Unraveling the Evolution of Protostars in Diverse Environments: The Herschel Orion Protostar Survey

Will Fischer
(U.Toledo)

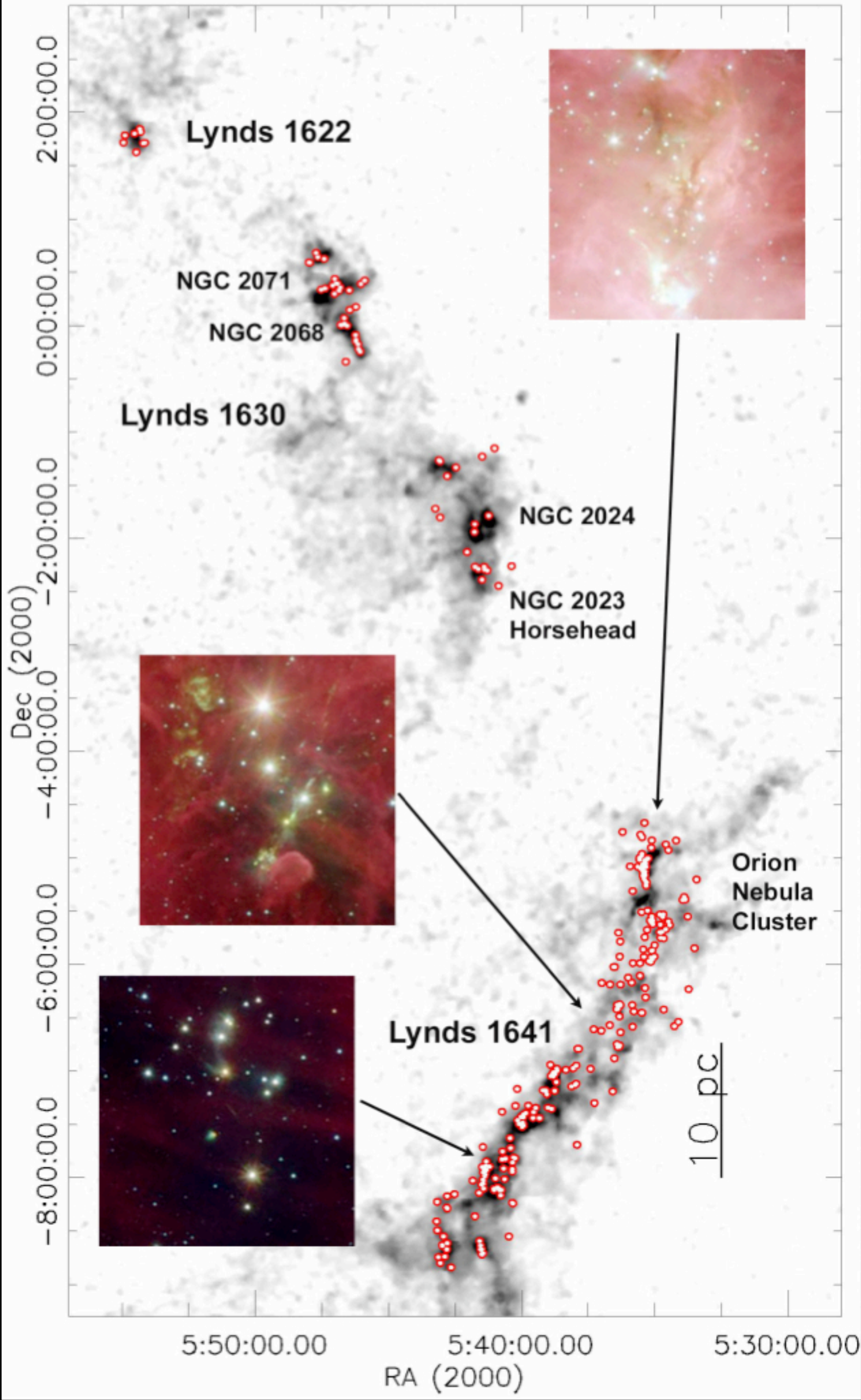
Tom Megeath (HOPS PI; U.Toledo)
Amy Stutz (MPIA)
John Tobin (NRAO)
Babar Ali (NHSC)
Thomas Stanke (ESO)
Mayra Osorio (IAA)
Elise Furlan (NHSC/NOAO)
Marina Kounkel (U.Michigan)
Lori Allen (NOAO)
Nuria Calvet (U.Michigan)
Lee Hartman (U.Michigan)
Charles Poteet (RPI)
Joseph Booker (U.Toledo)
James Muzerolle (STScI)

Dan Watson (U.Rochester)
P. Manoj (TIFR)
Beatriz Gonzalez (ESA)
Roland Vavrek (ESA)
David Neufeld (JHU)
Ted Bergin (U.Michigan)
Ruud Visser (U.Michigan)
Melissa McClure (U.Michigan)
Thomas Henning (MPIA)
James DiFrancesco (NRC)
Klaus Pontopiddan (STScI)
Tom Wilson (NRL)
Phil Myers (CfA)

HERSCHEL ORION PROTOSTAR SURVEY

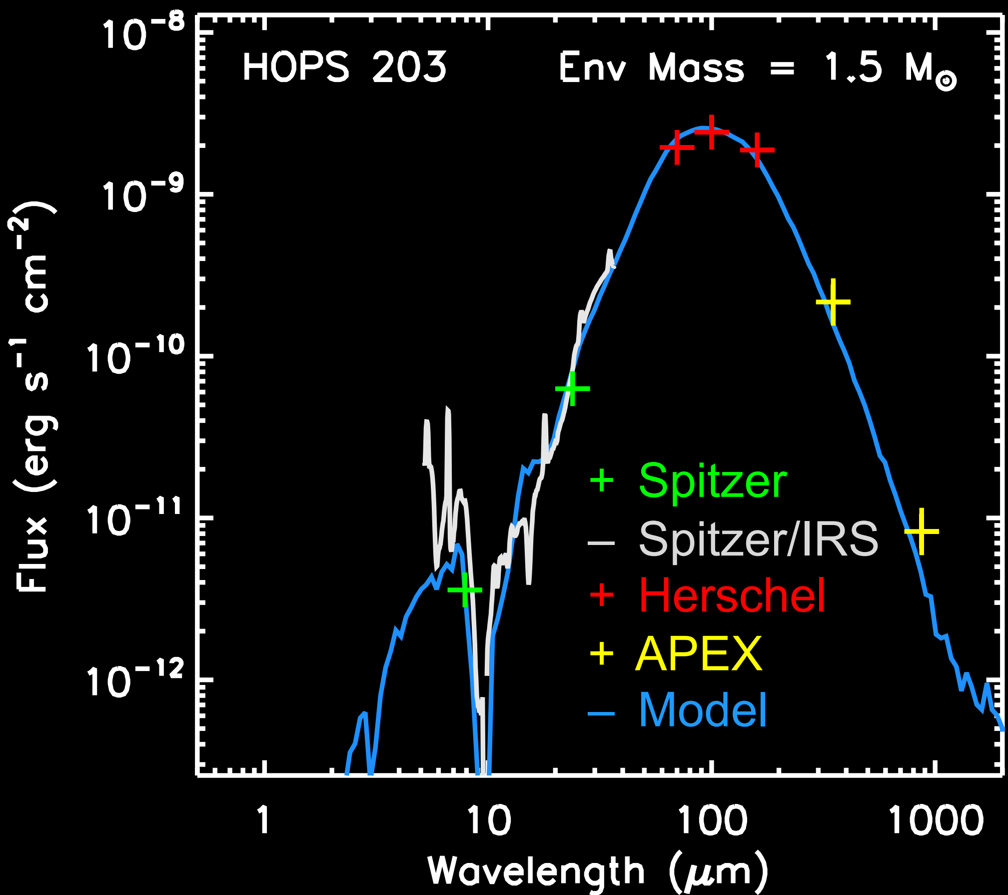
- Orion: over half the YSOs within 500 pc
- HOPS: PACS program to observe > 300 Orion protostars where their SEDs peak
- Imaging
  - 110 square fields of 5′ to 8′
  - 70 & 160 μm scans and cross-scans
- Spectroscopy
  - 33 targets; mix of pointed and mapping
  - Coverage from 55 to 200 μm

Goal: Study protostellar evolution with the large sample of protostars & diverse range of environments found in Orion

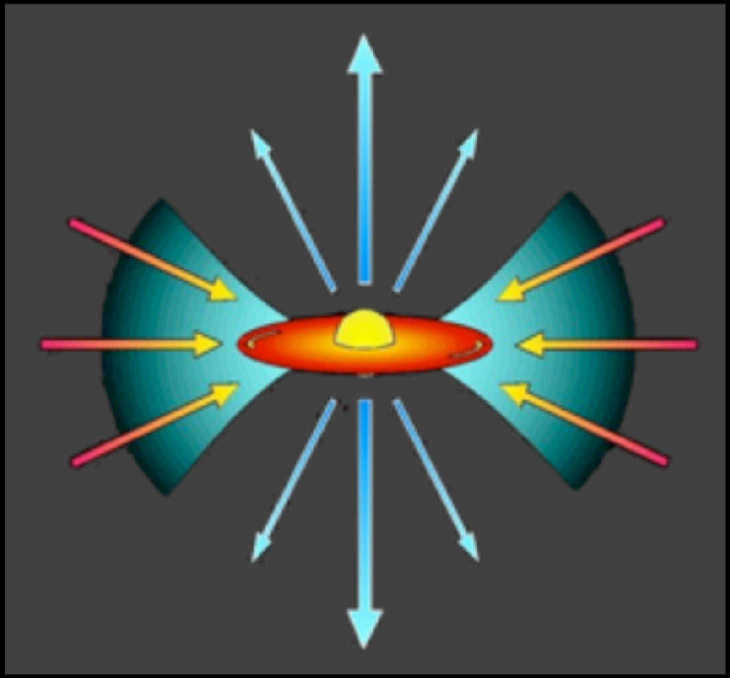


The HOPS SED Brewery

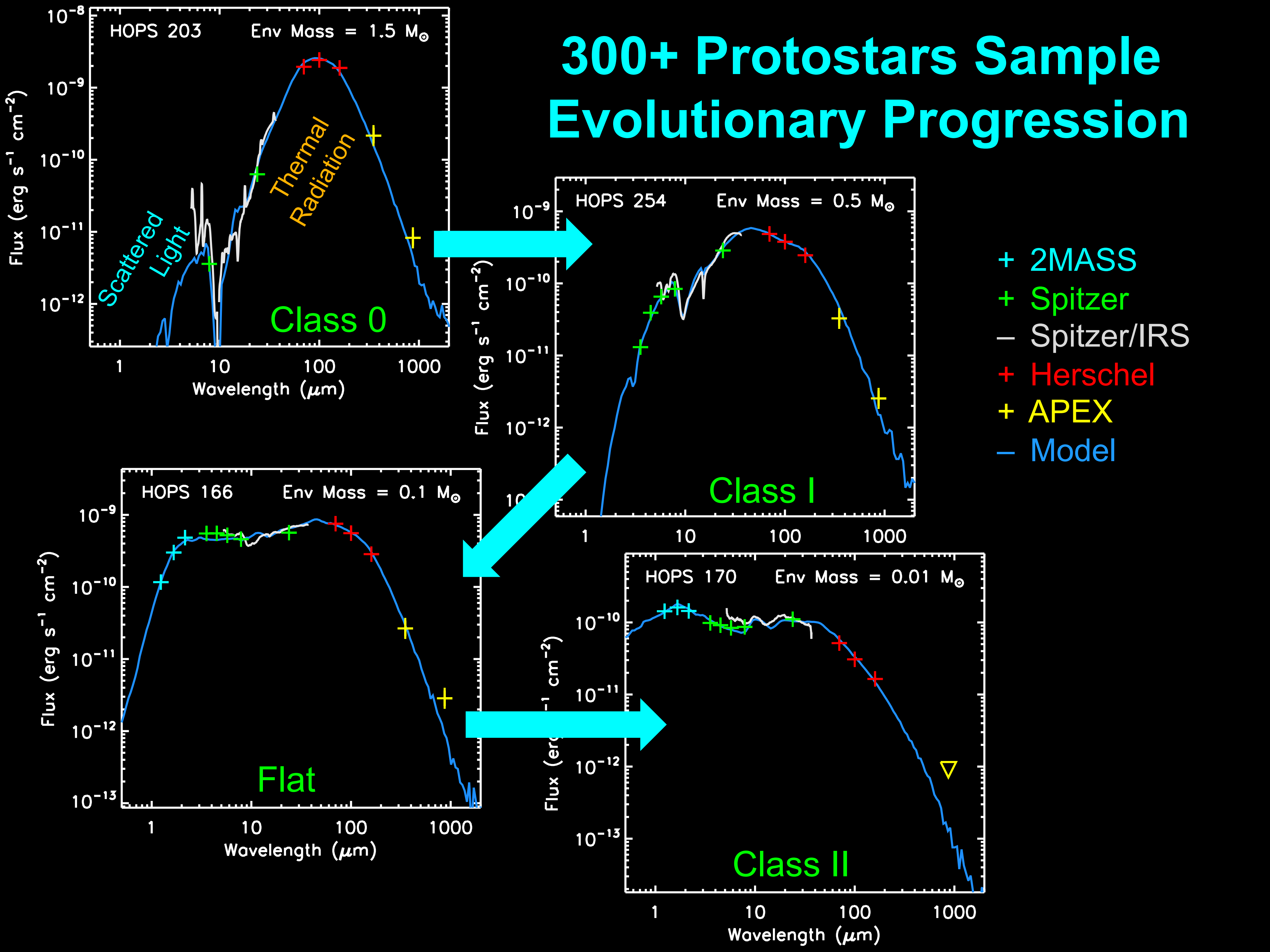
Combine data from 2MASS, Spitzer, Herschel, APEX



Model SEDs with the Whitney et al. radiative transfer code
(Ali et al. 2010, Furlan et al. in prep.)



300+ Protostars Sample Evolutionary Progression



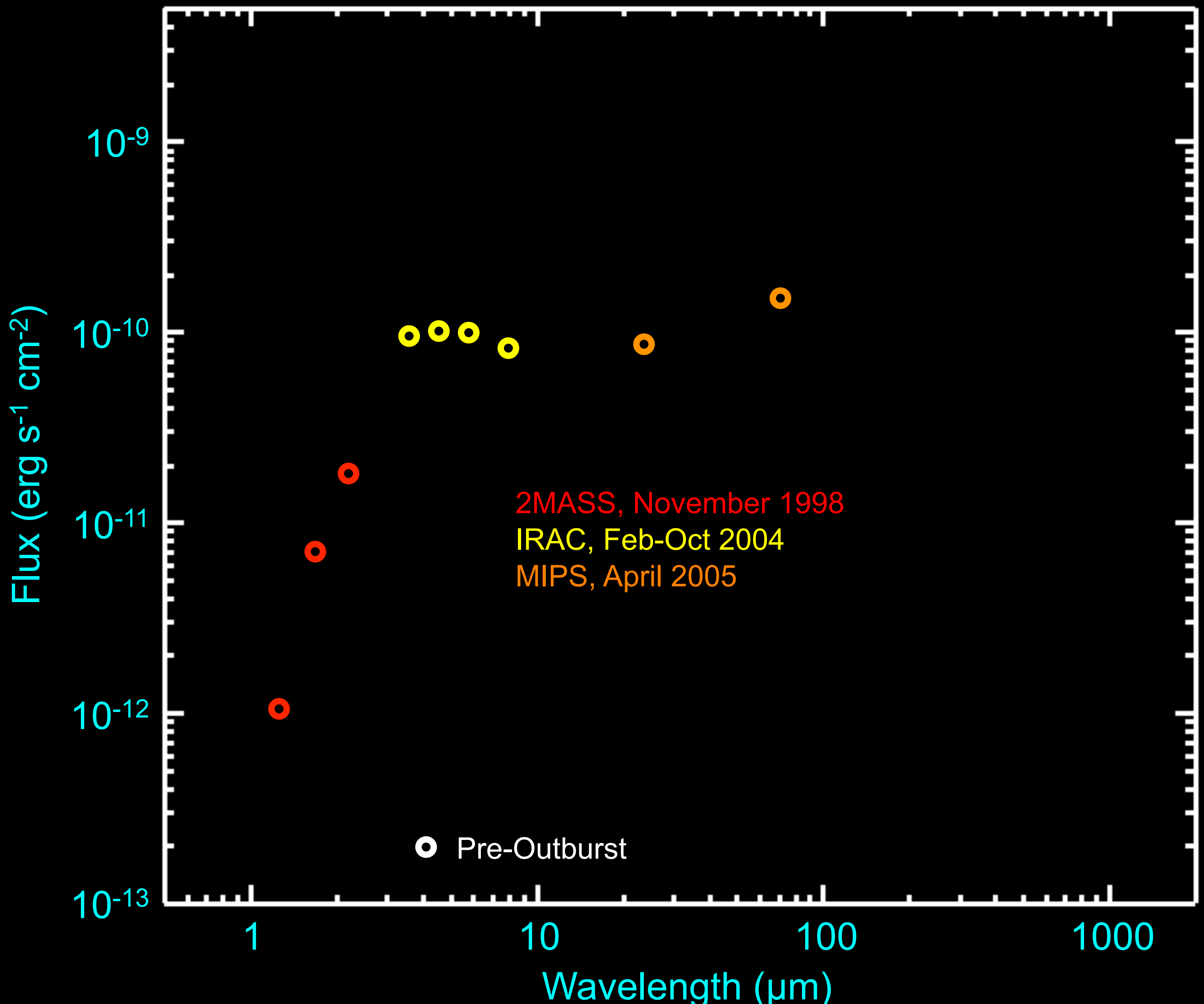
Key HOPS Questions

- How does Herschel contribute to our understanding of specific sources of interest?
- How do protostellar envelopes evolve?
- How does environment affect star formation?

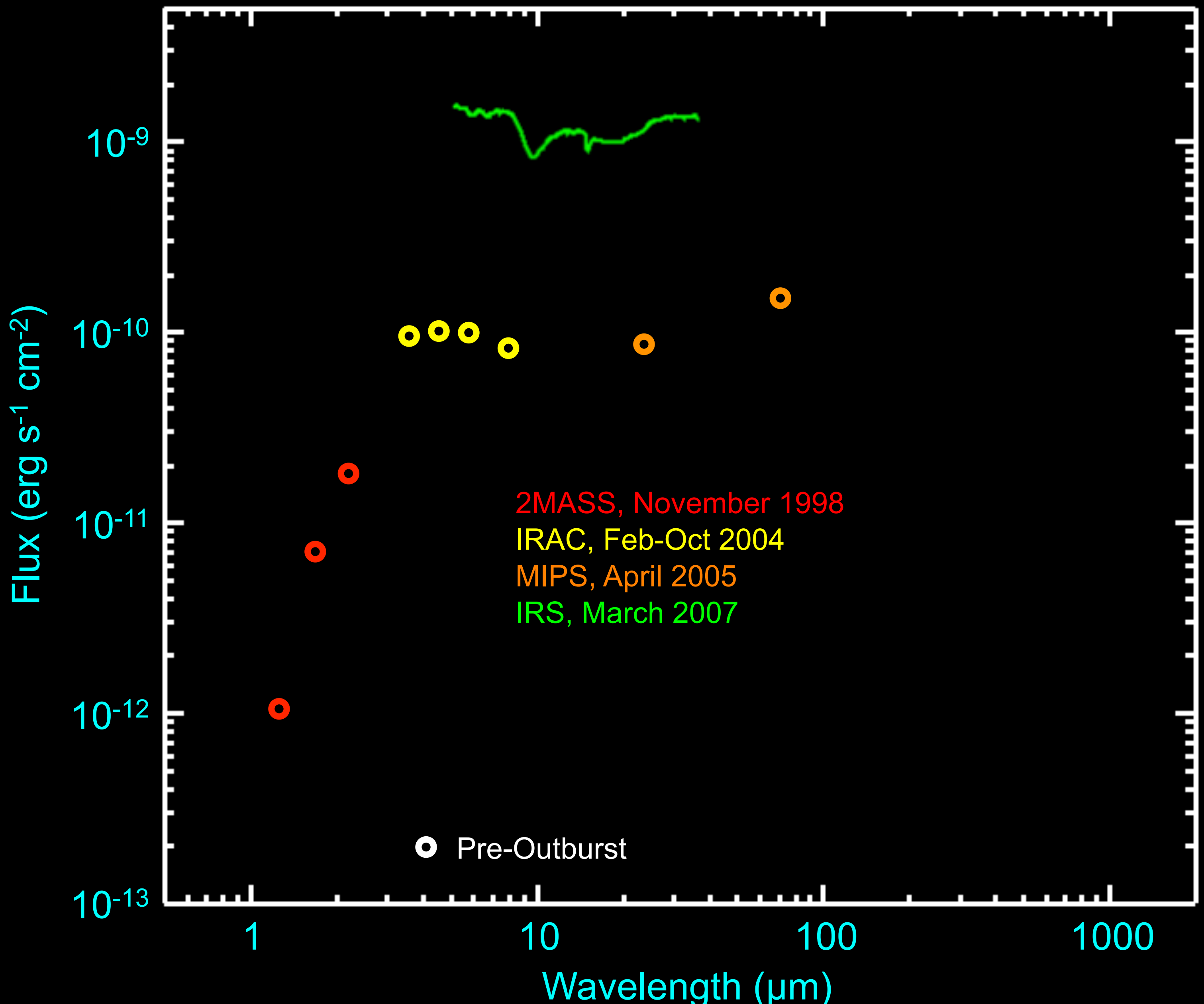
Key HOPS Questions

- How does Herschel contribute to our understanding of specific sources of interest?
- How do protostellar envelopes evolve?
- How does environment affect star formation?

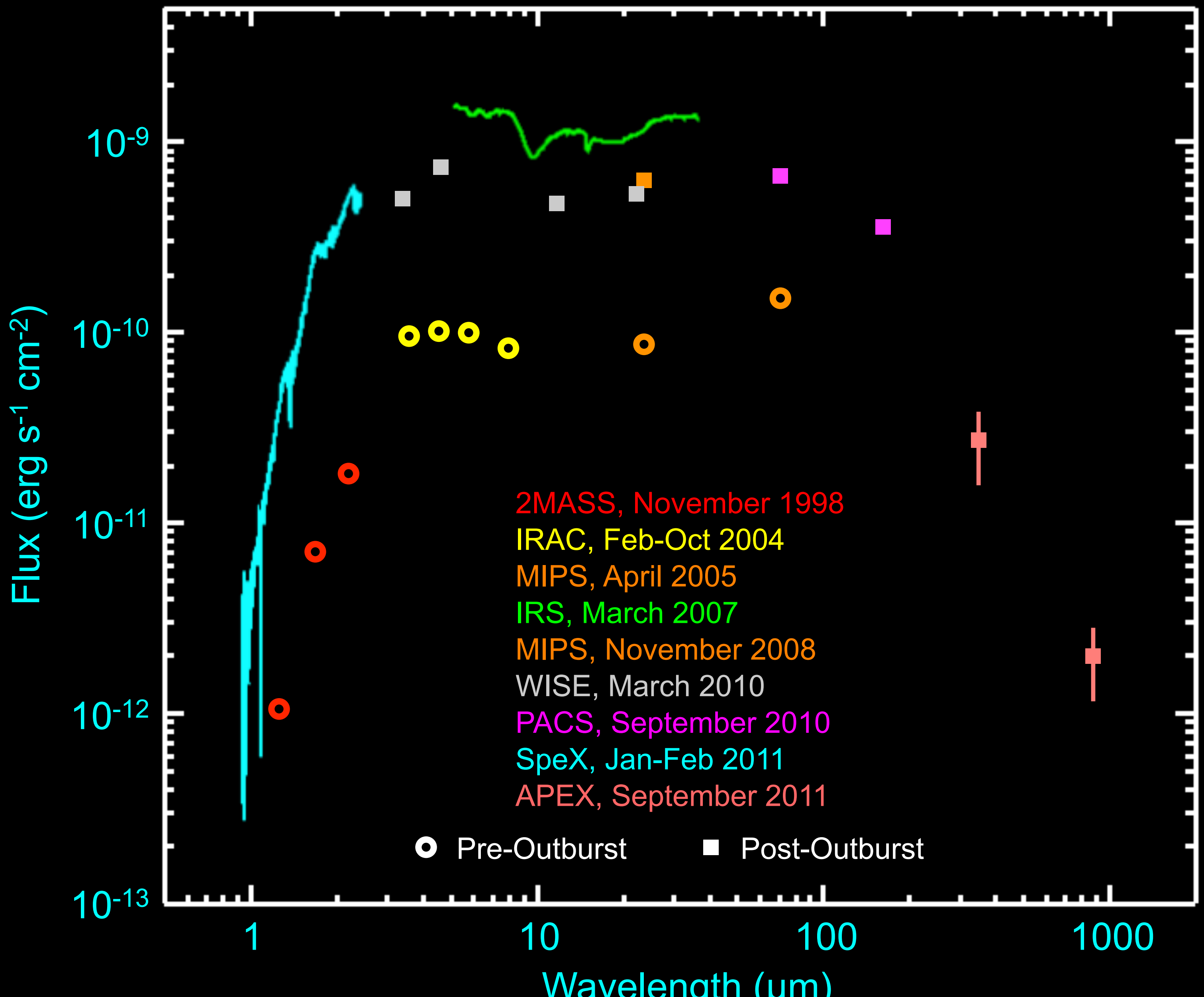
HOPS 223 (V2775 Ori): A New Orion Outburst



HOPS 223 (V2775 Ori): A New Orion Outburst

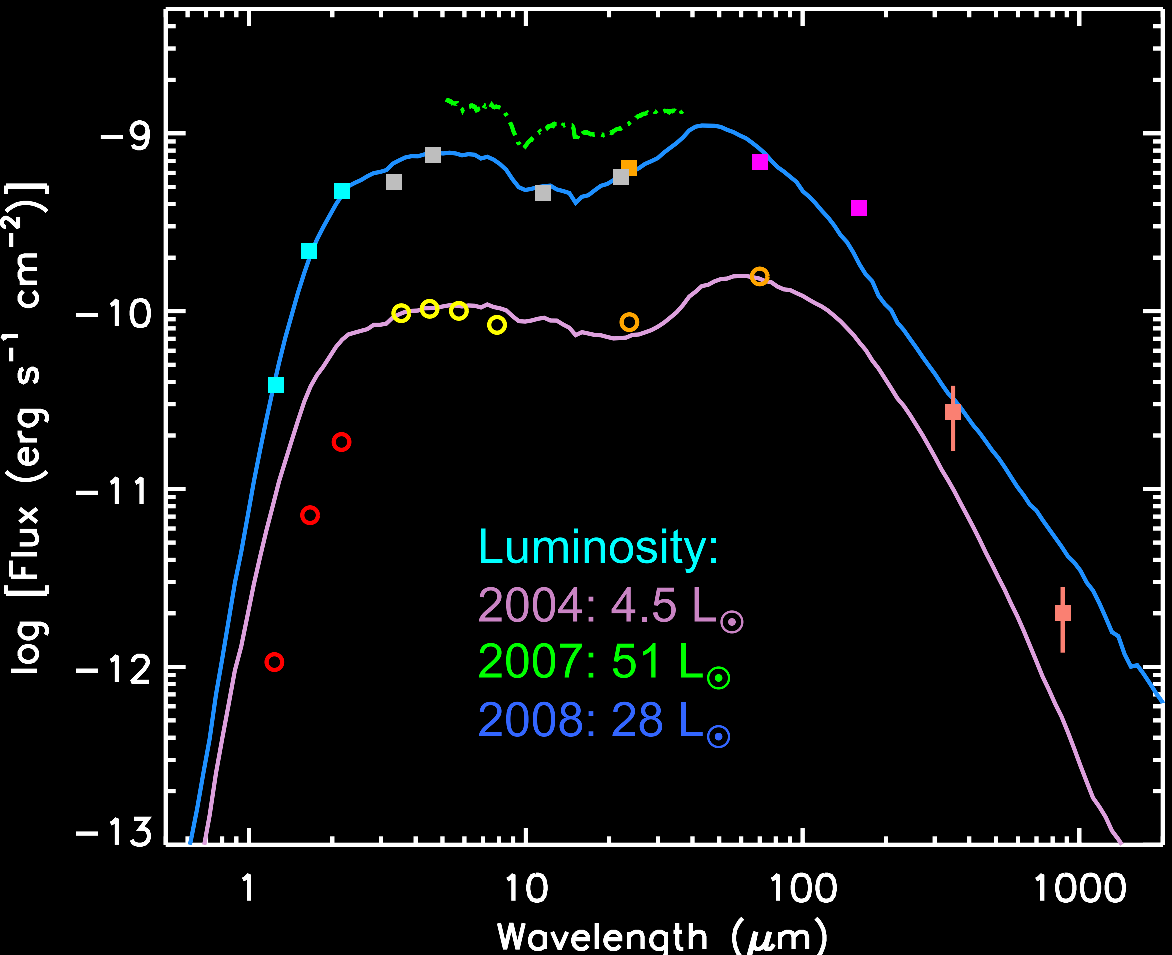


HOPS 223 (V2775 Ori): A New Orion Outburst

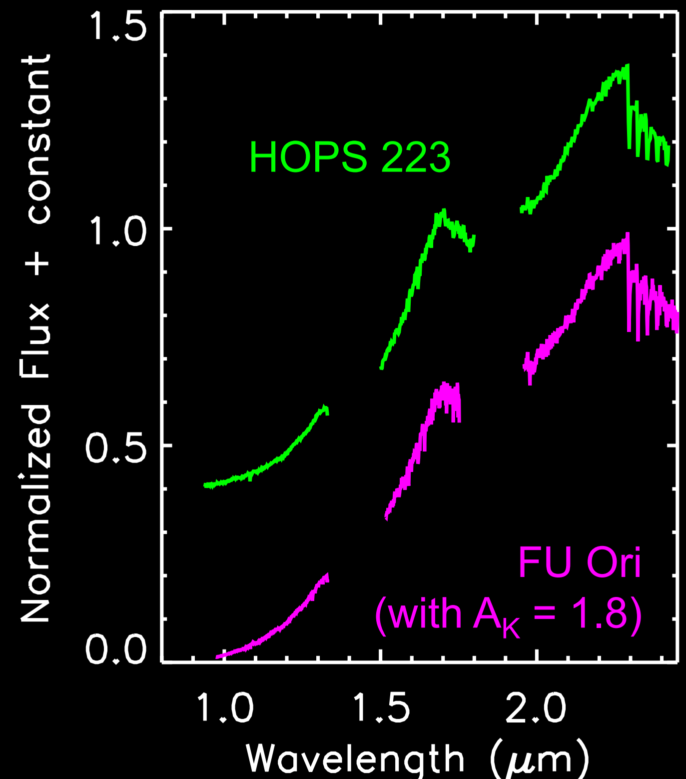


HOPS 223: A Low-Luminosity FU Ori Star with an Envelope

(Fischer et al. 2012)



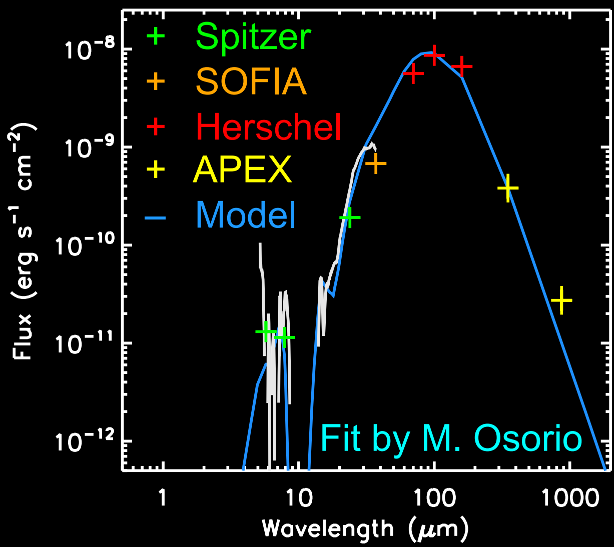
NIR spectrum confirms FU Ori status



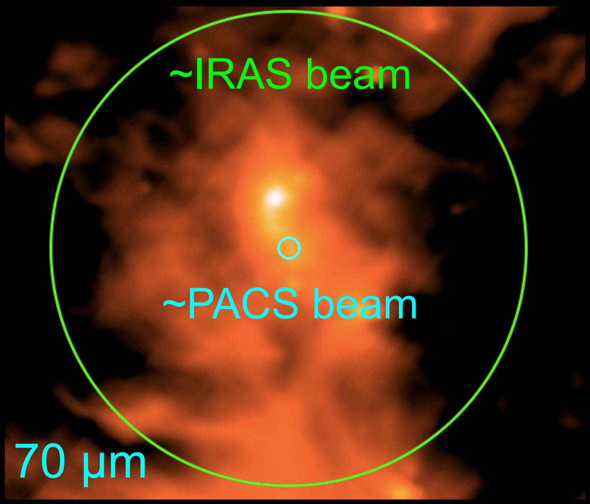
Lowest luminosity of any FU Ori star with an envelope (0.09 $M_\odot$)

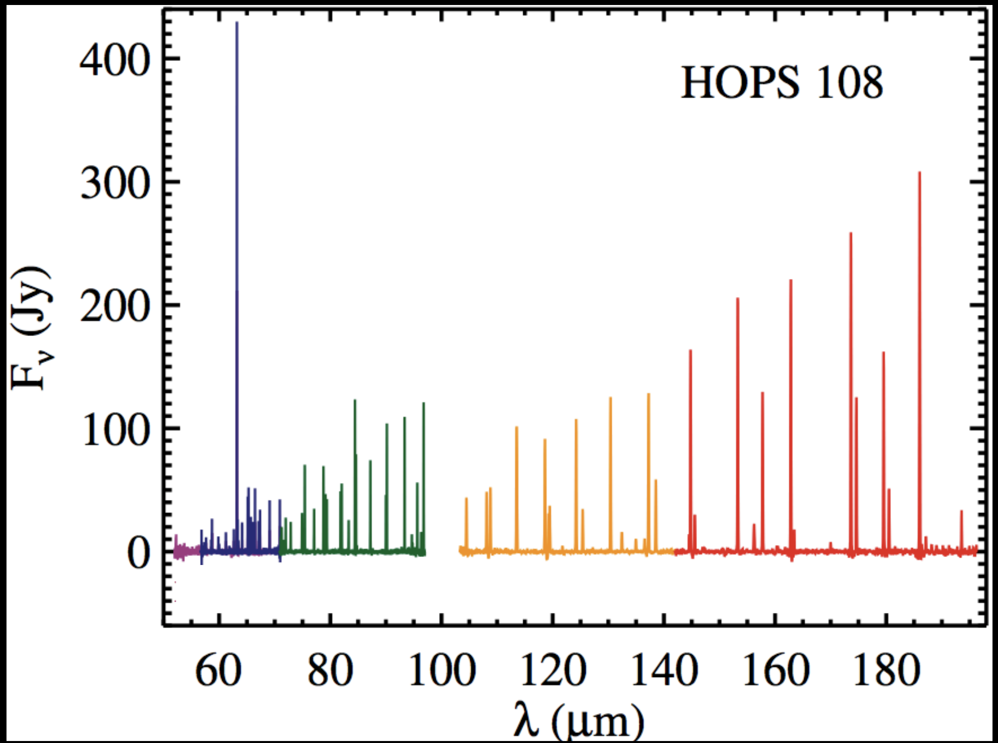
HOPS 108 (OMC 2 FIR 4): Brightest HOPS Line Source

(SED: Adams et al. 2012; Spectrum: Manoj et al. in prep.)



Luminosity ~ 50 $L_\odot$, vs. ~ 1000 $L_\odot$ reported pre-Herschel

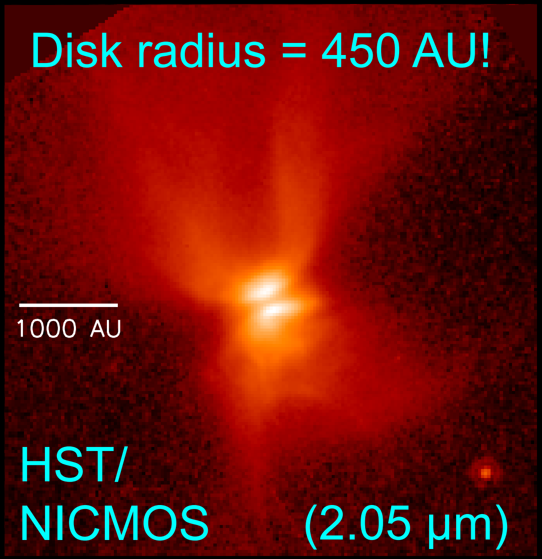


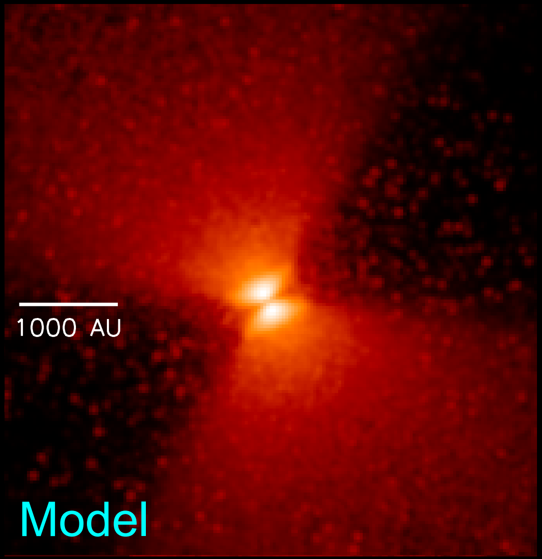


- 32 CO lines; highest is J=46–45
- Numerous H_2O lines; several have E_{up}/k > 1000 K. Highest excitation are the 56.7 μm ortho-para pair (E_{up}/k = 1320 K)
- Almost all OH lines in range
- Strong [OI]; [OI] 63 μm & [CII] 158 μm have extended components

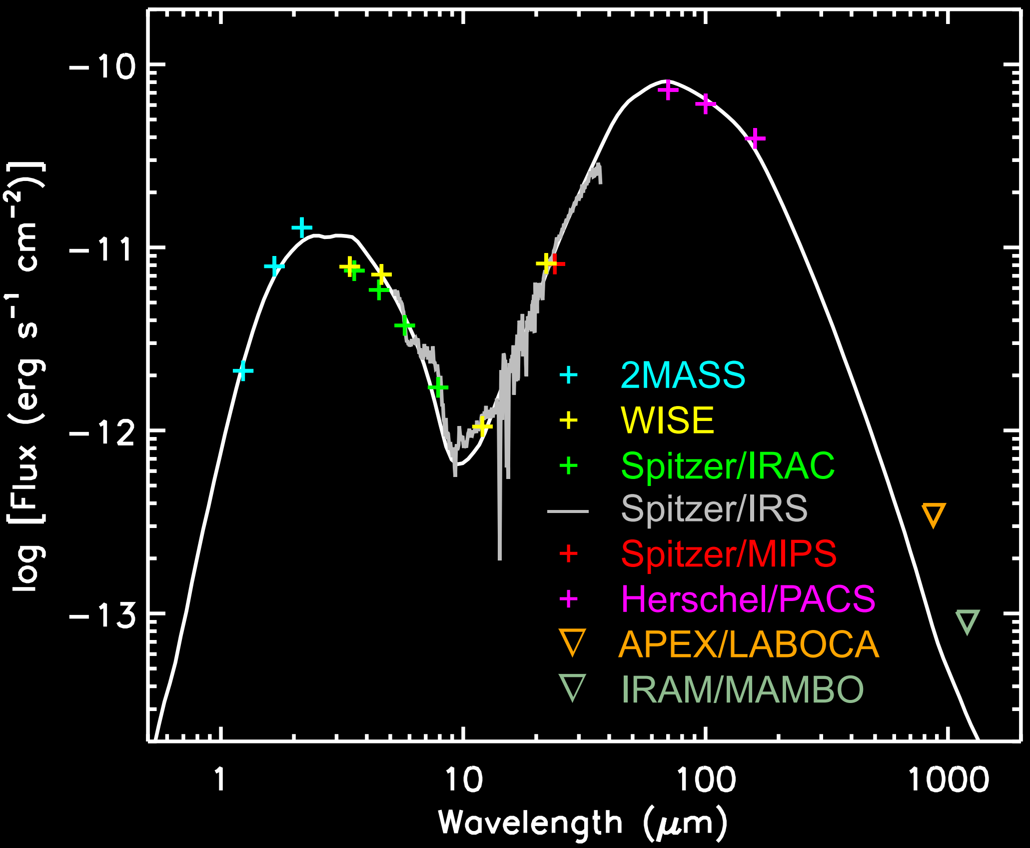
HOPS 136: The Late Stages of Envelope Evolution

(Fischer et al. in prep.)





- Stellar mass mostly assembled (~ 0.5 $M_\odot$)
- Disk mass typical of TTS (0.002 $M_\odot$)
- But Herschel data point to an envelope with 25x the disk mass (0.05 $M_\odot$)



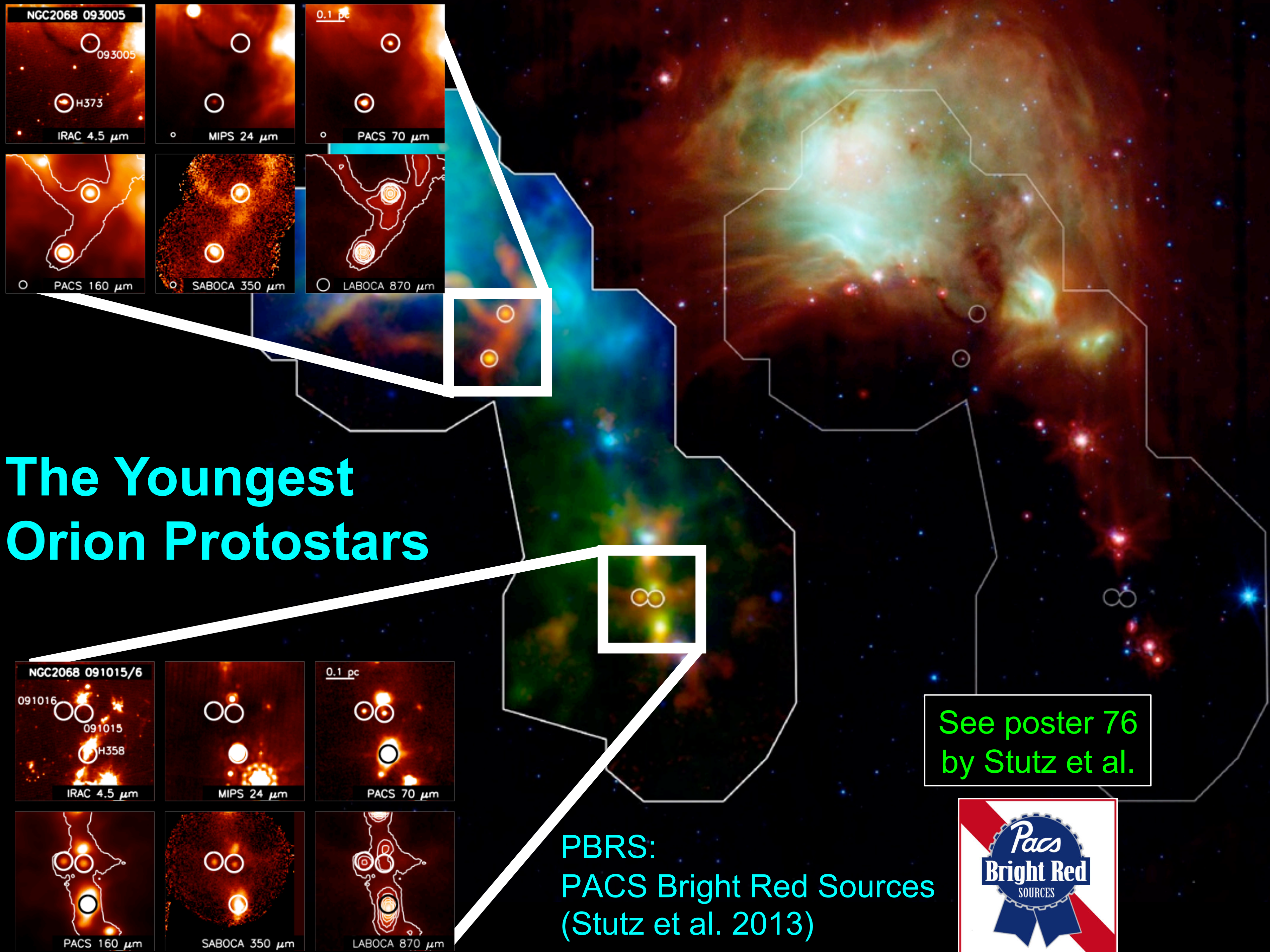
Key HOPS Questions

- How does Herschel contribute to our understanding of specific sources of interest?

- How do protostellar envelopes evolve?

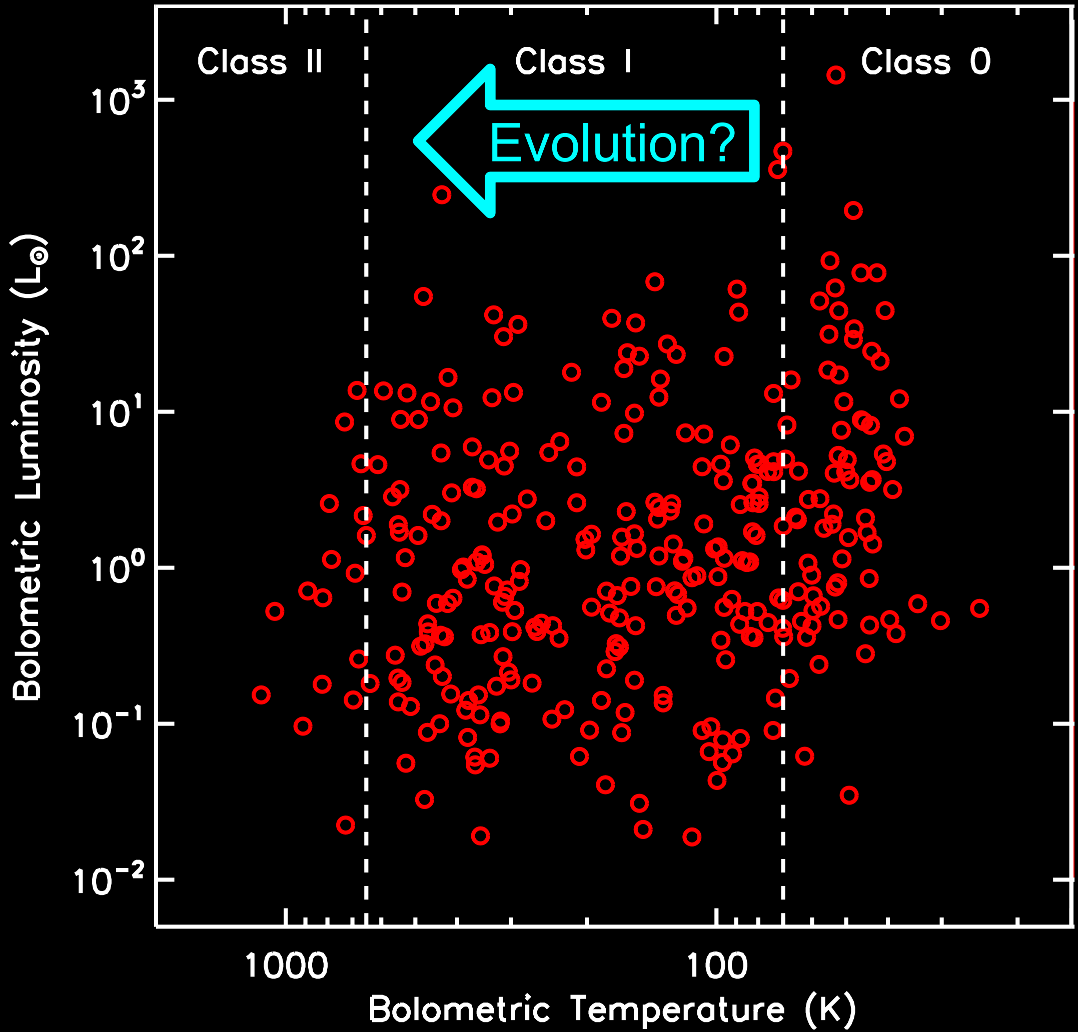
- How does environment affect star formation?

The Youngest Orion Protostars



See poster 76 by Stutz et al.

PBRS:
PACS Bright Red Sources
(Stutz et al. 2013)



Bolometric Luminosity and Temperature (BLT)

(Fischer et al. in prep.)

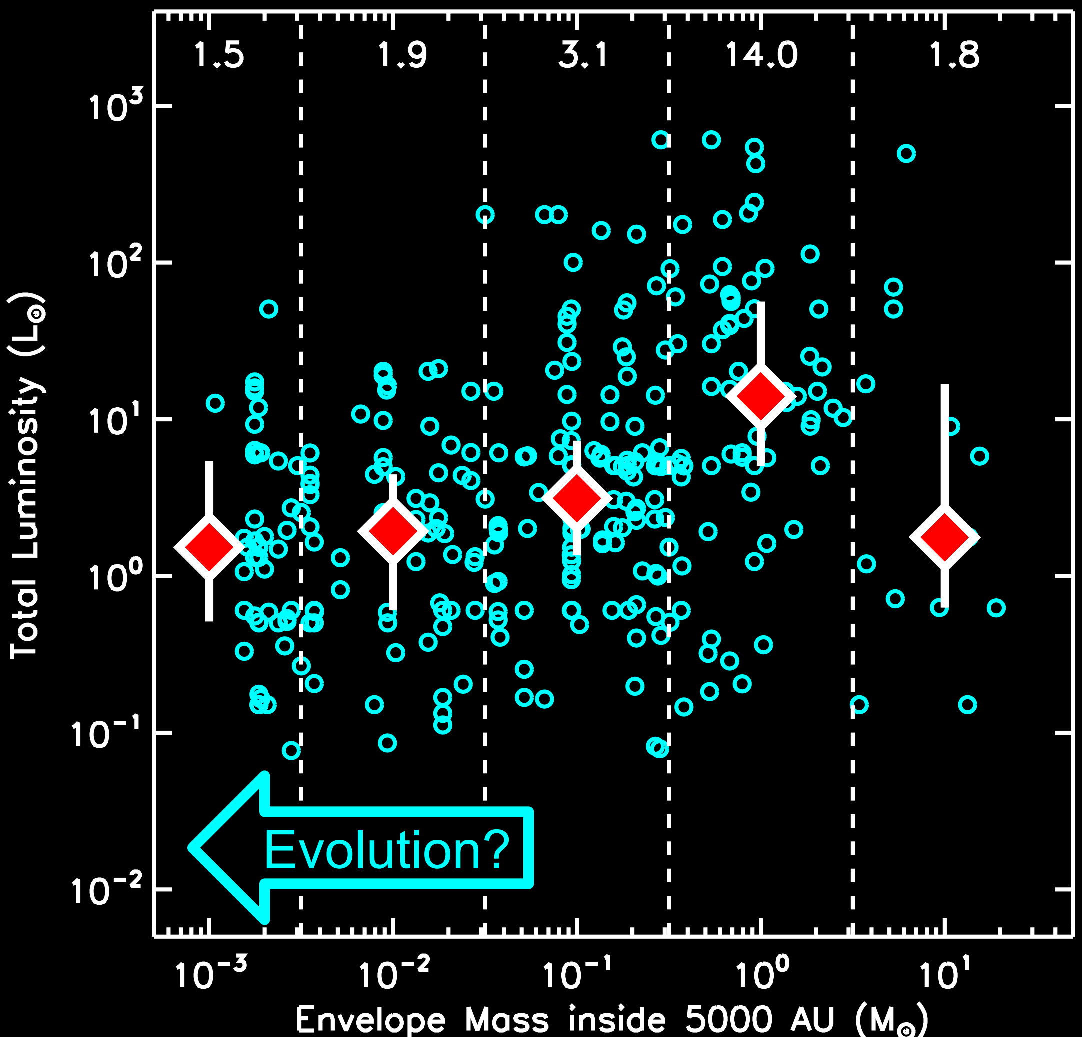
Unprecedented evolutionary diagram of 315 HOPS protostars from a single star-forming region

	Number	Fraction	Lifetime	Median Lum.
Class 0	93	0.30	0.15 Myr	3.5 $L_\odot$
Class I	222	0.70	0.35 Myr	1.0 $L_\odot$

Envelope Properties from SED Modeling

(Fischer et al. in prep.)

Median luminosity per bin:



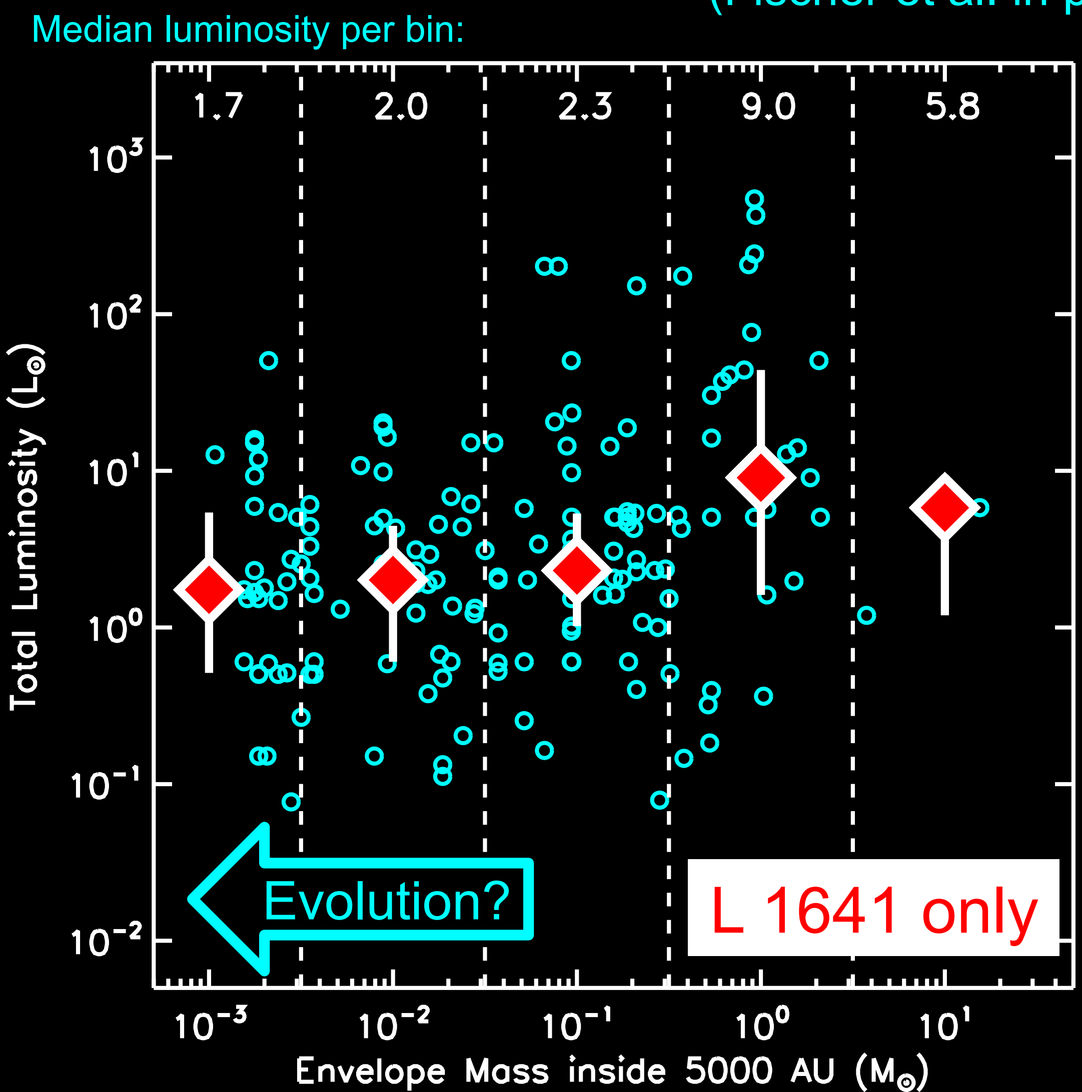
- Luminosity mostly due to accretion early on
- Median luminosities peak at $M_{env} \sim 1\ M_\odot$
- Possible explanations:

  1) Protostars with $\sim 1\ M_\odot$ envelopes are forming more massive stars

  2) Low-mass protostars have higher mass infall rates early in their evolution

Envelope Properties from SED Modeling

(Fischer et al. in prep.)



L 1641 is unlikely to be forming massive stars and shows a similar trend – supports scenario 2:

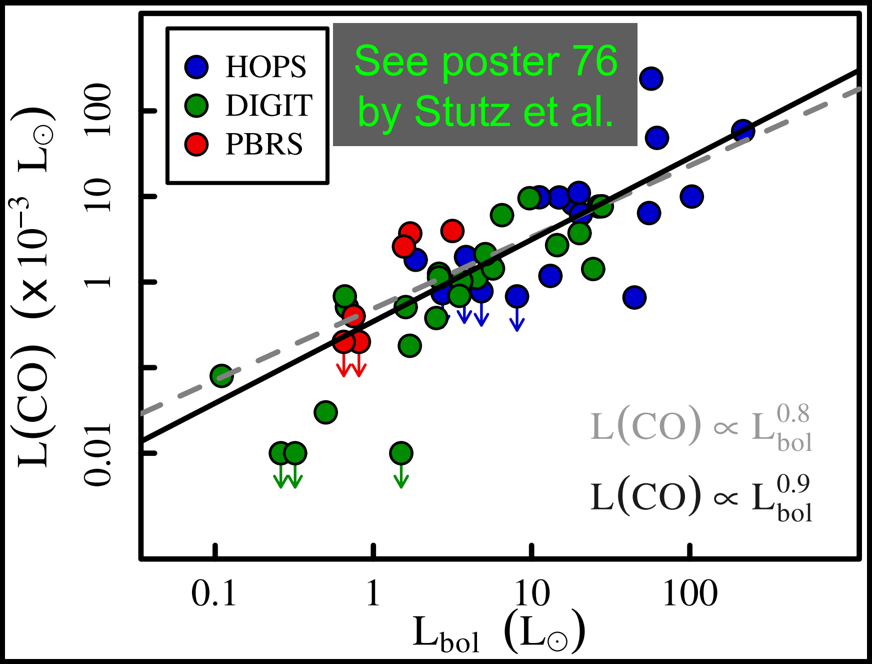
Low-mass protostars have higher mass infall rates early in their evolution

See poster 41 by Fischer et al.

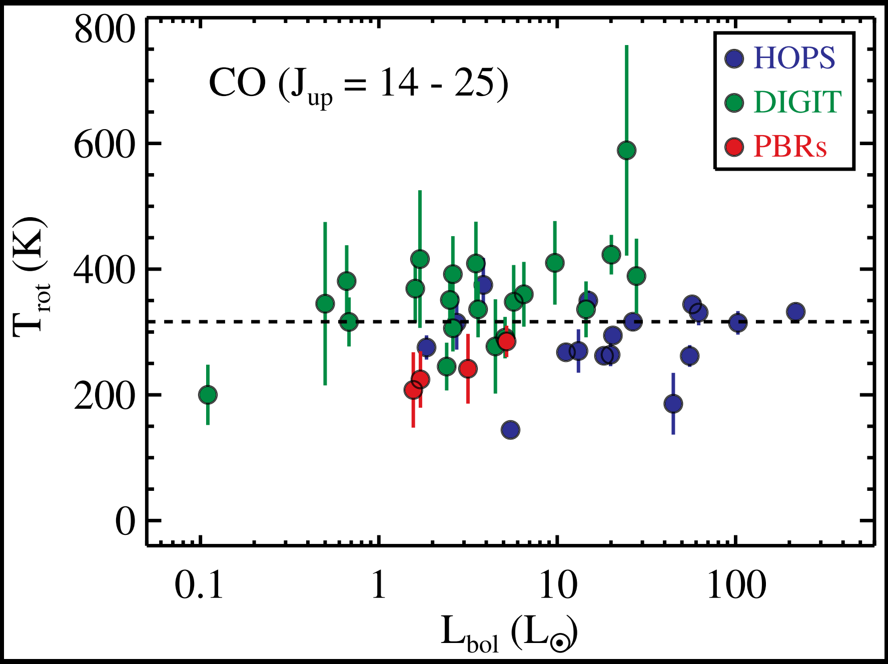
CO Emission from Accretion-Driven Outflows

(Manoj et al. 2013; DIGIT data provided by J. Green & N. Evans)

Absolute line fluxes L(CO) scale with L_{bol}



Line ratios (T_{rot}) remain ~ constant



T_{rot} curve for CO is independent of source luminosity and envelope density; most likely explanation is that emission is from shock-heated material in outflow.

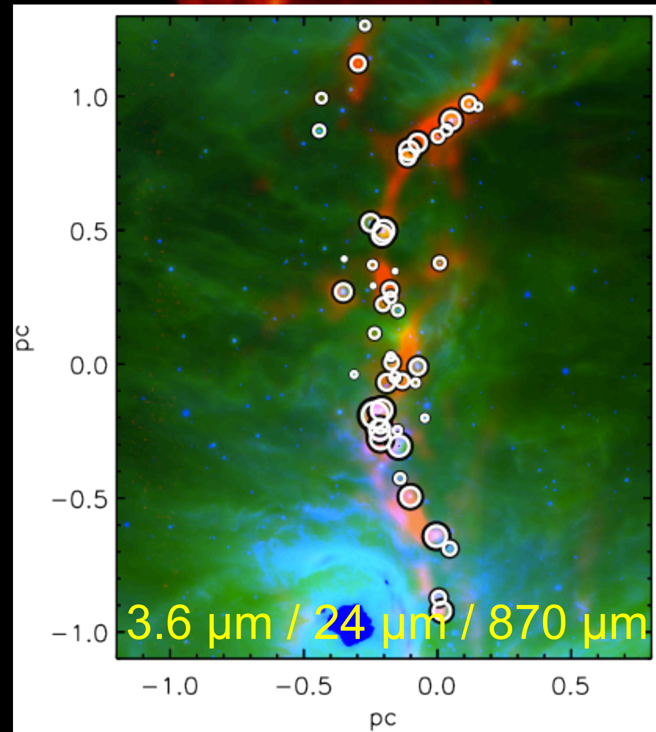
More luminous sources have more CO luminosity; suggests momentum and mass flow rates of the outflows correlate with bolometric luminosity: sources with high L_{bol} have higher accretion and outflow rates

Key HOPS Questions

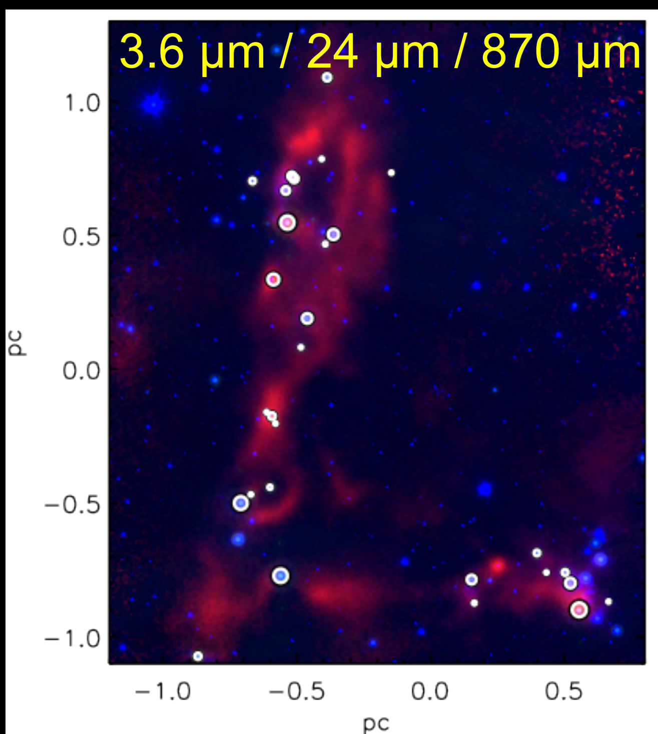
- How does Herschel contribute to our understanding of specific sources of interest?
- How do protostellar envelopes evolve?
- How does environment affect star formation?

The Role of Environment

$\langle L \rangle = 7.6\ L_\odot$
$\langle \mathrm{spacing} \rangle = 8000$ AU



$\langle L \rangle = 0.7\ L_\odot$
$\langle \mathrm{spacing} \rangle = 13000$ AU

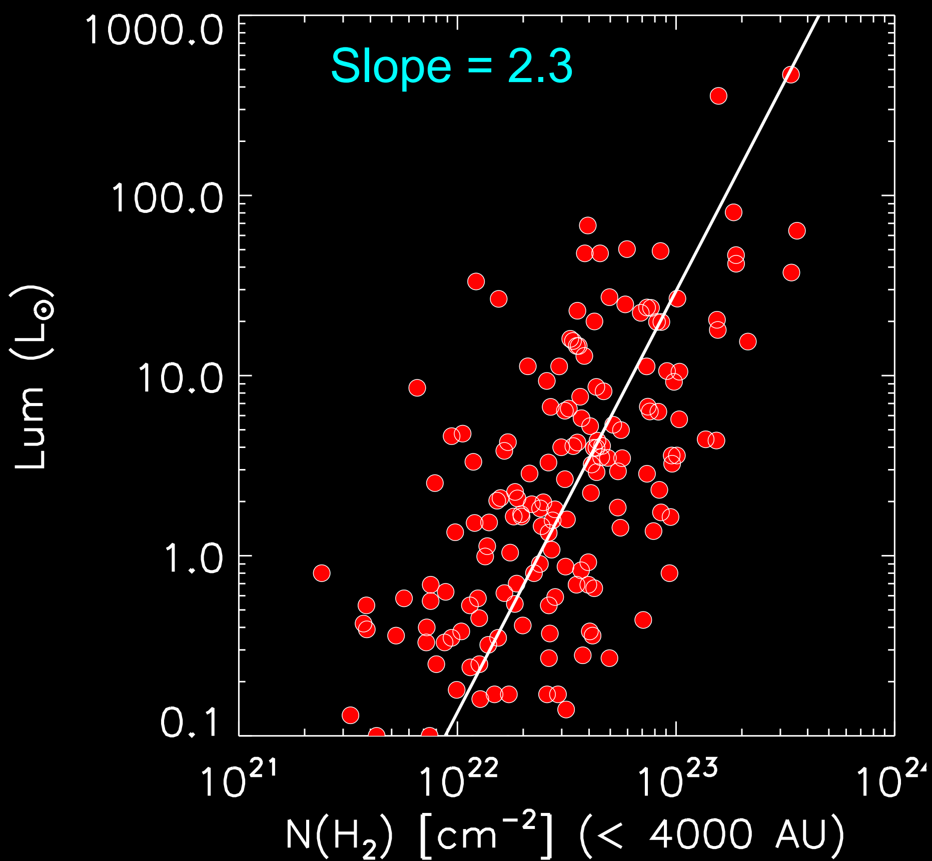


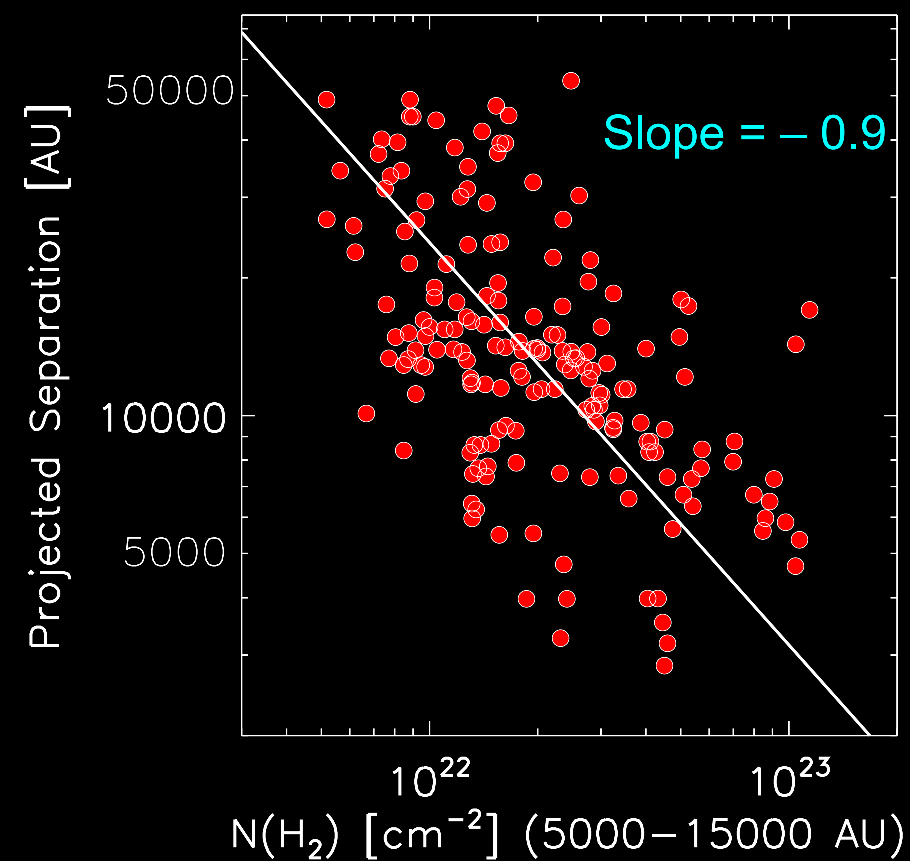
Herschel Gould Belt Survey 500 µm image (Polychroni et al. 2013; Roy et al. 2013)

The Role of Environment

(Megeath, Stanke, et al. in prep.)

Derive column density from APEX and Herschel data





With increasing gas density

- Protostellar luminosity increases
- Projected separation decreases

Spatial Distribution of PBRs

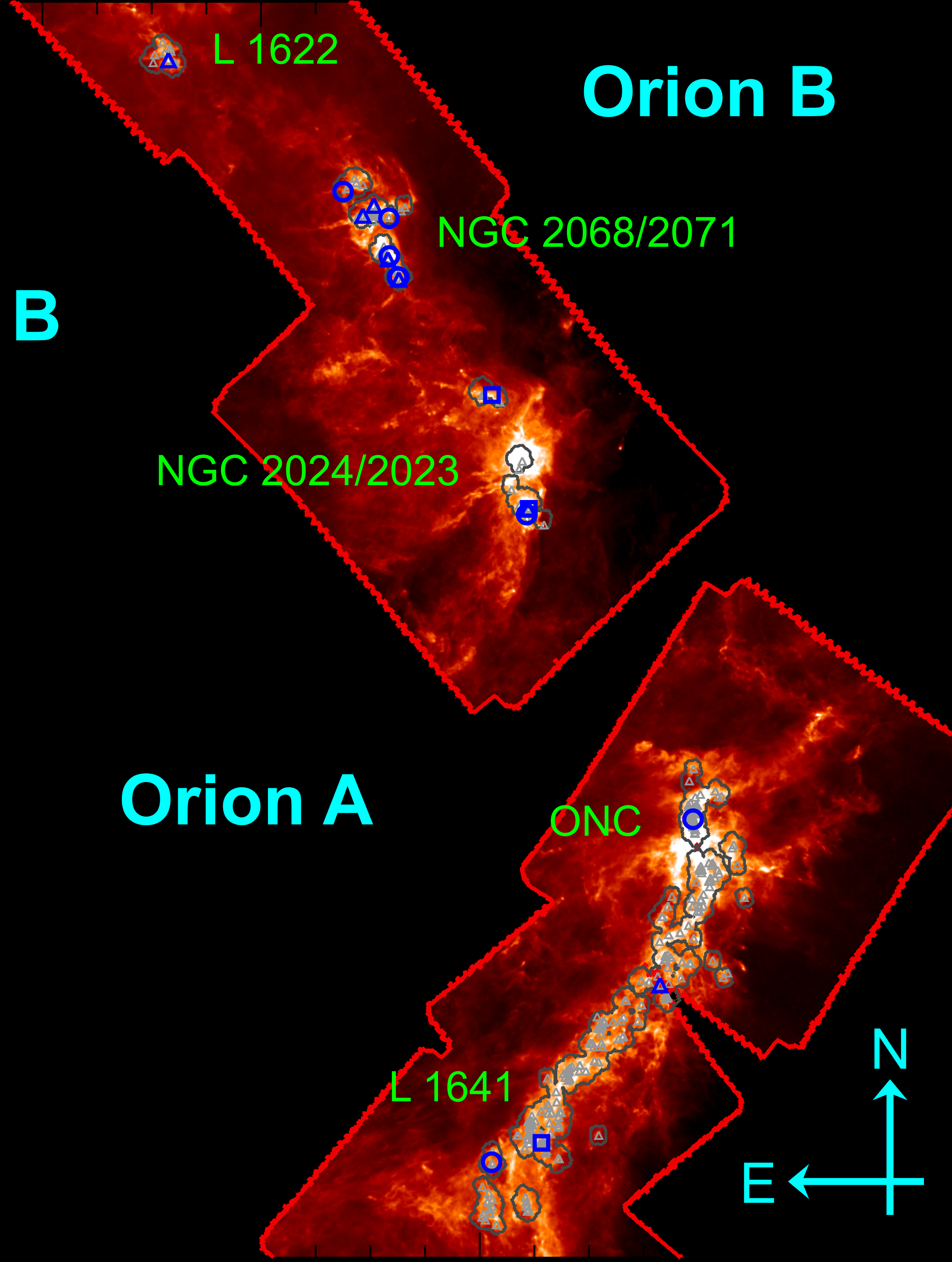
Enhanced PBRS Fraction in Orion B

(Stutz et al. 2013)

Fraction of protostars that are PBRS:

Orion A	0.01
Orion B	0.17

More vigorous star formation in Orion B?



Summary

- HOPS is a comprehensive survey of the largest star-forming region within 500 pc
  - 70 and 160 μm imaging of > 300 protostars
  - Spectroscopy of 33 protostars
- How does Herschel contribute to our understanding of specific sources of interest?
  - Large sample allows the study of short-lived phenomena, including accretion outbursts, unusually bright line sources, late-stage envelopes
- How do protostellar envelopes evolve?
  - PBRS: 5% of protostars are in a cold, very young stage not detected by Spitzer
  - Class 0 lasts for 150,000 yrs, 30% of the protostellar lifetime
  - Accretion rates peak near the Class 0 / Class I transition
  - CO lines demonstrate correlation between accretion energy and total luminosity
- How does environment affect star formation?
  - Density and luminosity of protostars increase with increasing gas density
  - PBRS fraction is 17% in Orion B; only 1% in Orion A