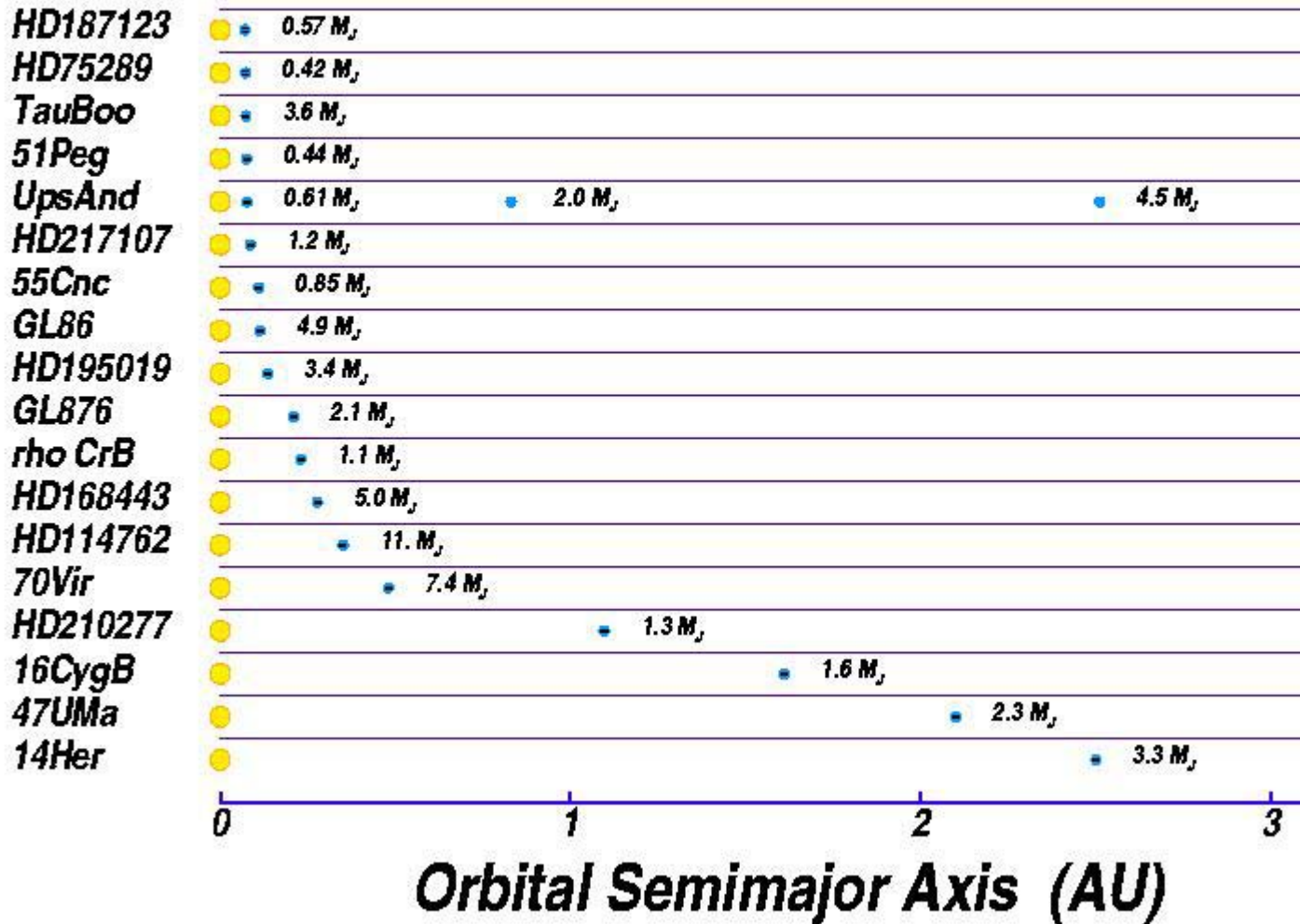


Gas in the Planet Formation Region of Disks:

Diagnosing Where and When Planets Form
During the Accretion Phase

Joan Najita & Steve Strom

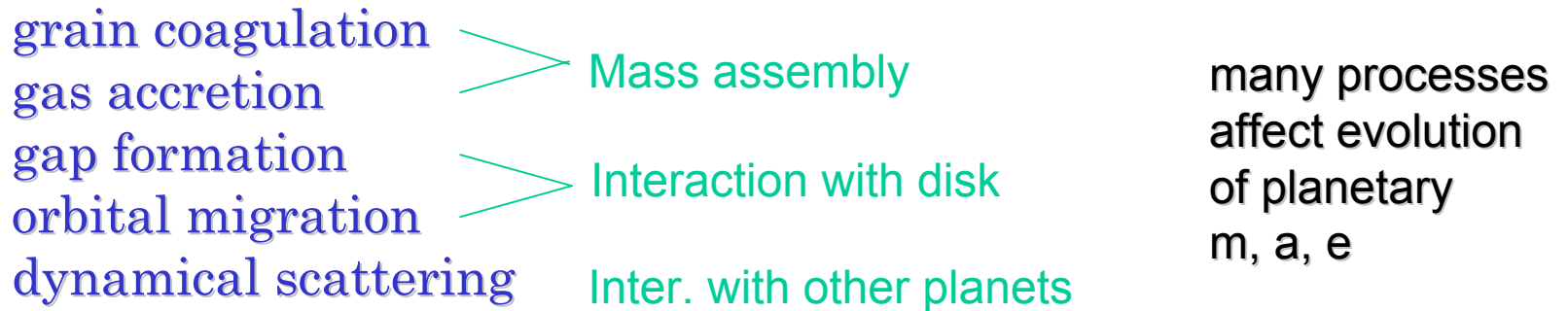
Planets around Normal Stars



How do Planetary Systems Form?

When, Where? How frequently?

Formation and evolution of planetary systems is complex...



Theory may need help from observations!

Approach: study solar system analogues in the process of formation

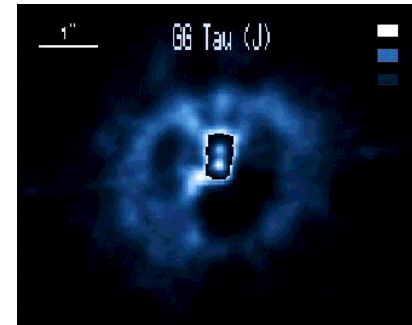
To date: outer disks (e.g., millimeter, scattering; > 30 AU)
very inner disks (< 0.2 AU)

Goal: planet formation region at $r < 10$ AU

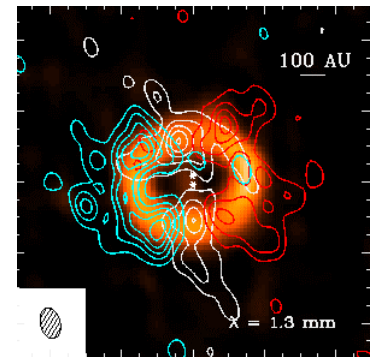
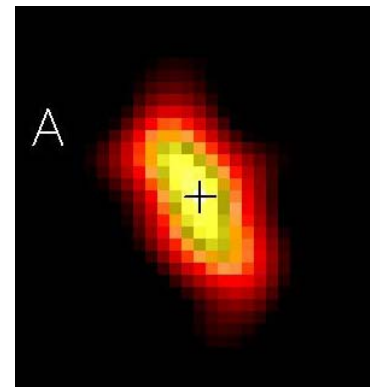
Studying Outer Disks

$r > 5 \text{ AU}$

Scattered light
Dust component
(Optical, NIR wavelengths)



Thermal emission
Dust (IR to mm)
Gas (e.g., CO in mm)



Studying Inner Disks

$r < 10$ AU

Spectral Energy Distributions

Dust component

Optical to mm wavelengths

Limitations:

No spatial information

Doesn't probe gas

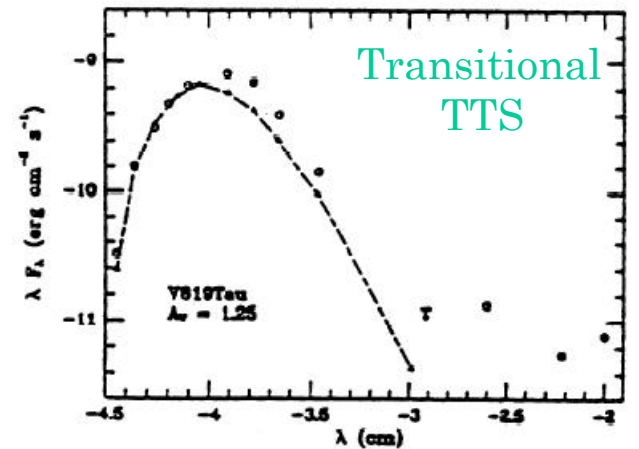
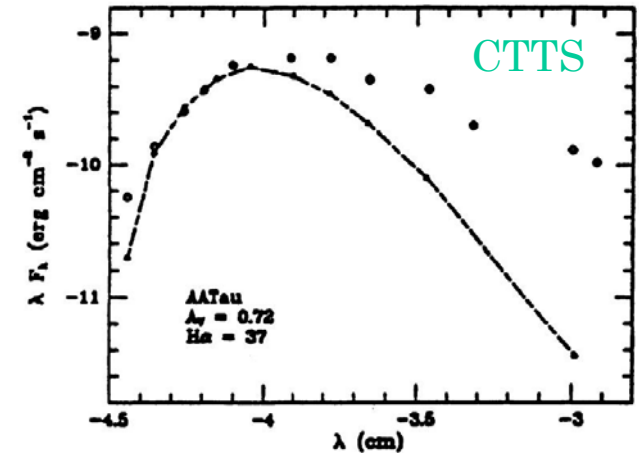
What is the timescale for giant planet formation?

Evidence for inner holes (in dust)

Do disks clear inside out?

(i.e., disks accrete or somehow disperse)

Or is this evidence for grain (and potentially planetary) growth?



Questions and Measurements

When Do Planets Form?

Measure gas dissipation timescale

(constrains giant planet formation timescale)

Look for residual gas in low continuum opacity regions

(distinguishes between disk dispersal and grain growth, the first step toward giant and terrestrial planet formation)

Where Do Planets Form?

Difficult to see young planet in the presence of a disk?

Search for dynamical signatures of planet formation, e.g., gap formation using spectral line diagnostics

(location and width of gap constrains planet orbital radius and mass)

Studying Inner Disks

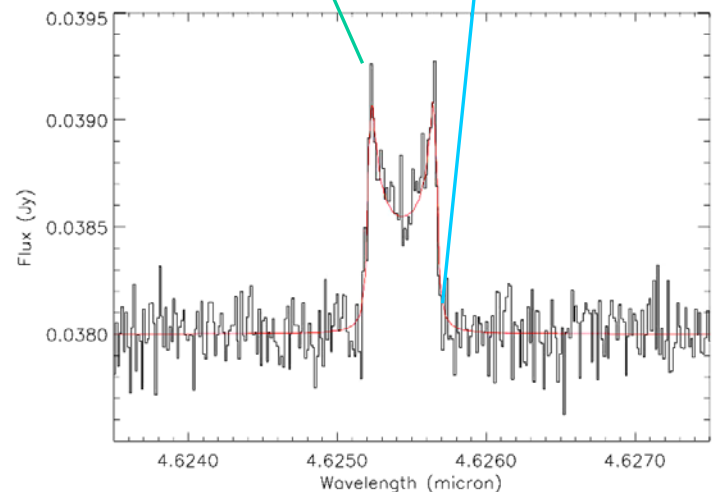
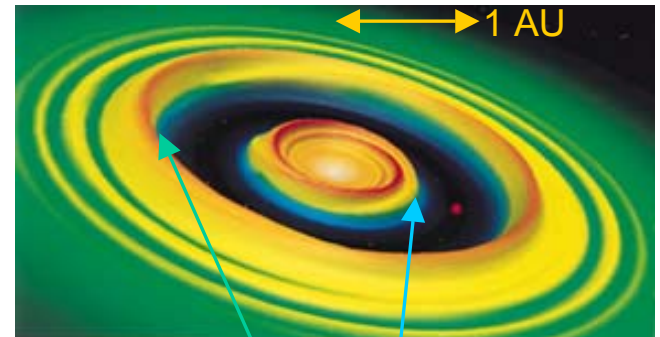
$r < 10$ AU

Challenge: inner disks too small to resolve at 150 pc at $> 2\mu\text{m}$.
Use high resolution spectroscopy of gas diagnostics to separate disk radii in velocity ($R \sim 100,000$ for structure within a few AU)

Probes: molecules in NIR—MIR.
CO and H_2O abundant in gas phase, many ro-vib transitions that probe disk n , T

Expect emission from

- disk atmospheres
- low column density regions (e.g., gaps)



Inner Disk Diagnostics

Work to date ($r < 5$ AU):

CO Overtone ($\Delta v=2$, $2.3\mu\text{m}$)

Evidence for rotating disks around young stars

(e.g., Carr et al. 1993)

H₂O ro-vib ($2\mu\text{m}$ region)

Evidence for differential rotation in disks

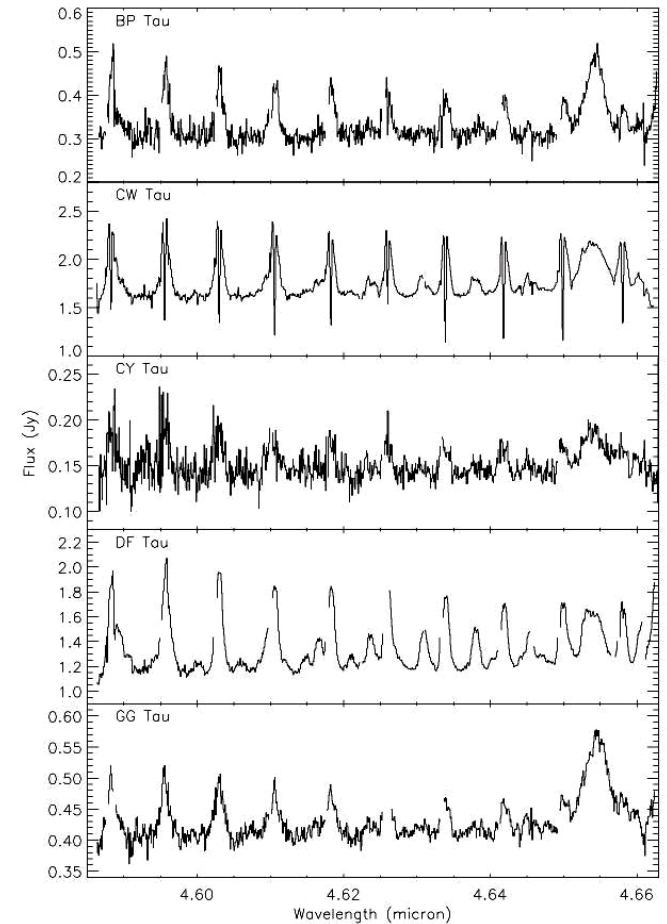
(e.g., Najita et al. 2000)

CO Fundamental ($\Delta v=1$, $4.6\mu\text{m}$)

Probes terrestrial planet region in disks
(based on line profiles and excitation)

(Najita et al. 2003)

CO fundamental emission



Najita et al. 2003

Inner Disk Diagnostics

Work to date ($r > 5$ AU):

H₂ ro-vib (2 μ m region)

Non-thermal (UV or X-ray excited)

So far unclear that it probes < 10 AU

(e.g., Weintraub et al. 2000; Bary et al. 2002)

H₂ rotational (17 μ m, 28 μ m)

Ideal for gas mass measurement

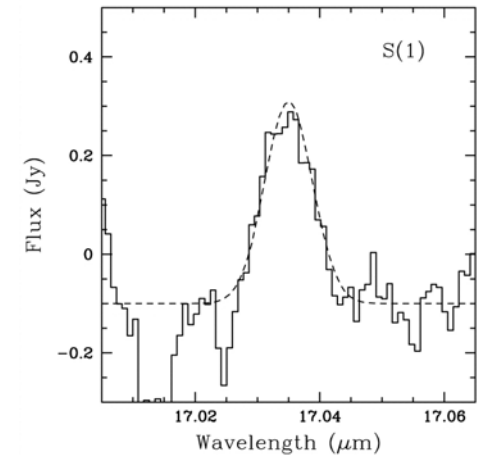
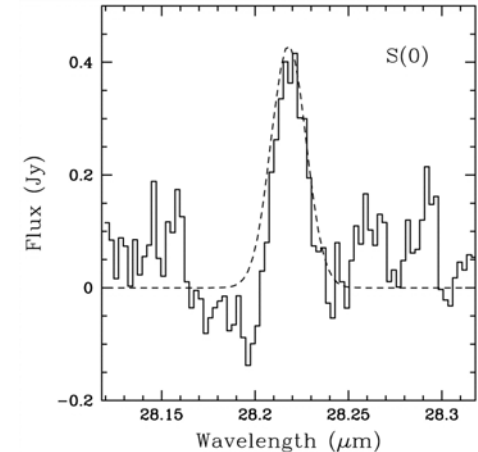
Detected by ISO? (T=100K, 0.01 Msun)

(Yes—Thi et al. 1999, 2001; No—Richter et al. 2002)

At large masses claimed by ISO, $r > 10$ AU.

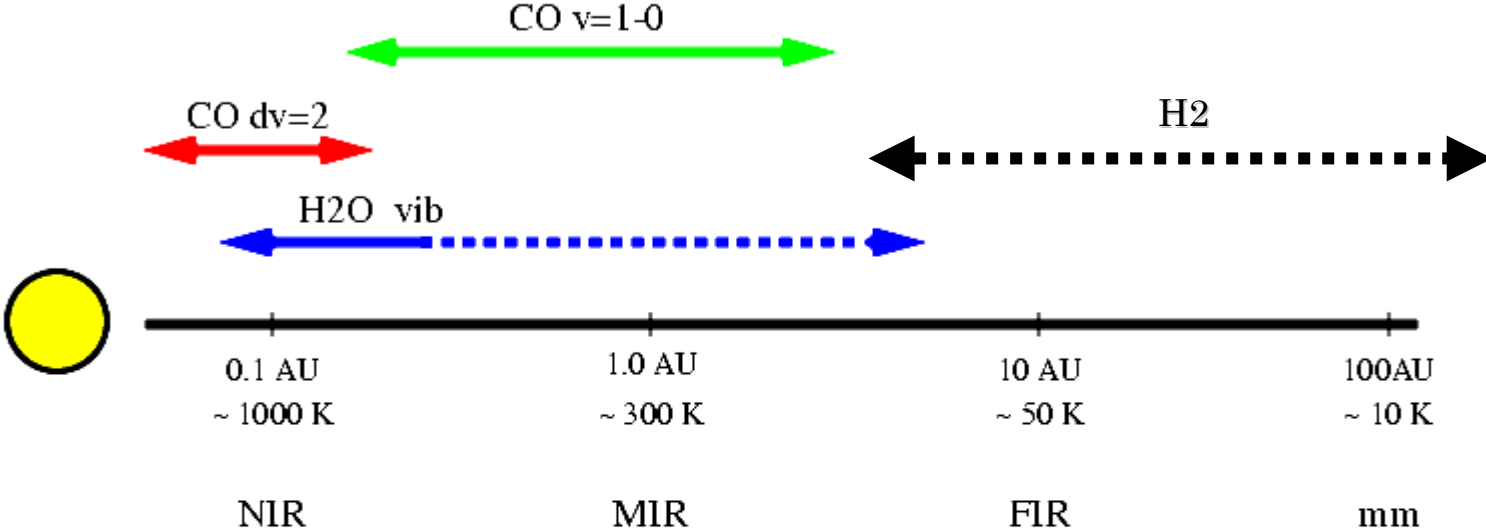
GSMT can detect smaller masses at smaller r as well as use velocities to locate gas in disk.

H₂ rotational

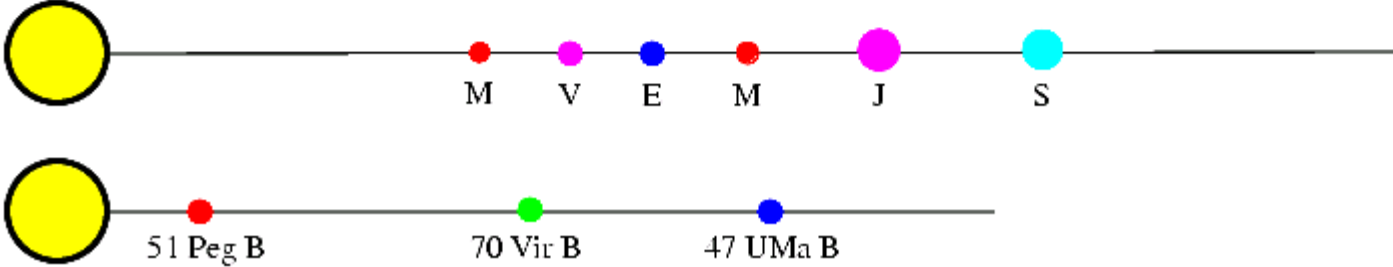


Thi et al. 1999

Infrared Diagnostics of Protoplanetary Disks



Planets Around Normal Stars



Role of Other Facilities

Ground-based 8 to 10-m Telescopes:

Quantify spectral line diagnostics and understanding of
disk atmospheres

Search for forming protoplanets in nearest star forming
regions (~ 150 pc)

e.g., NIRSPEC/Keck	1—5 μ m	R= 20,000
Phoenix/Gemini	1—5 μ m	R=100,000
Michelle/Gemini	8—25 μ m	R= 30,000

SIRTF:

Improve knowledge of dust opacity vs. disk radius

Potentially detect emission lines from disk gas

emission will be spectrally unresolved (R=600)

location in disk to be established by GSMT

e.g., IRS	10—37 μ m	R=600
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Role of Other Facilities

JWST:

(Spatial structure of MIR continuum emission on
~10 AU scales)

Limited ability to study gas diagnostics — due to lack
of high resolution spectroscopic capability.

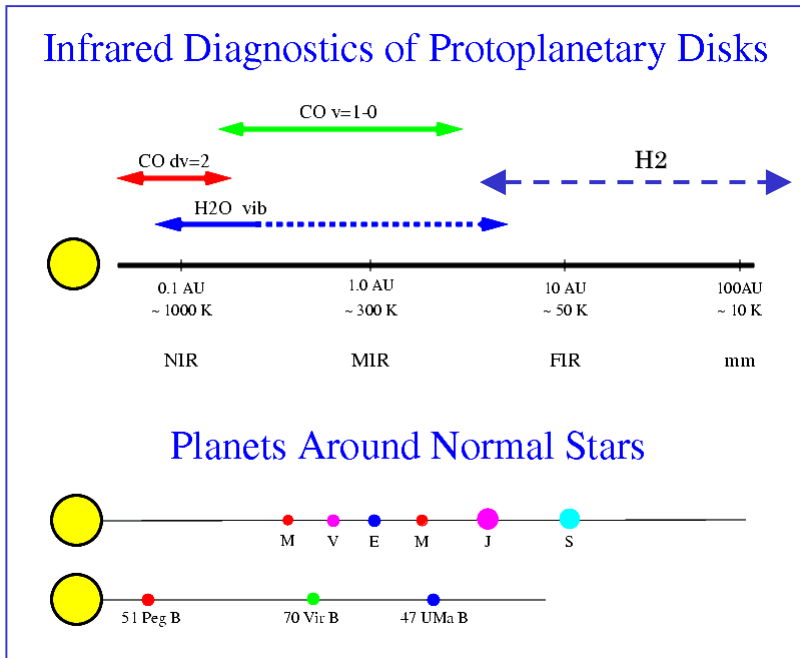
ALMA:

Sub-millimeter disk continuum structure on
~10 AU scales.

Spatial structure of cool dust and gas on scales >10 AU

Example GSMT Program: When do planets form?

Goal: Measure disk gas content vs. disk radius in sources over a range in age & environment, esp. dense cluster environment in which the solar system formed.



Sensitivity & Distance:

- 150 pc sparse associations (Taurus, Cha, Oph)
- 450 pc nearest dense cluster (Orion)
- 1 kpc other rich clusters

Target CO, H₂O, H₂

Time Requirement

30-m GSMT
10% emissivity

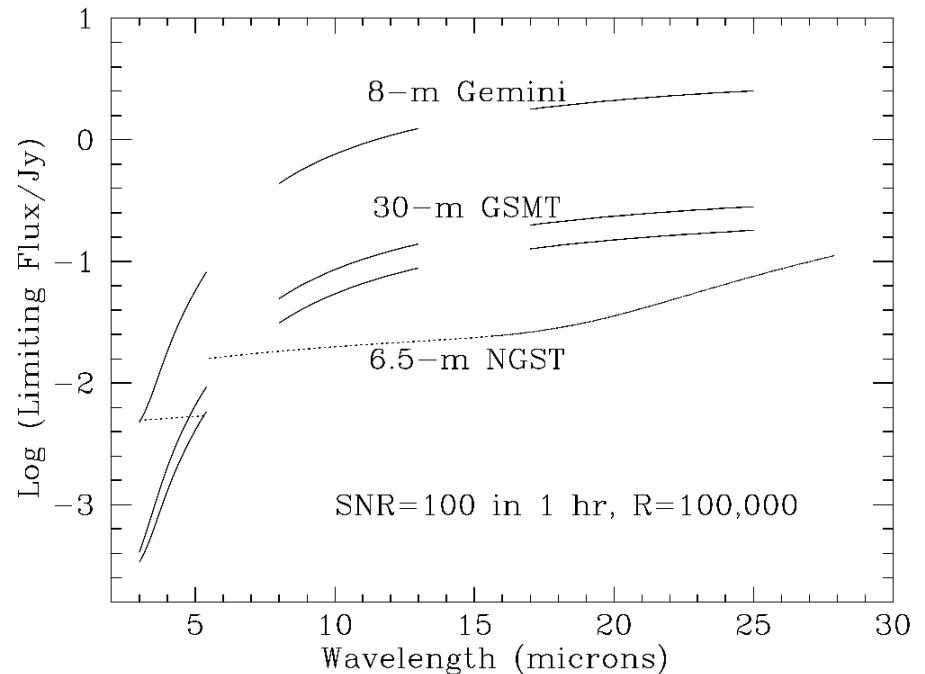
CTTS @ 1 kpc
10 μ m 9 mJy
20 μ m 16 mJy

H₂O @ 10 μ m s/n=25 in 5 hr
H₂ @ 20 μ m 20 7 hr

15 hr / target for 2 settings
with calibration and overhead

For 30 targets / cluster with a spread in age
5 clusters

= 250 nights



Example GSMT Program: Where do planets form?

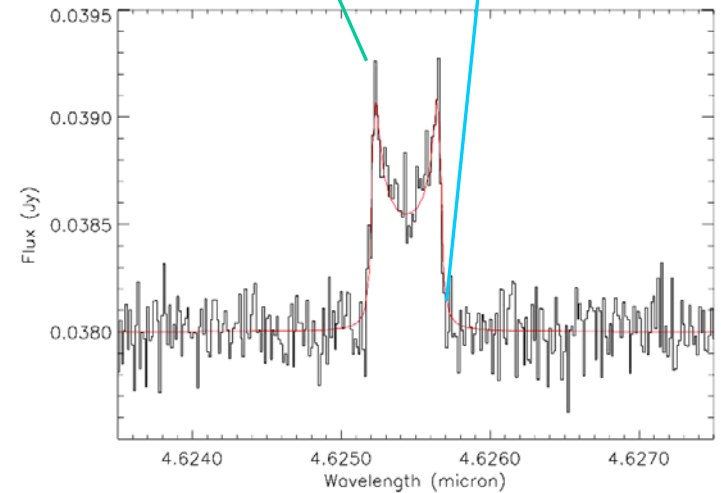
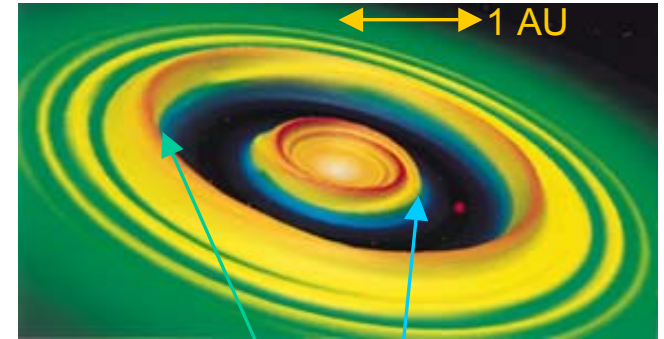
Goal: Measure M_p and a_p for a statistically significant sample of protoplanets in systems spread over a range of age and environment.

If 5—10% of stars form Jupiters,
→ Recovery of a sample of
~100 protoplanets requires
a survey of 1000 T Tauri stars
→ need to reach Orion (480 pc)

Sensitivity & Distance:	
150 pc	sparse associations (Taurus, Cha, Oph)
450 pc	nearest dense cluster (Orion)
1 kpc	other rich clusters

Forming Jupiter mass planet at 1AU
opens gap 0.3 AU wide.

S/N \sim 300 needed to search for
dynamical signature of protoplanet



Time Requirement

30-m GSMT
10% emissivity

CTTS at 450 pc (Orion)

4.7 μ m CO s/n=300 in 15min
45 min / target with
overhead and calibration.
→ 1000 targets in 100 nights

10 μ m H₂O s/n=100 in 4 hr
4.5 hr / target with
overhead and calibration
→ 1000 targets in 500 nights

