# Near-Infrared Spectroscopy of Circumstellar Disks: Understanding Planet Formation

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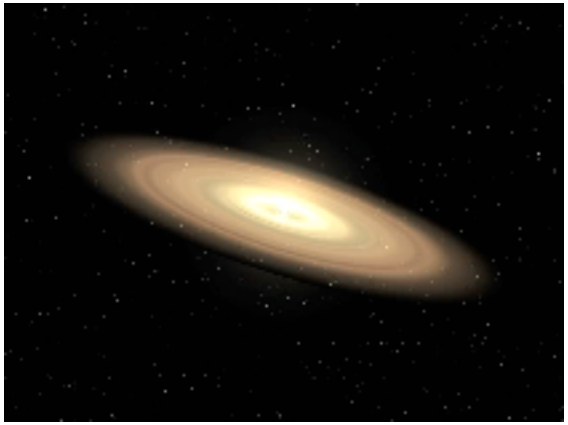
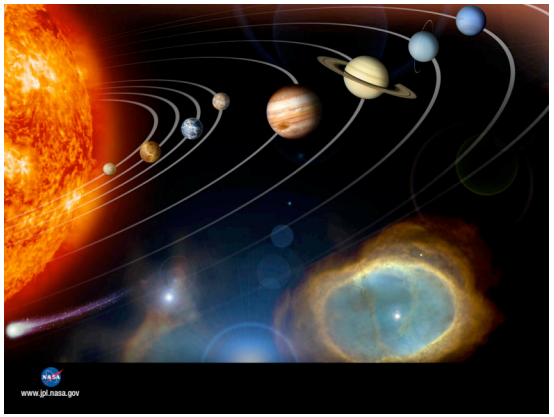


*Courtesy NASA/JPL-Caltech*




*Courtesy NASA/JPL-Caltech*

Collaborators: J. Najita (*NOAO*), T. Rettig (*Notre Dame*), T. Simon (*Hawaii*), C. Kulesa (*Steward*), E. Gibb (*Notre Dame*), M. Disanti & N. Dello Russo (*GSFC*)

# Radial Evolution of Gas in Circumstellar Disks

## I. Implications for planet formation timescales

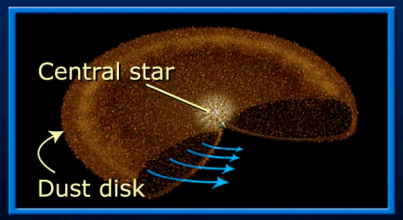
The lifetime of circumstellar gas defines the timescale for giant planet formation.

## II. Implications for gas/dust interactions

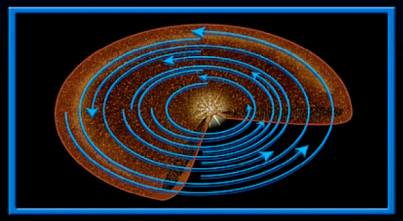
Interaction of dust and gas in optically thin disks can lead to the formation of dust rings and/or dust gaps.

# Two Planet Formation Scenarios

## Accretion model

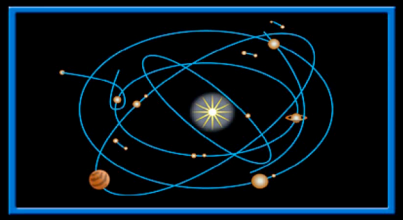



Orbiting dust grains accrete into "planetesimals" through nongravitational forces.



Planetesimals grow, moving in near-coplanar orbits, to form "planetary embryos."

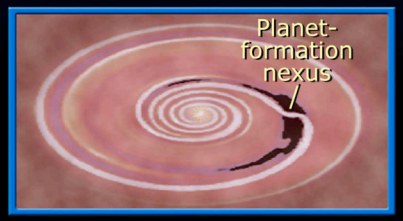
Gas-giant planets accrete gas envelopes before disk gas disappears.



Gas-giant planets scatter or accrete remaining planetesimals and embryos.

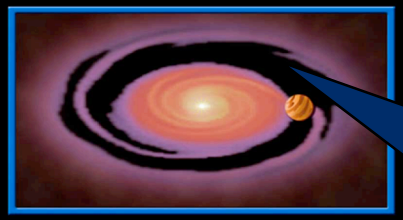
## Gas-collapse model

A protoplanetary disk of gas and dust forms around a young star.




Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.


Dust grains coagulate and sediment to the center of the protoplanet, forming a core.



The planet sweeps out a wide gap as it continues to feed on gas in the disk.

~1 Myr to form 10 $M_{Earth}$ Core

~10 Myr to accumulate 1 $M_{Jupiter}$ gas - disk is dust poor and gas rich

Jovian planets form ~1000 yrs. Dust and gas co-depleted

A. Field
(STScI)

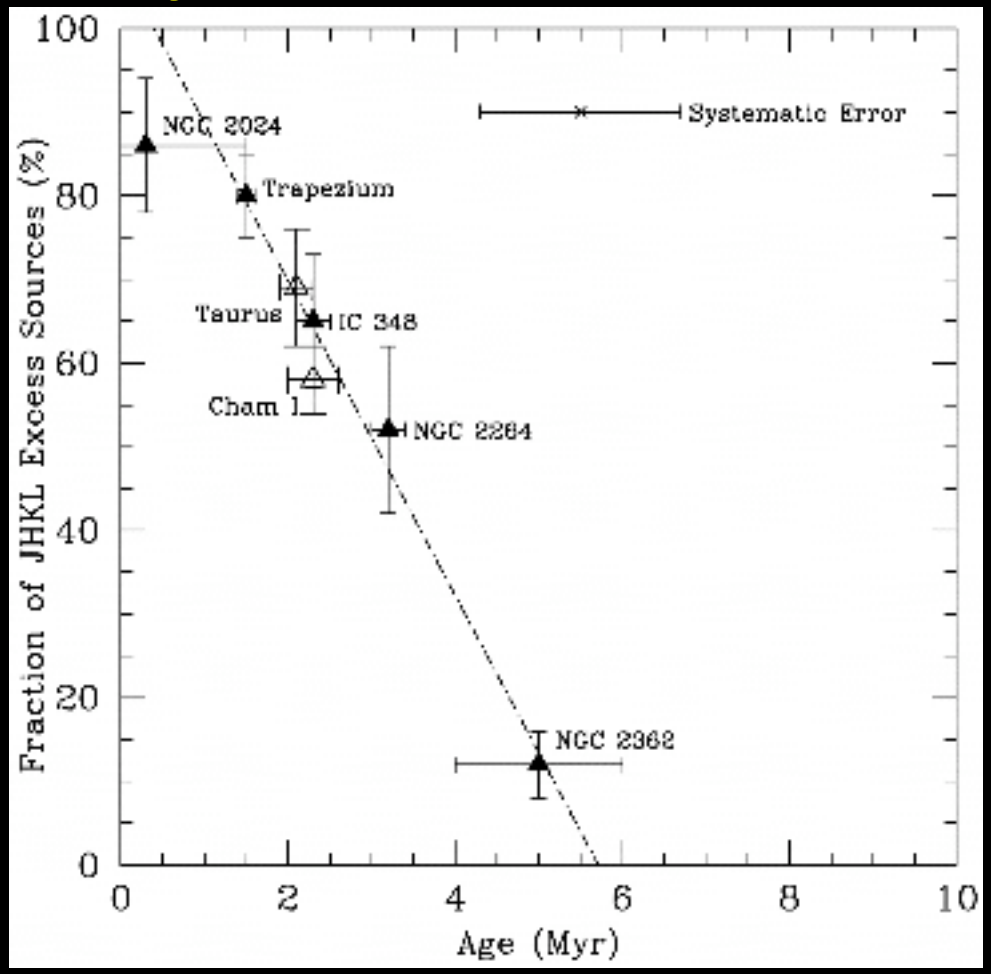
# Observational Implications

Core Accretion: A substantial population of circumstellar disks with a minimal NIR excess and significant MIR/FIR excess should also exhibit substantial gas emission

Gas Instability: Dust and Gas should dissipate on the same timescale so that there is a tight correlation between the strength of the NIR excess and gas line emission

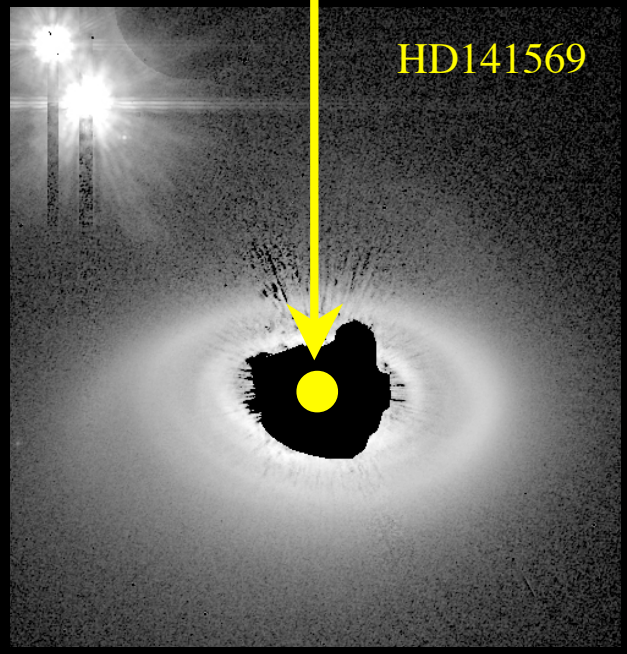
# Radial Evolution of Circumstellar Gas

Disks take a few Myr to become optically thin.
How does this compare to the dissipation rate of the gas in the inner 50 AU?



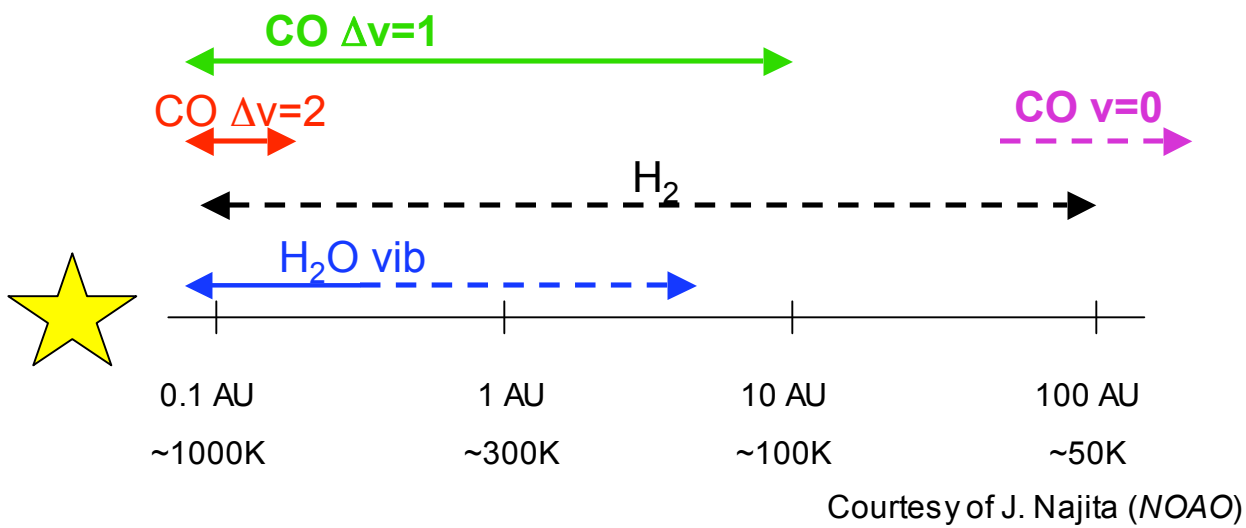

Haisch, et al. 2001, ApJ, 553, L153

**Region of interest**




Clampin, et al. 2003, AJ 126, 385

# Spectroscopic Diagnostics of Protoplanetary Disks




Courtesy of J. Najita (*NOAO*)

**$H_2$ Observations:**

•Pure rotational (MIR): Thi et al. 2001; Richter et al. 2002

•Rovibrational (NIR): Bary et al. 2003

•Electronic (UV): Herczeg et al., Bergin et al.

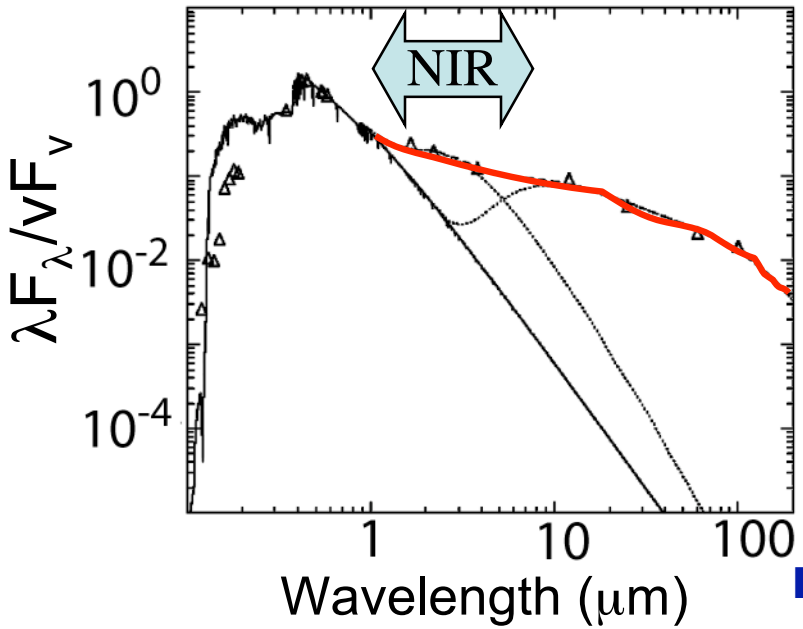
**$H_2O$ Observations**

•Carr et al. 2004

**CO Observations:**

•Overtone transitions: Scoville et al. 1979; Carr 1989

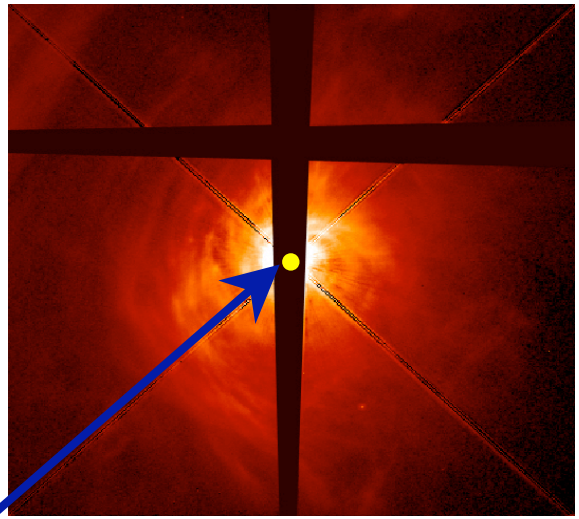
•Fundamental transitions: Najita et al. 2000; Blake & Boogert 2004




# AB Aurigae

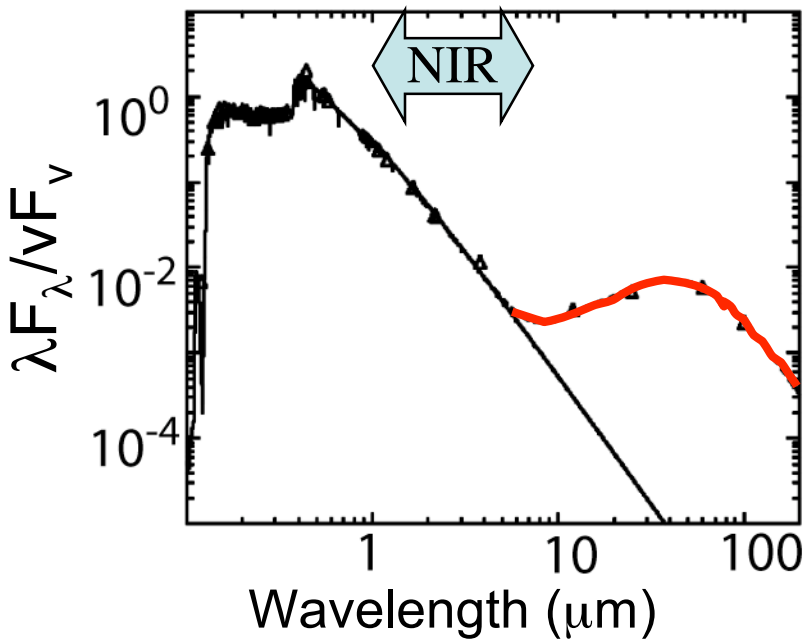
**A0 star**

**Age ~ 4 Myr**



Courtesy C. Grady, GSFC

**Regions of interest**

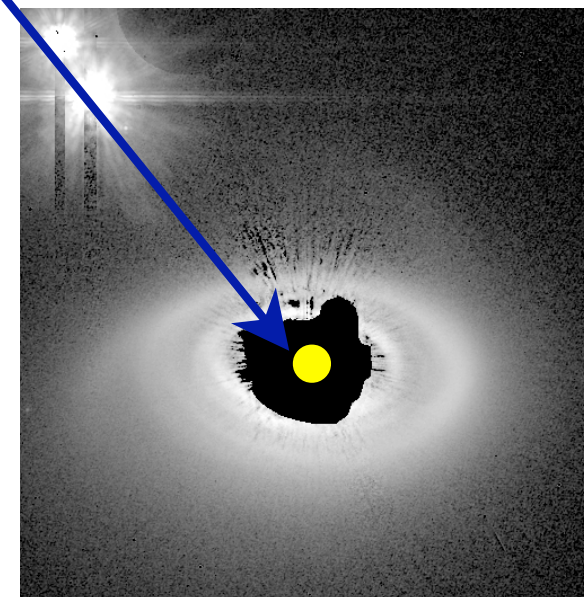



Malfait et. al. A&A **331**: 221 (1998)

# HD 141569

**A0 star**

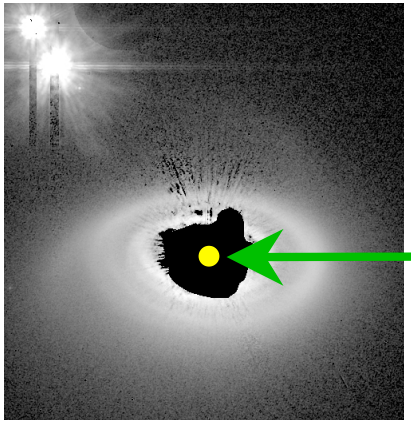
**Age ~ 6-8 Myr**

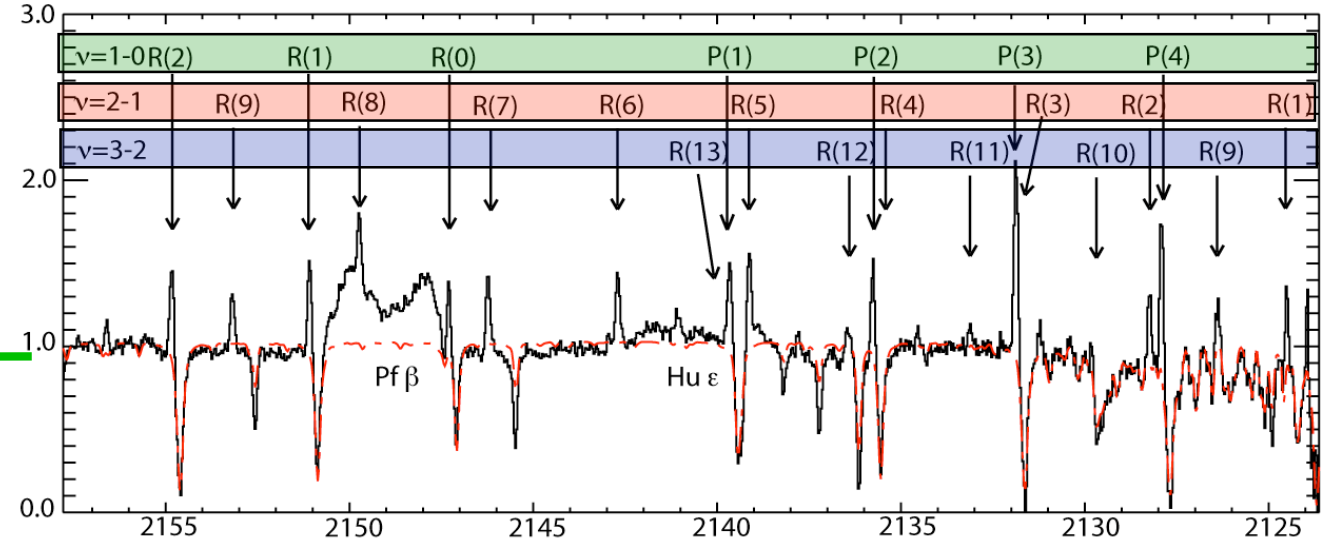


Clampin, et al. 2003, AJ 126, 385

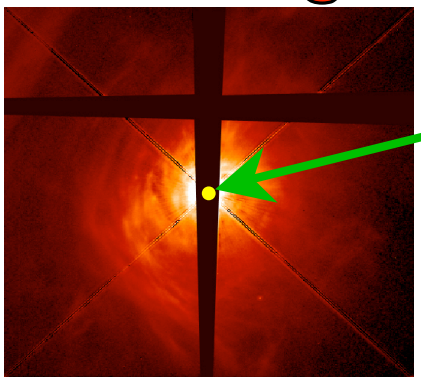
# Using NIR Spectroscopy to probe the inner disk: CO

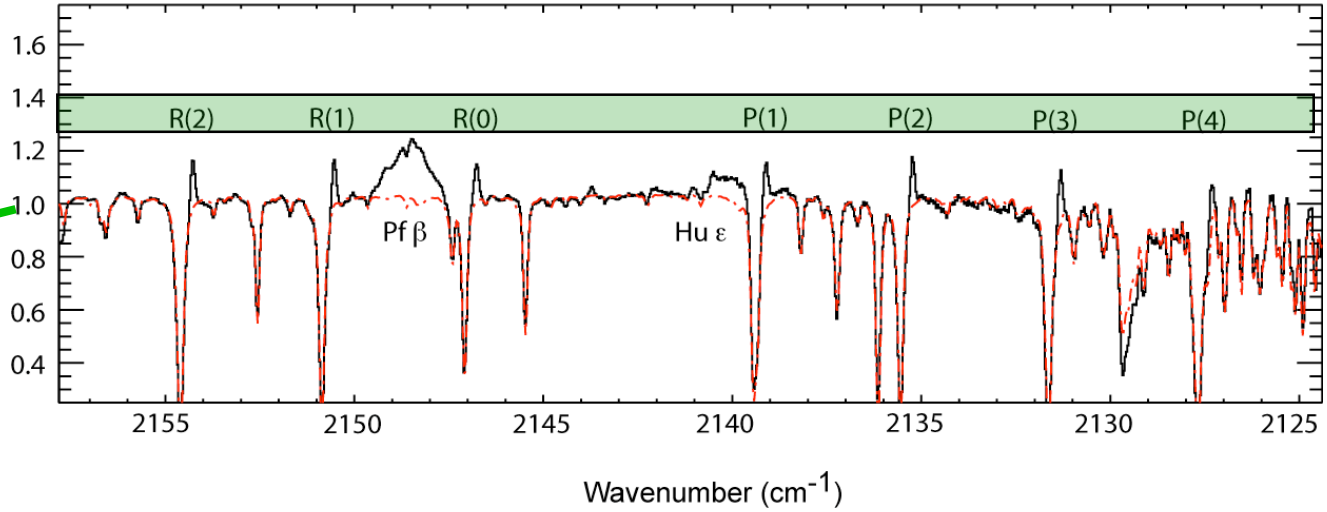
## HD 141569





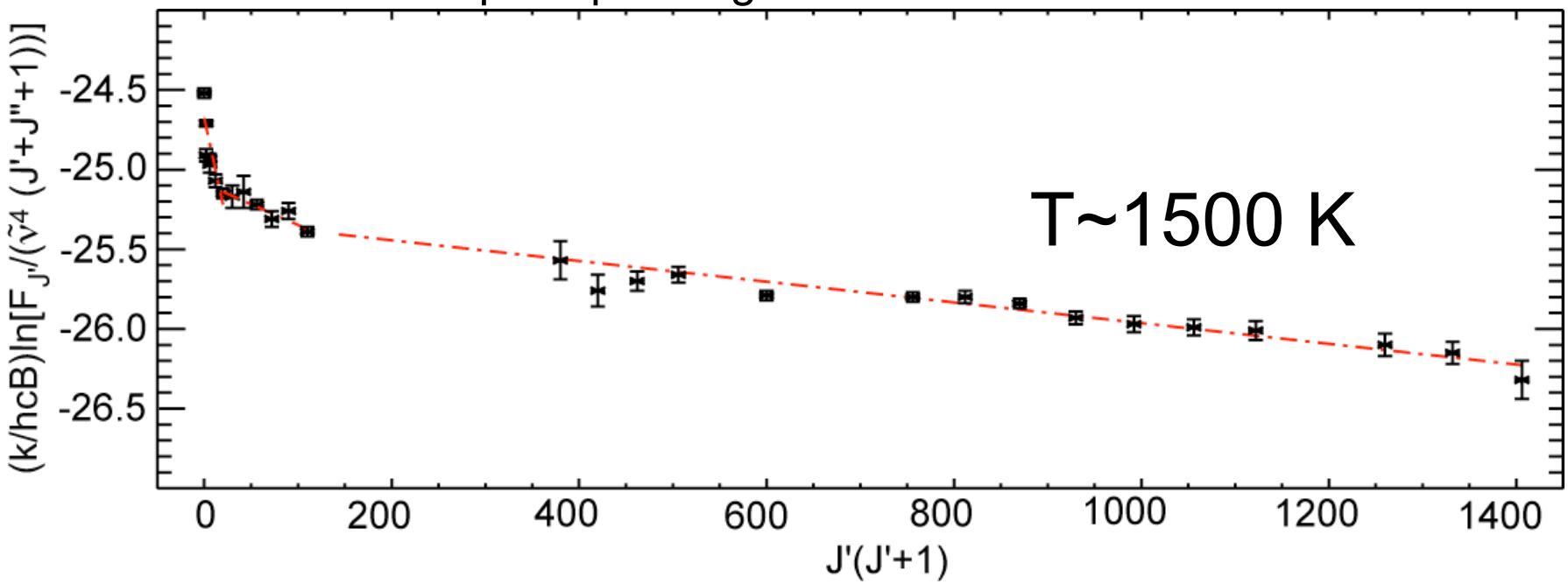

## AB Aurigae



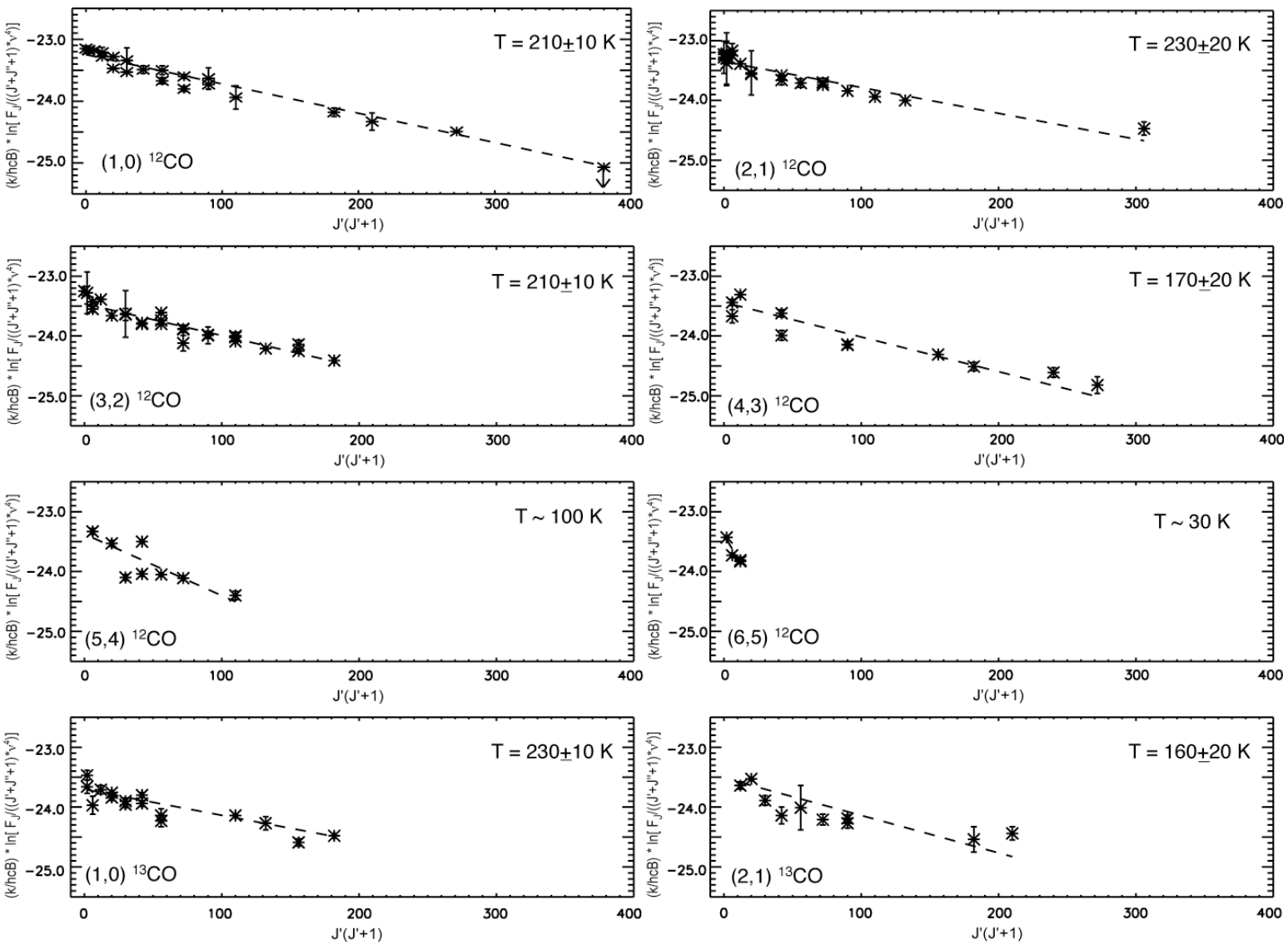


# AB Aurigae

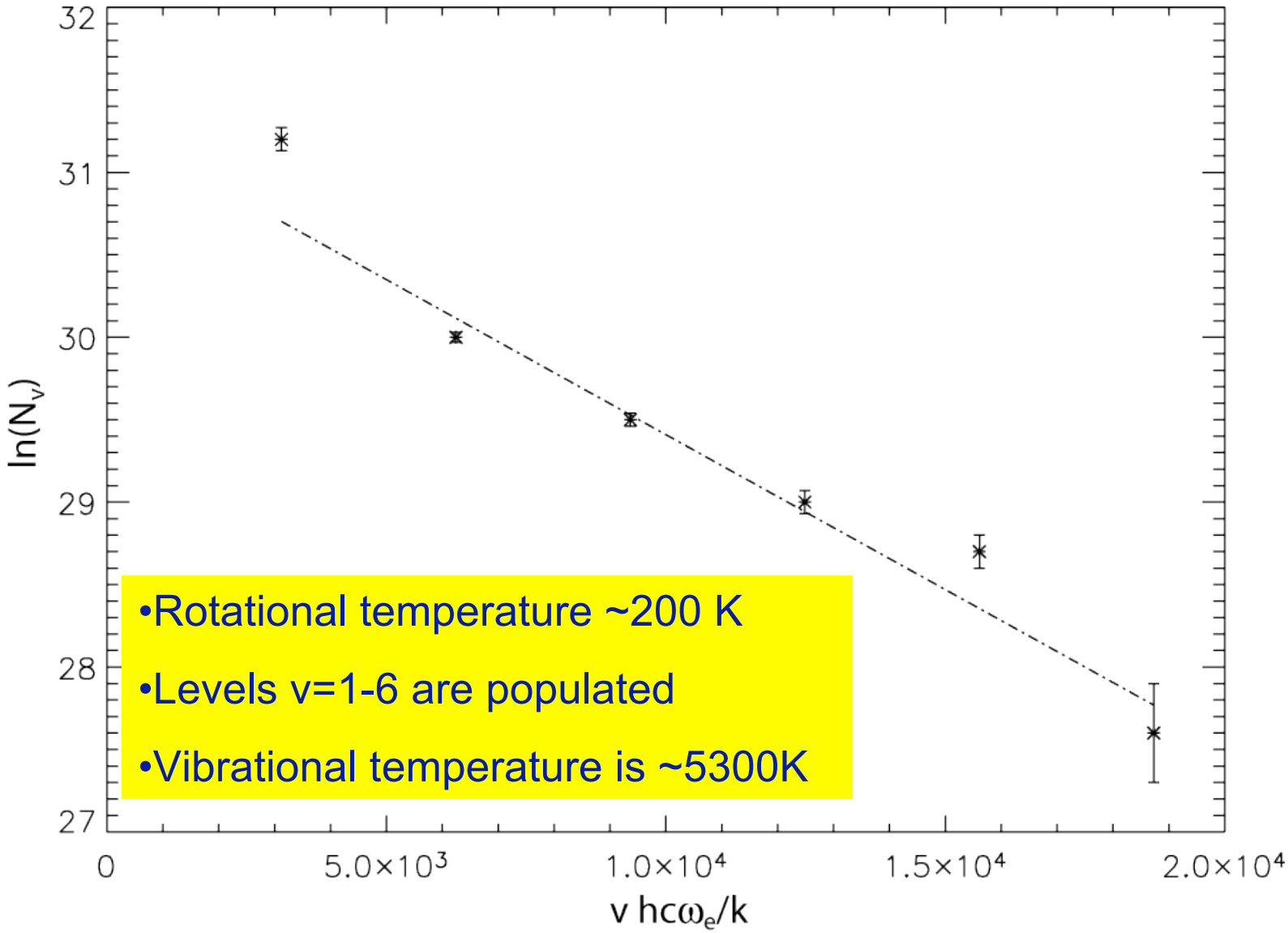
CO Excitation plot spanning J'=0-37



# HD 141569


T = 210±10 K
(1,0) 12CO
T = 230±20 K
(2,1) 12CO
T = 210±10 K
(3,2) 12CO
T = 170±20 K
(4,3) 12CO
T ~ 100 K
(5,4) 12CO
T ~ 30 K
(6,5) 12CO
T = 230±10 K
(1,0) 13CO
T = 160±20 K
(2,1) 13CO
(k/hcB) * ln[ F_J/((J'+J''+1)*ν^4)]
J'(J'+1)

# HD 141569




- Rotational temperature ~200 K
- Levels v=1-6 are populated
- Vibrational temperature is ~5300K

# Excitation of CO

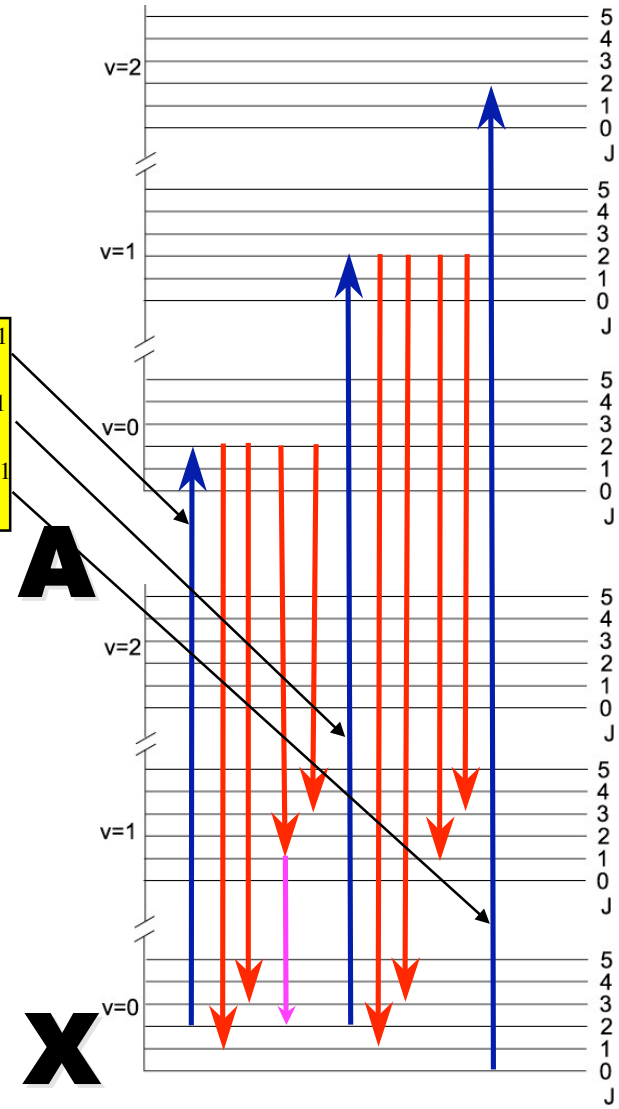
$$\frac{dn_X^{v=i}}{dt} = \sum_j A_{A-X}^{v'=j,\,v''=i} n_A^{v=j} + A_X^{v'=i+1,\,v''=i} n_X^{v=i+1} + g_X^{v''=i-1,\,v'=i} n_X^{v=i-1}$$
$$- \sum_j g_{X-A}^{v''=i,\,v'=j} n_X^{v=i} - g_X^{v''=i,\,v'=i+1} n_X^{v=i} - A_X^{v'=i,\,v''=i-1} n_X^{v=i} = 0$$

$$A_{A-X}^{v'v''} = \frac{8\pi^2 e^2 \tilde{\nu}^2}{\mu c} \frac{J''+1}{J'+1} f_{A-X}^{v'v''}$$

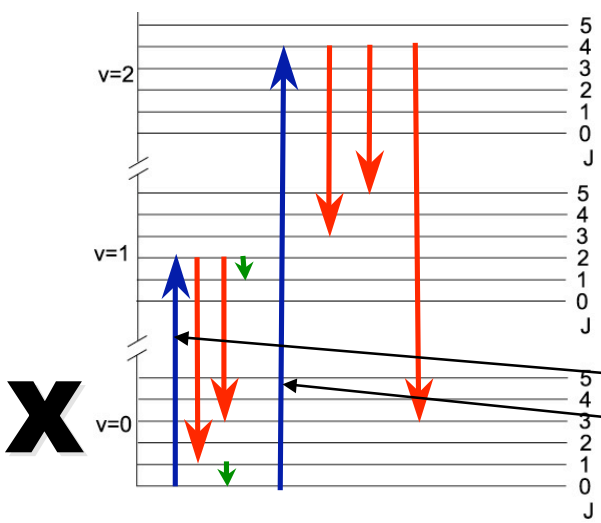
$$g_\lambda = \frac{\pi e^2}{mc^2} \lambda^2 f_\lambda(\pi F_\lambda)$$

$$g_{X-A}^{v=0-0} = 1x10^6\ photons\, s^{-1}\, mol^{-1}$$
$$g_{X-A}^{v=0-1} = 3x10^6\ photons\, s^{-1}\, mol^{-1}$$
$$g_{X-A}^{v=0-2} = 3x10^6\ photons\, s^{-1}\, mol^{-1}$$

## UV Fluorescence

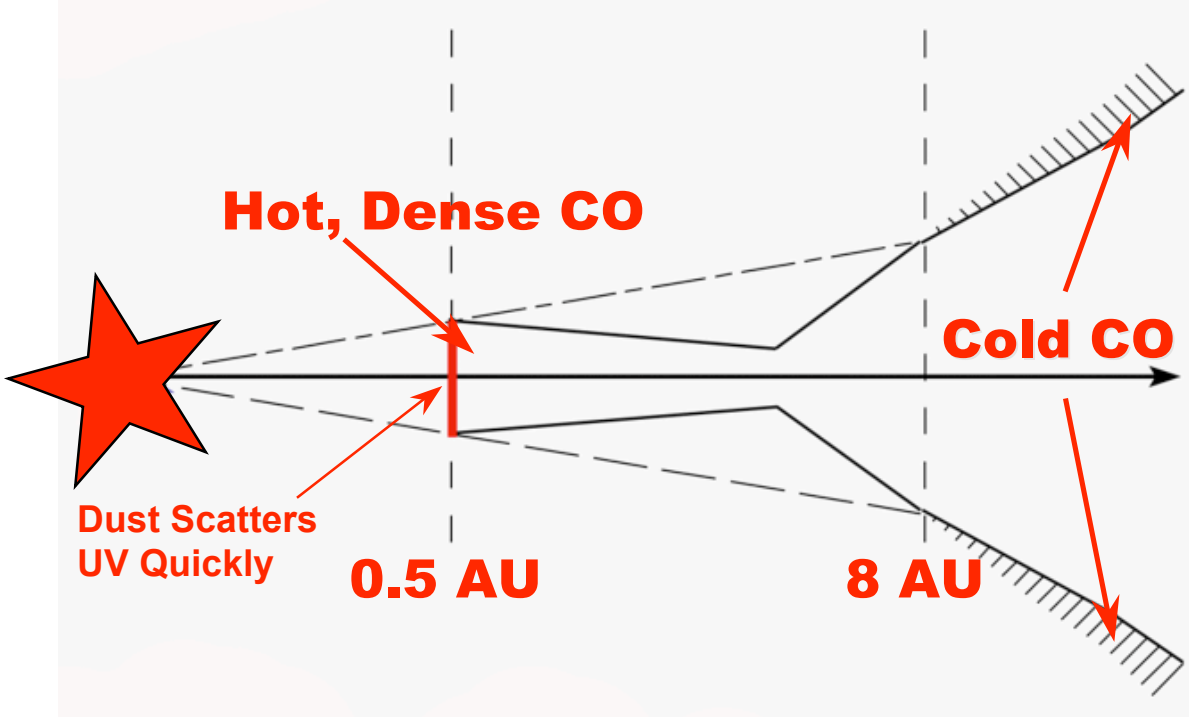



## IR Fluorescence

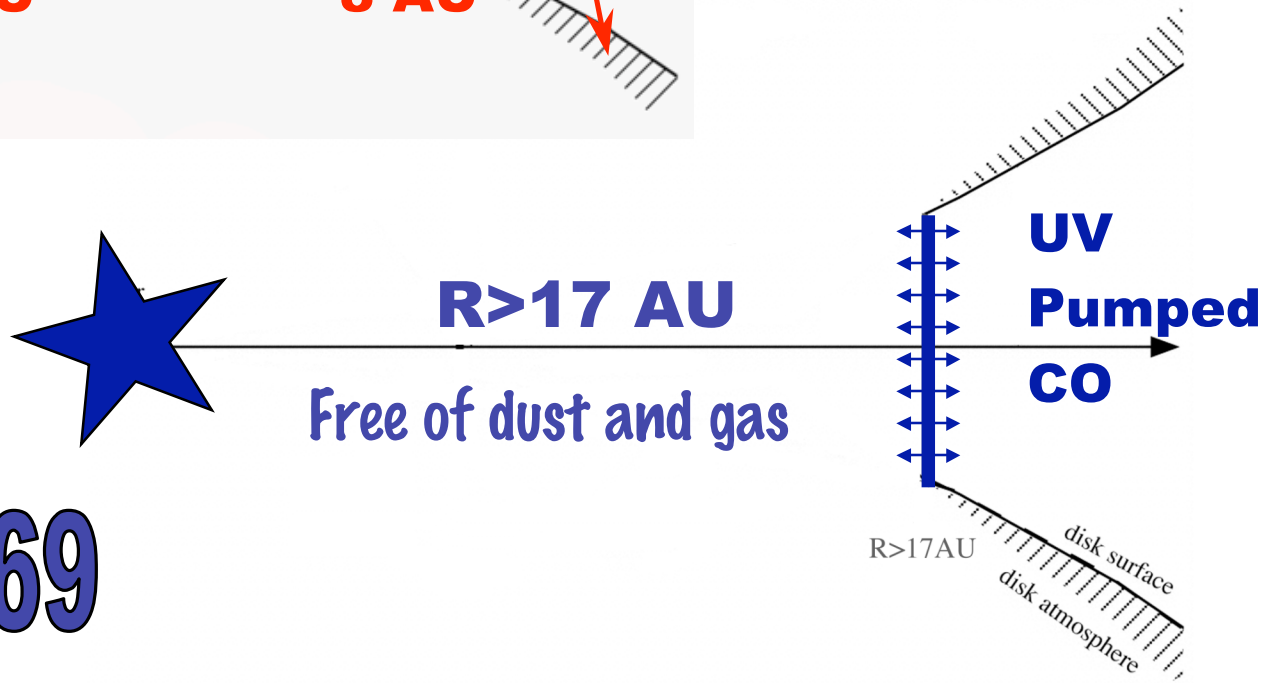



$$g_{X-X}^{v=0-1} \sim 10^{-5}\ photons\, s^{-1}\, mol^{-1}$$
$$g_{X-X}^{v=0-2} \sim 10^{-7}\ photons\, s^{-1}\, mol^{-1}$$
$$g_{X-X}^{v=0-3} \sim 10^{-10}\ photons\, s^{-1}\, mol^{-1}$$

# AB Aurigae




# HD 141569




Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957

# HD 141569

- CO is UV pumped
- Gas not in LTE
- CO 17<R<30 AU

**If planet formation has not yet occurred, it is unlikely to do so now as minimal gas remains**

# AB Aurigae

- Gas is hot & dense!
- CO 0.5<R<50 AU
- CO is optically thick

**If disk follows same evolutionary track as HD141569, gas and dust must be removed quickly**

# What's Next?

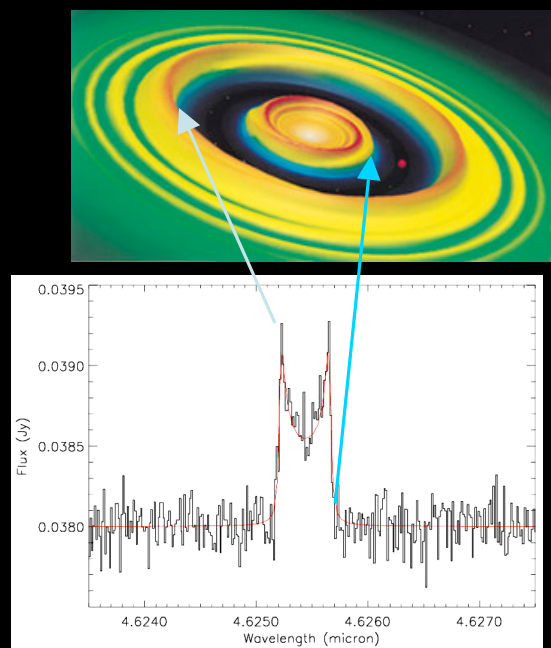
- Increase sample of transitional Herbig Ae/Be stars that exhibit CO emission
  - Does the gas in the disk evaporate quickly?
  - Is there an analogous state for T Tauri stars?
  - Explore the role of environment on circumstellar lifetime.
    - **Take advantage of Spitzer surveys of transitional HAeBe stars**

- Observe other markers that probe different conditions in the disk
  - Compare temperature, line profile (distribution) and abundance of $H_2O$, $H_2$, OH, HCN, $NH_3$
  - Observe metal lines such as S, Fe, and Si
    - **Take advantage of new MIR and sub-mm capabilities**

HR 4796A

*HST image by taken with NICMOS by Brad Smith (University of Hawaii) & Glenn Schneider (University of Arizona)*

# Are rings and gaps in disks formed by planets?




Courtesy of J. Najita (*NOAO*)

HR 4796A

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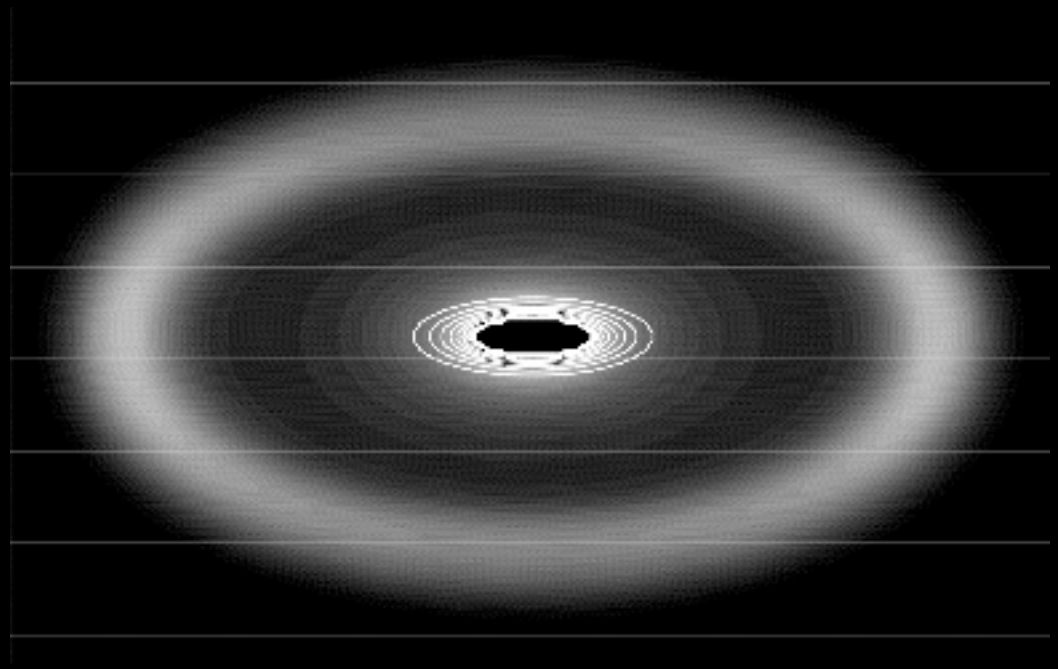
# Are rings and gaps in disks formed by planets?

Model of dust ring caused by gas/dust interaction



Takeuchi, T. & Artymowicz, P. 2001, ApJ, 557, 990

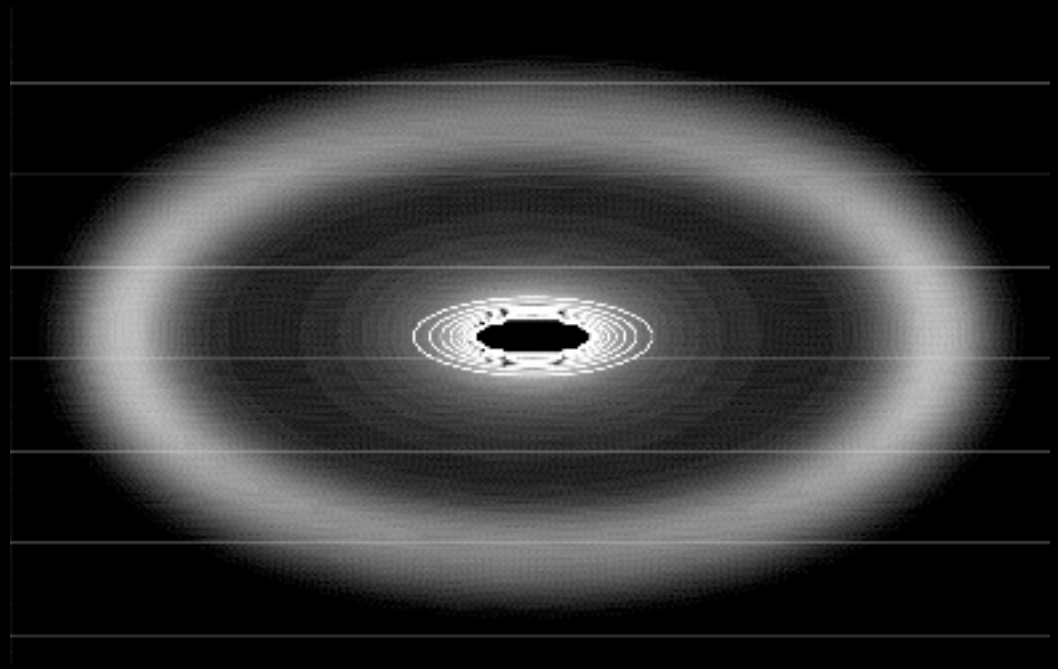
HR 4796A

*HST image by taken with NICMOS by Brad Smith (University of Hawaii) & Glenn Schneider (University of Arizona)*

## Are rings and gaps in disks formed by planets?

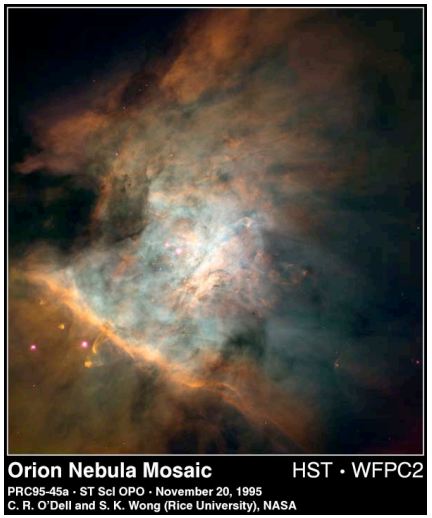
# Not necessarily!

Model of dust ring caused by gas/dust interaction



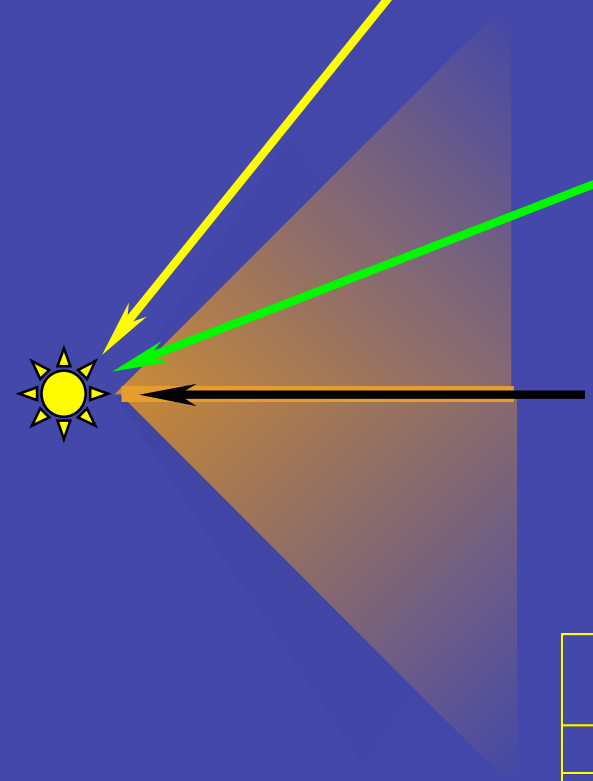
Takeuchi, T. & Artymowicz, P. 2001, ApJ, 557, 990

# Summary of Results




**Radial Evolution of Circumstellar Disks:**

- Excitation mechanism of gas tells us about disk structure
- Distribution of gas influences morphology of dust disk
- If a gas giant planet has formed around HD 141569 it must have done so in less than 6-8Myr



## Line of sight toward T Tau N (i<20º)

$A_V \sim 1 \Rightarrow N(H_2)=8\times10^{20} cm^{-2} \Rightarrow N(CO)=1.2\times10^{17}\ cm^{-2}$

$N_{obs}(CO)=1.7\times10^{18}$ ***Factor of 10 higher***

## Line of sight toward HL Tau (i~65º)

$A_V=24 \Rightarrow N(H_2)=1.9\times10^{22} cm^{-2} \Rightarrow N(CO)=2.9\times10^{18}\ cm^{-2}$

**$N_{obs}(CO)=7.5\times10^{18}$** ***Factor of ~2 higher***

## Line of sight toward T Tau S (i>80º)

$A_V \sim 45 \Rightarrow N(H_2) \sim 4\times10^{22} cm^{-2} \Rightarrow N(CO) \sim 6\times10^{18}\ cm^{-2}$

**$N_{obs}(CO)=9\times10^{18}$** ***About the same***

| Star | Inclination | $\eta_{Disk}$ $cm^{-2}\ mag^{-1}$ | $\eta_{Interstellar}$ $cm^{-2}\ mag^{-1}$ | $\eta_{Disk}/\eta_{Interstellar}$ |
|---|---|---|---|---|
| T Tau S | >80° | $2\times10^{17}$ | $1.4\times10^{17}$ | ~ 1.4 |
| HL Tau | ~65° | $3.2\times10^{17}$ | $1.4\times10^{17}$ | ~ 2.3 |
| T Tau N | <20° | $1.7\times10^{18}$ | $1.4\times10^{17}$ | ~12 |

$\eta = N(CO)/A_V$

$\eta_{Disk}/\eta_{Interstellar}$ decreases with inclination