Model Atmosphere for Stars and Brown Dwarfs

Resolved And unresolved Stellar PopUlaTIoNs (RASPUTIN)

ESO Garching, October 13 - 17, 2014

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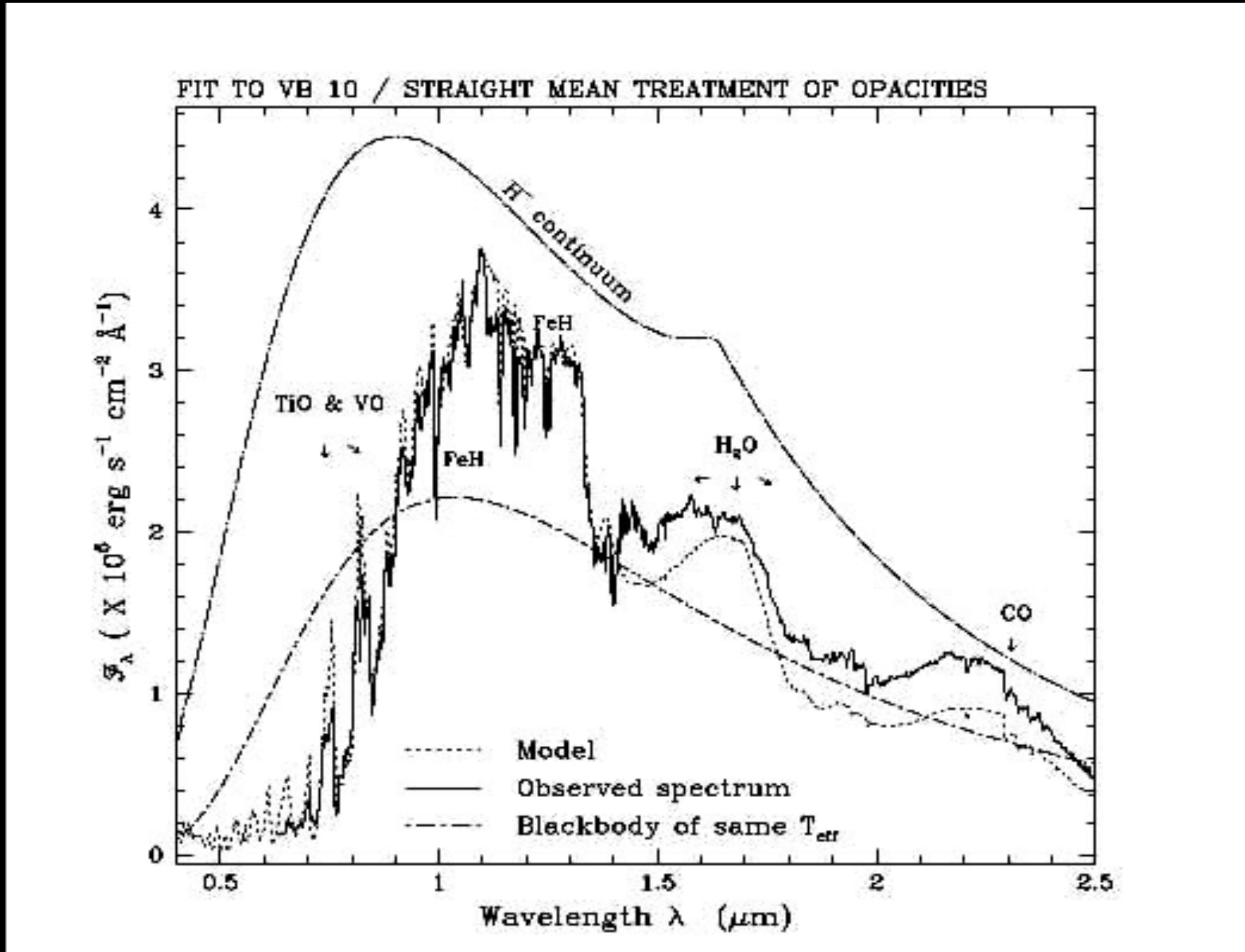
ENS DE LYON



Spectral Energy Distribution (SED) of a typical Very Low Mass star (VLMs) of effective temperature (T_{eff}) similar to that of a young brown dwarf (few million years). The SED of de dM8e VB10 (full line) is compared to a model (AH95, dotted lines) based on band model opacities. The spectrum where all discrete opacities (atomic & molecular line transitions) are omitted (dot-dashed), and the blackbody SED of same T_{eff} indicates the importance of "non-grey" opacities.

PHOENIX

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

- 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 with 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 64 types of grains
- Cloud Model based upon Rossow (1978) timescales (sedimentation, condensation)
- Supersaturation computed from chemical equilibrium tables.
- Mixing from Radiative HydroDynamic (RHD)

First Successful Model Atmosphere Grid of VLMs: NextGen

T_{eff}:

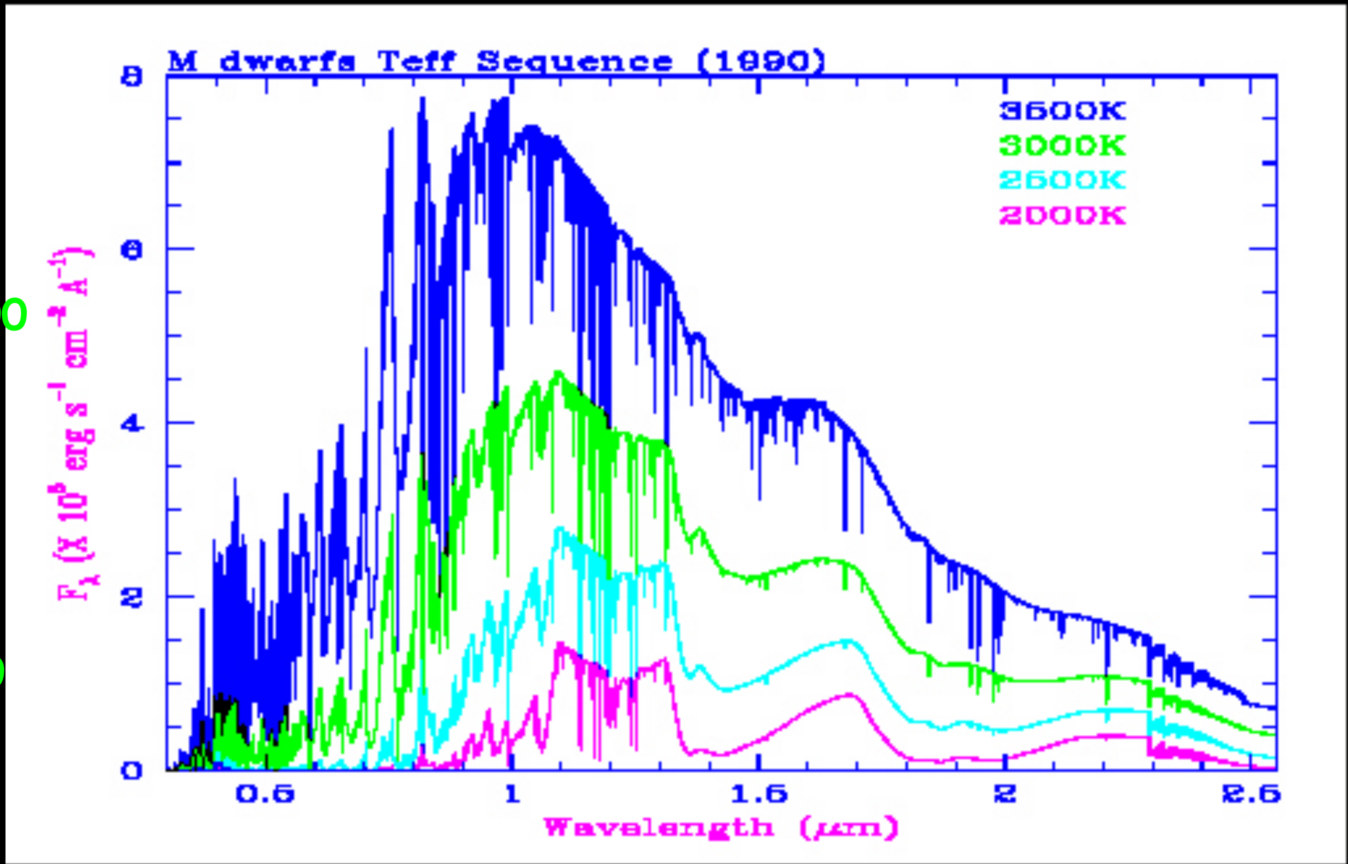
1500-10,000K

Logg:

3.5 - 6.0

[M/H]:

0.3 - -4.0



Spectral sequence of VLMs according to Allard et al. (1990, 1995, 1997) et Hauschildt et al. (1999).

First atmosphere+interior models

THE ASTROPHYSICAL JOURNAL, 446:L35–L38, 1995 June 10

NEW EVOLUTIONARY TRACKS FOR VERY LOW MASS STARS

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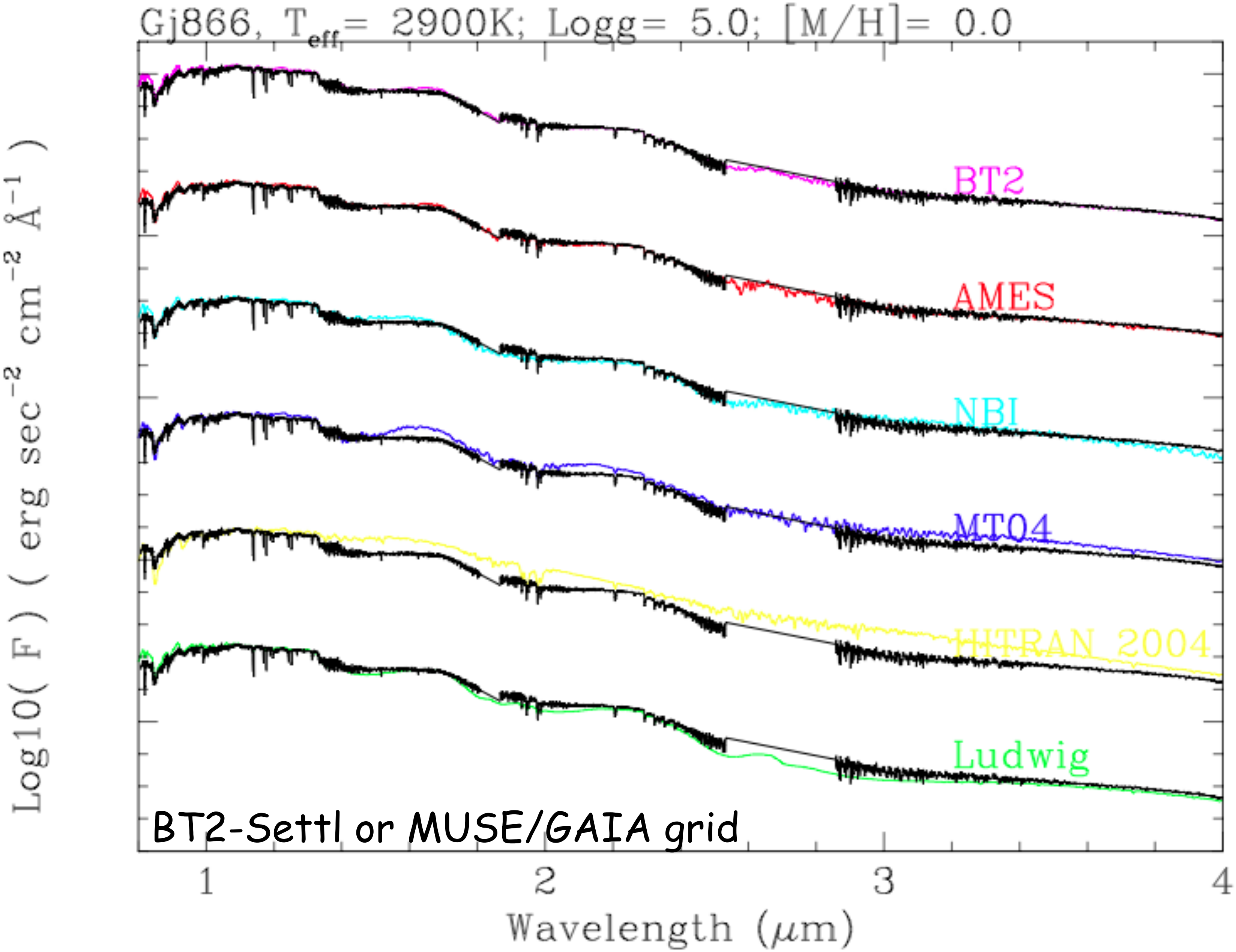
ABSTRACT

We present new evolutionary calculations for low-mass and very low mass M dwarfs, for a metallicity range $-2 \le [M/H] \le 0$, down to the hydrogen-burning minimum mass ($0.07 < M/M_{\odot} < 0.6$). We use the most recent atmosphere models calculated by Allard & Hauschildt (1995), based on *synthetic* spectra at finite metallicity, and gray atmosphere models based on Alexander & Ferguson (1994) Rosseland opacities.

Comparisons are made with observational results down to the bottom of the main sequence, for different metallicities, in magnitude-color and color-color diagrams. We find excellent agreement between theory and observations over the whole characteristic temperature/luminosity range. This enables us to determine the mass of the faintest objects observed, which is found to be $m_{\rm lim} \approx 0.085\ M_{\odot}$ for $[M/H] = 0$ and -0.5, and $m_{\rm lim} = 0.09\ M_{\odot}$ for $[M/H] = -1.5$, for an age of 10 Gyr.

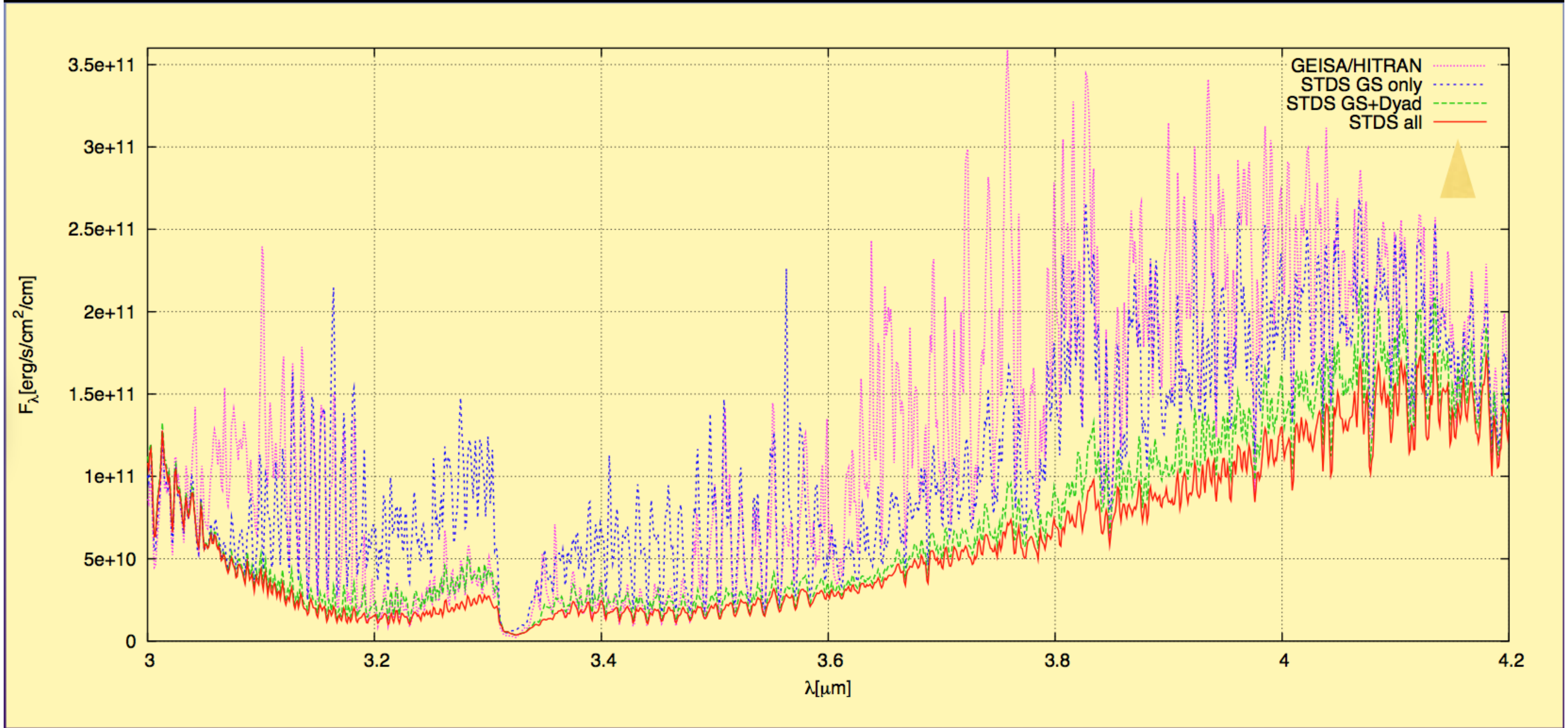
We also examine the effect of the age, the metallicity, and the outer boundary conditions on the evolution.

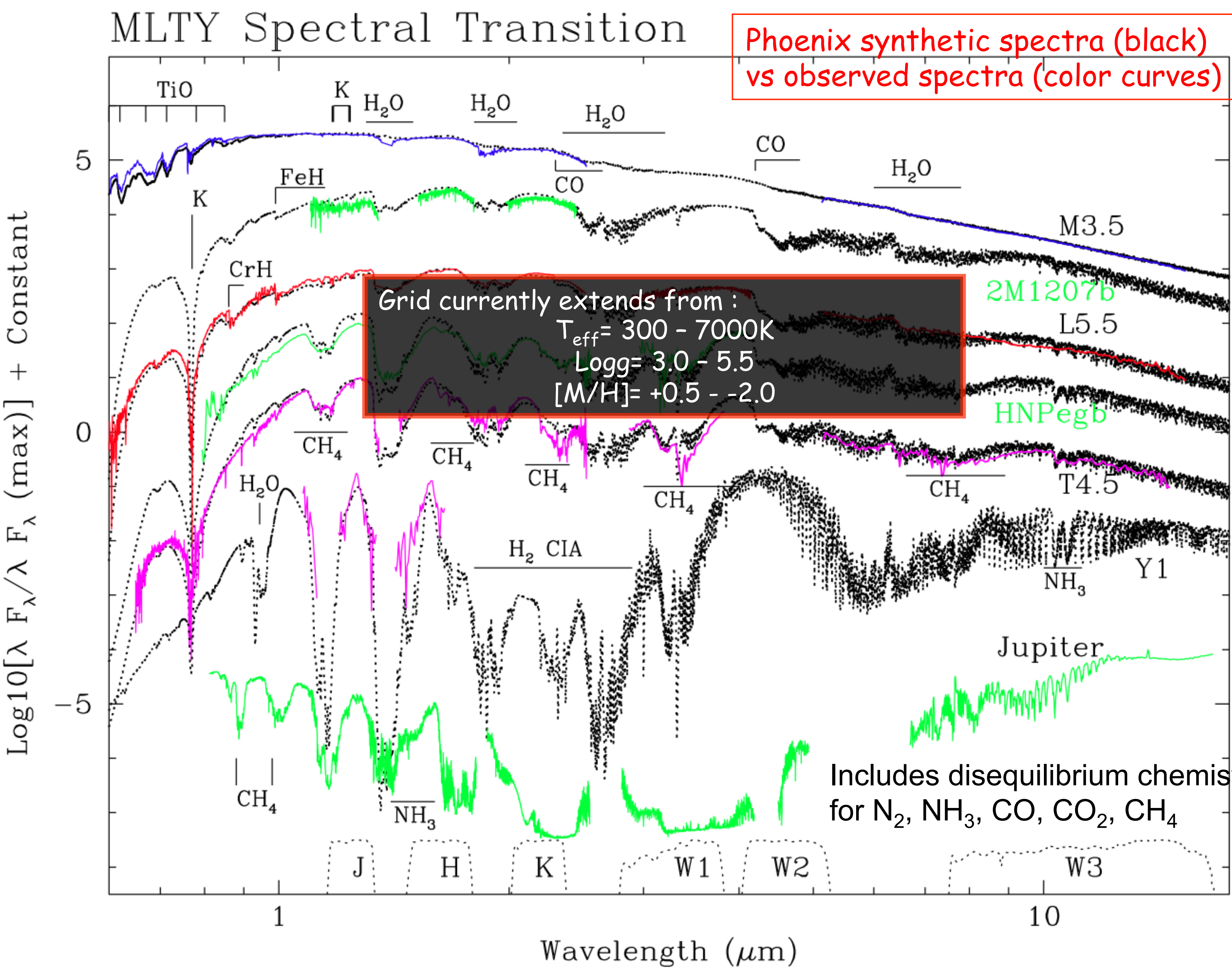
Subject headings: stars: low-mass, brown dwarfs — stars: evolution — stars: late-type


Gj866, T_eff = 2900K; Logg= 5.0; [M/H]= 0.0
BT2
AMES
NBI
MT04
HITRAN_2004
Ludwig
BT2-Settl or MUSE/GAIA grid
Log10(F) (erg sec^-2 cm^-2 Å^-1)
Wavelength (μm)
1
2
3
4

Molecular Blanketing: CH_4

- 30 Mio. Lines computed with the STDS program (U. Bourgogne – 2013 update: 80 Mio)
- Vibrational and rotational states up to ~ 8000 cm^{-1}
- Completeness : ~ 50% (mid-IR) – 10% (H band) – 0% (Y/J band)

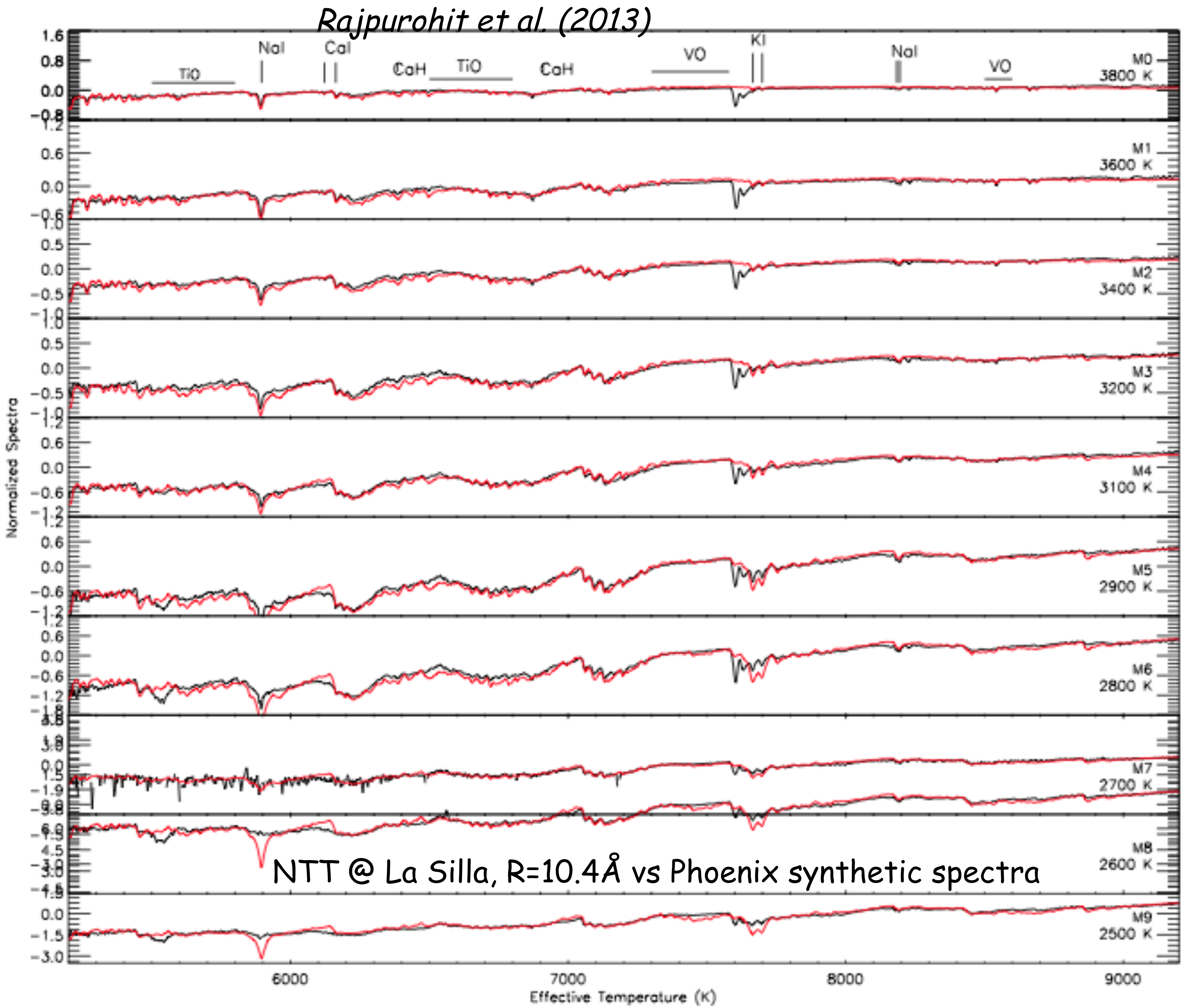




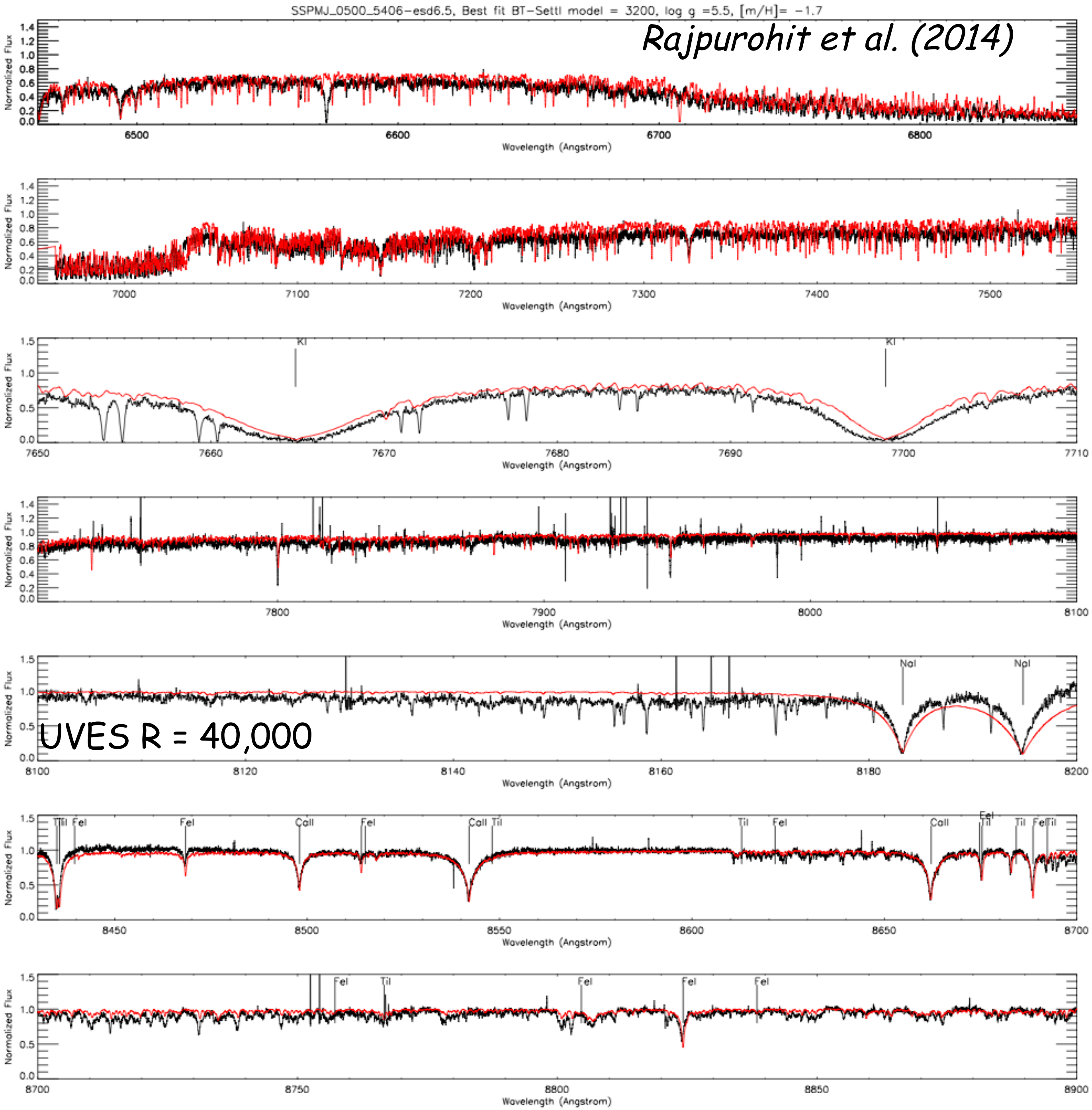
Phoenix synthetic spectra (black) vs observed spectra (color curves)

Grid currently extends from :
T_{eff}= 300 – 7000K
Logg= 3.0 – 5.5
[M/H]= +0.5 – -2.0

Includes disequilibrium chemistry for N_2, NH_3, CO, CO_2, CH_4



Rajpurohit et al. (2013)
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
NTT @ La Silla, R=10.4Å vs Phoenix synthetic spectra

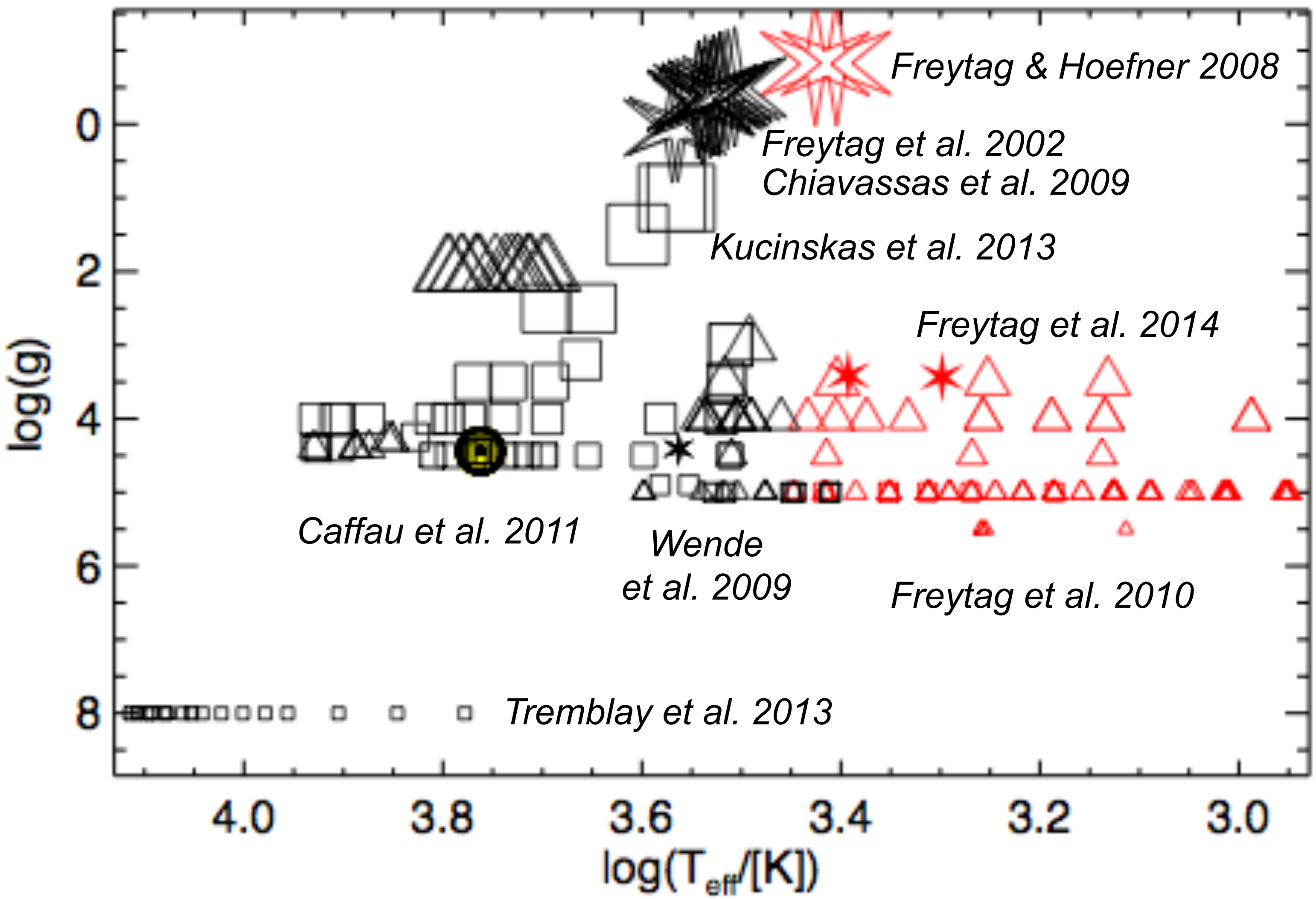

SSPMJ_0500_5406-esd6.5, Best fit BT-Settl model = 3200, log g =5.5, [m/H]= -1.7
Rajpurohit et al. (2014)
UVES R = 40,000
Normalized Flux
Wavelength (Angstrom)
KI
NaI
CaII
FeI
TiI

What model?

- **Classical (1D & static)** : PHOENIX, MARCS, etc.

(NLTE, detailed composition i.e. nb. of atoms, ions, molecules, dust grains taken into account, etc.)
  - Synthetic Spectra and Colors → atmospheric and structural parameters
  - Thermal Structures → classical interior and evolution models
- **Classical (3D & static)**: PHOENIX-3D, LinFor3D, etc.
  - Extreme High-Resolution Spectra → Line by line Abundance Determination
- Local **2-3D local RHD** : CO5BOLD, Stagger, etc.
  - Validation of the 1D thermal structure
  - Calibration of the Mixing Length (for the atmosphere)
  - Determination of the velocity field → disequilibrium chemistry
  - Determination of the diffusion coefficient (e.g. dust diffusion)
- **Global RHD with rotation** : CO5BOLD (but many others without atmosphere).
  - Influence on the thermal structure, spectrum, abundances
  - Calibration of the Mixing Length (for the interior)
  - Global velocity field → differential rotation
  - Surface inhomogeneities → brown dwarf and exoplanet variability studies
- **Global MHD** : MURaM, Bifrost, CO5BOLD, Stagger, etc.
  - Influence on the thermal structure, spectrum, abundances
  - Calibration of the Mixing Length (for the interior)
  - Study of the dynamo mechanism
  - Small-scale inhomogeneities (bright points...)

The CO⁵BOLD GRID

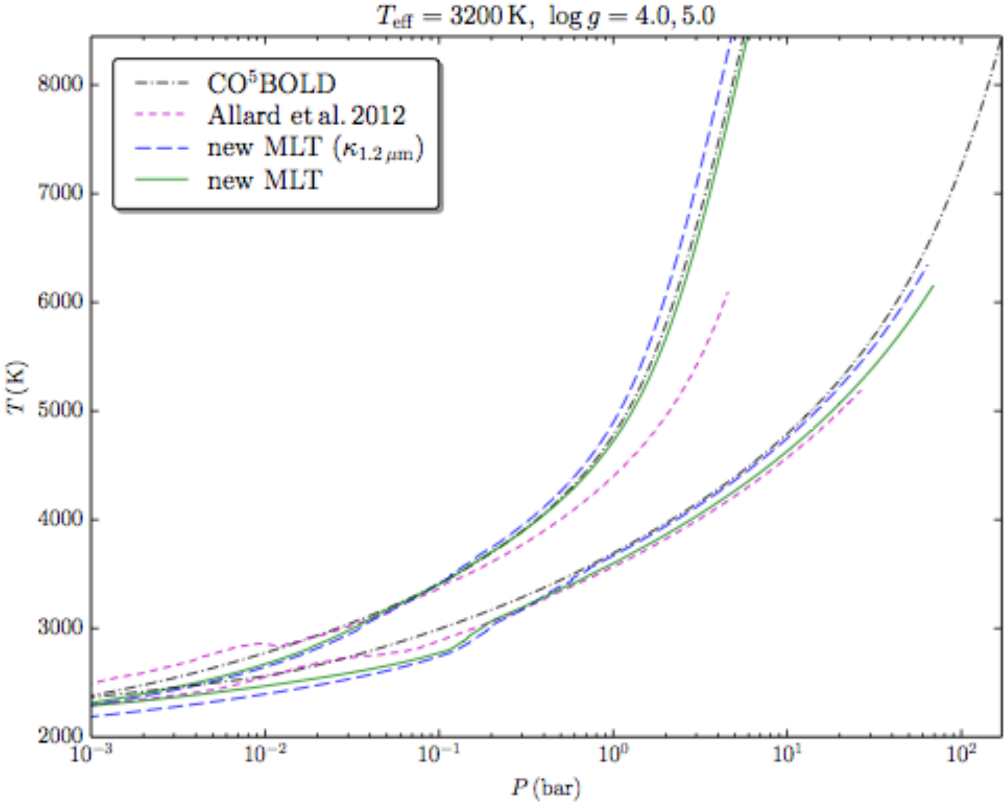


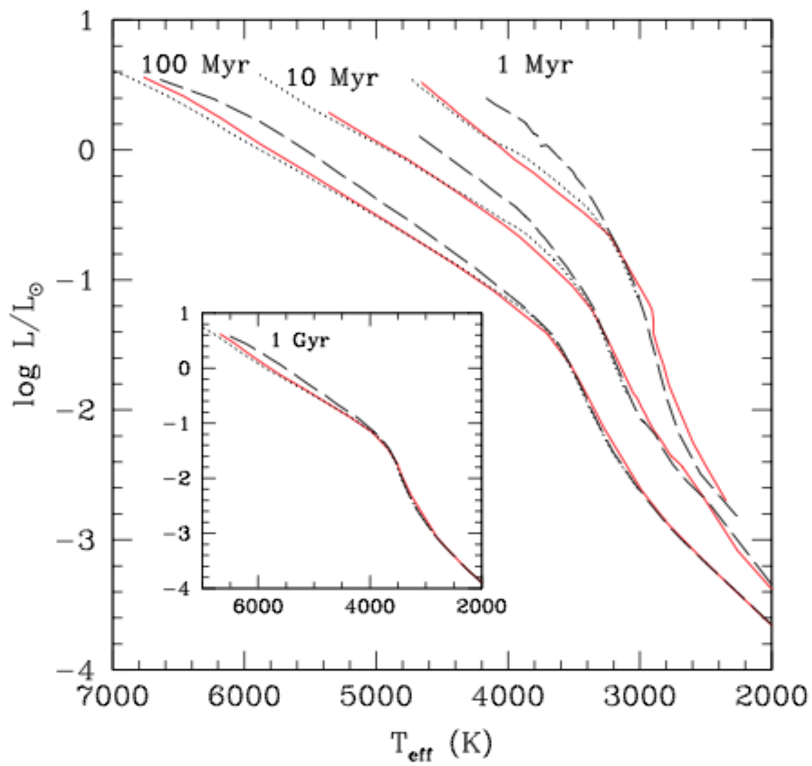
New evolution tracks

Table 1. Characteristics of previous and present atmosphere models.

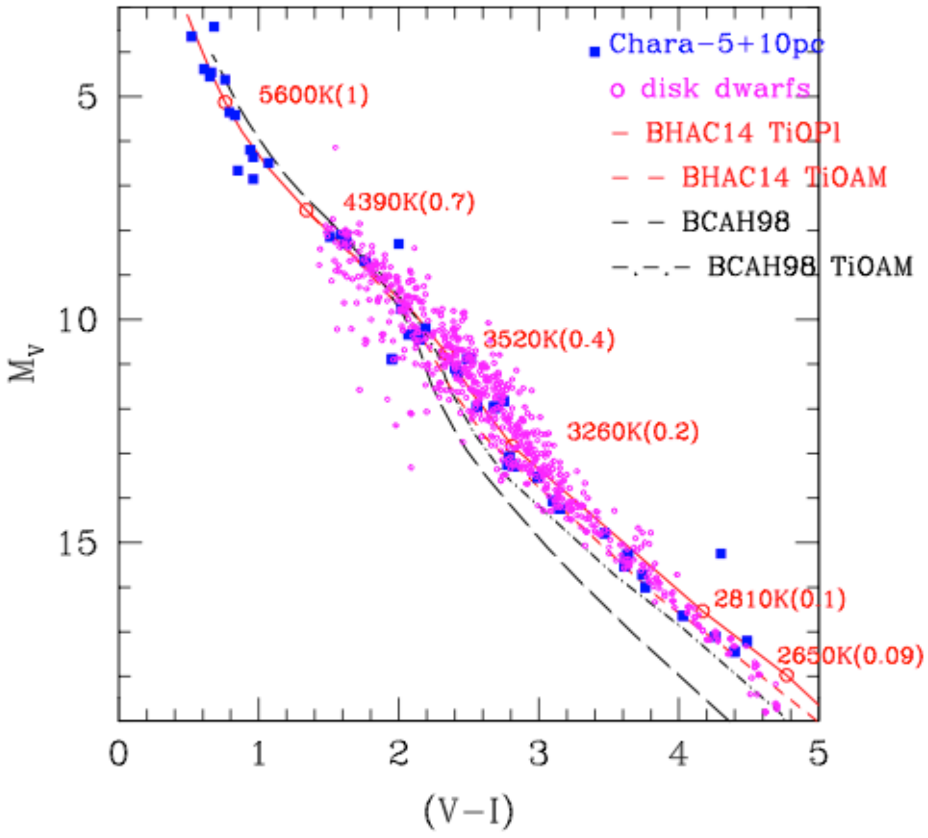
Models	Abundances	TiO	H_2O	MLT variant	l_{mix}/H_P	κ in τ_e
NextGen[1]	G93[3]	J94[5]	M94[8]	ML1	1	$\kappa_{1.2\mu m}$
Dusty/Cond[2]	G93[3]	S98[6]	PS97[9]	$f_3 = 24$, (f_4, f_5) from Eq. 2	1	$\kappa_{1.2\mu m}$
Allard et al. (2012a)	C11[4]	Pl98[7]	B06[10]	$f_3 = 24$, (f_4, f_5) from Eq. 2	2	$\kappa_{1.2\mu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

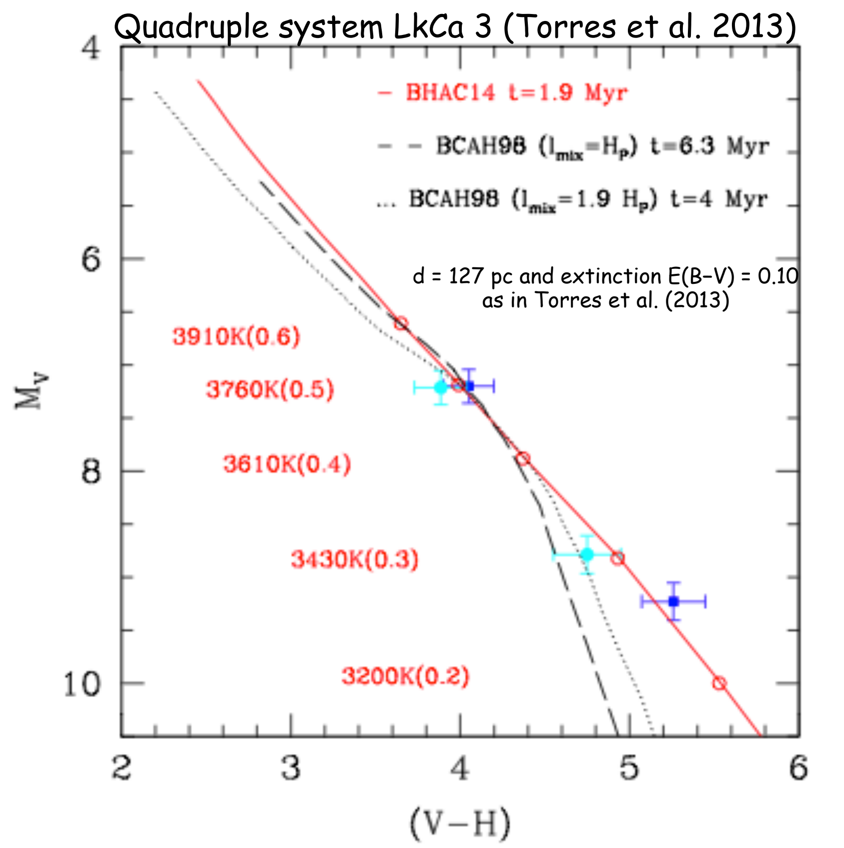
[1] Hauschildt et al. (1999) - [2] Allard et al. (2001) - [3]Grevesse et al. (1993) - [4]**DH: Asplund et al. (2009)**+Caffau et al. (2011)
[5]Jorgensen (1994) - [6]Schwenke (1998) - [7]Plez (1998) - [8]Miller et al. (1994) - [9]Partridge & Schwenke (1997) -
[10]Barber et al. (2006) - [11] Based on RHD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





New BT-Settl Interior Models

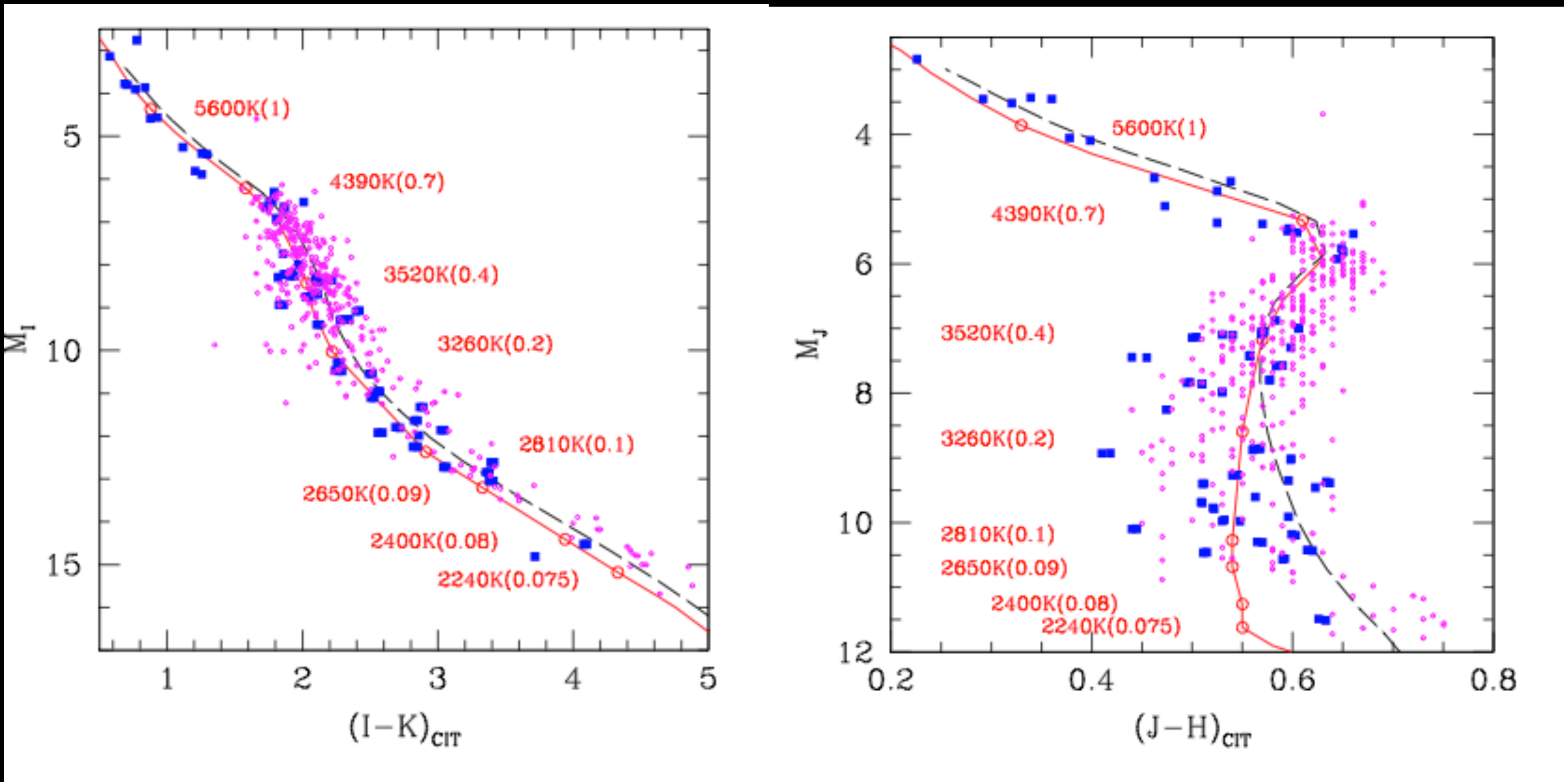


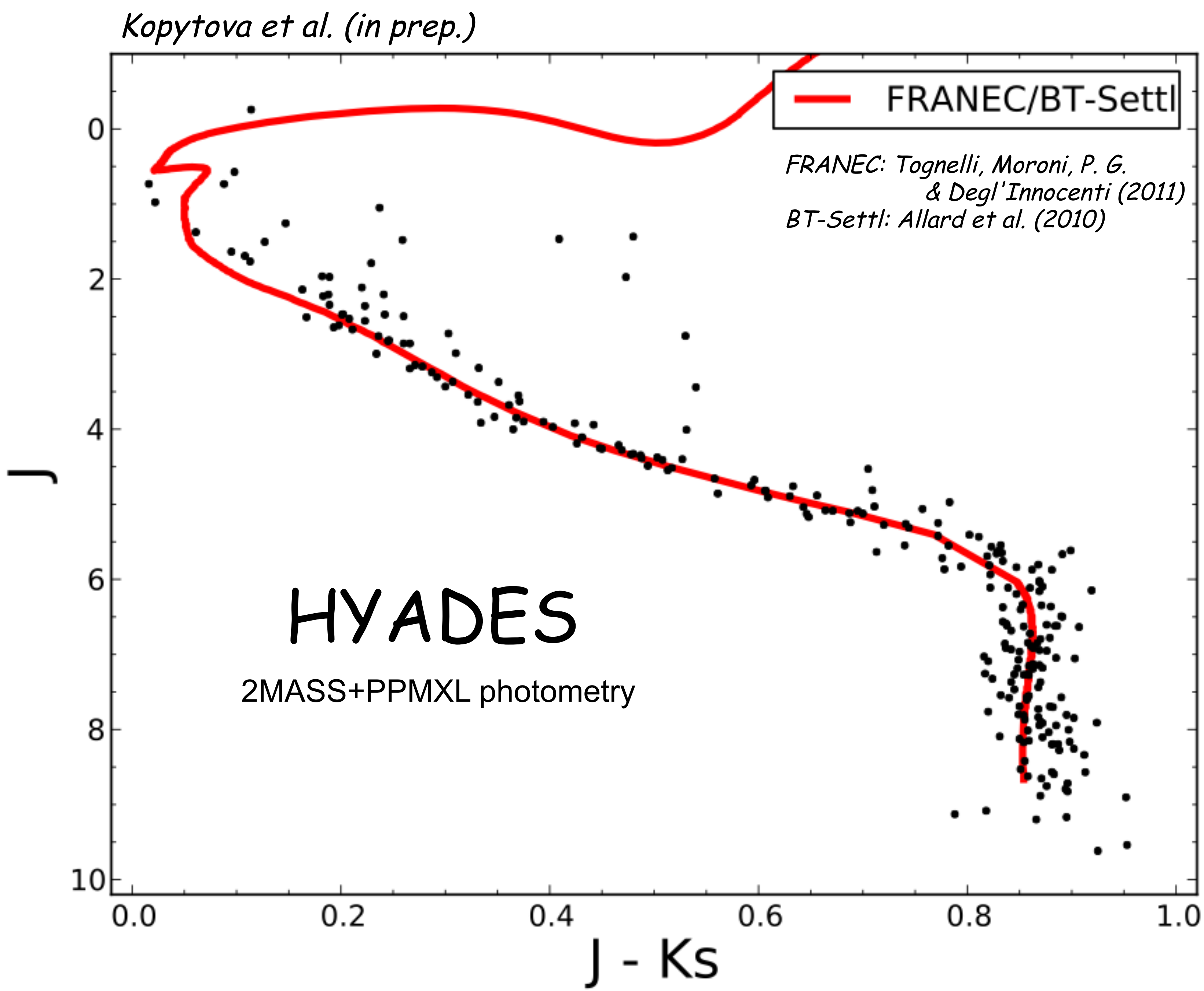


Incertainties on TiO opacities remain:
AMES TiO less accurate but more complete
vs Plez 2008 TiO more accurate but not
complete enough

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

New BT-Settl Interior Models





Kopytova et al. (in prep.)
FRANEC/BT-Settl
FRANEC: Tognelli, Moroni, P. G.
& Degl'Innocenti (2011)
BT-Settl: Allard et al. (2010)
HYADES
2MASS+PPMXL photometry
J
J - Ks
0
2
4
6
8
10
0.0
0.2
0.4
0.6
0.8
1.0

Scaled-down RHD simulation of an M dwarf

Work in progress!

T_{eff}= 3600K,
logg= 3.5,
[M/H]= 0.0

Scale factor= 1/100

No rotation yet

At term:
Calibration of the ML for the effects of rotation

And yet later:
Calibration of the ML for the effects of rotation AND magnetic field

Comparative Cloud Model Construction

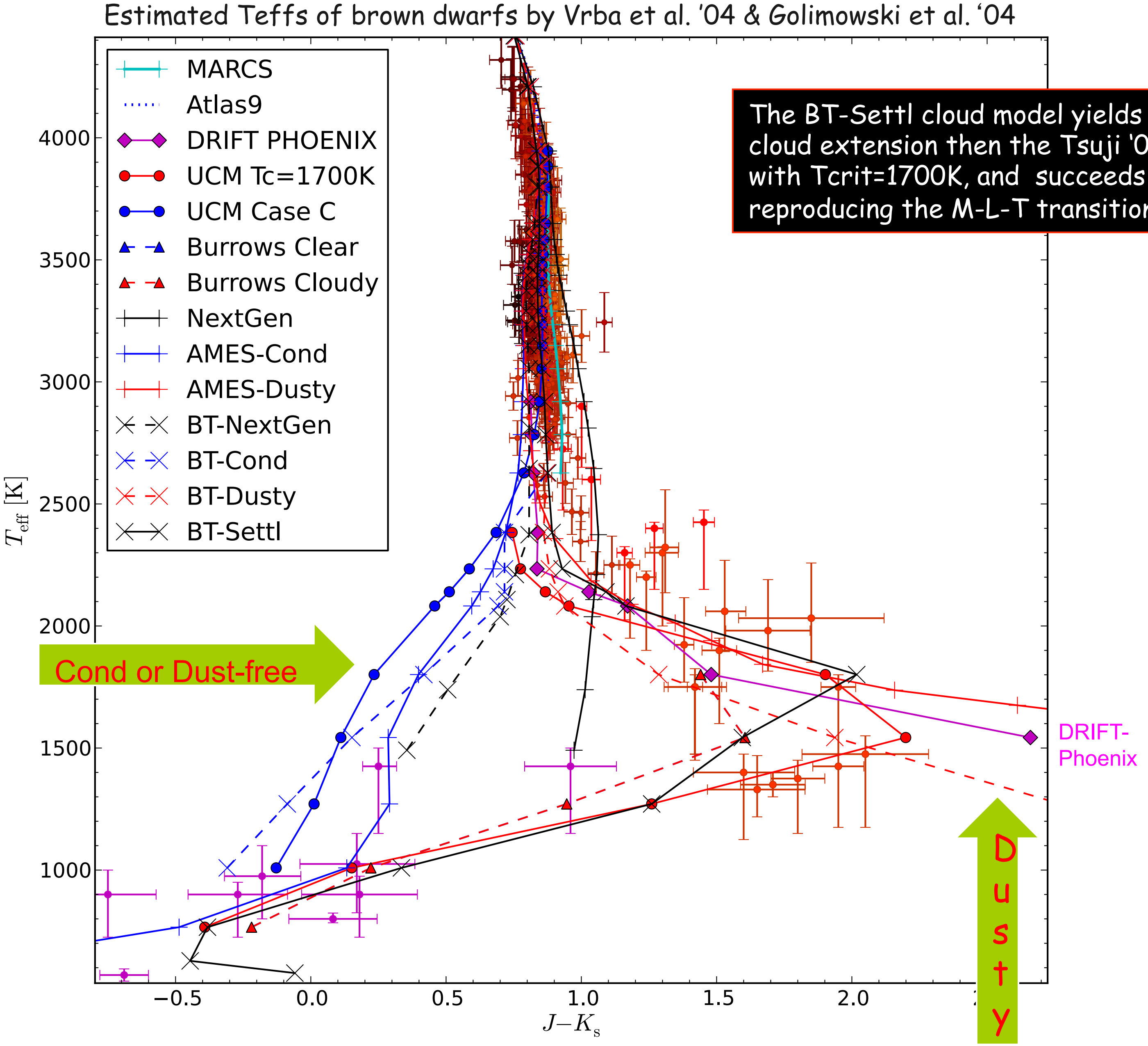
Parameter-free models

	Phenomenological model: PHOENIX BT-Settl (Allard et al. 2003,2012)	Microphysical model: DRIFT-PHOENIX (Helling et al. 2008)
Seed	= CE (iteration with cloud model*)	= TiO_2
Nucleation	= from cosmic rays (Tanaka 2005)	= DRIFT or 1D hydro (Gail 1984)
Condensation	= Rossow (1978)	= Gail 1984
Coalescence	= Rossow (1978)	= Gail 1984
Coagulation	= Rossow (1978)	= Gail 1984
Sedimentation	= Rossow (1978)	= Gail 1984
Supersaturation	= P_{VS}/Pgas using CE tables for P_{VS}	= Gail 1984
Advective Mixing	= from 2D RHD simulations	= from 2D RHD simulations (without overshoot)
Composition	= 64 types of condensates	= 5 types of condensates
Optical ctes	= pure condensates (Jena database)	= composite optical ctes
Model solved	= Updraft model with solar lowest layer	= up to down (stationary solution of moment equations)

* Cooling history of the gas is preserved

In effect, there isn't much difference between up-to-down and updraft models because grains do not DRIFT or settle through much (within one layer only!) under the conditions of M-L type dwarf atmospheres (Wende, private communication).

Comparing models from different authors

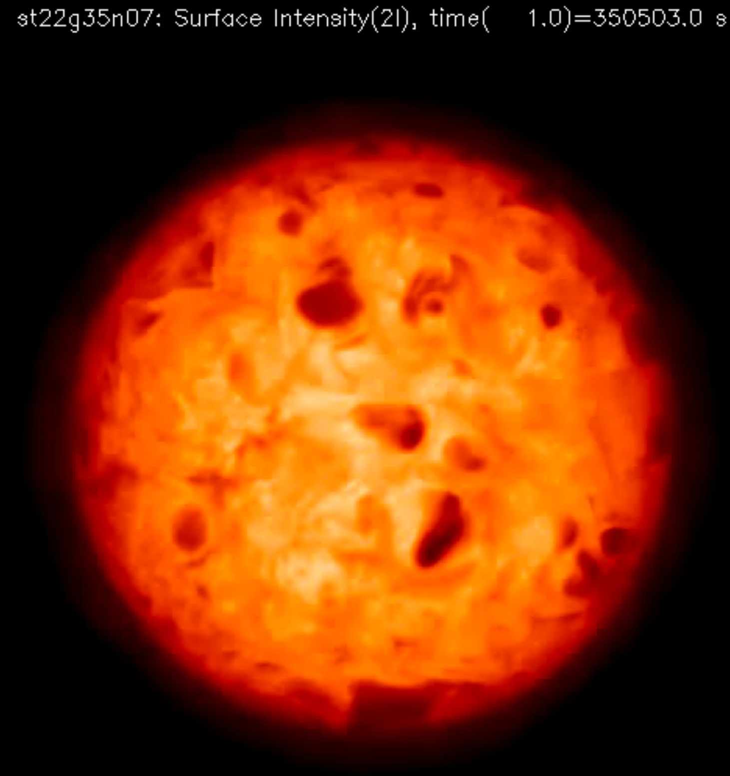


The BT-Settl cloud model yields similar cloud extension then the Tsuji '02 model with Tcrit=1700K, and succeeds globally in reproducing the M-L-T transition.

Global RHD simulations

Freytag, Schaffenberger & Allard 2014 (in prep.)

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



➔

Jupiter

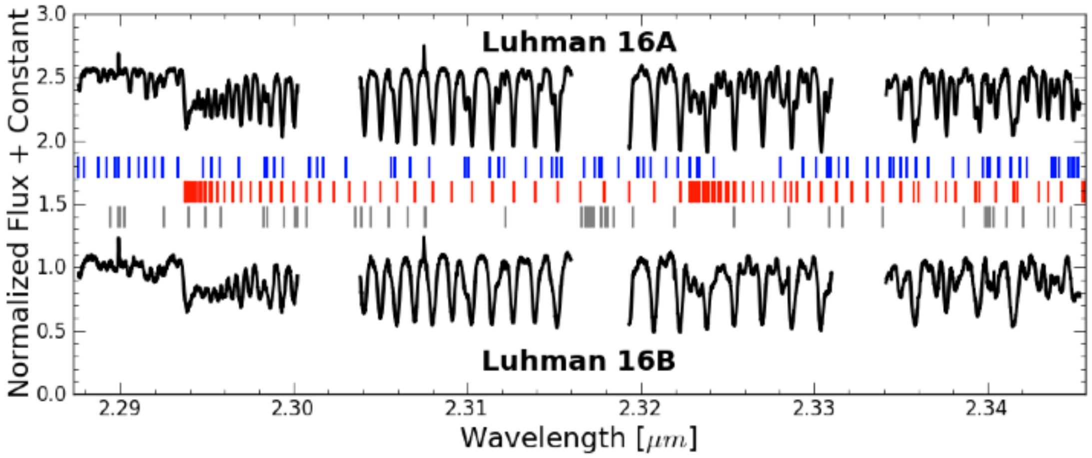
However radius scaled by a factor 20 !
Improvement expected with MPI 2015

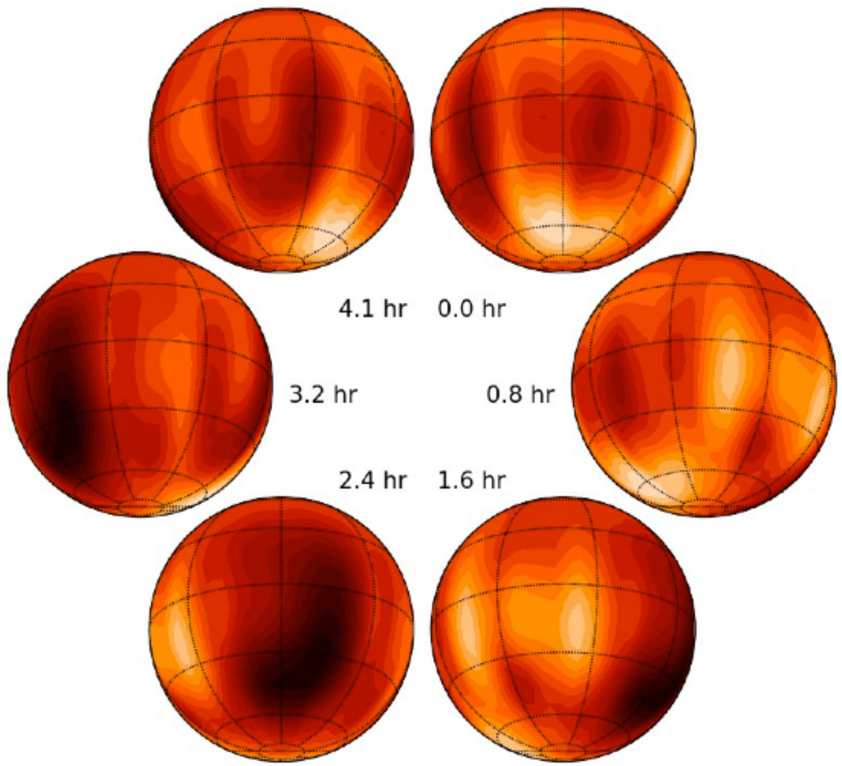
Surface inhomogeneities revealed by Doppler imaging tomography!

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.





Global Circulation Model

Case of an L/T dwarf
(T_{eff} of ~650 to 1150K)

Showman & Kaspi (2013)

The rotation significantly modifies the convective properties. The interaction of convection with the overlying, stably stratified atmosphere will generate a wealth of atmospheric waves, and we argue that, just as in the stratospheres of planets in the solar system, the interaction of these waves with the mean flow will lead to a significant atmospheric circulation at regional to global scales.

Fig. 7. Snapshots at different times of the temperature perturbations at 1 bar in a single model with rotation period of 10 hours.

Temperature perturbations are deviations of temperature from the reference state, in K. Time separation between frames is 4.8 hours.

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:

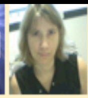
✓ stars

✓ 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 T_{eff} > 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 T_{eff} > 1700 K	Allard et al. '01 Chabrier et al. '00
• AMES-Cond	Same as AMES-Dusty with dust opacities ignored, "valid" for T_{eff} < 1400 K	Allard et al. '01 Baraffe et al. '03
• AMES-Cond-GAIA	Available down to T_{eff} = 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

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Web Simulator

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

ONLINE in Jan. '15 !

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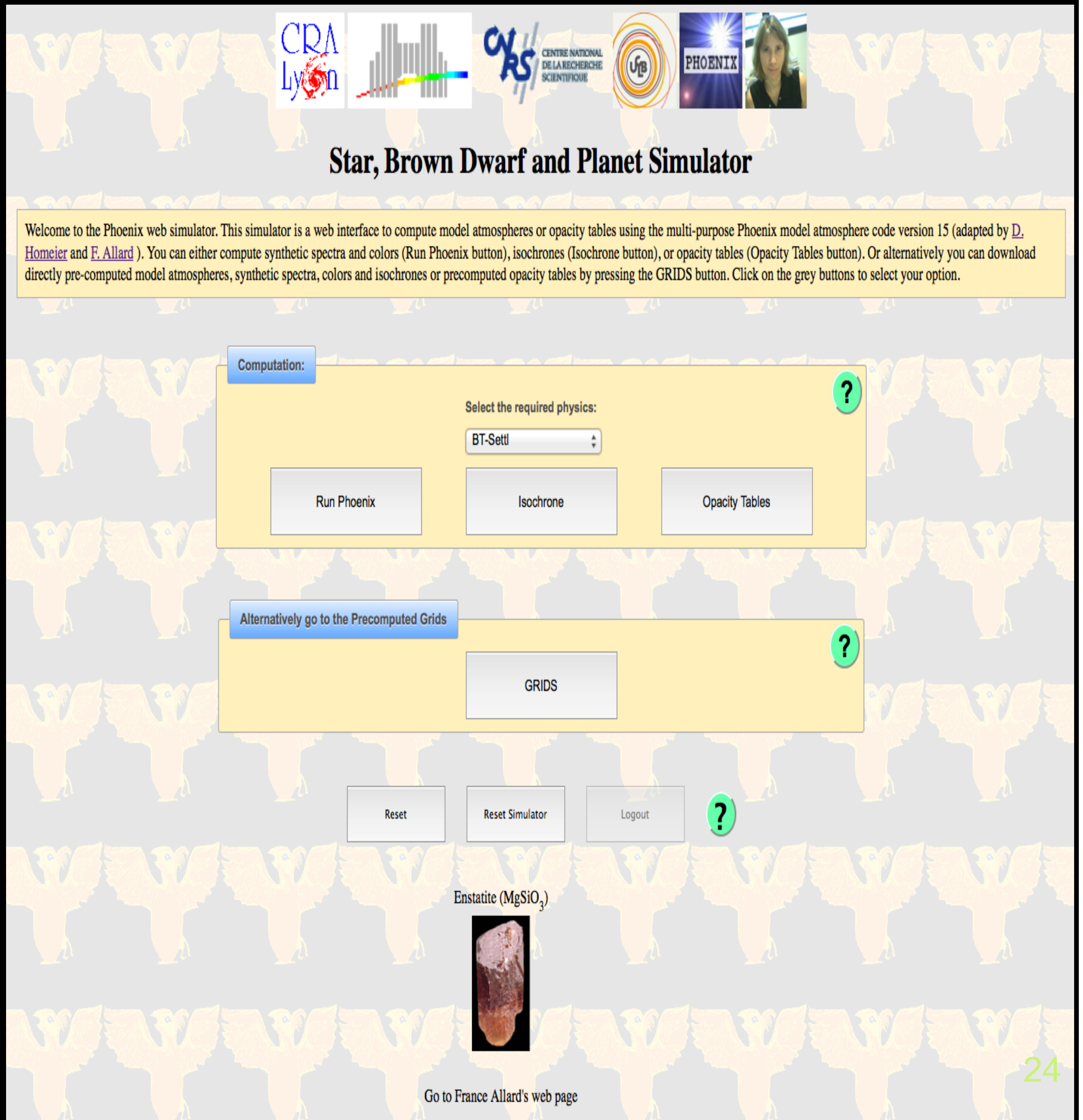

M-L transition: Comparing models from different authors