Adding HOPS to the Hunter's Brew: Insights from Herschel on Star Formation in Orion

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HOPS: Herschel Orion Protostar Survey

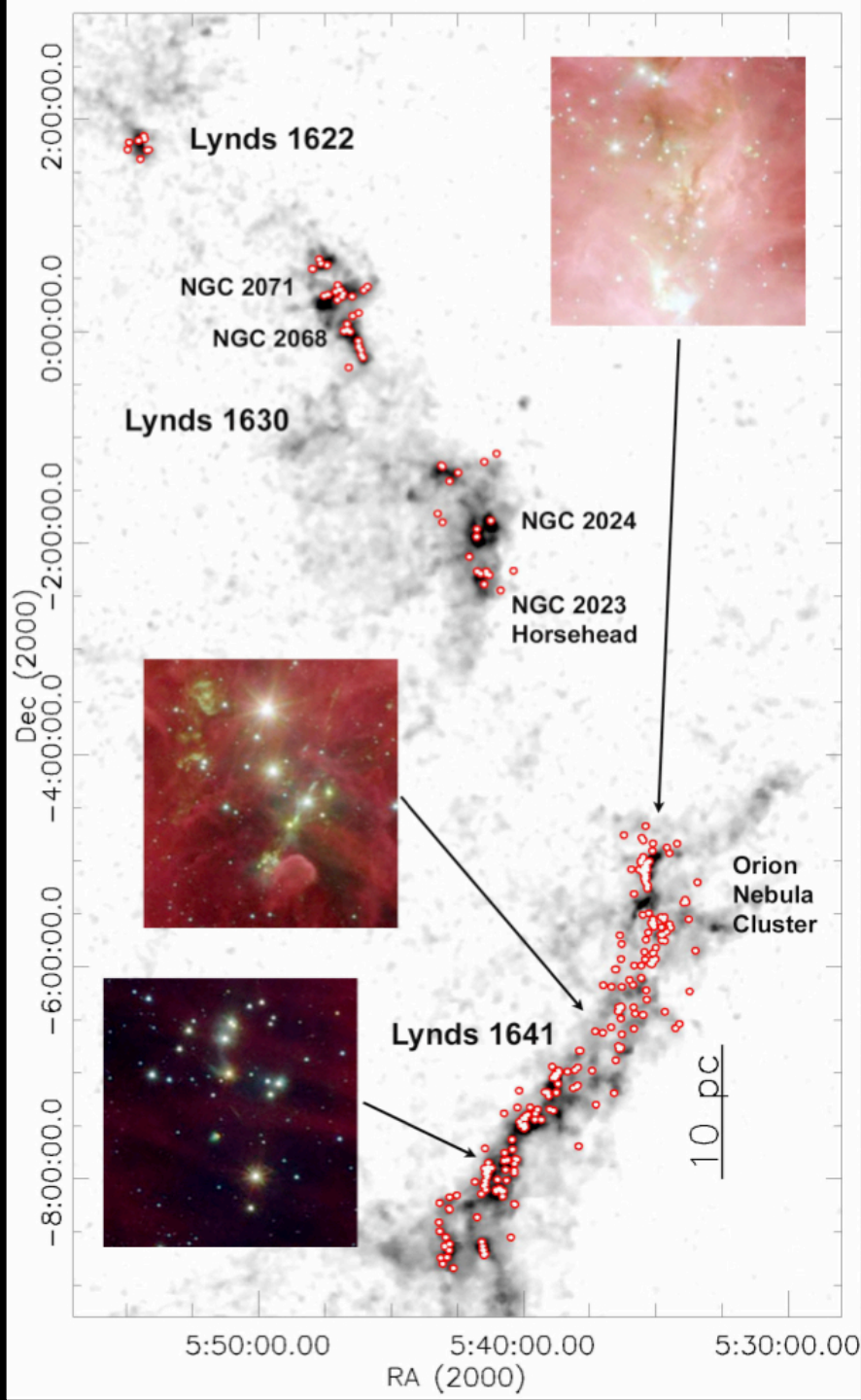
PACS imaging (286+ targets):

- Spitzer-identified protostars with extrapolated fluxes > 42 mJy at 70 μm (~0.2 $L_\odot$, but can detect fainter)
- 70 and 160 μm
- 114 fields of 5' to 8'
- Medium (20"/s) scan rate

And…

PACS spectroscopy (32 targets)
Spitzer imaging + spectra
Near-IR imaging + spectra
Sub-mm data

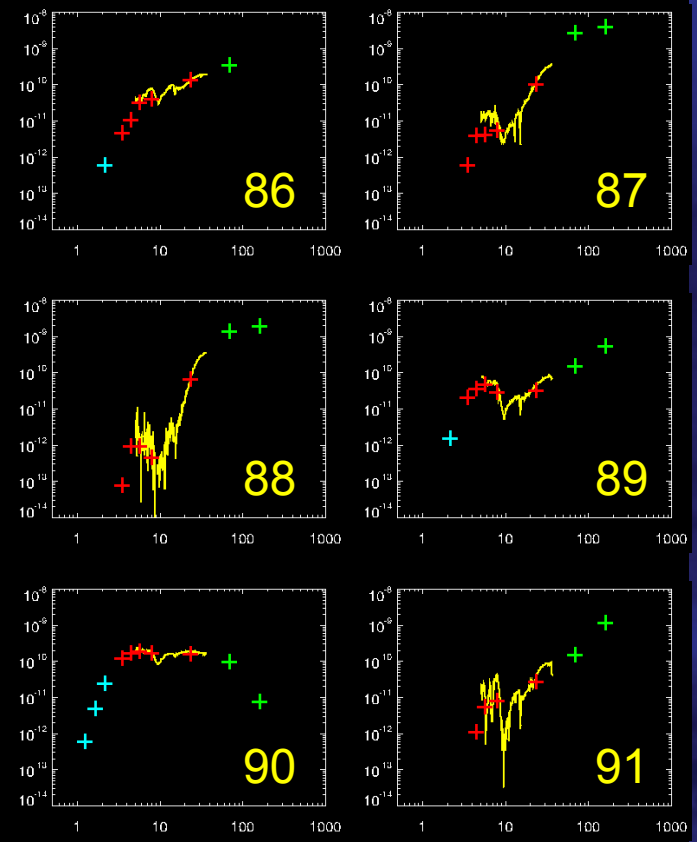
Sources sample environments from isolated to clustered

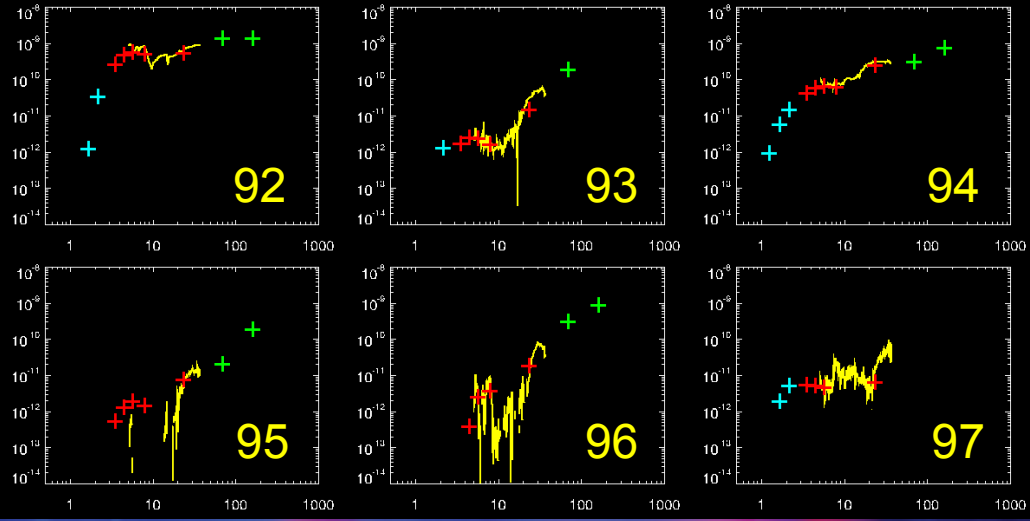


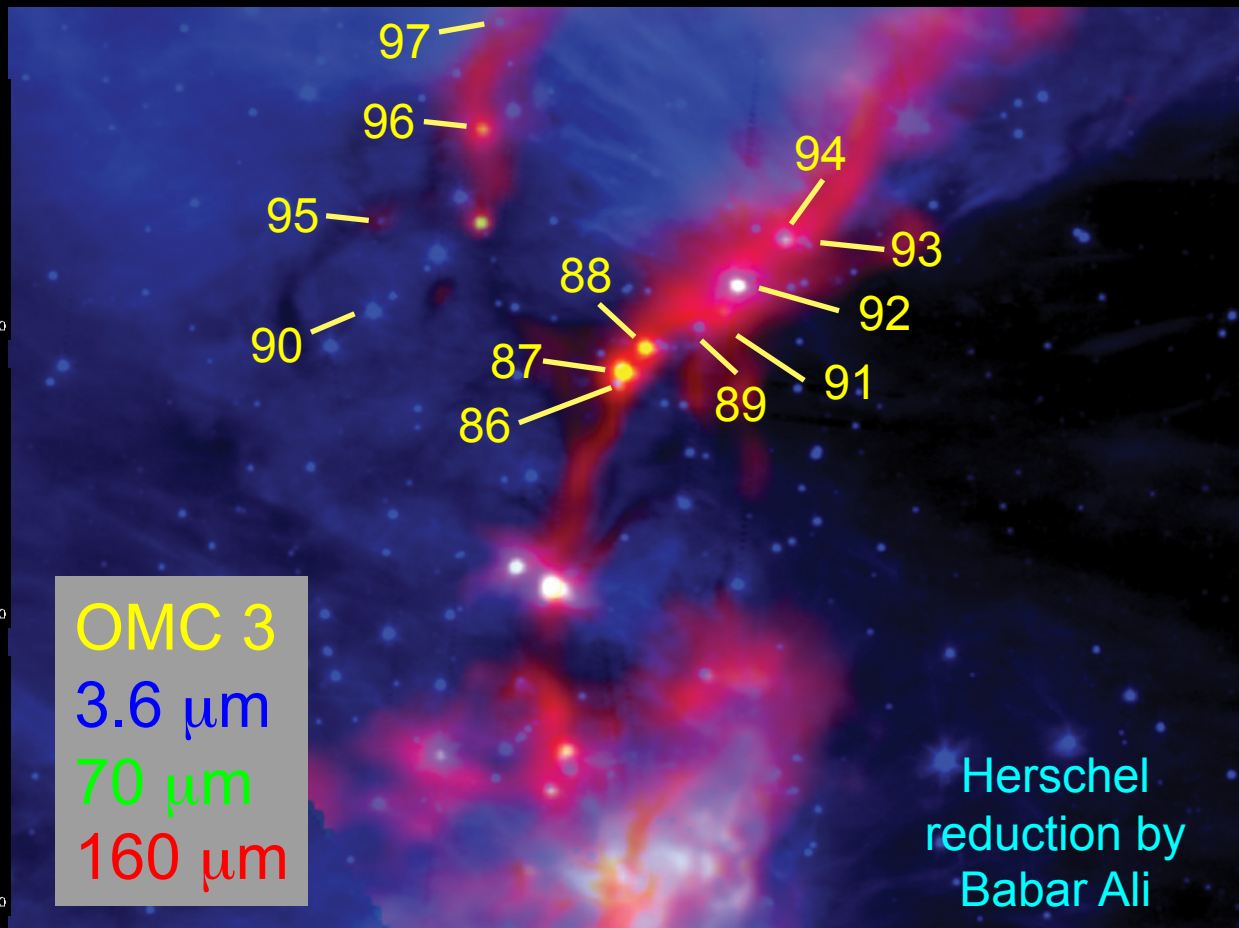
Construction of SEDs

370 Spitzer-identified sources

- 2MASS
- Spitzer IRAC + MIPS 24
- Spitzer IRS
- Herschel PACS 70, 160
- Sub-mm forthcoming



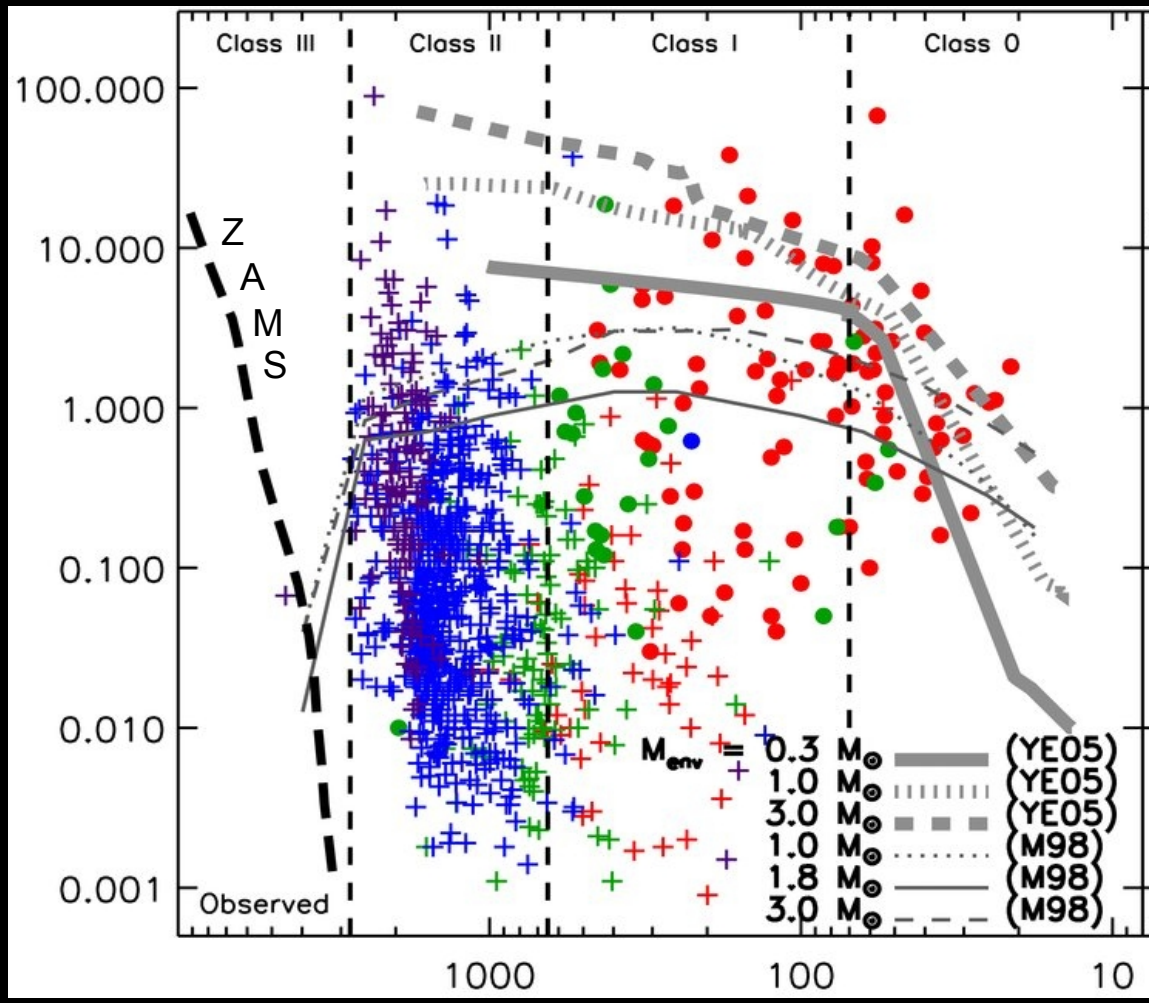




Bolometric Luminosity & Temperature (BLT)

(Myers & Ladd 1993)

- Integrated luminosity
- Bolometric temperature (T_{eff} of blackbody with same mean frequency)
- T_{bol} increases with envelope evolution *(Chen et al. 1995)*
  - Class 0: $T_{bol} < 70$ K
  - Class I: $70 \text{ K} < T_{bol} < 650$ K
  - Class II: $650 \text{ K} < T_{bol} < 2800$ K



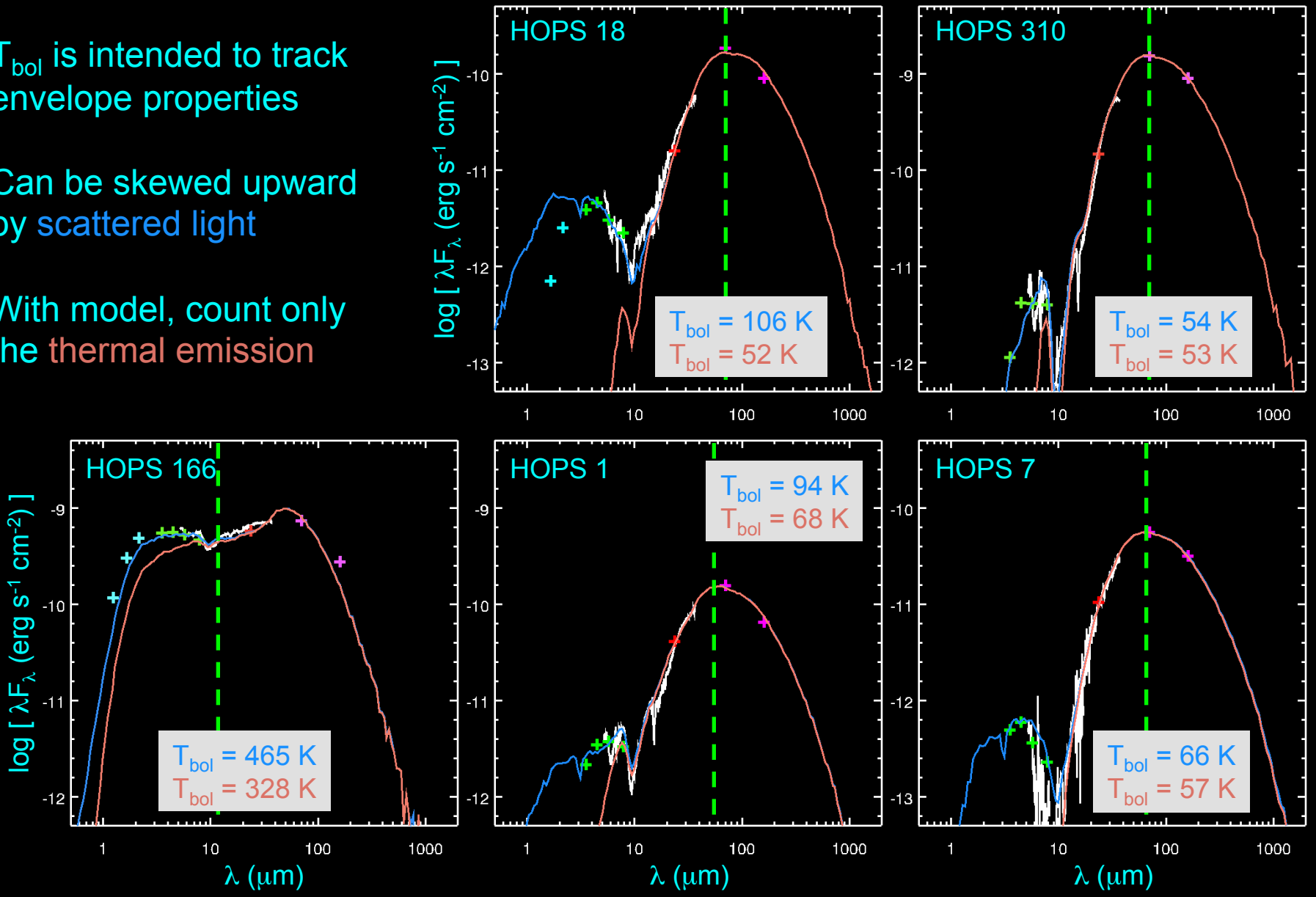
BLT for 5 nearby clouds (without A_V correction)
(Evans et al. 2009: Spitzer c2d)

BLT Methodology

- Integrating under SED yields systematic errors due to…
  - Incomplete λ coverage
  - Inclination angle
  - Foreground reddening
- Instead do grid-based fitting
  - In-house grid of 5,760 *Whitney et al.* models x 10 viewing angles = 57,600 SEDs (John Tobin)
  - Report intrinsic L and T_{bol} of best model
    - Corrected for inclination, foreground reddening
    - Robust properties (set of best models share ~ same L, T_{bol})

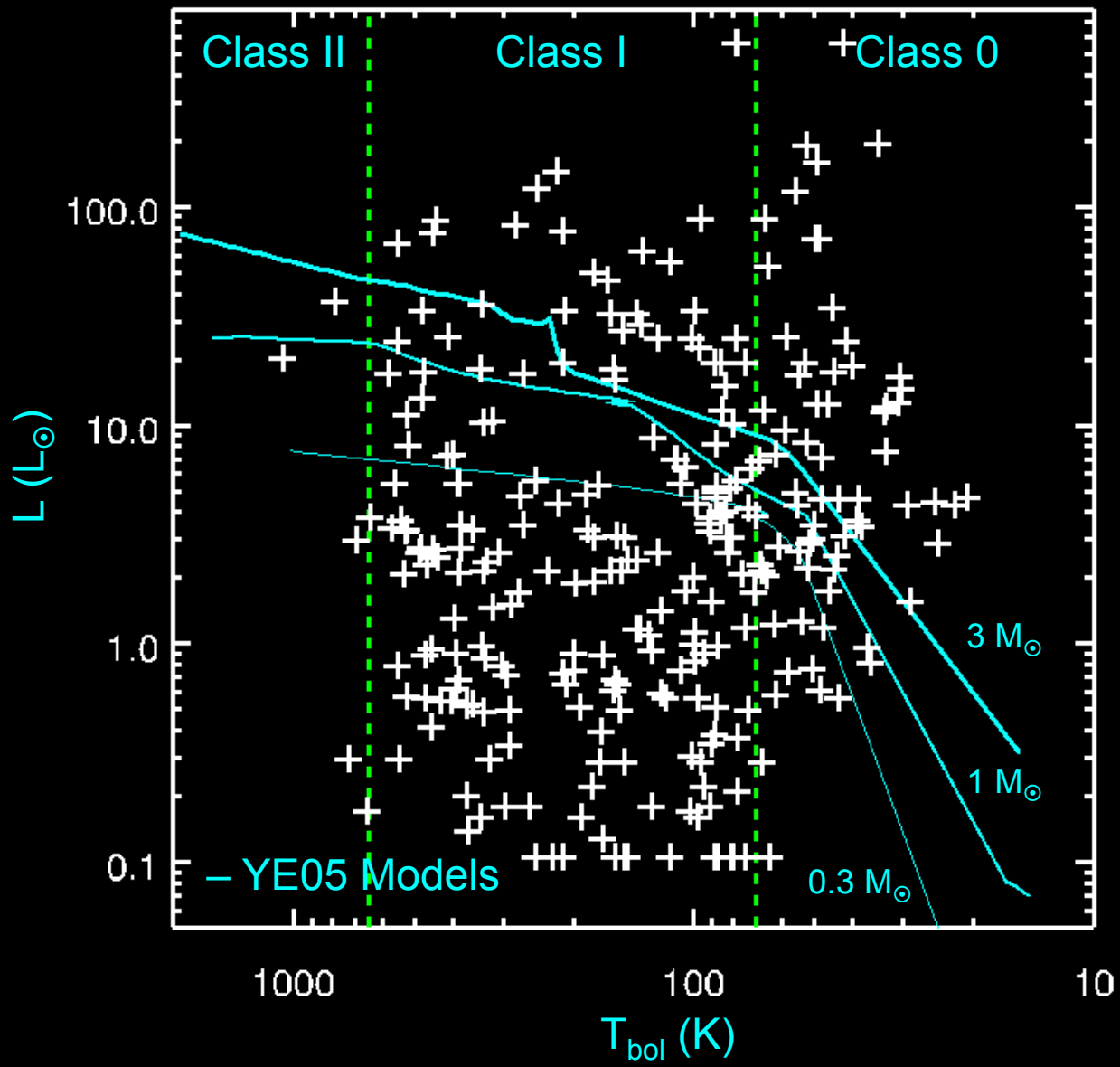
Alternative Definition for T_{bol}

- T_{bol} is intended to track envelope properties
- Can be skewed upward by scattered light
- With model, count only the thermal emission



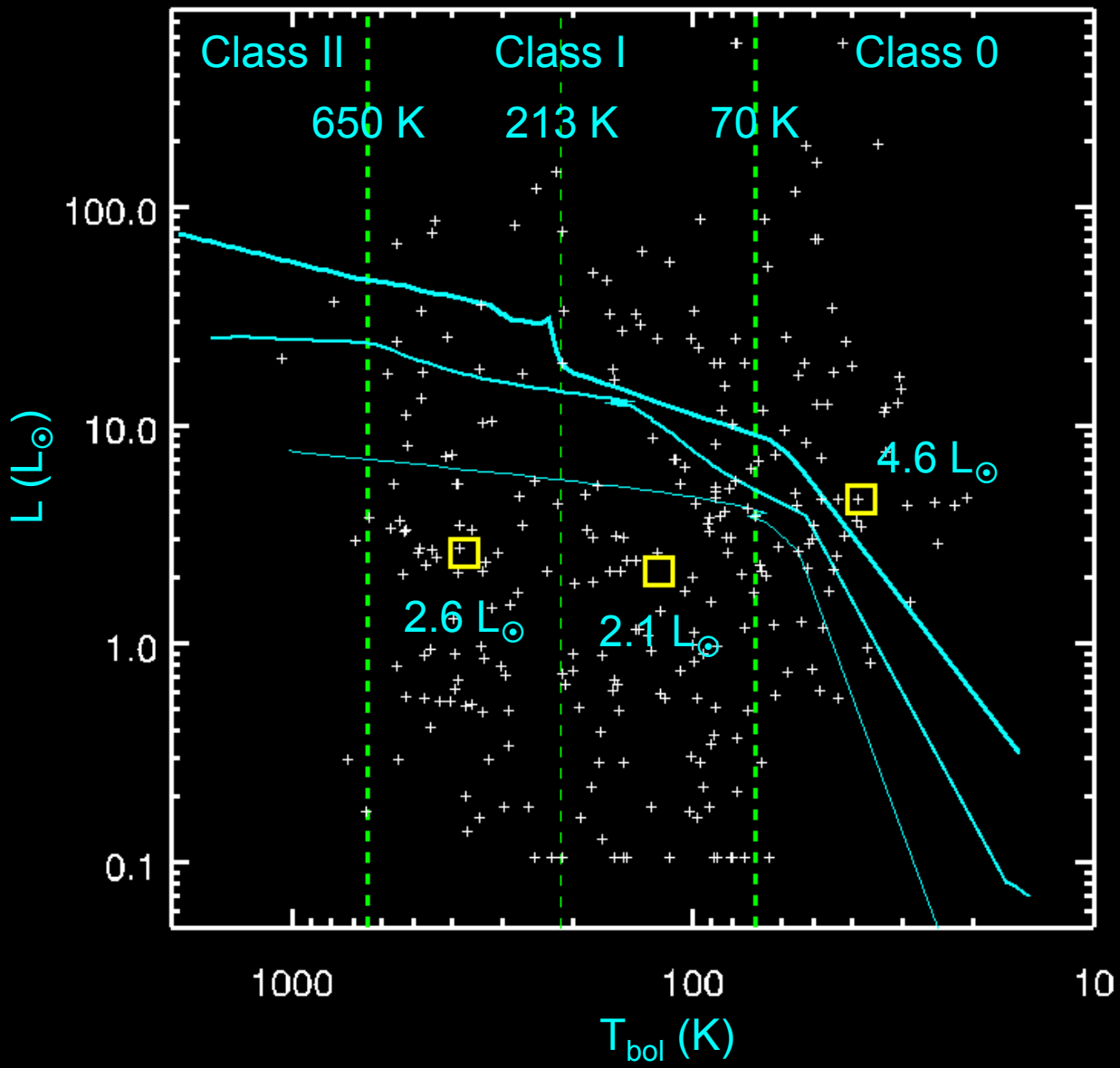
HOPS BLT

- 276 sources; about 75% of the sample
- Intrinsic L vs. T_{bol} of thermal emission for model fit to each source
- Significant spread compared to YE05 models
- Population of luminous Class 0 sources
  - Early stage of rapid accretion?
  - Undercounting of low-luminosity Class 0 sources?



HOPS BLT

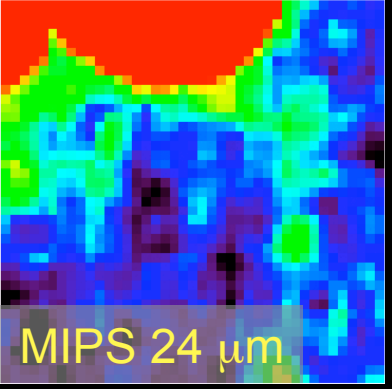
- Two Class I bins for ~equal sources per bin
  - Late Class I
  - Early Class I
  - Class 0
- Median luminosities
  - Late Class I: 2.6 $L_\odot$
  - Early Class I: 2.1 $L_\odot$
  - Class 0: 4.6 $L_\odot$
- Number counts
  - Class II: 5 interlopers
  - Class I: 75% (203)
    - 81 Late
    - 122 Early
  - Class 0: 25% (68)

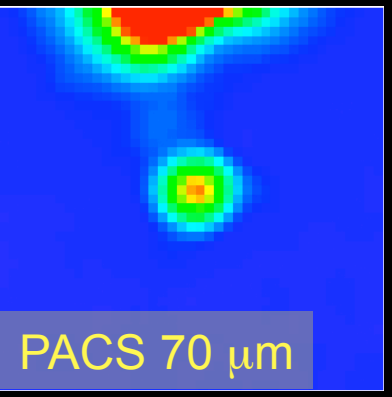


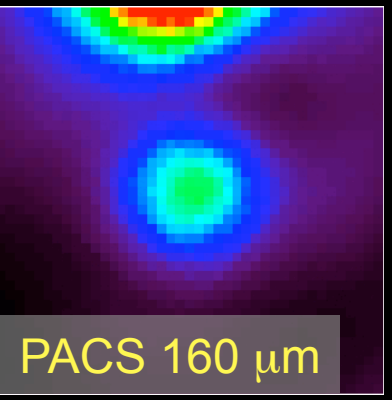
Ratio of Class 0/I = 0.33, consistent with 0.30 reported for nearby clouds

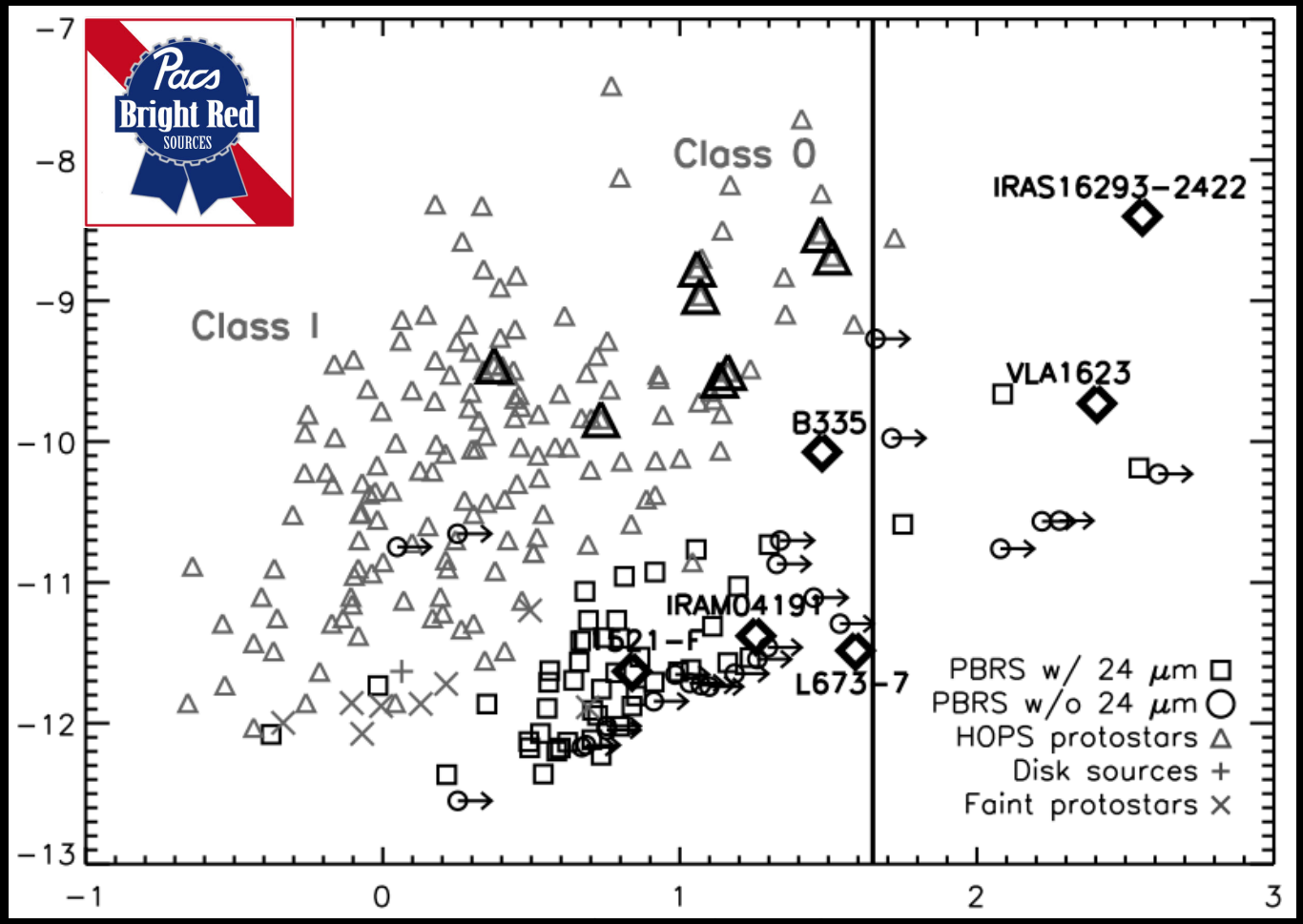
New Orion Protostars: PBRS

PACS Bright Red Sources







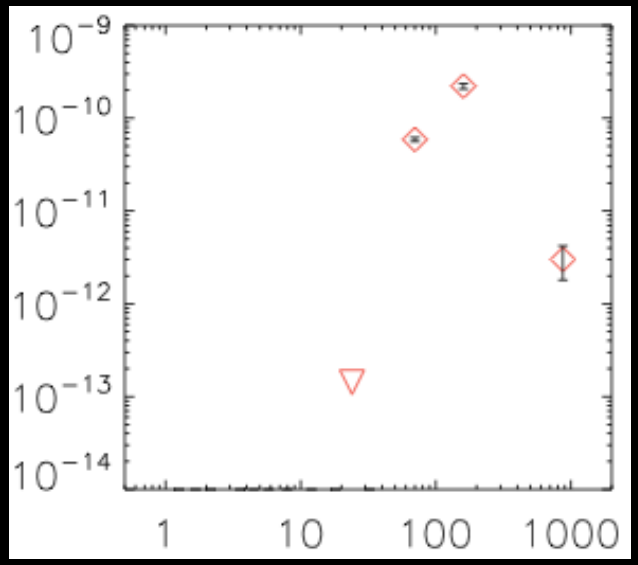


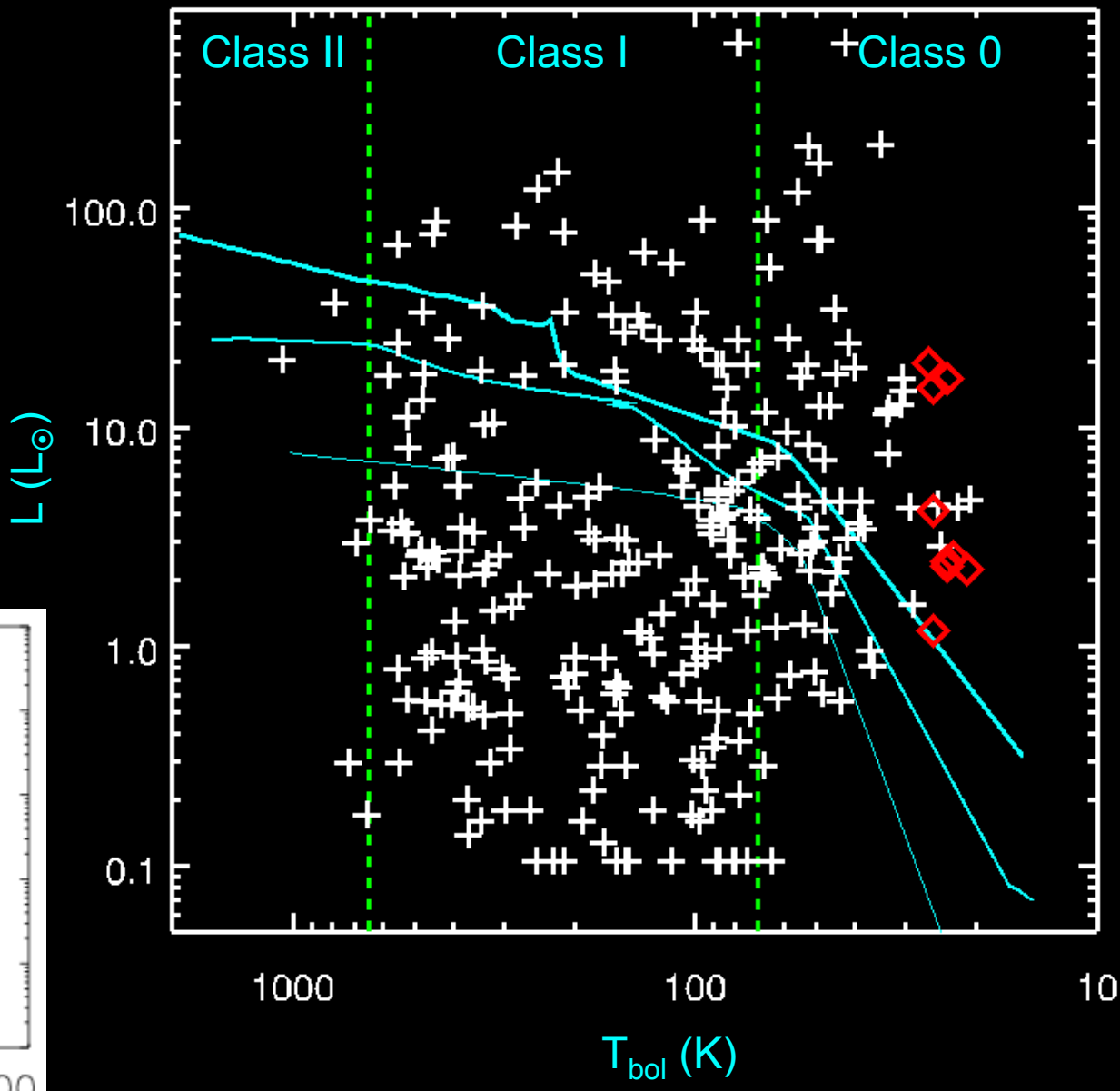
- 78 protostars newly identified in Herschel 70 μm images (Amy Stutz)
- Undetected or very faint in Spitzer 24 μm images

PBRS and BLT

- Nine reddest PBRS have
  T_{bol} ~ 25 K
  L = 1 – 10 $L_\odot$
- May be in a very early evolutionary stage

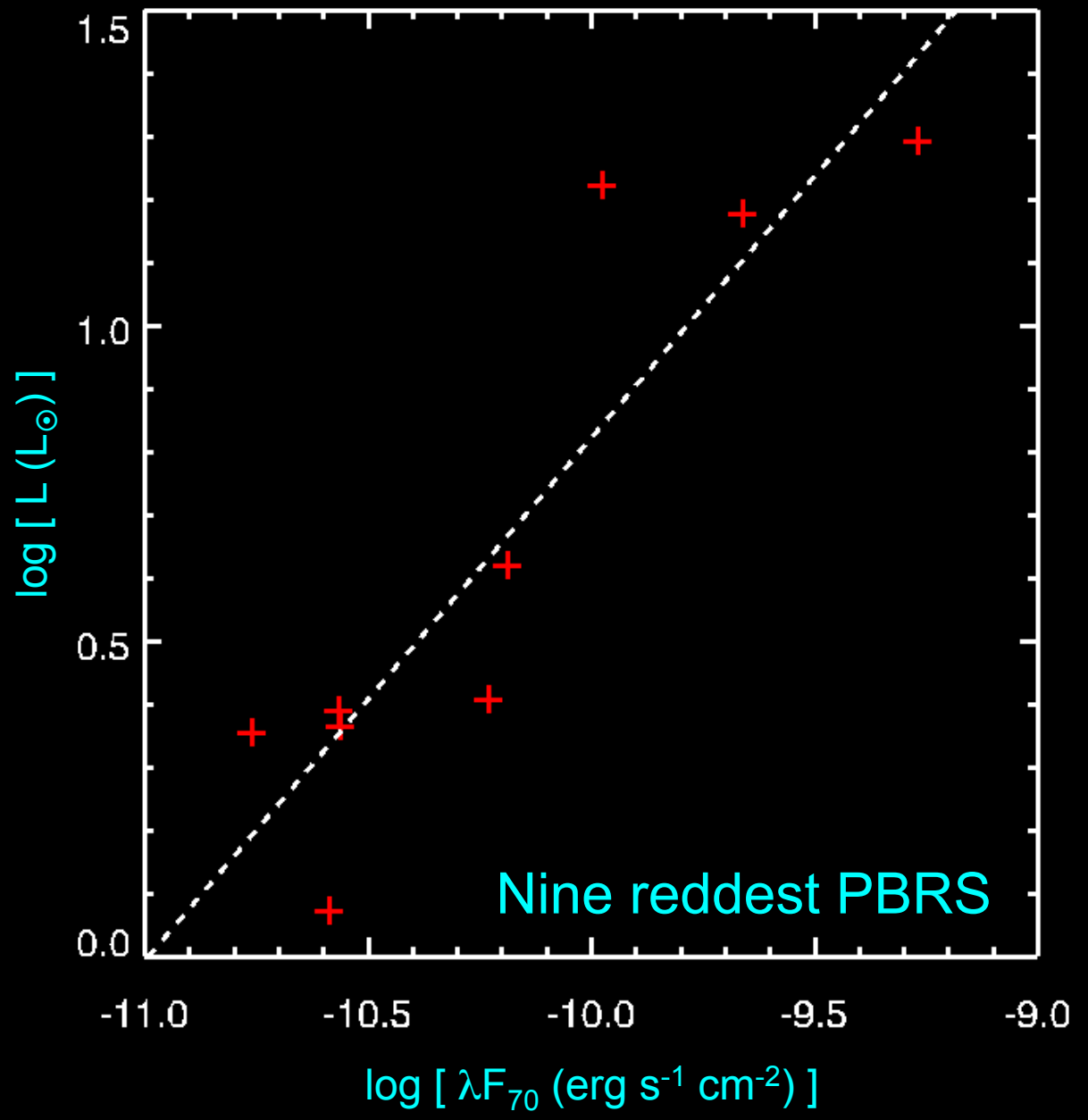
PBRS 093005





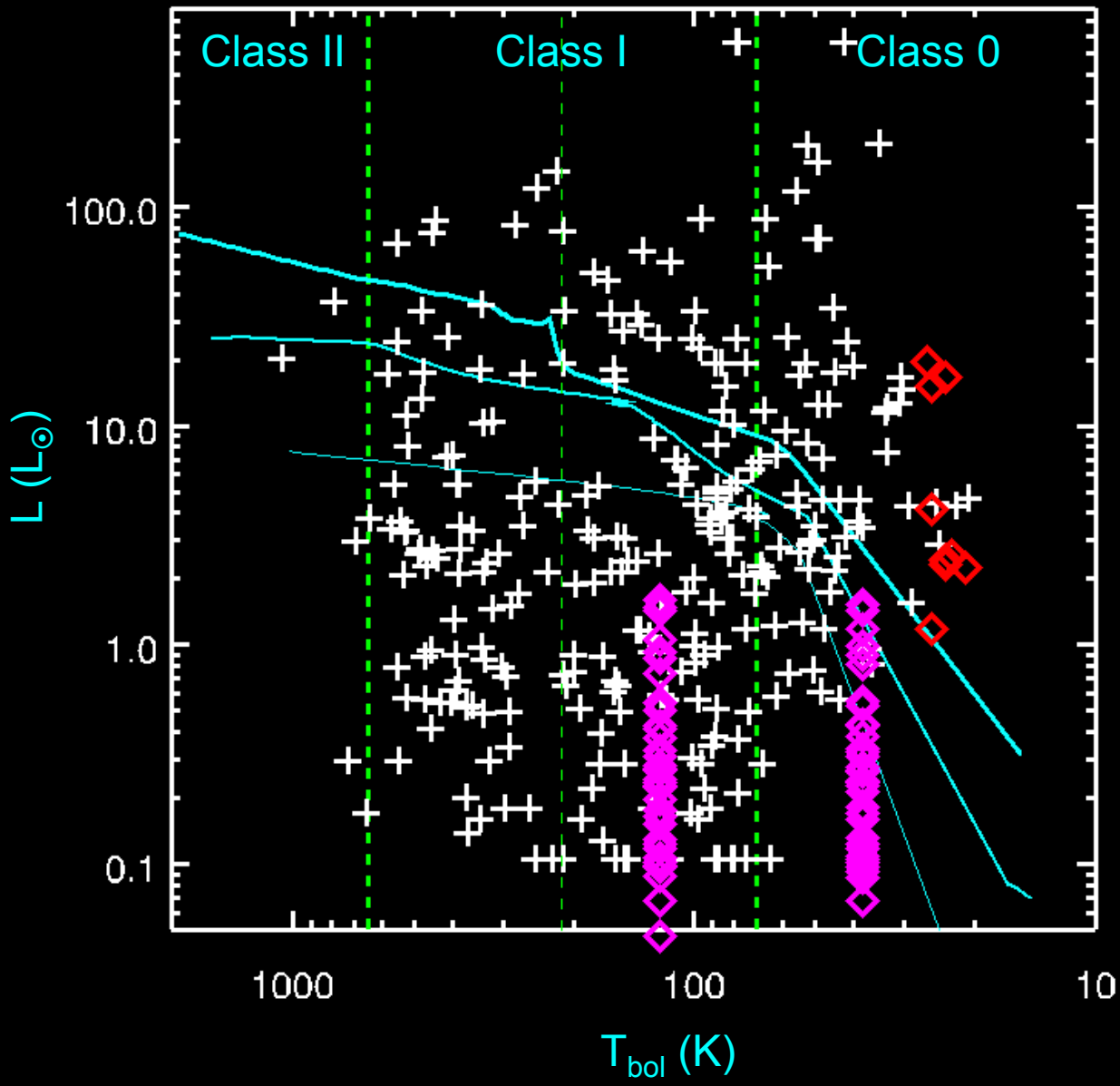
PBRS and BLT

- Remaining 69 PBRS are not as dramatically red, but likely have low L, T_{bol}
- Extend luminosity vs. F_{70} relationship for the modeled PBRS to the fainter PBRS
- $0.05 < L\ (L_{\odot}) < 1.6$ for the low-luminosity PBRS



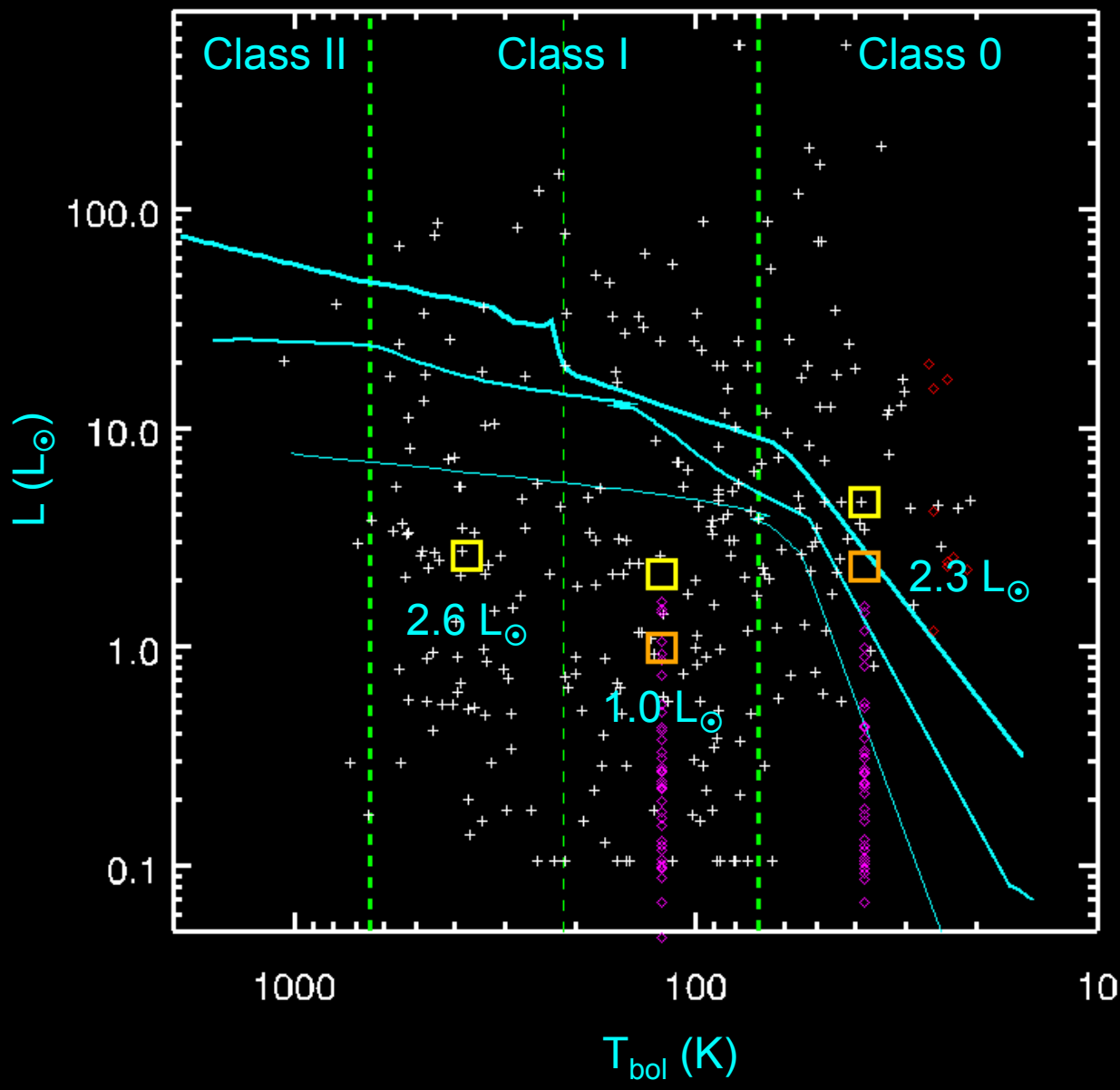
PBRS and BLT

- Add in luminosities of PBRS estimated from their 70 μm fluxes
- Assume half in Early Class I, half in Class 0 (based on location in the 70 vs. 70/24 plot)
- T_{bol} classfication of low-luminosity PBRS is uncertain; will be refined with modeling



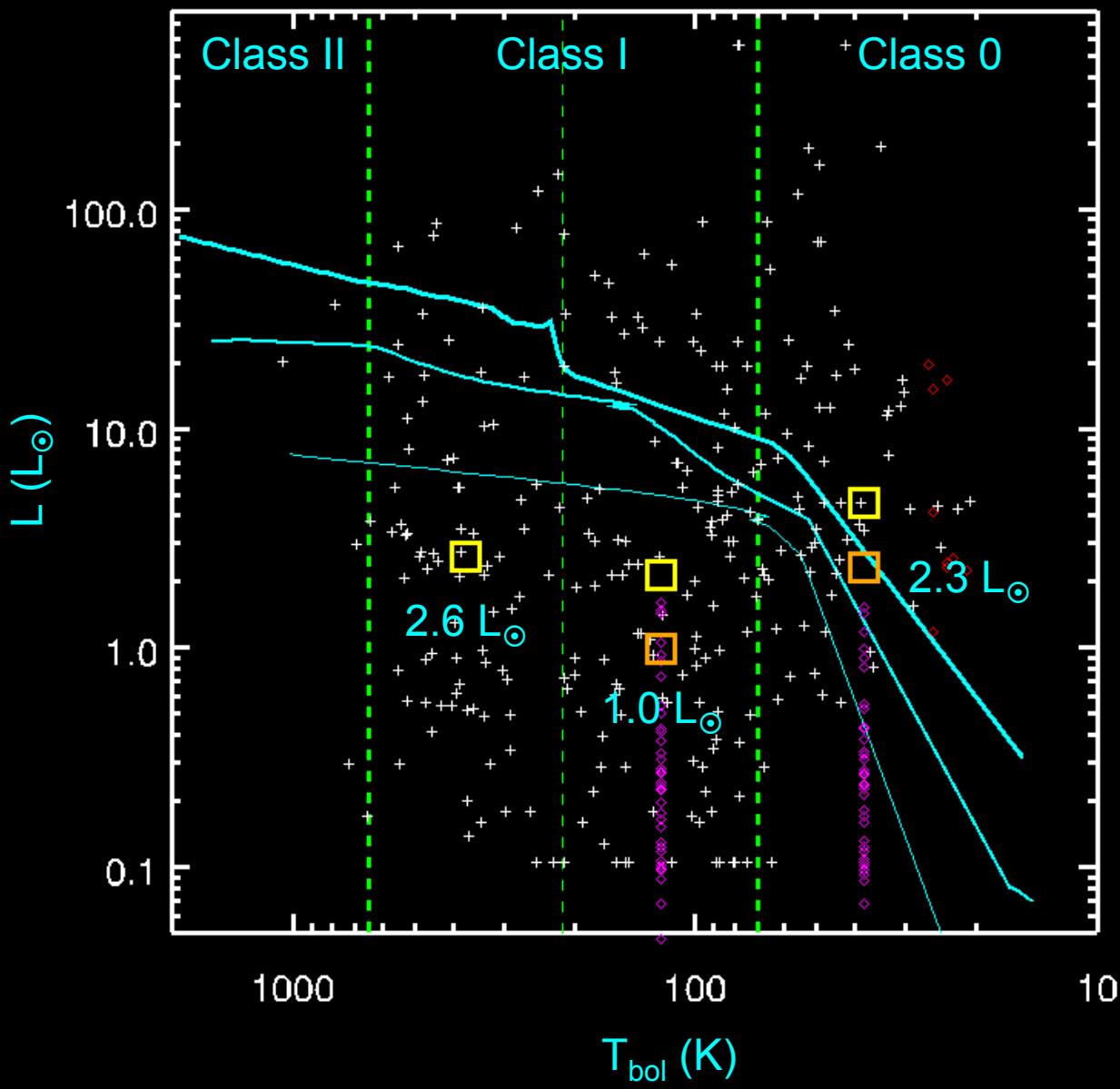
With PBRS…

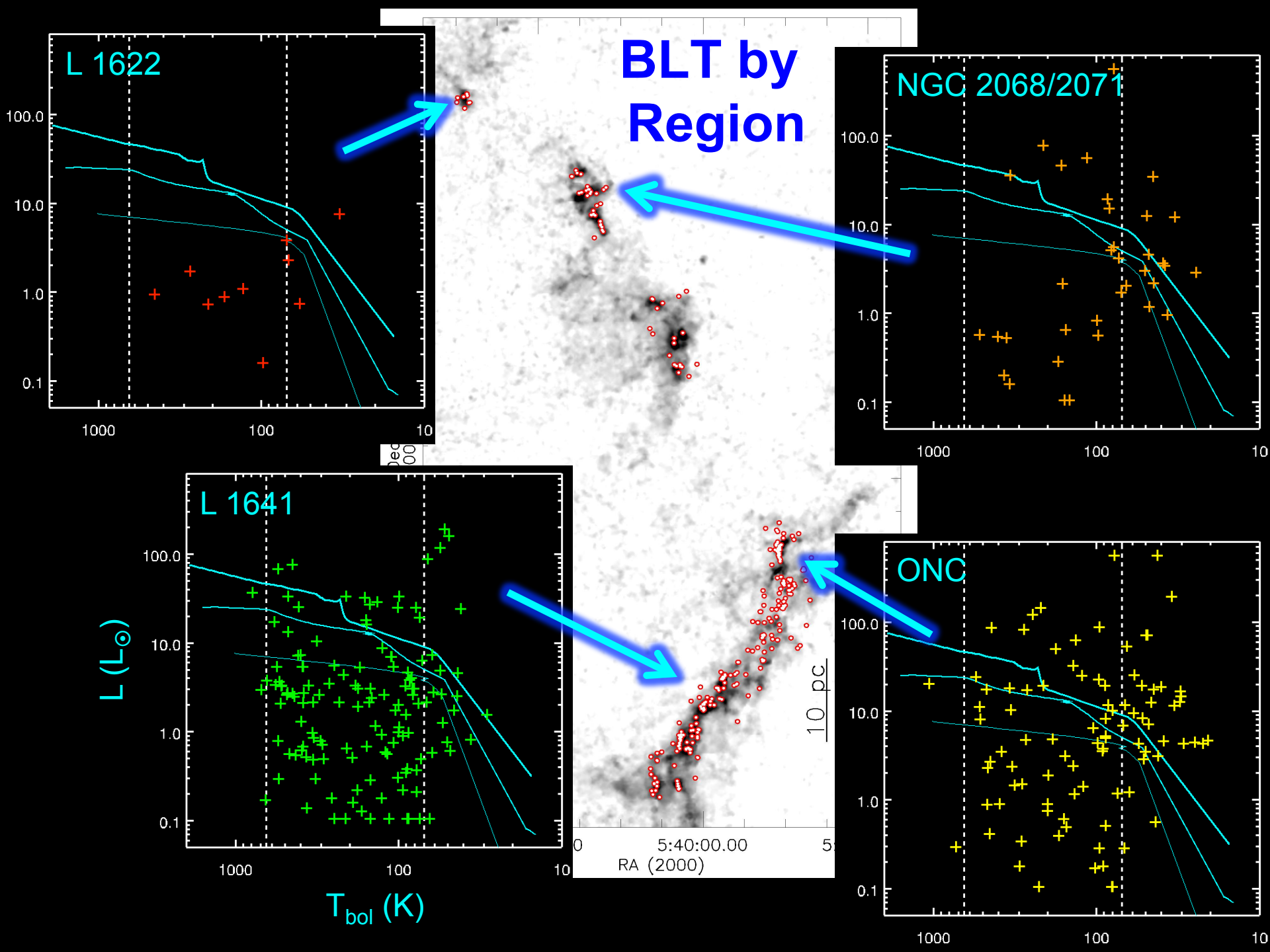
- Median luminosities drop
  Class 0: 4.6 to 2.3 $L_\odot$
  Early Class I: 2.1 to 1.0 $L_\odot$
- Class 0 median consistent with 0.3–3 $M_\odot$ tracks but wide scatter
- Class I medians substantially below tracks

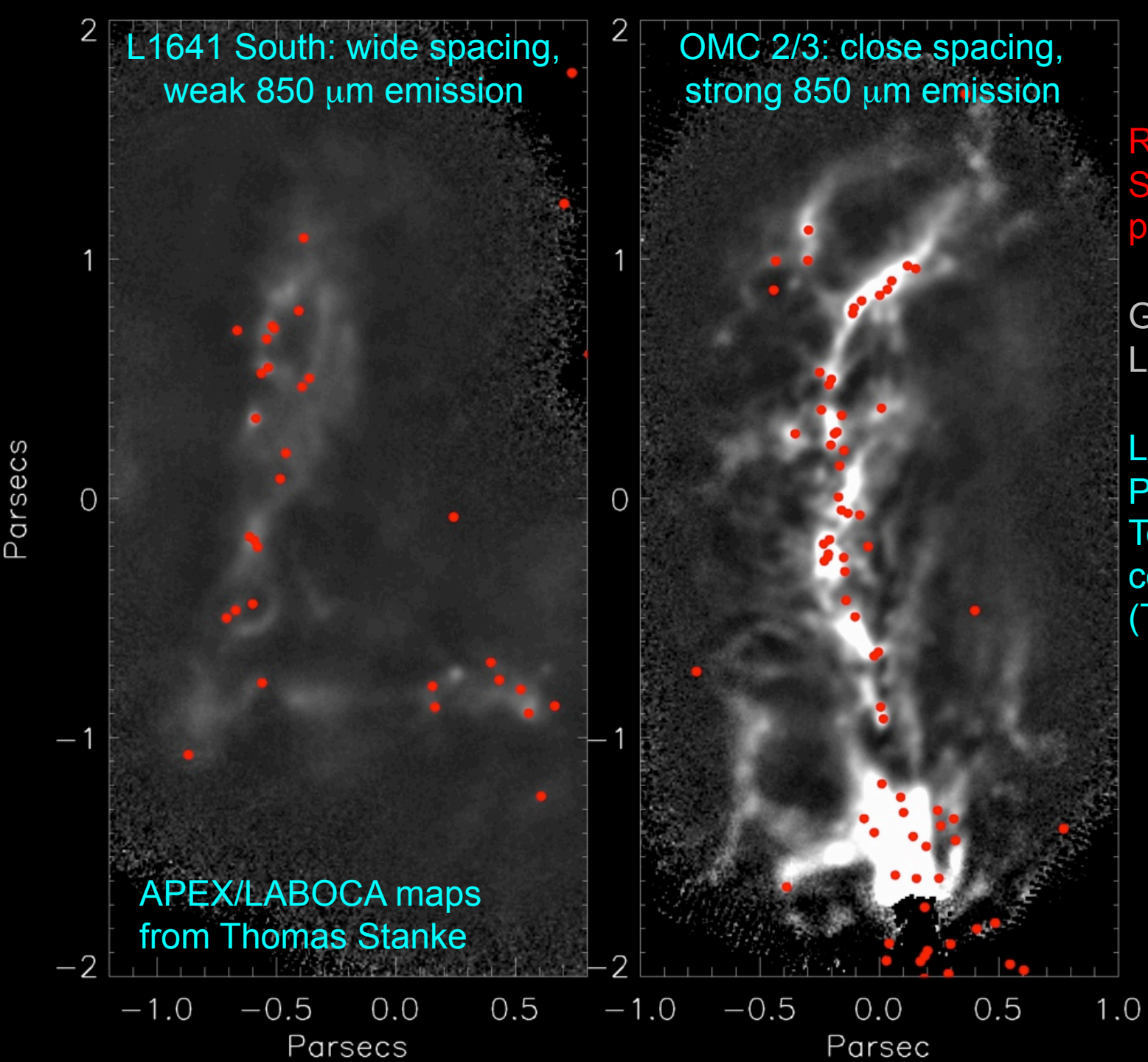


With PBRS…

- Number counts
  - Class II: 5 interlopers
  - Class I: 68% (238)
    - 81 Late
    - 157 Early
  - Class 0: 32% (111)
- Ratio of Class 0/I is 0.47, larger than previous reports
- Longer Class 0?




BLT by Region
L 1622
NGC 2068/2071
L 1641
ONC
L (L⊙)
T_bol (K)
100.0
10.0
1.0
0.1
1000
100
10
10 pc
5:40:00.00
RA (2000)

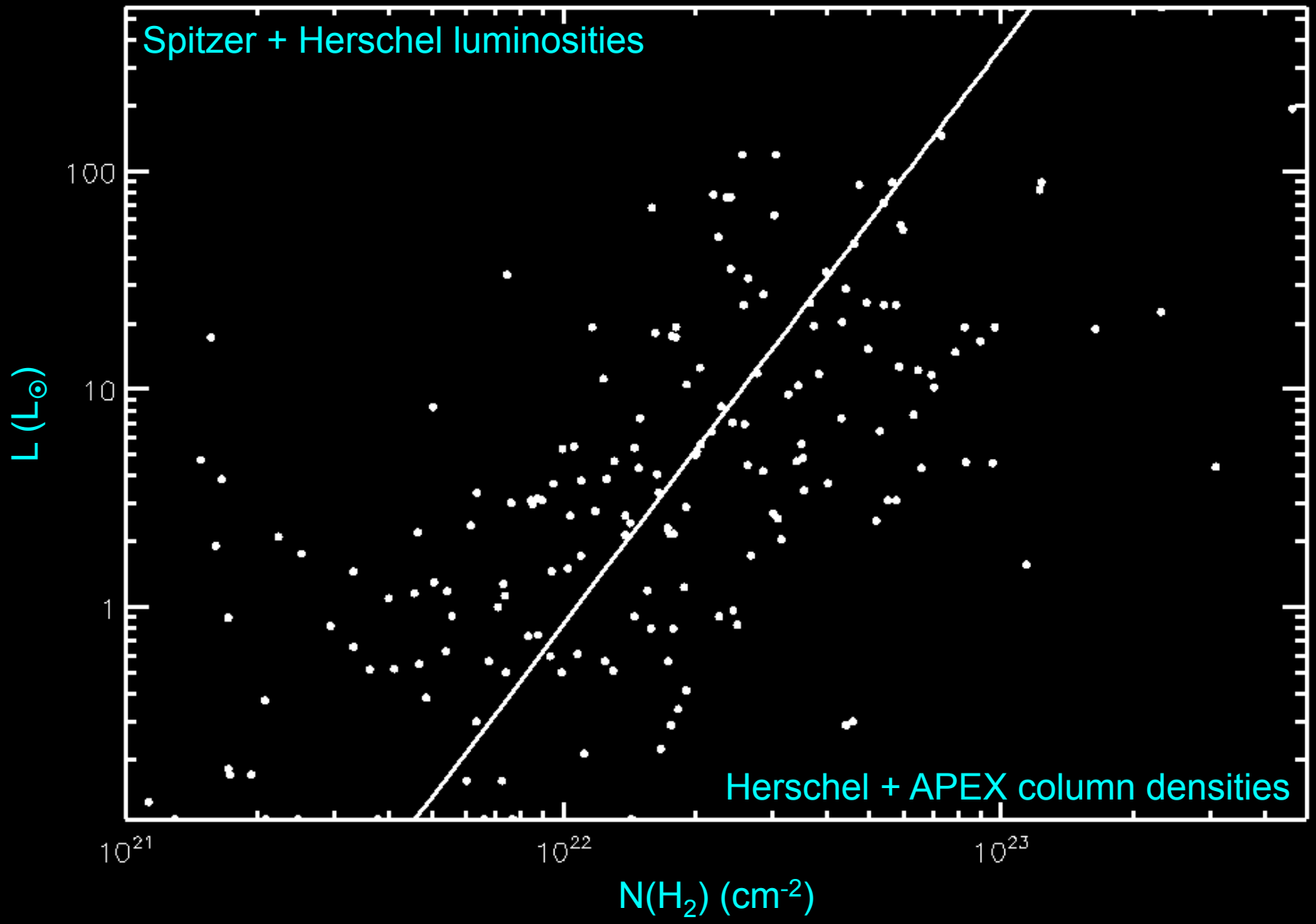


Red dots: Spitzer-identified protostars

Grayscale: LABOCA 850 μm

LABOCA 850 μm, PACS 160 μm: Temperatures & column densities (Tom Megeath)

Protostellar Luminosity vs Gas Column Density



Conclusions

SED fitting

- Fit 2MASS + Spitzer + Herschel SEDs of 276 Orion protostars
- Robust estimates of *intrinsic* L, *thermal* T_{bol}

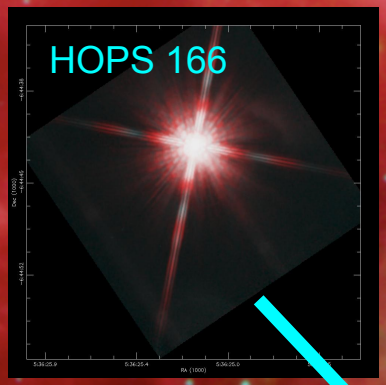
Newly discovered Herschel protostars (PBRS)

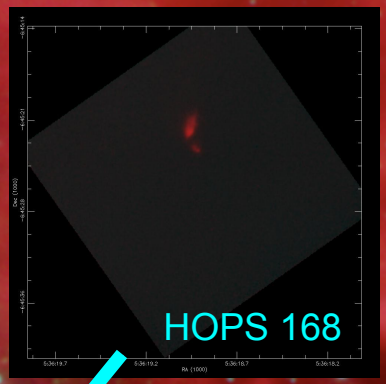
- 22% of total population was not identified by Spitzer
- Reddest 10% of these at a very young evolutionary state? (T_{bol} ~ 25 K)
- #(Class 0) / #(Class I) = 0.47, larger than previous reports (longer Class 0?)

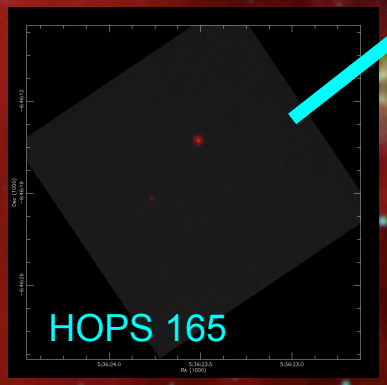
Luminosity dependence on environment and evolution

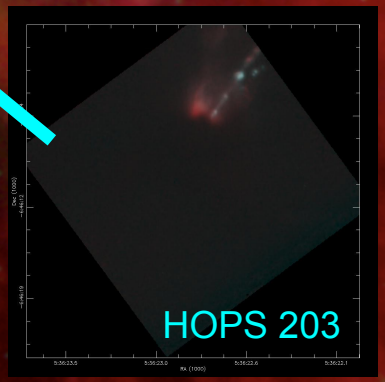
- Crowded regions, larger H_2 column density → more luminous protostars
- No evidence for luminosity evolution from Class 0 to Class I
  - Apparently inconsistent with constant infall
  - dM/dt decreases with increasing M?
  - Episodic accretion more important during Class I?

IRAC image: V380 Ori region







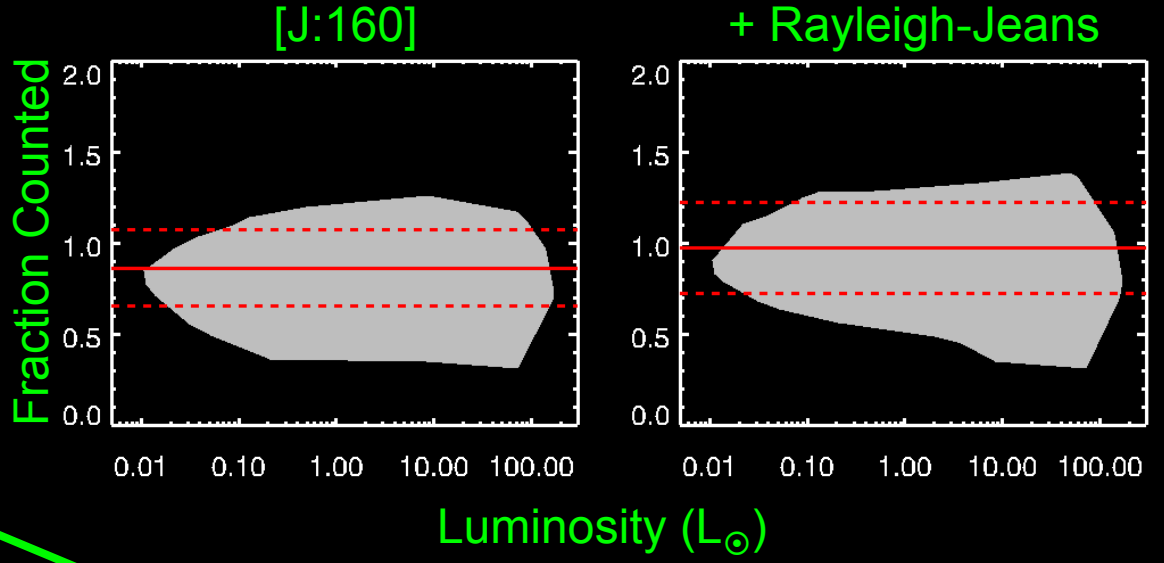


Supporting Data

- Spitzer
  - IRAC
  - MIPS 24 μm
  - IRS
- HST near-IR
  - NICMOS
  - WFC3
- Ground-based near-IR
  - Imaging
  - Spectra
- Ground-based sub-mm
  - Imaging

BLT Methodology

- Integrating under SED: systematic errors
  - Incomplete λ coverage
  - Inclination angle
  - Extinction



- Instead do grid-based fitting
  - 5,760 Whitney et al. models
  - 10 viewing angles
  - 57,600 SEDs
  - Report intrinsic L and T_{bol} of best model (Corrected for inclination, foreground reddening)
  - Explicit estimates of envelope, disk properties