The Physical Properties of Very Young Brown Dwarfs

We have come to the point where large samples of very low-mass young objects can be studied with photometry and low and high resolution spectroscopy. This offers the possibility to measure the fundamental physical properties of these objects, including mass, luminosity, temperature, and radius.

We are only beginning to directly test masses and evolutionary models, but are learning about how to use our diagnostics. There appear to be problems with the current models in this part of parameter space, but there are also still issues with the observational determination of fundamental parameters.

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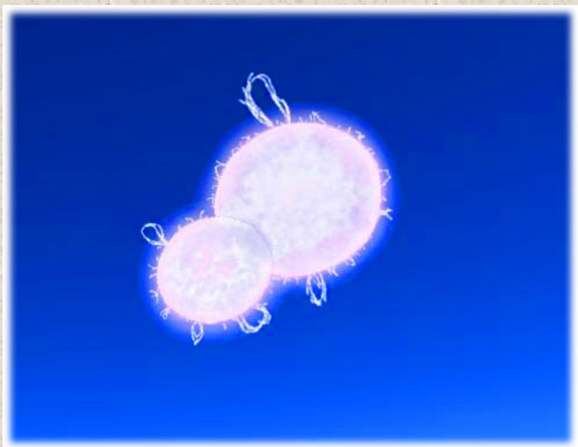
Deriving Fundamental Parameters: Binaries

The best method is, of course, to find eclipsing binary systems with very low masses. This is just beginning to happen. One still needs good temperatures and luminosities (distance), along with age.



June 3, 2005 | **At this week's American Astronomical Society meeting in Minneapolis, Minnesota, Vanderbilt University astronomer Yilen Gómez Maqueo Chew and five colleagues presented detailed observations of the first known eclipsing binary system containing two brown dwarfs — starlike gas balls not quite massive enough to sustain nuclear fusion in their cores. Seen from Earth as a single point of light, the system resides in the Orion Nebula (M42) and is therefore several million years old — ancient in human terms, but extremely young by the standards that apply to lightweight stars. Gómez Maqueo Chew's team has monitored the "star" over the past three years with the 1.3-meter SMARTS telescope at the Cerro Tololo Inter-American Observatory in Chile. The team nailed down the major characteristics of both of the system's brown dwarfs by garnering two complementary kinds of data: back-and-forth Doppler shifts, which yield orbital velocities, and light curves, which help establish the two bodies' sizes. The more massive member contains 0.053 solar mass and has a diameter of 0.89 Sun. The other contains 0.034 solar mass and has a diameter of 0.70 Sun. Because both objects are young, they have not had time to contract to their final sizes, which will be only about one-tenth the diameter of the Sun. Every 9.78 days, the objects complete one highly elongated orbit, with a semimajor axis of 8.52 solar radii, around a common center of mass.**

Fundamental Physical Parameters: Single Objects

An alternative method which works for any object in a star-forming region, is "fine analysis". Its presence in the region allows measurement of luminosities (photometry + distance), along with age. One can derive temperatures and gravities from high resolution spectra.

The procedure is:

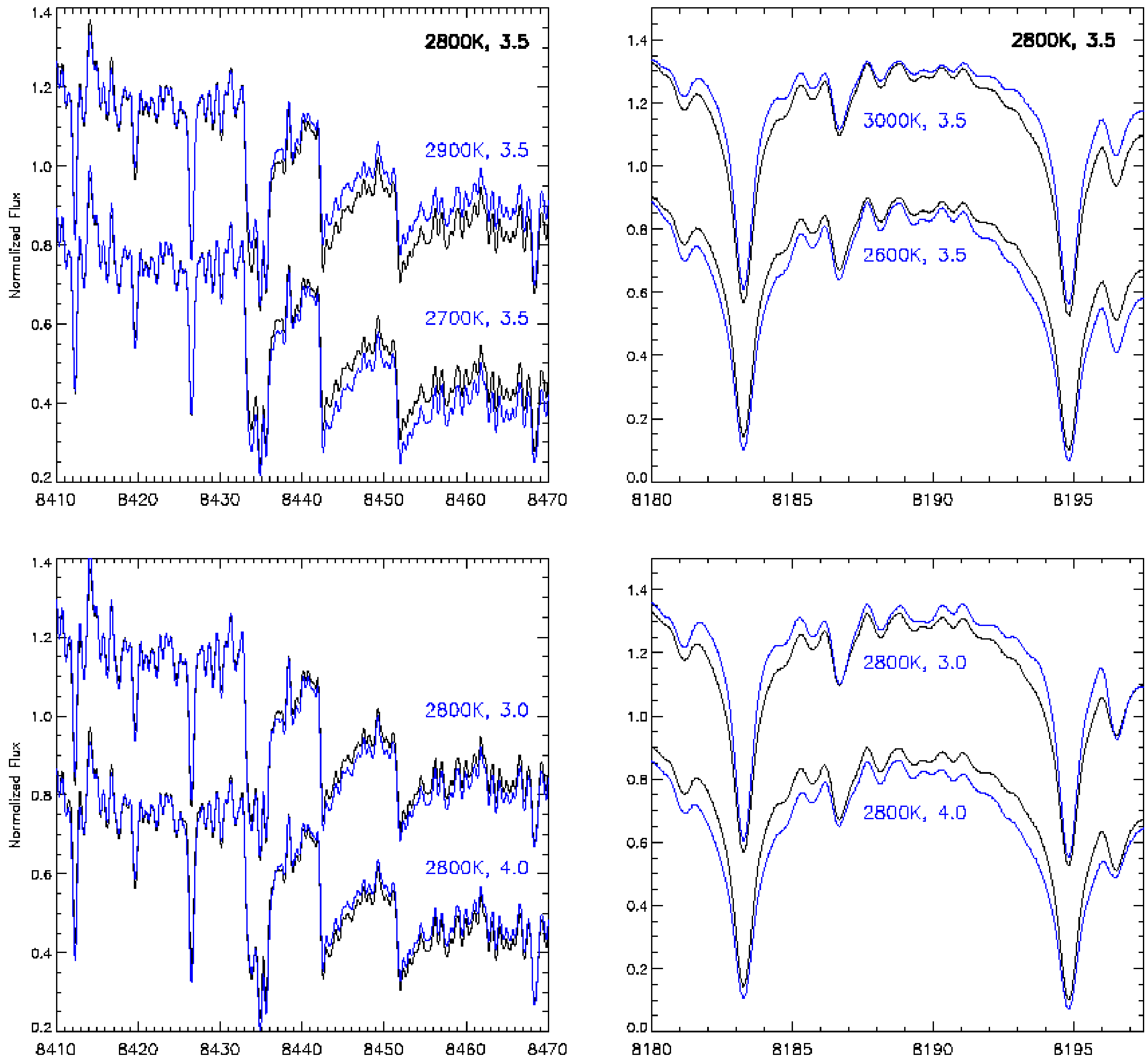
1) **Find an effective temperature from a spectroscopic diagnostic that is largely temperature-dependent**
2) **Find a surface gravity from a pressure-sensitive line**
3) Get the radius from the luminosity (which obtains from the observed brightness, coupled with a known distance to the region) and derived temperature
4) Find the mass from the radius and surface gravity
5) Assume all objects are coeval and check with isochrones

Sensitivities to T_{eff} and log(g)

TiO is sensitive primarily to temperature.

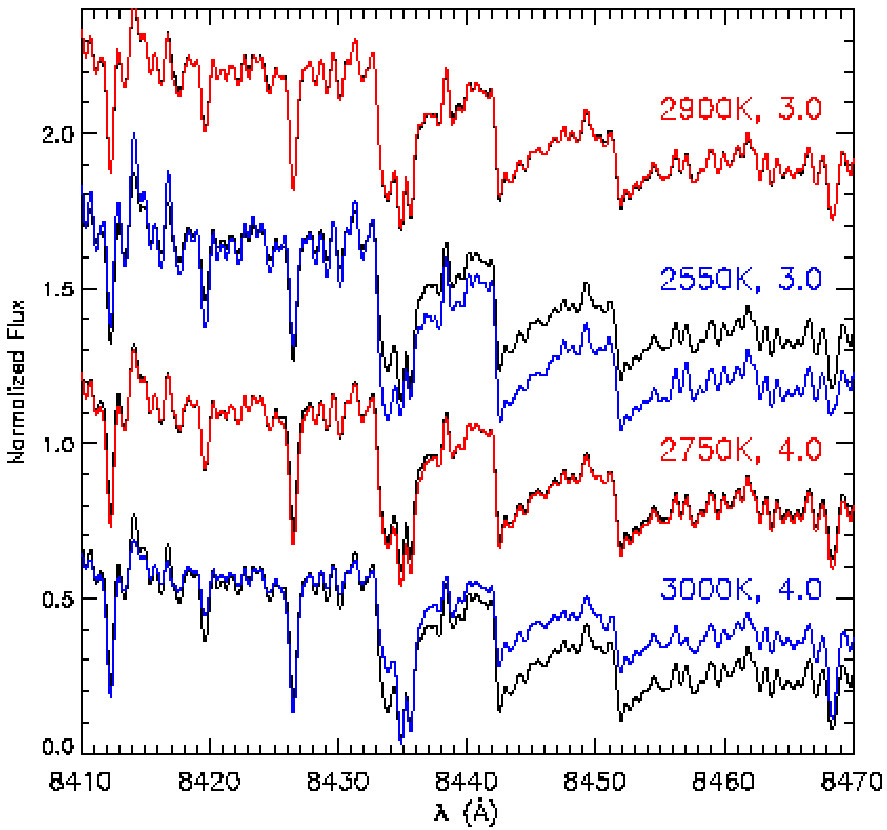
NaI is sensitive to both temperature and gravity.

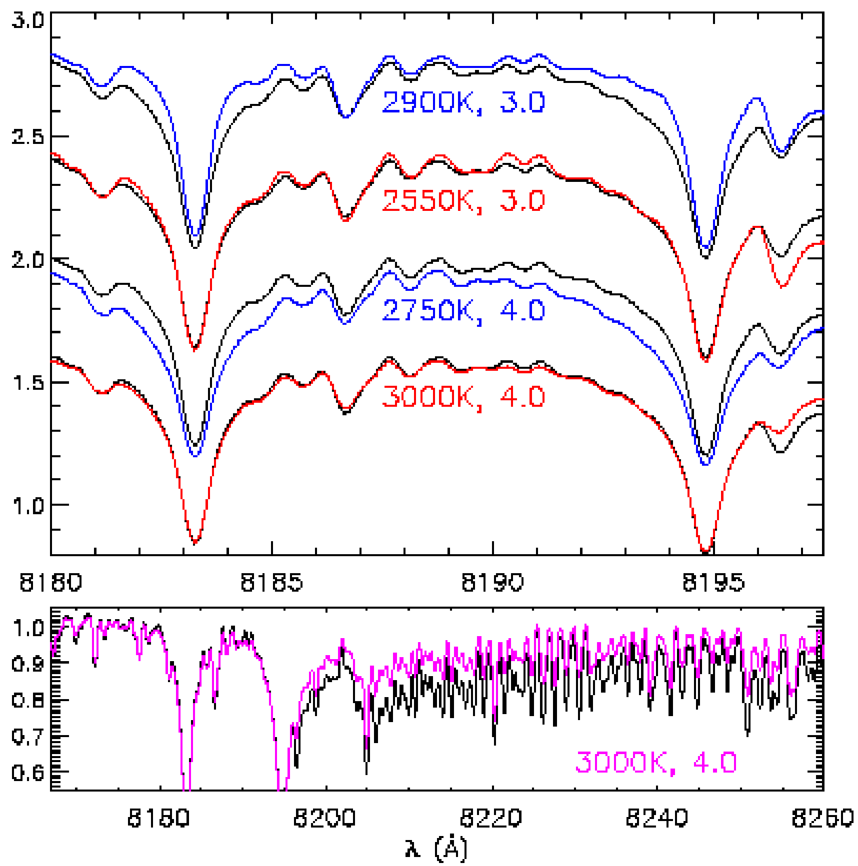
Mohanty et al. 2004



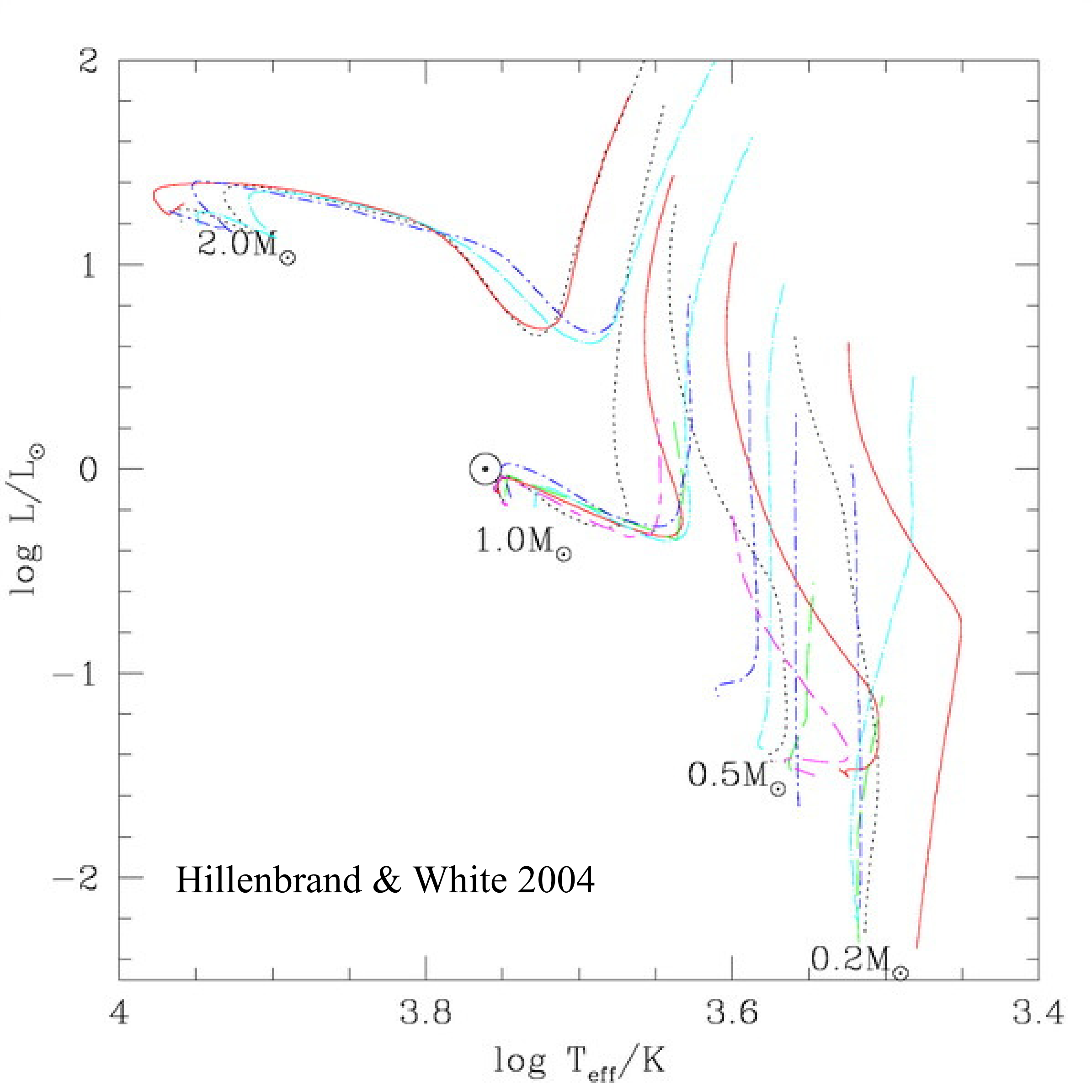
Breaking the Degeneracy

One can get good fits for different combinations of T and g in both TiO and NaI. For NaI an increase of log(g)=0.5 can be offset by an increase of T=200K. There is only one set of parameters that works for both. This is further confirmed by checking the TiO region surrounding NaI.



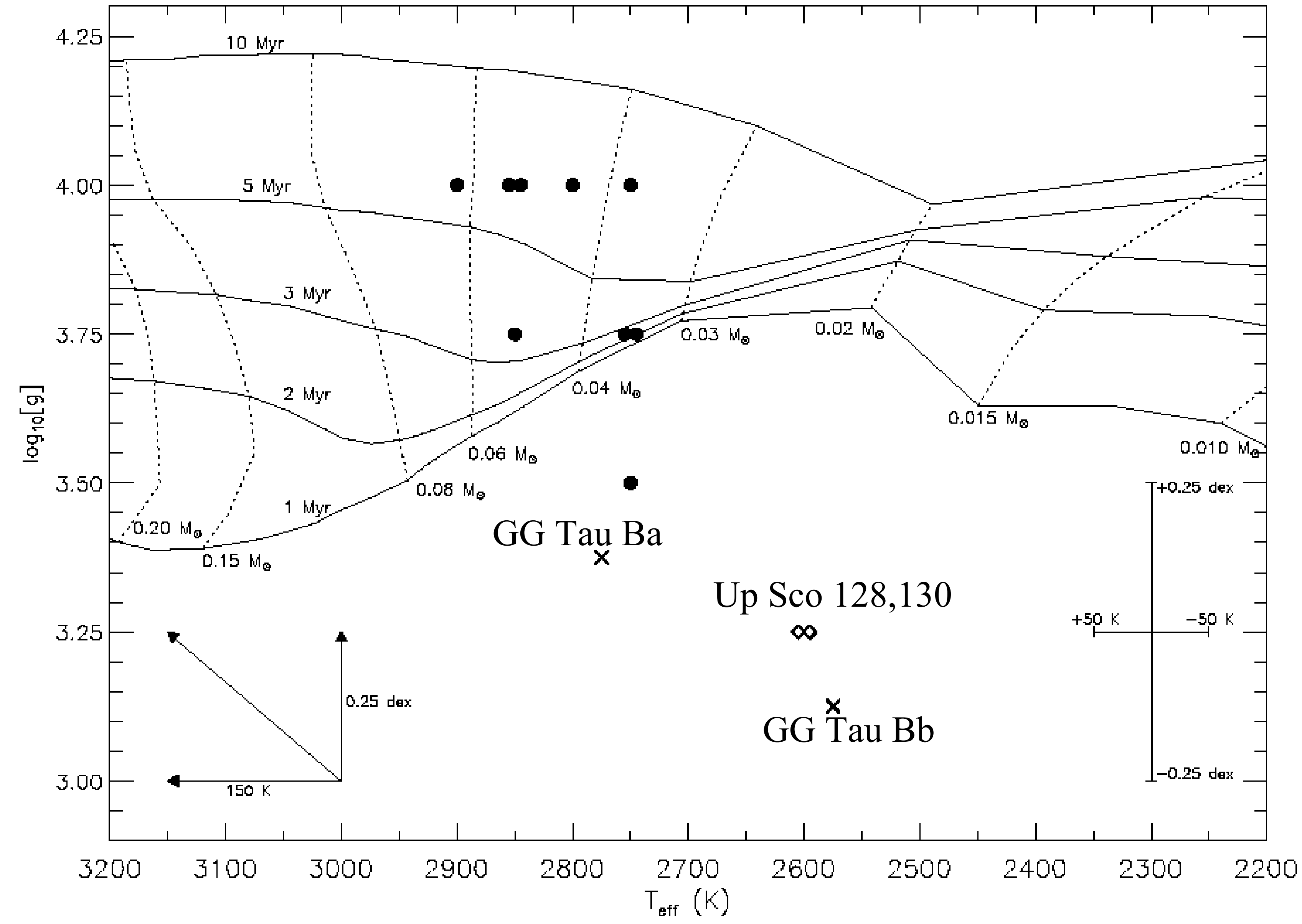


Pre-Main Sequence Models are Uncertain



Variation between pre main-sequence contraction tracks for masses 0.2, 0.5, 1.0, and 2.0 *M* for the following models: S93 (*solid line*), DM97, with 1998 correction (*dotted line*), B98 = 1.9 (*long-dashed line*), PS99 (*dot short-dashed line*), S00 (*dot long-dashed line*), and Y^2 (*long-dash short-dashed line*). Note that the PS99 models, for which no 0.5 *M* track is available, have both the 0.4 and the 0.6 *M* tracks plotted instead. Note also that the Y^2 models do not extend as low as 0.2 *M* .

Model Gravities and Ages



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Evolutionary Model Uncertainties

A somewhat arbitrary starting point is used (without accounting for accretion effects): >30 jupiter start at D ignition;
<30 jupiter start at log(g)=3.5 (higher than what we measure).

While D burning is occurring, the collapse of the object is slowed, so this can cause objects to remain at lower gravity and larger radius. These initial conditions will cause very low mass objects to appear too young for the first 1.5 Myr. This problem should be gone, however, by the age of Upper Sco

If D burning really starts at lower gravity (3.25) for the lowest mass objects, they take a very long time to complete it (>20 Myr), so they could be hung up in the state we find them (while 30 jupiter objects would be done by 5 Myr).

The gravity at which D-burning starts has decreased by 40% in the last 10 years in the D'Antona/Mazzitelli models.

Deriving Fundamental Physical Parameters

For objects in a star-forming region, one might hope to get their fundamental stellar parameters without requiring binaries (testing the untested evolutionary calculations for low masses and young ages).

The procedure is:

1) Find an effective temperature from a spectroscopic diagnostic that is largely temperature-dependent
2) Find a surface gravity from a pressure-sensitive line
3) **Get the radius from the luminosity (which obtains from the observed brightness, coupled with a known distance to the region) and derived temperature**
4) **Find the mass from the radius and surface gravity**
5) **Assume all objects are coeval and check with isochrones**

Note: *there has been no fundamental calibration of mass against models for very young, very low-mass objects.*

History of Substellar Sizes

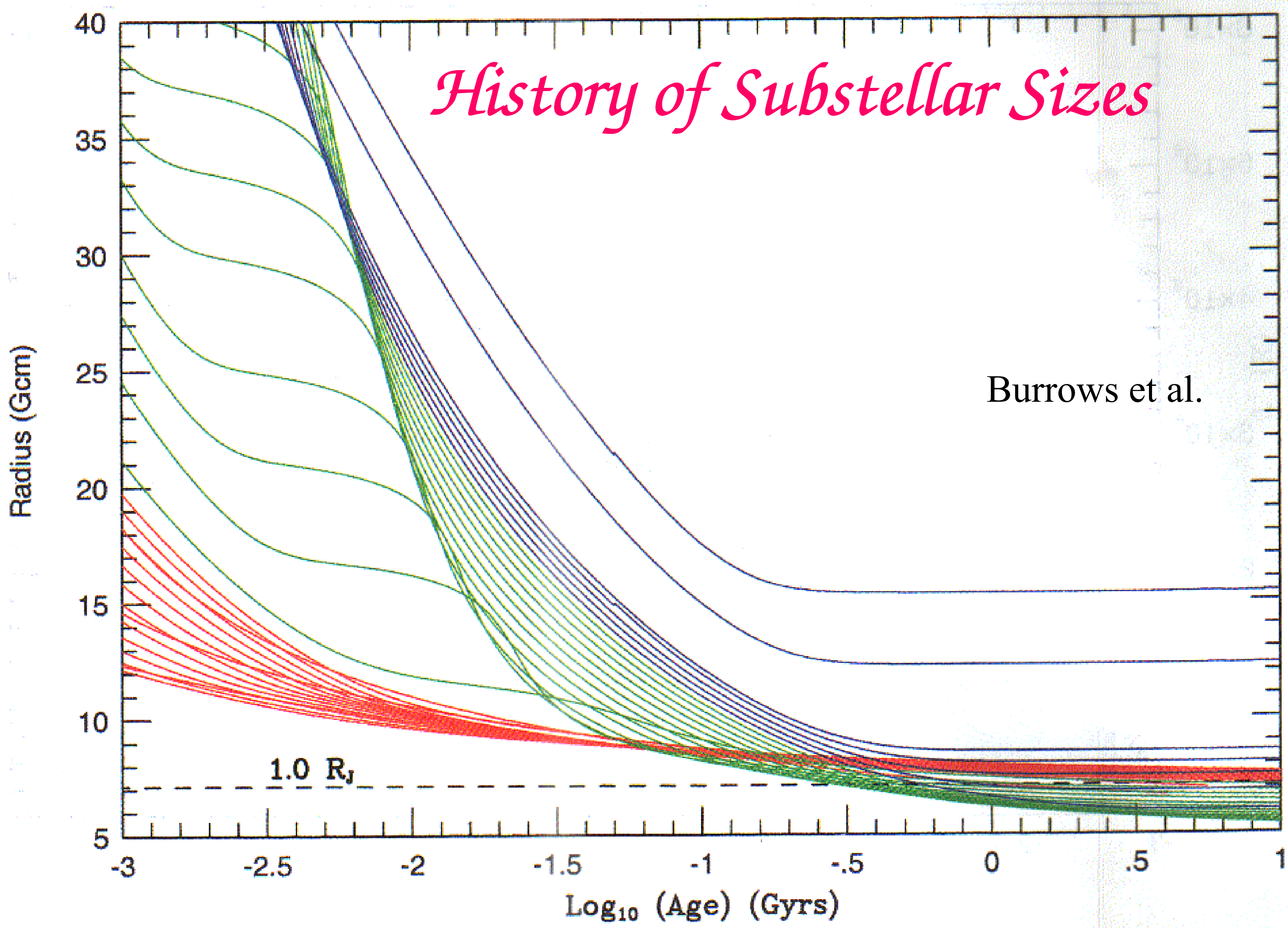
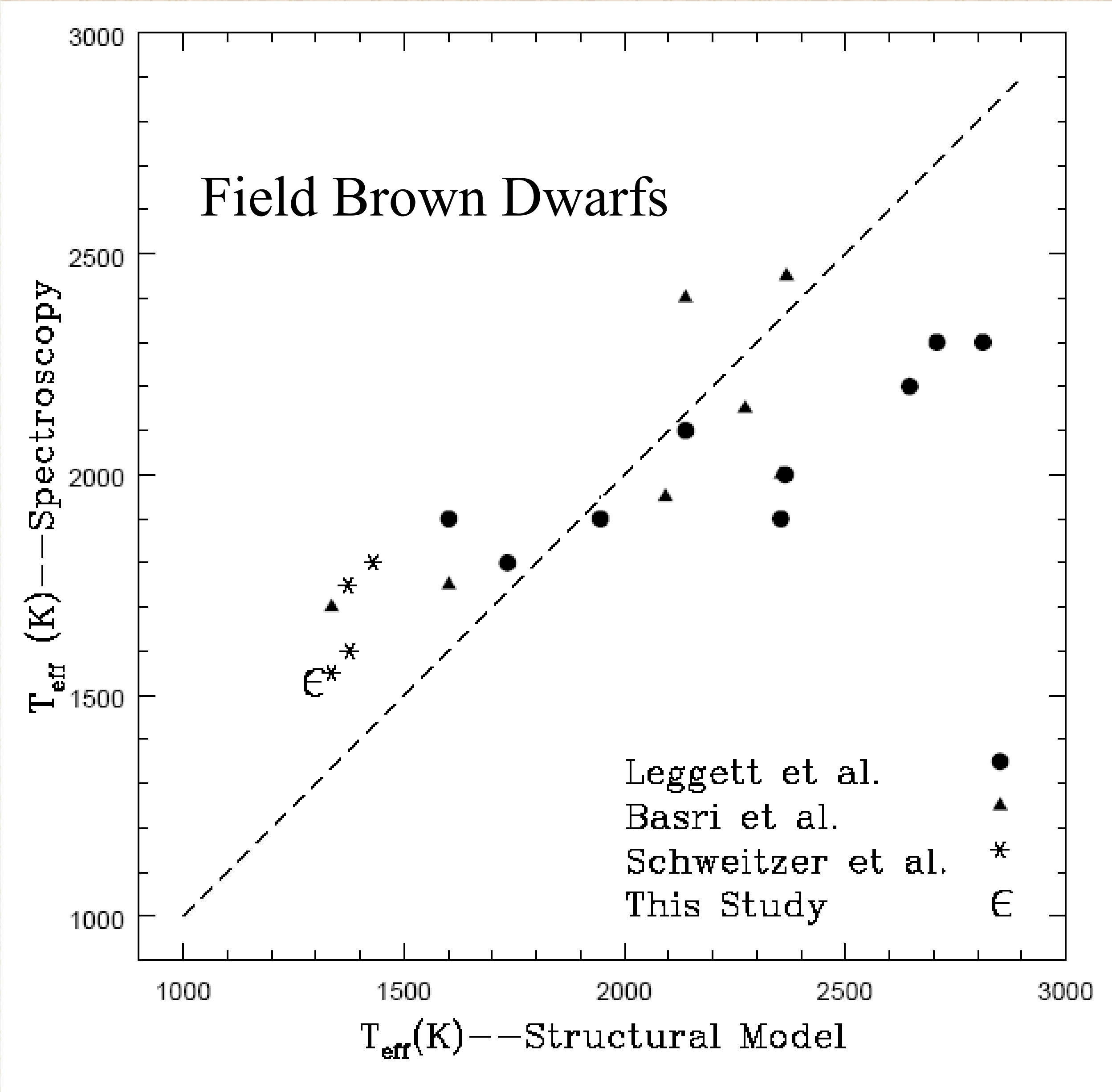


FIG. 3. The radius (in units of 10^9 c) of substellar-mass objects with the masses given in Fig. 1 vs the $\log_{10}$ of the age (in Gyr). The same color scheme that was used in Fig. 1 is used here. Red is for the low-mass substellar objects, green is for the intermediate-mass substellar objects, and blue is for the stars. Also shown is the radius of Jupiter. Note that the radii are not monotonic with mass and that they cluster near the radius of Jupiter at late times, despite the wide range of masses from 0.3 M_J to 0.2 $M_\odot$ represented. See text for details [Color].

"Fine Analysis" vs Structural Effective Temperatures

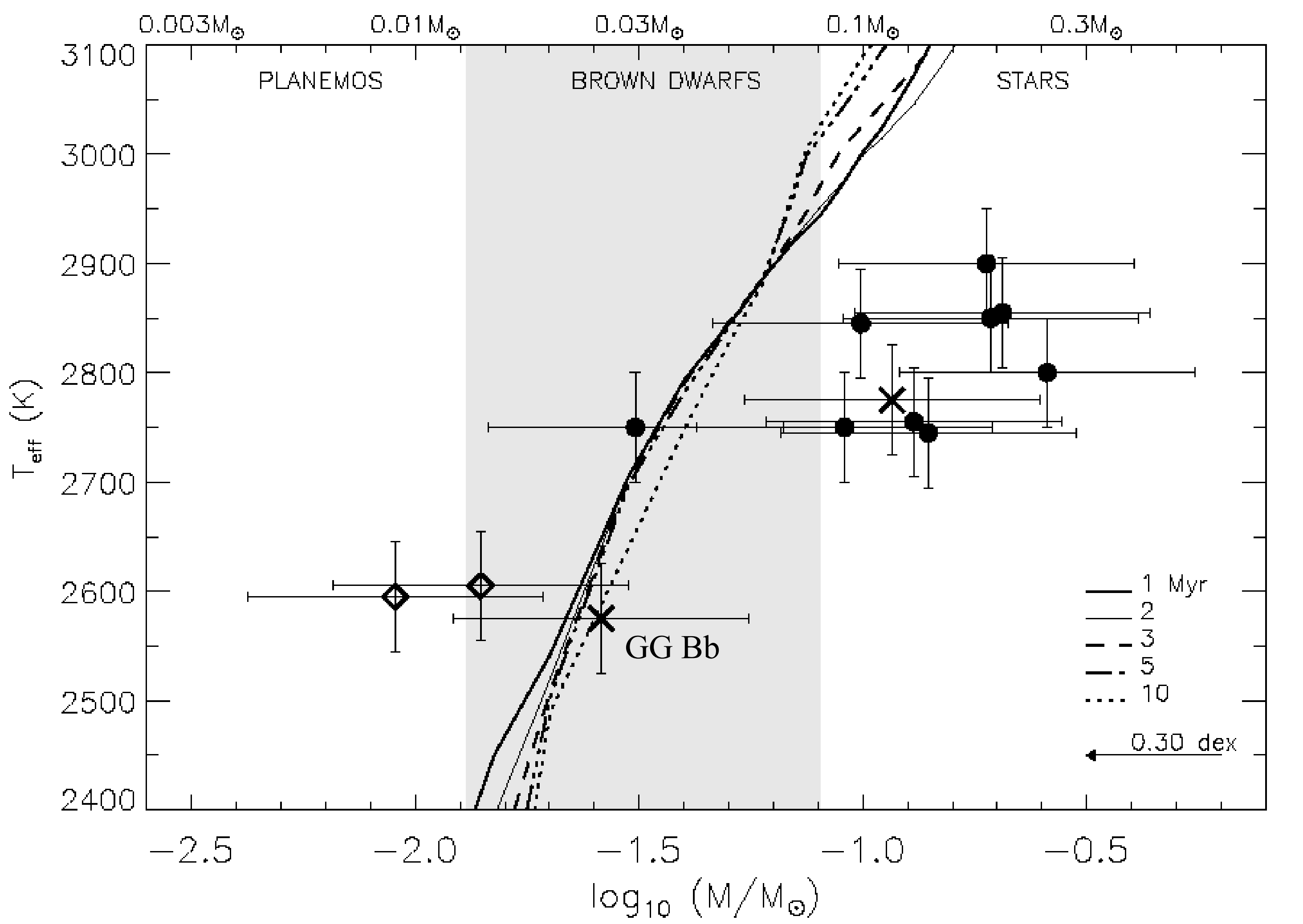
"Structural" temperatures are defined by measuring the luminosity (from photometry adjusted with a bolometric correction), combined with the parallax, then using theory to define a relation between bolometric luminosity and radius.

High resolution spectroscopy yields results that don't quite seem to agree with theoretical models (problems may be bolometric corrections, atmospheric models). The cooler objects are inferred to be smaller by spectroscopy than in the models.



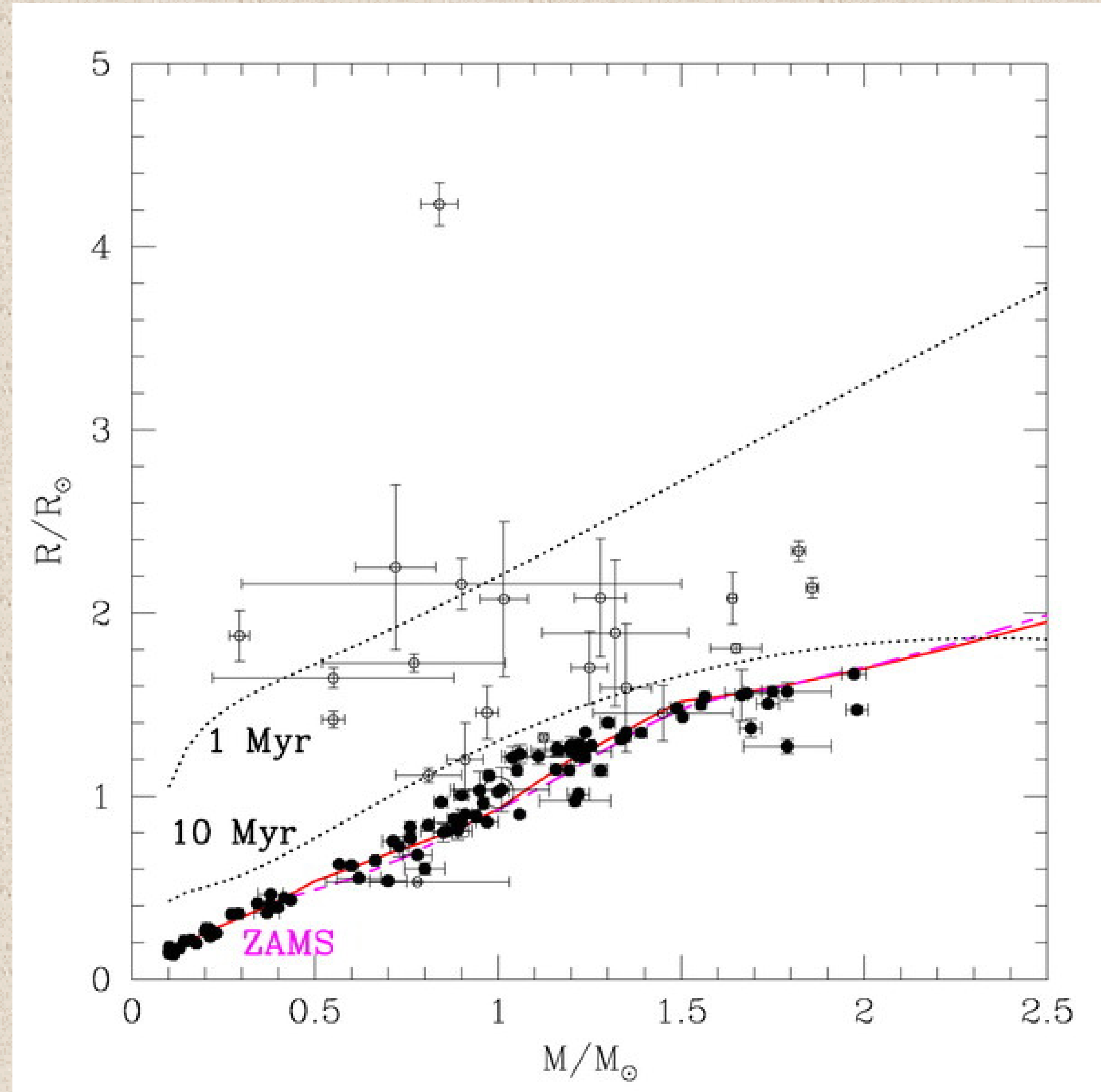
Smith et al. 2003 ApJ

Temperature vs Mass



The slope of the M-T relation is also wrong, and the radii of very low-mass objects are too small in the evolutionary models.

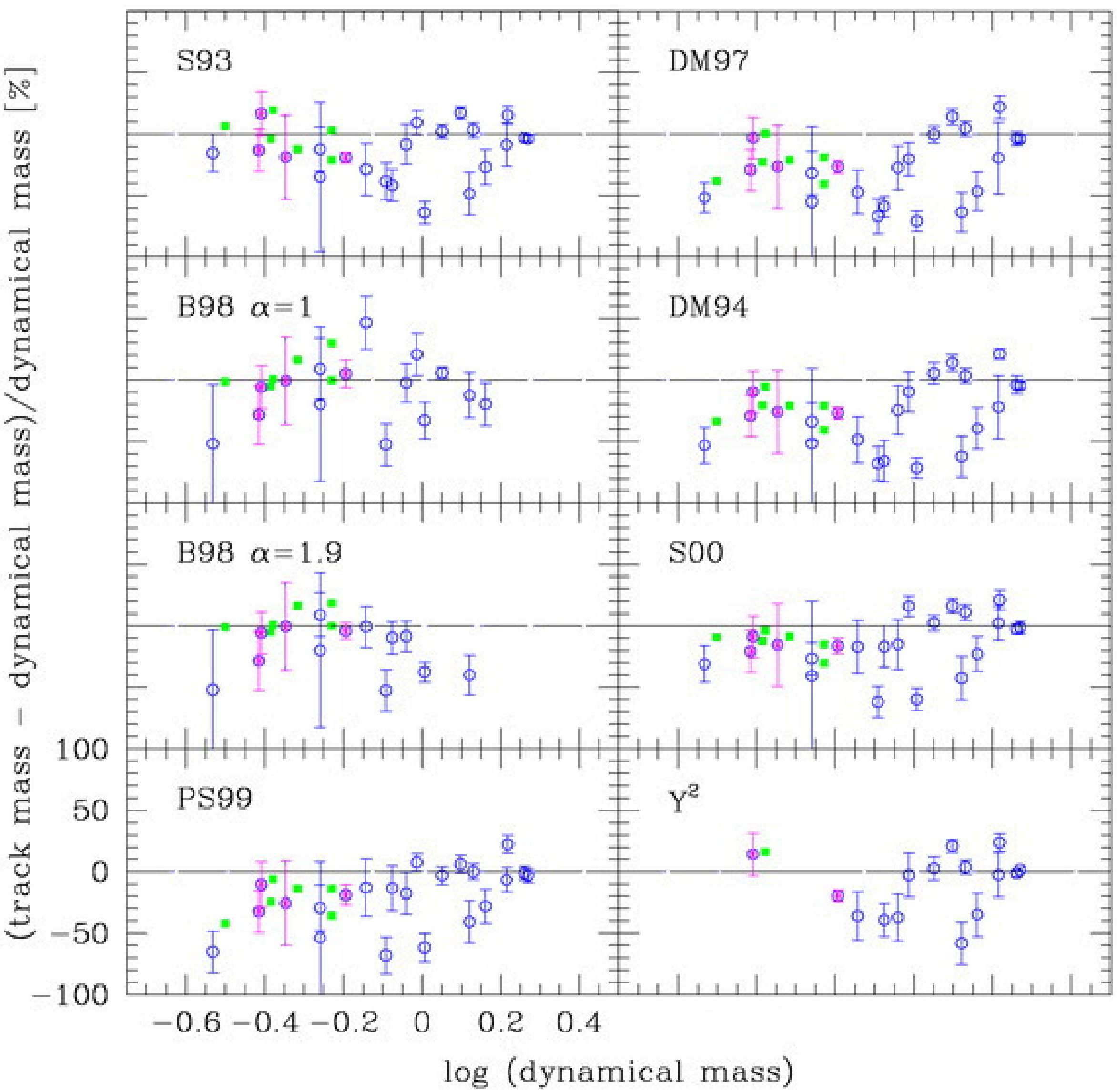
A Radius-Mass Calibration from Binaries



Mass and radius measurements for our sample stars. Open symbols represent pre main-sequence objects and filled symbols main-sequence stars. For the double-lined eclipsing systems both axes are fundamentally derived from observation, whereas for the non-eclipsing systems the masses are fundamental, but the radii are inferred from luminosity and effective temperature values. The 1 and 10 Myr isochrones of DM97 are indicated (*dotted lines*) as are the ZAMSs from S93 (*solid line*) and Y^2 (*dashed line*) models.

Hillenbrand & White 2004

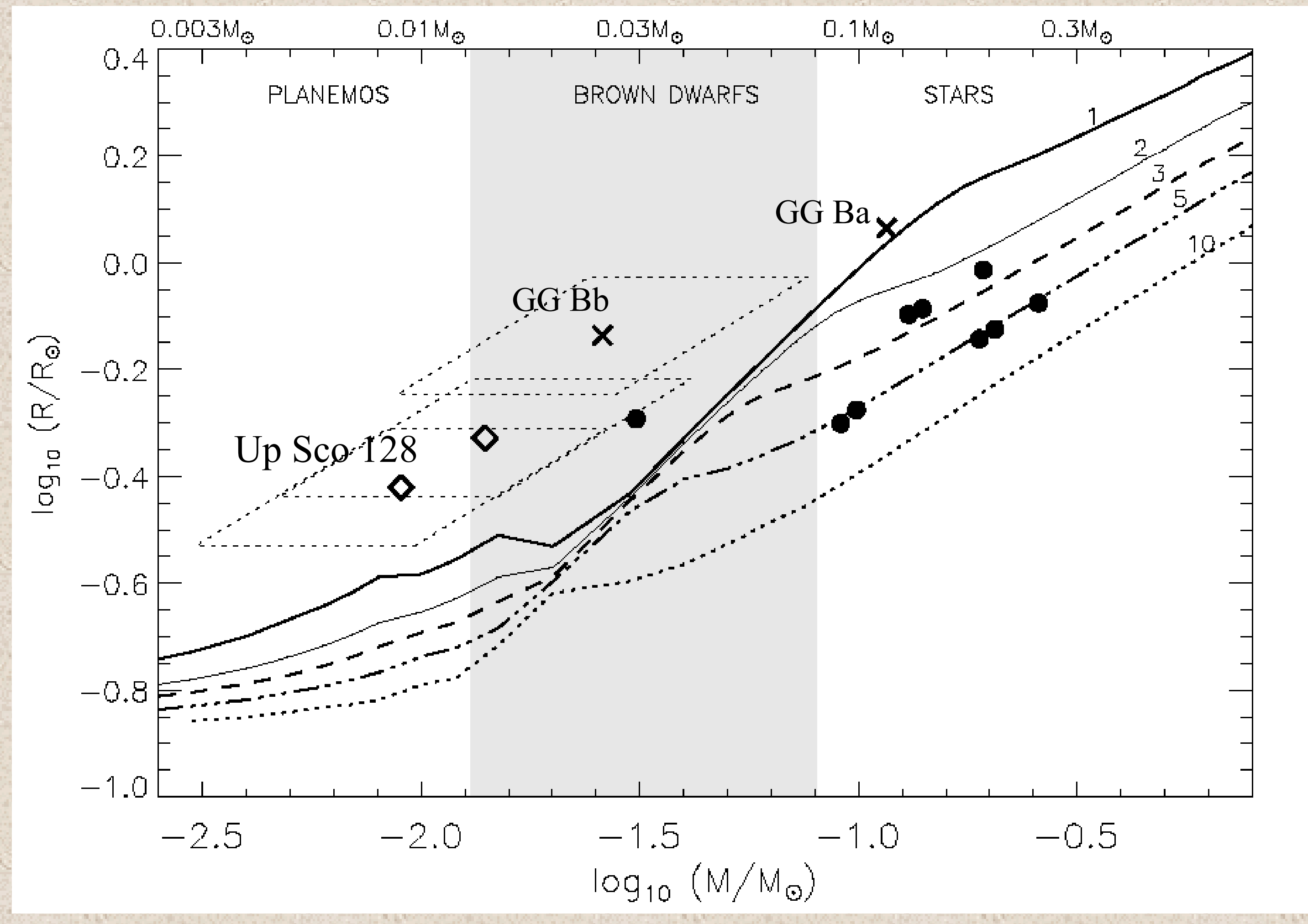
Higher Mass Binary Mass Calibration



Percentage mass offset vs. dynamically determined stellar mass for individual pre main-sequence stars. Vertical error bars indicate the root sum squared of the dynamical mass and the track mass error, the latter estimated from the log L and log T errors. To illustrate the effects of temperature scale choice, we show both the dwarf temperature scale adopted here (*circles*) and the warmer Luhman et al. (2003) temperature scale (*squares*) for stars later than M0, offset by +0.03 in log (dynamical mass) for clarity.

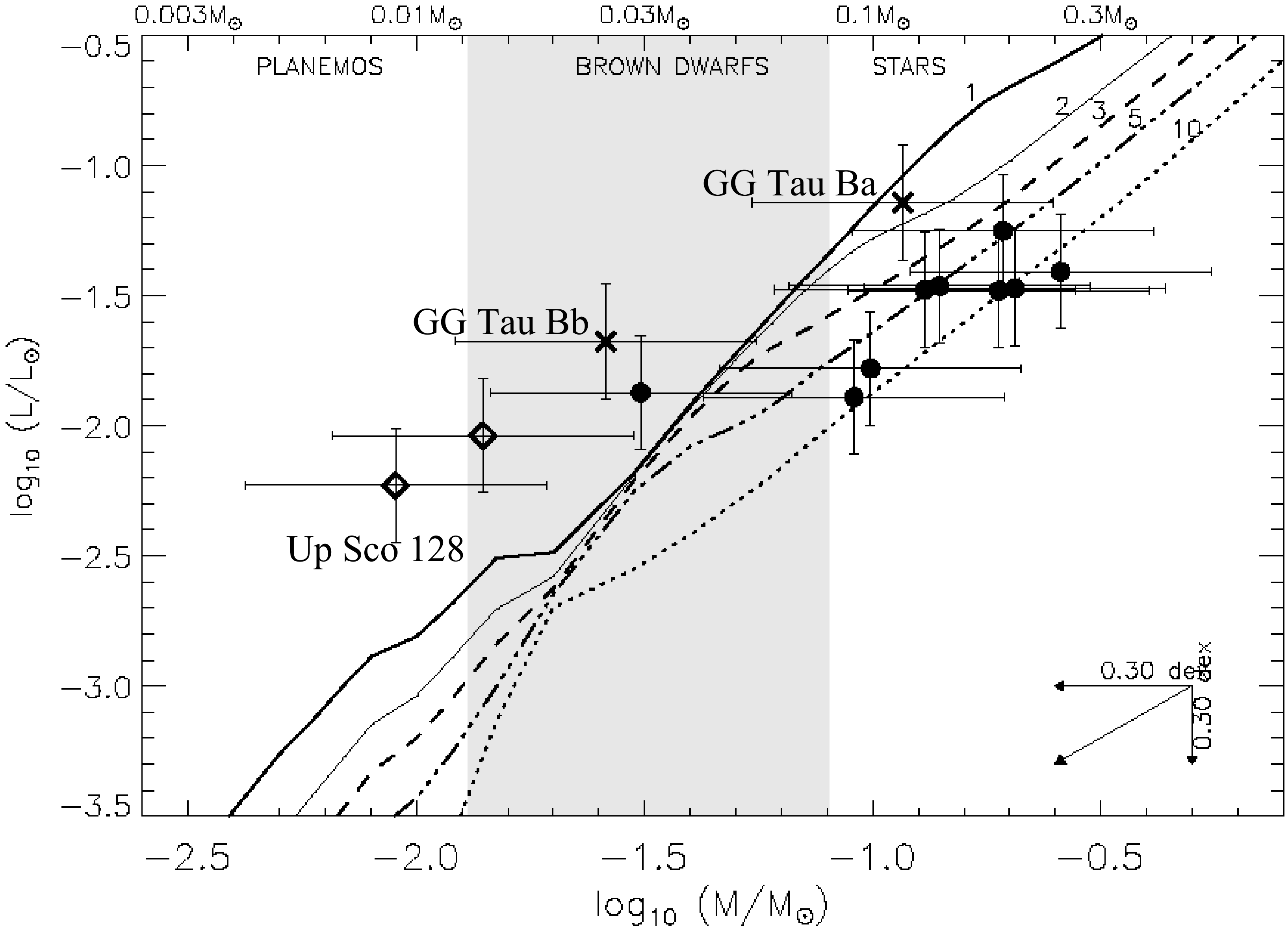
Hillenbrand & White 2004

Radius vs Mass (from L,T, and g)



Once again we find a problem between temperatures found by high resolution spectroscopy and models. The radii of very low-mass objects are too small in the evolutionary models. It is amazing that the model spectra can fit so well in detail if the model atmospheres are wrong (and clouds don't form).

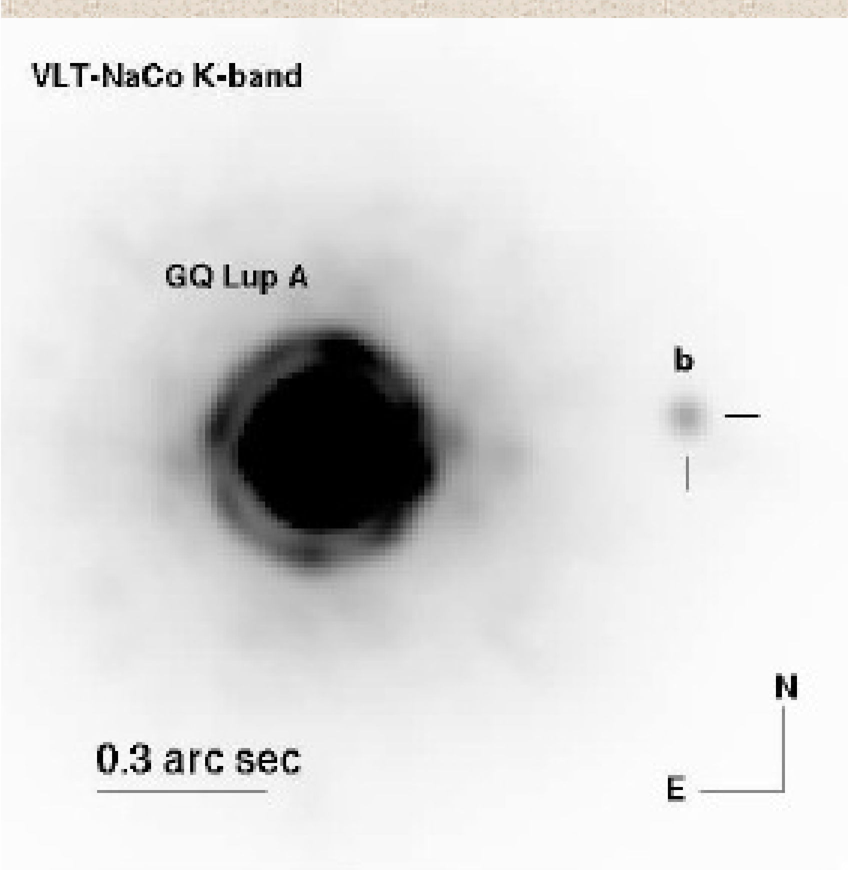
Mass-Luminosity Relation

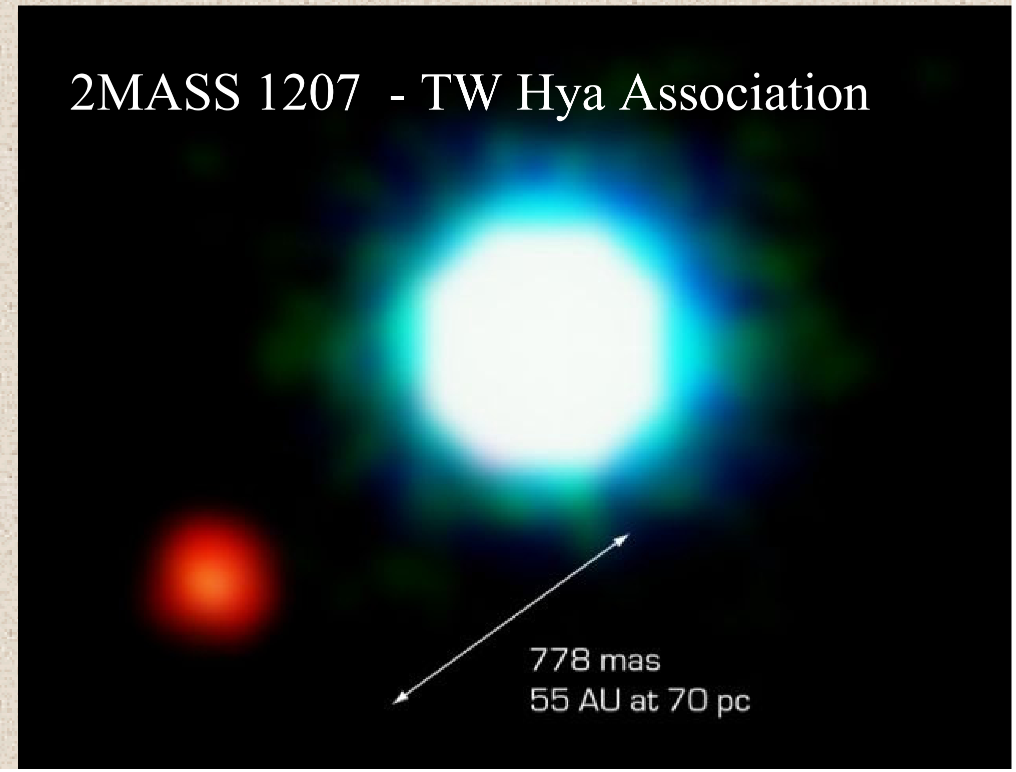


We suggest that the lowest free-floating objects being found may be below the D-burning limit!

Images of Exoplanets?

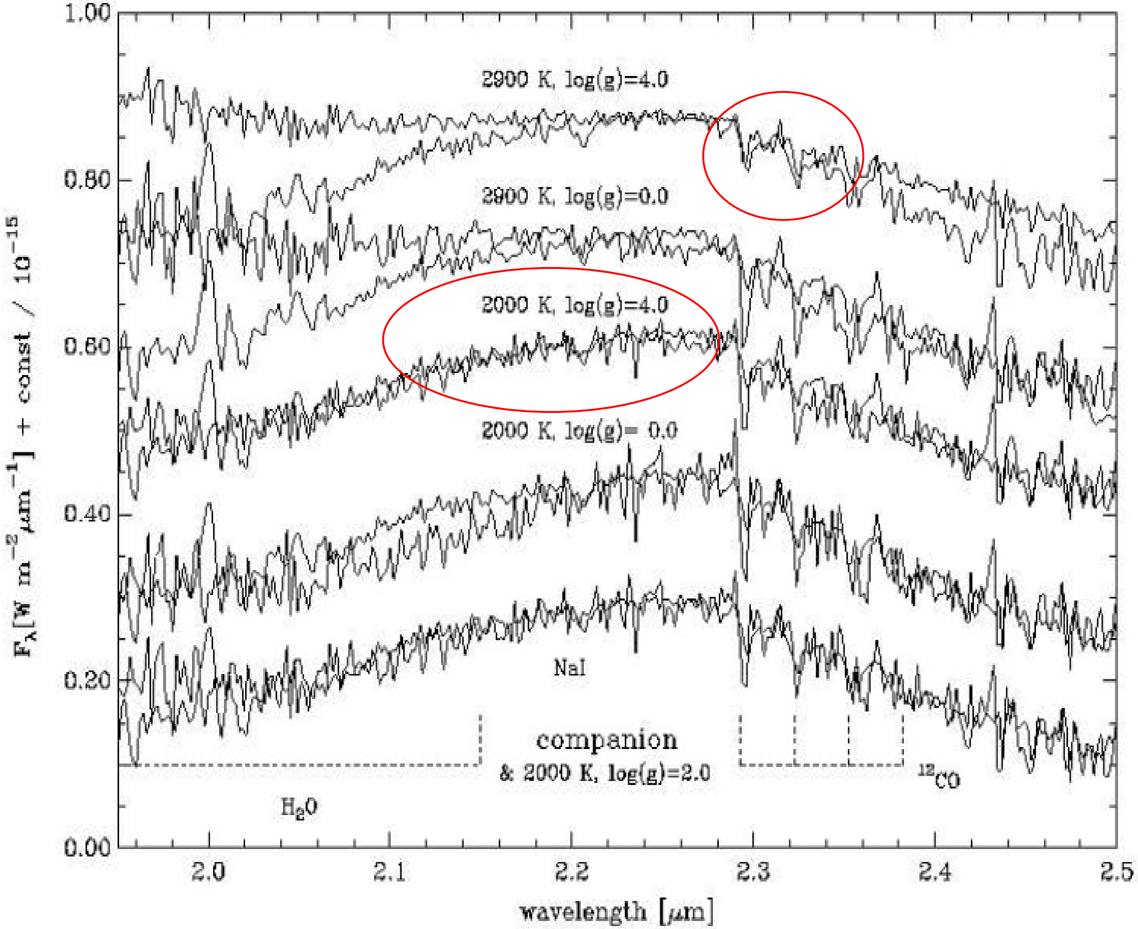
Recent claims have been made of the first images of massive young exoplanets. Are these planemos or brown dwarfs. Everything hinges on the model calibrations (and often on the temperature calibrations as well, though that is not required). Age and distance are also crucial to the estimates, but those are better in hand.





Estimating Mass the "Traditional" Way

For GQ Lupi, uncalibrated models and rough spectral typing were used to estimate mass. The spectral typing is difficult at low resolution; different features fit with different values of T and log(g). "Calibrated" models (eg. Lyon) yield brown dwarf rather than planetary masses, while new models claim to do a better job of the very early phases (but have not been tested against relevant observations at all).



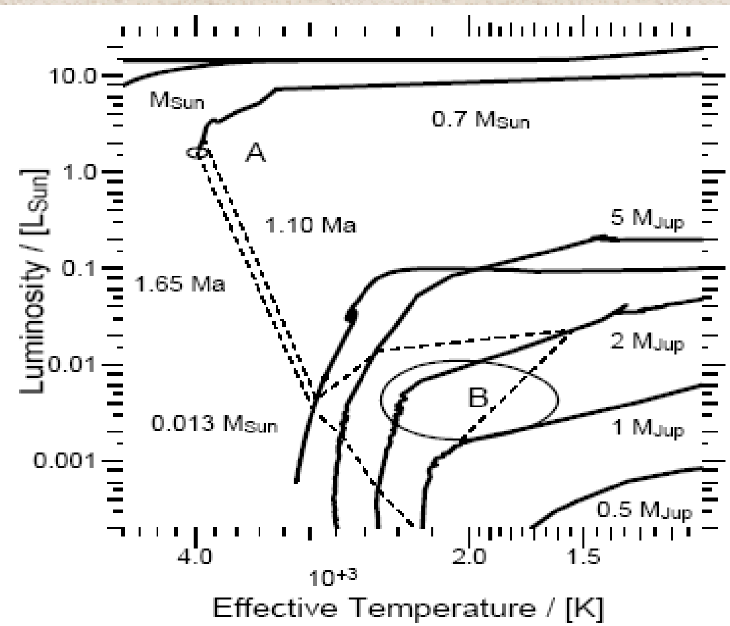
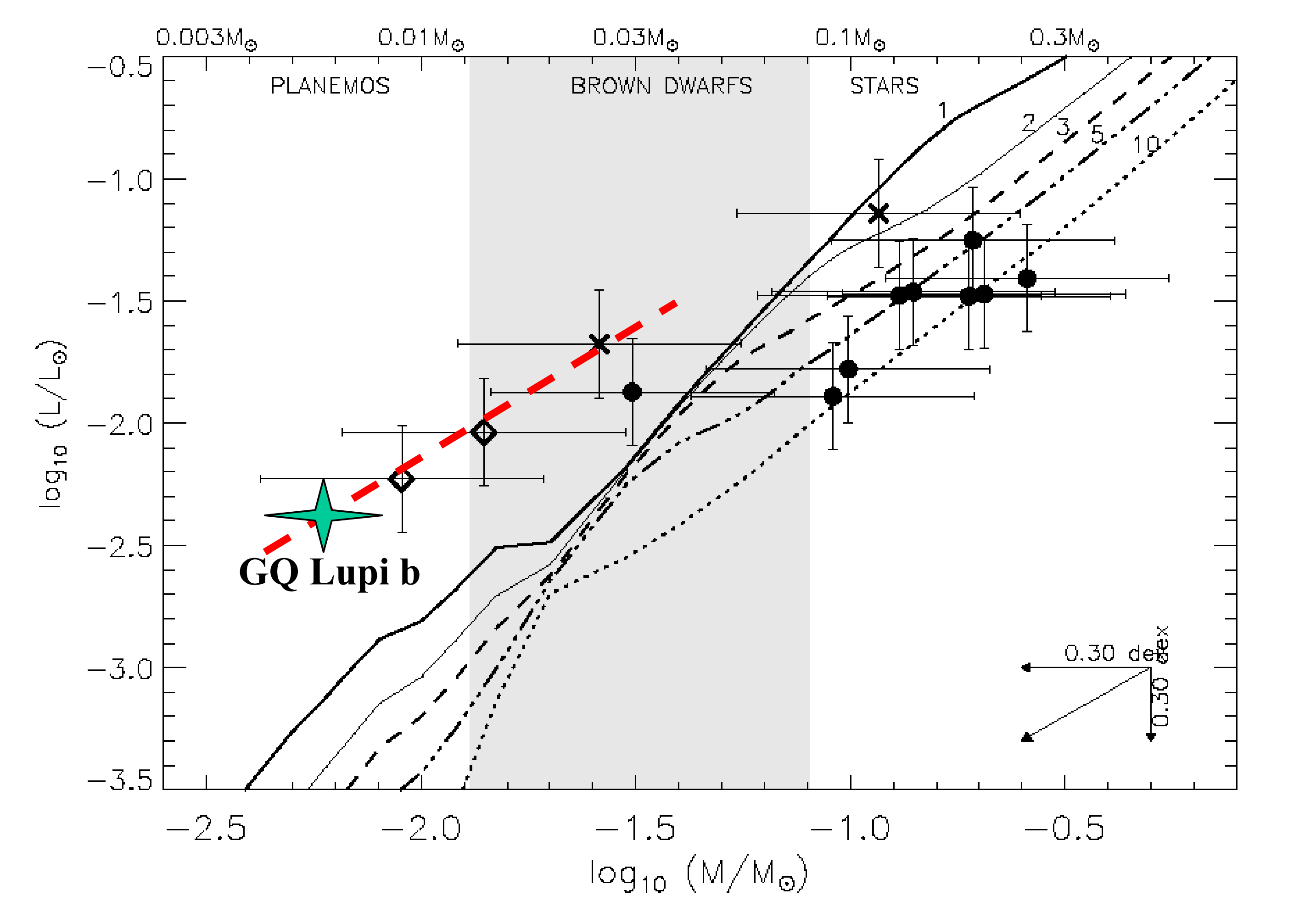


Fig. 4. H-R diagram with tracks from Wuchterl & Tscharnuter (2003) plus more tracks calculated by us (from top to bottom) for 1 and 0.7 $M_\odot$ as well as 13, 5, 2, 1, and 0.5 M_{Jup}. The isochrones (dashed) for 1.10 and 1.65 Myr connect the end of the 0.7 $M_\odot$ track (star A) with the planetary tracks. Components A and B (1σ errors) are co-eval at ~ 1.1 Ma.

Mass the "New" Way

GQ Lupi is younger, but still cooler and fainter than the faintest Upper Sco object. This may indeed mean it is a planemo.

The 2MASS object is older (and much fainter), and Lyon models yield 5 jupiters, so it is almost certainly a planemo.



A New Test of the Mass Calibration

One way to check on the gravity results is to find an independent way of estimating the mass of one of the Upper Sco objects. We are very fortunate in having found such a test: a double-lined spectroscopic binary at low mass with an orbital inclination high enough to yield meaningful mass limits.

Reiners, Basri, Mohanty 2005
(now available on astro-ph)

Table 2. Orbital solution; errors denote values at which $\chi^2 = 2\chi^2_{min}$

Parameter	Value
Period, P [d]	33.992 ± 0.006
$(M_1 + M_2)\sin i$ [$M_\odot$]	0.64 ± 0.02
Eccentricity, e	0.276 ± 0.008
Semimajor axis, a [AU]	0.177 ± 0.002
Longitude of periastron, Ω [°]	274.5 ± 0.8
Epoch (MJD), T [d]	52 799.974 ± 0.002

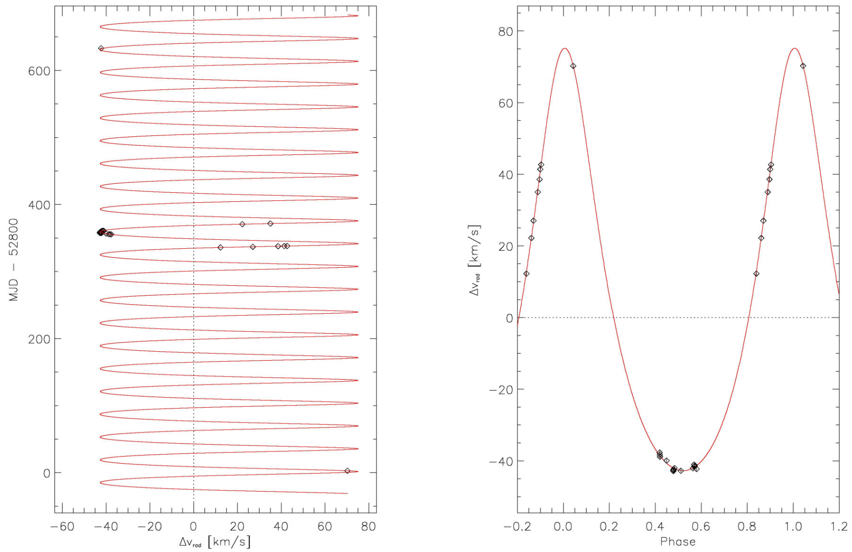
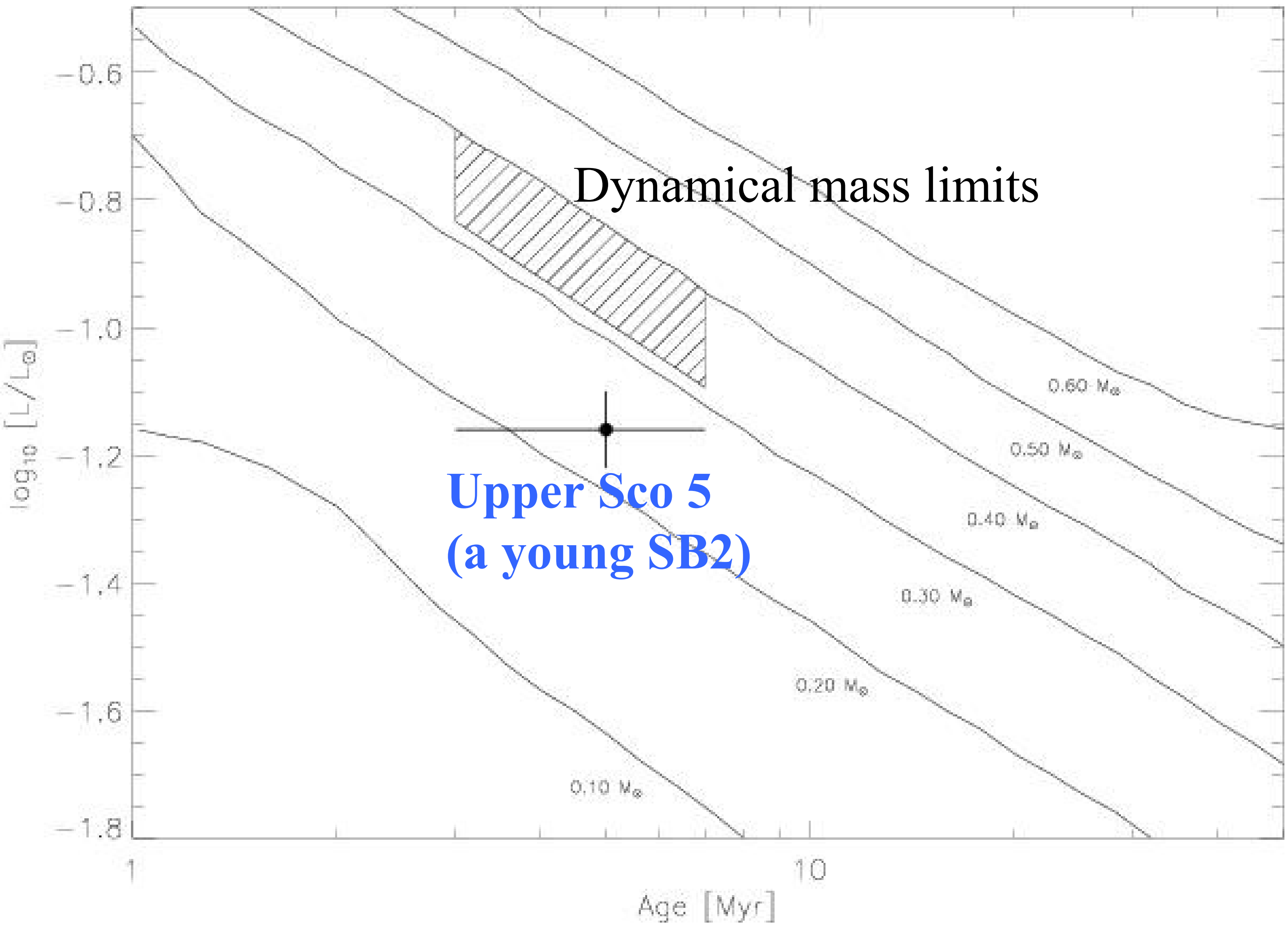


Fig. 2.— Measurements of differential radial velocity Δv_{rad} (symbols) and orbital solution (red line). *Left panel*: Δv_{rad} vs. MJD−52 800. *Right panel*: Phase binned Δv_{rad}. The rms scatter of Δv_{rad} is 480 m s^{-1}; these errors are smaller than the symbol size.

A New Test of the Mass Calibration



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Concluding Remarks

- **Calibrating models in luminosity, temperature, radius, and mass is one of the critical problems facing studies of ultra low-mass forming objects**

- **Observational calibration of these variables is in need of improvement, particularly temperature determinations**
- **Binaries (as always) provide the best hope to solve this**
- **High resolution spectroscopy is a good intermediate step, and can eventually serve to provide measurements for many single objects**
- **Surface gravity diagnostics can be applied successfully to obtain masses, if the model spectra can be trusted**

- **There seems to be a problem with the mass scales for models (they underestimate mass for most brown dwarfs)**
- **We appear to be imaging (and taking spectra) of objects below the fusion limit, both as companions and free-floating**
- **There is a problematic mass range 2-20 jupiters where current claims of mass determinations must be further confirmed**