The Herschel Orion Protostar Survey: Photometry in Complex Fields

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HOPS: Herschel Orion Protostar Survey

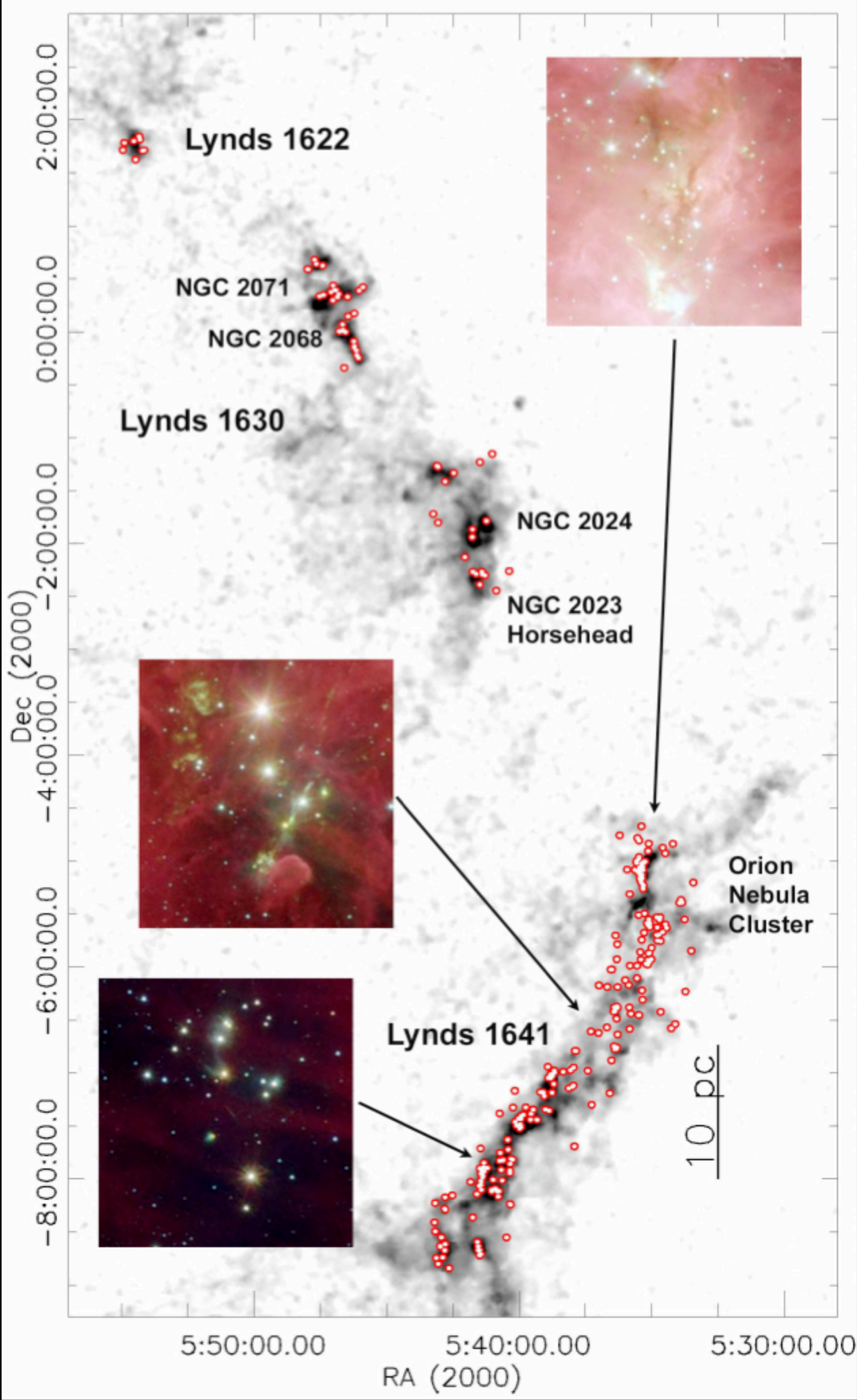
PACS imaging and spectroscopy of Spitzer-identified protostars in the Orion molecular clouds

Main components:

1. PACS imaging at 70 and 160 μm of 300+ protostars: 108 fields of 5′ to 8′ on a side
2. PACS spectroscopy of 33 targets

Plus…
HST imaging
Spitzer imaging, spectroscopy
APEX imaging
Other ground-based data

A complete survey of the largest star-forming region within 500 pc



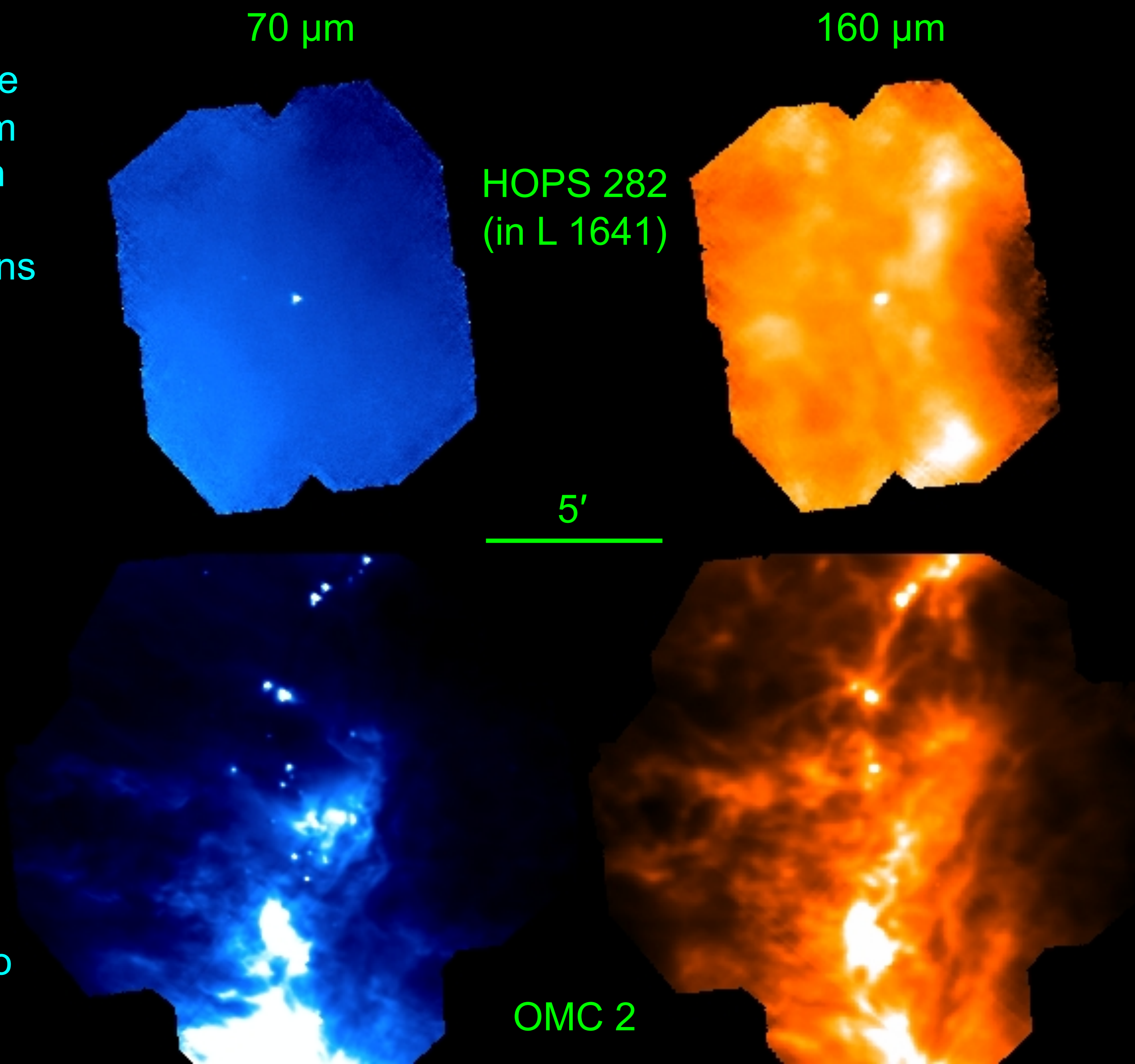
HOPS covers a range of environments: from single protostars with little nebulosity to highly complex regions

Mapping techniques:

Photproject for photometry
(HPF-30 at 70 µm; HPF-40 at 160 µm)

Scanamorphos or MADmap to study extended emission

Photometry agrees to within a few percent across techniques

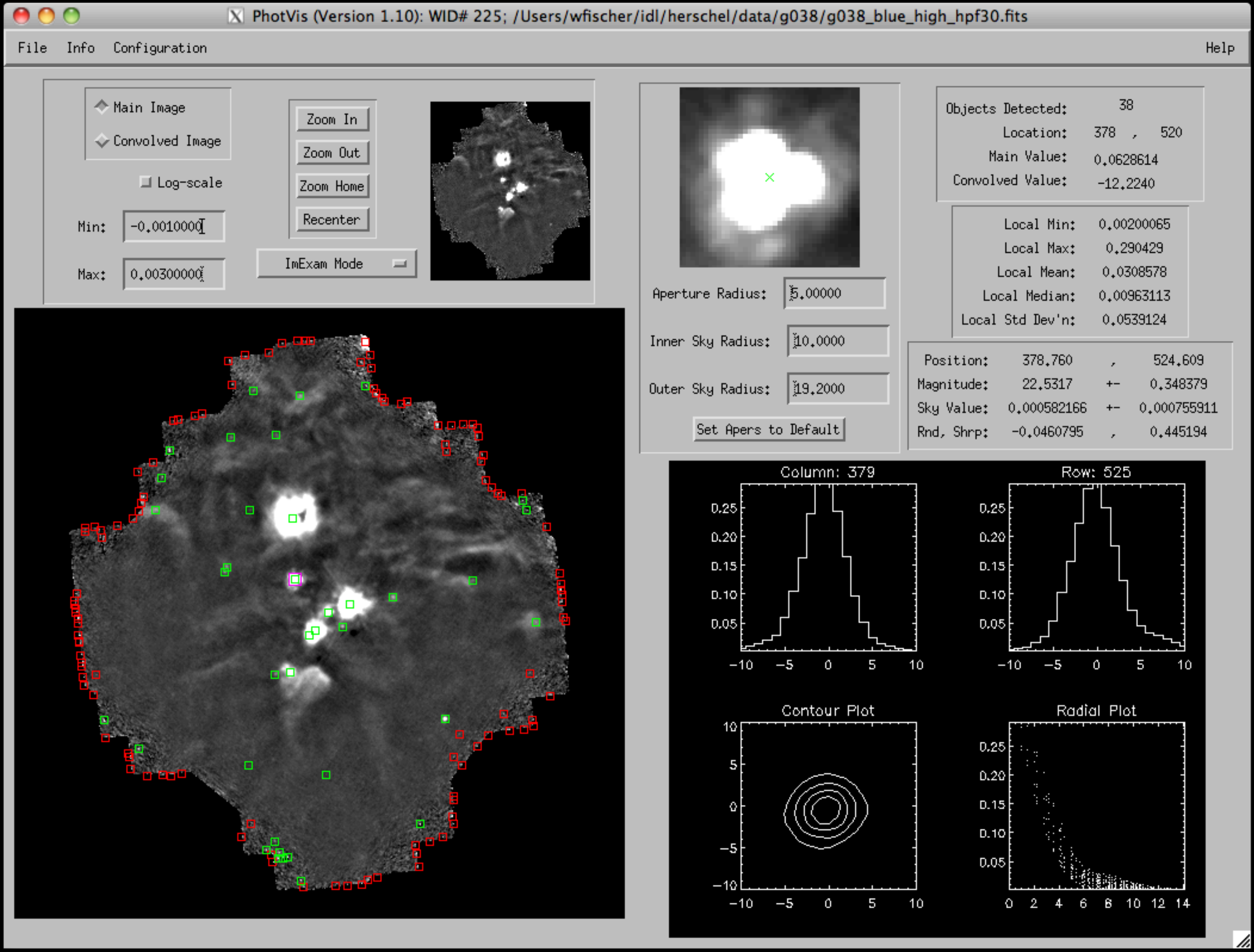


HOPS Aperture Photometry

- Use Rob Gutermuth's *Photvis* IDL app for source detection, aperture photometry *(http://www.astro.umass.edu/~rguter/Rob_Gutermuth_Astronomy/IDL_Page.html)*

Photvis extracts sources with width of order the PSF FWHM, an input parameter (5″ at 70 μm, 12″ at 160 μm)

User sets a S/N threshold (we use 7)



HOPS Aperture Photometry

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emacs22@maz.local

File Edit Options Buffers Tools Help

```
;Generated on Wed Sep 26 16:50:55 2012
;Filename used for sources:
;/Users/wfischer/idl/herschel/data/g312/g312_blue_high_hpf30.fits
;Wavelength = 70 um
;Positions are determined with PhotVis
;Fluxes and uncertainties (Unc) are in Jy
;Map coverage (Cov) is in detector pixels
;Ap/InSky/OutSky (arcsec):        9.6        9.6        19.20
;Aperture correction applied (flux is divided):        0.7331
;Source         Group      RA         Dec        Rnd       Shp      FWHM     Flux        Unc          Cov
;----------------------------------------------------------------------------------------------------------
g312s000        312    84.72284  -7.15867   0.44896  0.51408  2.54103  1.5344e-02  9.4327e-03    15.7
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g312s007        312    84.67249  -7.09983  -0.03806  0.44301  6.63903  1.5560e-01  8.1681e-03   566.4
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```

--:-- **g312_blue_cat.txt** All L37 (Text)----------------

FWHM, coverage are retained to be used as criteria in the final catalog

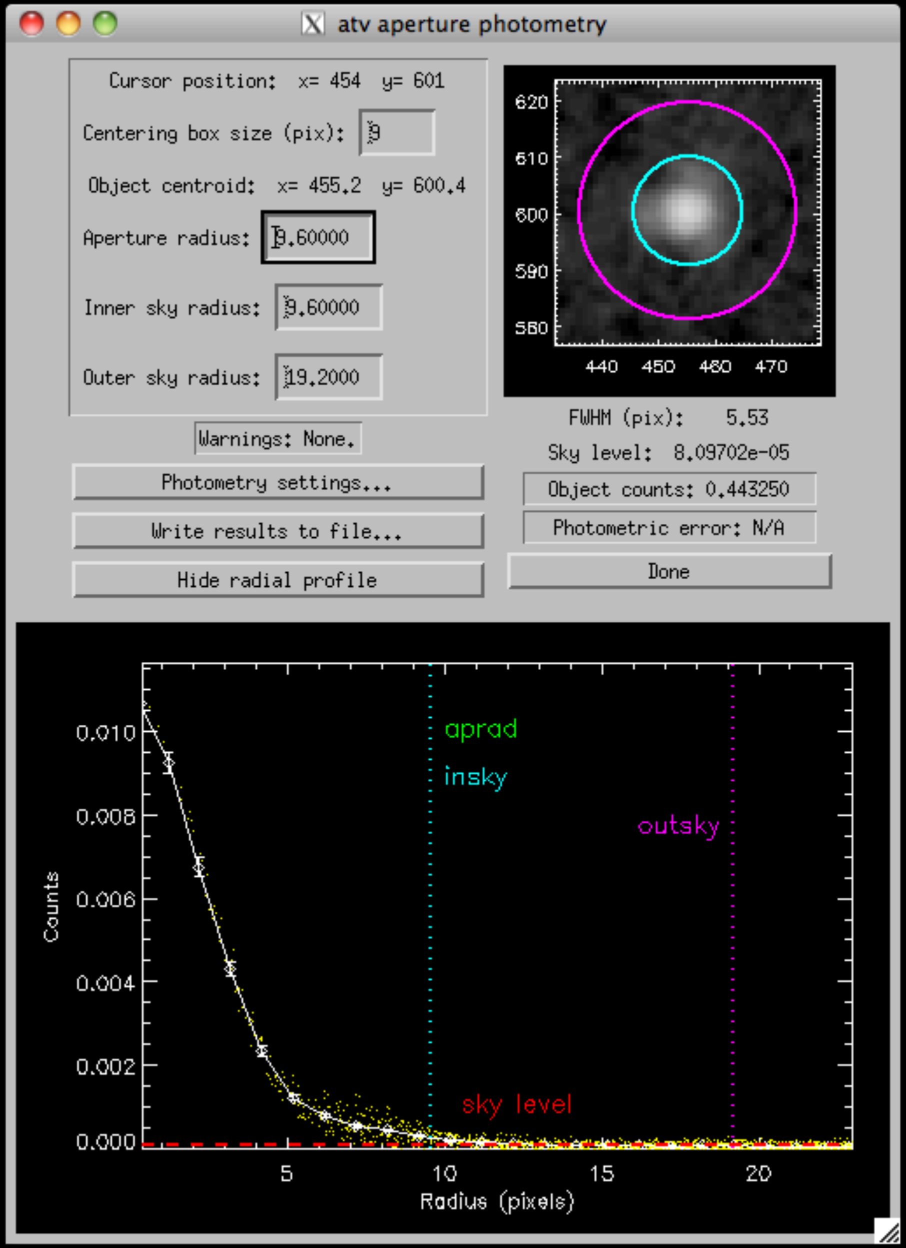
Reject edge sources (coverage $\lesssim 100$), extended sources (FWHM $\lesssim 8''$)

Aperture Parameters

- Orion nebular background can be strong and non-uniform
- To reduce contamination, we use small apertures and close-in sky annuli

λ	Ap Radius	Inner Sky	Outer Sky
70 µm	9.6″	9.6″	19.2″
160 µm	12.8″	12.8″	25.6″

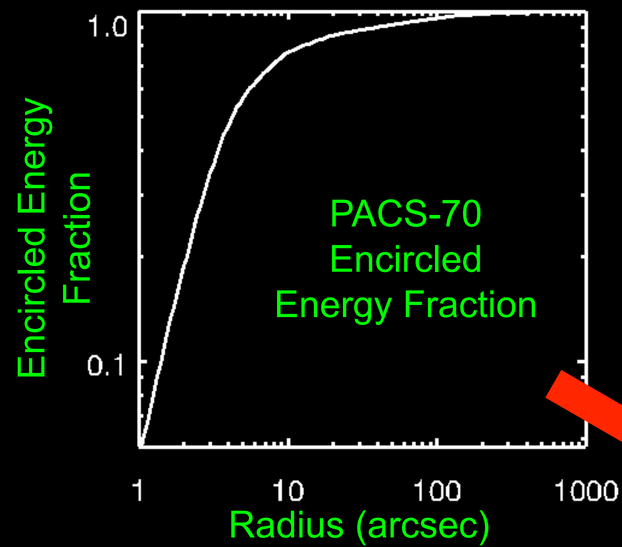
- Non-negligible source flux in small sky annuli means signal is subtracted
- HIPE does not account for annulus size in its aperture correction tool (*photApertureCorrectionPointSource*)
- Need custom aperture corrections to recover subtracted signal

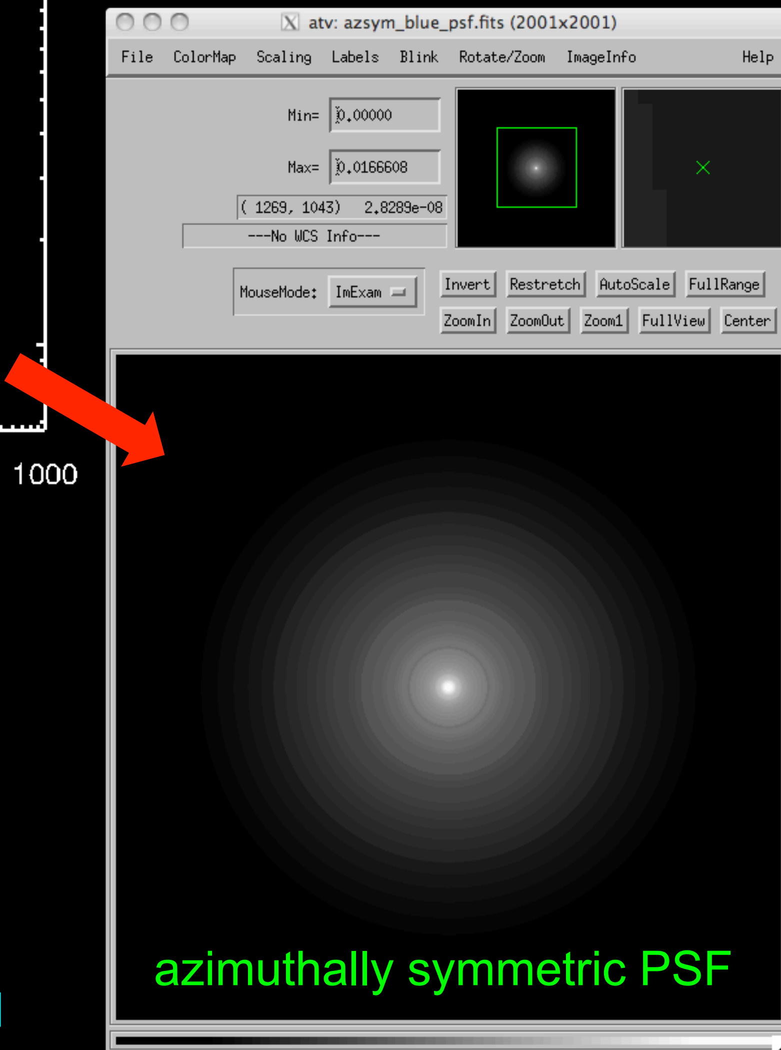


λ	Ap Radius	Inner Sky	Outer Sky	HIPE	Custom
70 μm	9.6″	9.6″	19.2″	0.7569	0.7331
160 μm	12.8″	12.8″	25.6″	0.6838	0.6602

(HIPE corrections are recovered for large sky annuli)

Custom Aperture Corrections

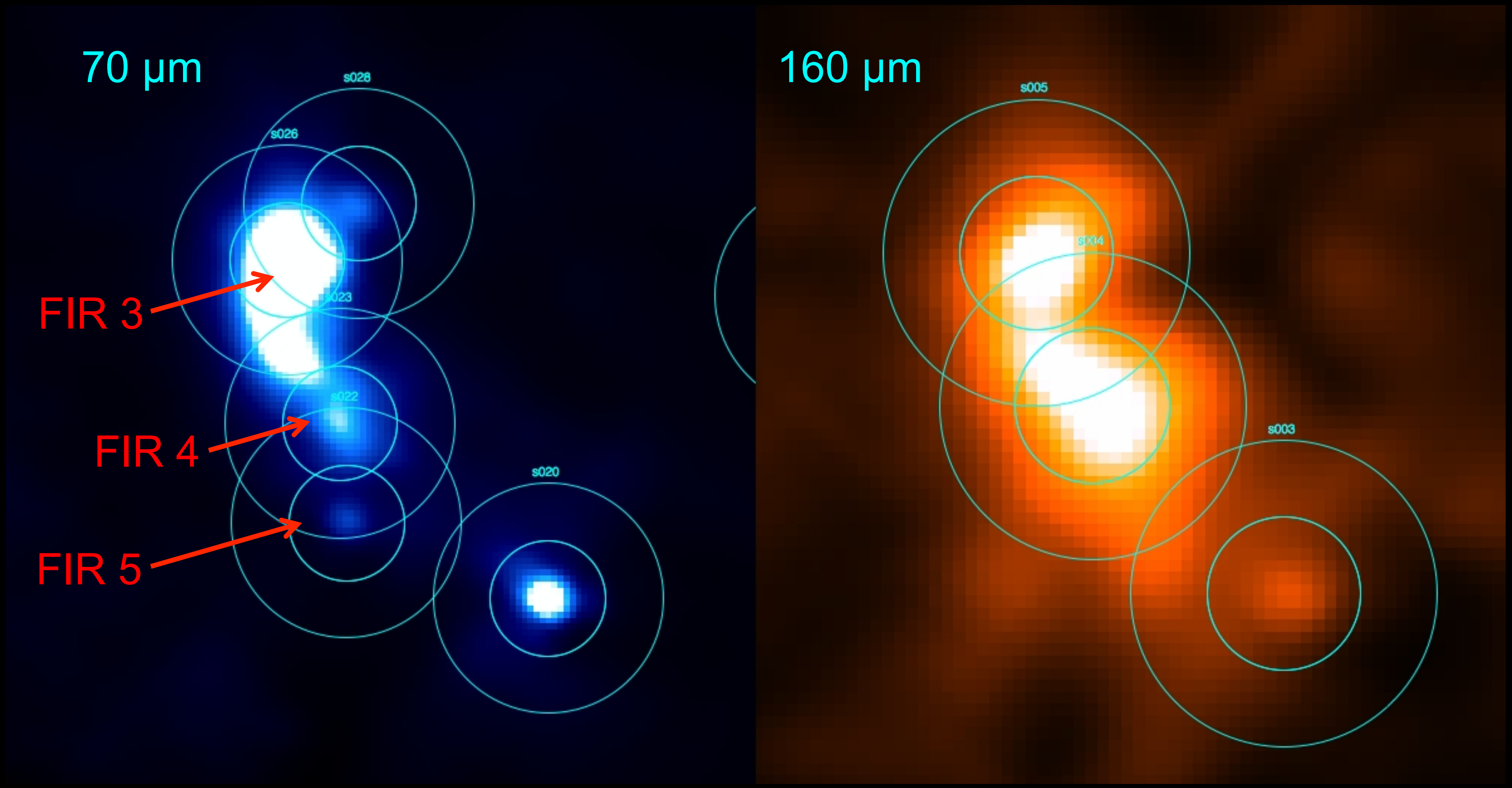




- Encircled energy fractions for each band are available as tables online or in HIPE
- HIPE's *photApertureCorrectionPointSource* interpolates these curves
- To estimate effect of sky subtraction, do photometry on an azimuthally symmetric PSF derived from the EEF
- For our apertures, fluxes were underestimated by 3.3% at 70 μm, 3.5% at 160 μm

HOPS PSF Photometry

OMC 2



Aperture photometry is problematic in crowded regions

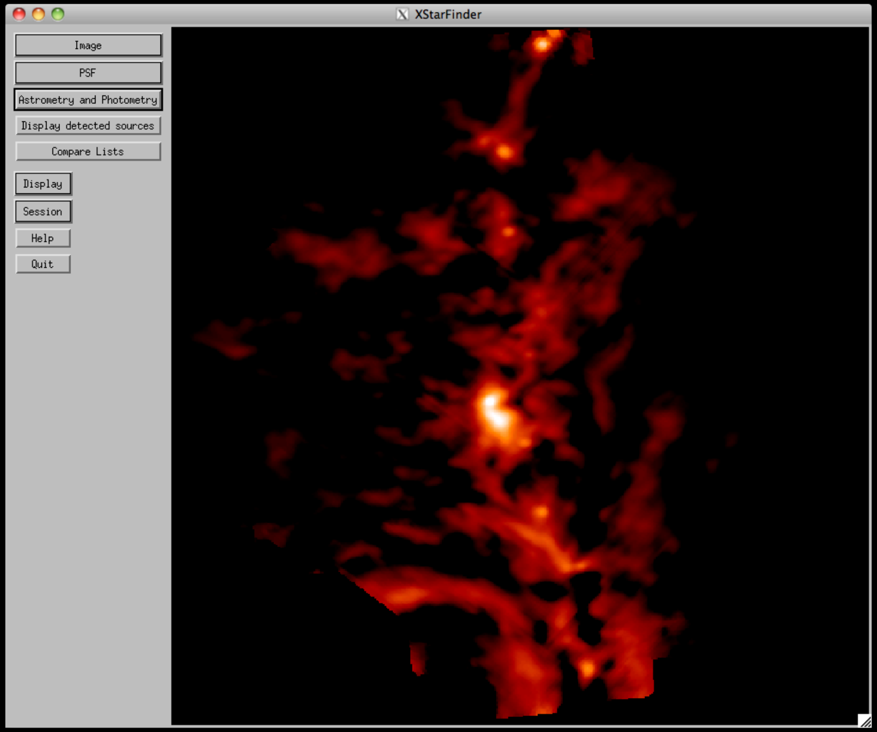
- Extended emission
- Blending of point sources

Mainly a concern at 160 µm (envelopes may be resolved)

PSF Photometry: StarFinder

- Testing StarFinder as a means of PSF photometry (Diolaiti et al. 2000, Proc. SPIE, 4007, 879)

- Uses spatial filtering to remove backgrounds – and thus, some of PSFs – so must recalibrate with aperture photometry of isolated sources

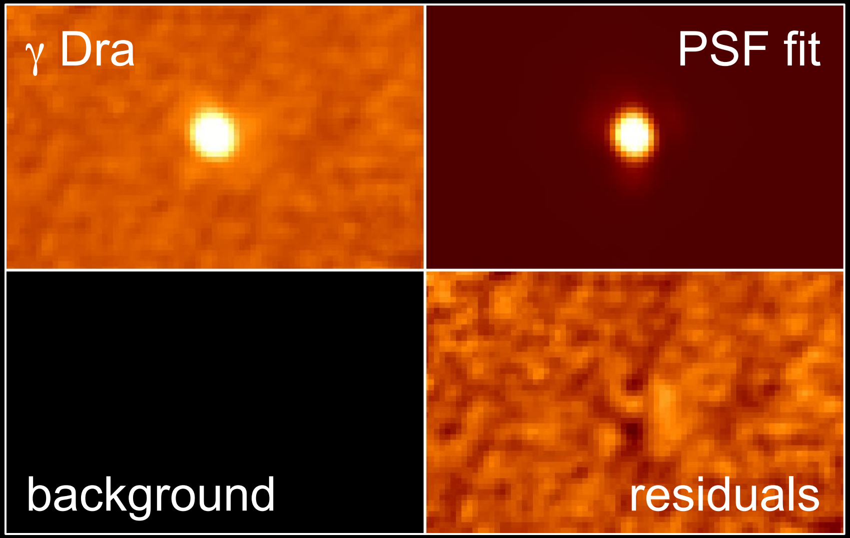


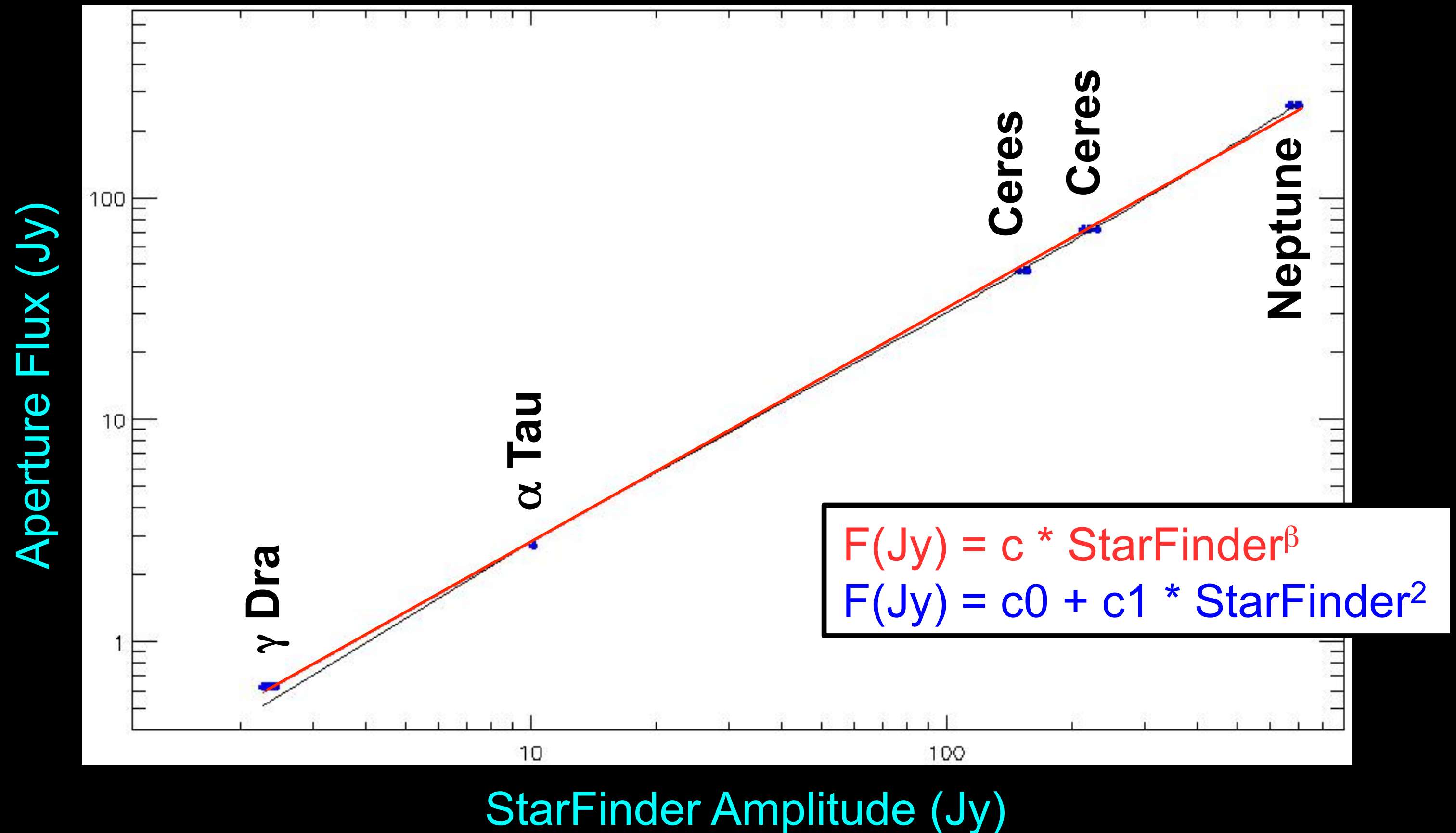
- Pros:
  - Used in the Herschel community
  - Allows treatment of complex backgrounds via spatial filtering
  - Relatively user-friendly

- Cons:
  - Requires independent calibration
  - Lacks documentation of some “sausage-making” details
  - Some potentially valuable functionality difficult to implement (e.g., fixed source positions)

StarFinder

- Mysterious that a power law is the best calibration; tests are ongoing
- Differences remain between aperture and PSF photometry for HOPS

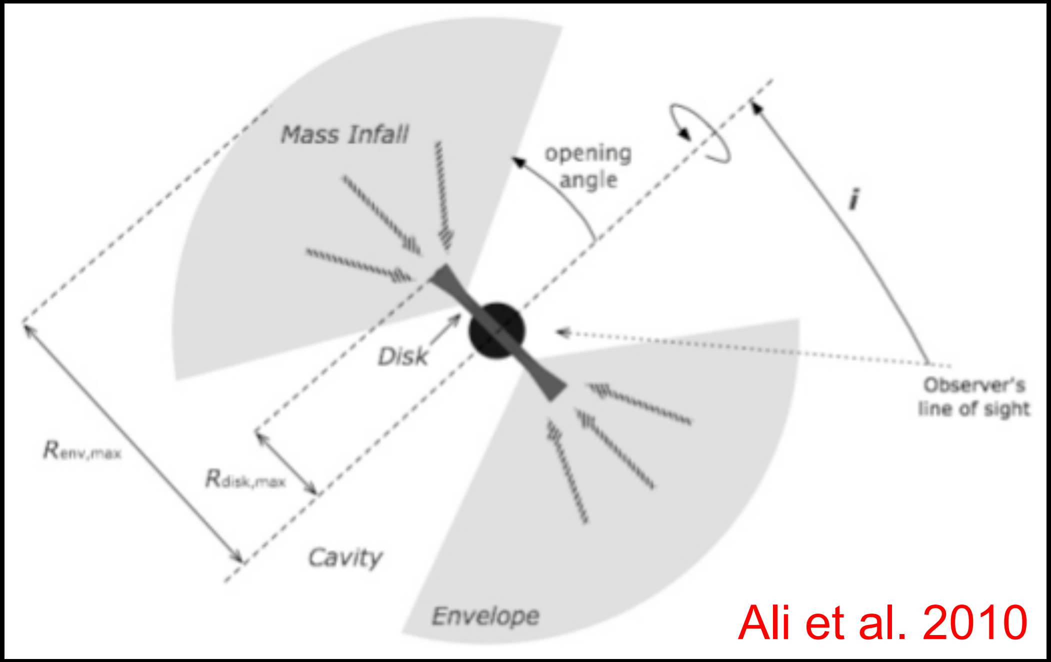




HOPS Analysis: Fitting SEDs with a Model Grid

- Use the Whitney et al. RT code
- 3040 model protostars
- 10 viewing angles
- 30,400 unique SEDs

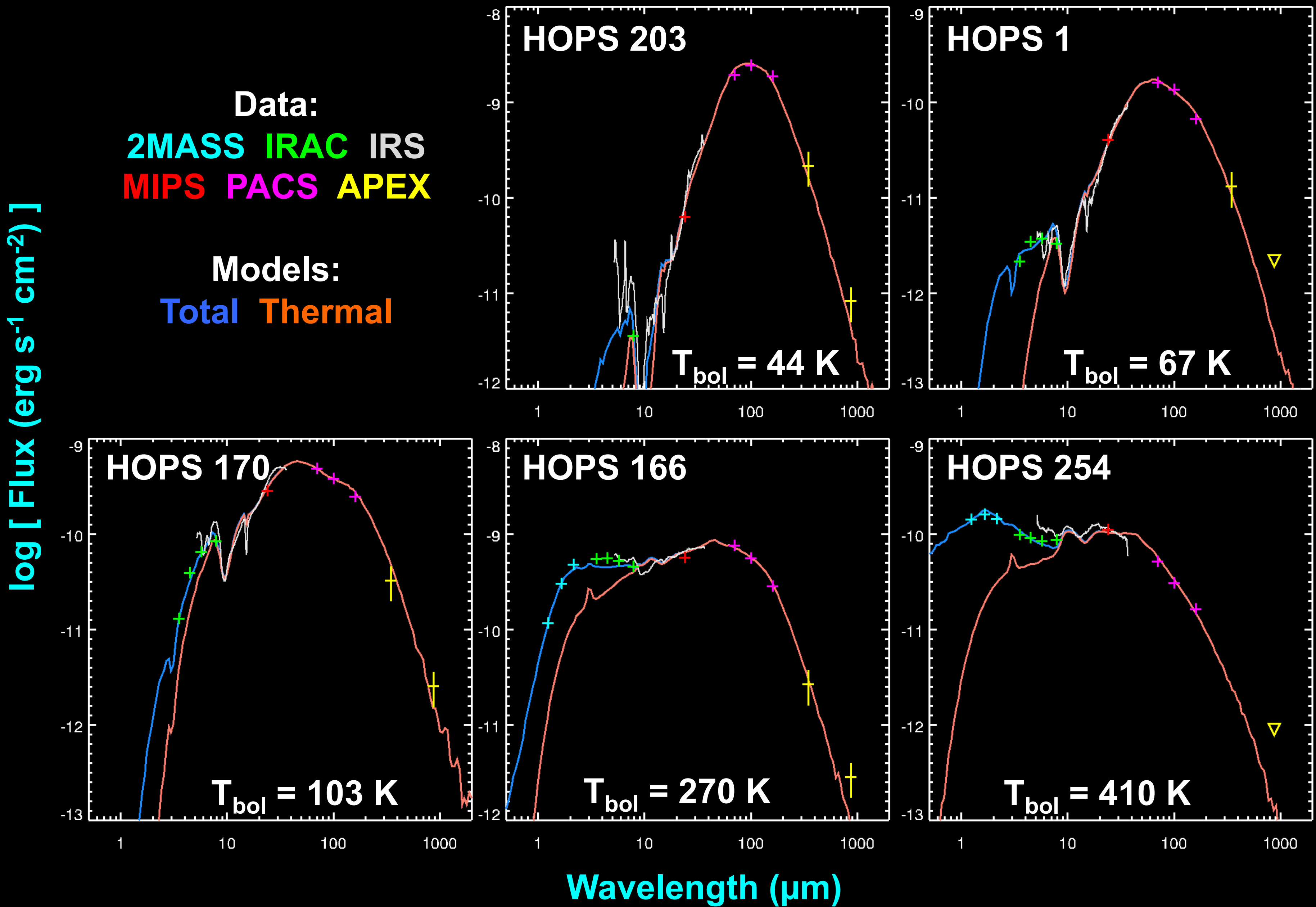
- Vary parameters relevant for protostars
  - Envelope density
  - Luminosity
  - Cavity opening angle
  - Disk radius



- Fits are evaluated with a χ^2-like statistic

- We track the bolometric properties of the best fits
  - Integrated luminosity
  - Bolometric temperature: effective temperature of a blackbody with the same mean frequency as the SED

Fitting SEDs with a Model Grid



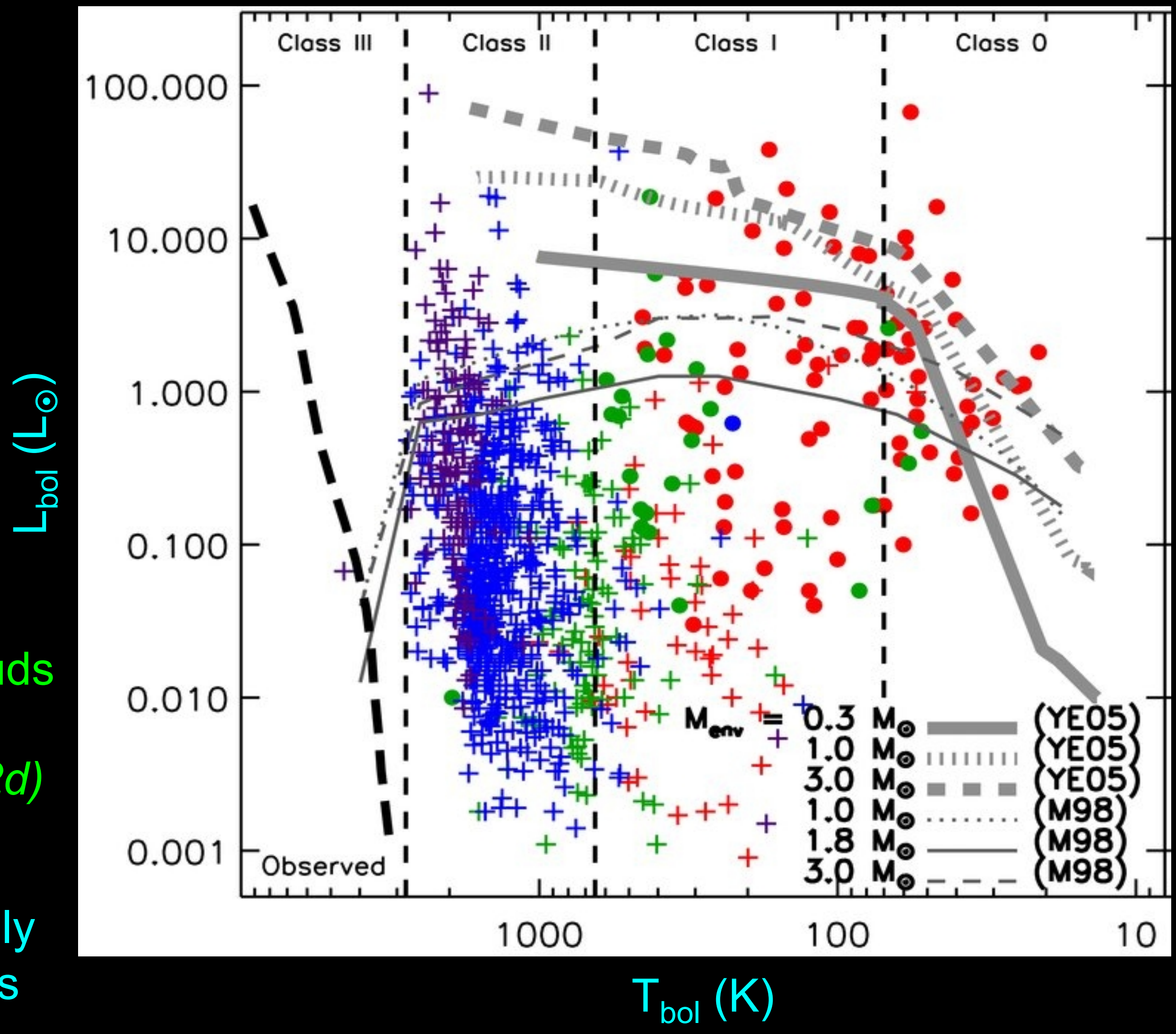
How does Herschel improve our understanding of the timeline for star formation?

- Do our estimates of source properties change with the inclusion of far-IR data?
- Are we missing a population of cold sources?

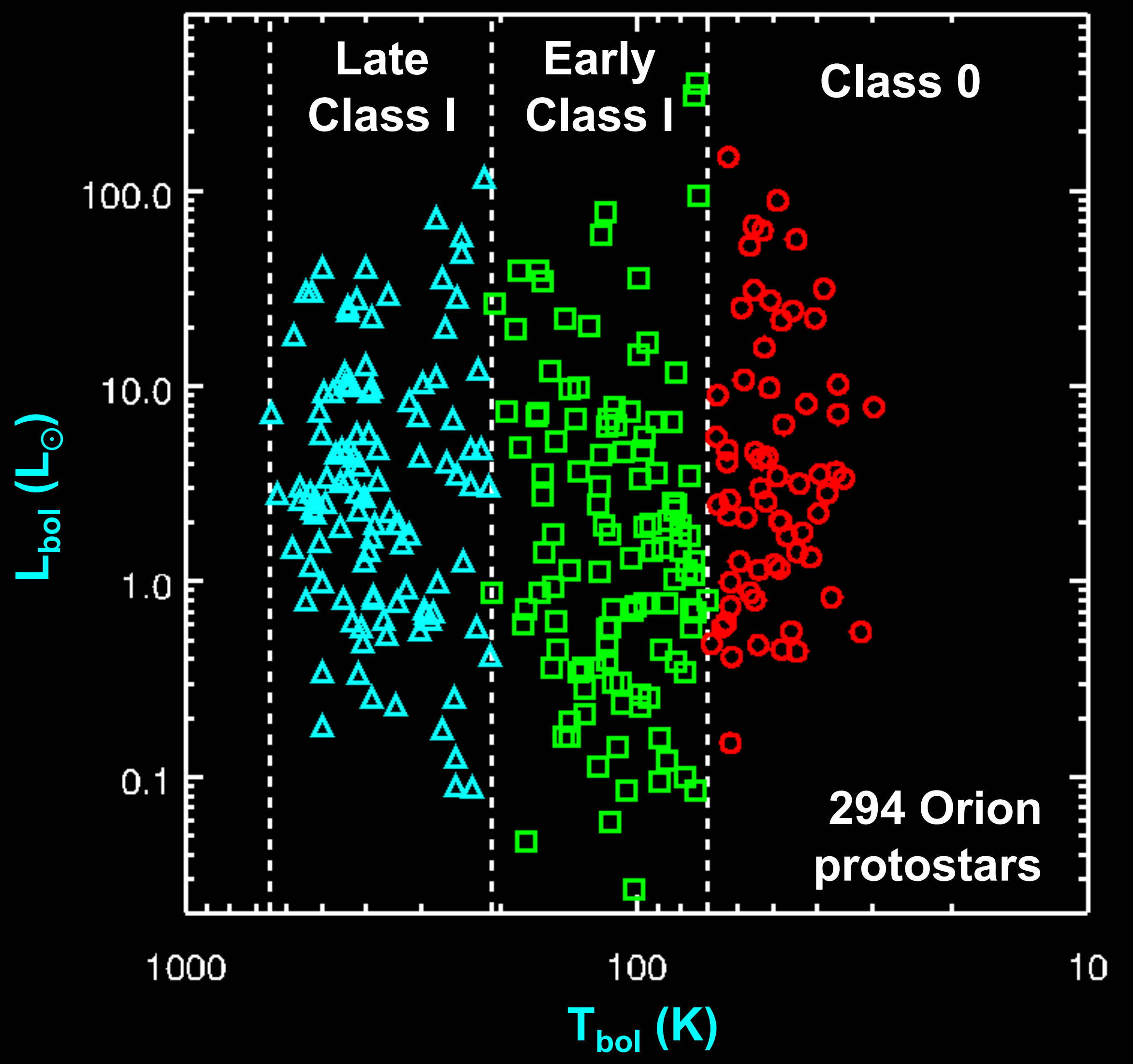
Pre-Herschel:
BLT diagram for 5 nearby clouds
(without A_V correction)
(Evans et al. 2009: Spitzer c2d)

→

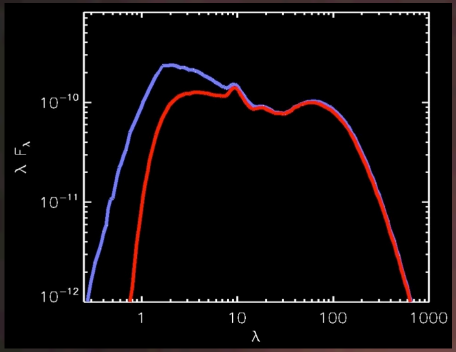
The BLT diagram is essentially an HR diagram for protostars



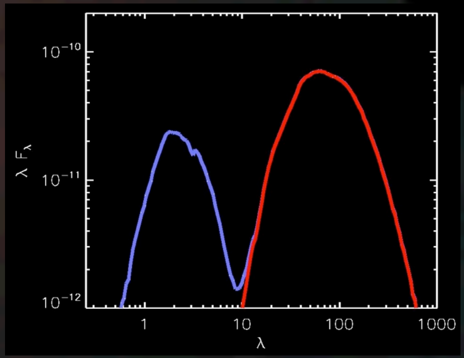
Tracing Protostellar Evolution with Bolometric Temperature



Effect of Inclination on Bolometric Temperature

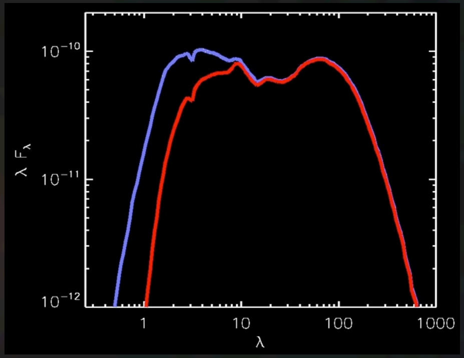


Inc = 18^o
T_{bol} = 606 K



Inc = 81^o
T_{bol} = 67 K

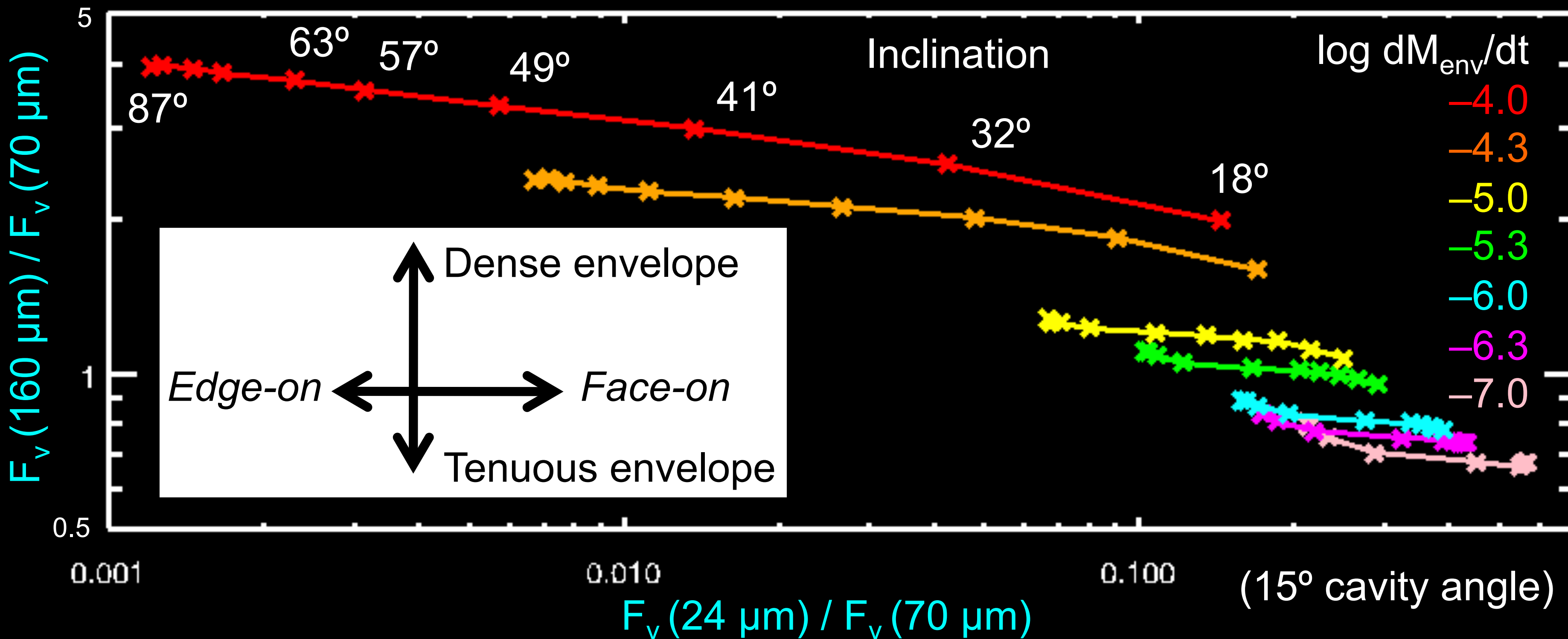
Inc = 57^o
T_{bol} = 371 K



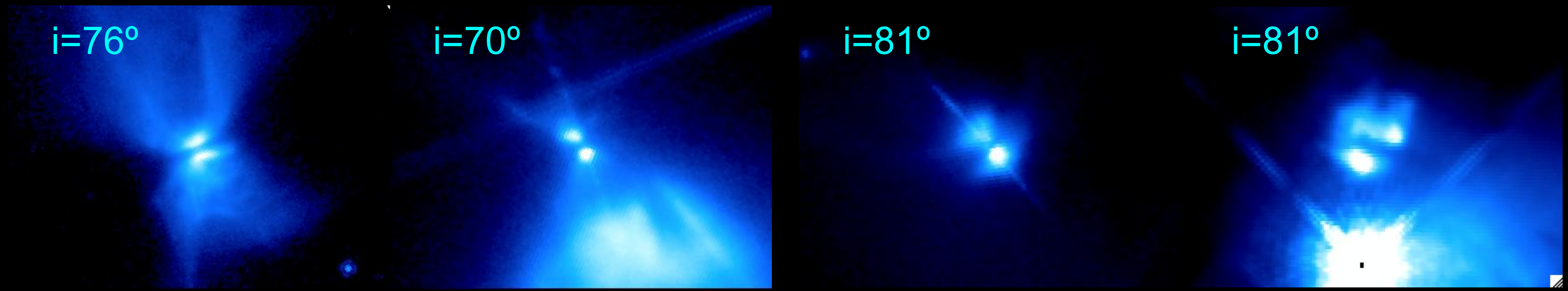
Red: Thermal Emission
Blue: Thermal + Scattered

Inclination-averaged bolometric temperature is $\langle T_{bol} \rangle$ = 393 K

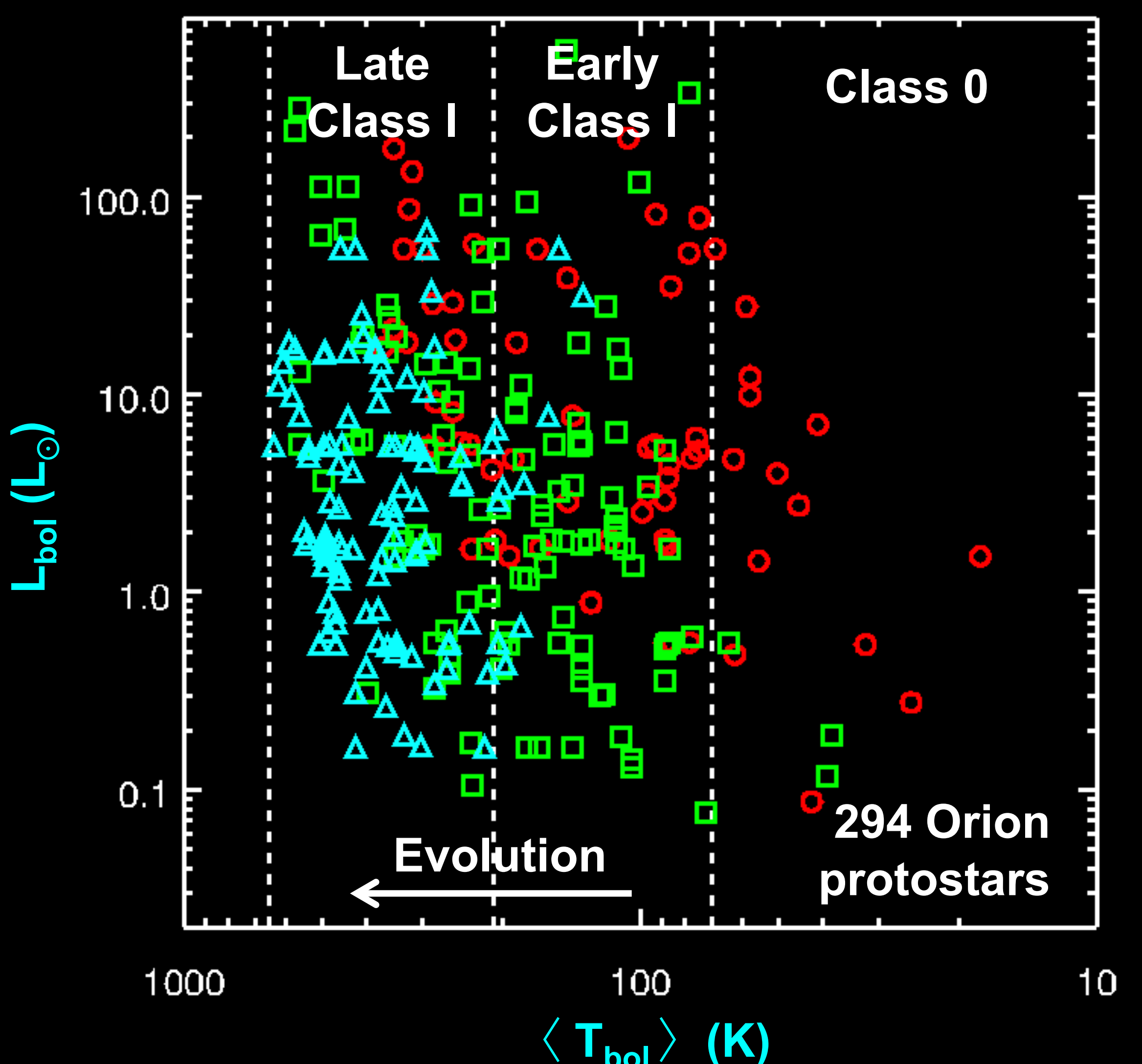
The 24 μm / 70 μm flux ratio traces inclination



(15º cavity angle)



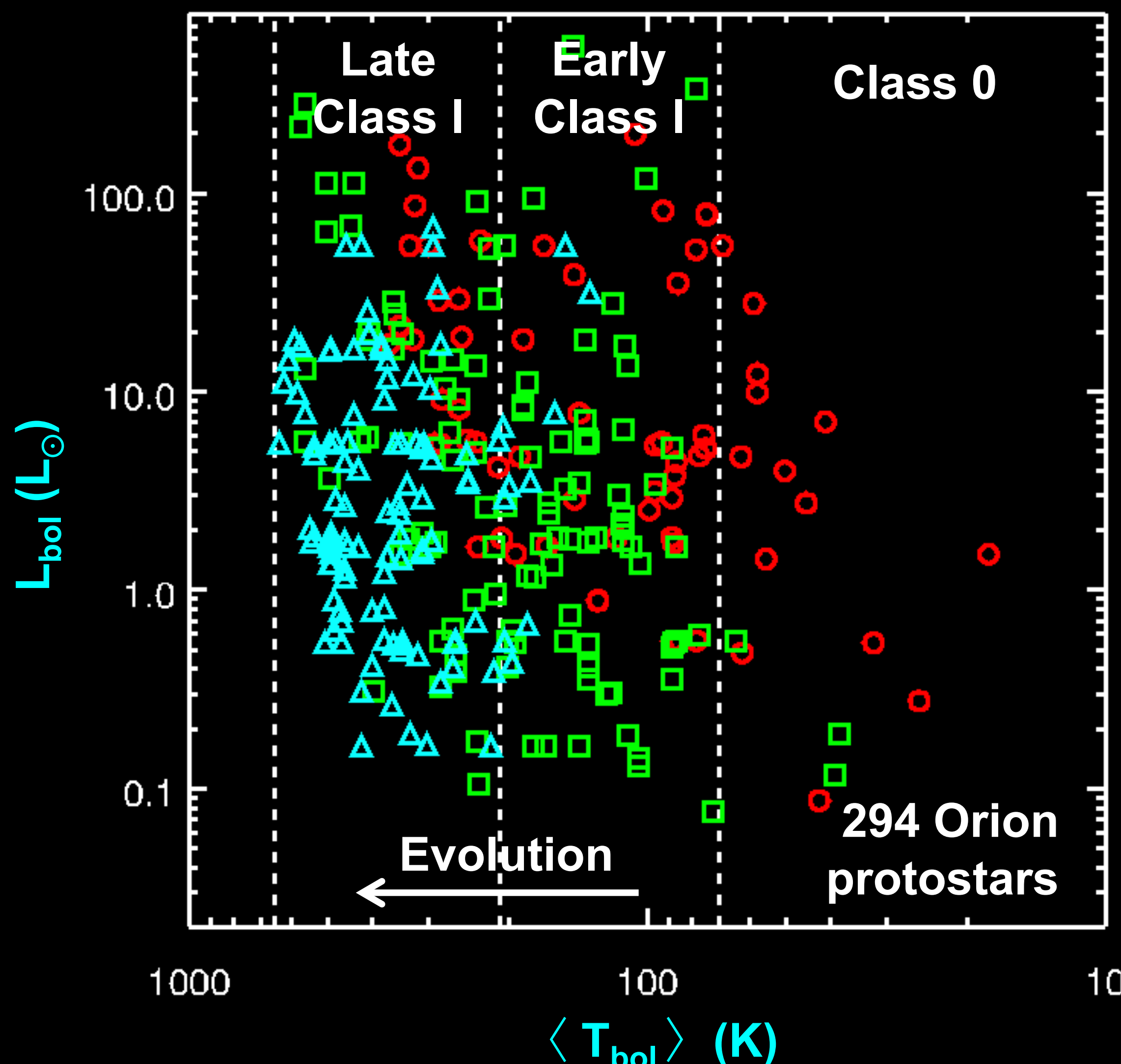
Tracing Protostellar Evolution with Inclination-Averaged Bolometric Temperature



Number = 168
$\langle L \rangle = 4.9\ L_\odot$
$\langle dM/dt \rangle = 5.0 \times 10^{-7}\ M_\odot\ yr^{-1}$
$\langle Inc \rangle = 63^{o}$

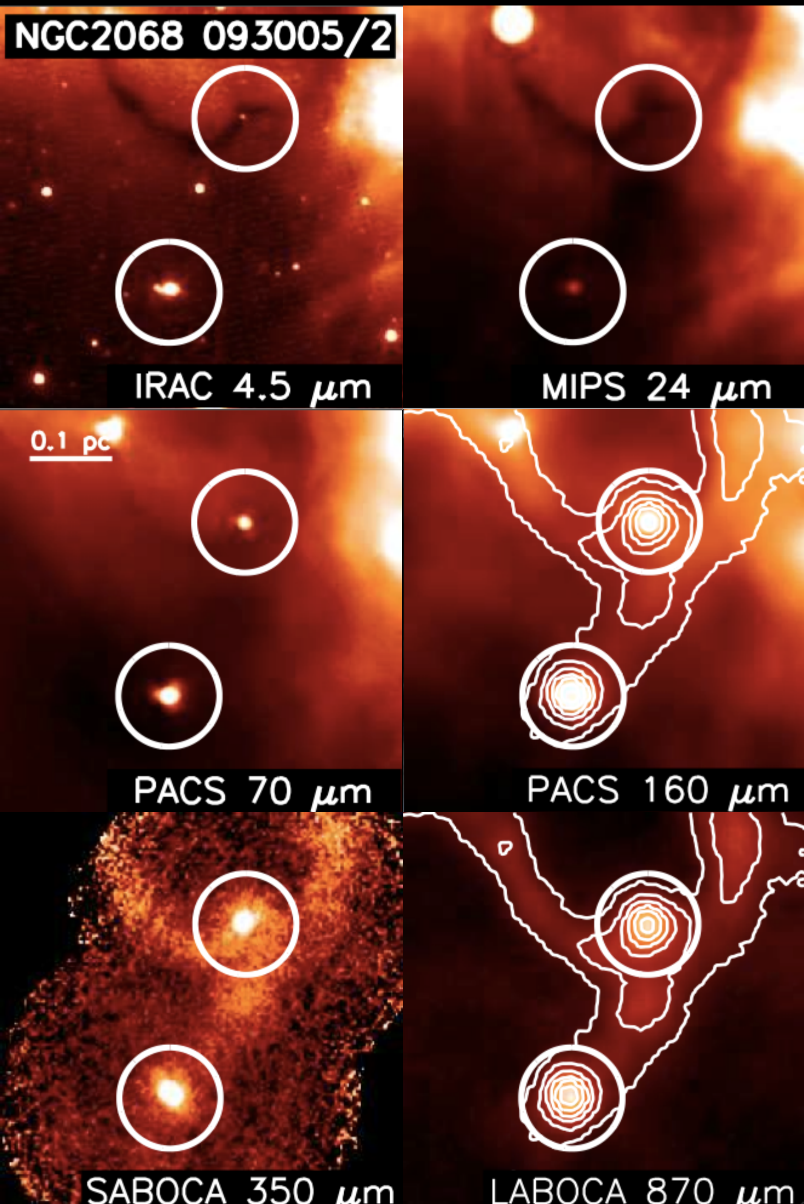
Number = 109
$\langle L \rangle = 2.5\ L_\odot$
$\langle dM/dt \rangle = 5.0 \times 10^{-6}\ M_\odot\ yr^{-1}$
$\langle Inc \rangle = 63^{o}$

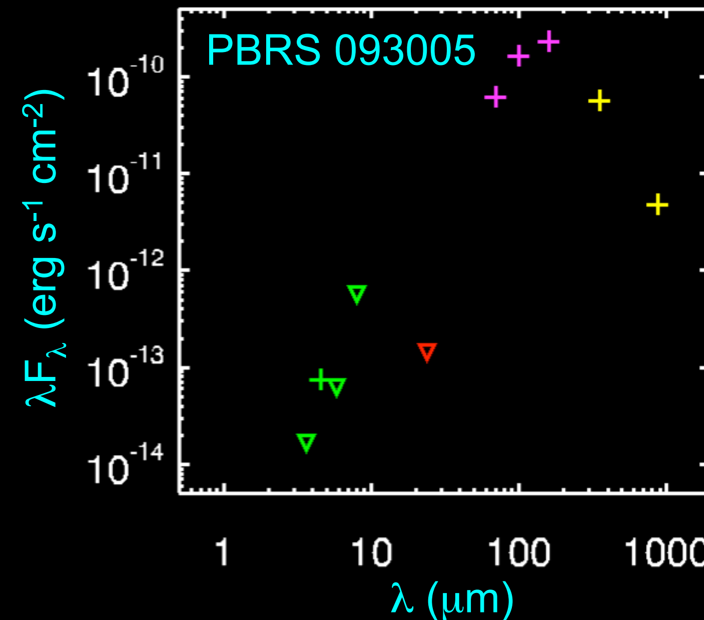
Number = 17
$\langle L \rangle = 1.5\ L_\odot$
$\langle dM/dt \rangle = 2.5 \times 10^{-5}\ M_\odot\ yr^{-1}$
$\langle Inc \rangle = 41^{o}$



New Orion Protostars: PBRS

PACS Bright Red Sources (Stutz et al. in press)





- PACS images: 55 new candidate protostars that are undetected or too faint to be classified as protostars in MIPS 24 μm

- 11 unambiguous Class 0
- 14 likely Class 0 or low-luminosity Class I
- 30 likely contaminants

- Class 0 PBRS partially restore the deficit left after the inclination correction

HOPS is characterizing the 300+ Spitzer-identified Orion protostars with PACS and extensive ancillary data

Photometric Techniques

- Nebular emission: small apertures, close-in sky annuli, custom aperture corrections
- PSF photometry with StarFinder: HOPS PSF fluxes differ from aperture fluxes (under investigation)

Effect of Herschel Imaging and Inclination Correction on Protostellar Properties

- Many apparent Class 0 protostars are more evolved but appear young due to edge-on orientations
- 70 μm / 24 μm flux ratio drives SED-based inclinations; generally confirmed with HST imaging of scattered-light nebulae
- After correcting for inclination, luminosity increases with evolutionary state
- Herschel revealed 11 new unambiguous Class 0 protostars and 14 more candidates
- Accounting for new Herschel sources, protostars spend about
  - 10% of their lifespan in a high-infall stage (Class 0)
  - 40% of their lifespan in a moderate-infall stage (early Class I)
  - 50% of their lifespan in a low-infall stage (late Class I)