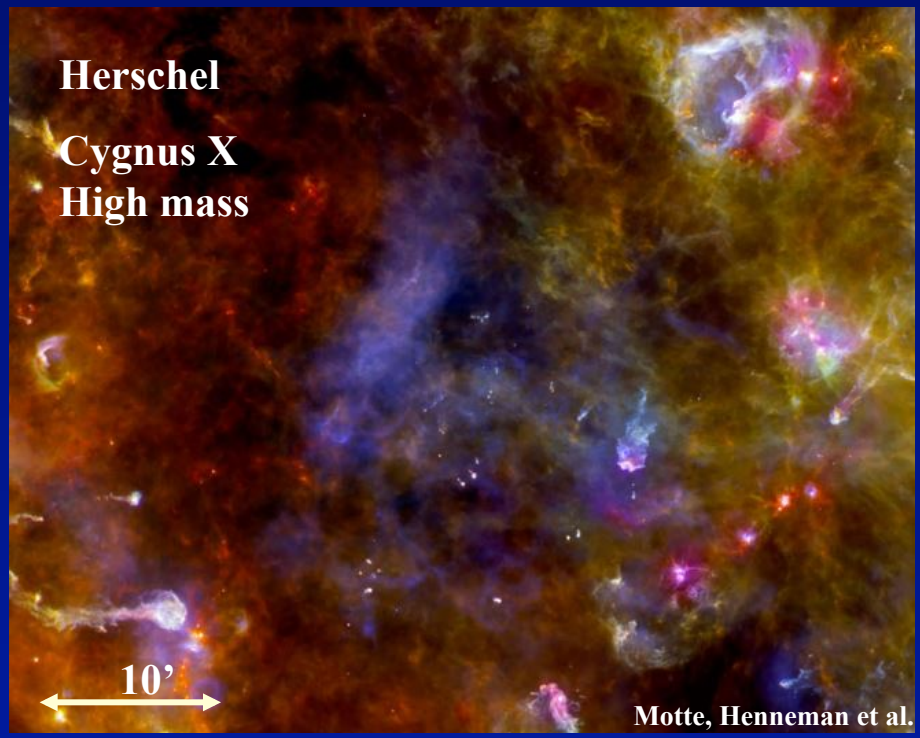
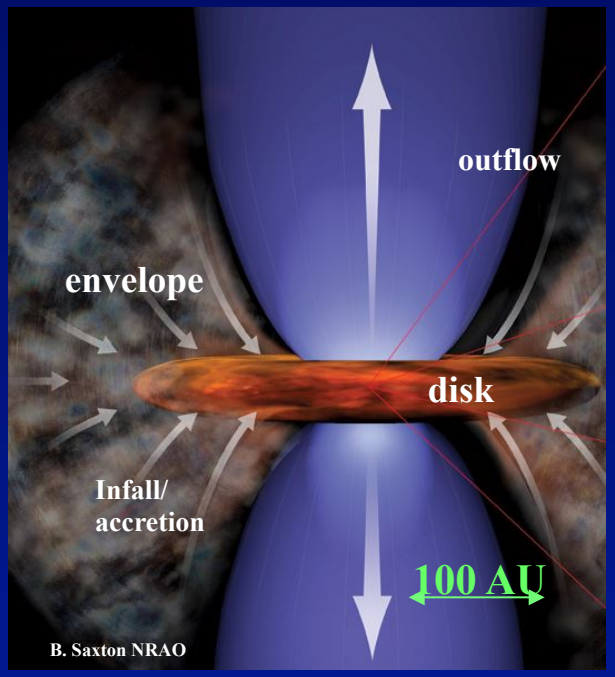
Probing the embedded phase of star formation with JWST spectroscopy

NIRSPEC

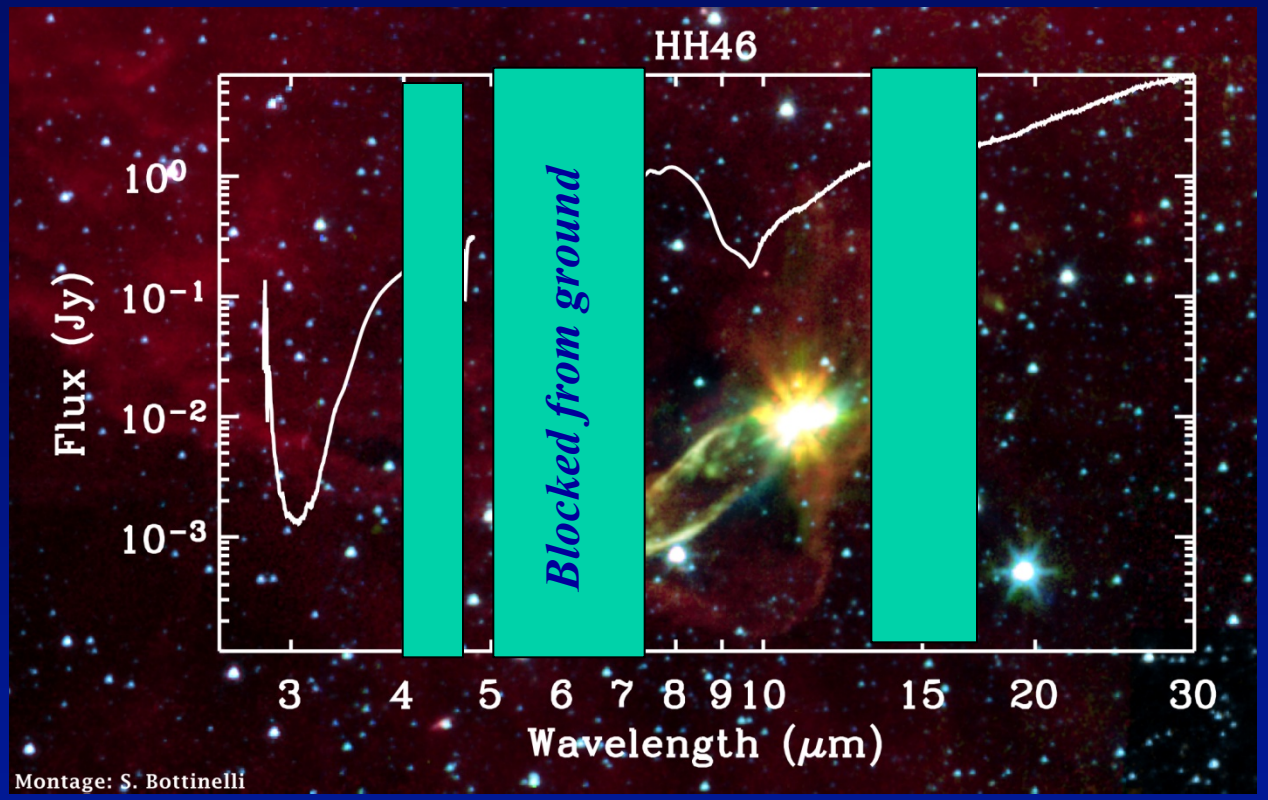


E.F. van Dishoeck, H. Beuther, T. Greene, M. Ressler, A. Caratti o Garatti, V. Geers, K. Justtanont, P. Klaassen, O. Krause, T. Ray, C. Waelkens

Embedded protostars



Rising SED with wavelength
Sizes well matched to IFUs



IR probes dust with temperatures 100-1500 K

- Complete inventories of protostars exist out to few kpc thanks to Spitzer, Herschel, WISE, ground-based submm, ... → large samples available

-Need NIRSPEC and MIRI IFU spectroscopy to characterize physics and chemistry on few 10 to few 1000 AU scales

Main questions

- How does matter flow from core → disk → star? What are the characteristics of protostars? Measure (episodic) accretion rates

- What are the properties of young disks? Evidence for accretion shocks? Disk and core fragmentation (→ young planets, binaries/multiples coevality)?

- What is the origin and location of chemical complexity? Composition and processing of ices? Gas/ice ratios?

- What is feedback of protostar on surroundings? Physics of jet/wind – envelope interaction? Importance shocks vs UV photons? Properties of youngest outflows?

- How do these characteristics change from low- to high-mass stars and with evolutionary stage?

IR diagnostics (unique!)

- **Protostar, disk: continuum**
- **Accretion: H I recombination**
- **Shock: [S I], [Fe I], [Fe II], [Ne II], H_2, H_2O, OH,…**
- **UV/PDR: H_2, PAHs, ….**
- **X-rays/high energy photons: [Ne II], [Ne III]**
- **Warm env/hot core: H_2O, HCN, C_2H_2, CH_4, CO_2 gas**
- **Cold envelope: ices, silicates**

Combine with far-IR lines (Herschel and spectrally resolved mm data (ALMA) to answer above questions

Modeling tools and laboratory data crucial!

Why JWST?

Progress from Spitzer: spatial + spectral resolution and sensitivity

Spatial resolution

		150pc	400pc	3kpc
<5 μm	0.1”	15AU	40 AU	300AU
5μm	0.19”	29AU	76AU	570AU
15μm	0.58”	87AU	232AU	1740AU
25μm	0.96”	144AU	384AU	2800AU

- Spatial resolution sufficient to resolve disks and envelopes

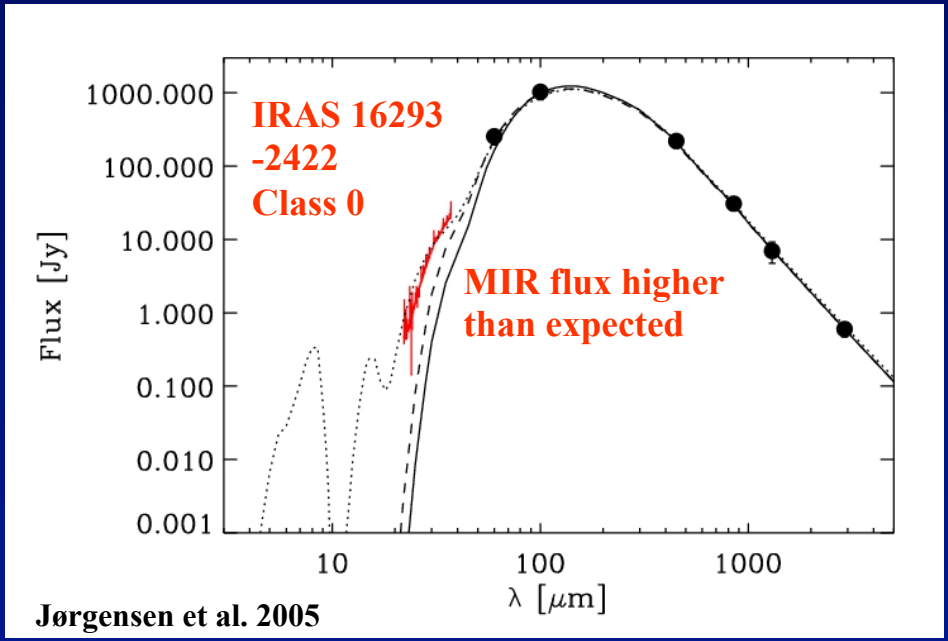
- Sensitivity ~(sub)mJy for spectra
-High spectral resolution boosts line/continuum ratio

→ Spatially resolved characterization of protostars, envelopes, disks and outflows

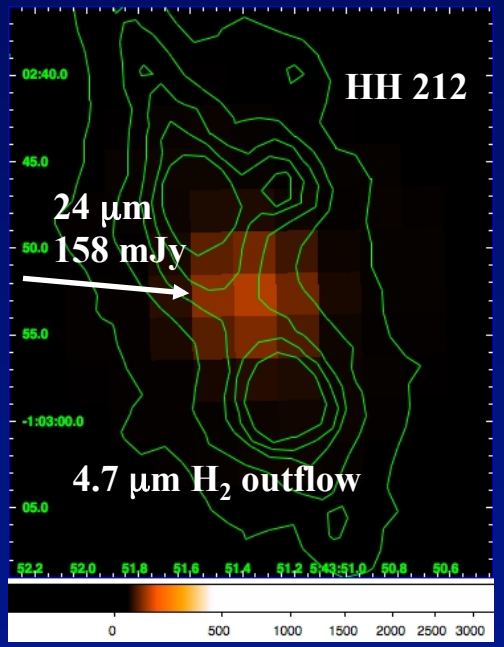
Optimal use of IFUs

See MIRI PASP papers

1. Protostars and their inner envelopes



Jørgensen et al. 2005



Beuther, from Spitzer archive

Questions

- What is physical structure warm dust? Geometry?
- Earliest stages massive star formation?

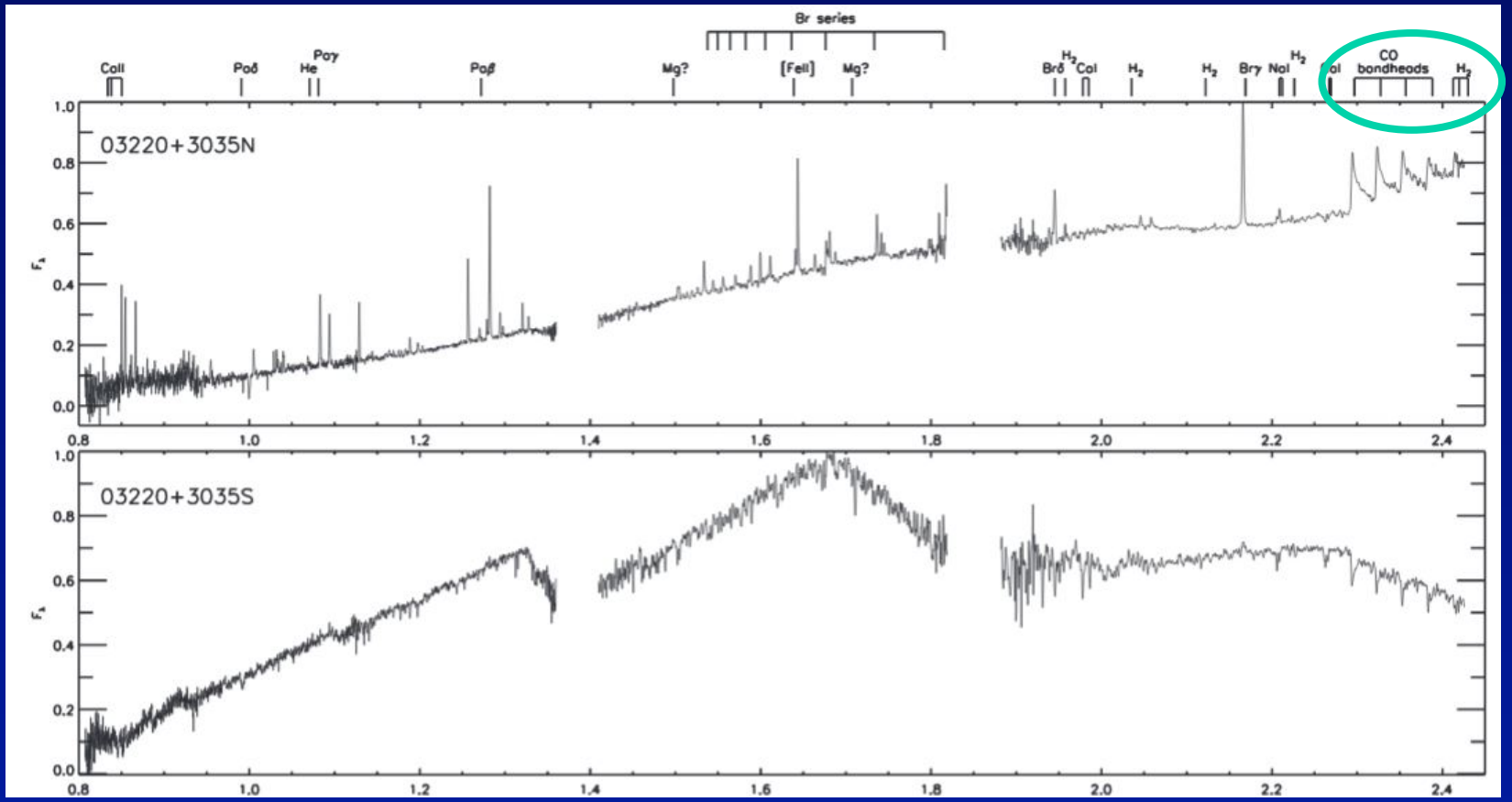
Deeply embedded Class 0 sources are predicted to have very weak mid-IR fluxes, yet several were detected with Spitzer

→ information on geometry

Stellar photospheric spectra

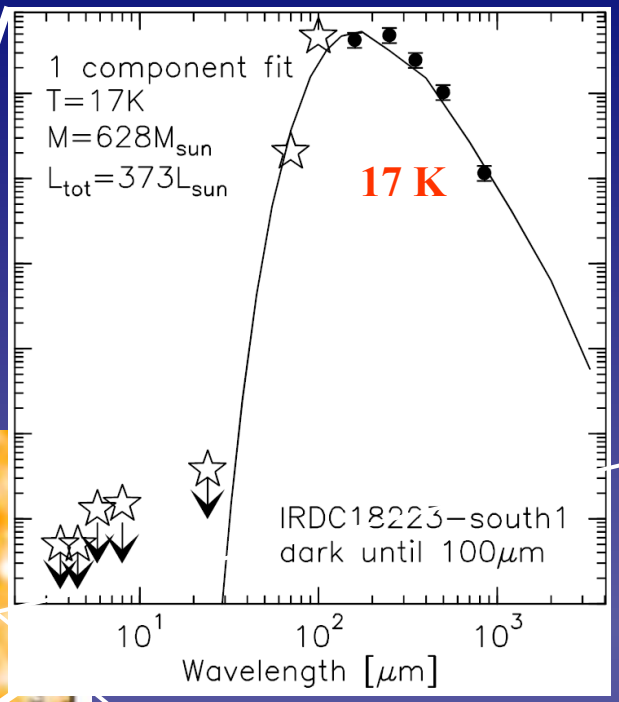
- NIRSPEC spectra of Class 0 / early Class I protostars themselves
  - Na, CO, H_2O stellar features
  - Expect heavy veiling
- Determine stellar T_{eff} and masses, radii
- Compare accretion rates from different diagnostics
  - Origin luminosity problem of protostars?
  - Variability?

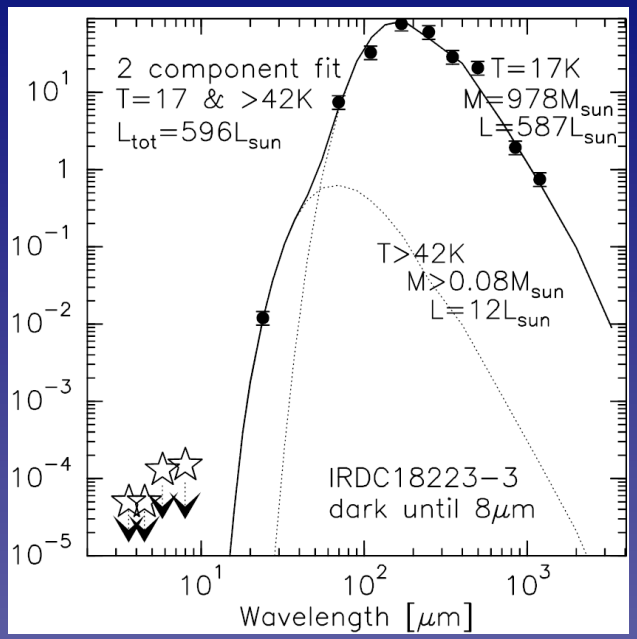
Near-IR spectroscopy Class I

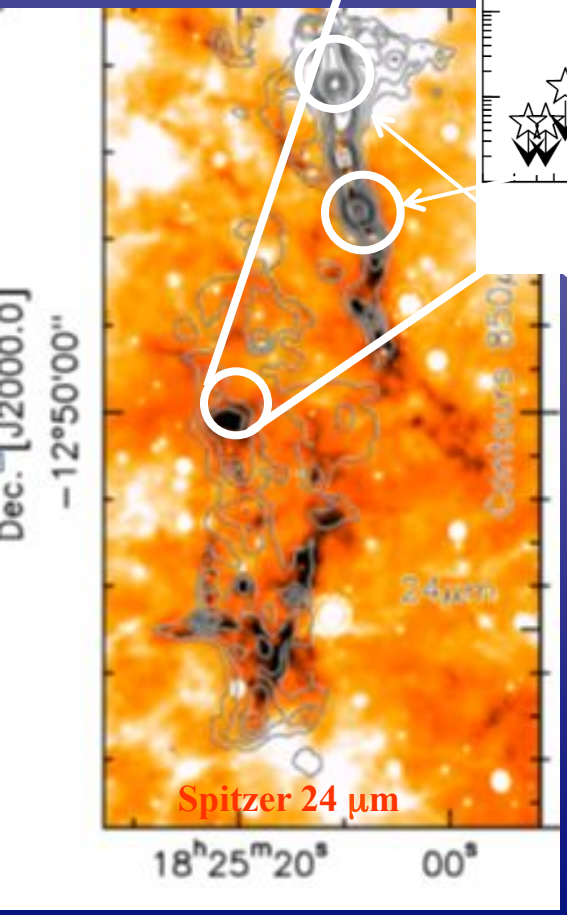


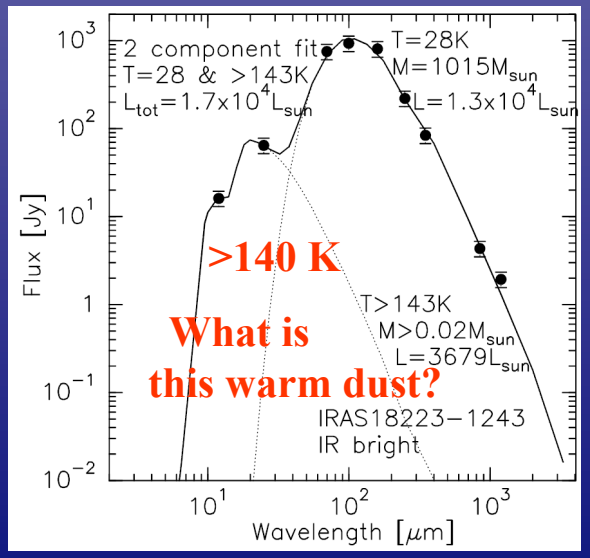
Connelley & Greene 2010

High mass protostars at different stages



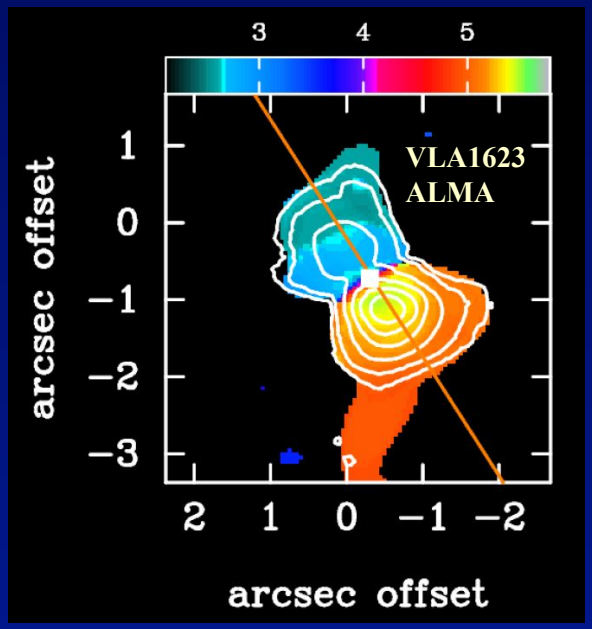




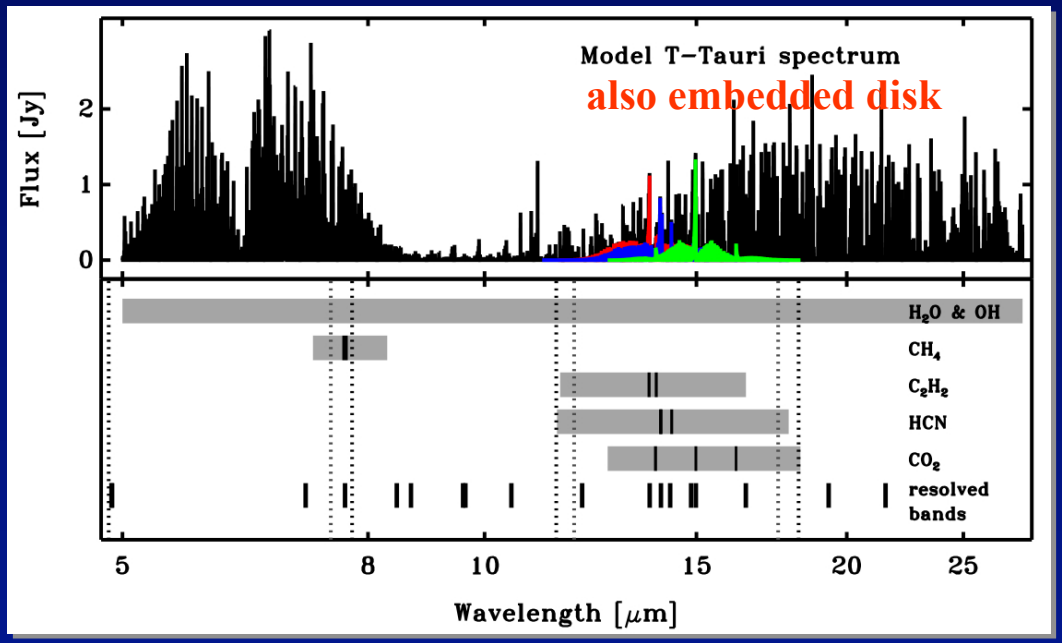


Beuther et al. 2010

2. Young disks in the embedded phase



Murillo et al. 2013, Tobin et al. 2013 Class 0
Lommen et al. 2008, Harsono et al. 2013



Herschel hot water detections
63 μm; Herczeg et al., Karska et al.

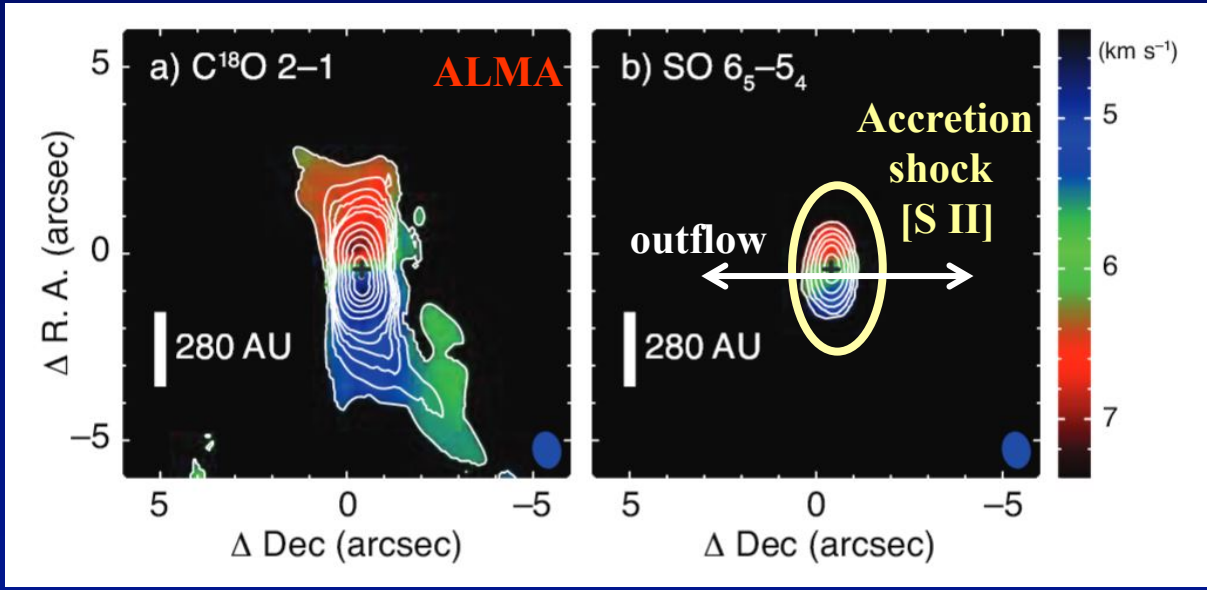
Lahuis, based on Pontoppidan et al. 2010

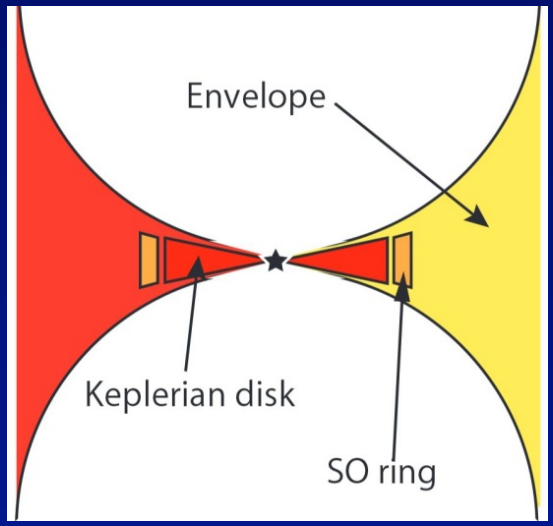
Questions

- Properties of disks in embedded phase? Where does most matter enter disk?
- Fragmentation of disks and cores?

MIRI provides physical and chemical characterization

Tracing the accretion shock

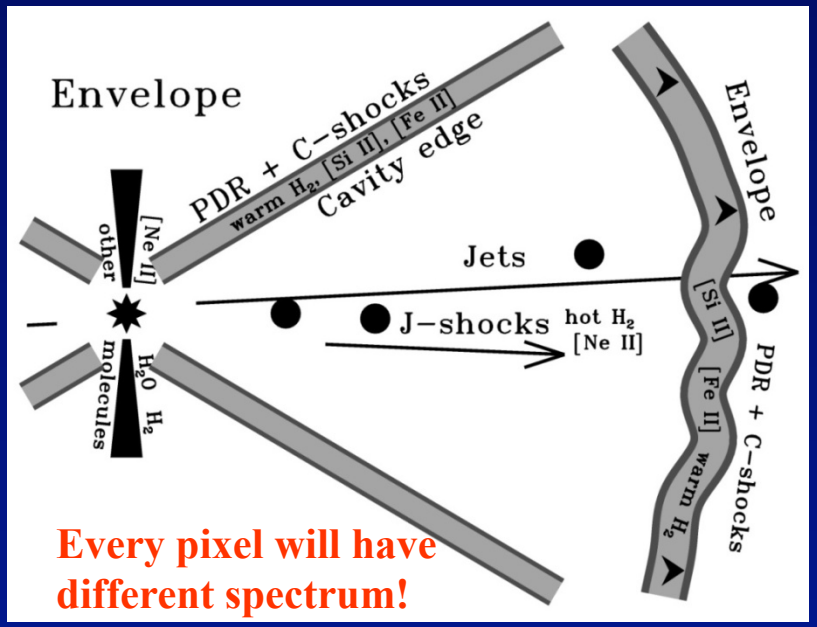




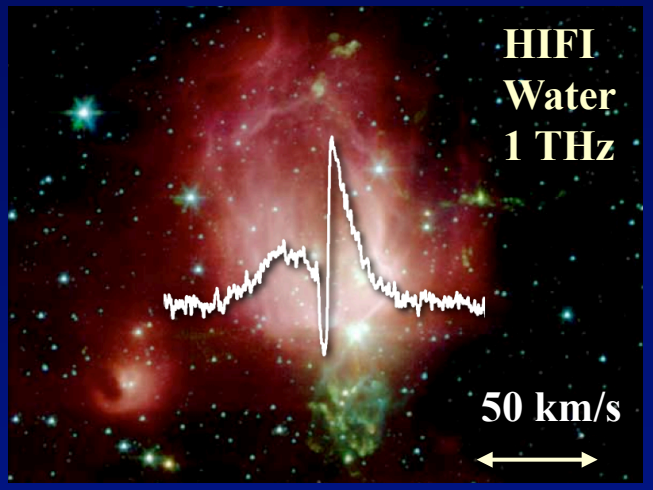
Sakai et al. 2014, Ohashi et al. 2014
Hollenbach & Neufeld models

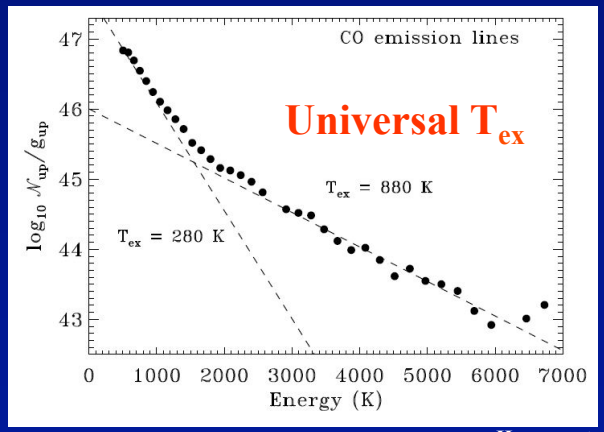
- Can we trace the accretion shock directly with [S II] and other shock tracers?
- JWST can spatially resolve accretion from outflow shocks

3. Protostellar jets and outflows



Lahuis et al. 2010





Herczeg et al. 2012
Karska et al. 2013

Questions

- How does protostar affect and disperse its surroundings: shocks vs UV? Evolution?
- Physics of shocks: dissociative vs non-dissociative shocks

Complete far-IR cooling budget observed with Herschel for ~100 low-mass protostars, but spatially unresolved in 9.4" spaxel

Mapping the inner envelope + outflows

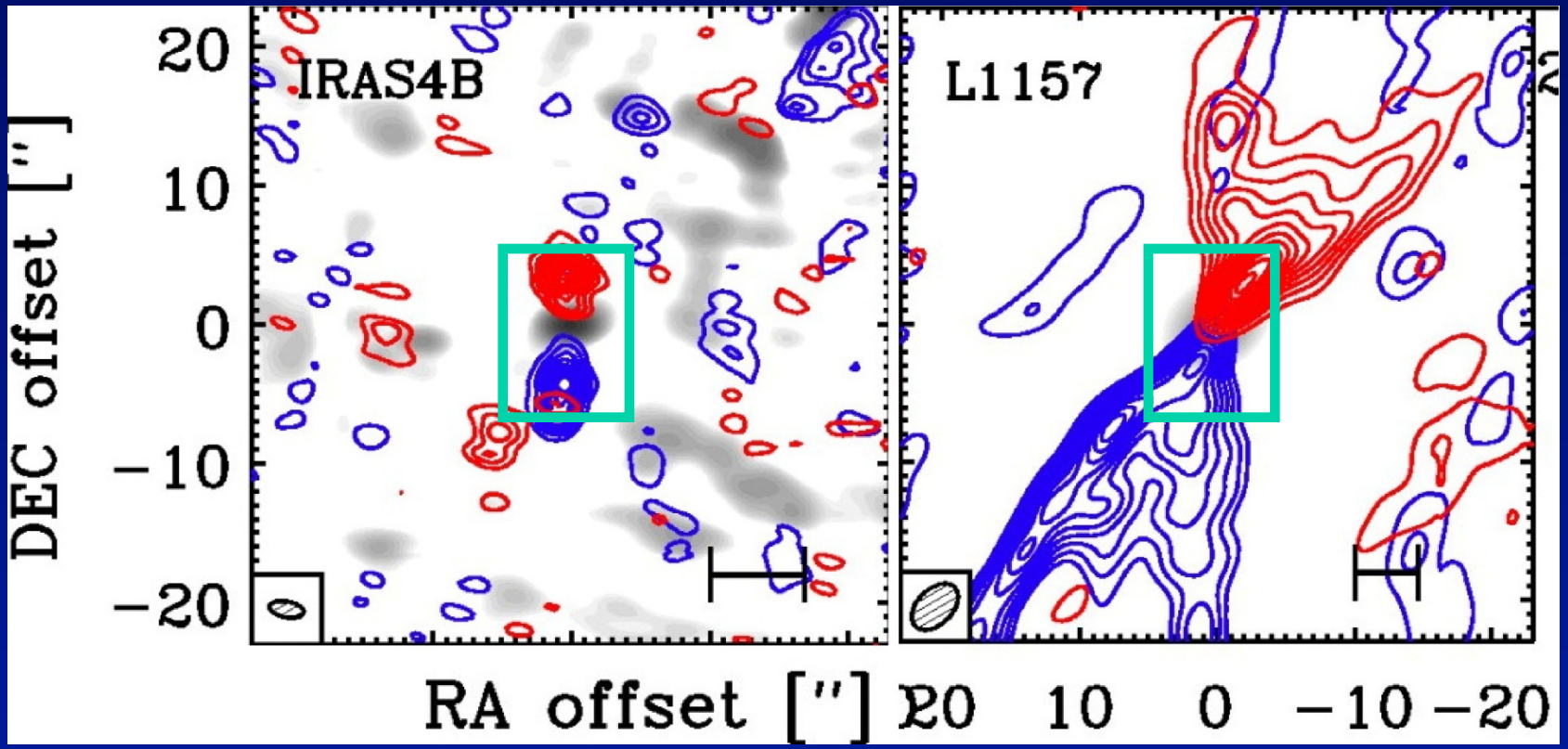
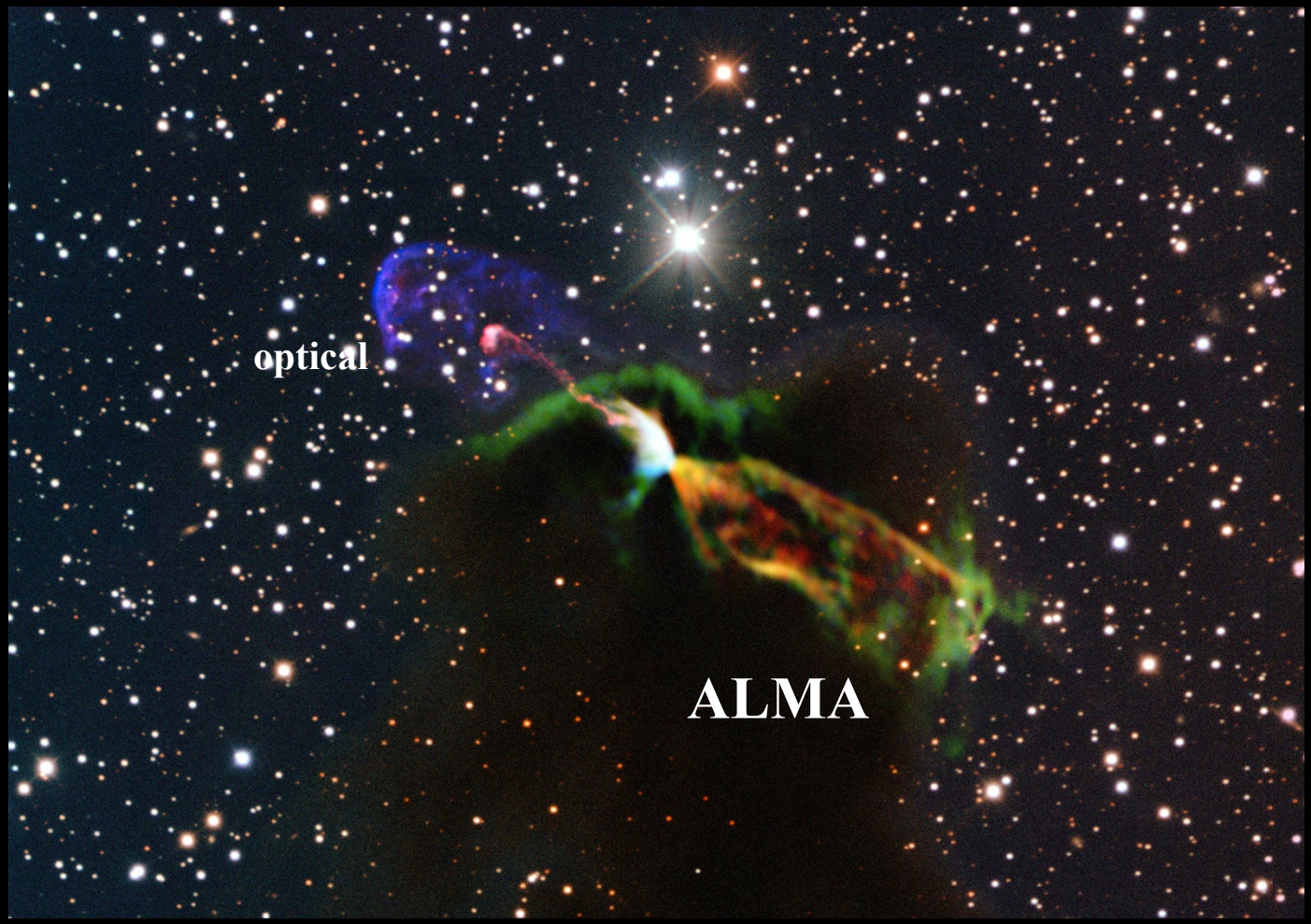


Image: SMA CO 3-2 outflow contours

Jørgensen et al. 2007

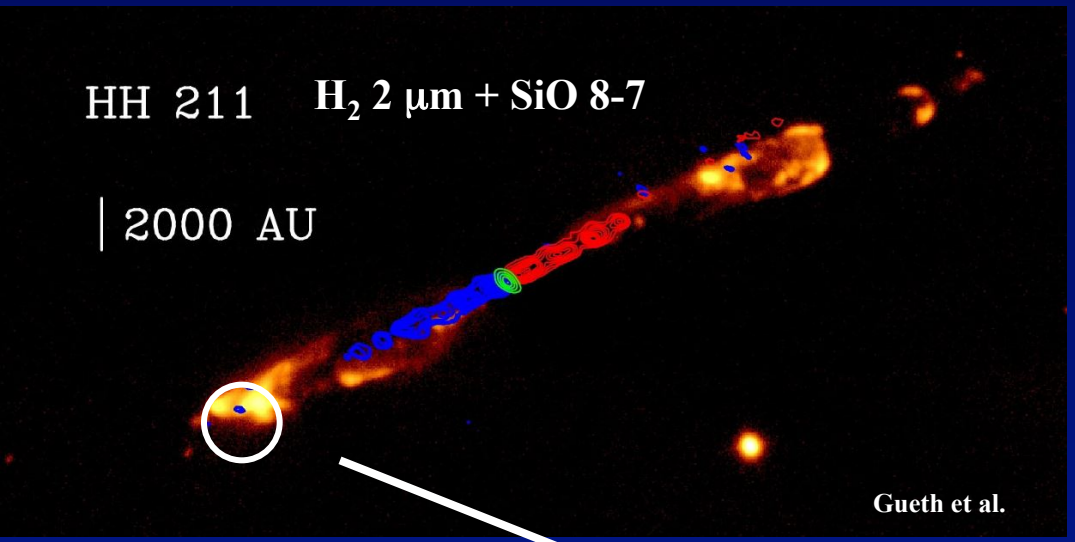
Small IFU maps well matched to size of interaction region

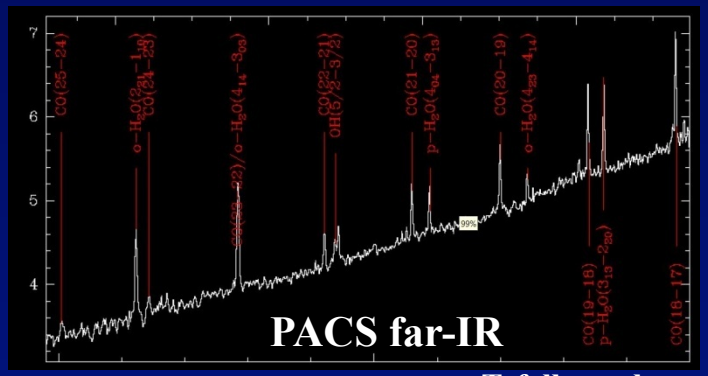
ALMA images of outflow



Arce et al. 2013

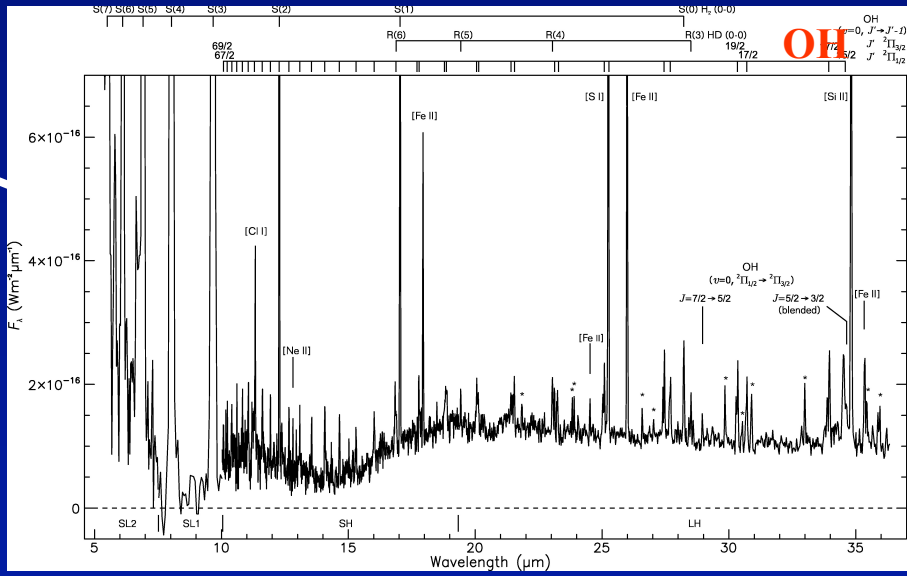
HH 211 outflow map





Tafalla et al.

Rich mid-IR spectrum: Spitzer

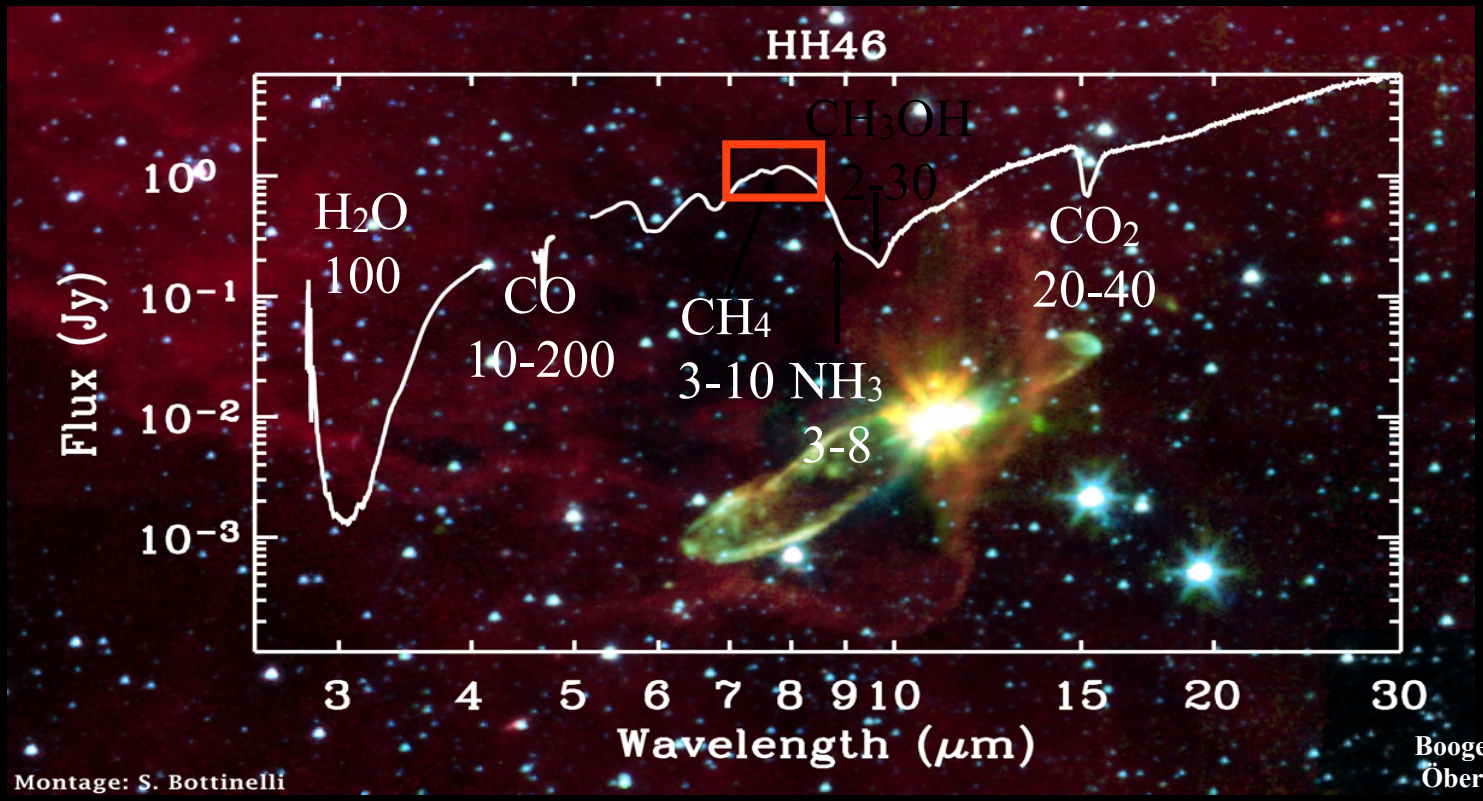


Tappe et al. 2008

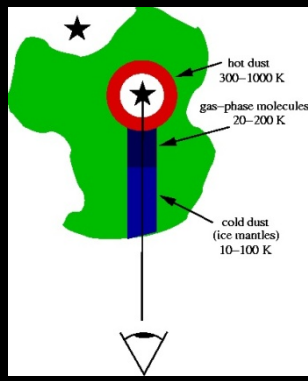
Map outflows over larger scales

-Do shock properties vary with distance from protostar? Role of UV?
-Is dust launched inside Class 0 jets?
-Is dust destroyed by shocks?

4. Chemistry: organics and water



HH46

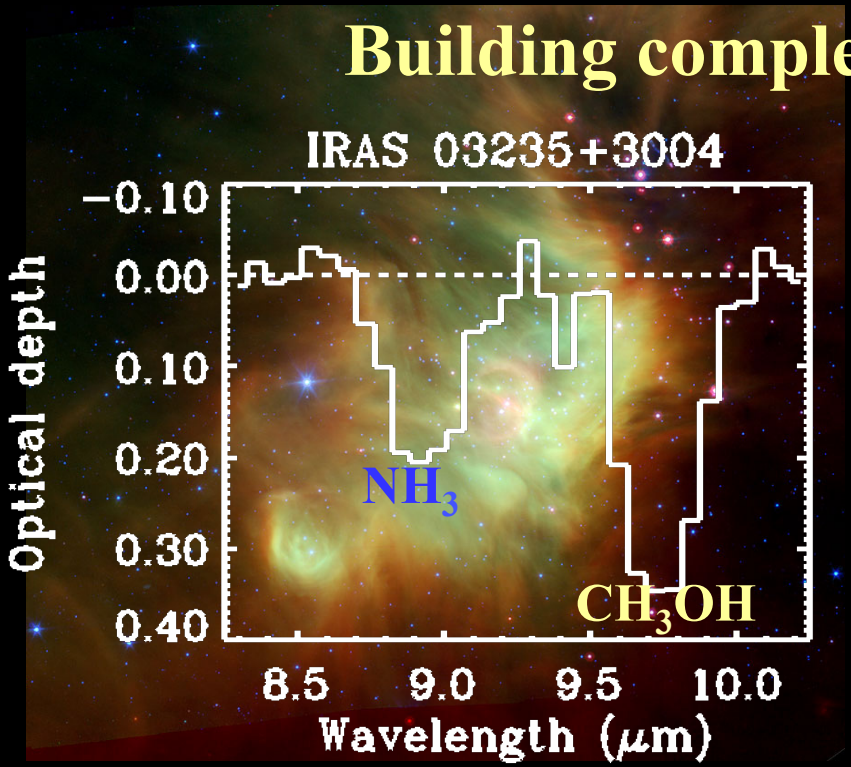


Boogert, Pontoppidan
Öberg et al. 2008

Questions

- Origin of chemical complexity: ice or gas? Thermal or UV processing?
- How is water transported from clouds to disks (→ planets): ice vs gas?
- Thermal history and evolutionary state sources (gas/ice ratio)?

Building complex organics in ices

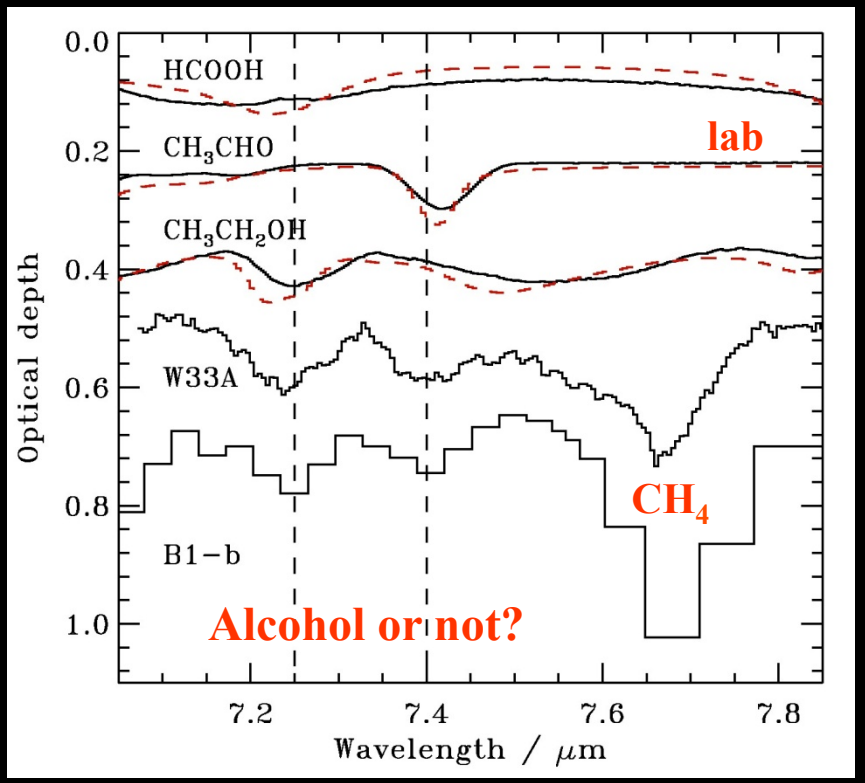


Bottinelli et al. 2010

- MIRI can resolve weak ice features in critical fingerprint region of organics

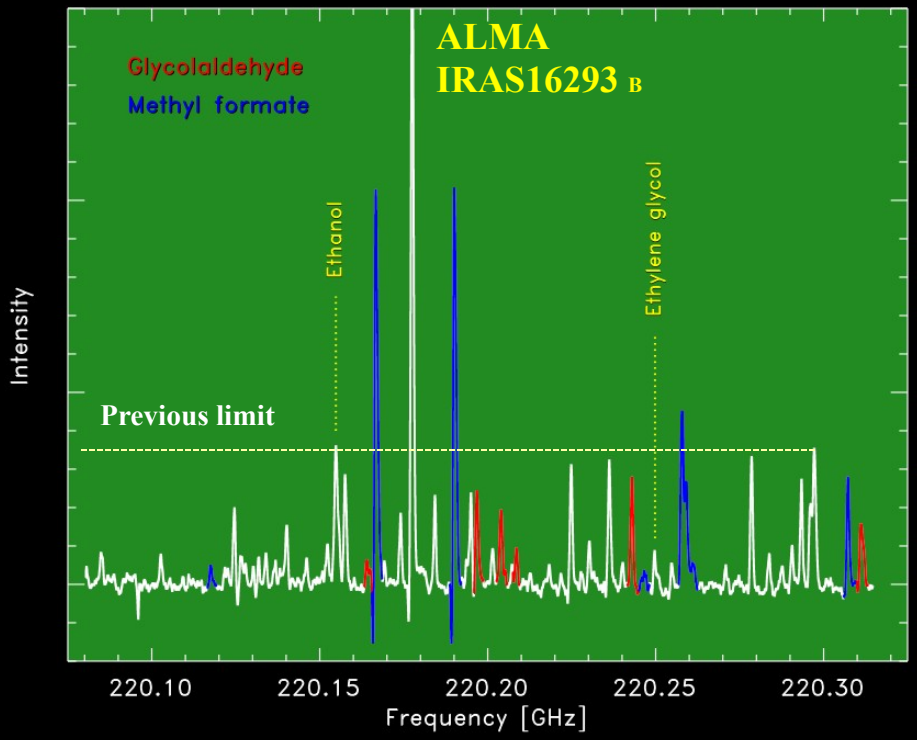
- Spitzer lacked spectral resolution 5-10 μm

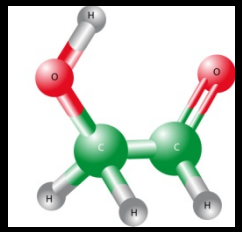
Larger organics 7-8 μm

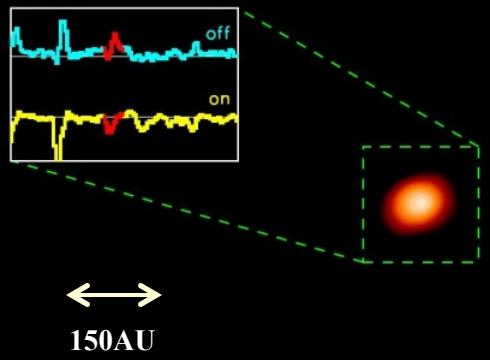


Öberg et al. 2011

Complex organic molecules with ALMA







Band 9, 0.2”

Small scale chemical diversity seen on 500 AU scales: due to ice variations?

Jørgensen et al. 12

Summary

- Protostars well suited for IFU Nirspec, MIRI spectroscopy
- Single data set can address multiple questions
- 'Cluster observing' ('smart accounting') mode will greatly increase efficiency and scientific return

Harvey et al. 2007