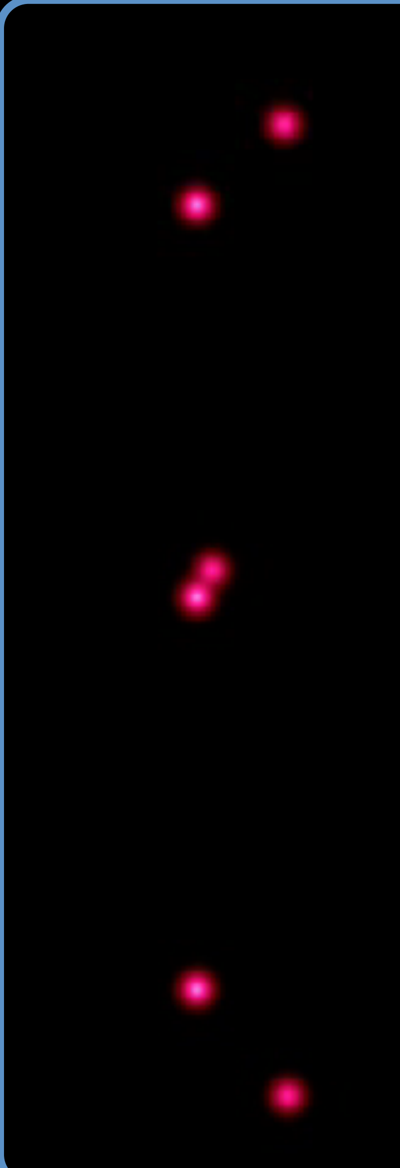
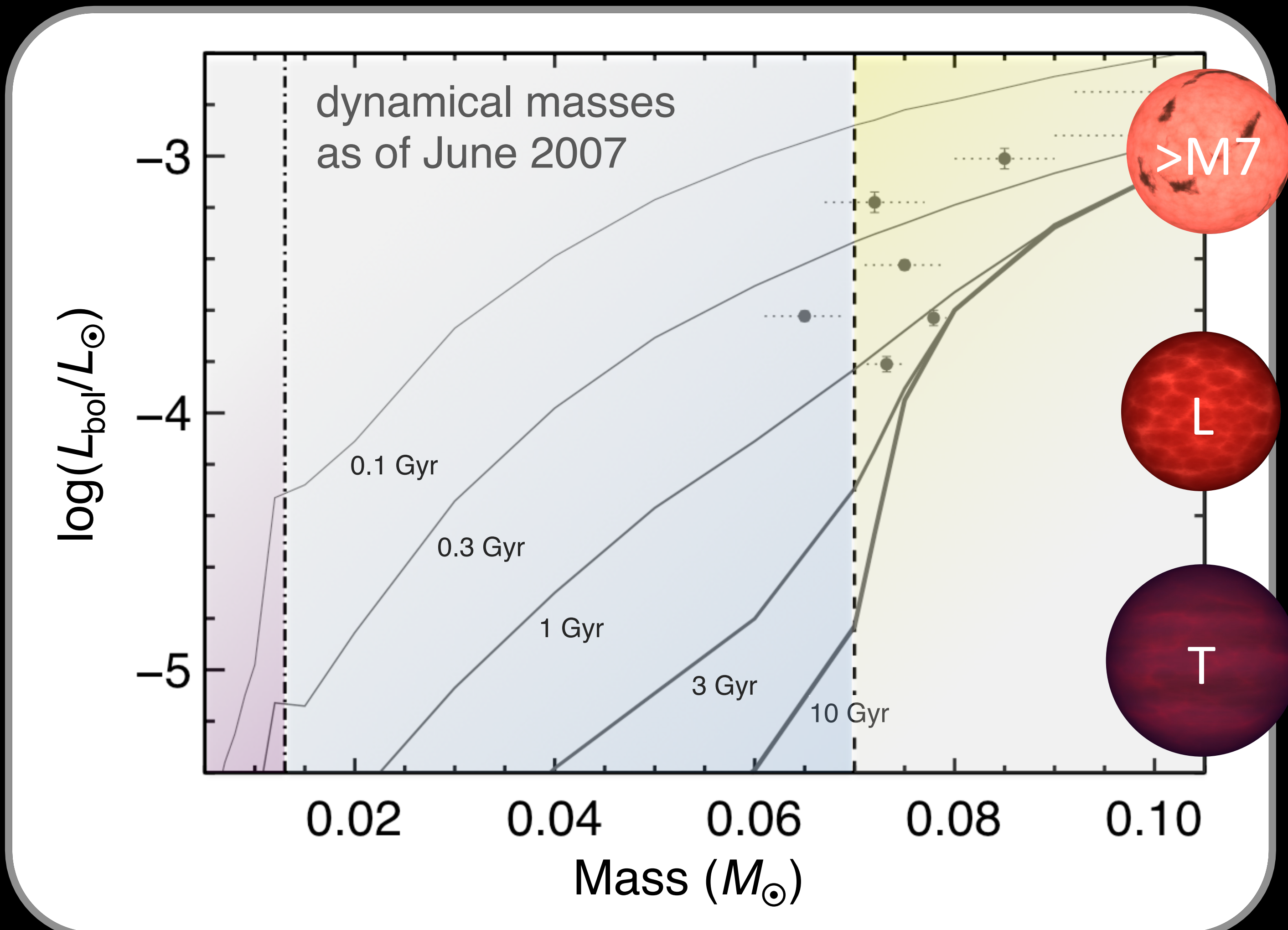


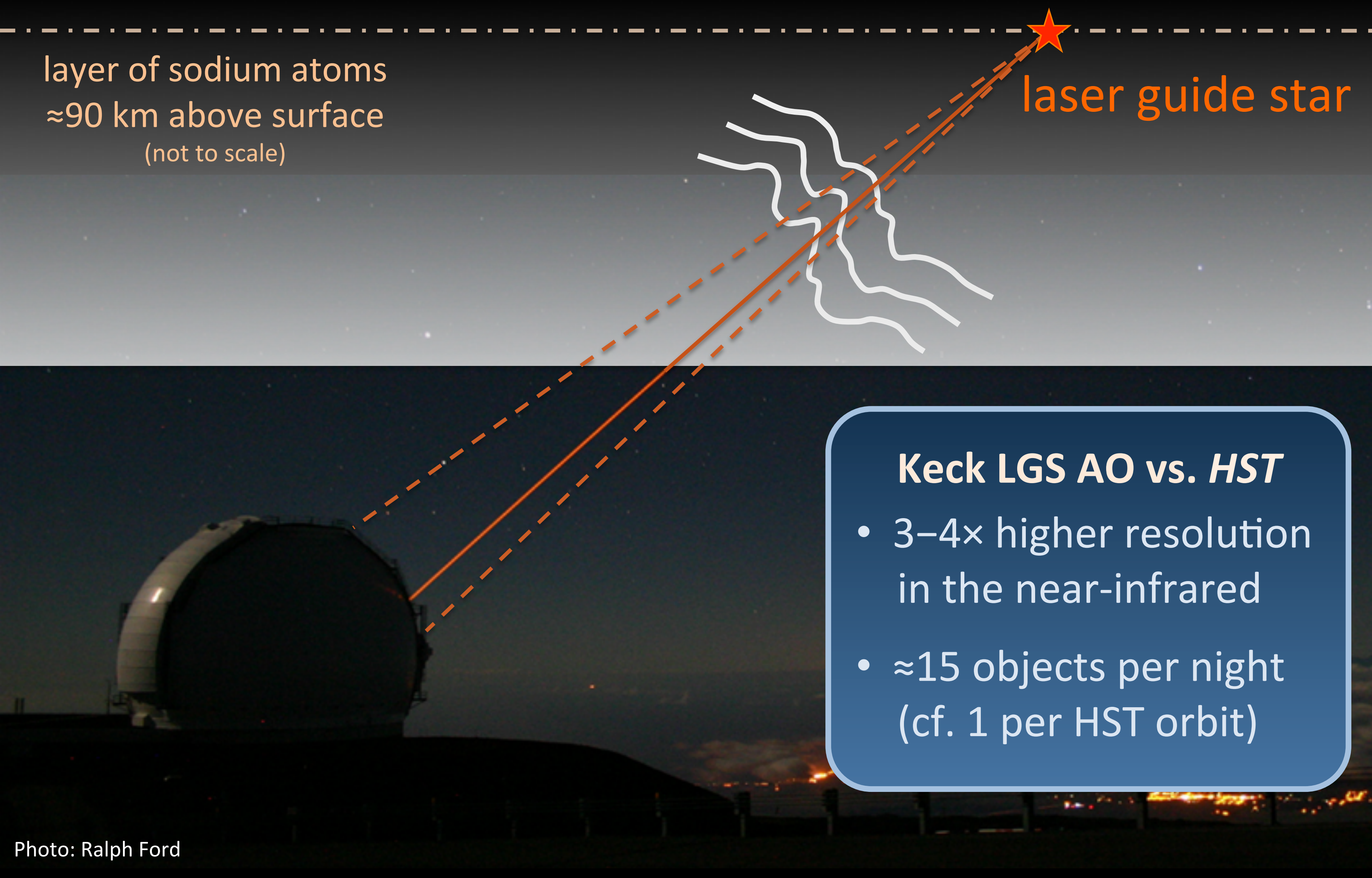
Testing Binary Formation with Brown Dwarfs in the Solar Neighborhood

Trent Dupuy
Harvard-Smithsonian Center for Astrophysics

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

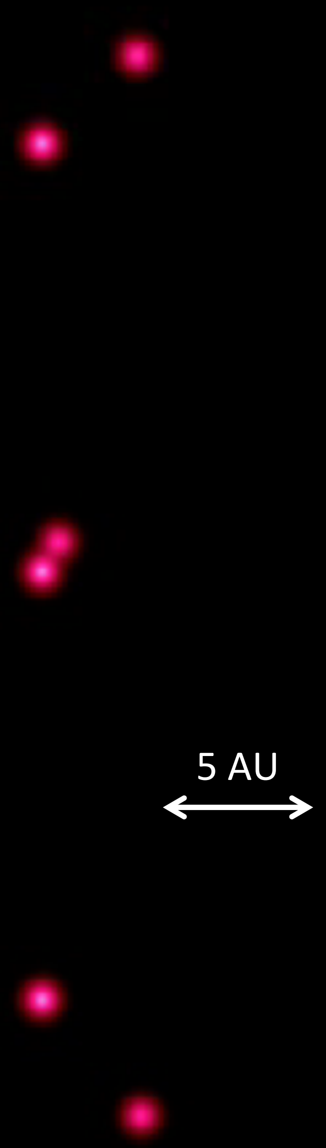
Ref: Leinert et al. (2001); Lane et al. (2001); Bouy et al. (2004)

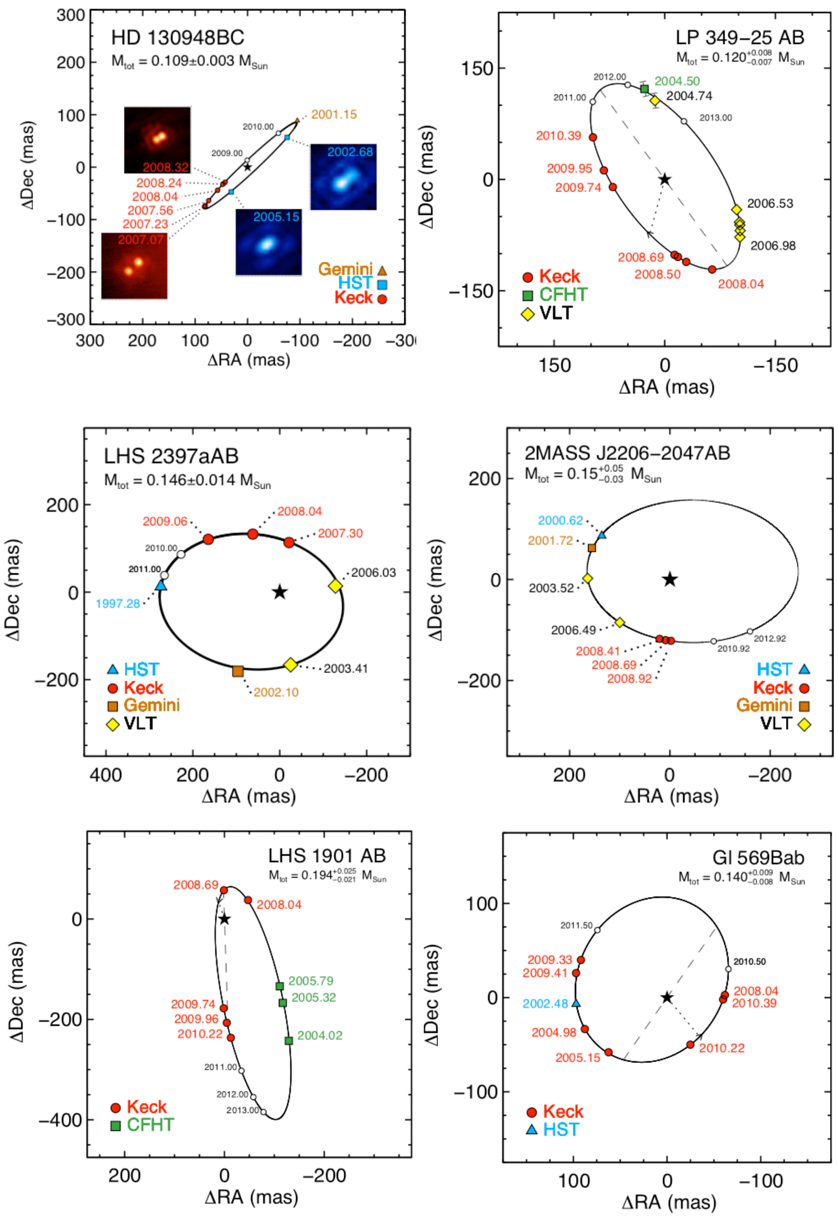

dynamical masses
as of June 2007
0.1 Gyr
0.3 Gyr
1 Gyr
3 Gyr
10 Gyr
>M7
L
T
−3
−4
−5
0.02
0.04
0.06
0.08
0.10
log(L_bol/L_⊙)
Mass (M_⊙)



Keck LGS AO vs. *HST*

- 3–4× higher resolution in the near-infrared
- ≈15 objects per night (cf. 1 per HST orbit)

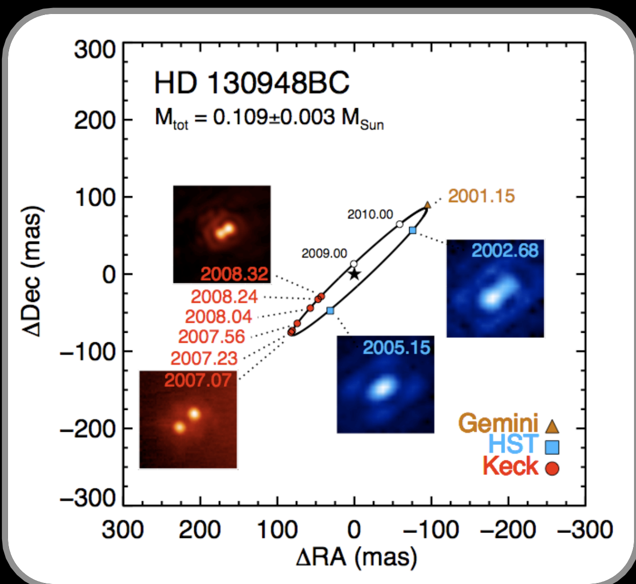

5 AU



Family Portrait of Keck Orbits

- Excellent Keck astrometry: typically 0.3–1.0 milliarcsec; **best is 100–200 μas**
- Bayesian orbit analysis from Markov Chain Monte Carlo
- All orbits have reduced $\chi^2 \approx 1$
- Dynamical mass precision **9% (median), as good as 2%**

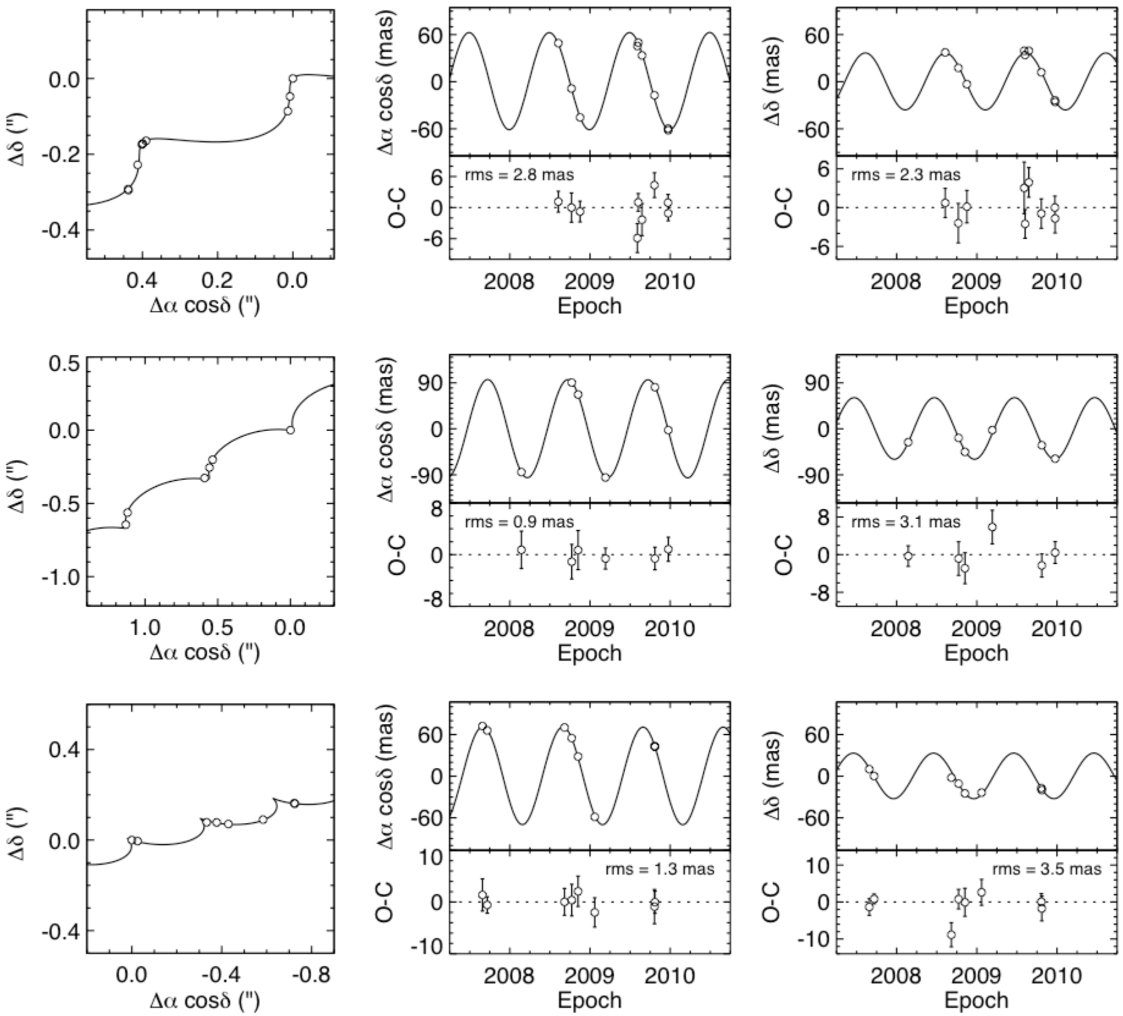
Dupuy et al. (2009a,b,c, 2010a,b)



$$M_{tot} = \frac{\alpha^3 d^3}{P^2}$$

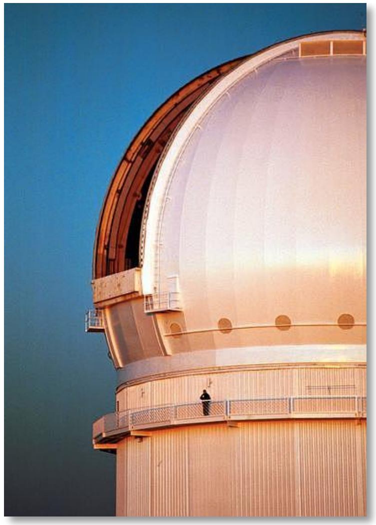
Kepler

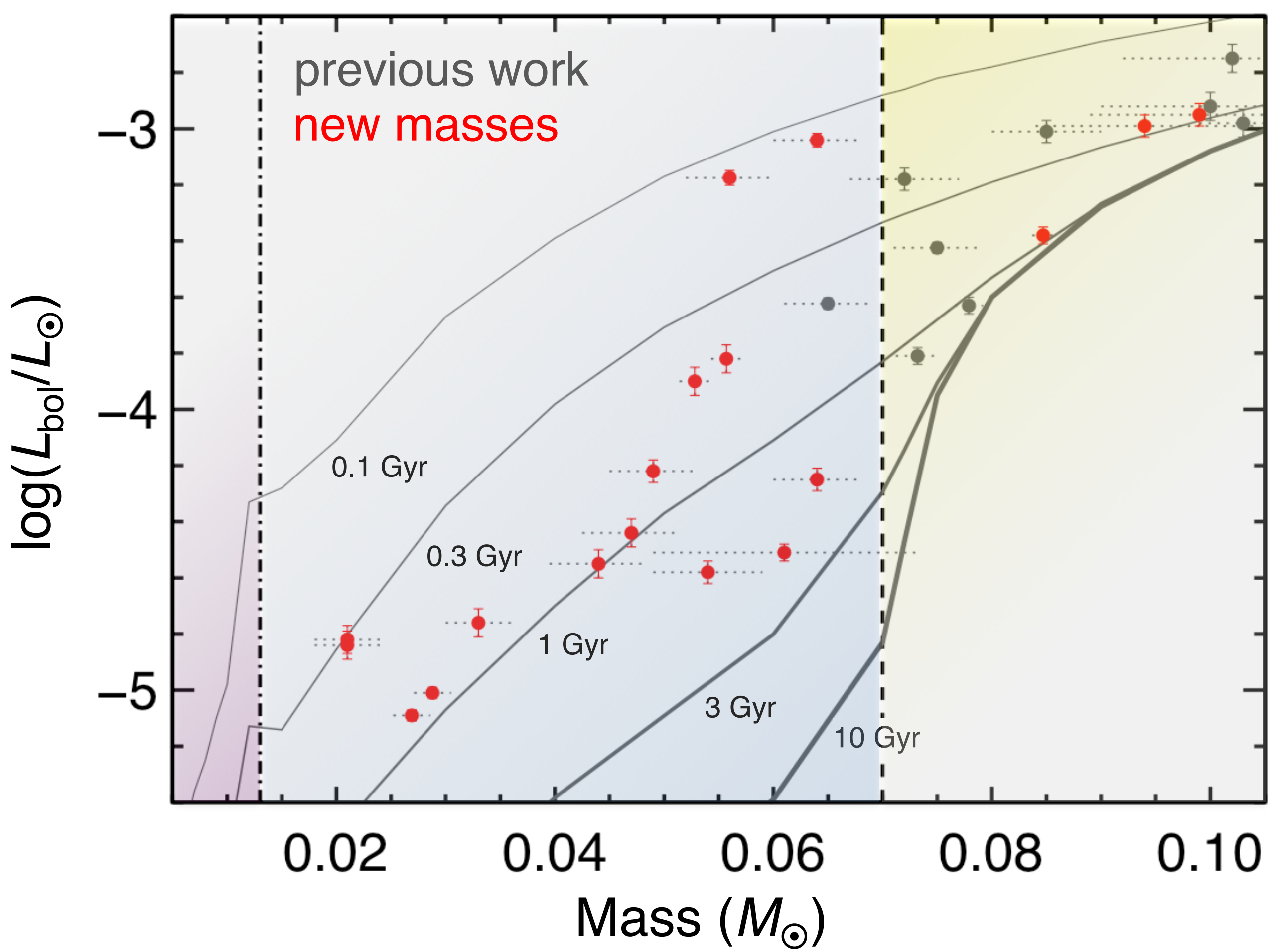
CFHT Parallaxes Enable ≈3× Larger Sample



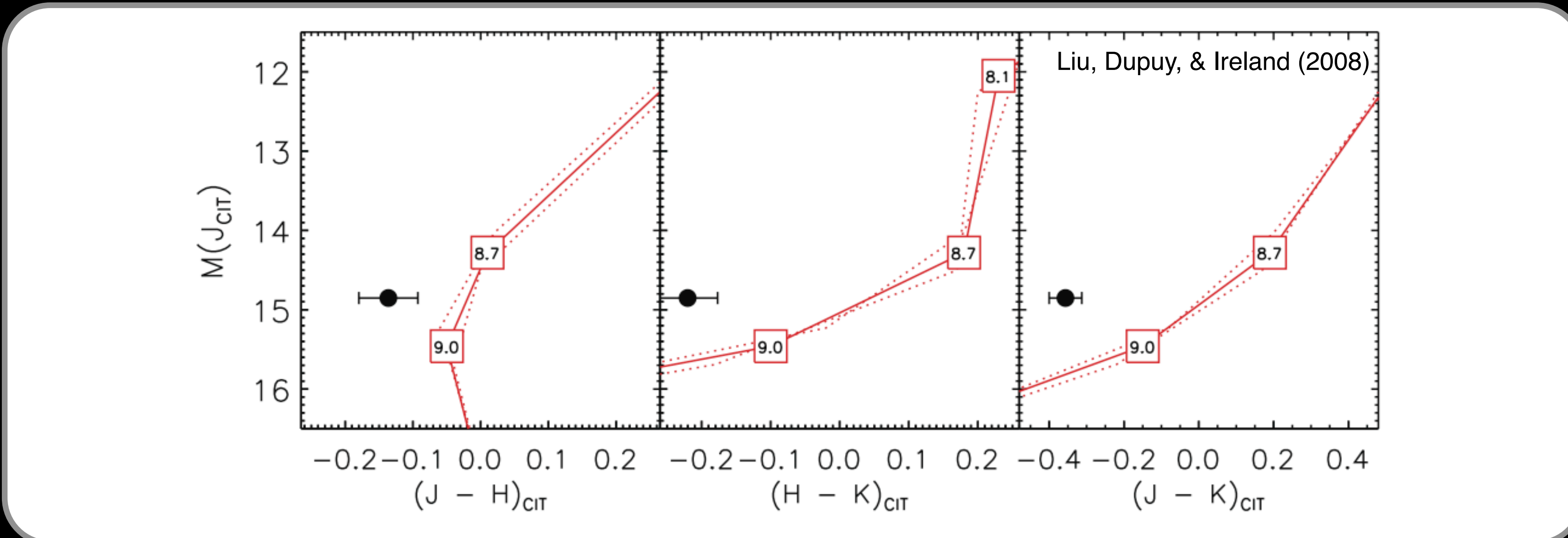
rms ≈ 1–3 mas

yields parallax errors of 1–3%

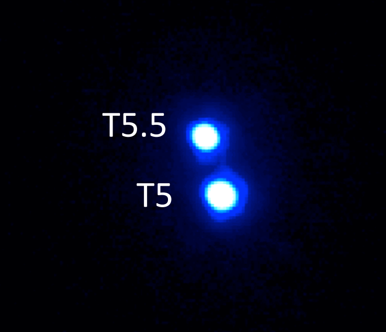



previous work
new masses
0.1 Gyr
0.3 Gyr
1 Gyr
3 Gyr
10 Gyr
−3
−4
−5
0.02
0.04
0.06
0.08
0.10
$\log(L_{bol}/L_{\odot})$
Mass ($M_{\odot}$)

Testing the Models: Color–magnitude diagram



2MASS J1534-2952AB

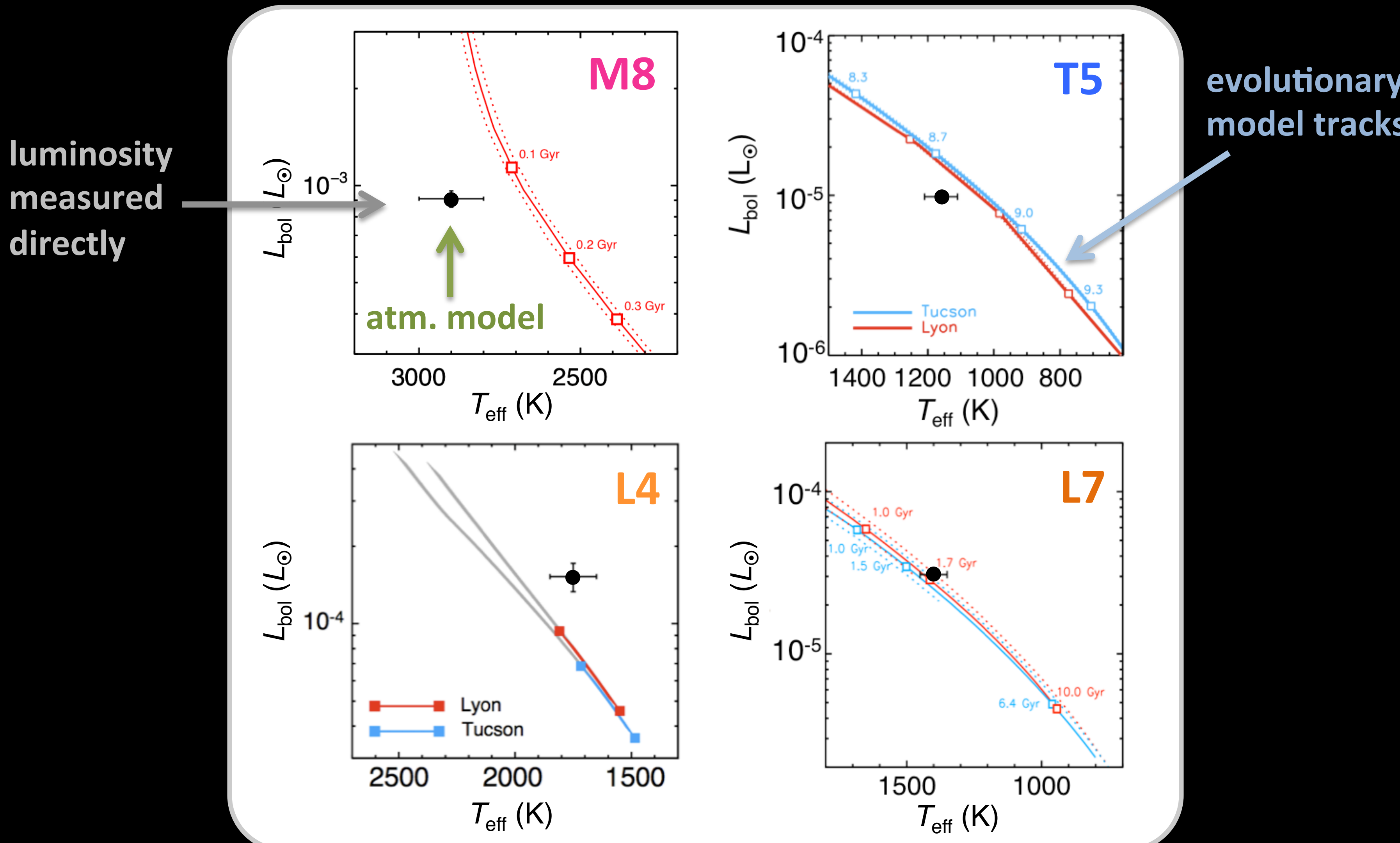


Liu, Dupuy & Ireland (2008)

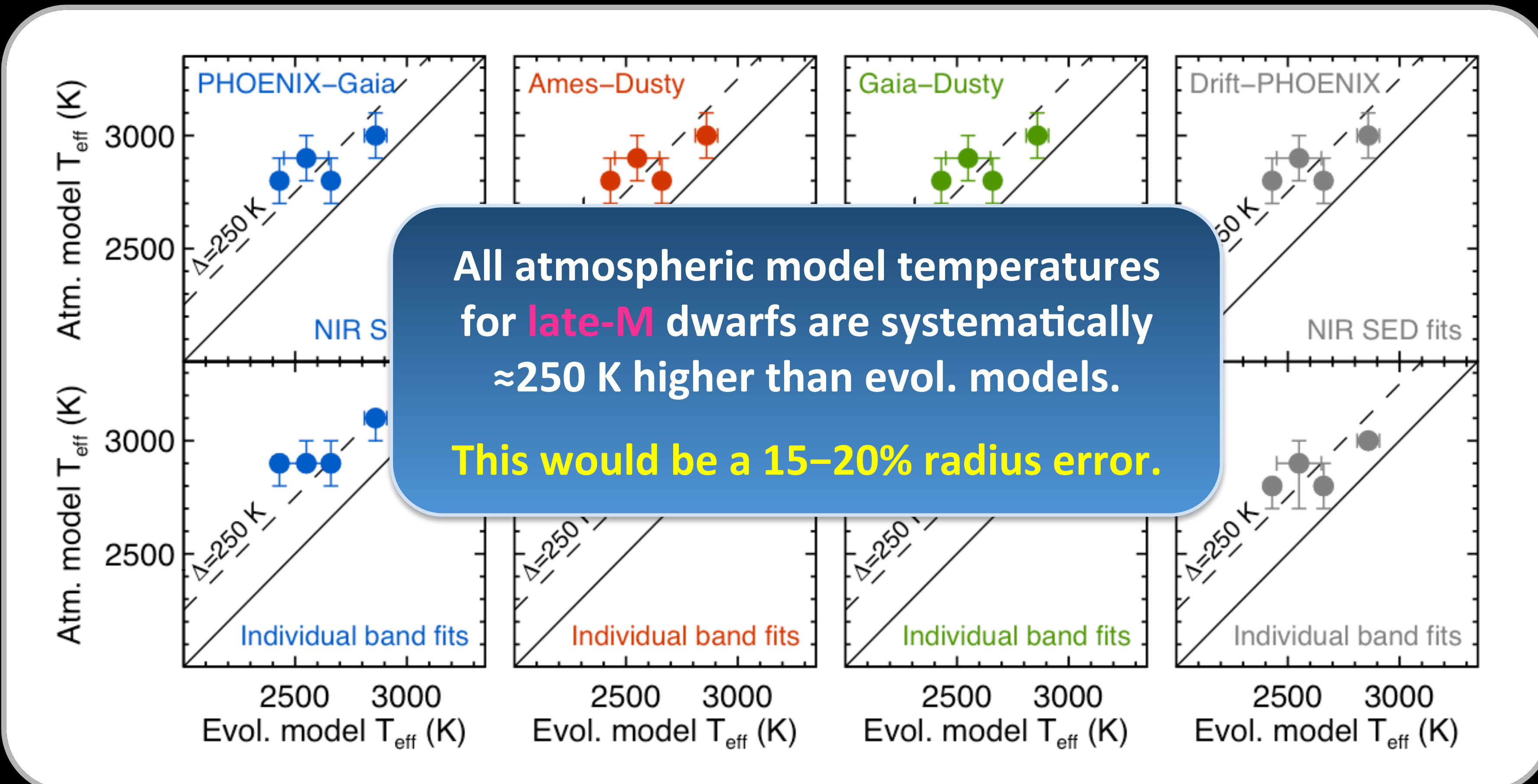
Testing the Models

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

Testing the Models: H-R Diagram



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



All atmospheric model temperatures for late-M dwarfs are systematically ≈250 K higher than evol. models.

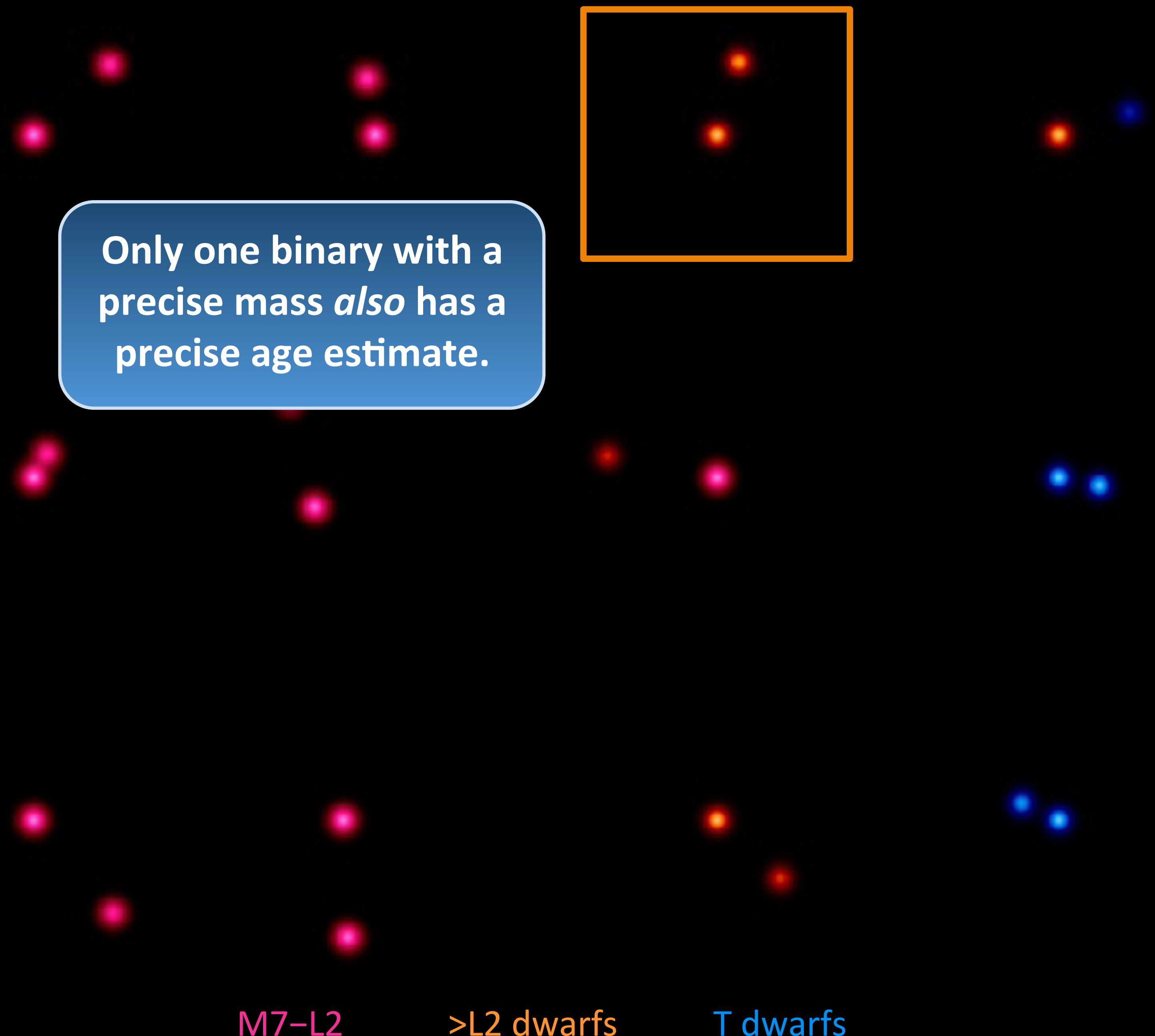
This would be a 15–20% radius error.

Dupuy et al. (2010a)

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_{eff} estimates (≈100−300 K)
  - Discrepancies observed from over broad range of spectral types
  - Offset is the same for objects of similar T_{eff} but with widely varying masses, ages, and activity levels


Only one binary with a precise mass *also* has a precise age estimate.
M7−L2
>L2 dwarfs
T dwarfs

Testing the Models:
The Gold Standard

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

↓

model-derived age: 450±50 Myr

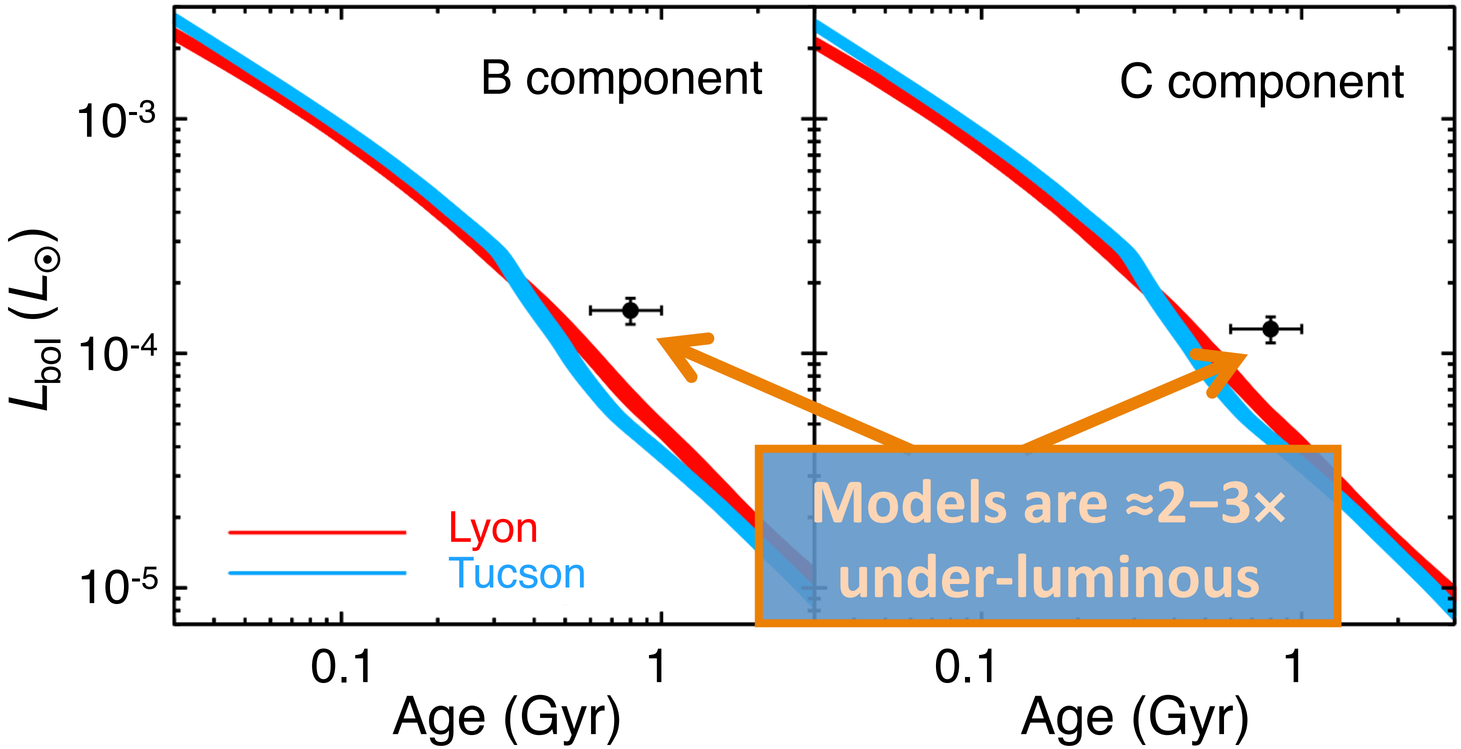
Age Indicator	Age (Myr)	Error
Gyrochronology	**800±200**	**25%**
Chrom. activity	500±300	60%
Isochrones	300–2500	≈2×
X-ray activity	≈Hyades	…
Lithium	≈Hyades	…

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)

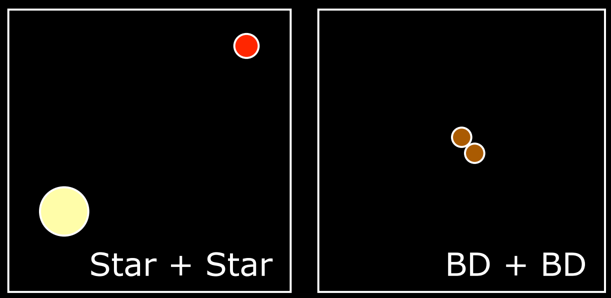
Testing the Models

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

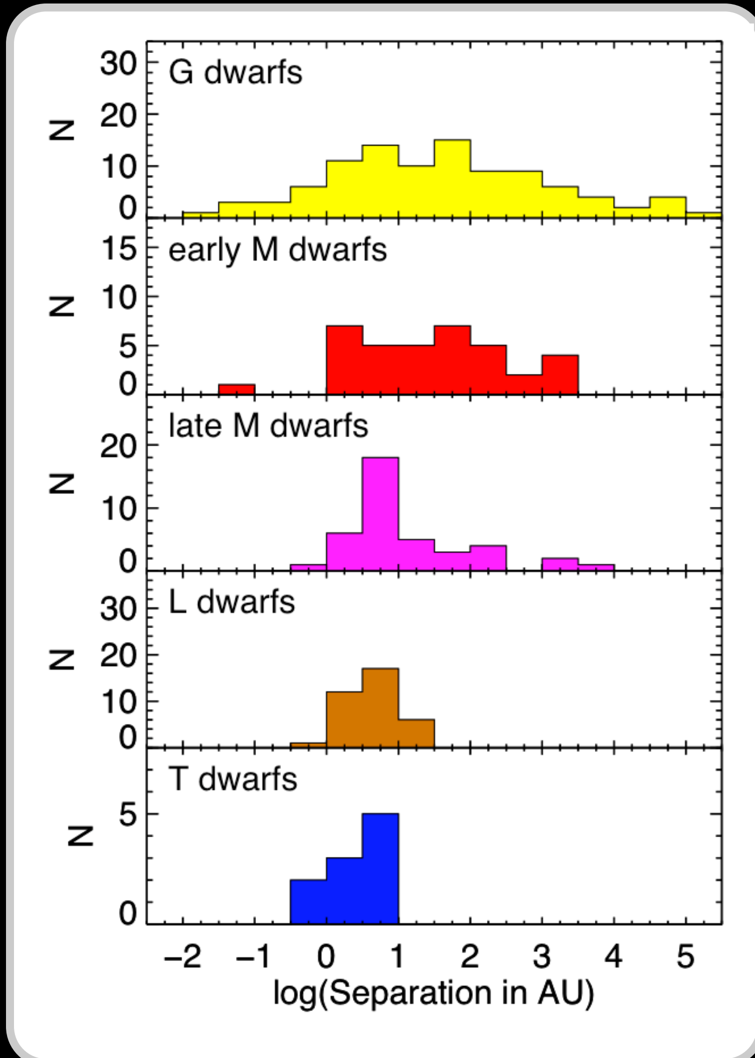
- **"Temperature Problem":** evolutionary and atmospheric models give inconsistent T_{eff} estimates (≈100−300 K)
  - Discrepancies observed from over broad range of spectral types
  - Offset is the same for objects of similar T_{eff} but with widely varying masses, ages, and activity levels

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

Brown Dwarf vs. Stellar Binaries



	Star+Star	BD+BD
Frequency	~50%	~15%
Mass Ratio	~0.3	~1.0
Separation	~30 AU	~6 AU



Duqennoy & Mayor (1991); Fischer & Marcy (1992); Close et al. (2002); Bouy et al. (2003); Burgasser et al. (2007); Liu et al. (in prep.)

The ensemble of orbital eccentricities enables novel tests of formation models.

$$E = -G\,M_{tot}\,(2a)^{-1}$$

$$L^2 = G\,M_{tot}\,a\,(1-e^2)$$

ON THE STATISTICS OF DOUBLE STARS

By *V. Ambarzumian*

The present paper deals with the distribution of elements of the double-star-orbits.

In § 1 the distribution of excentricities is considered. It is shown that in the case, when the density-function in the phase-space is an arbitrary function of energy of the system the number of binaries with excentricities smaller than ε will be proportional to ε^2. Therefore, from the observed proportionality of this number to ε^2 we cannot derive any conclusion about the specific form of the dependence of the density-function on the energy of pair. For example, from the observed distribution of excentricities we cannot decide whether the equipartition actually exists or not.

In § 2 the observed distribution of distances (Öpik) is considered and the distribution of major-axes (and energies) of orbits is derived. It is shown that the observed distribution of energies is in sharp discordance with the Boltzmann's law.

In § 3 the Opik's result about the distribution of distant companions is confirmed on the basis of Aitken's Catalogue.

In § 4 the time of relaxation for the binaries with $a = 10^3 - 10^4$ astr. units is calculated. It amounts about 10^{10}—10^{11} years. Therefore, the discrepancy between the observed distribution of energies (as it follows from Opik's law for distances) and Boltzmann's law is a very strong argument against the long-time scale of the evolution of stellar system. The statements of Jeans [2,3] on this subject are erroneous.

In § 5 is shown that the ratio of the number of the distant pairs and single stars in the state of dissociative equilibrium will be some millions times smaller than the observed ratio. According to § 4 the dissociative equilibrium sets in during 10^{10}—10^{11} years. The absence of the dissociative equilibrium is also a new argument against the long time-scale.

Astronomical Observatory
University, Leningrad

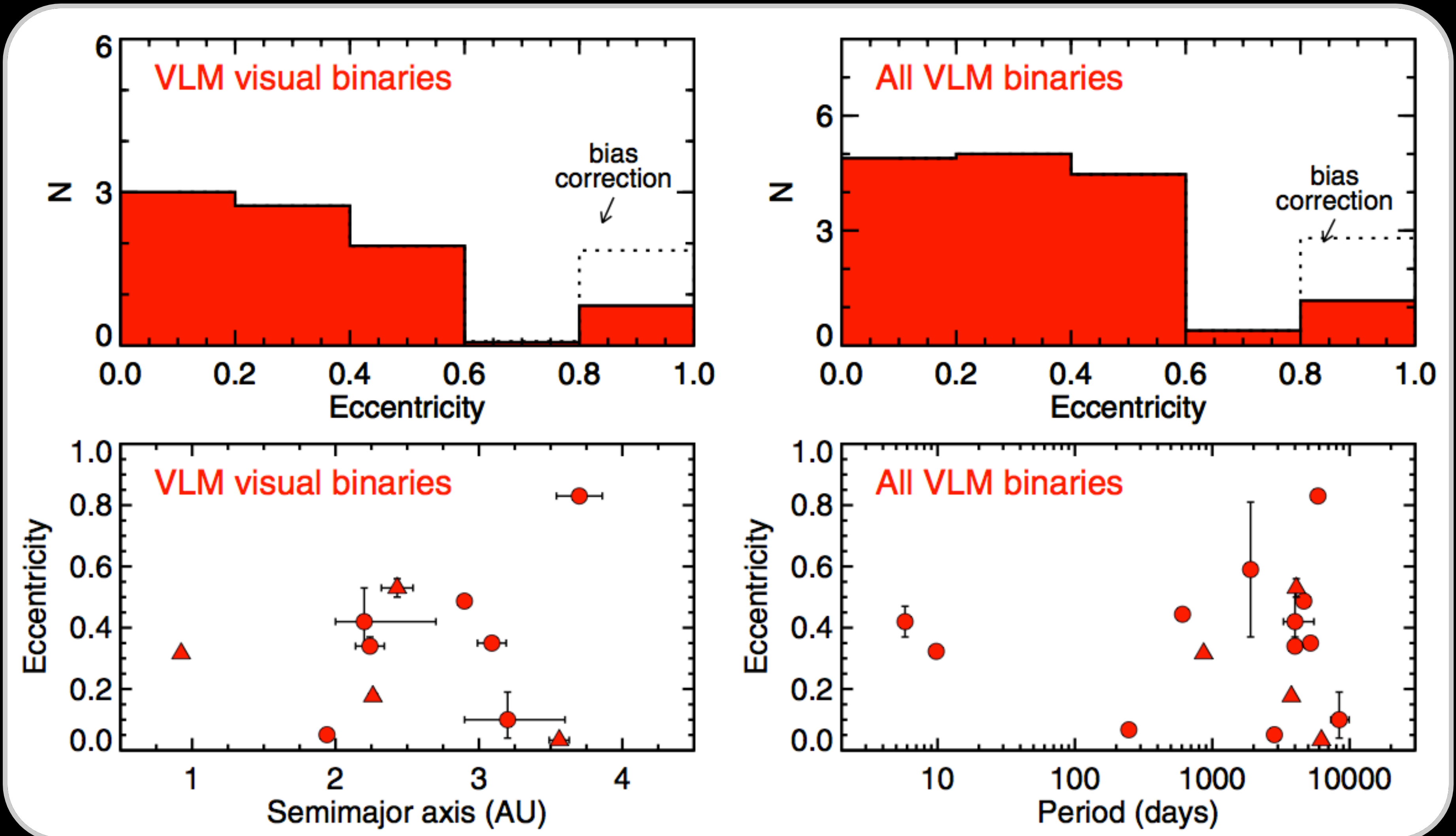
Ambartsumian (1937)

Distribution is:

$p(e) = 2e$

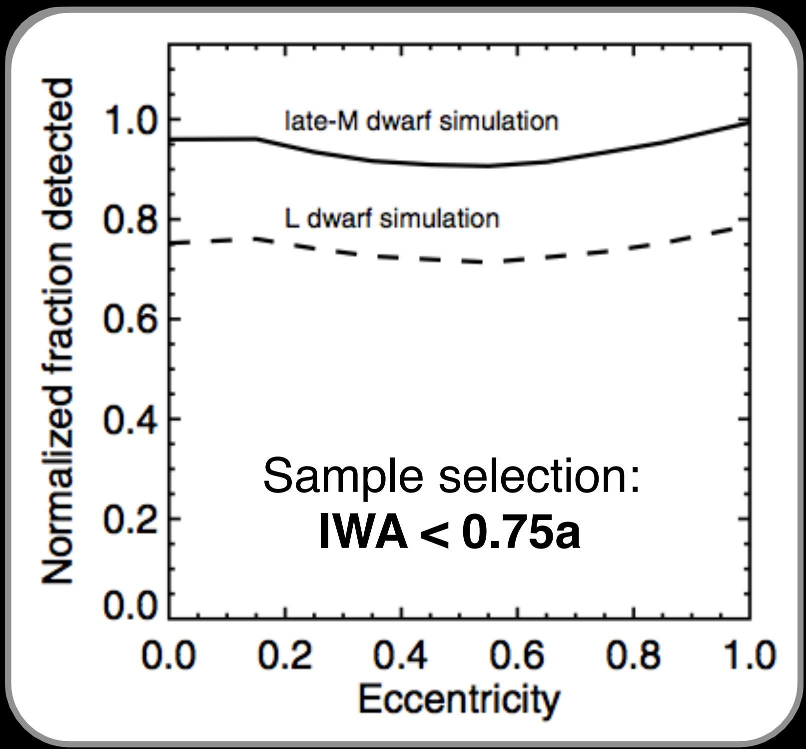
if energy of binary orbits follows a Boltzmann function

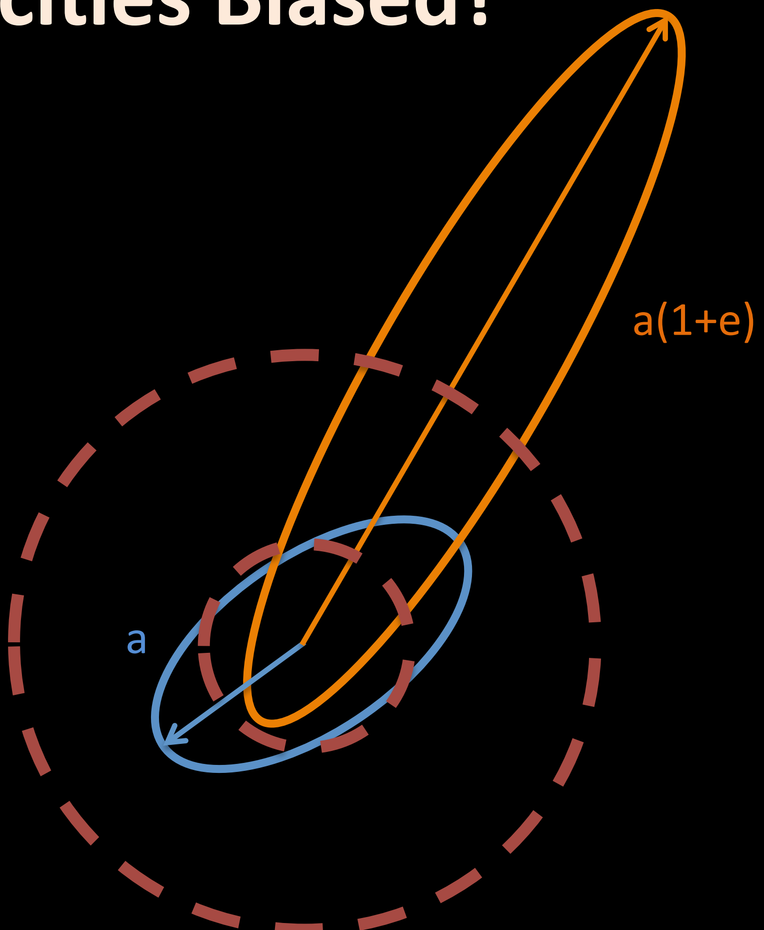
Binaries are not distributed this way, therefore the age of the Galaxy cannot be 100 Gyr.

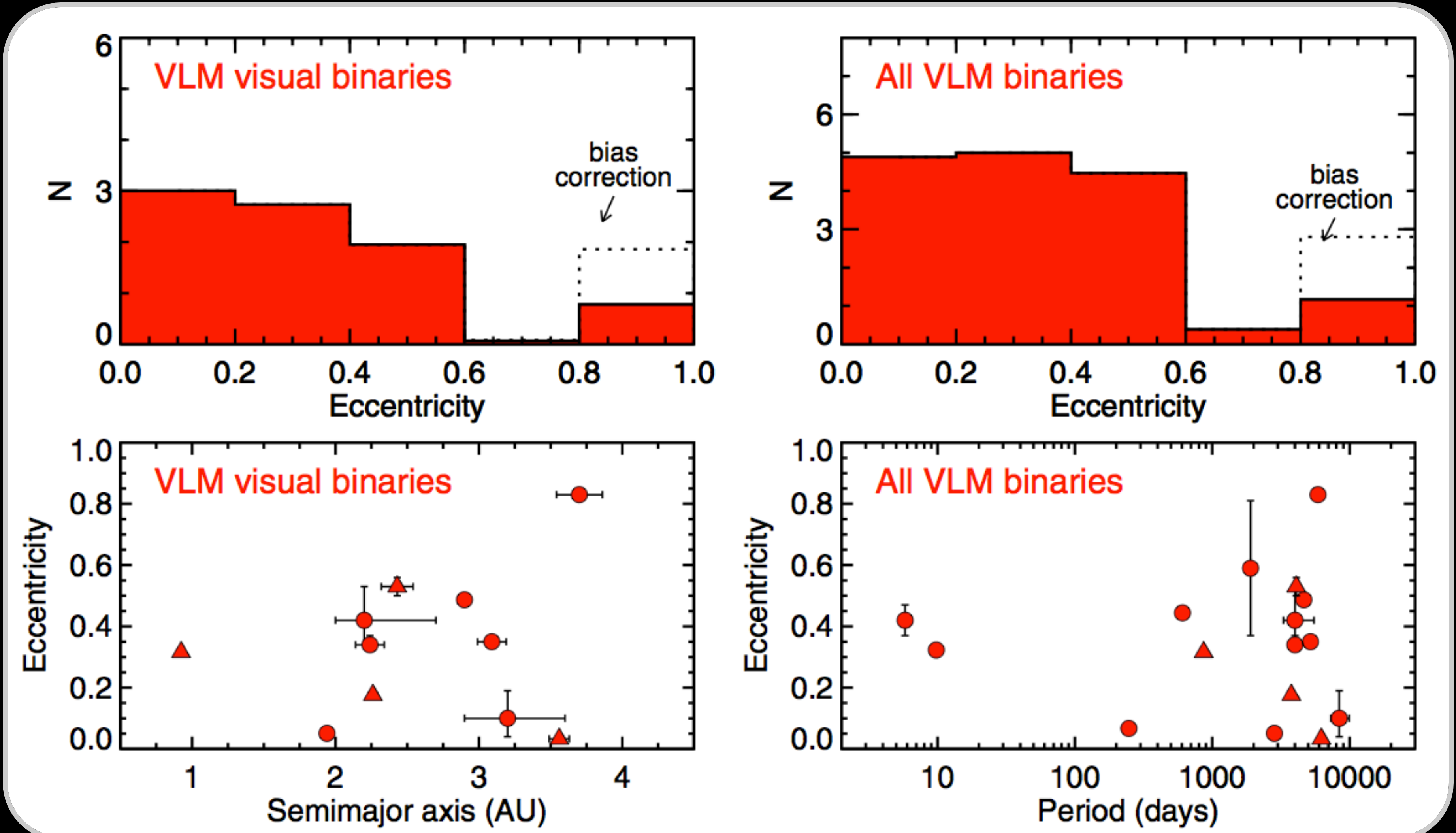


Dupuy & Liu (2011)

Are Observed Eccentricities Biased?



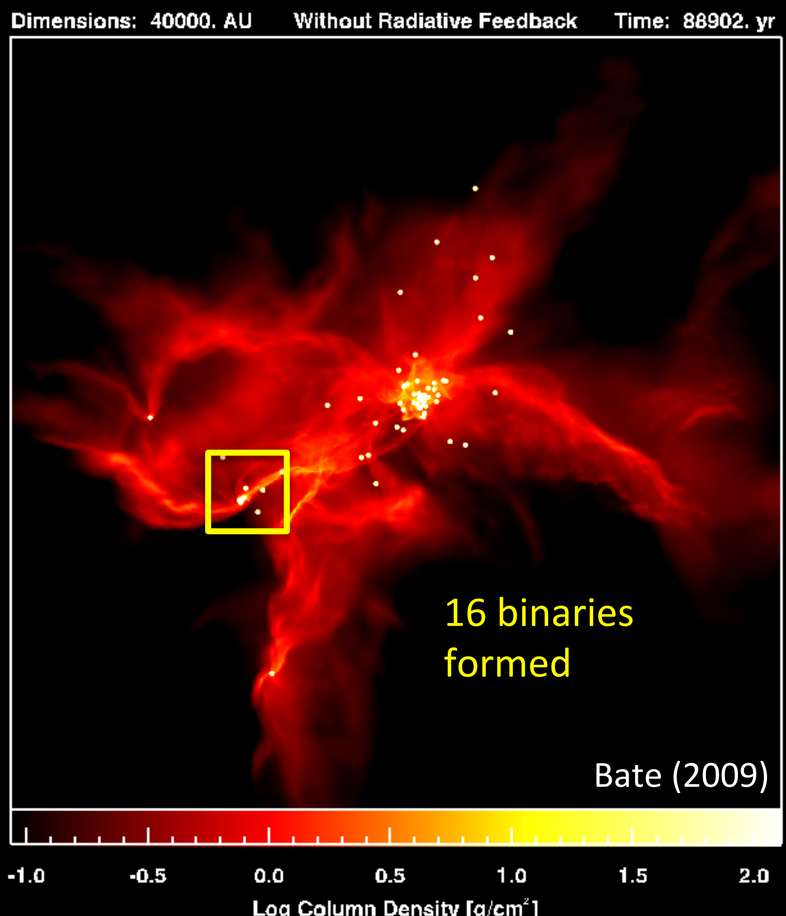




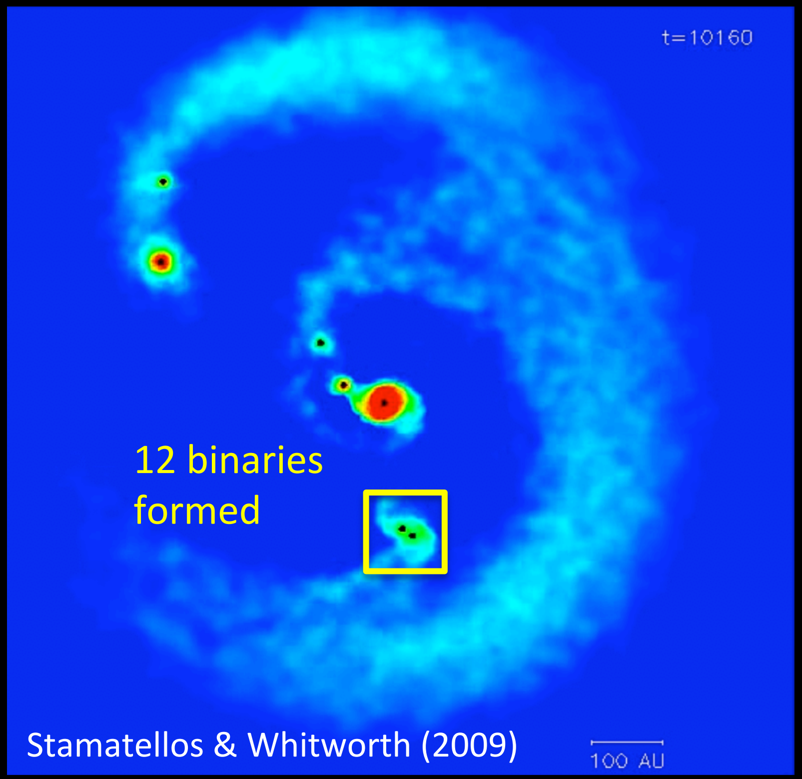
Dupuy & Liu (2011)

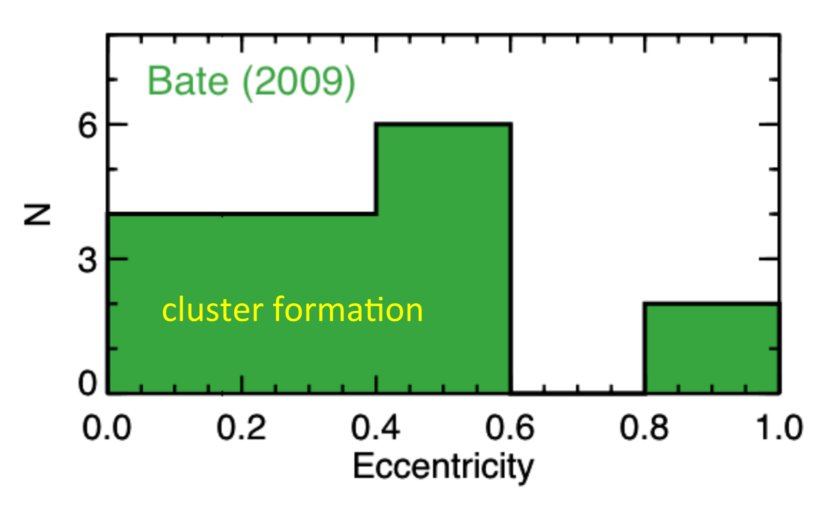
Testing Formation Models with Eccentricities

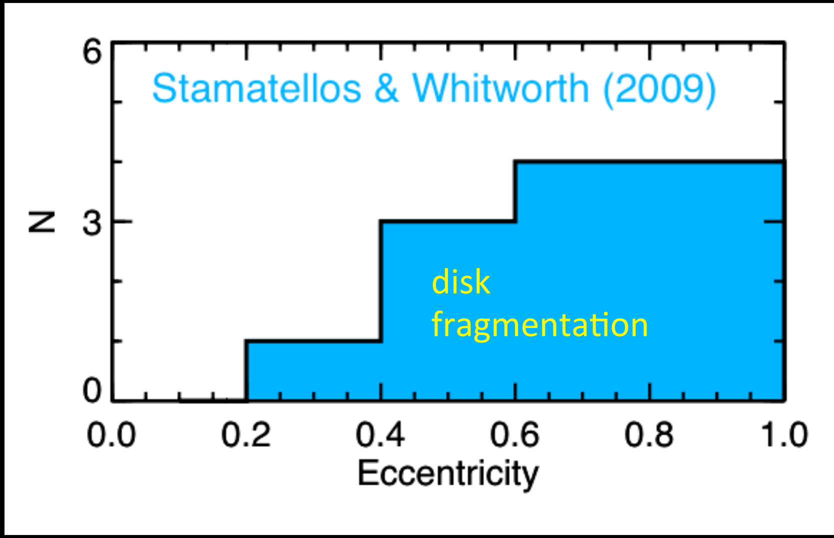
"cluster formation"

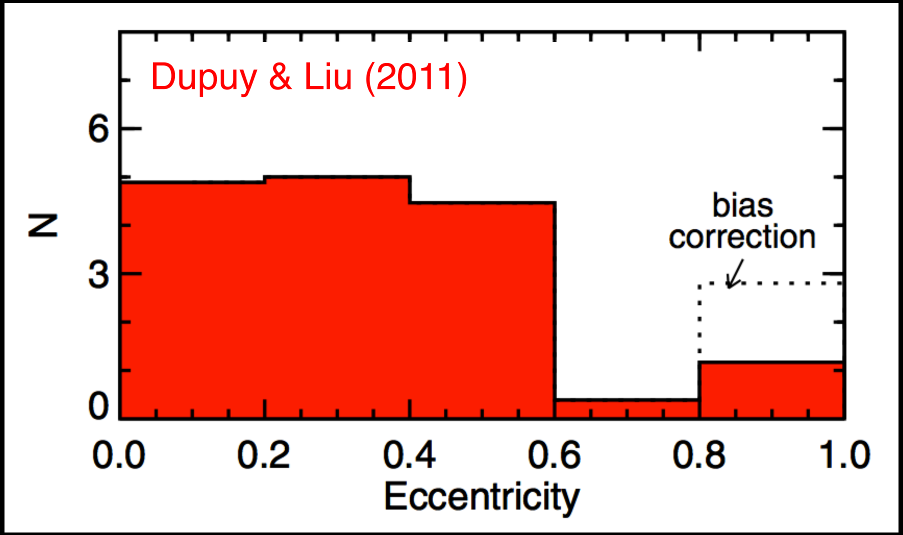


"disk fragmentation"



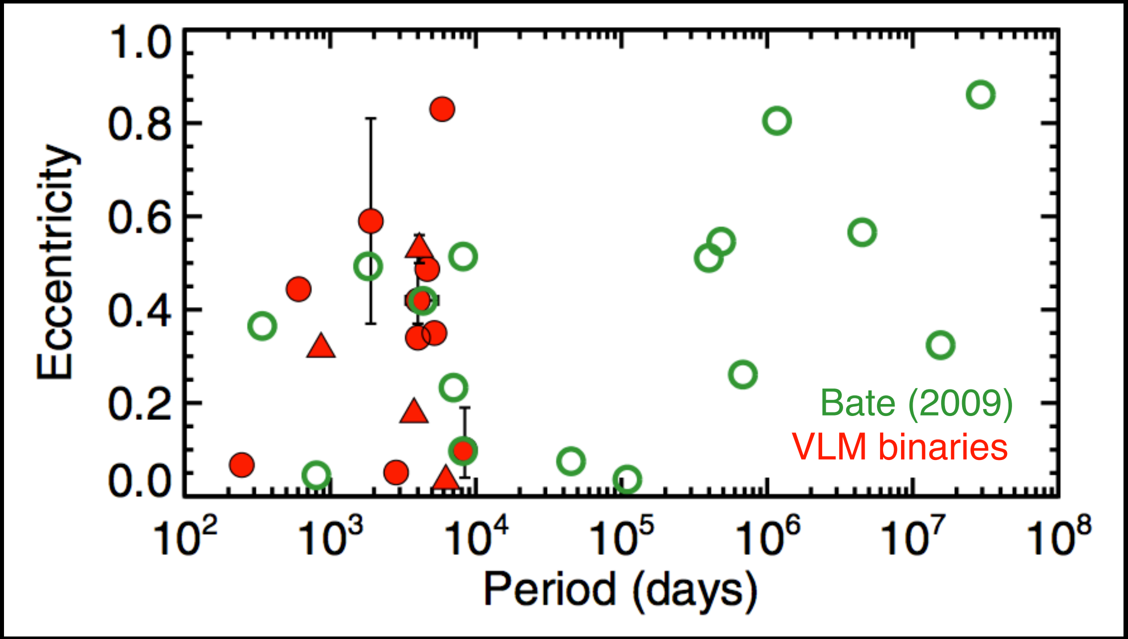






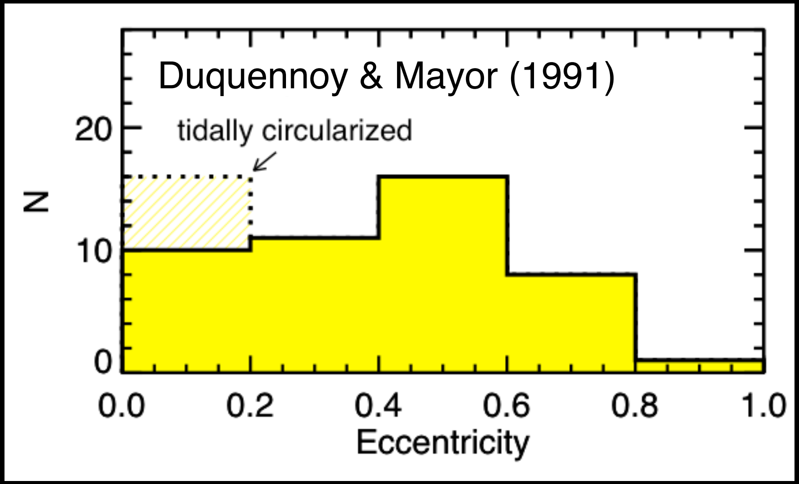
Stamatellos vs. Bate:
Gas treatment is very different.

Disks play important role in determining eccentricities?

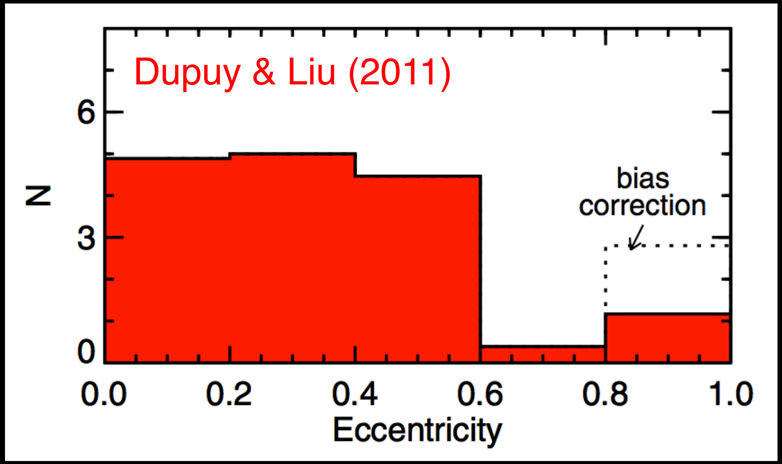


Cluster formation binaries have *much* longer periods than typical field binaries. **No high-*e* binaries predicted at periods comparable to our observations.**

Solar-type binaries

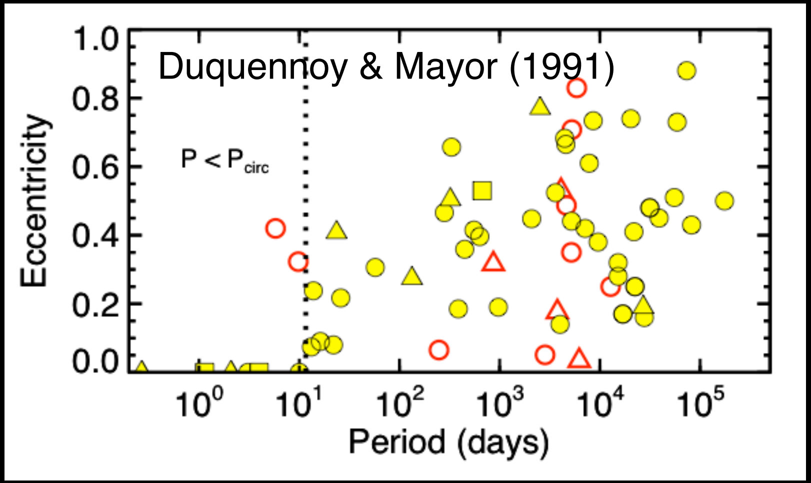


Very low mass



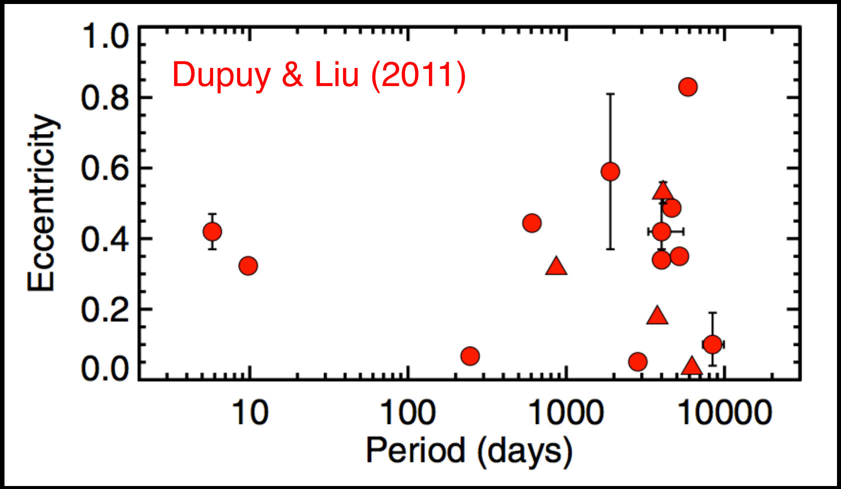
Solar-type binaries have a very similar eccentricity distribution to very low mass binaries ($P_{K\text{-}S}$ > 50%)

Solar-type binaries



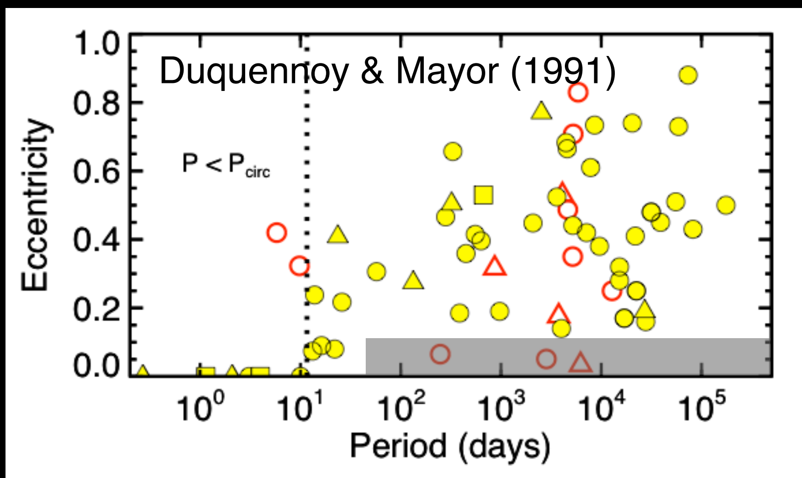
However, they show a correlation between period and eccentricity that VLM binaries do *not* display.

Very low mass



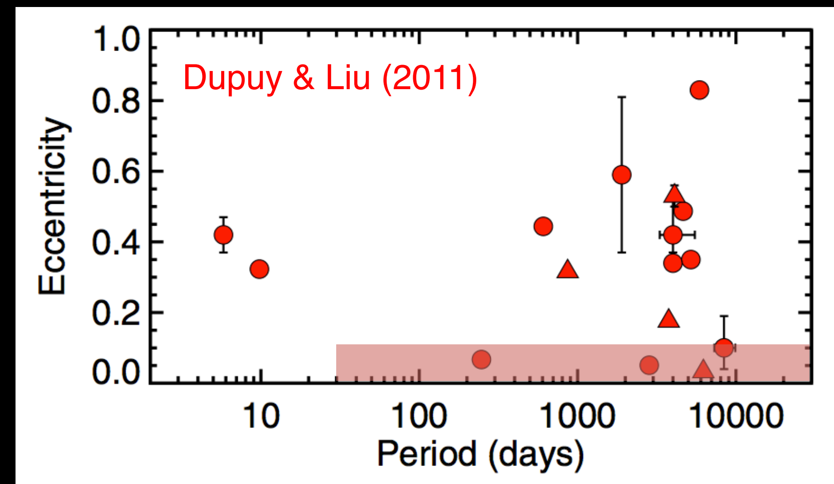
Rank correlation test shows no significant correlation between period and eccentricity.

Solar-type binaries



Also, both MS and PMS solar-type binaries show **strong deficiency** in low-eccentricities (e < 0.1).

Very low mass



Low eccentricity (e < 0.1) very **common** among VLM binares.

Summary

• Dynamical masses for field brown dwarf binaries provide the strongest tests of substellar models to date.

➔ Need dynamical masses for young BDs (e.g., Stassun et al. 2006).

• Eccentricities for VLM binaries are the latest addition to the set of parameters formation theories must match.

➔ Information fundamentally different from semimajor axes. Consistent with VLMS/BD formation being a "scaled down" version of star formation?