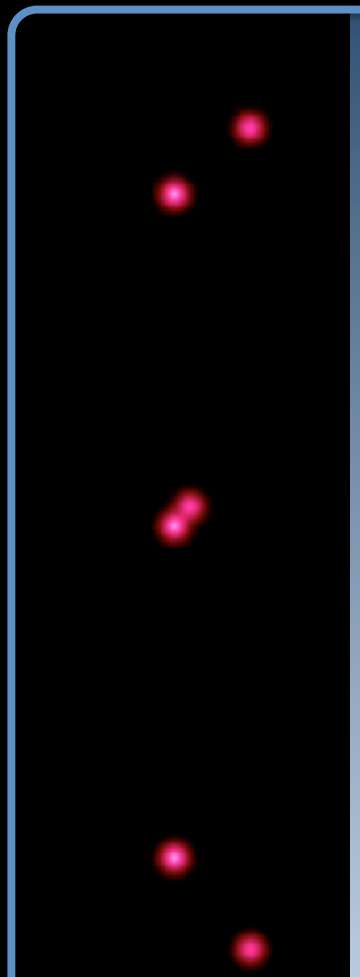


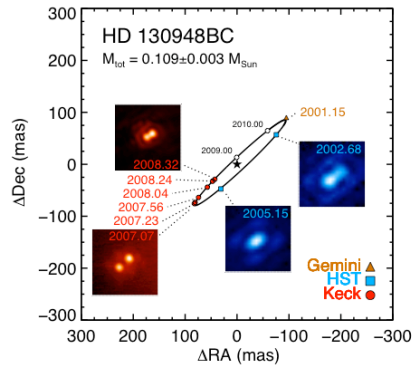
Testing Theory with Dynamical Masses and Orbits of Ultracool Binaries

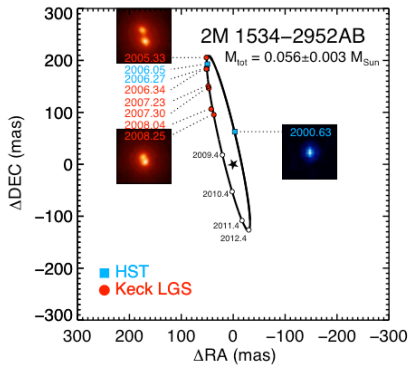
Trent Dupuy
Harvard-Smithsonian Center for Astrophysics

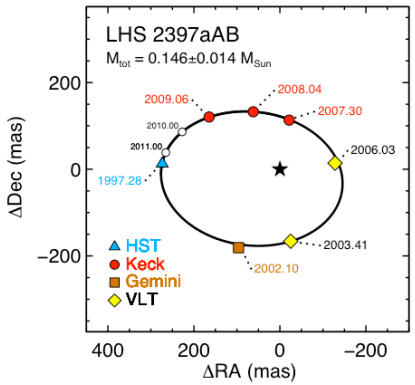
M. Liu, M. Ireland, B. Bowler
M. Cushing, Ch. Helling, S. Witte, P. Hauschildt

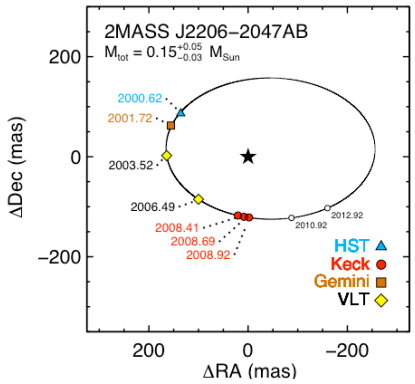
Ref: Leinert et al. (2000); Lane et al. (2001); Bouy et al. (2004)

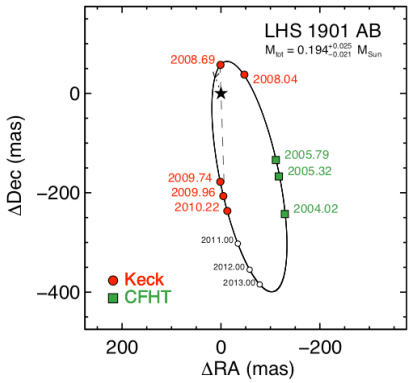
Liu et al. (2008); Dupuy et al. (2009a,b,c); Konopacky et al. (2010); Dupuy et al. (2010)

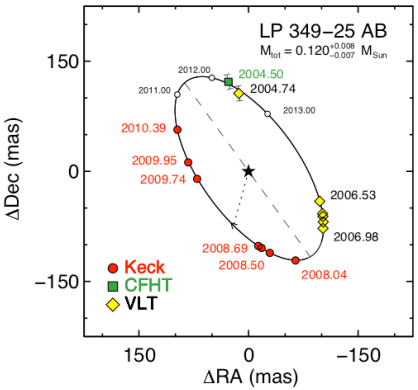


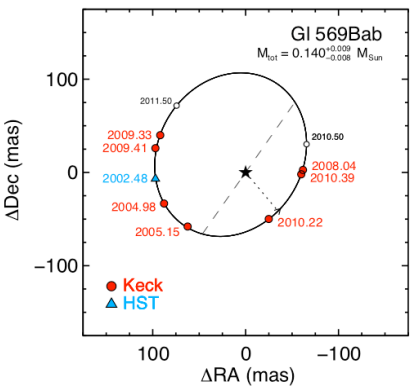










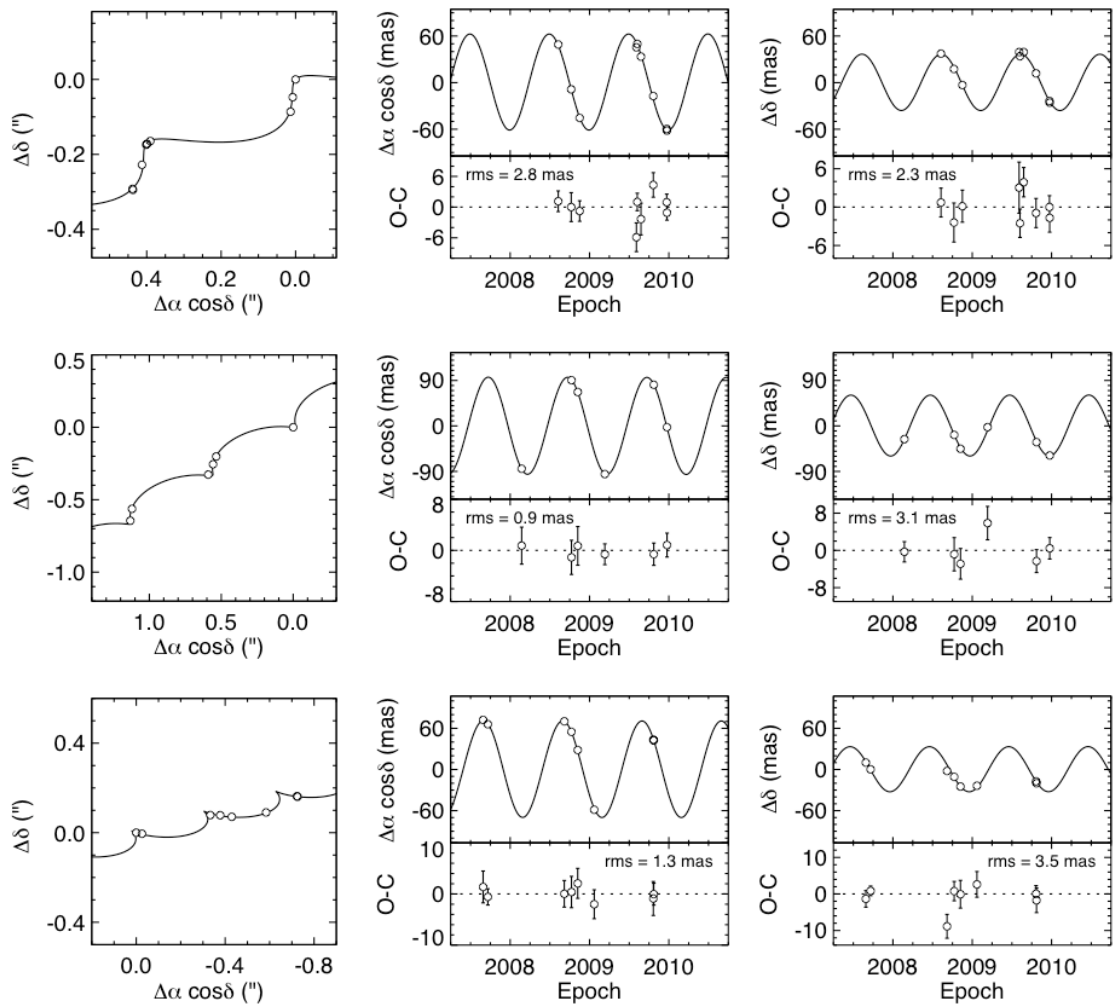


Family Portrait of Keck Orbits

- Excellent Keck astrometry: typically 0.3−1.0 milliarcsec; **best is 100–200 μas**
- Archival data enable even more precise orbits for free
- All orbits have reduced $\chi^2 \approx 1$
- Dynamical mass precision **6% (median), as good as 2%**

Liu et al. (2008); Dupuy et al. (2009a,b,c, 2010)

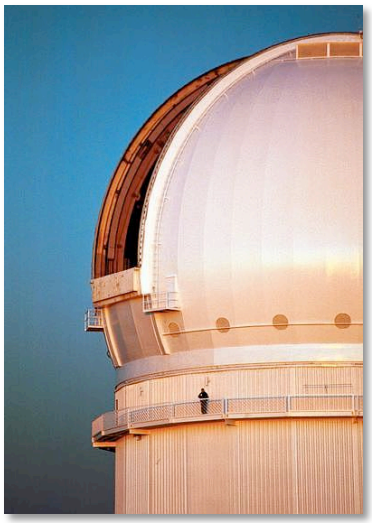
CFHT Parallaxes Enable ≈3× Larger Sample



Dupuy & Liu (2010b, in prep.)

rms ≈ 1–3 mas

yields parallax errors of 2–3%



Testing Models with Dynamical Masses

Directly Measured:

M_{tot}

$L_{bol,1}$ $L_{bol,2}$

evolutionary models

Model-derived:

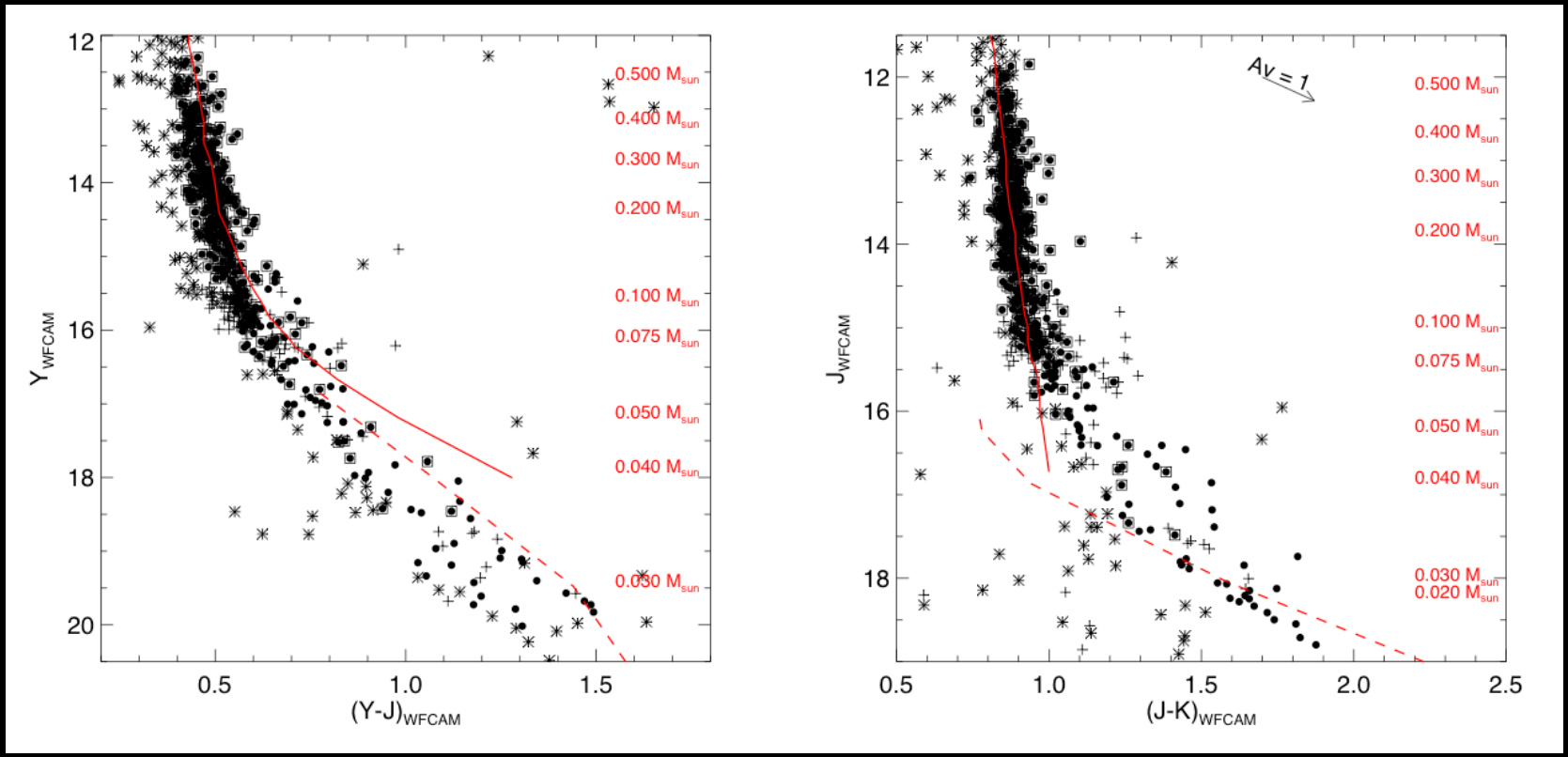
age

$T_{eff,1}$ $T_{eff,2}$

$\log g_1$ $\log g_2$

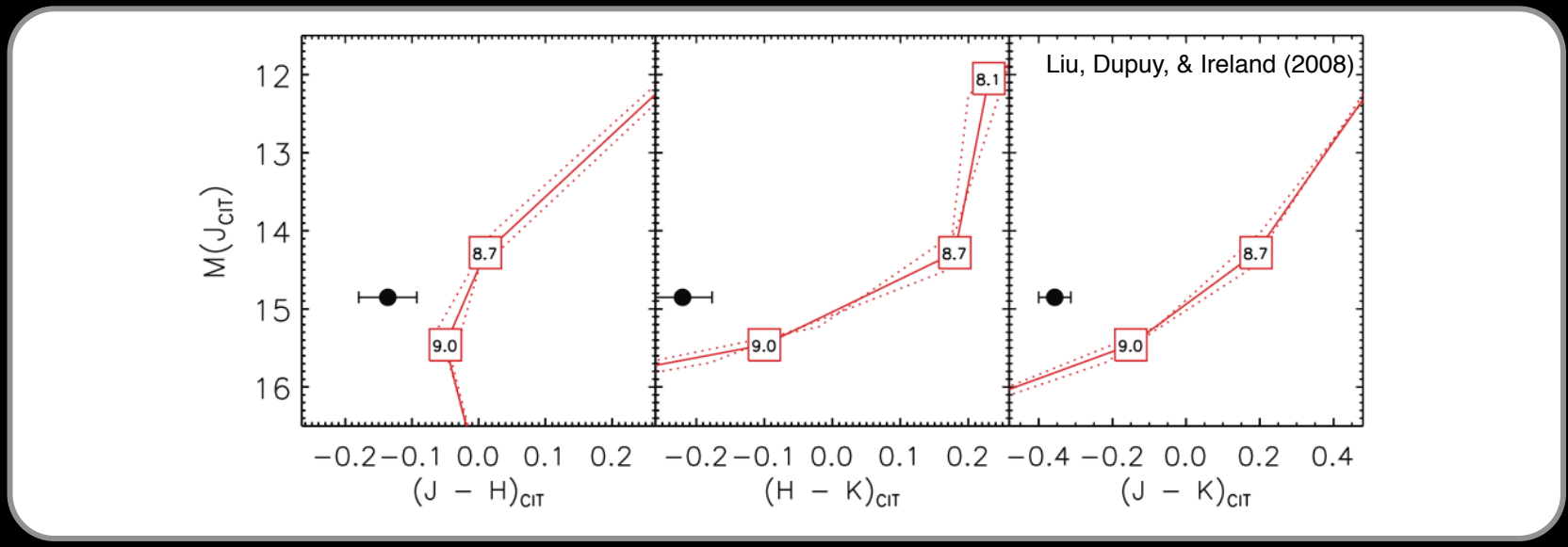
colors, etc.

Model color–magnitude diagrams widely used

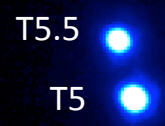


e.g., for new low-mass Pleiades members
(Lodieu et al. 2008)

Testing the Models: Color–magnitude diagram



2MASS J1534-2952AB



Liu, Dupuy & Ireland (2008)

Testing the Models

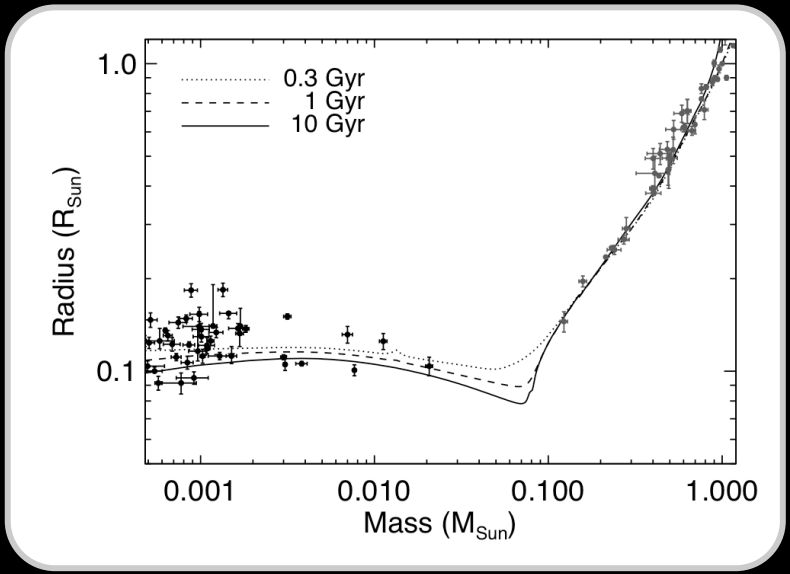
- **Color-magnitude diagram**
  - Model colors are inaccurate across *all spectral types and masses*

evolutionary models:

mass, age

↓

T_{eff}, R, L_{bol}



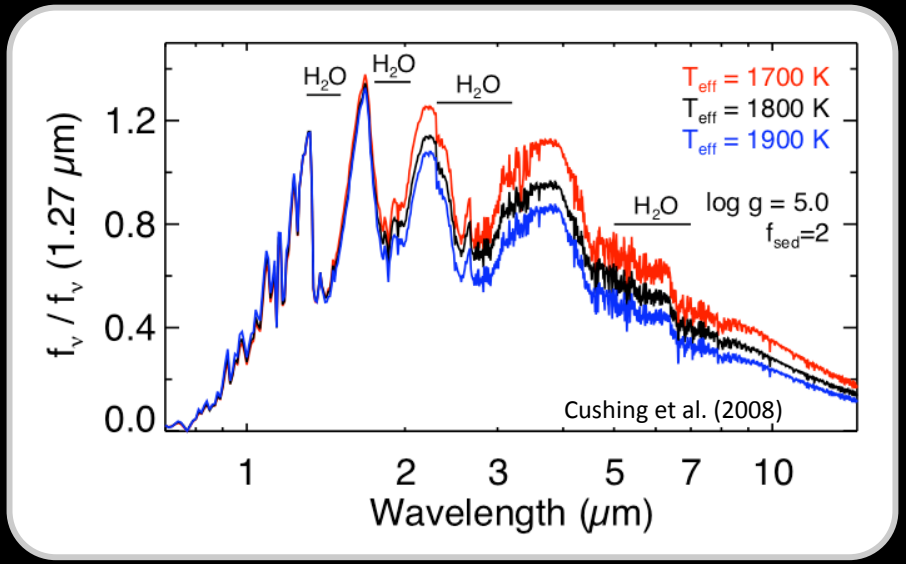
Burrows et al. (1997), Baraffe et al. (1998), Chabrier et al. (2000), Baraffe et al. (2003), Saumon & Marley (2008)

atmospheric models:

T_{eff}, log(g)

↓

spectrum

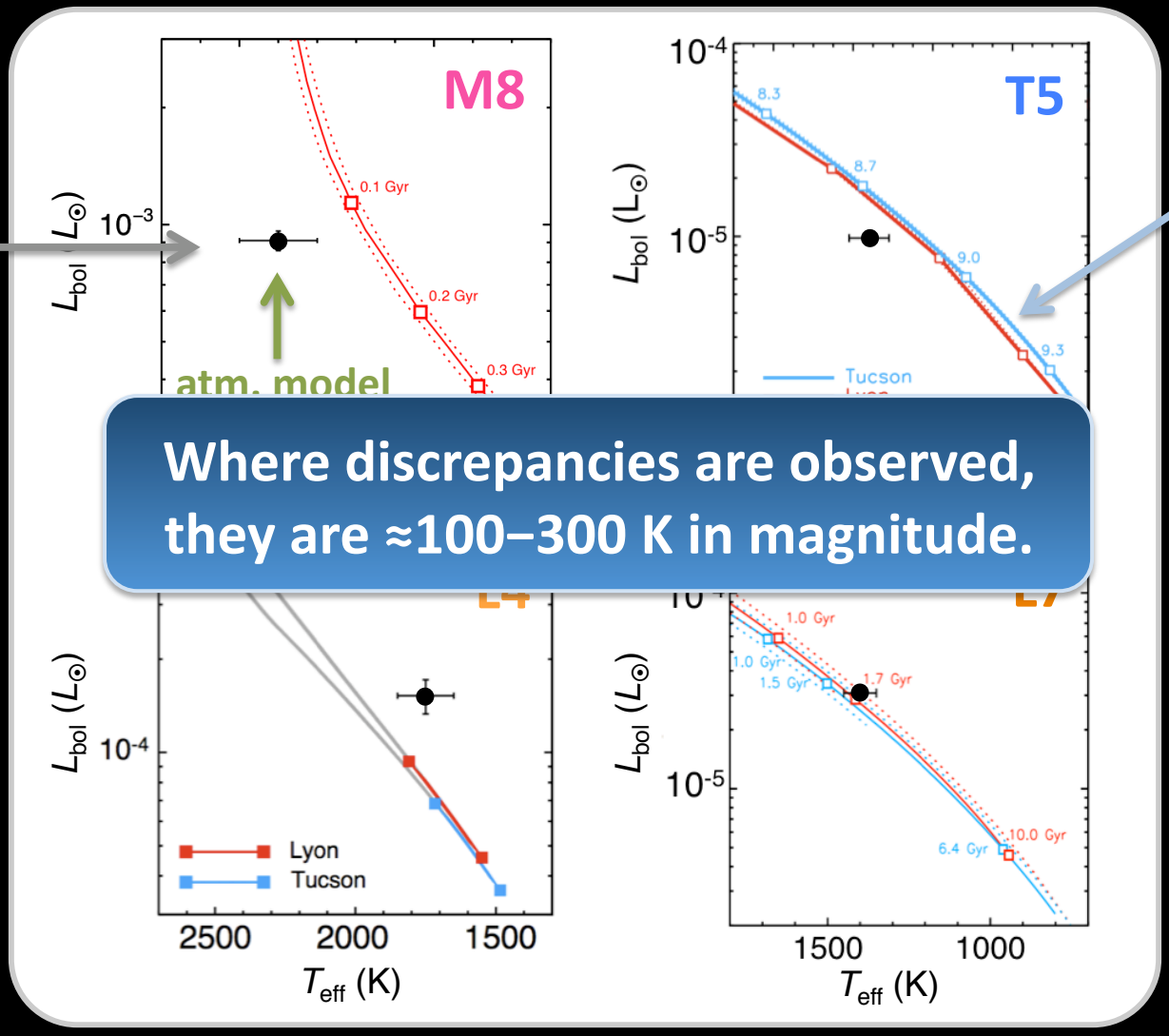


Allard et al. (2001), Marley et al. (2002), Burrows et al. (2002), Tsuji (2002)

Testing the Models: H-R Diagram

luminosity measured directly

evolutionary model tracks



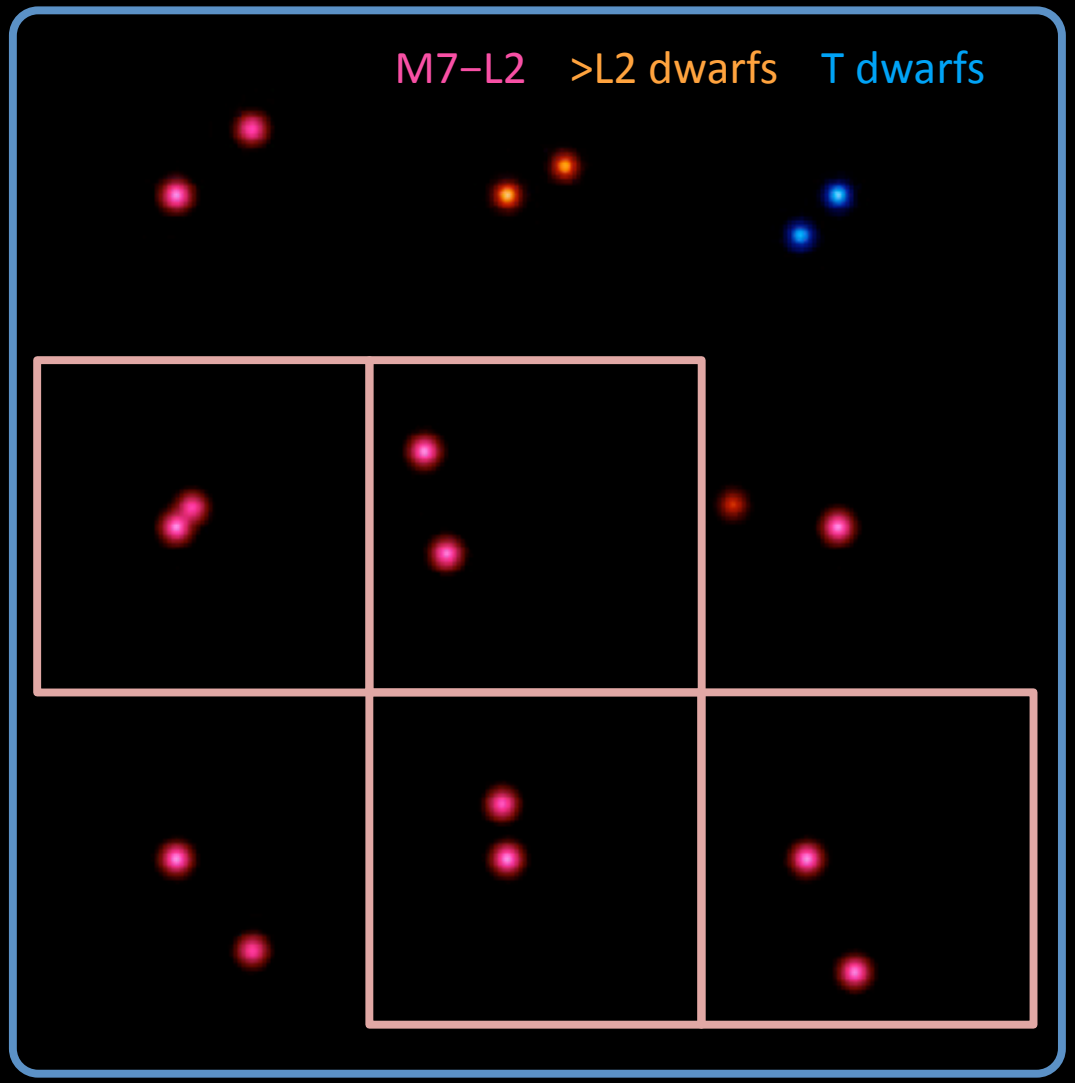
Where discrepancies are observed, they are ≈100–300 K in magnitude.

Testing the Models

- **Color-magnitude diagram**
  - Model colors are inaccurate across *all spectral types and masses*

- **"Temperature Problem":** evolutionary and atmospheric models give inconsistent $T_{\rm eff}$ estimates (≈100–300 K)
  - Discrepancies observed from over broad range of spectral types

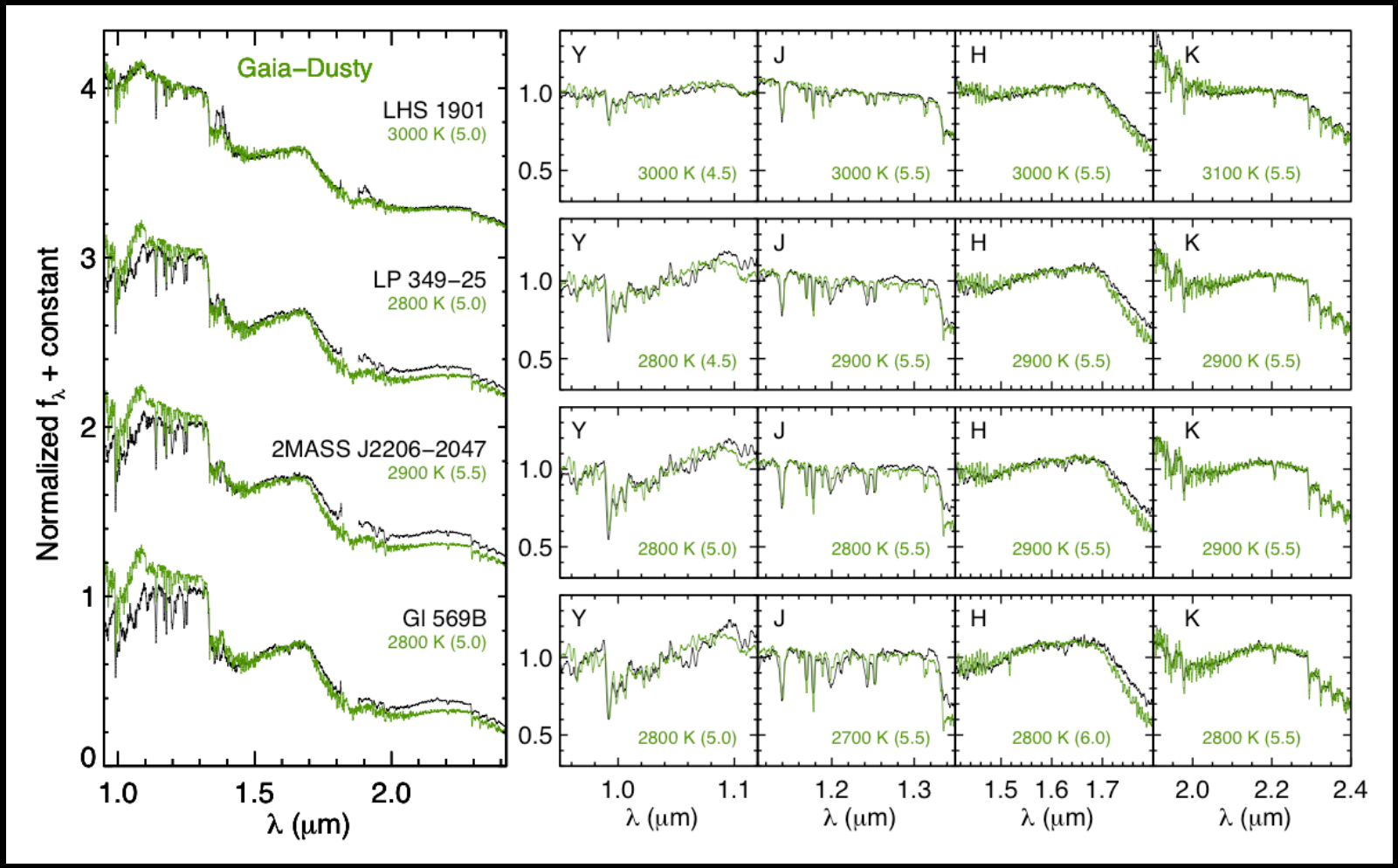
Trent Dupuy (CfA/SAO)



Obtained integrated-light NIR spectra for 4 late-M *twin* binaries

Leinert et al. (2000); Lane et al. (2001); Bouy et al. (2004); Liu et al. (2008); Dupuy et al. (2009a,b,c); Konopacky et al. (2010); Dupuy et al. (2010)

Testing the Models: NIR Spectra Fitting



Dupuy et al. (2010a)

Testing the Models: NIR Spectra Fitting

DRIFT—PHOENIX

non-equilibrium dust model ("Drift")

Witte et al. (2009)

GAIA—DUSTY

dust stays where it forms ("Dusty")

T. Barman (2010, priv. comm.)

AMES—DUSTY

dust stays where it forms ("Dusty")

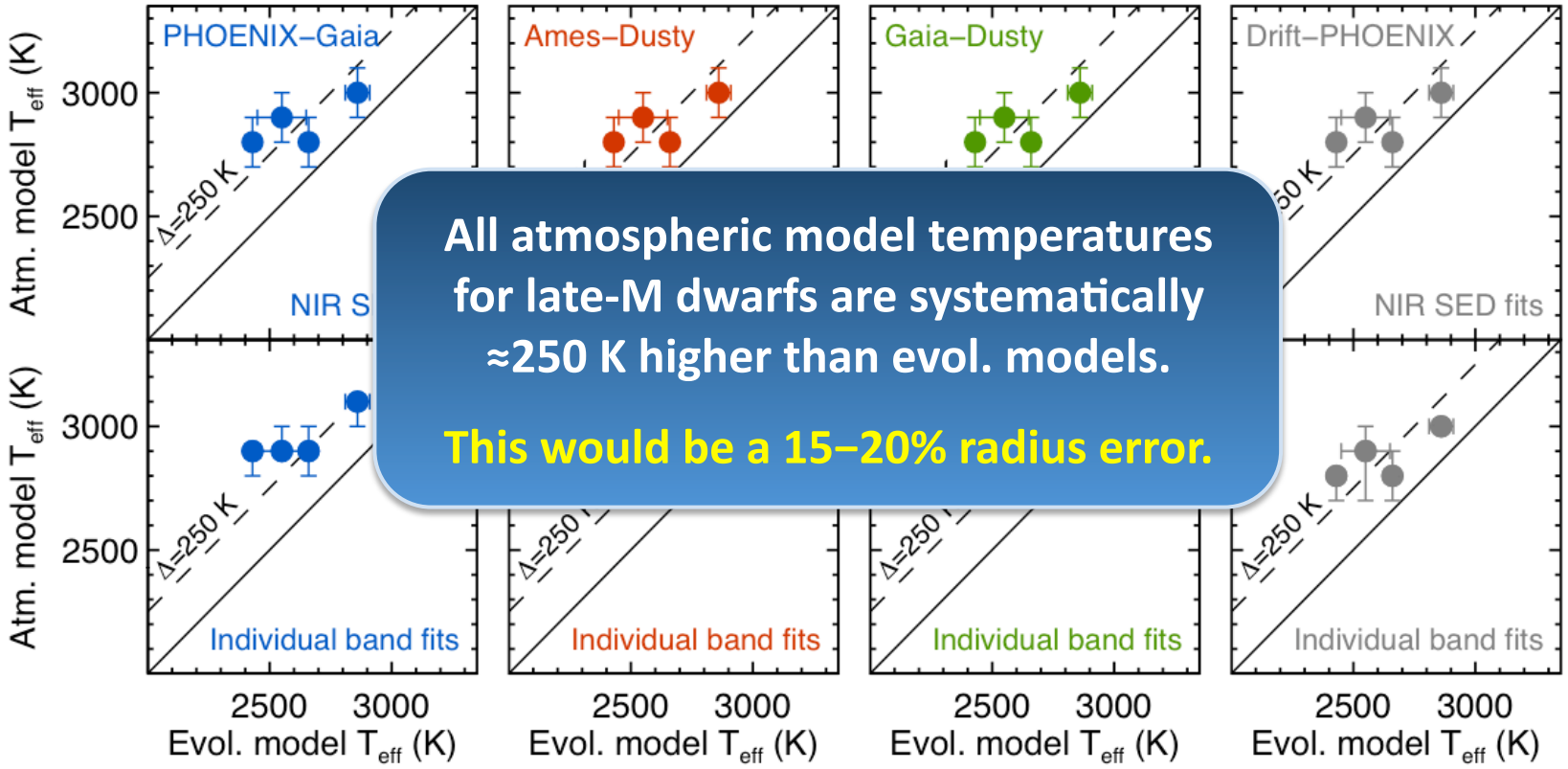
Allard et al. (2001)

PHOENIX—GAIA

dust forms and disappears ("Cond")

Brott & Hauschildt (2005)

Testing the Models: Atm. vs. Evol. $T_{\rm eff}$



Dupuy et al. (2010a)

Testing the Models

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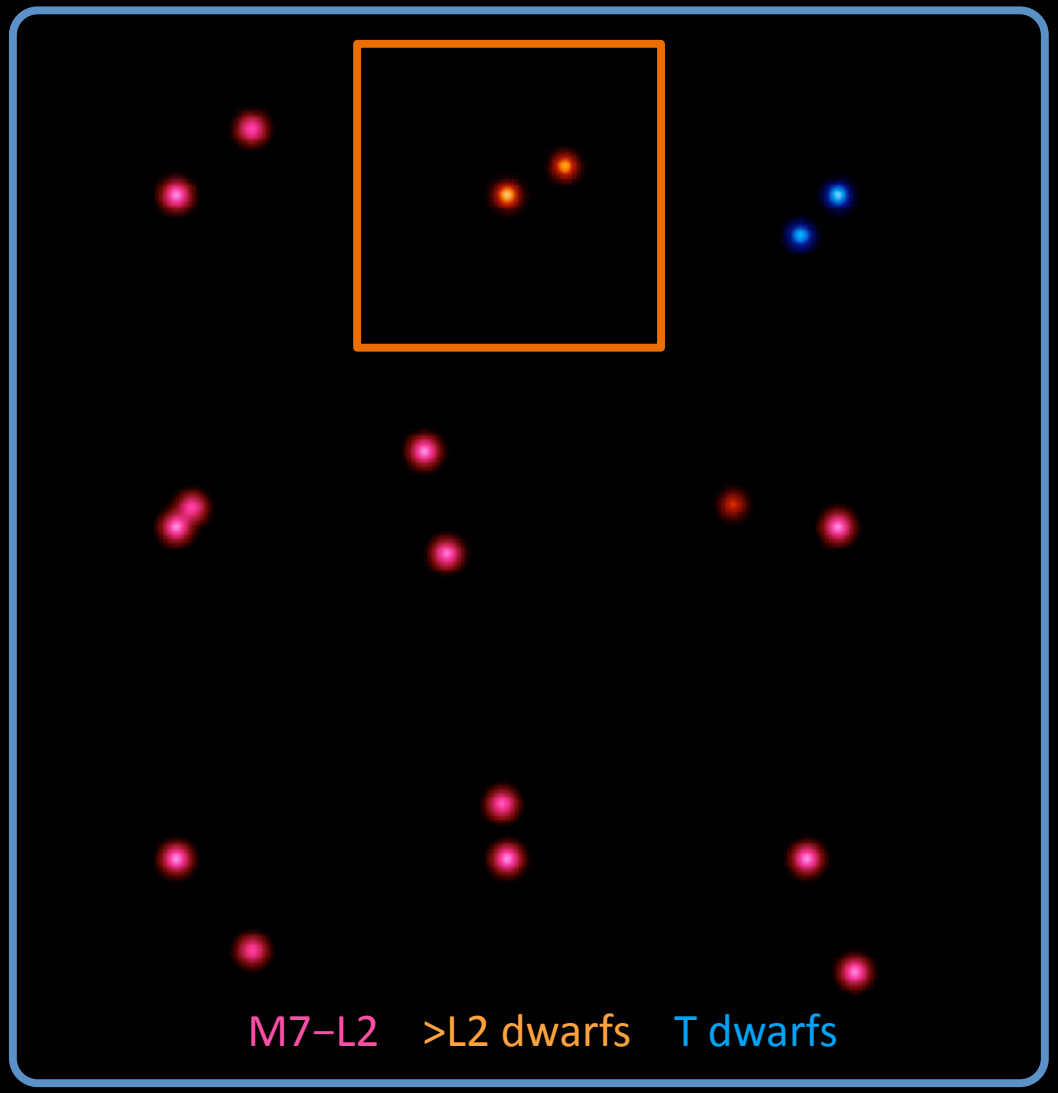
  - Offset is the same for objects of similar $T_{\rm eff}$ but with widely varying masses, ages, and activity levels

Trent Dupuy (CfA/SAO)



Only one binary with a precise mass *also* has a precise age estimate.

Orbit references: Leinert et al. (2000); Lane et al. (2001); Bouy et al. (2004); Liu et al. (2008); Dupuy et al. (2009a,b,c); Dupuy et al. (2010)

Trent Dupuy (CfA/SAO)

Testing the Models: The Gold Standard

$M_{tot} = 0.1095 \pm 0.0022\ M_{\odot}$

⬇

model-derived age: 450±50 Myr

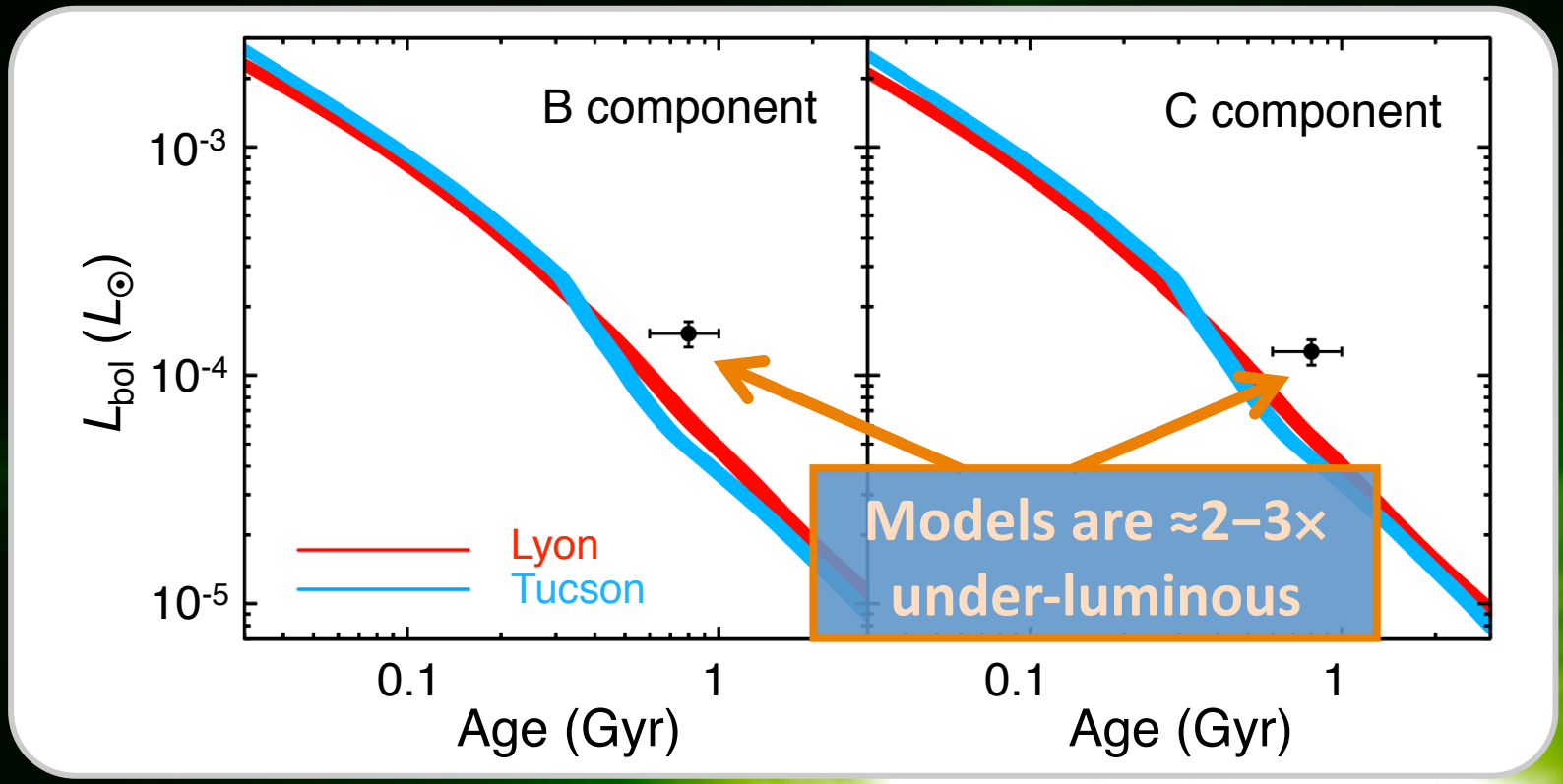
Age Indicator	Age (Myr)	Error
Gyrochronology	**800±200**	**25%**
Chrom. activity	500±300	60%
Isochrones	300–2500	≈2×
X-ray activity	≈Hyades	…
Lithium	≈Hyades	…

References — Mamajek & Hillenbrand (2008); Barnes (2007); Takeda et al. (2007); Stern et al. (1995); Gaidos (1998); Gaidos (2000); Hünsch et al. (1999); Stelzer & Neuhäuser (2001); Soderblom et al. (1993a,b,c)

HD 130948

Dupuy et al. (2009a)

Testing the Models: The Gold Standard



HD 130948

Dupuy et al. (2009a)

Testing the Models

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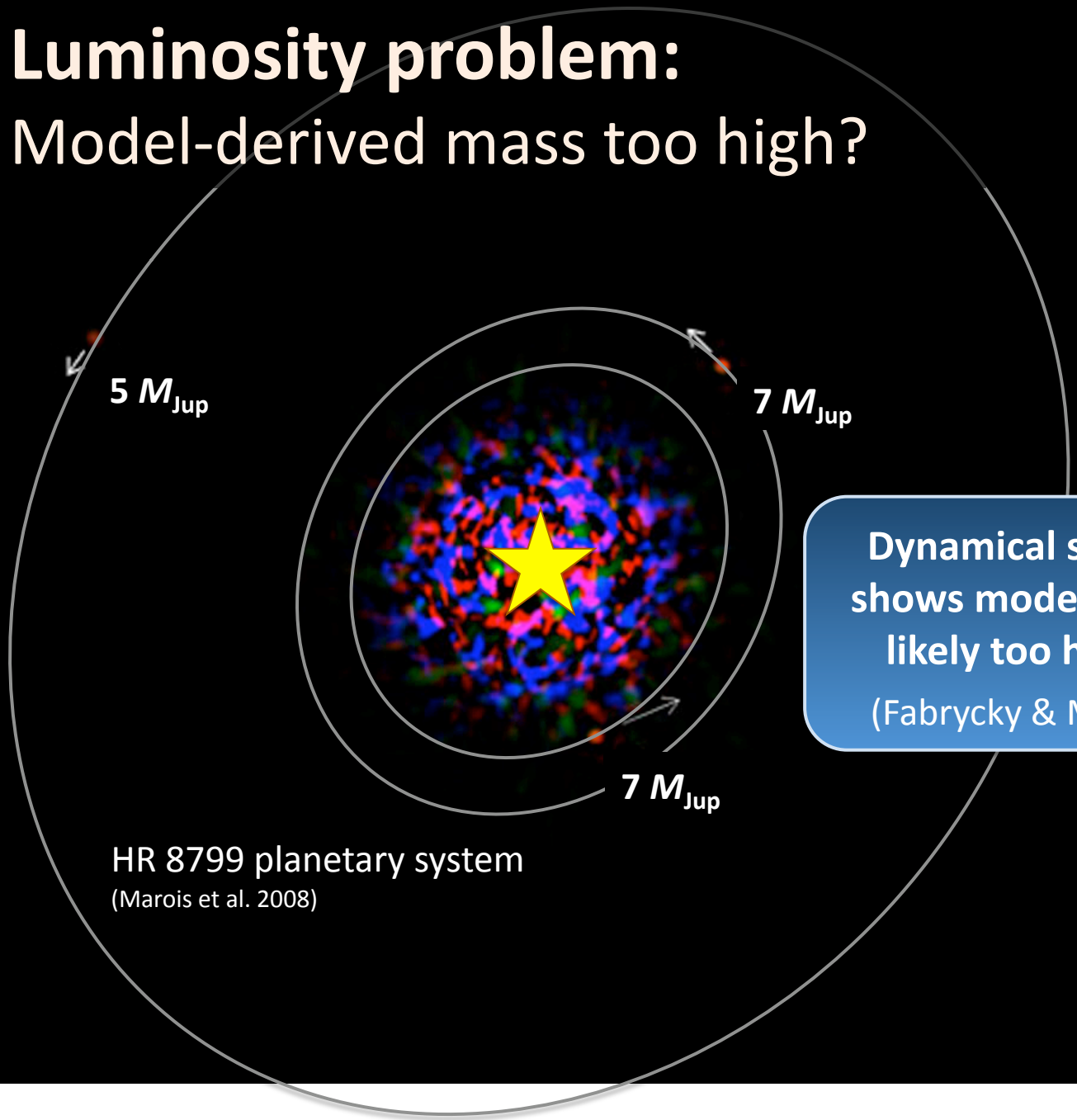
- **"Luminosity Problem":** evol. models under-luminous
  - HD 130948BC model age inconsistent with primary star

Trent Dupuy (CfA/SAO)

Luminosity problem:
Model-derived mass too high?

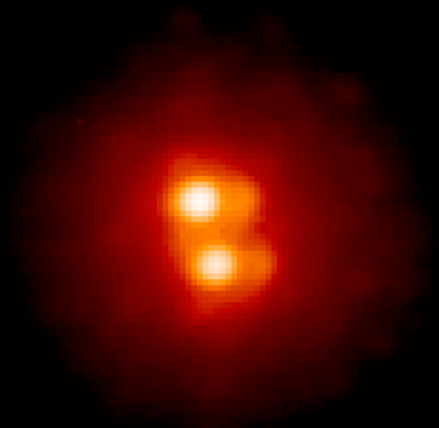


HR 8799 planetary system
(Marois et al. 2008)

Dynamical stability analysis shows model-derived masses likely too high by 20–30%

(Fabrycky & Murray-Clay 2010)

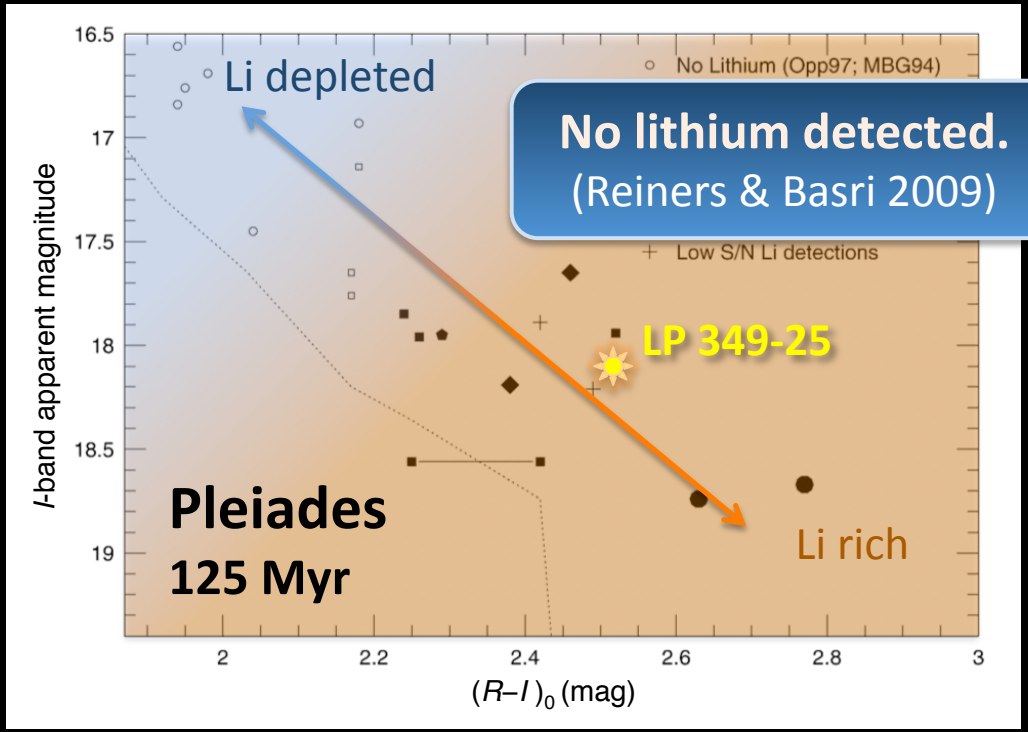
Luminosity problem:
Model-derived age too young?



LP 349-25 AB
M7.5+M8

Forveille et al. (2005);
Dupuy et al. (2010a)

Evol. model-derived age: 130±20 Myr.
Thus, should have abundant lithium.



No lithium detected.
(Reiners & Basri 2009)

Stauffer et al. (1998)

Testing the Models

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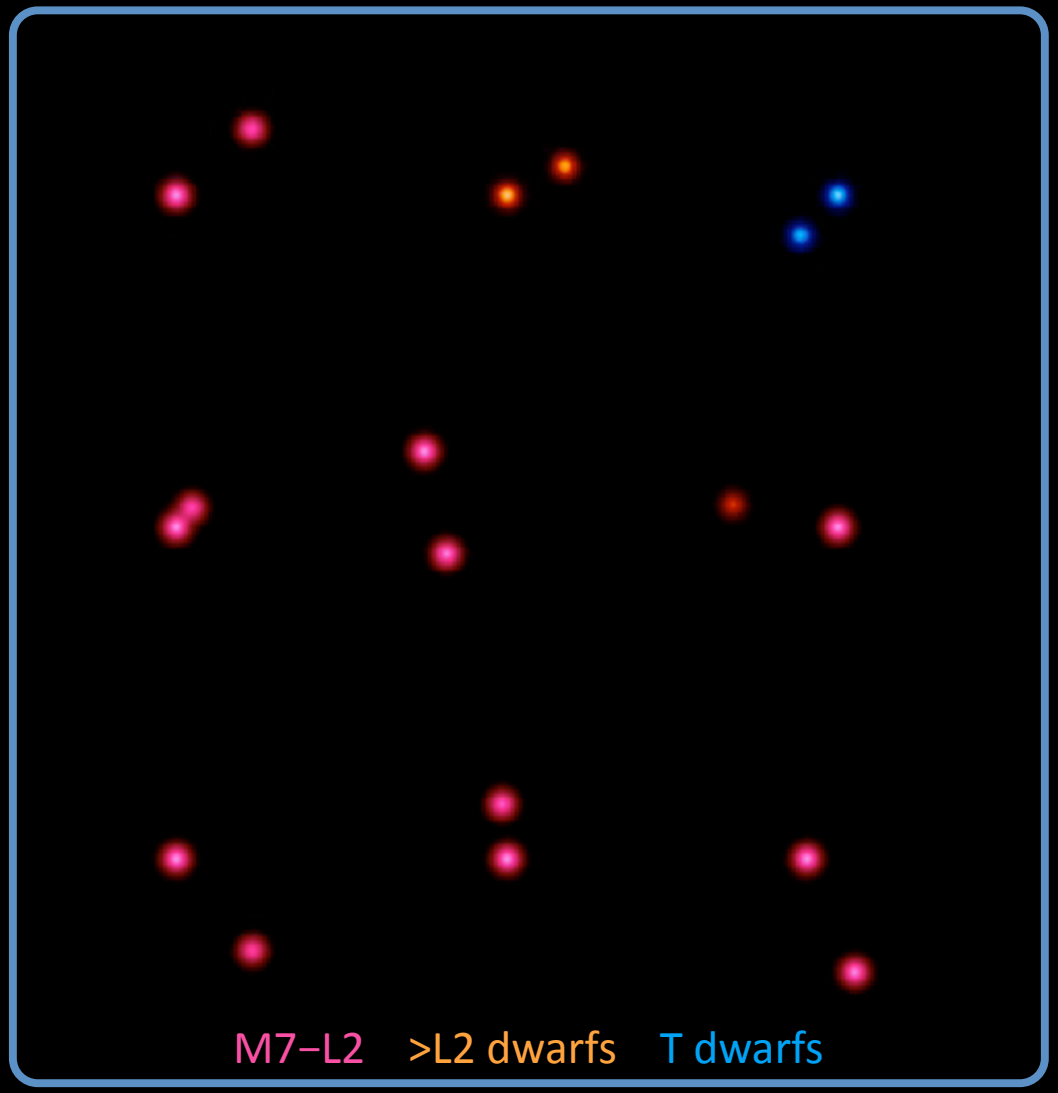
- **"Luminosity Problem":** evol. models under-luminous
  - HD 130948BC model age inconsistent with primary star
  - HR 8799bcd planets not dynamically stable—masses too high?
  - LP 349-25 *not* Li rich – not actually young? ("Li problem"?)

Trent Dupuy (CfA/SAO)

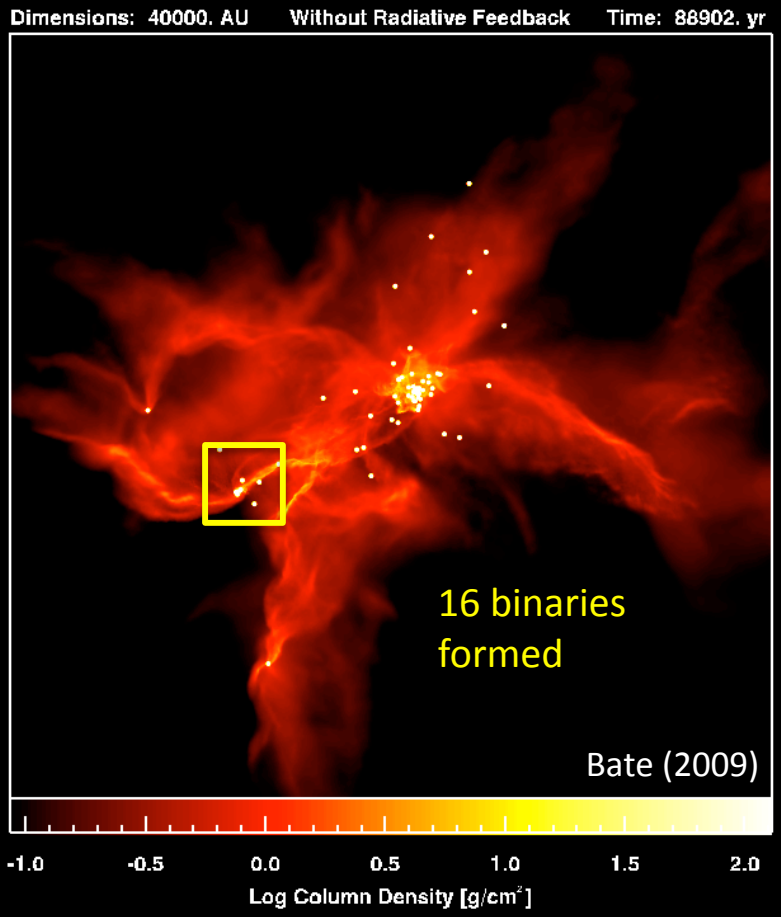


Orbit references: Leinert et al. (2000); Lane et al. (2001); Zapatero Osorio et al. (2004); Bouy et al. (2004); Simon et al. (2006); Liu et al. (2008); Dupuy et al. (2009a,b,c); Konopacky et al. (2010); Dupuy et al. (2010)

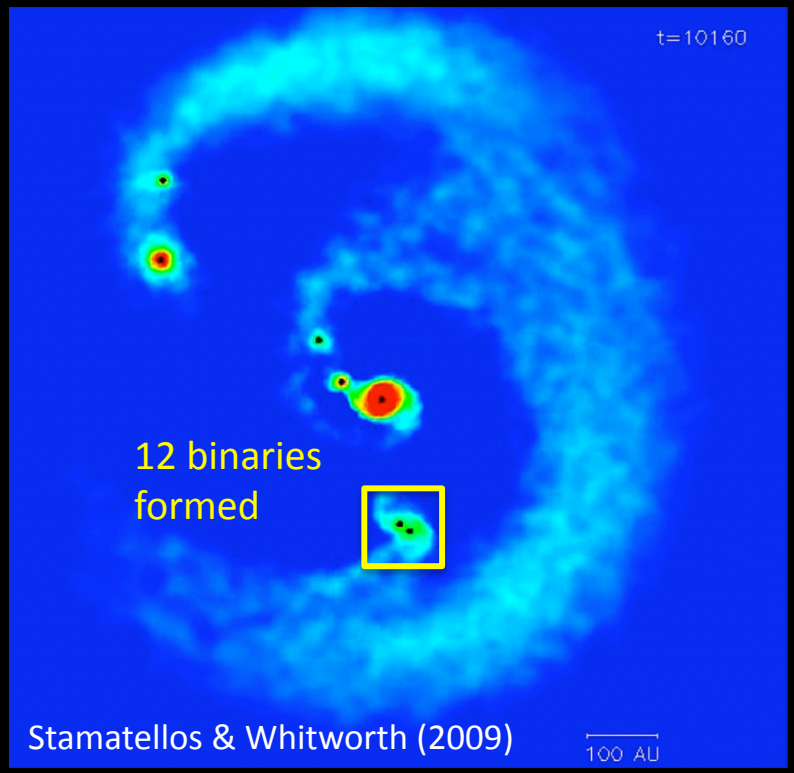
The ensemble of orbital eccentricities enables novel tests of very low mass formation models.

Testing Formation Models with Eccentricities

"cluster formation"

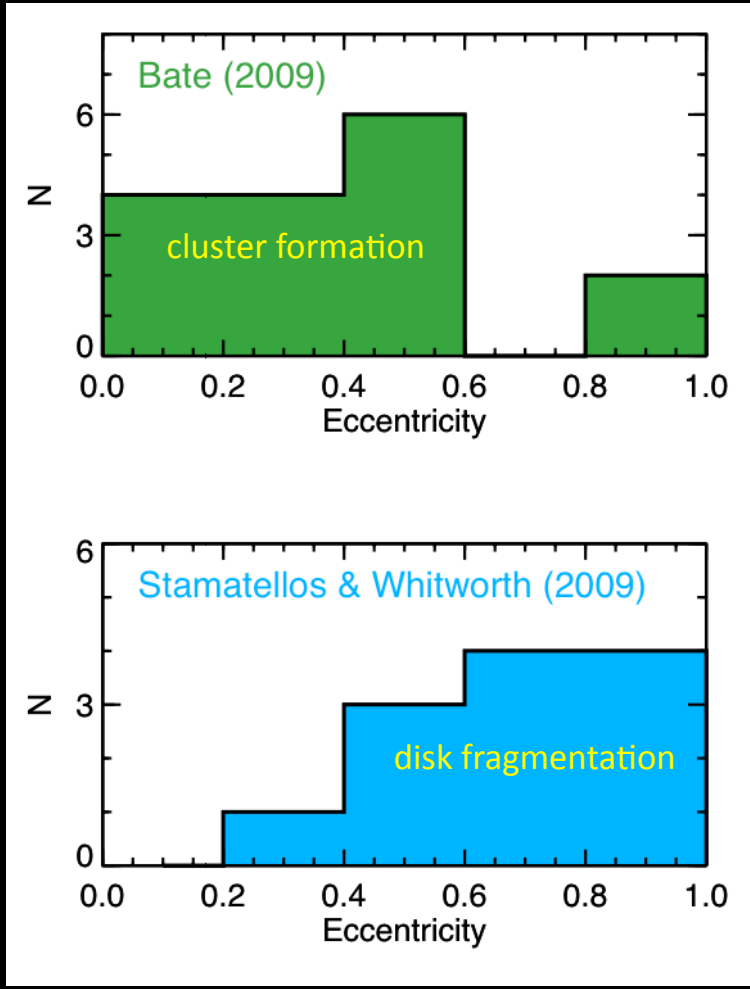


"disk fragmentation"

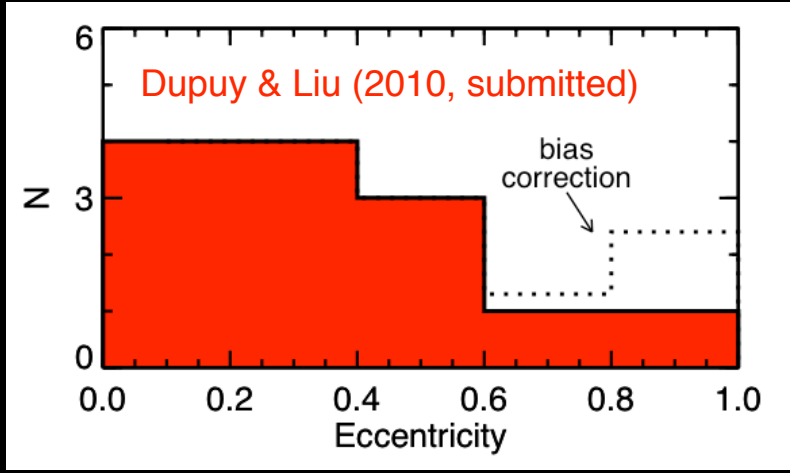


Testing Formation Models with Eccentricities

Theory



Observation

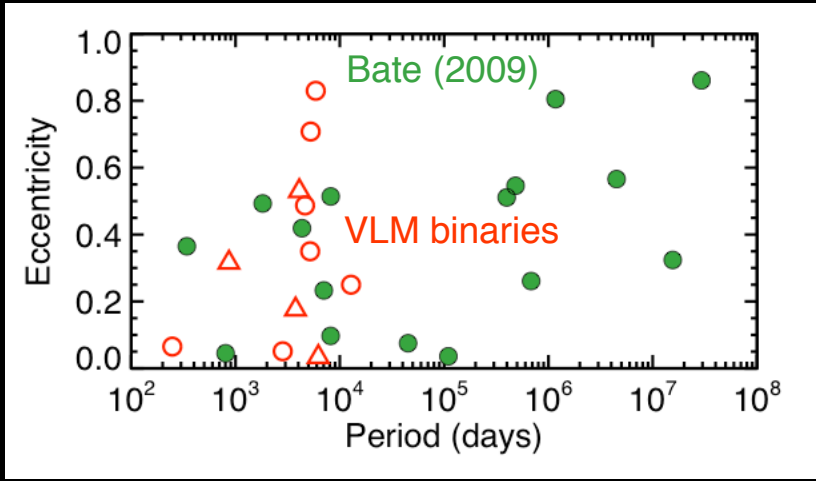


Very low-mass binaries typically have modest eccentricities but span a wide range: $0.03 < e < 0.83$.

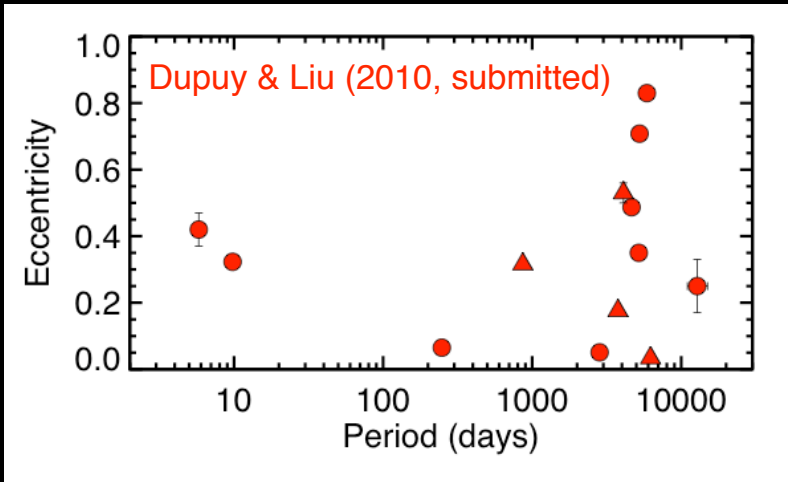
Highly inconsistent with disk fragmentation simulations.

Testing Formation Models with Eccentricities

Theory



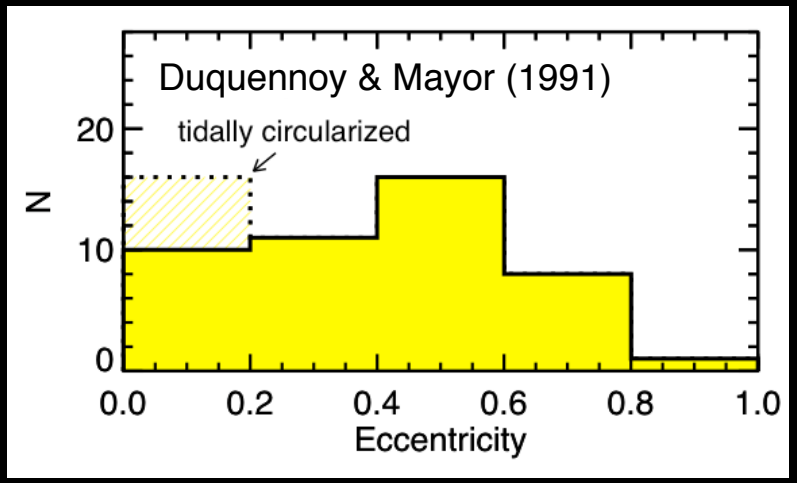
Observation



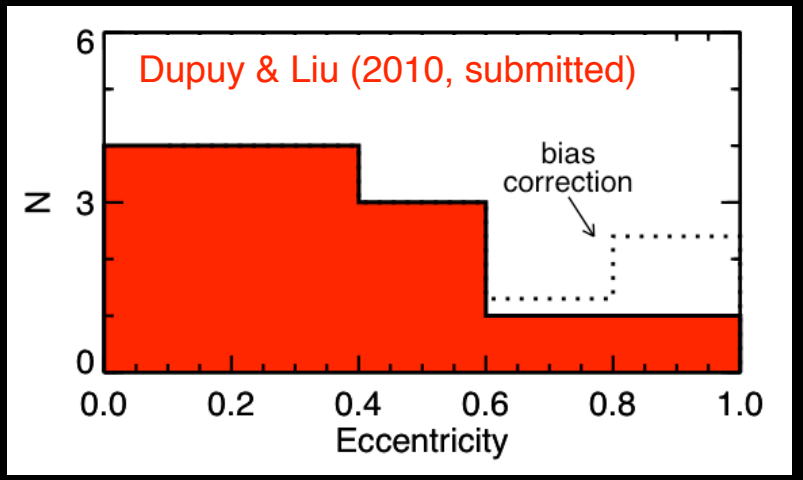
Cluster formation binaries have *much* longer periods than typical field binaries. **No high-*e* binaries predicted at periods comparable to our observations.**

Testing Formation Models with Eccentricities

Solar-type binaries



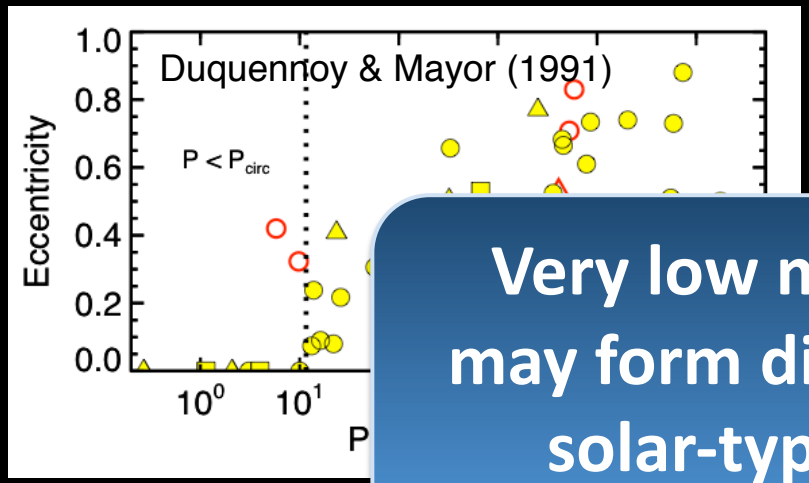
Very low mass



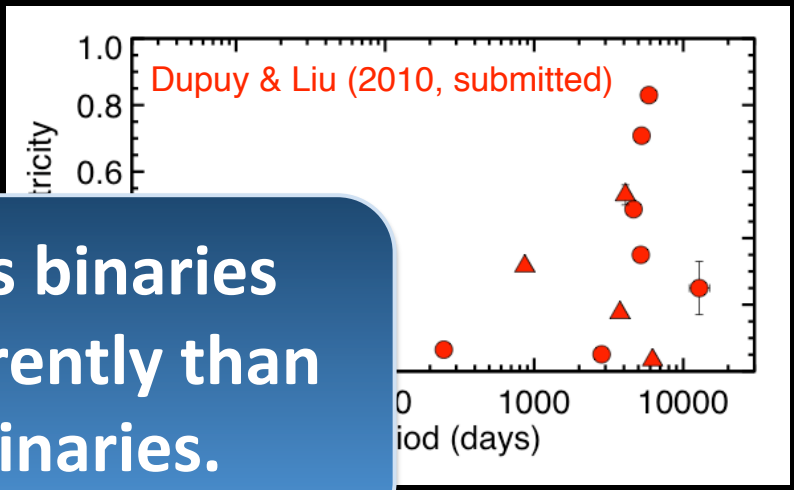
Solar-type binaries have a very similar eccentricity distribution to very low mass binaries ($P_{K\text{-}S} > 50\%$)

Testing Formation Models with Eccentricities

Solar-type binaries



Very low mass

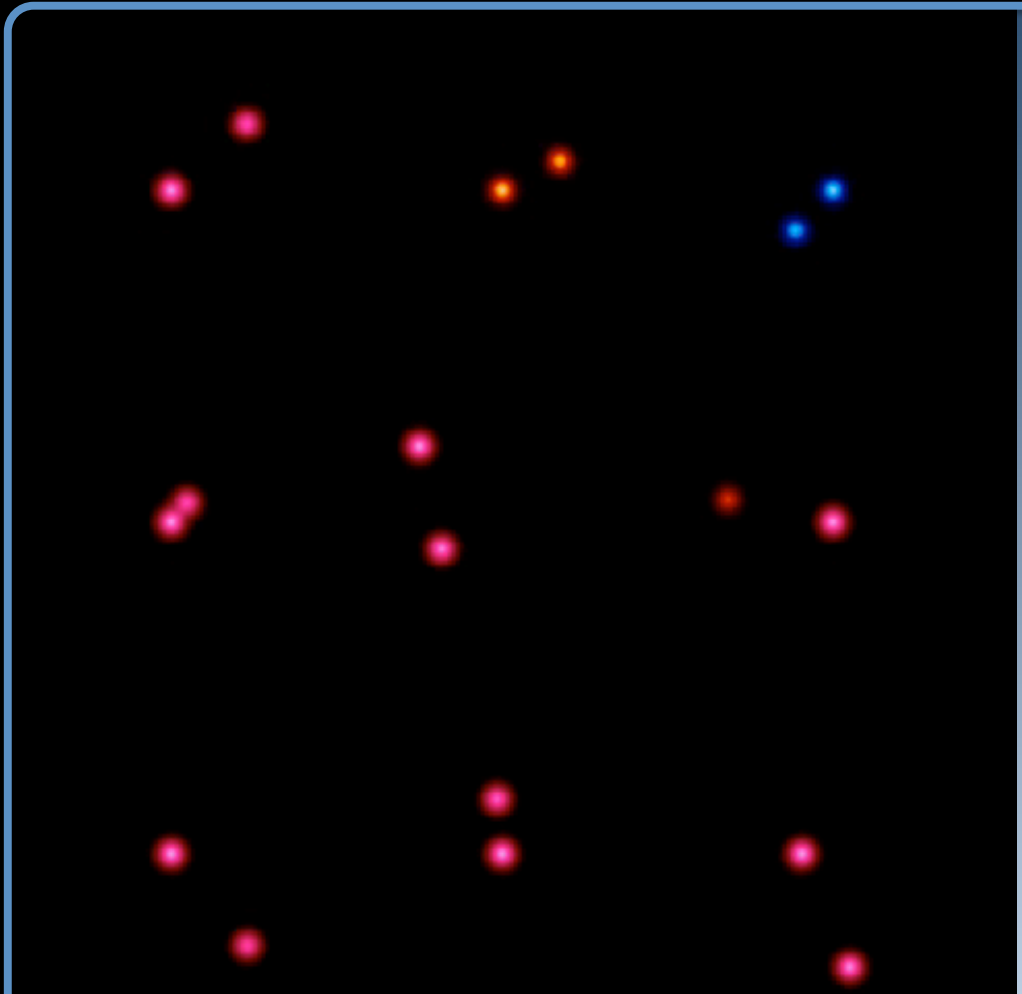


Very low mass binaries may form differently than solar-type binaries.

However, they show a correlation between period and eccentricity that VLM binaries do *not* display.

Rank correlation test shows no significant correlation between period and eccentricity.

The Future: Many More Orbits…



Many more masses are forthcoming with our new CFHT parallaxes…