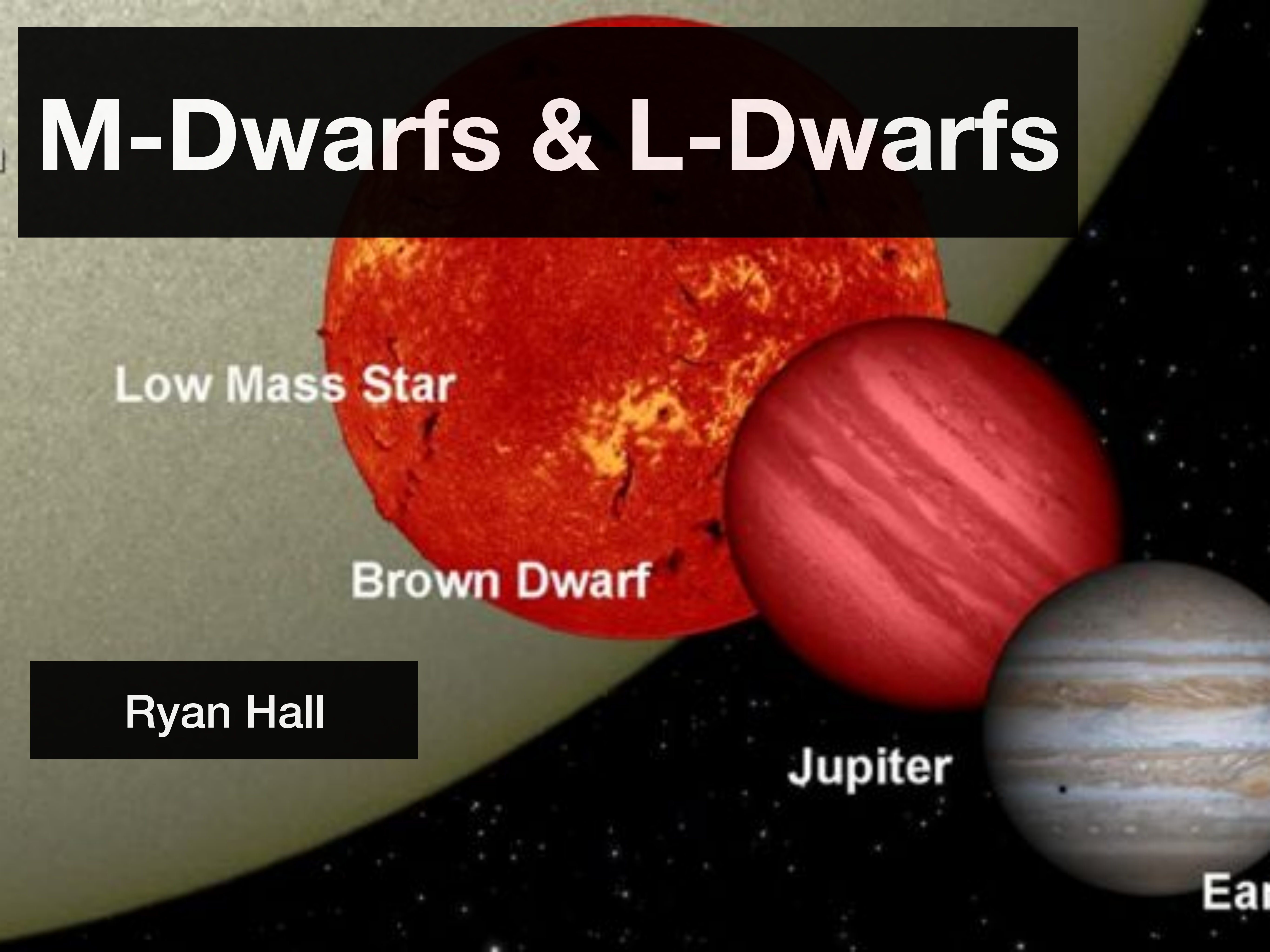
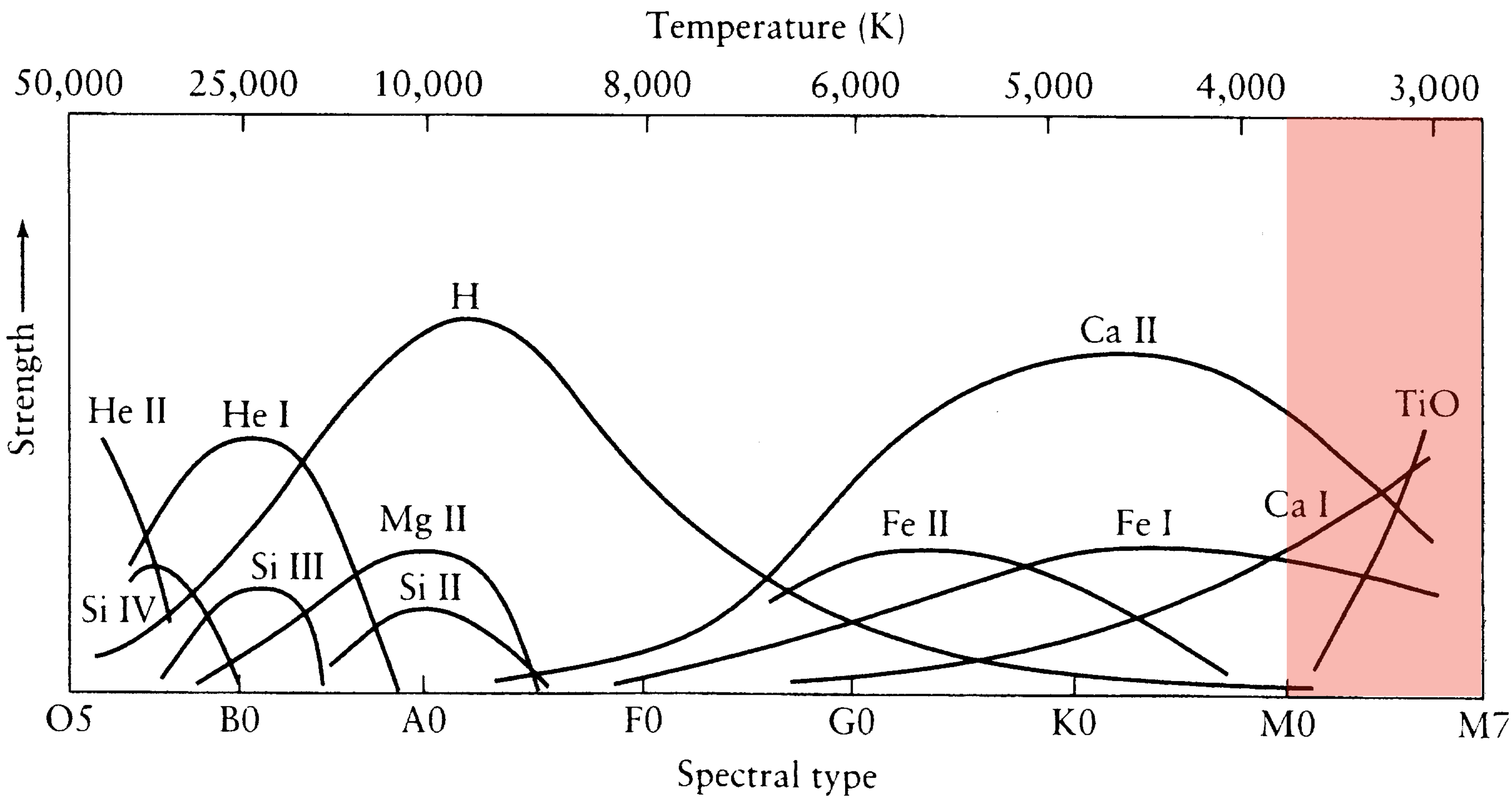
M-Dwarfs & L-Dwarfs

Ryan Hall



M-Dwarfs & L-Dwarfs



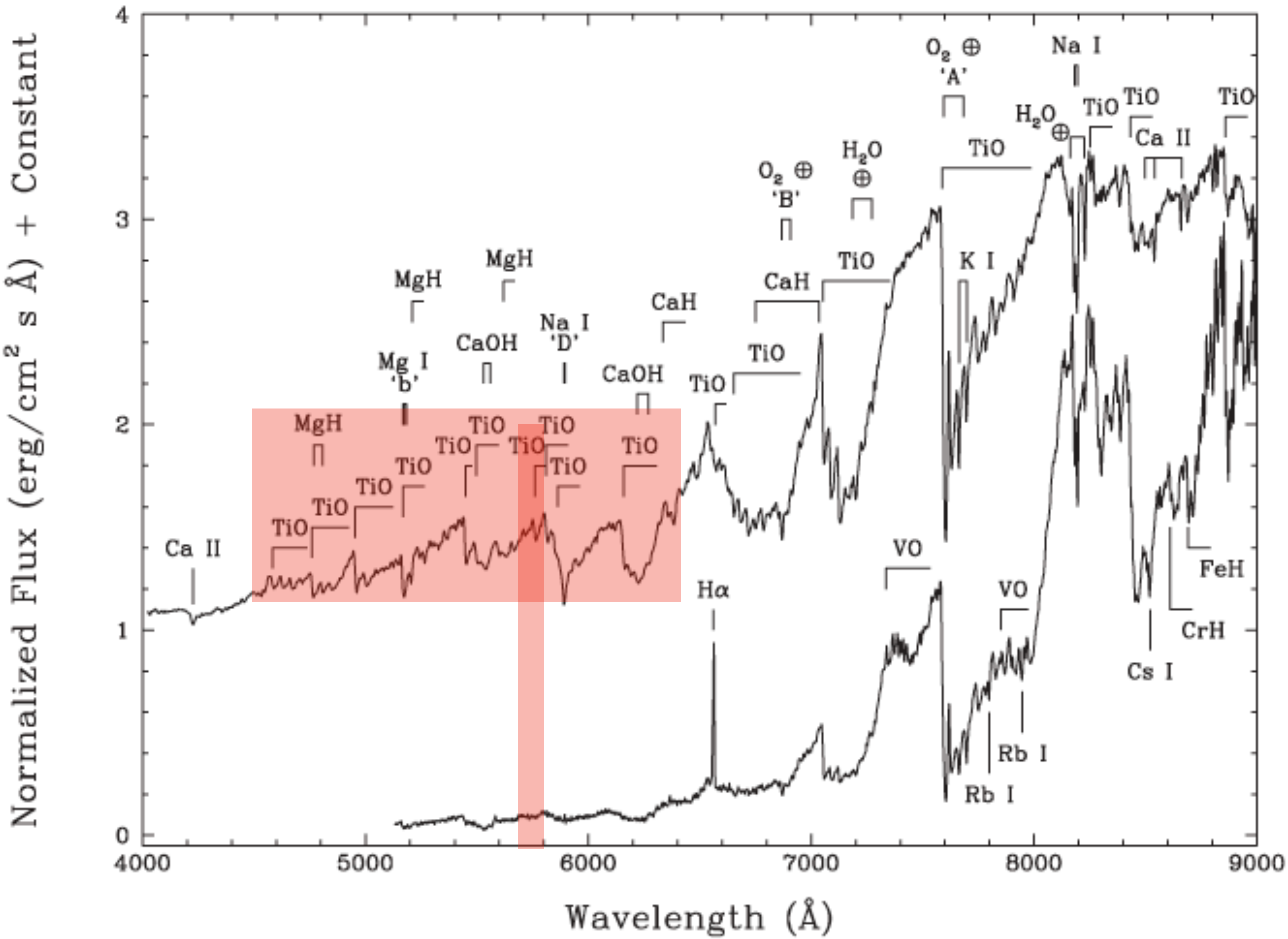
Introduction

- Where do H fusing stars end and brown dwarfs begin?
  - Temperature dependent on mass and age
  - Old low-mass star and young brown dwarf can be same temperature
    - Spectroscopically very similar
  - These spectral types can contain both stars and brown dwarfs
- Molecular spectral features
  - At cooler temperatures even grains form
  - Good diagnostics to study physical effects

M-Type Classification

Temperature Classification

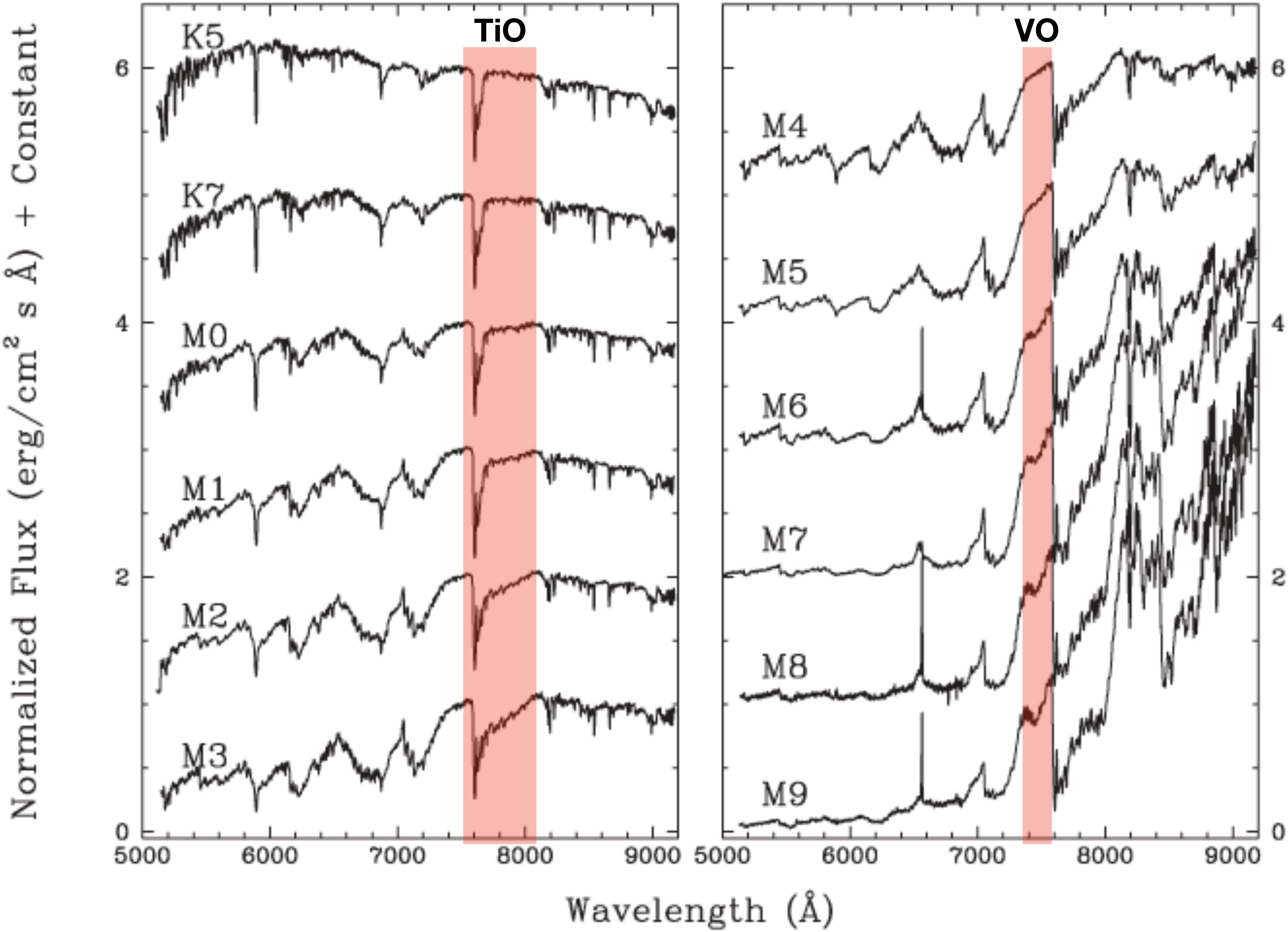
- Historically done in optical
  - Not a lot IR technology in early spectroscopy days
- TiO main subtype indicator
- Original MK system only classified early M-types
  - Kuiper (1942) and Joy (1947) systems for later types
  - Systems didn’t always agree
- Later revisions (Boeshaar 1976) used 5736Å VO to 5759Å TiO ratio and 5530Å CaOH for mid M-types


Normalized Flux (erg/cm² s Å) + Constant
Wavelength (Å)
Ca II
TiO
MgH
Mg I 'b'
CaOH
Na I 'D'
CaH
O₂ ⊕ 'B'
H₂O ⊕
O₂ ⊕ 'A'
K I
Na I
Ca II
Hα
VO
Rb I
Cs I
CrH
FeH

M-Type Classification

Temperature Classification

- Entire M-Dwarf classification done using red-NIR (Kirkpatrick et al. 1991)
- Created a set of standard stars for each subtype
- Classification of future stars done relative to standards
  - Least square minimization to standard
  - Many line ratio options
- Full NIR standards not yet defined
  - Same species in optical and NIR

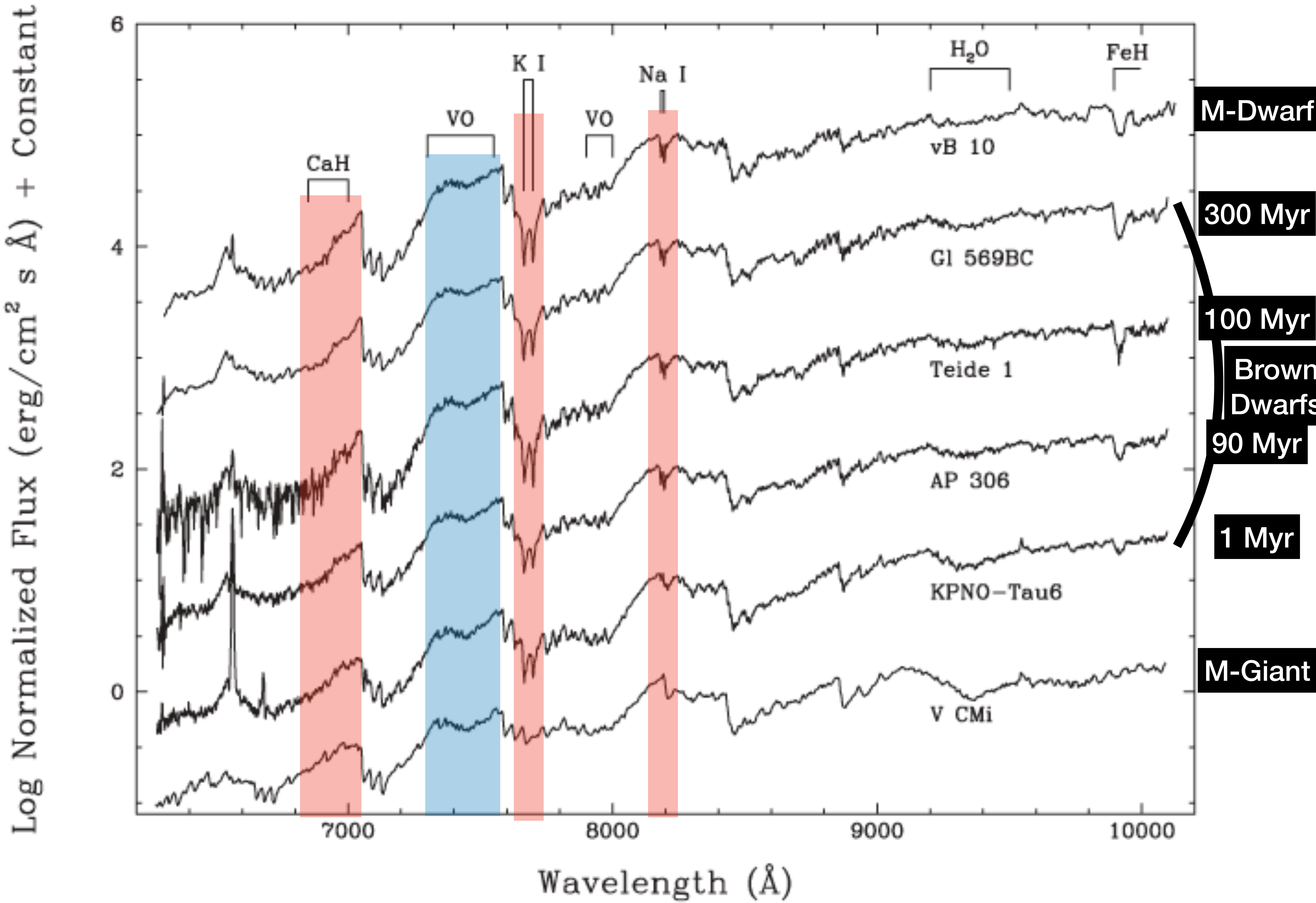


TiO
VO
K5
K7
M0
M1
M2
M3
M4
M5
M6
M7
M8
M9
Normalized Flux (erg/cm² s Å) + Constant
Wavelength (Å)
0
2
4
6
5000
6000
7000
8000
9000

M-Type Classification

Gravity/Luminosity Classification

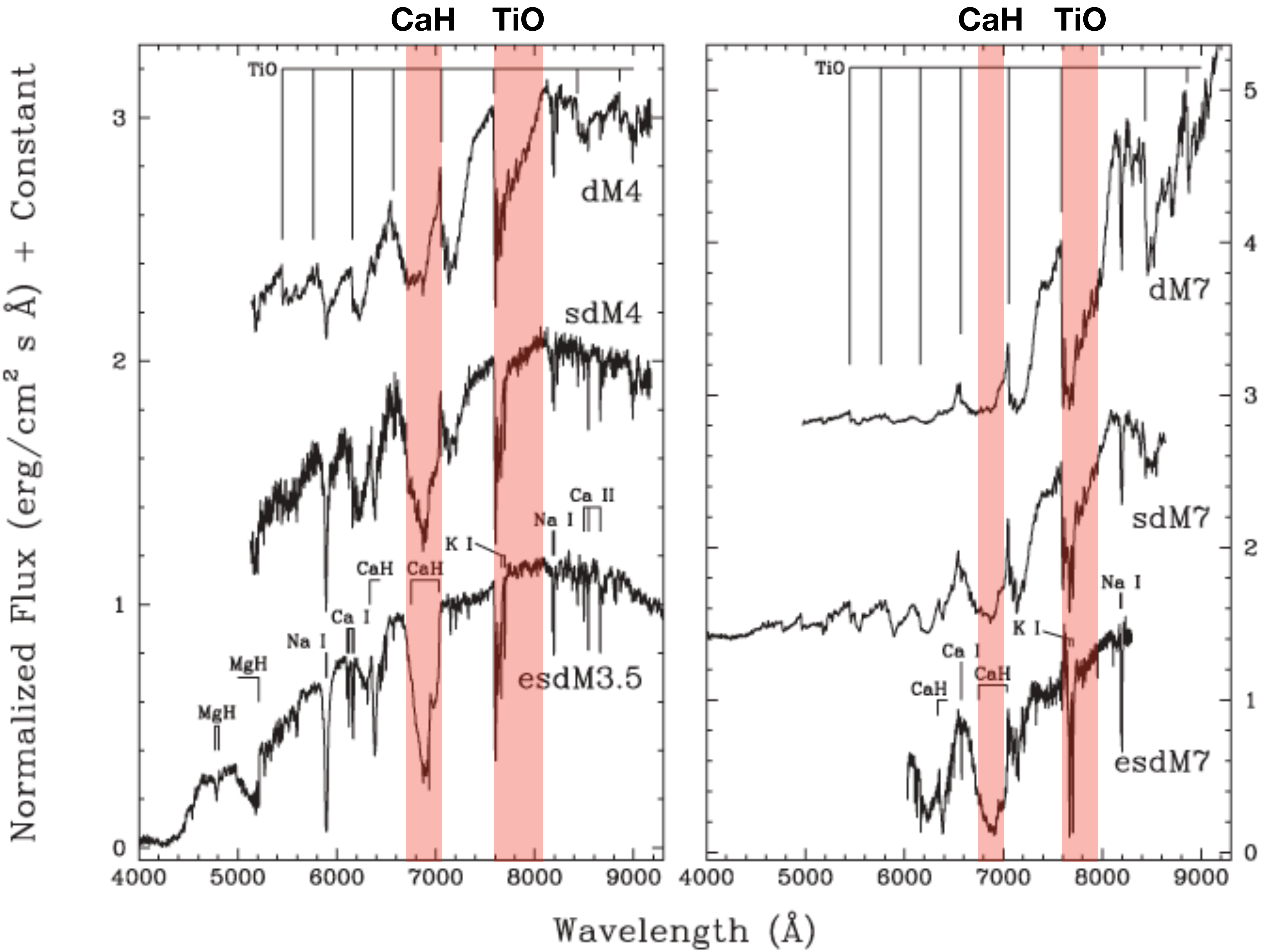
- Realized that M-type had two sequences (Dwarfs & Giants)
    - Density sensitive lines separated them (Na I, hydrides)
- The appearance of these spectral features is due to differing surface gravities
    - early-Dwarf log(g) ~ 4.5, early-Giant log(g) ~ 1.0
- Similar effect for brown dwarfs
    - Young brown dwarfs are hot like older M-stars
    - Contract as they age


Log Normalized Flux (erg/cm^2 s Å) + Constant
Wavelength (Å)
CaH
VO
K I
VO
Na I
H_2O
FeH
vB 10
Gl 569BC
Teide 1
AP 306
KPNO−Tau6
V CMi
M-Dwarf
300 Myr
100 Myr
Brown Dwarfs
90 Myr
1 Myr
M-Giant

M-Type Classification

Metallicity Classification

- Low-metal stars are called <u>subdwarfs</u>
  - d = dwarf, sd = subdwarf, esd = extreme subdwarf
- Varying abundance of metals will change the relative abundance of different molecules
- Lower metal abundance means less to metal-metal molecules compared to metal-hydride molecules
  - e.x. TiO (metal-metal), CaH (metal-hydride)
- For two stars with same TiO strength
  - The star with stronger CaH is more metal-poor

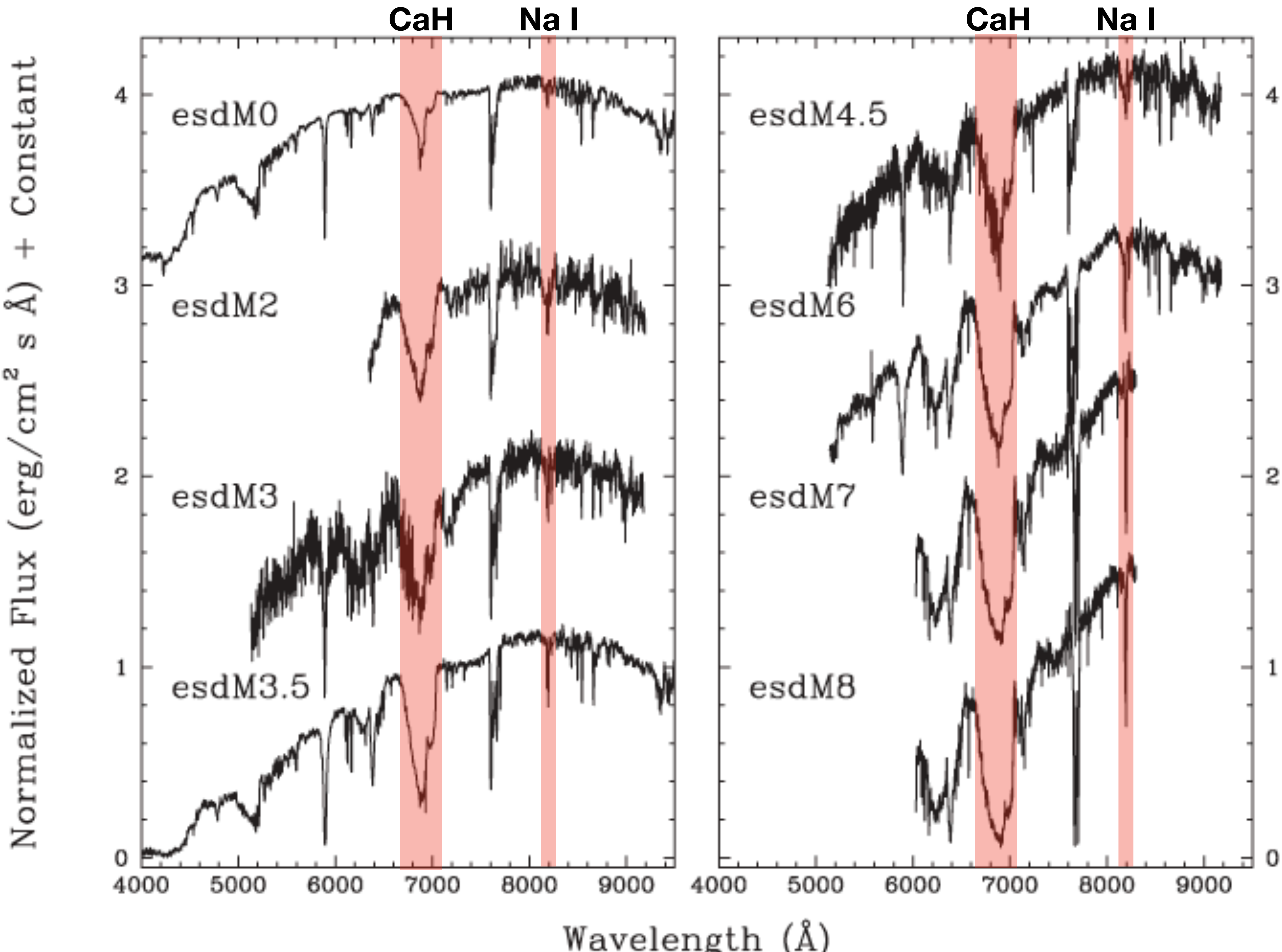


CaH
TiO
CaH
TiO
TiO
dM4
sdM4
esdM3.5
dM7
sdM7
esdM7
MgH
MgH
Na I
Ca I
CaH
CaH
K I
Na I
Ca II
Ca I
CaH
CaH
K I
Na I
Normalized Flux (erg/cm^2 s Å) + Constant
Wavelength (Å)

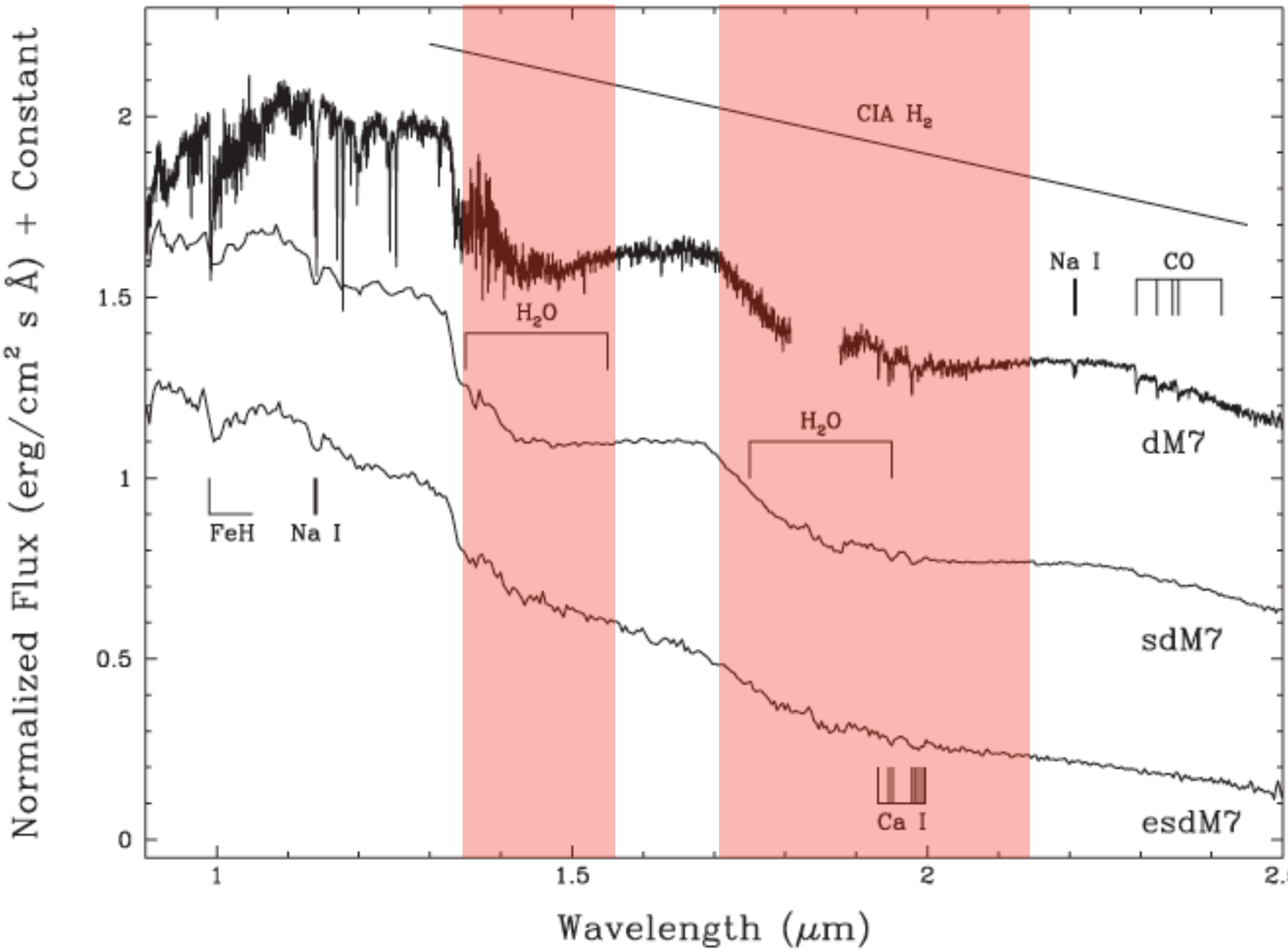
M-Type Classification

Metallicity Classification

- M-type sequence standards for subdwarf and extreme subdwarfs not yet defined
    - Classified relative to normal dwarfs (Gizis 1997)
    - Ratios of 6400 and 6950Å CaH to 7150Å TiO
    - Abundances calculated using fits with atmospheric models
- In NIR subdwarf and extreme subdwarf spectra are flattened
    - Collision-induced absorption (CIA) of H_2



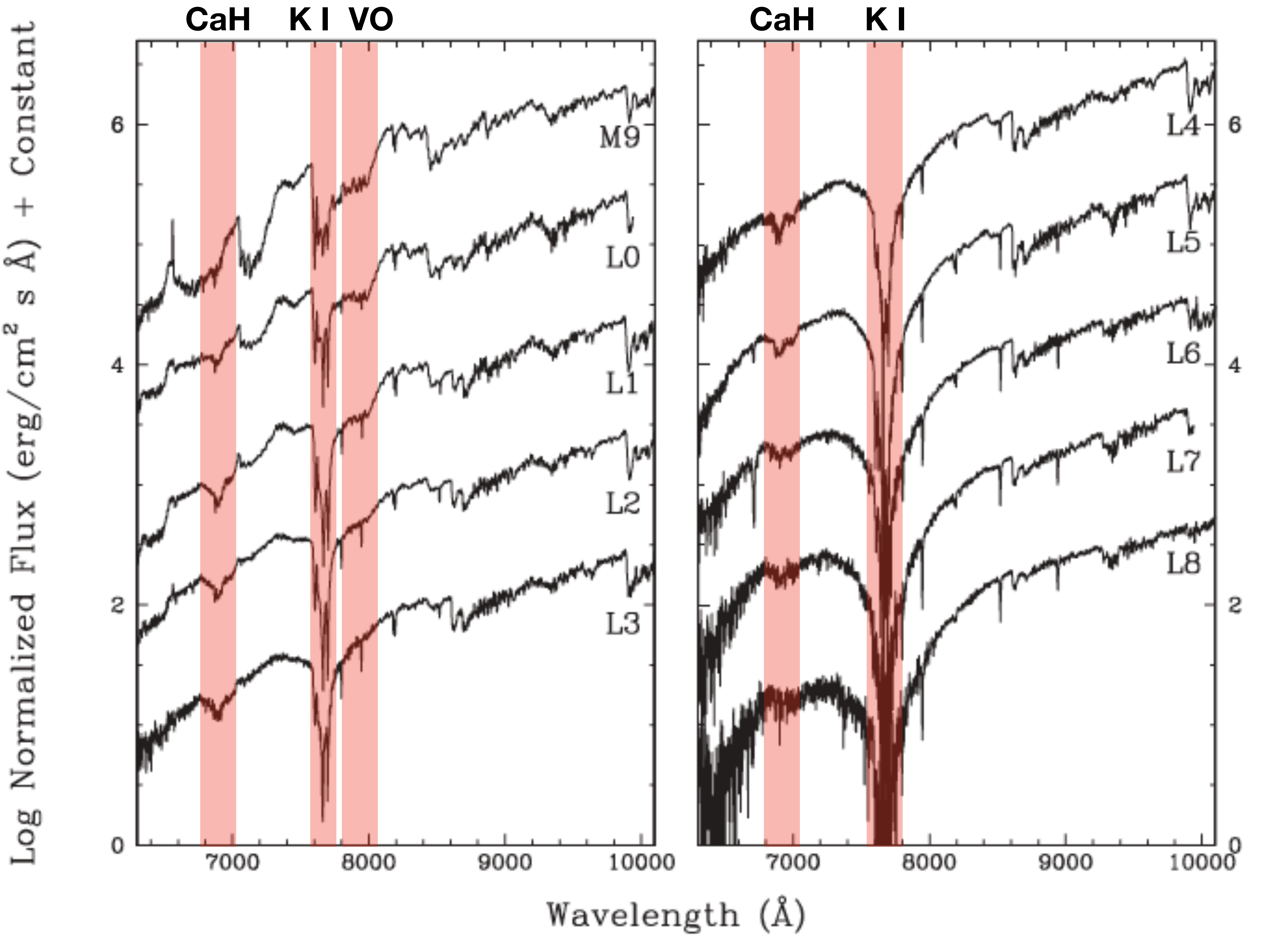
CaH
Na I
CaH
Na I
esdM0
esdM2
esdM3
esdM3.5
esdM4.5
esdM6
esdM7
esdM8
Normalized Flux (erg/cm² s Å) + Constant
Wavelength (Å)

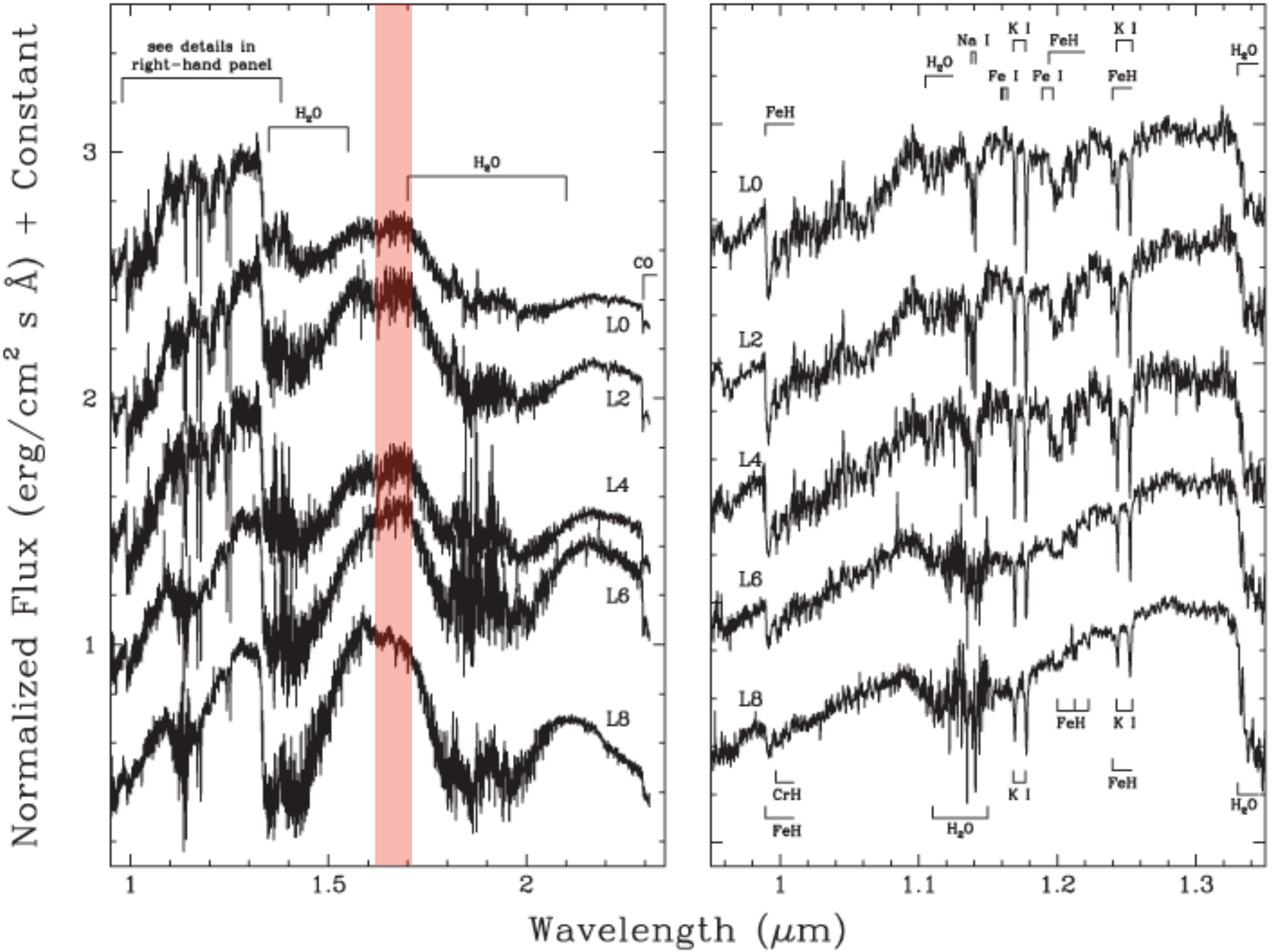

Normalized Flux (erg/cm² s Å) + Constant
Wavelength (μm)
CIA H₂
H₂O
H₂O
Na I
CO
FeH
Na I
Ca I
dM7
sdM7
esdM7
0
0.5
1
1.5
2
1
1.5
2
2.5

L-Type Classification

Temperature Classification

- Early L-Dwarf spectra:
  - Neutral alkalis (Na, K), hydrides (FeH, CaOH), and oxides (weak TiO, VO)
- Mid L-Dwarf spectra:
  - Stronger alkali resonance lines and hydrides, very weak oxides
- Late L-Dwarf spectra:
  - Strong alkali and H_2O, weakening hydride
- Optical standards set up by (Kirkpatrick et al 1999)


CaH
K I
VO
CaH
K I
Log Normalized Flux (erg/cm² s Å) + Constant
M9
L0
L1
L2
L3
L4
L5
L6
L7
L8
0
2
4
6
7000
8000
9000
10000
Wavelength (Å)

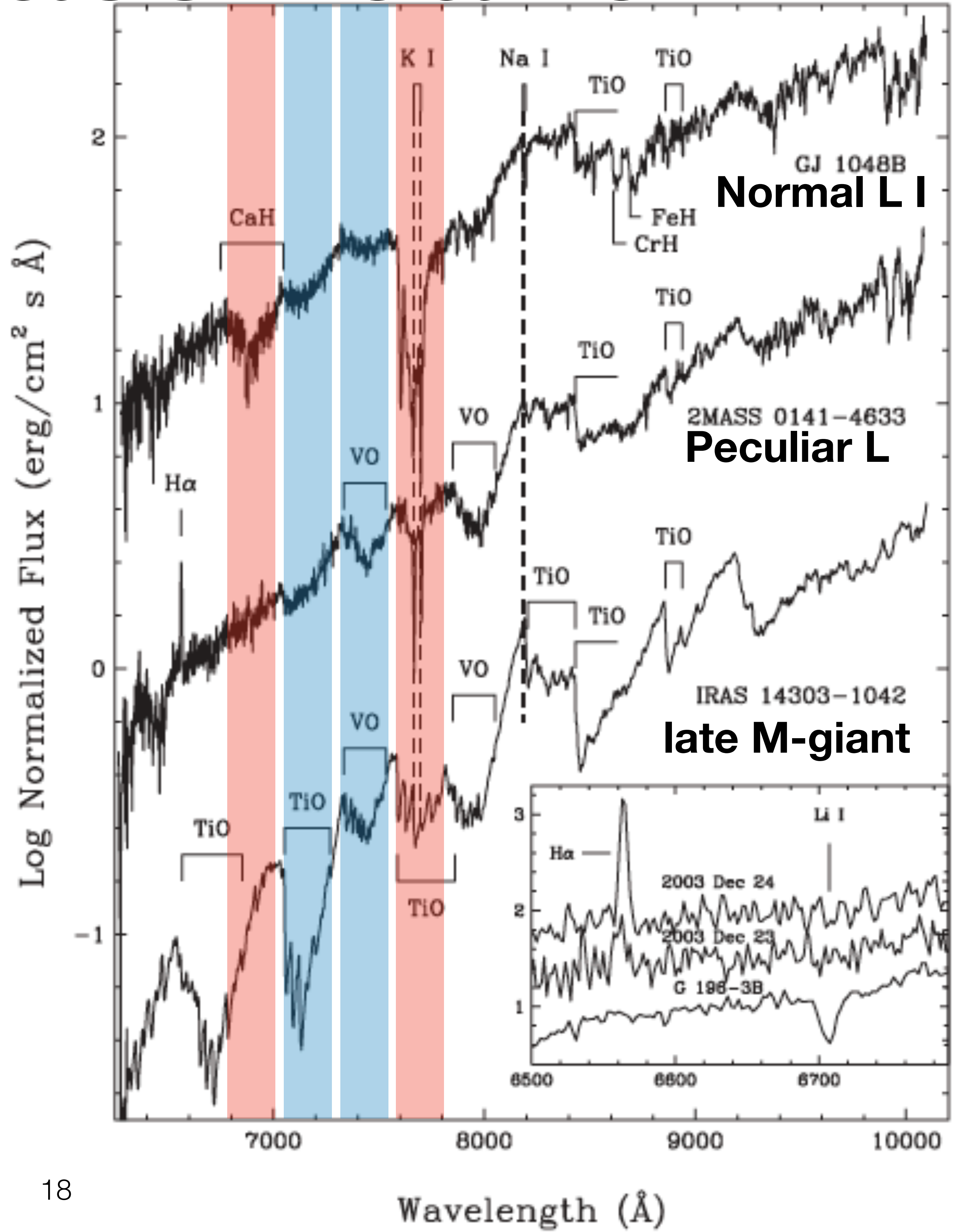


Normalized Flux (erg/cm^2 s Å) + Constant
Wavelength (μm)
see details in right-hand panel
H_2O
CO
L0
L2
L4
L6
L8
FeH
Na I
K I
Fe I
CrH

L-Type Classification

Gravity/Luminosity Classification

- No L-type Giants or Super Giants (unlike M-types)
    - Spectra still show surface gravity effects
- Peculiar is L-type because of low TiO/VO ratio
- Alkalis and hydrides are surface gravity diagnostics

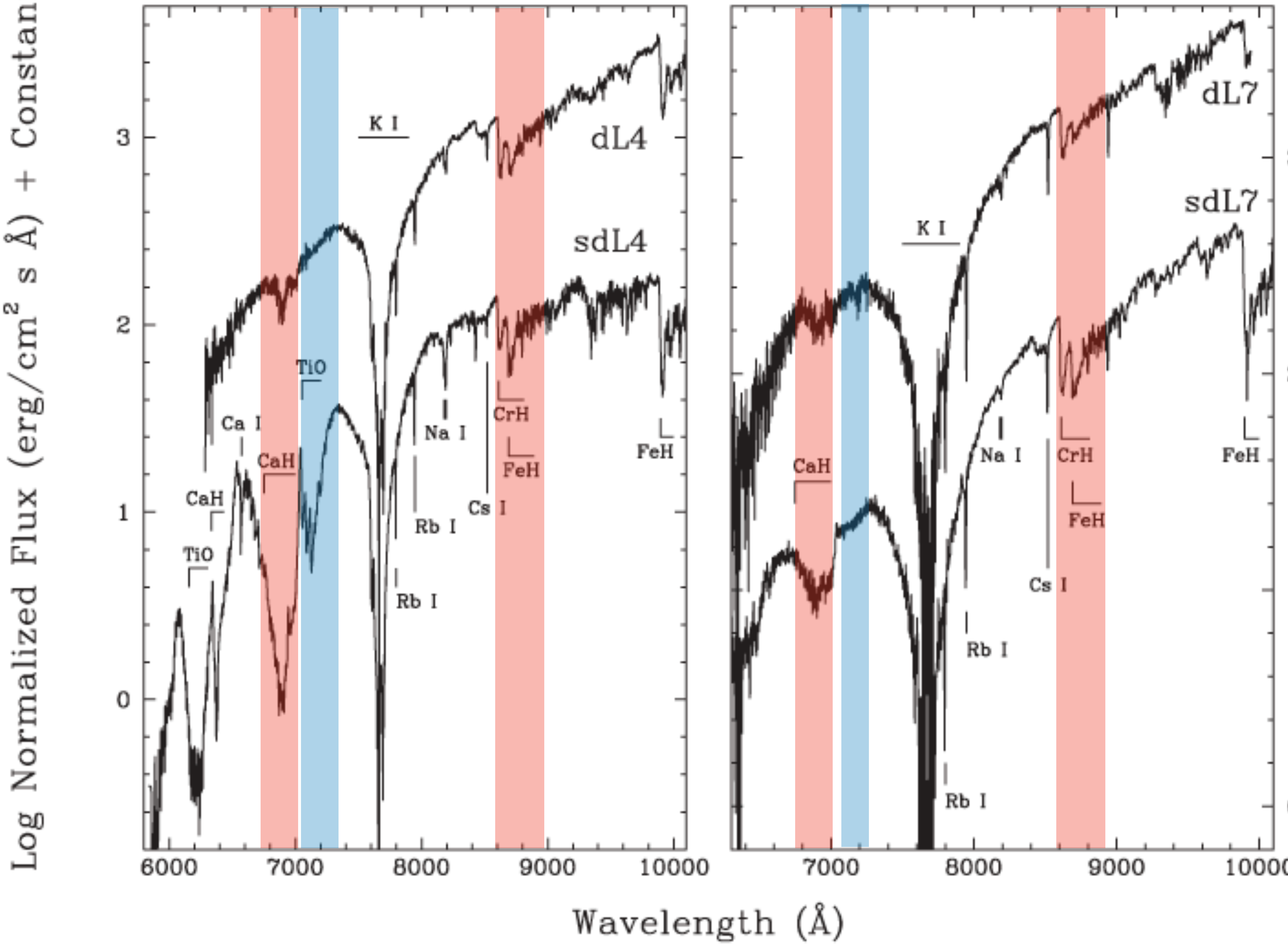


L-Type Classification

Metallicity Classification

- Some unusual L-type spectral features explained by metallicity
  - Cooler equivalents to M-type subdwarfs
  - L subdwarfs
- L subtype based on closest match to normal L-Dwarf standards
- L-subdwarfs have stronger hydride bands and alkali lines
- No subdwarf standards have been set yet
  - Few number of known L-subdwarfs

TiO?



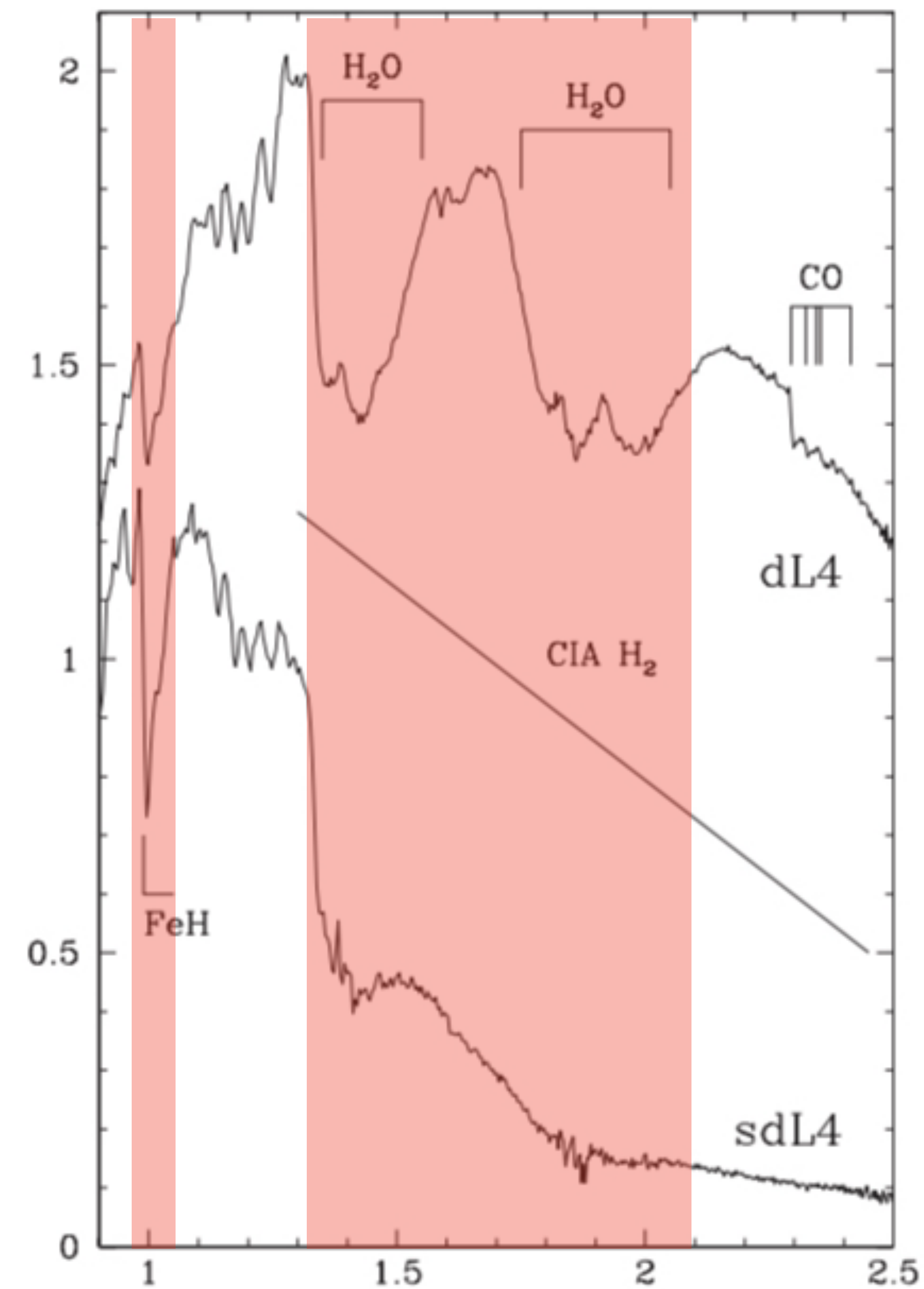
Log Normalized Flux (erg/cm² s Å) + Constant
dL4
sdL4
K I
TiO
Ca I
CaH
CaH
TiO
Na I
CrH
FeH
Cs I
Rb I
Rb I
FeH
dL7
sdL7
K I
CaH
Na I
CrH
FeH
Cs I
Rb I
Rb I
FeH
Wavelength (Å)

L-Type Classification

Metallicity Classification

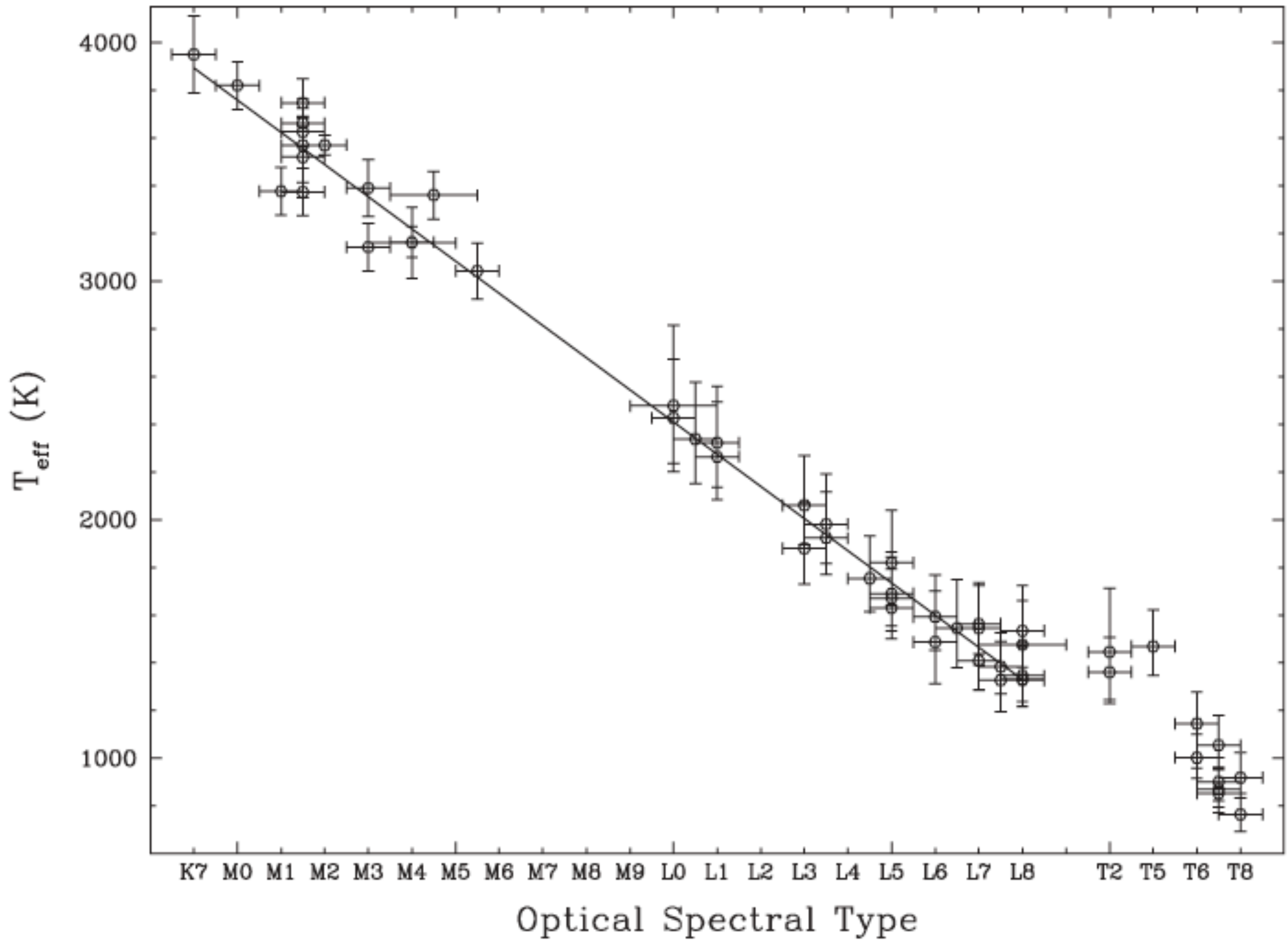
Near Infrared

- In 1-2.5 micron range
- Increased FeH
- H_2O band features in normal L-Dwarf
  - Suppressed in subdwarfs
    - CIA H_2
- Subdwarfs have bluer colors in NIR
  - Relative to normal dwarfs



Effective Temperature

- Is temperature most important factor for spectral appearance?
- Measuring Radii
  - Early to Mid M-type radii measured directly via binary system and interferometry
  - Late M-type and all L-type too dim and no eclipsing companions
    - Interior models used to estimate L-type
- Measuring Luminosity
  - Need distance and apparent magnitude (astrometry and photometry
- Effective temperature from R and L



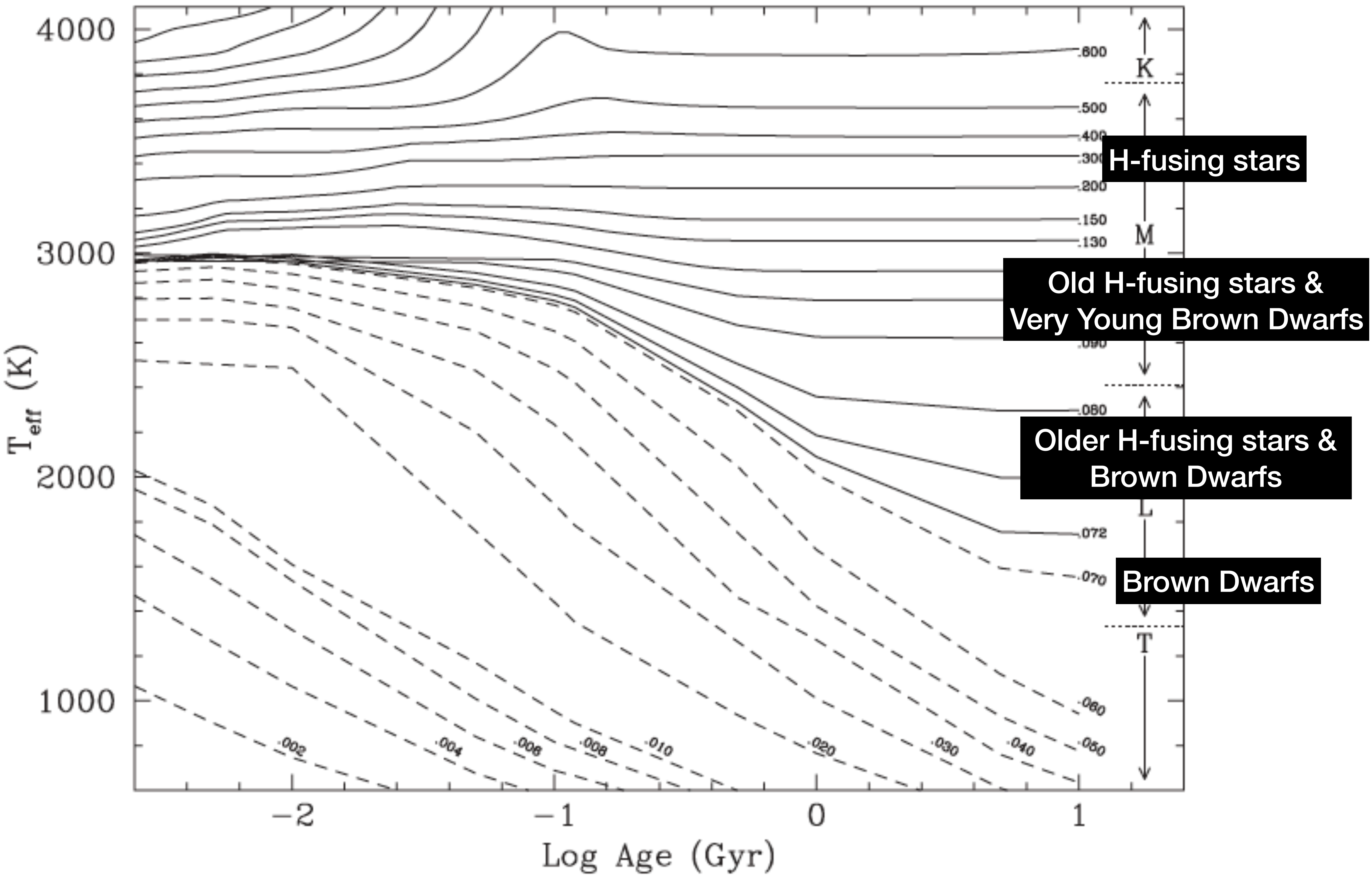
4000
3000
2000
1000
T_{eff} (K)
K7 M0 M1 M2 M3 M4 M5 M6 M7 M8 M9 L0 L1 L2 L3 L4 L5 L6 L7 L8 T2 T5 T6 T8
Optical Spectral Type

Chemistry of Atmosphere

- State a species is in dependent on Temperature
    - Ions -> Neutral -> Molecules -> Condensates
- Atmospheric models without dust don’t work on late M and L
- Why does TiO and VO disappear in L-Dwarfs
    - TiO, VO condense down to dust
    - VO never completely disappears
- Hydrides (FeH & CrH) in L-type strength peak and then decrease at same subtypes
- Starting at mid-L CO combines H_2 to make H_2O
    - Water bands strengthen

Stars or Brown Dwarfs

- For object with too low mass, electron degeneracy is reached in core before T is high enough for H fusion
    - Brown Dwarfs
- Evolutionary models used to see change in T_{eff} vs Age
    - Find that Mid-M to Mid-L contain stars and brown dwarfs



4000
3000
2000
1000
T_{eff} (K)
−2
−1
0
1
Log Age (Gyr)
.600
.500
.200
.150
.130
.080
.072
.070
.060
.050
.040
.030
.020
.010
.008
.006
.004
.002
K
M
L
T
H-fusing stars
Old H-fusing stars & Very Young Brown Dwarfs
Older H-fusing stars & Brown Dwarfs
Brown Dwarfs

Stars or Brown Dwarfs

- For object with too low mass, electron degeneracy is reached in core before T is high enough for H fusion
  - Brown Dwarfs
- Evolutionary models used to see change in T_{eff} vs Age
  - Find that Mid-M to Mid-L contain stars and brown dwarfs
- Lithium depletion -> tests to see if H-fusion
  - Problems:
    - Flux is low at Li resonance line
    - Li molecules form at low T (1500K)
    - low log(g) hides Li lines (young brown dwarfs)

Space Density

- How many M and L-Dwarfs are around?
- Solar neighborhood (<8pc) population studies
  - Good for spectral types $\leq$ M6 (parallax)
  - Majority of later types too dim
    - Parallax of few that are close

$$n(M0 - M6) \approx 6.7 * 10^{-2}\ pc^{-3} \quad n(M7 - M9.5) \approx 4.9 * 10^{-3}\ pc^{-3}$$

$$n(L0 - L8) \approx 3.8 * 10^{-3}\ pc^{-3}$$

$$n(T0 - T8) \approx 7.2 * 10^{-3}\ pc^{-3}$$

- Fewer L-Dwarfs than M-Dwarfs or T-Dwarfs
  - Brown dwarfs cool down fast & not a lot of stars

Peculiar Objects

Dwarf Carbon Stars

- Carbon Dwarfs (dC)
- Low luminosity dwarf object near M-Dwarf sequence
  - Large excess of carbon
- Mass transfer with evolved companion
  - Theory requires low metallicity (high Z still found)
- >120 dC found
  - Difficult to disentangle Carbon Giants

Peculiar Objects

Flare Stars

- Star shows sudden burst in luminosity for short time
  - Burst can exceed L_{bol}
  - Lasts only for few seconds
- Burst results in presence of multiple emission lines
  - Emission lines come from layers of atmosphere
- Magnetic field of star transfers energy to atmosphere
- Probability of flaring depends on Spectral-Type
  - Peaks at M7-M8
  - No flares after early-L

Peculiar Objects

Pre-Main-Sequence Objects

- Objects are surrounded by dust (envelope/disk)
  - Optical wavelengths blocked
- Classified in 2-25 micron band
  - Using alpha (flux) parameter

$$\alpha = \frac{d\ log(\lambda F_\lambda)}{d\ log\lambda}$$

- 3 Classes

1. Embedded Protostars - Steeply rising continuum $0 < a < 3$

2. T Tauri - “Flat” spectra $-2 < a < 0$

3. Weak-lined T Tauri - Falling spectra $-3 < a < -2$

Questions