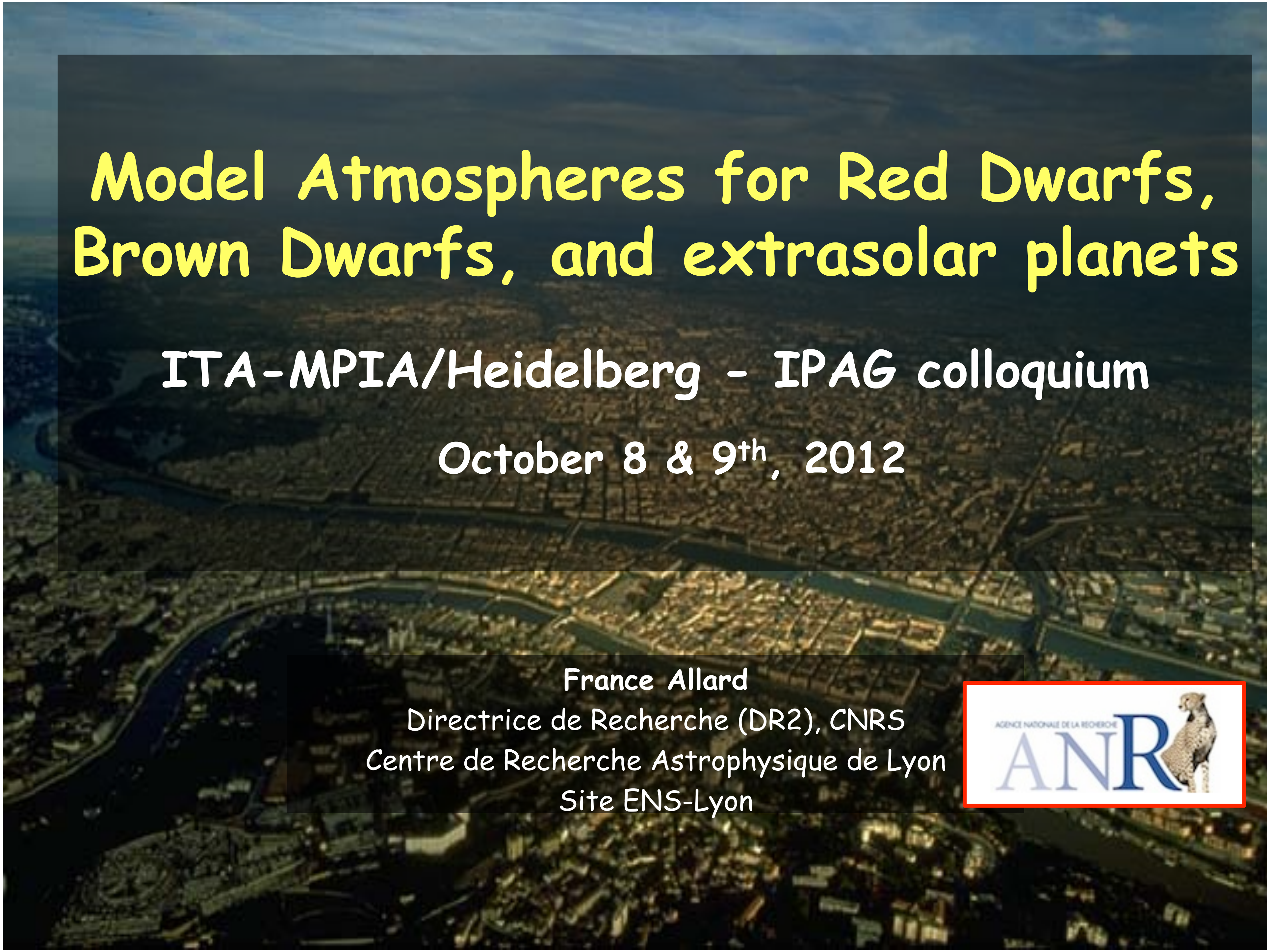


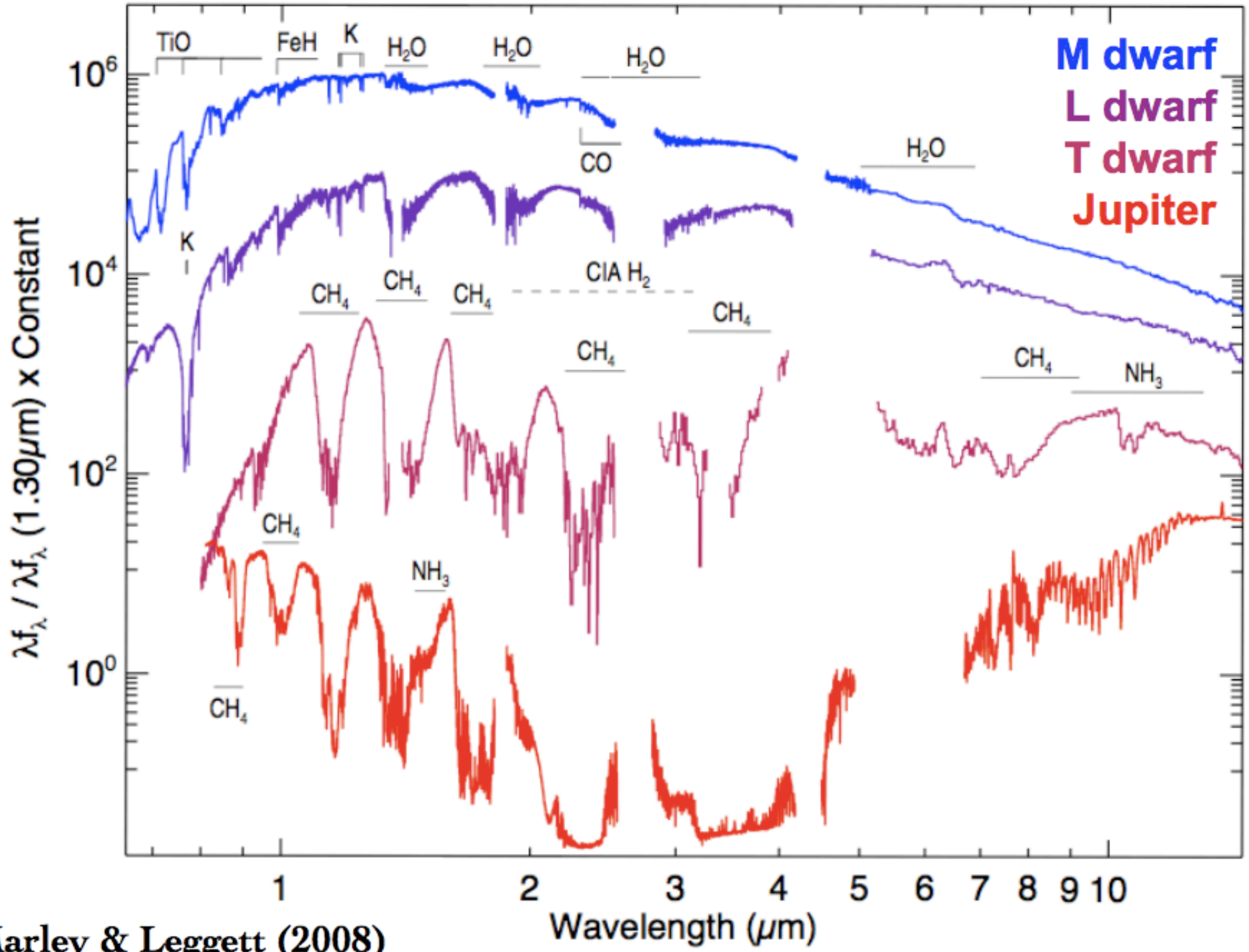
Model Atmospheres for Red Dwarfs, Brown Dwarfs, and extrasolar planets

ITA-MPIA/Heidelberg - IPAG colloquium

October 8 & 9th, 2012

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

The spectral transition from stars, via brown dwarfs, to planets



$T_{eff} \approx$

3000 K

1700 K

600 K

125 K

Coolest BD known today

370 K !!

Marley & Leggett (2008)

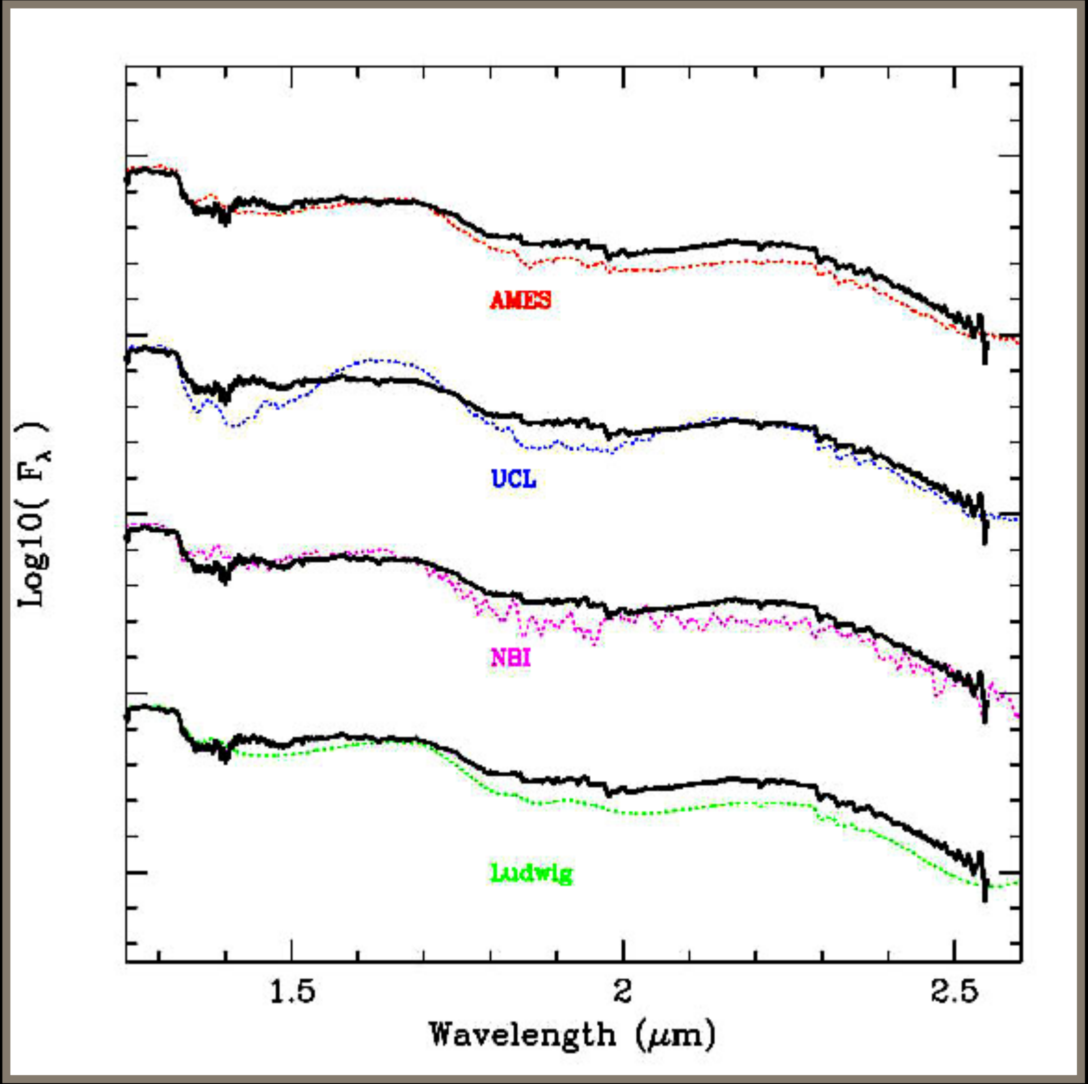
data from Cushing et al. (2005,2007)

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 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)

Synthetic spectra using various sources of water vapor opacities from 1990-2011



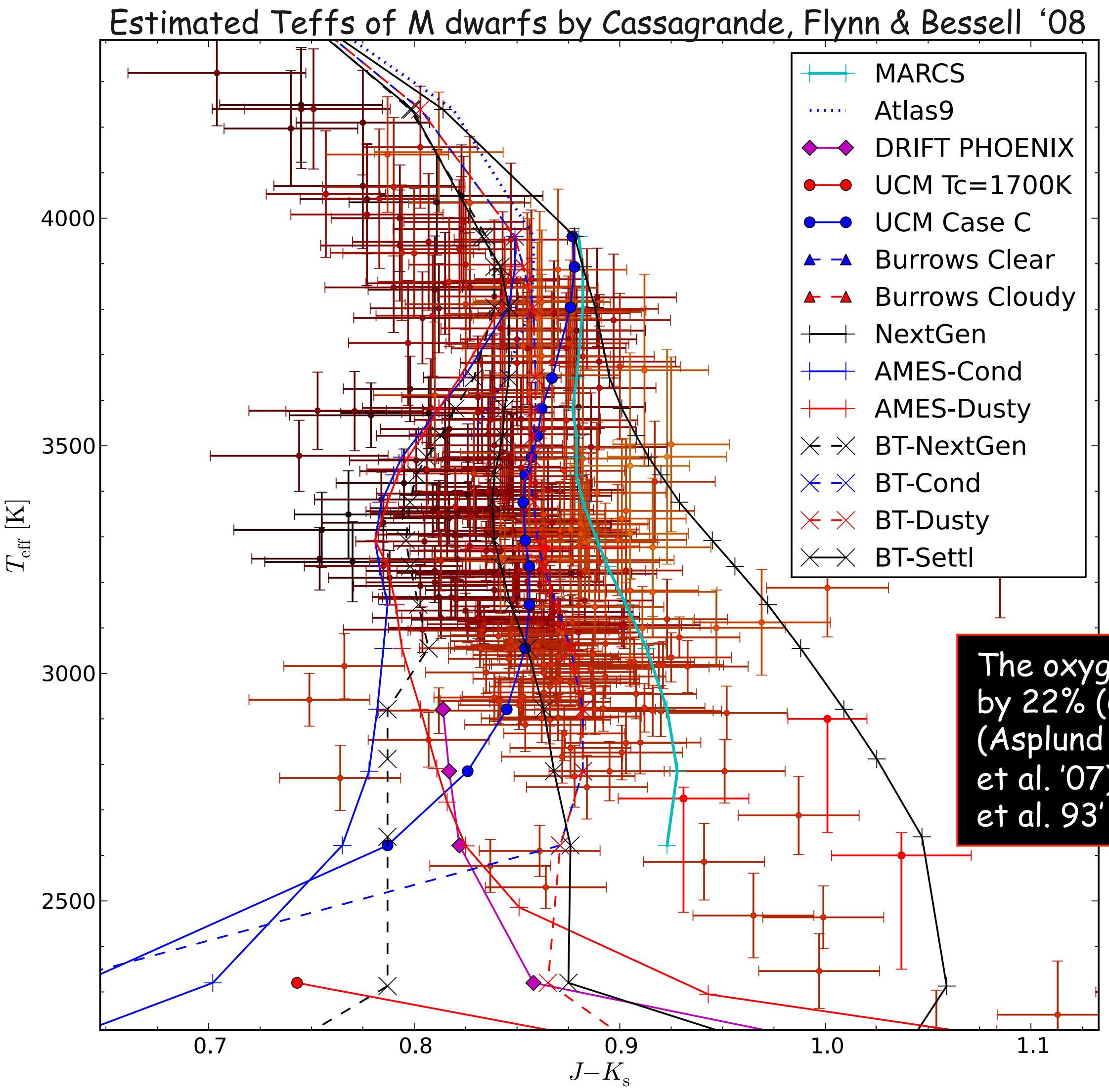
Dusty/Cond 2001

NextGen 1997-99

Test 1994

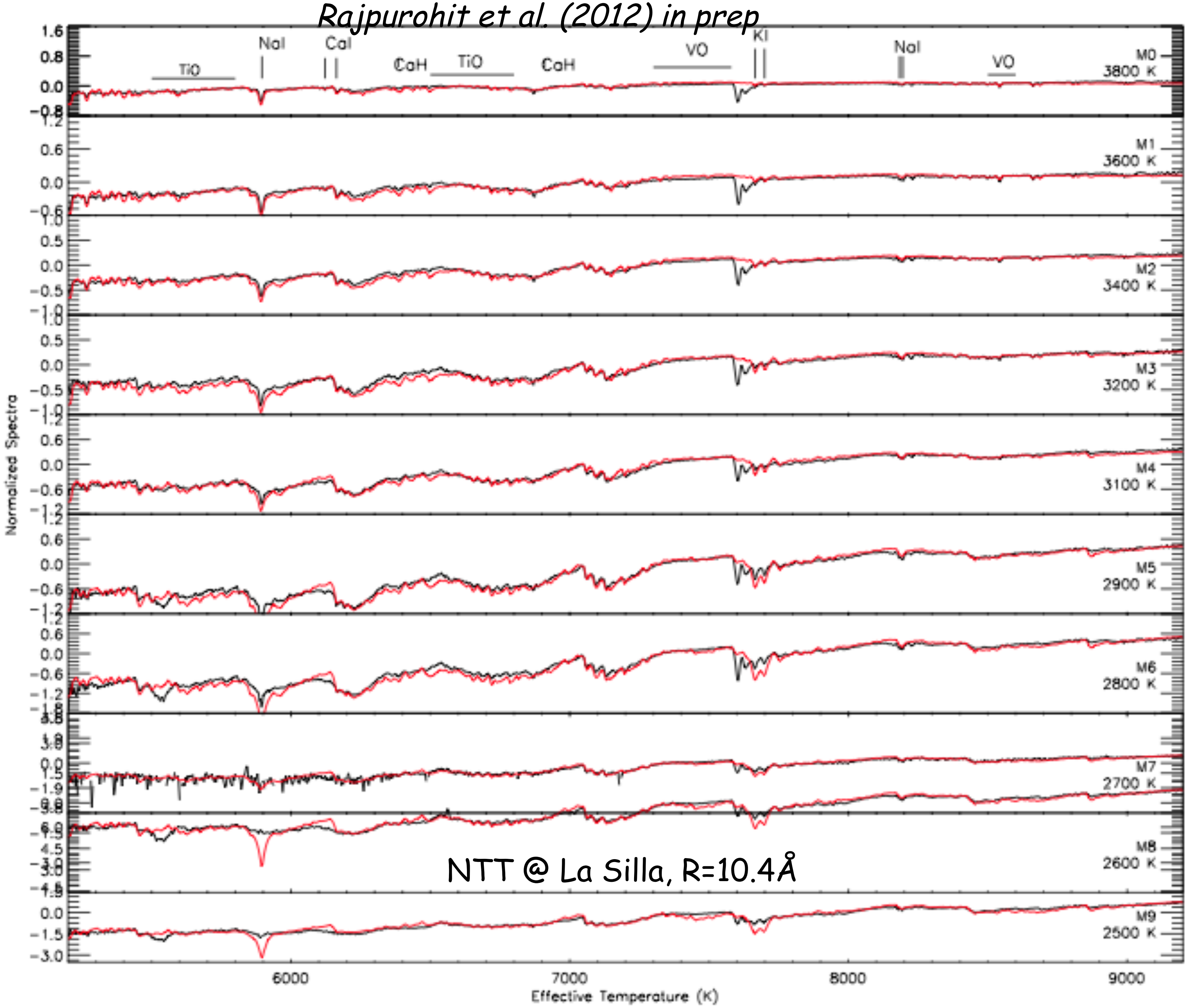
Base 1990-95

Comparing models from different authors



The oxygen solar abundance is reduced by 22% (Caffau et al. '11) and 34% (Asplund et al. '09) to 39% (Grevesse et al. '07) compared to the Grevesse et al. 93' value.

Rajpurohit et al. (2012) in prep



NTT @ La Silla, R=10.4Å

Cloud Pionneering Work

- Lewis (1969): An ’’updraft” model according to which the excess vapor from the saturation is left where it condenses (fairies):
  - Vitesse d’ “updraft” = sedimentation velocity
  - No treatment of grain sizes
- Rossow (1978): Has developed characteristic timescale as a function of particle size for the main microphysical processes, and the intersections of these characteristic timescale give an estimate of the mean size of grains
  - No treatment of the condensed mass (no nucleation)
  - Many explicit suppositions concerning the efficiency of the super-saturation, and for the coagulation, between other
- Lunine (1989, 1999): Variations on the previous models
- ….

- Allard et al.(2003, 2012): Variations on the Rossow model

Cloud physics as included in model atmospheres

- Mie equations are solved for full spherical grains

Phenomenological model

Phoenix BT-Settl (Allard et al. 2003,2012)

- Seed = CE (iteration with cloud model)
- Nucleation = from cosmic rays (Tanaka 2005)
- Condensation = Rossow (1978)
- Coalescence = Rossow (1978)
- Coagulation = Rossow (1978)
- Sedimentation = Rossow (1978)
- Supersaturation = P_{VS}/Pgas using CE tables for P_{VS}
- Advective Mixing= from RHD simulations
- Composition = 55 types of condensates
- Optical ctes = pure condensates (Jena database)
- Model solved = down to up assuming solar lowest layer

Microphysical model

DRIFT-PHOENIX (Helling et al. 2008)

- = TiO_2
- = DRIFT or 1D hydro (Gail 1984)
- =
- =
- =
- =
- =
- = from RHD simulations
- = 5 types of condensates
- = composite optical ctes
- = up to down (stationary solution of moment equations)

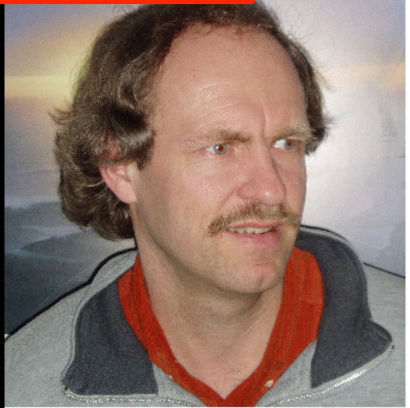
``COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions with L=2,3"

Bernd Freytag, IR2, ENS-Lyon
http://perso.ens-lyon.fr/bernd.freytag

CO5BOLD

R(M)HD simulations

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

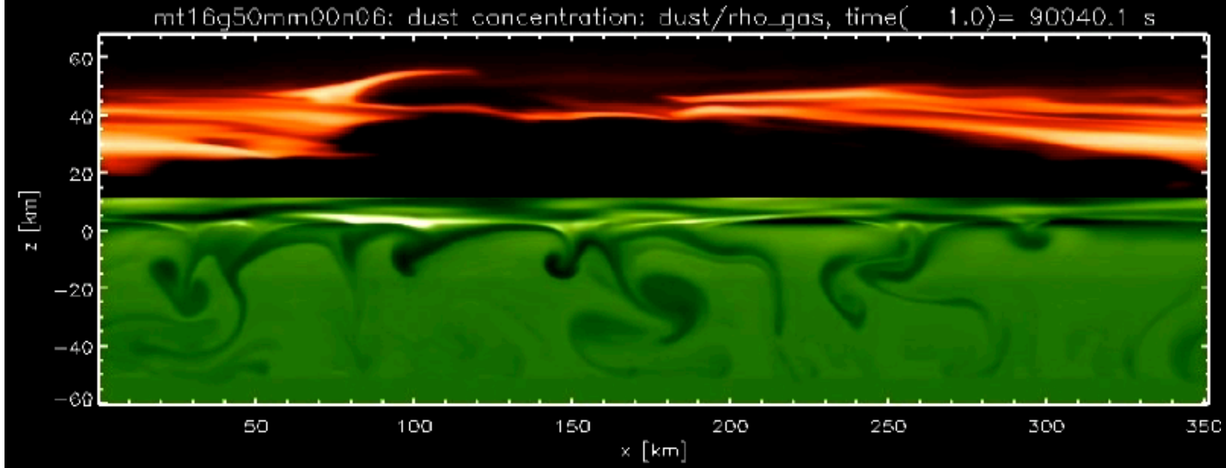


Matthias Steffen, AIP
Potsdam, Germany
http://www.aip.de/~mst/

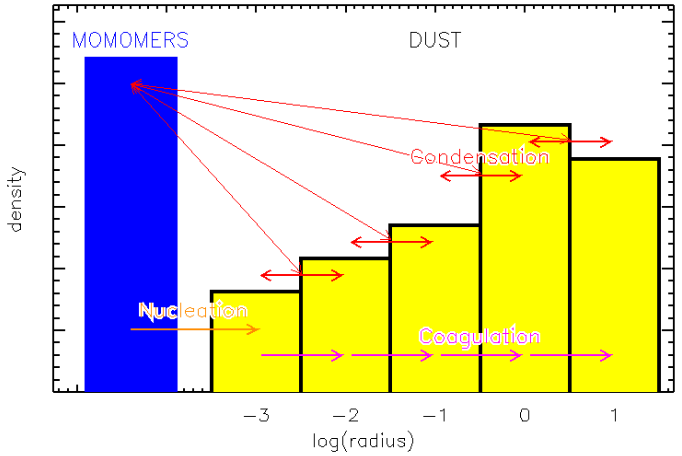
- General: 2D/3D Cartesian box, parallelized with OpenMP
- Magneto-Hydrodynamics (compressible):
  - ✓ HYD module: approximate Riemann solver (Roe type)
  - ✓ MHD module: HLLE solver
- Radiation transport:
  - ✓ Module for global "Star-in-a-Box" models (central potential)
  - ✓ Module for local "Box-in-a-Star" 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

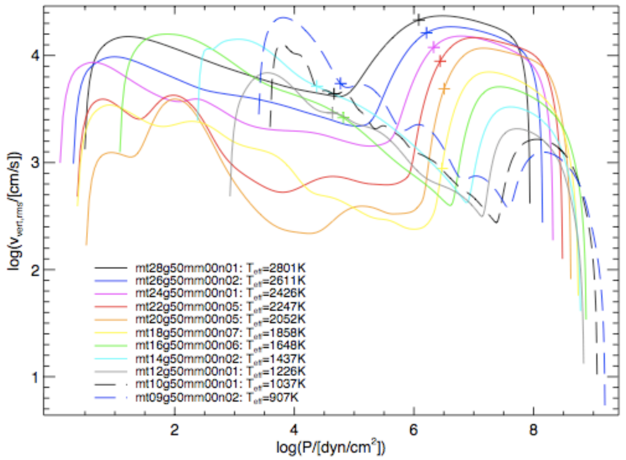
2D HDR simulations of dust cloud formation in brown

Gravity Waves !!!



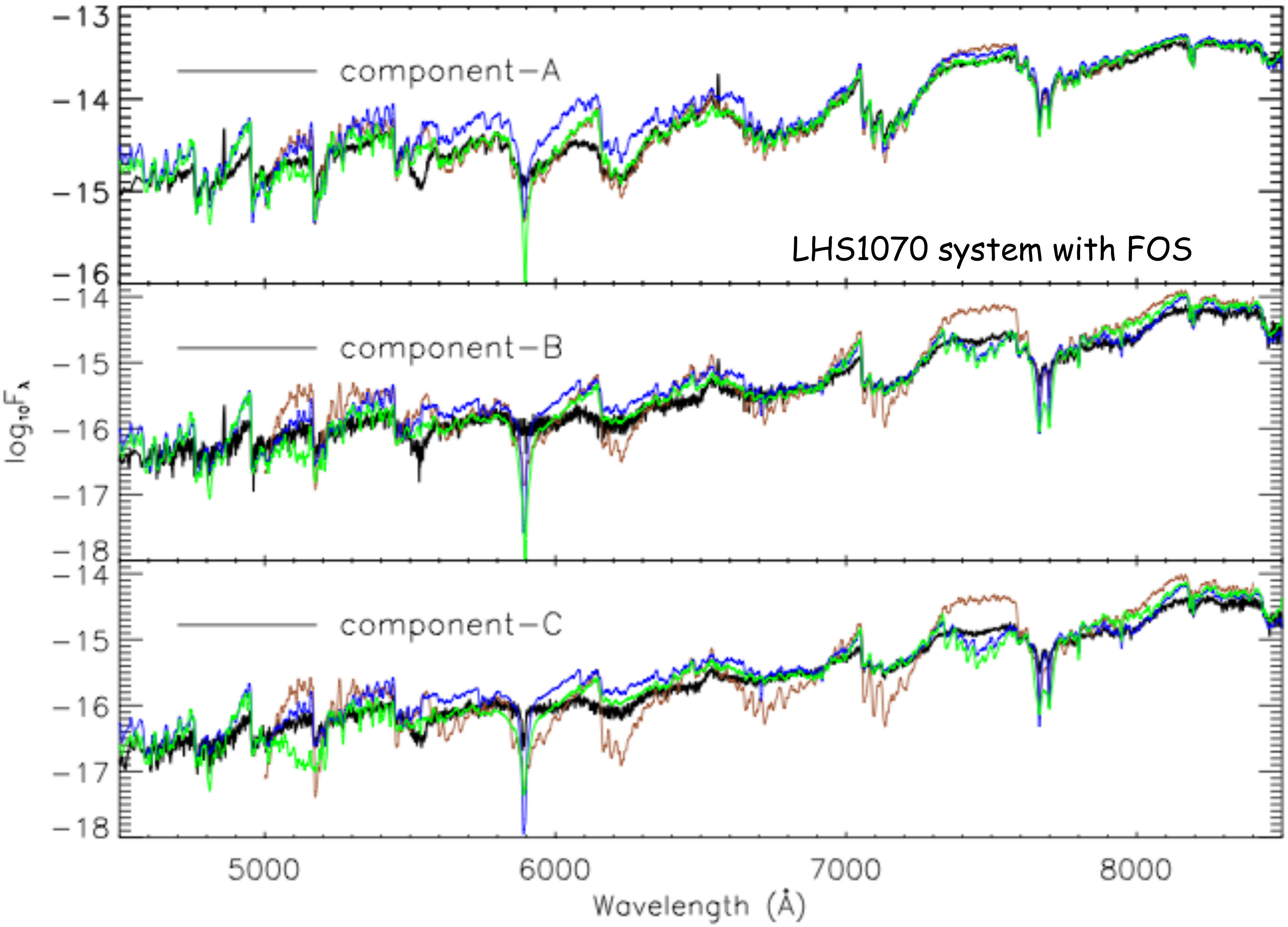
W350 x H80 km^2 during 36 hrs





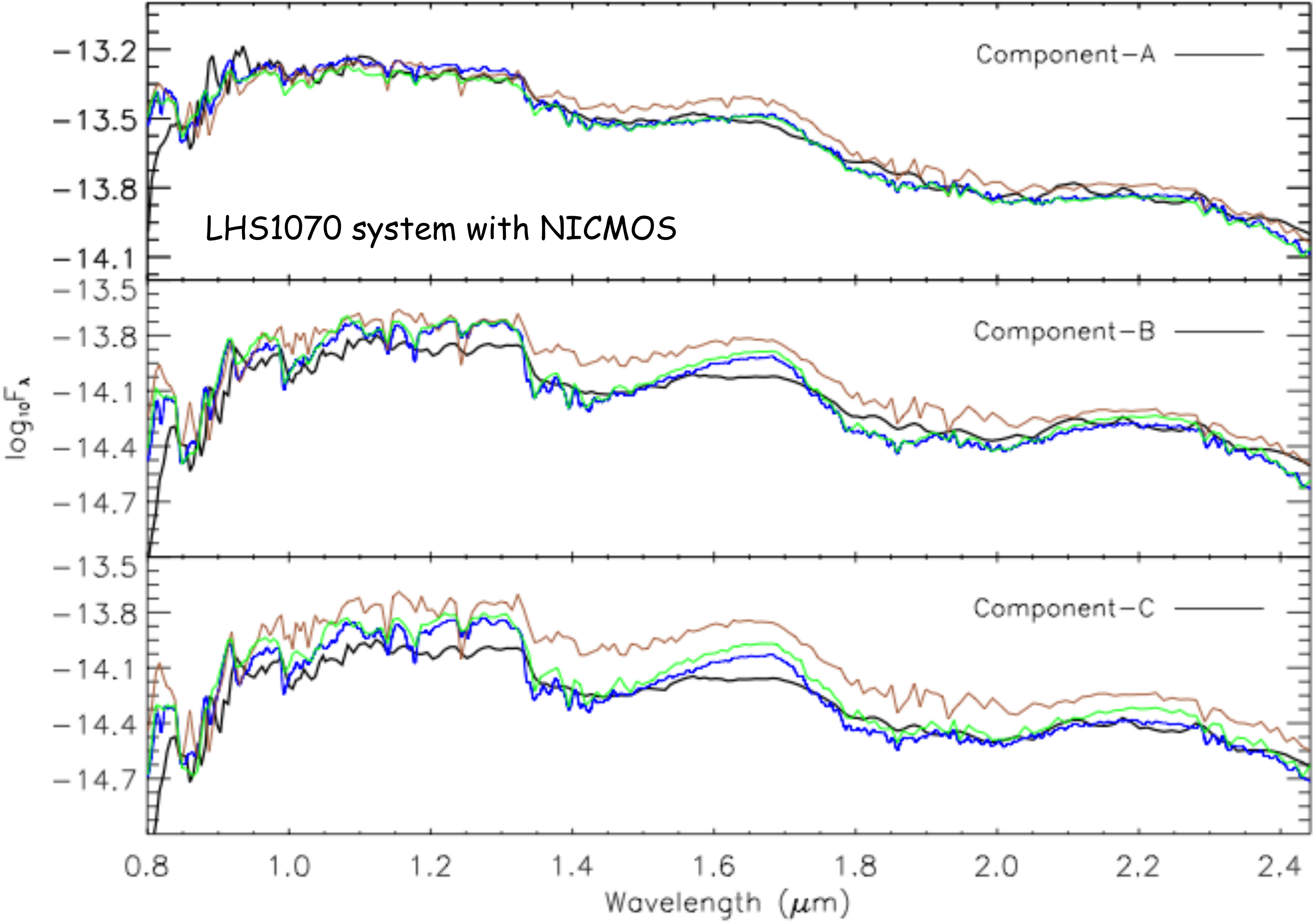
CO5BOLD simulations (Freytag et al. 2010) of the gas and forsterite (Mg_2SiO_4) dust based on Phoenix opacities, on a cloud model (dust size bon distribution), and on the nucleation, condensation, coagulation, and sedimentation rates by Rossow (1978). Shown, in red, the dust grain mass density, and,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

Rajpurohit et al. (2012)



LHS1070 system with FOS

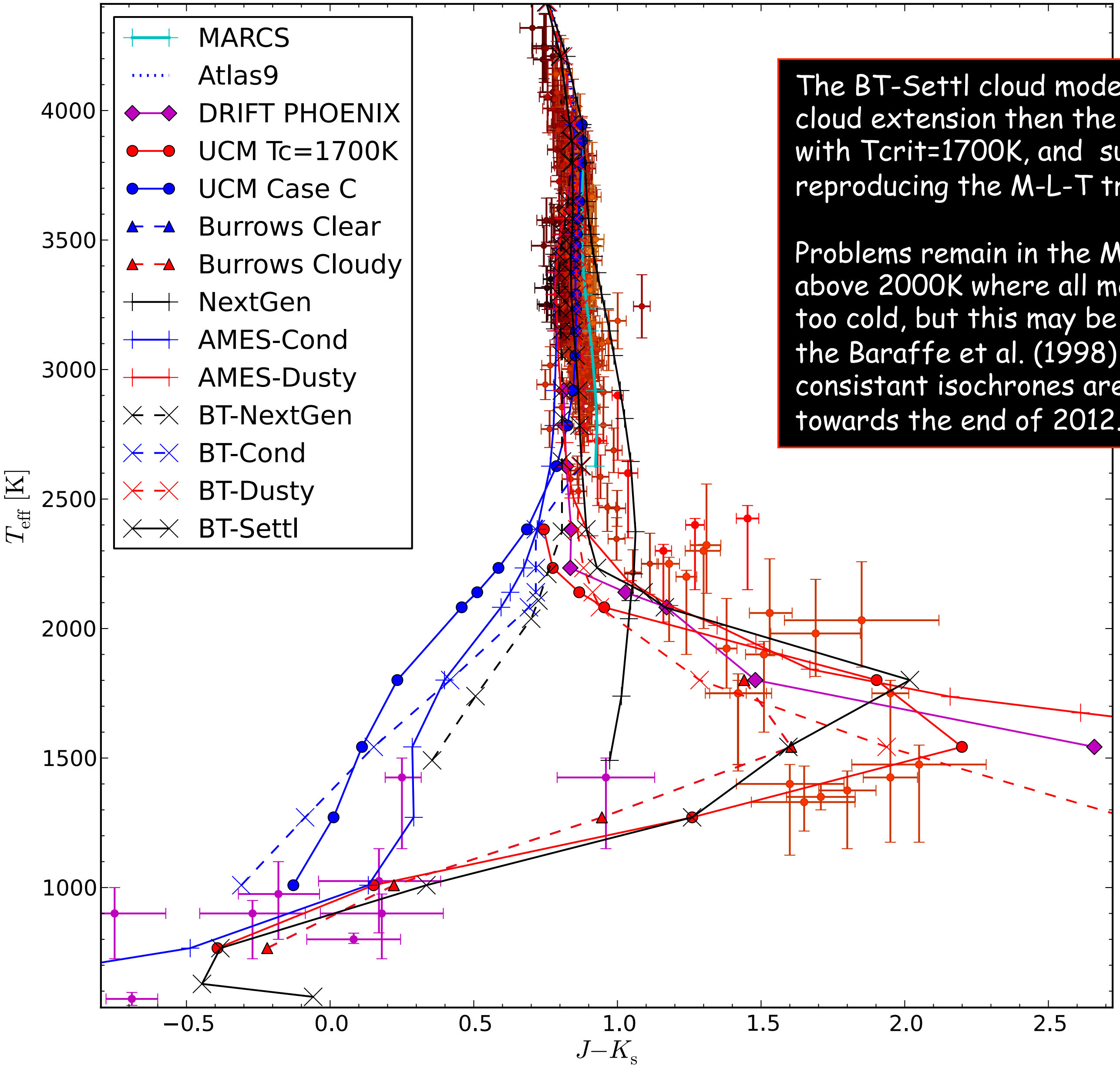
Rajpurohit et al. (2012)



LHS1070 system with NICMOS

Comparing models from different authors

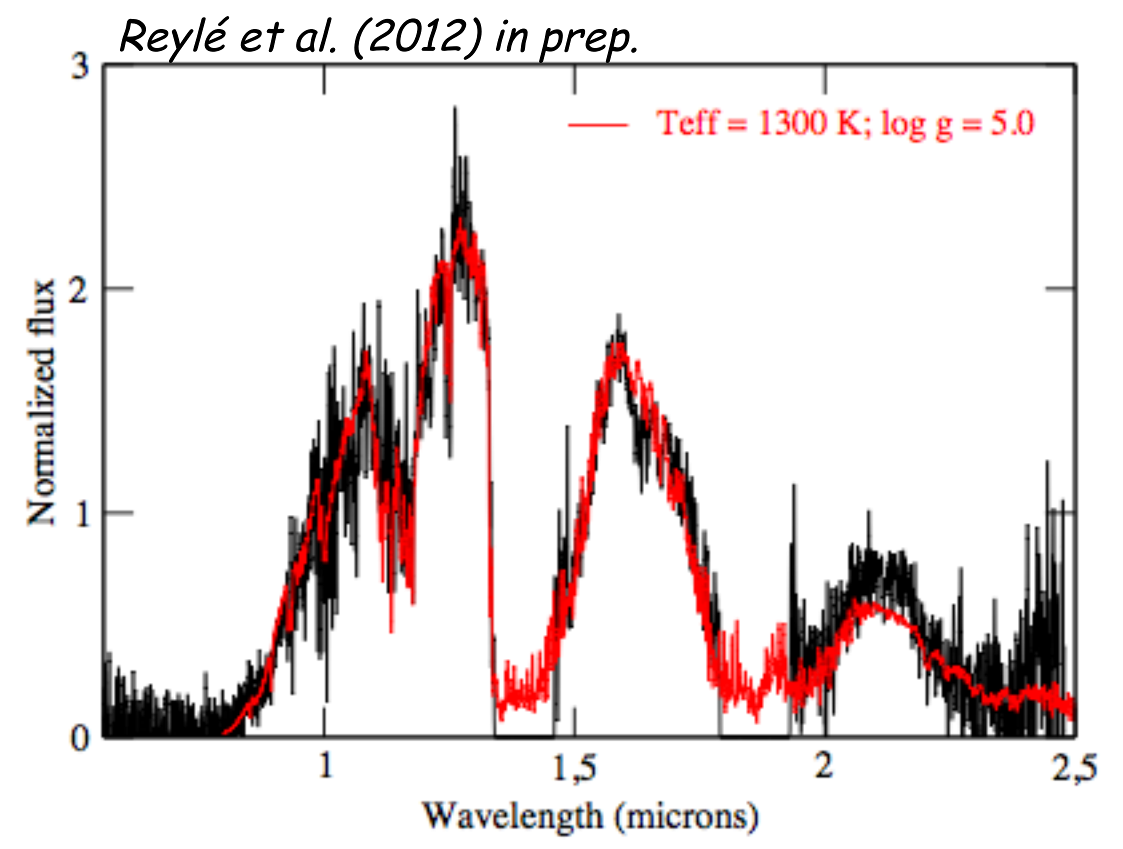
Estimated Teffs of brown dwarfs by Vrba et al. '04 & Golimowski et al. '04



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.

Problems remain in the M-L transition above 2000K where all models are slightly too cold, but this may be due to the use to the Baraffe et al. (1998) isochrones. New consistant isochrones are expected towards the end of 2012.

XSHOOTER SED of a T8.5 brown dwarf

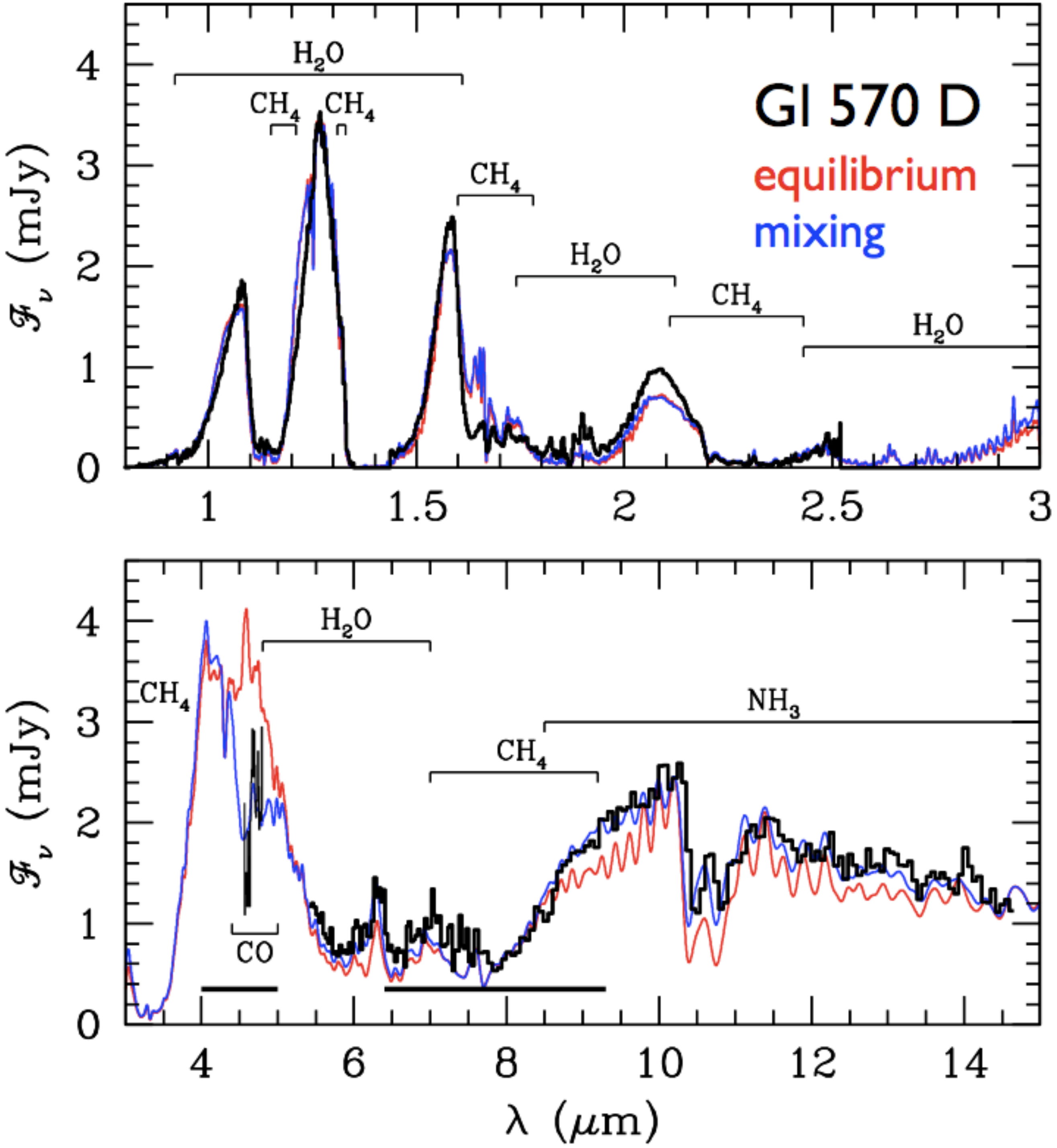

Reylé et al. (2012) in prep.

A chi-square analysis yields these paramaters using the BT-Settl model grid

Dynamical Transport

N_2 and CO is transported from inner/warmer regions of the atmosphere, depleting NH_3 (N_2) and CH_4 (CO)

Saumon et al. (2003)

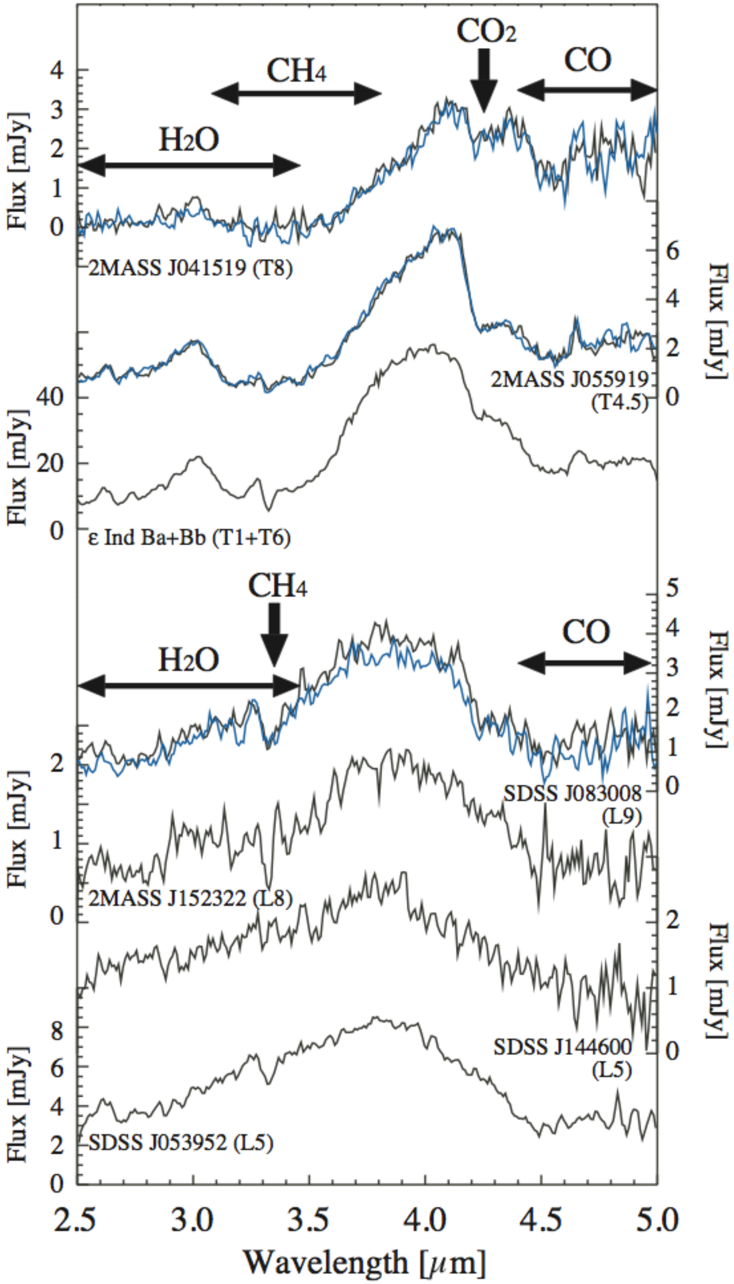


Dynamical Transport

CO_2 detection in brown dwarfs

The NIR spectra of brown dwarfs obtained by the AKARI/IRC. The spectra are ordered in the sequence of their spectral types from bottom (L5) to top (T8). When two observations were made for an object, the data were processed independently and the second spectrum is indicated in blue. The difference between the two observations represents the practical errors. Positions of major molecular bands are indicated.

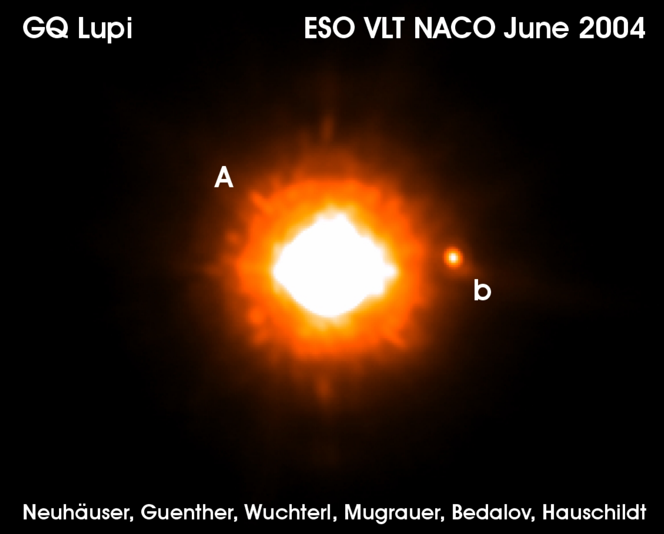
Yamamura et al. (2010)

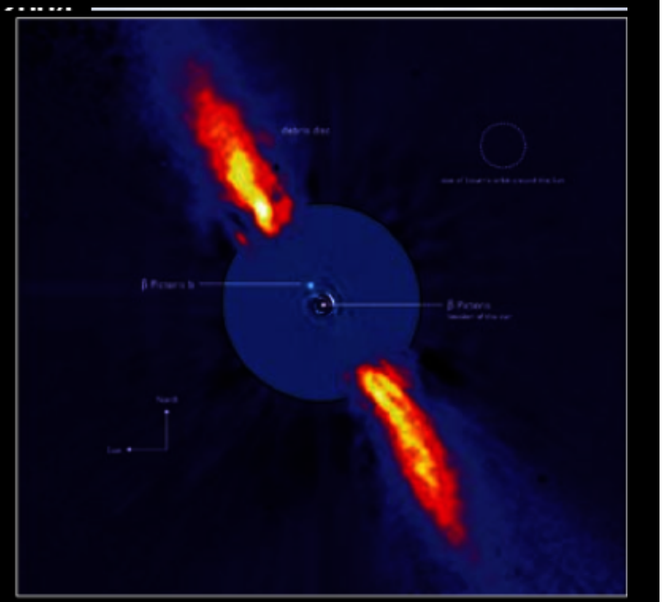


Imaged planets

27 systems, 31 planets, 2 multiple systems

Chauvin et al. (2004)





M= 5 ± 13 M_J
R= 1.5 R_J
a= 55 AU
age= 8 Myr

M= 20.5 ± 21.5 M_J
R= 1.8 R_J
a= 103 ± 37 AU
age= 1 ± 1 Myr

M= 8 -2/+5 M_J
R= ?
a= 12 ± 4 AU
age= 0.012 -0.004/+0.002 Gyr

First spectrum from an imaged planet !

Janson et al. (Science 2010)

10 M_{jup}
4 UA

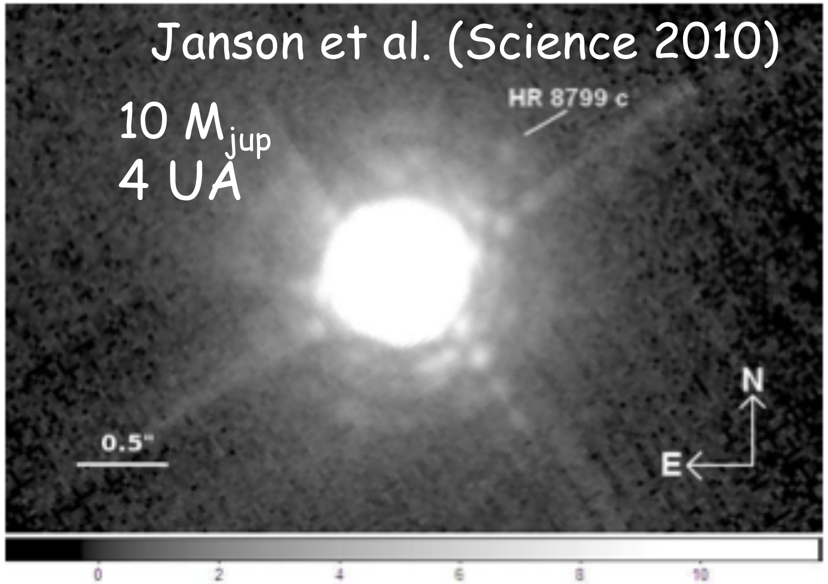


Fig. 1.— A 150 second L′-band image of HR 8799 with no high-contrast techniques applied. HR 8799 c can be spotted even in this very short exposure, demonstrating the advantage of this wavelength range for exoplanet spectroscopy.

Discovery by Marois et al.(2008), & Metchev, Marois & Zuckerman (2009) :
4 giants around an A5 with 1.5 $M_\odot$

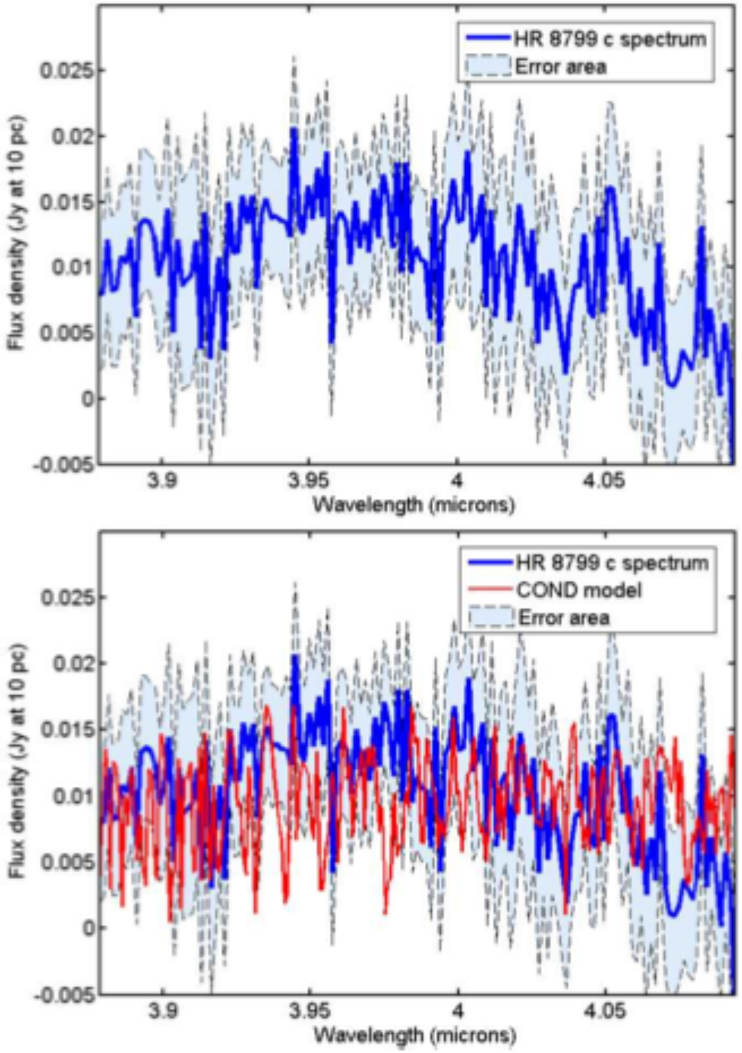
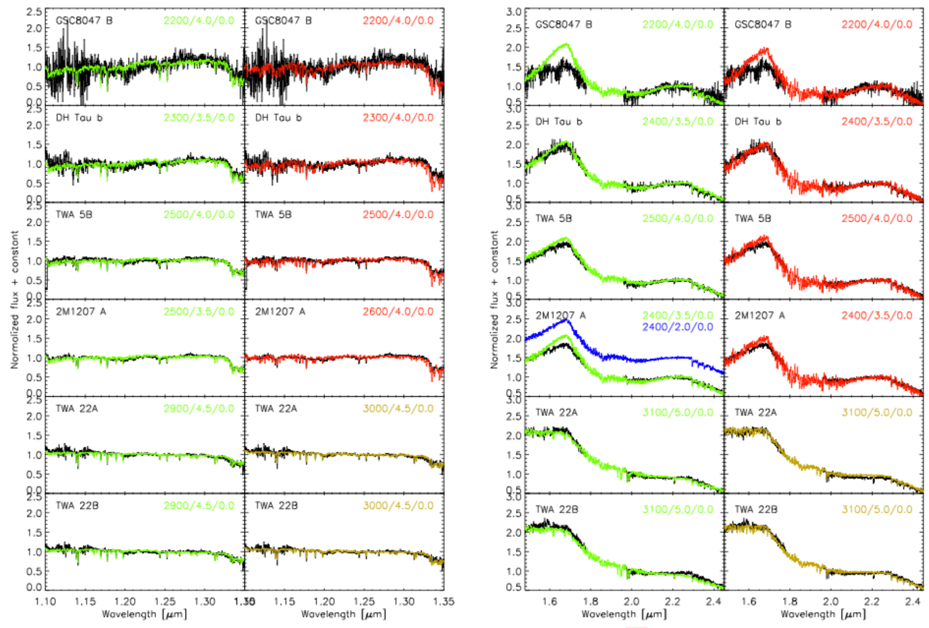


Fig. 3.— Upper: Spectrum of HR 8799 c. The dashed lines and faintly shaded area (light blue in the online version) denote the errors. Lower: Same figure but with a COND model spectrum overplotted as a thinner line (red in the online version).

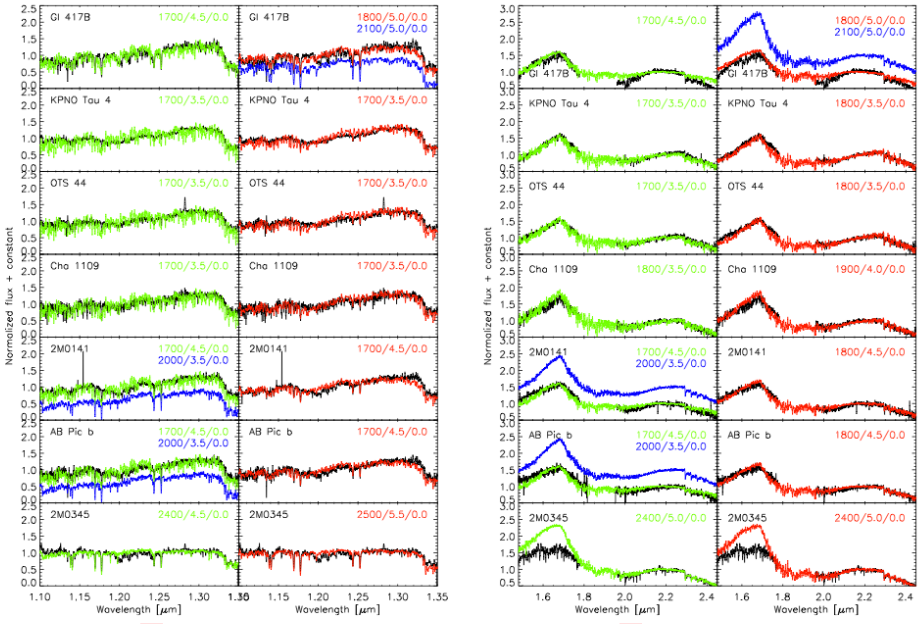
IFS VLT-SINFONI spectra of 1-3 Myrs M and L type

Comparison between BT-Settl and Drift-Phoenix (chi-sqrt)

J **hotter** K



J **cooler** K



Bonnefoy et al. (2012)

The models are missing dust formation efficient enough at the M-L transition for field dwarfs, but this problem is not seen for these very young objects of similar Teffs.

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:

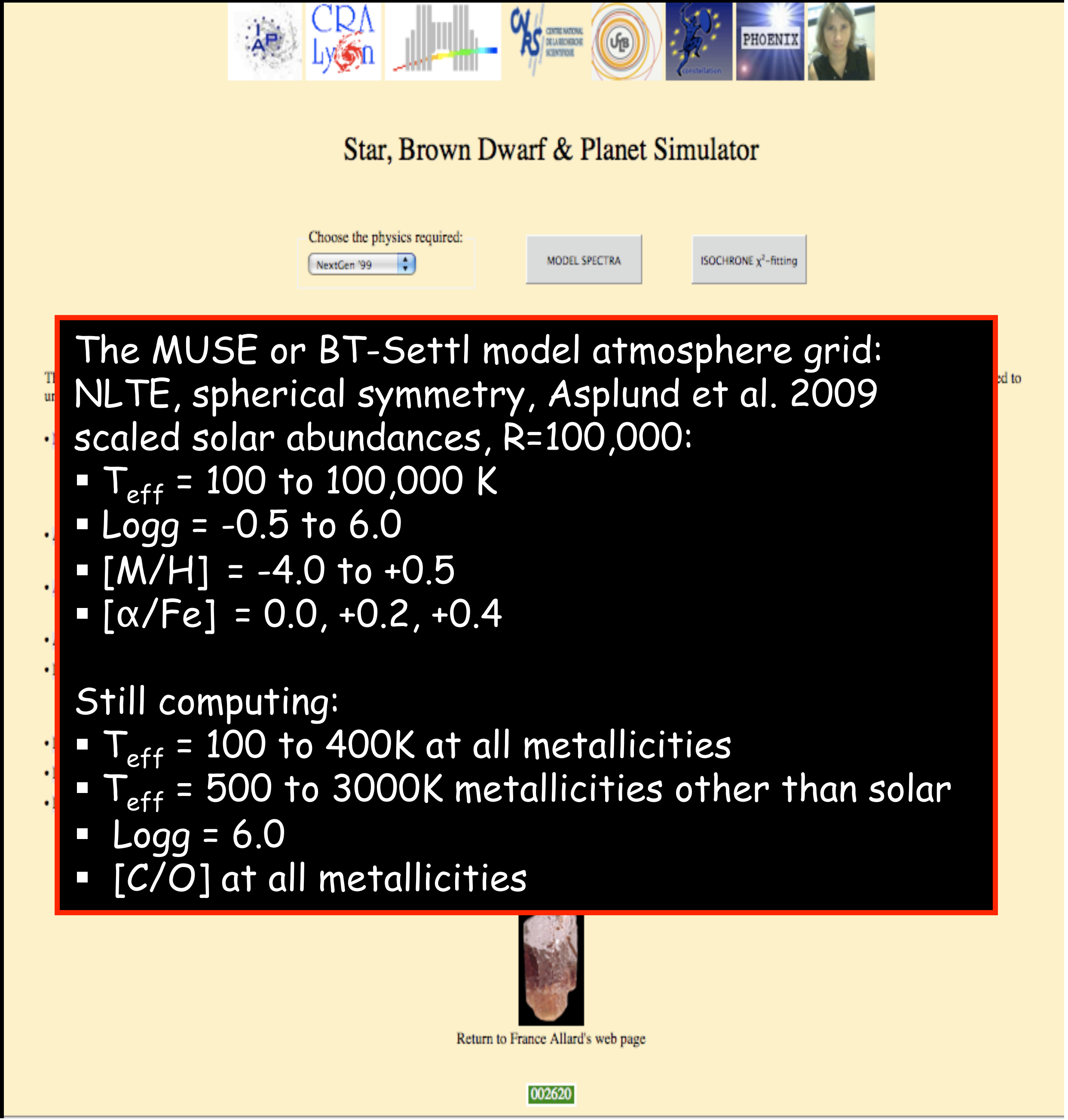
✓ stars

✓ brown dwarfs (1 Myrs - 10 Gyrs)

✓ extrasolar giant 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

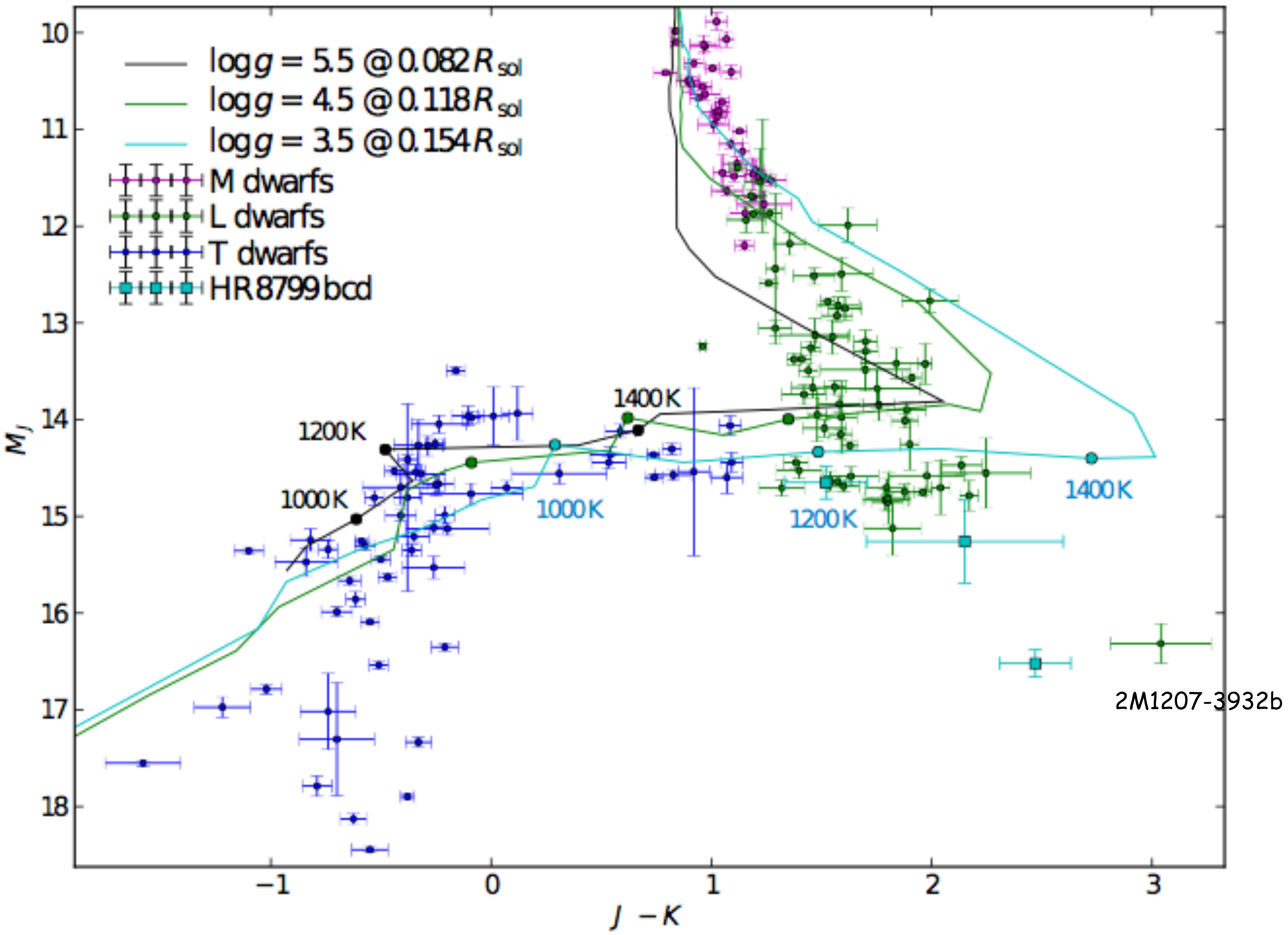
The MUSE or BT-Settl model atmosphere grid: NLTE, spherical symmetry, Asplund et al. 2009 scaled solar abundances, R=100,000:

- T_{eff} = 100 to 100,000 K
- Logg = -0.5 to 6.0
- [M/H] = -4.0 to +0.5
- [α/Fe] = 0.0, +0.2, +0.4

Still computing:

- T_{eff} = 100 to 400K at all metallicities
- T_{eff} = 500 to 3000K metallicities other than solar
- Logg = 6.0
- [C/O] at all metallicities

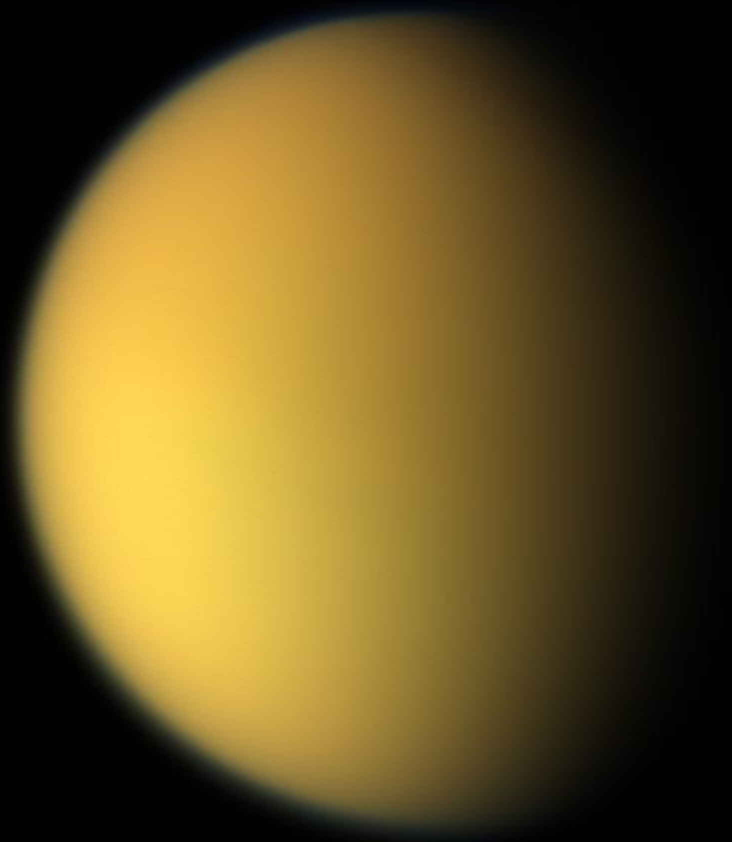
Return to France Allard's web page



2M1207-3932b

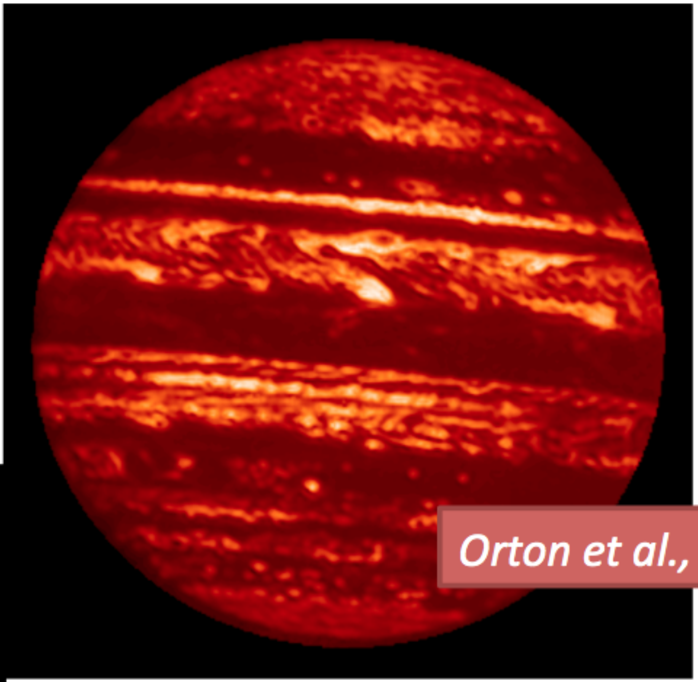
For example the case of Titan : Photochemistry/photolysis causes surface Hazes/Colors

PIA06230: Cassini's View of Titan: Natural Color Composite photo. Cassini spacecraft's April 16, 2005, flyby of Titan. The orange color is due to the hydrocarbon particles which make up Titan's atmospheric haze.

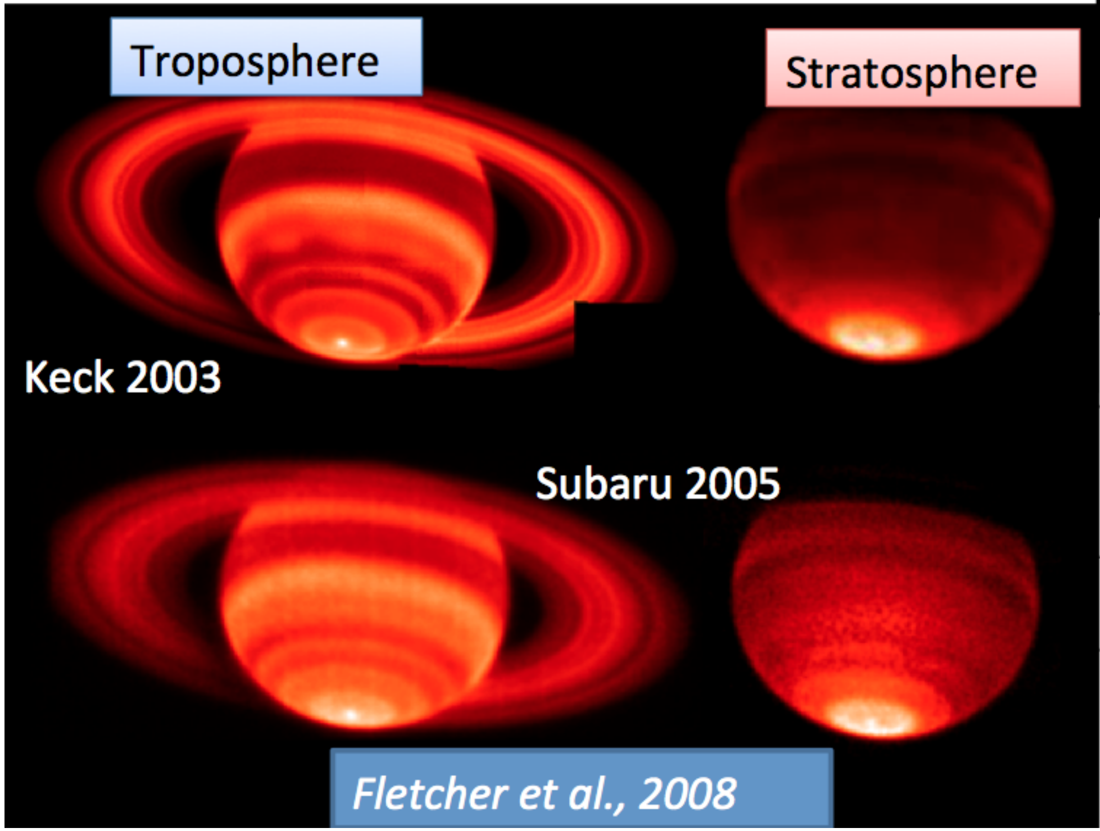


The Sun with MLT dwarfs & Jupiter

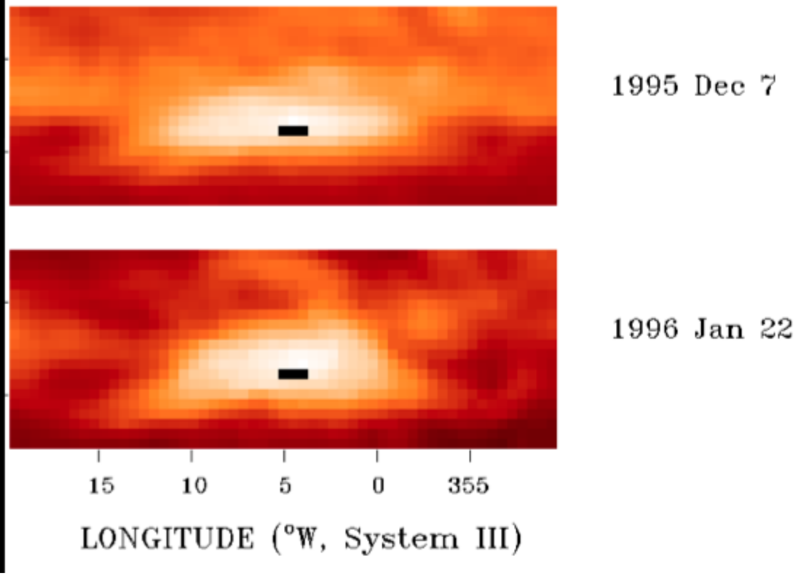
- Even in our Solar System, much of the high-resolution spectroscopy is disc-averaged. But there are pitfalls to interpretation of the composition from these measurements.
- Example I: Galileo Probe (1995) detects unusual hot spot meteorology, dominated disc-averaged emission.
- Example II: Polar dominance in CxHy emission, bias to polar physics/chemistry?



Orton et al., 1998



Fletcher et al., 2008

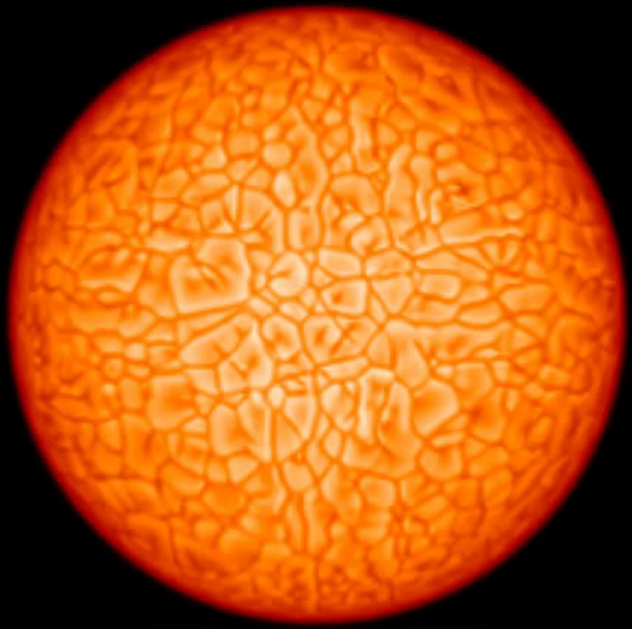


Global simulations

Brown dwarfs rotate with ~30 km/s (P < 4 hrs) !

Schaffenberger & Freytag 2012 (in prep.)

Teff= 3600K, logg= 4.5, solar, P=1 Hr

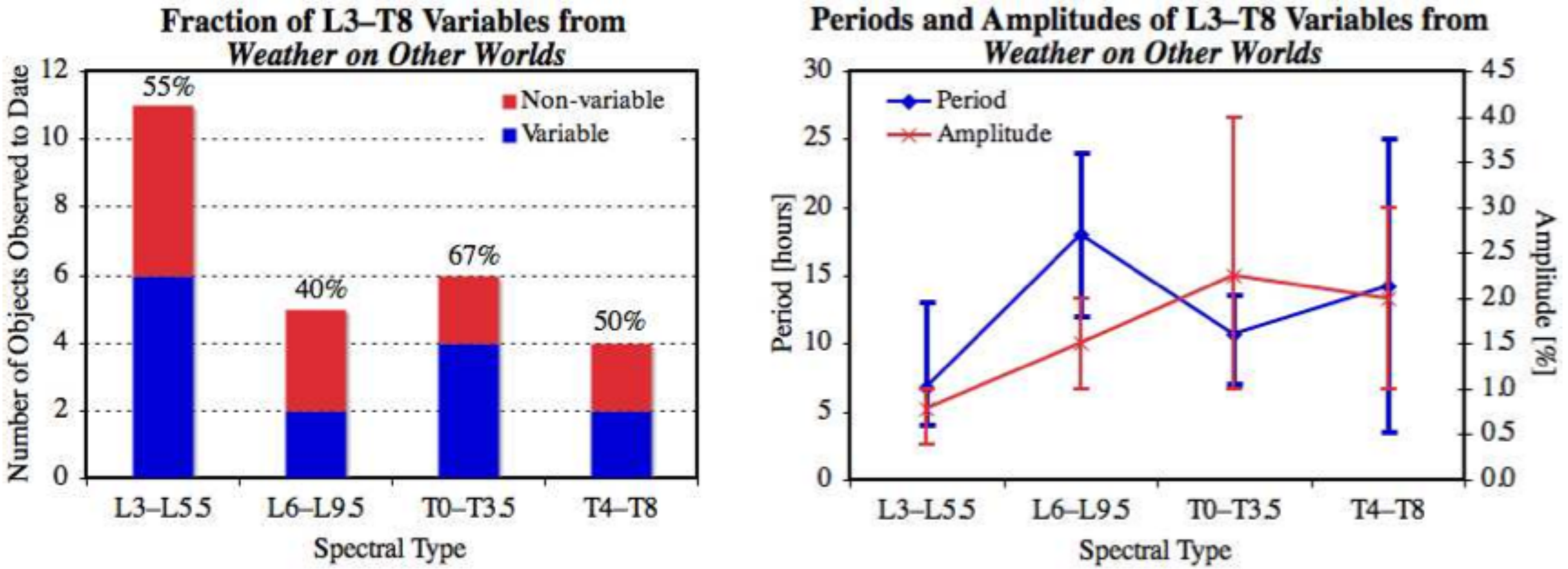


→

Jupiter

Interior mixing length calibration
work in Exceter

Brown dwarfs variability



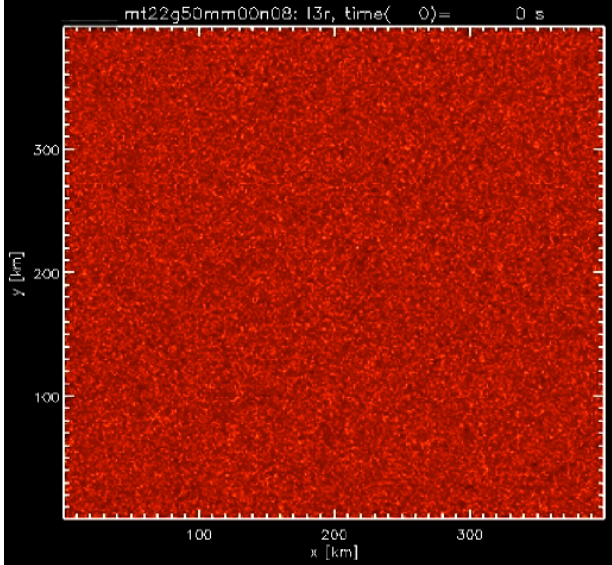
Fraction of L3–T8 Variables from *Weather on Other Worlds*

Periods and Amplitudes of L3–T8 Variables from *Weather on Other Worlds*

Figure 2: Preliminary results for the 26 observed (out of 44 total) L3–T8 dwarfs in our Cycle 8 Exploration Science program *Weather on Other Worlds*. Error bars denote the full range of observed periods and peak-to-peak amplitudes. The results demonstrate that patchy clouds are ubiquitous in 700–2000 K substellar atmospheres, and that their prominence likely continues even at cooler temperatures.

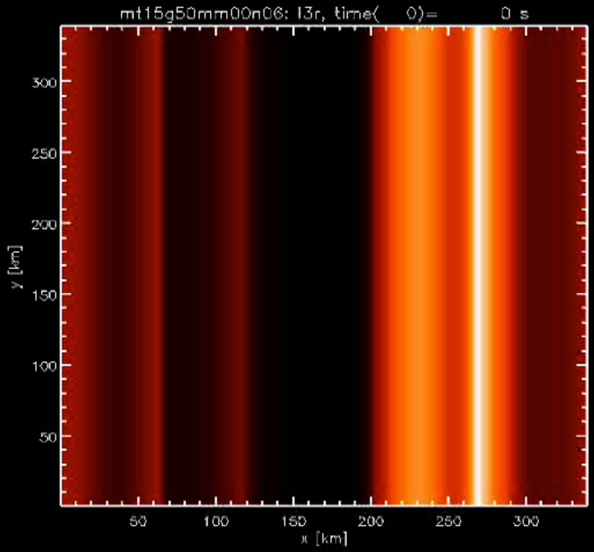
Artigau et al. (2009) were the first to detect highly significant, repeatable periodic (P = 2.4 hr, ΔJ = 50 mmag) variations in a cool brown dwarf. More recently, Radigan et al. (2011) have completed the most comprehensive ground-based variability survey of L and T dwarfs, detecting highly significant periodic modulations in five out of 56 objects.

3D Radiative Hydrodynamical simulations of the onset of dust cloud formation



2200K

1800K



1500K

The characteristic timescale of the local variations is tied to gravity waves and to the Brunt-Vaïsala frequency of 30 sec to one minute or more for the modes shown here, which is more rapid then the underlying convection timescale.