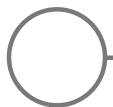
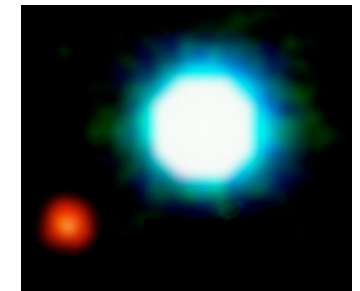
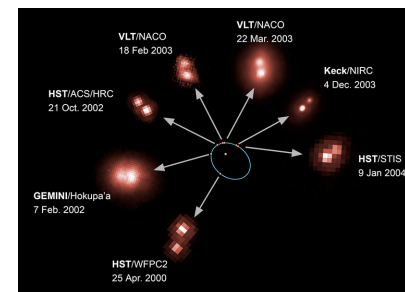
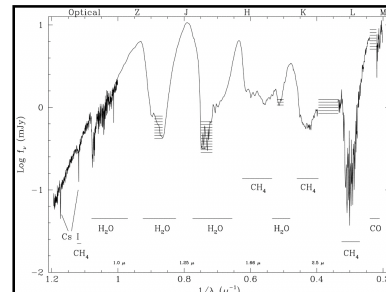
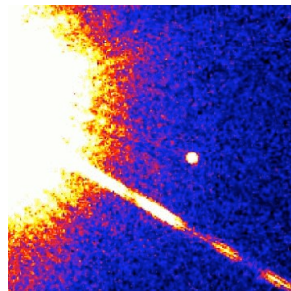


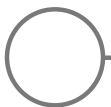
Lecture 2:

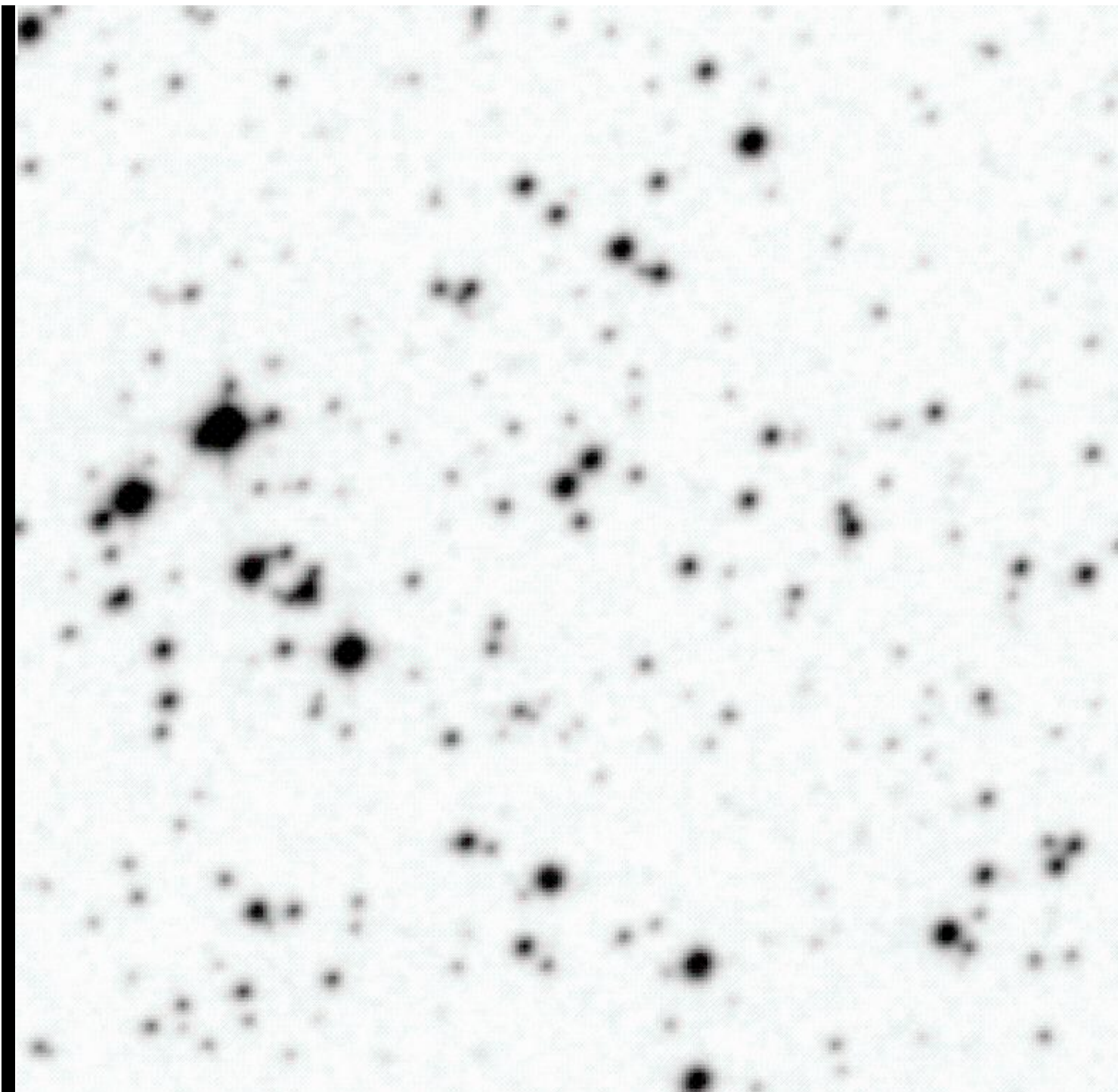
Brown Dwarf Detection



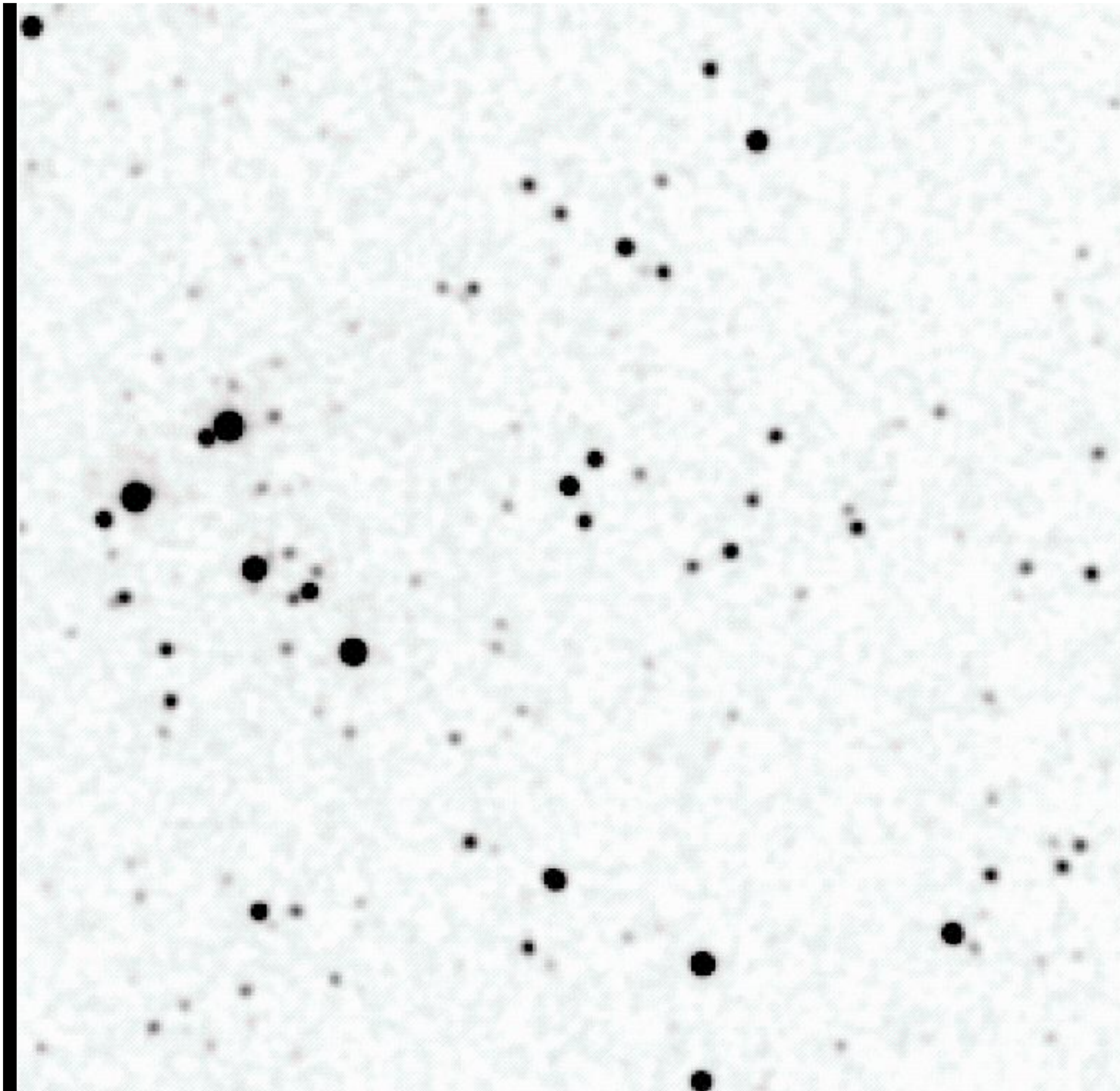
How to find a brown dwarf

- Look in the near-infrared
- Look for objects with weird (red) colors
- Look for high proper motion objects
- Look in young star forming regions
- Look around nearby stars

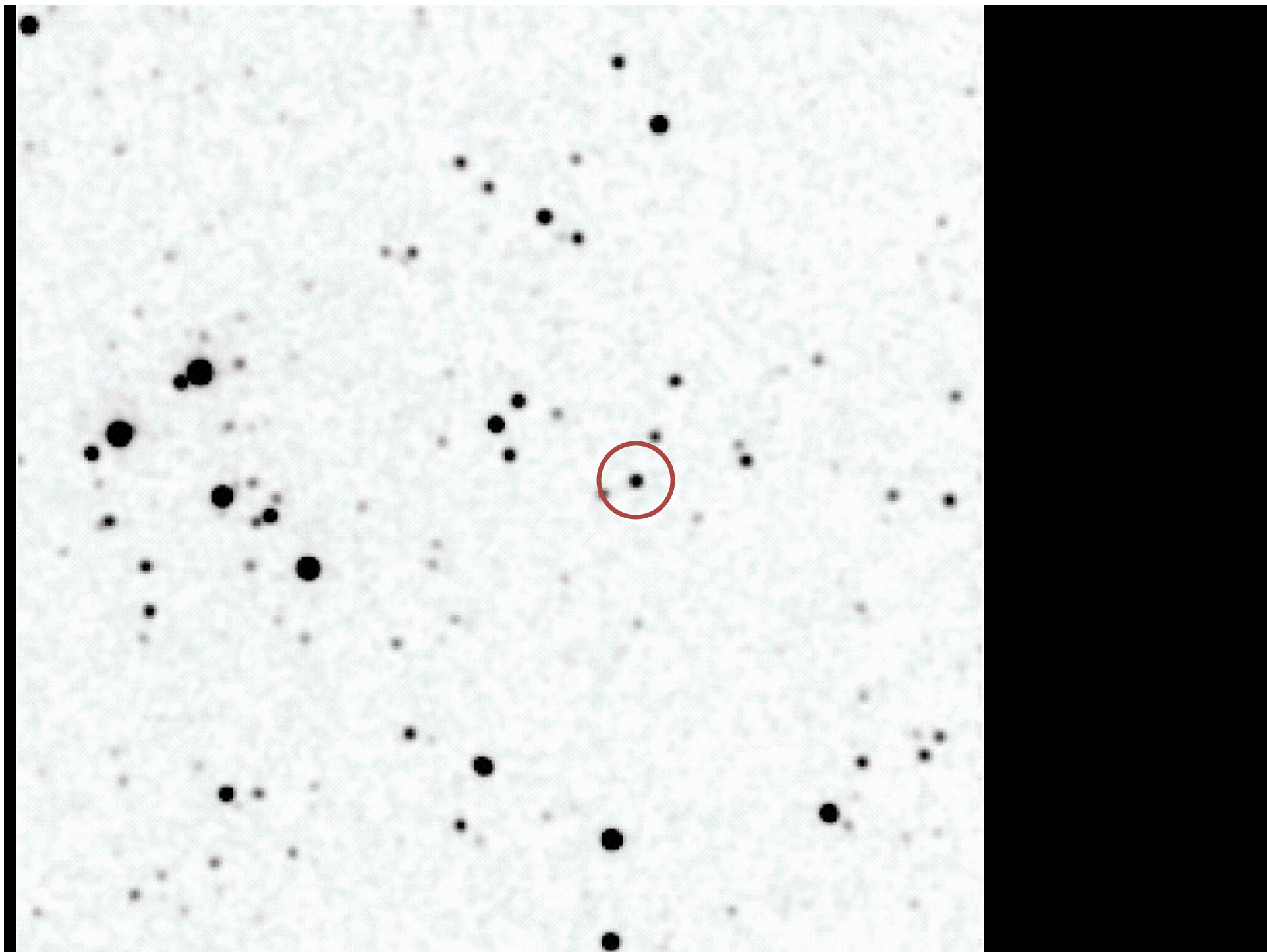




R-band

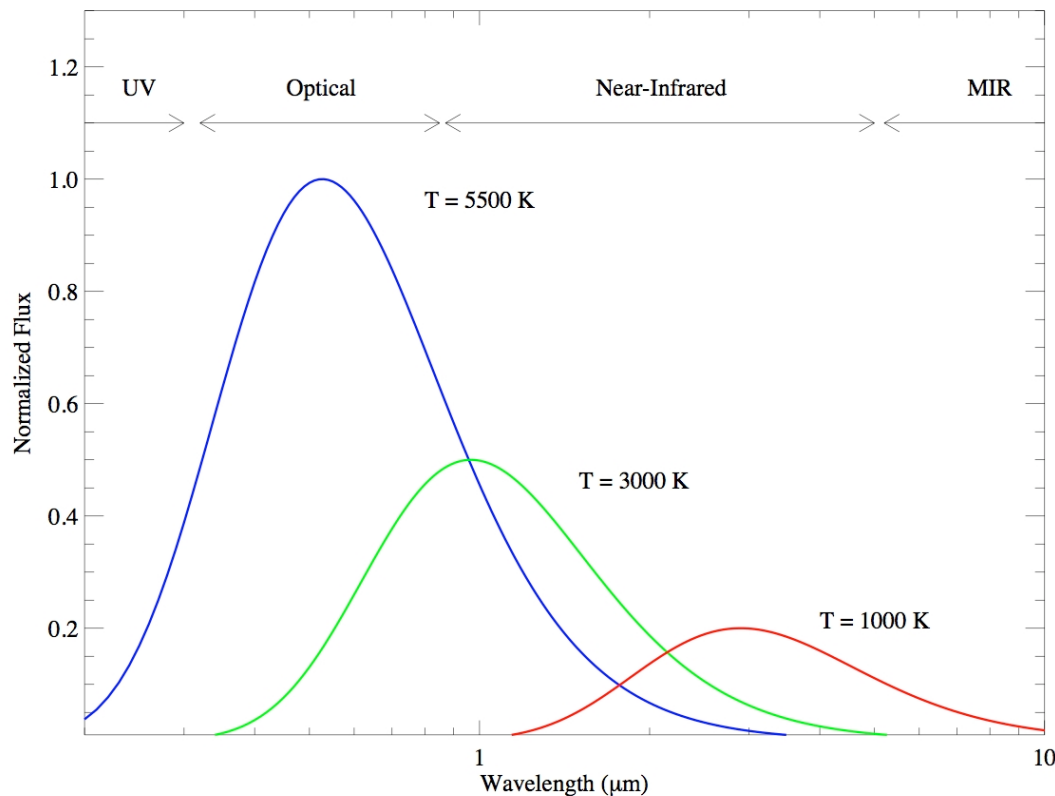


J-band



Cool stars are (near-infra)red stars

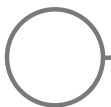
Blackbody flux distribution: $I_0(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T_{eff}}} - 1}$



Low temperature stars emit more flux at longer wavelengths: **Wien's Displacement Law:**

$$\lambda_{pk} T \approx 3000 \text{ K-}\mu\text{m}$$

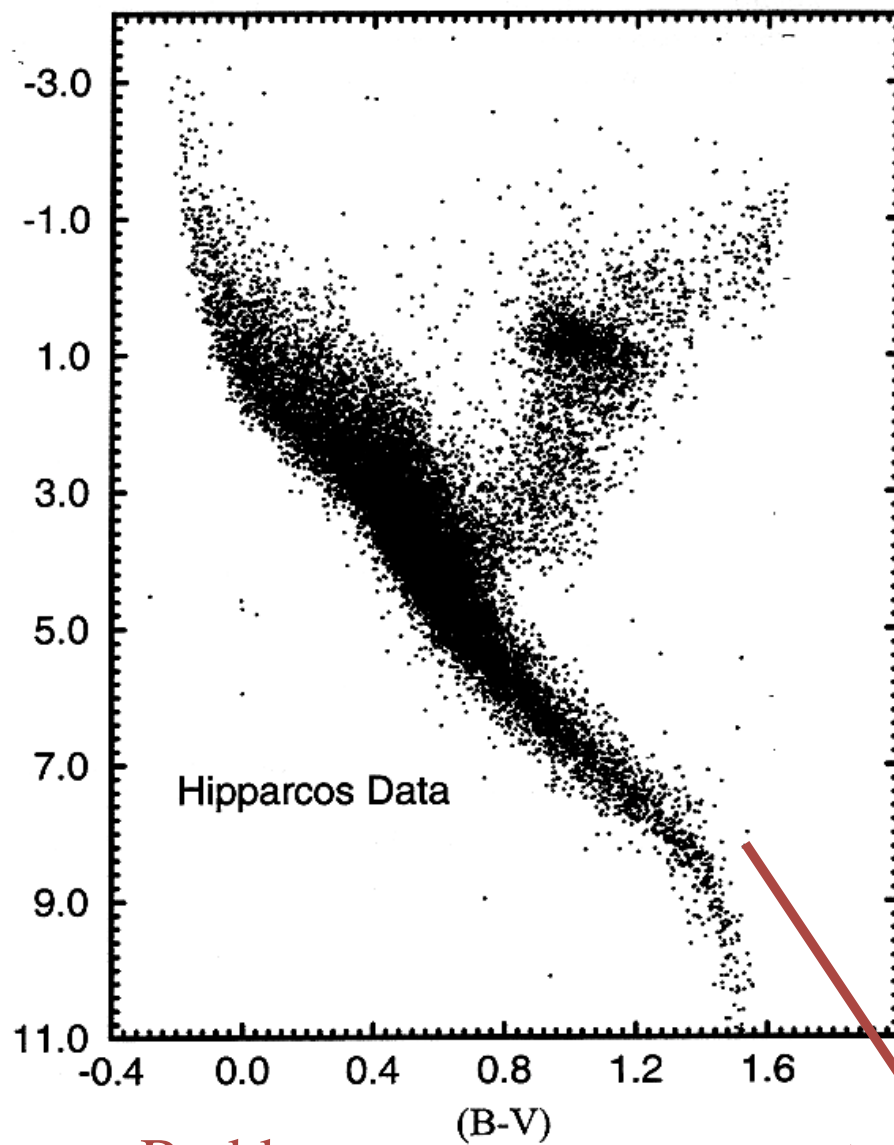
Easier to see cool BDs at longer wavelengths.



Fainter



Intrinsic Brightness (M_V)



Brown
Dwarfs

Redder



Big Near-infrared Surveys



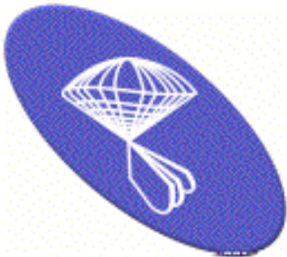
DENIS (1996-2001)

- I ($0.8 \mu\text{m}$), J ($1.25 \mu\text{m}$) & K ($2.16 \mu\text{m}$)
- Southern sky ($16,700 \text{ deg}^2$)
- 355,000,000 point sources (DR3)



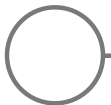
2MASS (1997-2001)

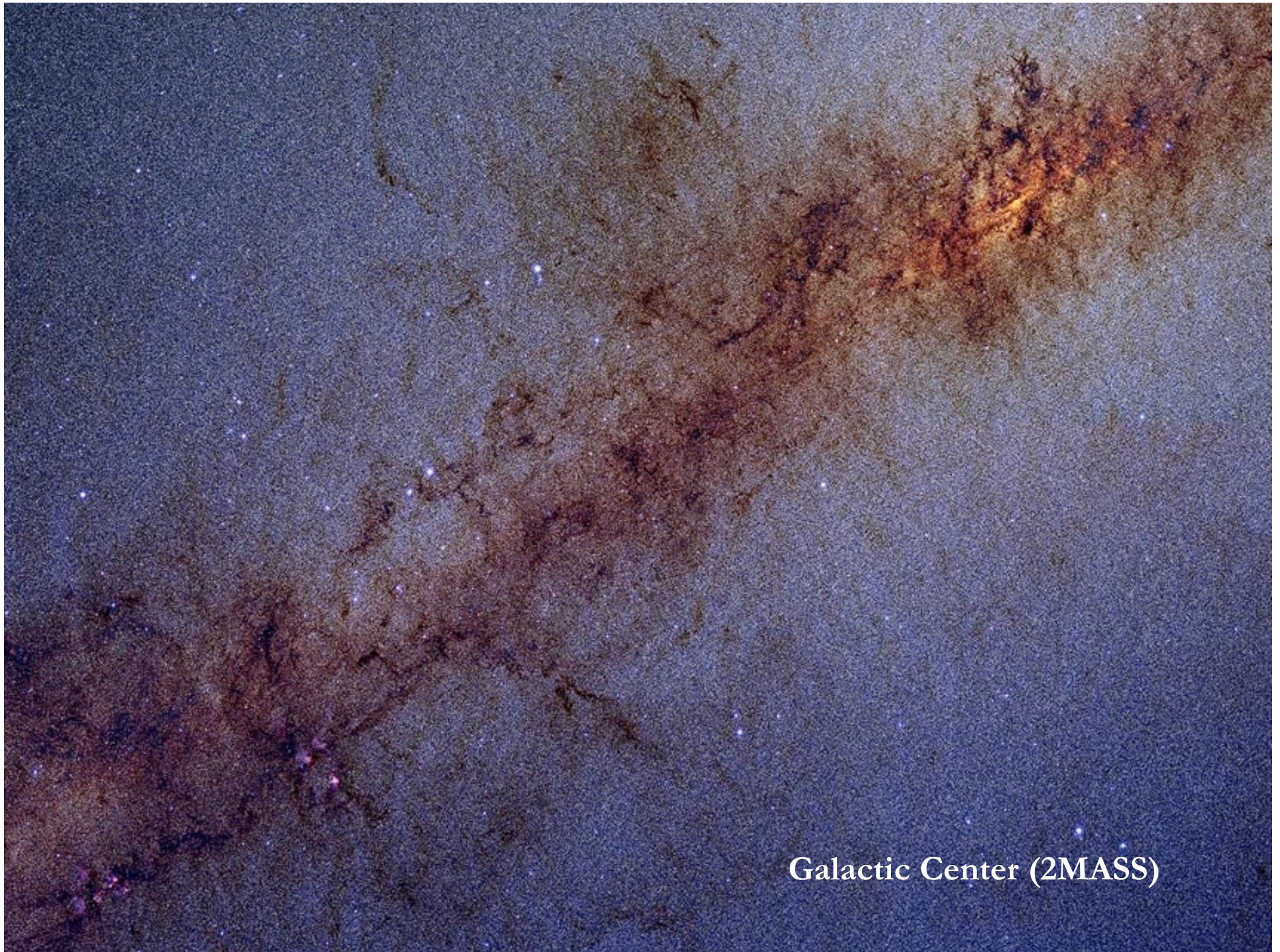
- 3 NIR bands J ($1.25 \mu\text{m}$), H ($1.6 \mu\text{m}$), K_s ($2.1 \mu\text{m}$)
- Whole sky ($40,000 \text{ deg}^2$)
- 471,000,000 point sources (ADR)



SDSS (1998-present)

- u, g, r, i, z ($0.35\text{-}0.90 \mu\text{m}$) + optical spectroscopy
- Northern sky and Galactic Plane ($8,000 \text{ deg}^2$)
- 215,000,000 point sources (DR5)





Galactic Center (2MASS)

Magnitudes and Colors

A common system for measuring the brightness of star in a given band is to use “Vega magnitudes”:

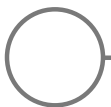
$$m_b = -2.5 \log \frac{f_b}{f_b^V}$$

where $f_b = \int_{\lambda_1}^{\lambda_2} f(\lambda) T_b(\lambda) d\lambda$

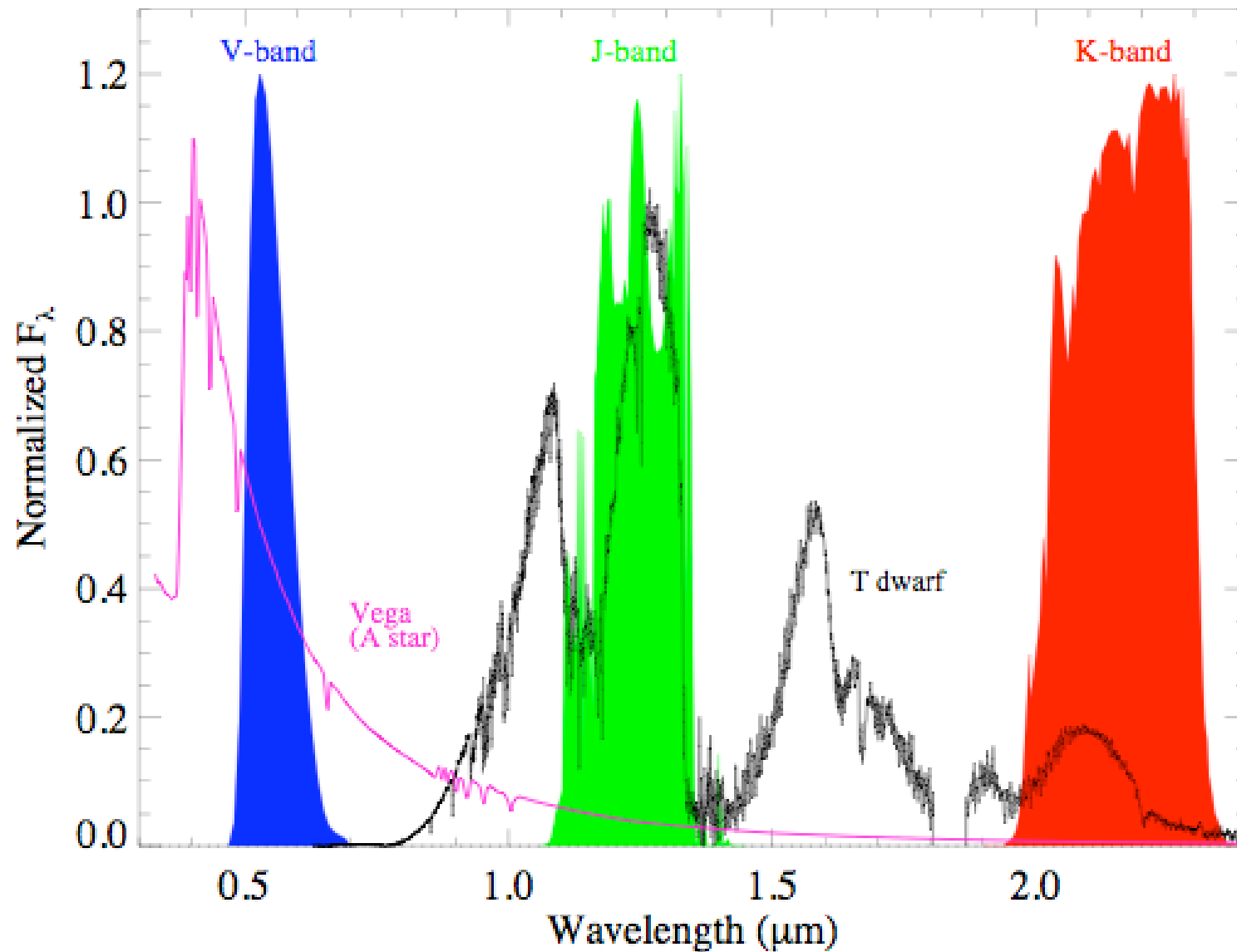
is the net flux emitted within the filter passband $T_b(\lambda)$ and f_b^V is the equivalent calculation for the star Vega.

A color is then:

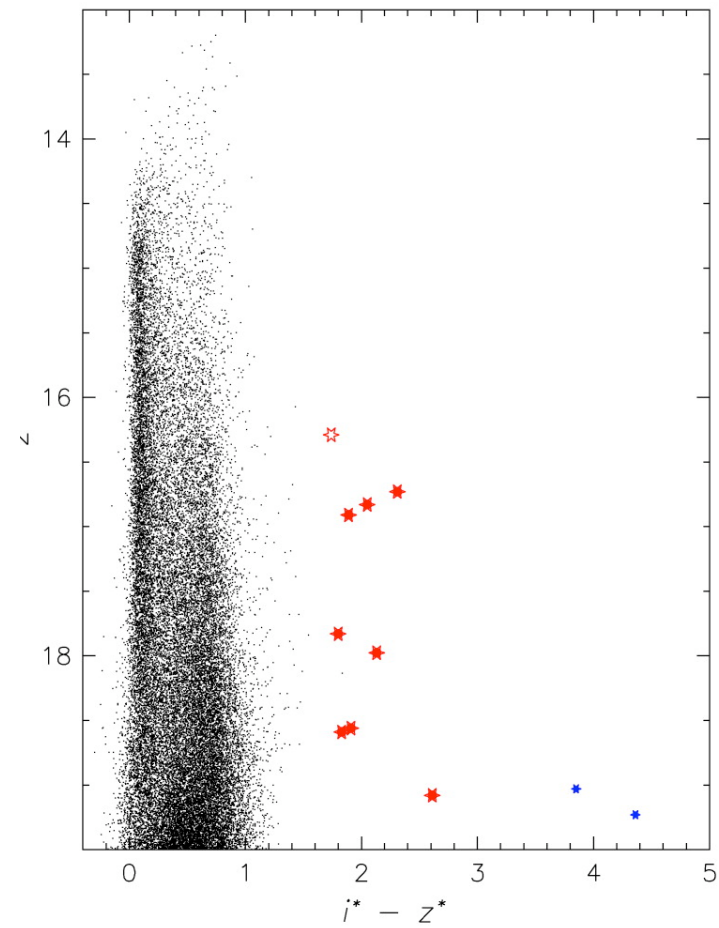
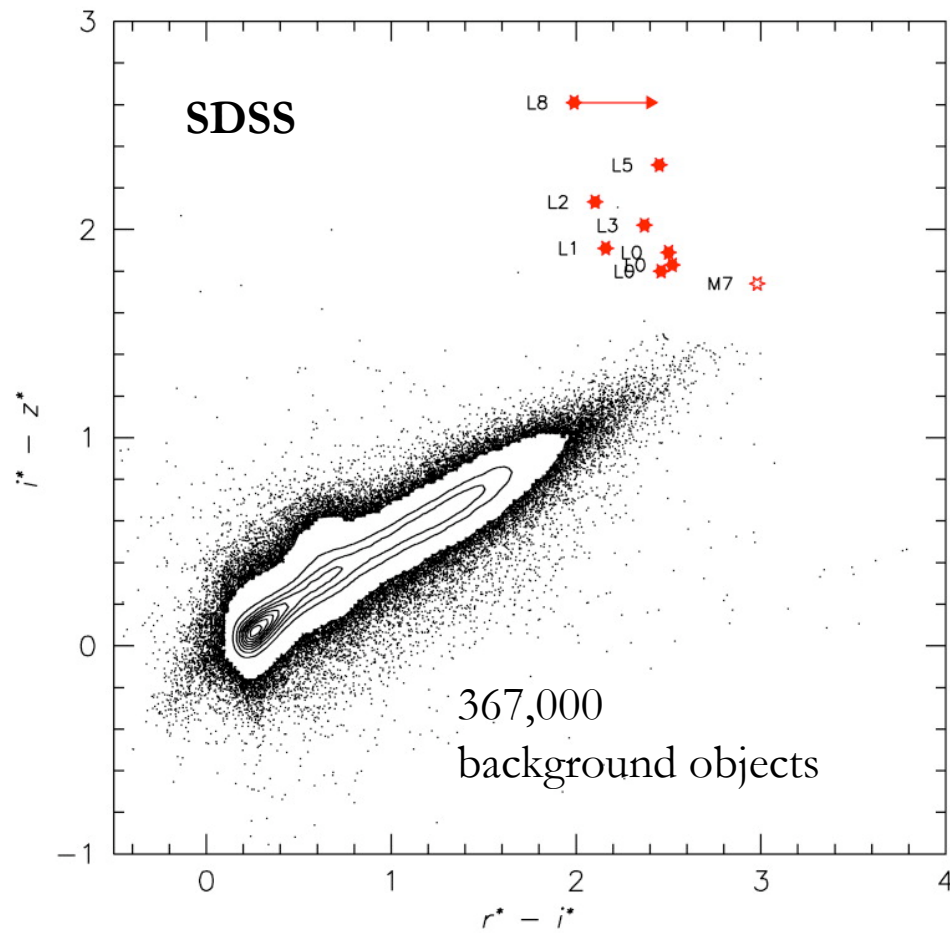
$$m_{b1} - m_{b2} = -2.5 \log \frac{f_{b1}}{f_{b2}} \frac{f_{b2}^V}{f_{b1}^V}$$



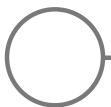
Choosing the right filters



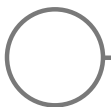
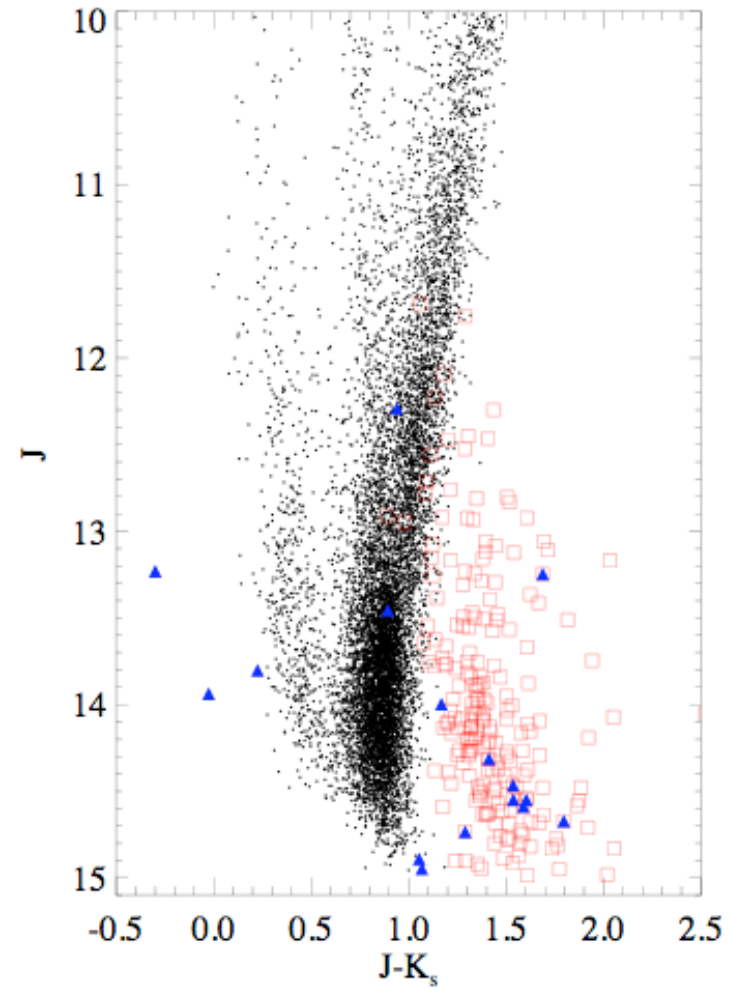
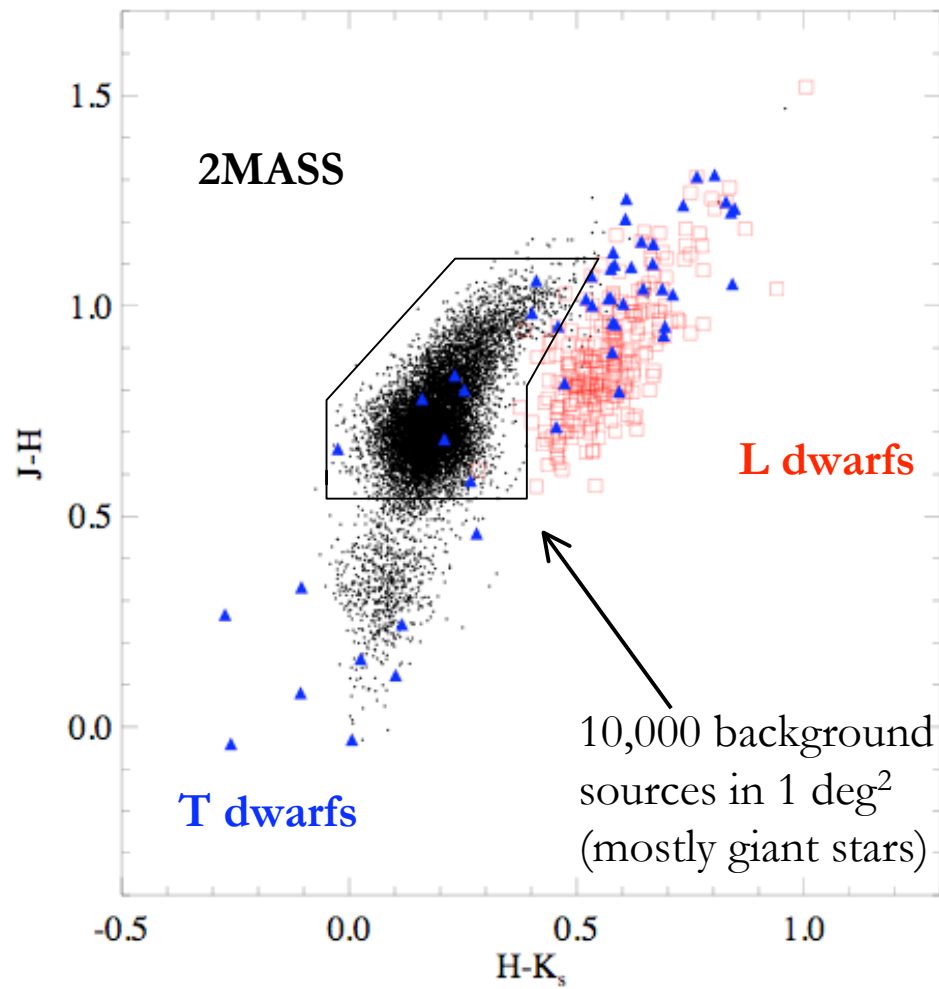
Sometimes easy...

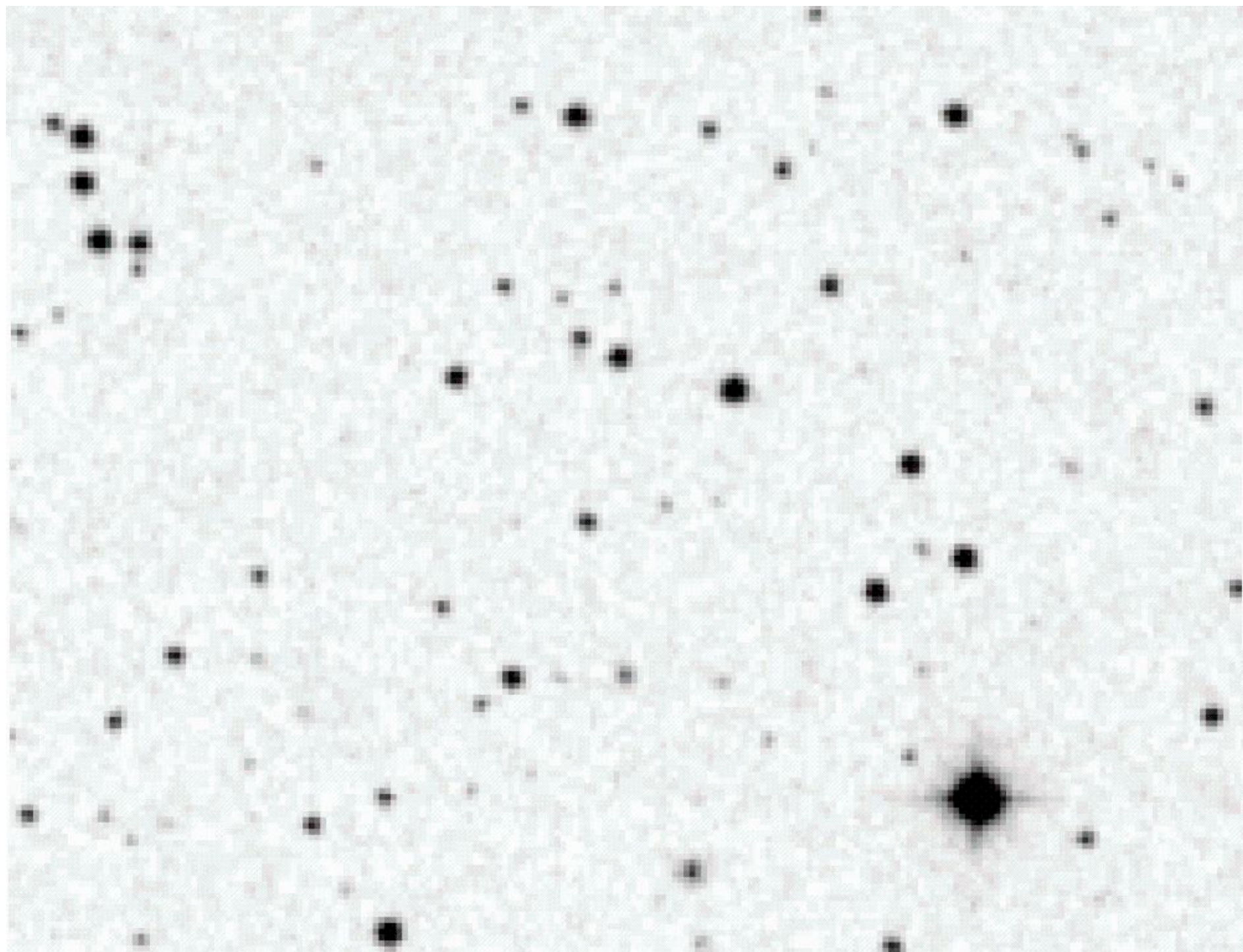


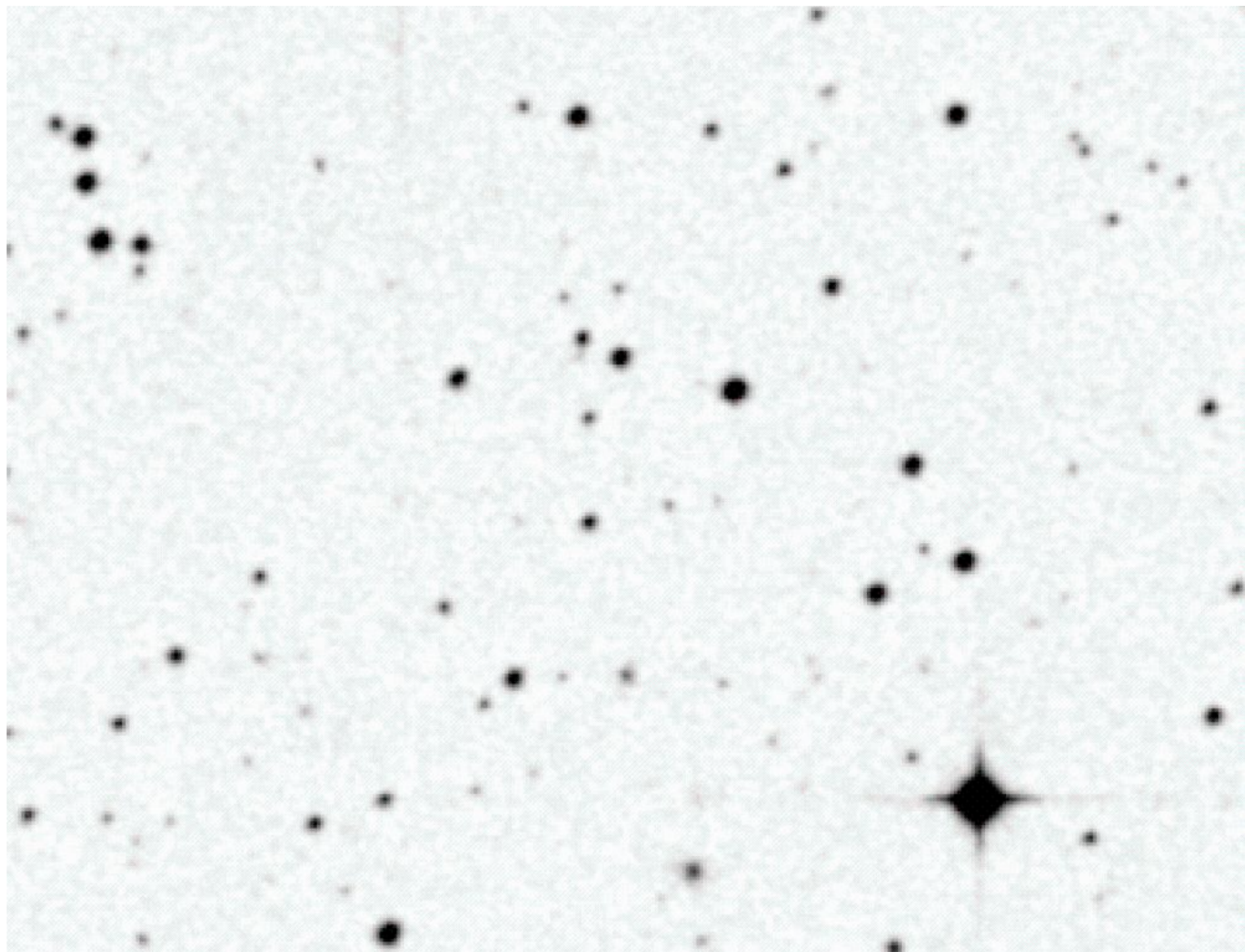
Fan et al. (2000)

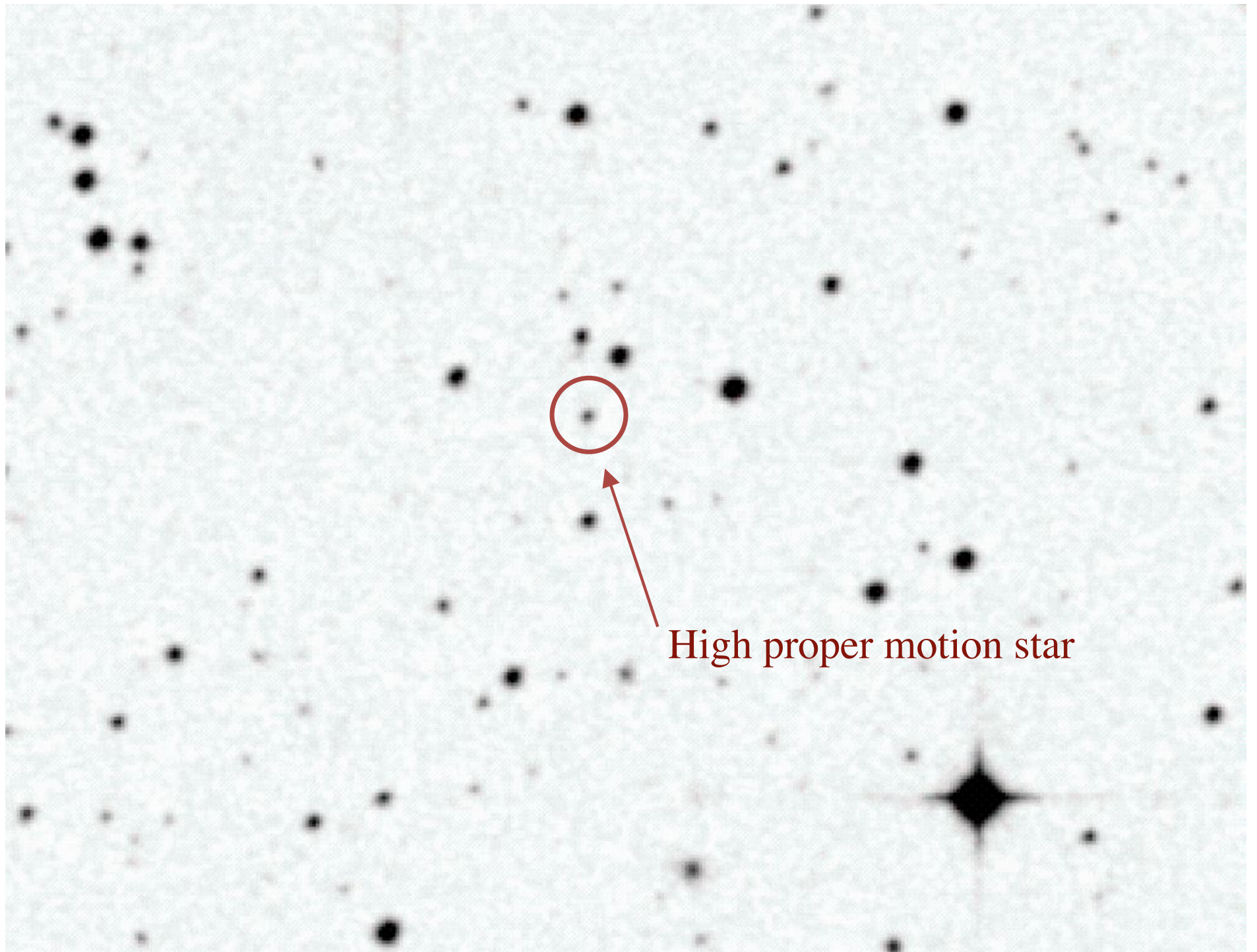


Sometimes not...

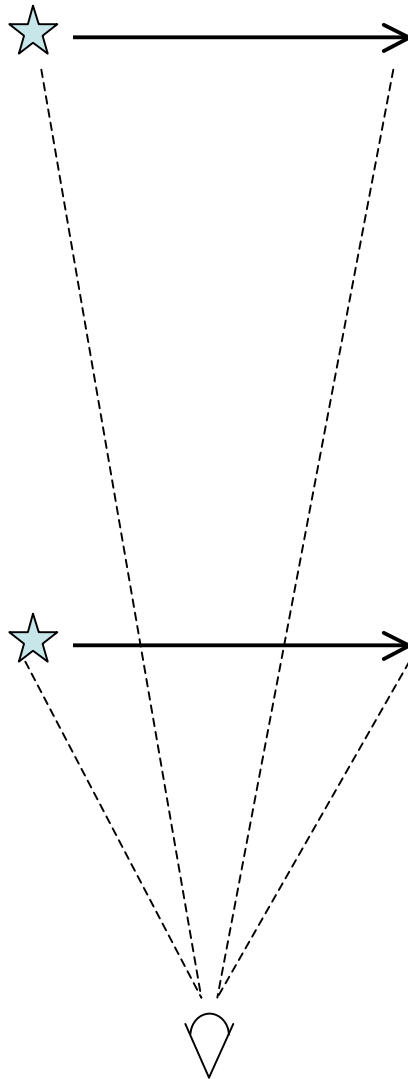








High proper motion star



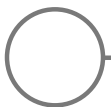
Using motion

Nearby stars and brown dwarfs tend to have higher **proper motions** than more distant sources - a projection effect:

$$\mu(" / yr) = 4.74 \times d(pc) \times V_{tan}(km/s)$$

A faint near-infrared source with a high proper motion is an excellent brown dwarf candidate

Motion can be used in addition to color criteria



Reduced proper motion

A useful statistic is the reduced proper motion:

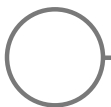
$$H_b \equiv m_b + 5 \log \mu + 5$$

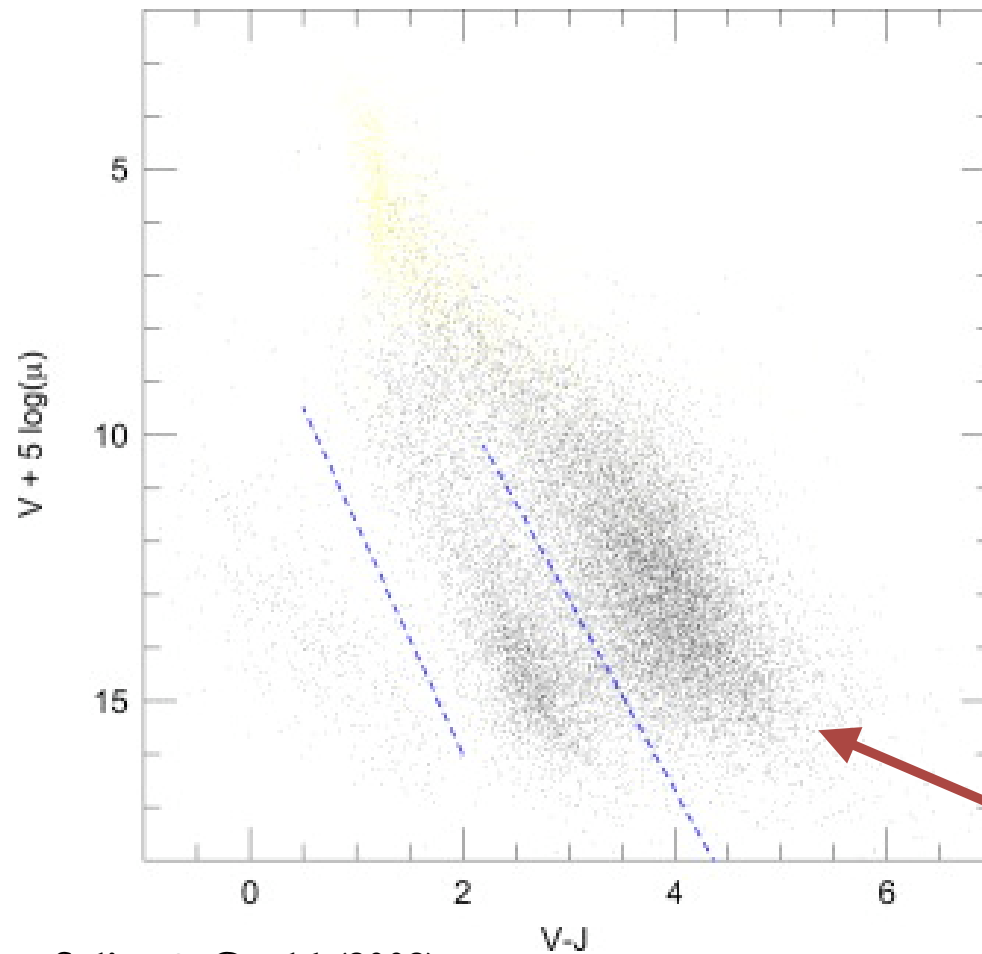
which is equivalent to

$$H_b = M_b + 5 \log V_{tan} + 3.38$$

where M_b is the absolute magnitude of a source and V_{tan} is its tangential velocity (motion in the plane of the sky)

Brown dwarfs will have large values of H_b because M_b is large.



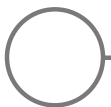


Salim & Gould (2002)

Both color and reduced proper motion can be used to make a “pseudo” color-magnitude diagram.

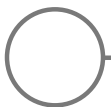
NB: Requires a proper motion survey - several now underway!

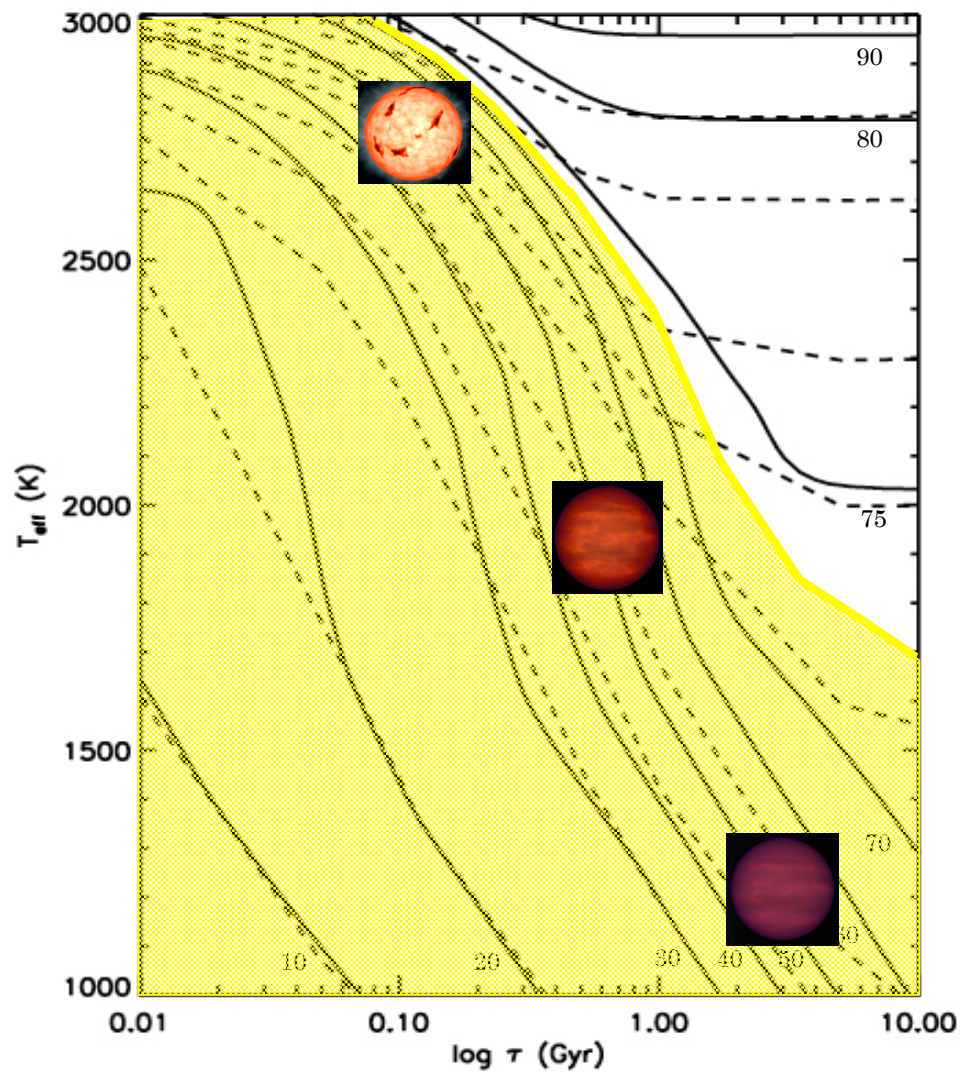
Brown
Dwarfs



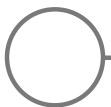
Searching for field brown dwarfs

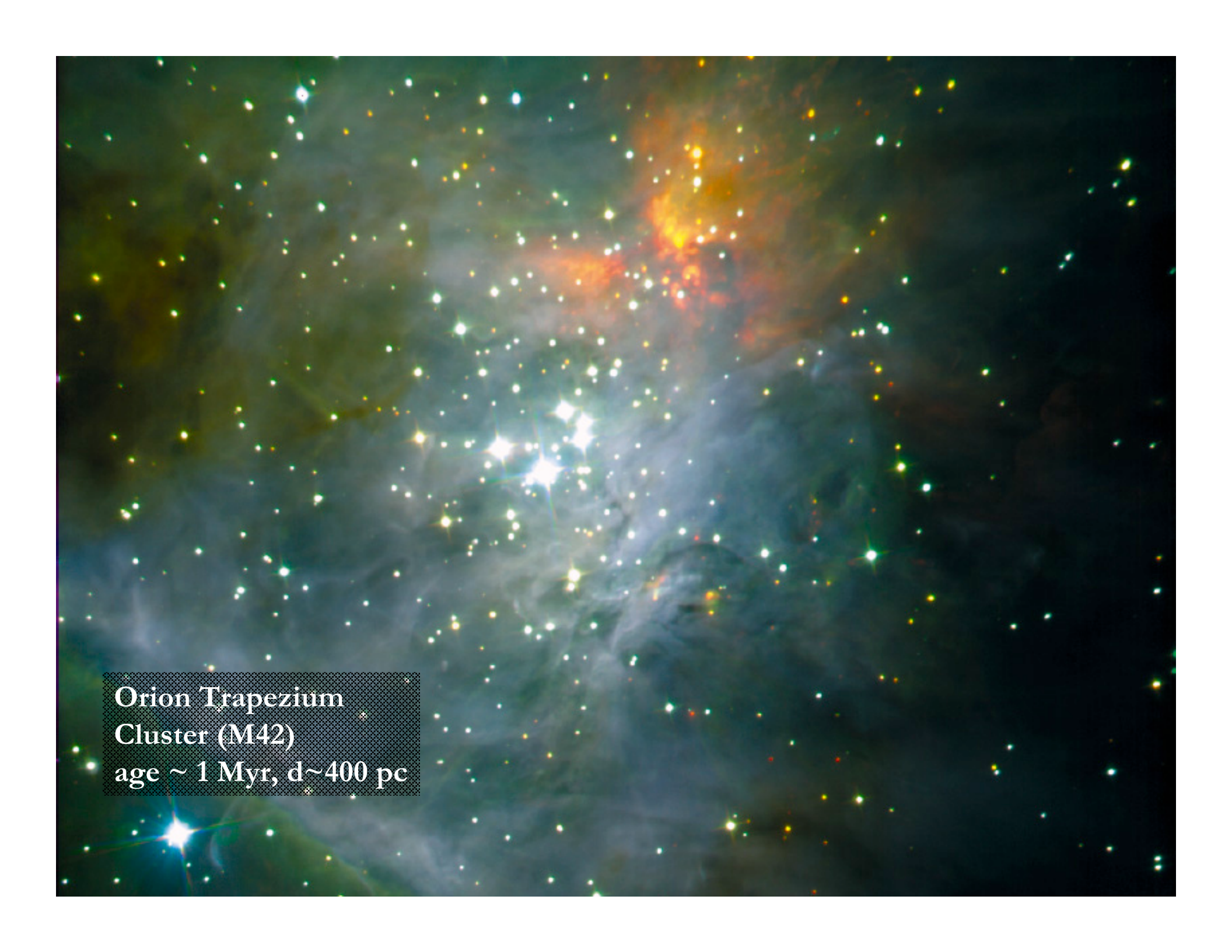
- Pros:
 - Nearest brown dwarfs to the Sun, more easily studied, can find faintest/coldest brown dwarfs
 - Can use existing wide field near infrared and proper motion surveys
- Cons:
 - Very faint, so very rare
 - Can't constrain individual properties well - unknown distance, age, mass, etc.
 - Selection can be difficult, biases may be present



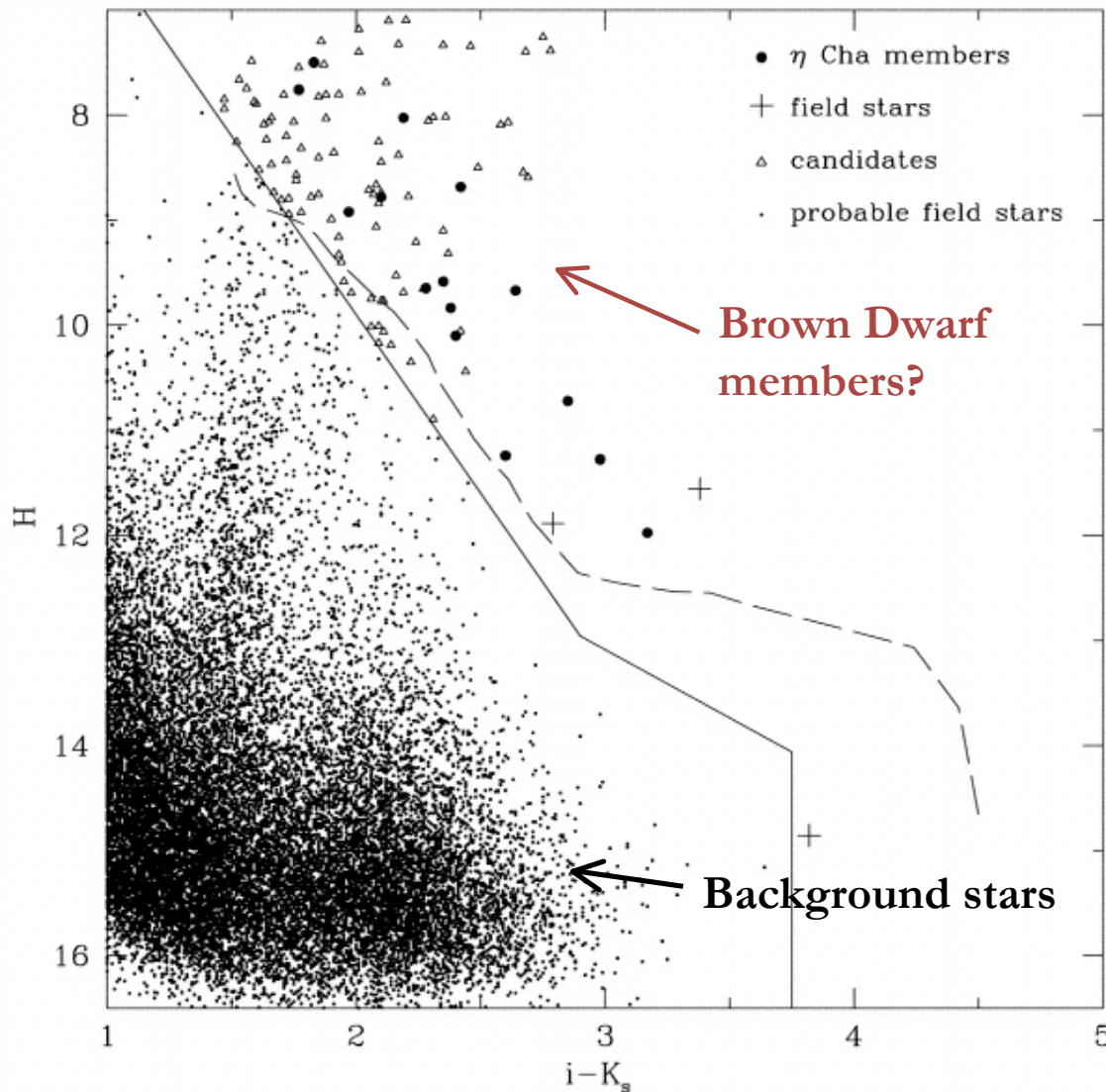


Brown dwarfs are brighter when they are young, so one strategy is to look in young star forming regions.



A wide-field astronomical image of the Orion Trapezium Cluster (M42). The image shows a dense field of stars of various colors (white, yellow, orange, red) against a dark background. A prominent blue-green nebula is visible in the lower-left quadrant. A semi-transparent black box with a white grid pattern is overlaid in the bottom-left corner, containing white text.

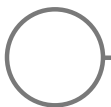
Orion Trapezium
Cluster (M42)
age ~ 1 Myr, $d \sim 400$ pc



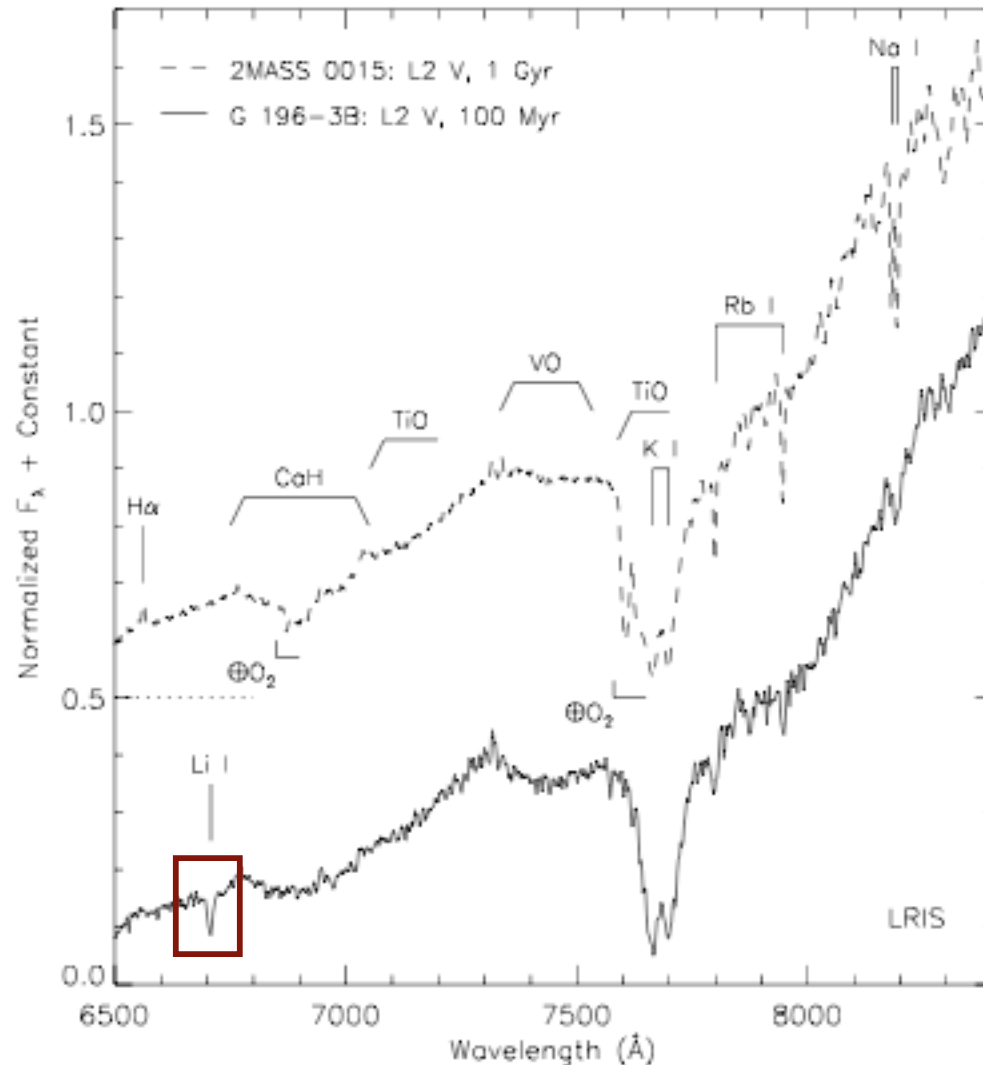
Luhman (2004)

Cluster members can be segregated in a color-magnitude diagram.

Problem: young brown dwarfs are M dwarfs, most common field stars/contaminants!



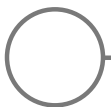
The Lithium Test



Li I is destroyed by nuclear reactions in the cores of stars/BDs more massive than $0.065 M_\odot$ (e.g., Rebolo et al. 1992)

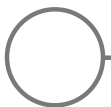
Fully convective interiors means all Li is destroyed, including photospheric Li

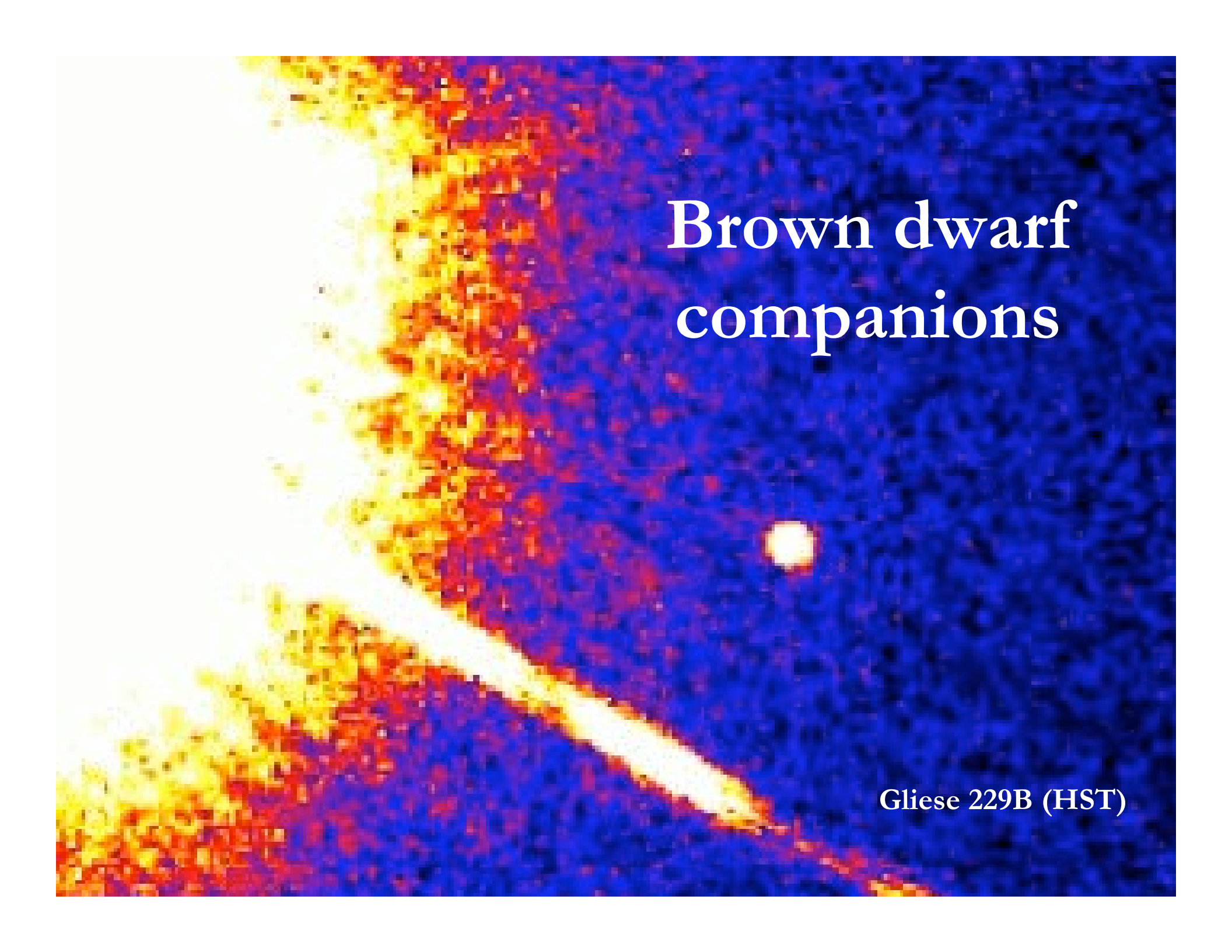
Detection of Li I in the spectrum of an M/L dwarf implies that it is a young brown dwarf



Searching for young brown dwarfs

- Pros:
 - Intrinsically brighter, so can find very low mass brown dwarfs when they are still hot
 - Ages are generally well constrained
- Cons:
 - Star forming regions are generally distant (> 100 pc)
 - Reddening effects may reduce brightness gains
 - Source confusion is a problem, follow-up required



The image is a full-page astronomical photograph. On the left side, there is a bright, elongated, and somewhat irregular white and yellowish structure, likely a nebula or a star-forming region. The rest of the background is a deep, dark blue, speckled with numerous small, distant stars. In the lower right quadrant, there is a single, prominent, small, bright orange-yellow sphere, which is the brown dwarf companion Gliese 229B.

Brown dwarf companions

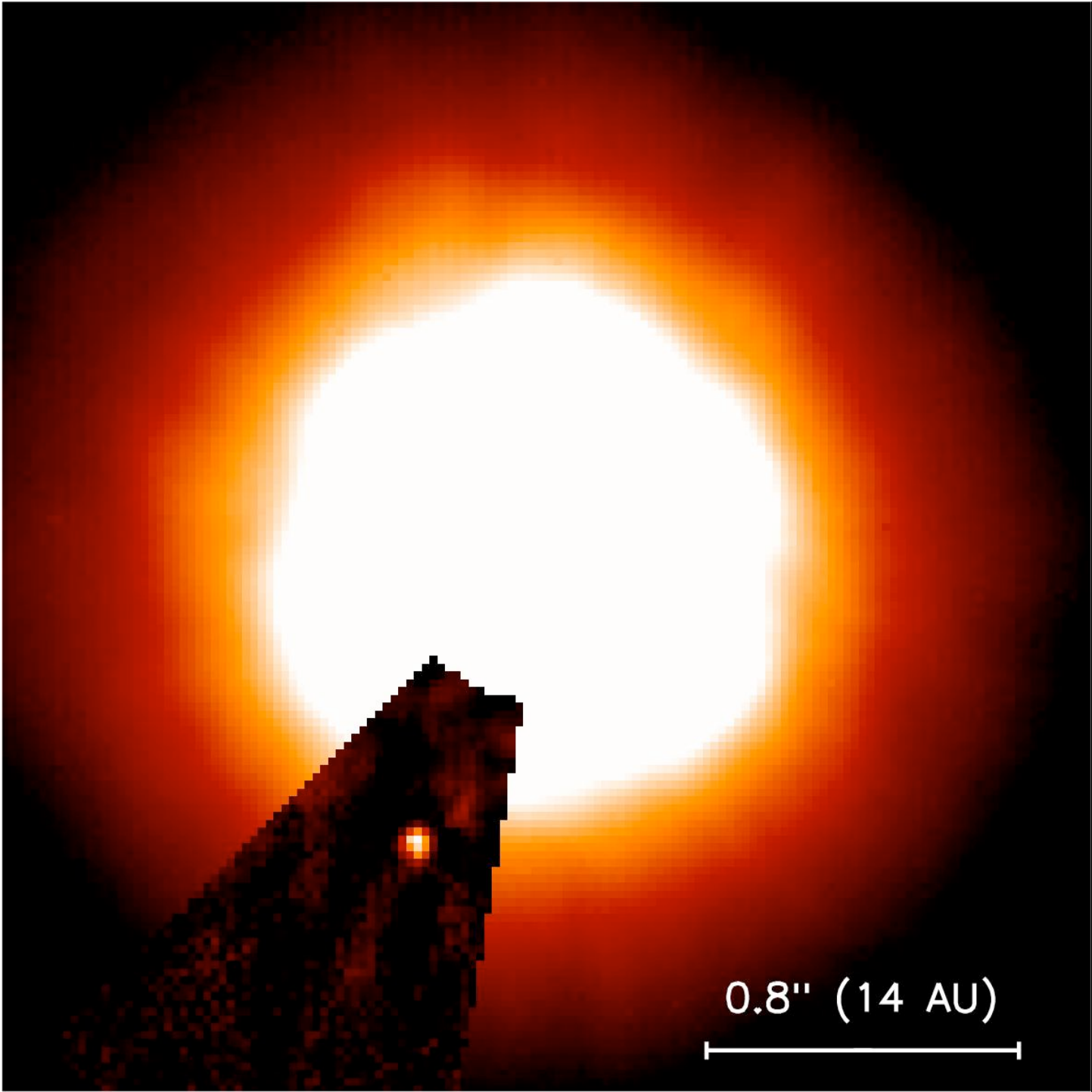
Gliese 229B (HST)



An easy case:
Gliese 570D
(Burgasser et al.
2000)

2MASS JHK_s

A hard case:
HR 7672B
(Liu et al. 2002)



0.8" (14 AU)

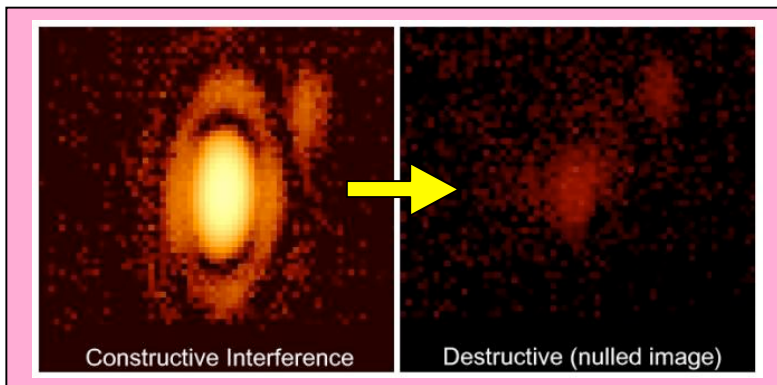
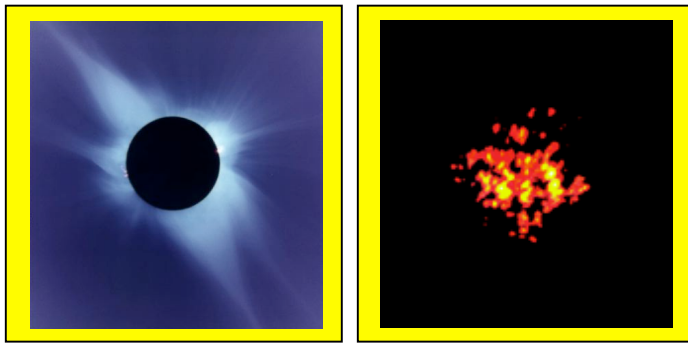
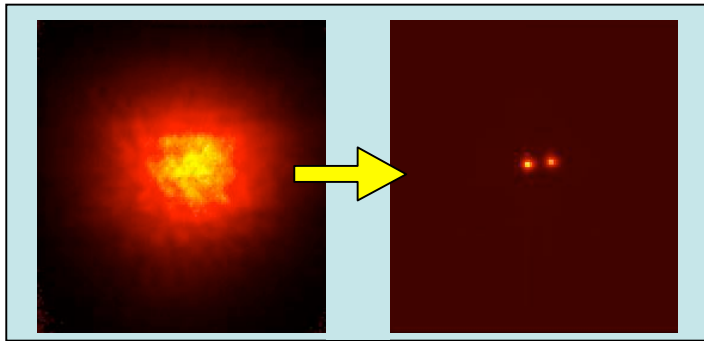
The image shows a large, bright, white-yellow star (HR 7672A) with a diffuse orange-red glow. In the lower-left foreground, there is a dark, irregularly shaped object. Within this dark object, a small, distinct orange-red point of light is visible, representing the companion star HR 7672B. A horizontal scale bar is located at the bottom right of the image area.

Gemini AO

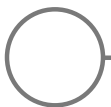
Techniques for finding BD companions

- Direct imaging (wide companions)
- Radial Velocity (rare!)
- Speckle Interferometry
- Adaptive Optics
- Coronagraphy
- Spectral Difference Imaging
- Interferometric nulling
- Combinations of the above!*

Correct for
atmospheric blurring

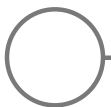


*See next Thursday's Astrophysics Colloquium by Ben Oppenheimer



Searching for BD companions

- Pros:
 - Can target nearby stars to find faintest companions
 - Distance, composition and age constraints from primary
 - Only need to search a limited area
- Cons:
 - Close in companions hard to see in glare of star
 - Brown dwarf companions to stars are rare ($\sim 5\%$)
 - Must confirm companionship (e.g., common proper motion)



How to find a brown dwarf

- Look in the near-infrared
- Look for objects with weird (red) colors
- Look for high proper motion objects
- Look in young star forming regions
- Look around nearby stars

