The Hitchhiker's Guide to Classifying T and Y Brown Dwarfs

By Azmain Nisak

Based on Chapter 10 of "Stellar Spectral Classification," by Gray and Corbally (T-dwarfs)

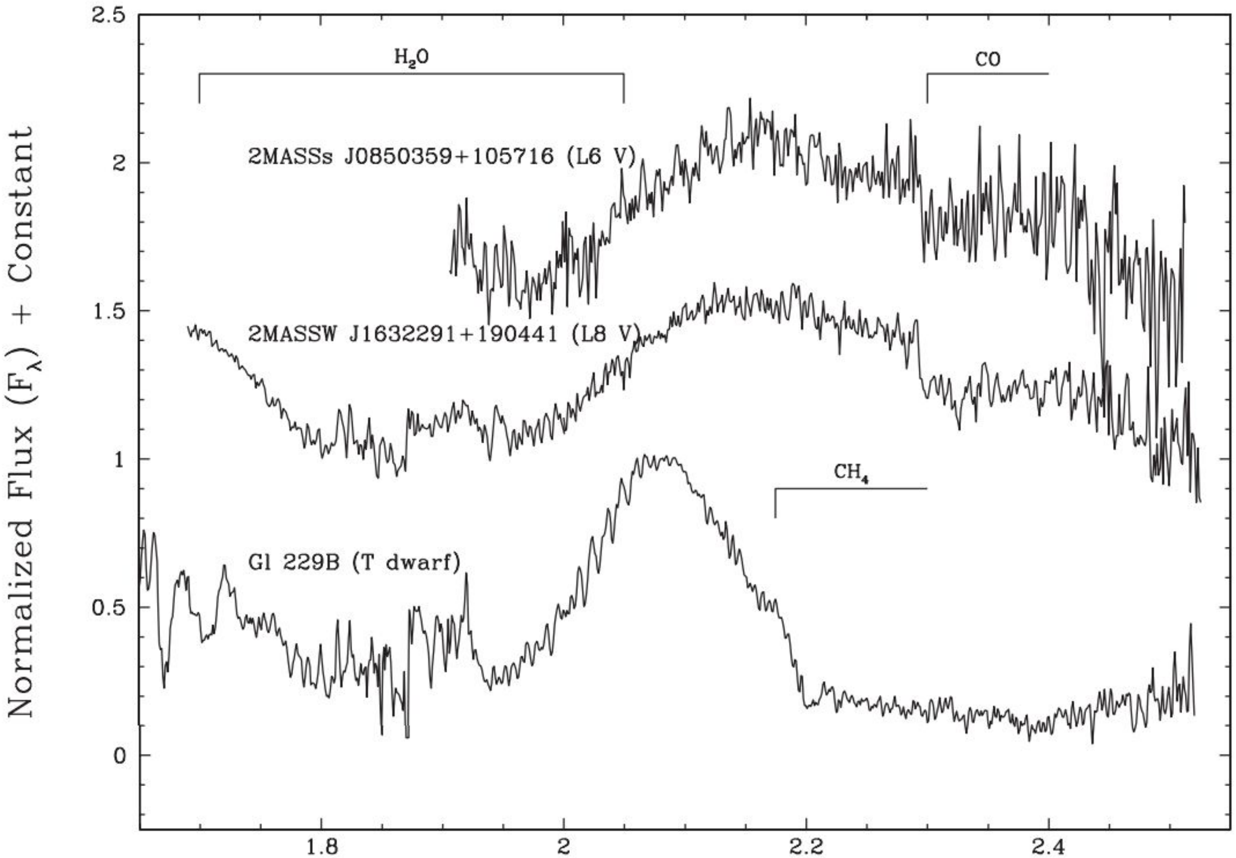
Based on Kirkpatrick, J. D., et al. 2012, ApJ, 753:156. (Y-dwarfs)

Overview

- **CH_4 absorption** – Key distinguishing feature!
- Strong H_2O and NH_3 bands
- Neutral metal-line features (Na I, K I, Rb I, Cs I)
- Collision-induced absorption (CIA) H_2
- Spectral energy distributions (SED) increasingly peaked in near- and mid-IR
- Classified based on features in the:
  - **Near-IR (1-2.5μm)**
  - Red-optical (0.6-1.0μm)
  - mid-IR (5-15μm)
- **Narrower J-band flux peak** (1.27μm) **and reversal of J-H color** from bluer to redder distinguish Y dwarfs from T dwarfs

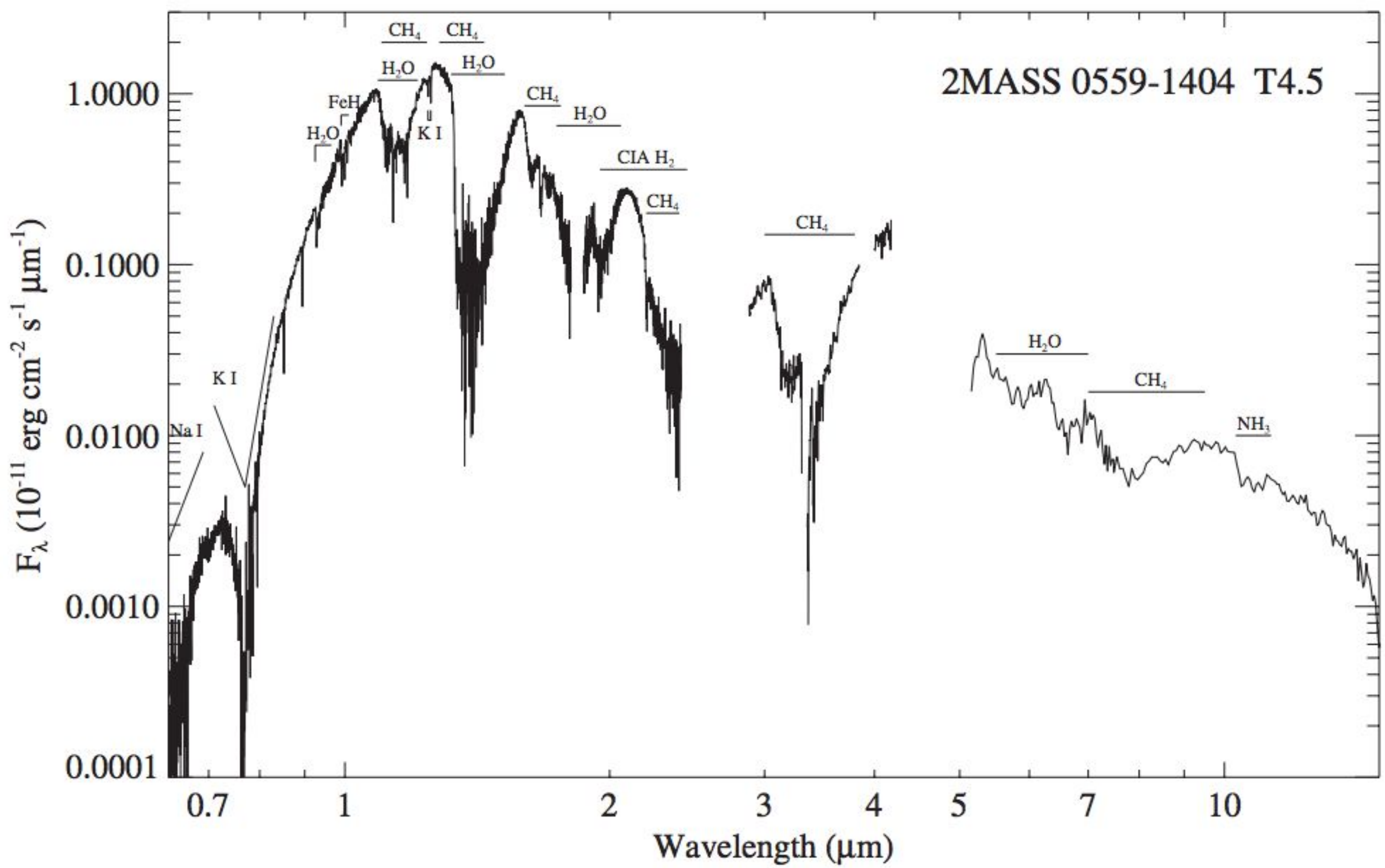
The First T dwarf

- 1995: The first T dwarf (Gliese 229B) is discovered!
- Notice the CH_4 absorption, separating it from the L dwarfs



General Spectral Properties

- SED of a typical mid-type T dwarf (T4.5)



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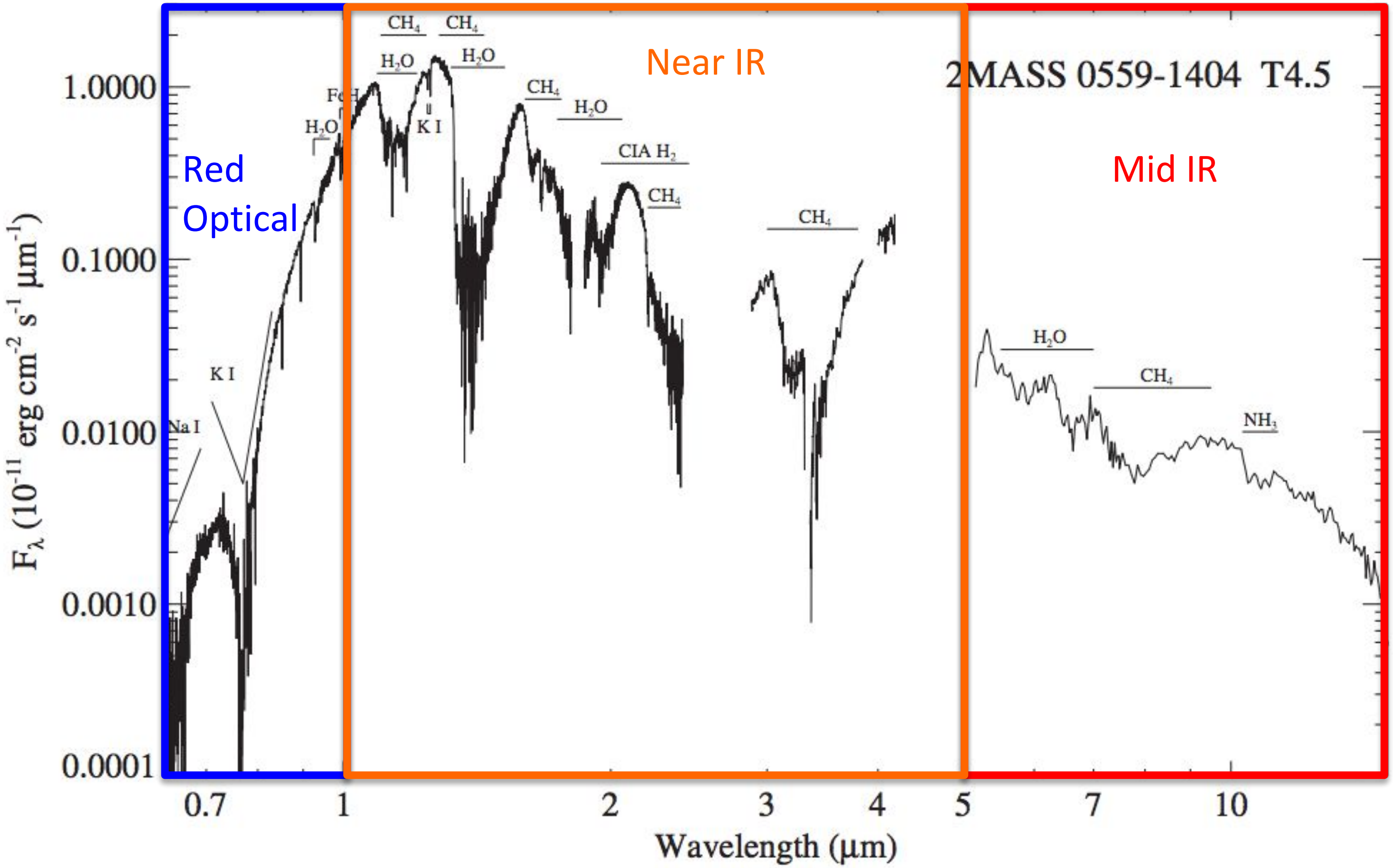
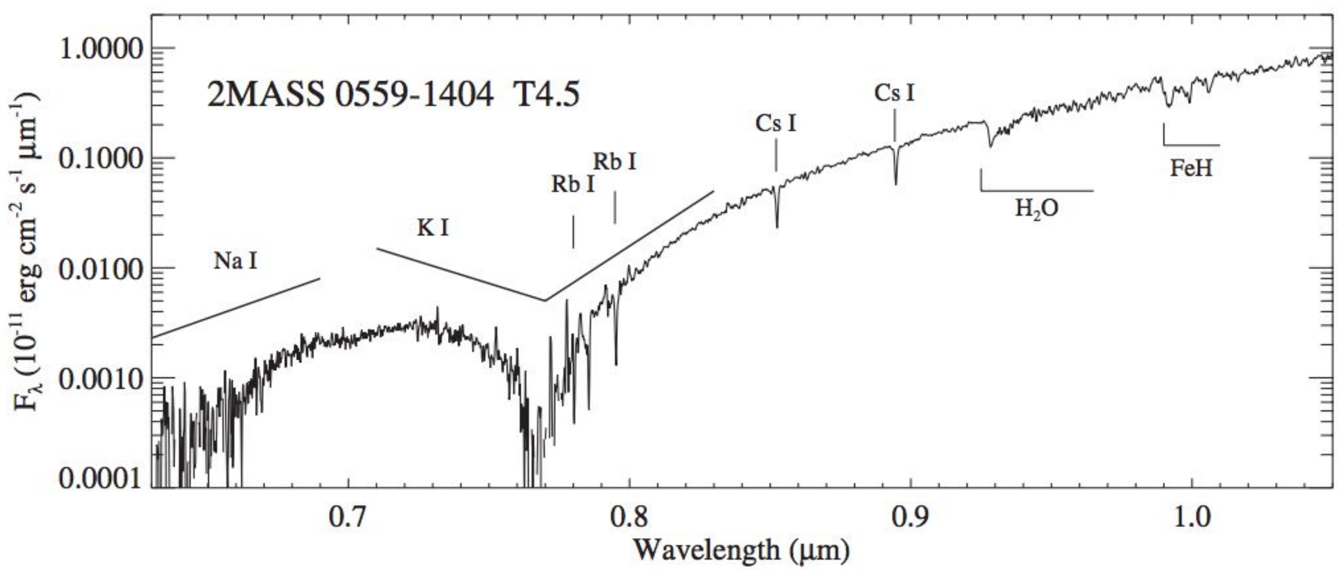


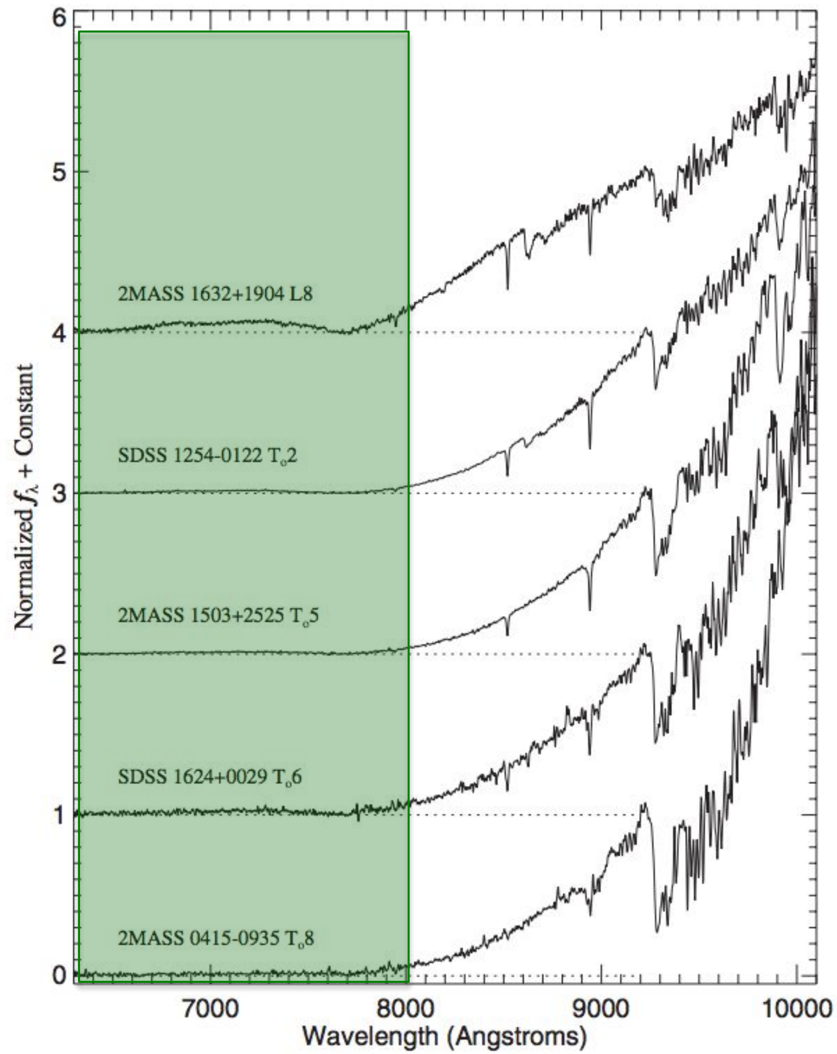
General Spectral Properties: Red-Optical

- Pressure-sensitive **K I and Na I** resonance doublets deepen and broaden
- **Blue bump** – peak-up in flux between K I and Na I
- Superimposed **Rb I and Cs I** lines
- **H_2O** absorption – found in all T dwarfs!
- **FeH** – found in L and mid-T but **NOT** found in late-T!



Red-Optical Standard Spectra

- 4 optical T dwarf standards
- **K I doublet absorption gets broader and deeper**
- 8000-10000 Å slope steepens
- H_2O band strengthens
- Cs I lines weaken
- FeH (8611 Å) and CrH (8692Å) bands weaken from L8 to T_o2; disappears T_o5 on
- Wing-Ford FeH strengthens from L8 to T_o5 but fades in later types



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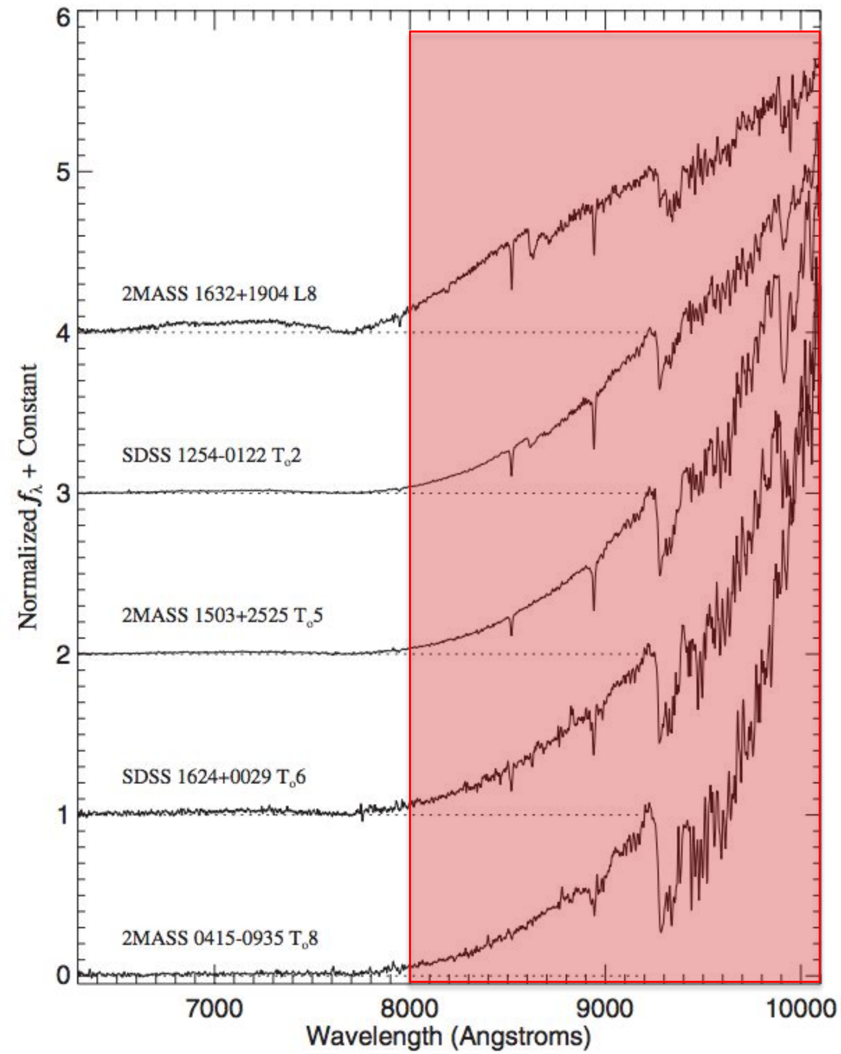

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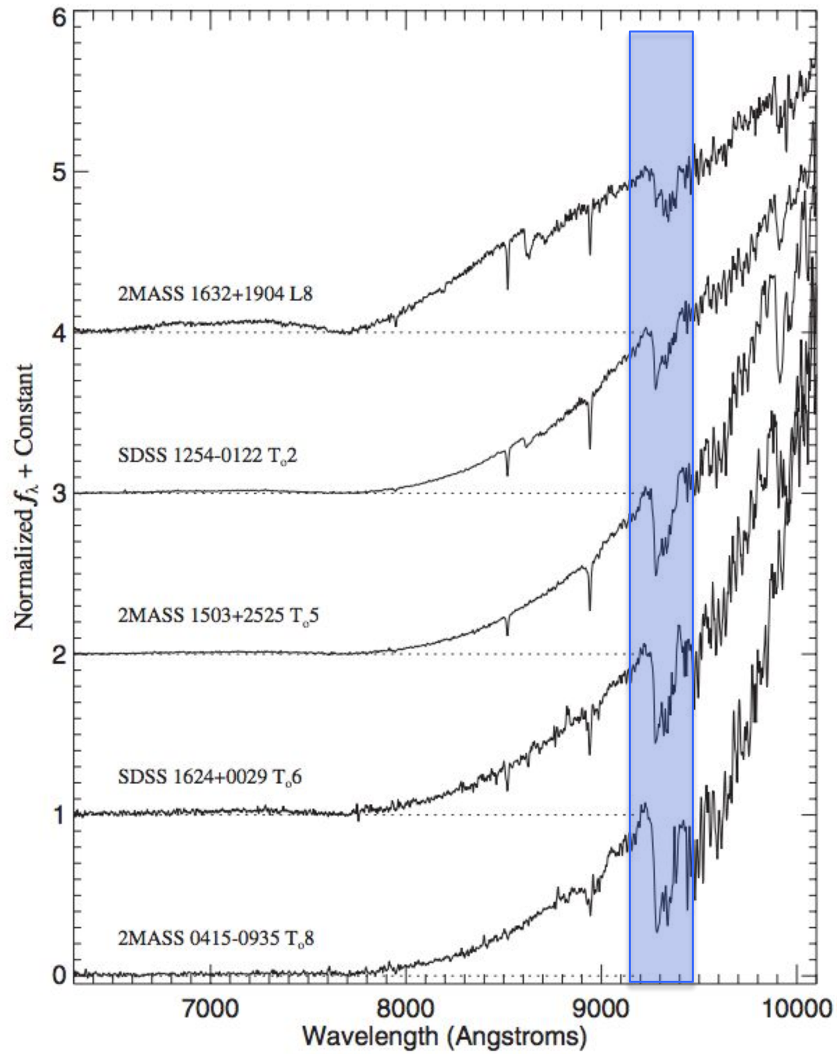

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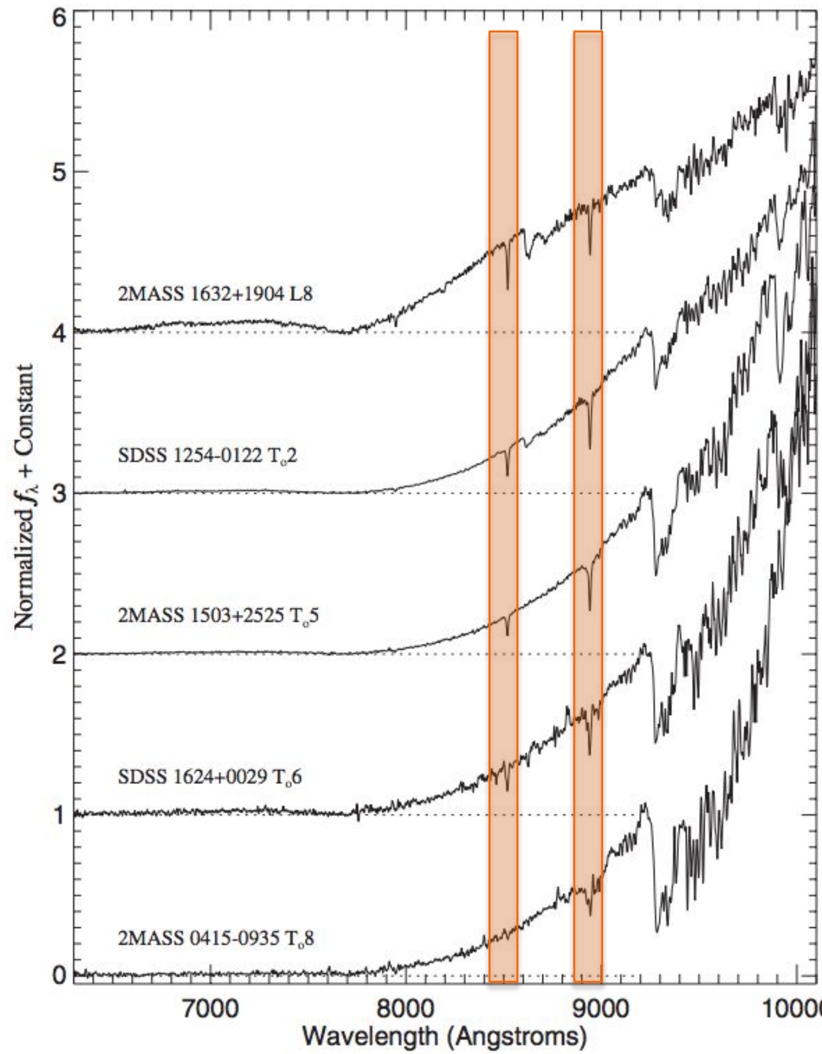

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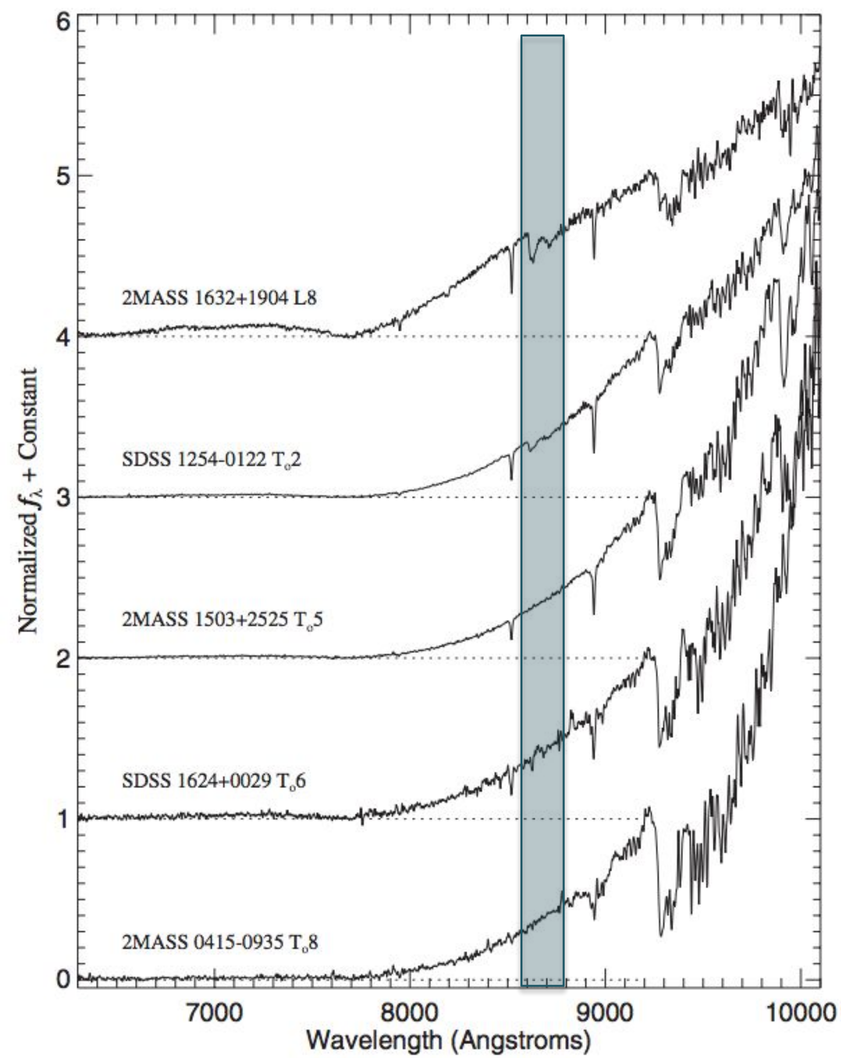

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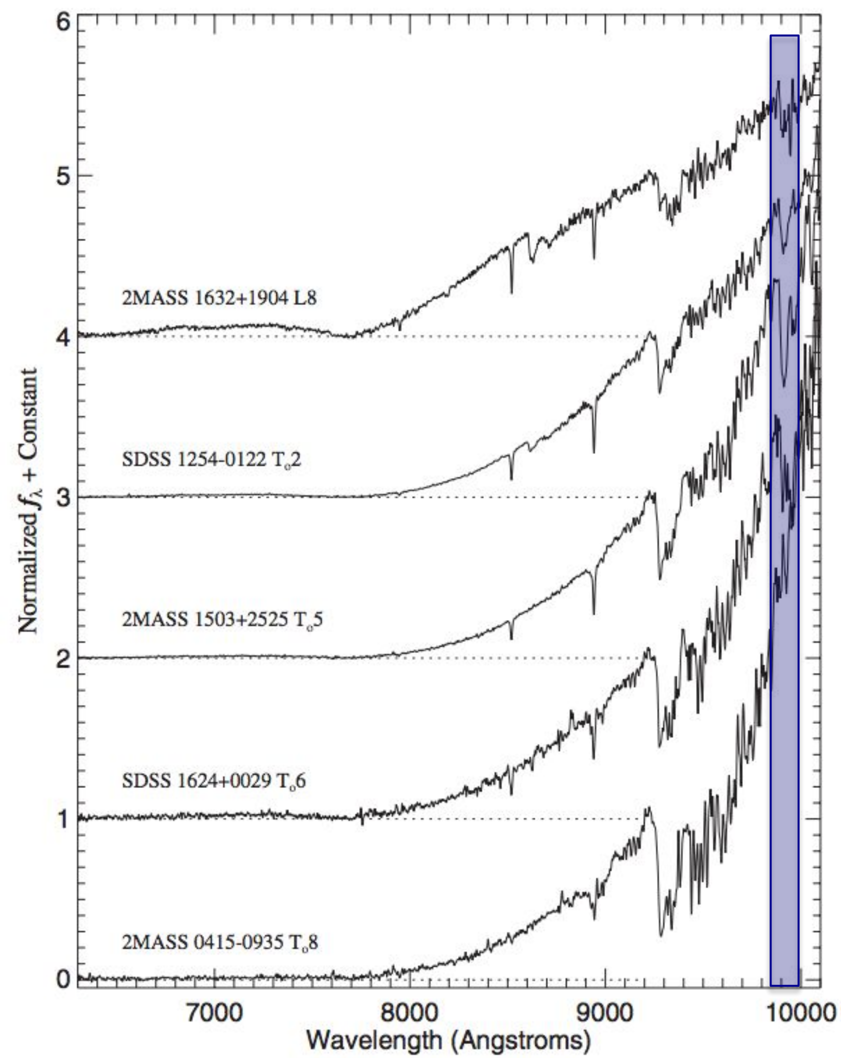
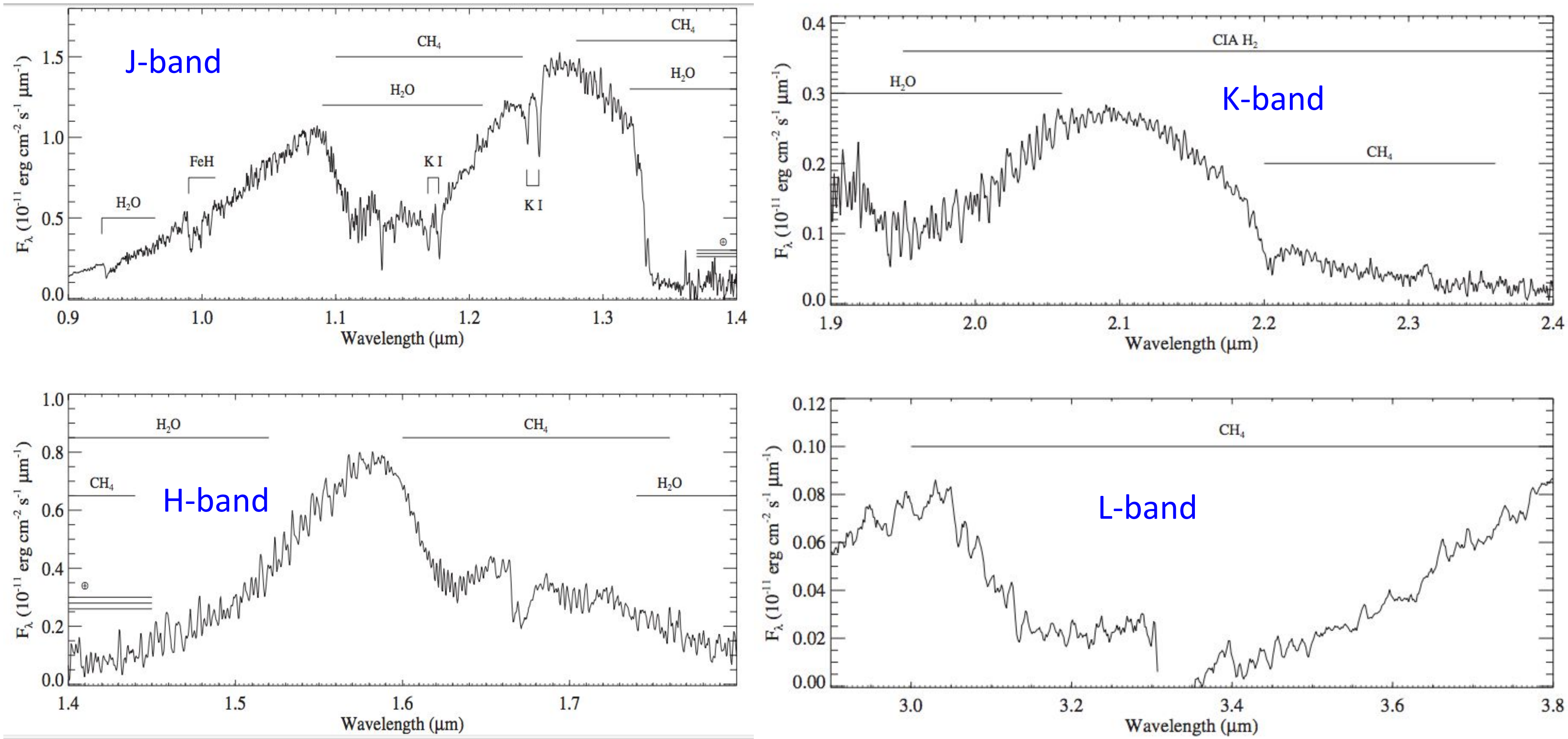


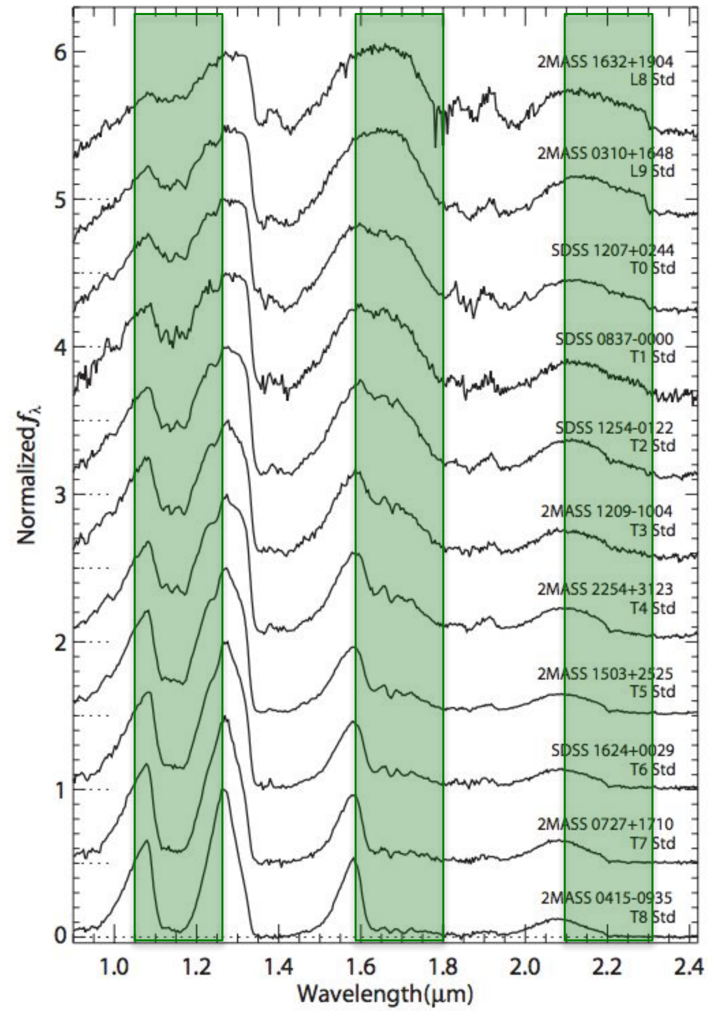
General Spectral Properties: Near-IR

- Strong **CH_4, H_2O; CO** (earliest-type); pressure-sensitive **CIA H_2; K I** (early/mid-type)



Near-IR Standard Spectra

- 8 near-IR T dwarf standards
- **CH_4 emerges at T0, strengthens in later types (1.15, 1.65, 2.2μm)**
- H_2O absorption strengthens in later types (1.15, 1.4, 1.8μm)
- CO absorption decreases in later types (2.3μm)
- Flux peaks (1.05, 1.25, 1.6, 2.1μm) strengthen in later types
- K-band peak suppressed compared to J band



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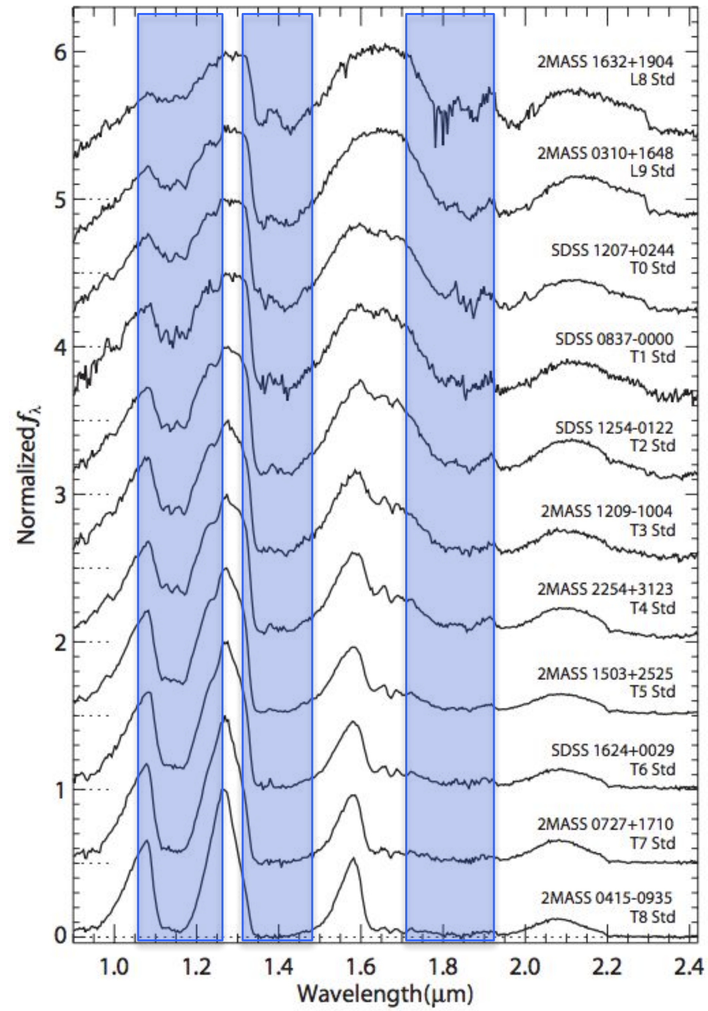

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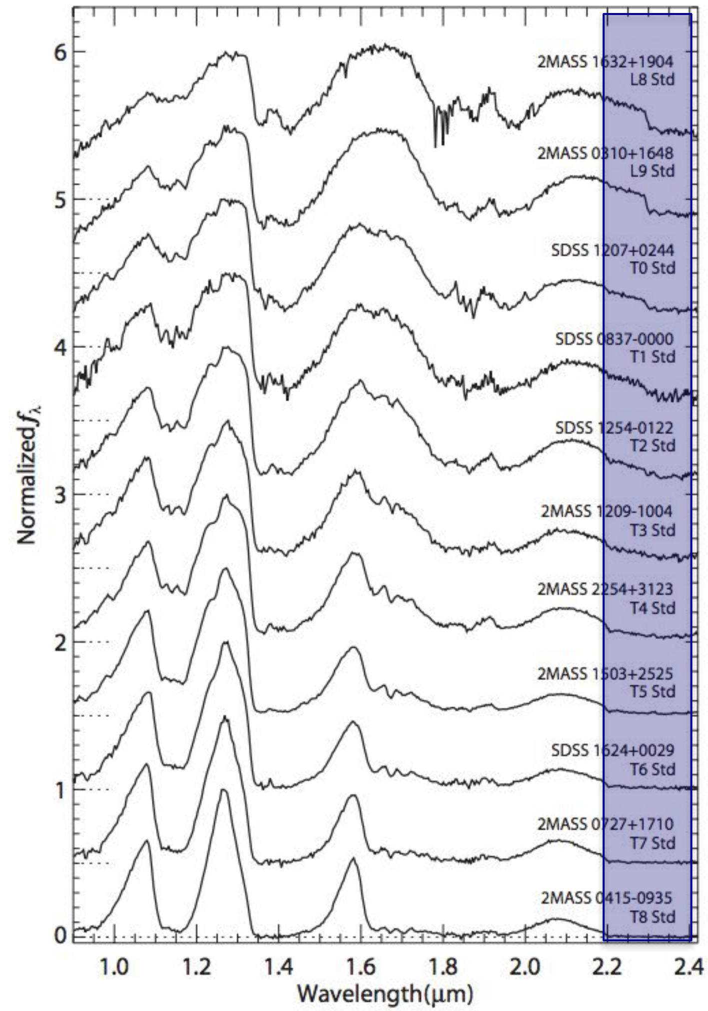

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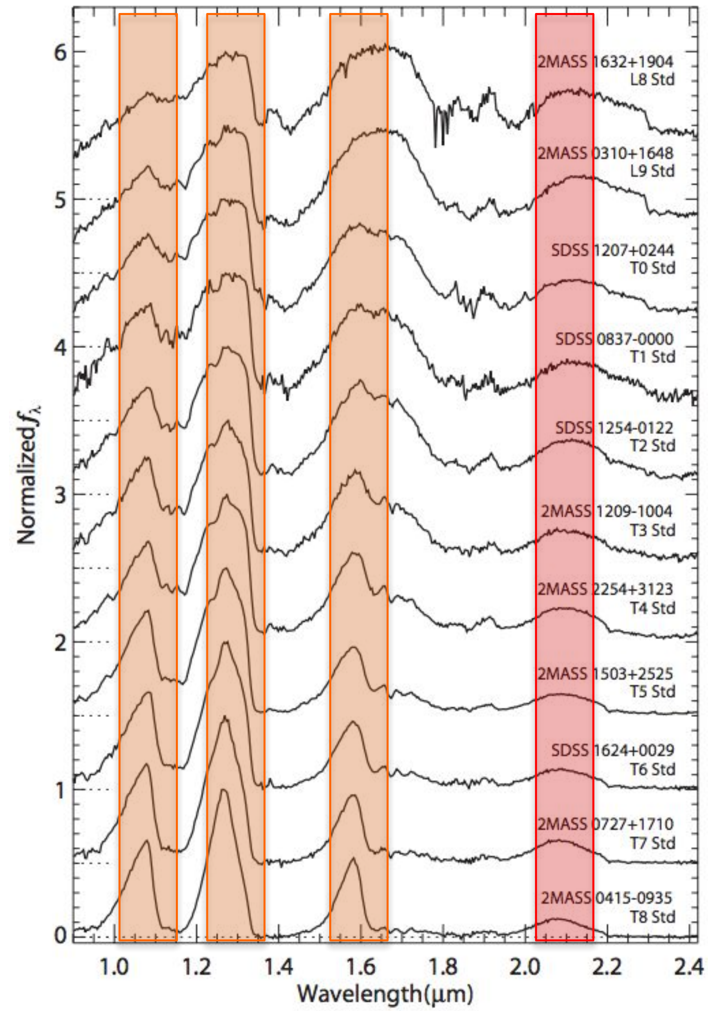

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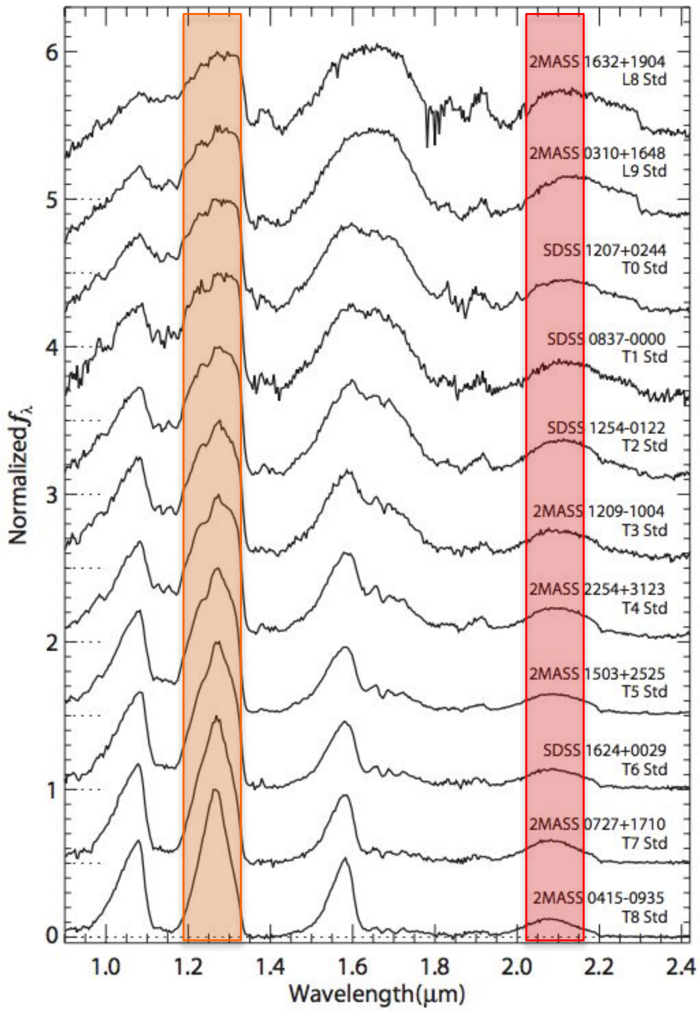
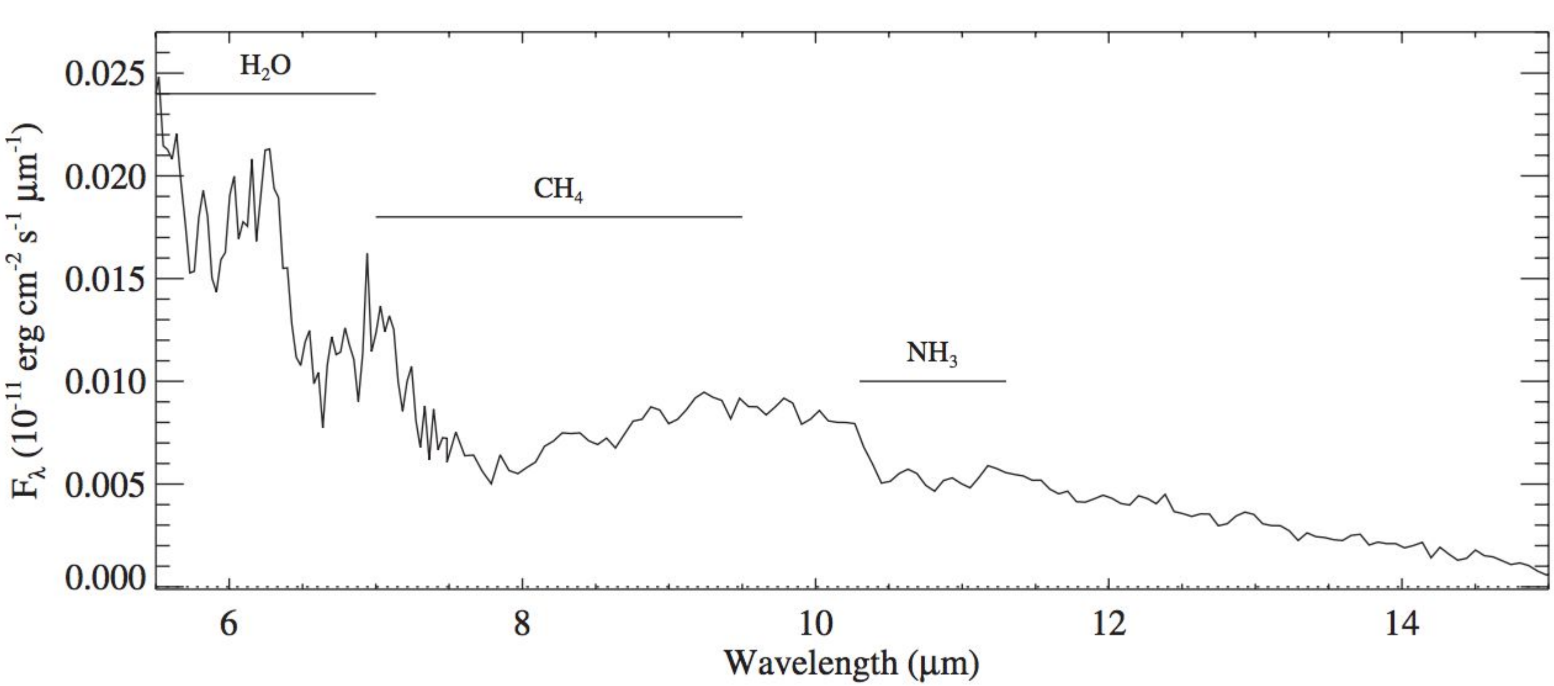


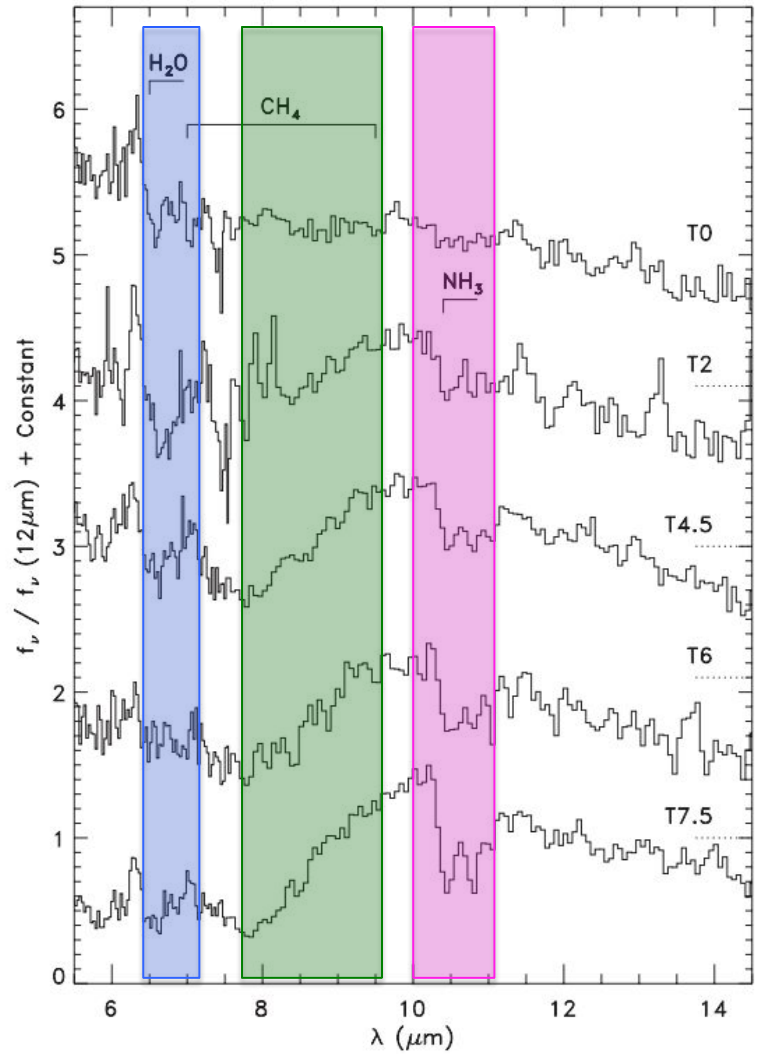
General Spectral Properties: Mid-IR

- 3 main absorbers:
  - **H_2O** (5.5-7.0µm)
  - **CH_4** (7.0-9.5µm)
  - **NH_3** (10.5µm; atmospheric mixing-sensitive!)



Mid-IR Spectra

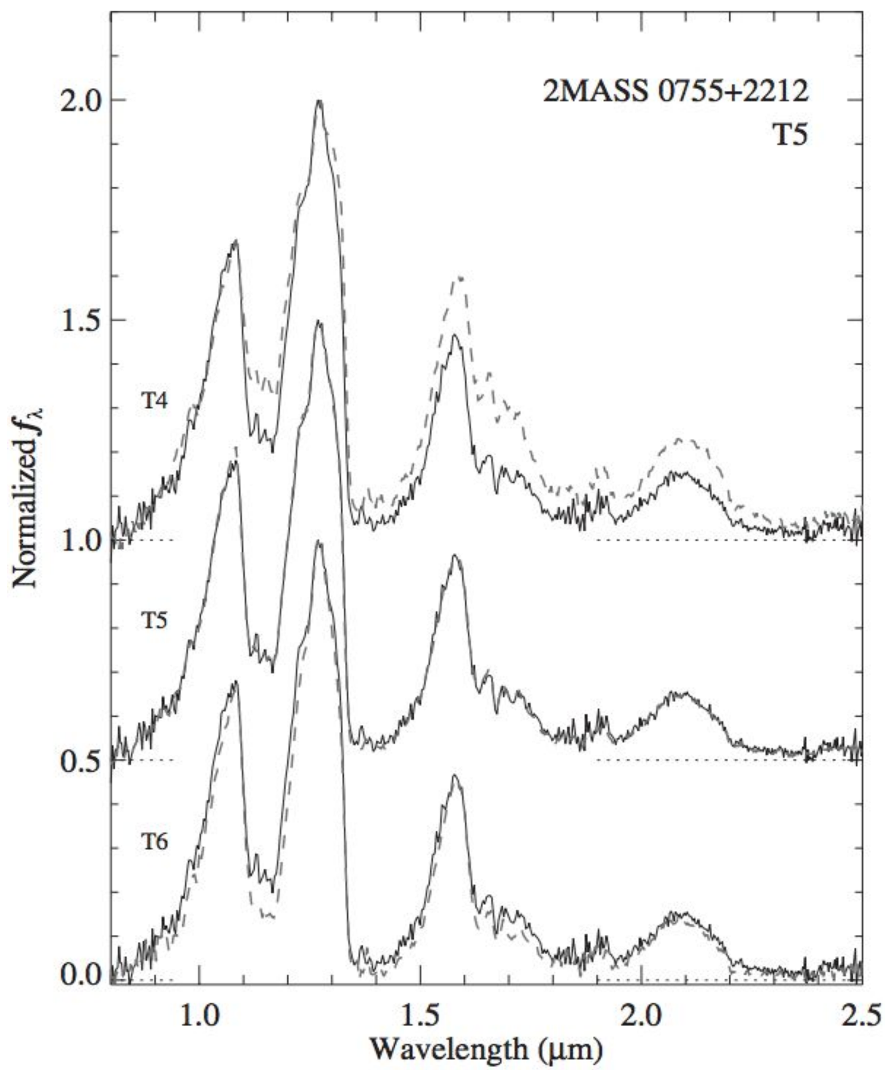
- A full set of mid-IR standards not yet established
- **H_2O, CH_4, and NH_3 absorption bands strengthen in later types**



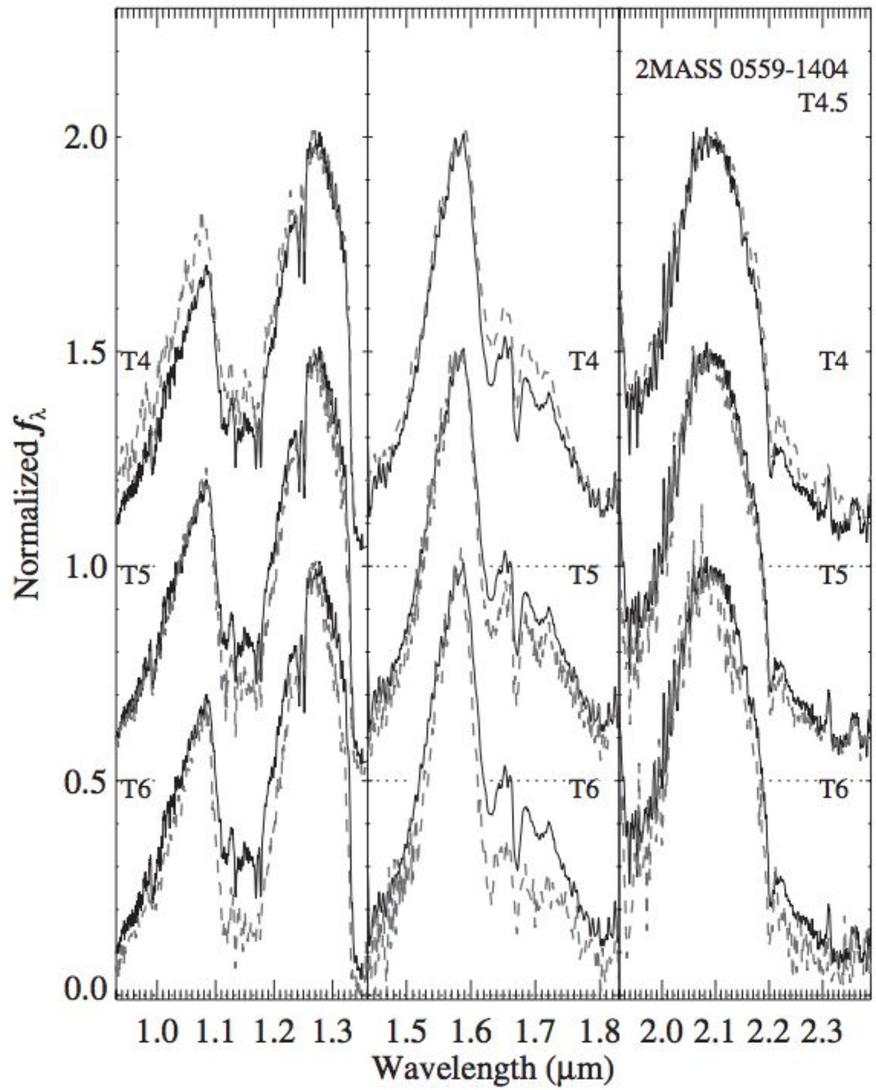
Methods of Classification

- 2 methods:
  - **Direct Spectral Comparison** – compare target with standards
    - Single dispersion order
    - Multiple dispersion order
  - **Spectral Indices** – flux ratio of absorption to pseudocontinuum
    - Compare with indices of standards
    - Compare with numerical ranges

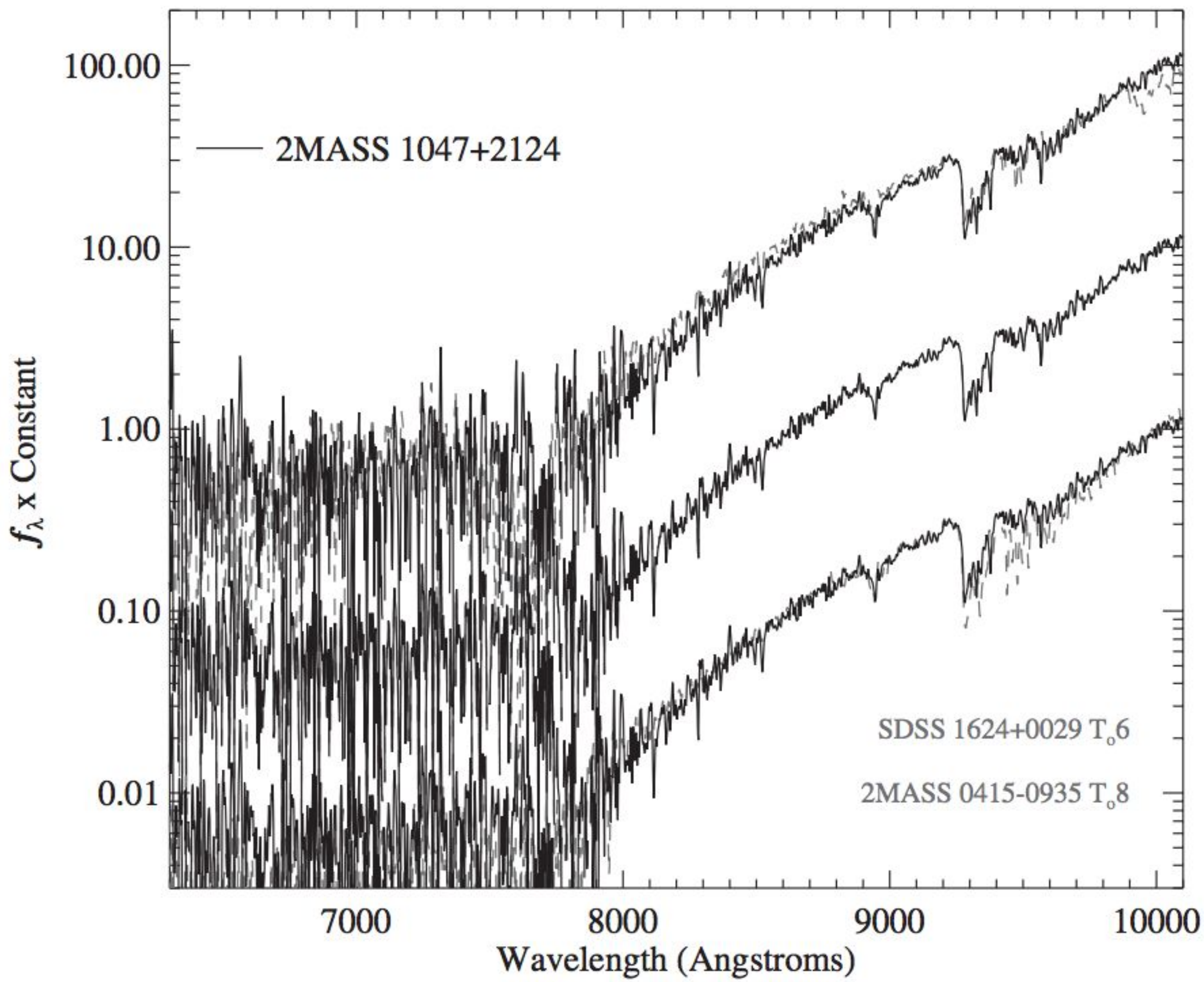
Direct Spectra Comparison (Near-IR Single-Order)



Direct Spectral Comparison (Near-IR Multiple-Order)



Direct Spectral Comparison (Red-Optical)

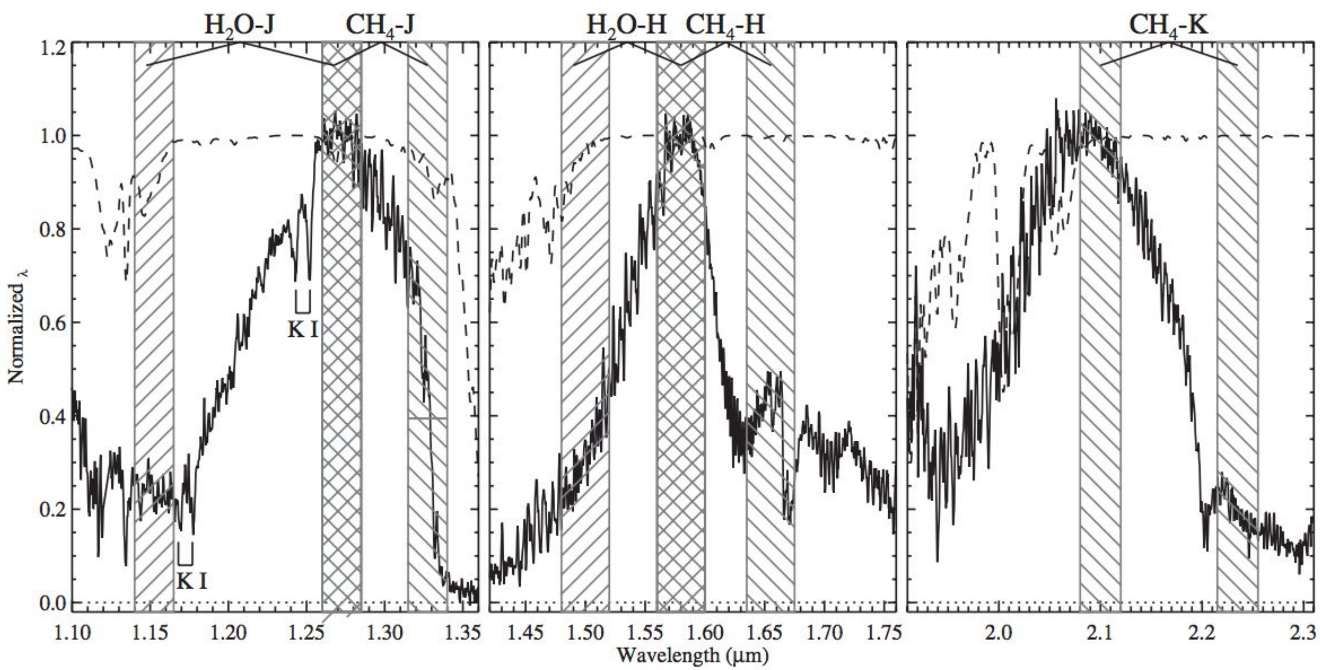


Measuring Spectral Indices

Table 10.4 Definitions of Near-Infrared Spectral Classification Indices

Index	Numerator (μm)	Denominator (μm)	Feature Measured
H_2O-J	$\int F_{1.140-1.165}$	$\int F_{1.260-1.285}$	1.15 μm H_2O
CH_4-J	$\int F_{1.315-1.340}$	$\int F_{1.260-1.285}$	1.32 μm CH_4
H_2O-H	$\int F_{1.480-1.520}$	$\int F_{1.560-1.600}$	1.4 μm H_2O
CH_4-H	$\int F_{1.635-1.675}$	$\int F_{1.560-1.600}$	1.65 μm CH_4
CH_4-K	$\int F_{2.215-2.255}$	$\int F_{2.080-2.120}$	2.2 μm CH_4

Note: $\int F_{\lambda 1-\lambda 2}$ denotes integrated flux measured over the wavelength interval λ1 to λ2.



Spectral Indices: Compare with Standards [Near-IR]

Table 10.5 Near-Infrared Spectral Indices for T-Dwarf Spectral Standards

Name	SpT	H_2O-J	CH_4-J	H_2O-H	CH_4-H	CH_4-K
		SpeX Prism Data, $\lambda/\Delta\lambda \approx 150$				
2MASS J16322911 + 1904407[a]	L8	0.706	0.879	0.705	1.077	0.881
2MASS J03105986 + 1648155[a]	L9	0.631	0.789	0.621	1.092	0.894
SDSS J120747.17 + 024424.8	T0	0.621	0.745	0.612	0.955	0.790
SDSSp J083717.22 − 000018.3	T1	0.584	0.738	0.563	0.981	0.724
SDSSp J125453.90 − 012247.4	T2	0.474	0.650	0.474	0.917	0.585
2MASS J12095613 − 1004008	T3	0.413	0.572	0.453	0.717	0.496
2MASS J22541892 + 3123498	T4	0.369	0.549	0.389	0.581	0.305
2MASS J15031961 + 2525196	T5	0.240	0.375	0.345	0.393	0.200
SDSSp J162414.37 + 002915.6	T6	0.154	0.375	0.280	0.301	0.149
2MASS J07271824 + 1710012	T7	0.085	0.247	0.224	0.181	0.062
2MASS J04151954 − 0935066	T8	0.041	0.189	0.183	0.104	0.050
		CGS4 Data, $\lambda/\Delta\lambda \approx 400$				
2MASS J16322911 + 1904407[a]	L8	0.701	0.834	0.705	1.036	0.888
2MASS J03105986 + 1648155[a]	L9	0.675	0.835	0.645	1.064	0.786
SDSS J120747.17 + 024424.8	T0	0.628	0.707	0.597	0.944	0.812
SDSSp J083717.22 − 000018.3	T1	0.646	0.714	0.586	0.936	0.689
SDSSp J125453.90 − 012247.4	T2	0.501	0.603	0.491	0.870	0.564
2MASS J12095613 − 1004008	T3	0.439	0.612	0.462	0.687	0.495
2MASS J22541892 + 3123498	T4	0.411	0.514	0.416	0.547	0.302
2MASS J15031961 + 2525196[b]	T5	0.239	0.398	0.332	0.381	0.200
SDSSp J162414.37 + 002915.6	T6	0.156	0.314	0.320	0.318	0.158
2MASS J07271824 + 1710012	T7	0.090	0.243	0.227	0.168	0.060
2MASS J04151954 − 0935066	T8	0.030	0.171	0.173	0.105	0.043

Spectral Indices: Compare with Standards [Red-Optical]

Table 10.7 T-Dwarf Spectral Classification Indices in the Red-Optical

Index	Numerator (Å)	Denominator (Å)	Feature Measured
CsI(A)	$\langle F_{8496.1-8506.1}\rangle+\langle F_{8536.1-8546.1}\rangle$	$2\times\langle F_{8516.1-8526.1}\rangle$	8521 Å Cs I
H_2O	$\int F_{9220-9240}$	$\int F_{9280-9300}$	9250 Å H_2O
CrH(A)	$\int F_{8560-8600}$	$\int F_{8610-8650}$	8611 Å CrH
FeH(B)	$\int F_{9855-9885}$	$\int F_{9905-9935}$	9896 Å FeH
Color-e	$\langle F_{9140-9240}\rangle$	$\langle F_{8400-8500}\rangle$	Spectral Slope

Table 10.8 Classification Index Values for Optical Spectral Standards

Object	SpT	CsI(A)	CrH(A)/H_2O	FeH(B)	Color-e
2MASS J16322911 + 1904407	L8	1.70	1.02	1.11	1.88
SDSSp J125453.90 − 012247.4[a]	T_o2	2.01	0.78	1.13	4.02
2MASS J15031961 + 2525196	T_o5	1.77	0.63	1.37	4.24
SDSSp J162414.37 + 002915.6	T_o6	1.68	0.47	1.15	3.83
2MASS J04151954 − 0935066[a]	T_o8	1.19	0.25	0.94	4.20

Mid-IR Spectral Indices

Table 10.9 T-Dwarf Spectral Ratios in the Mid-Infrared

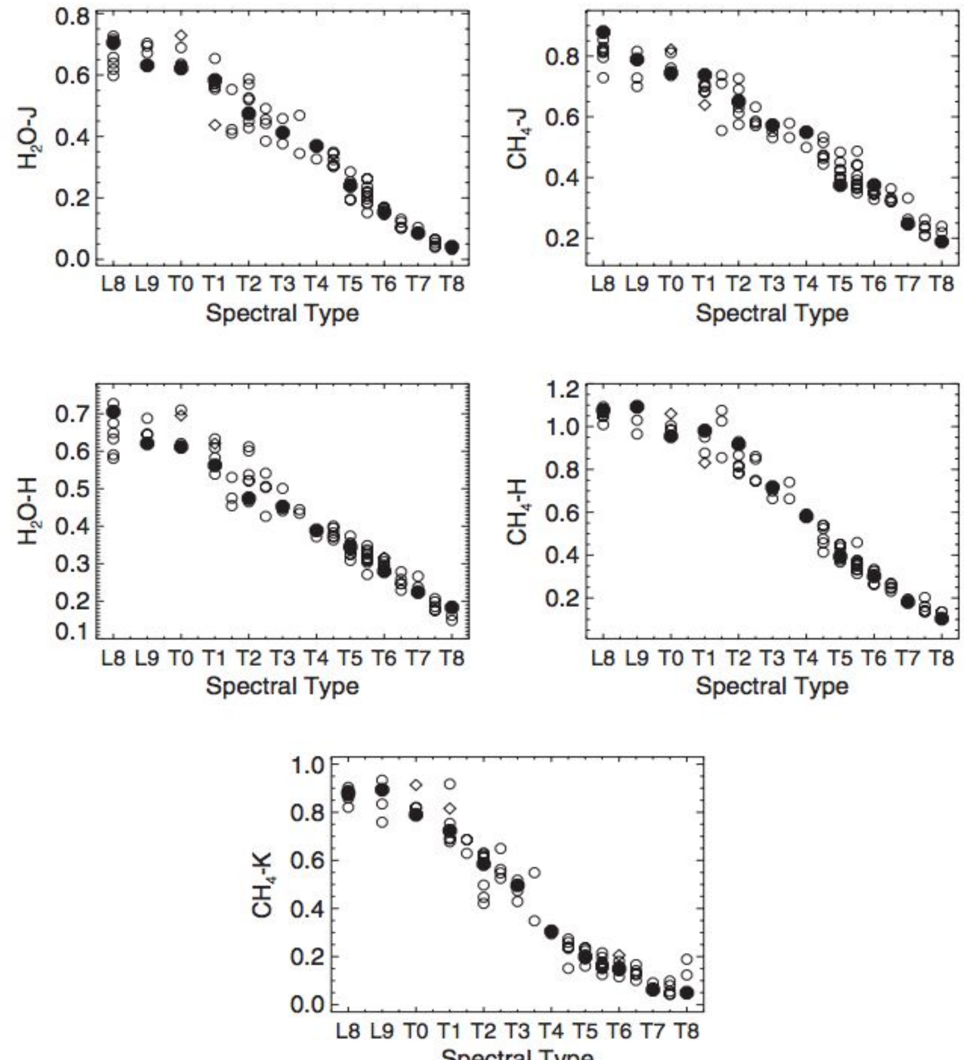
Index	Numerator (μm)	Denominator (μm)	Feature Measured
IRS-H_2O	$\langle F_{6.125-6.275} \rangle$	$0.562\langle F_{5.725-5.875} \rangle$ $+0.474\langle F_{6.675-6.825} \rangle$	6–6.5 μm H_2O bands
IRS-CH_4	$\langle F_{9.925-10.075} \rangle$	$\langle F_{8.425-8.575} \rangle$	7.65 μm CH_4 band
IRS-NH_3	$\langle F_{9.925-10.075} \rangle$	$\langle F_{10.725-10.875} \rangle$	10.5 μm NH_3 band

Spectral Indices: Compare with Numerical Ranges

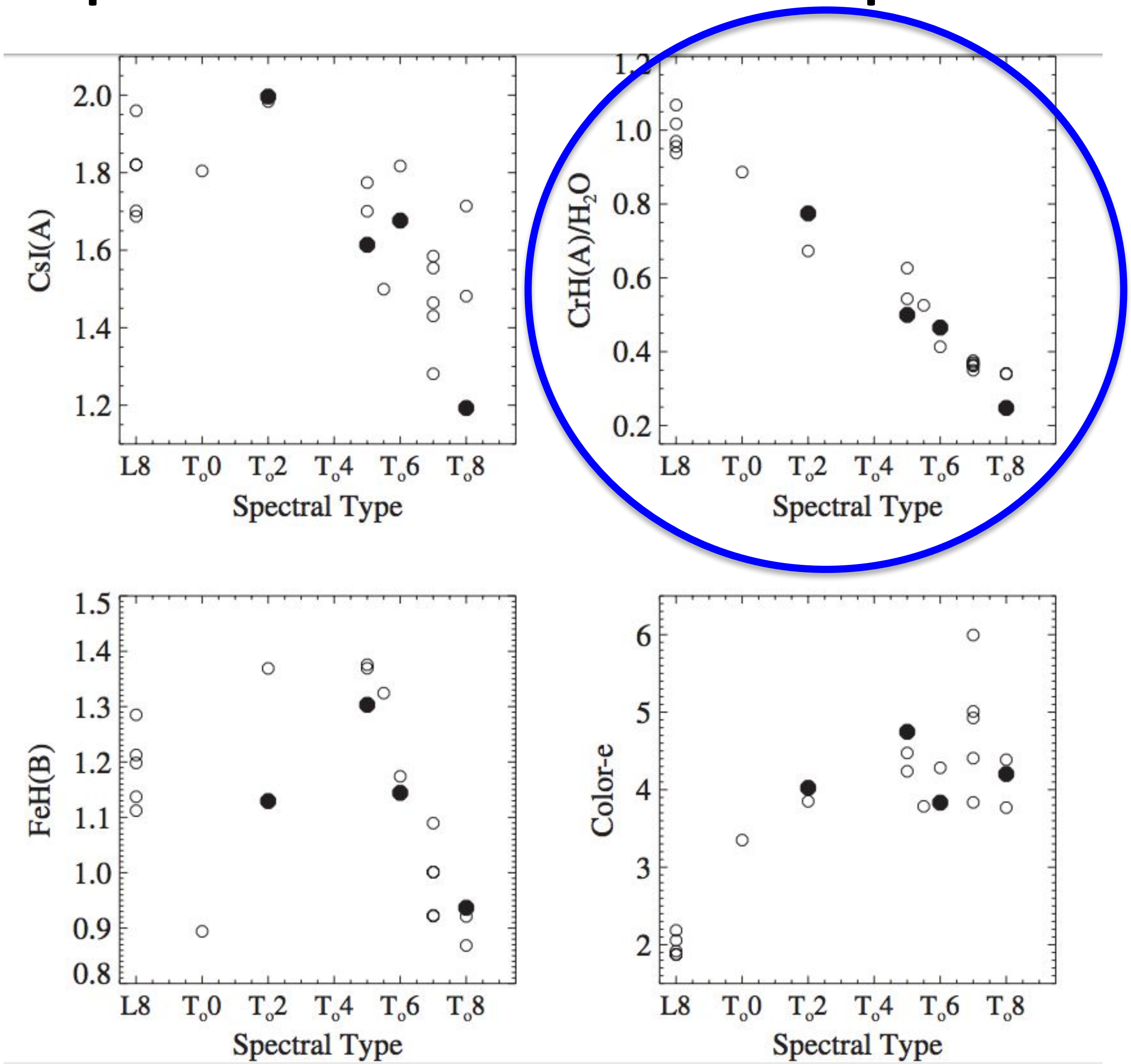
Table 10.6 Numerical Ranges of Near-Infrared Spectral Indices for T-Dwarf Subtypes

NIR SpT	H_2O-J	CH_4-J	H_2O-H	CH_4-H	CH_4-K
T0	...	0.73–0.78	0.60–0.66	0.97–1.00	0.75–0.85
T1	>0.55	0.67–0.73	0.53–0.60	0.92–0.97	0.63–0.75
T2	0.45–0.55	0.58–0.67	0.46–0.53	0.80–0.92	0.55–0.63
T3	0.38–0.45	0.52–0.58	0.43–0.46	0.60–0.80	0.35–0.55
T4	0.32–0.38	0.45–0.52	0.37–0.43	0.48–0.60	0.24–0.35
T5	0.18–0.32	0.36–0.45	0.32–0.37	0.36–0.48	0.18–0.24
T6	0.13–0.18	0.28–0.36	0.26–0.32	0.25–0.36	0.13–0.18
T7	0.07–0.13	0.21–0.28	0.20–0.26	0.15–0.25	<0.13
T8	0.02–0.07	0.15–0.21	0.14–0.20	0.07–0.15	...

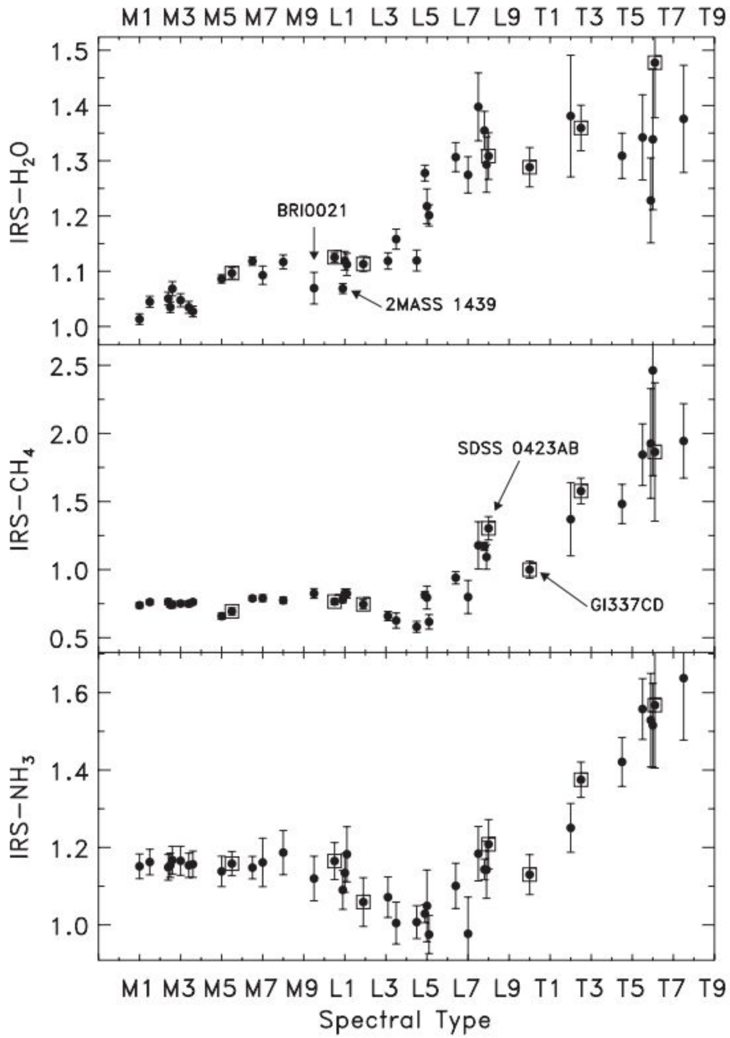
Spectral Index versus Spectral Type [Near-IR]



Red-Optical Index versus Spectral Type

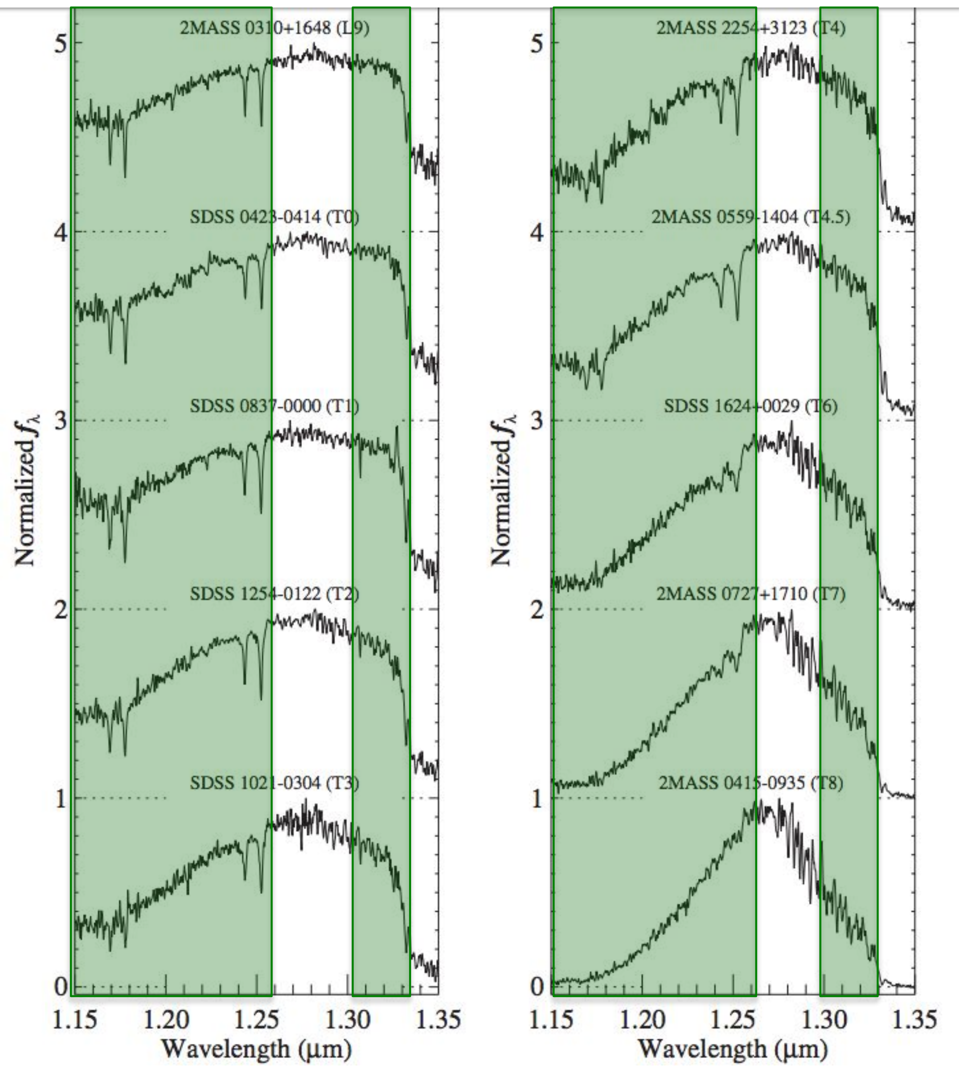


Mid-IR Spectral Indices



- IRS-H_2O: poorly distinguishes subtype
- **IRS-CH_4 & IRS-NH_3**: great for classifying!
- Standards need to be better established

Does Higher Resolution Make a Difference?



- Low Resolution ($\lambda/\Delta\lambda \approx 100$ – 400):
  - Classification from direct comparison and indices agree!
- Higher Resolution ($\lambda/\Delta\lambda = 2000$):
  - **CH_4 and H_2O absorption reproduced**
  - K I doublets now resolved! (strange)
  - Classification from lower and higher resolutions agree!
  - Spectral coverage > Higher Resolution

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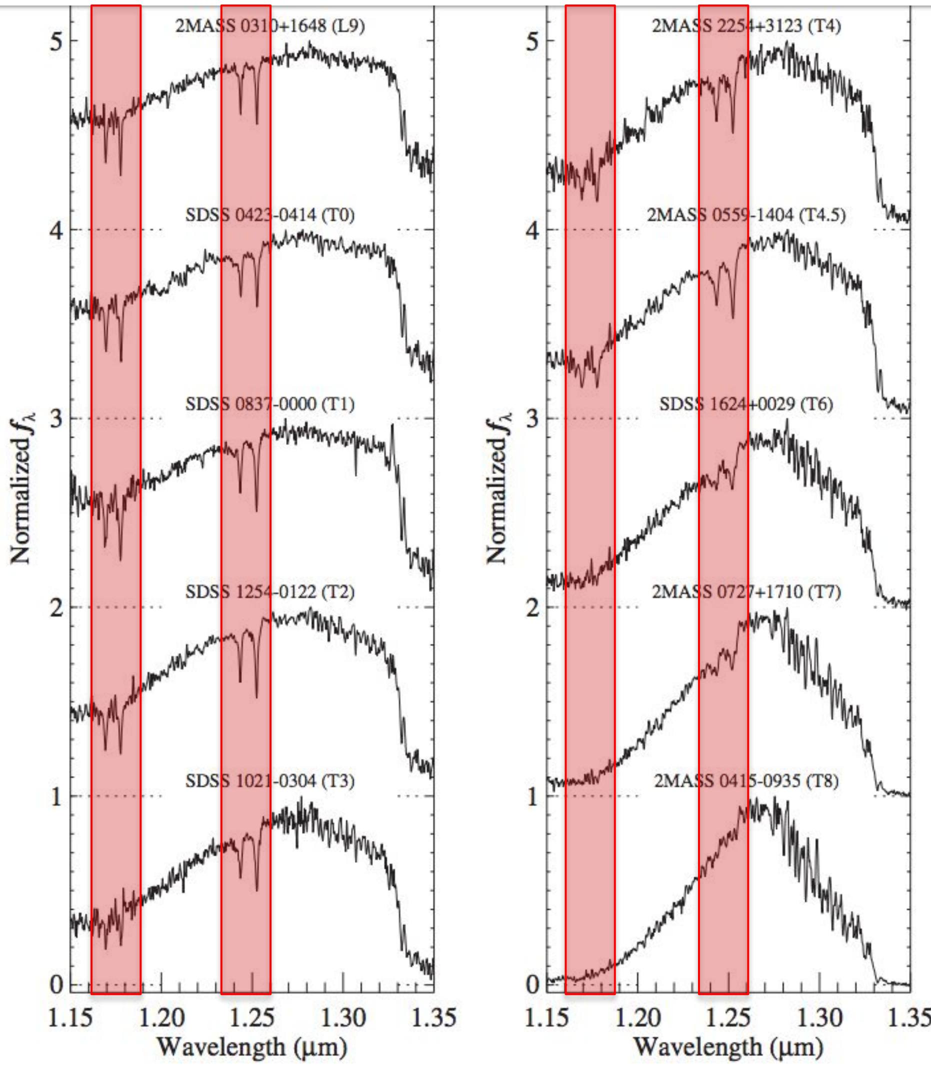

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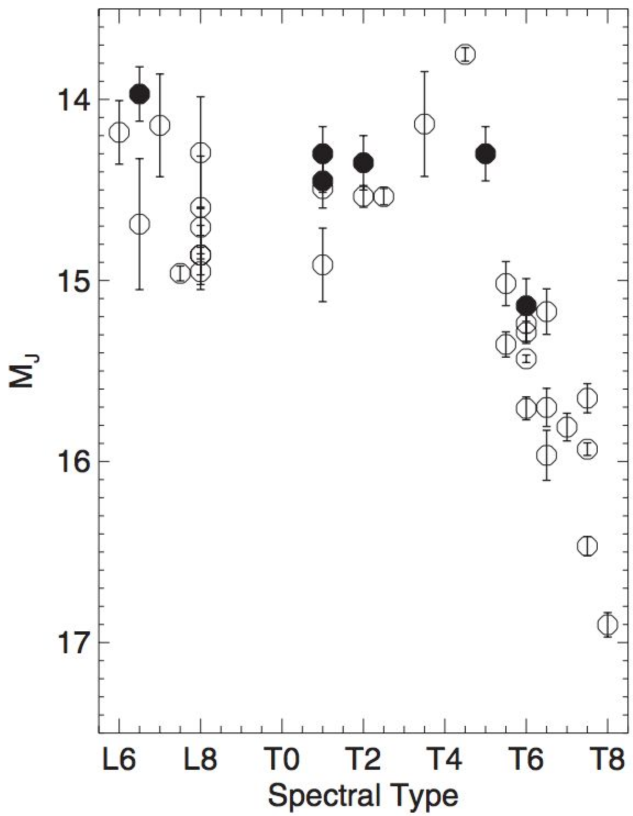
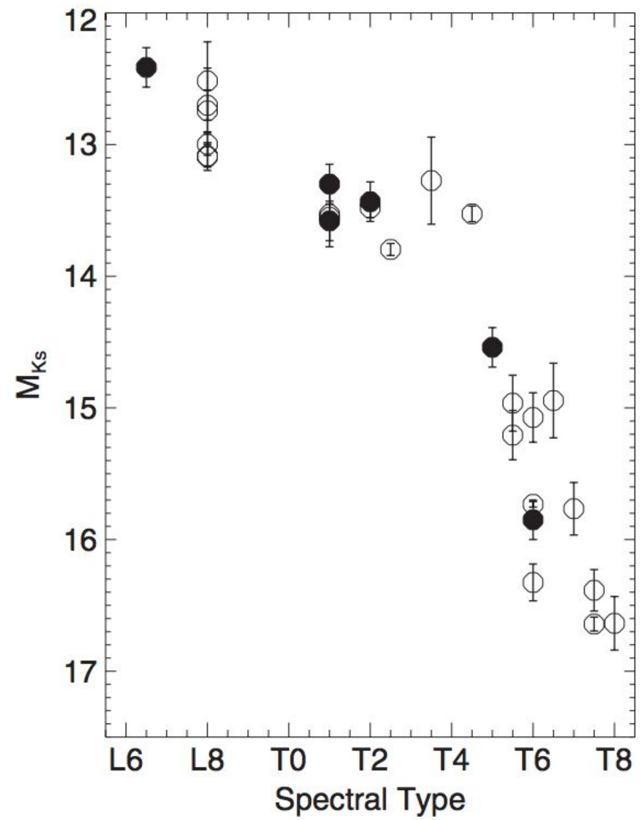
Luminosity versus Spectral Type: The J-Band Bump

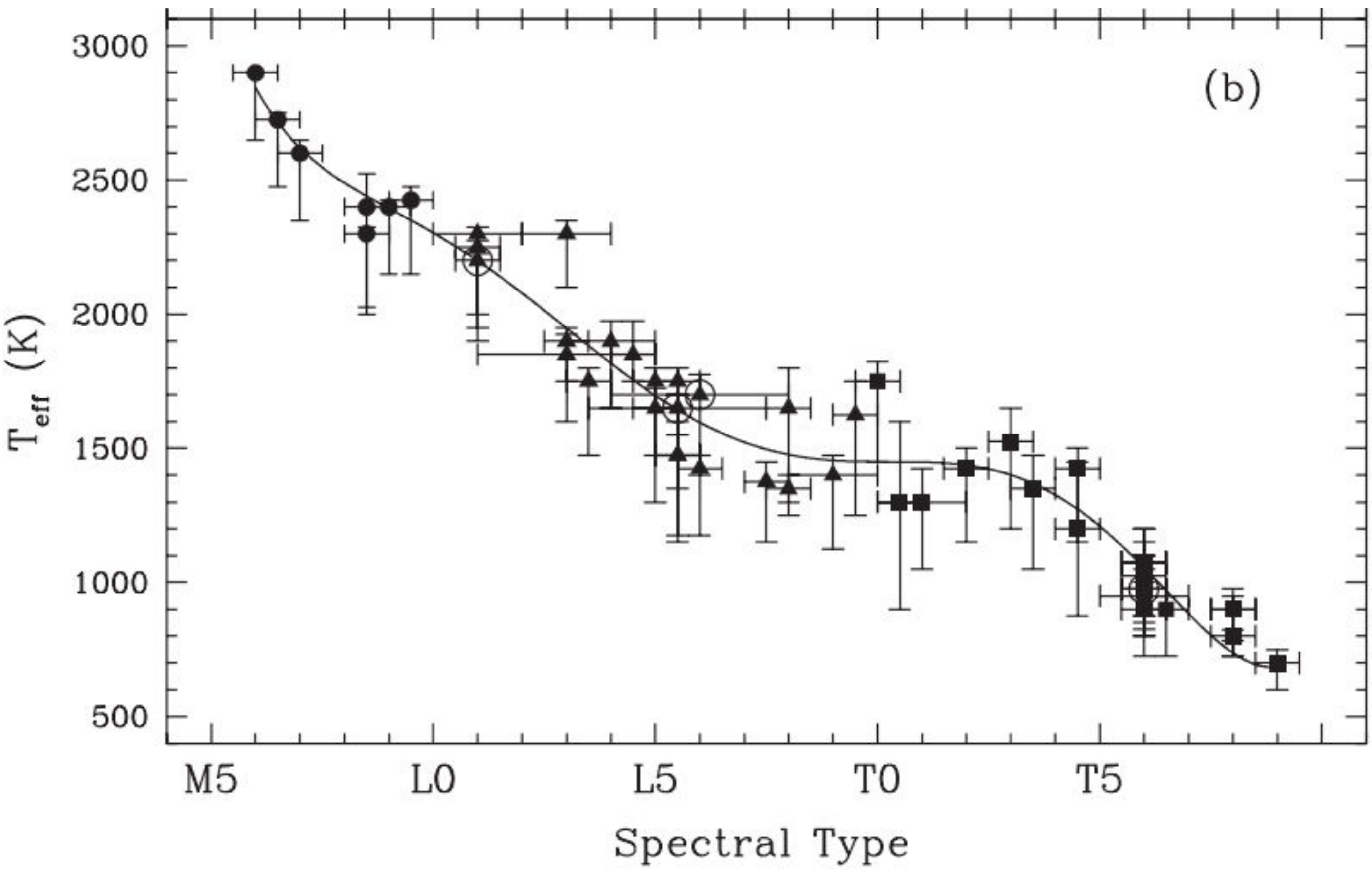
- **J-Band Bump** – phenomenon whereby early-type T dwarfs are as bright or even brighter than late-type L dwarfs in the J-band.
- **Physical Cause**: Depletion of condensate dust clouds across L/T transition





Effective Temperature versus Spectral Type

- Early-type T dwarfs also have the same effective temperatures as late-type L dwarfs!

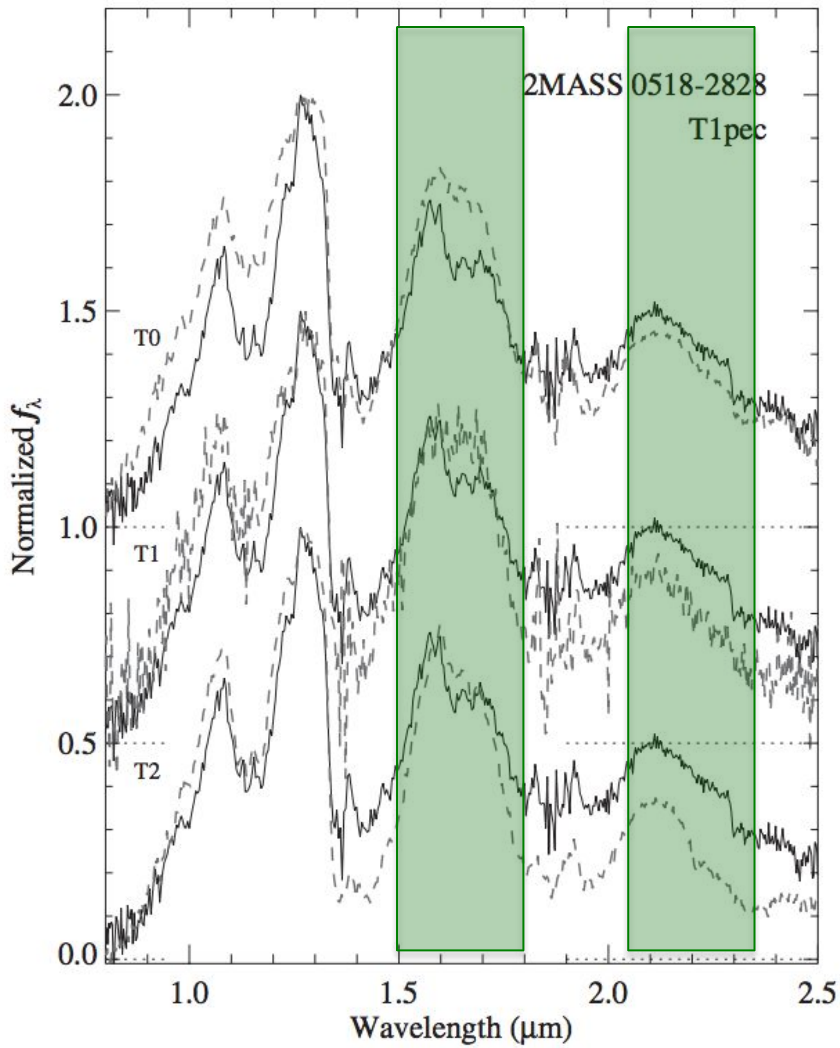


Peculiar T dwarfs

- **Peculiar T Dwarfs**: T dwarfs whose spectra don't follow the sequence defined by standards.
  - Large scatter in classifications based on different spectral indices
  - Low S/N: Uncertain ":" (e.g. T4:)
  - High S/N: Peculiar "p" or "pec" (e.g. T4pec)
- 3 main sources of peculiarity:
  - Unresolved multiplicity
  - Surface gravity/metallicity effects
  - Condensate cloud effects

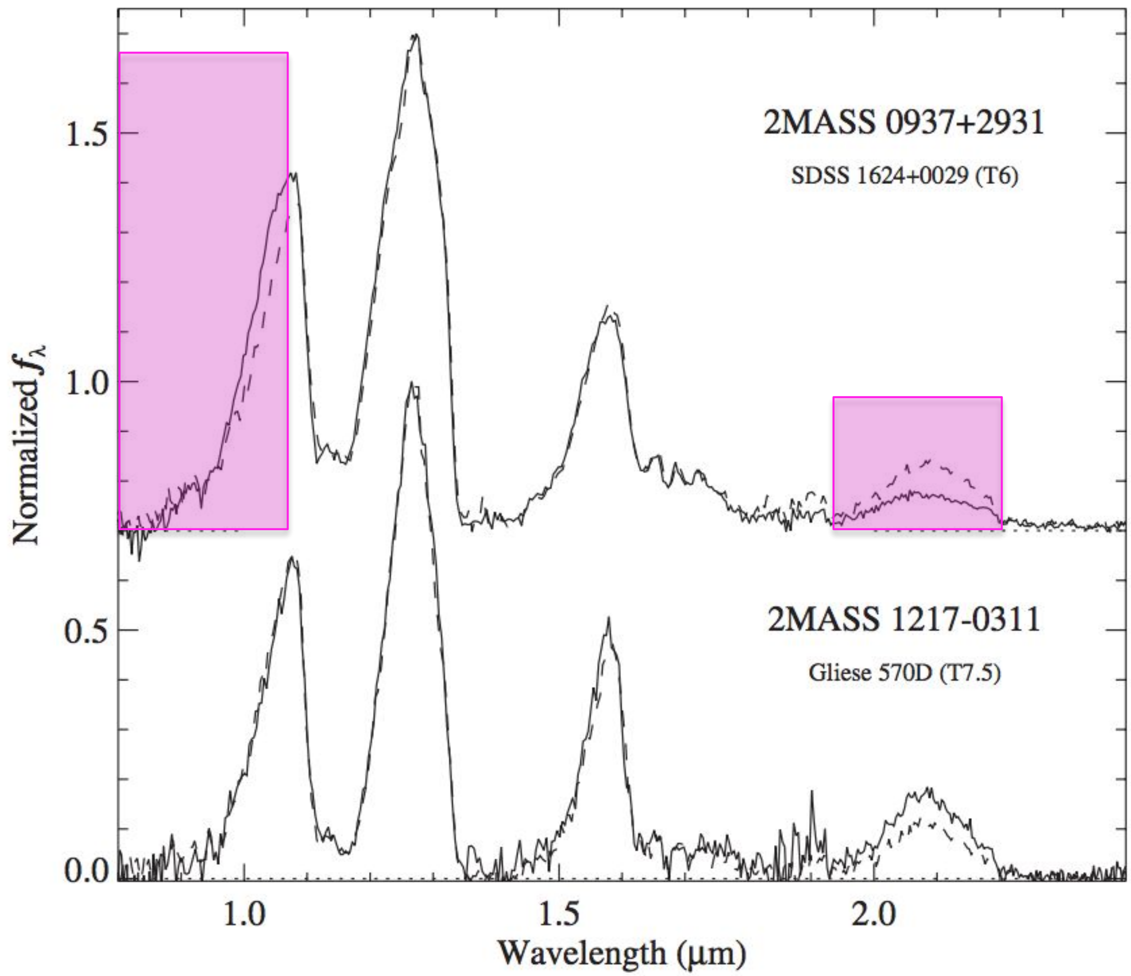
Unresolved Multiplicity

- T1pec: L-dwarf/T-dwarf binary
- **Shows CH_4 absorption at 1.6μm but not at 2.2μm**
- Early-types most susceptible due to sharp transition at L/T boundary



Surface Gravity and Metallicity Effects

- **2MASS 0937+2931**:
  - Weak K-band emission – due to enhanced CIA H_2 → **high surface gravity!**
  - Strong 1.05µm peak and steep slope – due to low K I → **metal-poor!**
- 2MASS 1217-0311:
  - Strong K-band peak → low surface gravity!
  - Possibly metal-rich



Surface Gravity and Metallicity Effects

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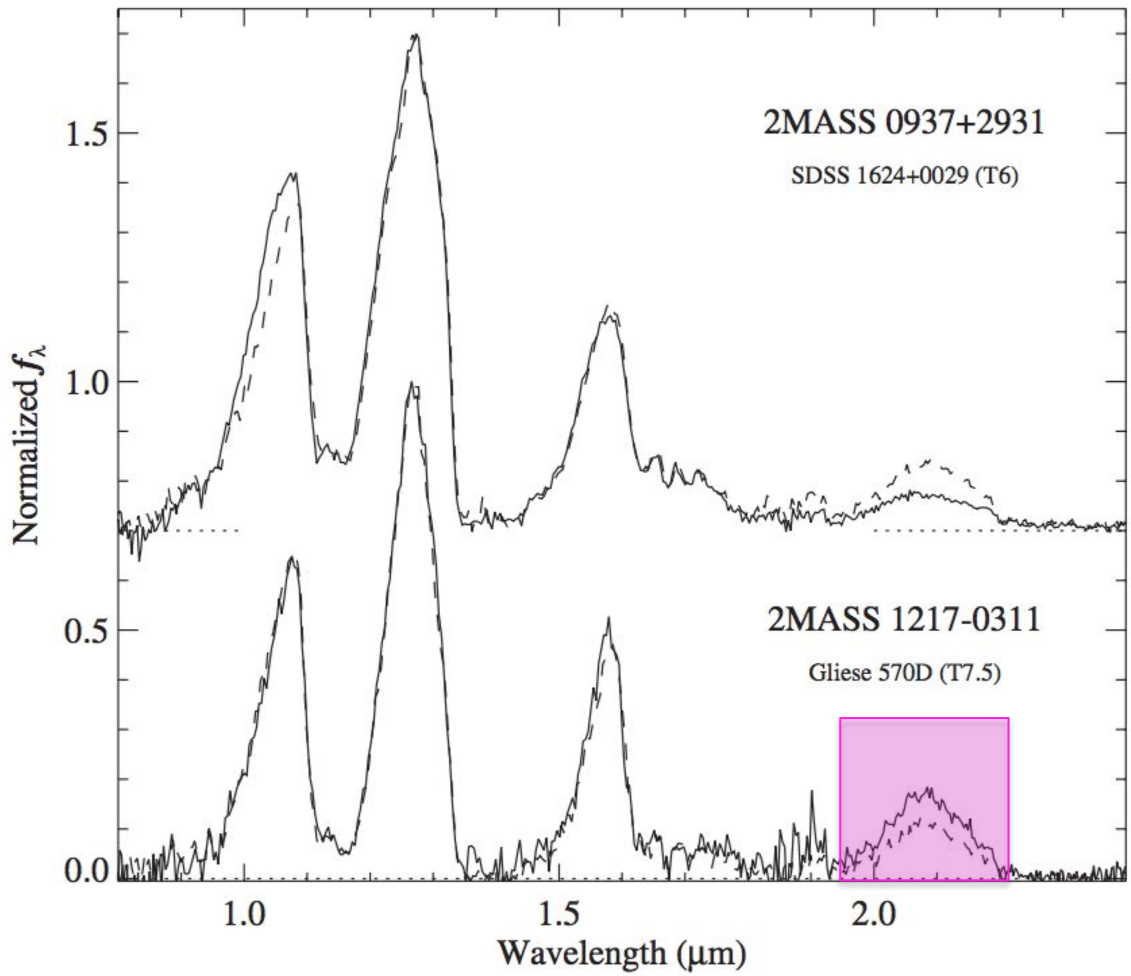
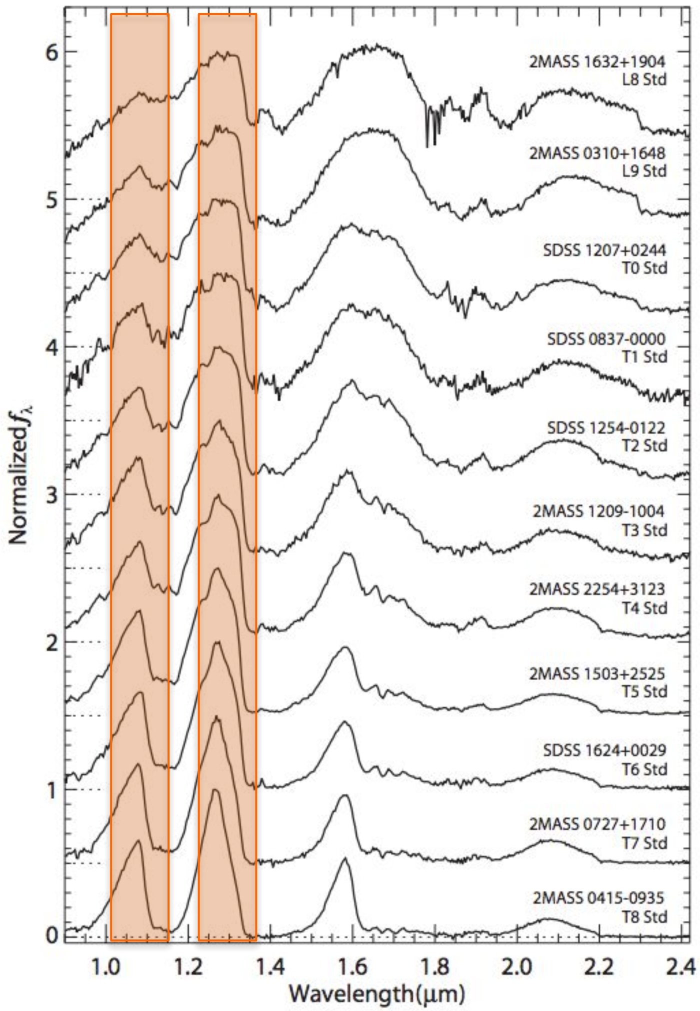


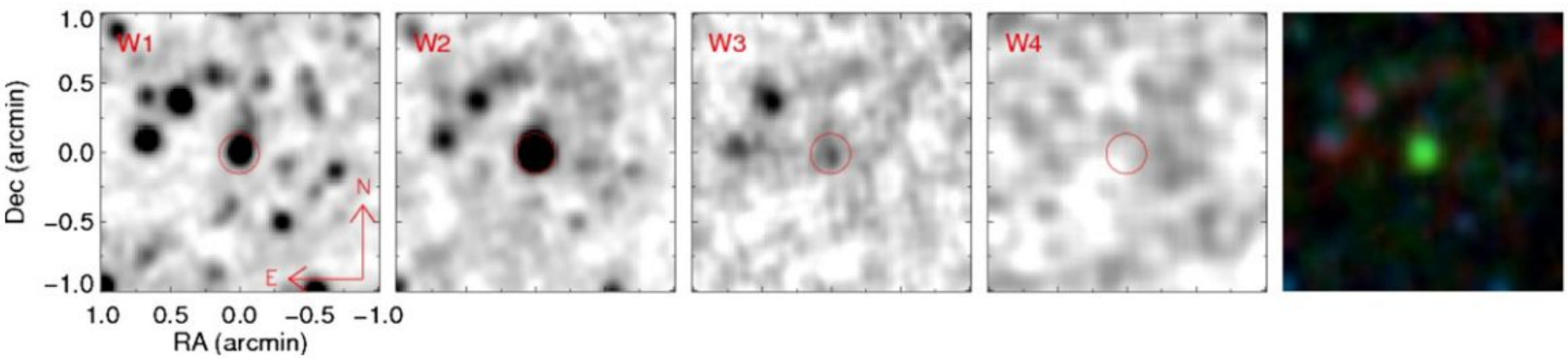
Condensate Clouds and Temporal Variation

- L and early-T: clouds present
- Mid- and late-T: clouds absent
- **1.05μm and 1.27μm peaks: condensate-dependent**
- Time-dependence of peaks in early T dwarfs need to be investigated

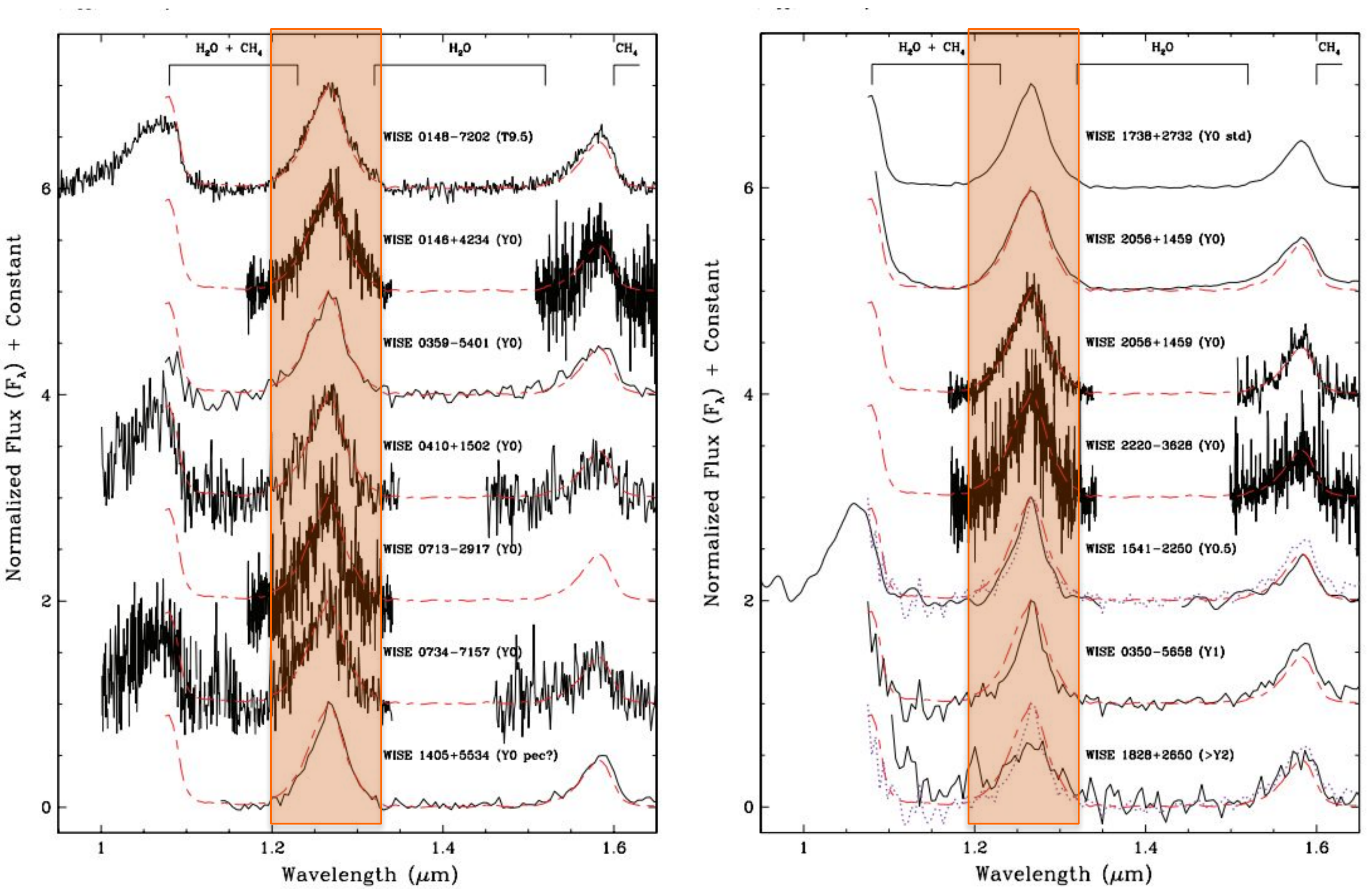


Detecting the Coldest Brown Dwarfs

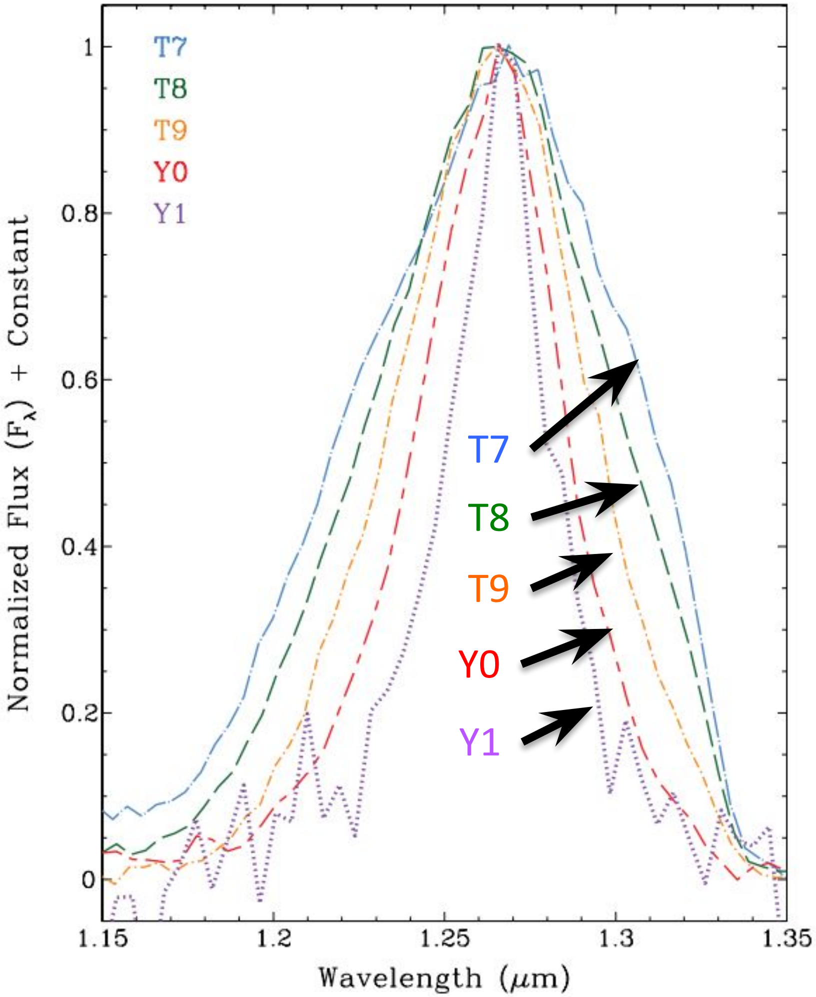
- Wide-field Infrared Survey Explorer (WISE) :
  - W1 (3.4μm) – in middle of strong CH_4 band (3.3μm)
  - W2 (4.6μm) – transparent to radiation; deeper, hotter layers
  - W3 (12μm) & W4 (22μm) – eliminate non-brown dwarfs
  - W1-W2 – identifies brown dwarf because color should be very red
  - Notice how T7 dwarf appears in W1 & W2 but disappears in W3 & W4

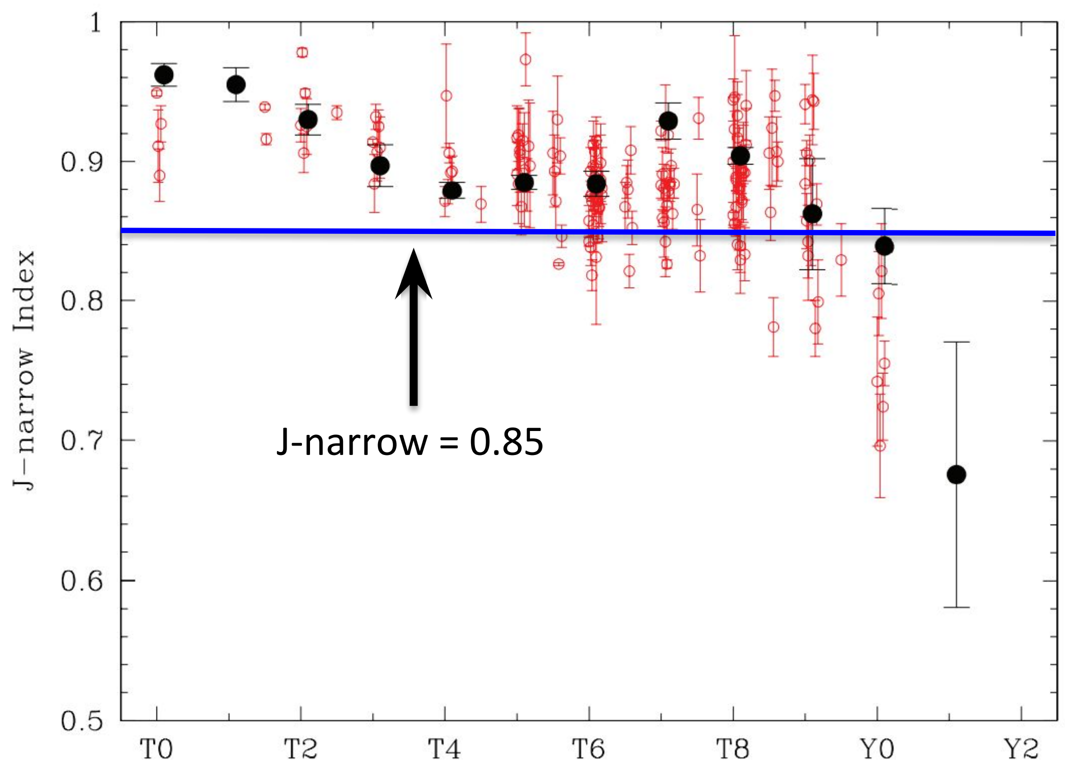


Spectra of Y dwarfs



Classifying New Discoveries: J-narrow index

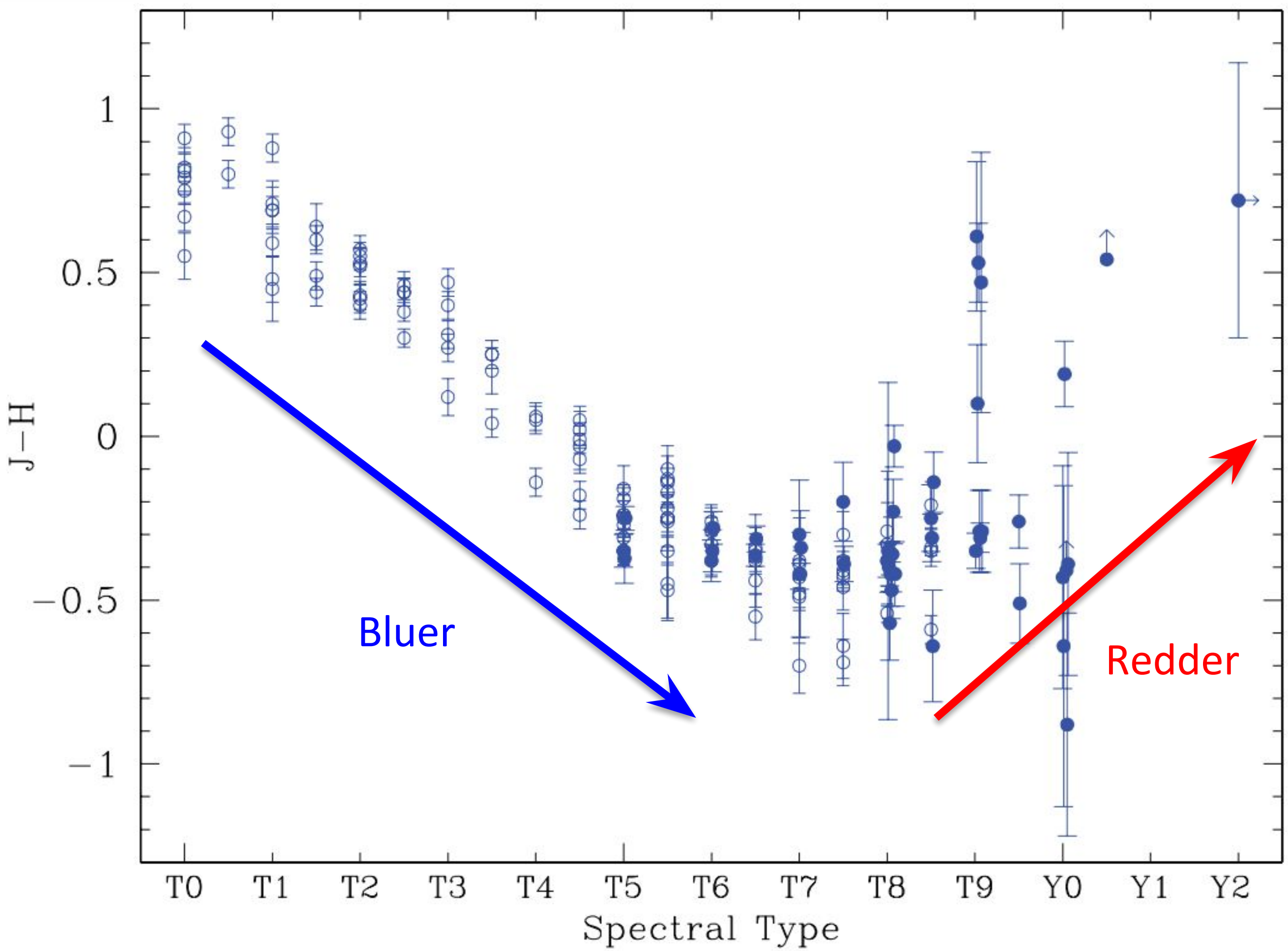




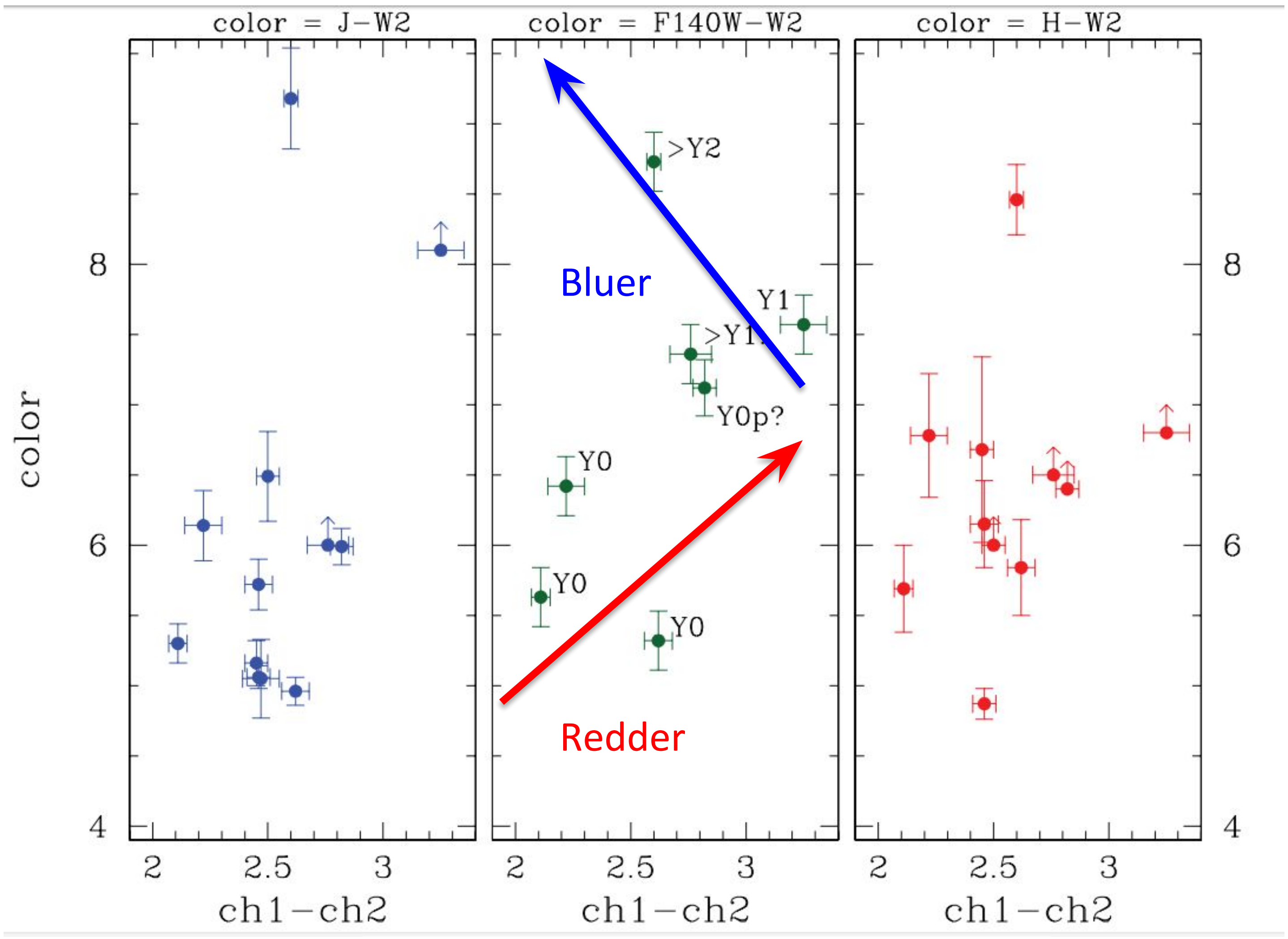
Defining the Y dwarf class

1. *Disappearance of alkali resonance lines (Na I and K I) near 450 K*
   - Y band (1.07μm) peak gets brighter because K → KCl
   - Need higher S/N to test this
2. *Water cloud formation below 400-500 K*
   - Need new atmosphere models to predict changes in spectra
3. *NH_3 absorption below 2.5μm*
   - Need higher S/N
4. *Collapse of optical and near-IR flux relative to those > 5μm below 350 K*
   - Trend of J-H color getting bluer reverses to the red
   - **CONFIRMED!** → Great way for defining the Y class
5. *Shift of the 5μm peak*
   - Reversal of *Spitzer* ch1-ch2 color trend → **CONFIRMED!**

Confirmation of J-H color reversal

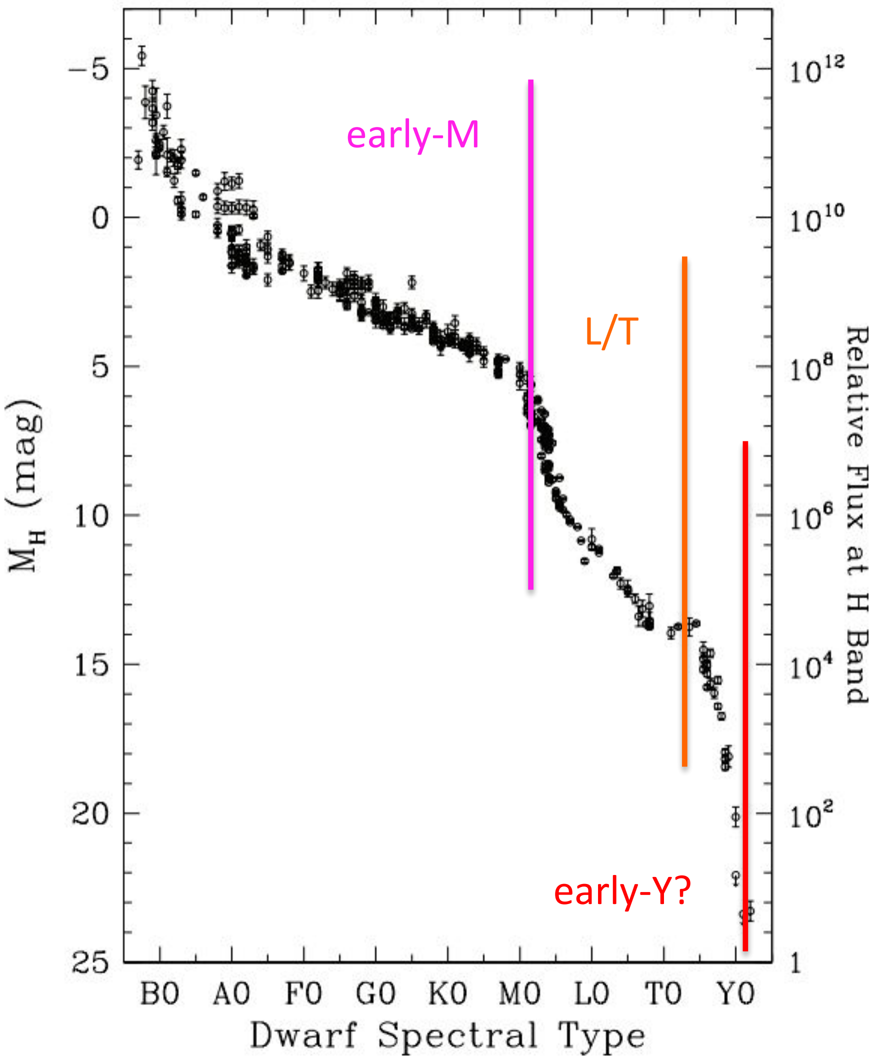


Confirmation of Spitzer color reversal

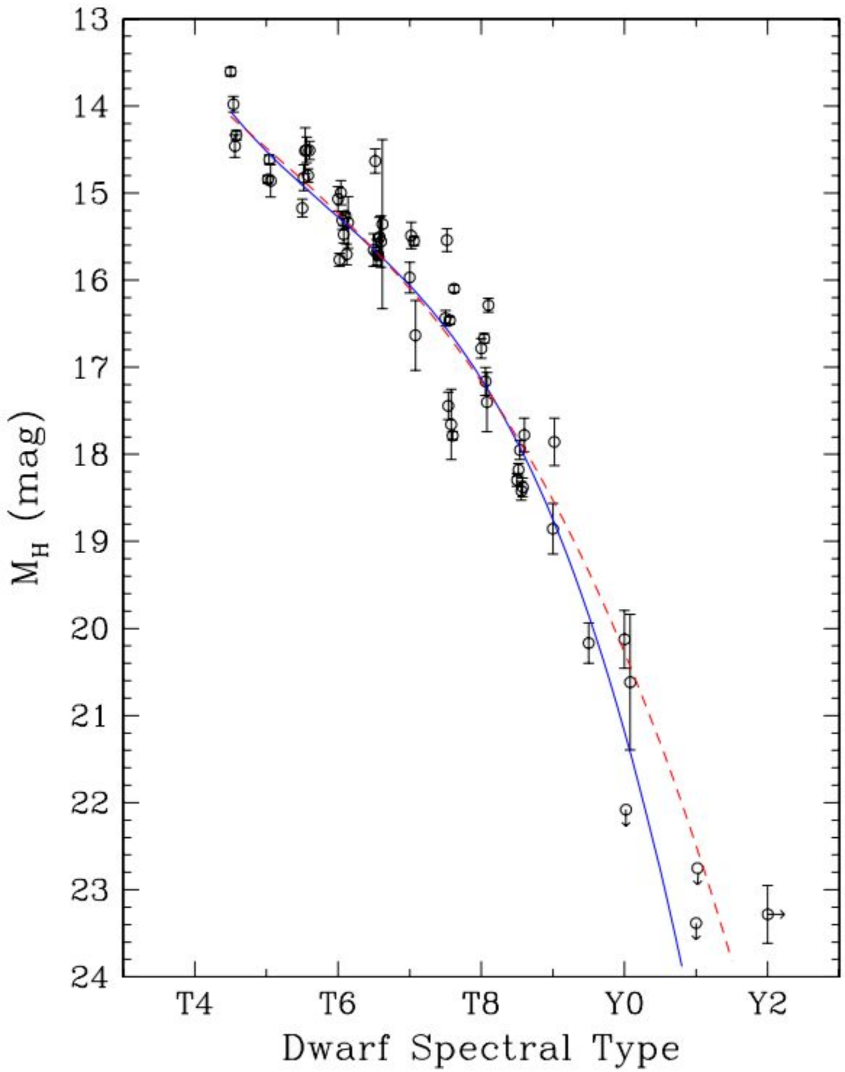


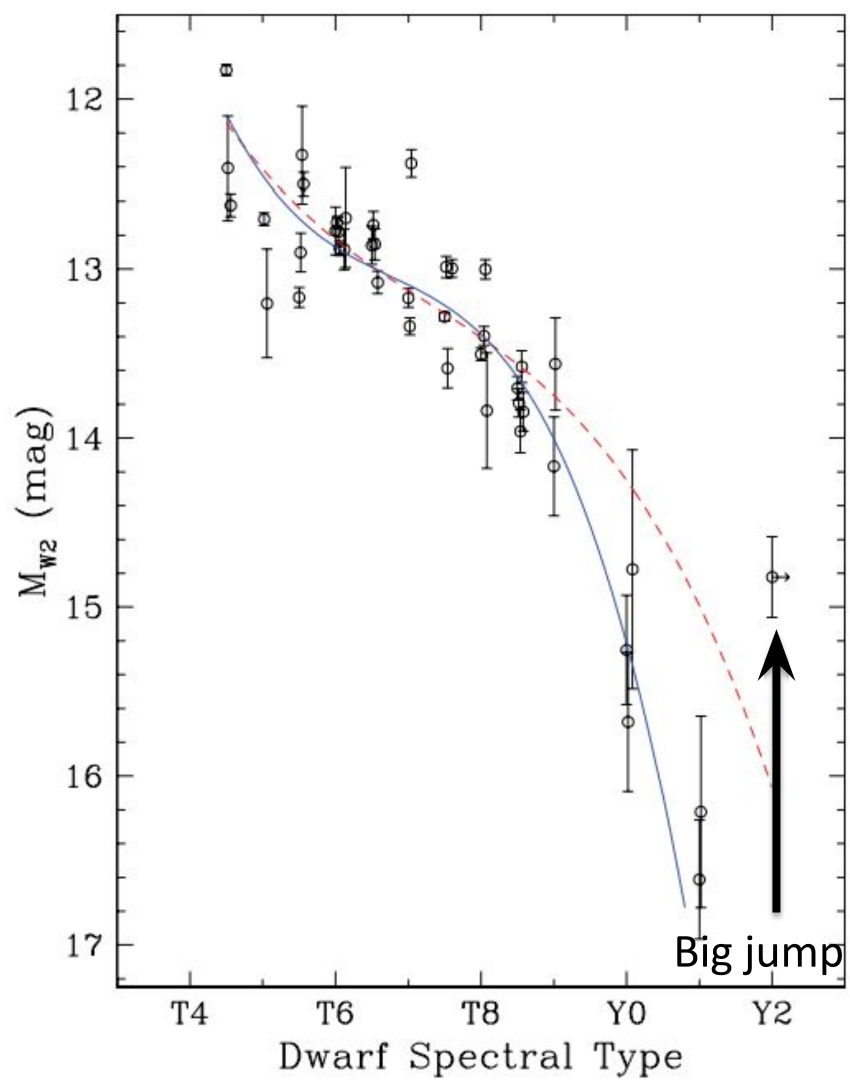
Luminosity of Y dwarfs

- Y dwarfs are faint! (12 orders of magnitude fainter than O-star)
- Two known inflection points:
  - Early-M: Hydrogen → H_2 (temperature < 4000 K)
  - L/T boundary: flattening/brightening due to condensate clouds
- Possible new inflection point on H-R diagram at early-Y?

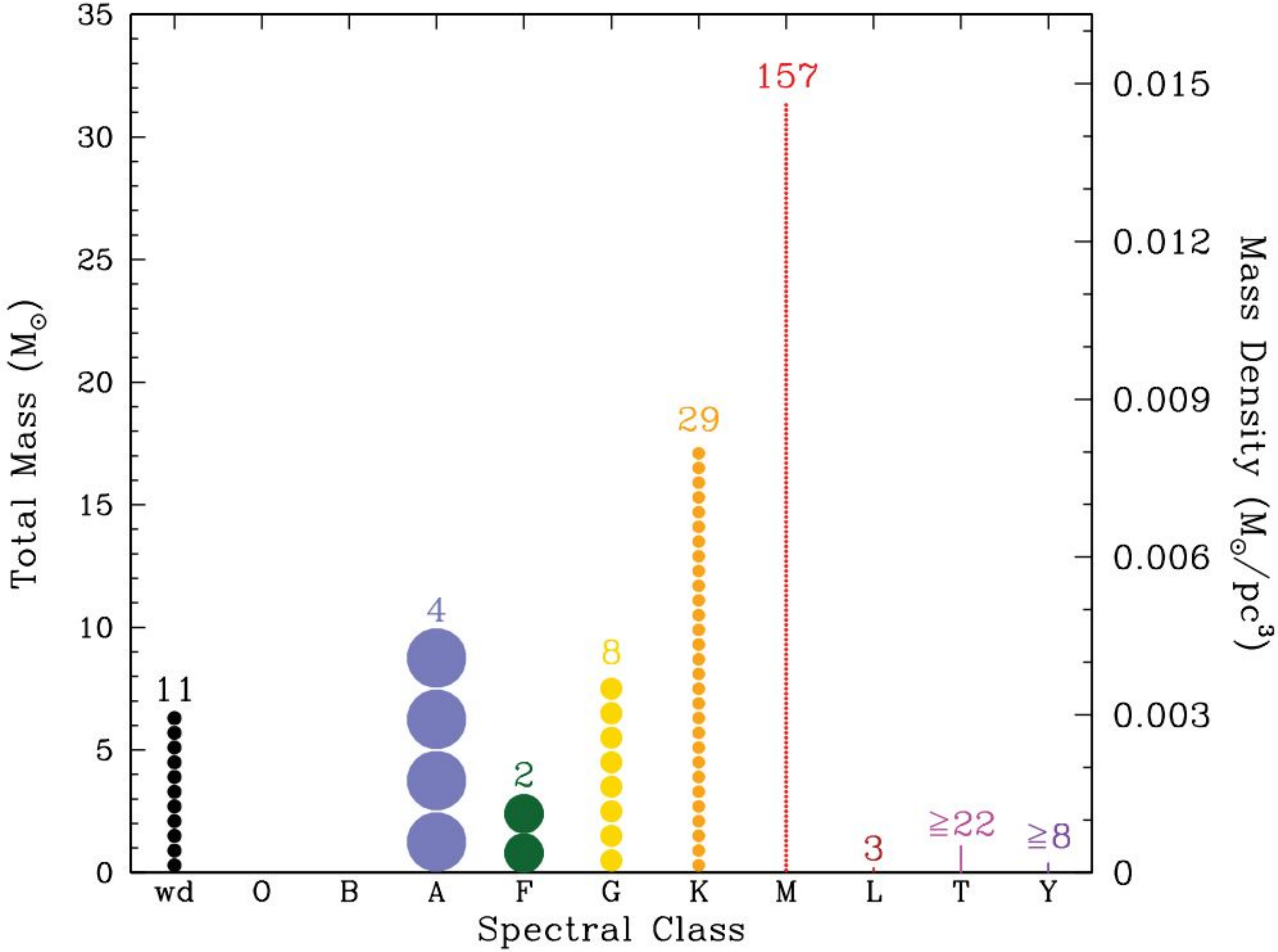


A New Inflection Point?





Space Density of Brown Dwarfs



Mass Function of Coldest Brown Dwarfs

- $dN/dM \sim M^{-\alpha}$
- Power law works for late-type T at α = -1.0
- Power law approximation doesn't work for cooler Y dwarfs