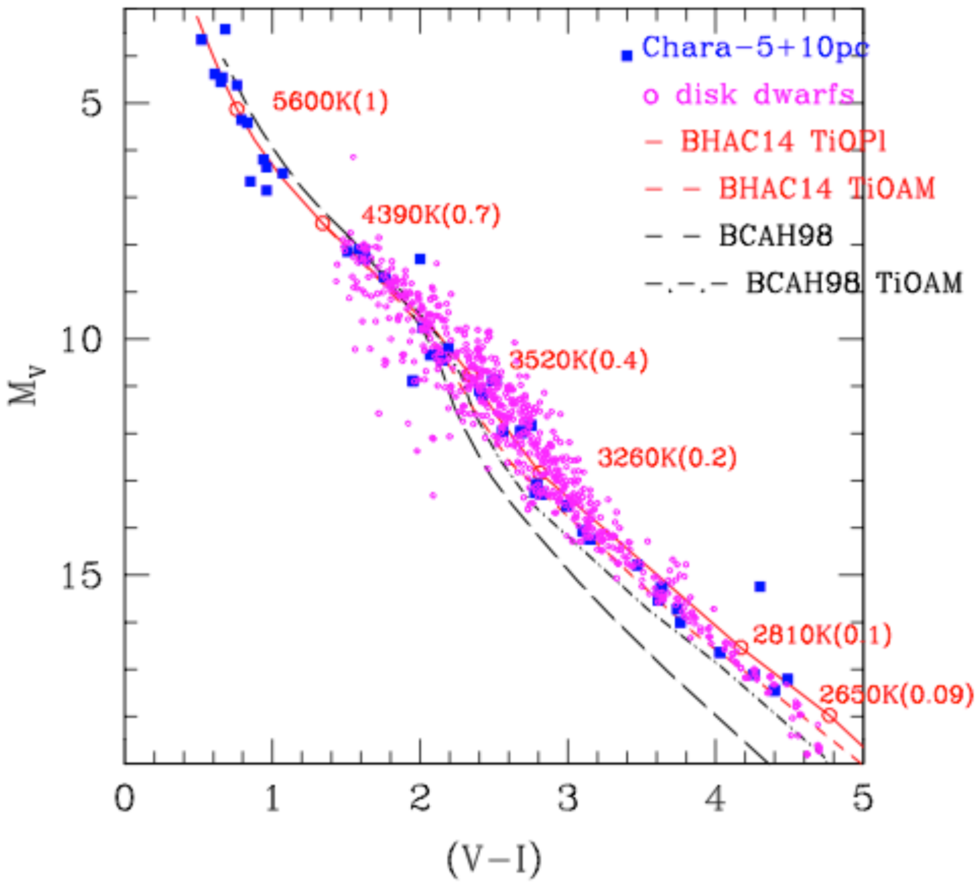
Fig. 7: X-SHOOTER spectra (black) compared with the best-fit BT-Settl synthetic spectra (red) from spectral sequence of sdM3 to sdM7 which includes esdM and usdM.



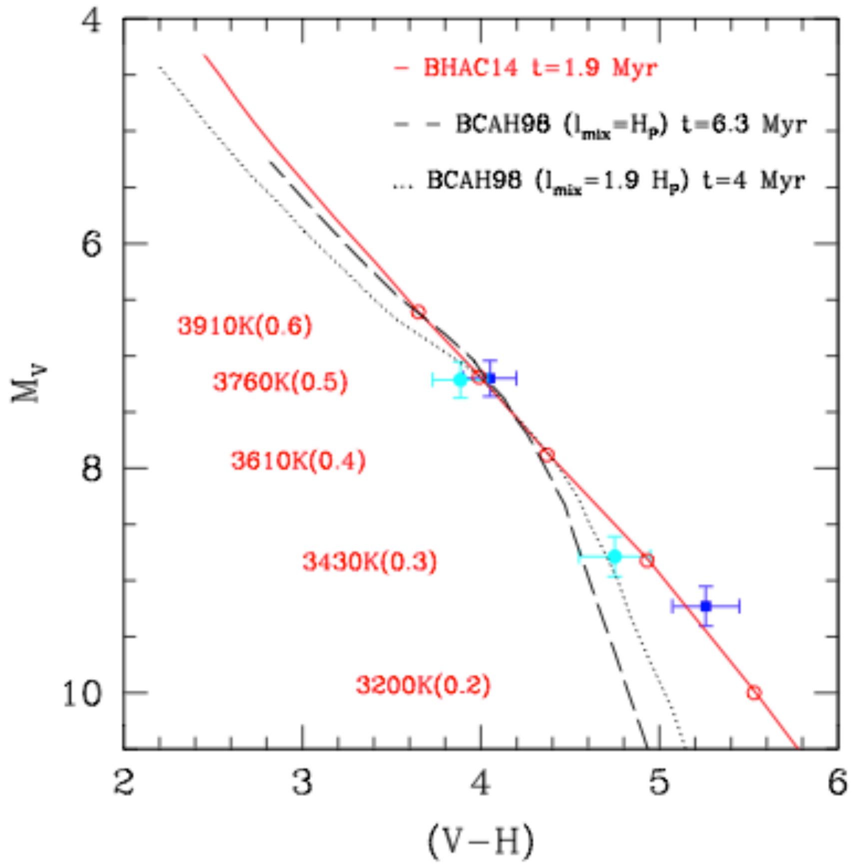
SSPMJ_0500_5406-esd6.5, Best fit BT-Settl model = 3200, log g =5.5, [m/H]= -1.7
Rajpurohit et al. (2014)
UVES R = 40,000
Normalized Flux
Wavelength (Angstrom)
KI
NaI
TiI
FeI
CaII

New BT-Settl Interior Models

Baraffe, Homeier, Allard & Chabrier (2015)



Incertainties on TiO opacities remain:
AMES TiO less accurate but more complete vs Plez 2008 TiO more accurate but not complete enough



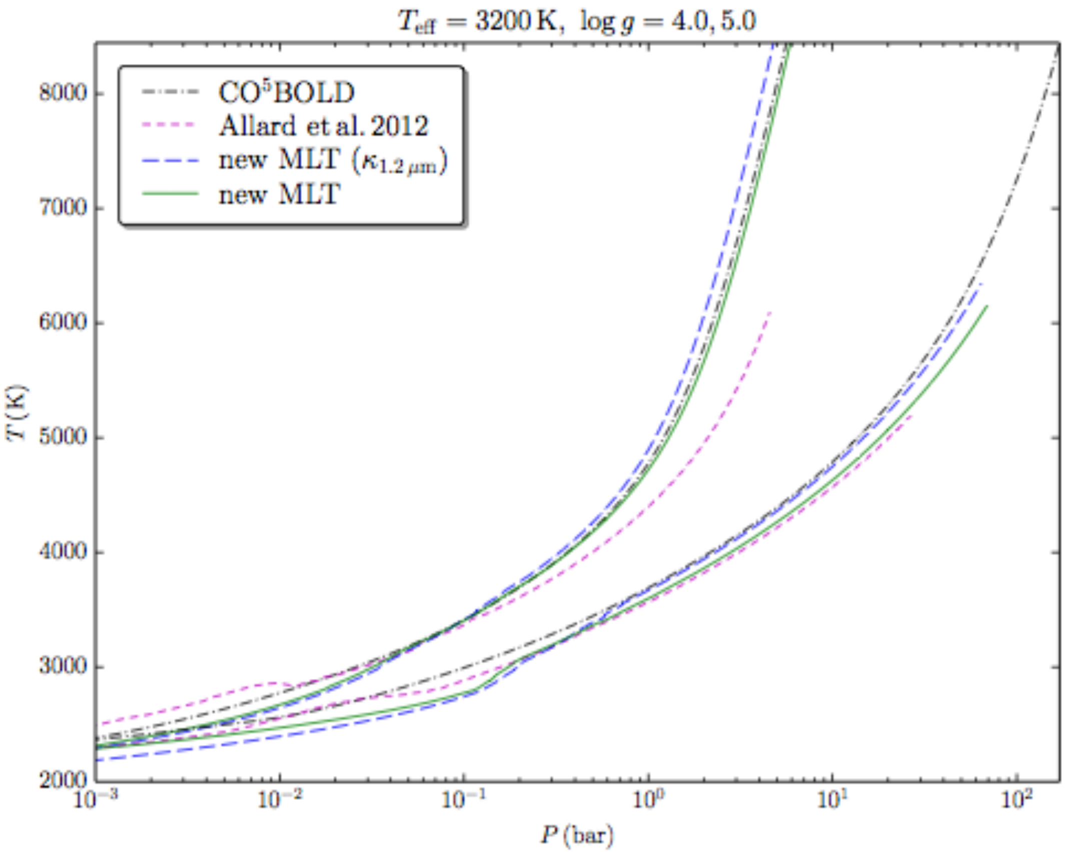
ML calibration improve the models for young stars, BDs & Exoplanets

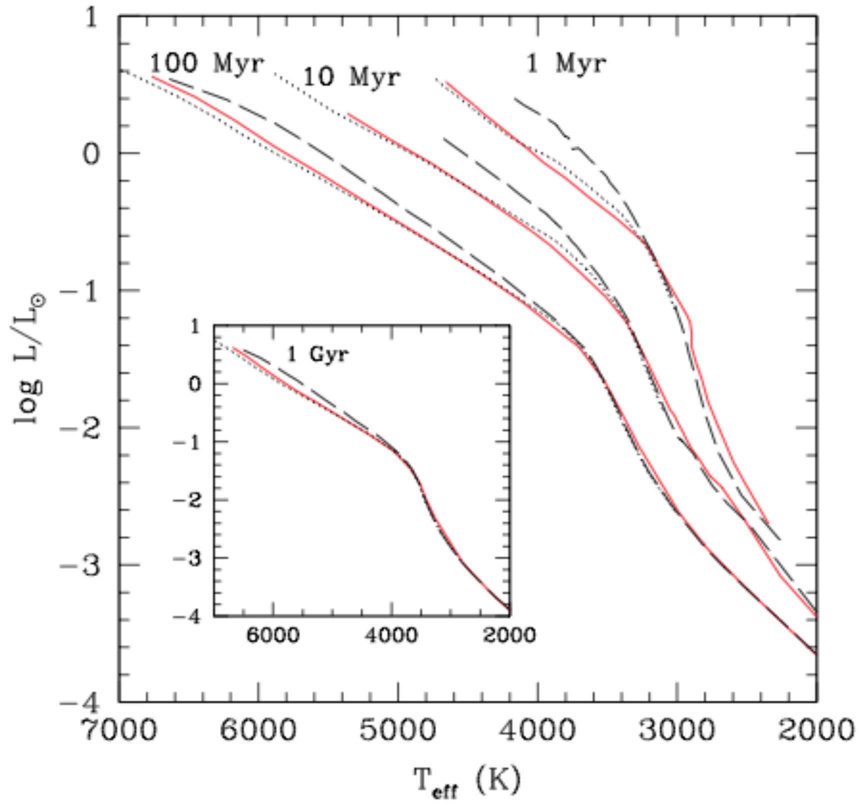
New evolution tracks

Table 1. Characteristics of previous and present atmosphere models.

Models	Abundances	TiO	H_2O	MLT variant	l_{mix}/H_P	κ in τ_e
NextGen[1]	G93[3]	J94[5]	M94[8]	ML1	1	$\kappa_{1.2\mu m}$
Dusty/Cond[2]	G93[3]	S98[6]	PS97[9]	$f_3 = 24$, (f_4, f_5) from Eq. 2	1	$\kappa_{1.2\mu m}$
Allard et al. (2012a)	C11[4]	Pl98[7]	B06[10]	$f_3 = 24$, (f_4, f_5) from Eq. 2	2	$\kappa_{1.2\mu m}$
Present models	C11[4]	Pl98[7]	B06[10]	$(f_3, f_4, f_5) = (24, 3, 1)$	~1.6-2[11]	κ_I^{12}

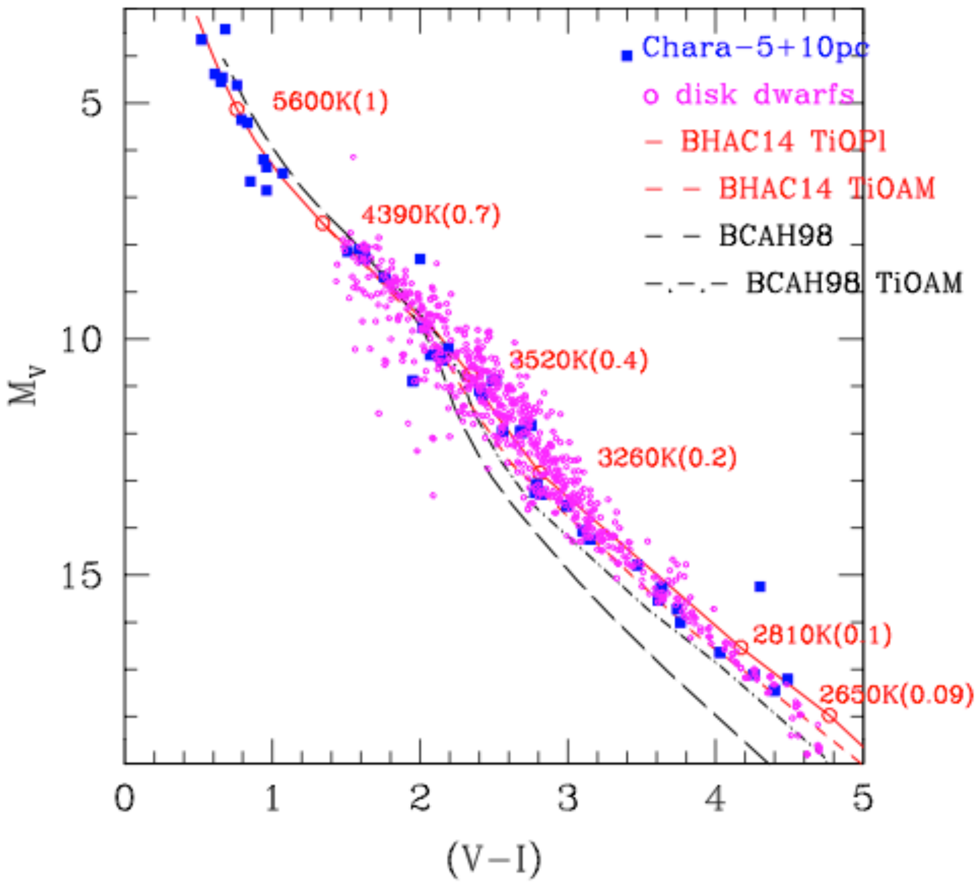
[1] Hauschildt et al. (1999) - [2] Allard et al. (2001) - [3]Grevesse et al. (1993) - [4]**DH: Asplund et al. (2009)**+Caffau et al. (2011) [5]Jorgensen (1994) - [6]Schwenke (1998) - [7]Plez (1998) - [8]Miller et al. (1994) - [9]Partridge & Schwenke (1997) - [10]Barber et al. (2006) - [11] Based on RHD calibration - [12]Harmonic interpolation between κ_{Ross} and κ_{Planck}

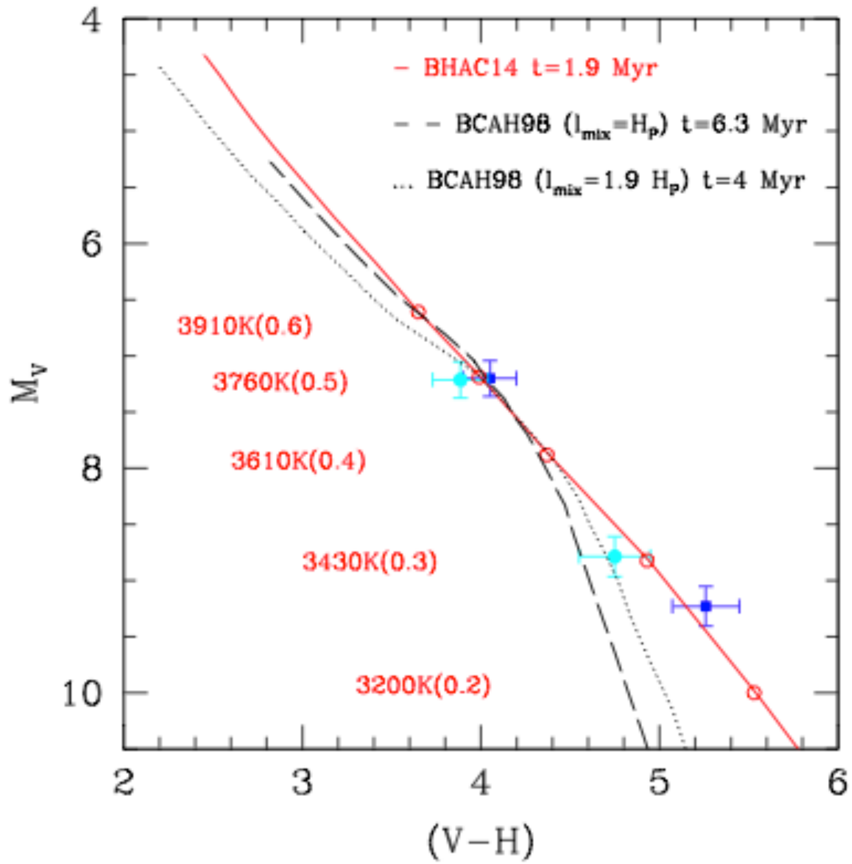




New BT-Settl Interior Models

Baraffe, Homeier, Allard & Chabrier (2015)





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ML calibration improve the models
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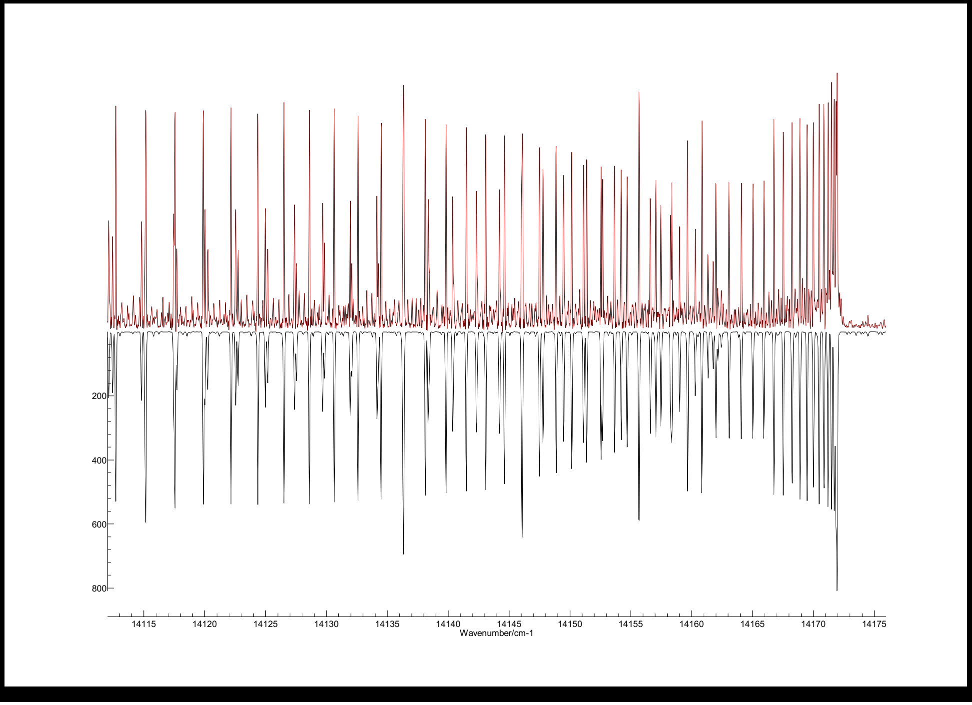
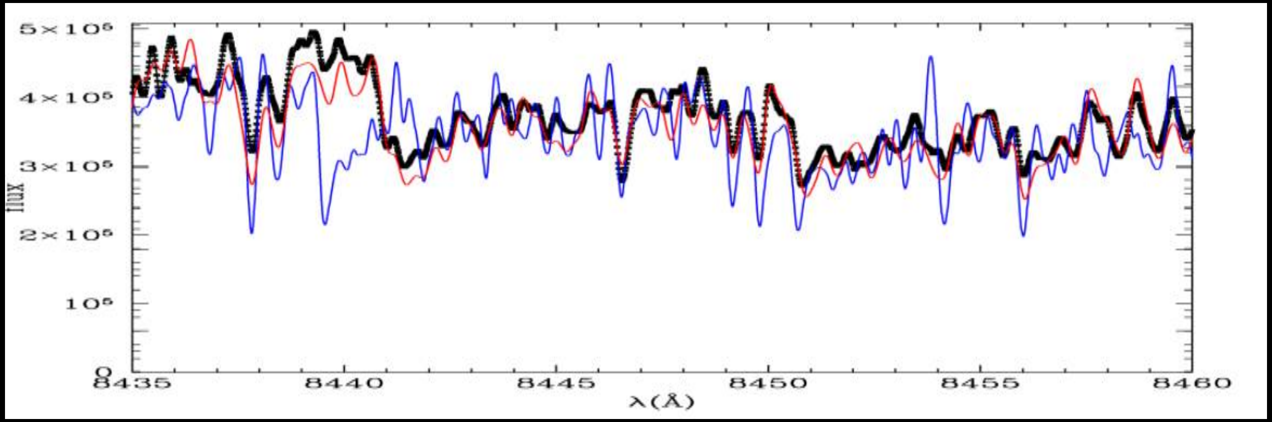
Revised TiO Line List



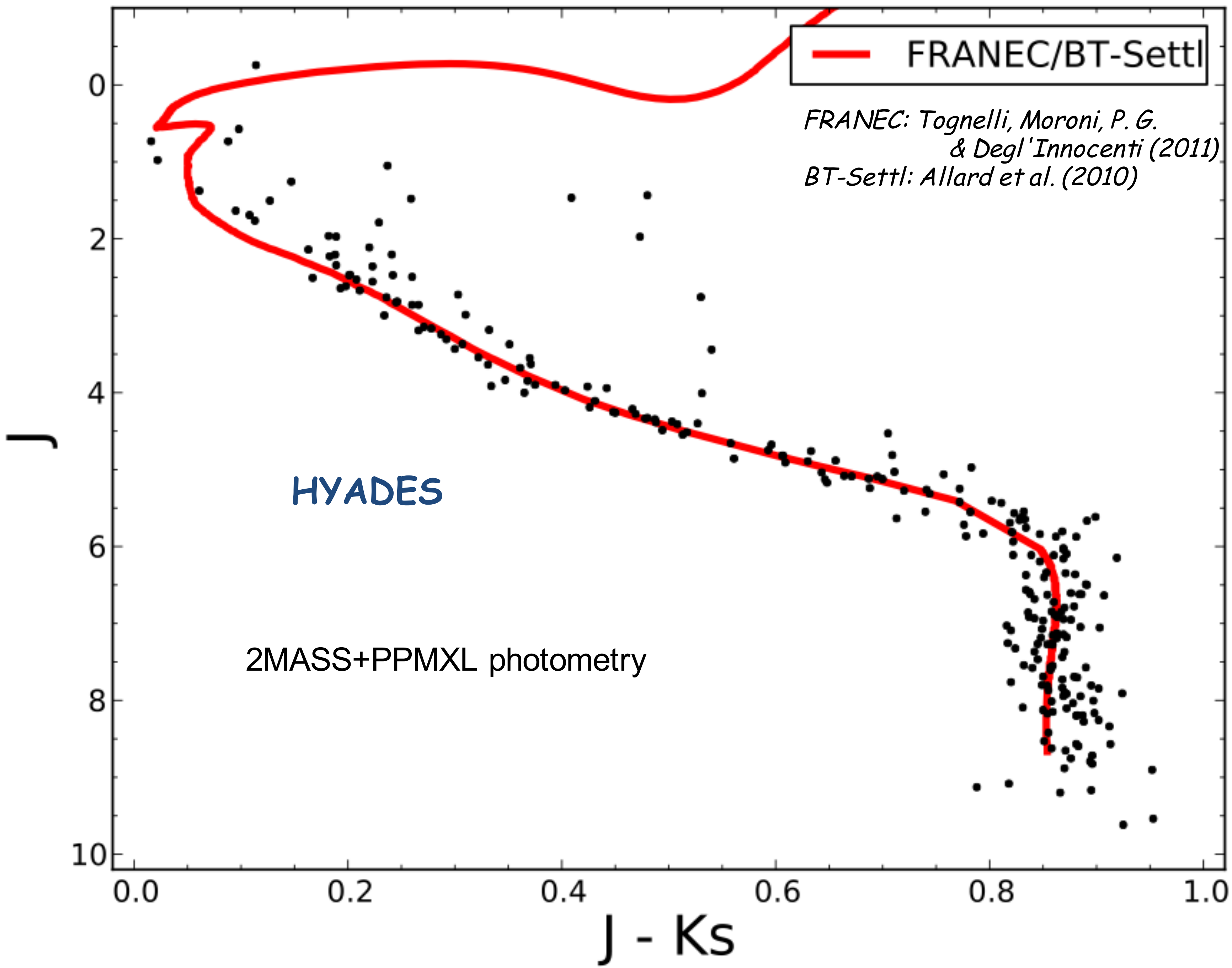
The ExoMol group in collaboration with Thomas Masseron

Are developping a new TiO line list that allies accuracy and precision



Masseron & McKemmish (in preparation)

Kopytova et al. (A&A, 585, p.7, 2016)



Bernd Freytag, ENS-Lyon, now Uppsala
http://perso.ens-lyon.fr/bernd.freytag

CO5BOLD

R(M)HD simulations

H. G. Ludwig, W. Schaffenberger, S. Wedemeyer-Böhm, S. Höfner, F. Allard

Matthias Steffen, IAP
Potsdam, Germany
http://www.aip.de/~mst/

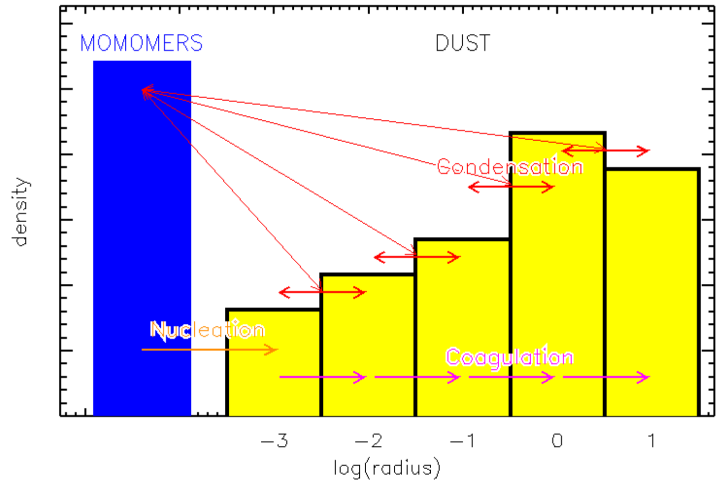
- General: 2D/3D Cartesian box, parallelized with OpenMP
- Magneto-Hydrodynamics (compressible):
  - ✓ HYD module: approximate Riemann solver (Roe type)
  - ✓ MHD module: HLLE solver
- Radiation transport:
  - ✓ Module for global "Star-in-a-Box" models (central potential)
  - ✓ Module for local "Box-in-a-Star" models (constant gravity)
  - ✓ Non-local transport, grey/non-grey opacity scheme
  - ✓ opacities from ATLAS, MARCS, PHOENIX
- Molecules, dust; additional densities:
  - ✓ Dust; 2-bin: monomers + grains, one size per grid cell, forsterite (Mg_2SiO_4)
  - ✓ Dust; multi-bin: monomers + several grain sizes, forsterite (Mg_2SiO_4)
  - ✓ Dust; 4-moment method: amorphous carbon
  - ✓ Molecules: network for CO
- Rotation: Coriolis and Centrifugal Forces in each grid cell
- Impinging radiation from a parent star

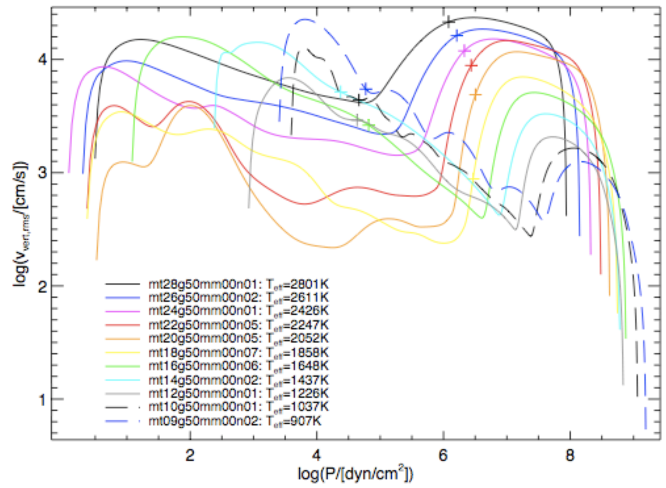
2D RHD simulations of dust cloud formation in brown dwarfs' atmospheres

Gravity Waves !!!

Calibration of mixing processes into 1D static model atmosphere code Phoenix:

- Micro-turbulence
- Convective mixing length
- Overshoot
- Gravity waves
- Particle diffusion coefficient

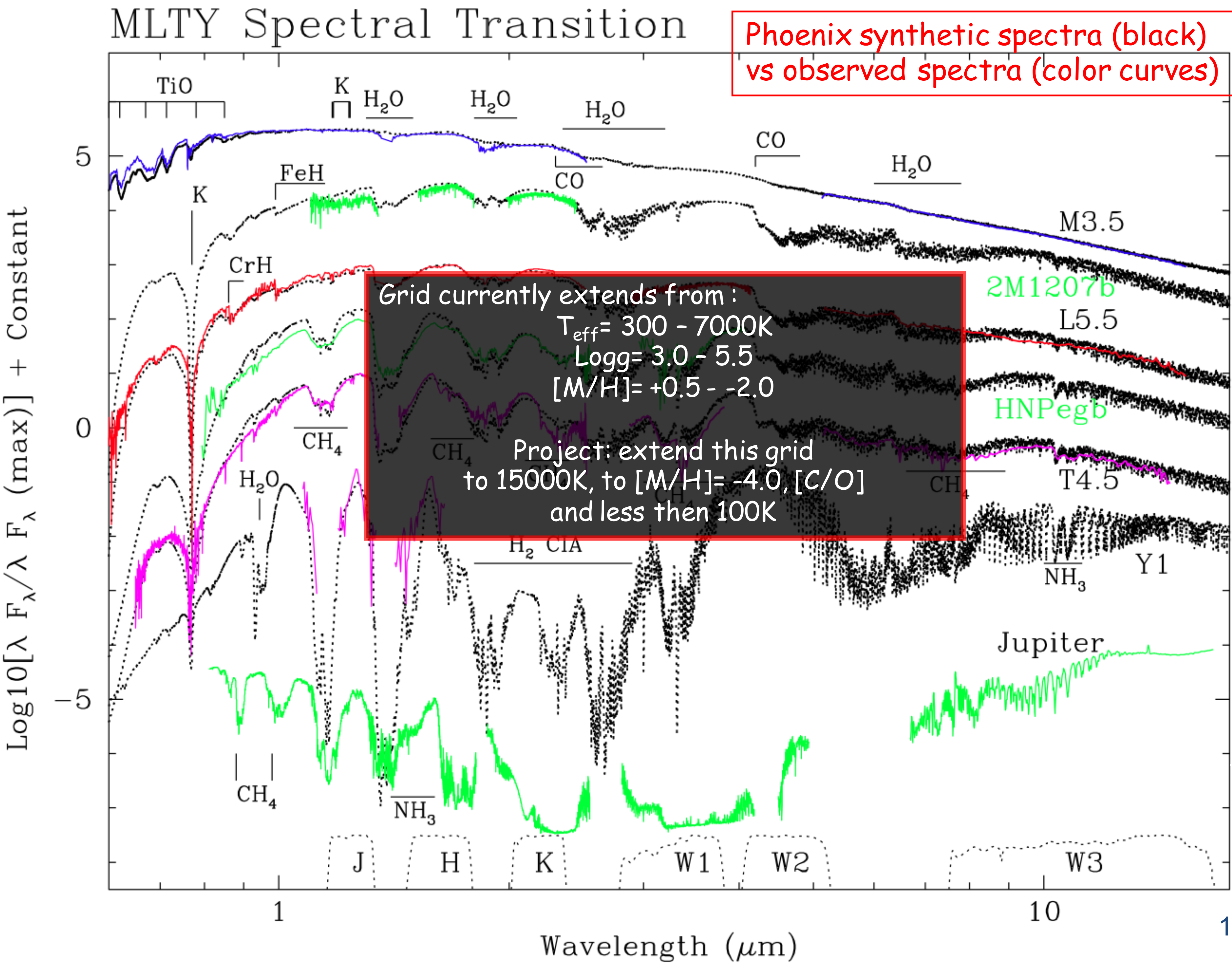




W350 x H80 km² during 36 hrs

CO5BOLD simulations (Freytag et al. 2010) of the gas and forsterite (Mg_2SiO_4) dust based on Phoenix opacities, on a cloud model (dust size bon distribution), and on the nucleation, condensation, coagulation, and sedimentation rates by Rossow (1978). Shown, in red, the dust grain mass density, and, in green, the entropy indicates the convection.

Phoenix synthetic spectra (black) vs observed spectra (color curves)



Grid currently extends from :

T_{eff}= 300 - 7000K

Logg= 3.0 - 5.5

[M/H]= +0.5 - -2.0

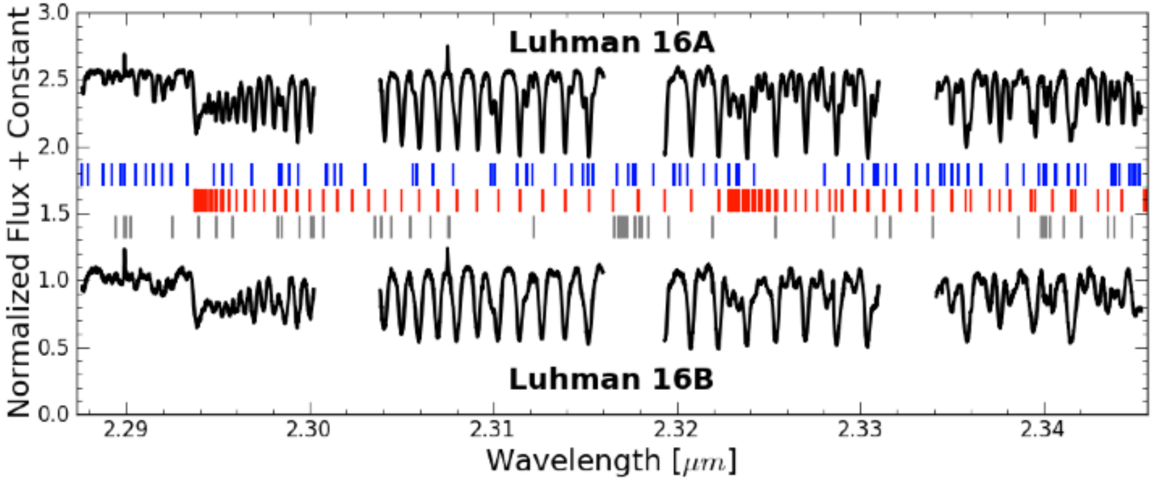
Project: extend this grid to 15000K, to [M/H]= -4.0, [C/O] and less then 100K

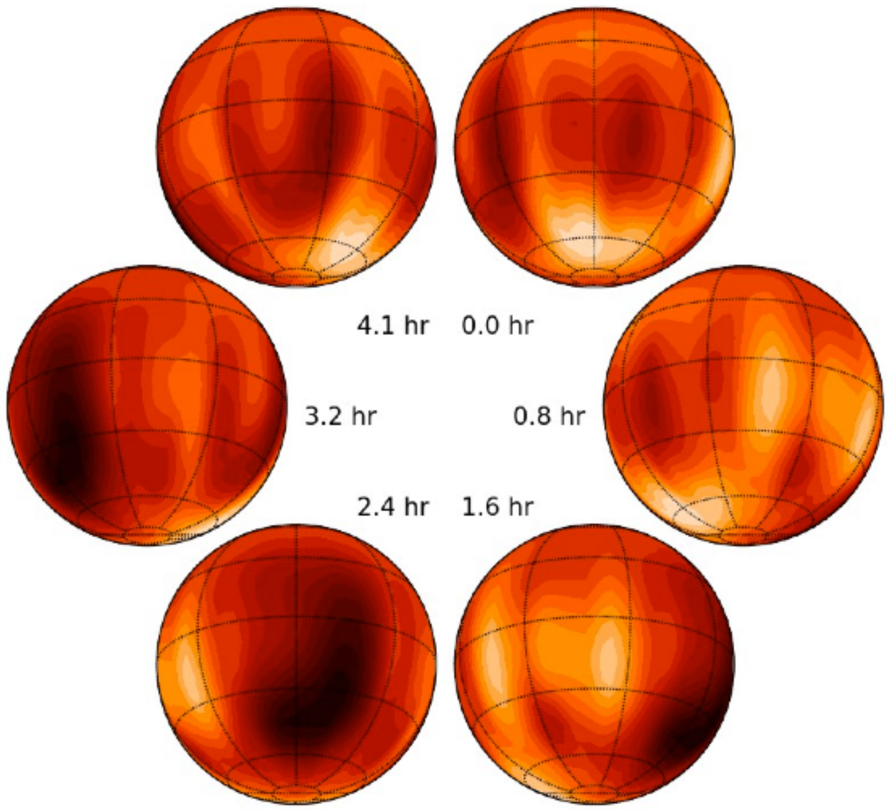
Surface inhomogeneities revealed by Doppler imaging tomography!

Crossfield et al. (Nature 505, 2014)

High-resolution, near-infrared spectra of the Luhman 16AB brown dwarfs (black curves). The vertical ticks indicate absorption features: H_2O (blue) and CO (red), and residual telluric features (gray). The lines of the B component are broader.

Surface map of brown dwarf Luhman 16B, which clearly depicts a bright near-polar region (seen in the upper-right panels) and a darker mid-latitude area (lower-left panels) consistent with large-scale cloud inhomogeneities. The lightest and darkest regions shown correspond to brightness variations of roughly ±10%. The time index of each projection is indicated near the center of the figure.





Local High Spatial Resolution « box-in-a-star » simulations of M – L – T dwarfs

Freytag, Allard, Homeier (2016)
In preparation

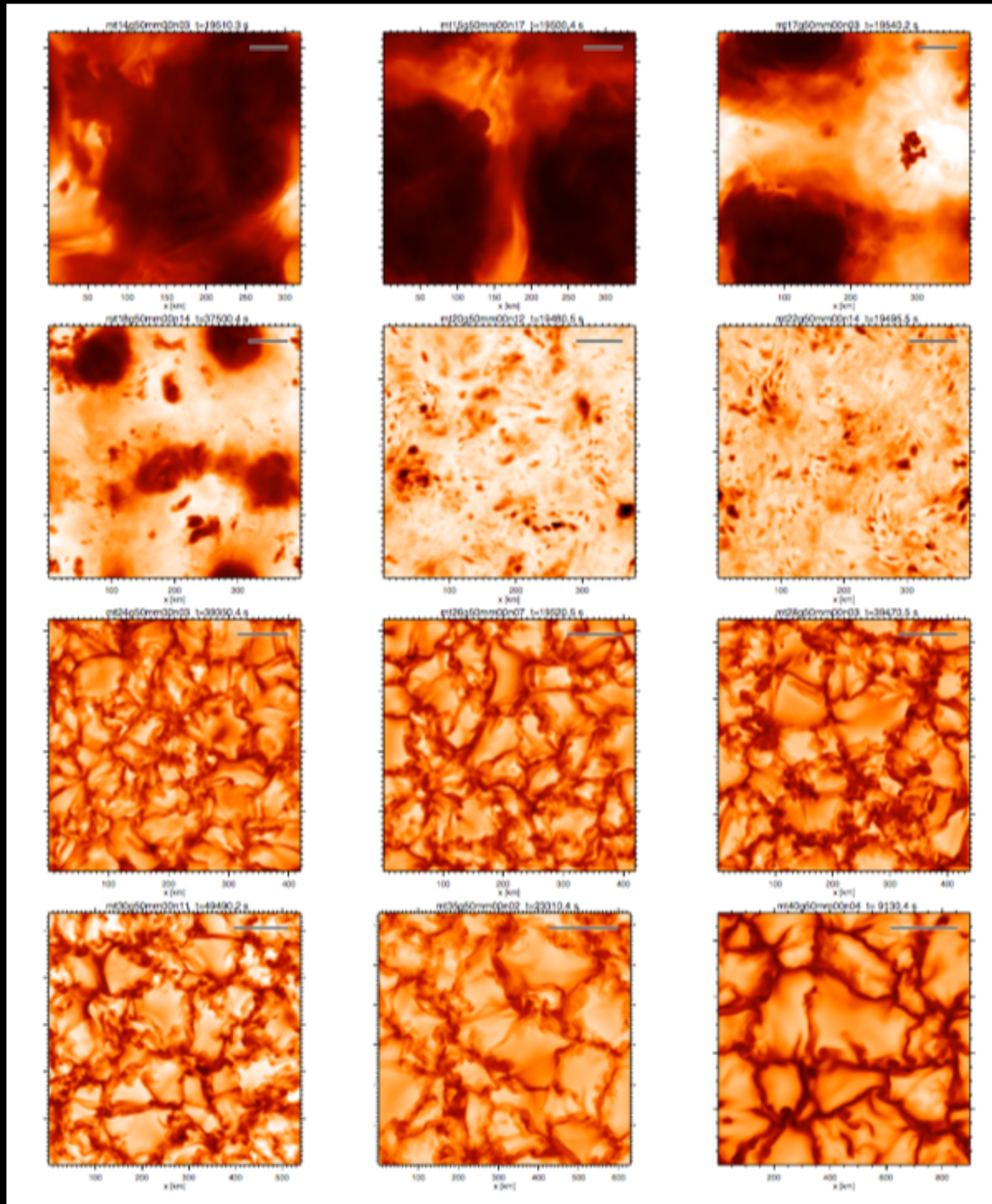
3D Box-in-a-star simulations

$4000 \geq T_{eff} \geq 1400$K, dT=100K

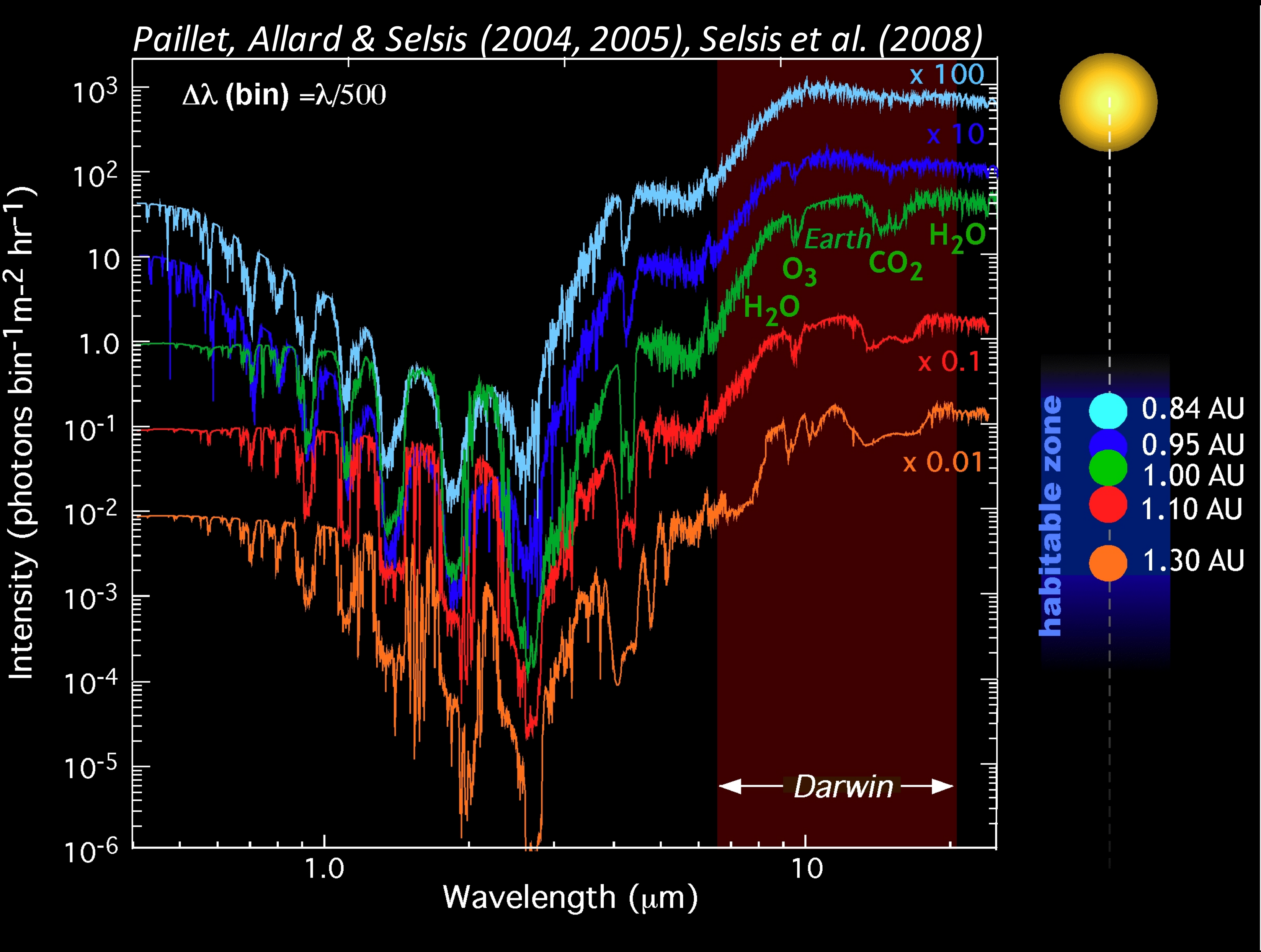
with **high spatial resolution**

448^2x 560 – 270 points

3000 - 238 x 1630 – 114 km/s



Application to Telluric Planets



Web Simulator

http://phoenix.ens-lyon.fr/simulator

ONLINE!

Offers synthetic spectra and thermal structures of published model grids and the relevant publications.

- Computes synthetic spectra, with/without irradiation by a parent star, and photometry for:

✓ stars

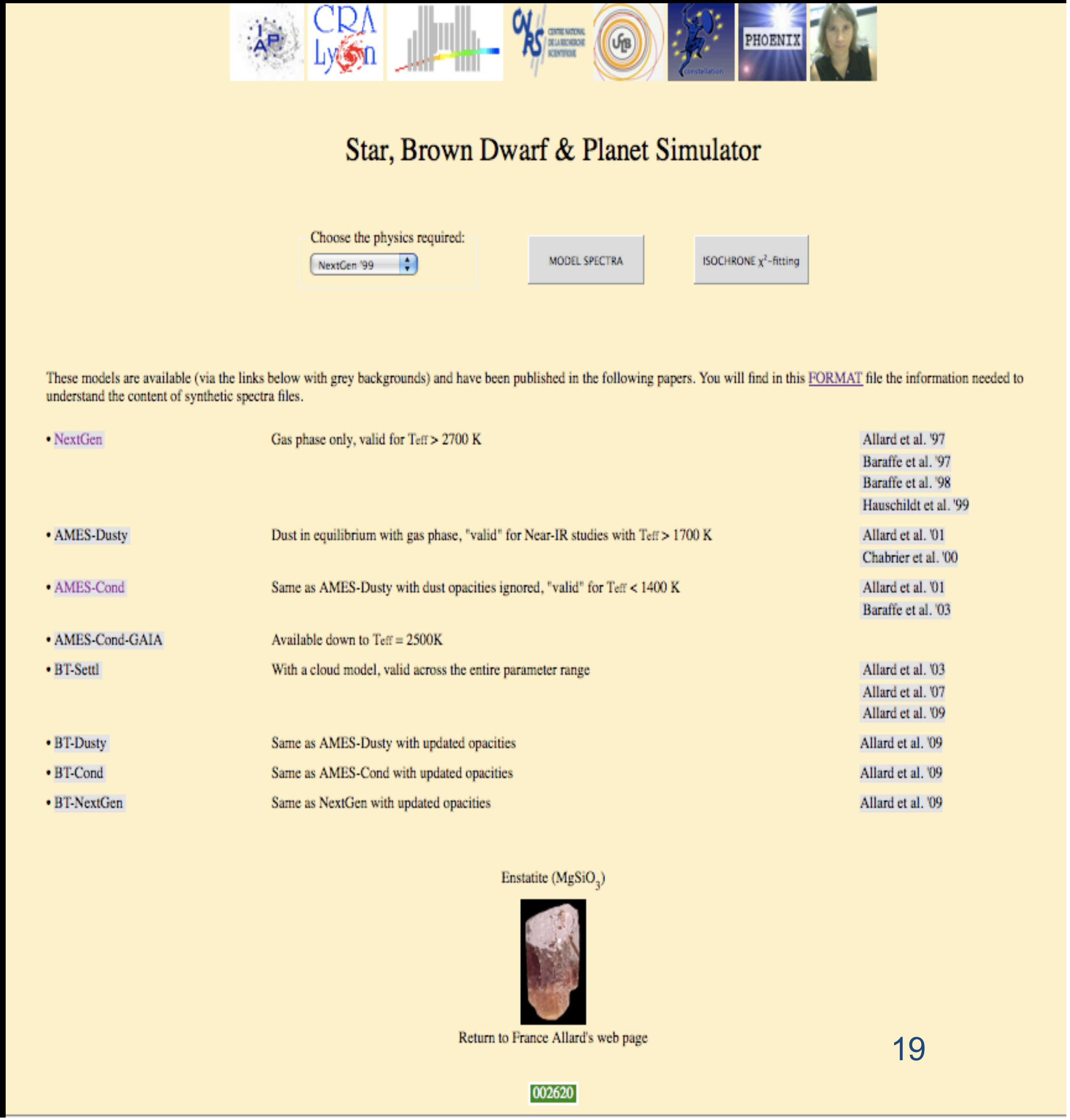
✓ brown dwarfs (1 Myrs - 10 Gyrs)

✓ irradiated stars or planets

✓ telluric exoplanets

Computes isochrones and finds the parameters of a star by chi-square fitting of colors and/or mags to the isochrones.

- Rosseland/Planck as well as monochromatic opacity tables calculations.



Star, Brown Dwarf & Planet Simulator

Choose the physics required: NextGen '99

MODEL SPECTRA

ISOCHRONE χ^2-fitting

These models are available (via the links below with grey backgrounds) and have been published in the following papers. You will find in this FORMAT file the information needed to understand the content of synthetic spectra files.

• NextGen	Gas phase only, valid for Teff > 2700 K	Allard et al. '97 Baraffe et al. '97 Baraffe et al. '98 Hauschildt et al. '99
• AMES-Dusty	Dust in equilibrium with gas phase, "valid" for Near-IR studies with Teff > 1700 K	Allard et al. '01 Chabrier et al. '00
• AMES-Cond	Same as AMES-Dusty with dust opacities ignored, "valid" for Teff < 1400 K	Allard et al. '01 Baraffe et al. '03
• AMES-Cond-GAIA	Available down to Teff = 2500K	
• BT-Settl	With a cloud model, valid across the entire parameter range	Allard et al. '03 Allard et al. '07 Allard et al. '09
• BT-Dusty	Same as AMES-Dusty with updated opacities	Allard et al. '09
• BT-Cond	Same as AMES-Cond with updated opacities	Allard et al. '09
• BT-NextGen	Same as NextGen with updated opacities	Allard et al. '09

Enstatite ($MgSiO_3$)

Return to France Allard's web page

002620

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In Test Mode !

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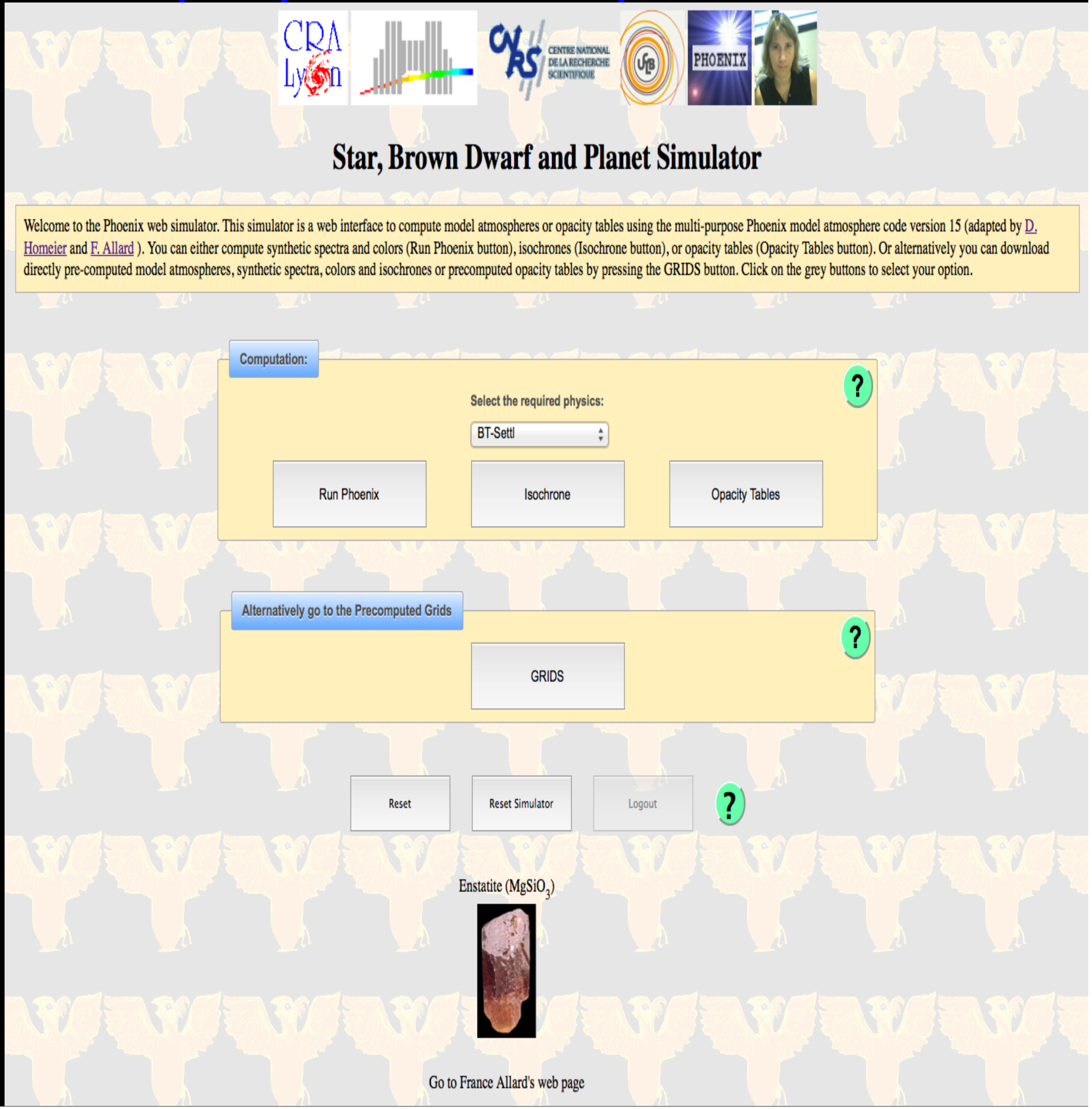
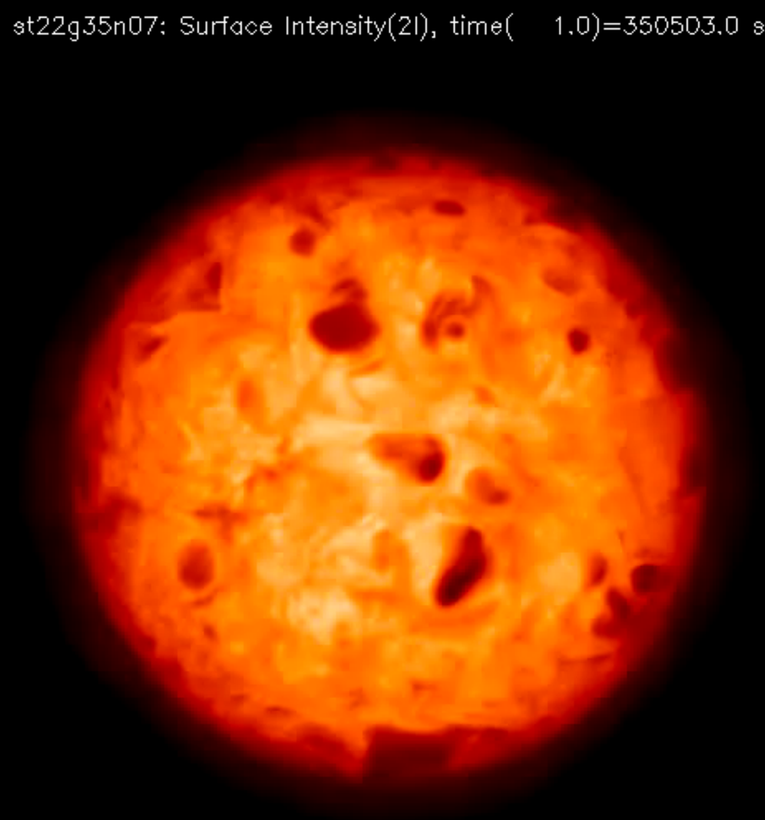
- Rosseland/Planck



Global RHD simulations

Freytag, Allard & Homeier 2016 (in prep.)

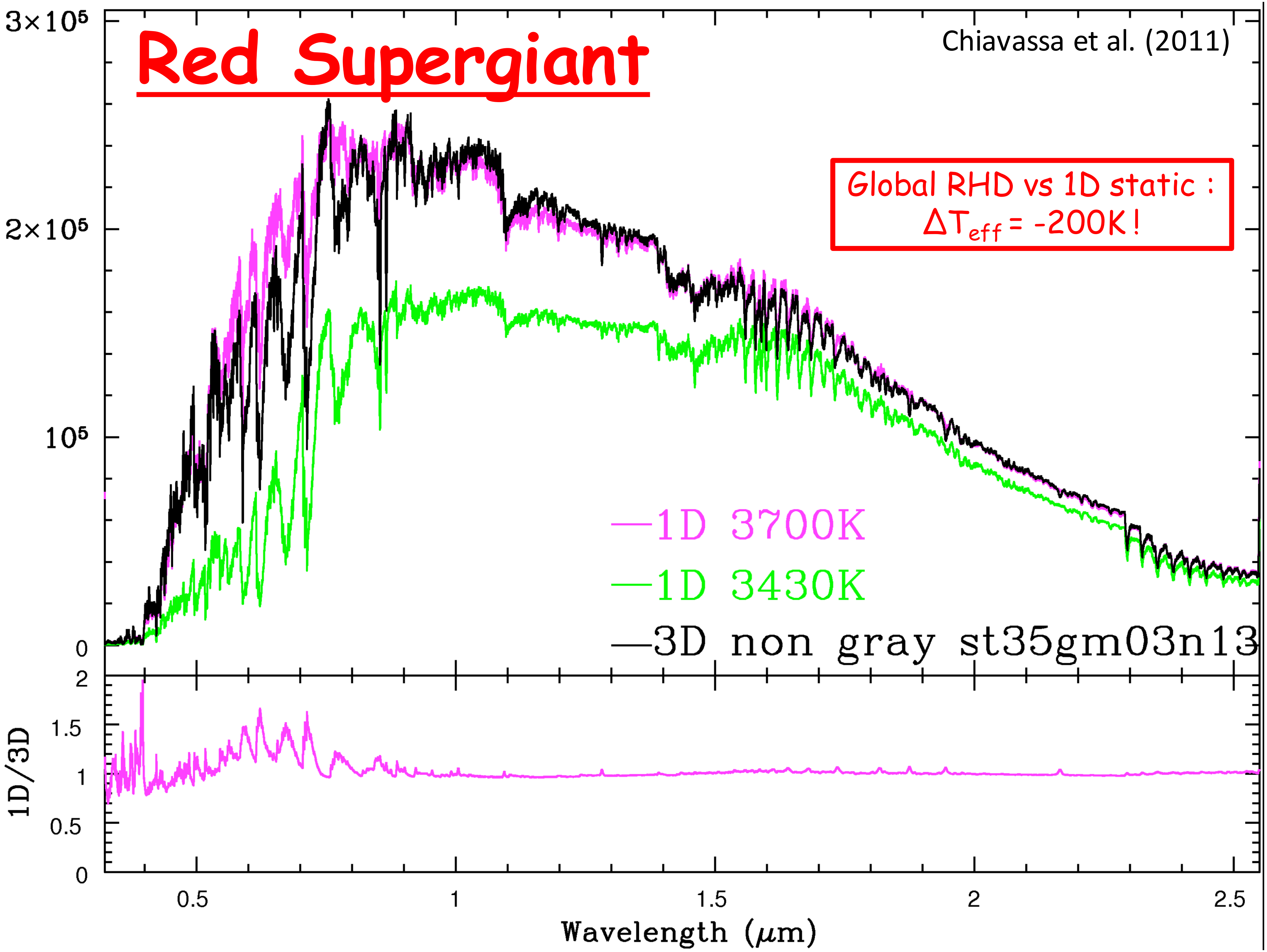
T_{eff}= 2200K, logg= 3.5, solar, P=8 Hr



➔

Jupiter

However radius scaled by a factor 20 !
Improvement expected with MPI 2017



Red Supergiant
Chiavassa et al. (2011)
Global RHD vs 1D static :
ΔTeff = -200K !
—1D 3700K
—1D 3430K
—3D non gray st35gm03n13
3×10⁵
2×10⁵
10⁵
0
2
1.5
1
0.5
0
1D/3D
0.5
1
1.5
2
2.5
Wavelength (μm)