Young Stellar Objects

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Where we’re going

- Definition of young stars
- Motivation for studying young stars
- Terminology / phenomenology of young stars and our current model for understanding them
- Differences between high- and low-mass young stars
- Some current, outstanding questions in understanding young stars

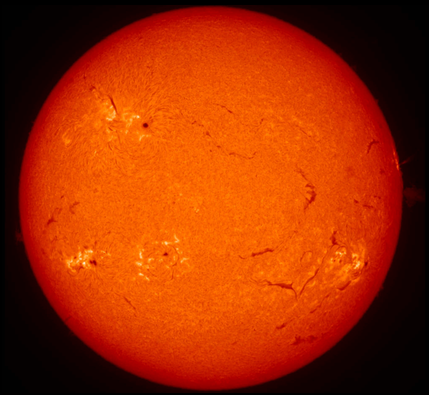
Low-mass young stars

- "Young" means pre-main-sequence.
- For low-mass stars, this means ages of 10^5 to 10^8 years.
- 10^5 to 5×10^6 years: still associated with molecular clouds: *T Tauri stars*
- 10^7 to 10^8 years: blend in with field stars unless in clusters: *Post T Tauri stars*

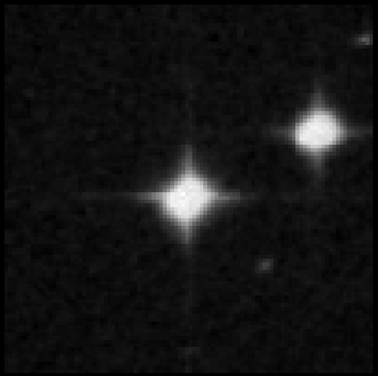
Young, massive stars

- All high-mass stars are young!
- Stars earlier than ~ B2 have no optically visible pre-main-sequence phase
- Later B stars and A stars do have pre-main-sequence lives, but they are short compared to those of low-mass stars.
- These are the Herbig Ae/Be stars

What is “young”?



Sun (middle-aged):
4.5 billion years
(4.5×10^9 yr)

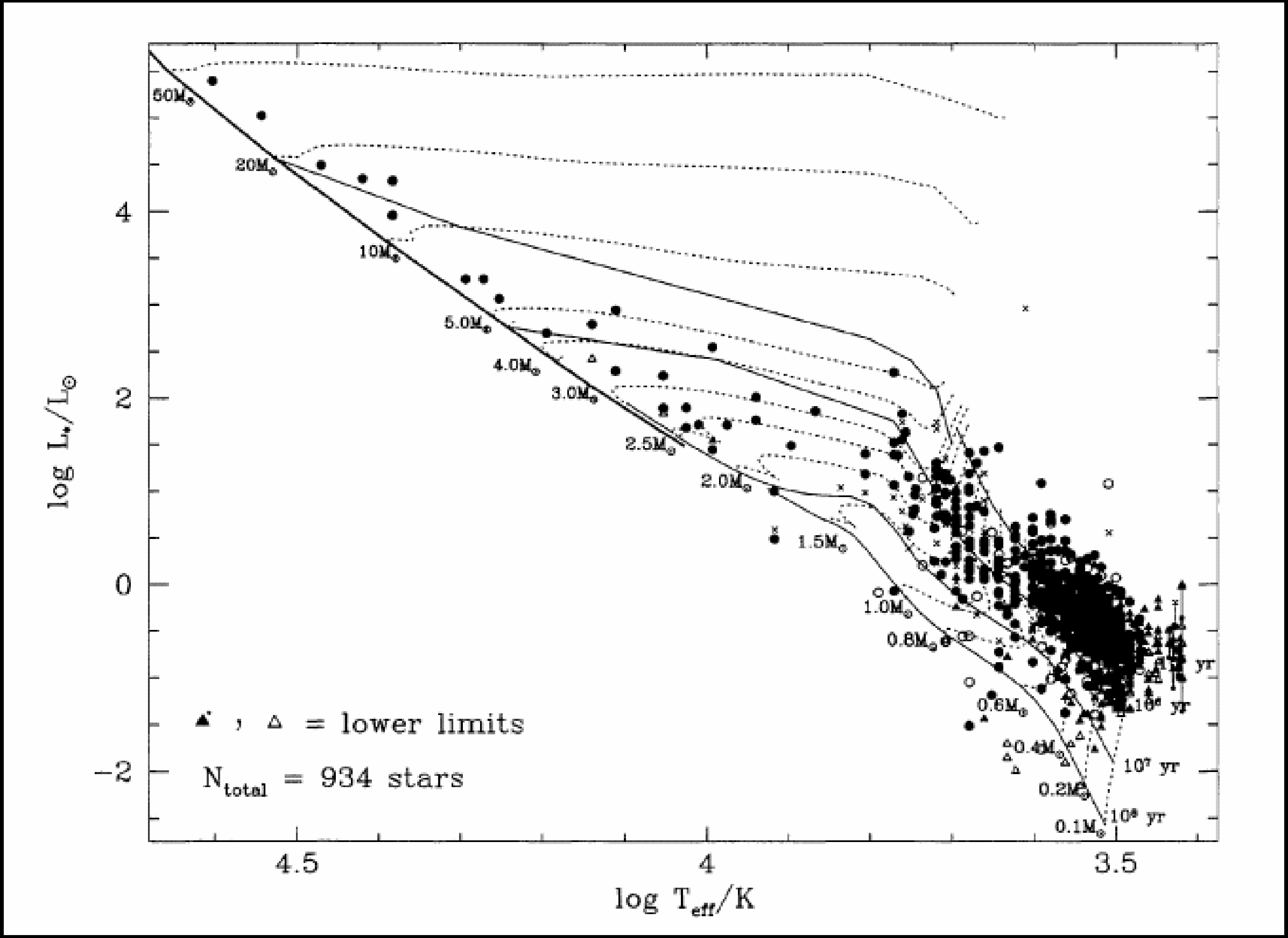


TYC 5853 1318 1
(young):
30 million years
(3.0×10^7 yr)

Middle-aged (37 years)

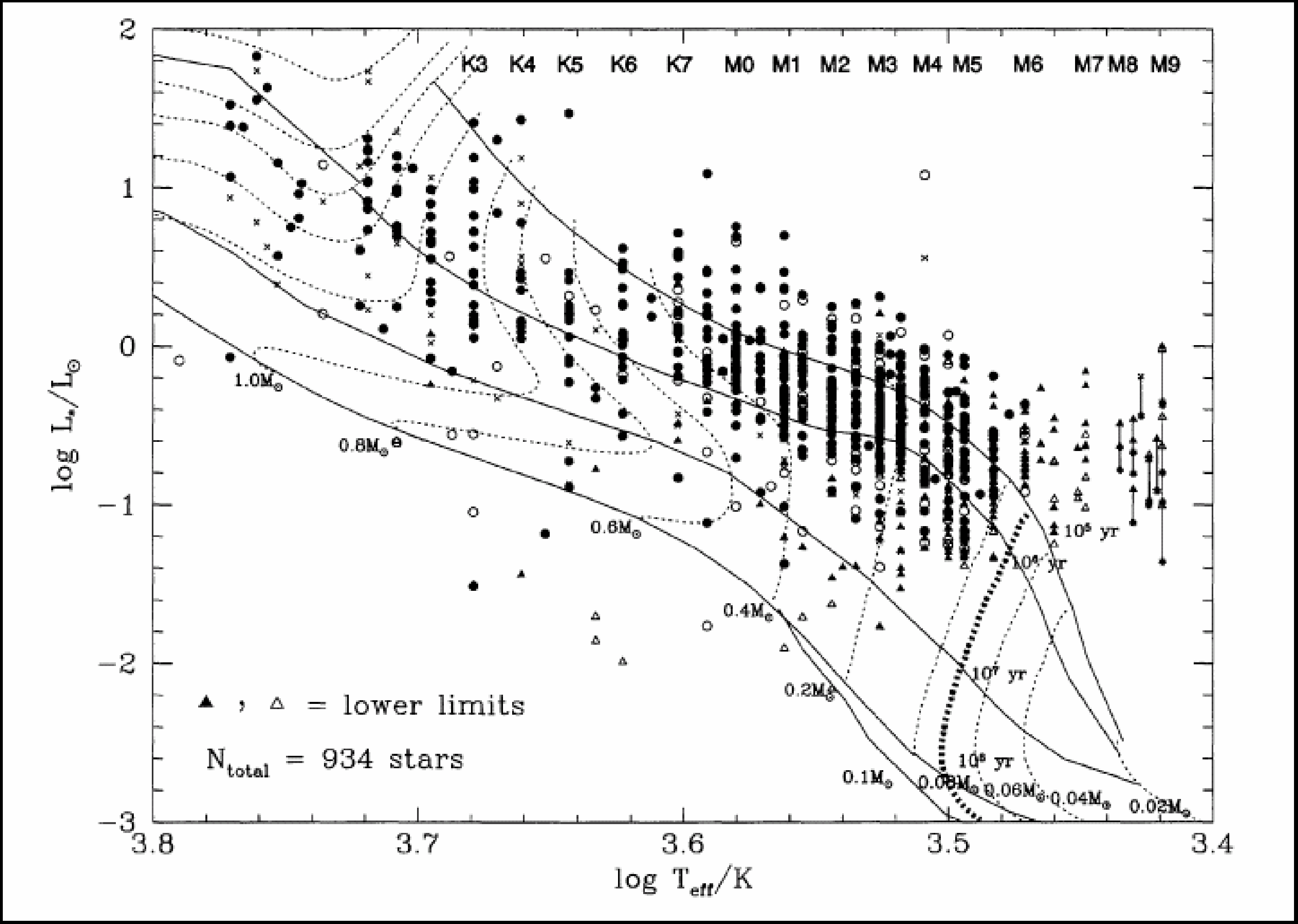
Young (3 months)

Orion Nebula Cluster



Hillenbrand 1997 AJ 113:1733

Orion Nebula Cluster



Hillenbrand 1997 AJ 113:1733

Many young stars are associated with clouds of gas and dust…

Orion Nebula from 2MASS

… but some young stars are more obvious than others.

Orion Nebula

TYC 5853 1318 1

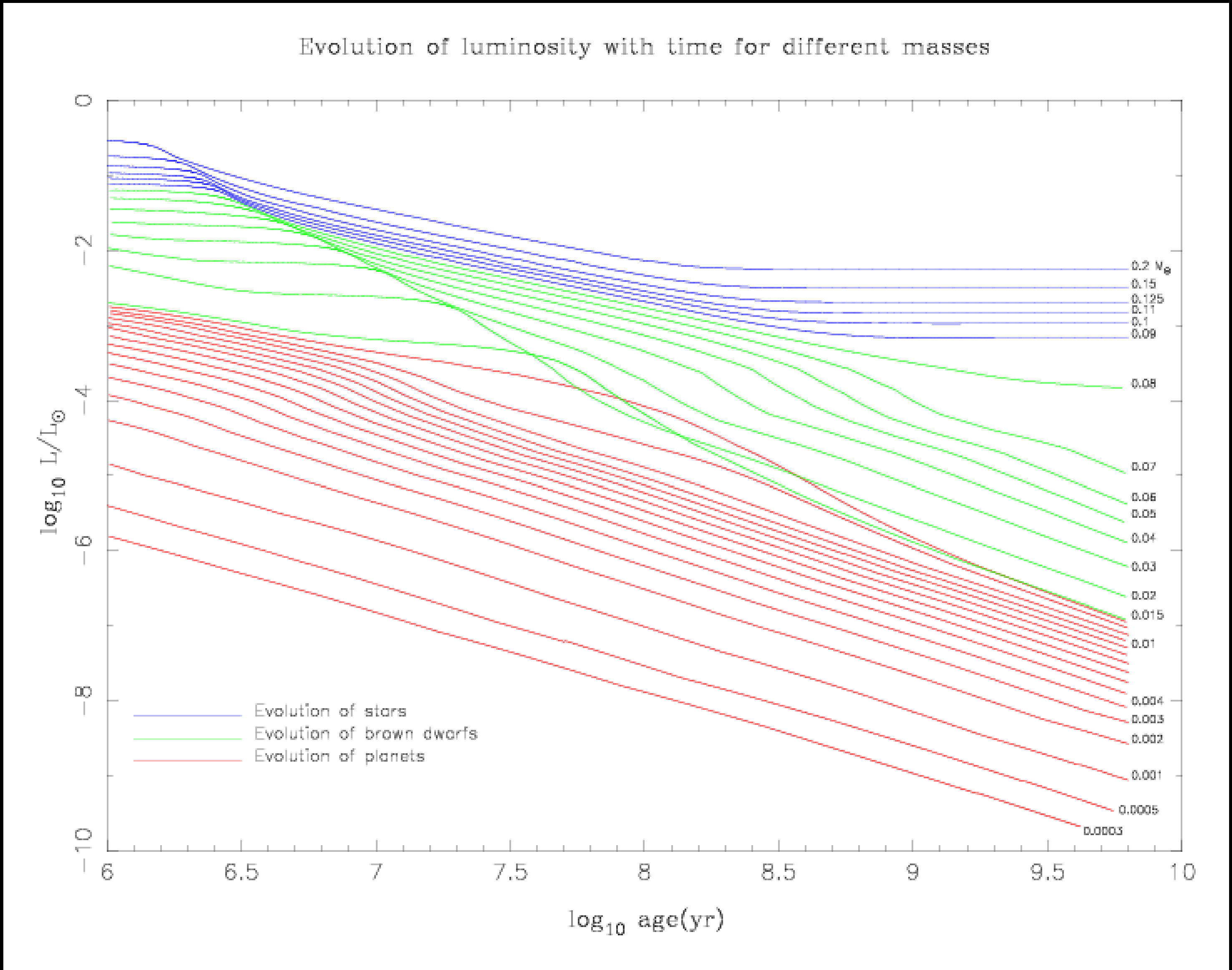
(30 Myr old)

1 degree x 1 degree fields of view

Why study young stars?

- Get a general understanding of stellar evolution.
- Watch planet formation as it happens:
  - Observe protoplanetary disks
  - Detect the planets themselves, either by imaging or astrometry
- Practical motivators for interferometry of young stars:
  - Disks are big
  - Young planets are bright, i.e. they have a higher contrast with their host stars when young

Planet-star contrast is better at young ages



Tracks from A. Burrows

T Tauri stars: observed properties

- Low-mass (< 1-2 M_{Sun}), pre-main-sequence stars
- Excess infrared and ultraviolet emission
- Excess blue continuum “veiling”
- Large photometric variability
- Strong Hα emission (also Hβ, Brγ)
- Strong X-ray emission
- Strong Li λ = 6708 Å absorption

Classical vs. Weak-line TTS

CTTS

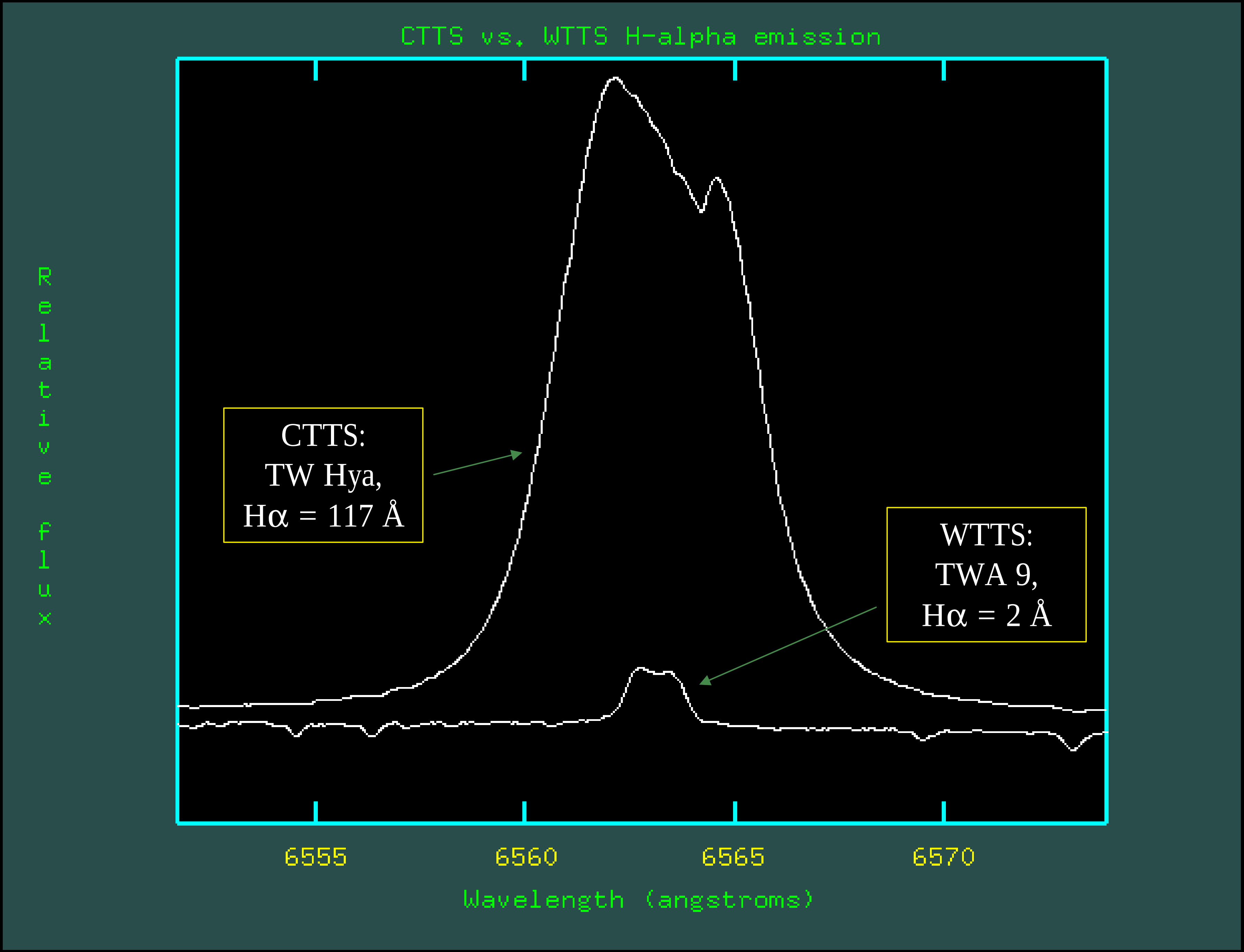
- Hα equiv width > 10 Å
- Infrared excess
- UV excess and veiling

- Strong x-ray emission
- Strong Li absorption
- Photometric variability
- Coeval with WTTS

WTTS

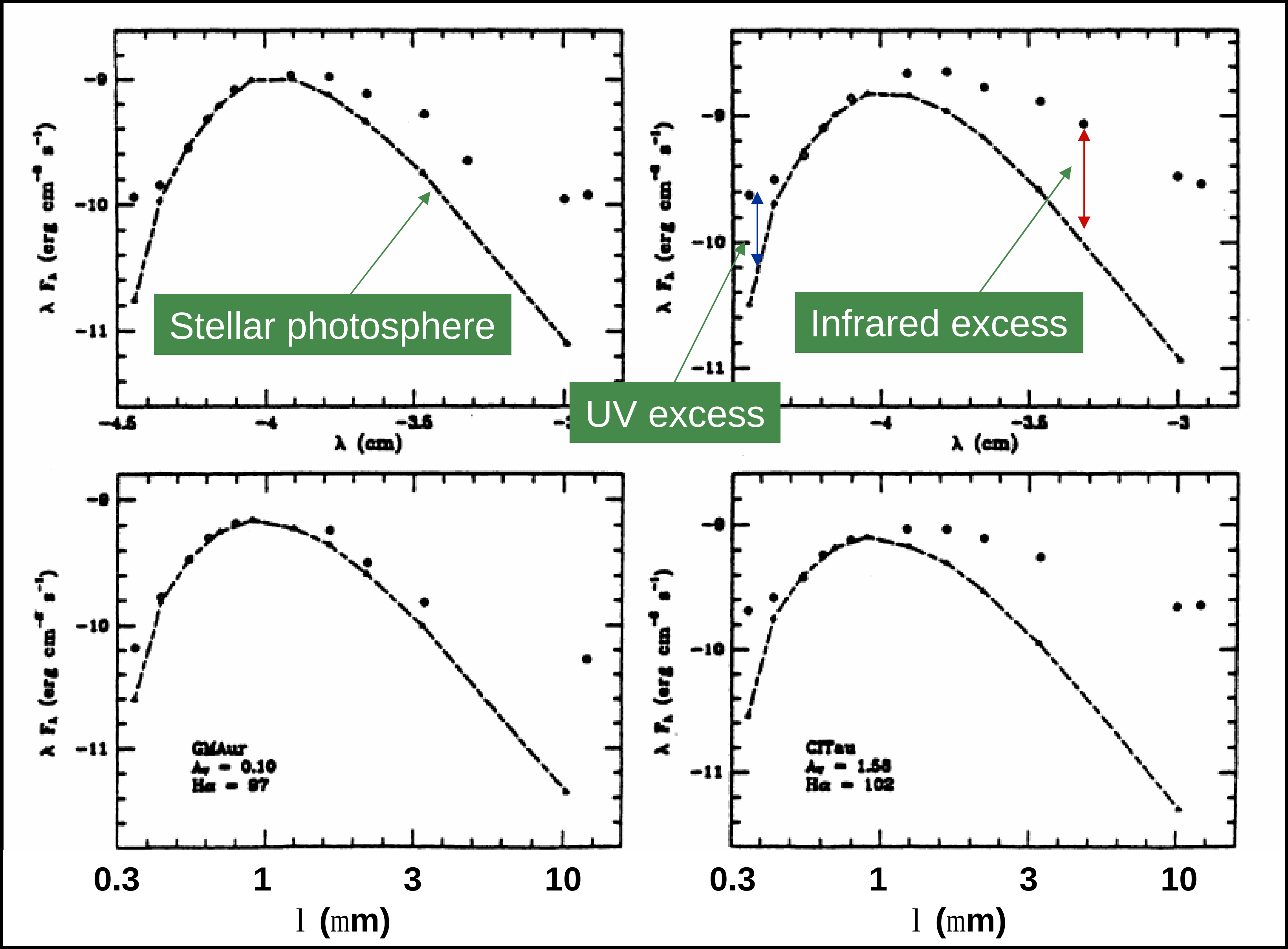
- Hα equiv width < 10 Å
- Little or no IR excess
- Little or no UV excess

- Strong x-ray emission
- Strong Li absorption
- Photometric variability
- Coeval with CTTS



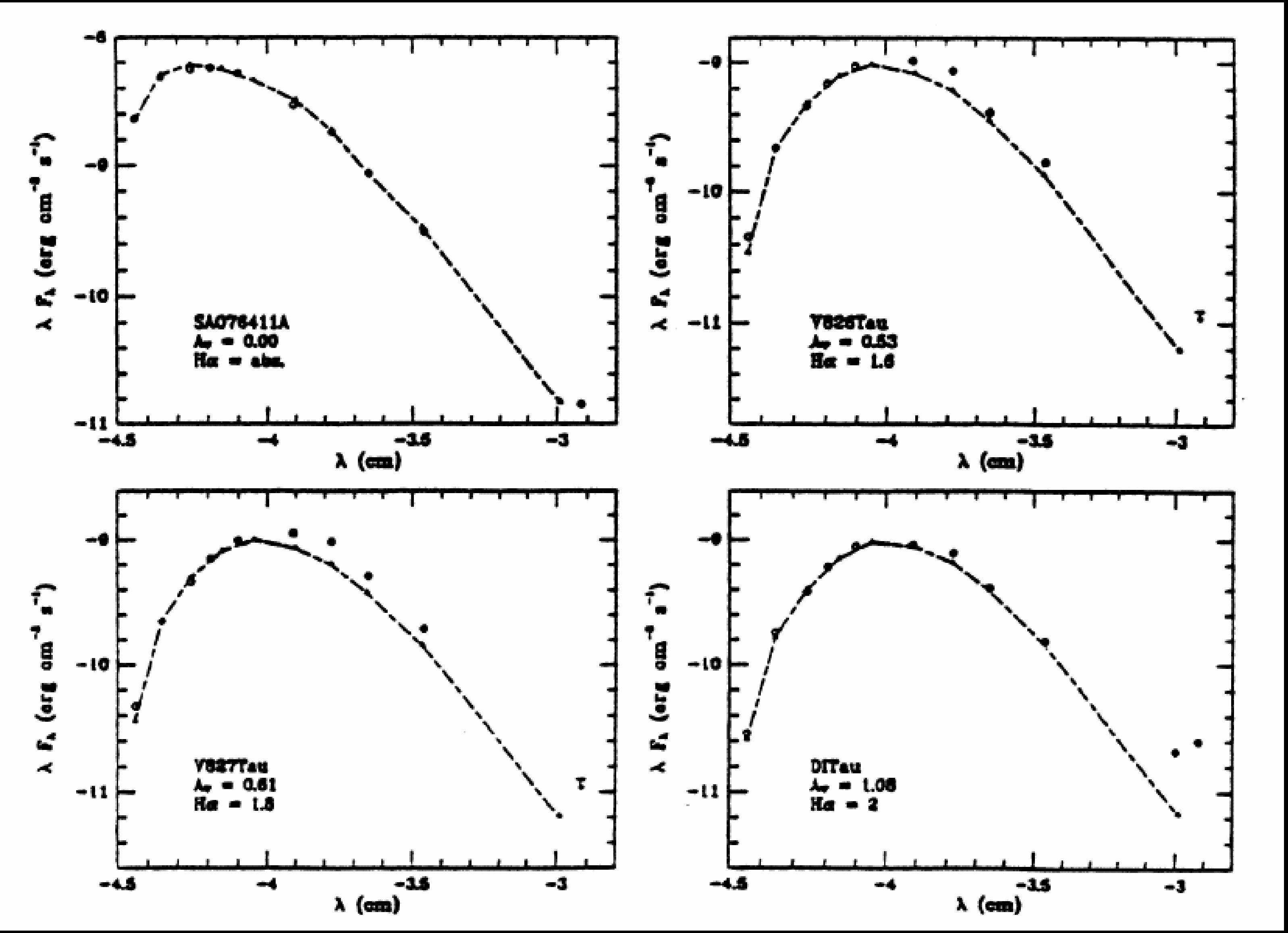
CTTS vs. WTTS H-alpha emission
Relative flux
6555
6560
6565
6570
Wavelength (angstroms)
CTTS:
TW Hya,
Hα = 117 Å
WTTS:
TWA 9,
Hα = 2 Å

CTTS Infrared and UV excesses



Strom et al. 1989 AJ 97:1451

WTTS: Little or no excess



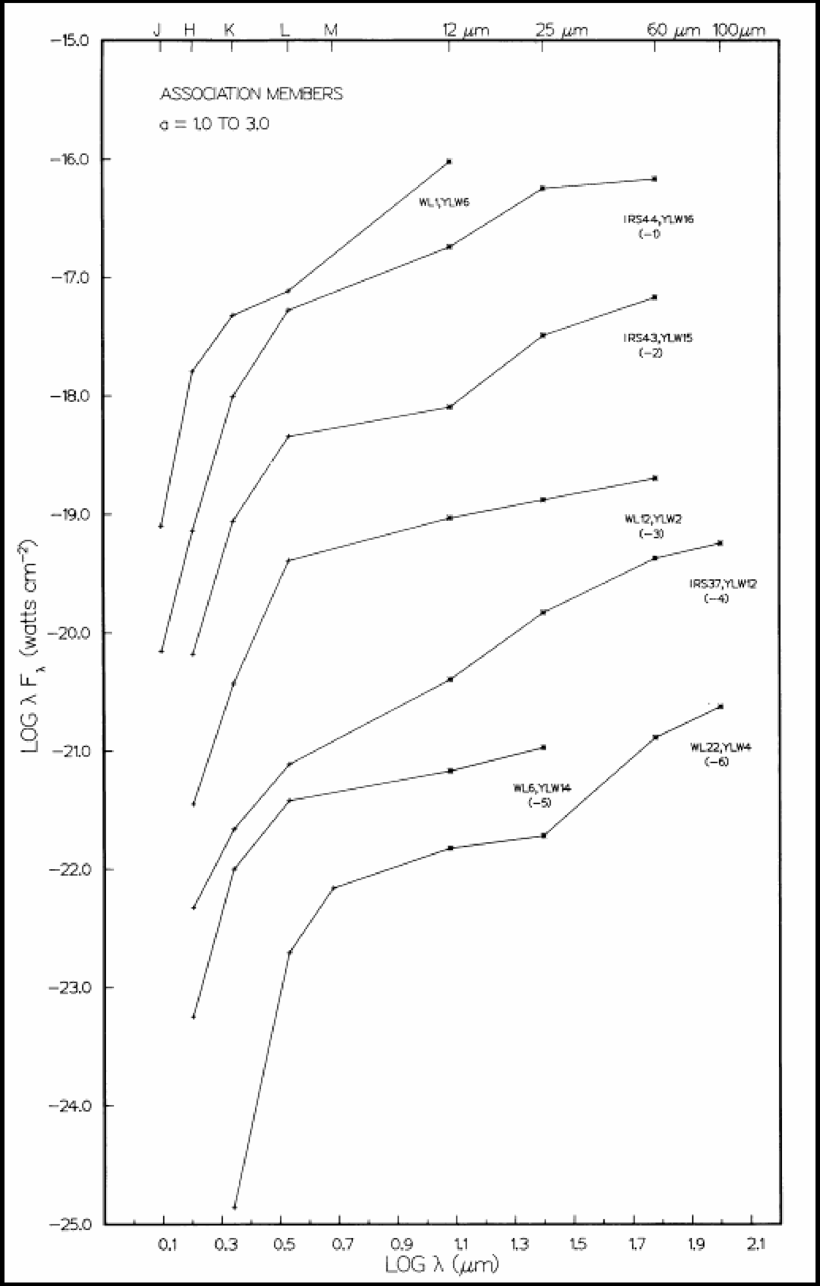
Strom et al. 1989 AJ 97:1451

Circumstellar disks: CTTS vs. WTTS

- Classical T Tauri stars (CTTS) are actively accreting material from circumstellar disks
  - Hα emission and veiling continuum arise in a hot "boundary layer" where disk accretes onto star
- Weak-line T Tauri stars (WTTS) have little or no on-going accretion because:
  - Disks are no longer present; or
  - Dust grains in the disks have started to coalesce into larger bodies

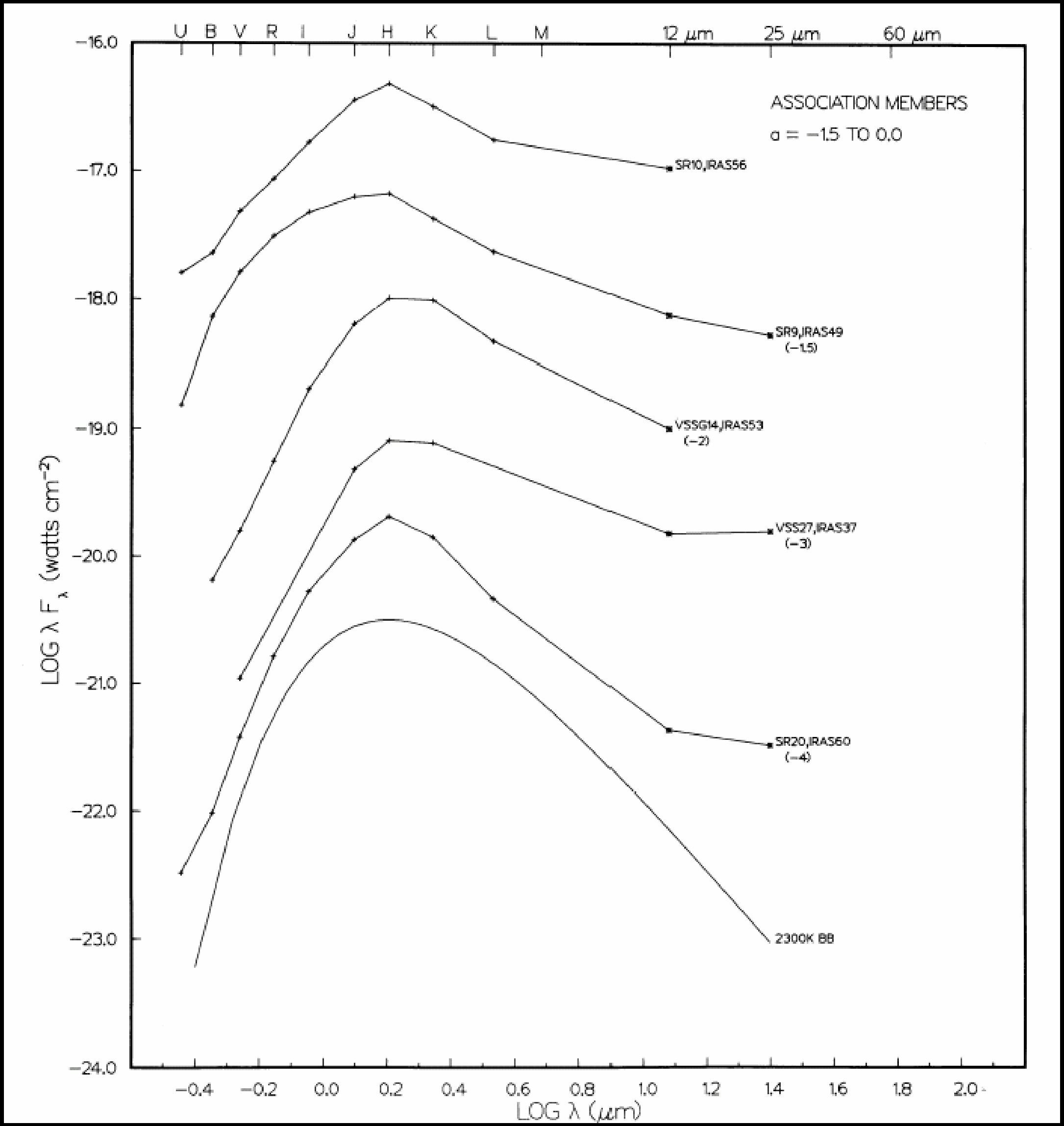
T Tauri star "classes"

- Class I : Flat or rising spectral energy distribution (SED) with wavelength. (Slope of $\log \lambda F_\lambda$ vs. $\log \lambda = 0$)
- Class II: Declining SED with wavelength, but some infrared excess
- Class III: Photospheric SED



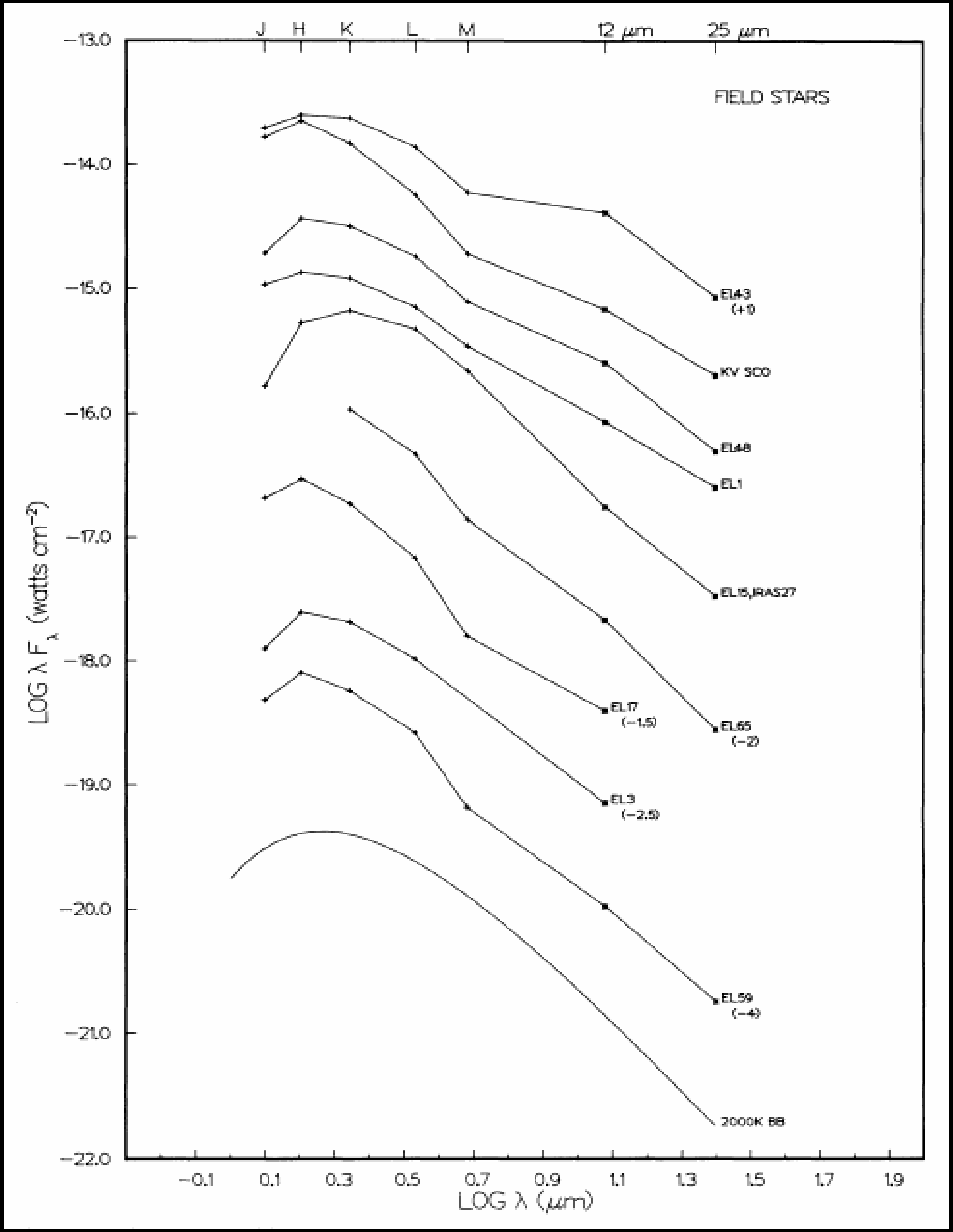
Young et al. 1989 ApJ 340:823

Class I: Heavily embedded sources



Class II: Disk present but star is not heavily embedded in envelope

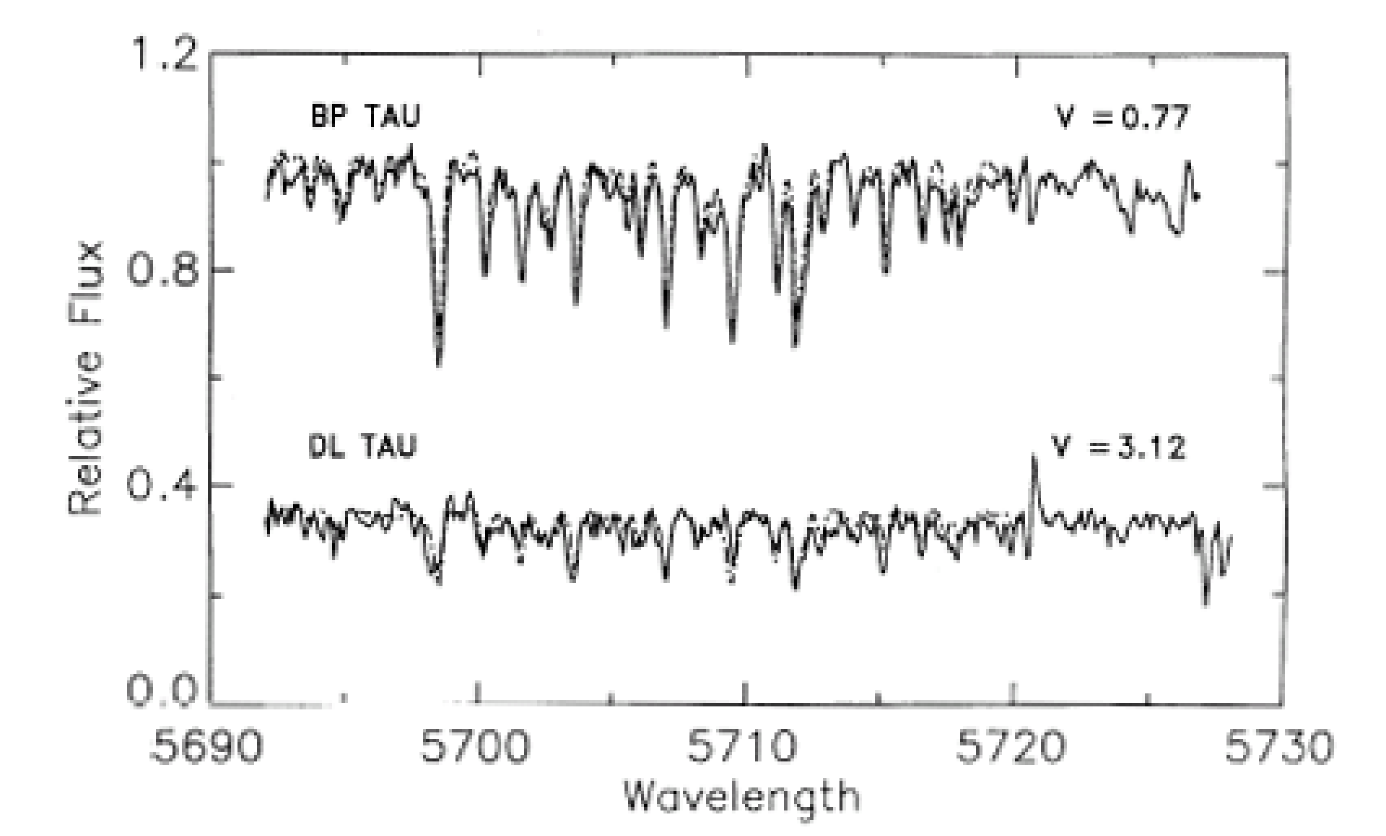
Young et al. 1989 ApJ 340:823



Class III: No dusty disk present

Young et al. 1989 ApJ 340:823

Excess blue emission “veils” absorption lines

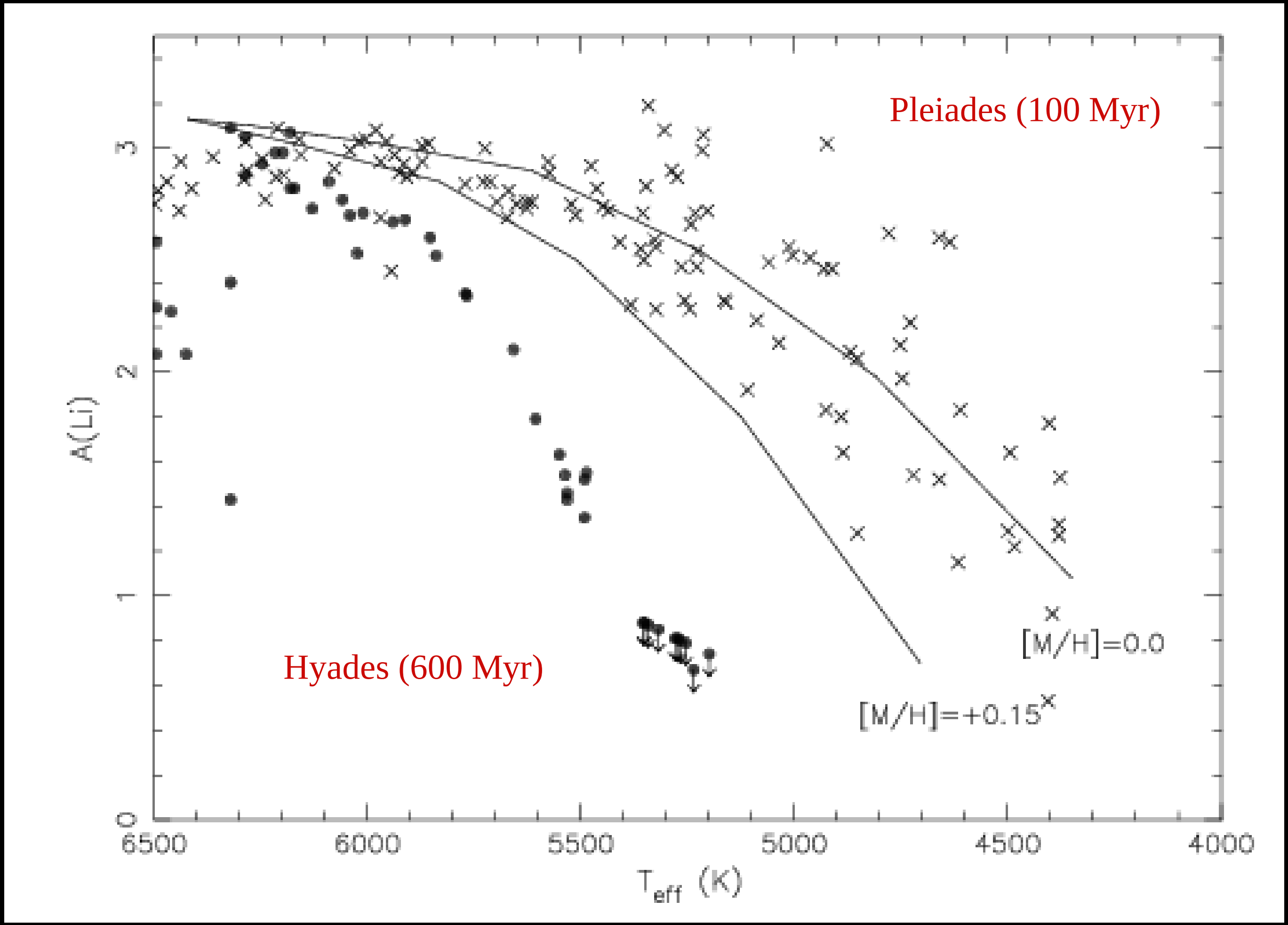


Little veiling

Heavily veiled

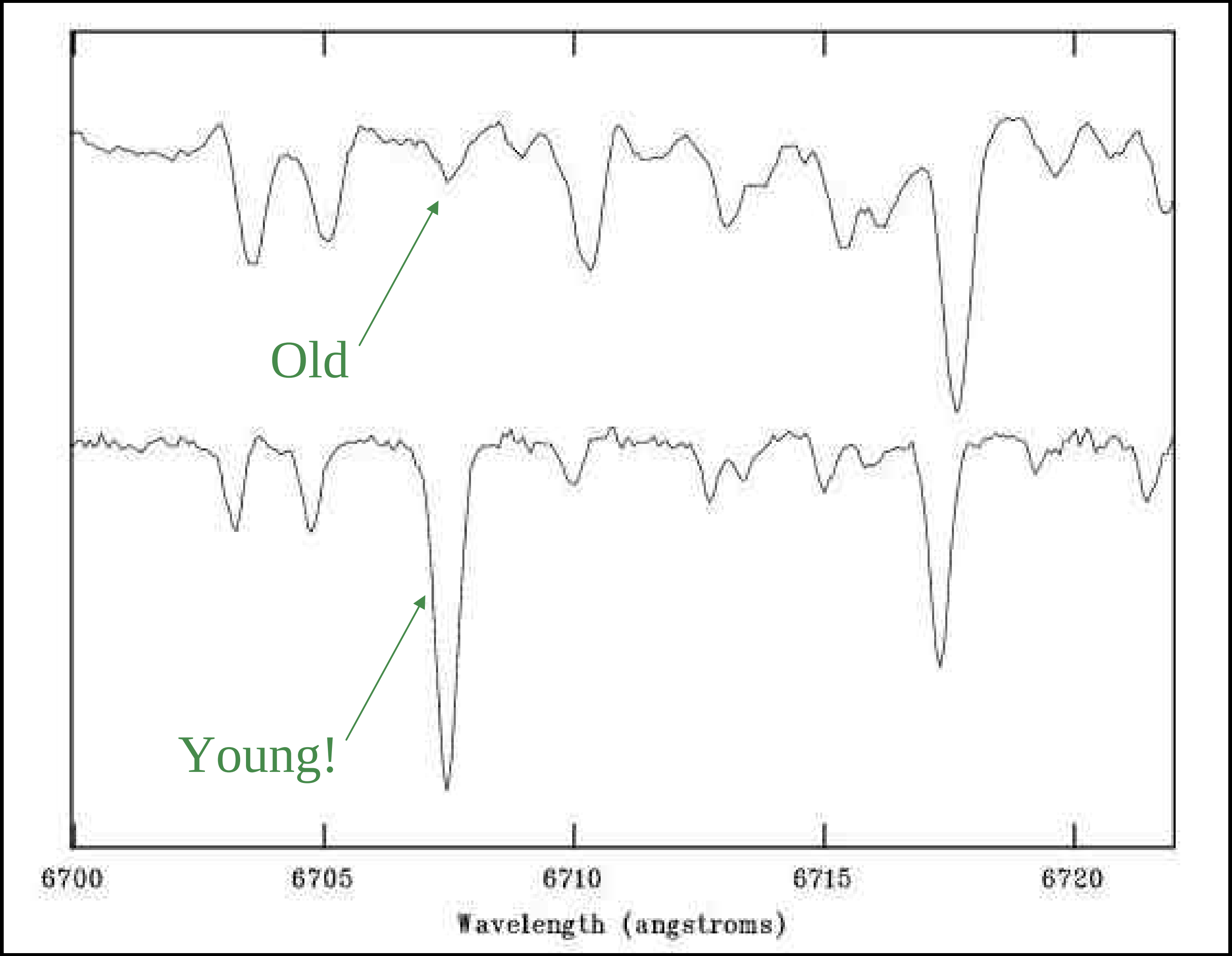
Basri & Batalha 1990 ApJ 363:654

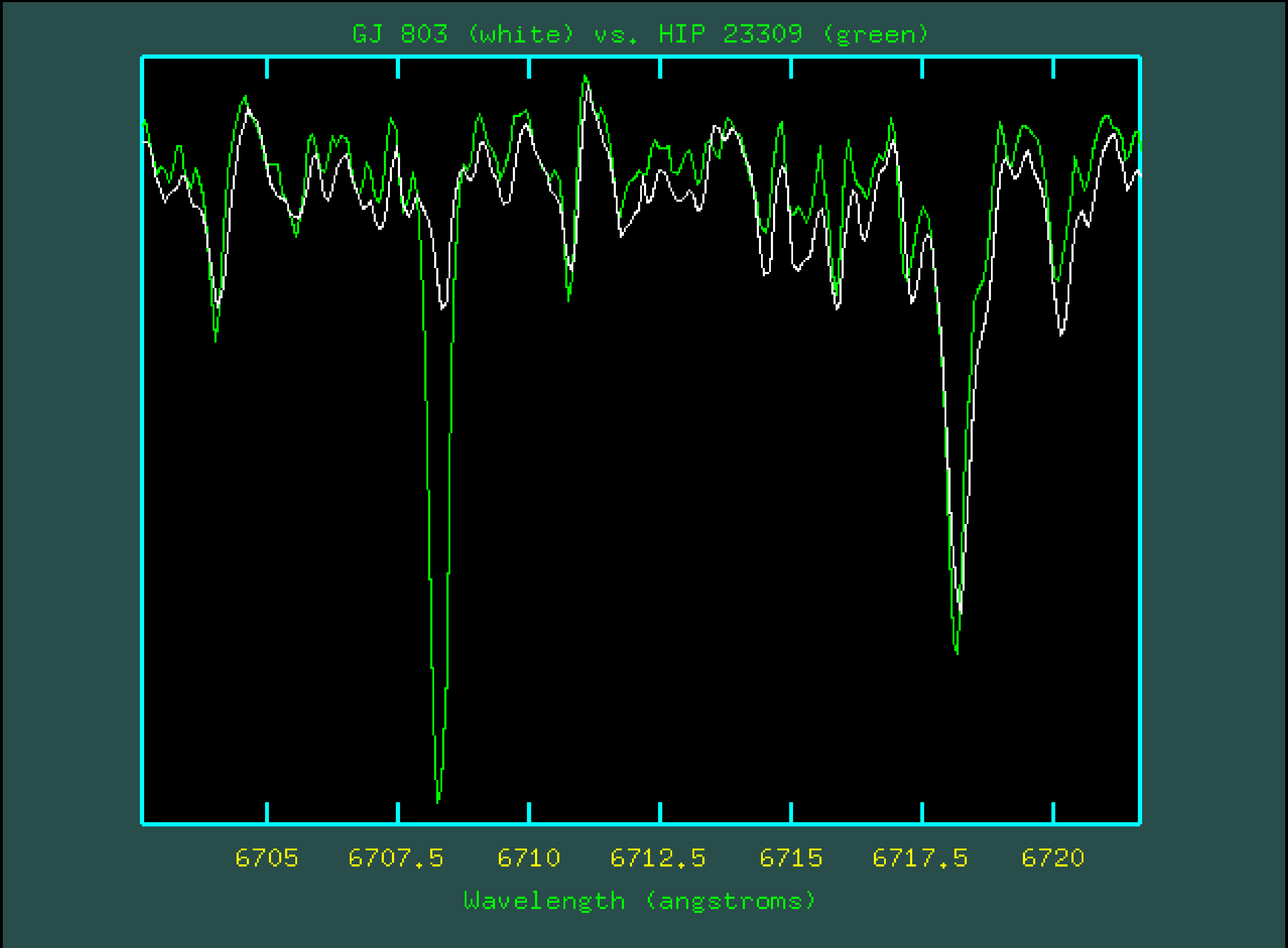
Lithium depletes with age



Pinsonneault 1997

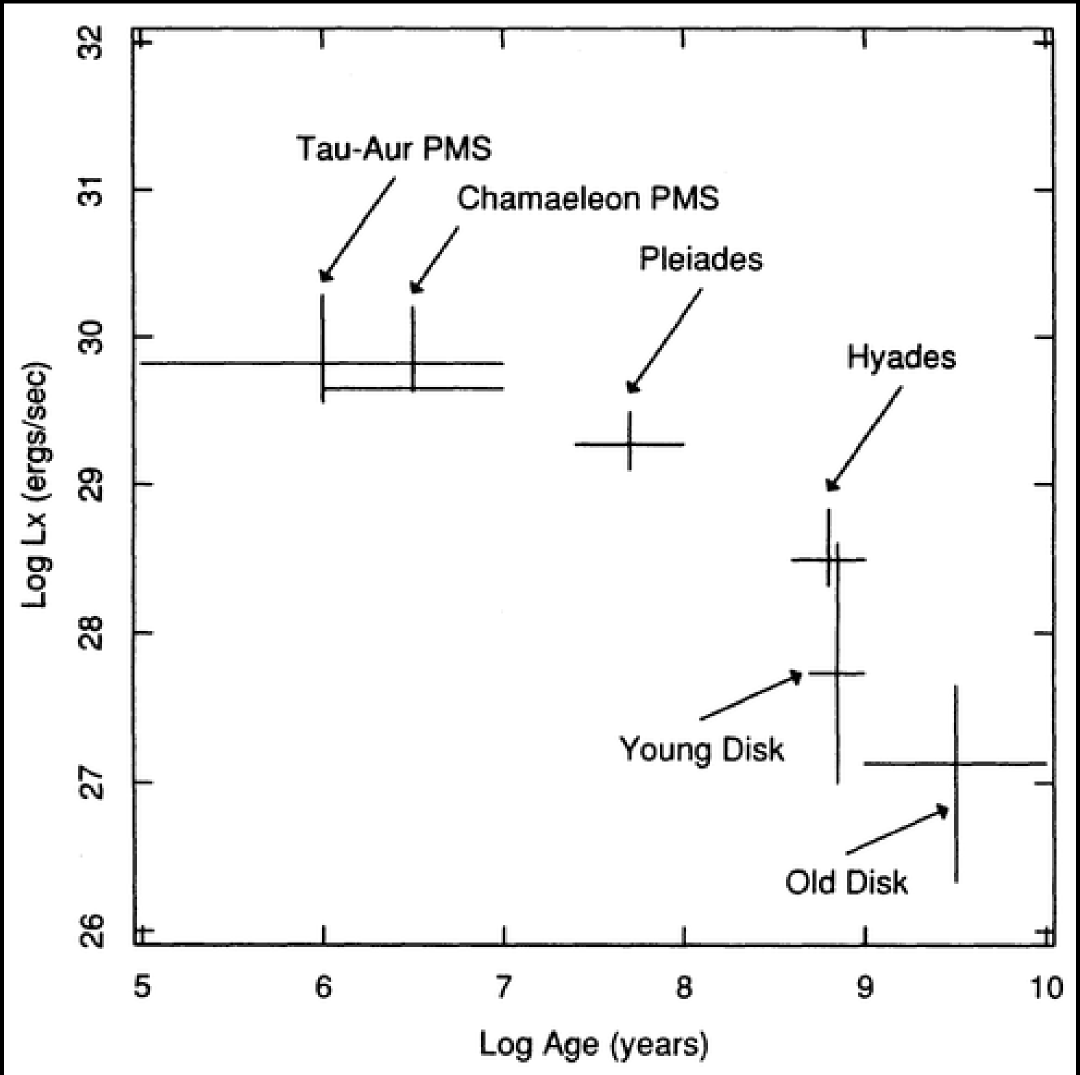
Large lithium abundance = young star




GJ 803 (white) vs. HIP 23309 (green)
6705
6707.5
6710
6712.5
6715
6717.5
6720
Wavelength (angstroms)

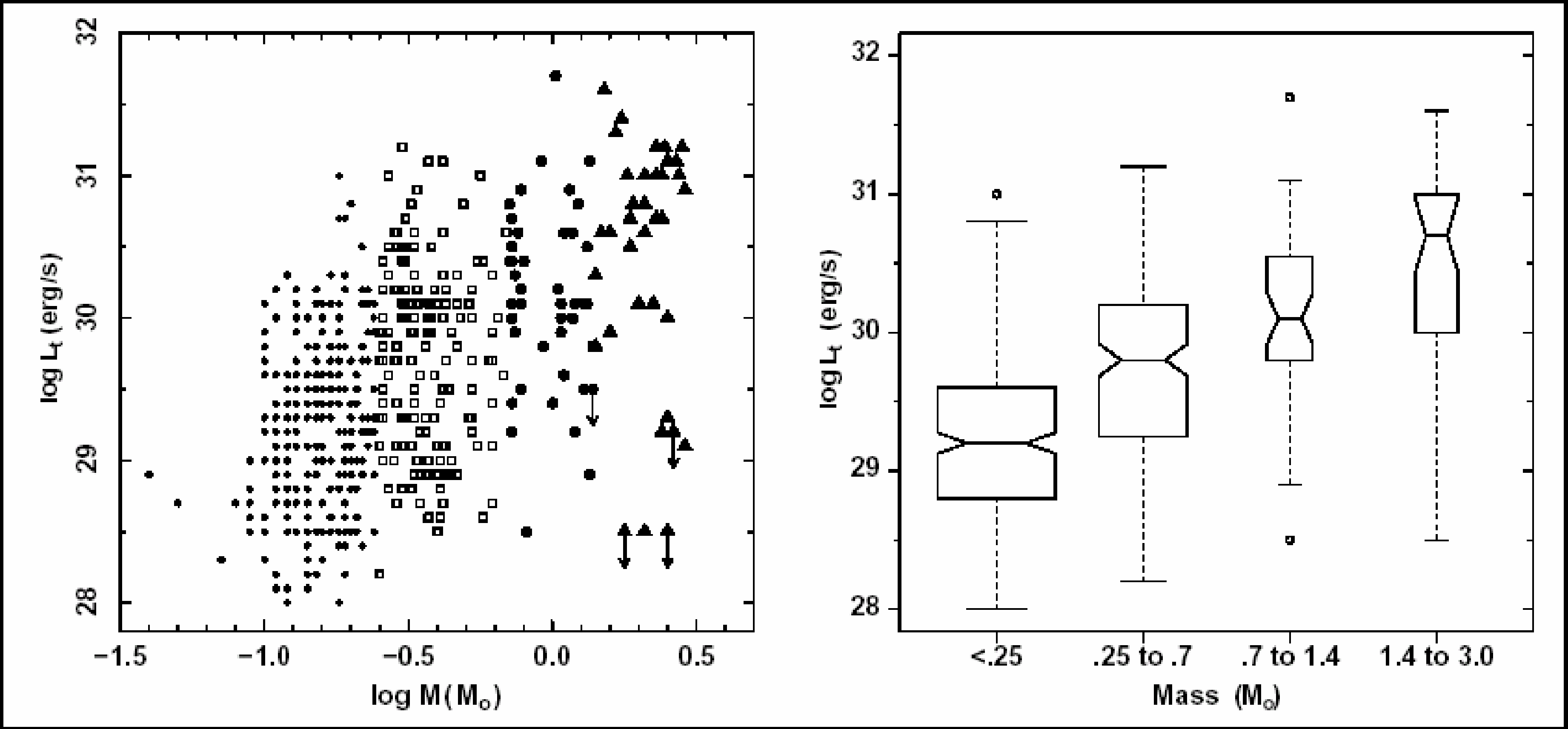
X-ray emission of low-mass stars declines with age

Median x-ray luminosity



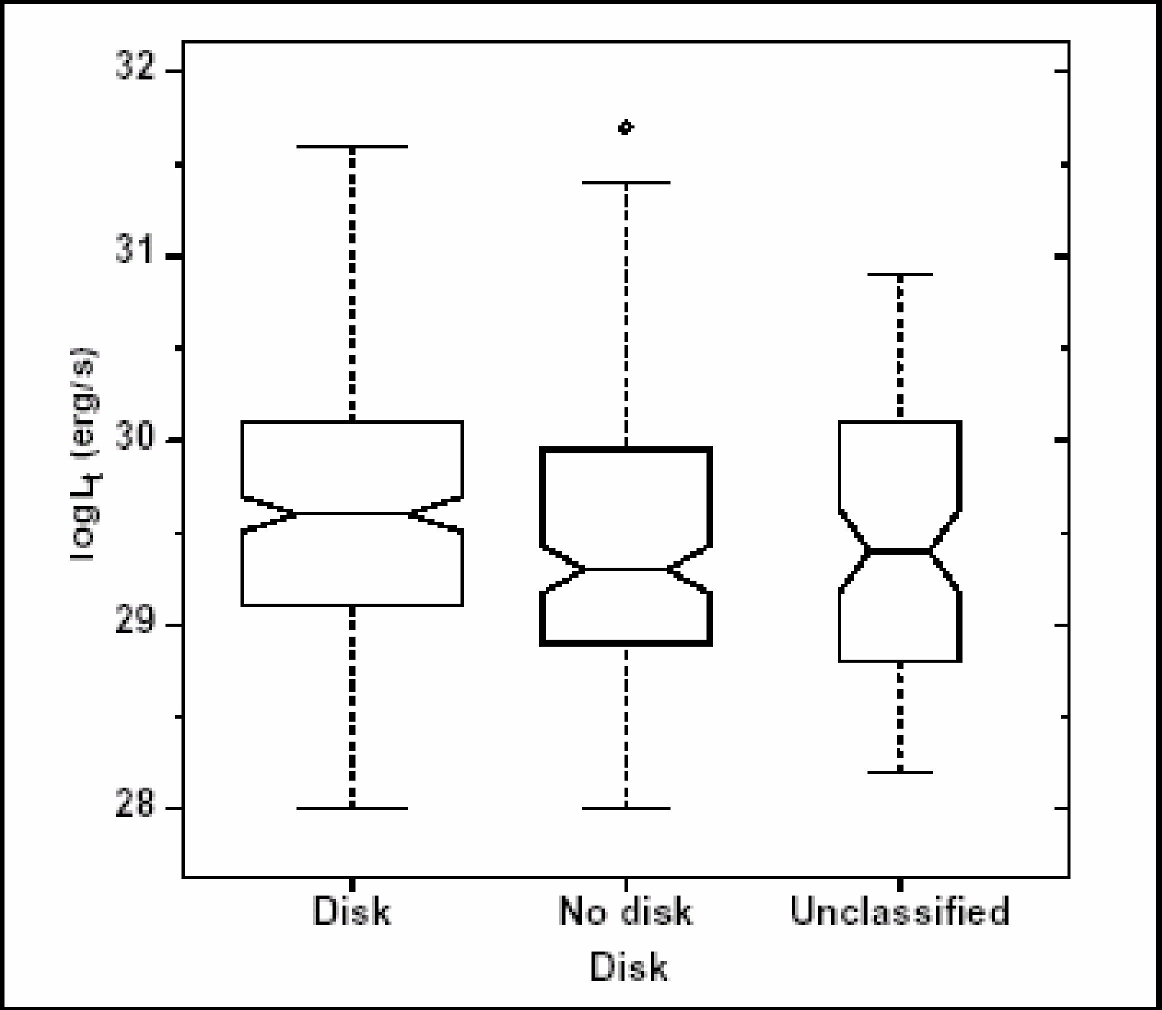
Damiani *et al*. 1995

X-ray emission vs. stellar mass



Feigelson et al. 2003, ApJ 548:911

X-ray emission is unaffected by disks



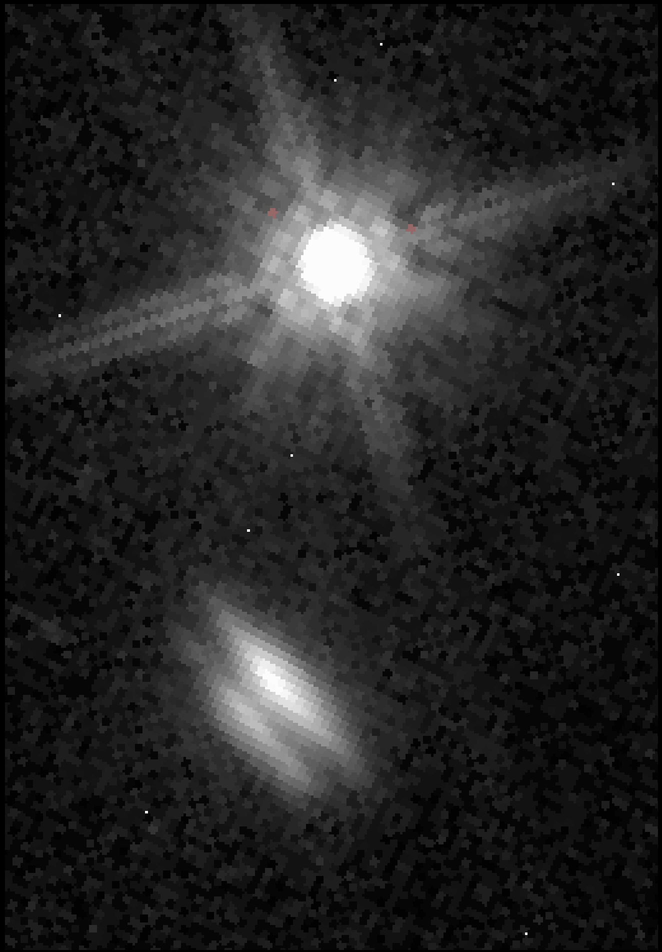
Feigelson et al. 2003, ApJ 548:911

Detecting disks in T Tauri stars

- Disks manifest themselves via infrared and UV excesses, veiling, and $H\alpha$ emission
- Can we detect them more directly?

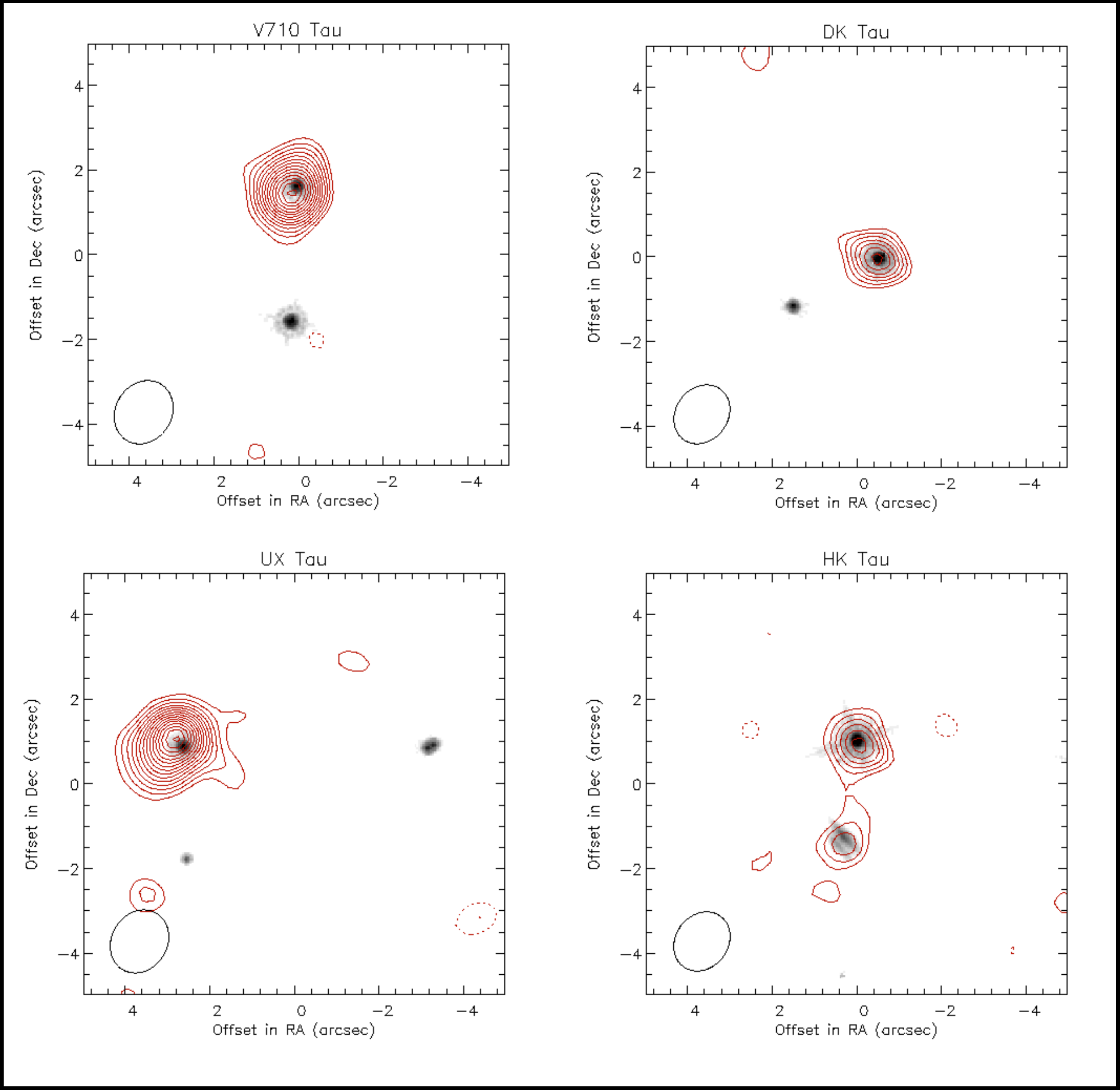
Edge-on disks can be imaged in scattered visible or IR light

Grosso et al. 2003 ApJ 586:296

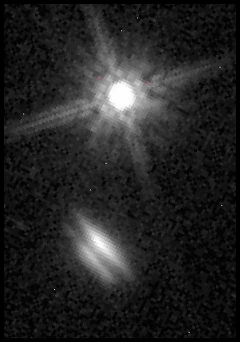


Stapelfeldt et al. 1998 ApJ 502:L65

Scattered light isn't the whole story:

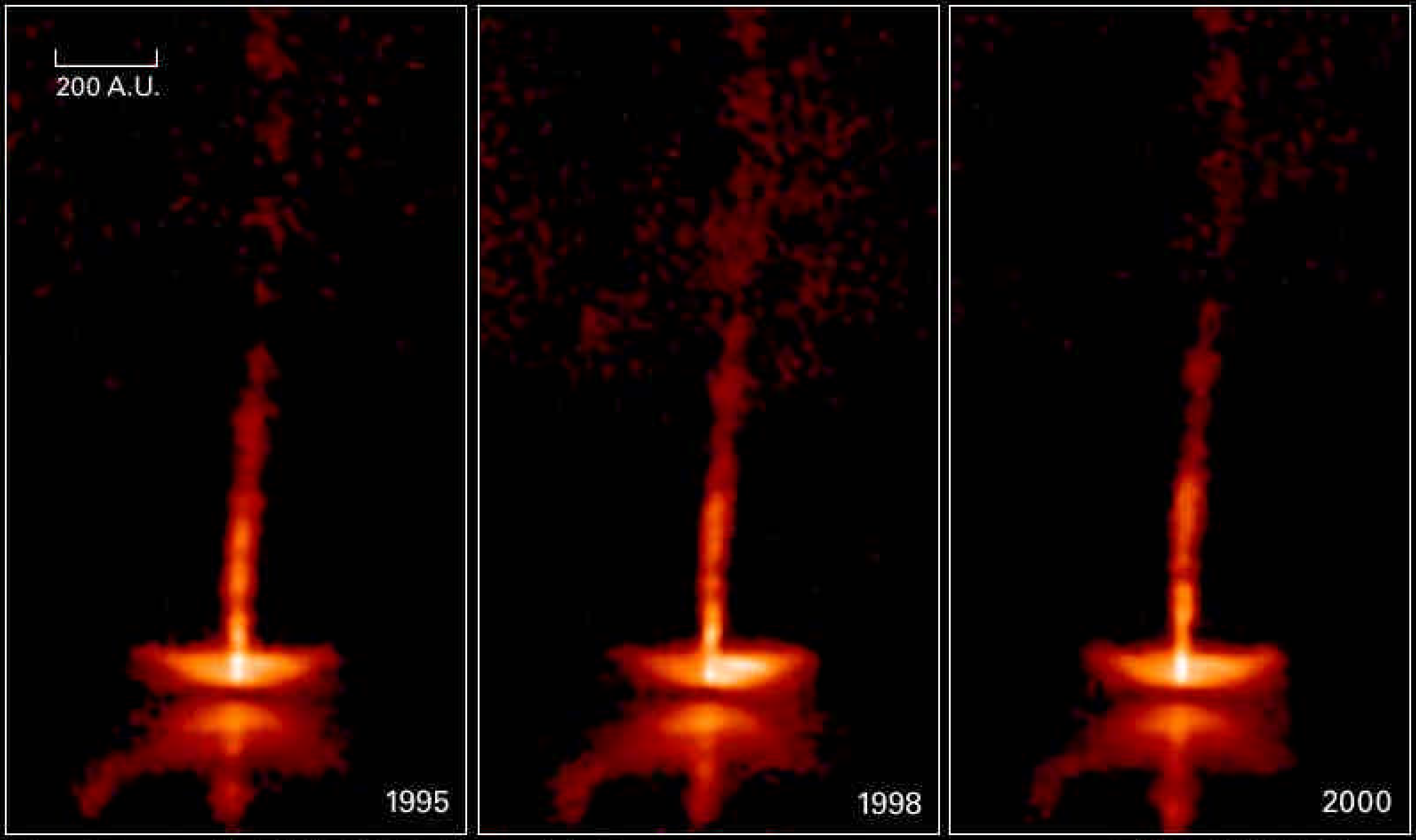


Red contours show 1.3 mm emission, which traces the disk mass.



Jensen & Akeson 2003 ApJ 584:875

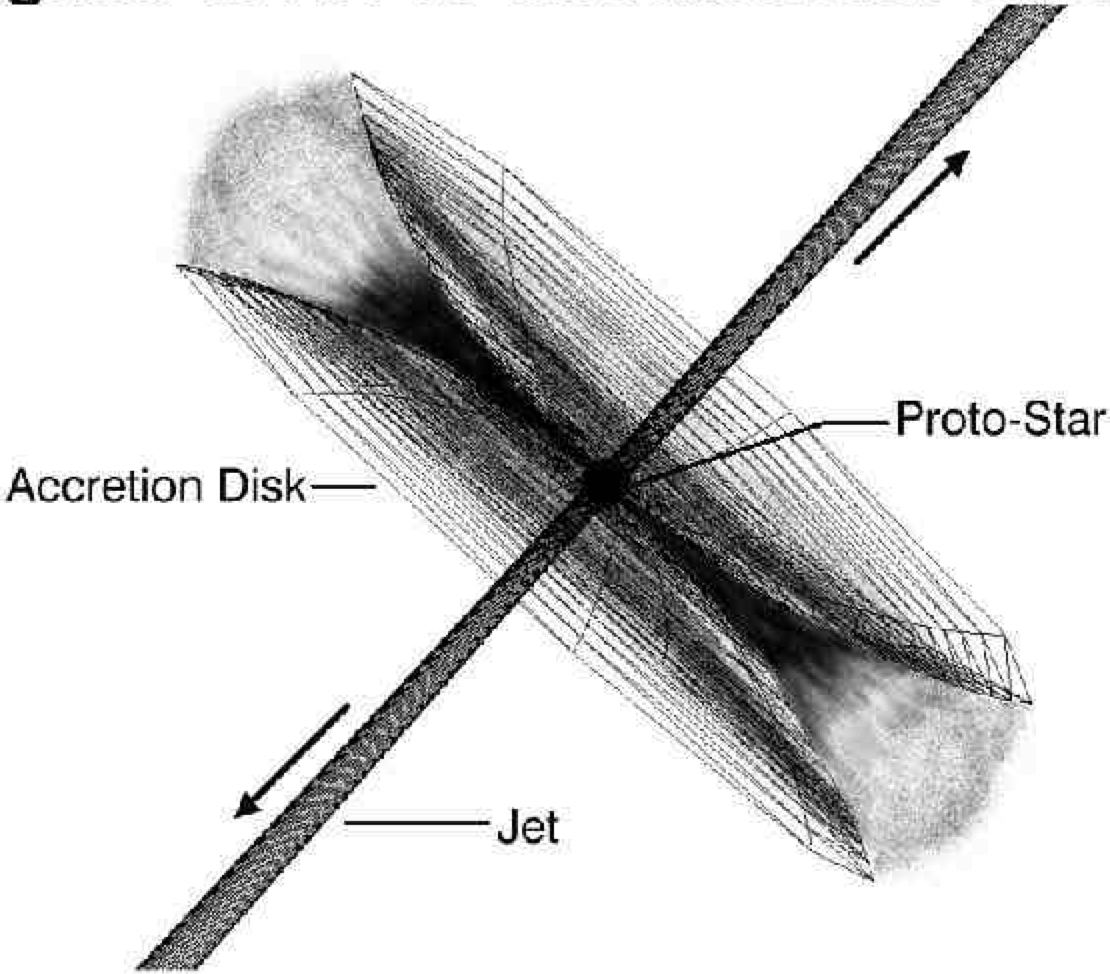
Many TTS have bipolar jets



The Dynamic HH 30 Disk and Jet HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b

Diagram of HH 30 Circumstellar Disk & Jet



Detecting disks in T Tauri stars

- Disks manifest themselves via infrared and UV excesses, veiling, and Hα emission
- Can we detect them more directly?
- Yes, but only in special cases (edge-on geometry) or with limited resolution (~ 0.1 arcsec with millimeter interferometry or thermal infrared imaging with large telescopes)
- Optical/IR interferometers can explore disk structure on AU scales

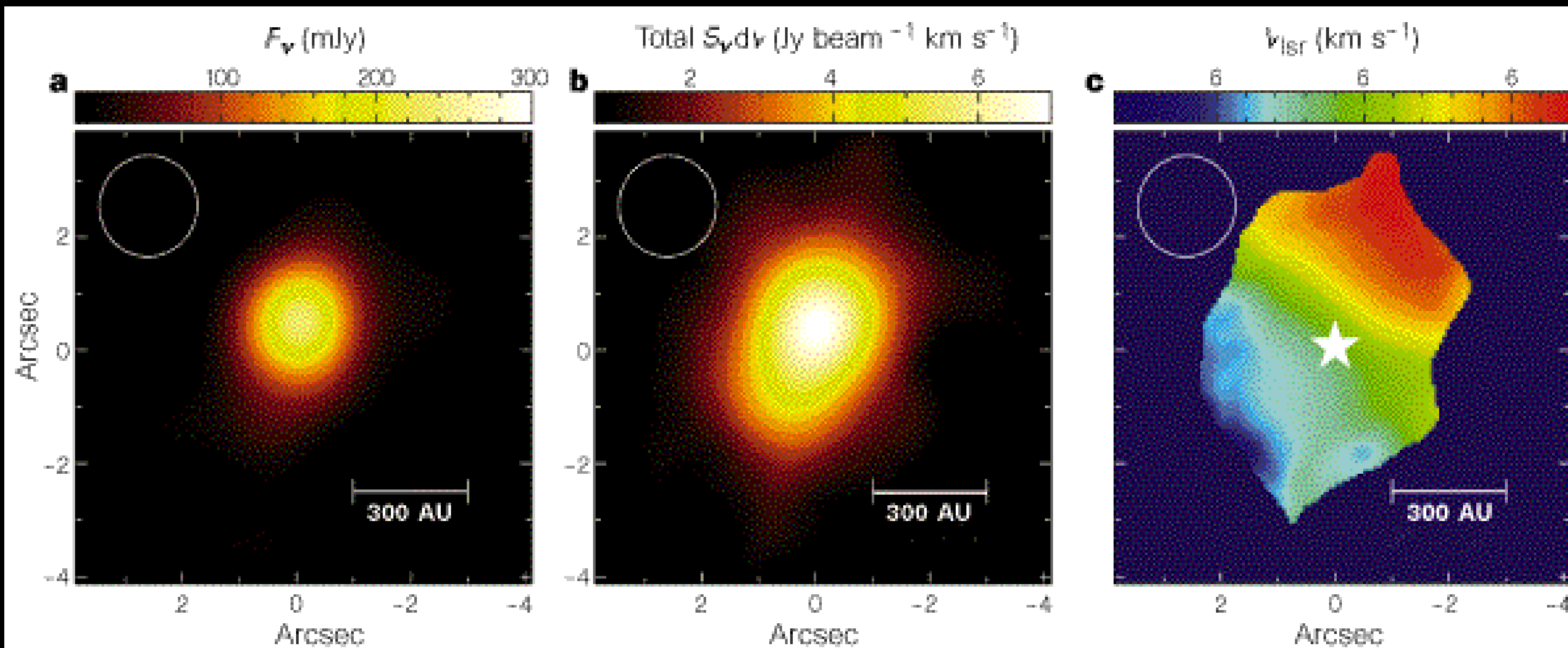
Herbig Ae/Be stars

- Intermediate mass (2-10 M_{Sun}) counterparts to T Tauri stars.
- Defined as:
  - Spectral type of A or B
  - Shows emission lines
  - Infrared excess due to circumstellar dust
  - Luminosity class III, IV, or V
  - (This differs from Herbig's original definition; doesn't require association with nebulosity)

Herbig Ae/Be circumstellar material

- Disks or envelopes?

Circumstellar material around the Herbig Ae star MWC 480

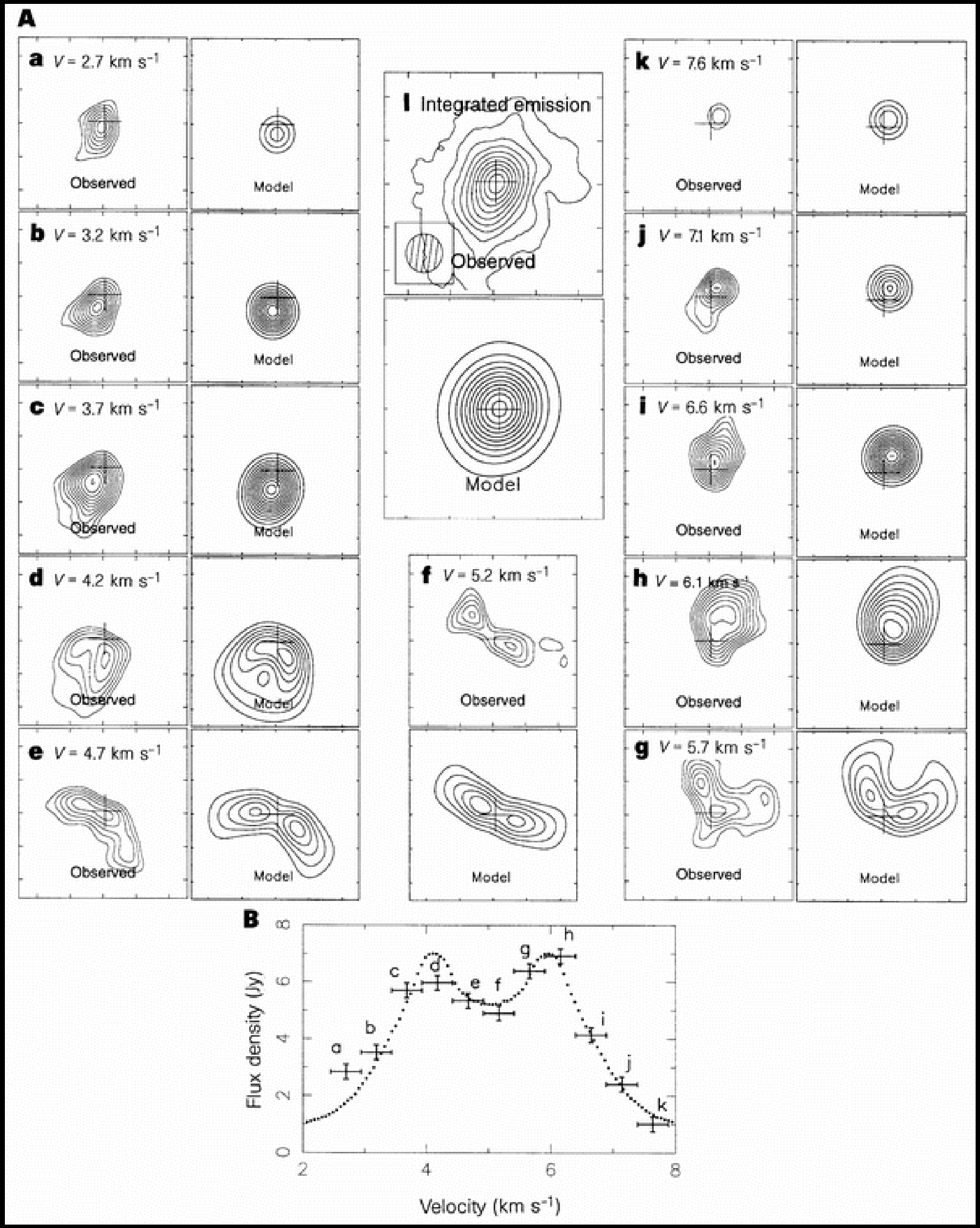


1.3 mm continuum

CO 2→1

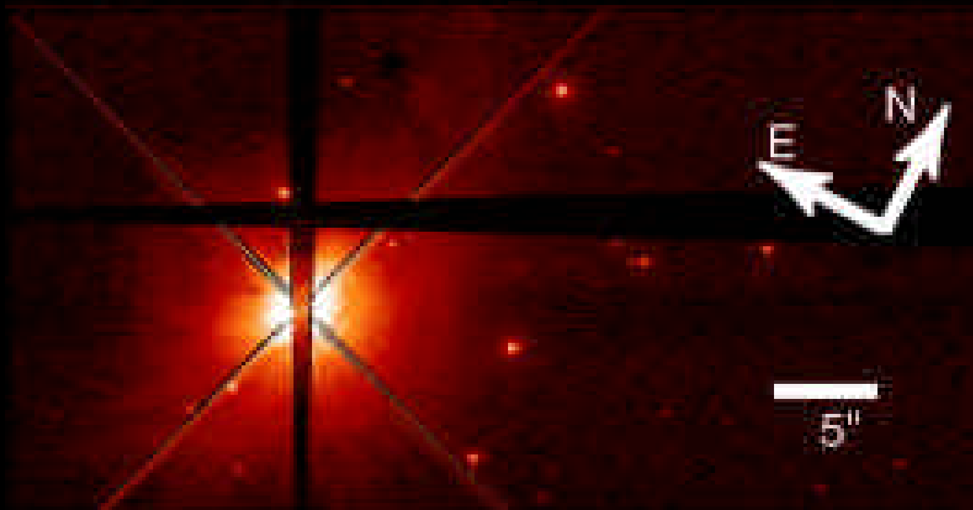
Velocity of CO emission

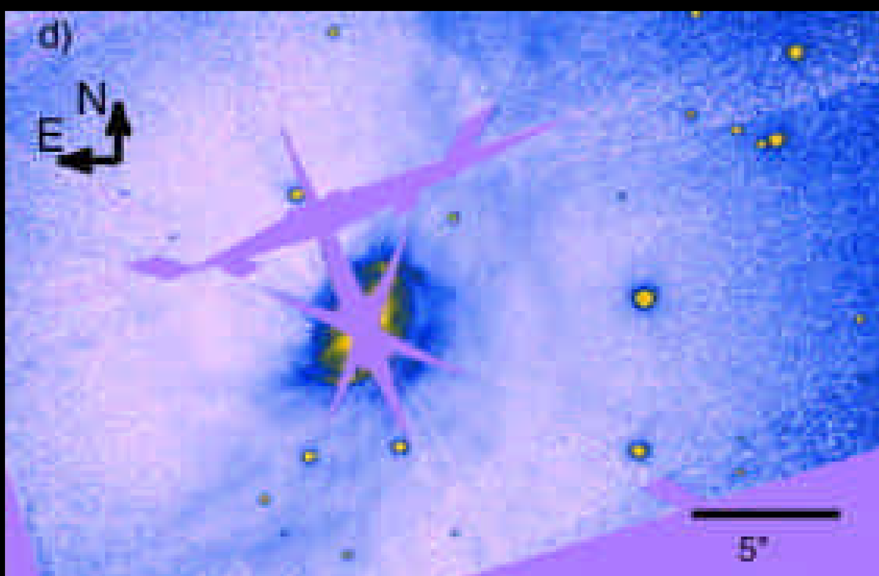
Mannings, Koerner, & Sargent 1997 Nature 388:555



CO emission at different velocities is well-matched by a model of a disk in Keplerian rotation

Mannings, Koerner, & Sargent 1997 Nature 388:555





The Herbig Be star HD 100546: both a disk and an envelope?

STIS coronagraphic imaging from Grady et al. 2001 AJ 122:3396

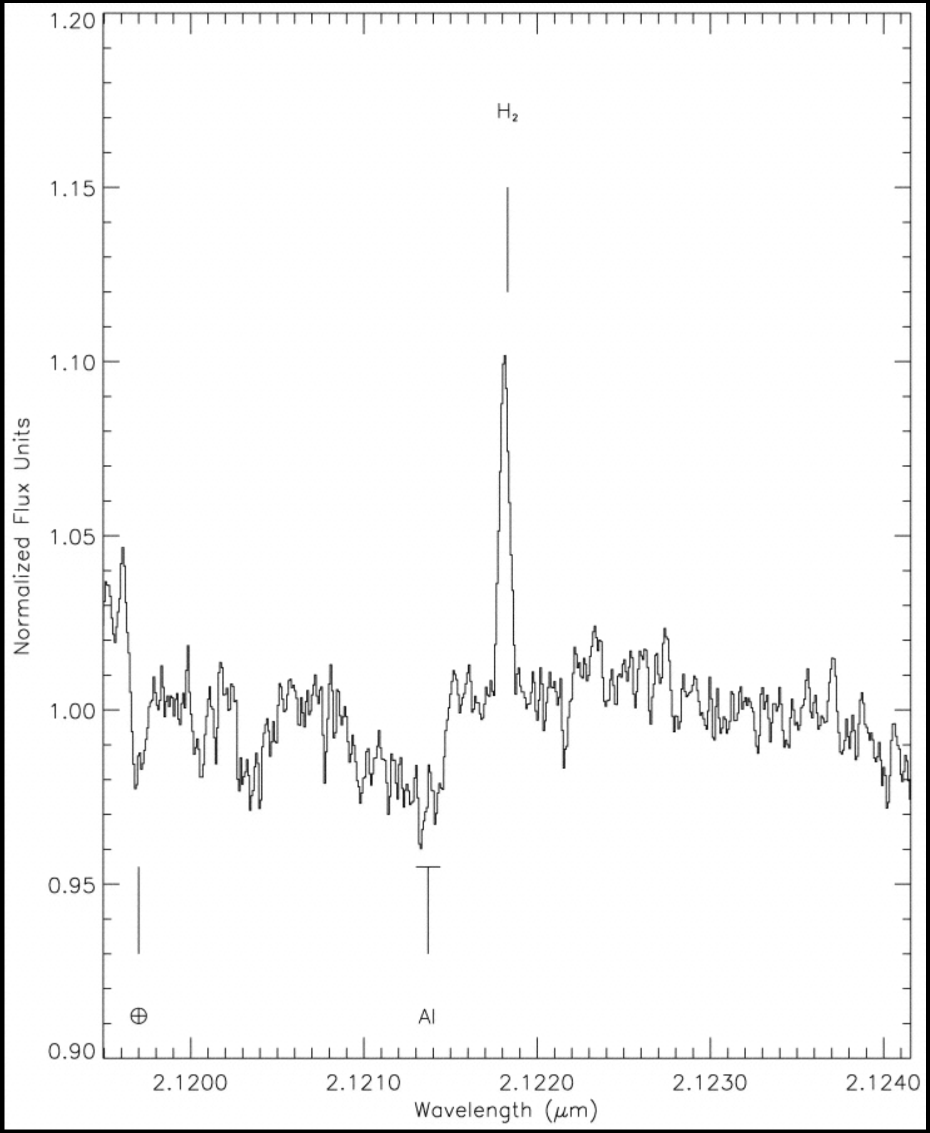
T Tauri star vital statistics

- Distances: Most are 125 pc (Taurus-Auriga, Ophiuchus) or farther (Orion is 400 pc)
- Some of the isolated “Post T Tauri stars” (e.g. TW Hya) are closer: 50-100 pc
  - Star with $R = 1\ R_{Sun}$ at d=50 pc has angular diameter of 0.2 mas
- Typical K magnitudes: 7-10
- Typical R magnitudes: 9-13

Open questions in young star research

- How long do disks persist?
- Do gas disks persist after the dust goes away?
- What is the relationship between disks and stellar rotation?
- What is the geometry of the circumstellar material in Herbig Ae/Be stars?
- Whatever your next interferometric observations shows…

A gas-only disk?



- H_2 emission detected in a WTTS with no IR excess
- Perhaps dust has clumped or dispersed?

Bary et al. 2003 ApJ 576:L73

Some stars are binaries!