Spectroscopic Probes of Turbulence in the Planet Formation Region of Disks

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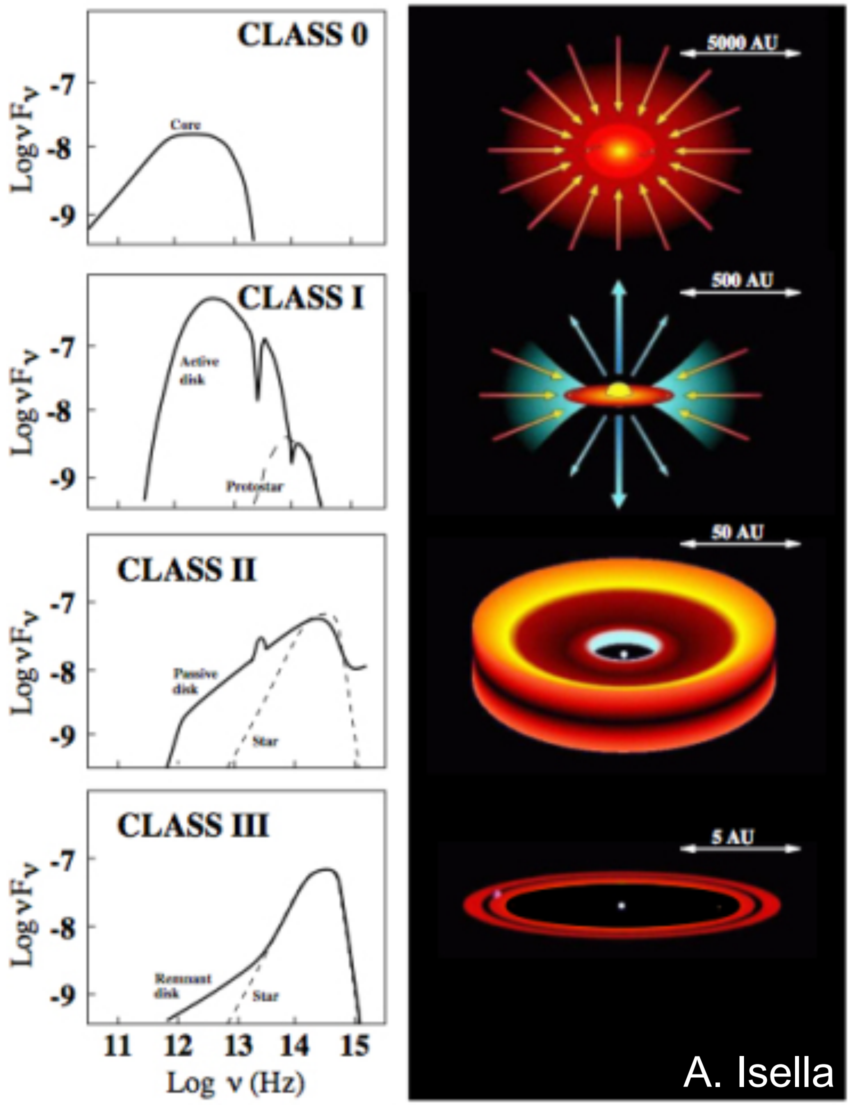
In this talk…

How "primordial" are protoplanetary disks?

Possible ways to probe turbulence in inner disks (i.e., at < 10 AU)

- Available spectral line diagnostics (molecular)
- **#1 Chemical mixing (challenging?)**
- **#2 Heat signature**
- **#3 Turbulent motions**
- **Constraints on disk winds?**

Evolutionary Stages of Star Formation



What is a protoplanetary disk?
When do planets form?

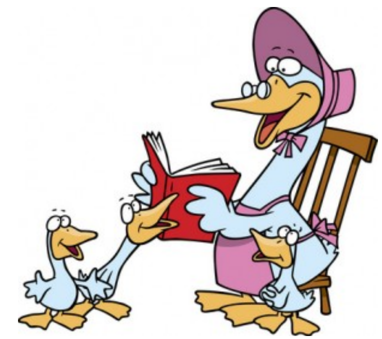
Embedded object:
Star assembling its mass;
has a disk, outflow, envelope.

Classical T Tauri star:
Star essentially formed;
has a disk.

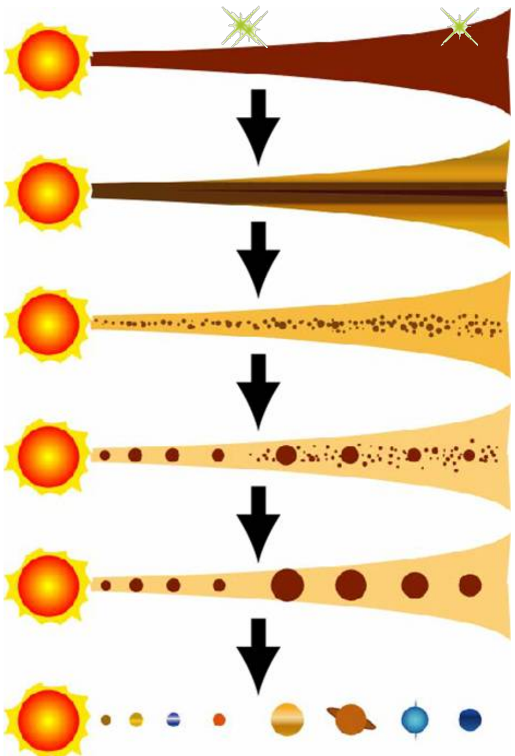
Weak T Tauri star:
Little/no accretion, gas, and dust
Possible planetesimals for later
debris production

How Do Planets Form?

The Story of Core Accretion



Once upon a time…



Grains (μm) grew…

Planetesimals (km) that grew…

Protoplanets (~1000s km) that grew…

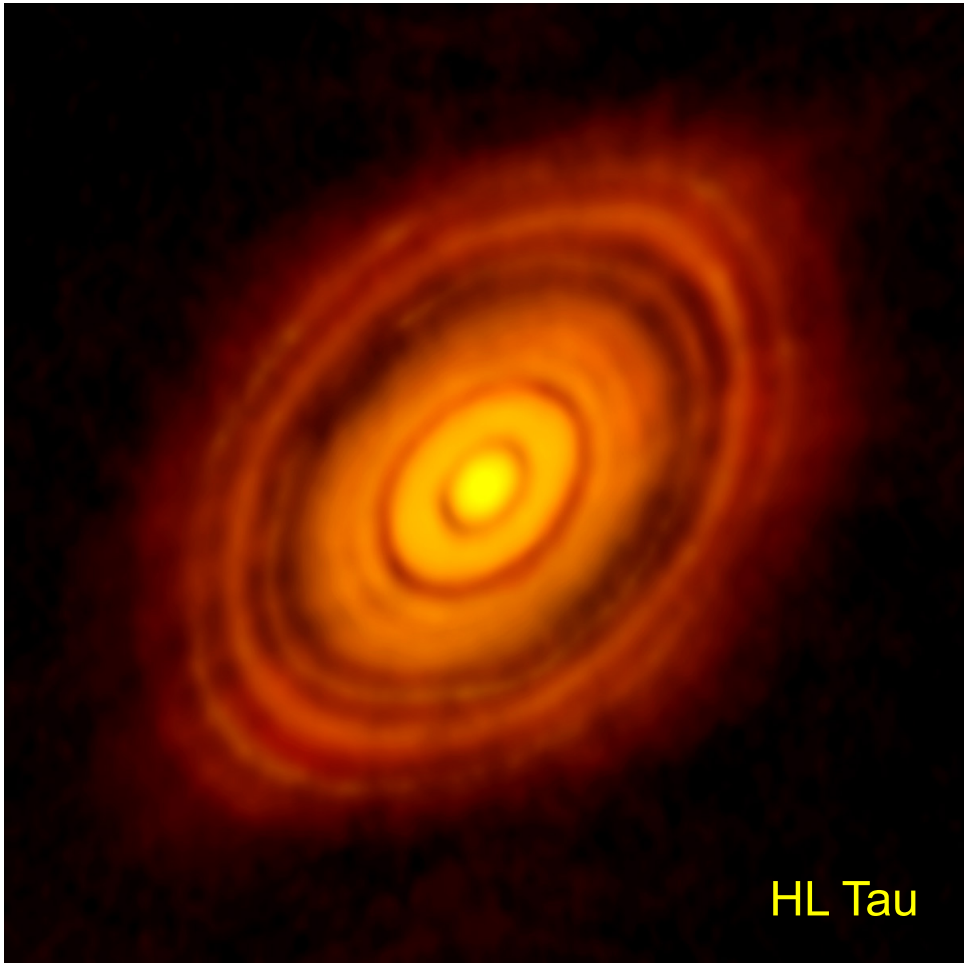
Giant planets (10^5 km)

- 5-10 M_{Earth} core
- accretion of gaseous envelope

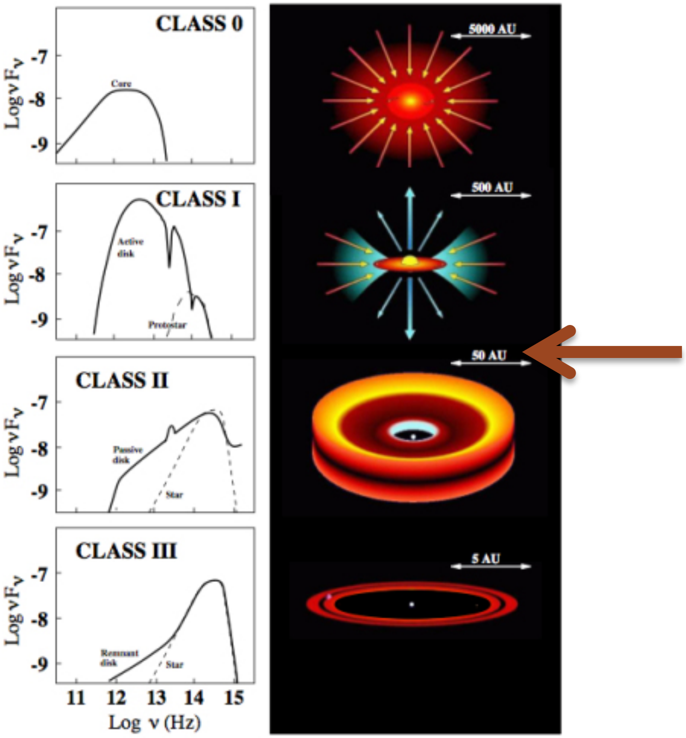
Remnant disk cleared…tada!

The End

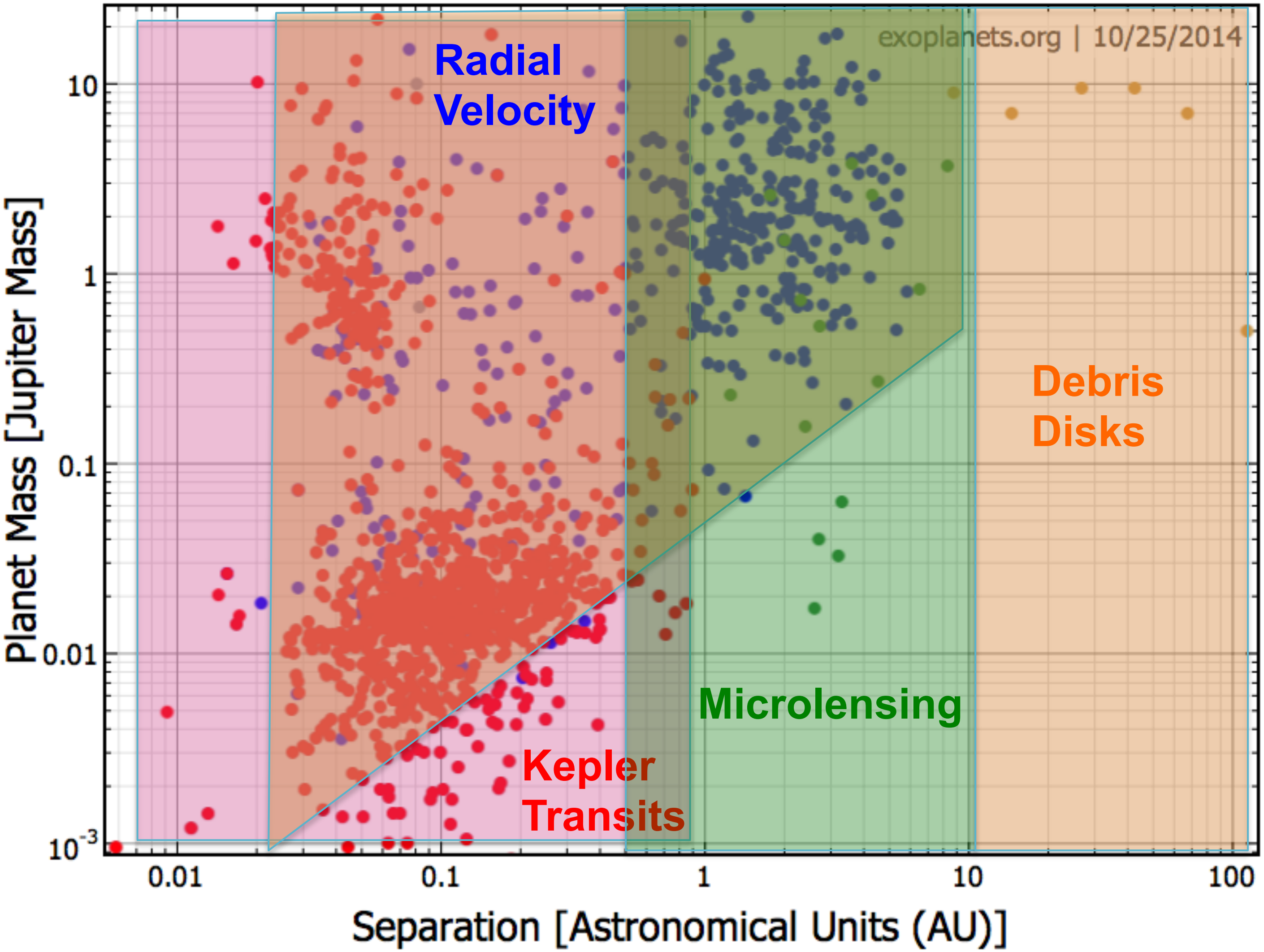
Birth of Planets Revealed in Astonishing Detail in ALMA's 'Best Image Ever'



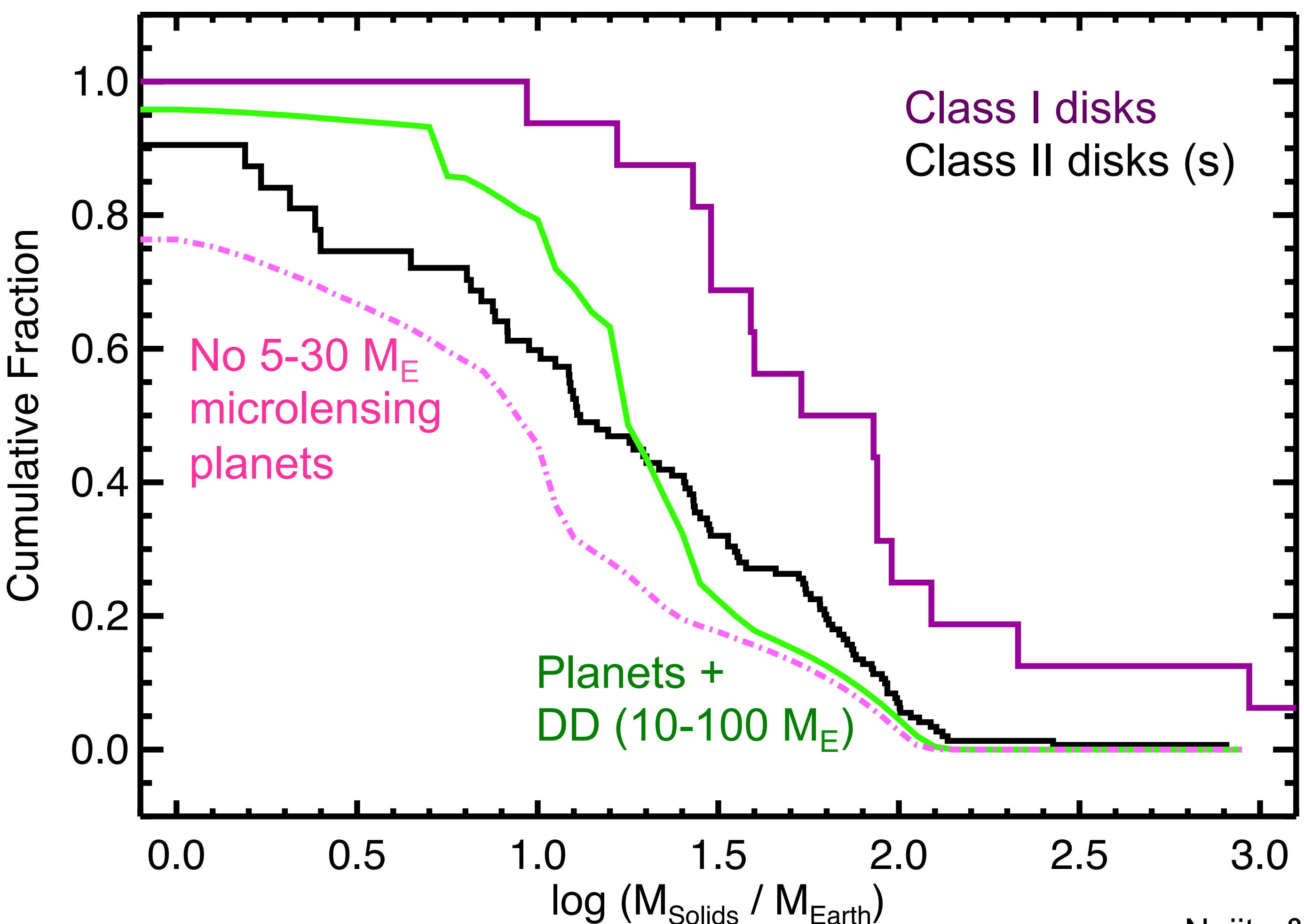
- Flat-spectrum source (Class I.5)
- What's the situation for most disks?



Exoplanet Populations



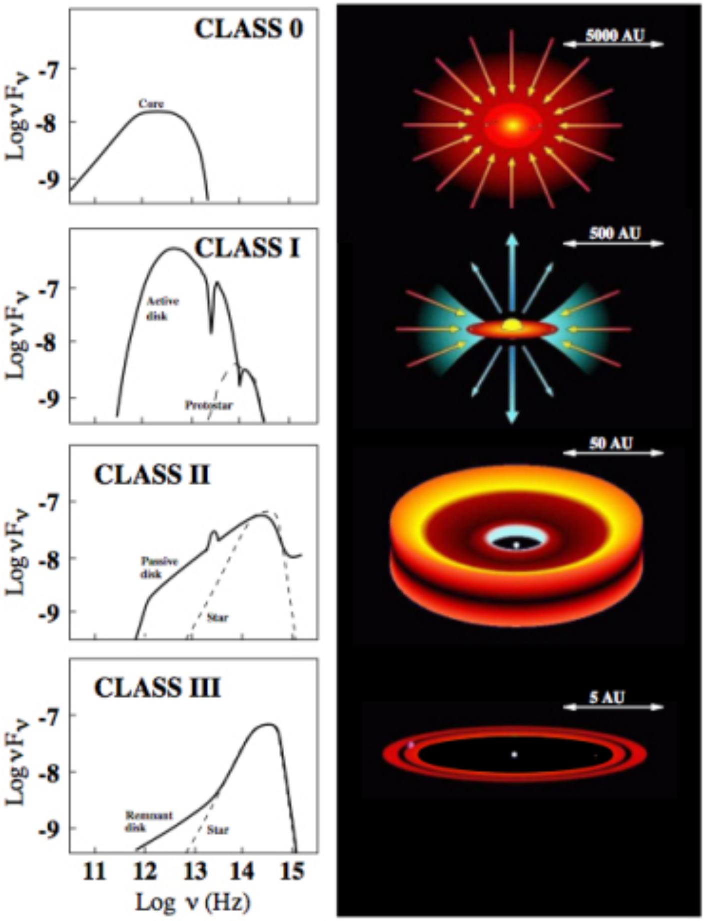
Synthetic (Monte Carlo) Exoplanet & Debris Disk Populations



Najita & Kenyon 2014

Are Protoplanetary Disks Primordial?

Not so much.

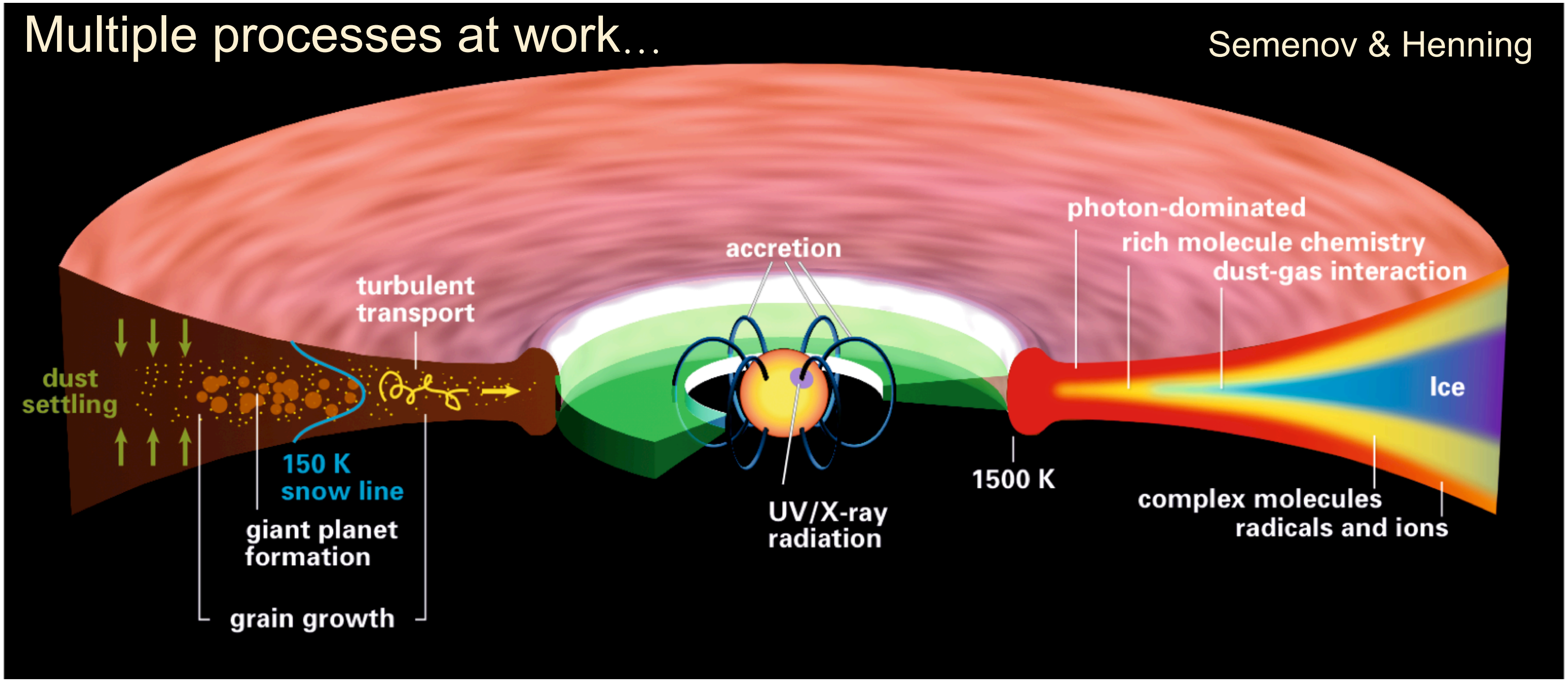


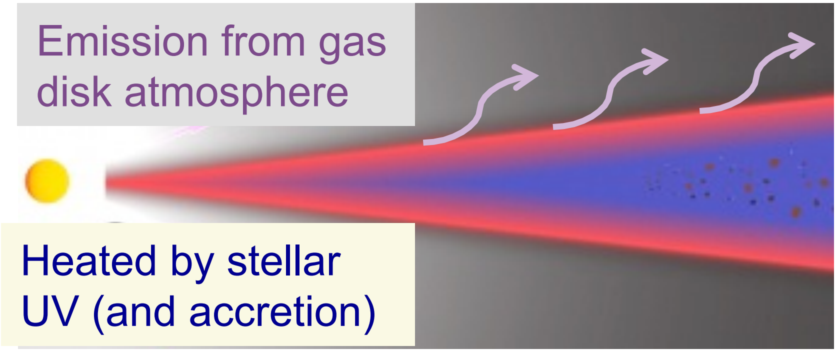
T Tauri disks: highly evolved as a class

Are T Tauri disks like this….?

Or this….?

Studying Disks Spectroscopically

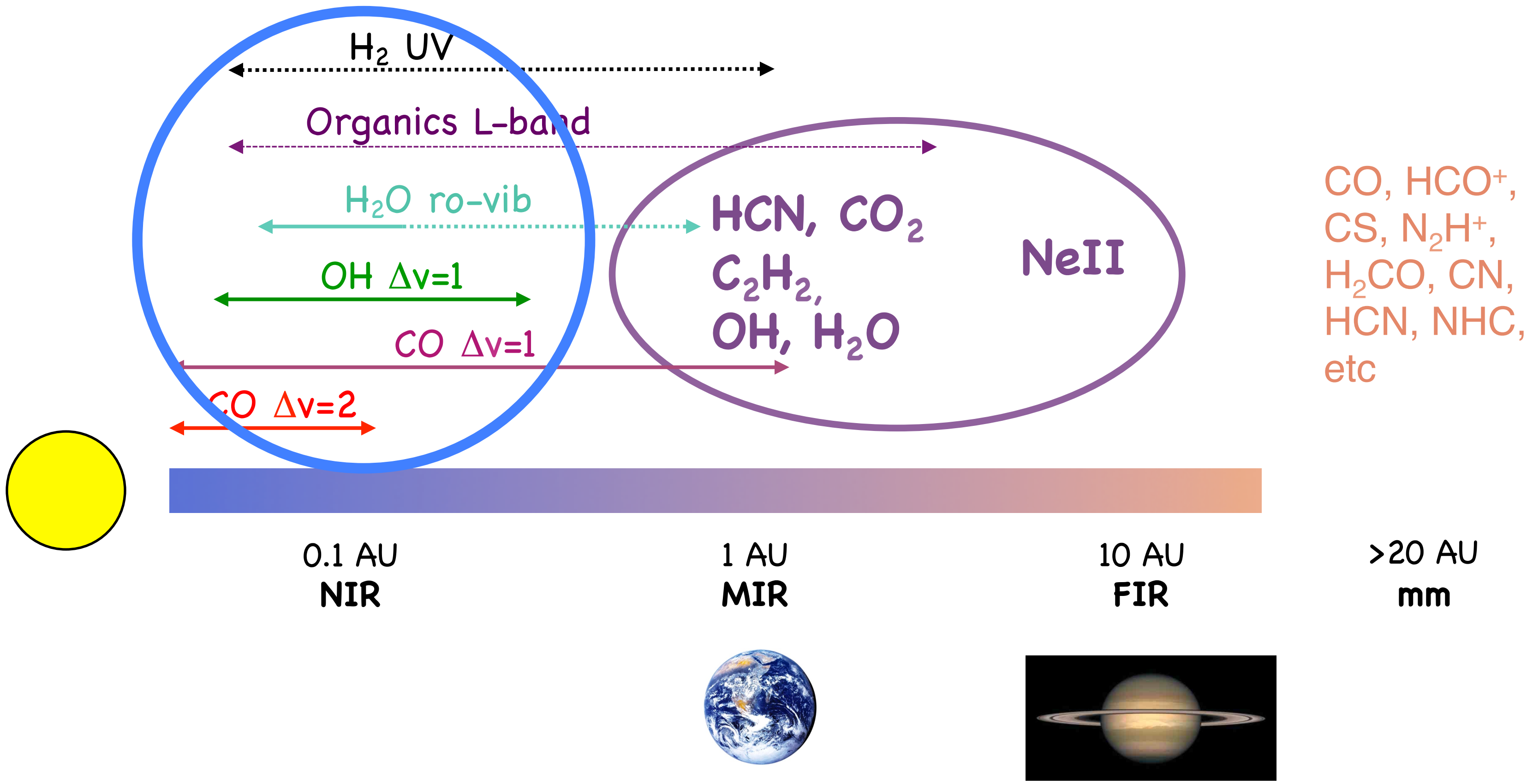




Clues from disk atmospheres:

- **Chemistry**
- **Heating ($T_g > T_d$)**
- **Motions**

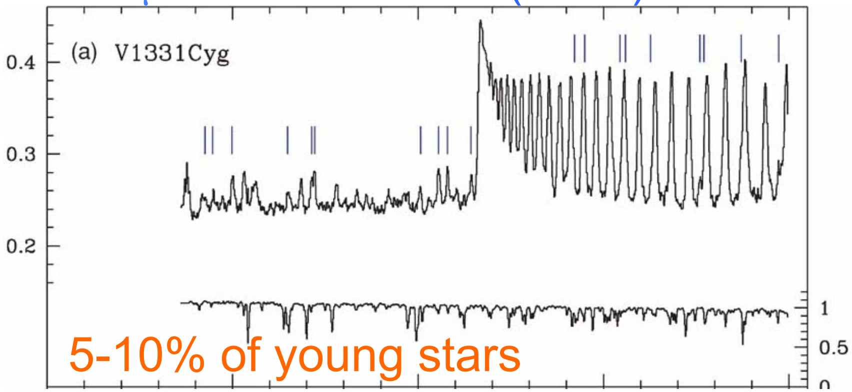
Gaseous Probes of Inner Disks



NIR, UV, MIR diagnostics probe planet formation distances

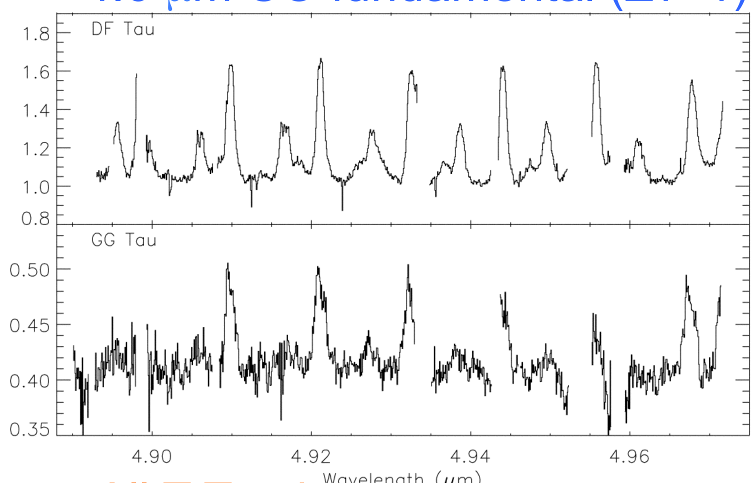
Spectral Line Diagnostics NIR

2.3 μm CO overtone (Δv=2)



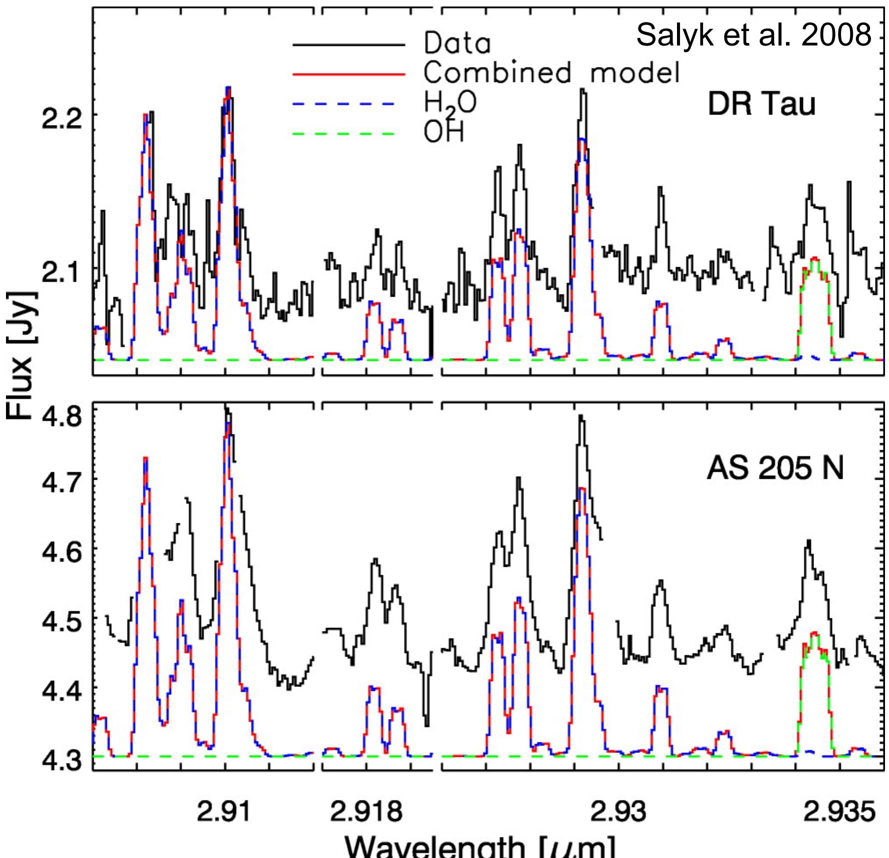
5-10% of young stars

4.6 μm CO fundamental (Δv=1)



~All T Tauri stars

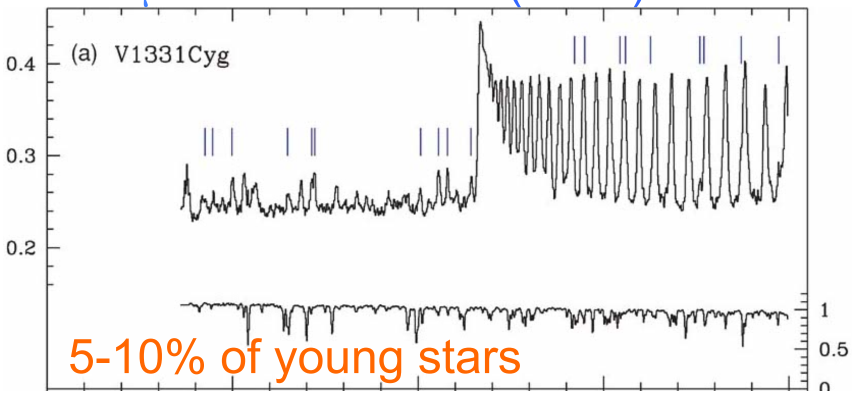
3 μm H_2O and OH rovibrational



May be common? (stellar photospheres)

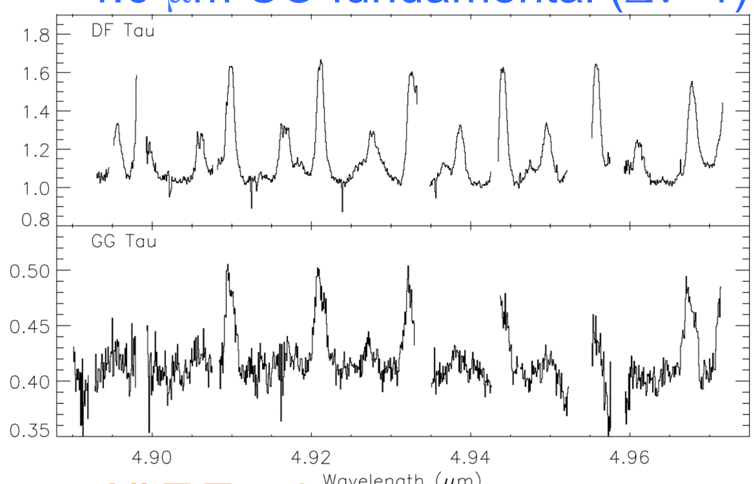
Spectral Line Diagnostics NIR

2.3 μm CO overtone (Δv=2)



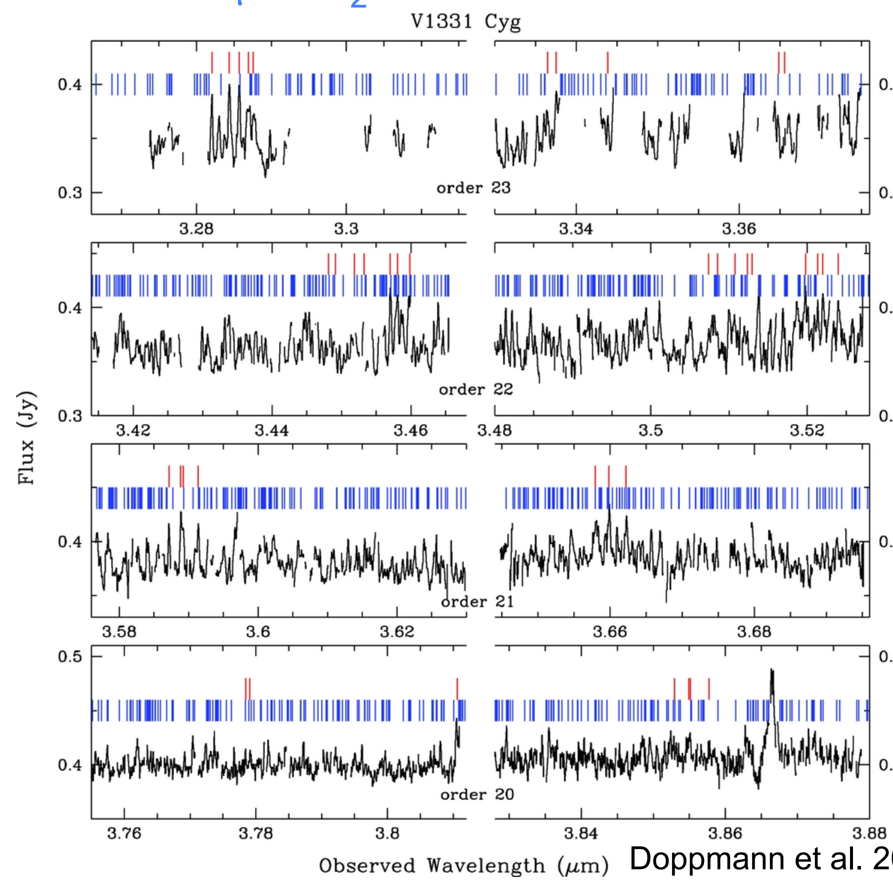
5-10% of young stars

4.6 μm CO fundamental (Δv=1)



~All T Tauri stars

3 μm H_2O and OH rovibrational

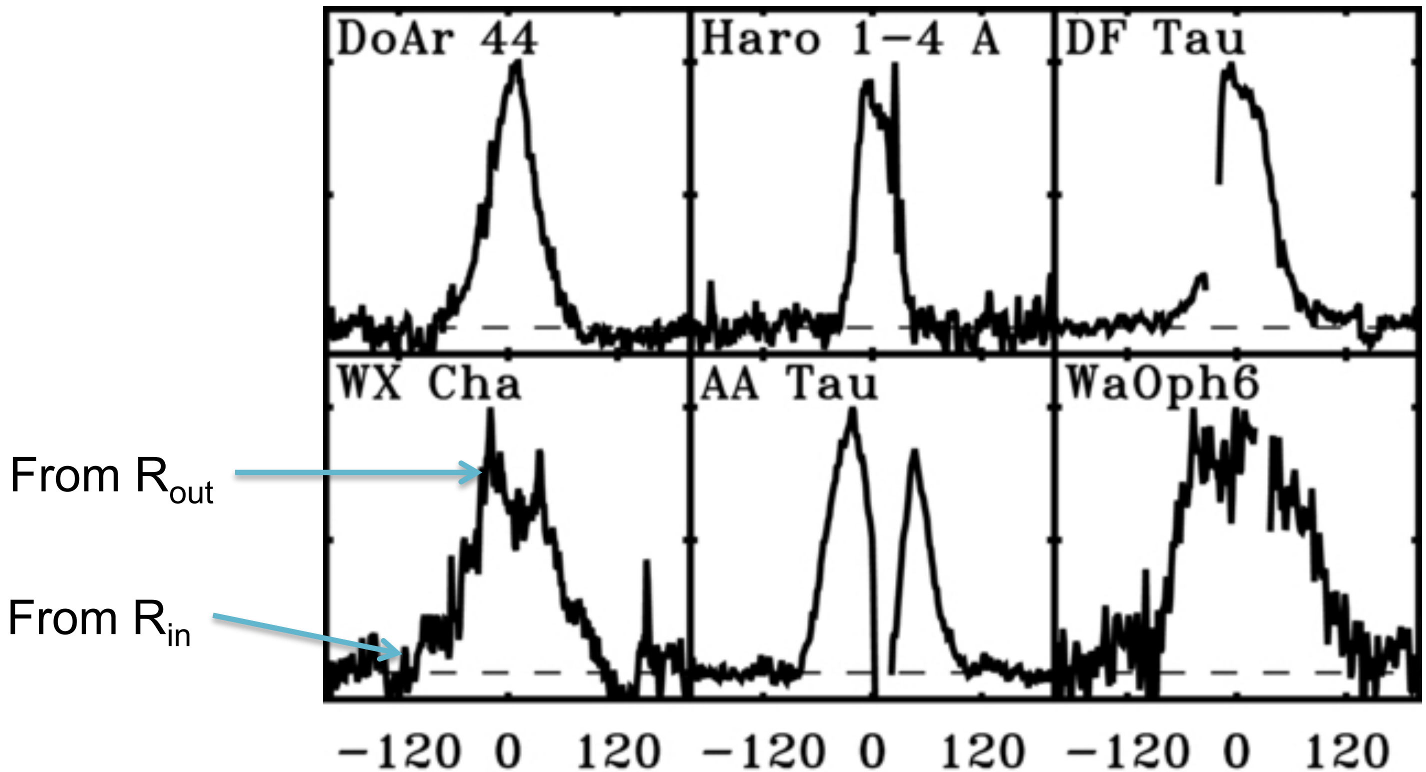


Doppmann et al. 2011

Rarely this dense

Spectral Line Profiles NIR

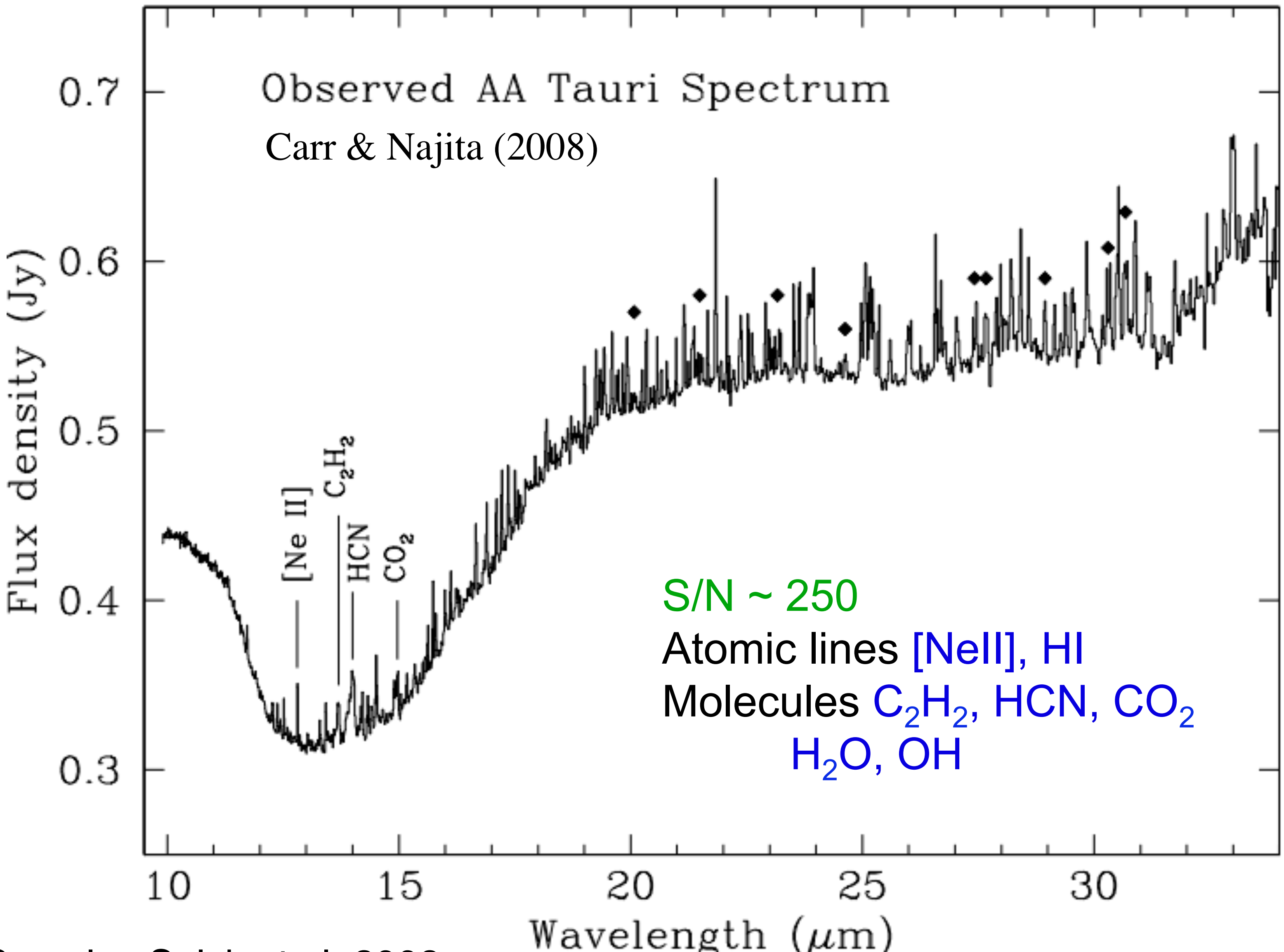
Line profiles used to infer emission radii, physical conditions in the atmosphere



Brown et al. 2013

CO fundamental emission from disk truncation radius (0.05 AU) to ~ 1AU

Spectral Line Diagnostics MIR



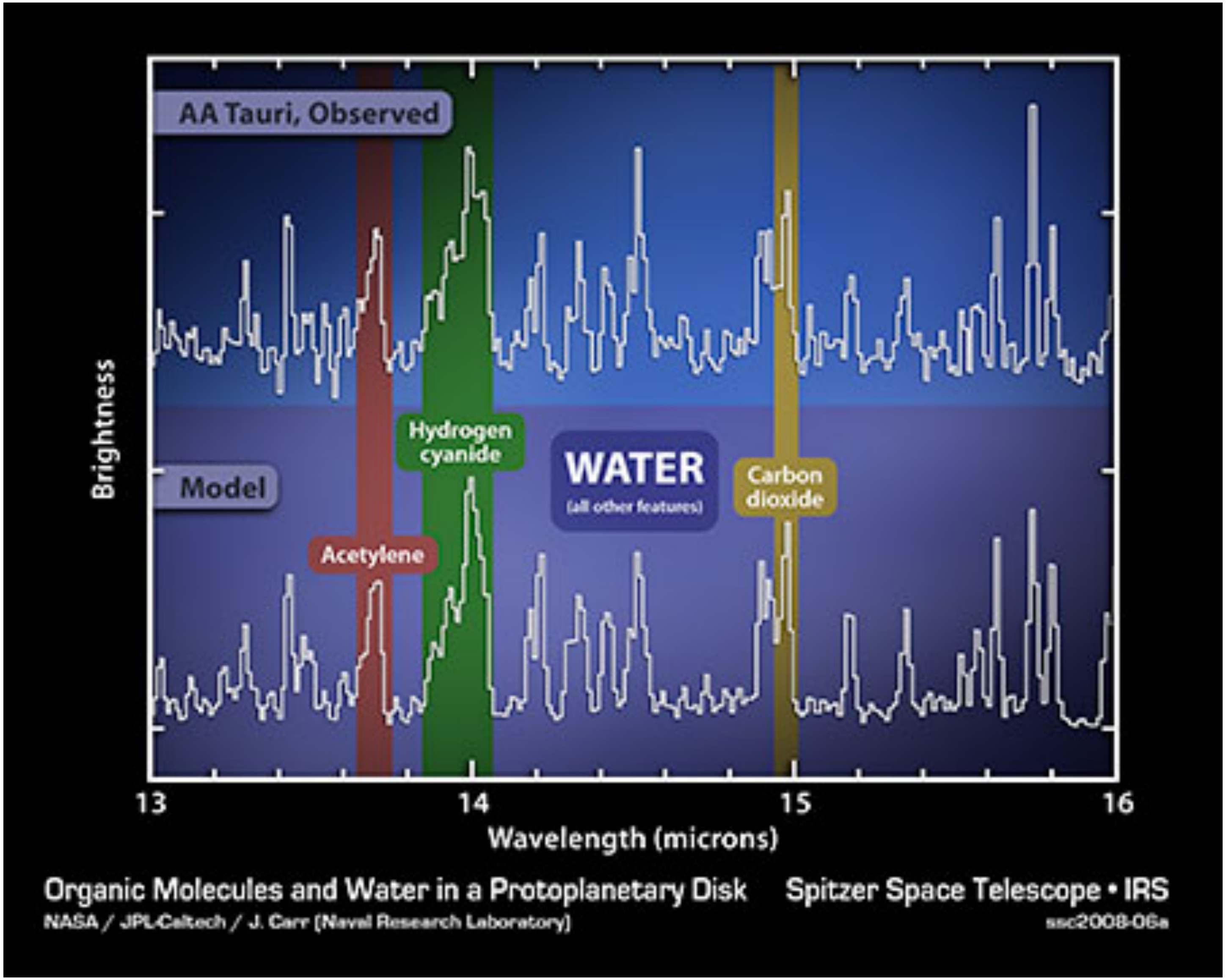
S/N ~ 250

Atomic lines [NeII], HI

Molecules C_2H_2, HCN, CO_2
H_2O, OH

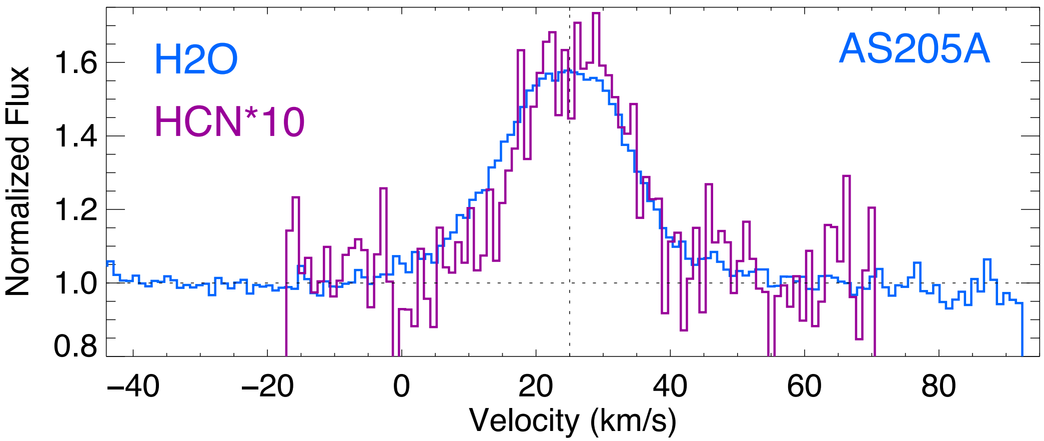
See also Salyk et al. 2008

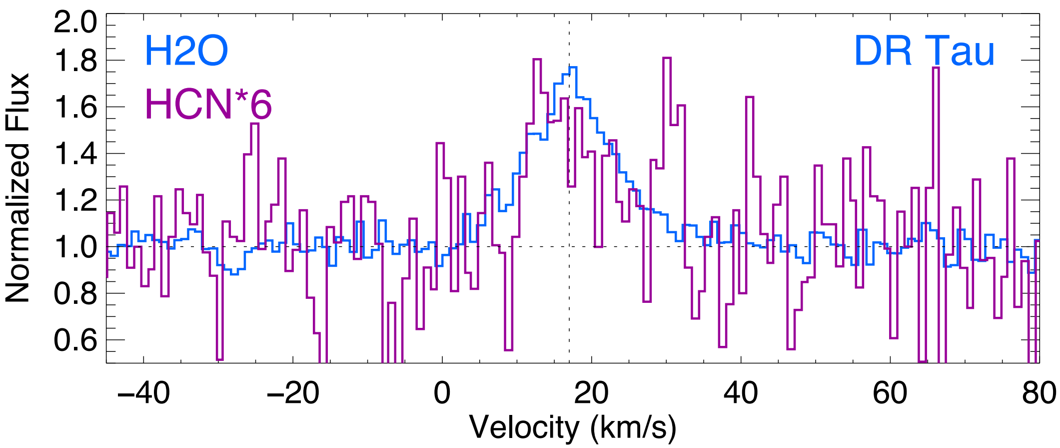
Spectral Line Diagnostics MIR



Line Profiles for Water and Organics

MIR Spectra from TEXES on Gemini





R=100,000
$\lambda \sim 12\mu m$

- **Water** (high quality profiles)
- **Organics – HCN, C_2H_2** (10x weaker, challenging)

Najita et al., in prep

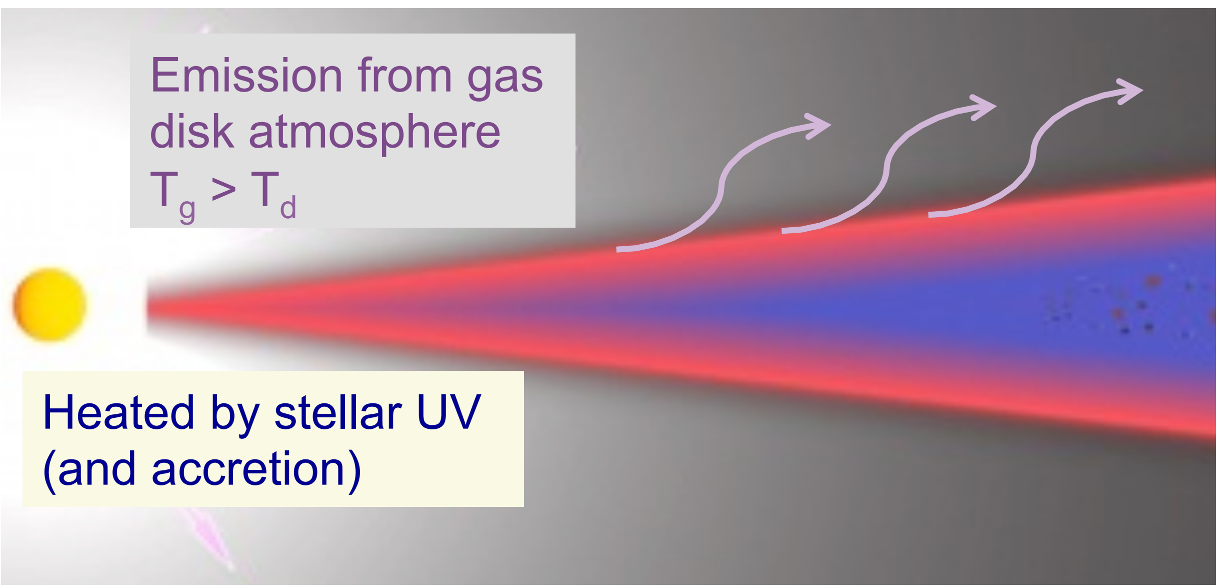
MIR line profiles locate emission in the **terrestrial planet region** (< few AU)

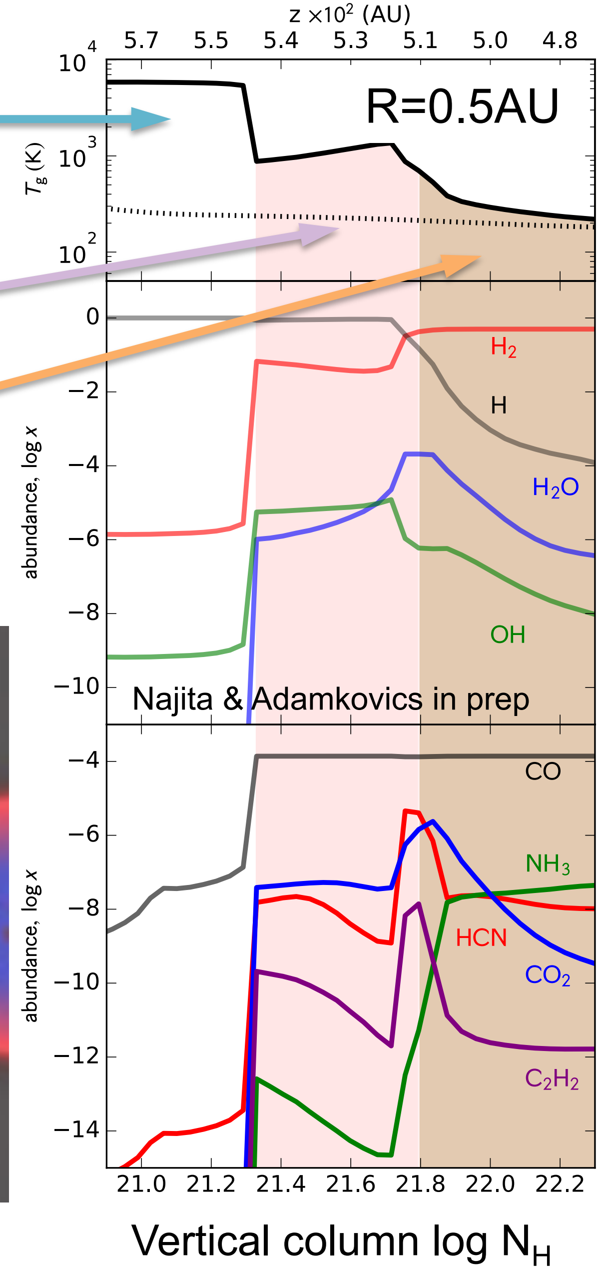
Emission from Disk Atmospheres

Hot Atomic Layer
4000K

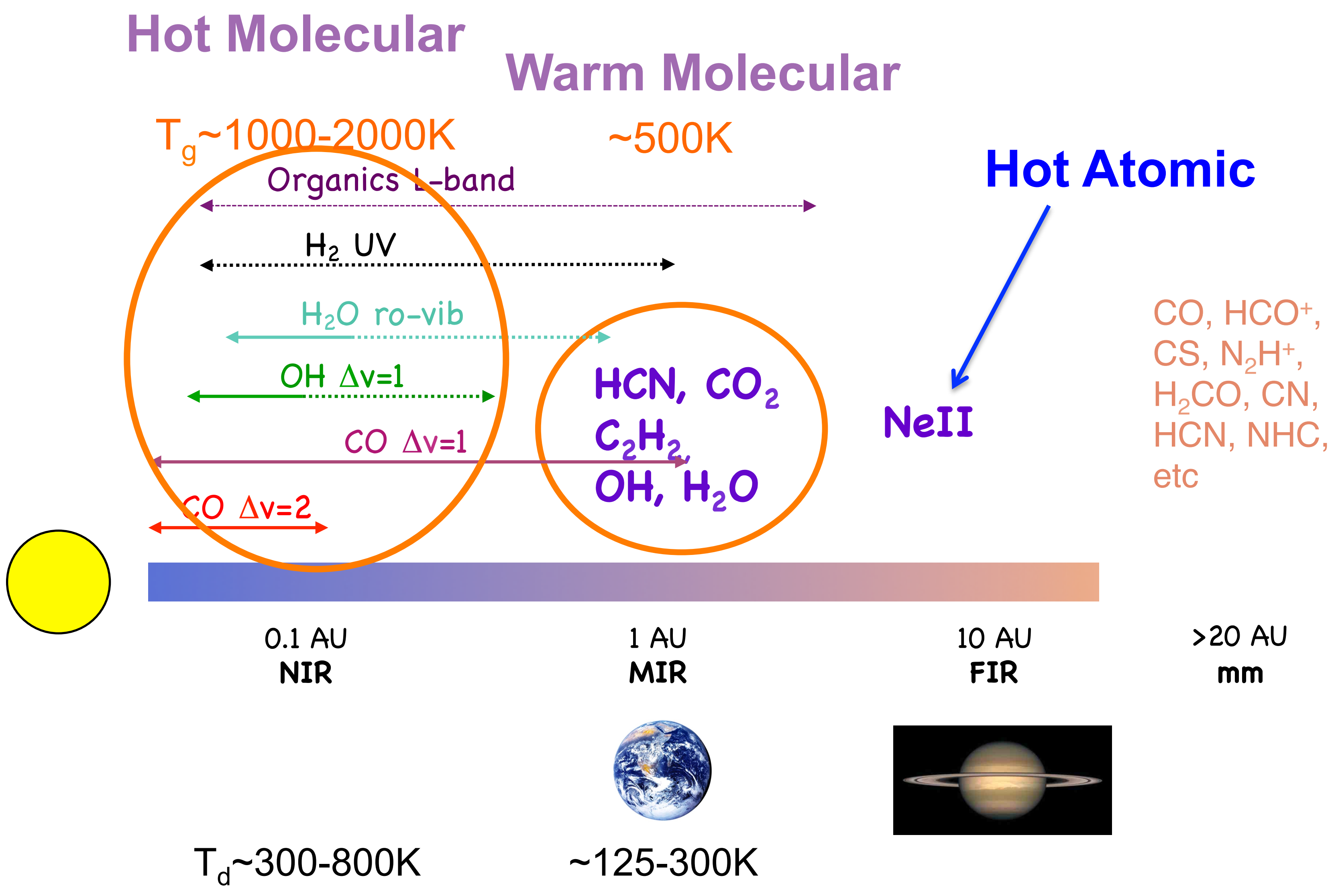
Hot/warm Molecular Layer
400-2000K

Cool Molecular Layer
< 400K



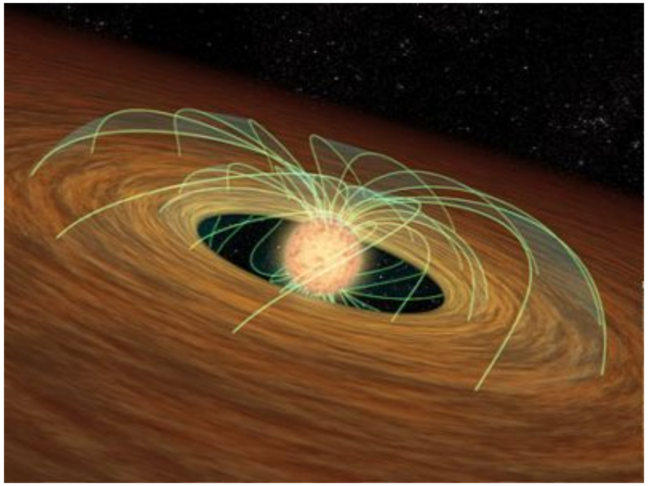


Gaseous Probes of Inner Disks

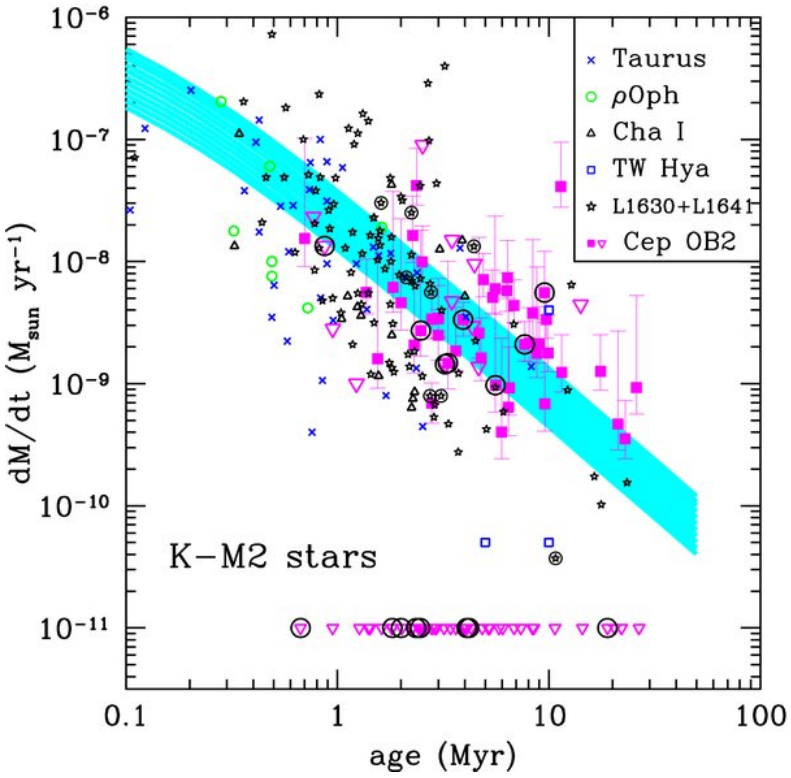


Still accreting after all these years...

Young stars accrete…and more slowly with age

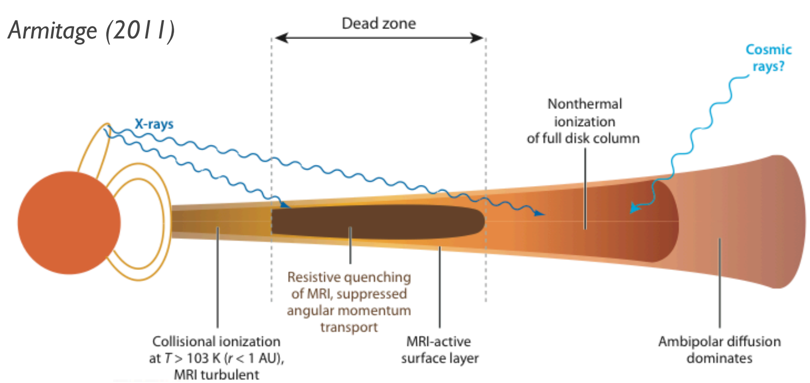


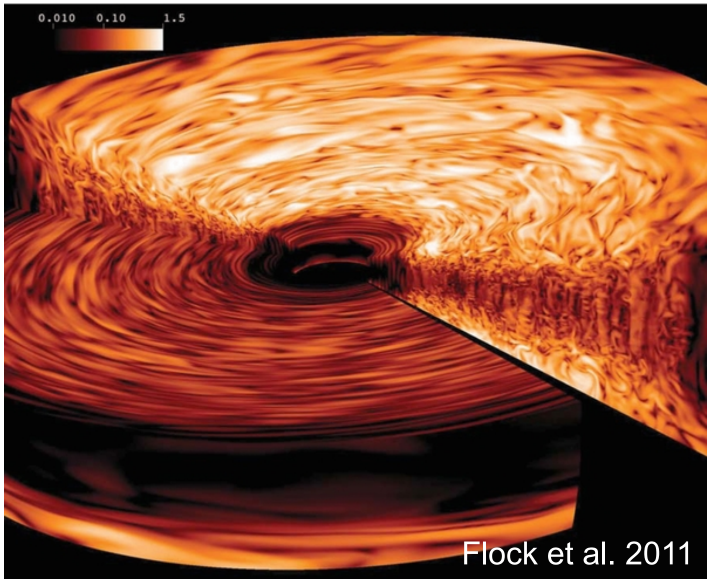
Sicilia-Aguilar et al. 2010



How do they do it?

Magnetorotational Instability?



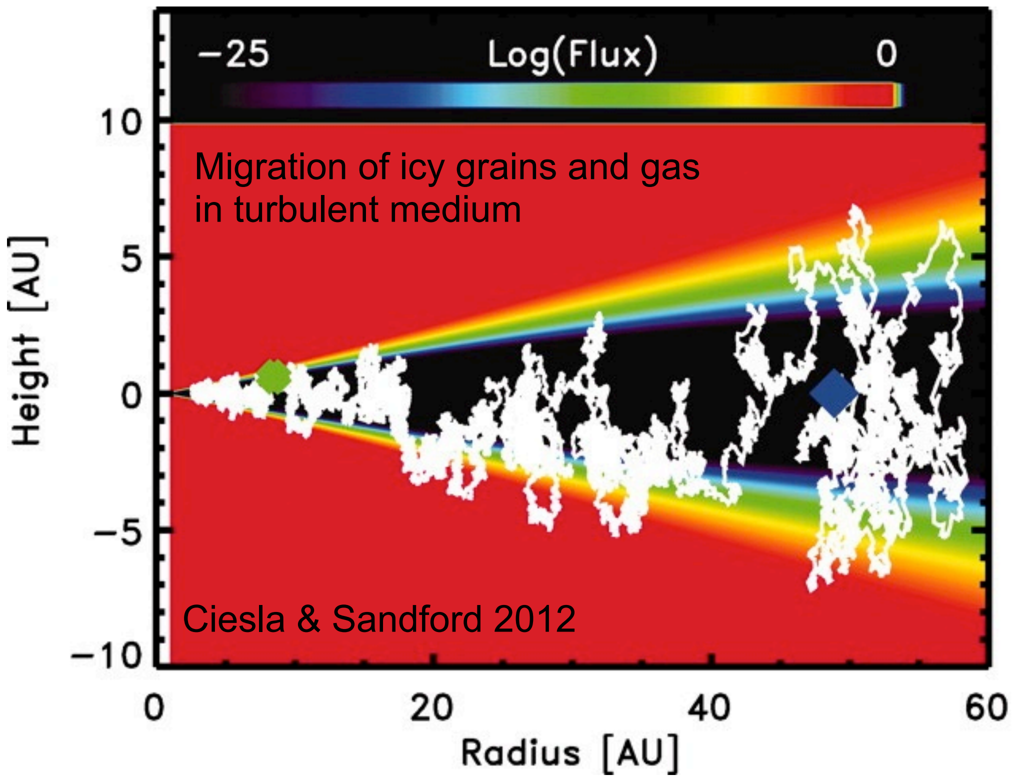


Low ionization in disk midplane – is the disk dead at planet formation distances?

How can we look for evidence of MRI in action?

- **Chemical mixing**
- **Mechanical heating**
- **Turbulent motion**

#1 Chemical Mixing



Migration of icy grains and gas in turbulent medium

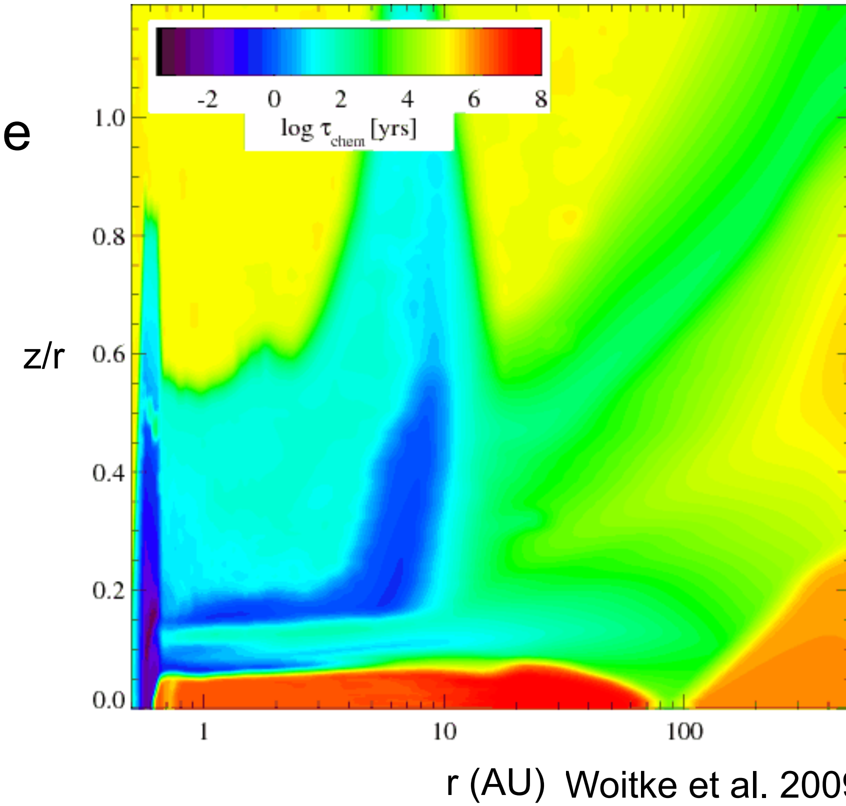
- Vertically
- Radially

Looking for something chemically out of place…

Molecular Diagnostics of Chemical Mixing

- Chemical timescale is generally short in atmosphere, long at large r and small z.
- History is lost, for known diagnostics within few AU.

Chemical Timescale



Woitke et al. 2009a

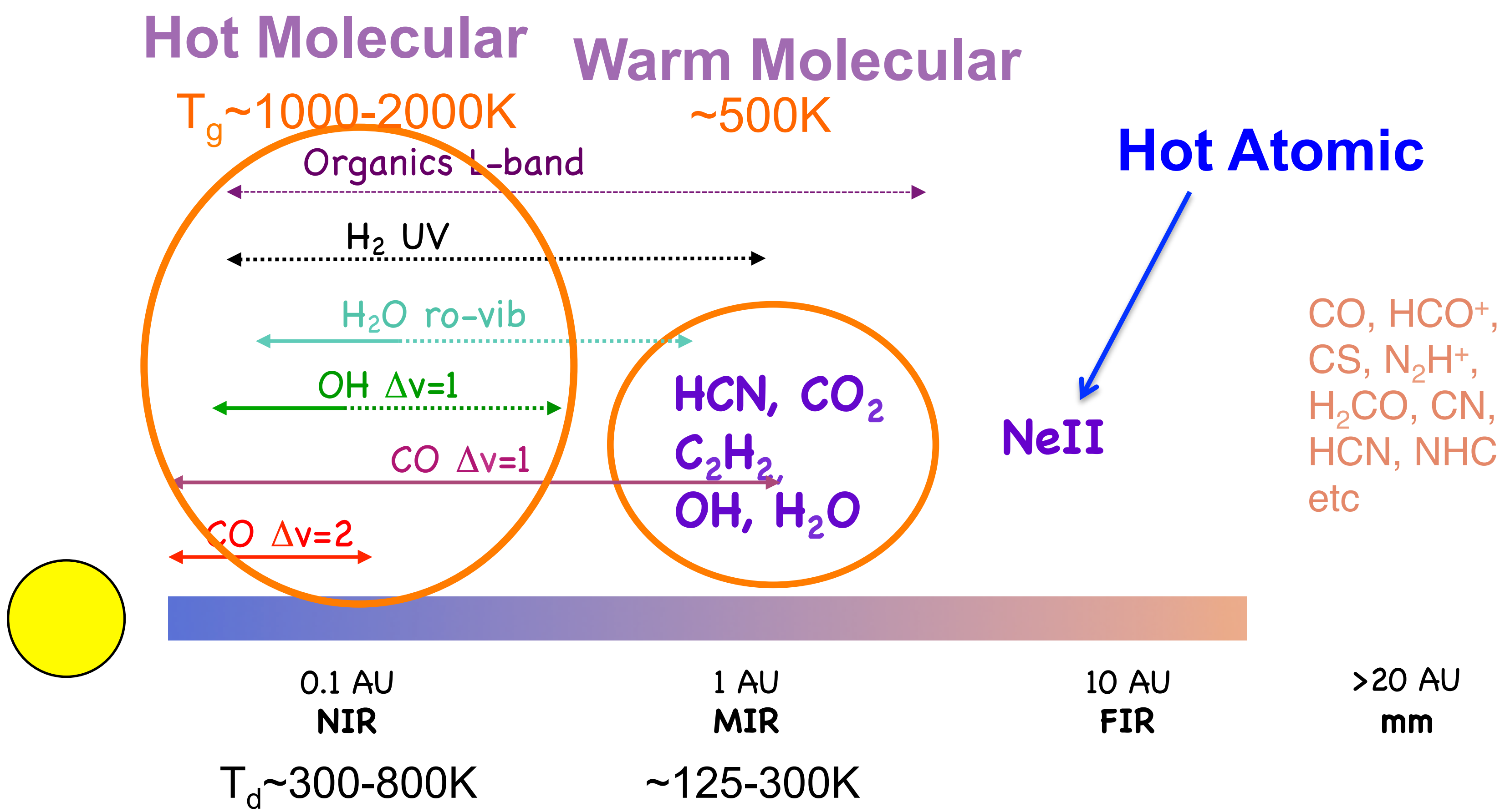
- Need observable chemical species with long chemical lifetimes…
- Or look at effects from changes to elemental abundance ratios.

#1 Chemical Mixing

- **Seems challenging.**
- **Questions**:
  - How much mixing is predicted?
  - What is a useful probe?
- **Molecular probes**: Looking for molecules with long chemical timescales to serve as probes of turbulent mixing
- **Elemental abundance probes**: Does mixing affect elemental abundance ratios in an observable way? (e.g., planetesimal formation example)

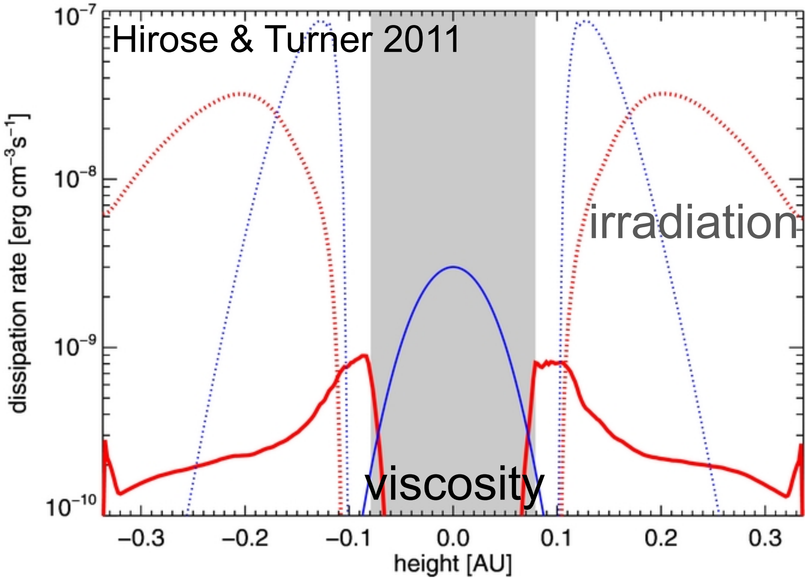
#2 MRI Heating?

Gas temperatures of IR spectral line diagnostics (500-2500K) exceed dust temperatures in the same region of the disk.
→ Are elevated temperatures powered by mechanical heating?



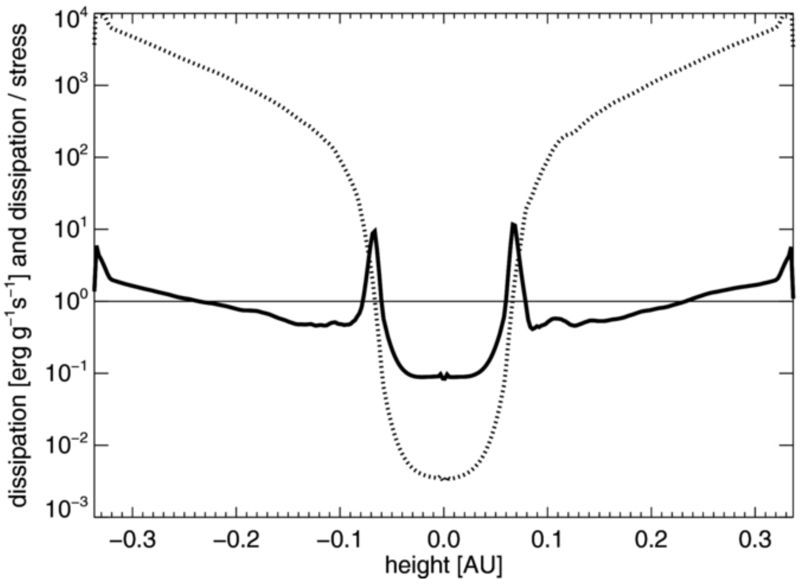
#2 MRI Heating?

More dissipation at disk surface with MRI (current sheets, shocks) than with classical α disk



Turbulent heating rate equiv to α~1

- Is atm heated mechanically?
- Need to rule out other possibilities.



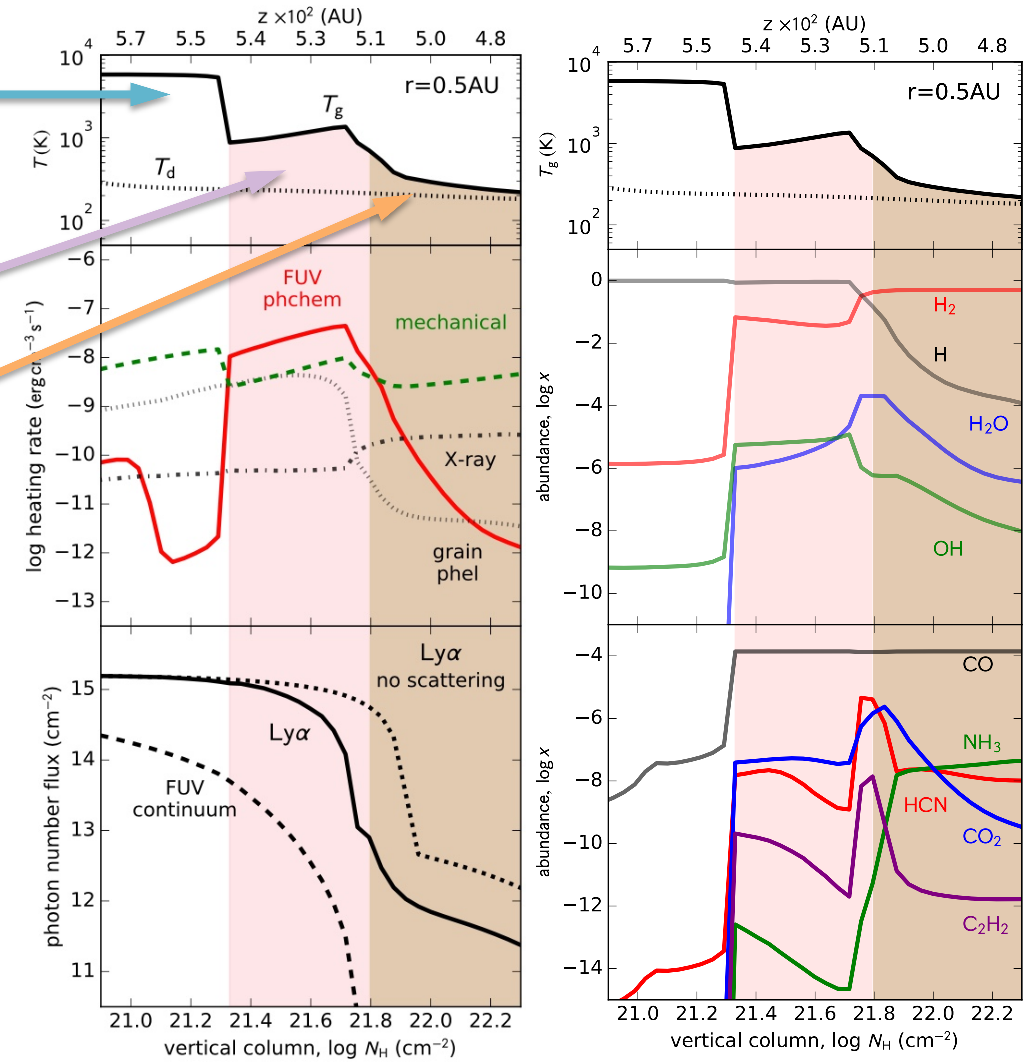
Model Disk Atmospheres with FUV (Lya + Continuum) and Accretion Heating

Hot Atomic

Hot/warm Molecular
(Lya + mechanical)

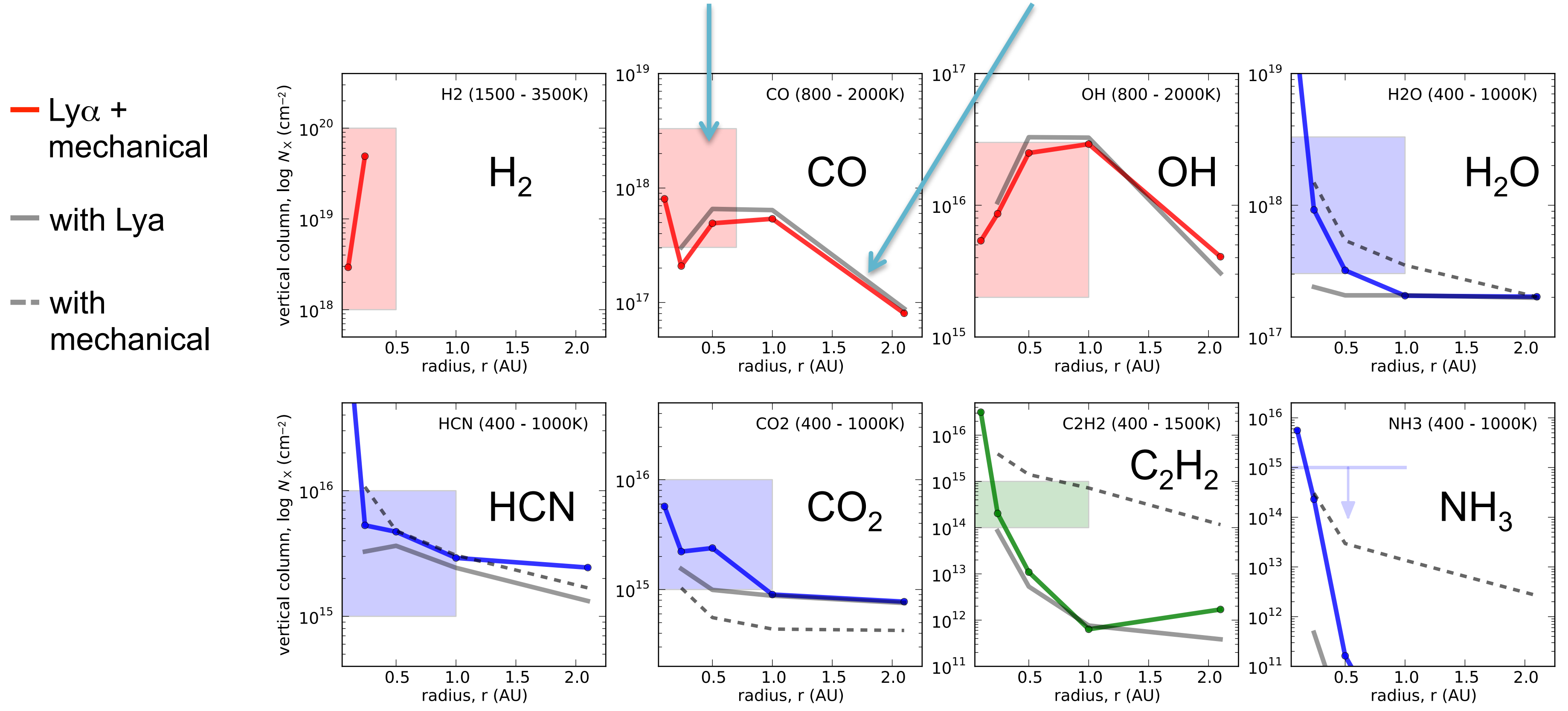
Cool Molecular
(mechanical)

At 0.5 AU
$L_{FUV} = 0.0025 L_{sun} + Ly\alpha$
$\alpha_h = 0.5$
$a_g = 0.7$



Najita & Adamkovics in prep

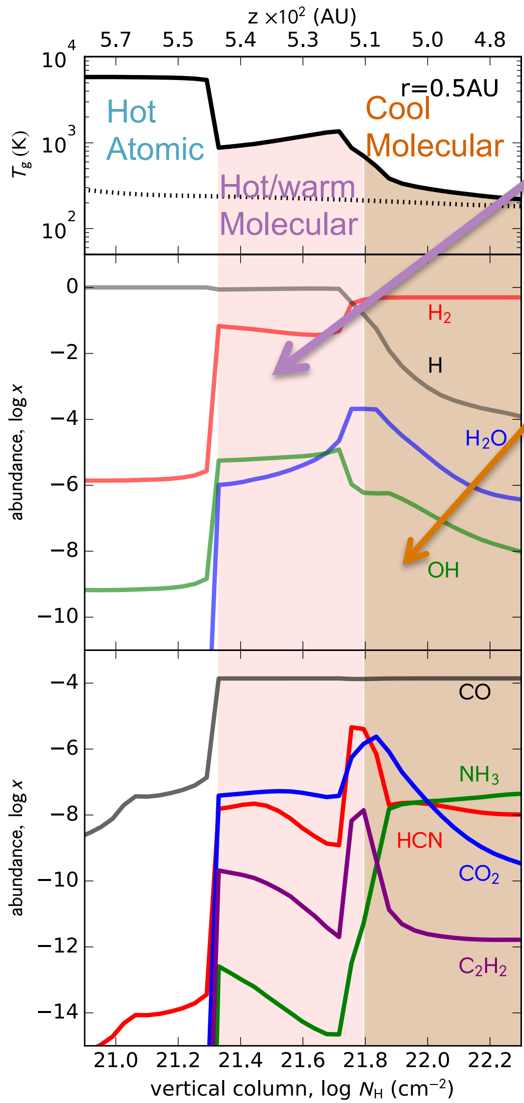
Warm Molecular Columns: Observation & Theory



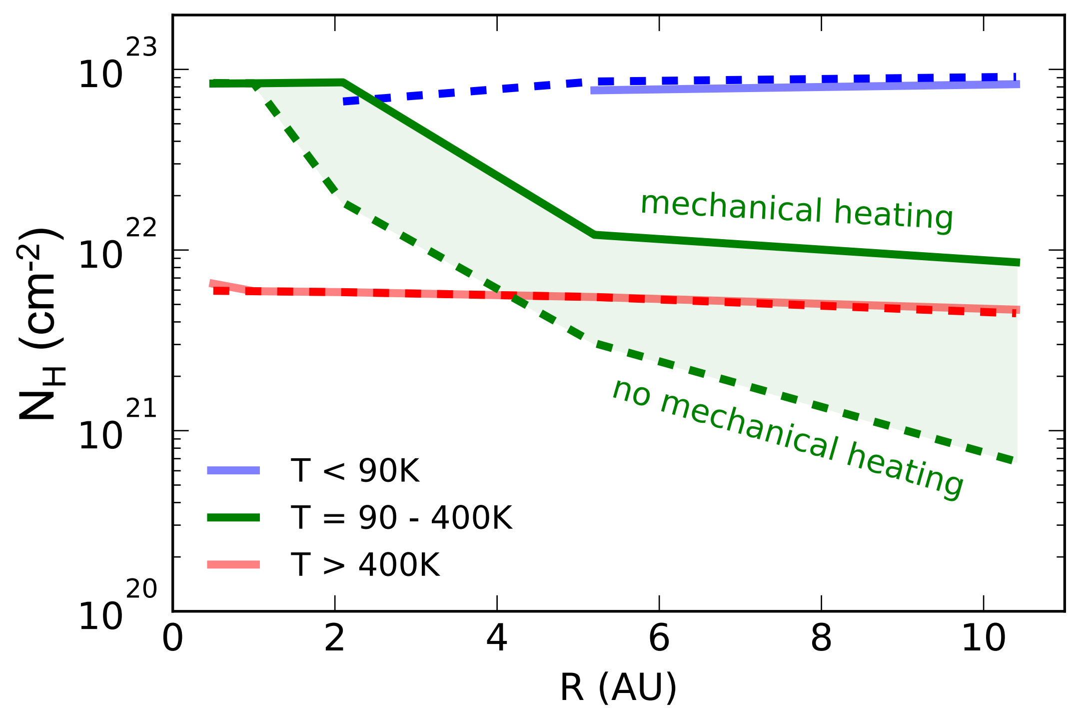
Observations best fit with Lya + mechanical heating, but Lya does much of the heavy lifting

- **Lyα important for hot molecules**
- **Mechanical heating enhances H_2O, HCN, CO_2**

Heat Signature of Accretion in Protoplanetary Disks



- FUV (Lya + continuum) impacts the hot/ warm molecular layer where most of the known diagnostics arise.
- Look below the FUV-heated layer, in cool molecular layer, for evidence of accretion-related heating.



#2 MRI Heating

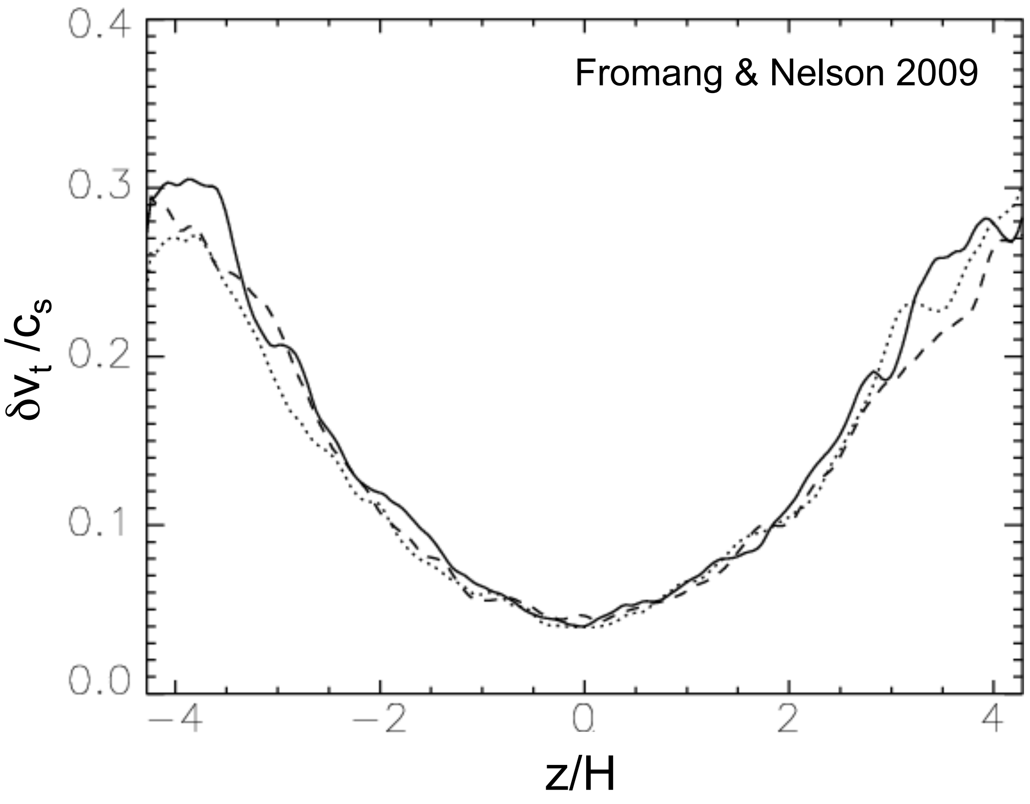
Looks like:

- Known diagnostics do not provide strong evidence.
- Heat signature of accretion below the FUV-heated layer?

Caveats:

- How strong is accretion heating (what is α_H?)
- Does detailed Lyα radiative transfer (scattering + absorption) change this picture?

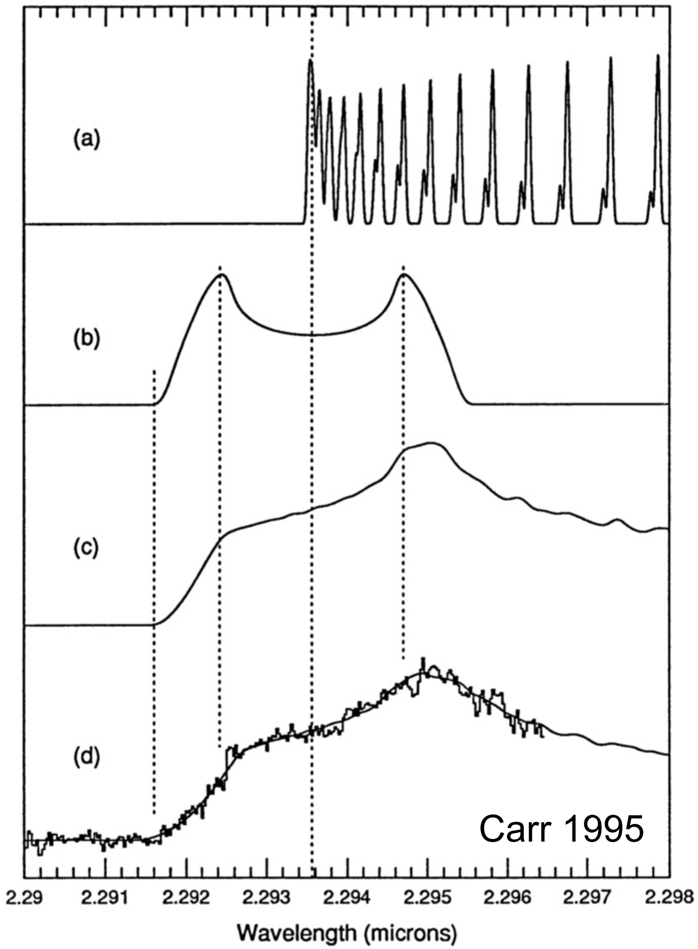
#3 Turbulent Line Broadening



Turbulent velocity fluctuations rise with height, reaching ~ sound speed in the disk atmosphere.

Probing Turbulent Broadening in Spatially Unresolved Disks

2.3 μm CO overtone emission



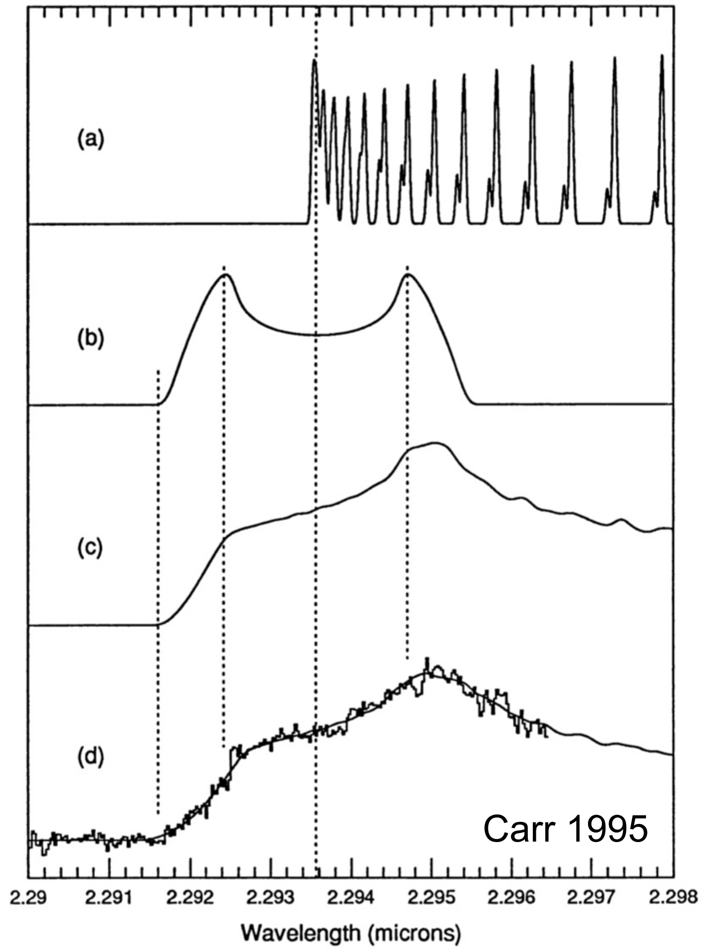
Emission spectrum if no disk rotation

Line profile for a rotating disk (single line)

Convolution fits the data

Probing Turbulent Broadening in Spatially Unresolved Disks

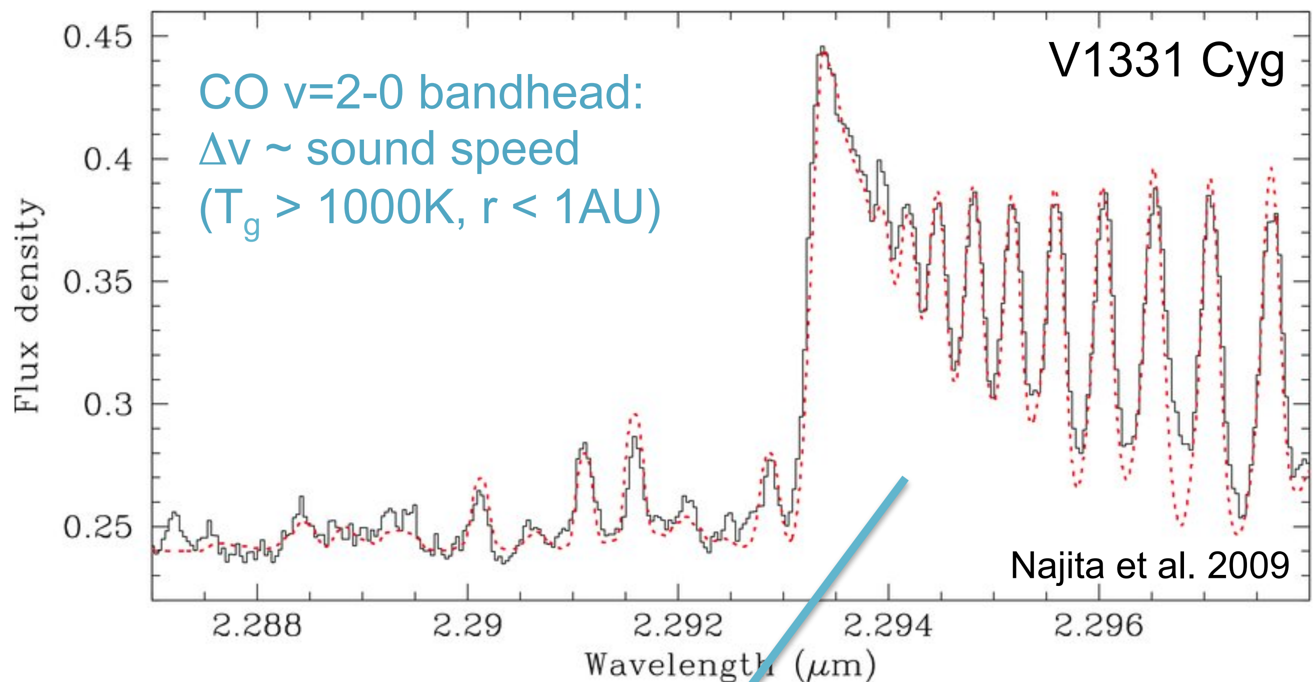
2.3 μm CO overtone emission

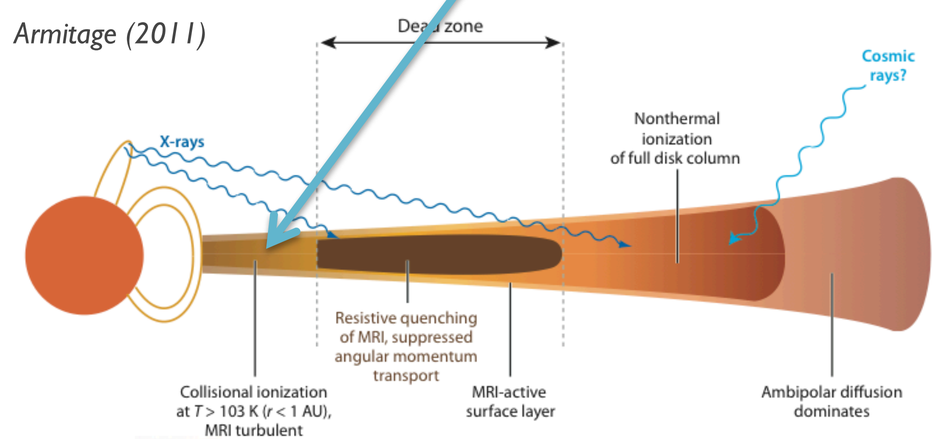


Range in interline spacing probes line broadening

Rotation and excitation/ broadening separable because of large number of lines and spacing

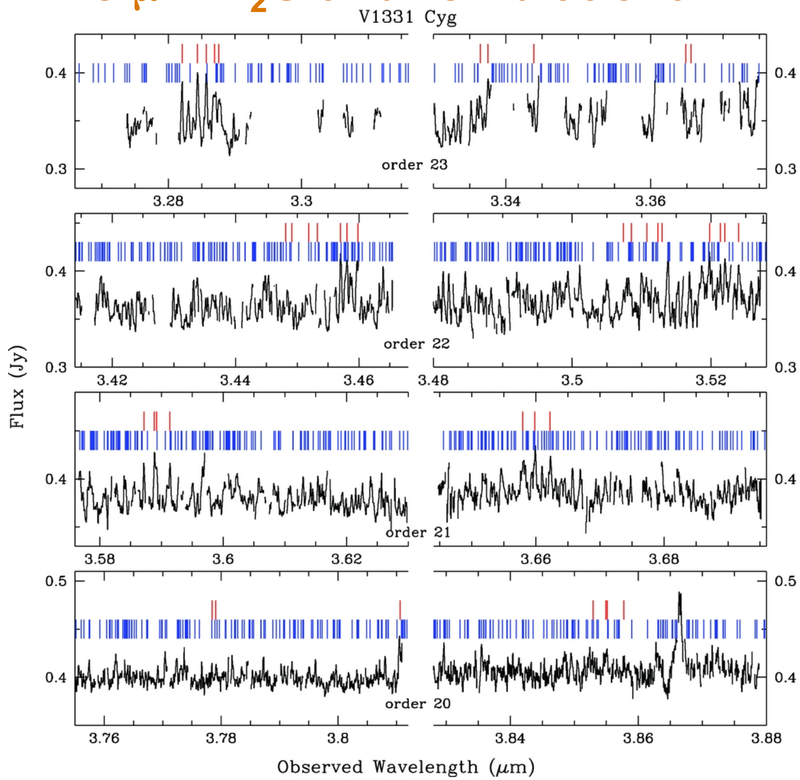
Turbulent Line Broadening



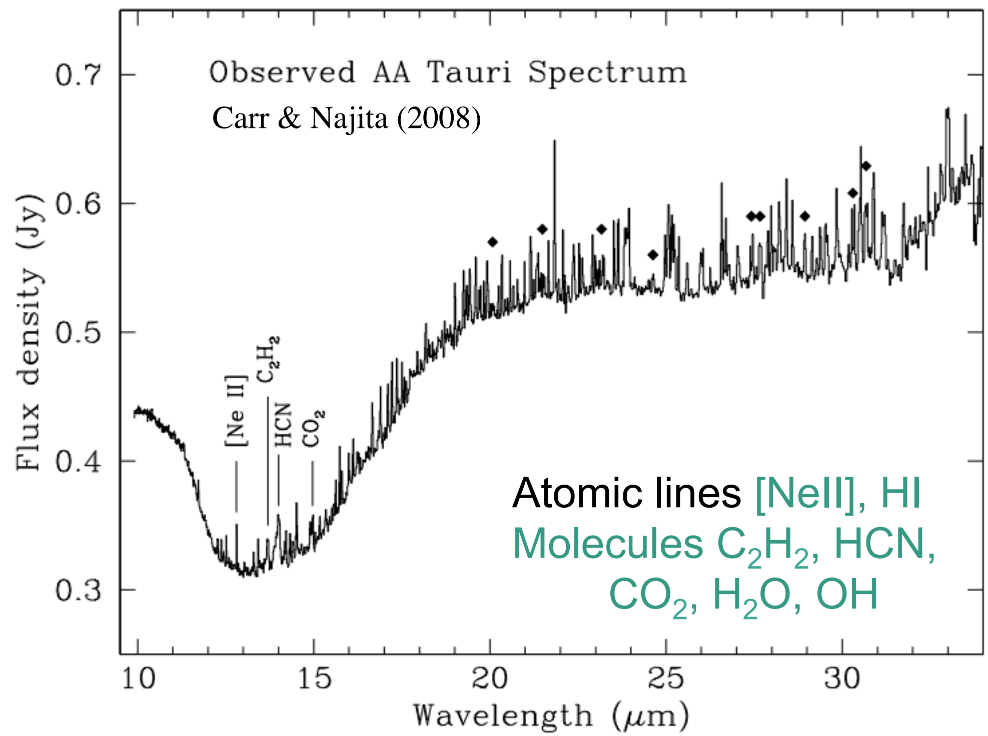


Turbulent Line Broadening at Dead Zone Radii

3 μm H_2O and rovibrational



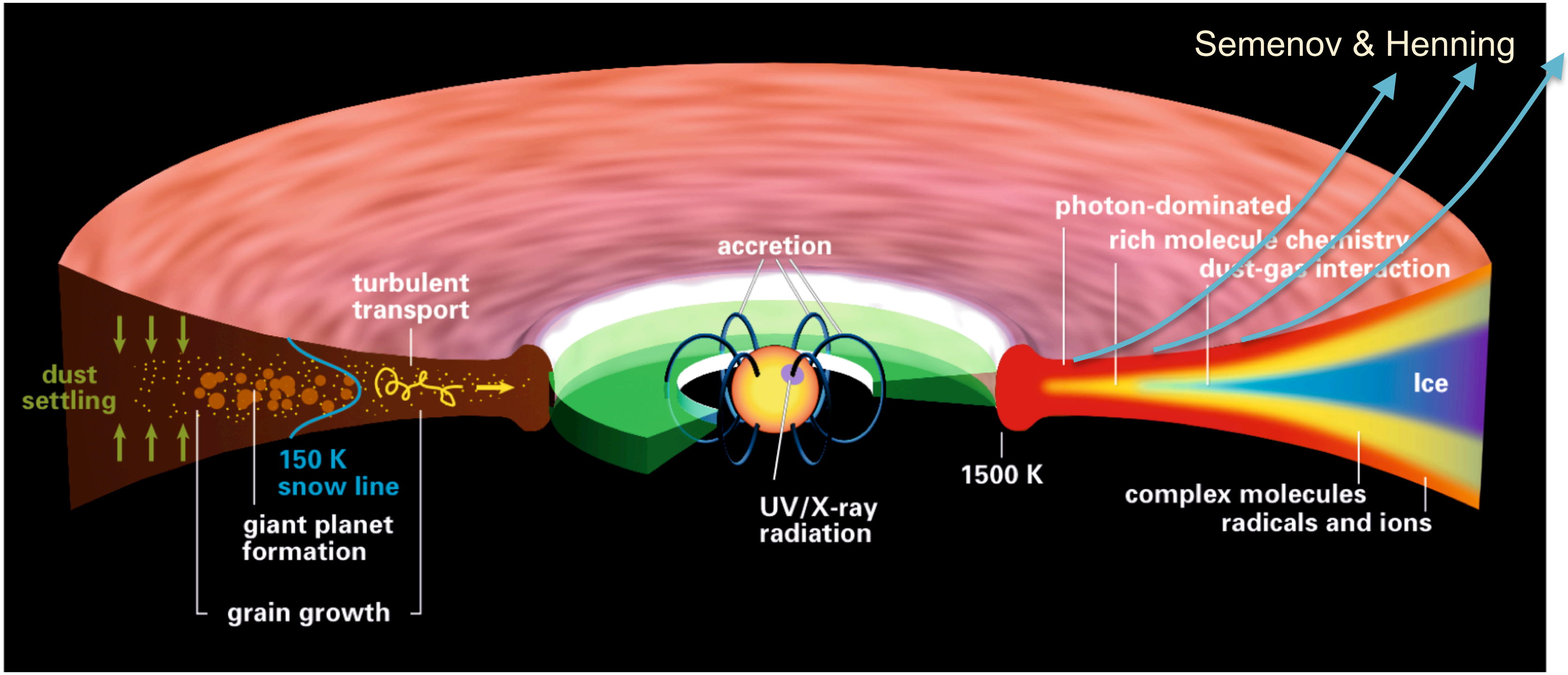
+ Dense emission spectrum
- Poor line list
- Rich spectra are rare



Atomic lines [NeII], HI
Molecules C_2H_2, HCN, CO_2, H_2O, OH

MIR transitions?
+ Emission is common
- Need to identify appropriate lines

Winds?



Clues from existing diagnostics:

- **No large velocity offsets from v_{star}** (winds not molecular?)
- **Massive winds may absorb/scatter FUV, reducing great agreement between models and observations** (would increase need for mechanical heating?)

Summary

Where everyone agrees we should see turbulence, we do

- Non-thermal broadening within few 0.1 AU (CO overtone)

Where disk may be dead, we don’t (but observations don’t rule out MRI either)

- Inconclusive heat signature within few AU
- Line broadening not yet probed

Summary

Evolutionary status of protoplanetary disks

- Highly evolved as a class (from solid mass budget)
- Built planetesimal or larger objects beyond snowline (from C/O)

Chemical signature of turbulence?

- Look for molecules with long chemical timescales
- Any expected changes in elemental abundance ratios?

Heat signature of turbulence?

- No definitive signature from known diagnostics
- Look below FUV-heated layer?

Turbulent line broadening?

- Detected close to star where thermal ionized (CO overtone)
- Search for closely-spaced lines probing larger radii

Winds?

- Not molecular? (large velocity offsets not seen)
- If they absorb/scatter FUV, reinvestigate disk heating