Planetary Systems and Star Formation Astro 2010

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The Birth of Stars and Planetary Systems, and the Search for Habitable Worlds

1. *How do stars form?*

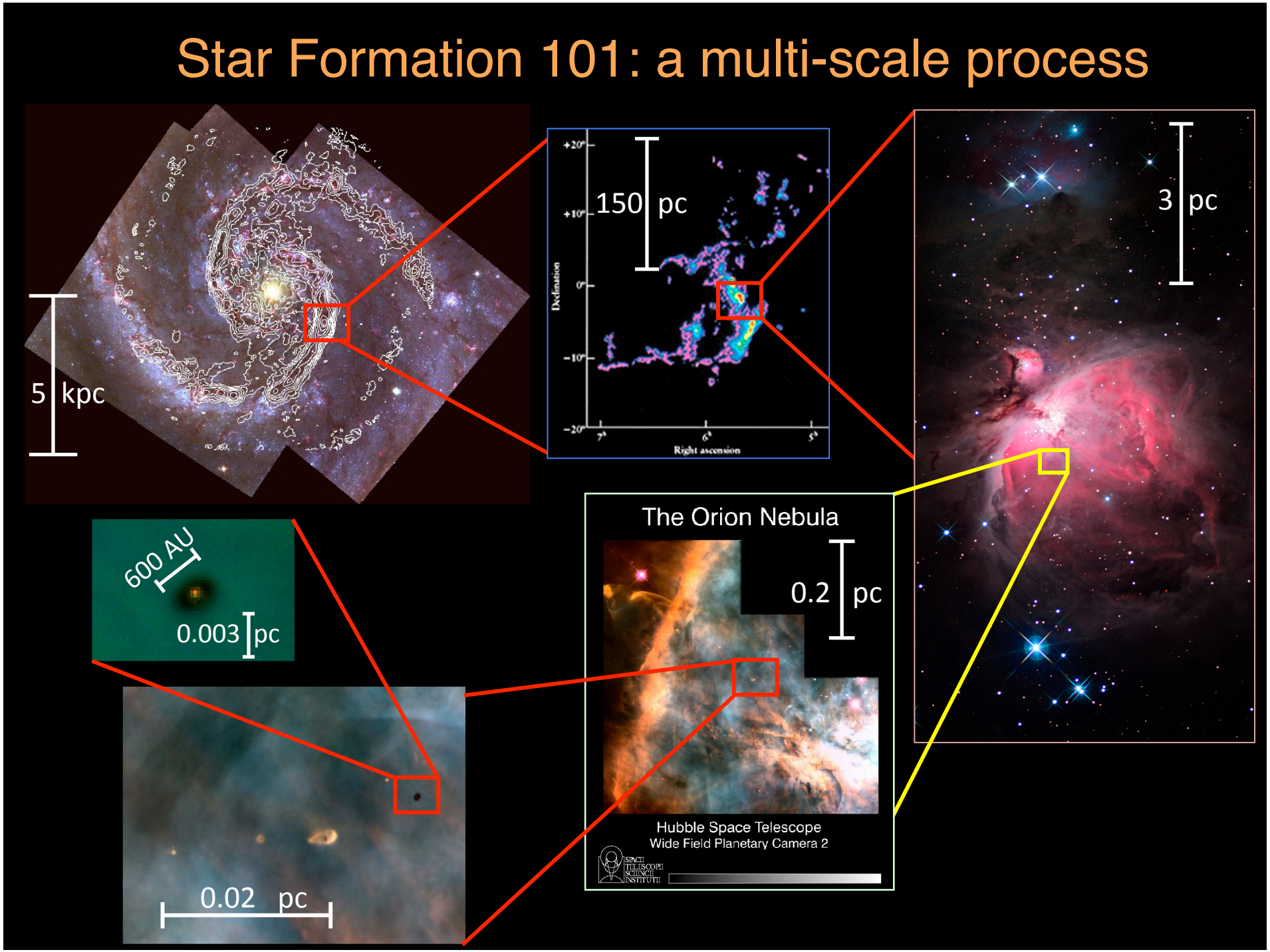
2. *How do circumstellar disks evolve and form planetary systems?*

3. *How diverse are planetary systems?*

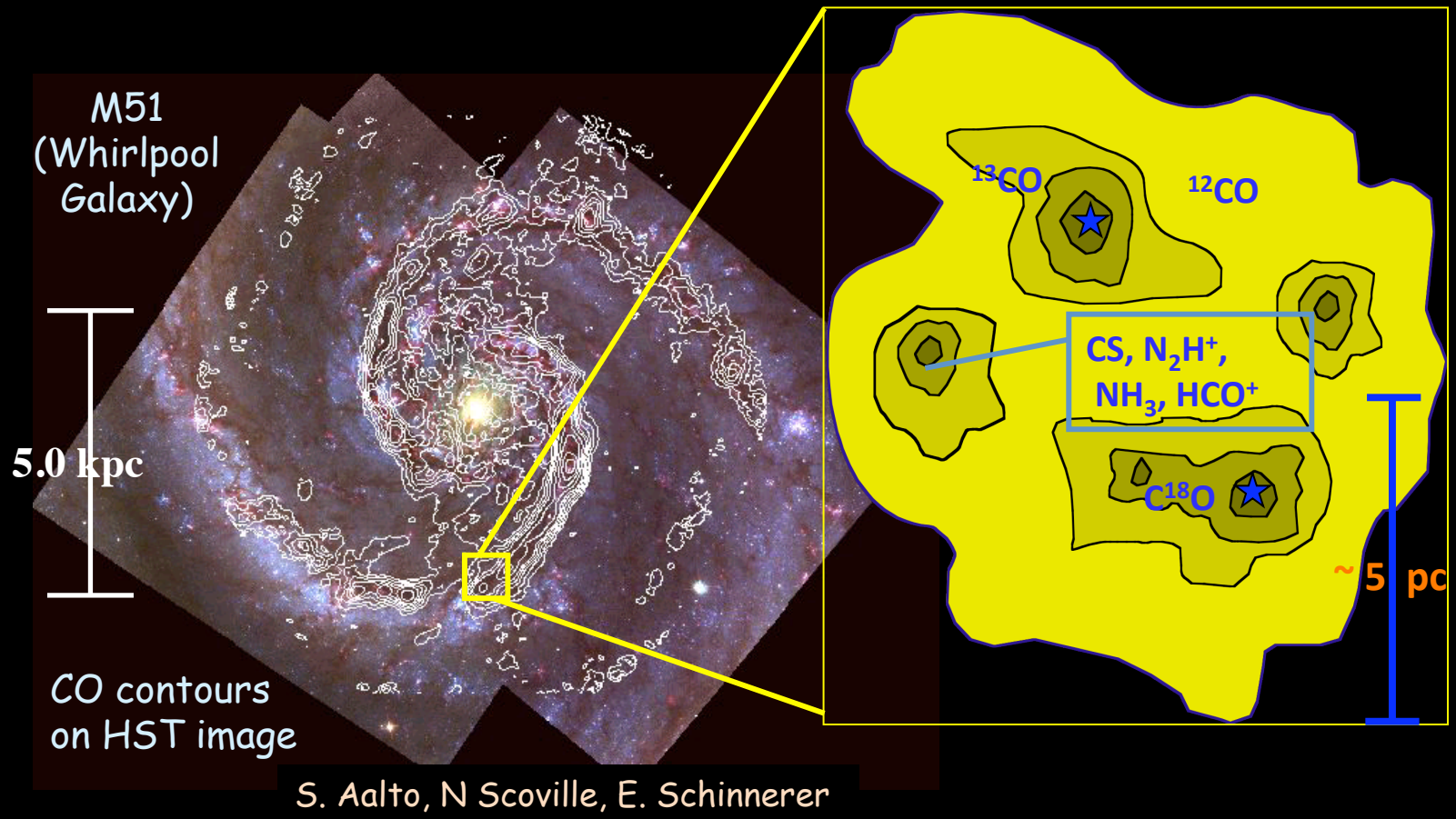
4. *Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?*

5. *Discovery Area: Identification and characterization of a nearby super-Earth*

Star Formation 101: a multi-scale process

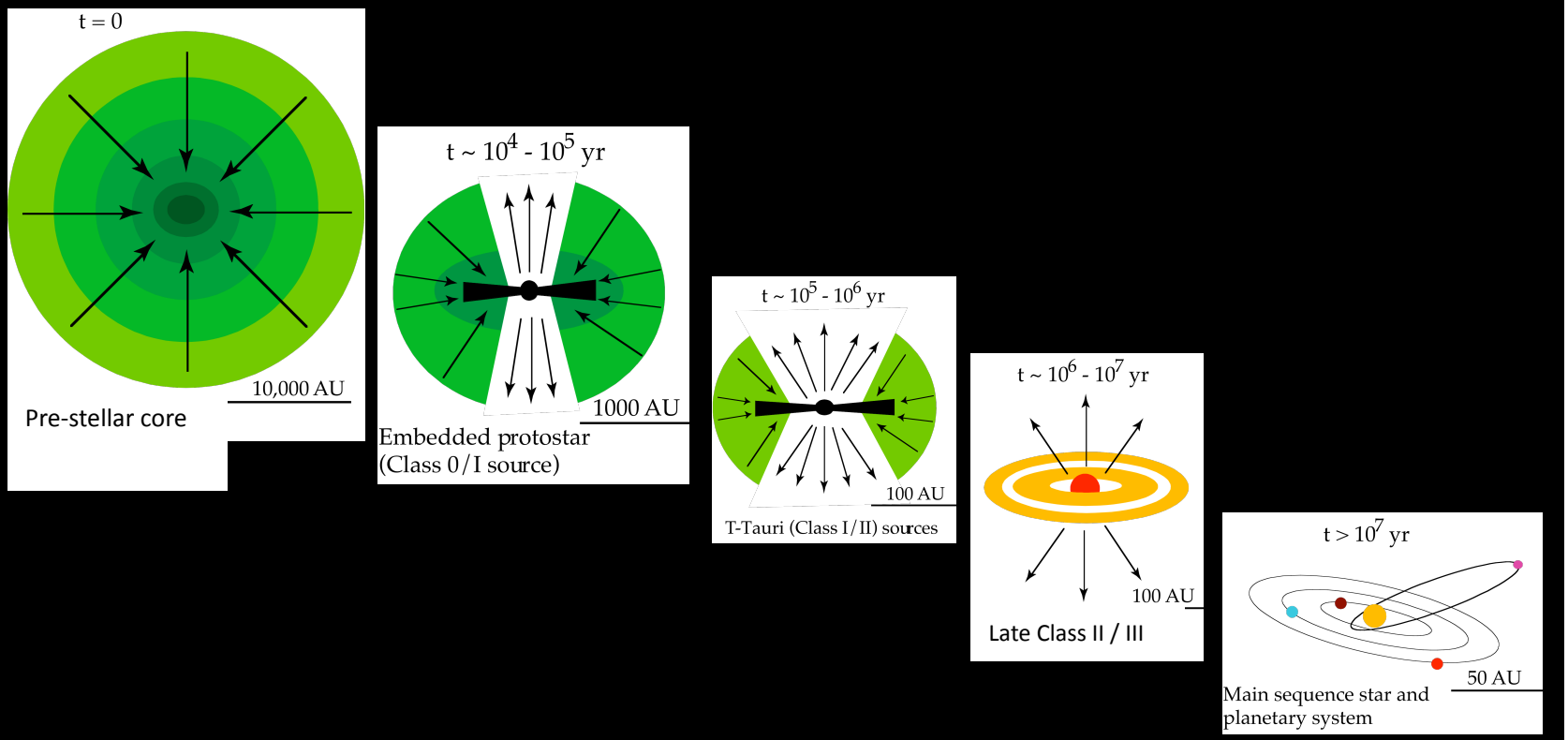


Star Formation 101 - Molecular Clouds



S. Aalto, N Scoville, E. Schinnerer

(Low-mass) Star Formation 101 - timescales and evolution



time

1. How do stars form?

- What determines Star Formation Rates and Efficiencies in Molecular Clouds?
- What determines the Properties of Pre-stellar Cloud Cores?
- What is the origin of the Stellar Mass Function?

What determines the properties of pre-stellar cloud cores?
What is the origin of the Stellar Mass Function?

Recent observational studies suggest that IMF of stars may be set during the early stages of core formation

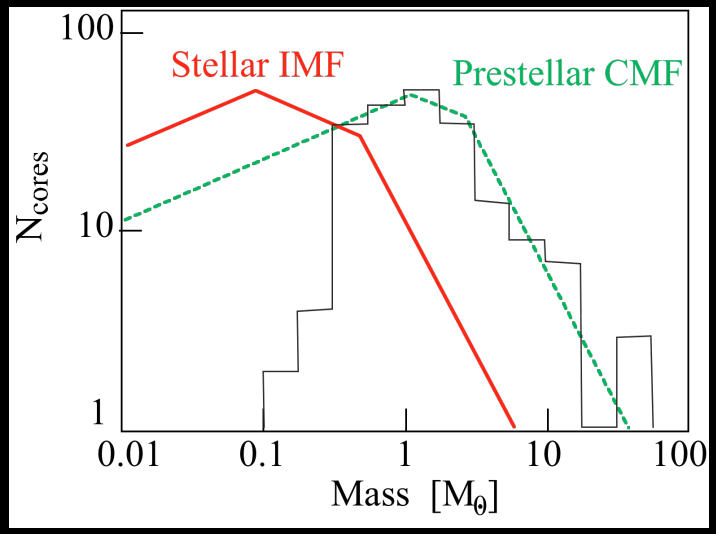
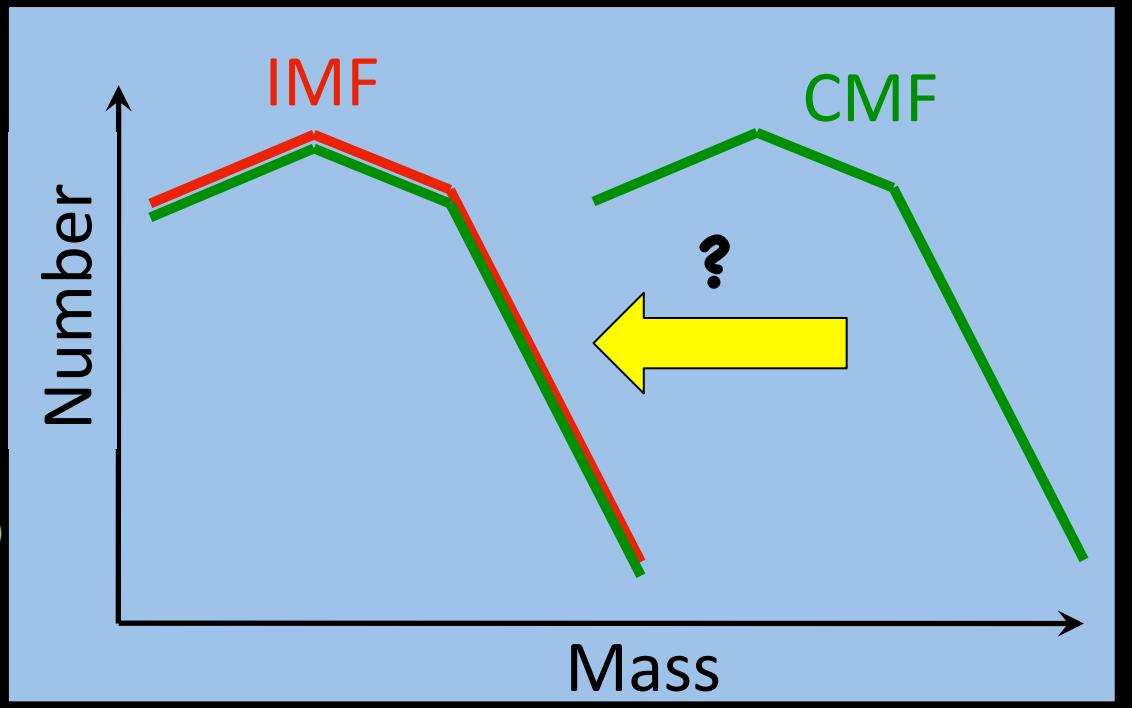


Figure from Nutter & Ward-Thompson (2007)
See also:
Alves et al. (2006)
Enoch et al. (2008)
Rathborne et al. (2009)
and others…



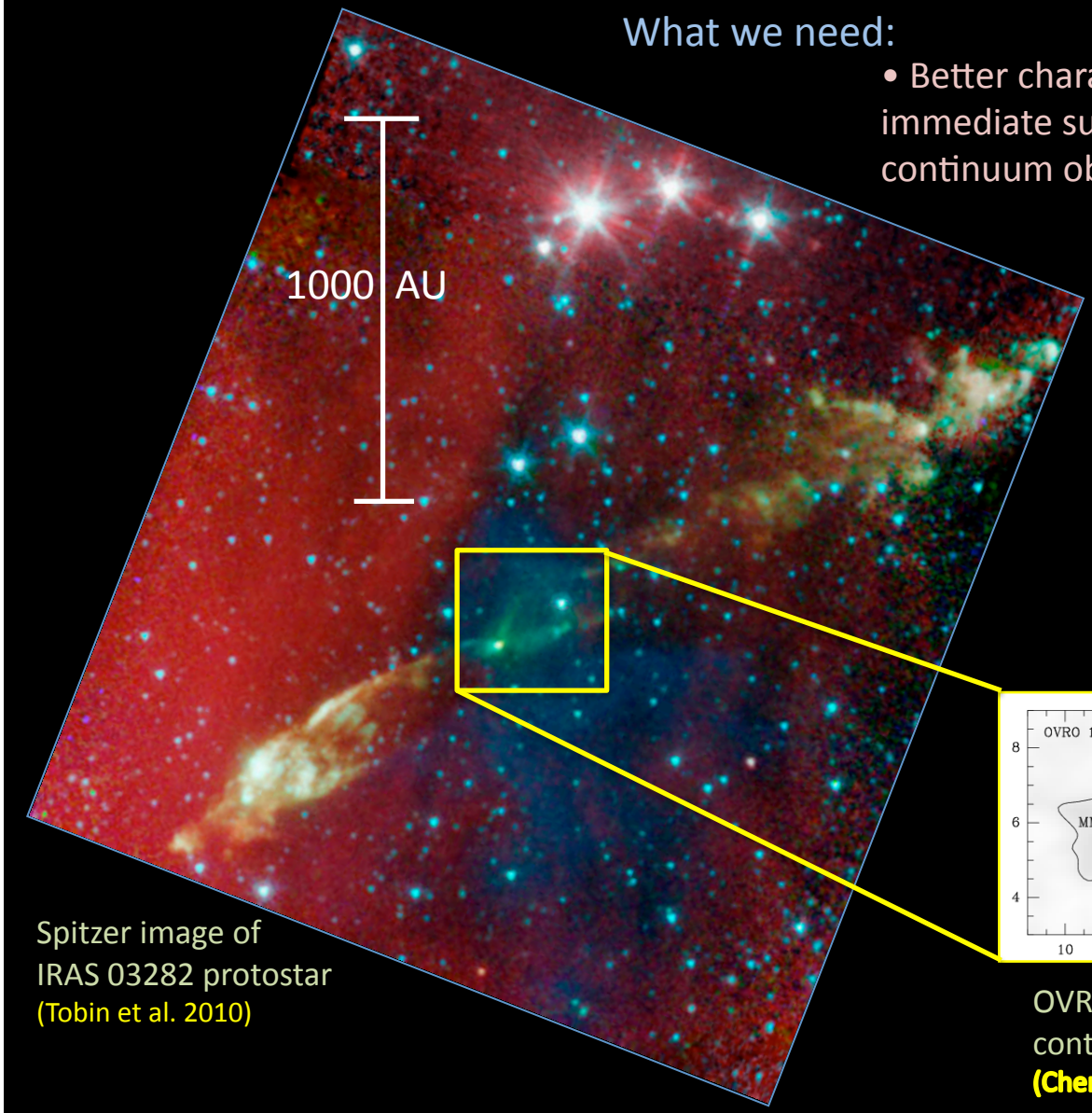
What determines determines the properties of pre-stellar cloud cores?

What is the origin of the Stellar Mass Function?

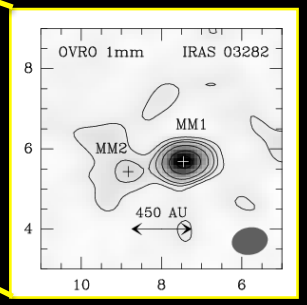
What we need:

- Better characterization of core properties and their immediate surroundings using molecular line and continuum observations

- High ang.-res studies of molecular line emission in cores to resolve transition zone from envelope to disk (~100 AU) where further fragmentation may occur

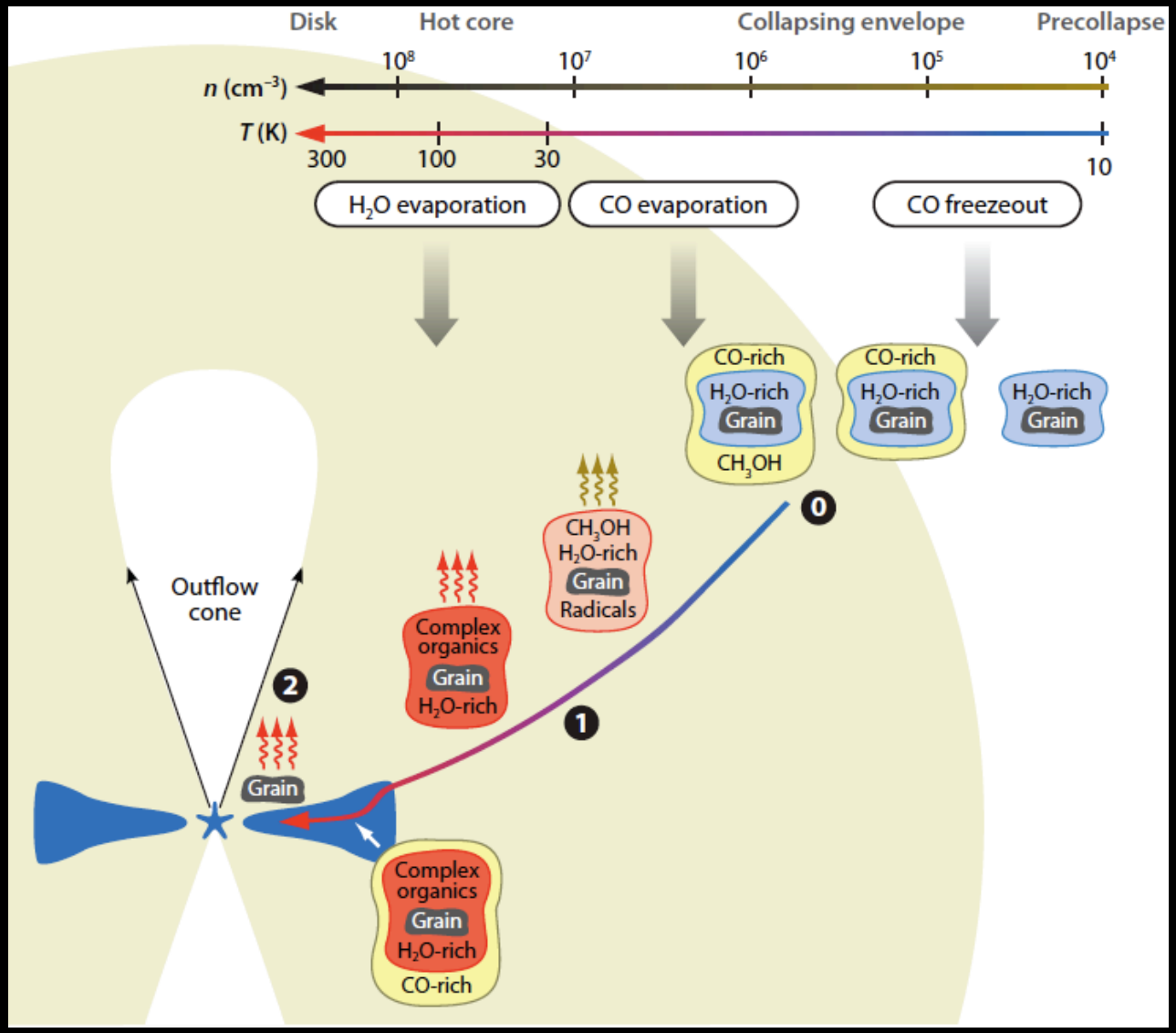


Spitzer image of IRAS 03282 protostar (Tobin et al. 2010)



OVRO mm array continuum obs. **(Chen et al. 2008)**

Different lines arise in different parts of the core/envelope/disk

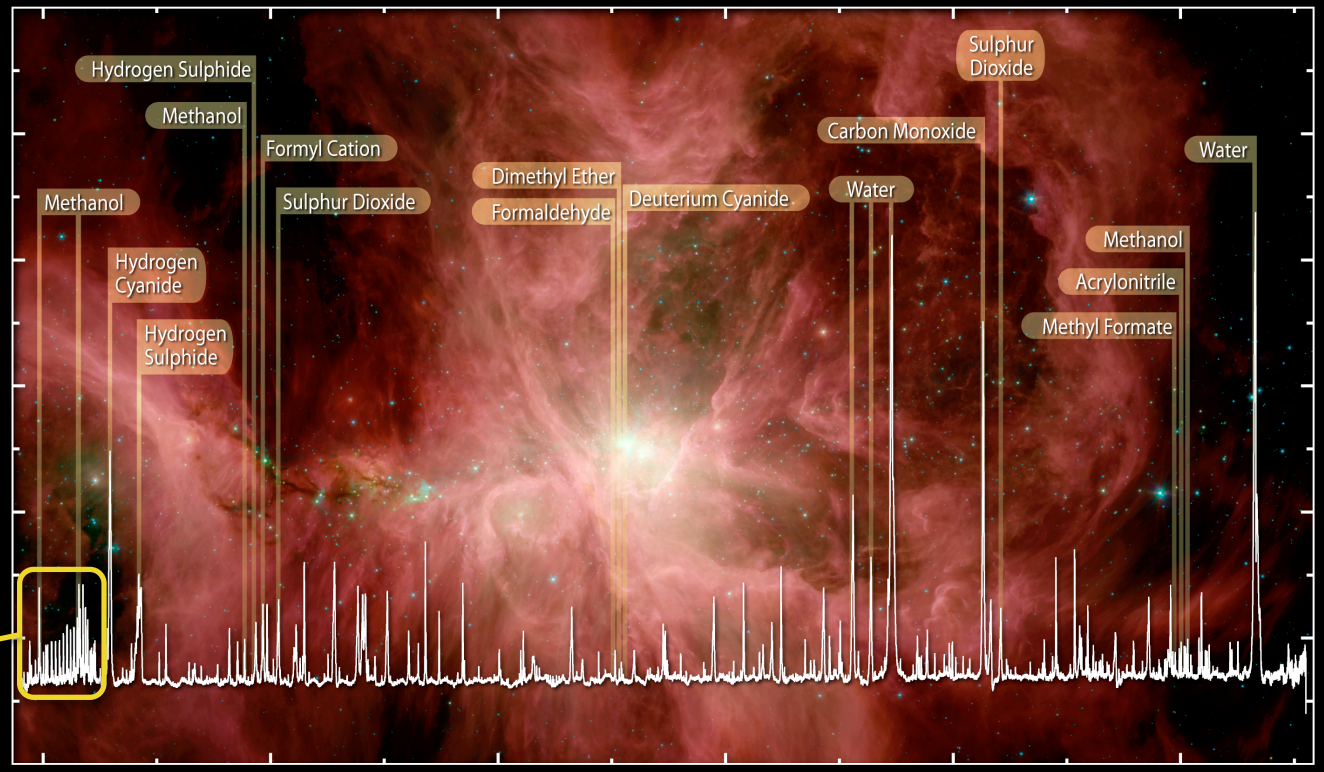


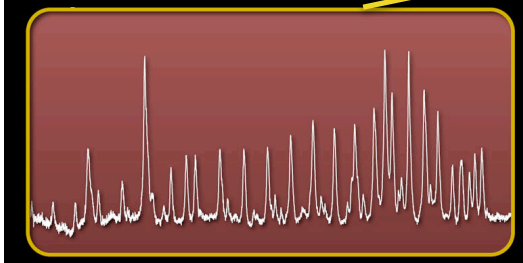
0.03 pc

Herbst & van Dishoeck (2009)

Example: Forest of lines in Orion

Herschel HIFI Observations of Orion





HIFI Spectrum of Water and Organics in the Orion Nebula

© ESA, HEXOS and the HIFI consortium
E. Bergin

Regions with high temperature and density show many lines in sub-mm and FIR range from organic molecules that could be used to probe protostar.

SOFIA has spec. res. to study dynamics of hot (~10^3 K) and high-ρ gas (~10^7 cm-^{3}) in MIR (ro-vib. tran)

But many lines are unidentified in this poorly studied region of the spectrum

Recommendations

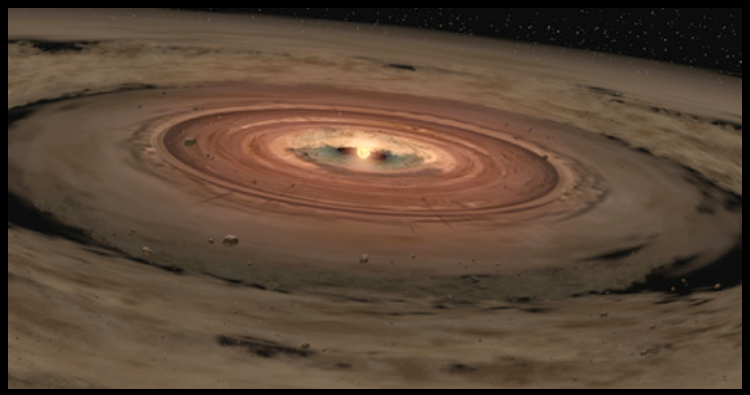
Almost all FIR/sub-mm/mm observations rely on molecular lines as probes of molecular gas evolution. Thus, in order to answer questions the following are needed:

-Expand lab work in poorly studied FIR and sub-mm regions of spectrum

-Improve understanding of chemical processes in cores, especially knowledge of surface reaction rates (and stochastic effects on small particles) by laboratory and theoretical methods

- Better models of chemical evolution (that include dynamically evolving cloud) to make detail test of theories by comparison with observations.

2. How do circumstellar disks evolve and form planetary systems?



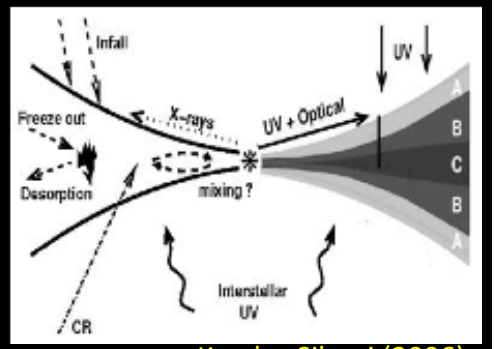
Artist rendition of circumstellar disk
(image source: NASA)

- What is the nature of the Planet-Forming environment?
- How do giant planets form and interact with disks, and what are these young planets like?

What is the nature of the planet-forming environment?

What we know:

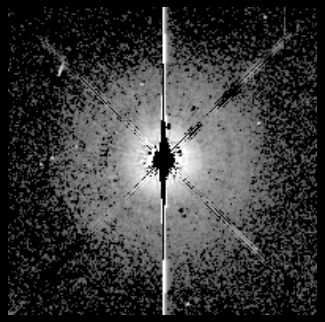
- Only 148 disks have been spatially resolved. 121 pre-main sequence, 27 debris disks see http://circumstellardisks.org/
- Continuum emission has been used to detect, estimate mass (and map in some cases)
- Molecular lines used for studying gas content, kinematics, chemistry
- We have general idea of physical and chemical processes that take place in disks

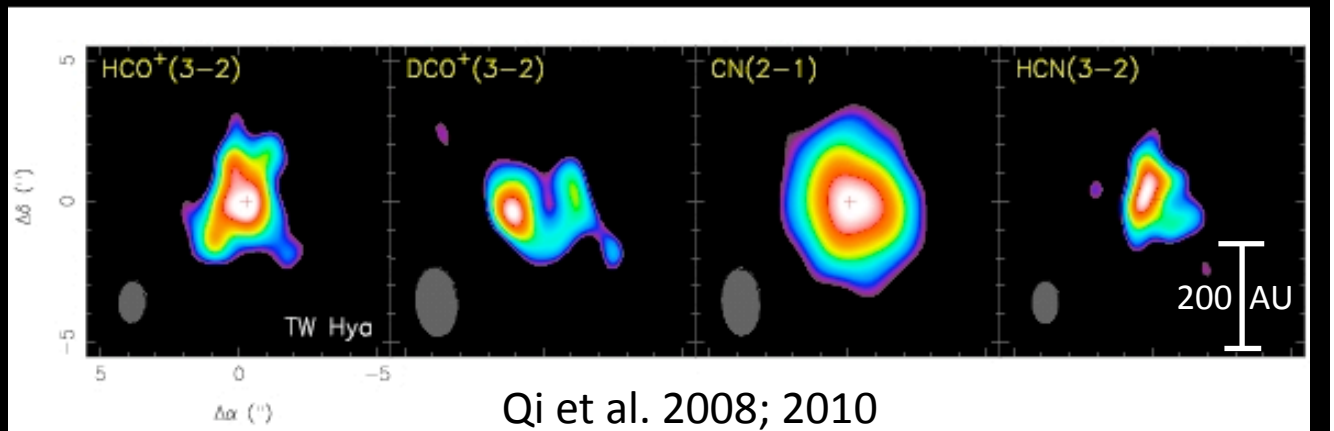


Kessler-Silacci (2006)

Chemistry in disks: important for planet formation (and life?)

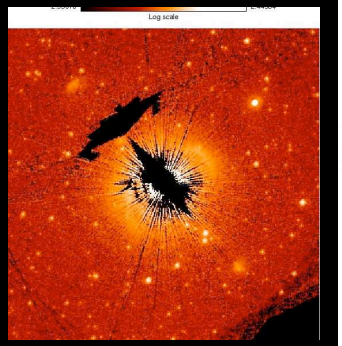
TW Hya
(low-mass T-Tauri)

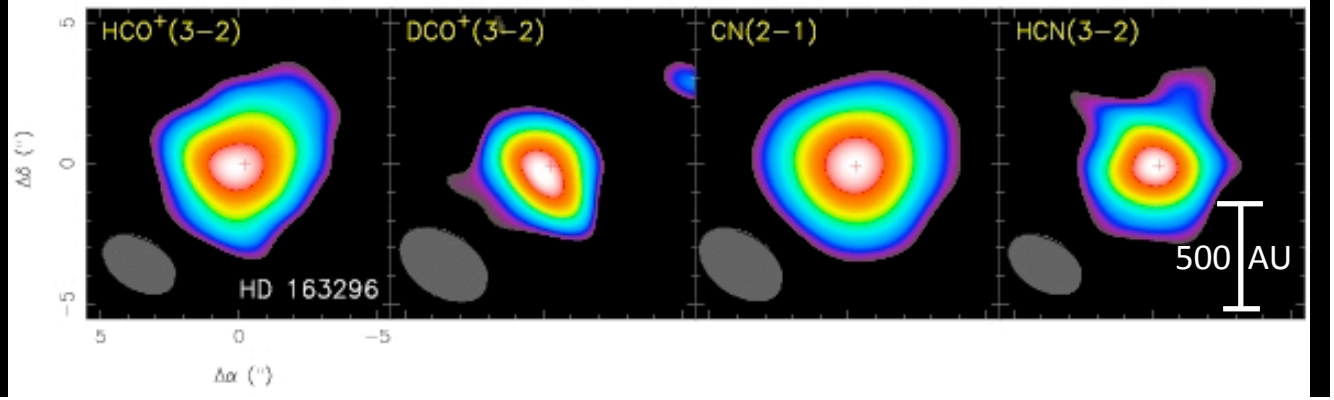




Qi et al. 2008; 2010

HD 163296
(inter.-mass Herbig Ae)



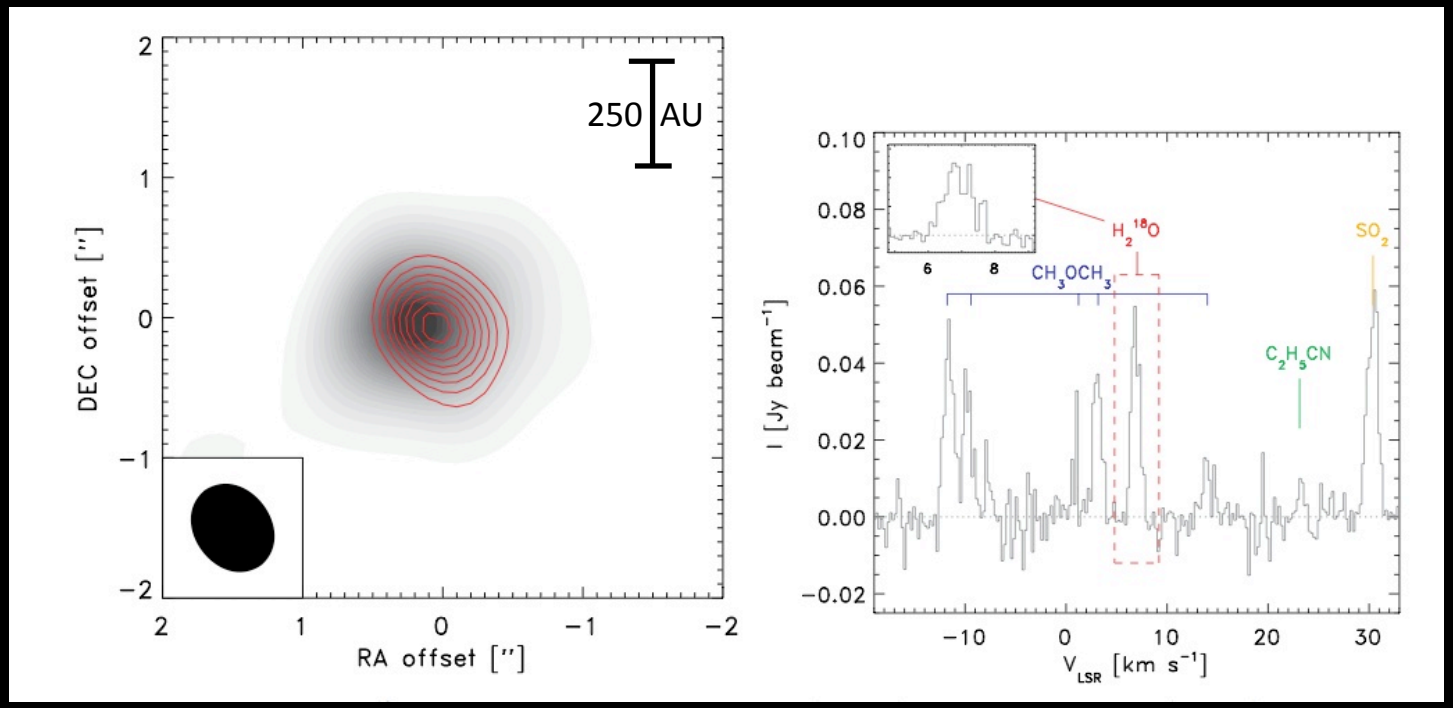


What is the nature of the planet-forming environment?

What is the chemical makeup of disks?

What we know:

Water vapor observed in disks
(using mm interferometer observations)



Plateau de Bure Interferometer observations at ~200 Ghz

Jorgensen & van Dishoeck 2010

What is the chemical makeup of disks?

What we want to know:

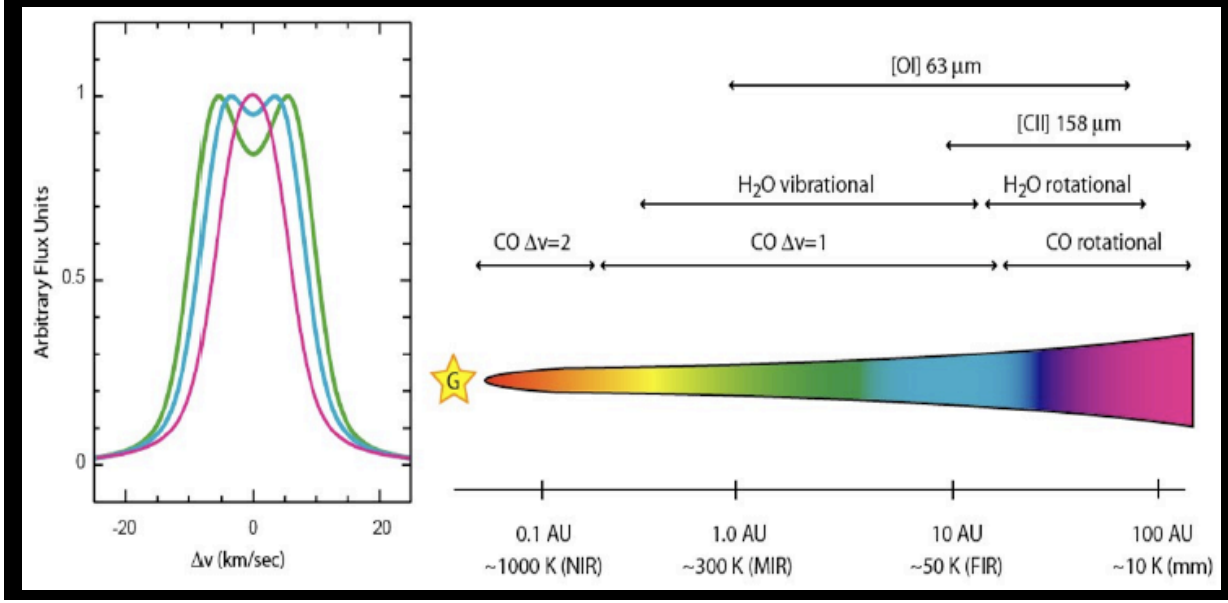
Chemical structure of disk

- distribution of water
- where are complex pre-biotic molecules?
- disk ionization fraction (and dist.)

What is needed:

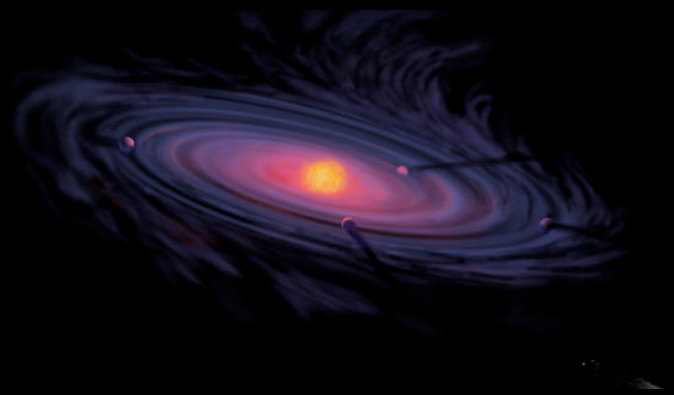
- ALMA observations (res. ~few AU ~ 0.02-0.05")
  - -map disks using different molecules (including complex mol.)
  - (-map HDO/H_2O ratio in disks)
- High-res spec with SOFIA of molecular vib.
  - -to provide constrains on ionization fraction → accretion
- High-res imaging with JWST
  - -to trace structure of disk via scattering by small grains
- Major effort in chemical modeling and lab astrophysics
  - -to understand molecule formation in the disks.
  - -studies of molecular spectra at FIR/sub-mm to help interpret Herschel/ALMA/SOFIA spectral data.

Example of possible SOFIA spectral observations of disks

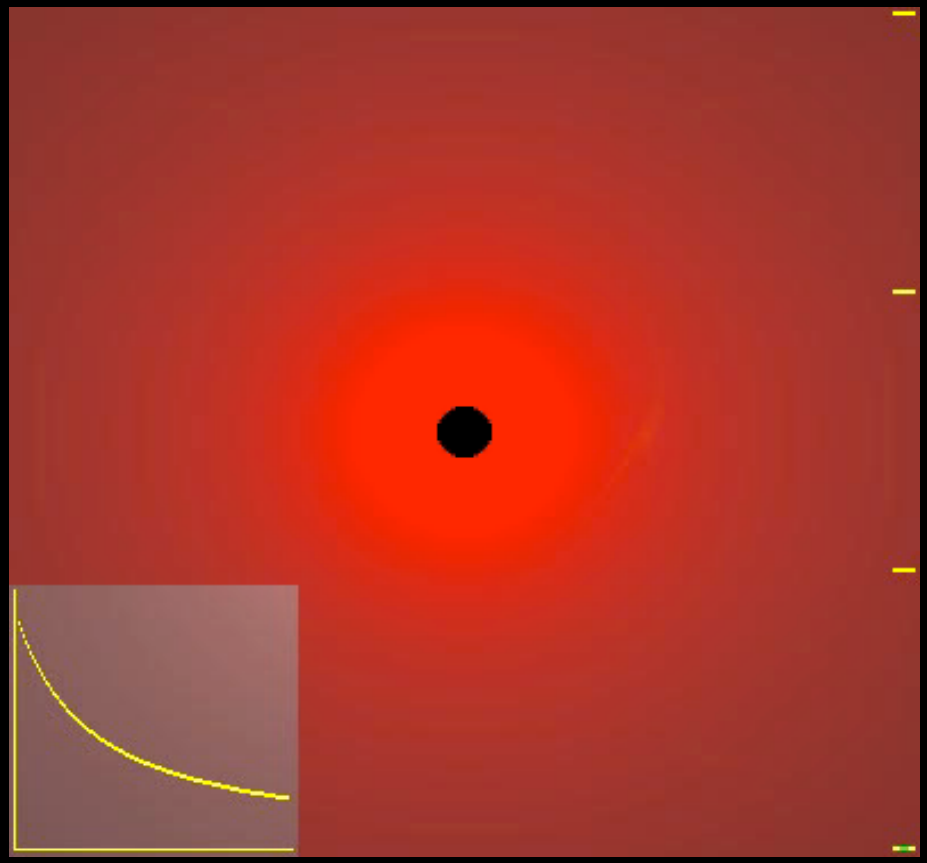


How do giant planets form and interact with disks, and what are these young planets like?

What we would like to observe



Artist conception of planet-forming disk
(image source: NASA)

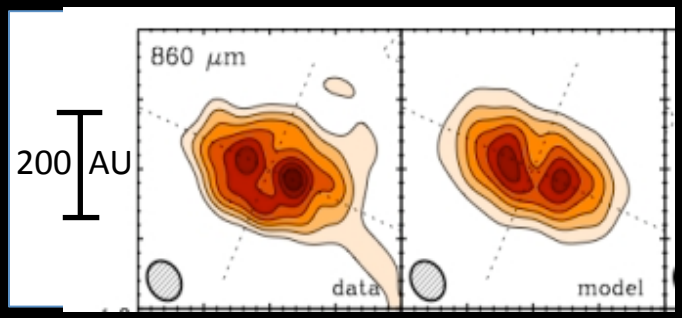


Model of Planet formation and migration, and effect on disk

Armitage (2005)

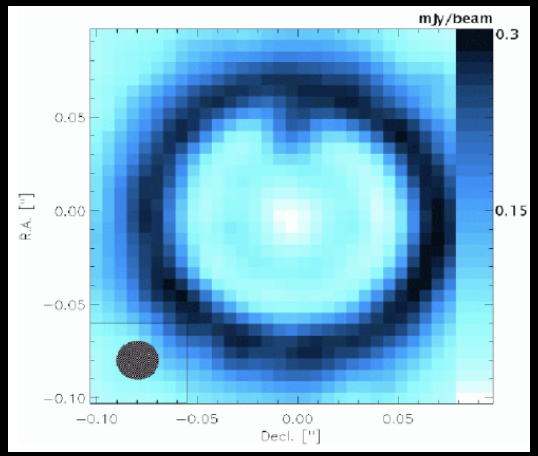
How do giant planets form and interact with disks, and what are these young planets like?

We see gaps in disks
(due to planet forming?)



Disk around GM Aur (a T-Tau star)
Hughes et al. (2009) SMA observations

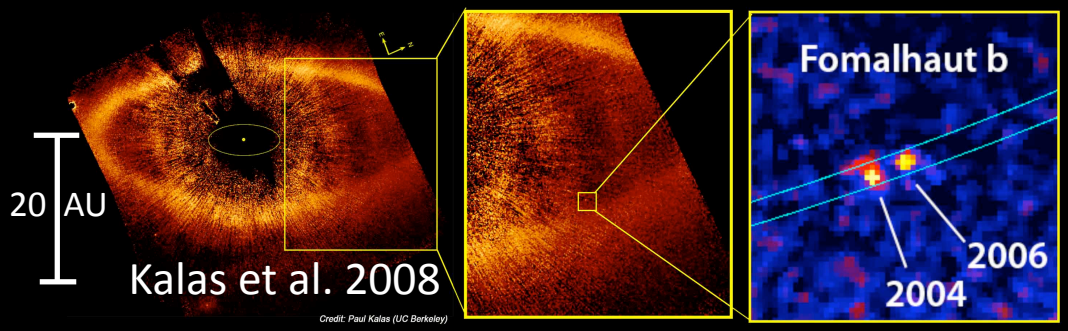
What we would like to see:
(Imaging protoplanets with ALMA)



Wolf & D'Angelo 2005

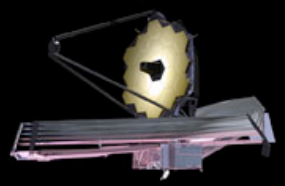
Simulation of 8-hour, 345 GHz ALMA observation of a 0.01 M_sun circumstellar disk, with a recently formed planet of $1M_{Jup}$, *orbiting* 5 AU away from a 0.5M_sun star.

Young Planets have been imaged with HST
JWST will do more



Kalas et al. 2008

Credit: Paul Kalas (UC Berkeley)



Just a small example of what JWST can do (and better) for more disks.

3. How diverse are planetary systems?

We need to

- Extend the exoplanet census
- Infer bulk compositions
- Characterize atmospheres of exoplanets

with more radial velocity, transit, micro-lensing obs.
with systems observed with both radial vel. + transit
with more reliable data and models

Known planets as of Jan. 2010

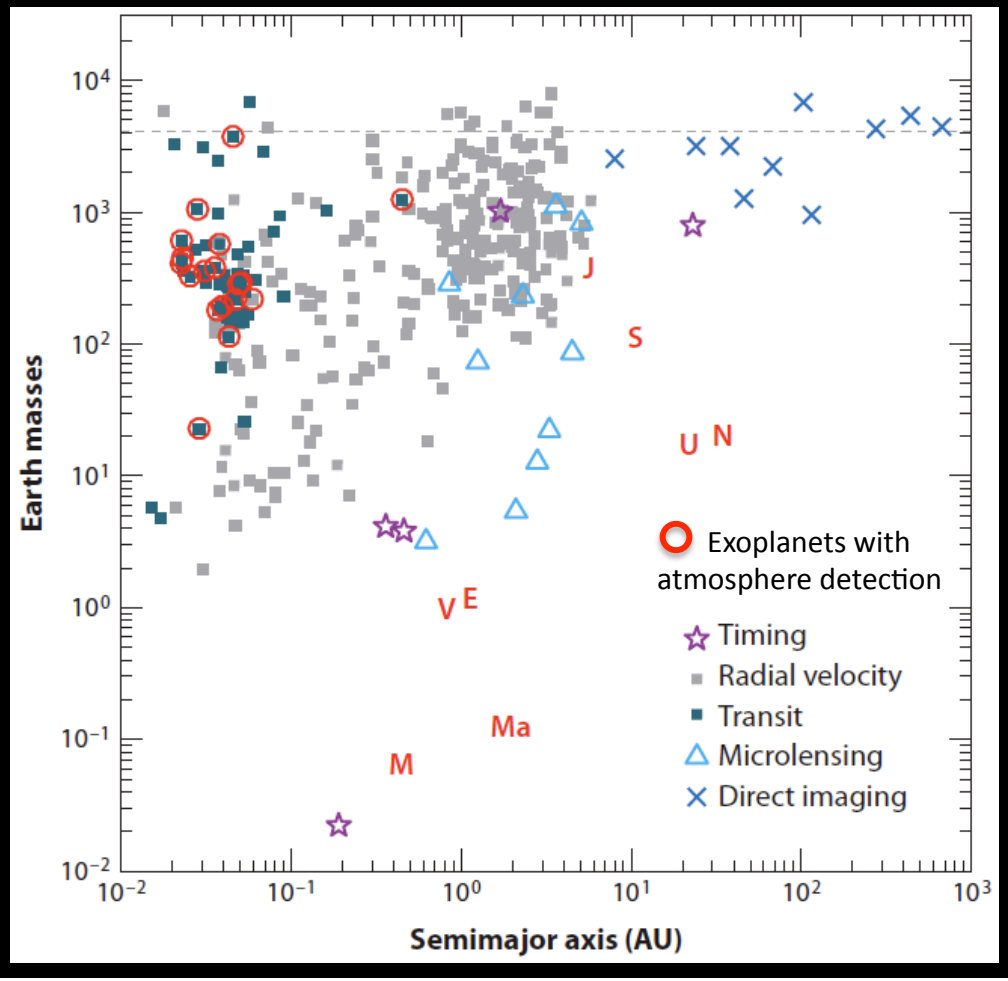


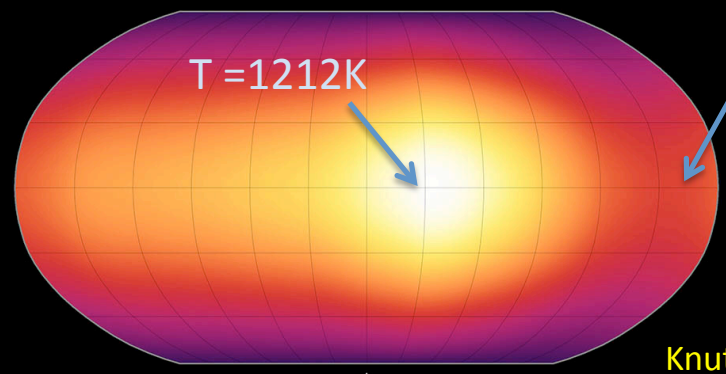
Figure form Seager & Deming (2010), based on data taken from http://exoplanet.eu

Total exoplanets so far ~490

How diverse are planetary systems?
Exoplanet atmospheres

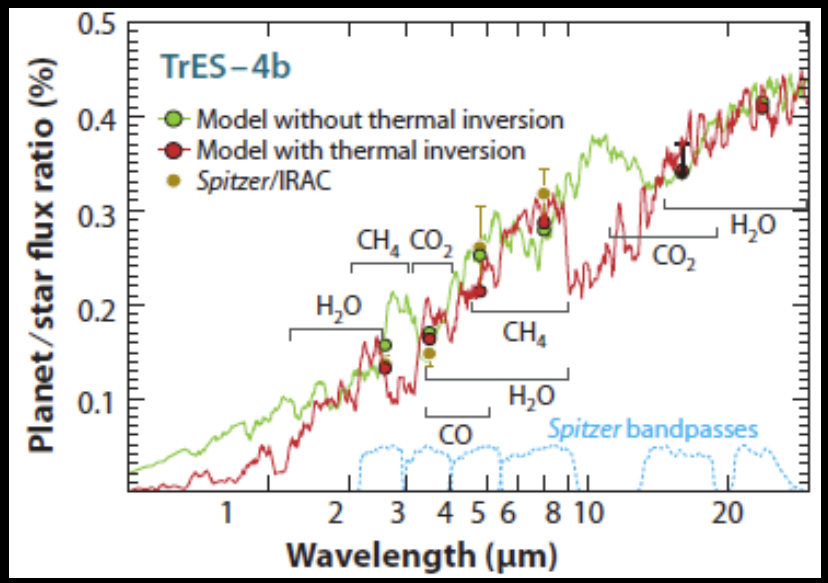
What we know and what we can do now:

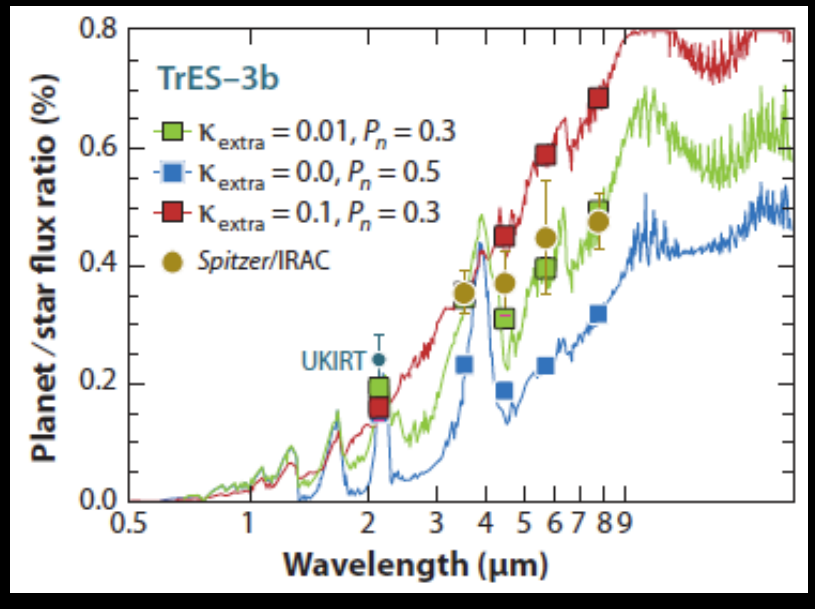
"weather" (temperature) map over surface of exoplanet HD 189733b



Knutson et al. (2007)

Exoplanet atmosphere modeling based on wide-band photometry

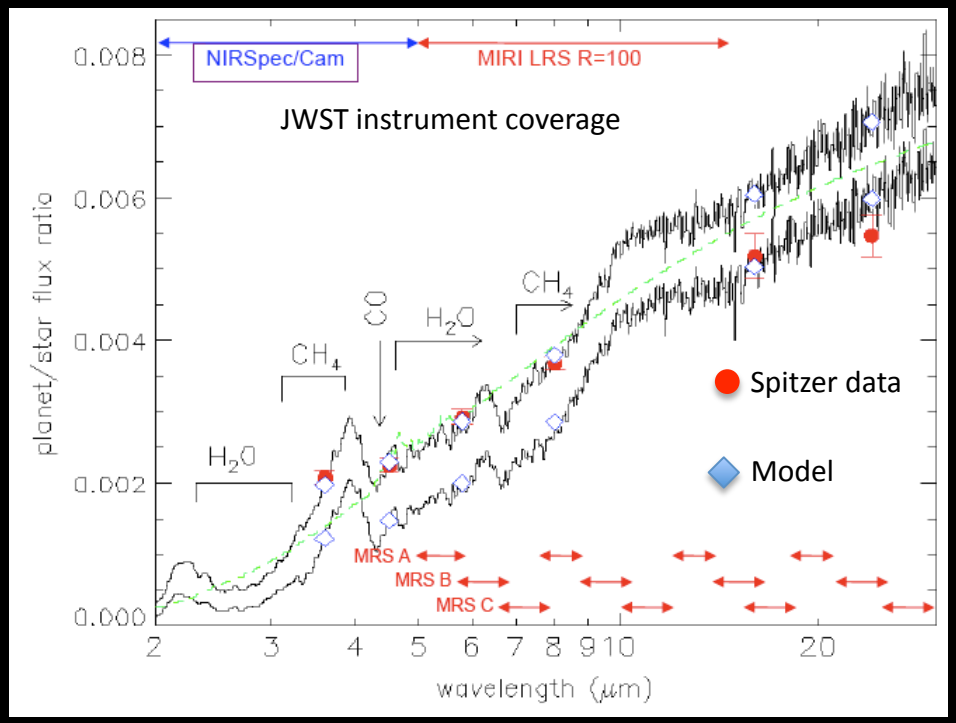


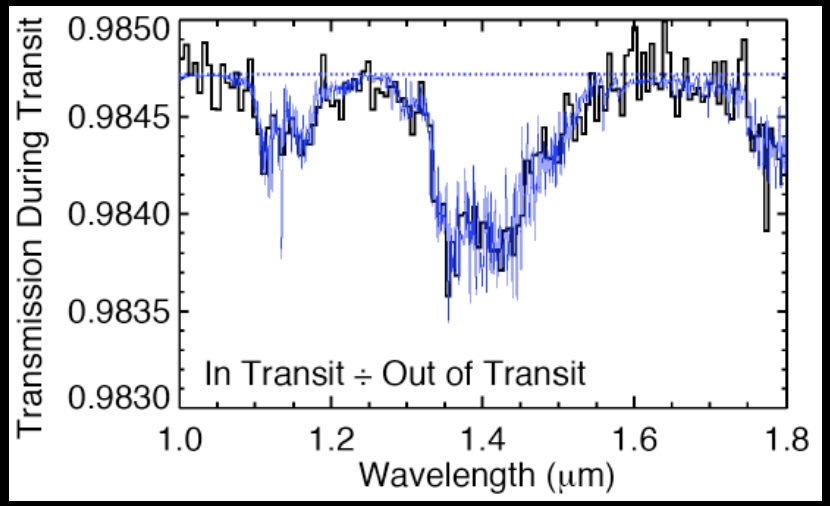


How diverse are planetary systems?

What do we need to answer question (in terms of atmospheres):

- Development of models of exoplanet atmospheres of varying composition and under different levels of radiation, including the study of clouds and photochemistry
- Tabulation of molecular line data supported by laboratory astrophysics needed for these modeling efforts
- Sensitive and high-res. observations with JWST to constrain atmospheric models



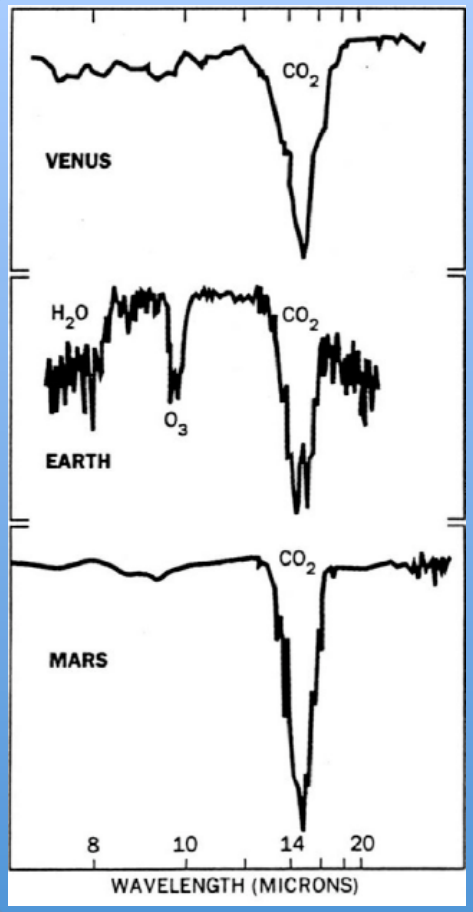


Black line = Simulated NIRSpec obs. (6-hr exposure)
Blue line = Model spectrum of hot Jupiter
(from Camplin et al. 2010)

Model spectrum of HD 189733b, also shown are Spitzer data
Also shown: coverage of JWST NIRCam, NIRSpec, and MIRI spec. modes (from Camplin et al. 2010)

4. Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?

Kepler should find Earth-sized planets orbiting Sun-like stars at about 1AU, and follow-up observations may help obtain the mass, radius and density. Yet, little will be known on composition, surface or atmosphere

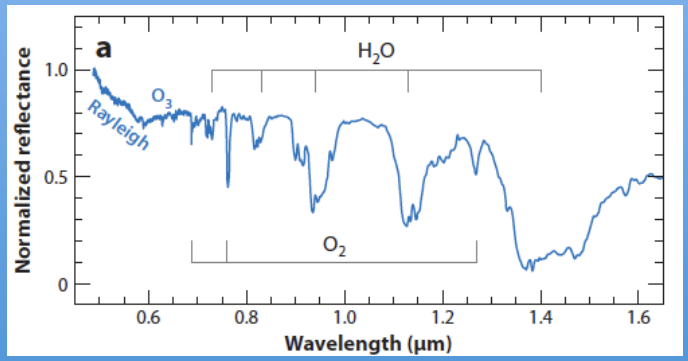


Comparison of IR spectrum of Venus, Earth. and Mars

(3 planets about to 1AU from, but VERY different)

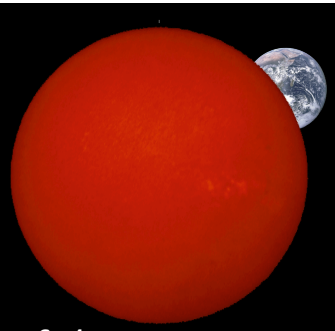
Recommendations:

- **lay the necessary ground-work for a successful terrestrial planet finder mission**
- **study of biosignatures:**
  - **is detection of water and a non-equilibrium chemistry enough?**
  - **what other spectral signatures can we use as bio-markers? (e.g., red edge)**
  - **advances in planet atmosphere models are needed (to permit positive ID of biomarkers)**

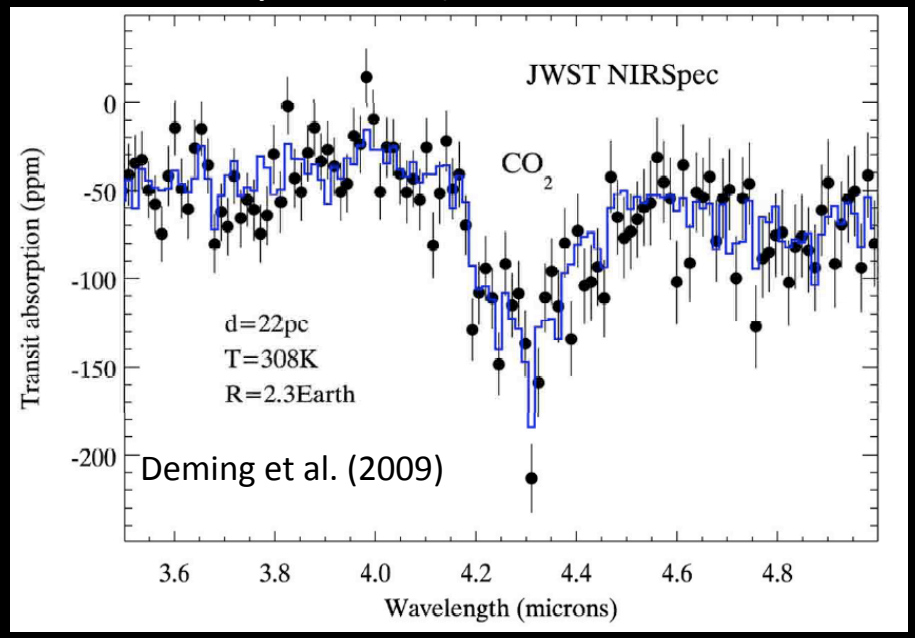


Earth spectrum from Earthshine (Turnbull et al. 2006)

5. Discovery Area: Can we identify and characterize a nearby (super-) Earth?



- A super-Earth (1 – 2 $R_\oplus$, 1 – 10 $M_\oplus$) orbiting within HZ of mid to late M-dwarf (0.1 – 0.4 Msun) would present both a transit signal and a radial-velocity signal measurable with existing (ground-based) technology. (One recently discovered: Gliese581g by Voigt et al. 2010)
- Such planets could then be characterized by JWST, providing an ***opportunity to study the atmosphere of a potentially life-bearing world in the 2010–2020 decade.***
- Super-Earths are expected to be very diverse (because of formation and evolution of atms.)



S/N ~ 28
after 85x2 hrs of int.

Simulated JWST NIRSpec observations (black points) of a habitable zone Super Earth

Summary

The Birth of Stars and Planetary Systems, and the Search for Habitable Worlds

1. *How do stars form?*
2. *How do circumstellar disks evolve and form planetary systems?*
3. *How diverse are planetary systems?*
4. *Do habitable worlds exist around other Sun-like stars? Can we detect biosignatures?*
5. *Discovery Area: Identification and characterization a nearby super-Earth*

Current and future NASA missions (Herschel, SOFIA, JWST), as well as other (ground-based) facilities (e.g., ALMA, CCAT, GSMT) will help answer these questions….

But advances in chemical modeling and further laboratory work are needed to help answer these questions and interpret the wealth of data that will be available.