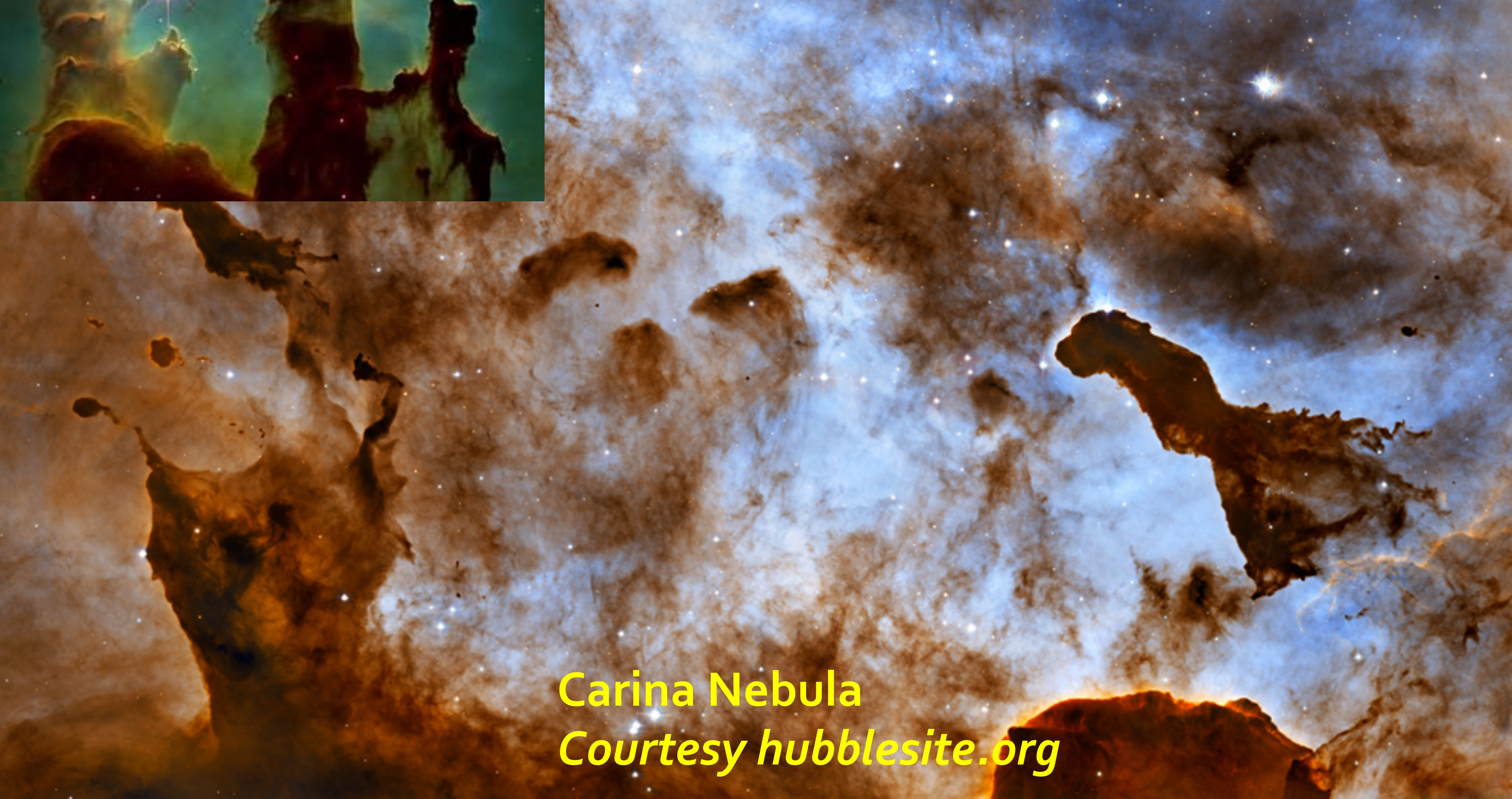
Challenges in low-mass star formation in the (space) ultraviolet

Gregory J. Herczeg
Kavli Institute for Astronomy and Astrophysics,
Peking University

Eagle Nebula
Courtesy hubblesite.org



Carina Nebula
Courtesy hubblesite.org

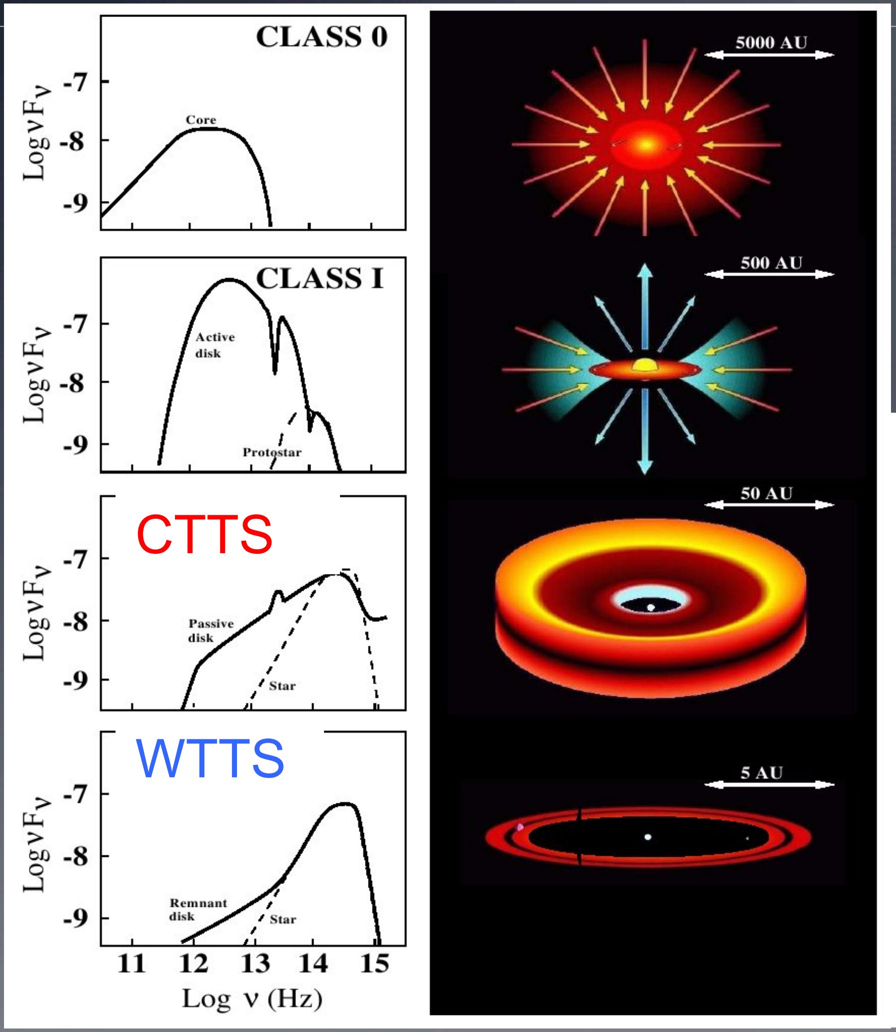
Orion with Proplyds

Courtesy hubblesite.org

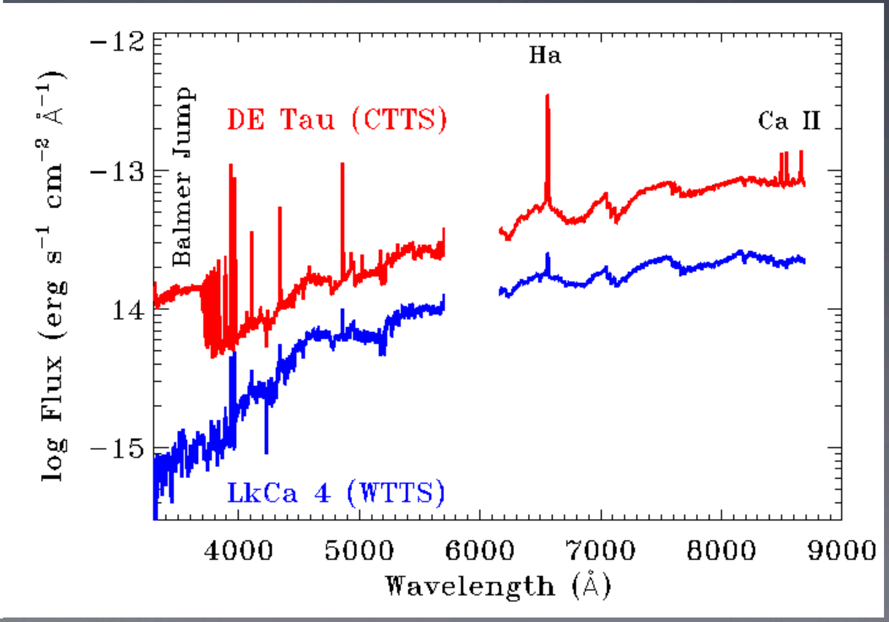
UV and Star Formation

- Massive Star Formation: feedback
  - PDRs (Hollenbach & Tielens)
  - Proplyds (O stars photoevaporating nearby disks)
- **Low-mass star formation and the FUV**
  - **Envelope and disk chemistry**
  - **Accretion/outflow physics**
- Challenges for the next decade+ in low-mass star formation for the UV

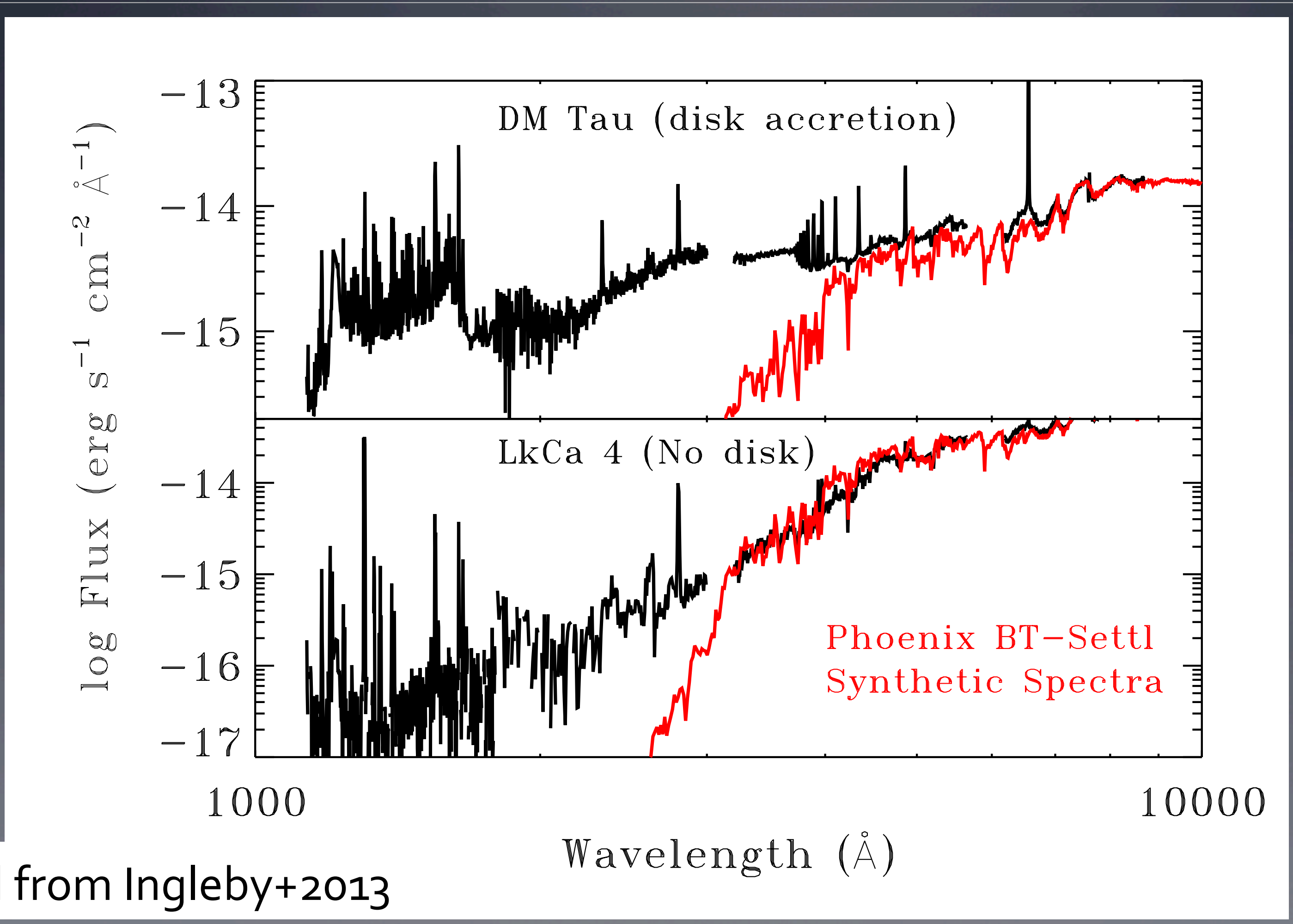
Pre-main sequence stellar evolution



Class 0 and I protostars: Embedded in envelopes, only visible in IR-mm



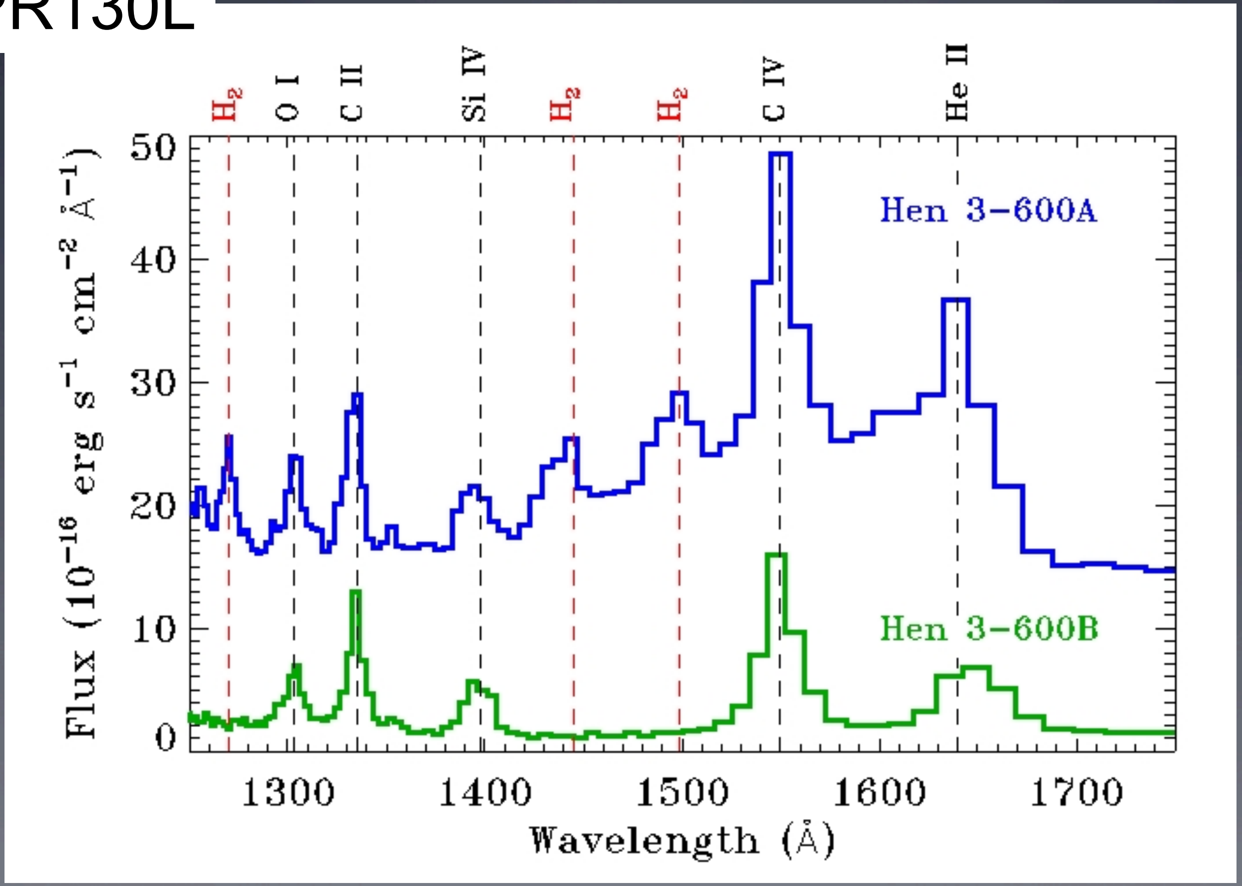
Excess NUV/FUV emission



Adapted from Ingleby+2013

Excess NUV/FUV emission

ACS SBC/PR130L

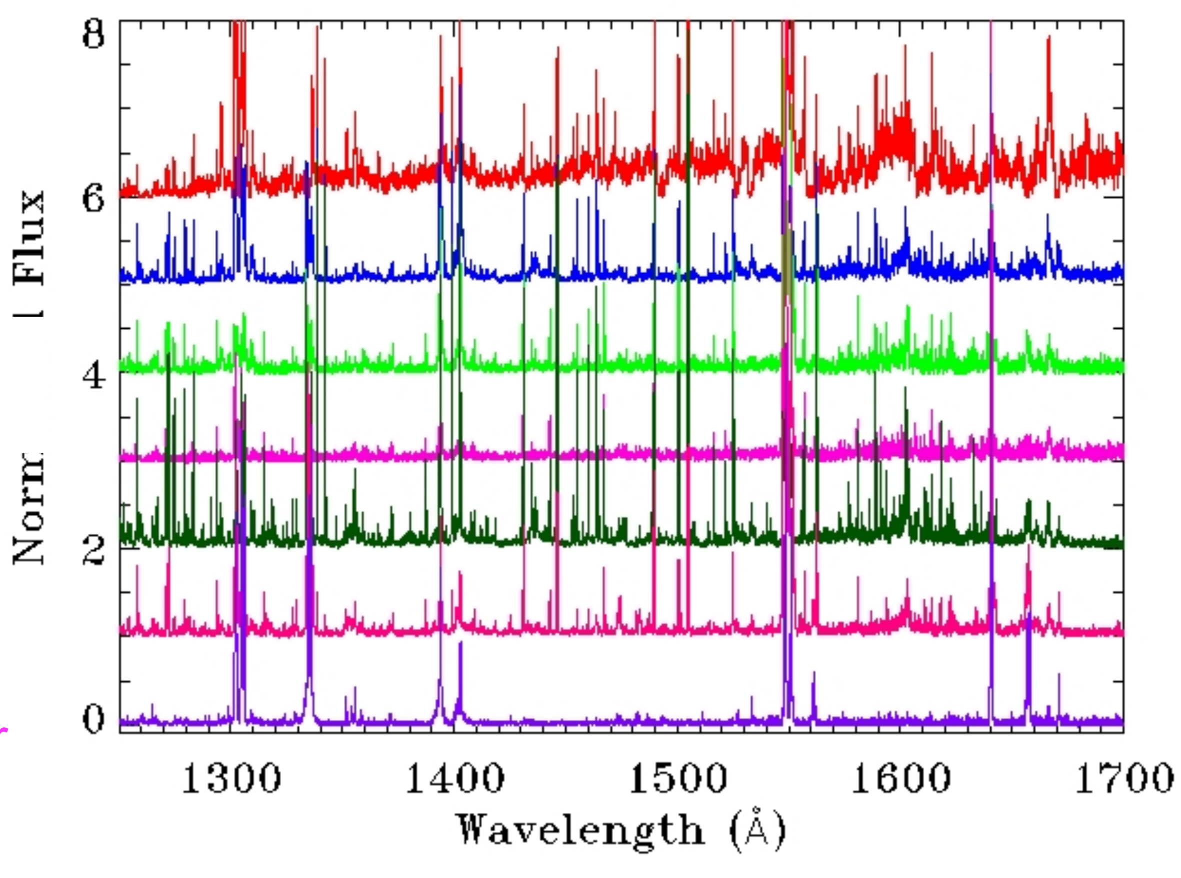


Excess NUV/FUV emission

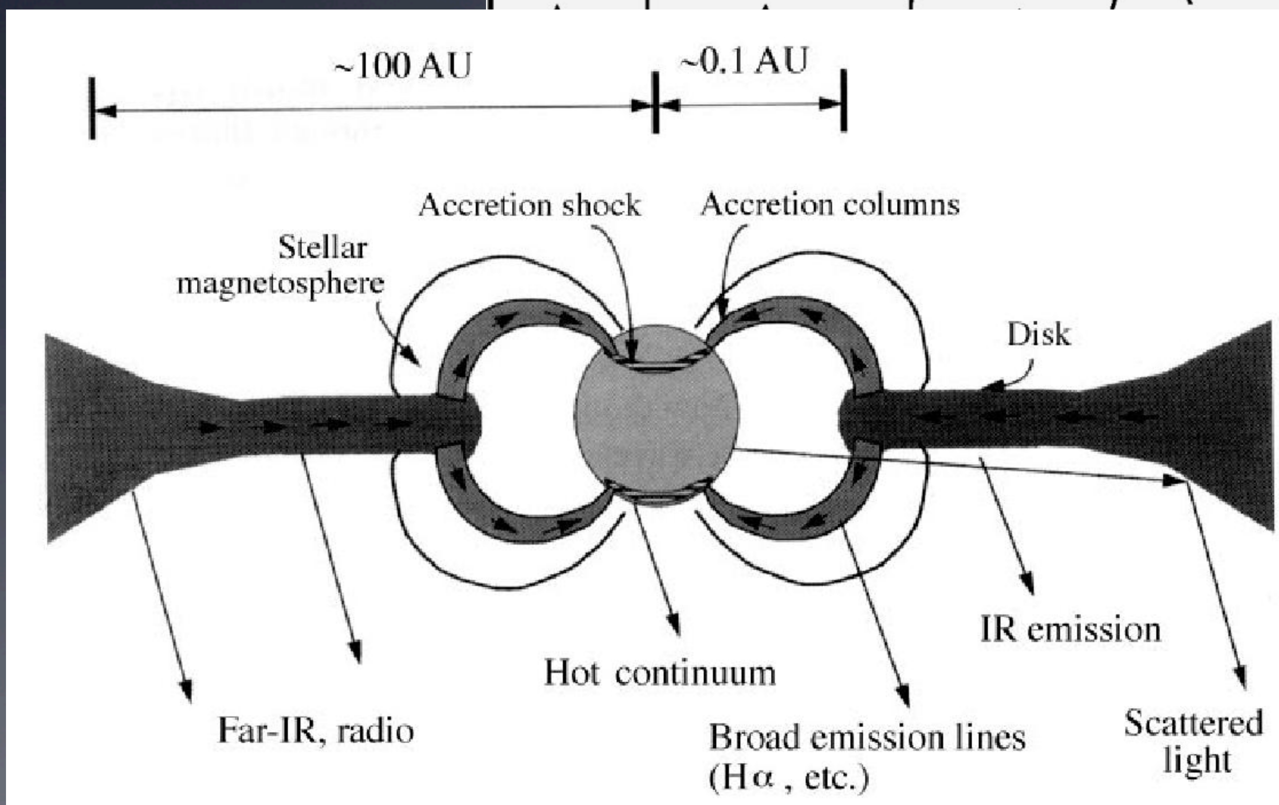
COS

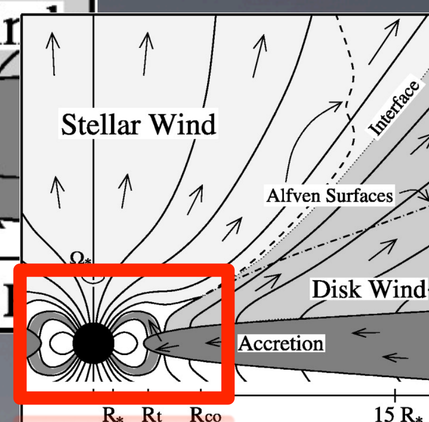
Classical T Tauri Stars

Weak-lined T Tauri Star



Cartoon physics of young stars



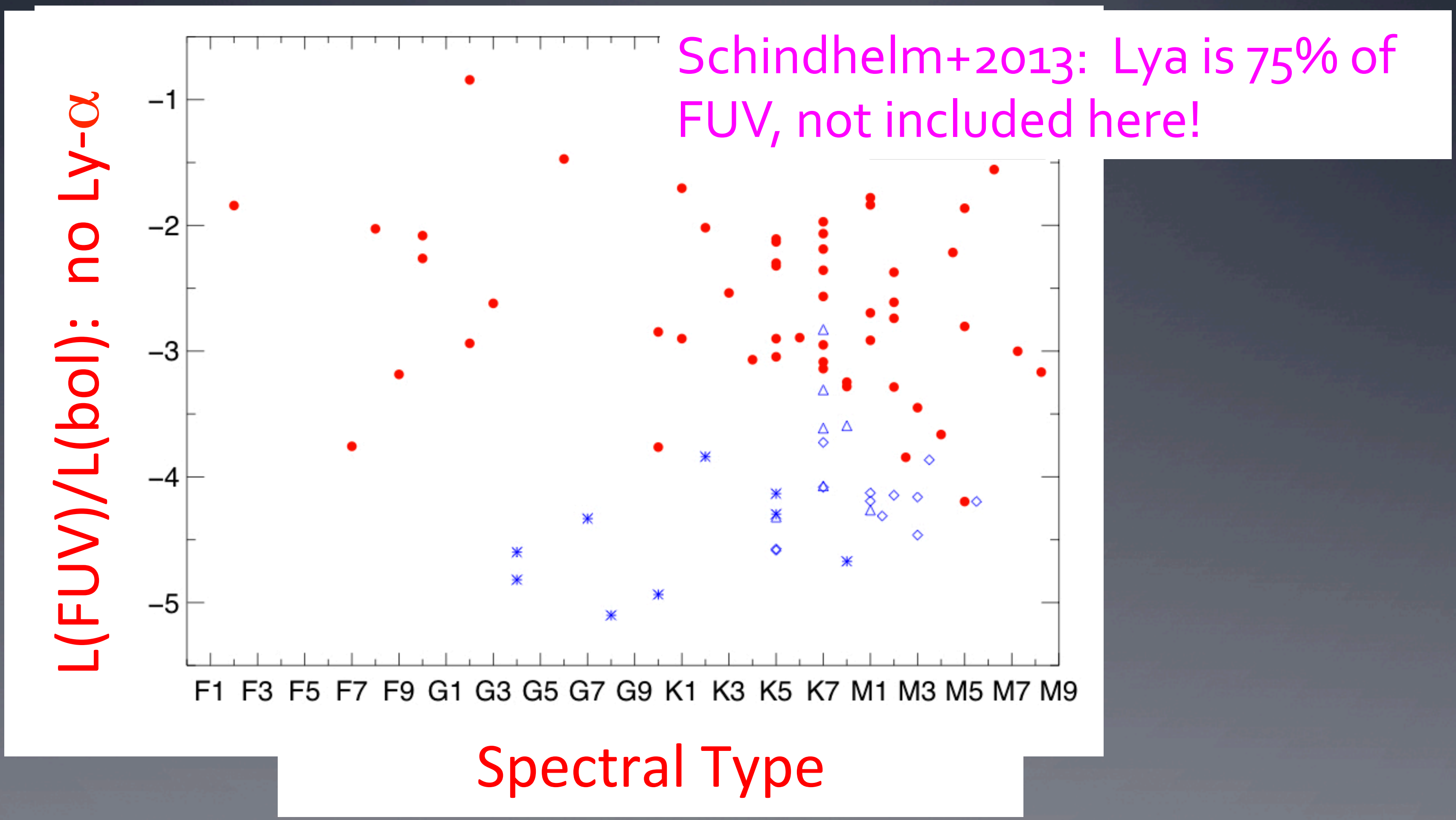


Hartmann (1998)

Matt & Pudritz 2005

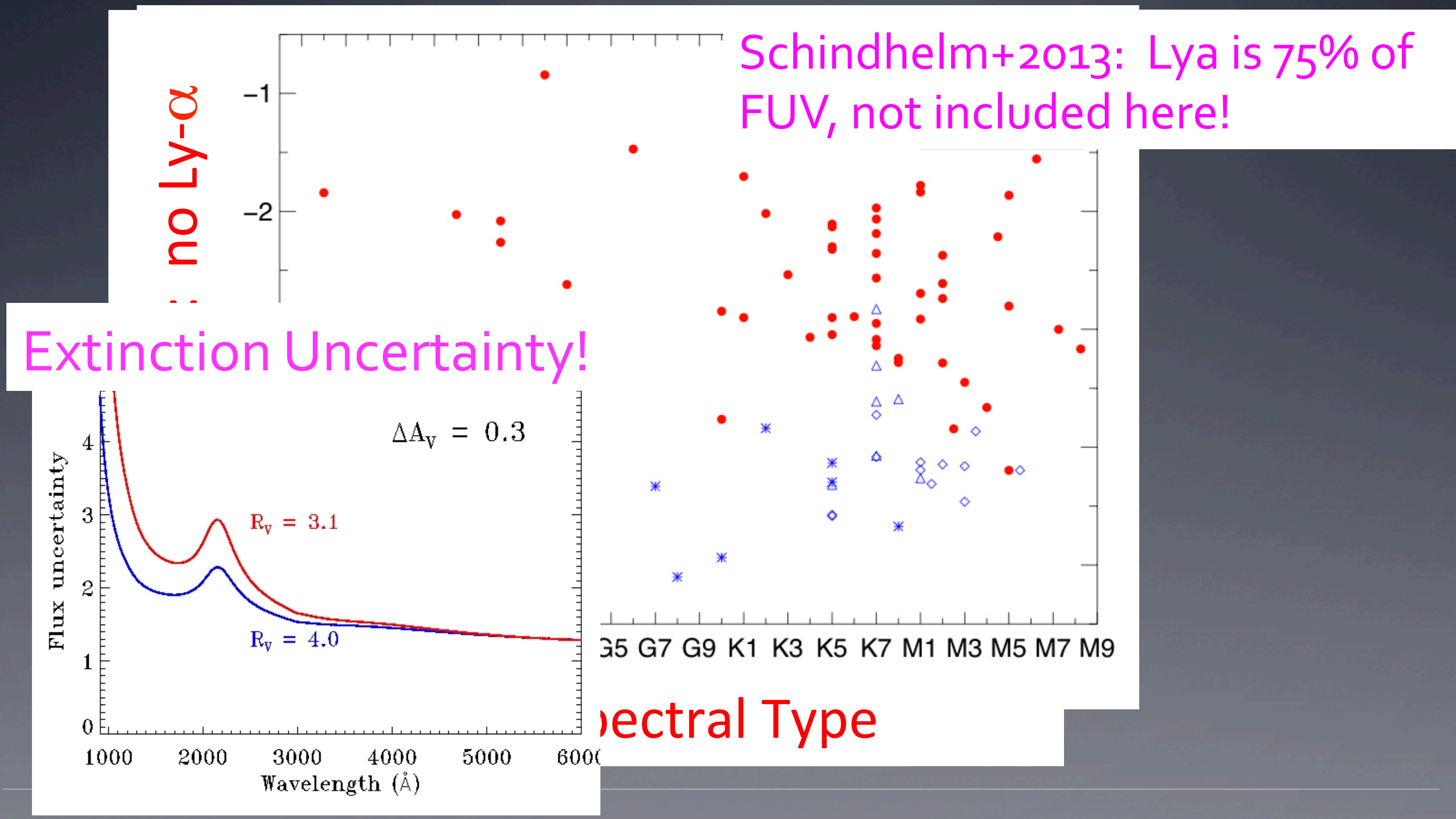
FUV radiation fields

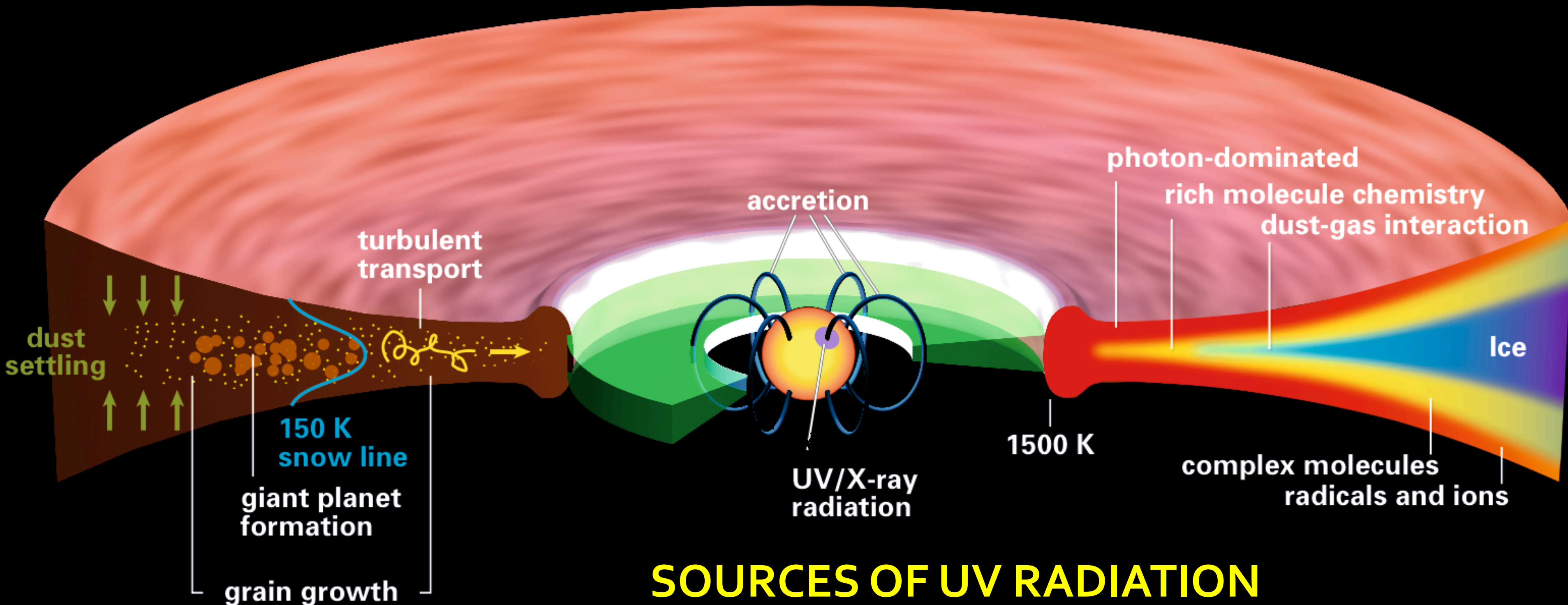
(Ingleby+2011, Yang+2012, Gomez de Castro & Marcos-Arenal 2012)

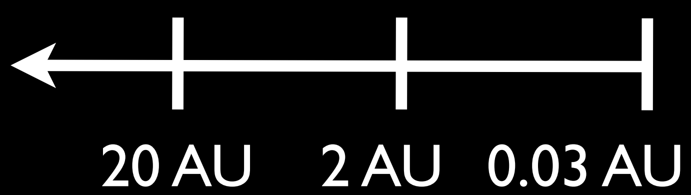


FUV radiation fields

(Ingleby+2011, Yang+2012, Gomez de Castro & Marcos-Arenal 2012)







Cartoon from Semenov & Henning review

SOURCES OF UV RADIATION

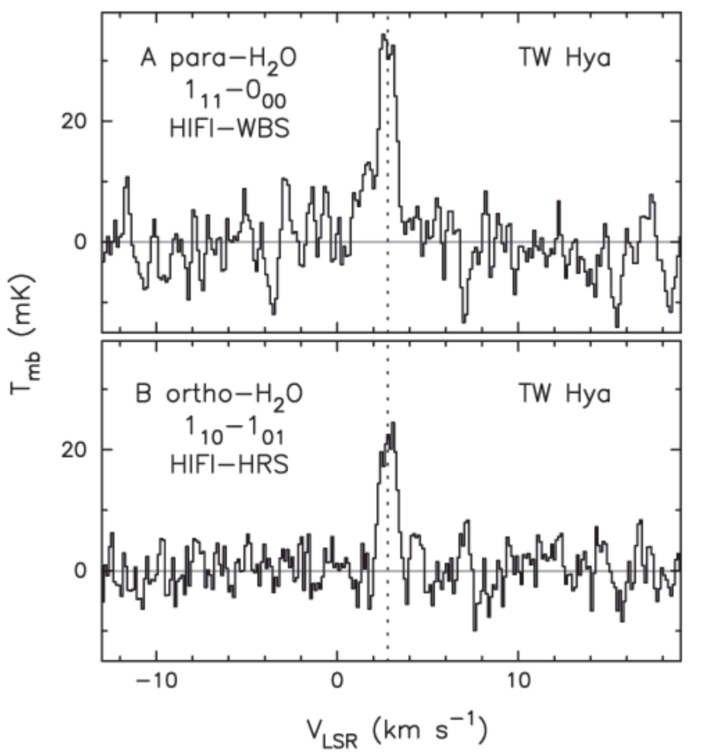
Disk Surface: Central Star; nearby O stars

Internal fields: X-rays, Cosmic Rays?, Radioactive decay
(e.g., Glassgold+1997, Finocchi & Gail 1997, Walsh+2012, Cleeves+2013

Disk/Solar System and the FUV

- H_2O photo-dissociation and photo-desoprtion (Hogerheijde+2010)
- Molecular dissociation of some molecules (Bergin+2003, Pascucci+2009)
- CO isotopic fractionation (Lyons+)
- General disk modeling: chemistry and PAH heating (e.g., van Zadelhoff+, Woitke+, Bruderer+, Aikawa+,Aresu+)
- Tests: disk chemistry and solar system abundances

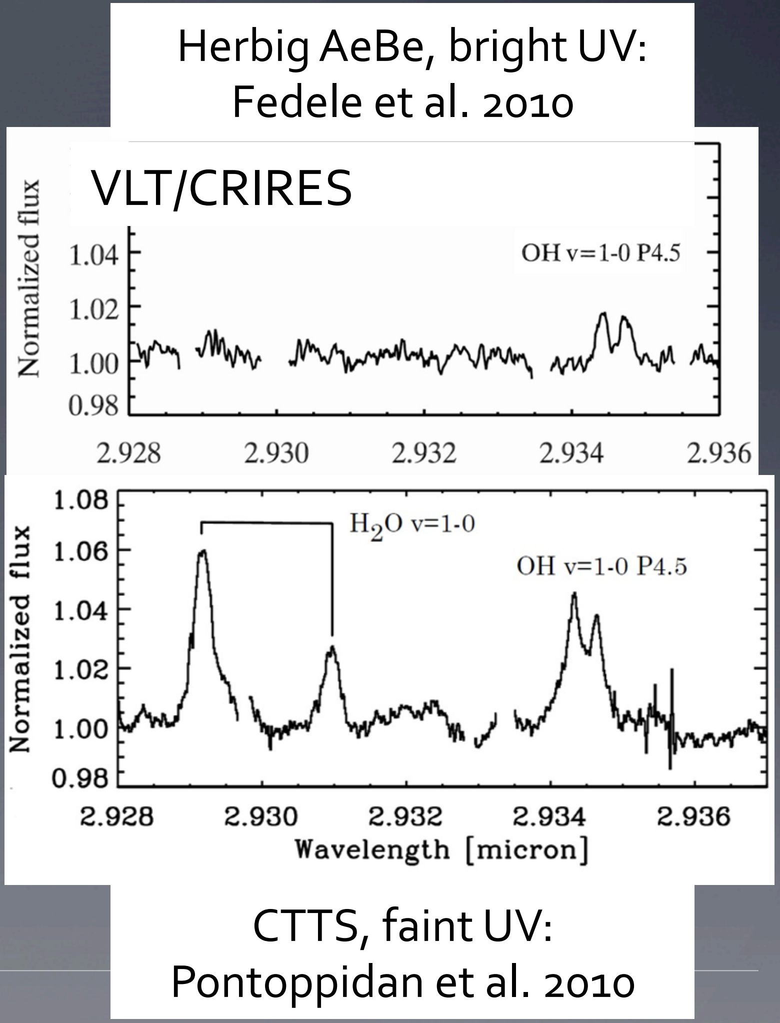
Herschel/HIFI



Cold H_2O in the TW Hya disk
Hogerheijde+2010

Disk/Solar System and the FUV

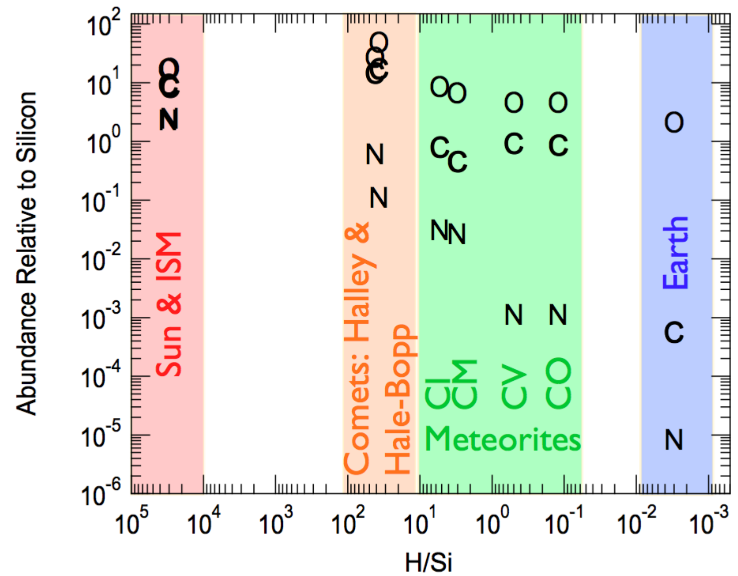
- H_2O photo-dissociation and photo-desoprtion (Hogerheijde+2010)
- Molecular dissociation of some molecules (Bergin+2003, Pascucci+2009)
- CO isotopic fractionation (Lyons+)
- General disk modeling: chemistry and PAH heating (e.g., van Zadelhoff+, Woitke+, Bruderer+, Aikawa+,Aresu+)
- Tests: disk chemistry and solar system abundances



Disk/Solar System and the FUV

- H_2O photo-dissociation and photo-desoprtion (Hogerheijde+2010)
- Molecular dissociation of some molecules (Bergin+2003, Pascucci+2009)
- CO isotopic fractionation (Lyons+)
- General disk modeling: chemistry and PAH heating (e.g., van Zadelhoff+, Woitke+, Bruderer+, Aikawa+,Aresu+)
- Tests: disk chemistry and solar system abundances

Evidence for reset in the solar system:
C,N,O content of solar system bodies

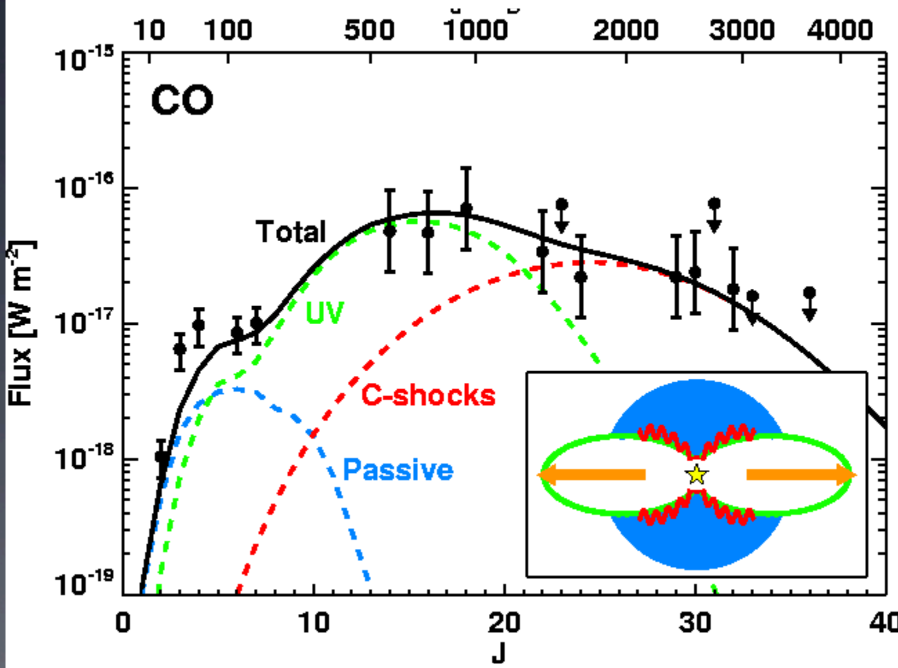


Adapted from Lee et al. by Pontoppidan/Salyk PPVI review

Envelopes and the UV

(modelling by Visser+2011)

Herschel/PACS



Van Kempen, Kristensen, et al. 2010

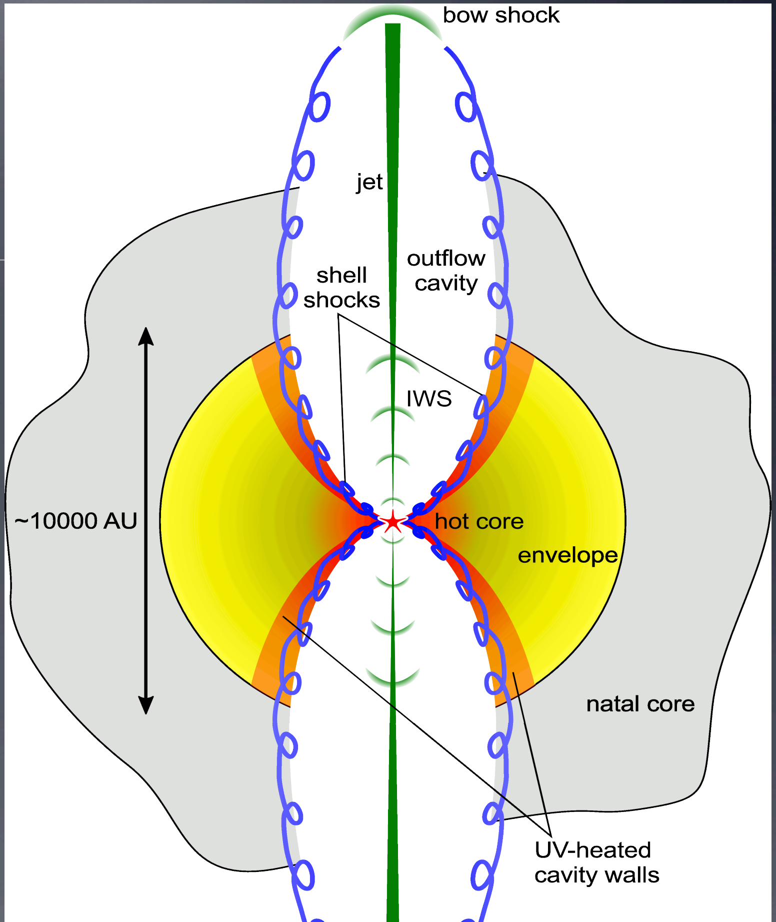


Figure courtesy R. Visser

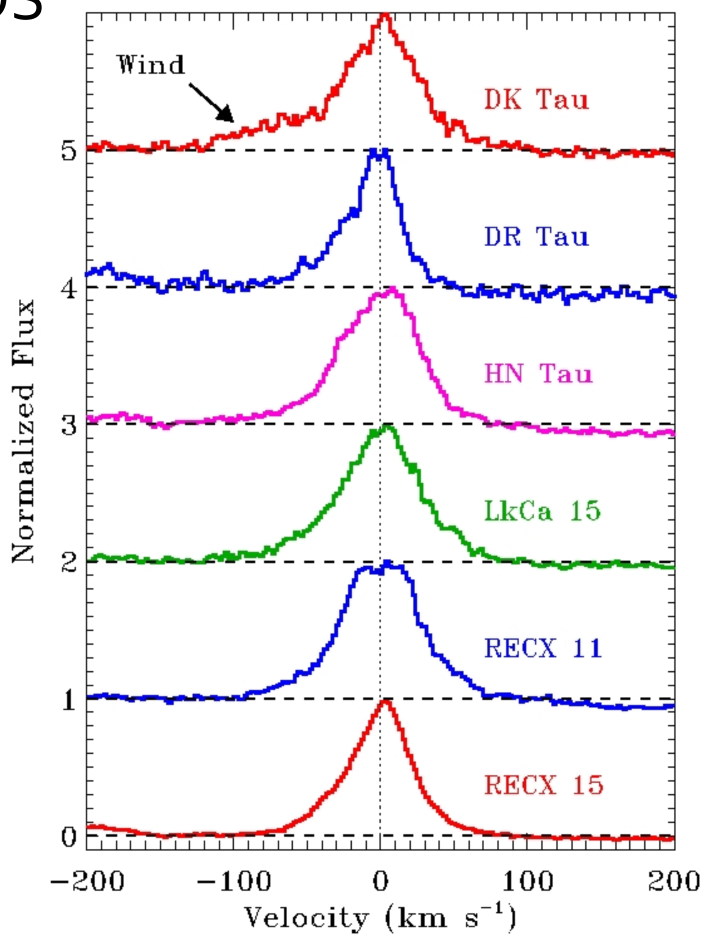
Envelopes: similar chemistry, few constraints on the UV luminosity

often assumed to be a free parameter!

H_2 and CO emission from CTTSs

e.g., Herczeg+2004, France+2011,2012, Schindhelm+2012

COS



Co-added H2 lines, adapted from France+2012

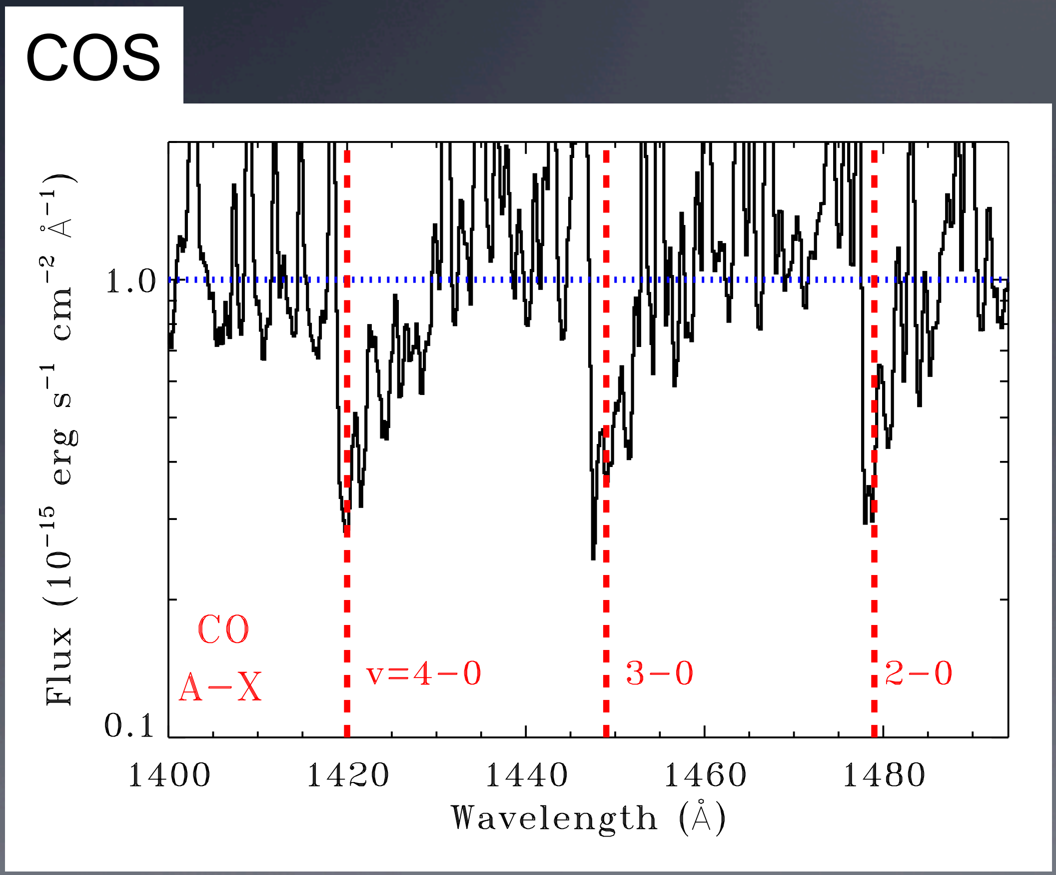
- Hundreds of lines in spectra
- Excited by wavelength coincinces with Ly-alpha (whopping bright!)

- H2: 2500 K
- CO: 500 K

- Usually probes warm disk surface layer within a few AU
  - Some cases of wind emission
  - Some cases of photoevaporation?

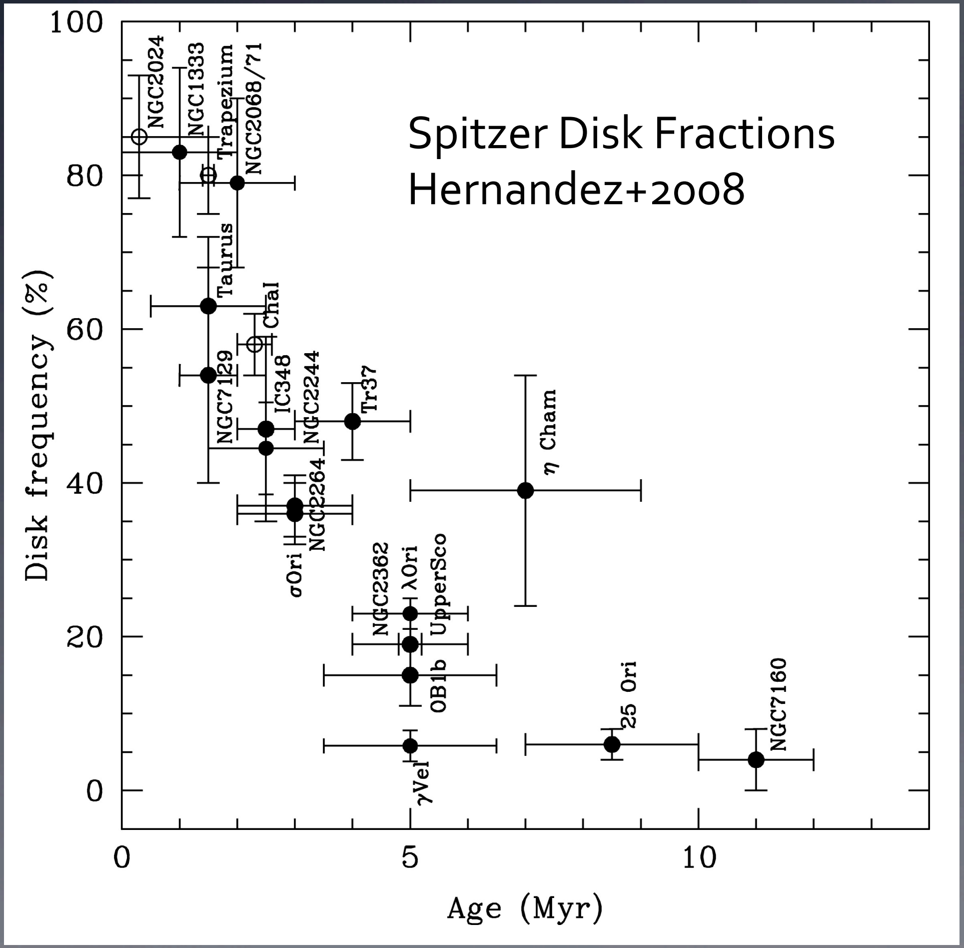
Molecular Absorption in the UV

(France et al. 2012; McJunkin et al. 2012; Yang et al. 2011)



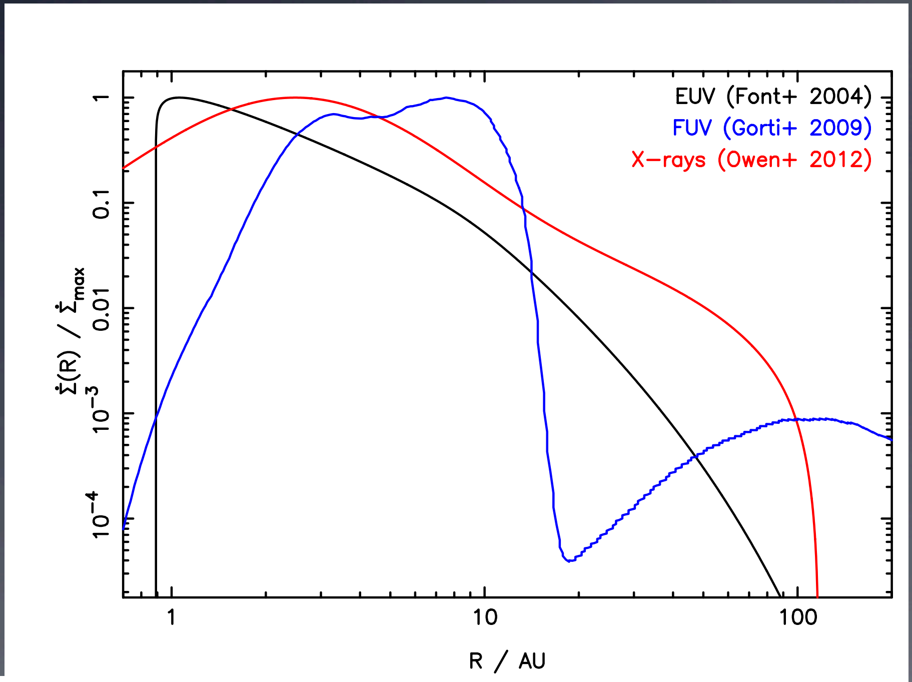
- Line of sight through disk surface
- CO: 500 K
- H_2 absorption against Ly-a: 2500 K
- X-Factor (CO/H_2) with cold H_2 absorption measurements?

Disk lifetimes set the timescale for giant planet formation



- Typical lifetime of 3 Myr
- Viscous accretion cannot fully deplete disk
- Timescale affects gas accretion, eccentricities

Photoevaporation by the central star

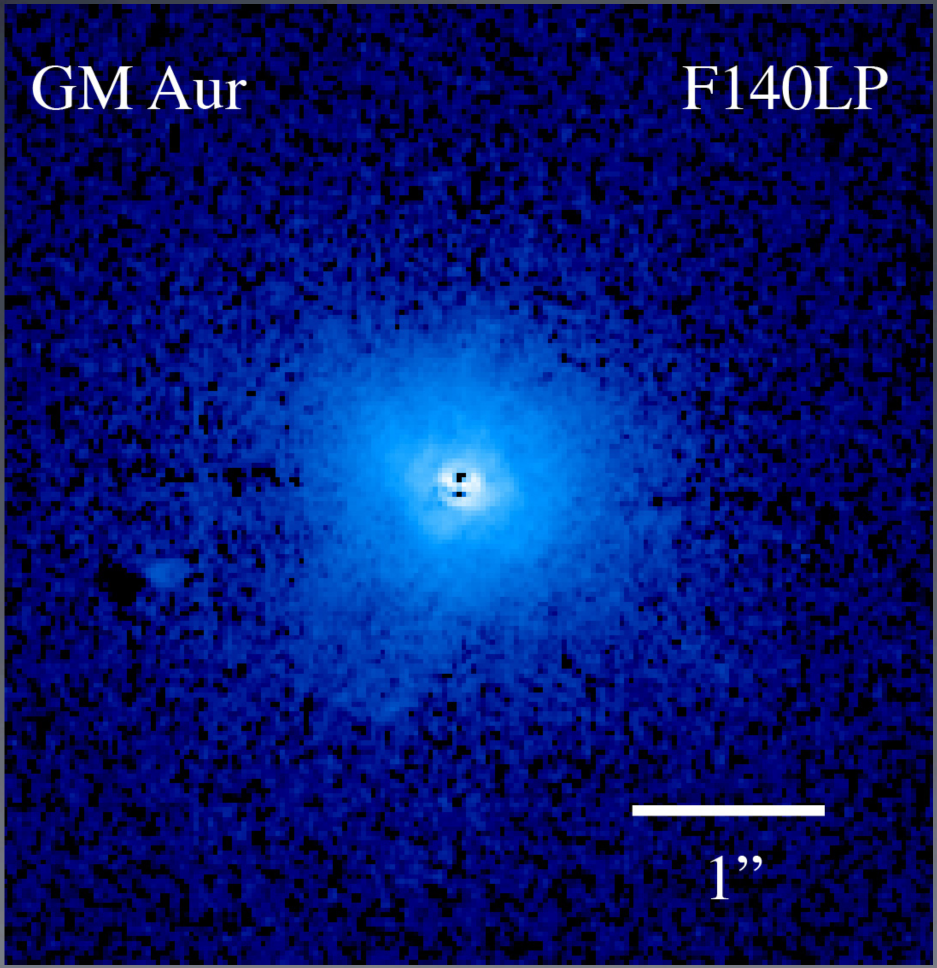


Photoevaporation rates
Alexander/Pascucci PP VI review

- Models by Alexander, Ercolano/Owen, and Gorti/Hollenbach
  - Rates depend critically on FUV and EUV luminosity
- Observational evidence from [Ne II] and [O I] spectra (Pascucci+; Rigliaco+2013)

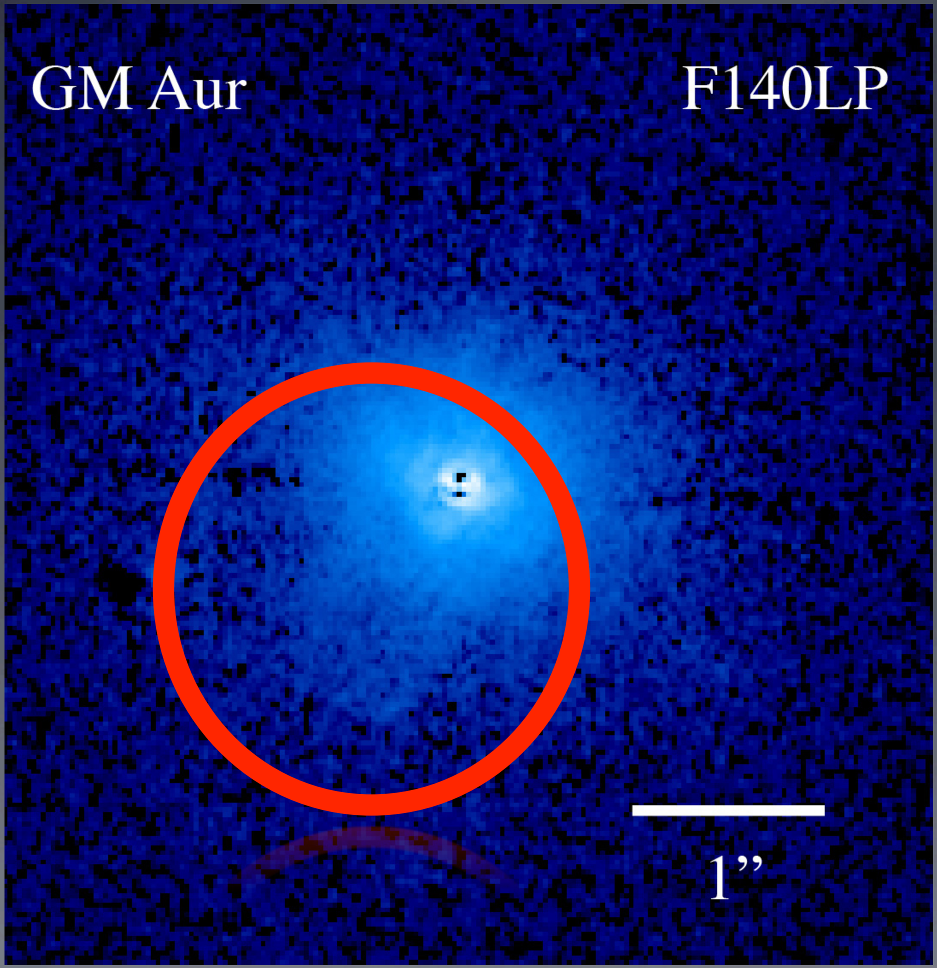
H_2 conical disk wind: photoevaporation?

(Hornbeck, Grady et al. submitted)



H_2 conical disk wind: photoevaporation?

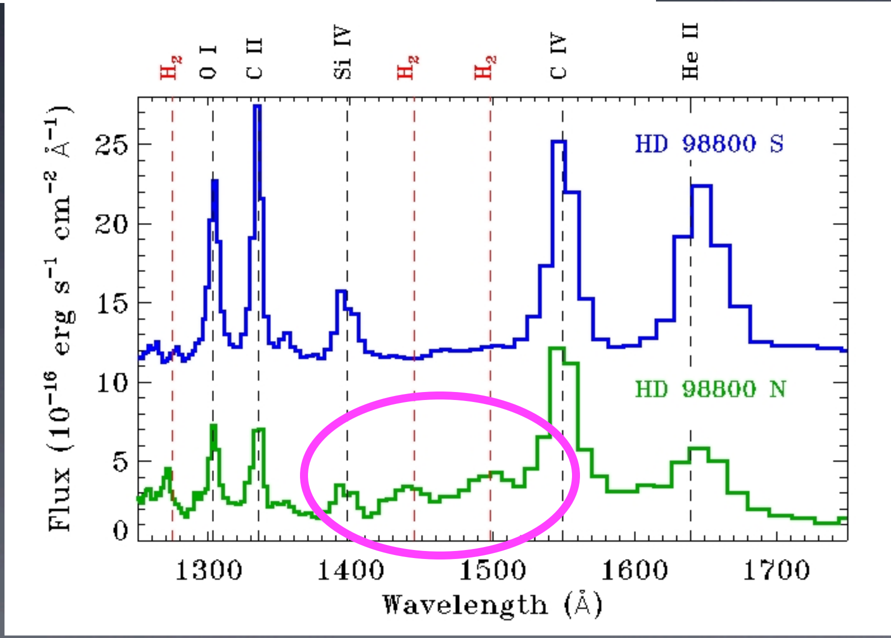
(Hornbeck, Grady, et al. submitted)



The end of gaseous disks: FUV H2 emission and gas in dissipating disks

(Ingleby+2009,2012)

ACS SBC PR130L

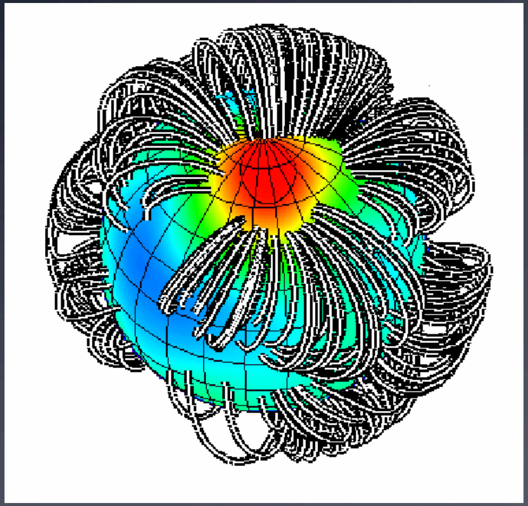


Adapted from Yang+2012

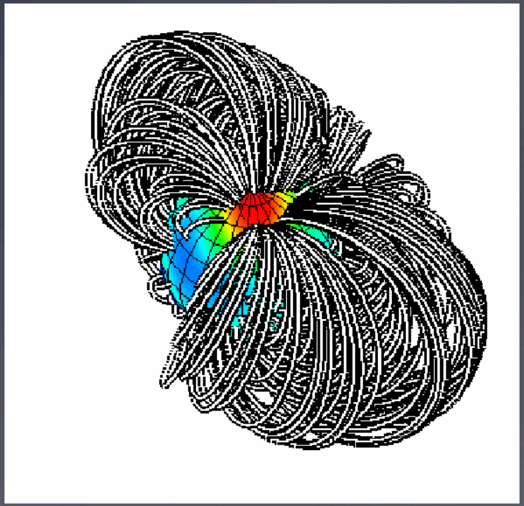
- Warm H_2 only detected to CTTSs, never in WTTSs
  - Transition time short
  - Upper limits of gas mass roughly 9 orders of magnitude lower than minimum mass solar nebula
- Most sensitive gas diagnostic?
- HD 98800 N: thought to be a debris disk, but shows warm H2 indicative of accretion

Magnetospheric accretion geometry

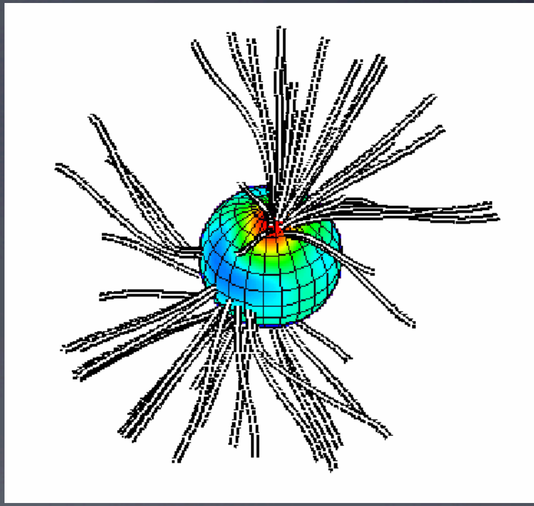
(V2129 Oph; Donati, Gregory, et al.)



Complex field lines



Dipole field lines



Open field lines

Field geometry from Zeeman Doppler Imaging

Accretion along dipole field lines (Adams & Gregory 2012)

See also spectropolarimetry of He I: Yang+2007, Johns-Krull+2013

High Energy Photons from T Tauri Stars: Accretion + Corona/Chromosphere

(few Myr decay time) (few hundred Myr decay time)

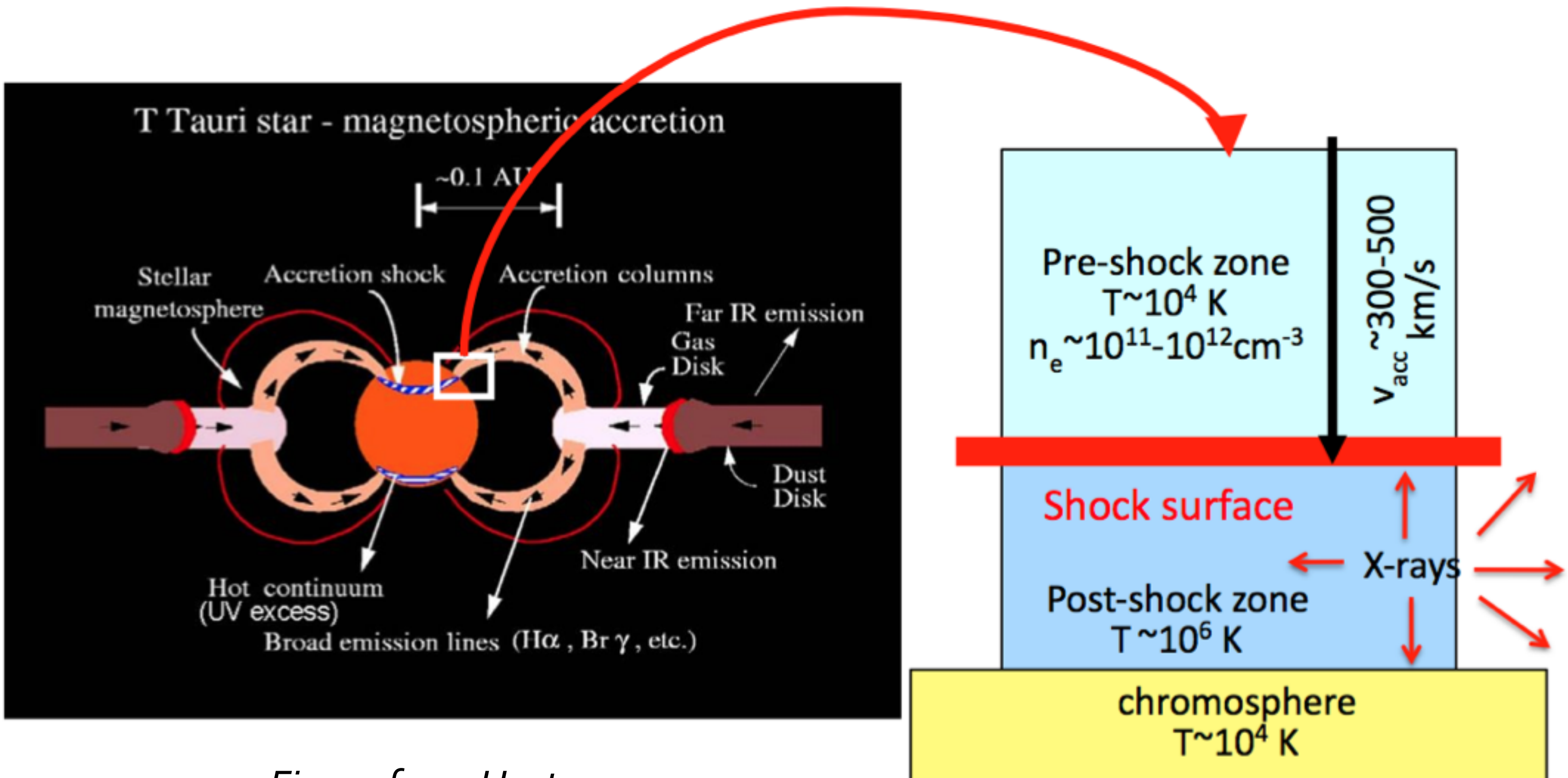


Figure from Hartmann

High Energy Photons from T Tauri Stars: Accretion + Corona/Chromosphere

(few Myr decay time) (few hundred Myr decay time)

Models: Calvet & Gullbring 1998; Lamzin 1998; Sacco+2009; Orlando+2013

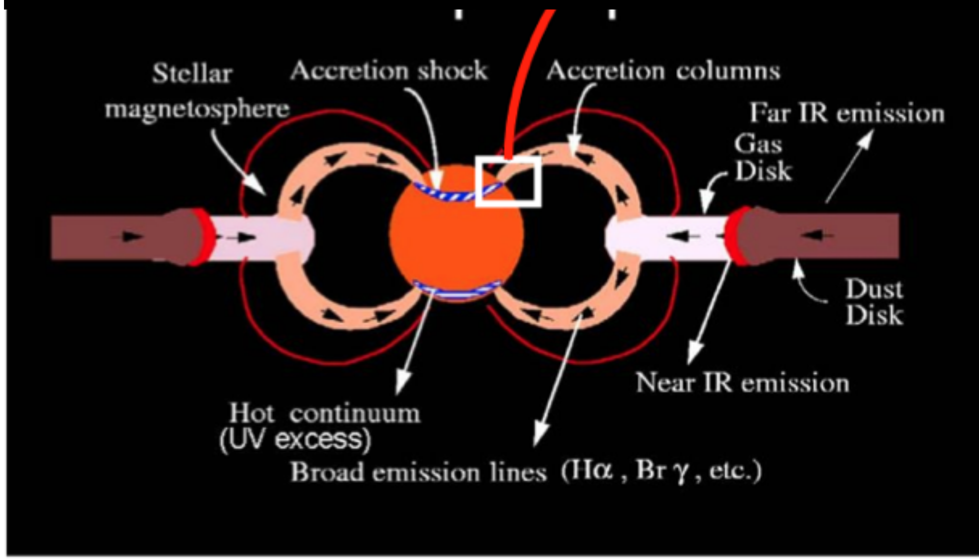
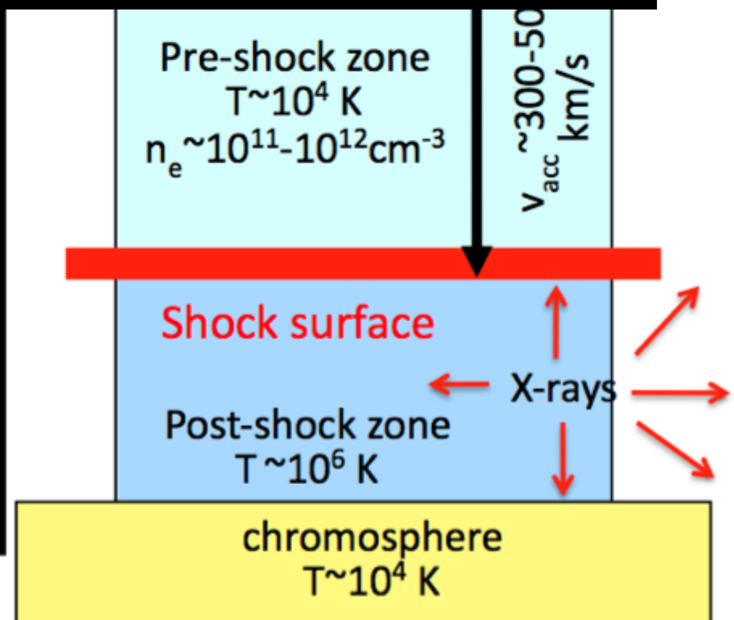
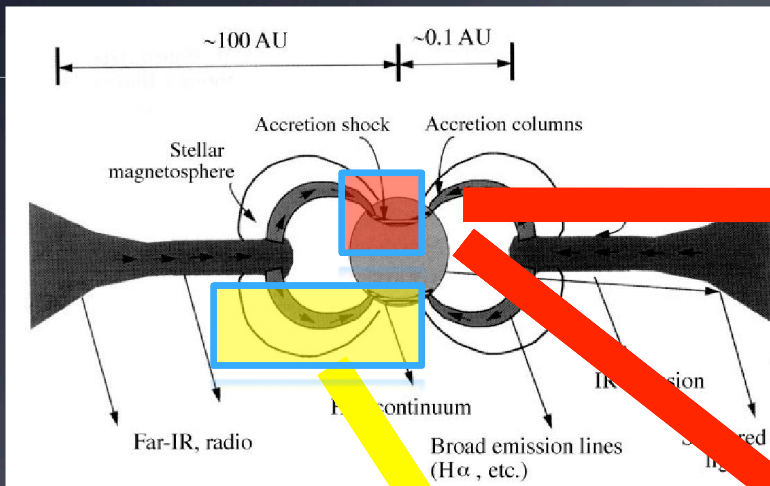
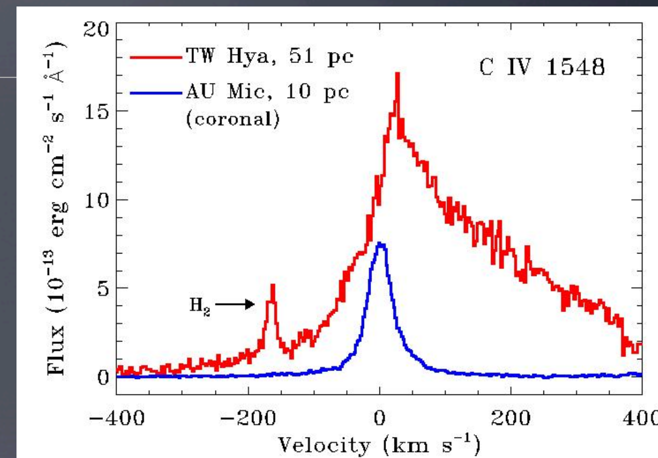


Figure from Hartmann

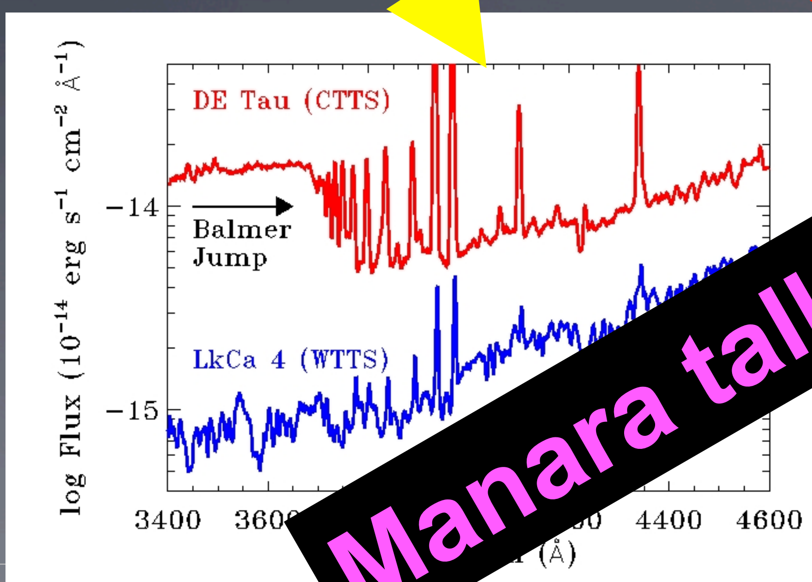


Funnel flow and shock

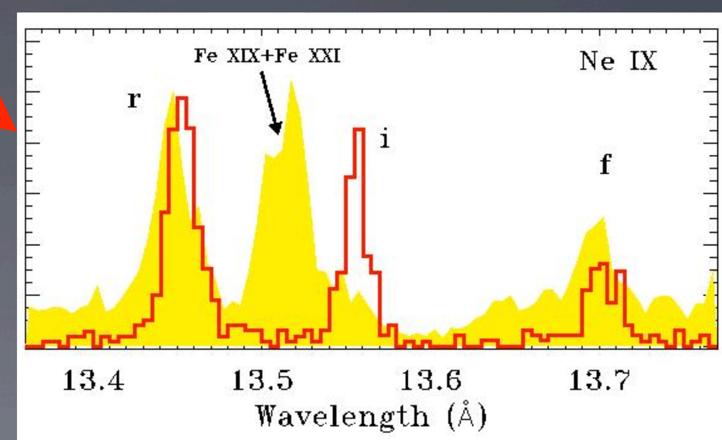




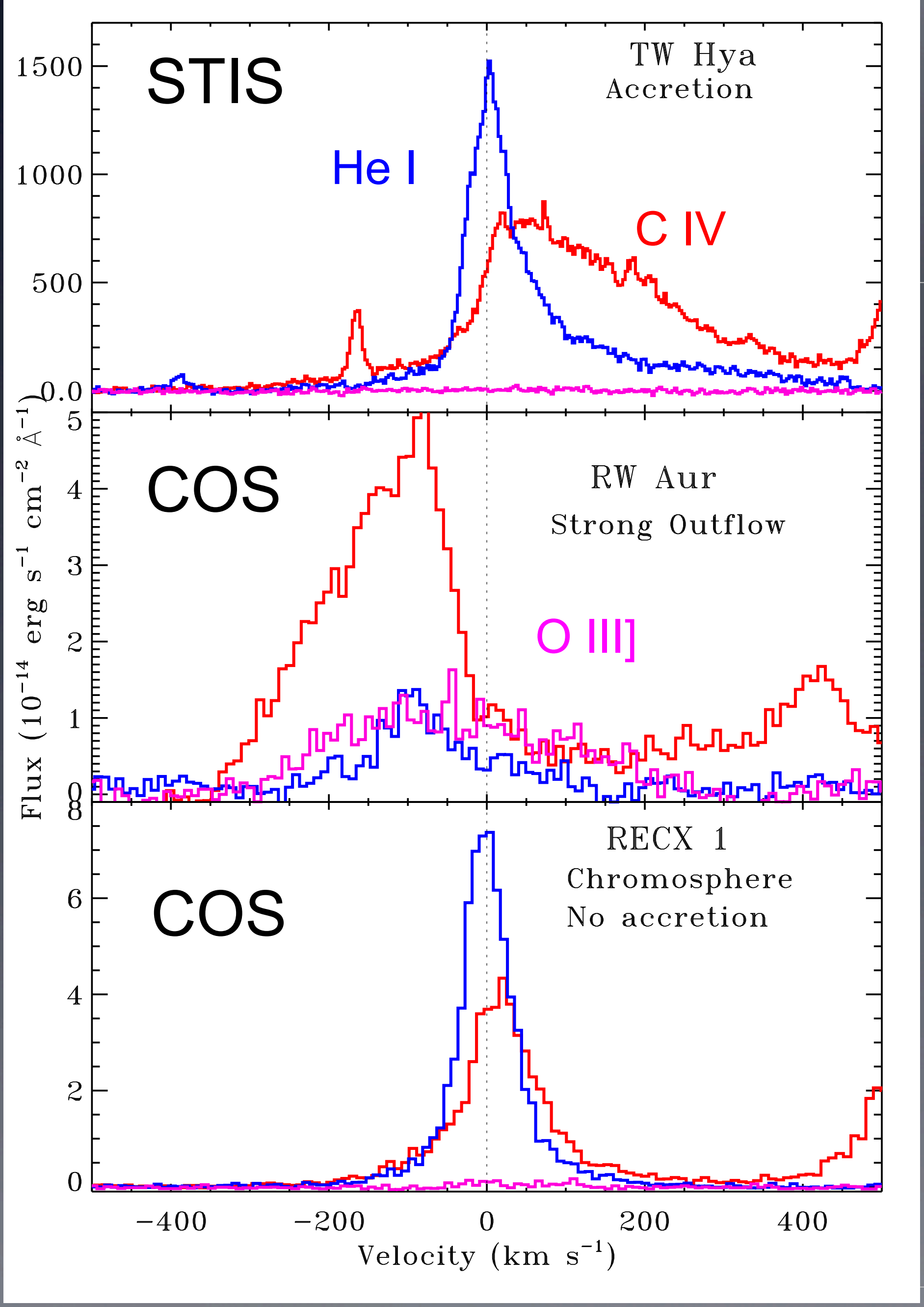
Herczeg+2002; Lamzin 2003



Manara talk!



Adapted from Günther & Schmitt 2007



Hot lines and accretion flows

(Lamzin 2003; Günther+2008; Ardila +2013, Gomez de Castro 2013)

- Broad emission in hot lines (He II, C IV, N V, O VI) produced by accretion flow
- Broad component: pre-shock gas, highly photoionized
- Narrow component: post-shock gas or extended chromospheric structure
- Some jet sources: C IV blueshfited

Extended structures: semi-forbidden lines

(Gomez de Castro+2005,2007,2011)

- Dense (10^{10} cm^{-3}) regions
- Small emitting regions
- Contributions from stellar winds and macroturbulent fields near the disk-star interface

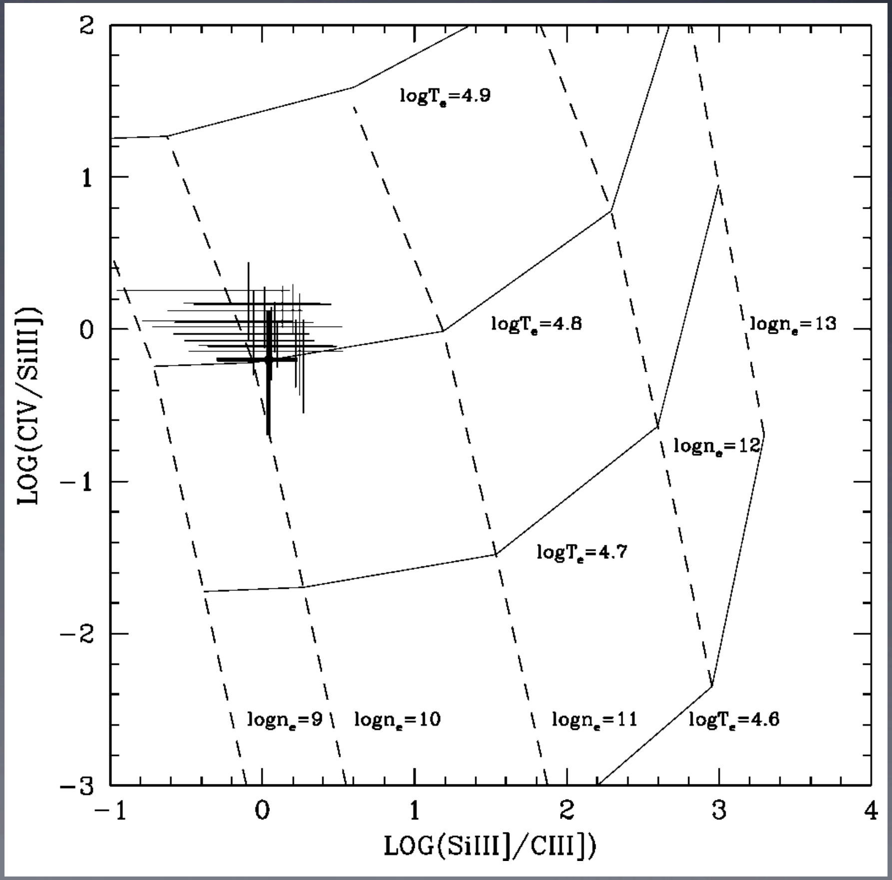
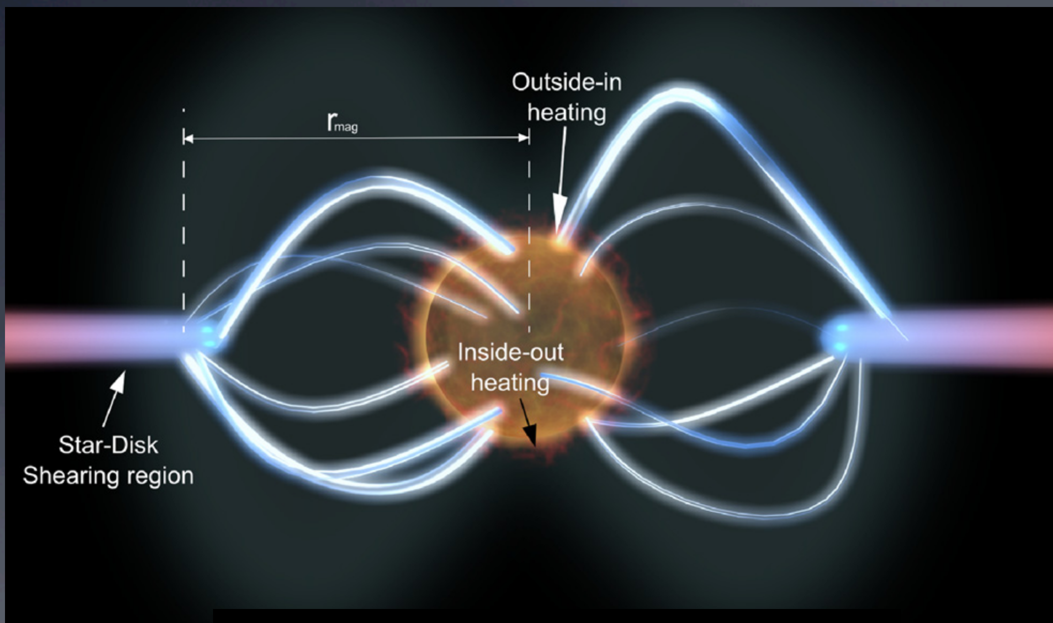


Photo-ionized accretion flow

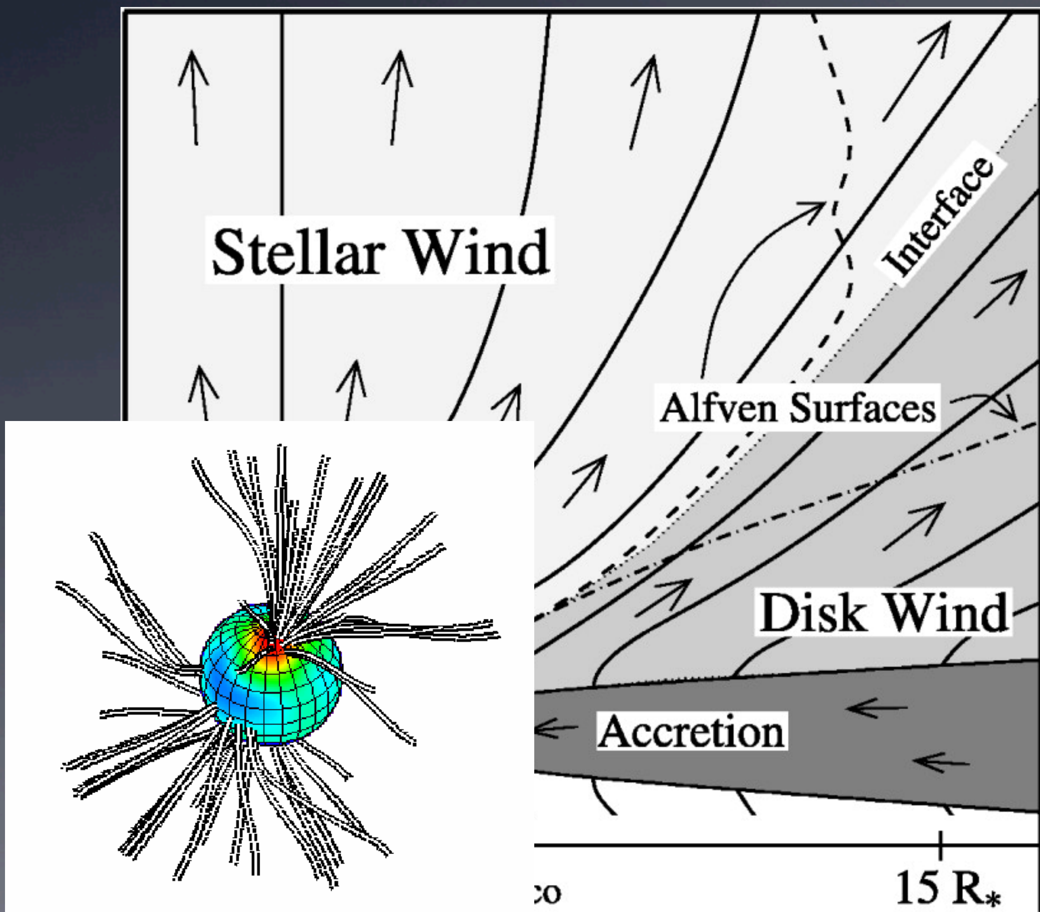
(Gomez de Castro & Marcos-Arenal 2012; Gomez de Castro 2013; Ardila+2013)



From Gomez de Castro 2012

- Lines have multiple components, possibly multiple flows
- Extended magnetospheres, photo-ionized pre-shock gas
- Shock heats nearby photosphere

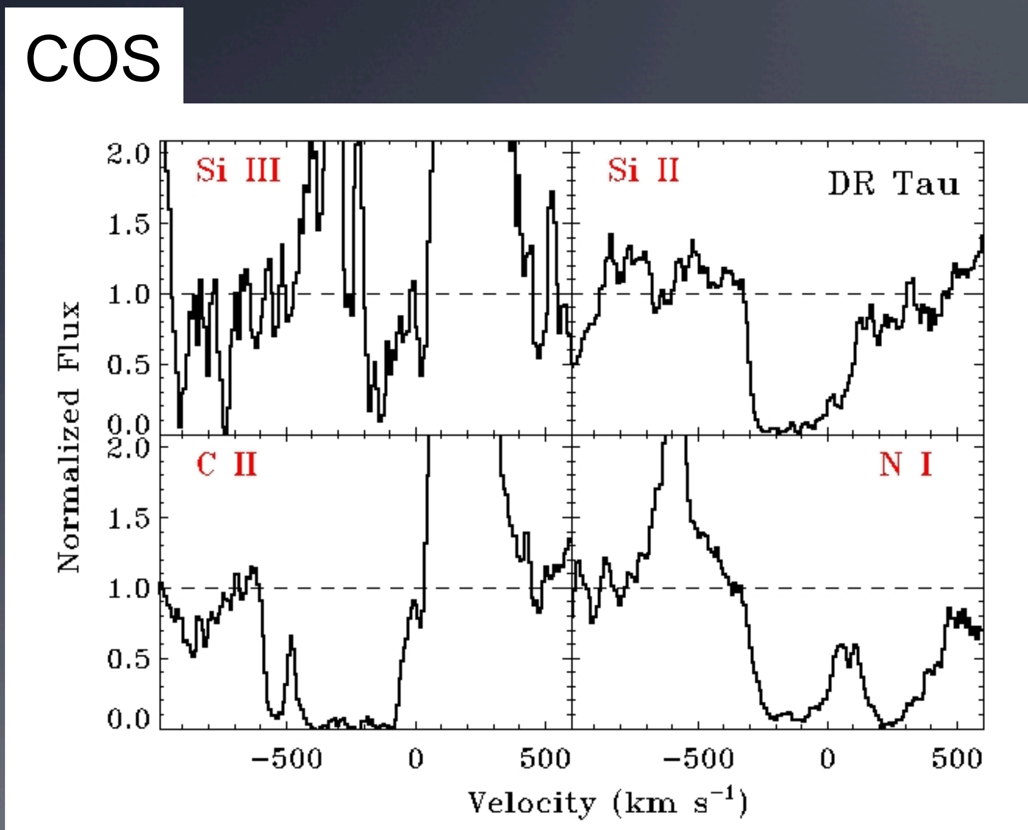
Accretion/Outflow connection



Matt & Pudritz (2005)

- Breaks angular momentum
- Launch mechanism uncertain
  - Disk wind (Ferreira 2007, Bai & Stone 2013)
  - Shu X-wind
  - Coronal winds (Matt & Pudritz)

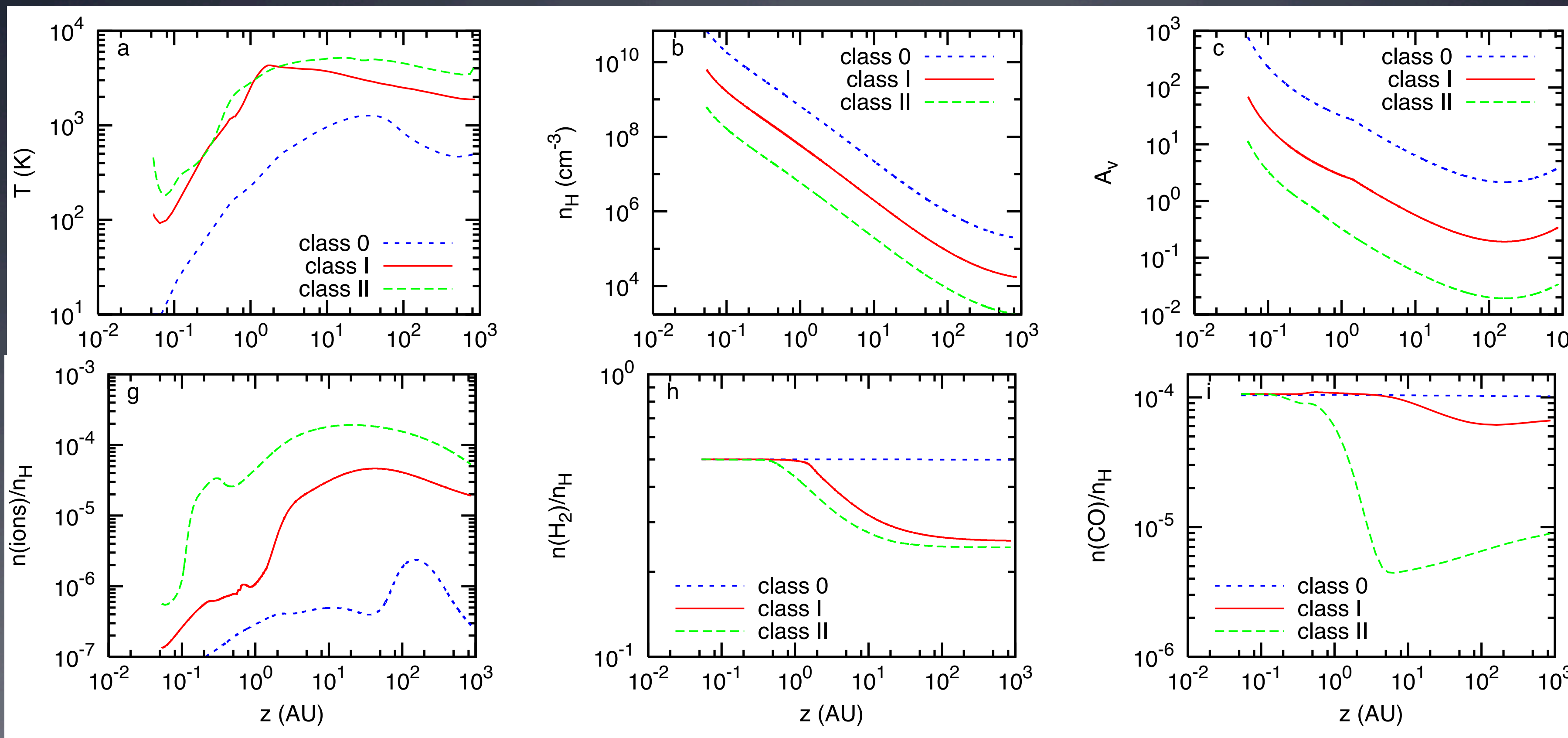
Wind temperature: a probe of wind launching



Analysis from Johns-Krull & Herczeg (2007) for TW Hya

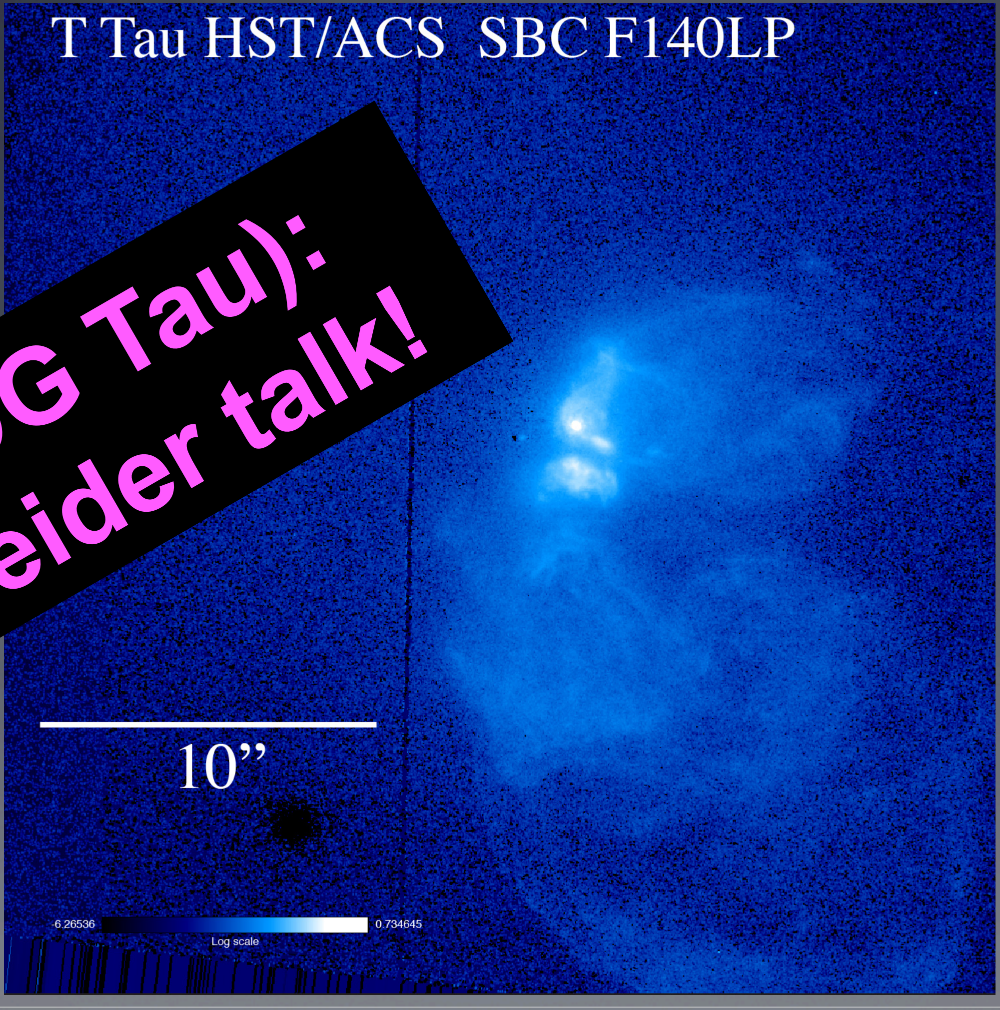
- Fast absorption (200 km/s)
- Mostly in atomic/singly ionized lines
- Typically consistent with cool, FUV-photoionized disk wind
- No evidence for a hot coronal wind
  - Rules out hot Matt & Pudritz model

Wind chemistry: similar to disk and PDR
(Panoglou, Cabrit et al. 2012)



Optical depth of outflow determines molecular fraction

Collimation of wind into a jet

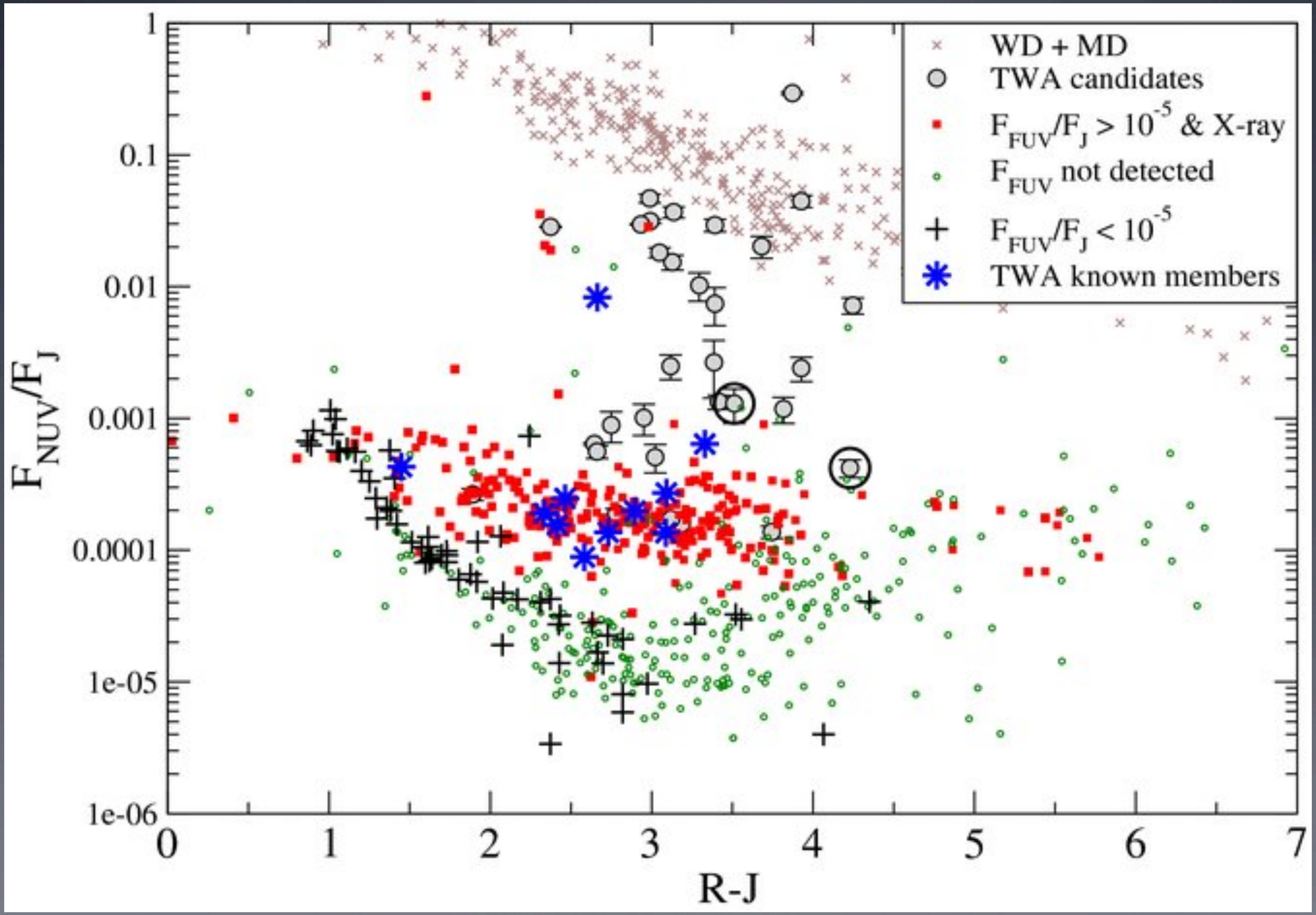


Jets (DG Tau): Schneider talk!

Alexander Brown et al., 2006, Cool Stars 14

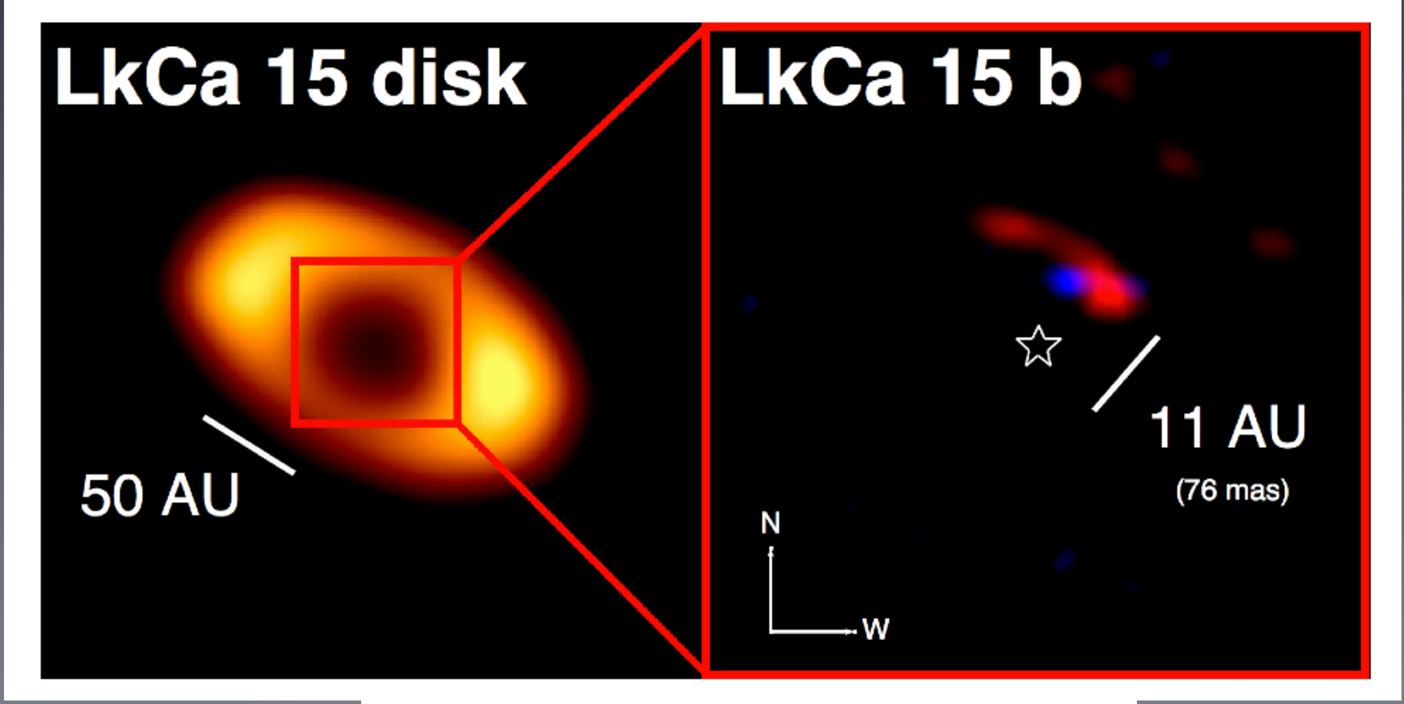
GALEX and YSO Identification

(Sholnik+ 2011; Rodriguez+2013)



Best low-mass SF science cases for a new UV Observatory

- Forming protoplanets: U-band/NUV, spatial resolution of UV
- Spatially and spectrally resolved disk emission (high-res IFU)



Kraus & Ireland 2012, Keck AO

Past and Future of FUV Observations and Low Mass Star Formation

- Primary results from last few years:
  - Disks: FUV fields; tracers of PDR at disk surface, end of accretion
  - Accretion: probes of accretion stream and shock
  - Outflows: Wind temperatures, molecular winds as test of jet launching
- Currents needs (after fully digesting COS data)
  - Wider range of targets (35 stars: mass, accretion rate, disk inclination)
  - Variability information
  - SBC Imaging/STIS spectral imaging of disks, winds, and jets
- Science with future UV observatories
  - Planet formation, H_2/CO/? disk imaging at terrestrial radii (10m)
  - Competitive instrumentation: MOS? IFU? Dichroic? Interesting Filters? Large detector format?