ADAPTIVE OPTICS IMAGING OF VLM STELLAR AND BROWN DWARF BINARIES

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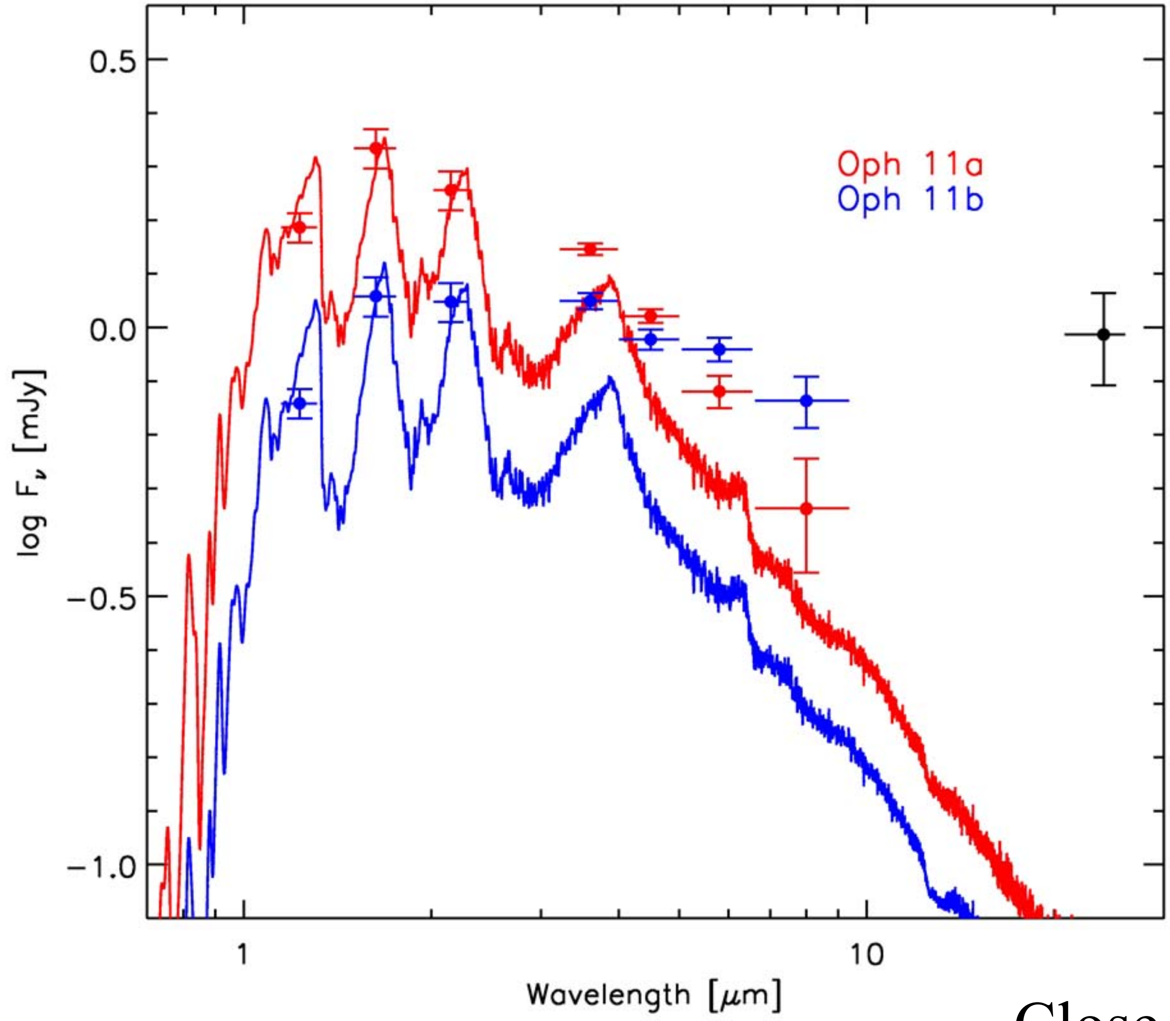
Adaptive Optics is an important tool that has had a major impact on our understanding of the nature of companions of all types

Some reasons why AO on large scopes has been critical to such studies:

- HIGHLY SENSITIVE TO POINT SOURCES: AO offers a $\sim D^4$ increase in the signal from a faint point source companion
- LARGE SURVEYS: With very efficient scripting and TCS to AO system handshaking it is possible to survey >30 targets a night with AO (often with LGS as well).
- CLEAR OBSERVABLES: AO imaging is well suited to measuring the fluxes, separations, and position angles for binaries to very high accuracy.
- HIGH CONTRAST: AO will always increase the detectability of a faint companion near a bright source
- SKY COVERAGE: These surveys work well for NGS or LGS modes

Very Low Mass Objects have their Peak Signal/Noise in the NIR…



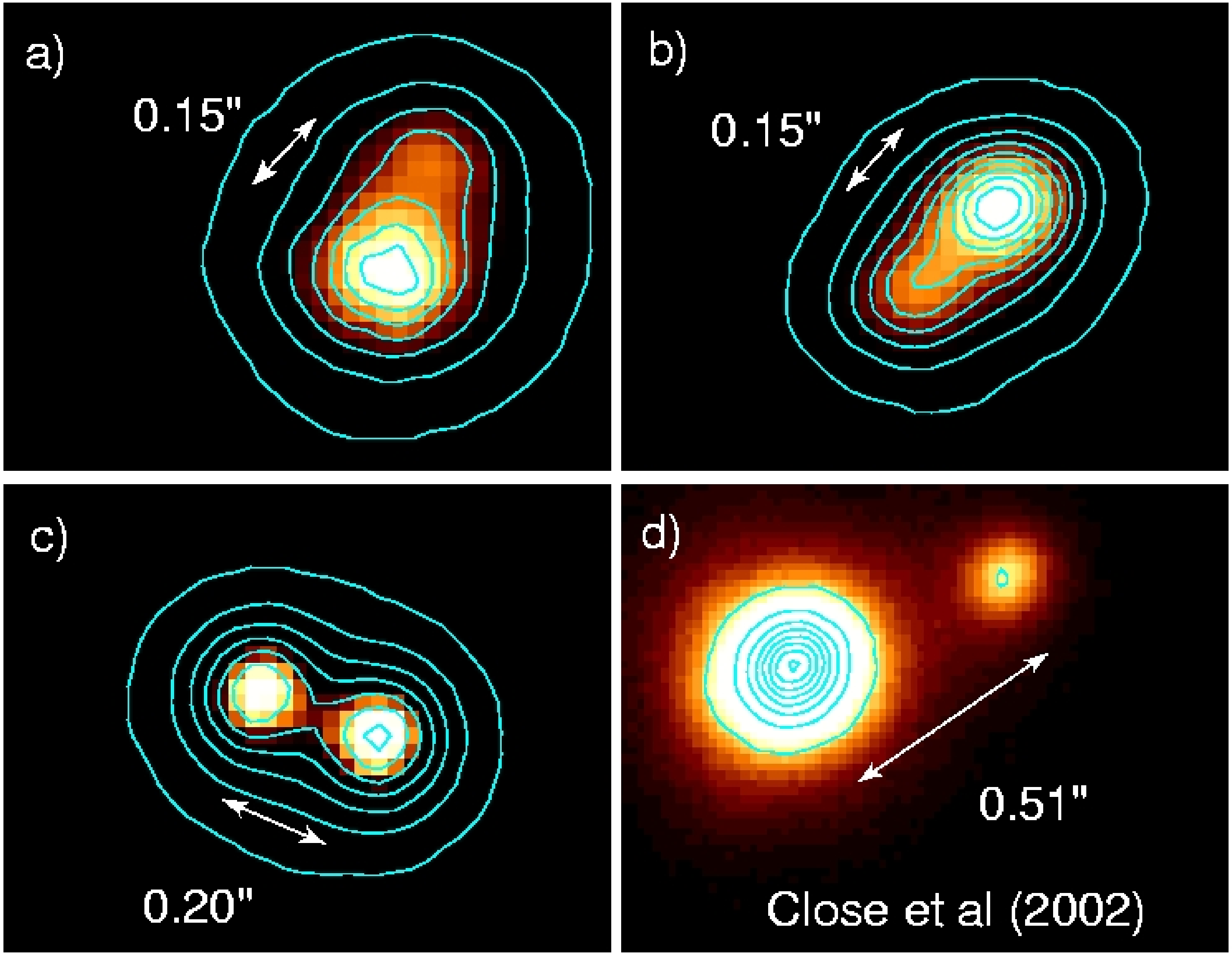
Close et al. 2007

In particular, AO has really informed today's knowledge of VLM and Brown dwarf binaries

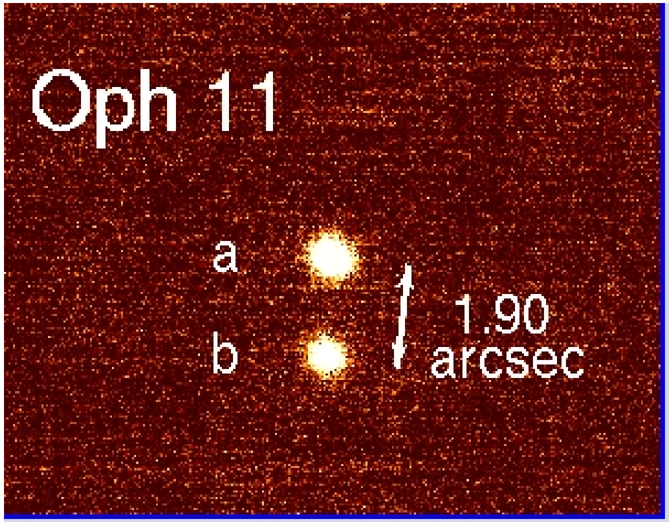
Some reasons why AO on large scopes has been critical to VLM and Brown Dwarf studies:

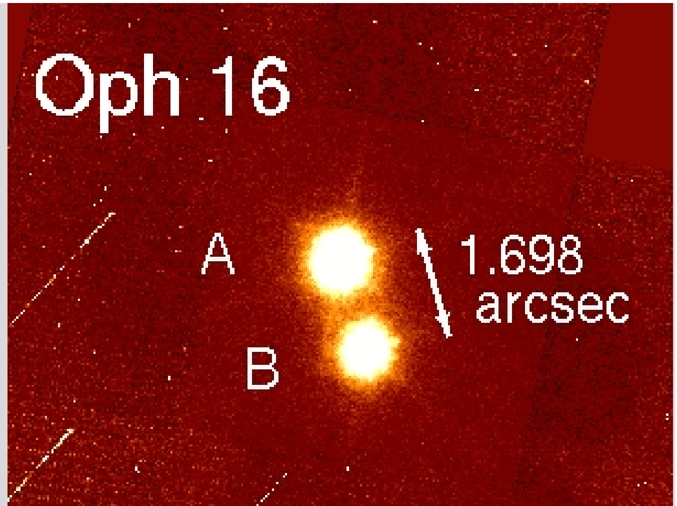
- NEAR INFRARED OPTIMIZED: Since $r_o \sim \lambda^{6/5}$ it occurs that in the 1-2.3 μm (NIR) range is where 6.5-8m AO systems are optimal with Strehls>20% yet low sky/telescope backgrounds
- LOW MASS OBJECTS ARE COOL: Since these objects typically run between M6-T8 objects the emission of these objects peaks (w.r.t to the background) in the NIR.
- GOOD NGS GUIDE STARS: The primaries are often R=10-15 mag which allows NGS techniques,
- GOOD LGS TARGETS: if they are fainter (R=15-20 mag) then they are good TT guide stars for LGS systems.

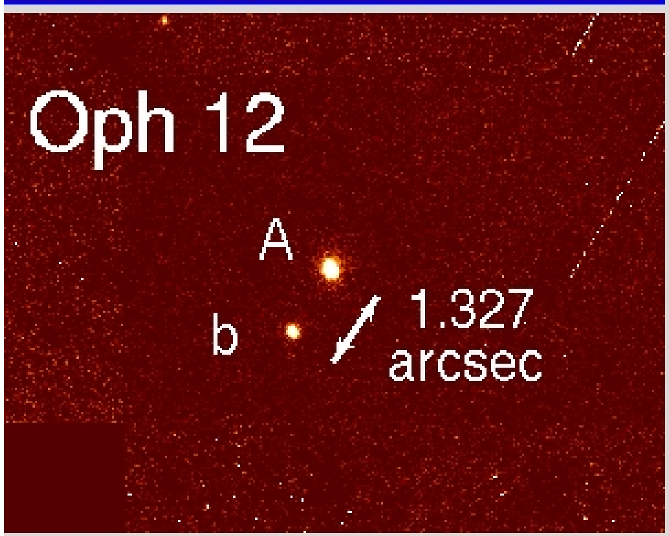
You can use NGS (dark time helps, like these Gemini/Hokupa'a images)



You can detect them with LGS

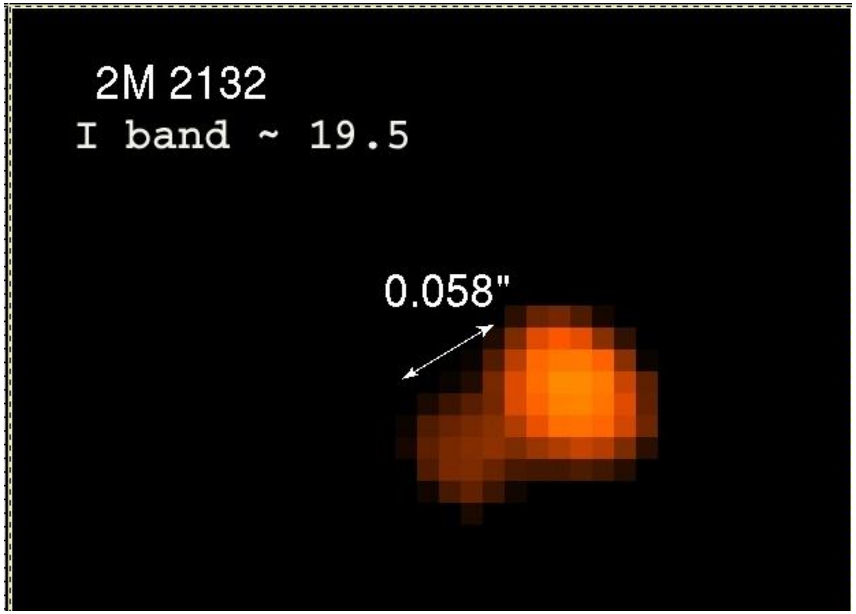






- Oph 11AB (aka Oph 1622) at a sep~243 AU and with a 17+/-5 Jupiter primary and 14+/-6 Jupiter mass secondary ***was the least bound binary known***.
- Oph 16AB has sep=212 AU and 100 and 73 Jupiter masses
- Oph 12 is a chance projection of a z=2 QSO (12b) and G giant (12A).

You can even use LGS on very faint targets with another nearby star as the TT star



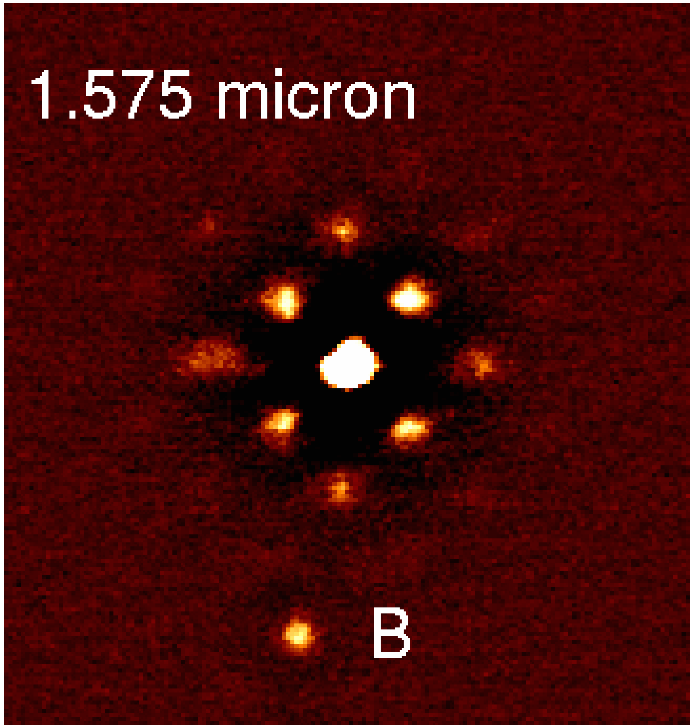
Discovery of a 66 mas Ultracool Binary with Laser Guide Star Adaptive Optics

•Siegler & Close et al. 2007

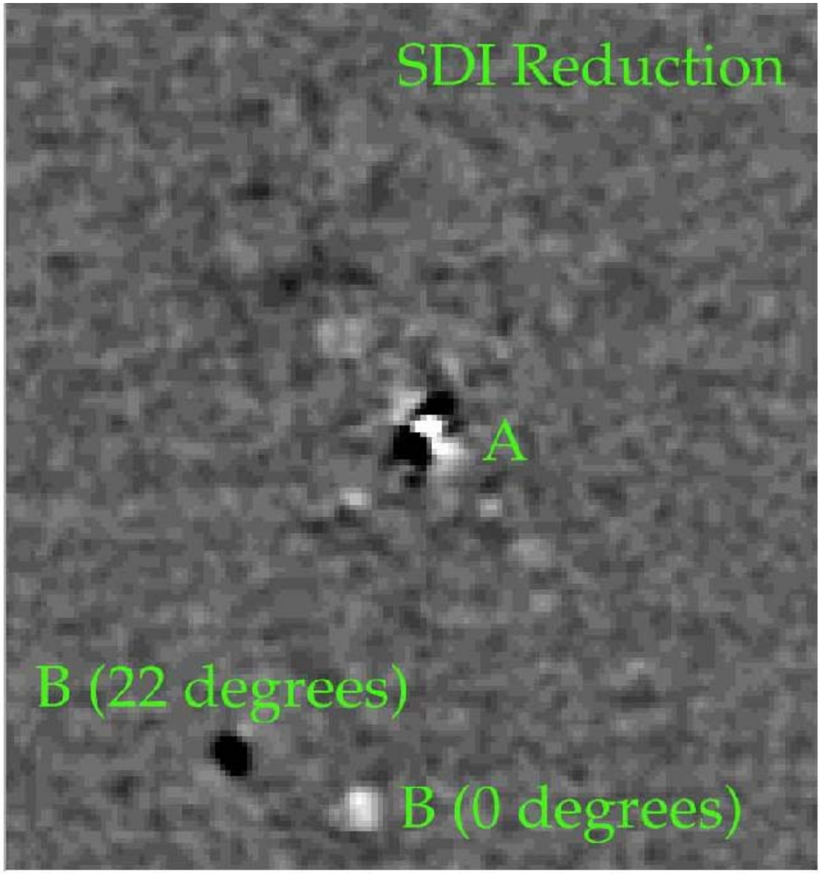
- Discovery of a very low mass (tight) brown dwarf binary (L6 +L8)
- *These could only be detected from the ground with the Keck LGS AO system.*

You can find ultracool brown dwarfs with Simultaneous Differential Imaging (SDI)–

(In fact all 3 brown dwarfs within 5 pc were discovered with AO+SDI)

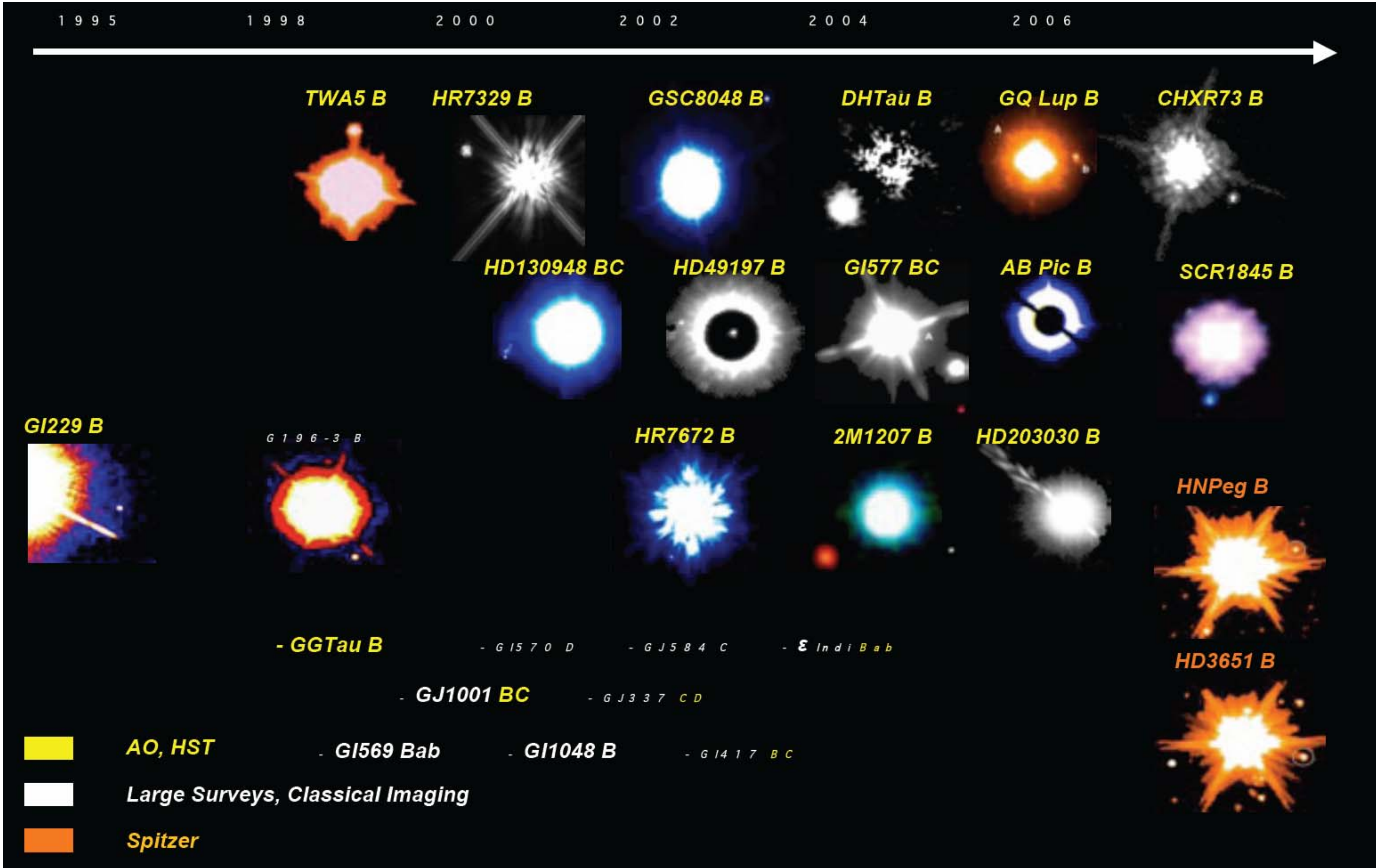


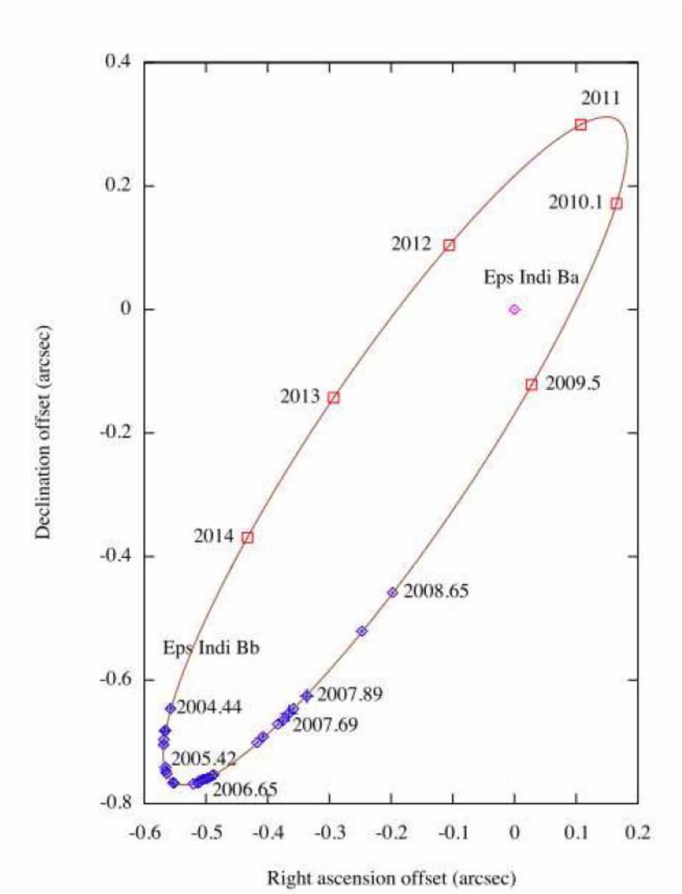
M8.5 + T5.5 SCR 1845B
Separation: 4.5 AU



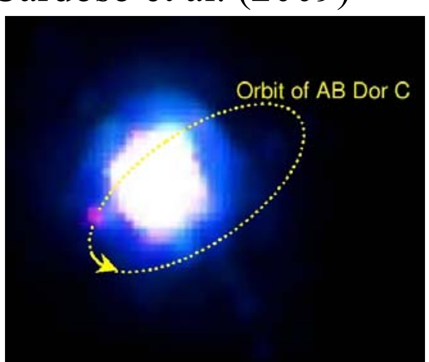
Biller, Kasper, Close, Brandner, and Kellner 2006

AO has discovered most of the Substellar and planetary Mass Companions Imaged today (Image from Gael Chauvin)

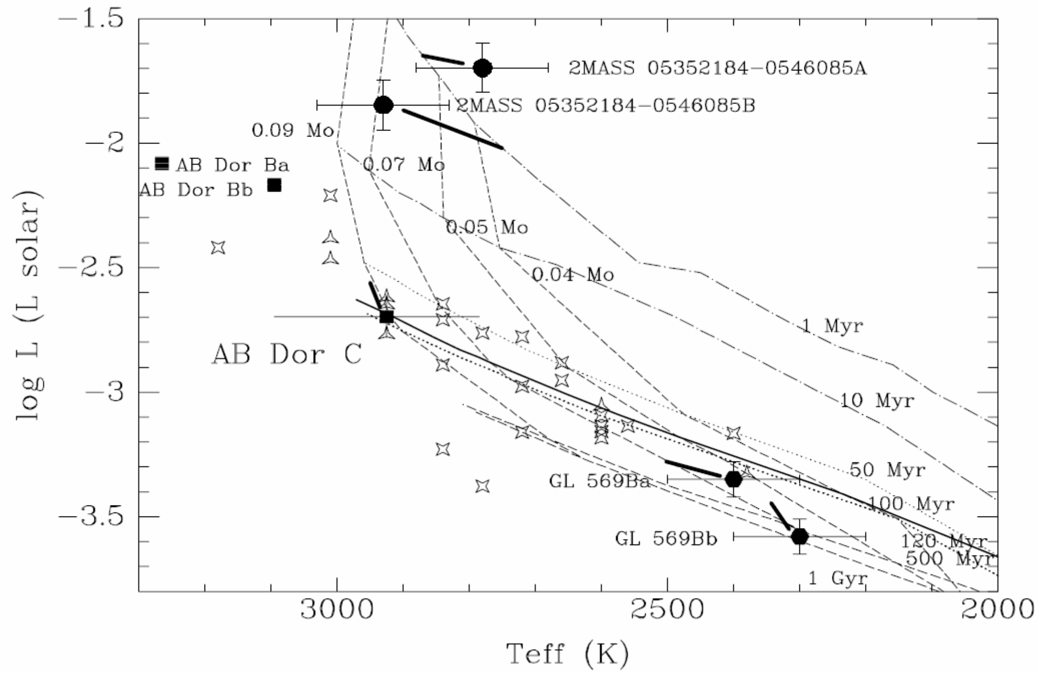




Double T-dwarf orbit of Eps Indi Ba/Bb; Cardoso et al. (2009)



To get dynamical masses requires time (>10 yr) (note Trent Dupuy's talk) but are critical to calibrating the models



Calibration check of DUSTY models; Close et al. (2007b)

Faster approach to getting masses:

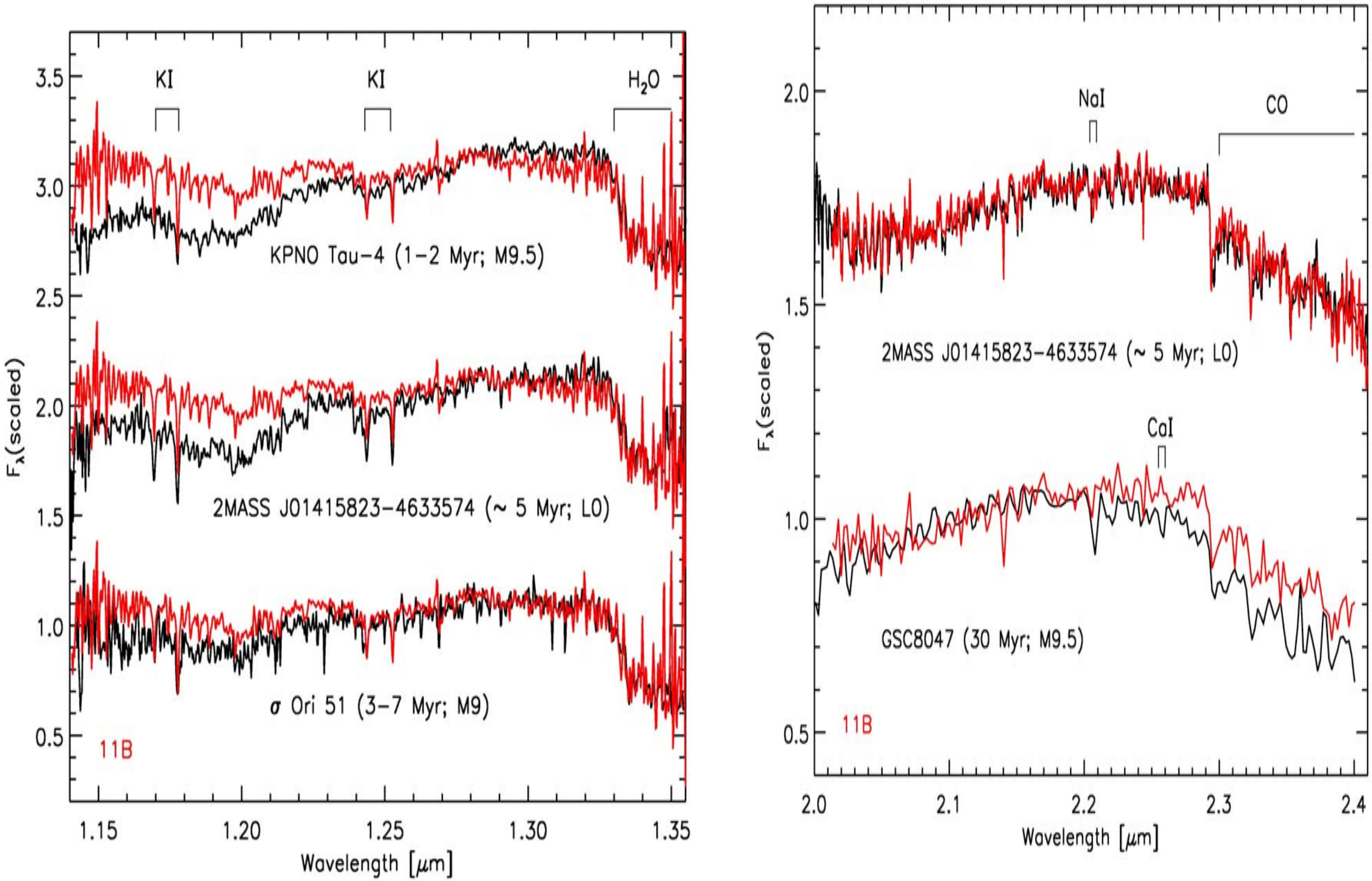
1. If we can calibrate atmospheric models then,
2. given observations of the:

age of the primary,
spectra, and
fluxes

3. We can calculate the:

age (tricky, sometimes a factor 2x uncertainty),
Teff and *log(g)* (lack of young cool standards), and
Luminosity (pretty straight forward given BC)

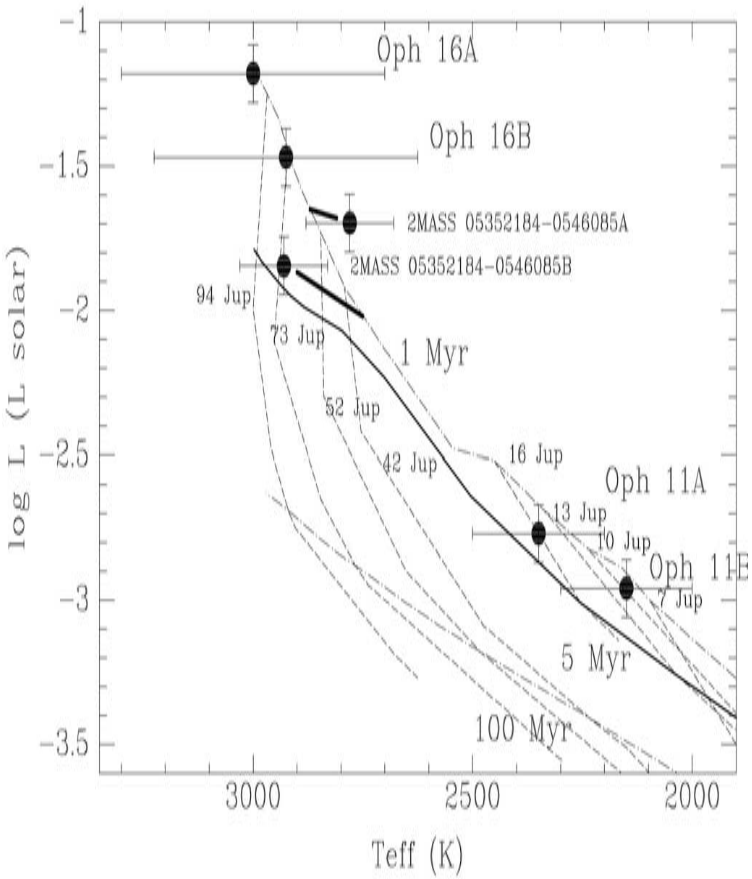
4. Then using calibrated evolutionary models we can estimate the mass of the companion either in the HR diagram (*L* vs. *Teff*) or *Log(g)* vs. *Teff* diagram.

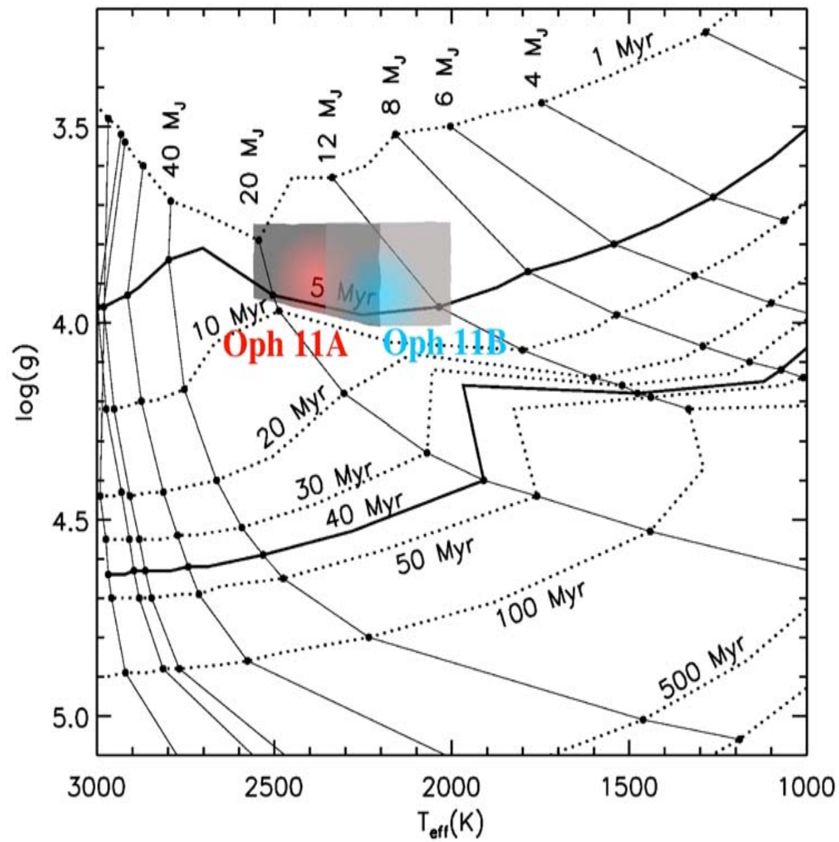


Our J & K band spectra also suggests 5 Myr with a slightly hotter M9.5±1 spectral type for Oph 12b (black line). There is a poor fit to the gravity sensitive features of 1 Myr standards like KPNO Tau-4

Close et al. 2007a

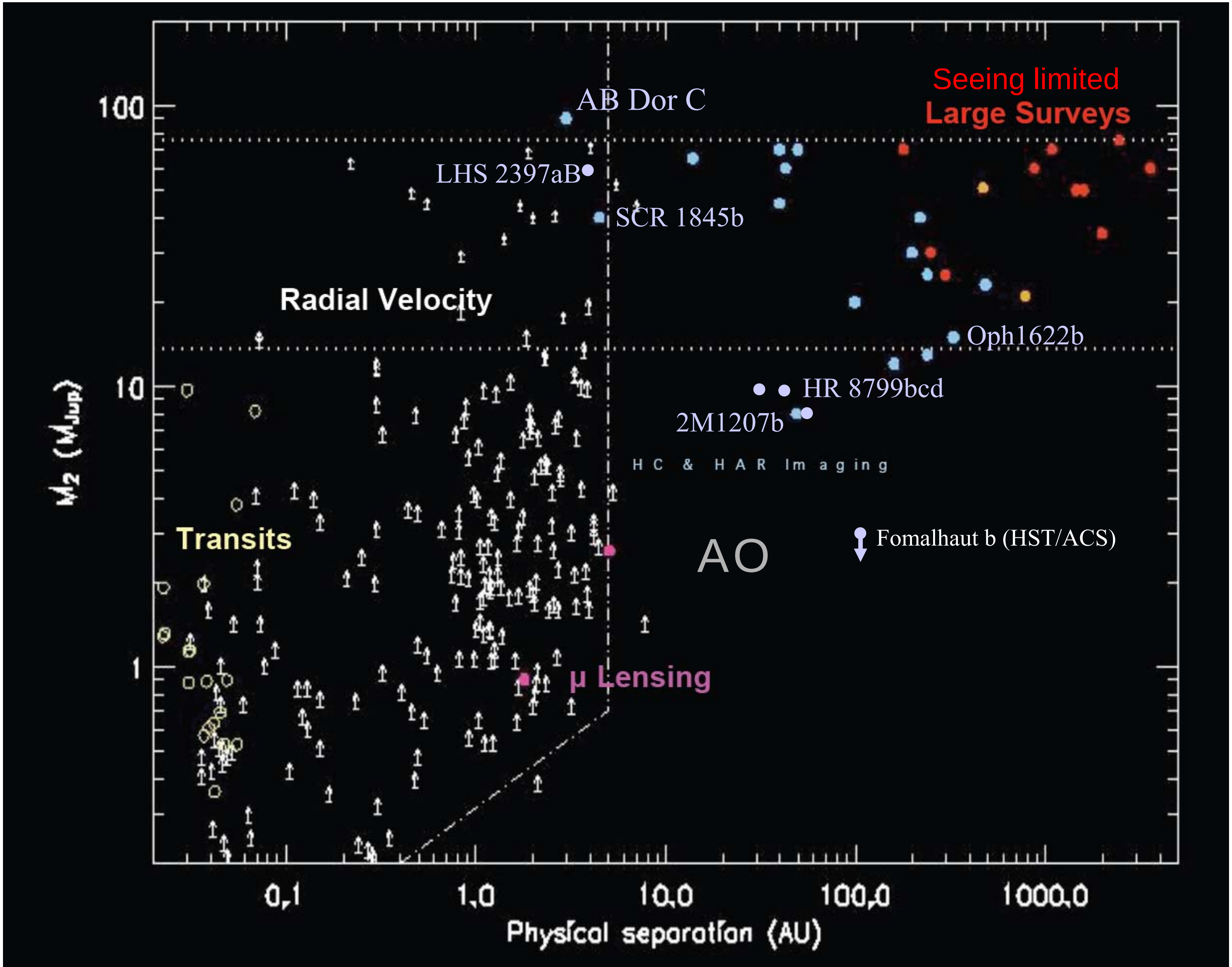
Estimating masses for Oph 1622A and B from the HR diagram and Dusty (Lyon) Models





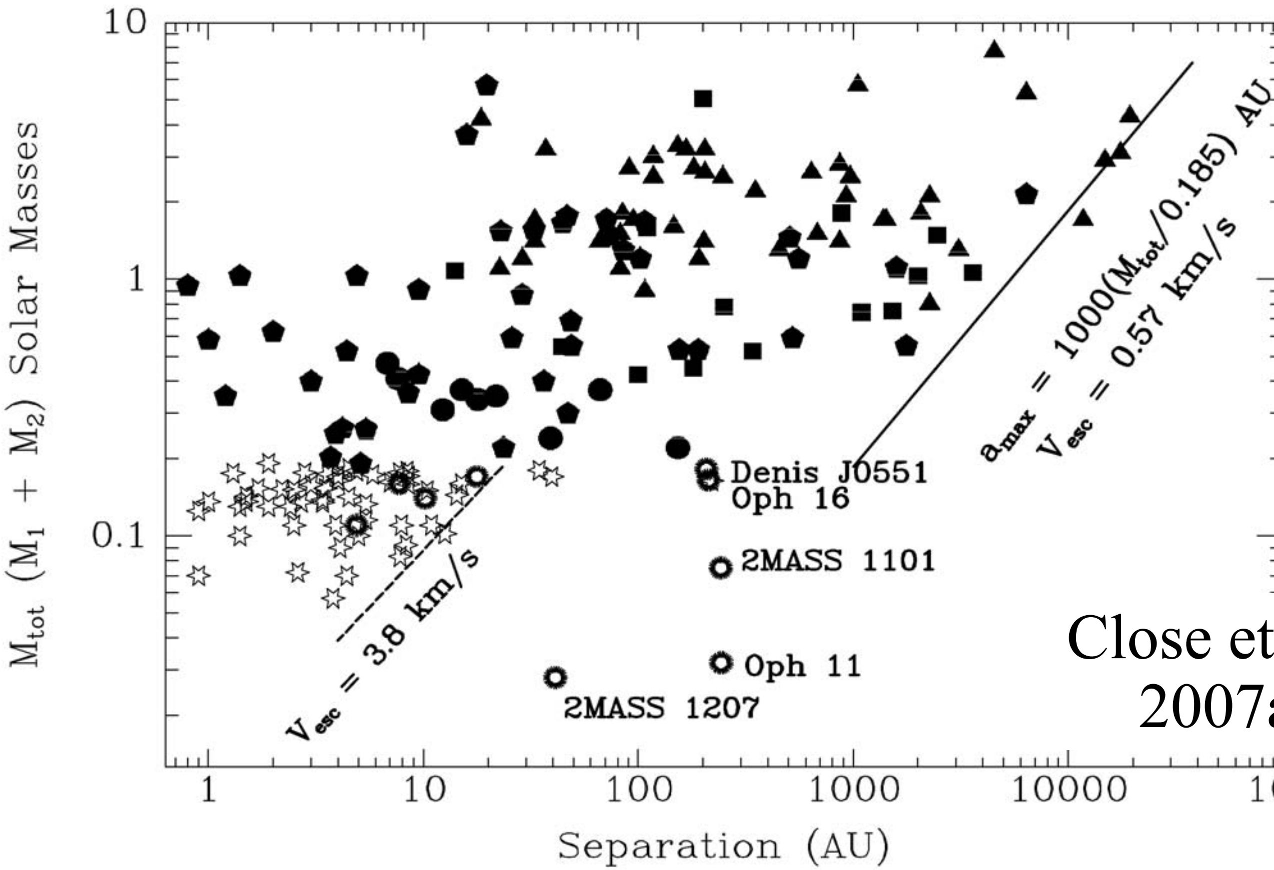
The log(g)/T_{eff} plane of the Chabrier et al. dusty models (and the HR diagram) suggests 17±5 and 14±6 Jupiter masses as the most consistent fit to the models (which have additional systematic errors). Close et al. 2007a

How AO compares to the rest of the techniques (modified from Gael Chauvin)



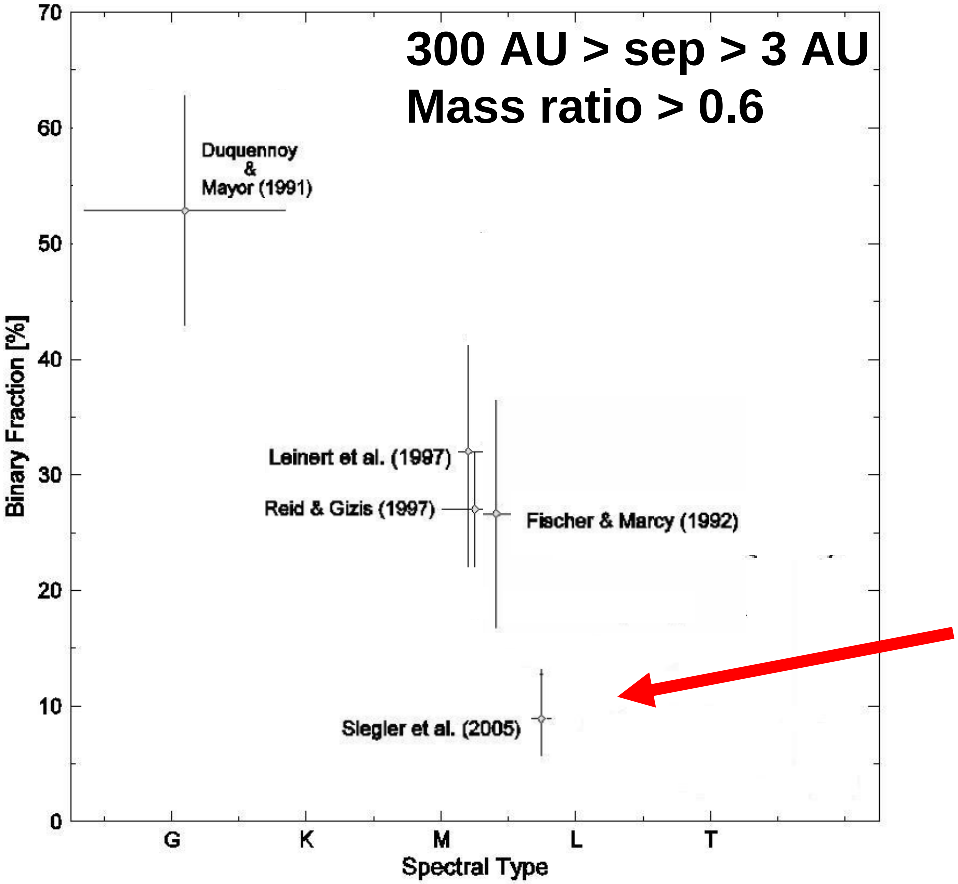
WHAT CAN WE LEARN ABOUT HOW NATURE MAKES LOW MASS BINARIES?

They really are different…



Close et al. 2007a

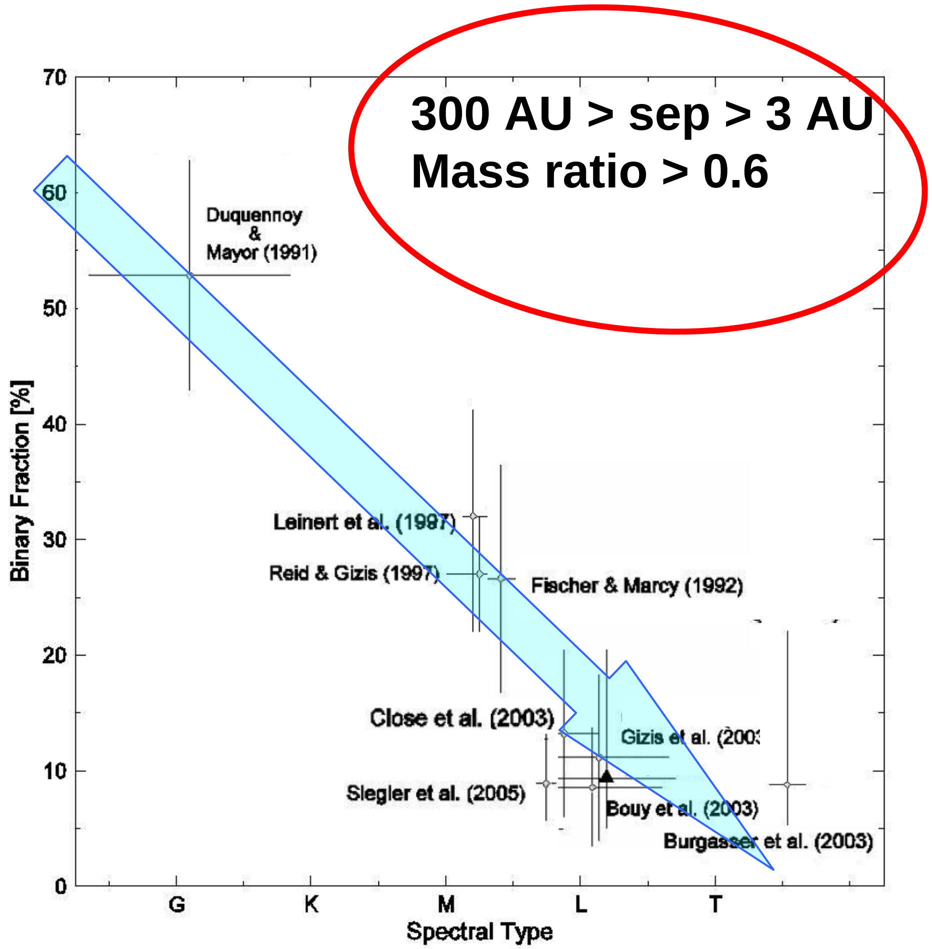
Binary Fraction vs. Spectral Type



binary fraction of $9^{+4}_{-3}\%$

Slides from Nick Siegler

Binary Fraction vs. Spectral Type



Slides from Nick Siegler

Nick Siegler's VLM Binaries Archive

http://www.vlmbinaries.org/

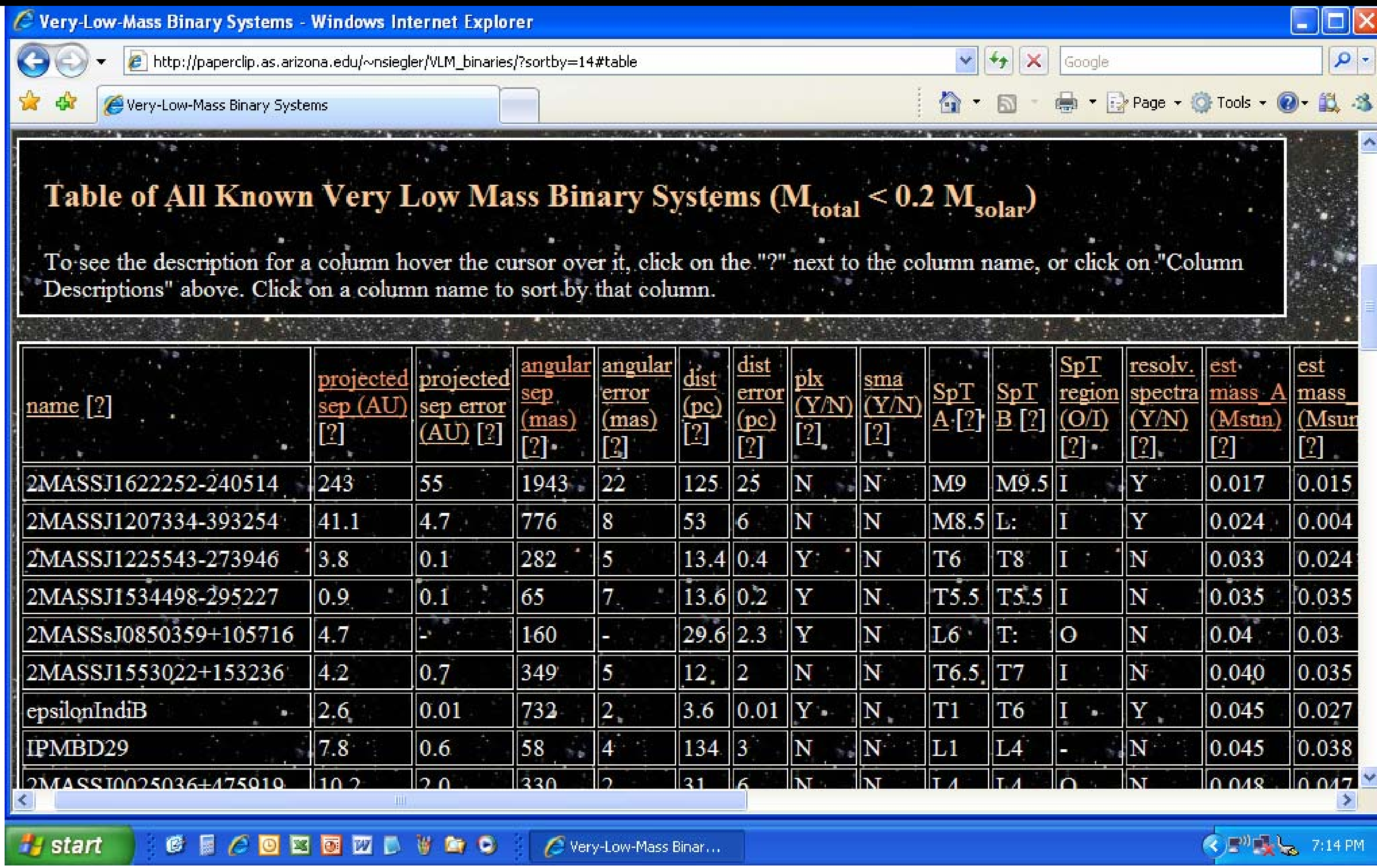
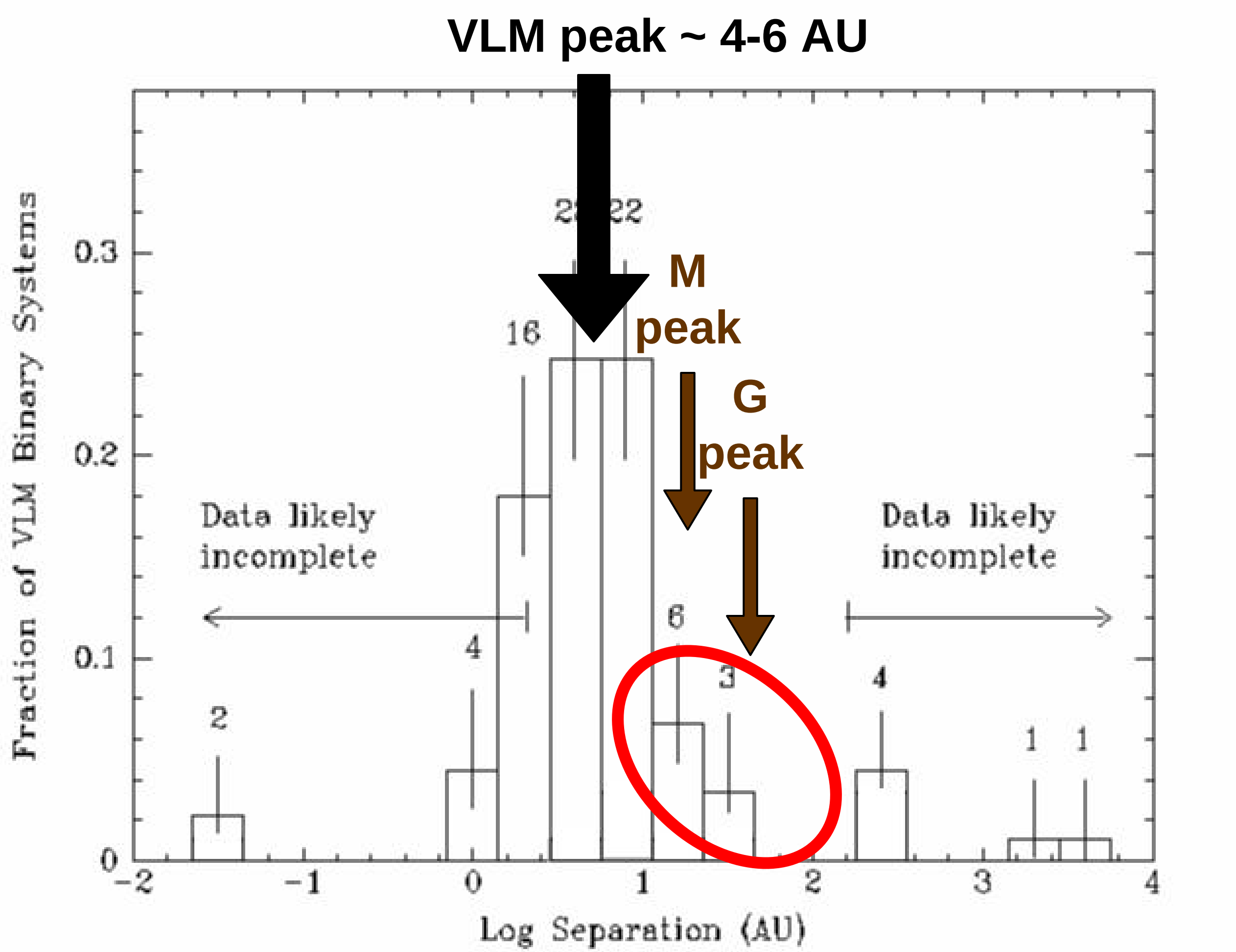


Table of All Known Very Low Mass Binary Systems (M_{total} < 0.2 M_{solar})

To see the description for a column hover the cursor over it, click on the "?" next to the column name, or click on "Column Descriptions" above. Click on a column name to sort by that column.

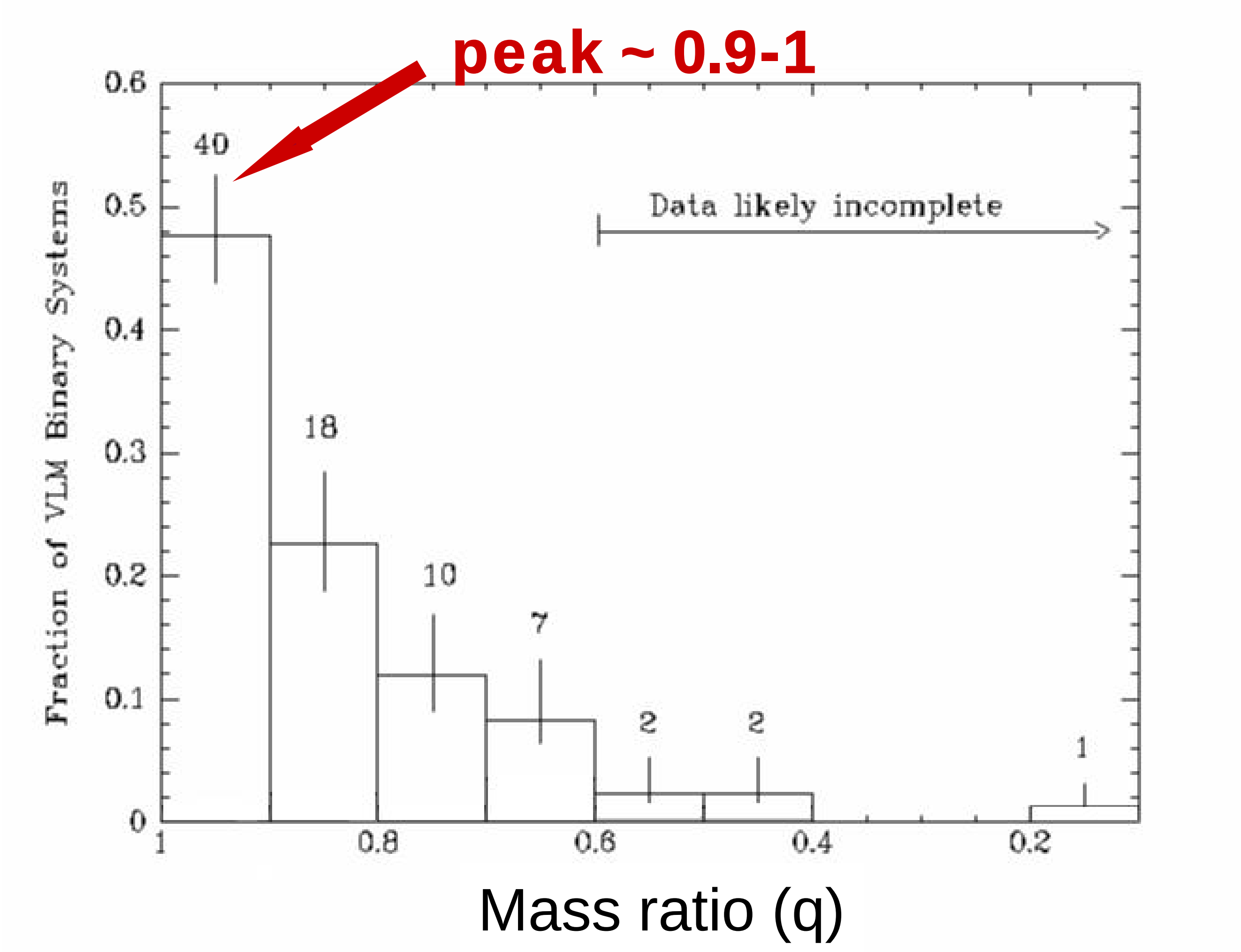
name [?]	projected sep (AU) [?]	projected sep error (AU) [?]	angular sep (mas) [?]	angular error (mas) [?]	dist (pc) [?]	dist error (pc) [?]	plx (Y/N) [?]	sma (Y/N) [?]	SpT A [?]	SpT B [?]	SpT region (O/I) [?]	resolv. spectra (Y/N) [?]	est mass_A (Msun) [?]	est mass_ (Msun [?]
2MASSJ1622252-240514	243	55	1943	22	125	25	N	N	M9	M9.5	I	Y	0.017	0.015
2MASSJ1207334-393254	41.1	4.7	776	8	53	6	N	N	M8.5	L:	I	Y	0.024	0.004
2MASSJ1225543-273946	3.8	0.1	282	5	13.4	0.4	Y	N	T6	T8	I	N	0.033	0.024
2MASSJ1534498-295227	0.9	0.1	65	7	13.6	0.2	Y	N	T5.5	T5.5	I	N	0.035	0.035
2MASSsJ0850359+105716	4.7	-	160	-	29.6	2.3	Y	N	L6	T:	O	N	0.04	0.03
2MASSJ1553022+153236	4.2	0.7	349	5	12	2	N	N	T6.5	T7	I	N	0.040	0.035
epsilonIndiB	2.6	0.01	732	2	3.6	0.01	Y	N	T1	T6	I	Y	0.045	0.027
IPMBD29	7.8	0.6	58	4	134	3	N	N	L1	L4	-	N	0.045	0.038
2MASSJ0025036+475919	10.2	2.0	330	2	31	6	N	N	L4	L4	O	N	0.048	0.047

VLM Separation Distribution

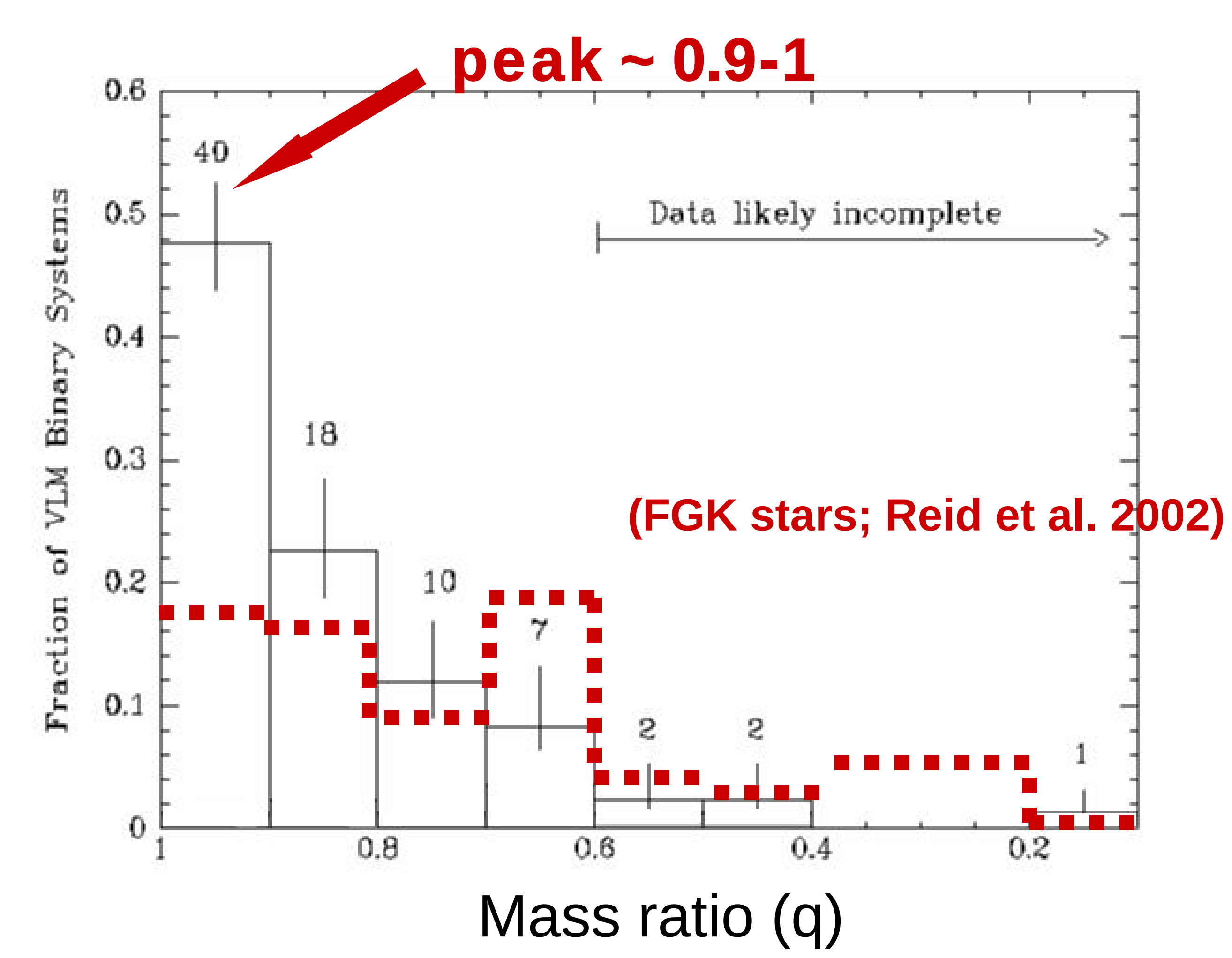


Modified from Burgasser, Reid, Siegler, Close, Allen, Lowrance, & Gizis 2006 PPV

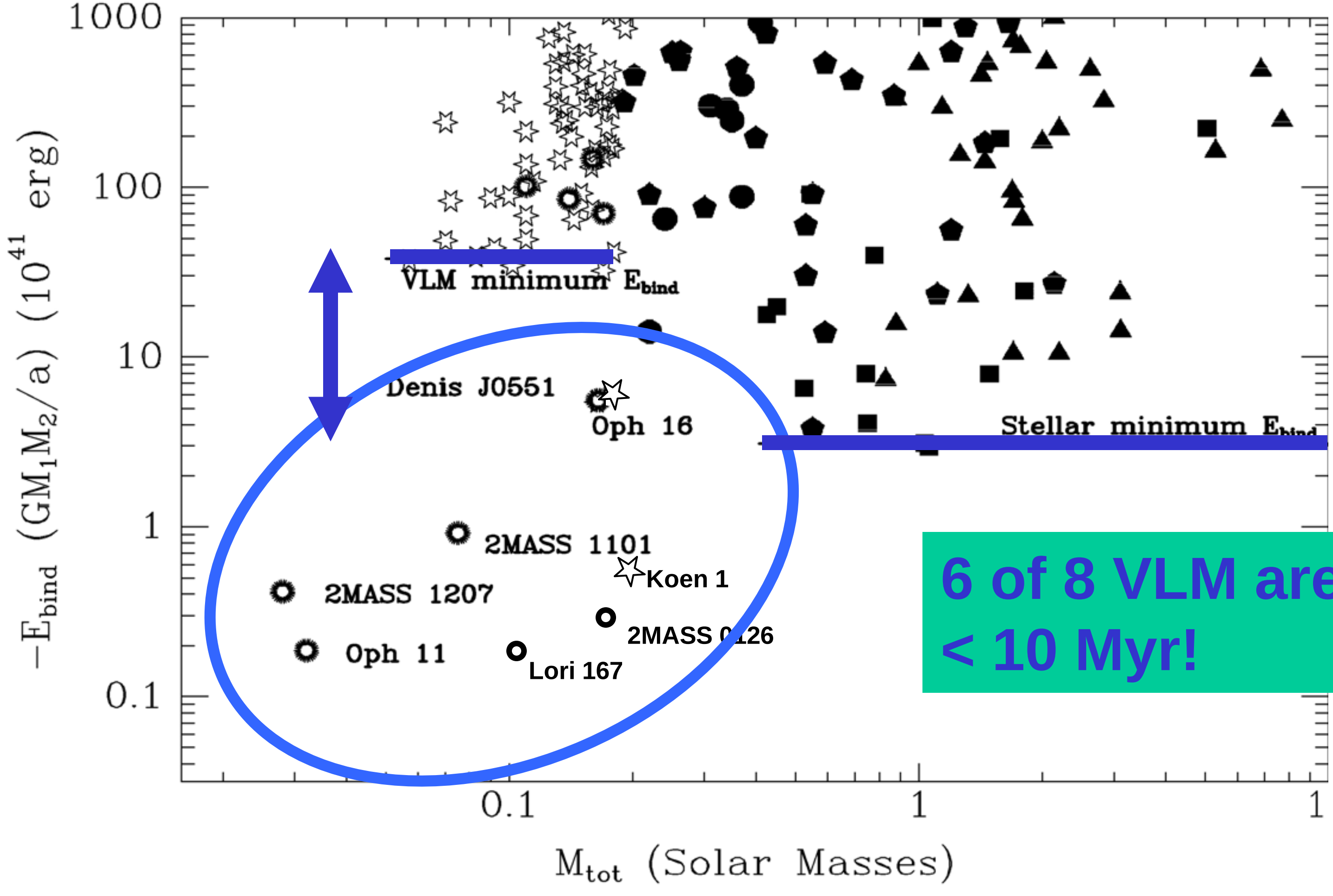
VLM Mass Distribution



VLM Mass Distribution

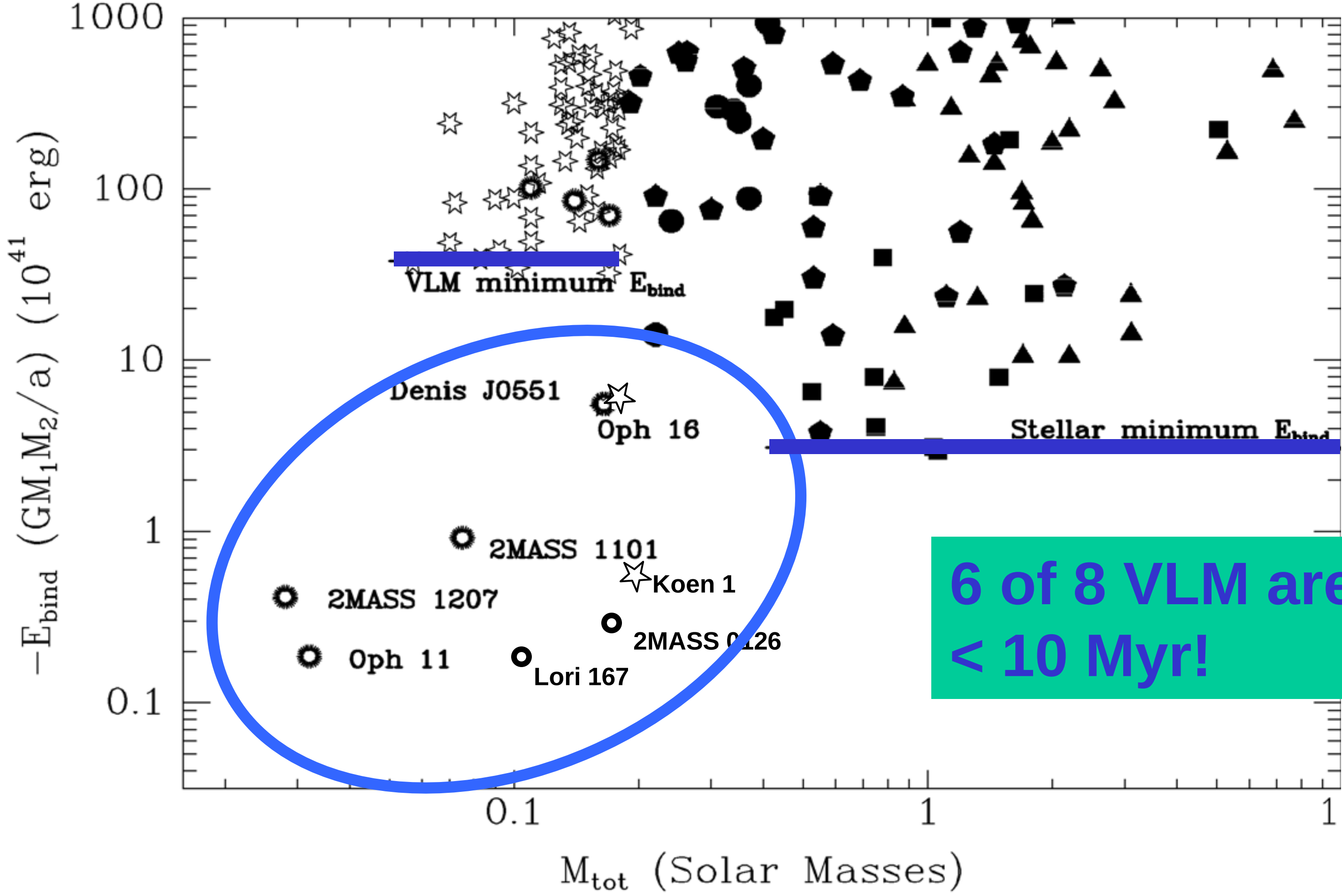


Binding Energies



6 of 8 VLM are < 10 Myr!

Binding Energies



6 of 8 VLM are < 10 Myr!

The Fokker-Planck equations can help us estimate if these binaries can be evaporated by encounters in their clusters and in the field…

To investigate the stability of wide binaries we note that Weinberg et al.(1987)'s analytic solution of Fokker-Planck (FP) coefficients describing advective diffusion of a binary due to stellar encounters is $t_*(a_o) \sim 3.6 \times 10^5 (n_*/0.05pc^{-3})^{-1} * (M_{tot}/M_\odot) * (M_*/M_\odot)^{-2} * (V_{rel}/20kms^{-1})(a_o/AU)^{-1}$Gyr where $t_*(a_o)$ is the time required to evaporate a binary of an initial semi-major axis of a_o, the number density of stellar perturbers is n_* of mass M_* and relative velocity V_{rel} (adopted from Weinberg (1987); assuming, as they do, that their $ln\Lambda \sim 1$). Hence, the *maximum* projected separation of a bound binary (assuming semi-major axis $a = 1.26 \times sep$; Fischer & Marcy 1992) after 10 Gyr in the field is given by:

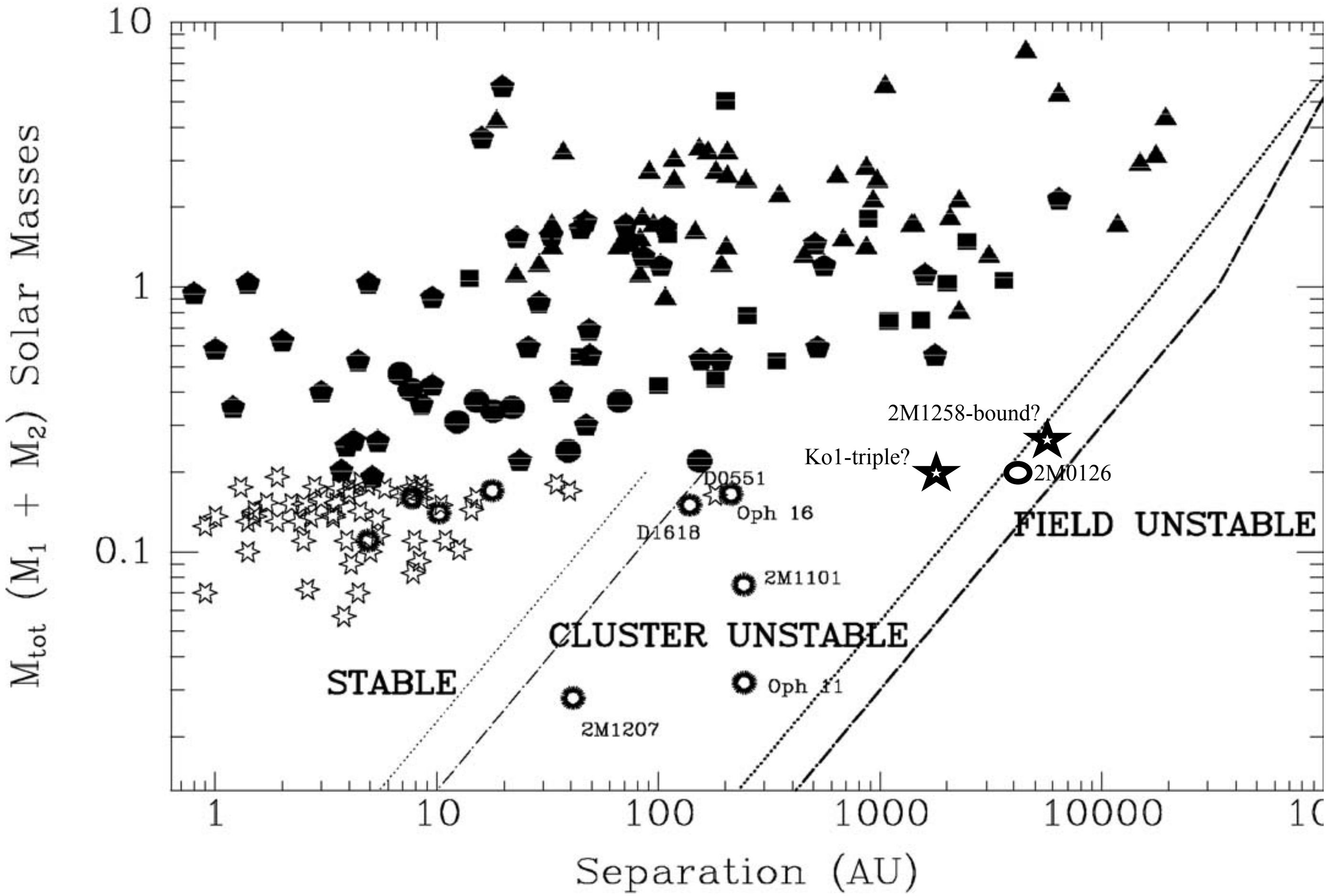
$$sep_{field}^{diffusive*} \lesssim 28 \times 10^3 \left(\frac{0.16}{0.05pc^{-3}}\right)^{-1} \left(\frac{M_{tot}}{M_\odot}\right) \left(\frac{0.7}{M_\odot}\right)^{-2} \sim 1800 \left(\frac{M_{tot}}{0.1M_\odot}\right) AU \quad (1)$$

where we have used the measured Galactic disk mass density of $0.11 M_\odot/pc^{-3}$ and an average perturber mass of $0.7M_\odot$, and $V_{rel} \sim 20$ km/s (Pham et al. 1997; Holmberg & Flynn 2000).

In addition to the evaporation of binaries due to diffusion there is also the chance of a catastrophic encounter evaporating the binary. While such encounters are less important than diffusion, they cannot be completely ignored. From the work of Weinberg et al. we find the *maximum* projected separation (*sep*) of a binary to stay bound w.r.t. close encounters over 10 Gyr in the field is:

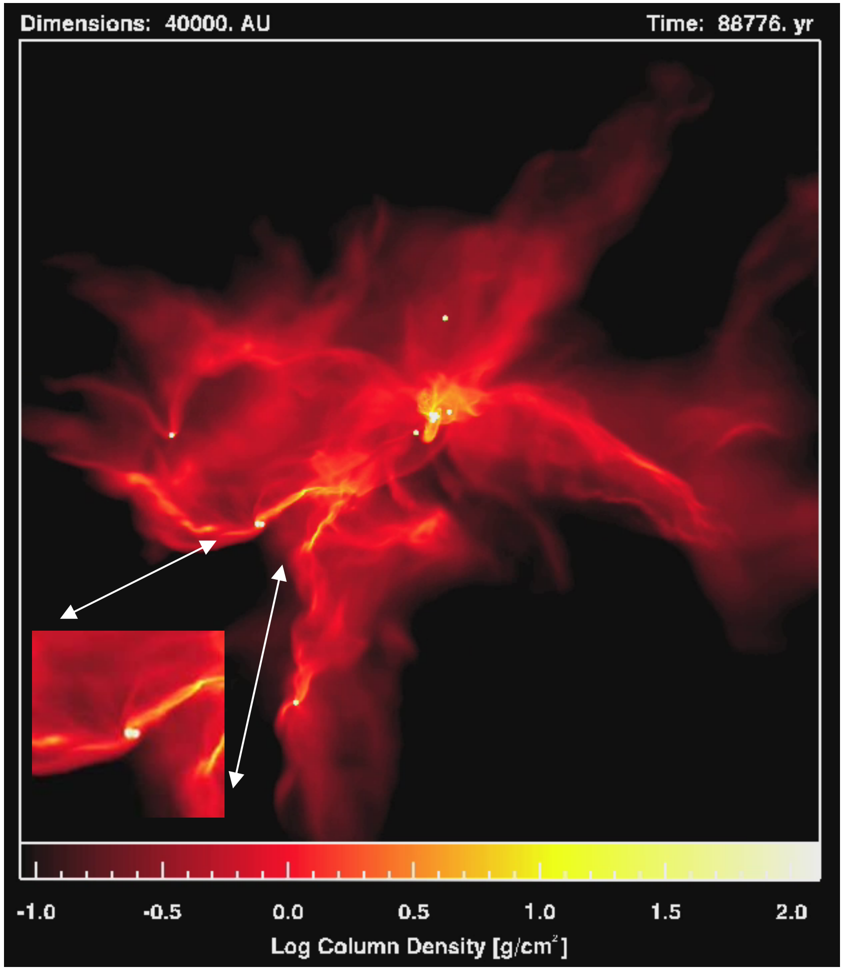
$$sep_{field}^{catastrophic*} \lesssim 52 \times 10^3 \left(\frac{0.16}{0.05pc^{-3}}\right)^{-1} \left(\frac{M_{tot}}{M_\odot}\right) \left(\frac{0.7}{M_\odot}\right)^{-2} \sim 3300 \left(\frac{M_{tot}}{0.1M_\odot}\right) AU \quad (2)$$

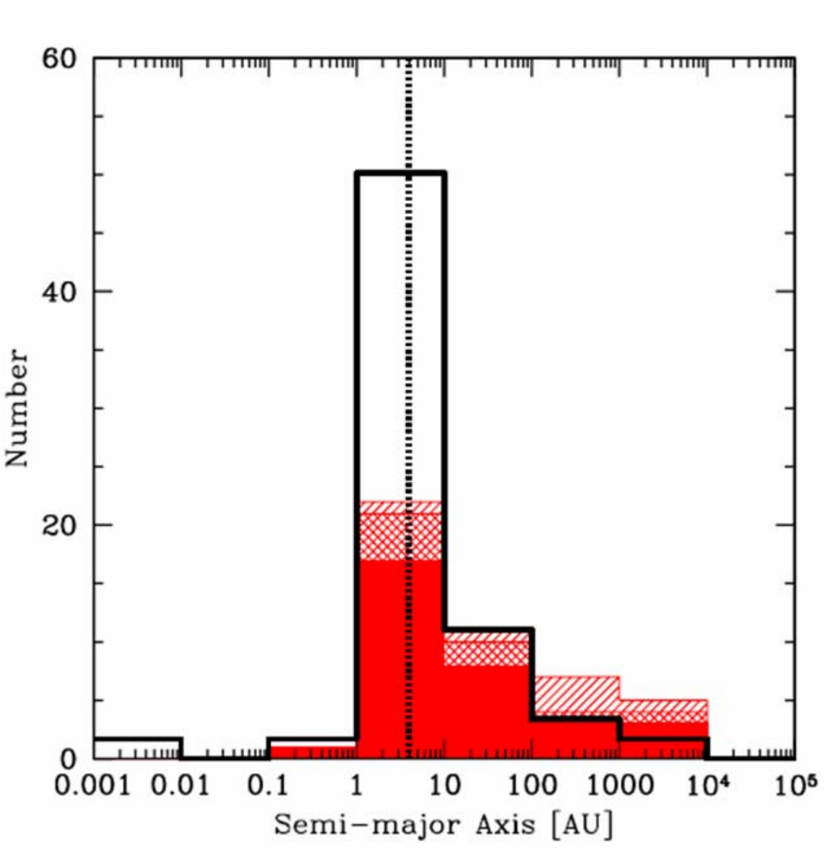
We can estimate "instability" zones the Fokker-Planck solutions of Weinberg et al. (1987) applied to different stellar densities: This approach can explain most of the features we observe…



In Close et al (2007) there is the first derivation of "zones" of stability w.r.t. the mass and separation and formation cluster density of binary brown dwarfs. They show that most known wide binary brown dwarfs are young (open circles) and will likely be dissolved in their natal clusters before they join the field (old) population (open stars).

These binary distributions can guide theory to the correct physics of star and brown dwarf formation





In Bate et al (2008) there are very detailed simulations (with radiative transfer) of the formation of VLM and Brown Dwarf binaries (solid red colors) which still have difficulty matching observations (black curve).

CONCLUSIONS:

1. AO has been critical to measuring VLM and Brown Dwarf dynamical masses. These masses and AO spectra have been utilized to calibrate evolutionary models.
2. Low mass binaries (M<0.2 Msun) are much tighter (Sep. <<30 AU) than their higher mass counterparts. This is likely due the binary formation mechanism and dynamical sculpting of the distribution.
3. Wide low mass binaries do exist at young ages in star formation associations like Oph, combining our study with that of Upper Sco by Bouy et al. 2006 we estimate 6±3% of young VLM objects are in such wide systems.
4. For example, Oph 1622 is one of the most extreme low-mass, wide (>243 AU) binary known. Such systems cannot be formed by “ejection” mechanisms.
5. We deduce that 6±3% of young (< 10 Myr) VLM objects are in such wide systems. However, only 0.3±0.1% of old field VLM objects are found in such wide systems. Thus, young, wide, VLM binary populations may be evaporating, due to stellar encounters in their denser natal clusters, leading to a field population depleted in wide VLM systems.