AB Dor C: Observational Calibration of Theoretical Cooling Curves for Young, Low-Mass Objects

Eric L. Nielsen, Steward Observatory

Ultra-Low Mass Star Formation and Evolution Workshop
La Palma 2005

- “A Dynamical Calibration of the Mass-Luminosity Relation at Very Low Masses and Young Ages”
  - Laird M. Close[1], Rainer Lenzen[2], Jose C. Guirado[3], Eric L. Nielsen[1], Eric Mamajek[4], Wolfgang Brandner[2], Markus Hartung[5], Chris Lidman[5], Beth Biller[1]
    - 1: Steward Observatory, USA
    - 2: Max-Plank-Institut fur Astronomie, Germany
    - 3: Department d'Astronomia i Astrofisica, Universitat de Valencia, Spain
    - 4: Center for Astrophysics, USA
    - 5: European Southern Observatory, Chile
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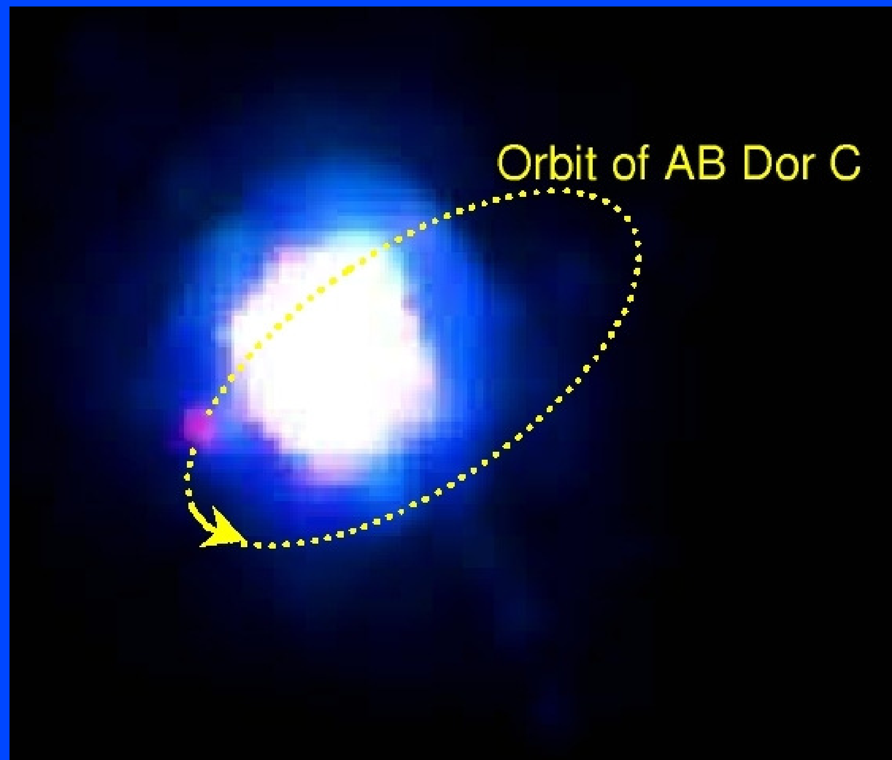
  - 20 January 2005



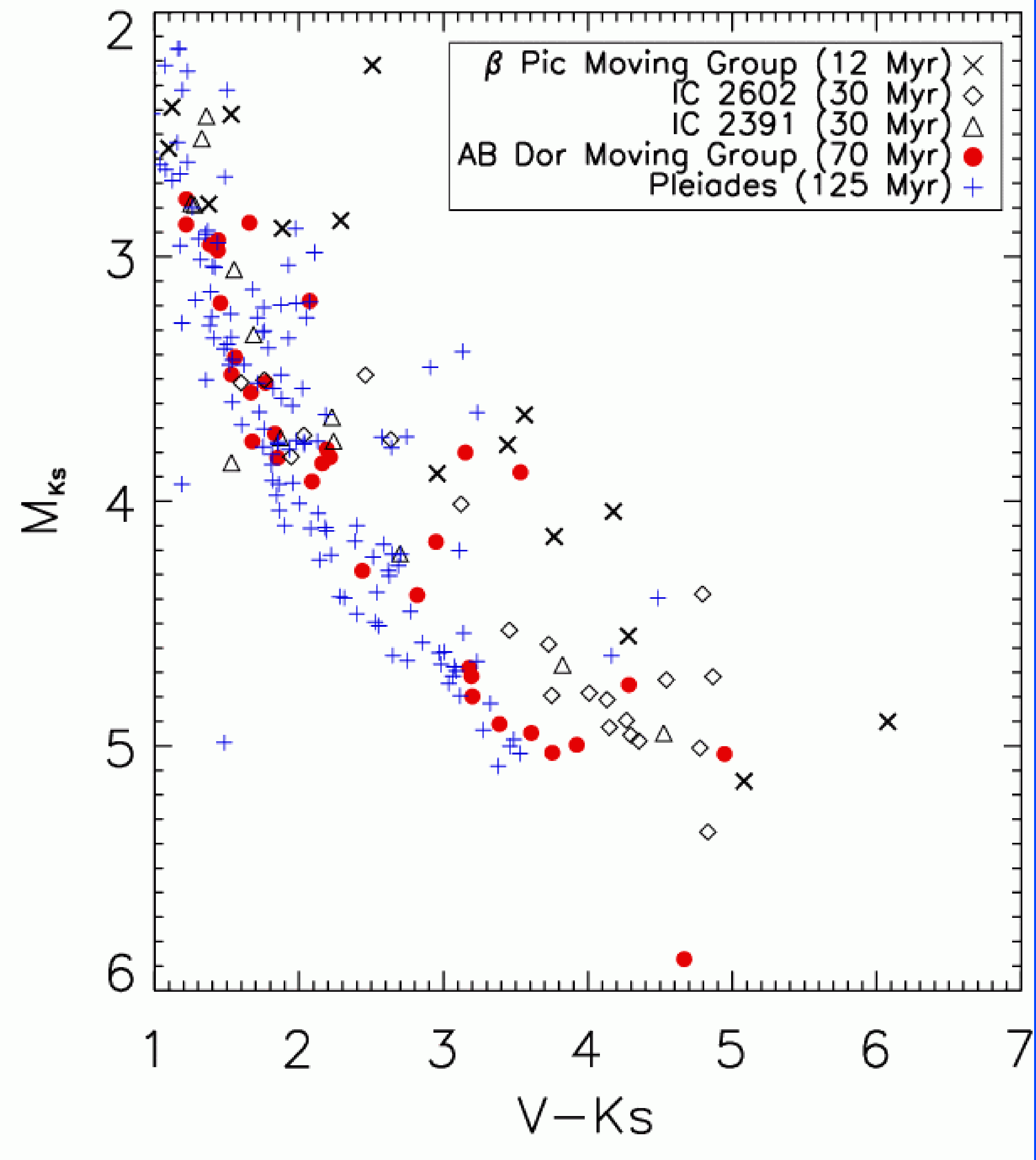
Motivation

- Masses of young substellar objects are notoriously difficult to measure
- Most surveys of young objects measure photometric (and possibly spectral) data and use cooling curves to obtain predicted mass.
- So determinations of the low-mass IMF relies heavily on the accuracy of these models.
- For young, low-mass objects these theoretical tracks are very poorly constrained by dynamical masses.

AB Doradus A

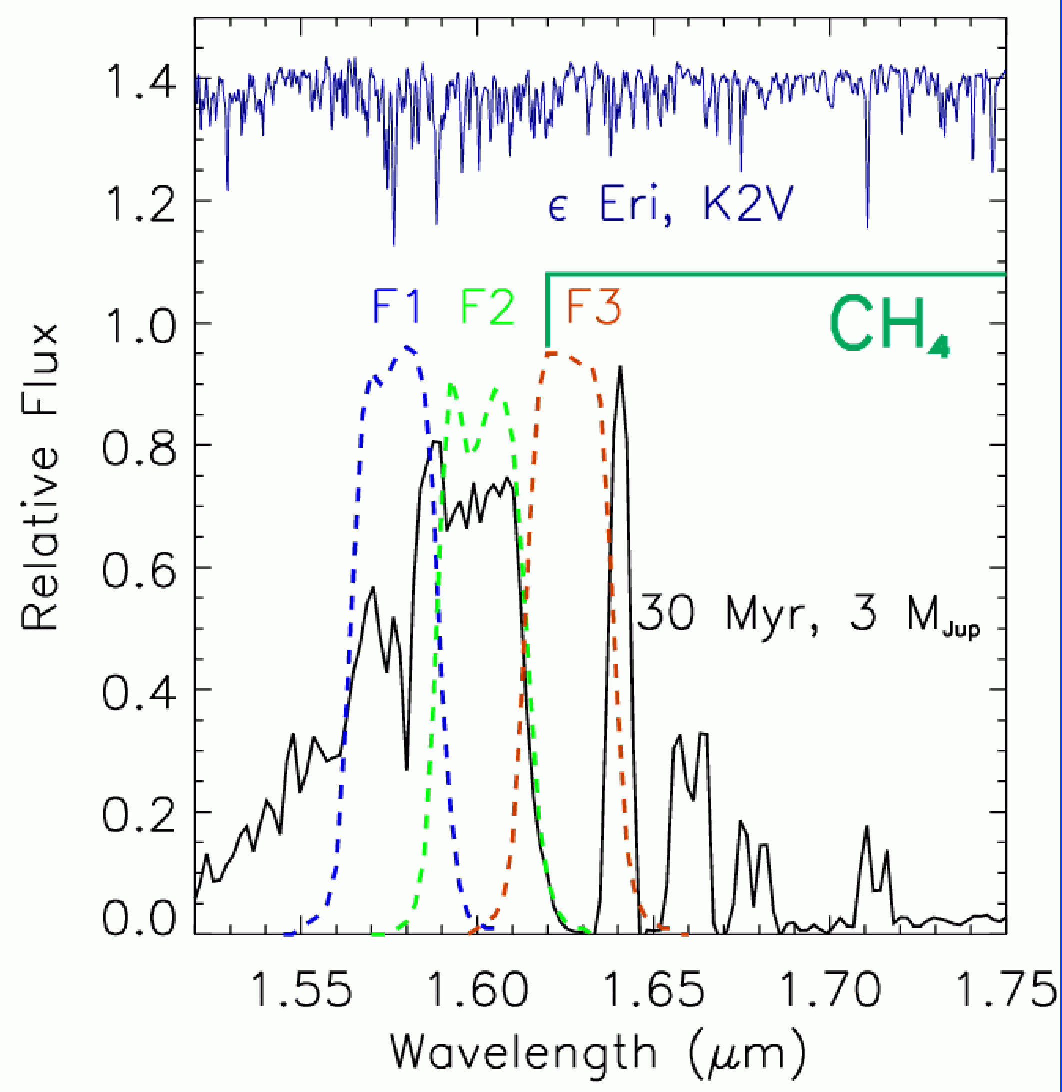
- K1, Age ~ 70 Myr (30 Myr – 100 Myr)
  - Lithium Rich (EW ~ 279 mA)
  - Extremely chromospherically active
  - Large UV, X-ray activity
  - Fast rotator (P = 12.3 hours)
  - Member of AB Dor moving group
- Has wide (9”) companions: AB Dor Ba,Bb (Binarity of AB Dor B discovered with our observations)
- Only 14.9 pc from the sun
- Combination of Hipparcos and VLBI astrometry led to indirect detection of AB Dor C, from reflex motion of AB Dor A, in 1997 (Guirado, J. C. et al., ApJ 490, 835 1997)

The Age of AB Dor



- AB Dor moving group main sequence seems best constrained between IC 2606/IC 2391 and Pleiades

Simultaneous Differential Imaging (SDI)



Model planet spectrum from D. Sudarsky (private communication), eps Eri spectrum from Meyer et al. 1998.

- Technique for imaging close companions at very high contrasts.
- Wollaston beam splitters produce four identical beams, passed through a quad-filter, with narrow band passes at 1.575, 1.600, and 1.625 microns.
- Cameras installed and collecting data at MMT (PI: Laird Close and Don McCarthy) and VLT (PI: Laird Close and Rainer Lenzen)

Speckles with SDI

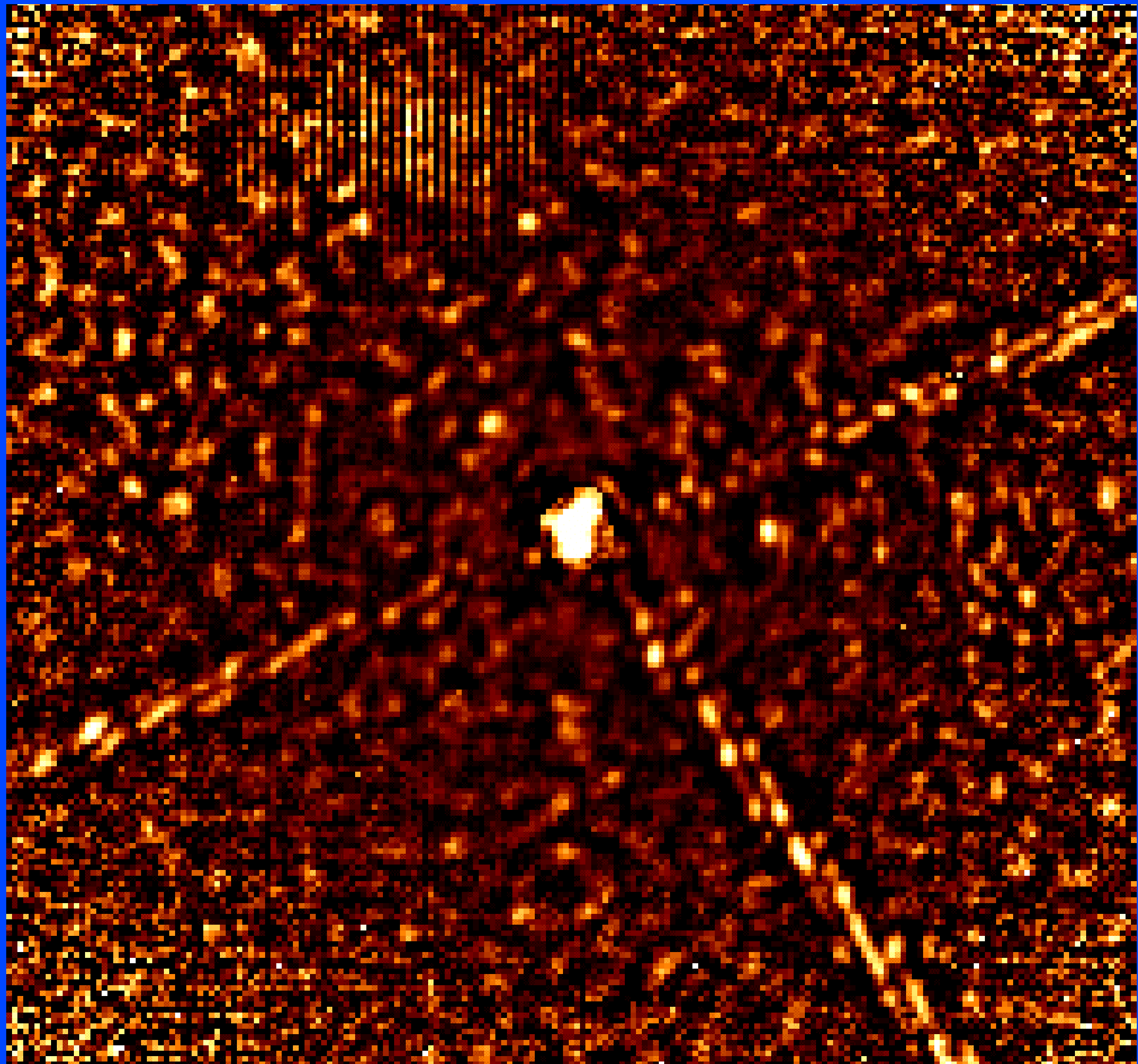


Image from Laird Close and Beth Biller

SDI: Suppressing Speckle Noise

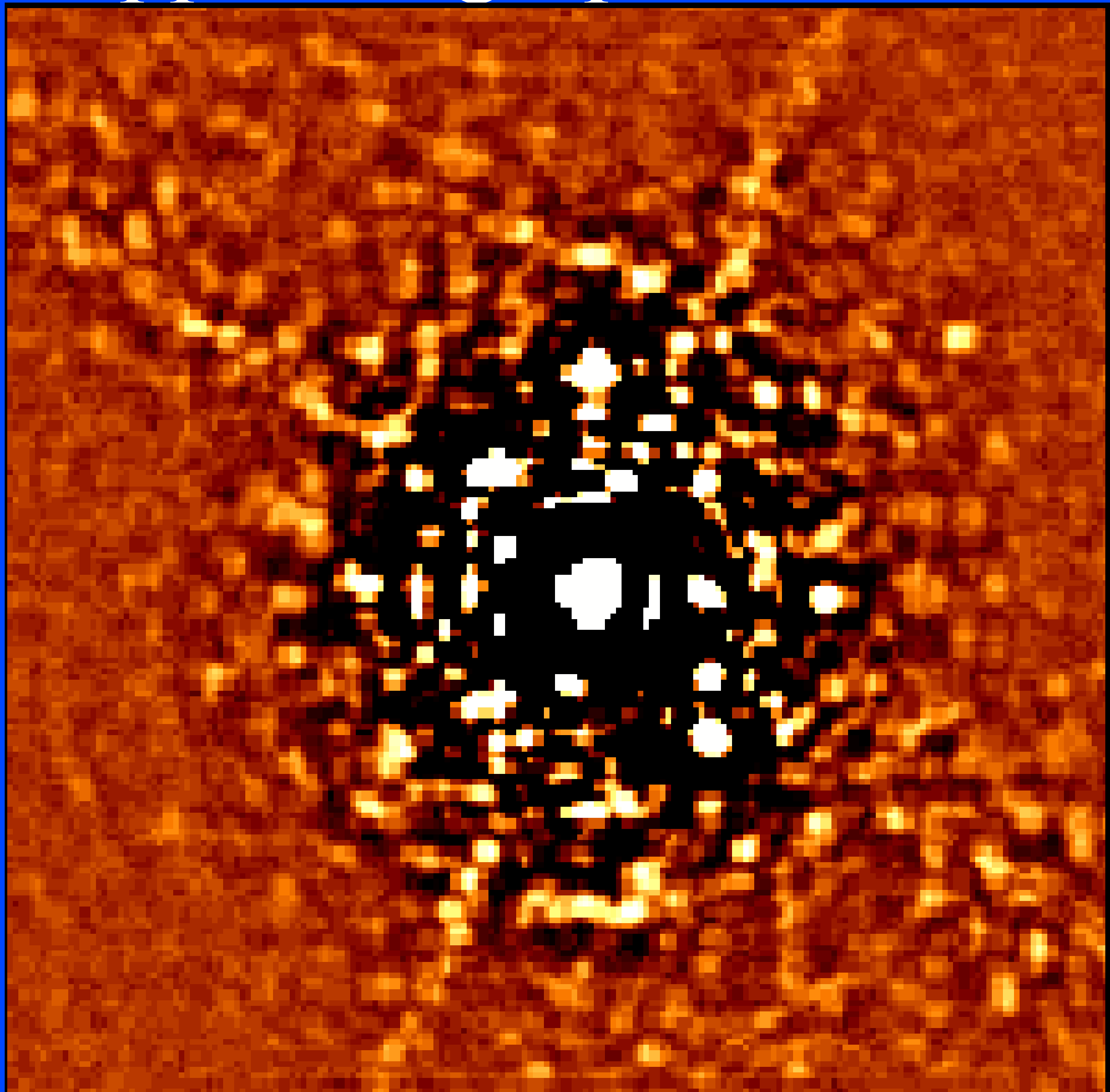
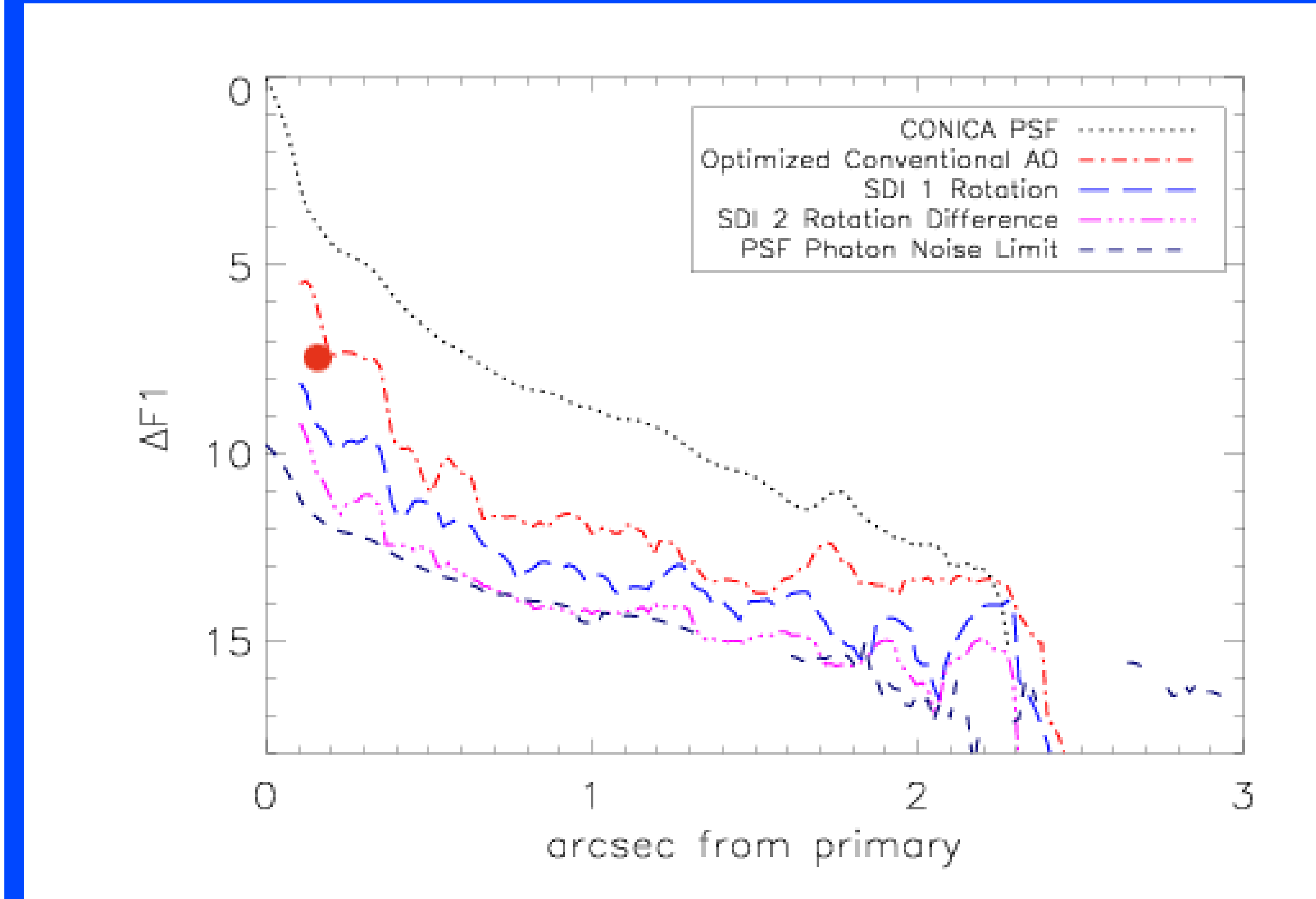


Image from Laird Close and Beth Biller

Looking for AB Dor C with NACO SDI at the VLT



B. Biller et al. SPIE, 2004.

- With VLT adaptive optics, AB Dor C is still a 1-sigma detection after 40 minutes
- SDI allows for a very convincing detection

SDI detection of AB Dor C

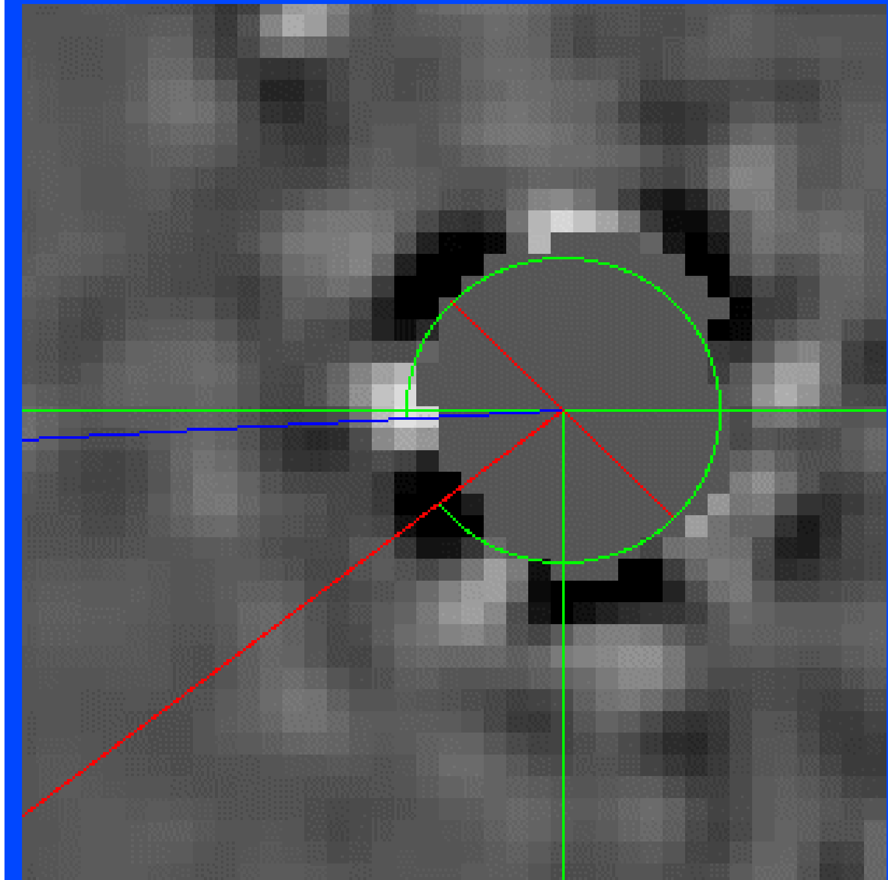
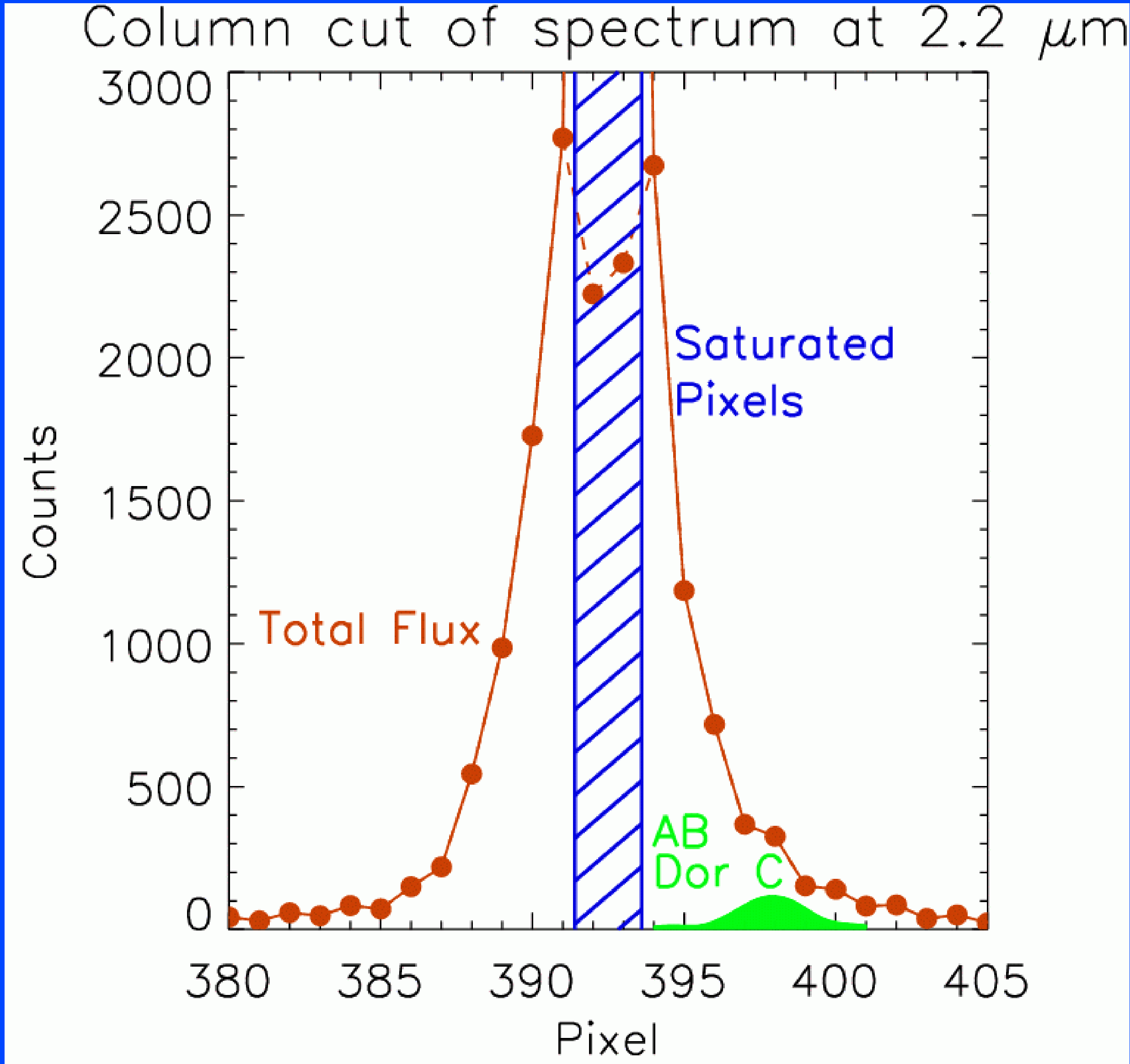


Image from Laird Close

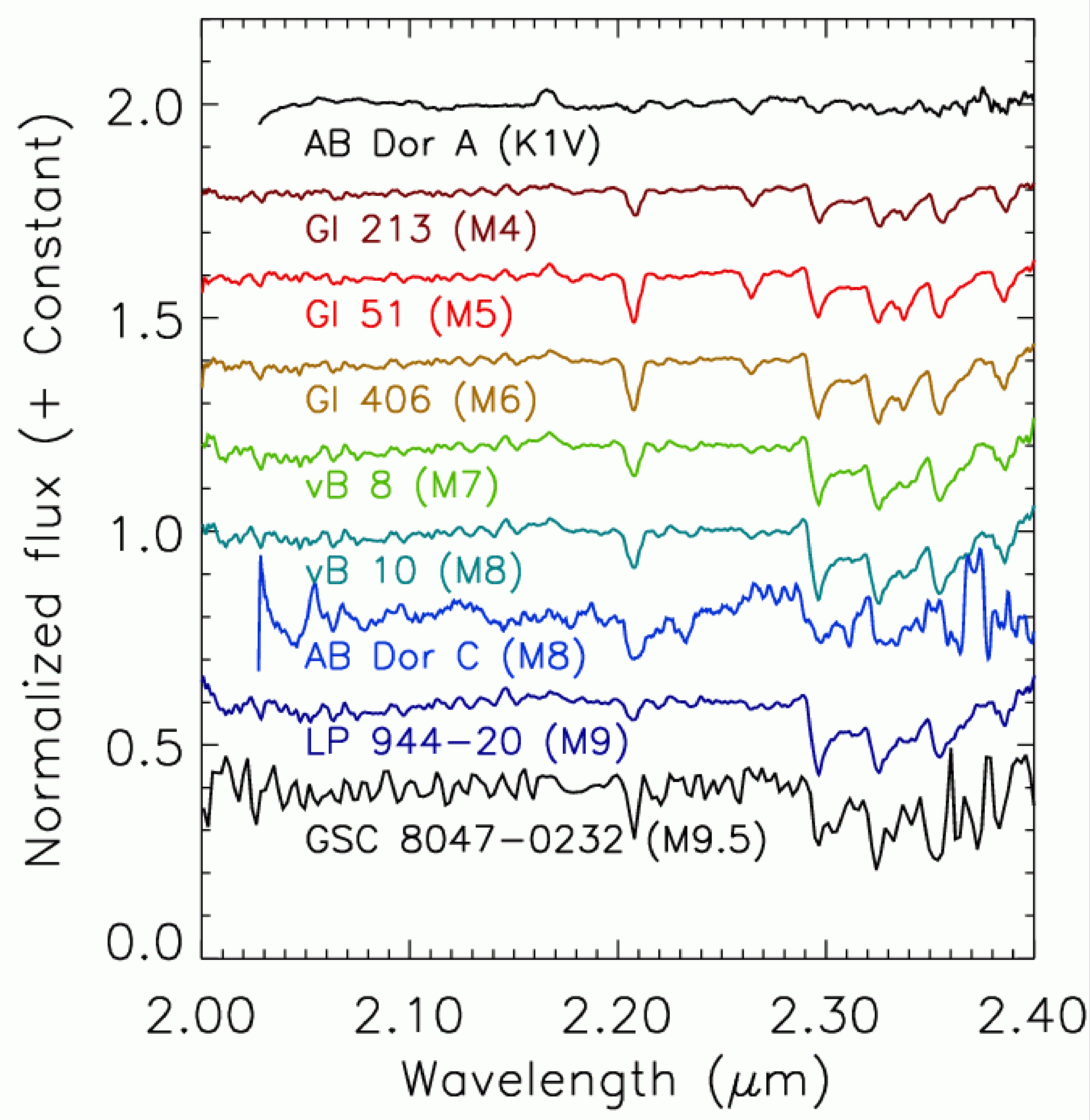
- Commissioning run of VLT SDI device in February 2004
- Offset from AB Dor A is 0.156 arcseconds (2.3 AU)
- Initial detection with standard SDI pipeline (B. Biller et al. SPIE symposium 5490 in press 2004). Companion spotted within one hour of observations.
- Immediate detection allowed follow-up spectroscopy and photometry.

Spectral Reduction

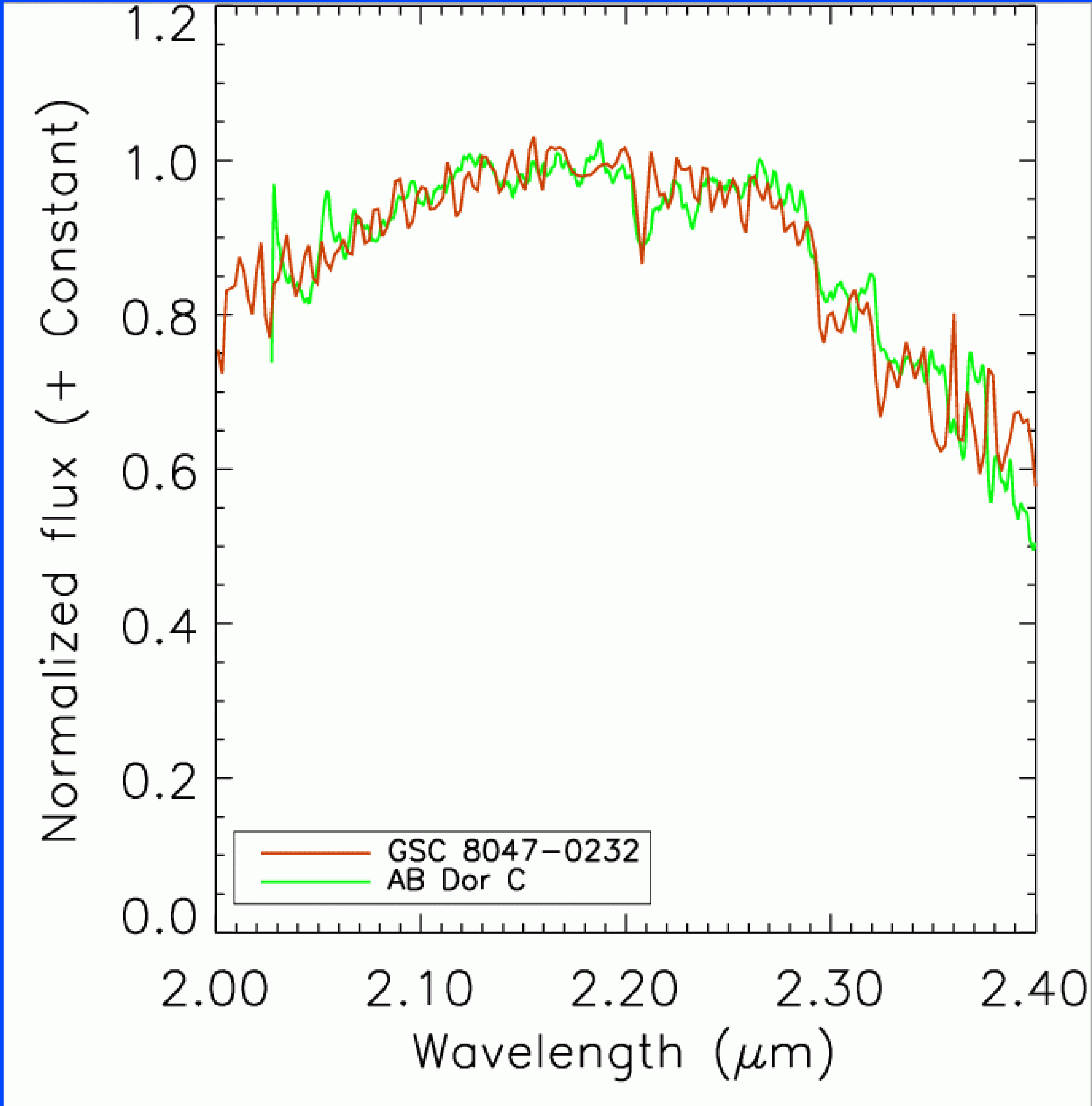


- AB Dor C is ~80 times fainter at K-band
- Offset from AB Dor A is 162 mas (6 pixels)
- Inner pixels of AB Dor A spectrum are intentionally saturated
- Derotator rotated by 180^{o} between exposures, allowing subtraction of AB Dor A spectrum

AB Dor C Spectrum

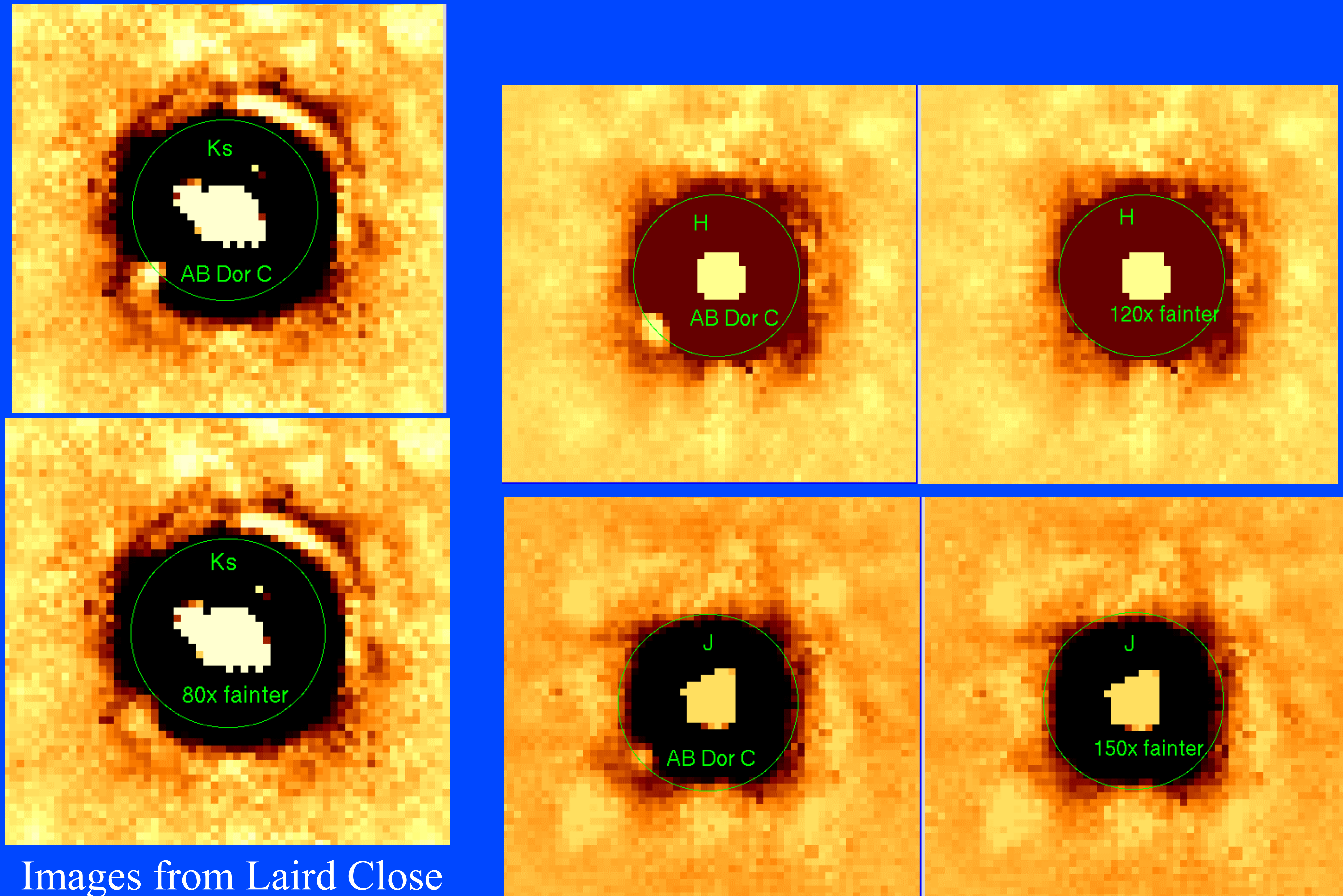


- Spectrum still noisy after subtraction, but is consistent with M8 (+/- 1) spectral type
- Spectrum qualitatively similar to young (30 Myr) M9.5, GSC 8047-0232
- From Luhman et al. ApJL, 489, L165 (1997), this gives T_{eff}=2600 +/- 150 K (dwarf sequence)
- M4-M9 templates from Michael Cushing (Cushing et al. 2005), GSC 8047-0232 courtesy of Gael Chauvin (Chauvin et al. 2005)



GSC 8047-0232 spectrum from Gael Chauvin

Photometric Reduction

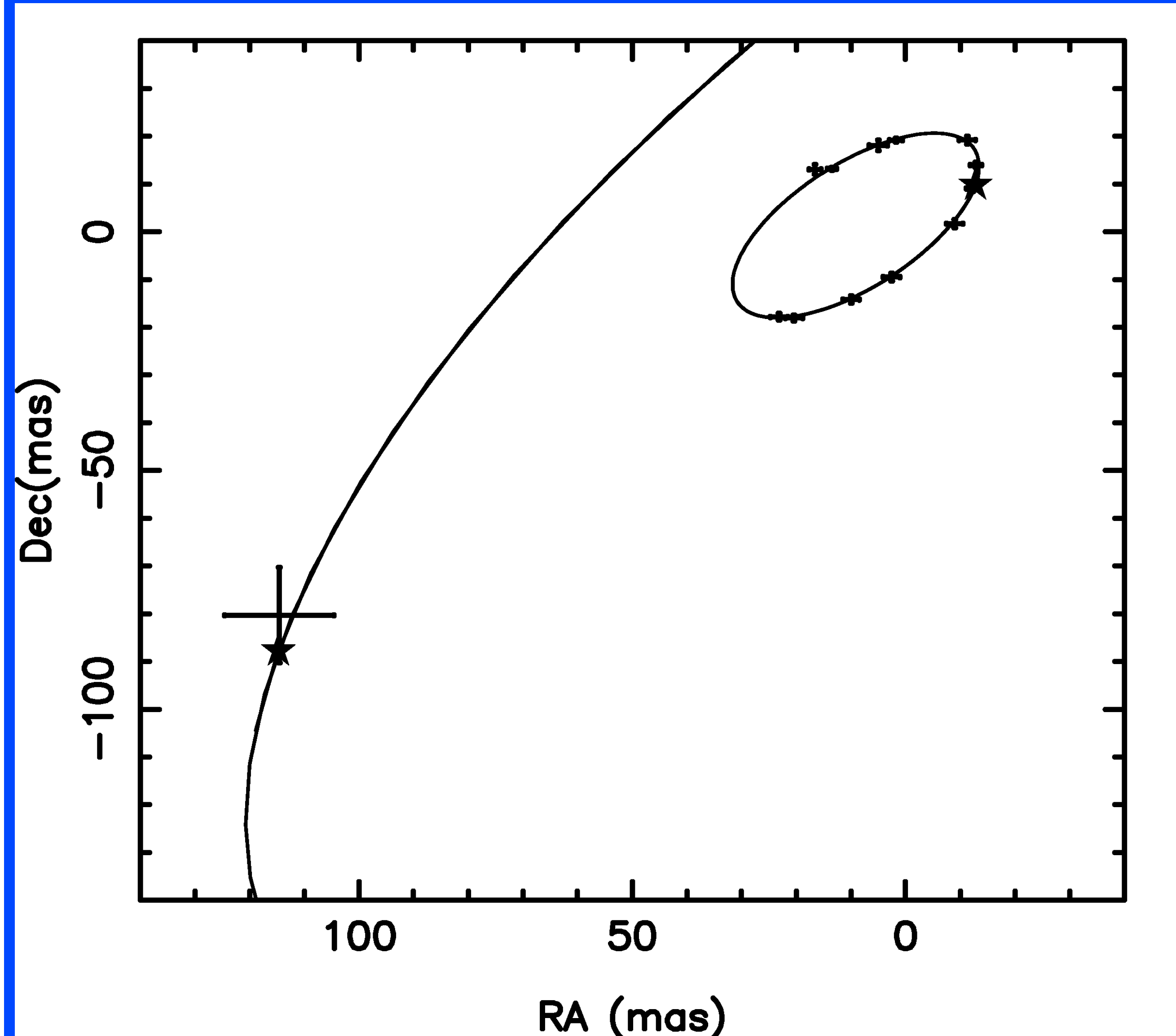


Images from Laird Close

AB Dor C Photometry

- NACO images, taken three days after initial detection, allow differential photometry between AB Dor A and C
- 2MASS Photometric data from AB Dor A and Hipparcos parallax gives absolute magnitudes:
  - $M_J = 9.89\ (+0.19, -0.24)$
  - $M_H = 9.19\ (+0.13, -0.15)$
  - $M_{KS} = 8.57\ (+0.12, -0.15)$
- Colors suggest L0 spectral type

AB Dor dynamic orbit



Close et al., 2005

- Small crosses are astrometry from Hipparcos and VLBI interferometry (1990-1997)
- Stars are VLT measured positions for AB Dor A and C (2004)
- J. Guirado refit orbital solution with new data

Mass of AB Dor A

- Tracks are more reliable on the main sequence
- Models give
  - 0.853 M_{sun} (Chabrier et al. 2000)
  - 0.853 M_{sun} (D'Antona & Mazzitelli AJ 456, 329-349 1996)
- Extrapolating from empirical tracks (using measurements of binaries) gives
  - 0.893 M_{sun} (Hillenbrand & White AJ 604, 741-757 2004)
- We use a value of 0.865 (+/- 0.034) M_{sun} for AB Dor A

AB Dor dynamic orbit (continued)

- Reflex motion of AB Dor A over six years and observed positions of the system from VLT images give excellent orbital solution.
- Orbital solution and mass of AB Dor A of 0.865 (+/- 0.034) M_{sun} , gives mass of AB Dor C of 0.090 (+/- 0.005) M_{sun}
- Additional parameters:
  - P = 11.75 +/- 0.25 years
  - a = 0.032 +/- 0.002" (0.48 +/- 0.03 AU) (AB Dor A)
  - a = 0.308 +/- 0.02" (4.6 +/- 0.3 AU) (AB Dor C)
  - e = 0.59 +/- 0.03, i = 67 +/- 3^{o}

Following the Orbit of AB Dor C

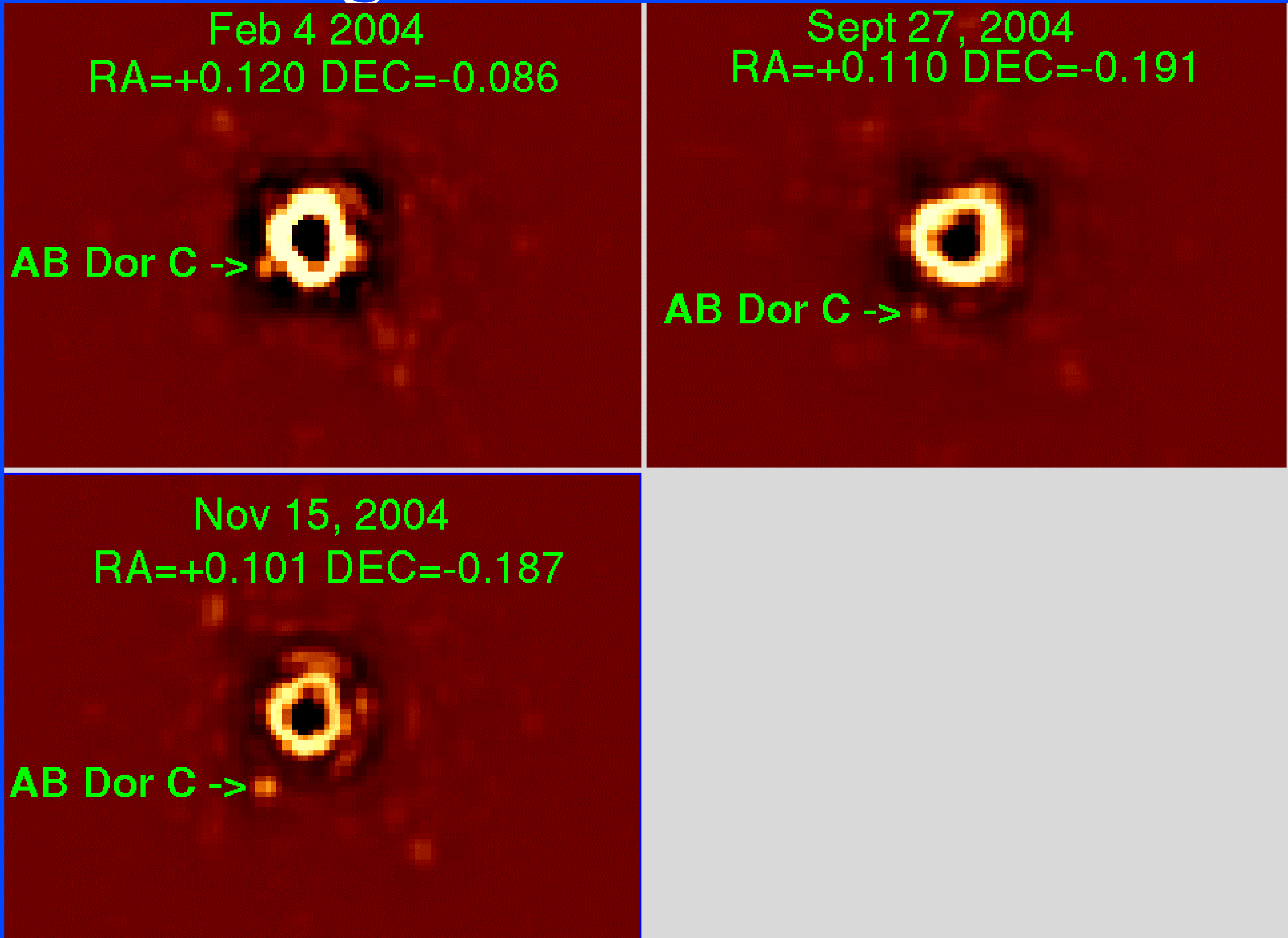
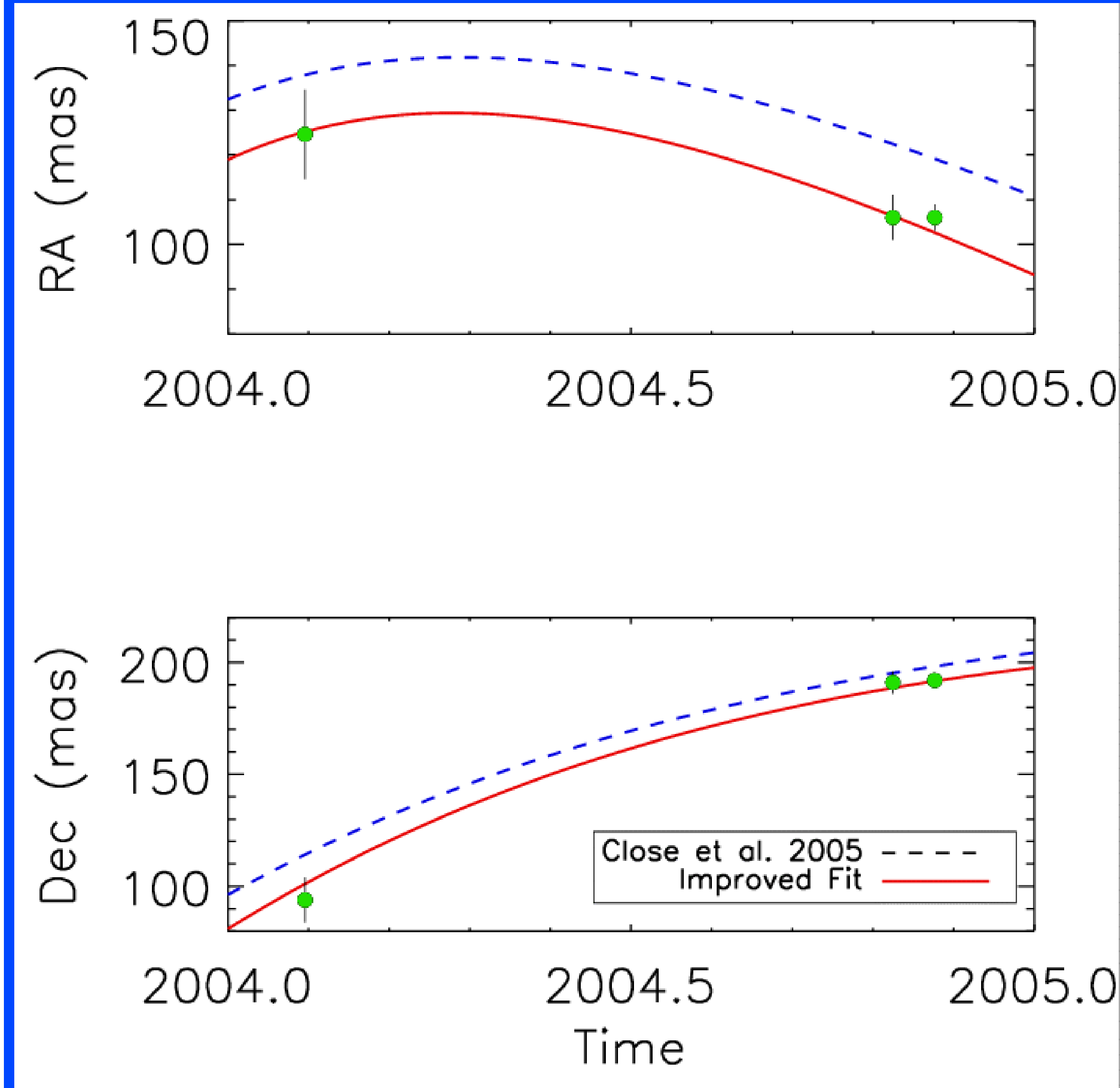


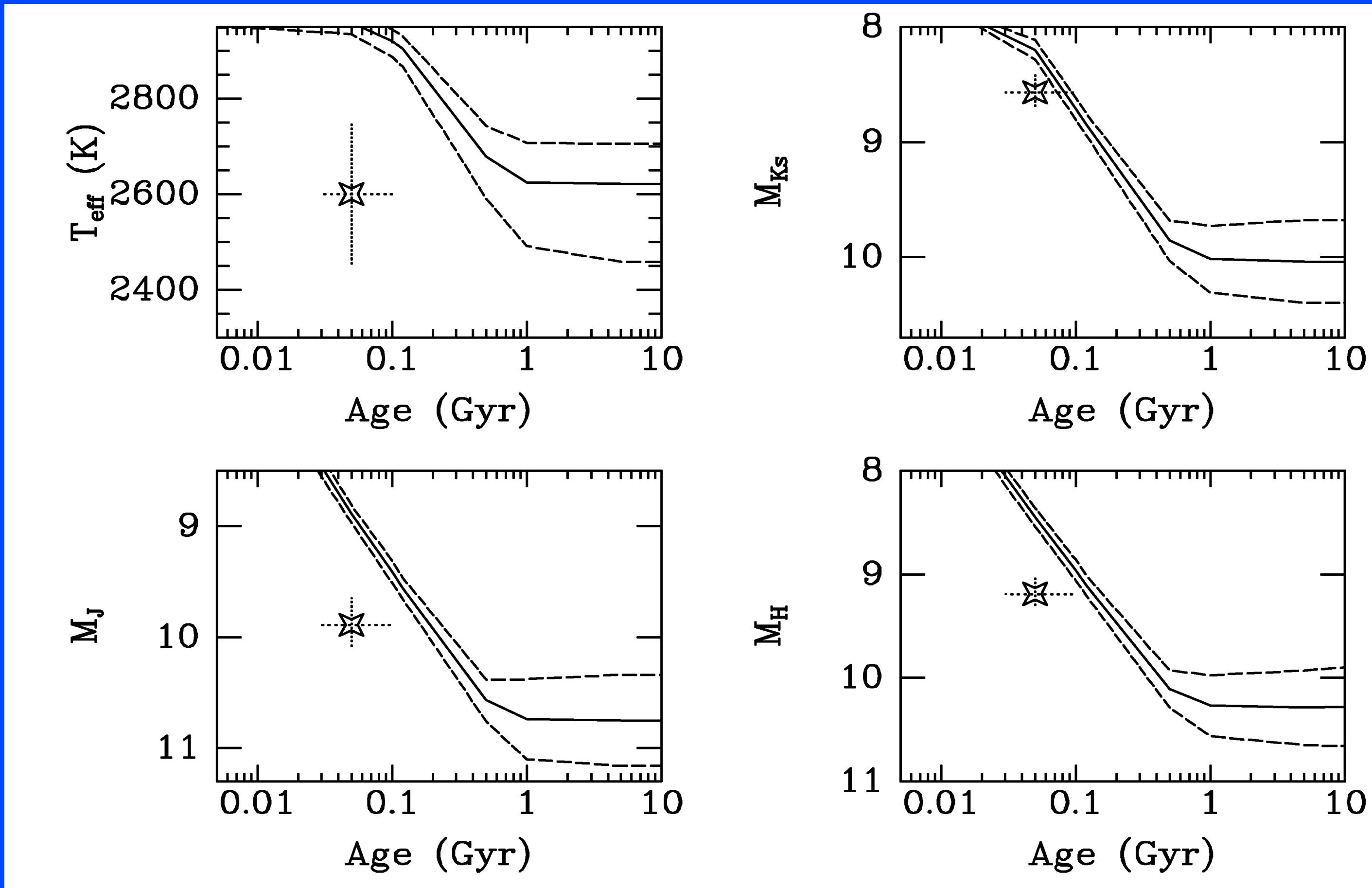
Image from Laird Close

Improved Orbit of AB Dor C



- Further epoch observations showed AB Dor C to be roughly following predicted orbit
- Improved fit achieved with minor changes to orbit parameters
- Mass of AB Dor C now 0.090 (+/- 0.003) M_{sun}

AB Dor C and Cooling Models



Close et al., 2005

- 0.085, 0.090, and 0.095 solar mass models, for an object of the age of AB Dor C, over-estimate luminosity and temperature
- Using models from Chabrier et al., ApJ 542, 464-472 (2000) [Available online: http:// perso.ens-lyon.fr /isabelle.baraffe/ DUSTY00_models]

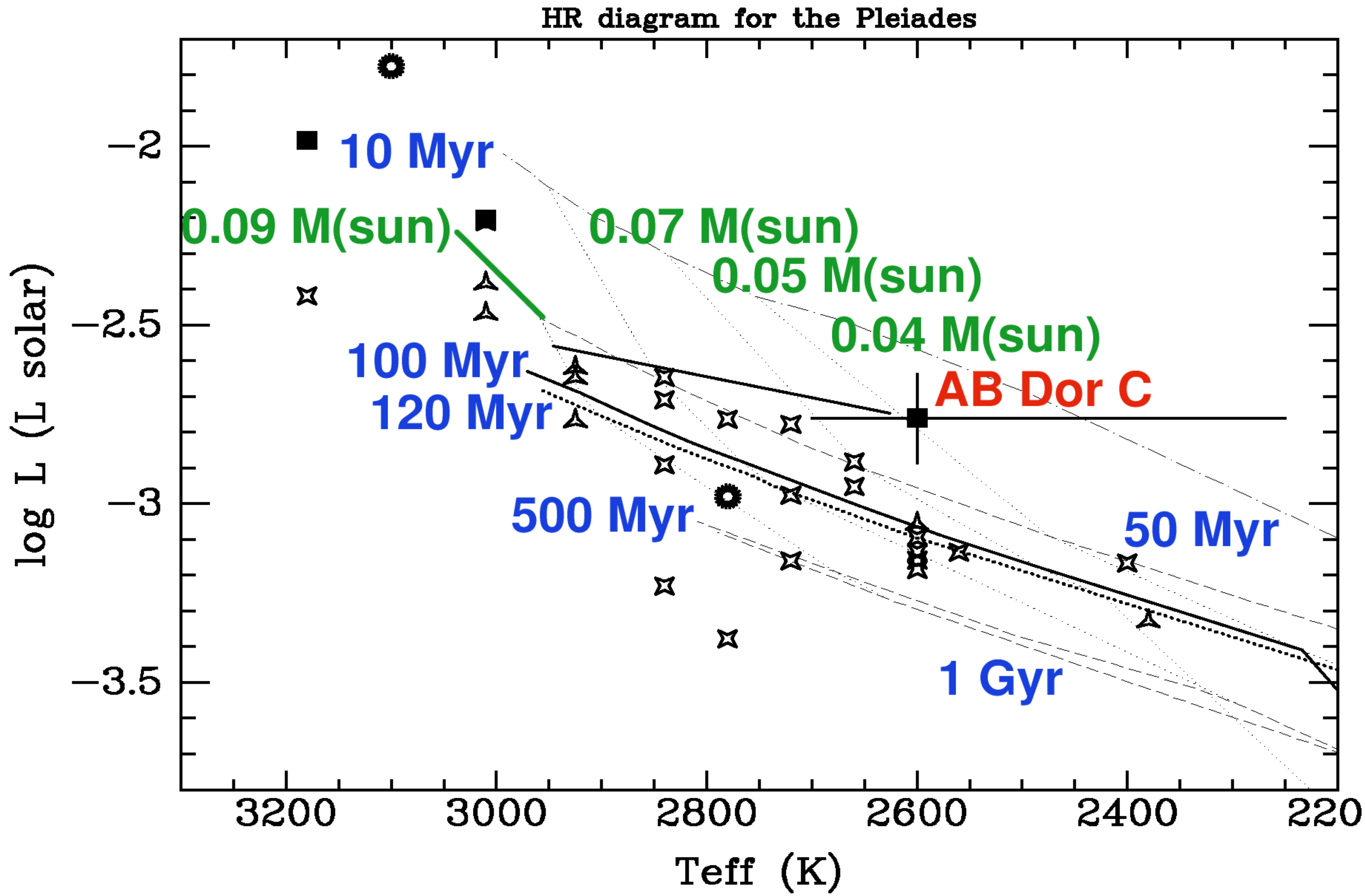


Image from Laird Close

Another Calibrator: U Sco CTIO 5

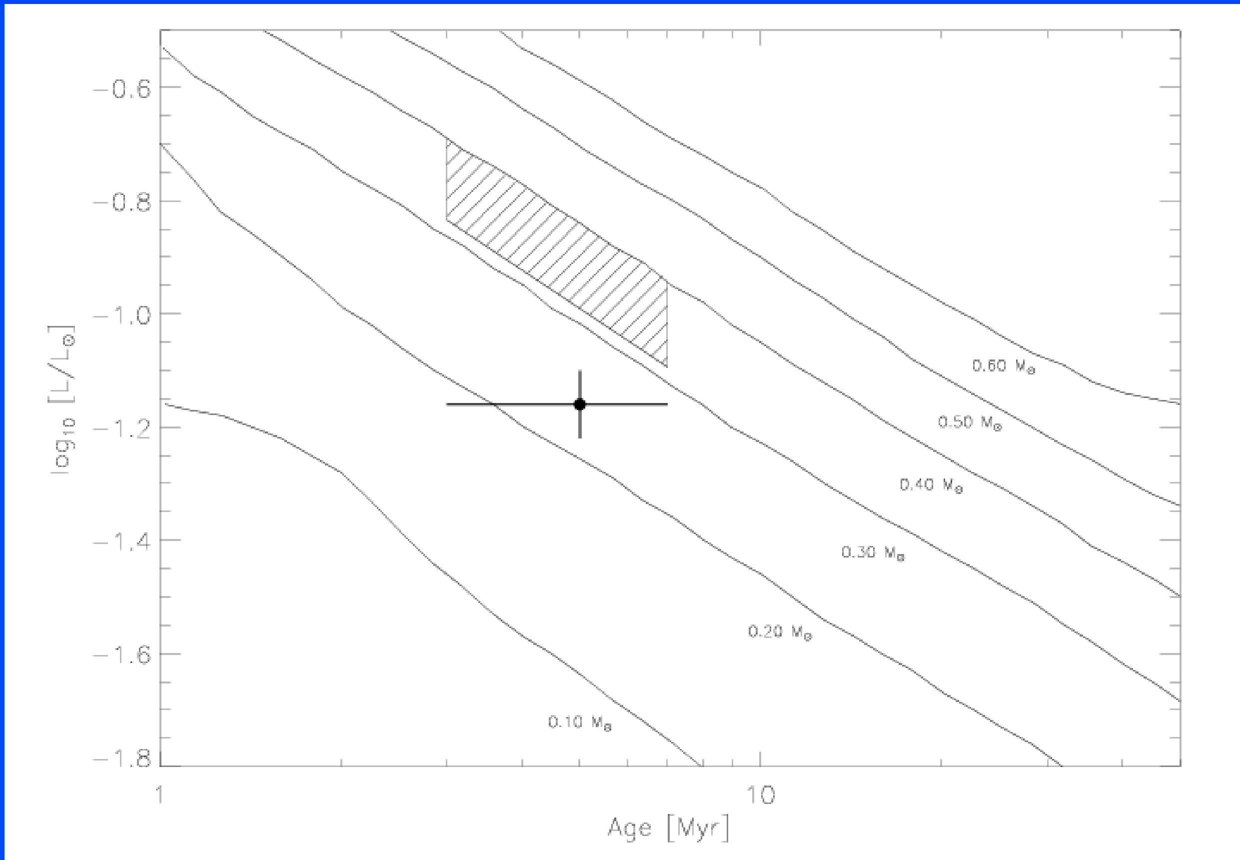


Fig 3 from Reiners et al. 2005

- Spectroscopic binary in Upper Scorpius allowed Reiners et al. 2005 to make a mass measurement for an M4 at < 10 Myr
- Again, models shown to be overluminous for low-mass stars at young ages

Models: Luminosity and Temperature

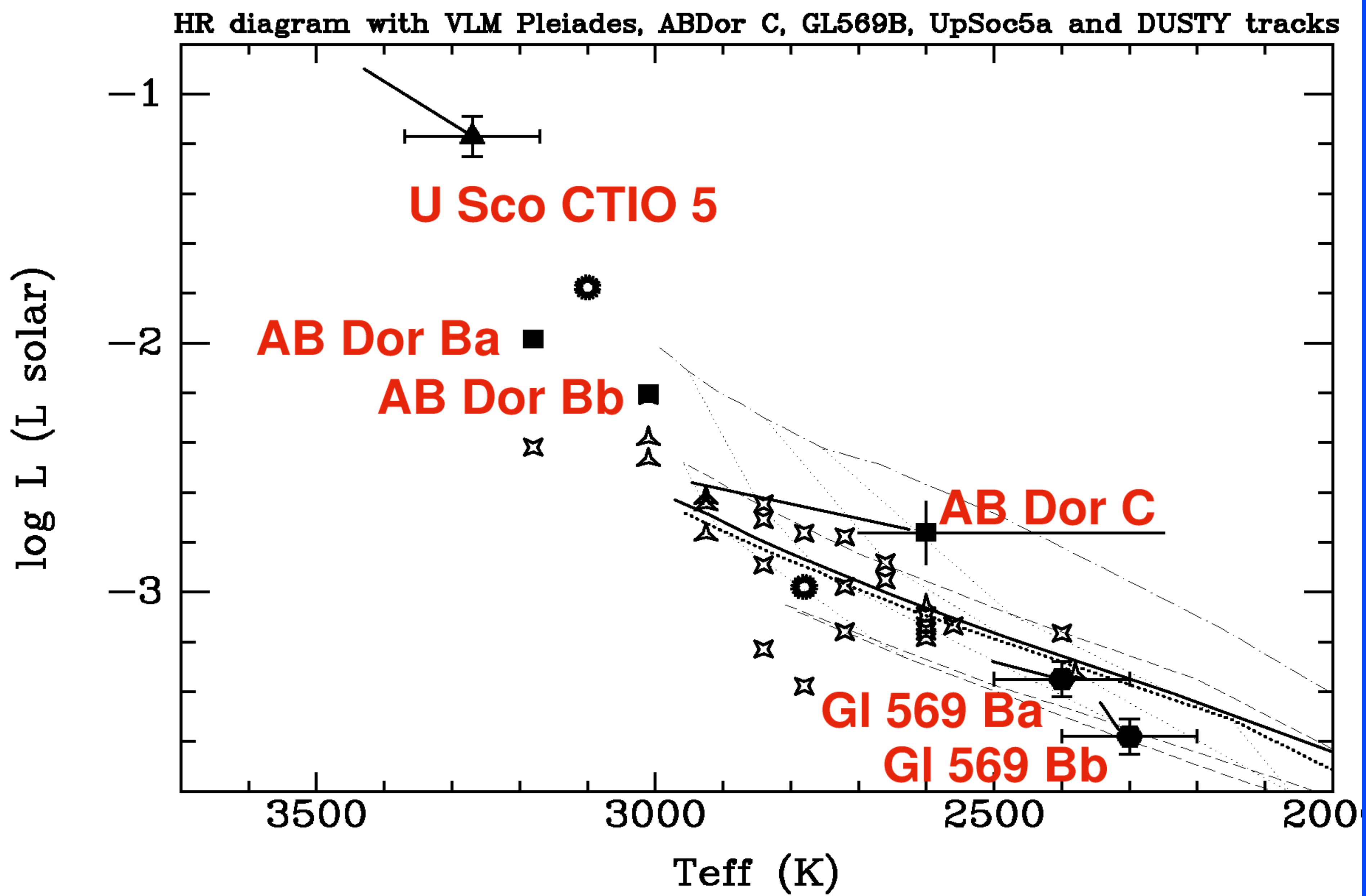
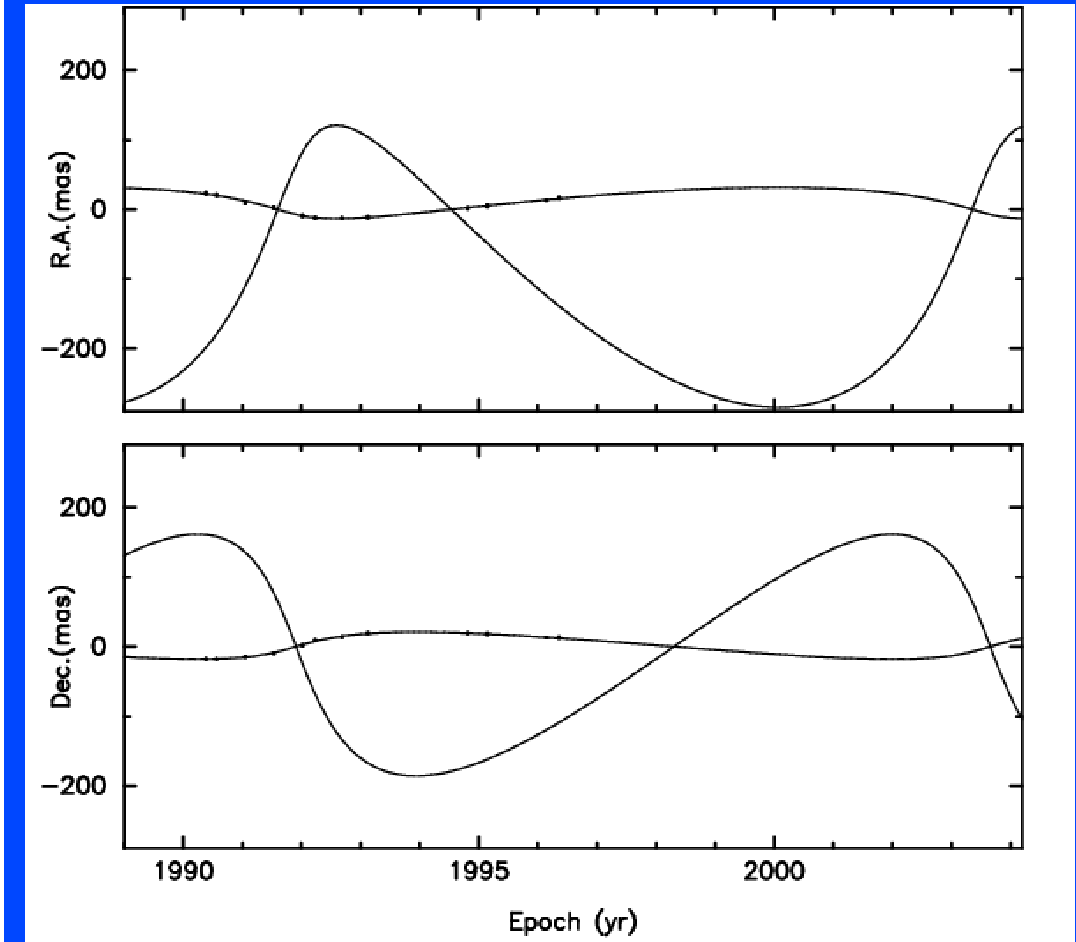


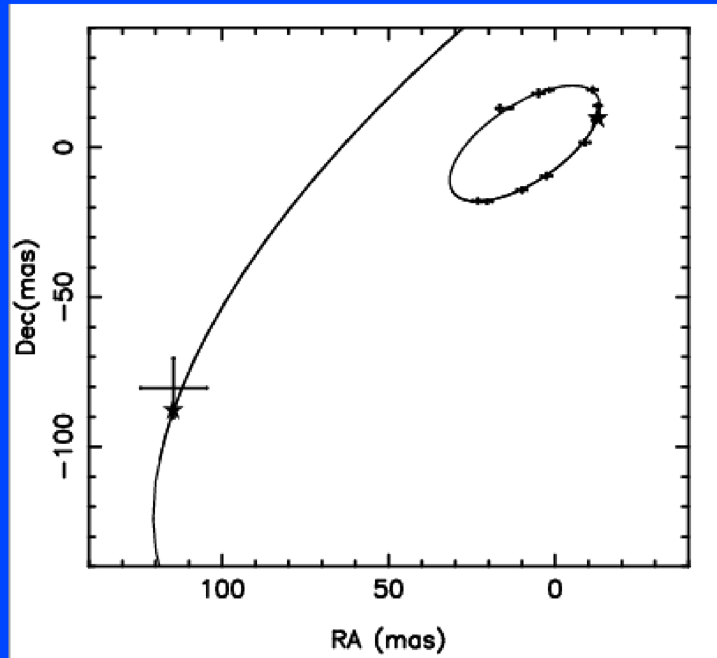
Image from Laird Close

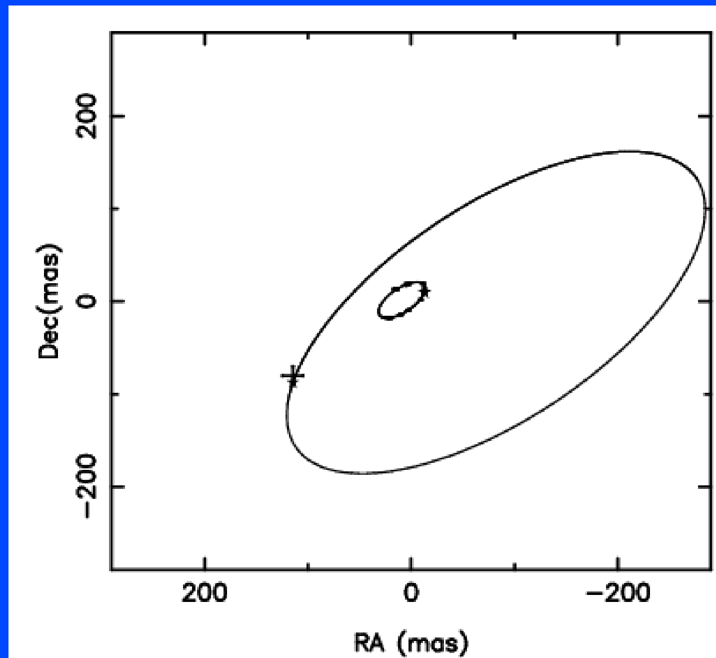
Conclusions

- AB Dor C is a rare object that allows the calibration of cooling curves for young, sub-stellar objects
- Most direct imaging surveys for low-mass companions cannot directly measure mass, and so rely on models to convert age and luminosity measurements into mass.
- Cooling models for photometric and spectral data of AB Dor C underestimate mass by a factor of 2:
  - Chabrier 2000 models (DUSTY) predict mass for AB Dor C (50 Myr) of $0.048M_{sun}$ (J=9.89), $0.052M_{sun}$ (H=9.19), and $0.070M_{sun}$ (Ks=8.57)
  - Using $L = 0.0018\ L_{sun}$ and 2600 K gives mass of $0.040\ M_{sun}$ with DUSTY
  - Burrows 2003 models give $0.038\ M_{sun}$ ($T_{eff} = 2600$ K)
  - Actual astrometric mass of AB Dor C is $0.090\ M_{sun}$ (+/- 0.003)
- These results suggest that surveys for young substellar objects are systematically underestimating the masses of brown dwarfs and extrasolar planet candidates.

Astrometric Orbit

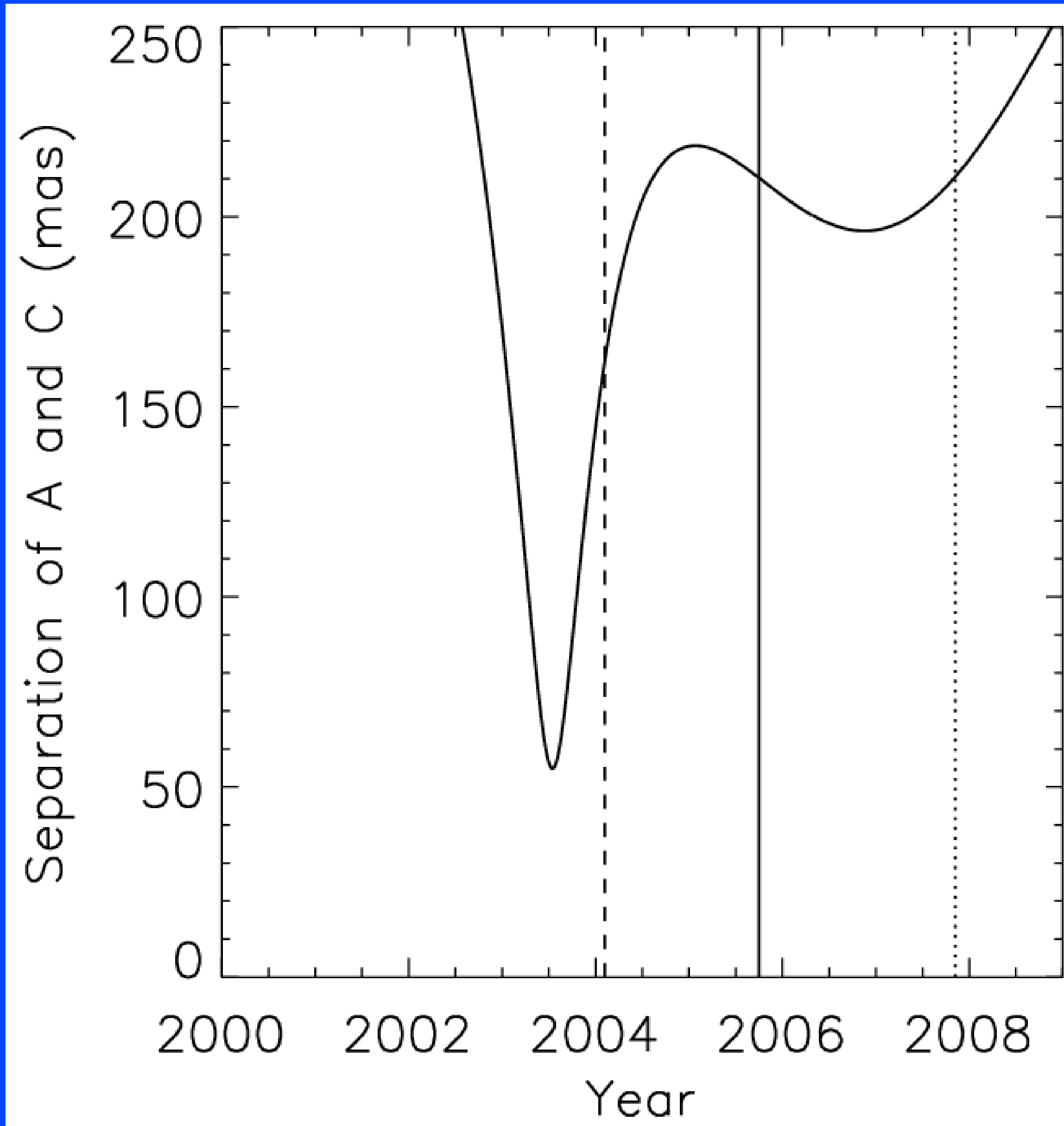




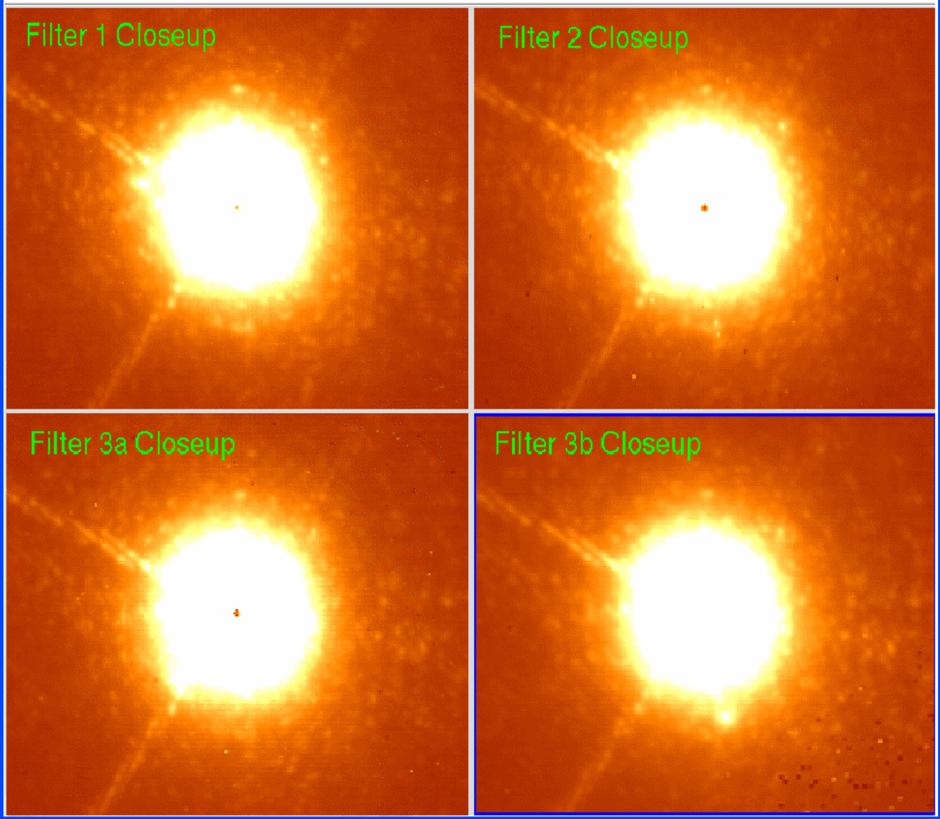


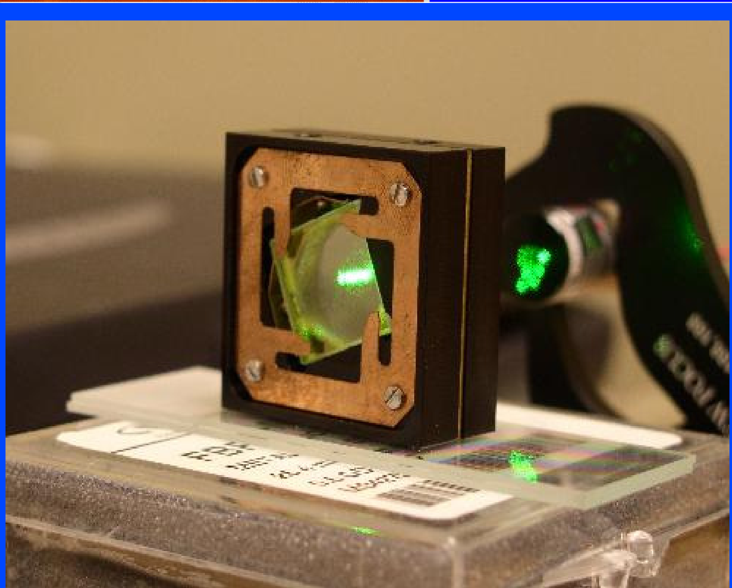
Images from Jose Guirado

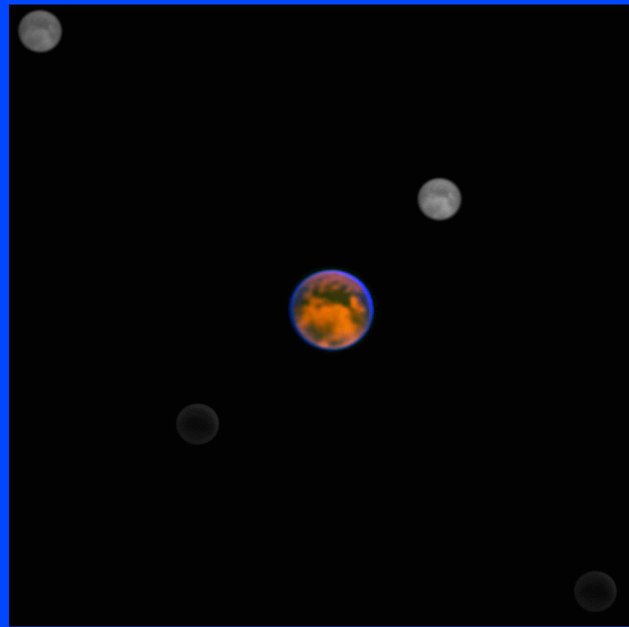
Future AB Dor System Separation

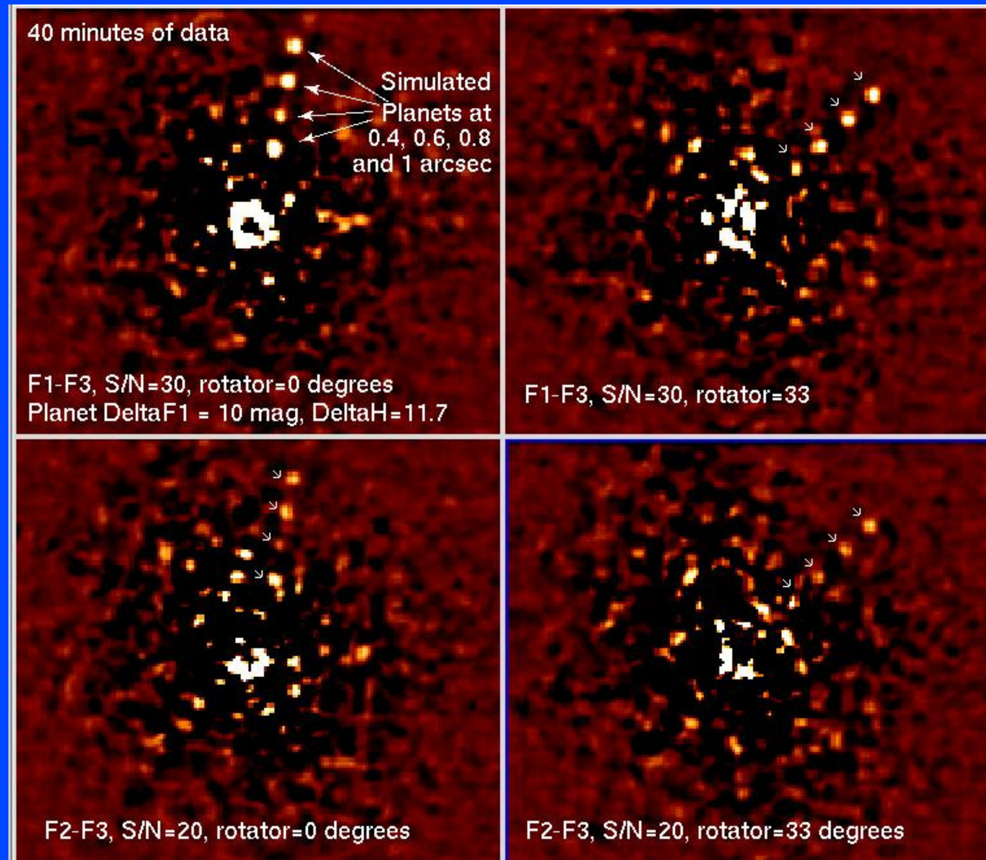


SDI



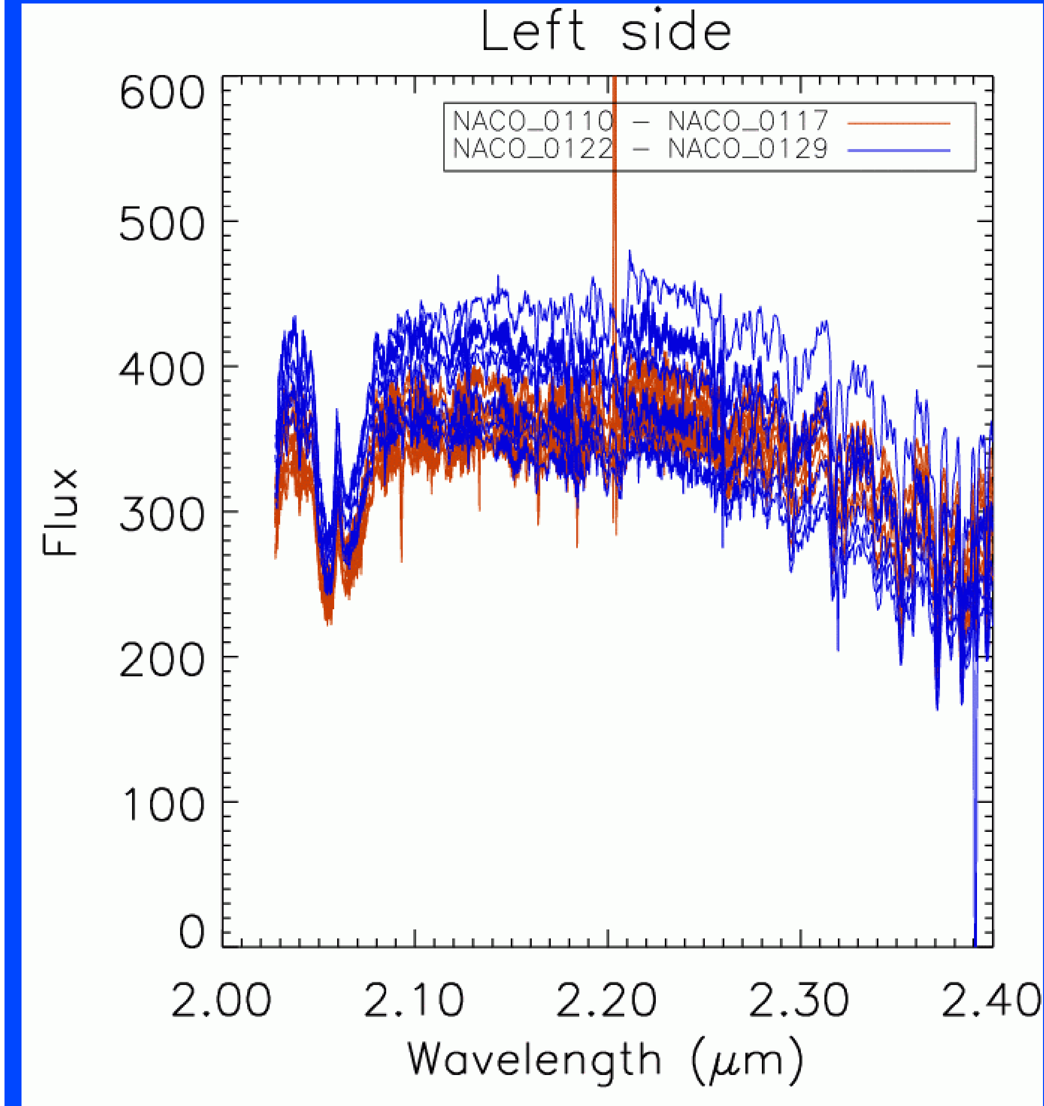


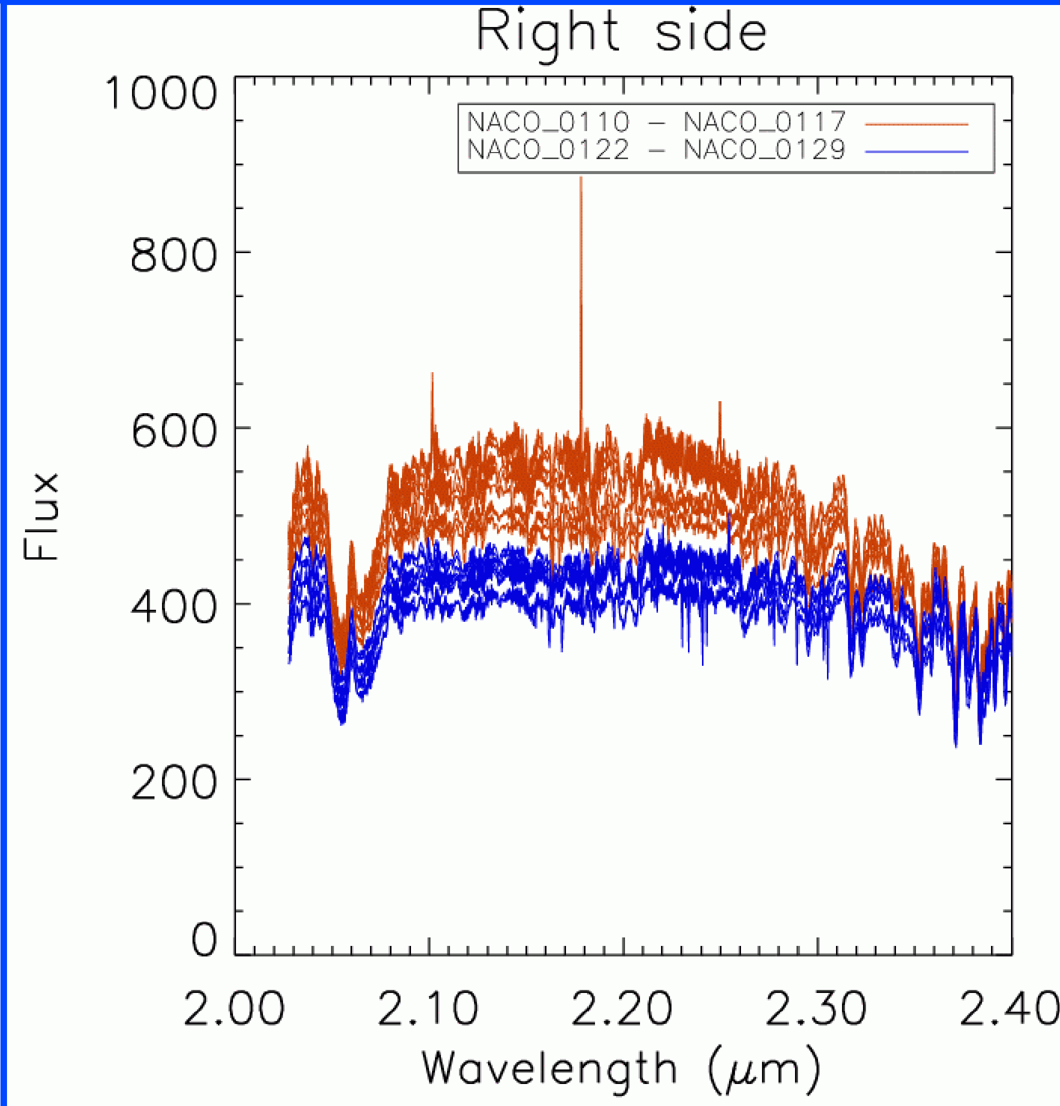




Images from Laird Close, Beth Biler, and Markus Hartung

Detection of AB Dor C Spectrum





Age of AB Dor

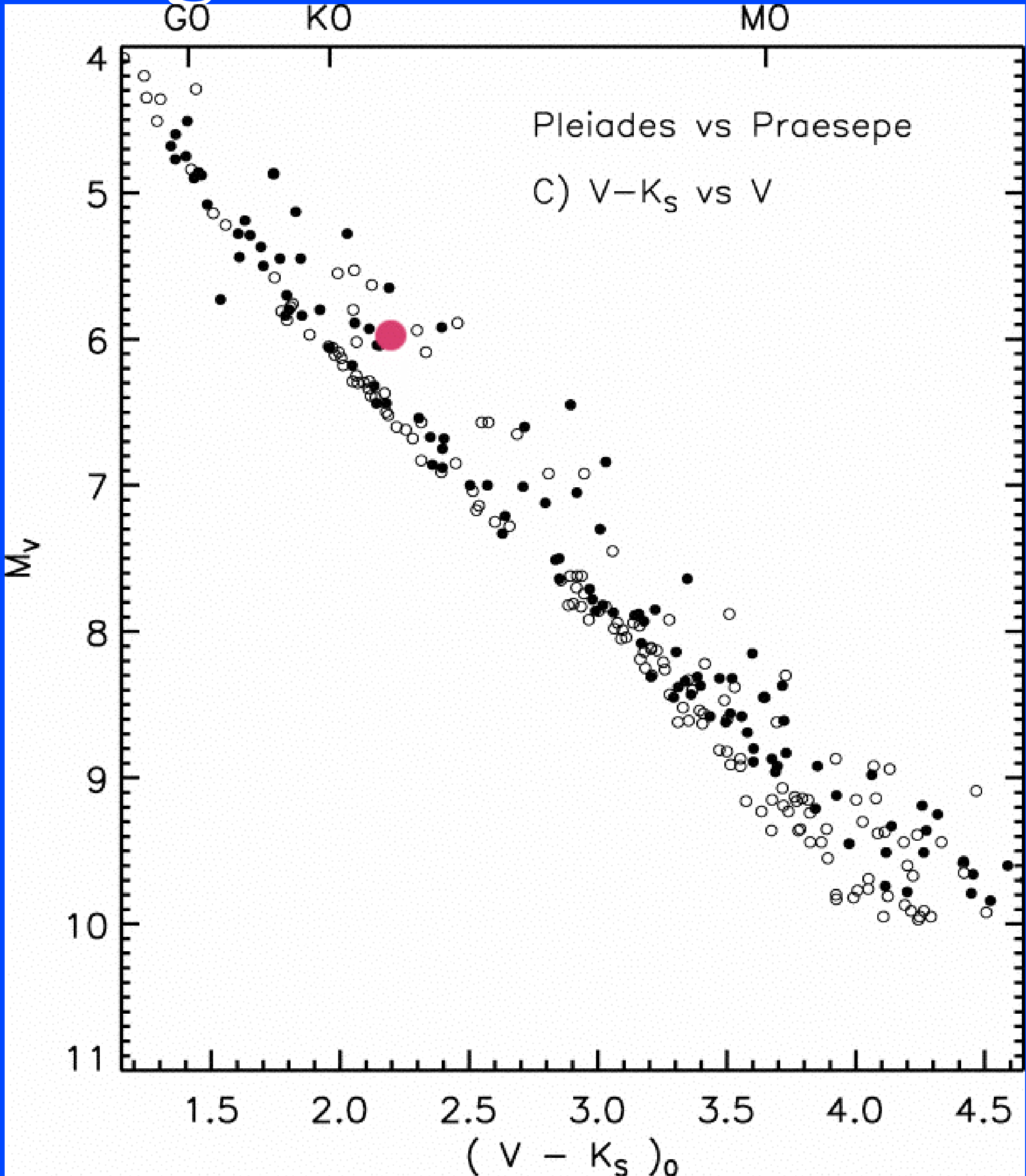


Fig 4 from Stauffer et al. 2003 (AJ 126, 833-847)