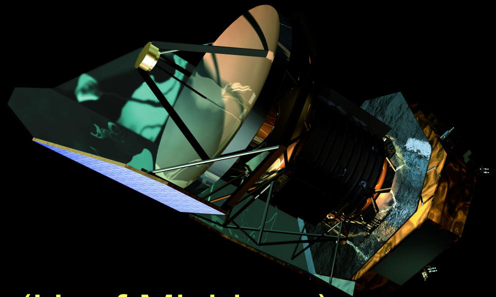
The “Herschel” Orion Protostar Survey (HOPS)

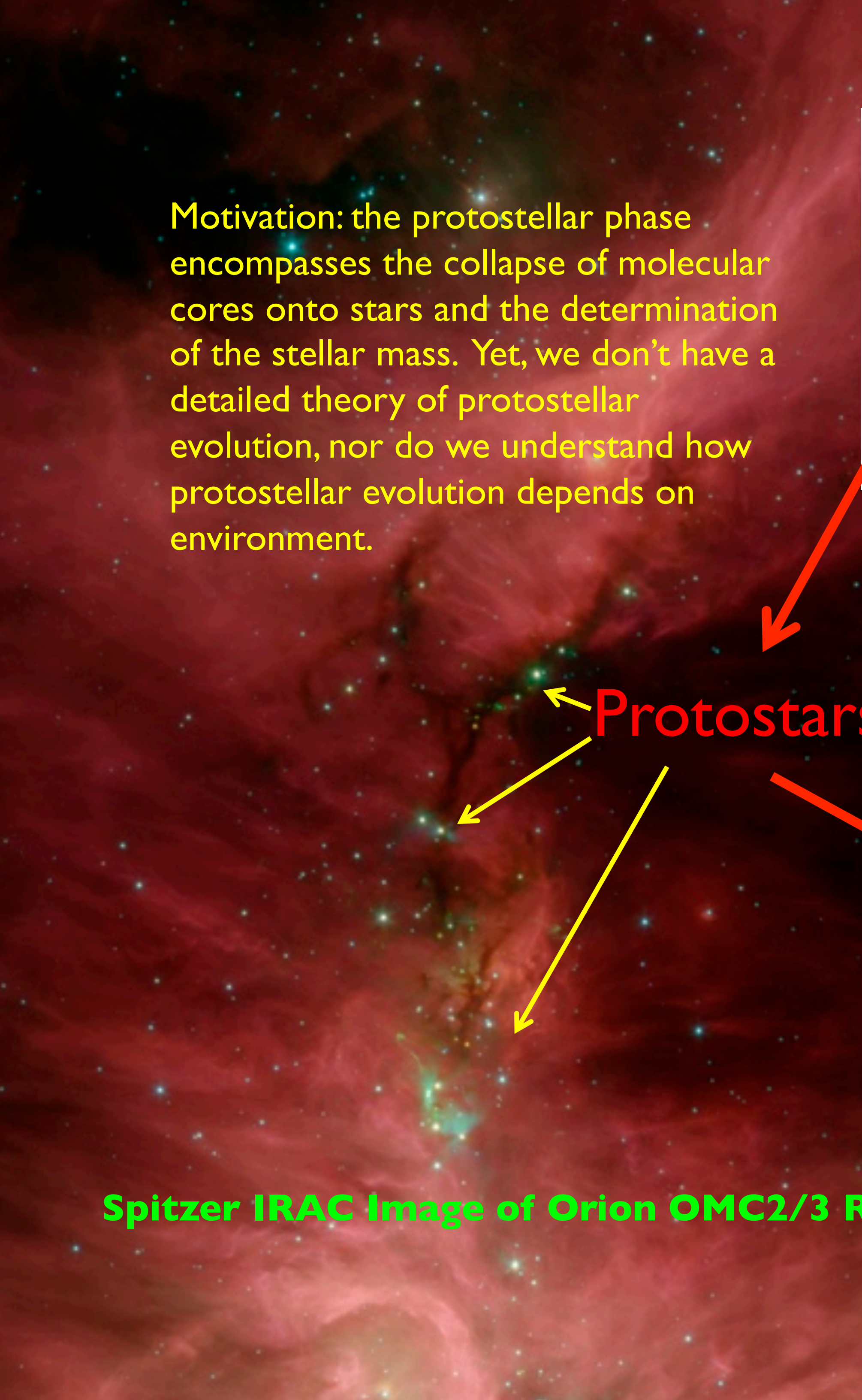
A multi-observatory survey of Spitzer identified Protostars in the Orion Molecular clouds

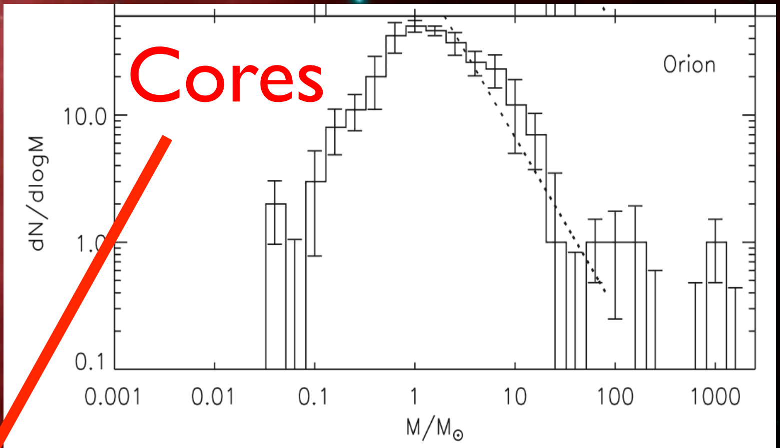


Tom Megeath (U. of Toledo)

Co-Is: Babar Ali (NHSC), Lori Allen (NOAO), Ted Bergin (U. of Michigan),
Nuria Calvet (U. of Michigan), James Di Francesco (Herzberg Institute),
Will Fischer (U. of Toledo), Elise Furlan (JPL), Lee Hartmann (U. of Michigan),
Thomas Henning (MPIA), Oliver Krause (MPIA), Sébastien Maret (Grenoble Observatory),
James Muzerolle (STScI), Phil Myers (SAO), David Neufeld (Johns Hopkins U.),
Mayra Osorio (Instituto de Astrofisica de Andalucia), Klaus Pontoppidan (Caltech), Charles Poteet (U. of Toledo), Manoj Puravankara (U. of Rochester),
Thomas Stanke (ESO), Amy Stutz (MPIA), John Tobin (U. of Michigan),
Dan Watson (U. of Rochester), and Tom Wilson (ESO)

Motivation: the protostellar phase encompasses the collapse of molecular cores onto stars and the determination of the stellar mass. Yet, we don't have a detailed theory of protostellar evolution, nor do we understand how protostellar evolution depends on environment.

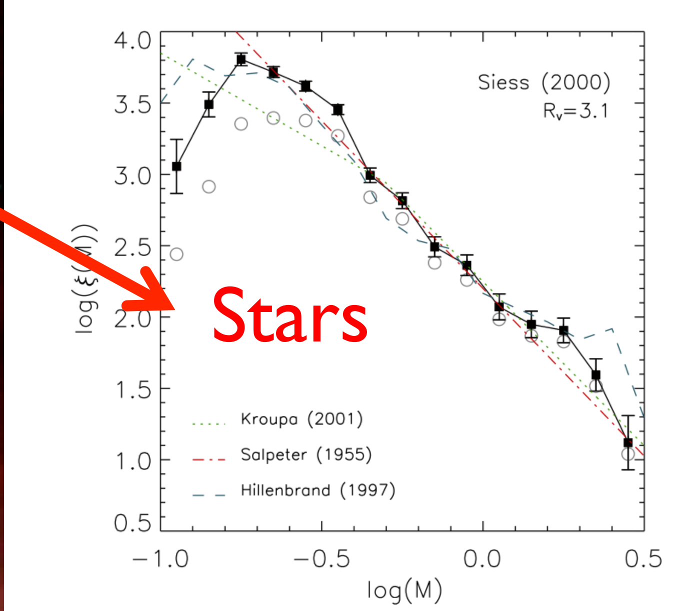




Sadavoy et al. 2010

Protostellar luminosity:

$$L = L_* + L_{acc} = L_* + \frac{GM\dot{M}}{r}$$

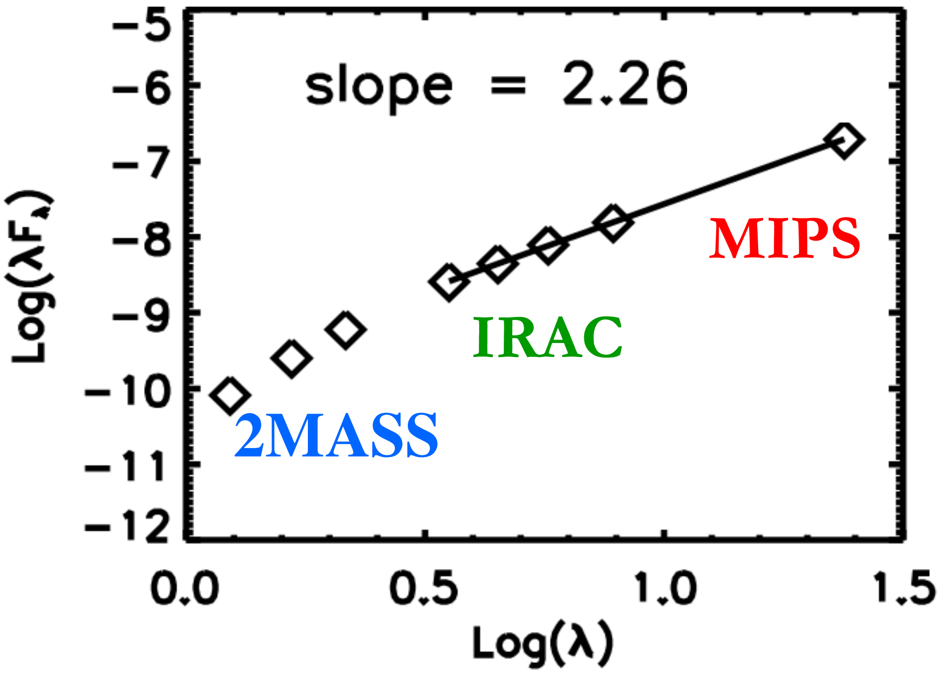


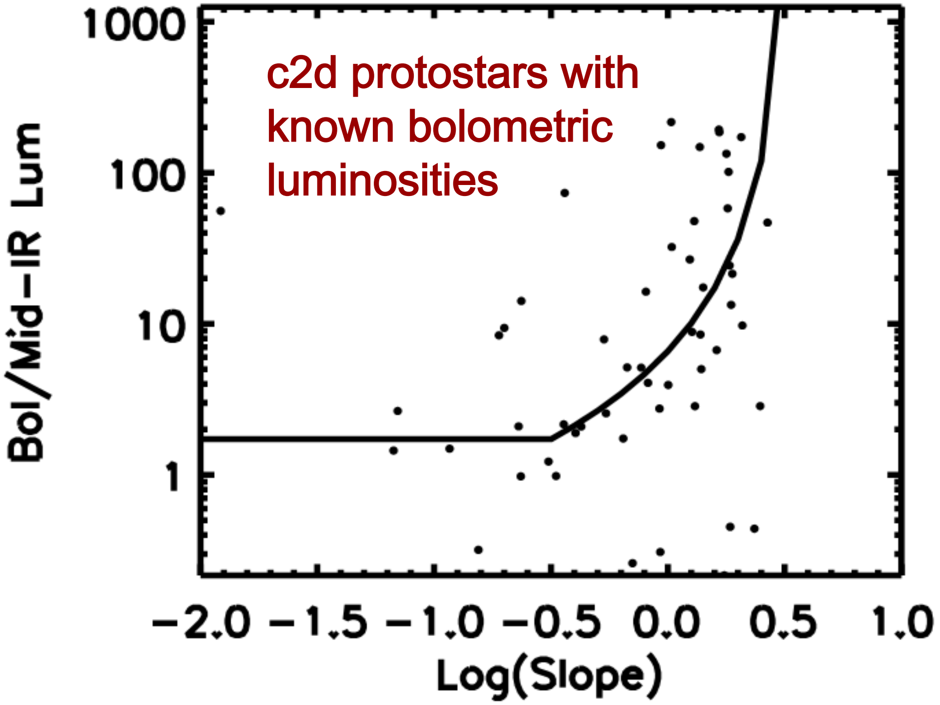
Da Rio et al. 2010

Spitzer IRAC Image of Orion OMC2/3 Region

Prelude: Studying Protostars From Spitzer Alone: Luminosity-Slope Relationship

Erin Kryukova





1. Calculate 3-24 micron SED slope from IRAC and MIPS data.
2. Integrate over 1-24 micron bands to calculate mid-IR luminosity.
4. Convert mid-IR to bolometric luminosities using an empirically derived relationship.

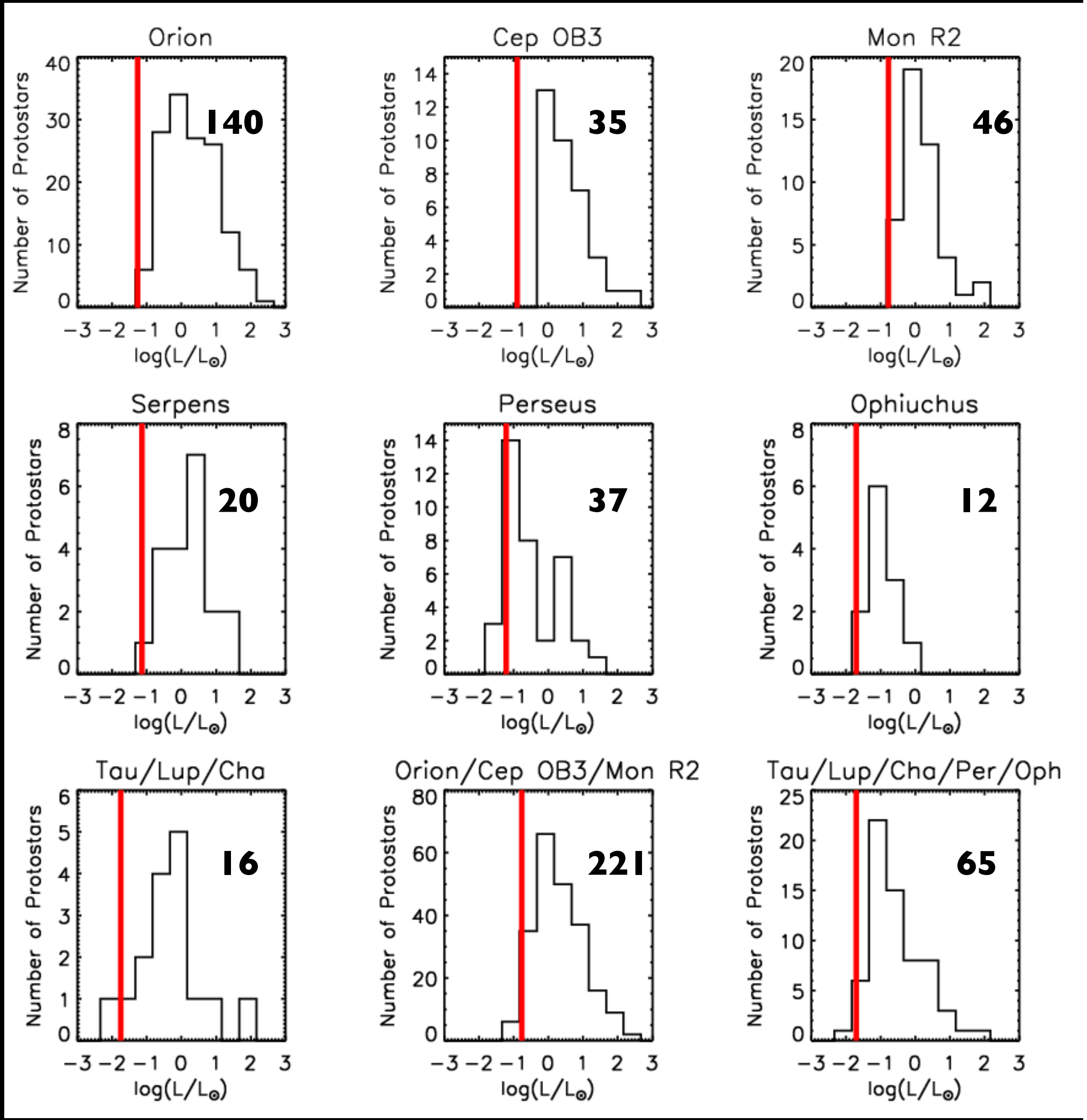
Prelude: Luminosity Functions for Nearby Clouds

Spitzer derived luminosity functions for nine nearby clouds (including Orion)

Luminosity functions peak near 1 L_{sun} for clouds which form high mass stars, and at 0.1 L_{sun} for Perseus and Ophiuchus.

Orion, Cep OB3, and Mon R2 show tails extending to luminosities > 100 L_{sun}.

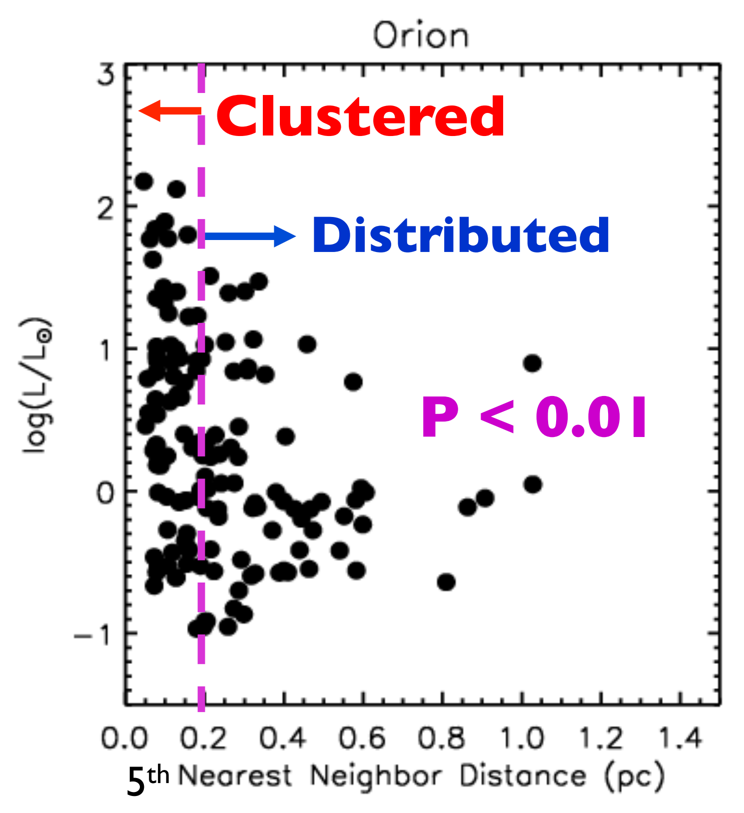
Combined luminosity functions differ between high mass SF clouds and low mass SF clouds, with a KS test probability P = 0.02

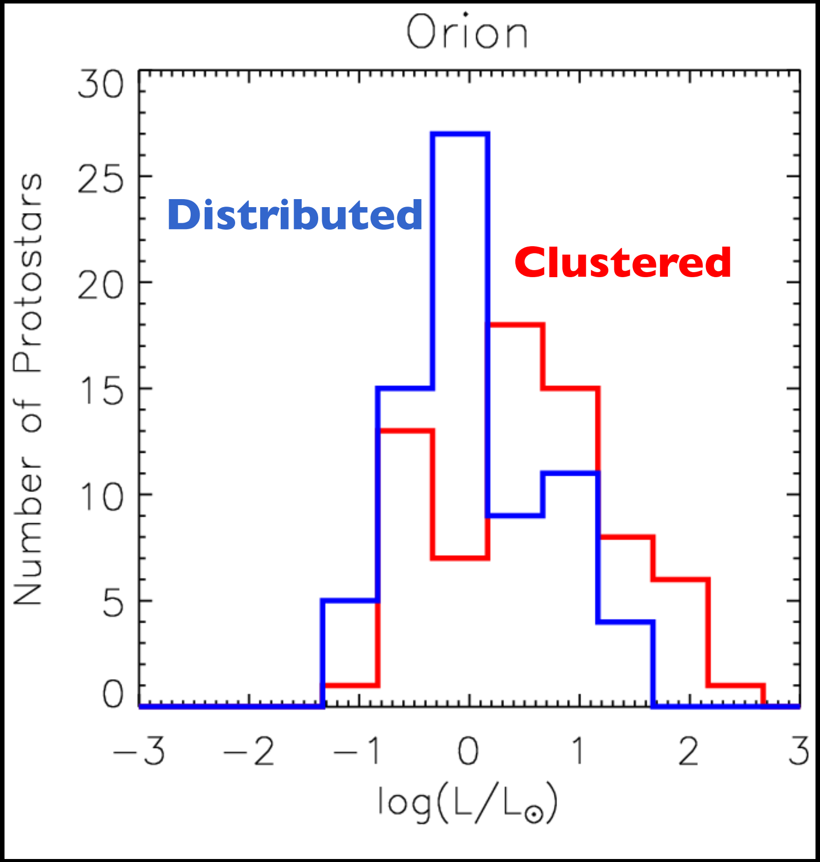


Sensitivity limit based on [24] cutoff

Erin Kryukova

Prelude: Luminosity Dependence on Environment?





Clustering cutoff length to 5th nearest neighbor YSO selected so that there are equal numbers of clustered and distributed protostars.

Orion clustered protostars extend to higher luminosities, clustered and distributed luminosity functions are statistically different.

Erin Kryukova

HOPS Observations

(200 hours)

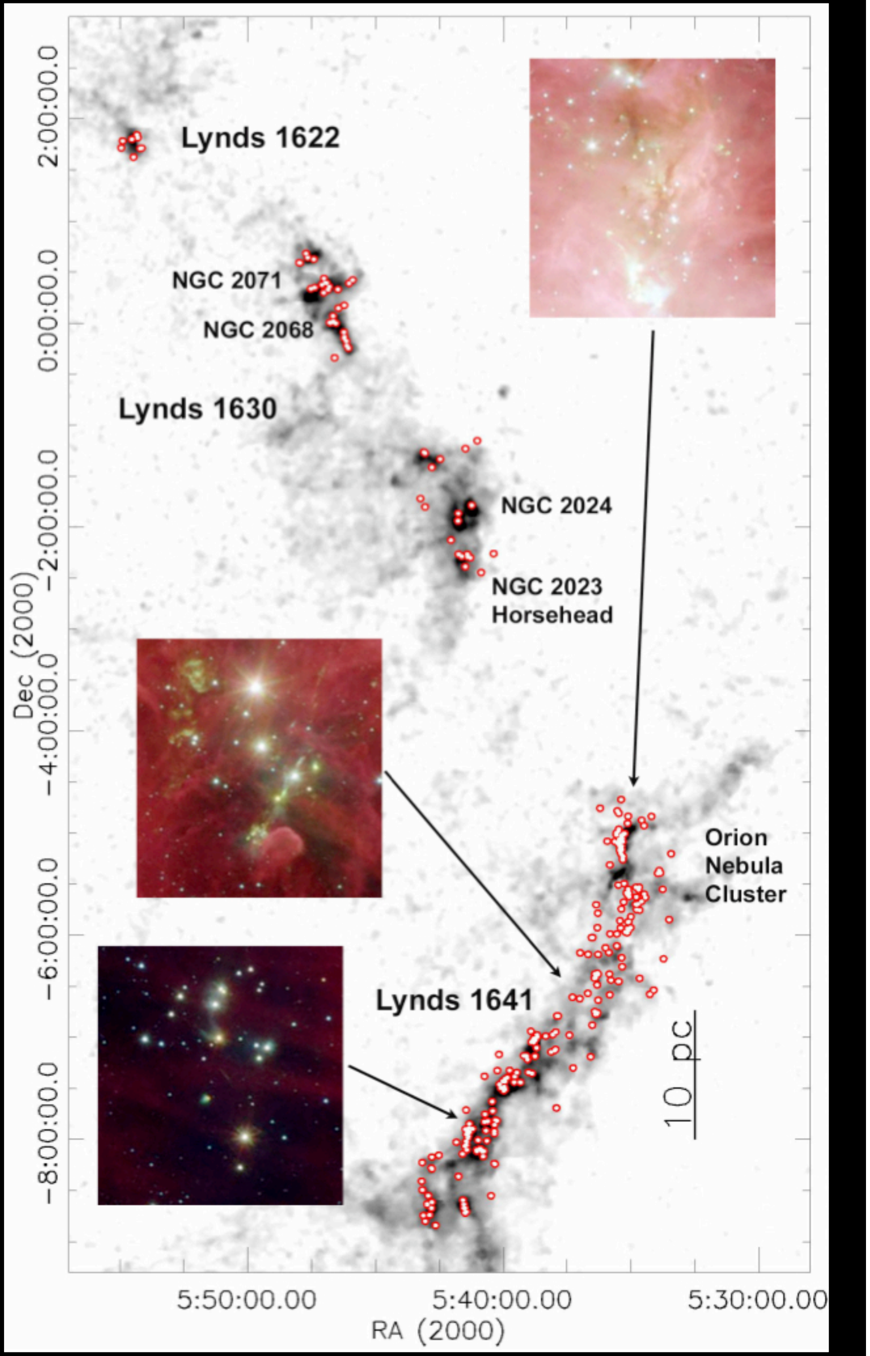
PACS imaging of 278 protostars:

- Spitzer-identified protostars with extrapolated fluxes > 42 mJy at 70 μm
- 5’ to 8’ square fields
- Medium (20”/s) scan rate
- 70 and 160 μm scans & cross-scans

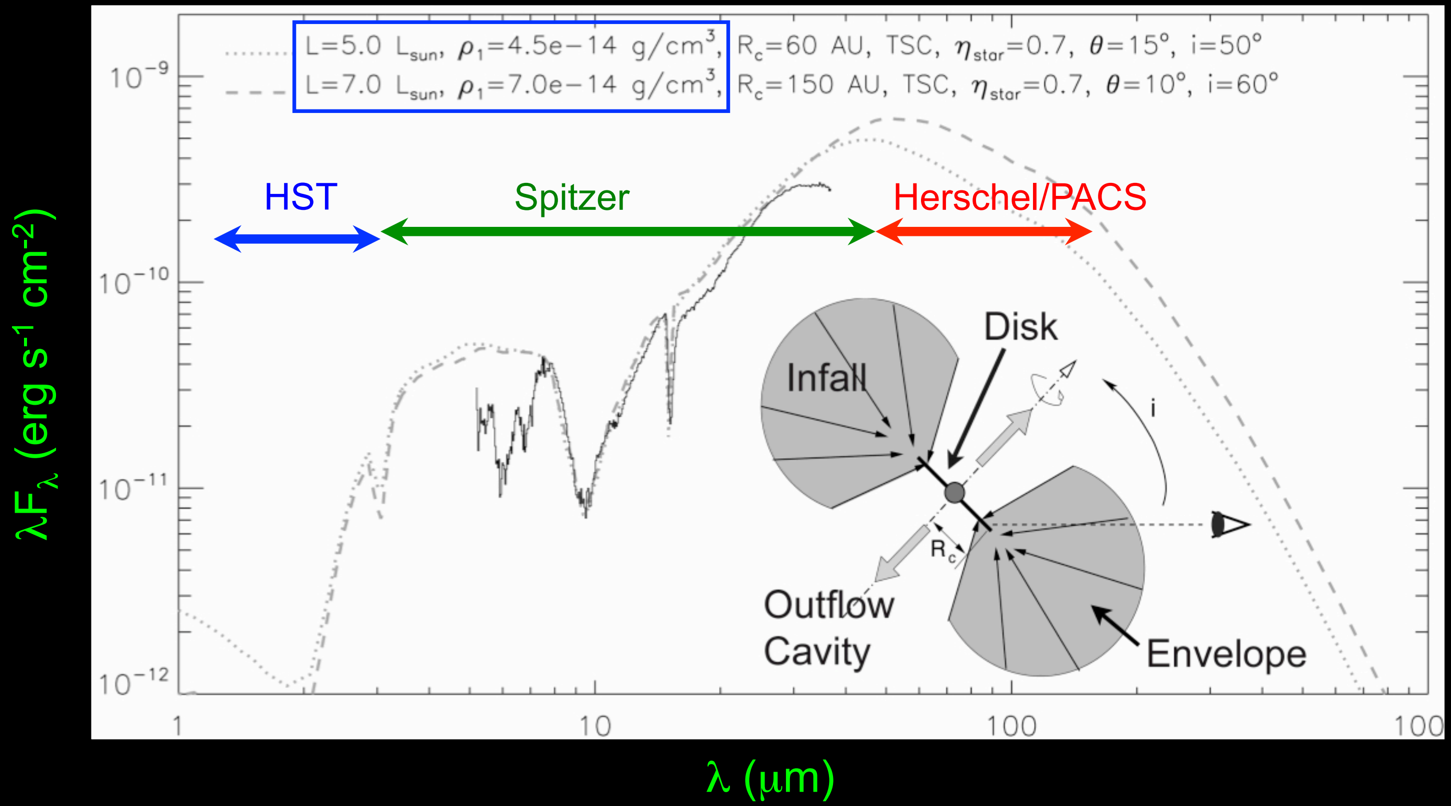
PACS spectroscopy of 37 protostars:

- 25 face-on sources, 12 at other inclinations
- Source fluxes from 100 mJy to ~10 Jy
- Spectral coverage from 57 to 185 μm
- Water, OH, CO, and [OI] (63 μm) lines

Sources sample environments
from isolated to clustered



Science Goals



Study a large sample of protostars in a single cloud with combined Herschel, Spitzer, Hubble and ground-based data

- Robustly determine protostellar envelope properties
- Determine the influence of initial conditions
- Examine the role of environment
- Study protostellar evolution with a large sample
- Measure disk accretion vs envelope infall rate

HOPS: a multi-observatory survey

of Spitzer identified protostars in Orion

- Spitzer IRAC & MIPS (Megeath et al.)
- Spitzer IRS: *SL-LL for all; LH for half the sample*
  - Detection of crystalline dust in a protostellar envelope (Poteet et al.)
  - Envelope-disk accretion in protostars (Sheehan et al.)
- Herschel PACS
  - Imaging: HH 1-2/NGC 1999 field (Fischer et al., Stanke et al. 2010)
  - Spectroscopy: HOPS 203 & HOPS 32 (Manoj et al.)
- NIR imaging & spectroscopy
  - HST (*NICMOS/WFC3*): multiplicity survey of HOPS targets (Kounkel et al.)
  - VLT *(NACO)*, NEWFIRM, PANIC (Megeath, Tobin, Allen et al.)
  - IRTF *(SPEX/NSFCAM2)* (Fischer, Megeath et al.)
- Submm & mm imaging
  - Apex (LABOCA & SABOCA), IRAM (Stanke, Maret et al.)
  - JCMT *(HARP)*: CO (3-2) & HCO+ (4-3) line mapping of HOPS targets (Di Francesco et al.)

CARMA: measuring various flow rates in protostars (Watson, Manoj et al.)

A sample of science results:

Detection of crystalline material in a protostellar envelope.

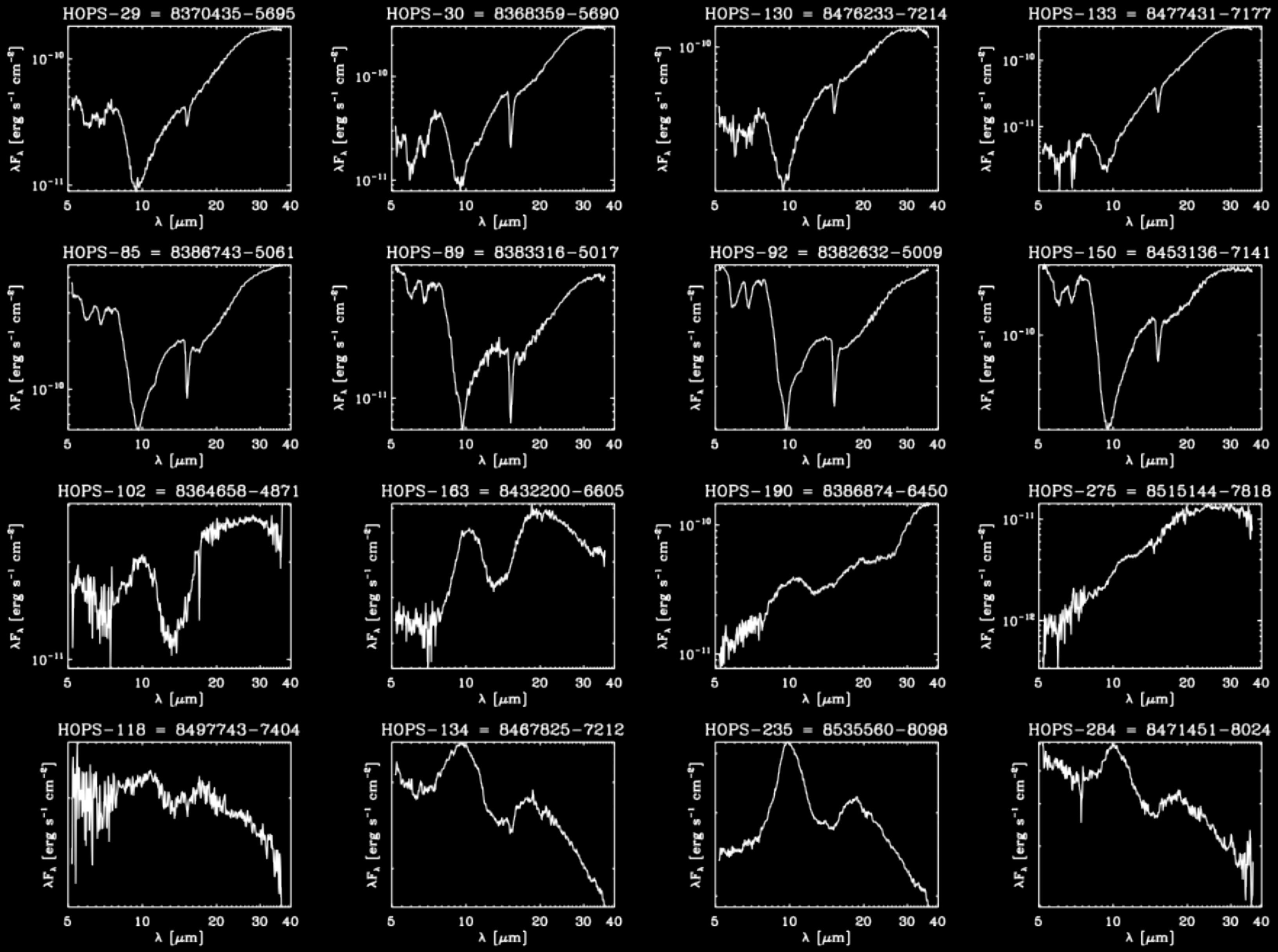
Identification of companions to HOPS protostars.

Modeling of protostars using 1.6-160 micron SEDs plus near-imaging.

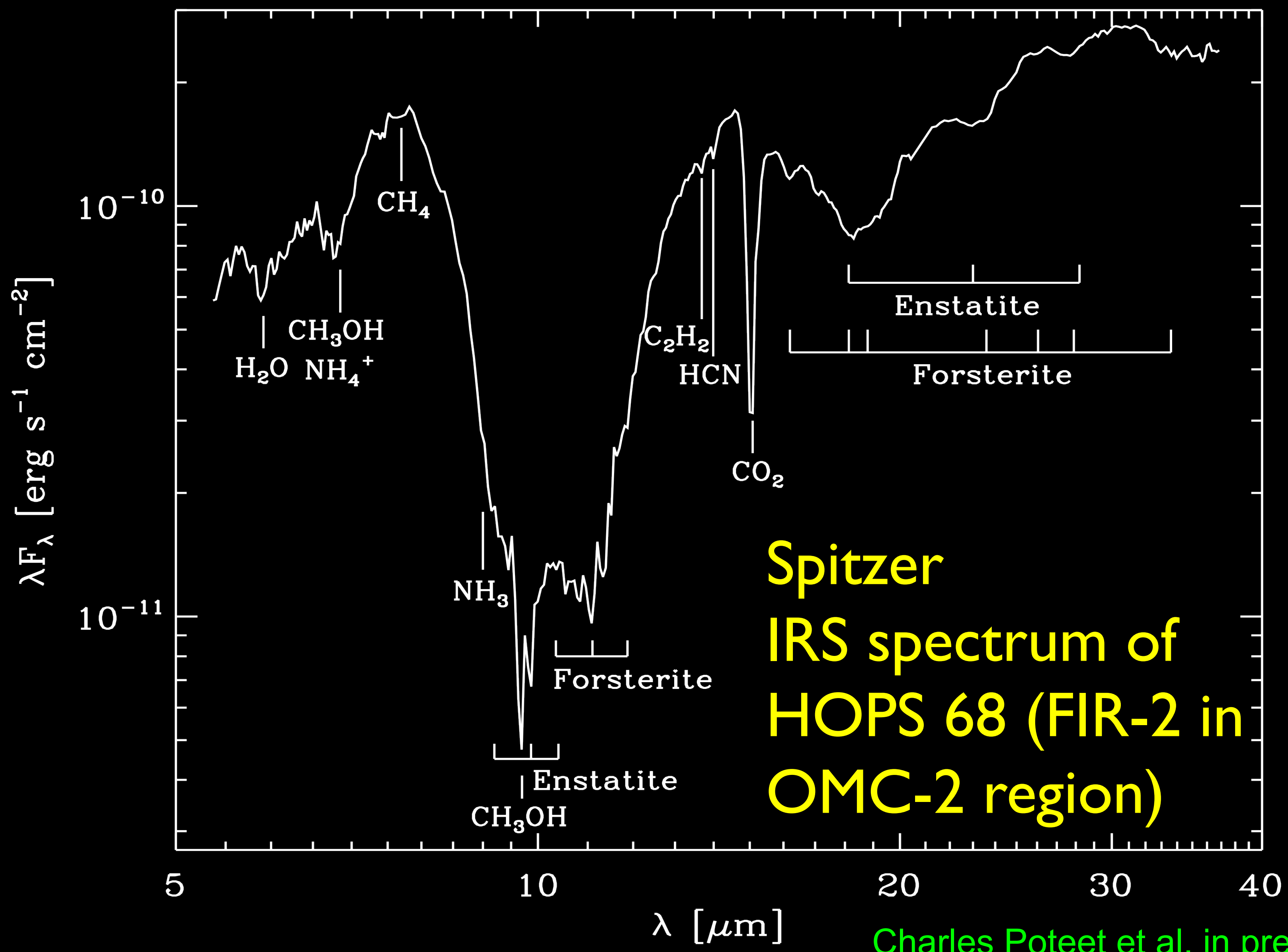
The detection of the “hole” in NGC 1999.

Far-IR spectra of the source of HH1-2.

Sample of IRS Spectra

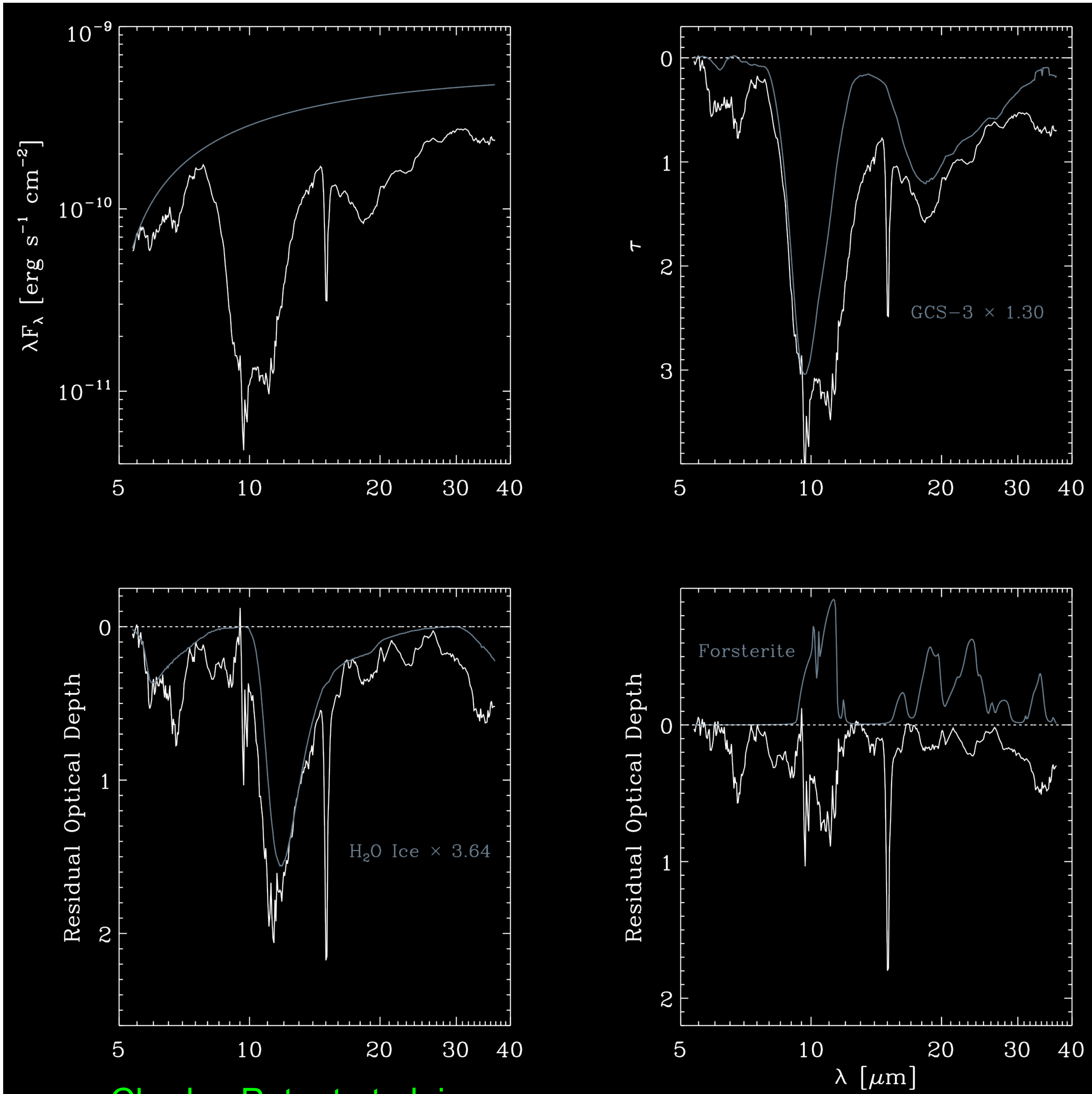


HOPS Science with the IRS: The Crystalline Protostar



Spitzer
IRS spectrum of
HOPS 68 (FIR-2 in
OMC-2 region)

Charles Poteet et al. in prep.



Charles Poteet et al. in prep.

Identification of Forsterite (Mg_2SiO_4) in HOPS 68

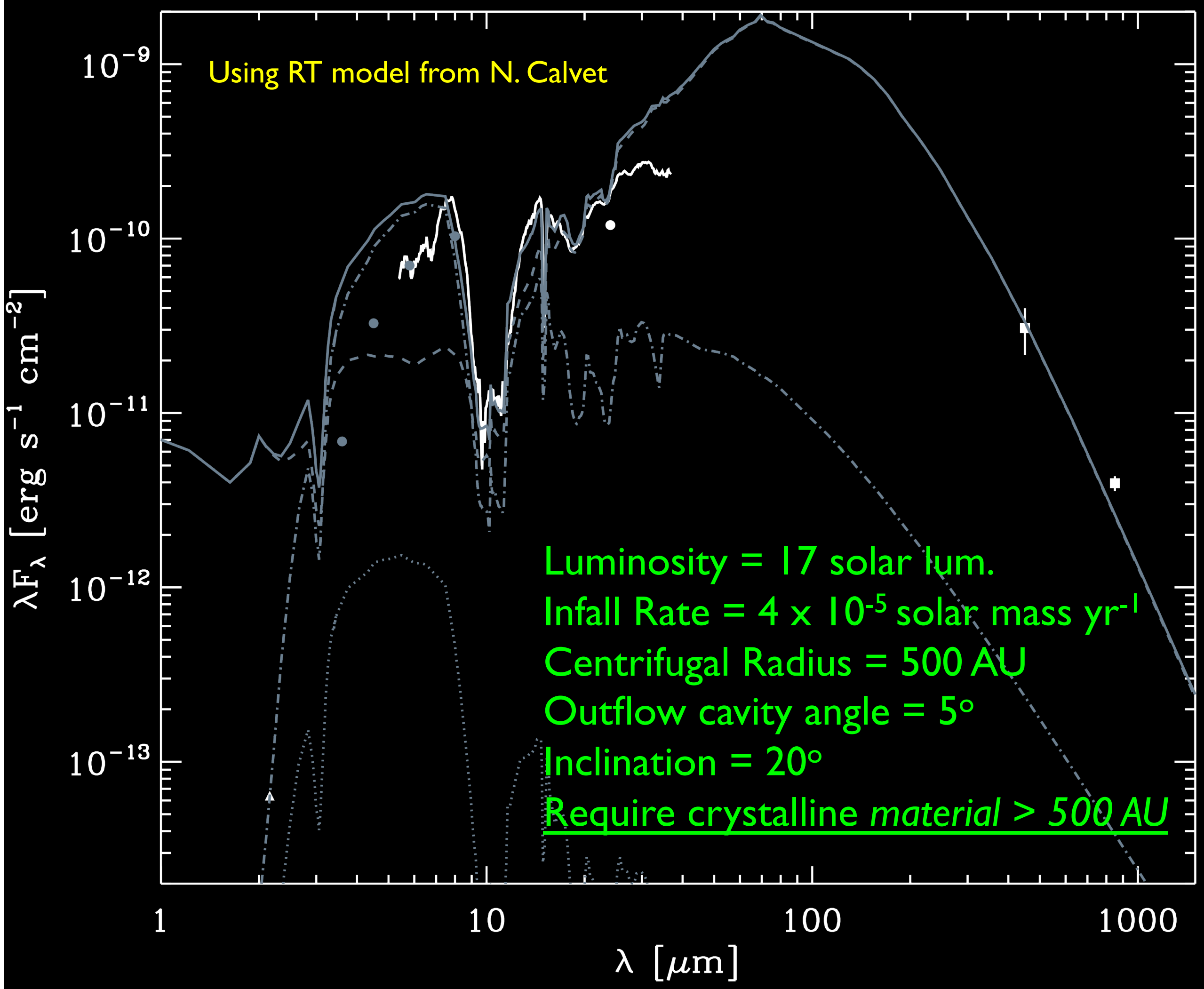
Once amorphous silicates and water ice is subtracted, remaining features matched by Forsterite plus other ices.

Abundance of crystalline Fosterite relative to amorphous silicates:

0.16 - 0.27

(depending on method)

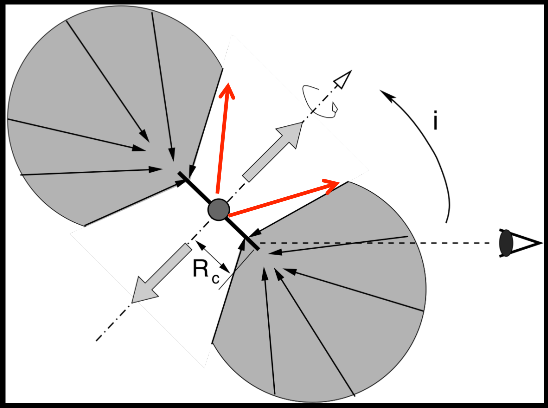
The Abundance of Forsterite in HOPS 68



Using RT model from N. Calvet

Luminosity = 17 solar lum.
Infall Rate = 4 x 10^{-5} solar mass yr^{-1}
Centrifugal Radius = 500 AU
Outflow cavity angle = 5°
Inclination = 20°
Require crystalline *material > 500 AU*

Charles Poteet et al. submitted

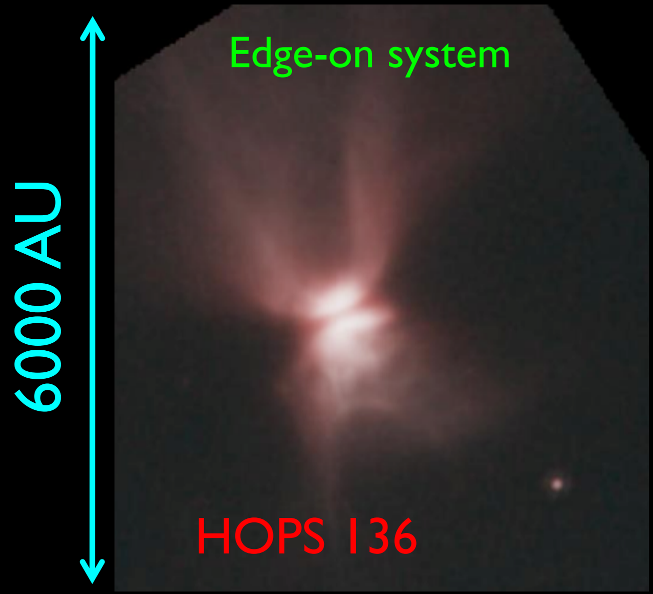


Temperatures of 900 K needed to anneal grains

Forsterite commonly seen in emission toward Class II sources but very rare in absorption toward Class 0/I.

We suggest that crystalline material is formed in disk and transported to envelope by winds.

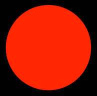
HOPS Science with the HST:
NICMOS 1.60 and 2.05 micron Imaging of HOPS Protostars



6000 AU

Edge-on system

HOPS 136



Spitzer beam

The “ring” protostar (outflow cavity)

HOPS 204

Marina
Kounkel et al.
in prep.

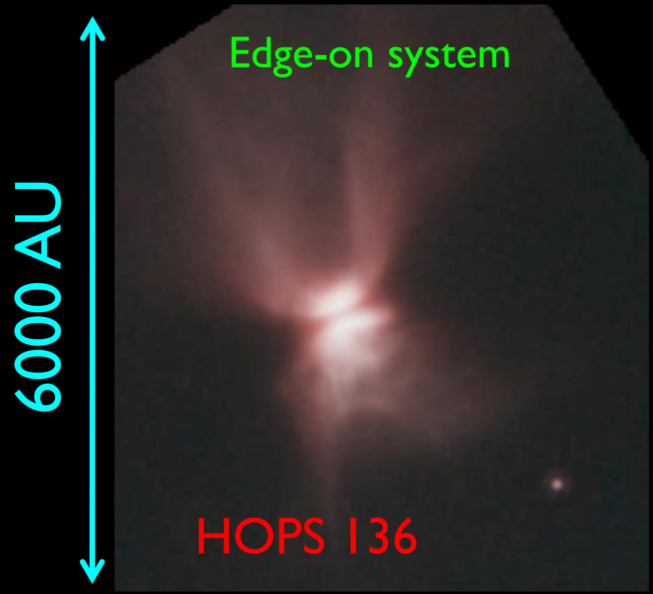
Binary

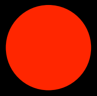
HOPS 189

Multiple System

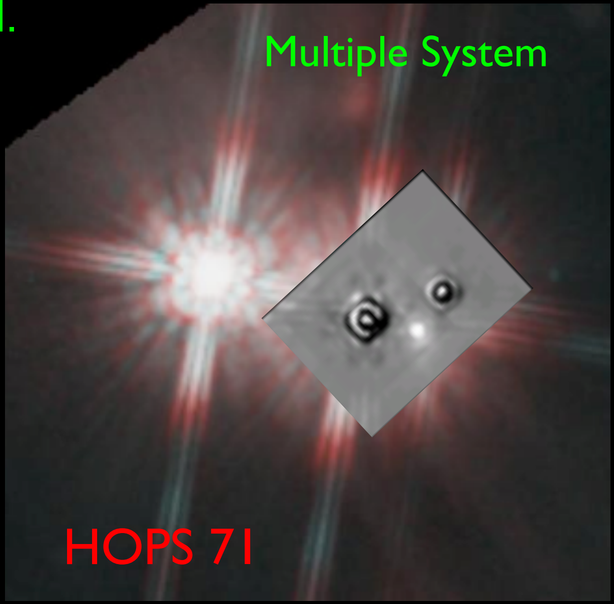
HOPS 71

HOPS Science with the HST:
NICMOS 1.60 and 2.05 micron Imaging of HOPS Protostars

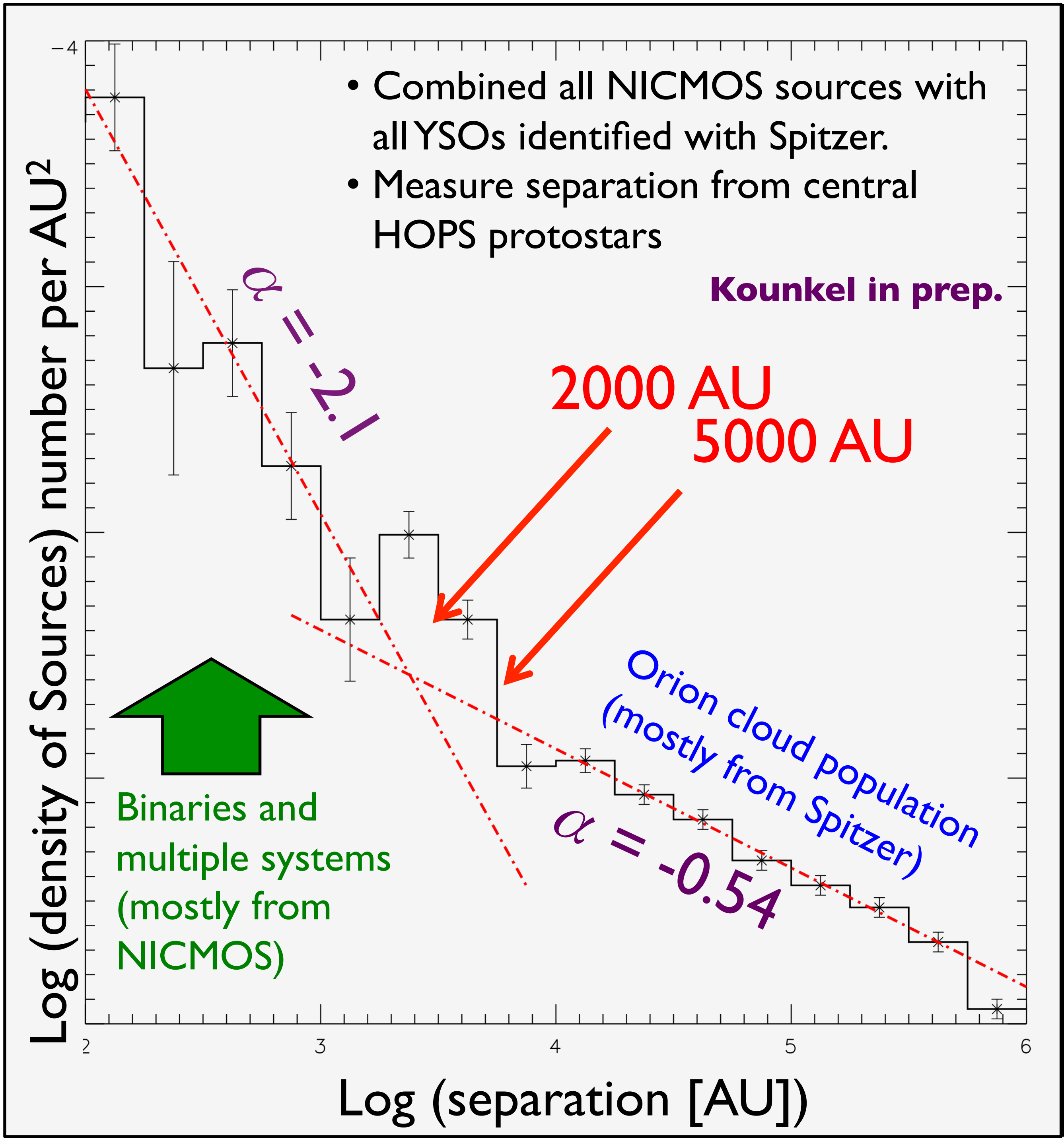




Marina
Kounkel et al.
in prep.



Stellar Density vs. Separation from HOPS Protostars



- Combined all NICMOS sources with all YSOs identified with Spitzer.
- Measure separation from central HOPS protostars

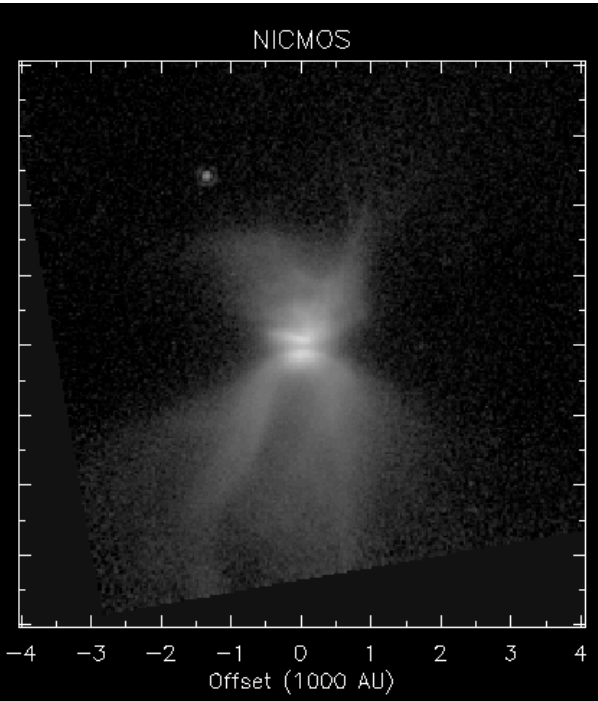
Kounkel in prep.

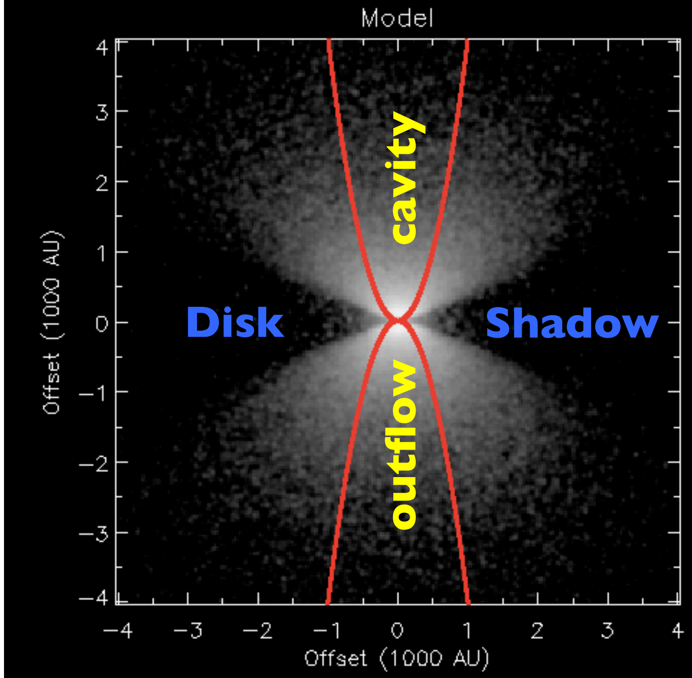
Out of 72 protostars, 33 companions are found within 5000 AU

Companion star fraction slightly higher (but consistent) withfield G-star binary fraction.

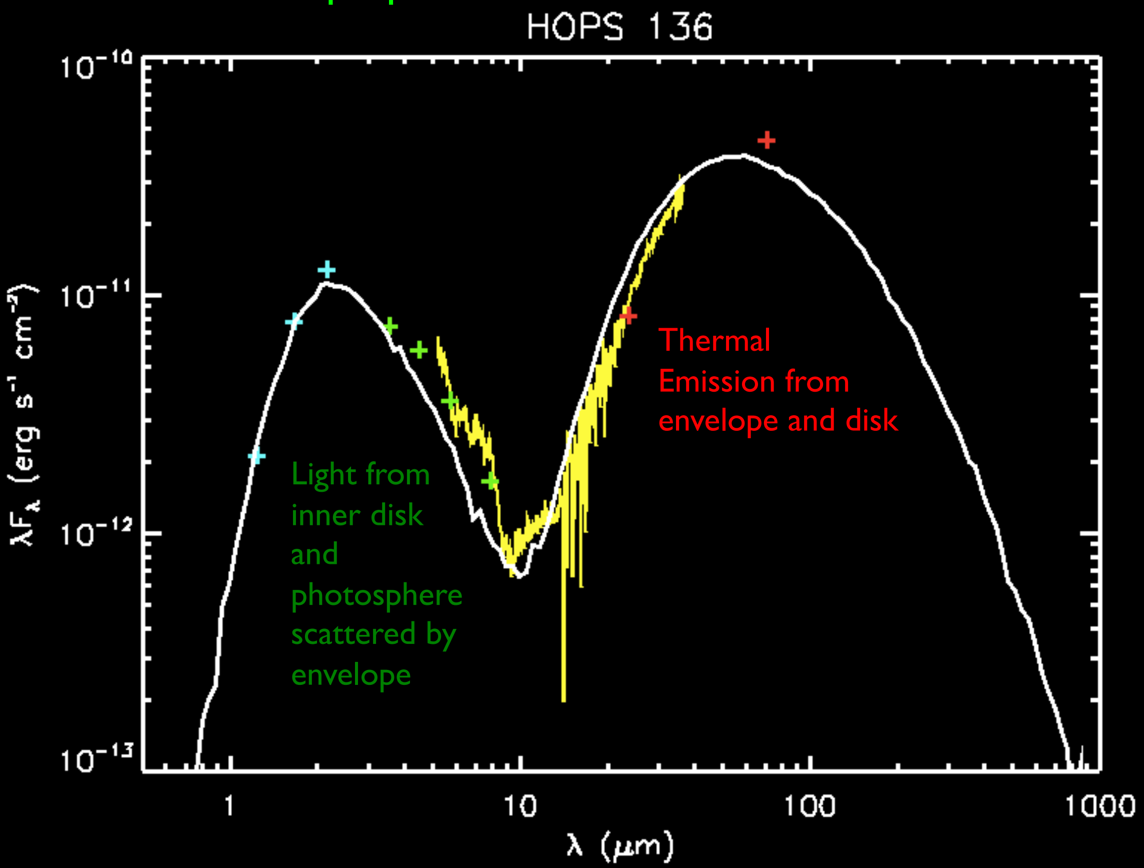
Power-law for companions similar to Taurus (Larson1995) and Ophiuchus (Allen et al 2002.)

HOPS 136: A Case Study of an Edge-on Protostar





Fischer et al. in prep.



Light from inner disk and photosphere scattered by envelope

Thermal Emission from envelope and disk

Luminosity = 3.8 solar lum.

Mass infall = 3×10^{-7} solar masses per year

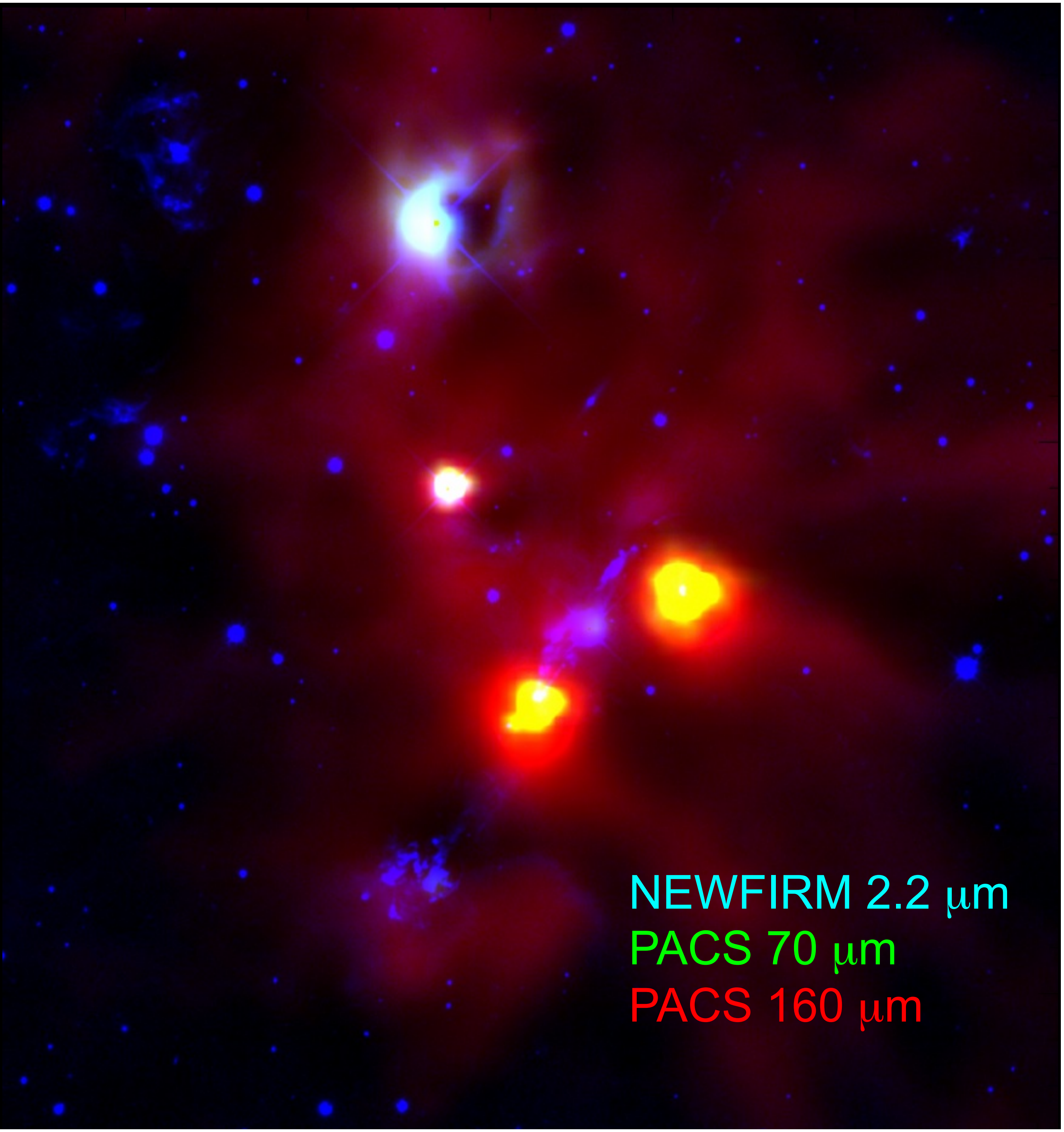
Rc = 500 AU

Inclination = 90° (opposed to 81° from Robitaille fitter)

Science with Herschel: the HOPS Science Demo Field

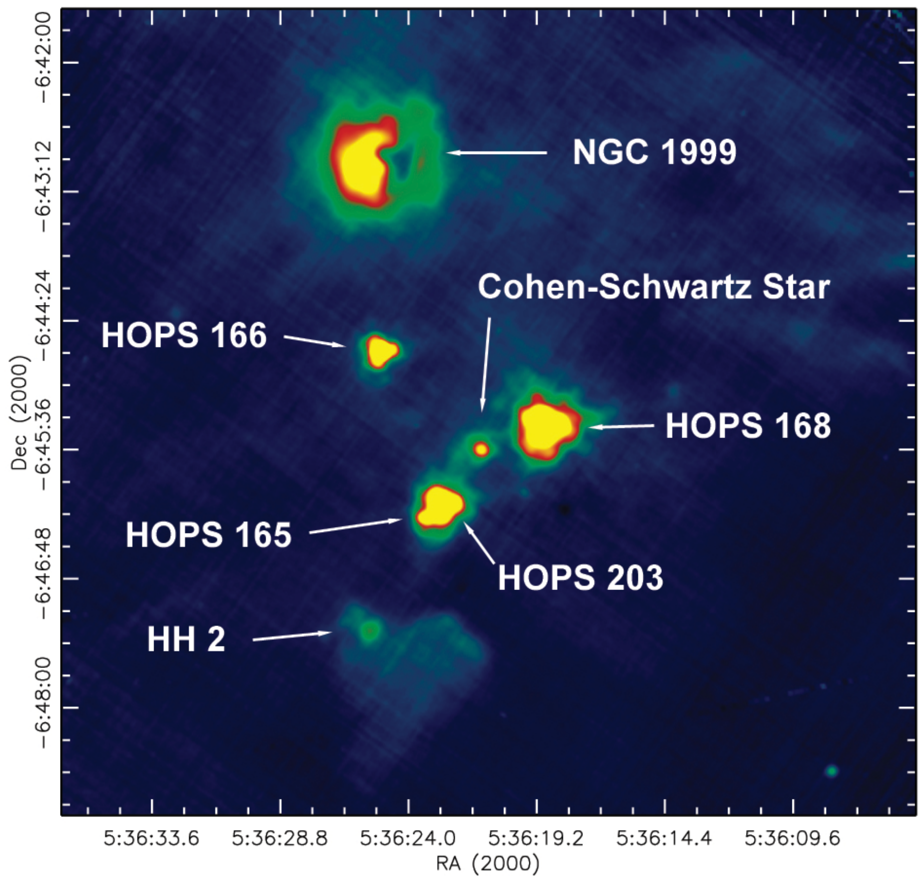
V380 Ori / HH 1-2 region in L1641

8’ square field centered at $5^{h}36^{m}22.1^{s}$, $-6^{o}45’41”$

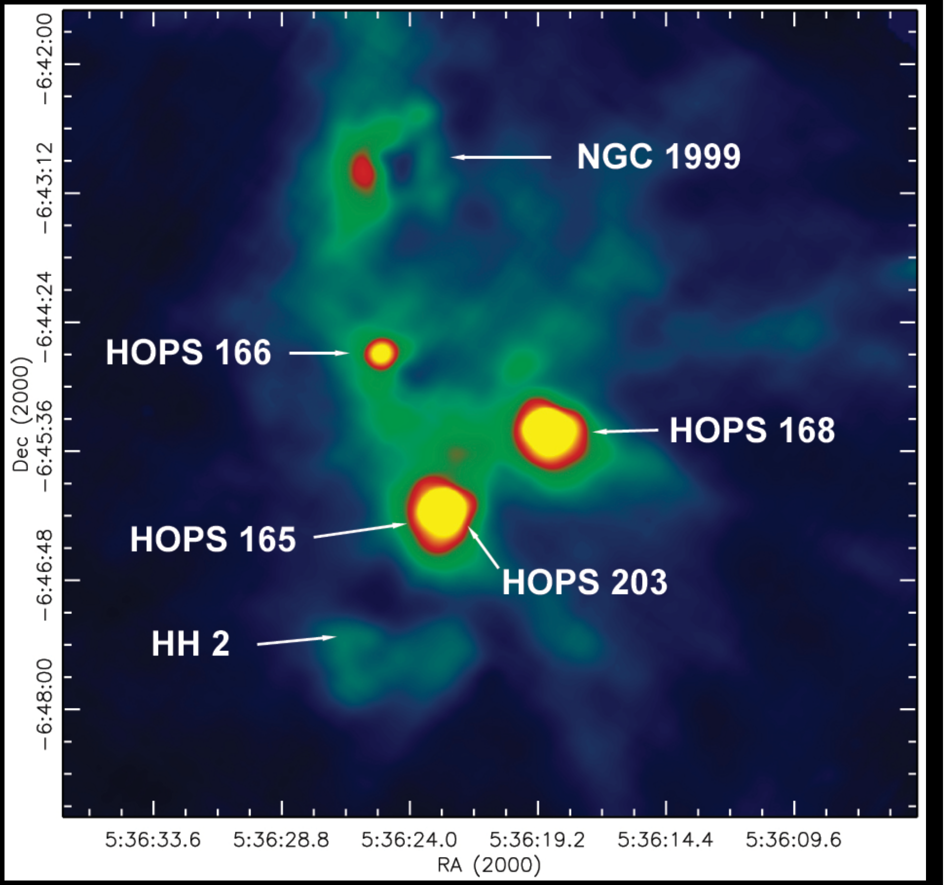


PACS Images

70 μm



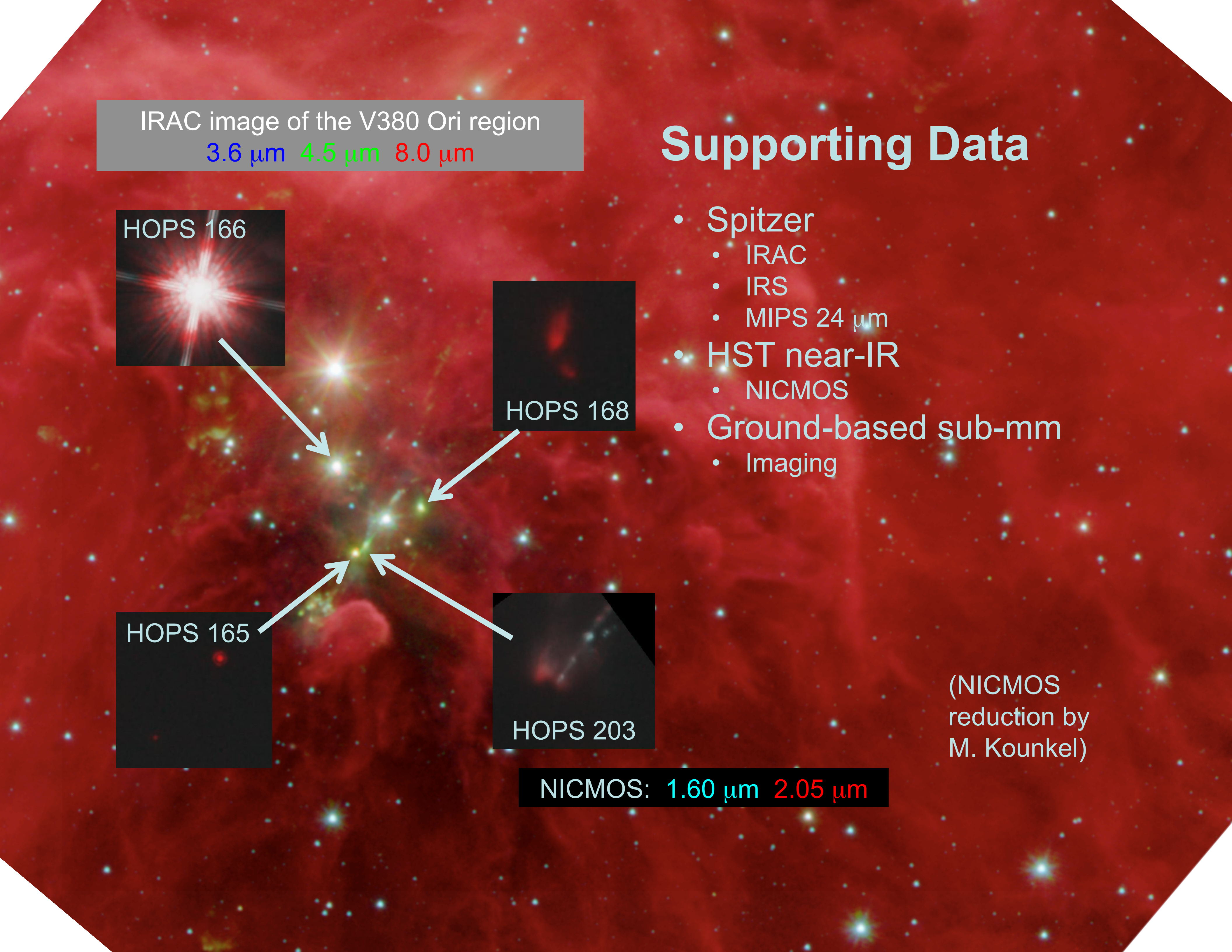
160 μm



(Reduction by B. Ali)

Supporting Data

- Spitzer
  - IRAC
  - IRS
  - MIPS 24 µm
- HST near-IR
  - NICMOS
- Ground-based sub-mm
  - Imaging

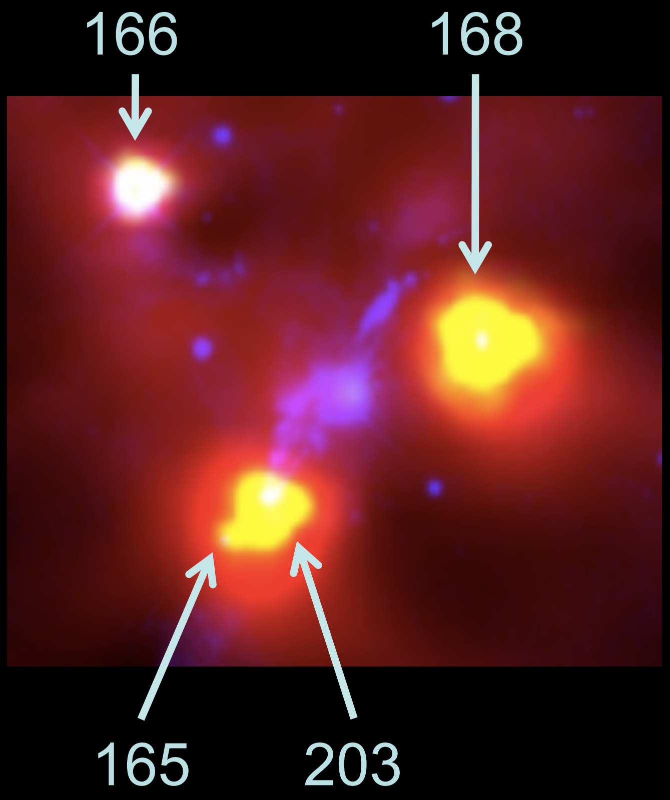


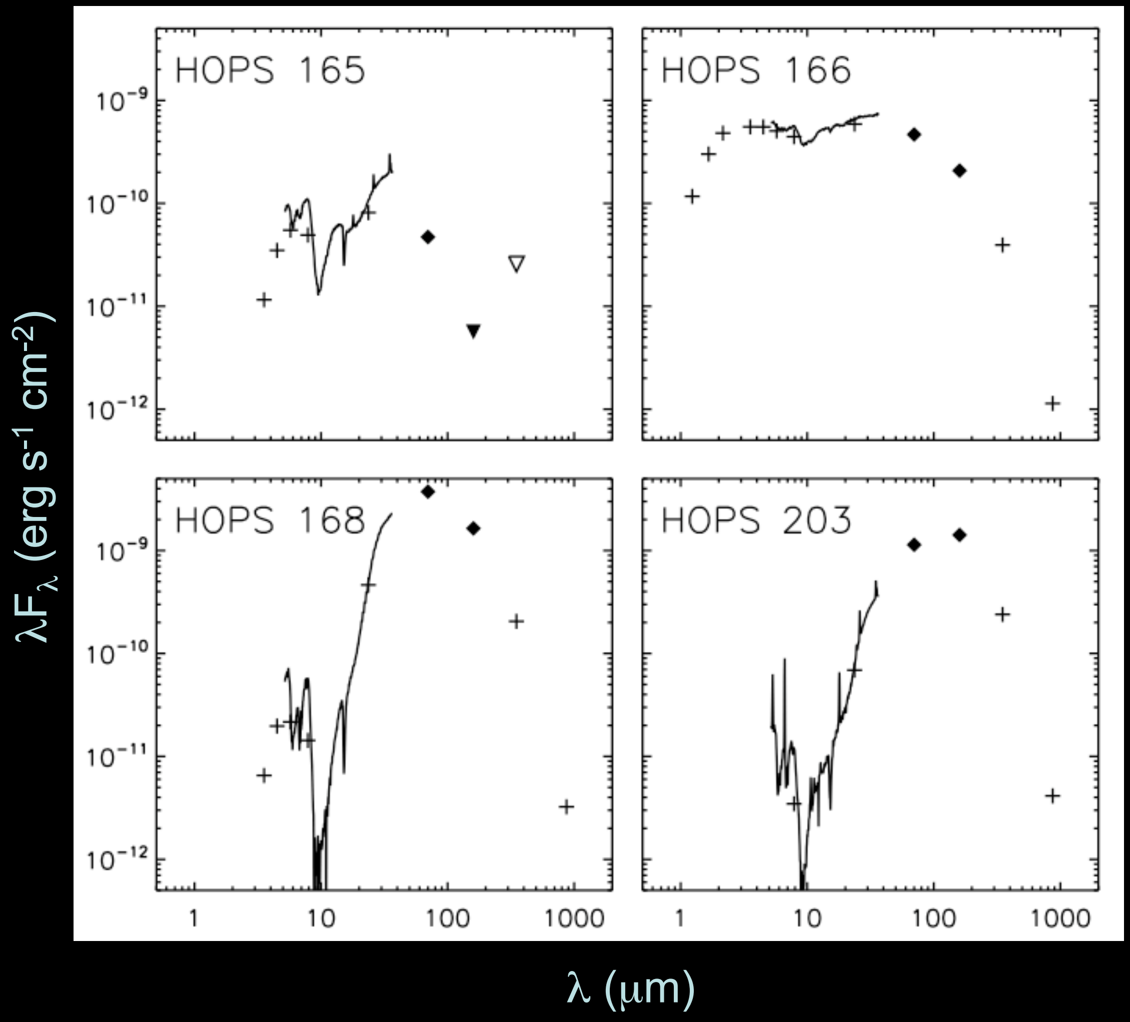
(NICMOS reduction by M. Kounkel)

Protostellar SEDs

(Fischer et al. 2010, A&A special issue)

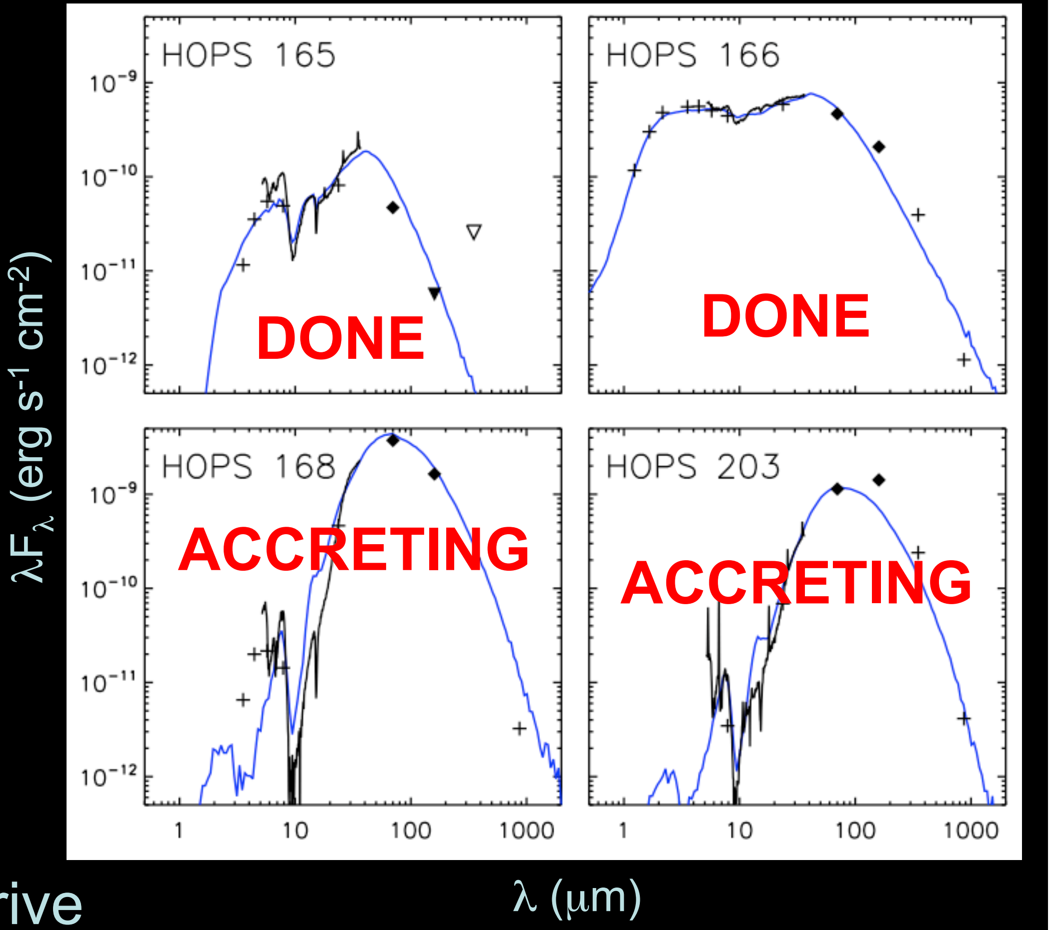
Construct SEDs from
2MASS, Spitzer, Herschel, APEX





SED Modeling

	L (L_{sun})	dM_{env}/dt (M_{sun}/yr)	L_{acc} / L
165	12	2 x 10^{-7}	0.1
166	23	4 x 10^{-7}	0.2
168	84	3 x 10^{-5}	~ 1
203	23	2 x 10^{-5}	~ 1

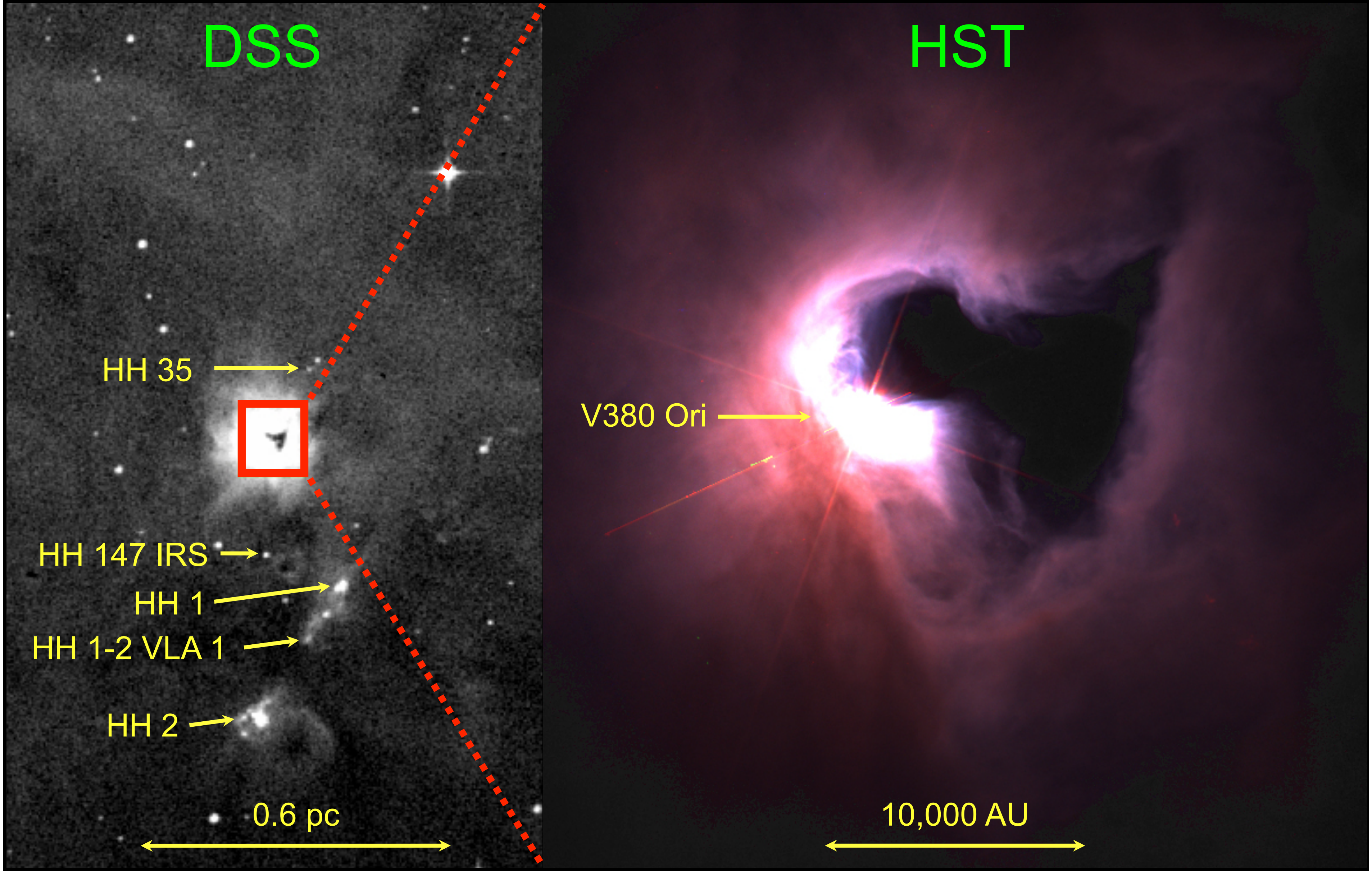


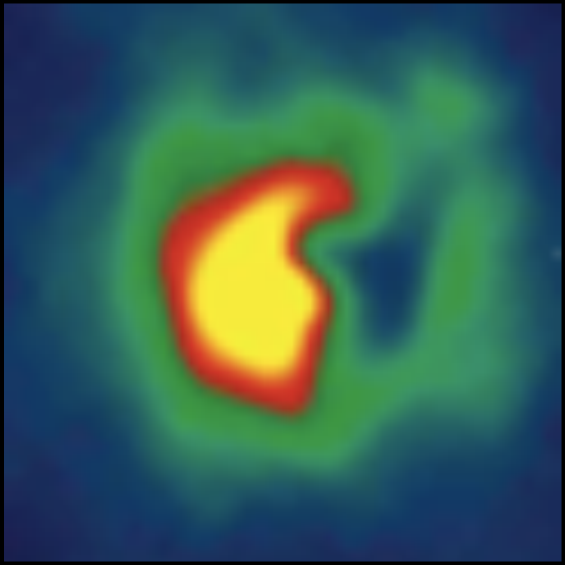
(Fischer et al. 2010, A&A special issue)

- Modeled SEDs with B. Whitney's RT code
- Key parameters
  - Luminosity
  - Envelope density
- With stellar parameters, derive
  - Envelope infall rate
  - Accretion luminosity
- HOPS 168, 203: $dM_{disk}/dt = dM_{env}/dt$ implies $M_{star} \sim 0.1\ M_{sun}$
  - Episodic accretion would allow larger masses

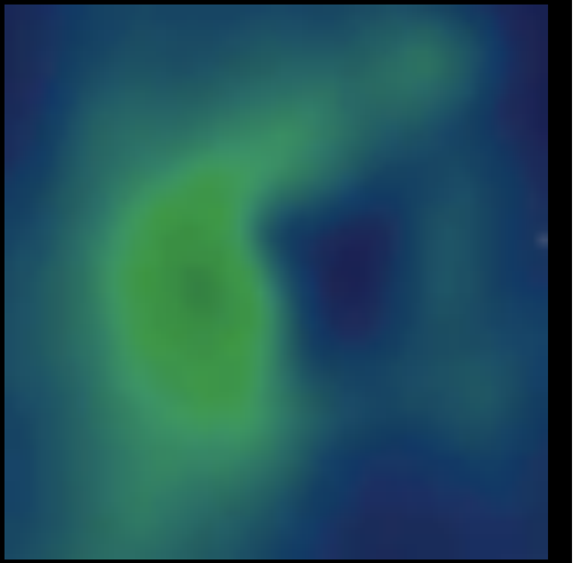
NGC 1999

(Stanke, Stutz, Tobin et al. 2010, A&A special issue)





PACS 70 μm



PACS 160 μm

- The region remains dark at 70 and 160 μm: a far-IR dark cloud?
- Mass responsible for the flux decrement is wavelength-dependent!? (A. Stutz)
  - ~ 0.1 M_{sun} at 70 μm
  - ~ 2.5 M_{sun} at 160 μm

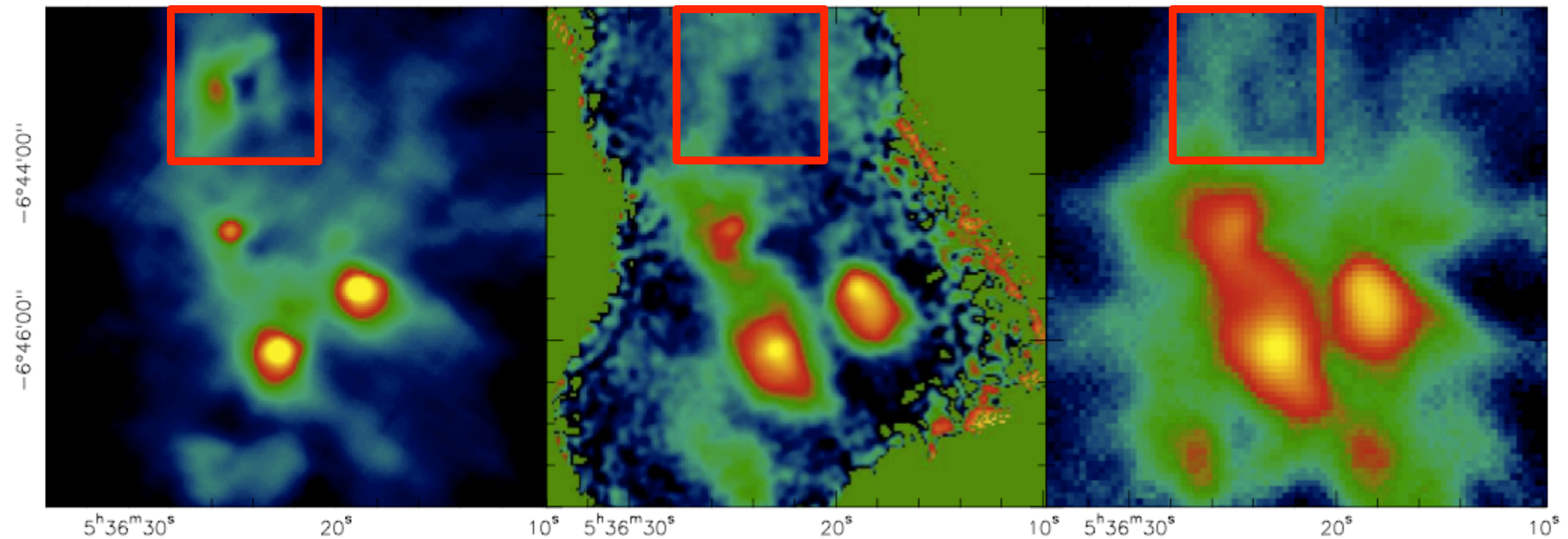
$$\tau = -\ln [(f + f_{BG}) / (f_0 + f_{BG})]$$

- Obtained ground-based follow-up

(Stanke, Stutz, Tobin et al. 2010, A&A special issue)

APEX

PACS 160 μm SABOCA 350 μm LABOCA 870 μm

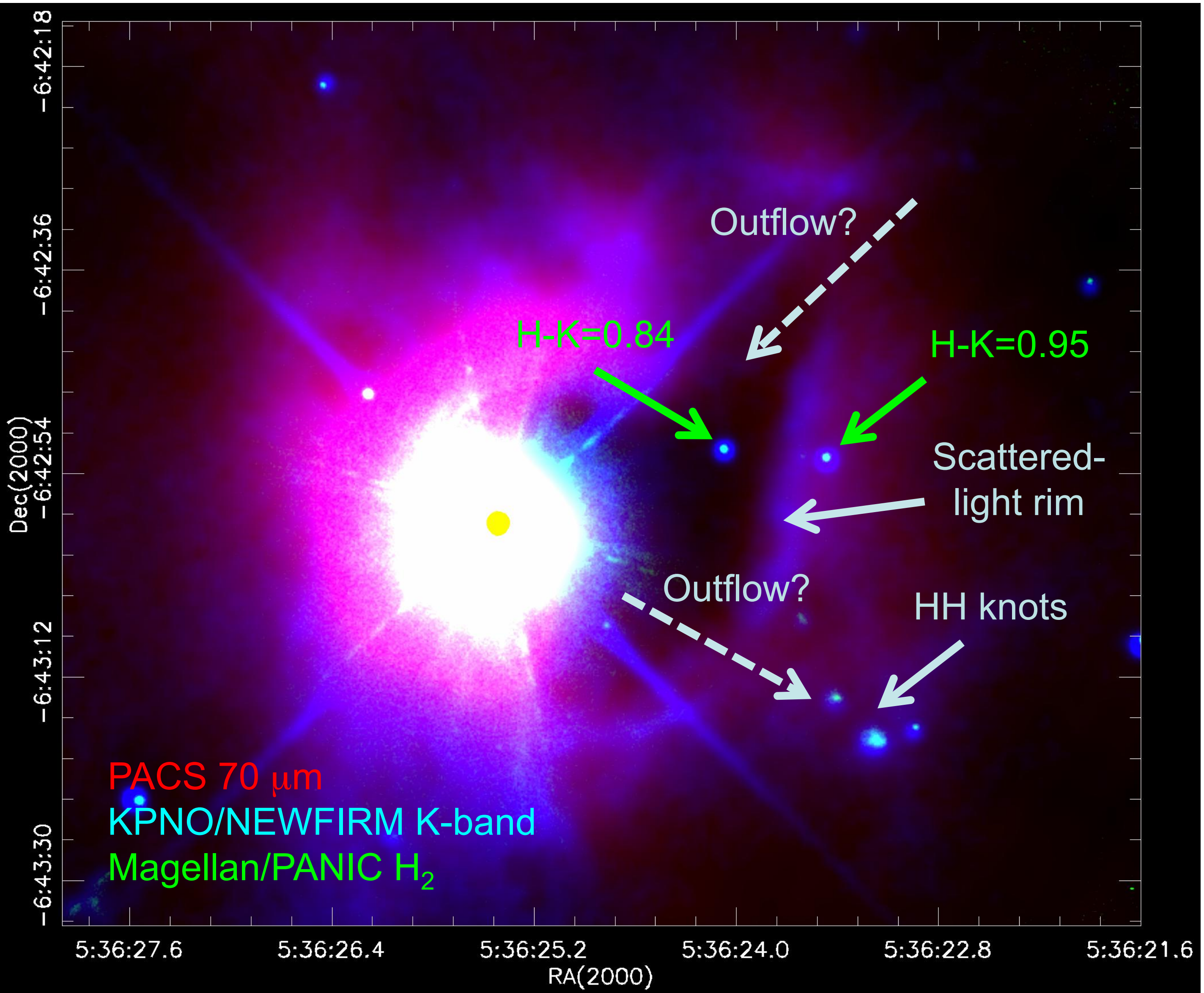


- IR dark cloud should be bright in sub-mm
  - Not detected
  - SABOCA (350 μm) upper mass limit: 2.4 x 10^{-2} M_{sun}

(Stanke, Stutz, Tobin et al. 2010, A&A special issue) (T. Stanke, ESA DDT)

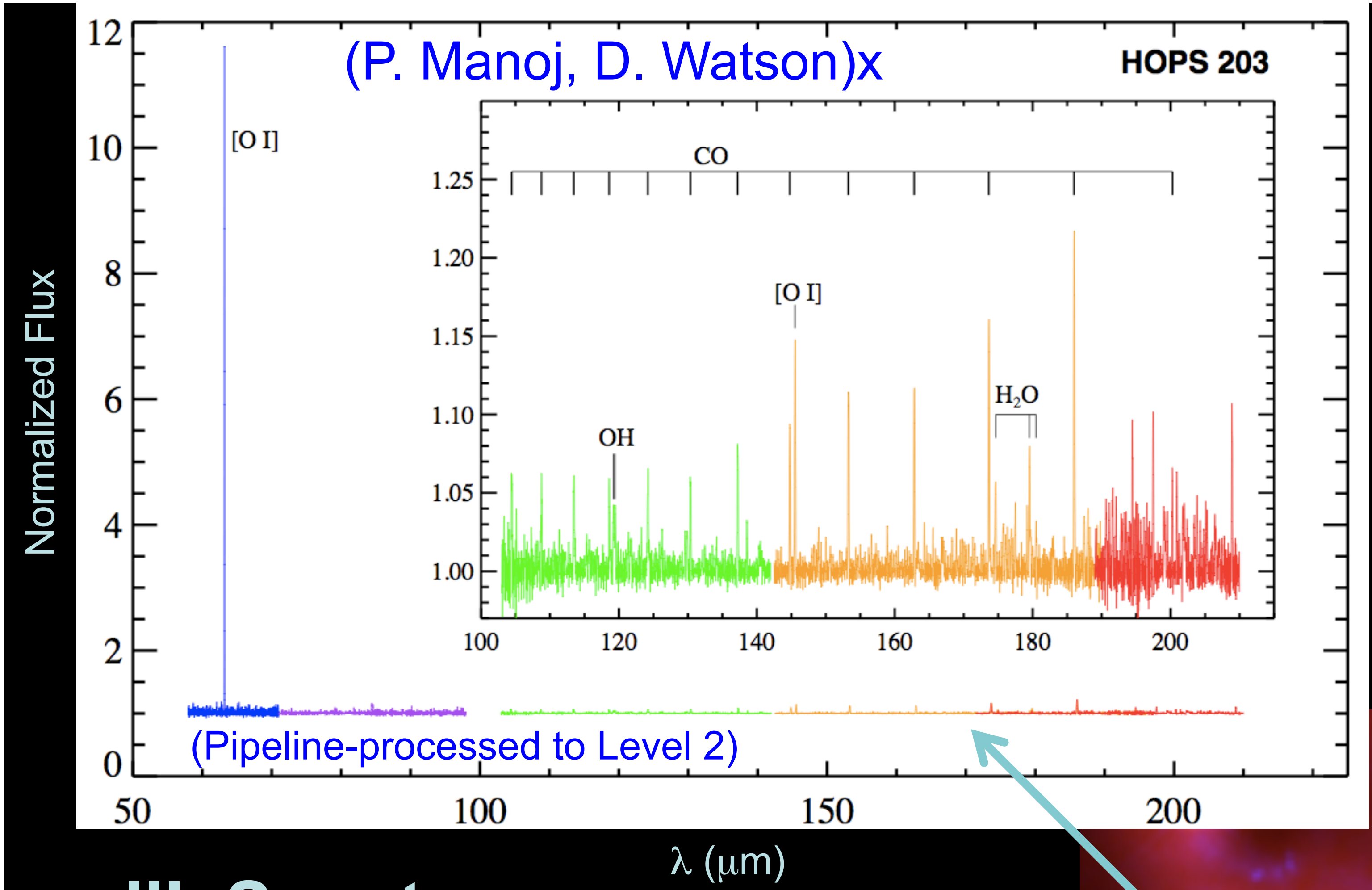
Near IR

(J. Tobin,
L. Allen,
E. Kryukova)



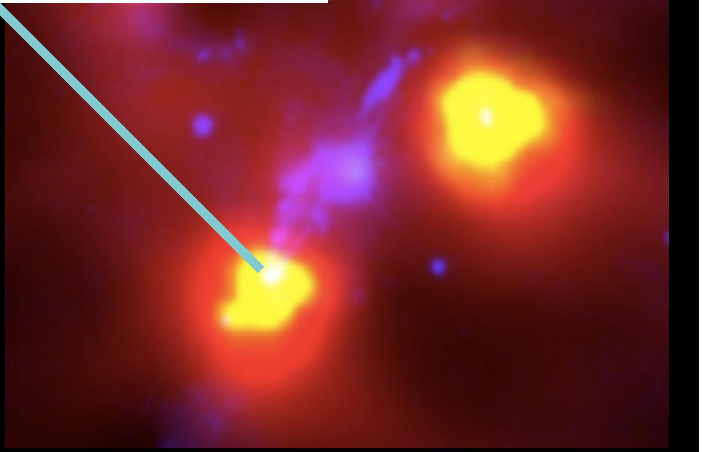
- H-K colors of stars imply A_V~10, not 100
- H-K colors of stars inside the dark patch are bluer than those of stars outside the patch
- This is not a dark cloud but a genuine *hole in the nebula* -- Carved by outflows?

(Stanke, Stutz, Tobin et al. 2010, A&A special issue)



(P. Manoj, D. Watson)x

(Pipeline-processed to Level 2)



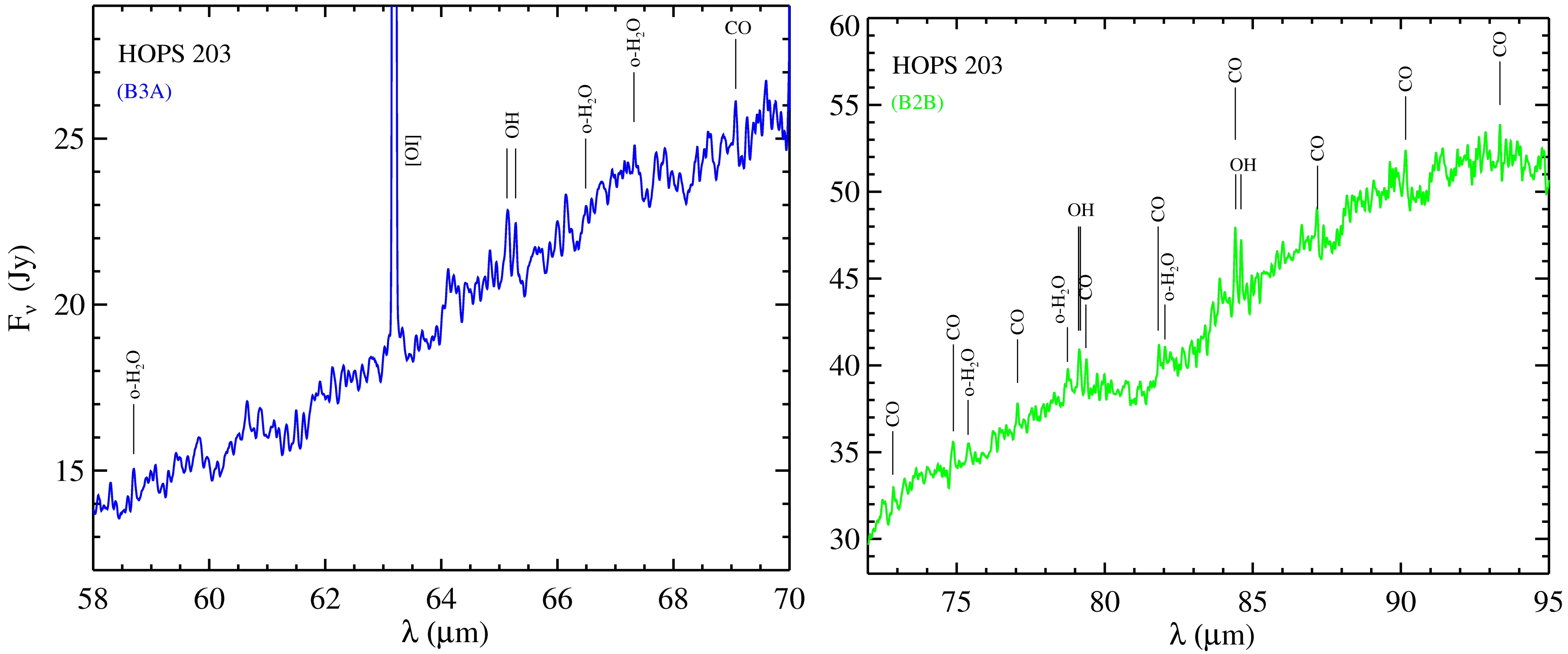
III. Spectra

- PACS spectra have recently been acquired for HOPS 203
- Strongest lines appear to form in outflow shocks from HH 1-2

HOPS 203 spectrum: P. Manoj

FS lines : [OI] @ 63.18 & 145.52 μm

Molecular lines: H_2O, OH & CO



HOPS 203 spectrum: P. Manoj

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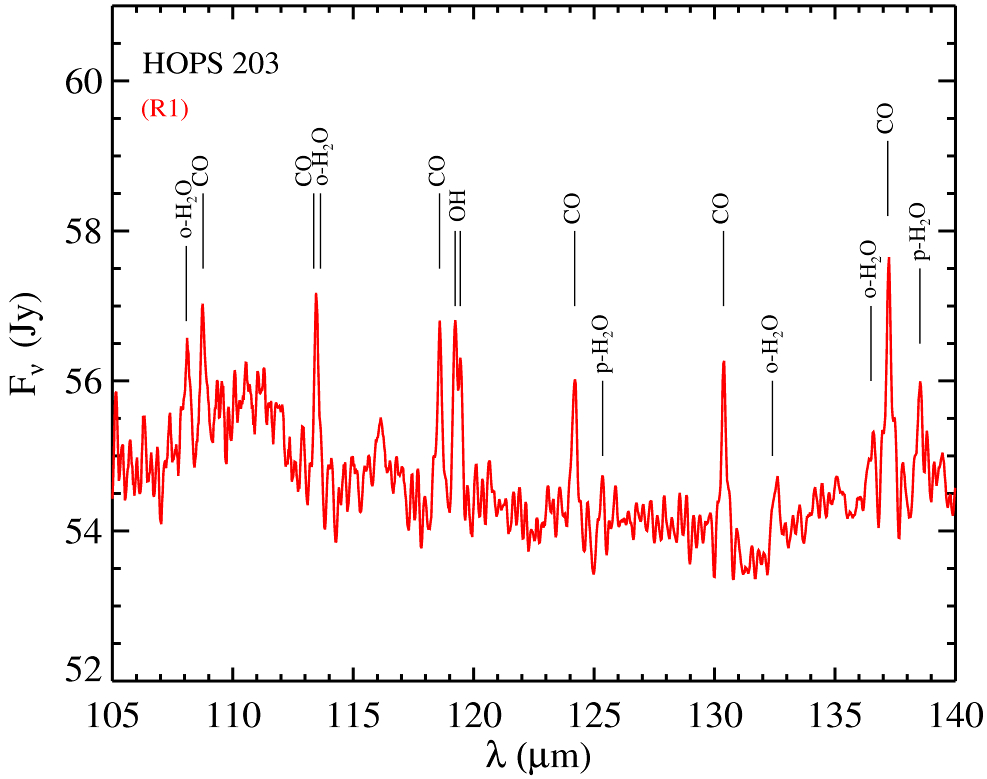
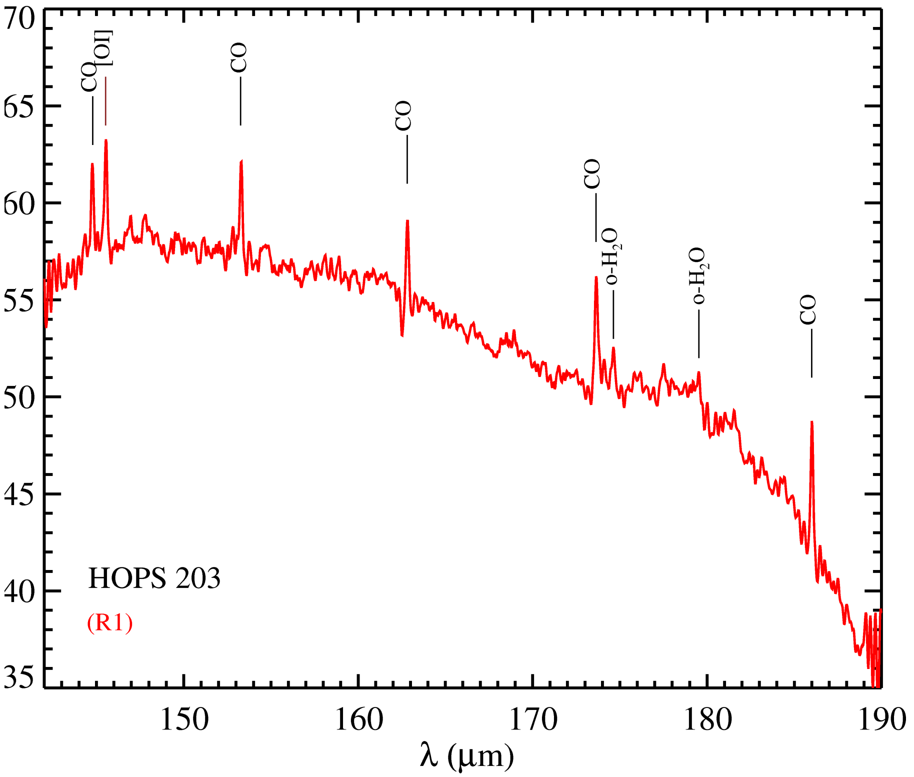
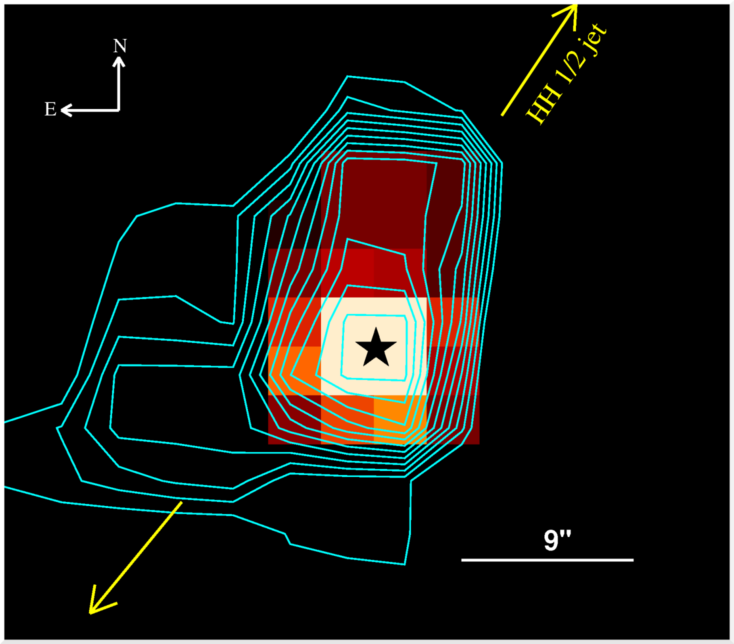


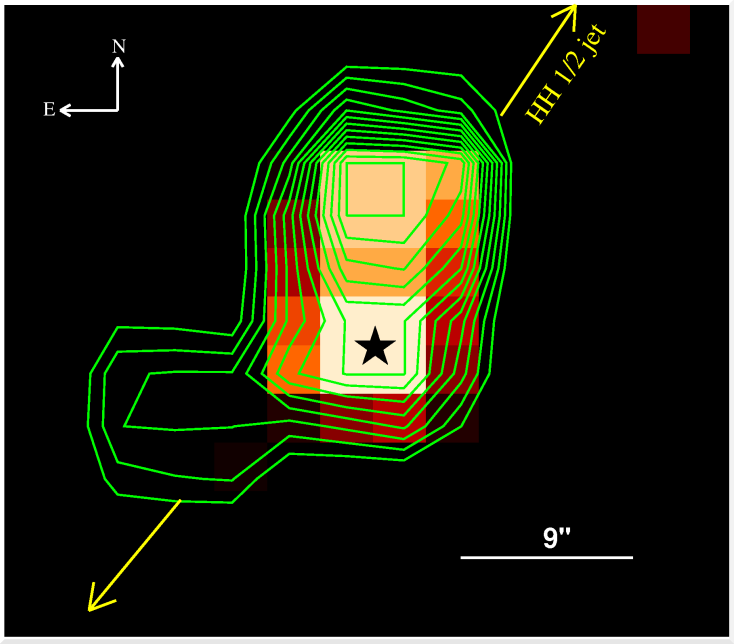


HOPS 203: [O I] & CO emission: P. Manoj

CO (14-13) contours + 160 µm continuum

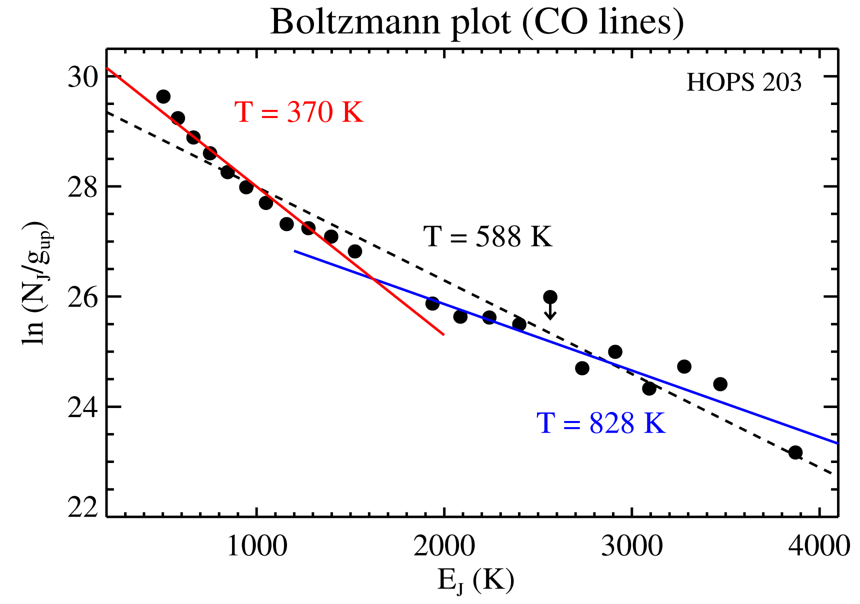


[O I] 63 µm contours + 70 µm continuum

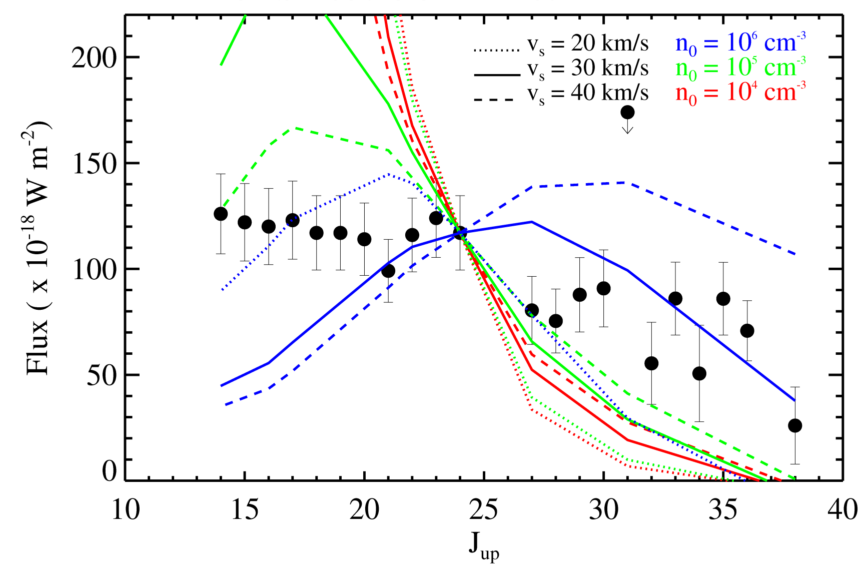


- [O I] peak is offset from CO & continuum peak
- [O I] emission from J-shocks which decelerate the jet
- CO emission from C-shocks / UV-heating

HOPS 203: CO lines: Preliminary



- multiple components of CO emitting gas at different temperatures



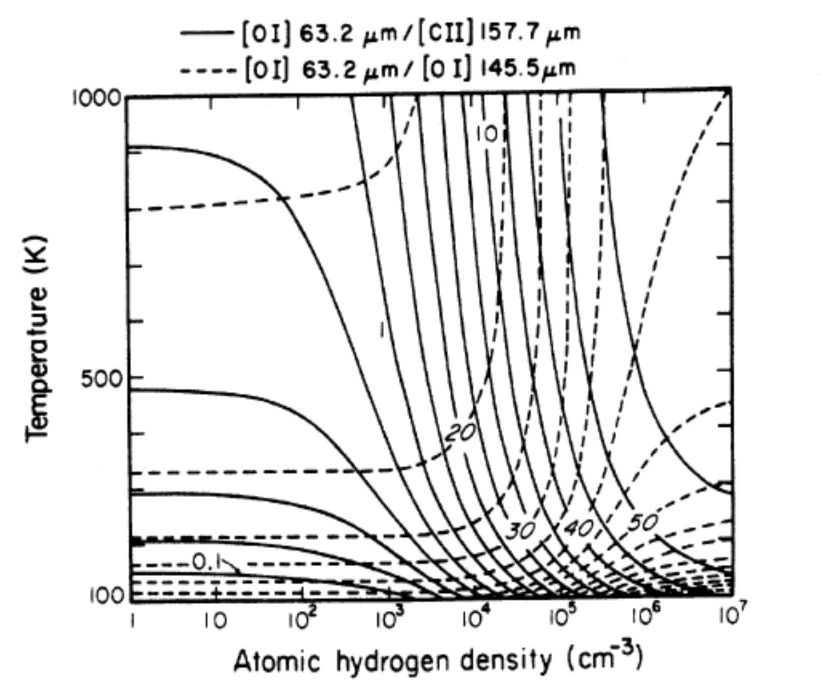
- C-shock models (Kaufman & Neufeld 1996)
- no single shock model can reproduce observed CO emission over a large enough range of J_{up}
- preshock density ~ 10^6 cm^{-3} ??
- slow & fast C-shocks + UV- heating or passively heated component for the lowest-J lines

HOPS 203: [O I] lines

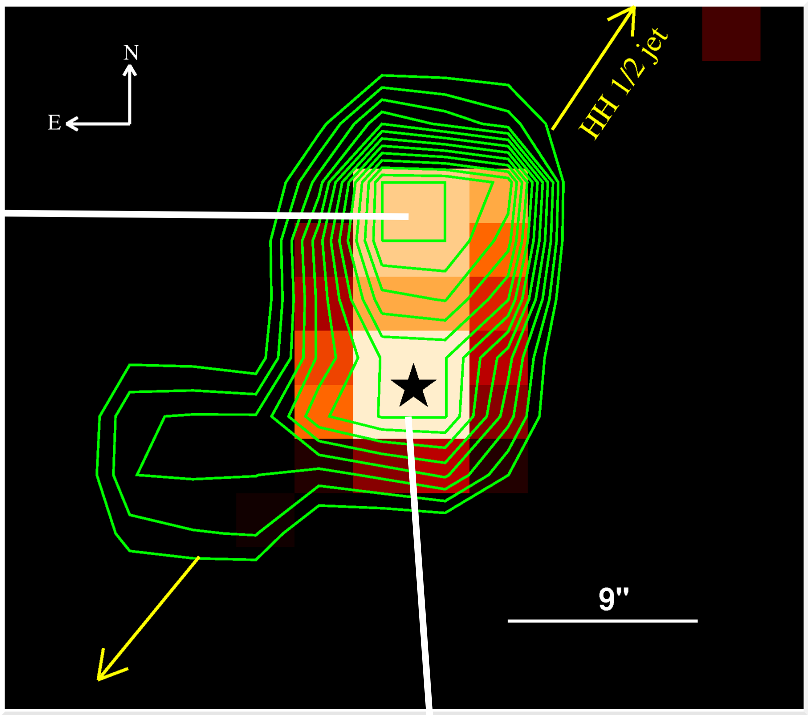
[O I] in J-shocks Þ T > 1000 K

$$\frac{[O\ I]63\ \square m}{[O\ I]145\ \square m}=41$$

postshock density ≥ 10^6 cm^{-3}



Watson (1984)



$$\frac{[O\ I]63\ \square m}{[O\ I]145\ \square m}=26$$

postshock density ~ 10^5 cm^{-3}

Summary

- Detection of Crystalline Silicates in one Orion protostar: may suggest the transport of grains from the inner disk into the envelope
- Identified companions to targeted protostars, 33 companions out of the 73 protostars imaged with NICMOS
- Near-IR Imaging plus SEDs is a powerful means for modeling (example edge-on source)
- PACS imaging of two of the four protostars in the V380 Ori region are actively accreting from their envelopes, while two have only residual envelopes
- The NGC 1999 “dark globule” is really a cavity in the cloud carved by outflows
- PACS spectroscopy detected [OI], CO and H_2O Far-IR lines toward the source of the outflow HH ½.