THE HERSCHEL ORION PROTOSTAR SURVEY: CONSTRAINING PROTOSTELLAR MODELS WITH NEAR- TO FAR-INFRARED OBSERVATIONS

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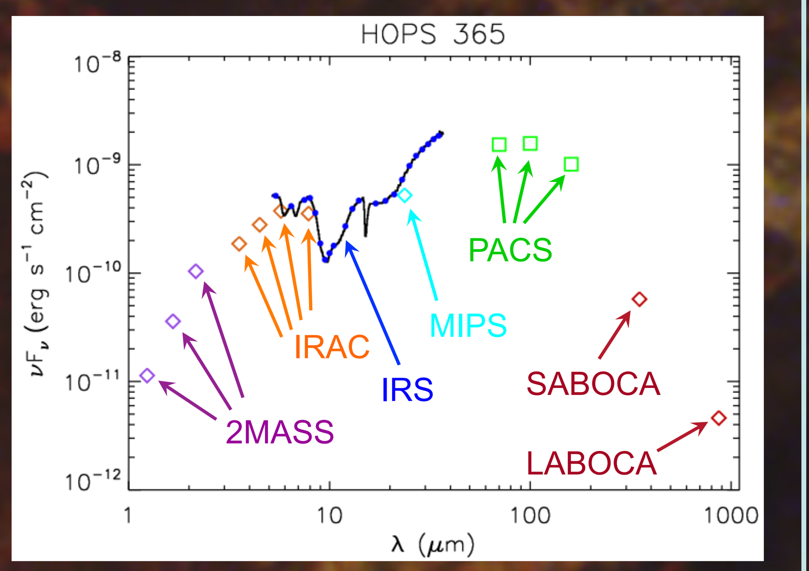
During the protostellar stage of star formation, a young star is surrounded by a large infalling envelope of dust and gas; the material falls onto a circumstellar disk and is eventually accreted by the central star. The dust in the disk and envelope emits prominently at mid- to far-infrared wavelengths; at 10 µm, absorption by small silicate grains typically causes a broad absorption feature. By modeling the near- to far-IR spectral energy distributions (SEDs) of protostars, properties of their disks and envelopes can be derived.

As part of the Herschel Orion Protostar Survey (HOPS; PI: S. T. Megeath), we have observed a large sample of protostars in the Orion star-forming complex at 70 and 160 µm with the PACS instrument on the Herschel Space Observatory. For most objects, we also have photometry in the near-IR (2MASS), mid-IR (Spitzer/IRAC and MIPS), at 100 µm (PACS data from the Gould Belt Survey), sub-mm (APEX/SABOCA and LABOCA), and mid-infrared spectra (Spitzer/IRS). For the interpretation of the SEDs, we have constructed a large grid of protostellar models using a Monte Carlo radiative transfer code.

Here we present our SED fitting techniques to determine the best-fit model for each object. We show the importance of including IRS spectra with appropriate weights, in addition to the constraints provided by the PACS measurements, which probe the peak of the SED. The 10 micron silicate absorption feature and the mid- to far-IR SED slope provide key constraints for the inclination angle of the object and its envelope density, with a deep absorption feature and steep SED slope for the most embedded and highly inclined objects. We show a few examples that illustrate our SED fitting method and present some preliminary results from our fits.

Fits:

- use observations from 2MASS (1.2, 1.6, 2.2 µm), IRAC (3.6, 4.5, 5.8, 8.0 µm), IRS (5-38 µm), MIPS (24 µm), PACS (70, 100, 160 µm), APEX/SABOCA (350 µm) and LABOCA (870 µm)
- rebin IRS spectrum to fluxes at 16 wavelengths to represent continuum emission and 10 µm feature (no ice absorption features), smooth over noisy parts of the spectrum, and scale IRS spectrum to MIPS 24 µm flux value if deviation is larger than 10% and roughly matches deviation between IRS and IRAC 5.8 and 8.0 µm fluxes
- assign weights to photometry and IRS spectrum
  → 1/0.1 for photometry at $\lambda < 3$ µm,
  1/0.05 for photometry at 3 µm < λ < 70 µm,
  1/0.04 for photometry at λ = 70 µm and λ = 100 µm,
  1/0.07 for photometry at λ = 160 µm
  1/0.075 for IRS spectrum at 8-12 µm and 18-38 µm,
  1/0.1 for IRS spectrum at 5-8 µm and 12-18 µm
  1/0.3 for photometry at λ>200 µm



Example SED of a HOPS protostar

- fit models from grid including scaling factor ranging from 0.5 to 2.0 (to tweak luminosity) and extinction (to account for interstellar extinction along the line of sight from A_V=0 to A_V=30)
- assess goodness of fit using

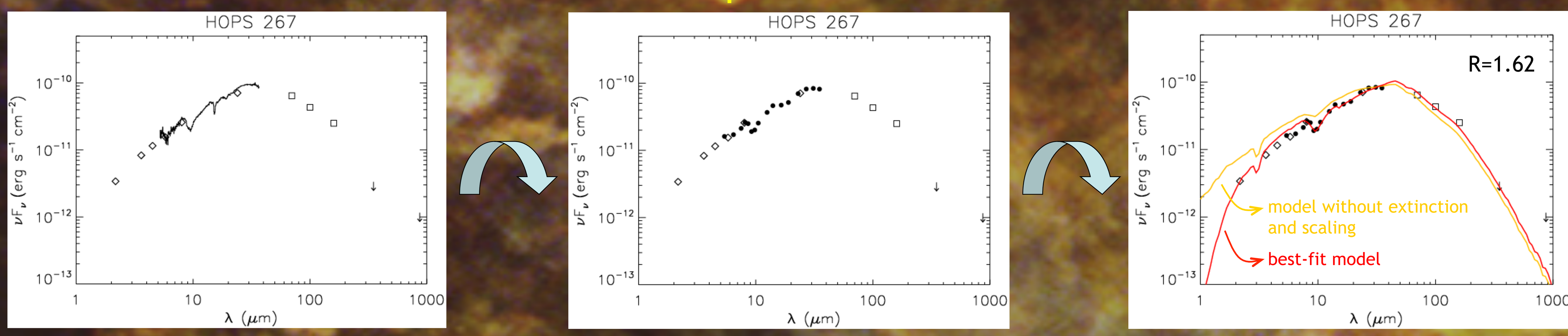
$$R = \frac{\sum_i w_i \left| \ln\left(\frac{F_{obs}}{F_{model}}\right) \right|}{N}$$

where the sum is over the various data points (each has a weight w_i), F_{obs} and F_{model} are the observed and model fluxes, respectively

⇒ R is the distance of the model from the data in units of the average fractional uncertainty of the data (valid for small R).

→ Differences between the data and the models are mostly due to the idealized nature of the models, the discrete sampling of the model grid, and potential intrinsic variability of the sources between the different epochs of the multi-wavelength observations; uncertainties in the measured fluxes are less important.

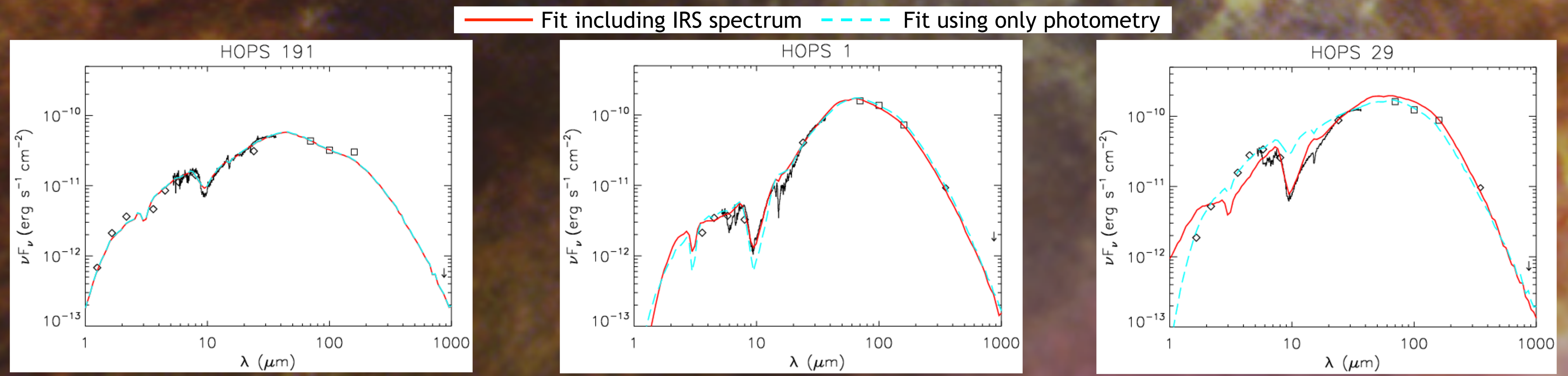
Example Model Fit



multiply IRS by 0.89 to match MIPS 24 µm flux, rebin to 16 data points

code finds best-fit model with A_V=10.7 and scaling factor= 1.32

Fitting with and without Mid-Infrared Spectra: Examples



HOPS 191:

$L_{tot}[L_\odot]$	$L_{acc}[L_\odot]$	R_{disk}	dM_{infall}/dt	θ	i	A_V
2.70	1.82	50 AU	1.0e-5 $M_\odot$/yr	45°	63°	9.0
2.75	1.85	50 AU	1.0e-5 $M_\odot$/yr	45°	63°	9.0

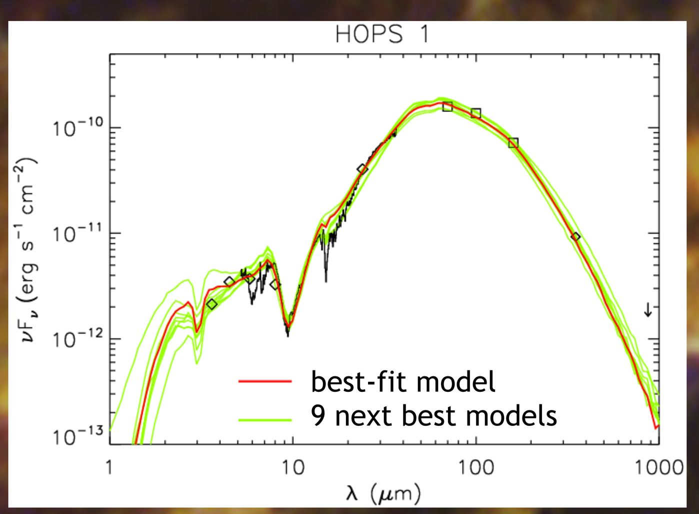
HOPS 1:

$L_{tot}[L_\odot]$	$L_{acc}[L_\odot]$	R_{disk}	dM_{infall}/dt	θ	i	A_V
2.31	1.55	100 AU	2.5e-6 $M_\odot$/yr	5°	63°	15.2
1.89	1.27	100 AU	5.0e-6 $M_\odot$/yr	5°	63°	2.7

HOPS 29:

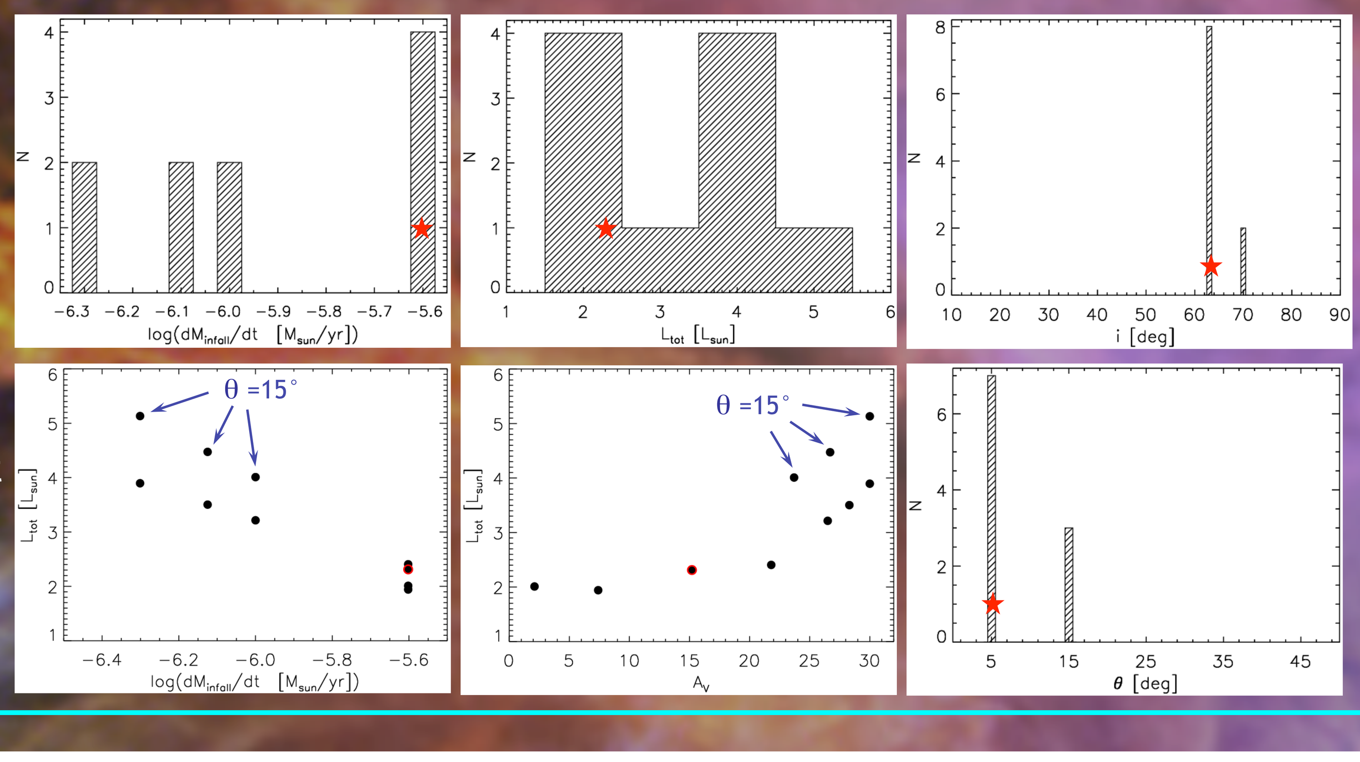
$L_{tot}[L_\odot]$	$L_{acc}[L_\odot]$	R_{disk}	dM_{infall}/dt	θ	i	A_V
6.30	5.68	500 AU	5.0e-6 $M_\odot$/yr	45°	63°	2.6
8.00	7.20	50 AU	2.5e-6 $M_\odot$/yr	35°	63°	15.6

Parameter Ranges derived from Model Fits



distribution of model parameters for the 10 best models of HOPS 1

(★ = best-fit model)



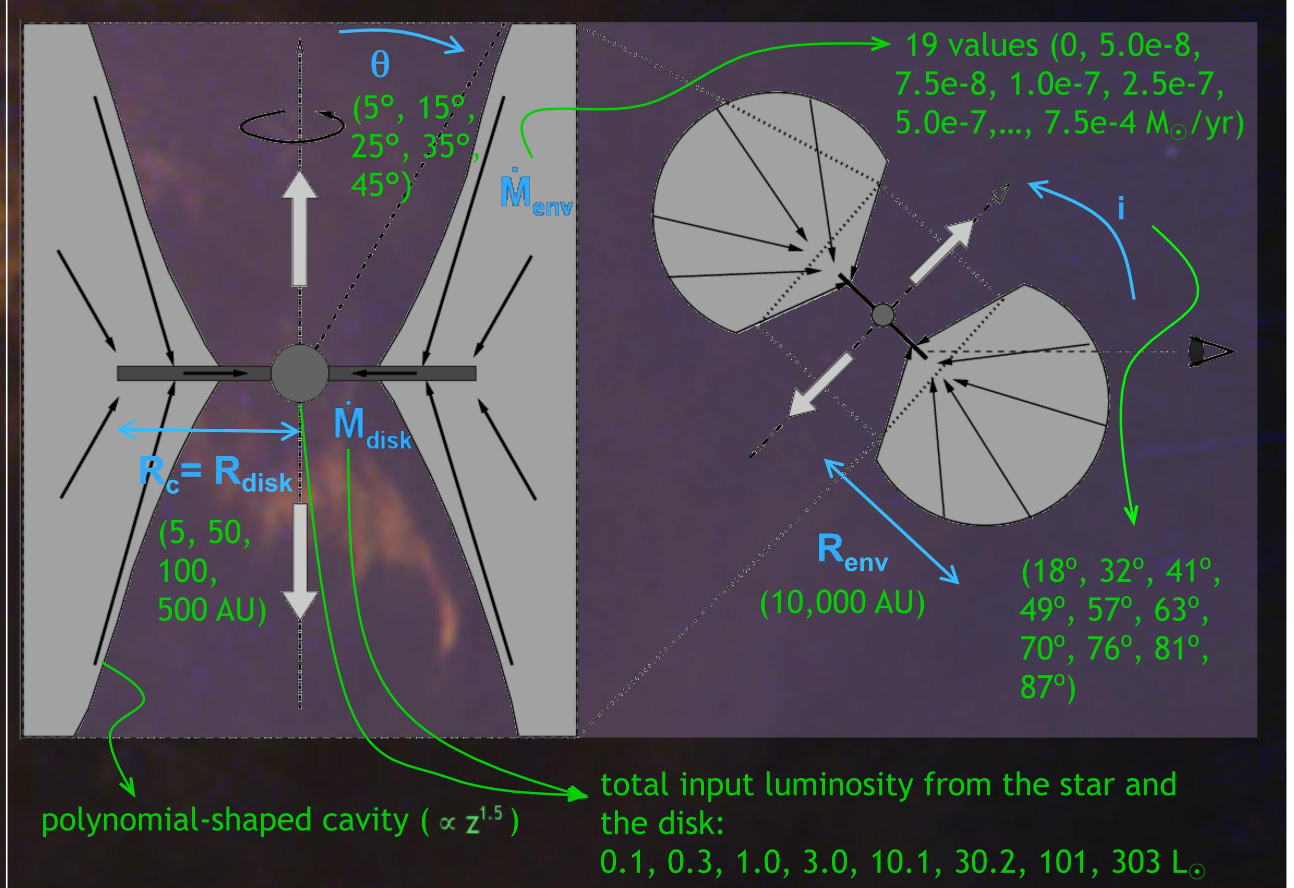
Herschel Orion Protostar Survey (HOPS):

- Herschel Open Time Key Program
- observed ~350 Spitzer-identified protostars in the Orion star-forming region (see Megeath et al. 2012) at 70 and 160 µm with the PACS instrument on the Herschel Space Observatory
- ancillary data: 2MASS catalog, Hubble Space Telescope and ground-based near-infrared images, Spitzer Space Telescope mid-infrared images and spectra, ground-based sub-mm images

Model Grid using Radiative Transfer Modeling Code of Whitney et al. (2003a,2003b):

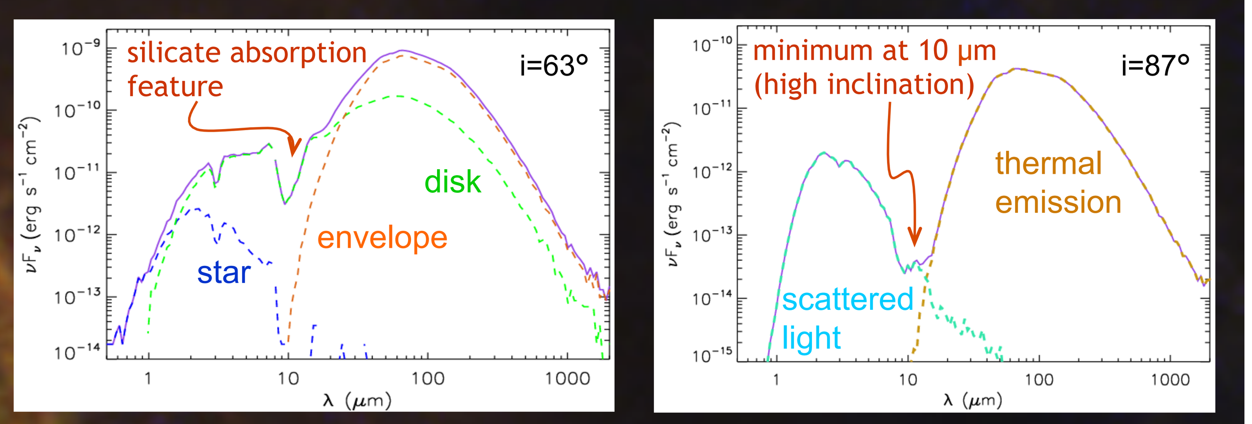
infalling envelope + circumstellar accretion disk + protostar

(dust opacities from Ormel et al. (2011) → larger, icy grains)

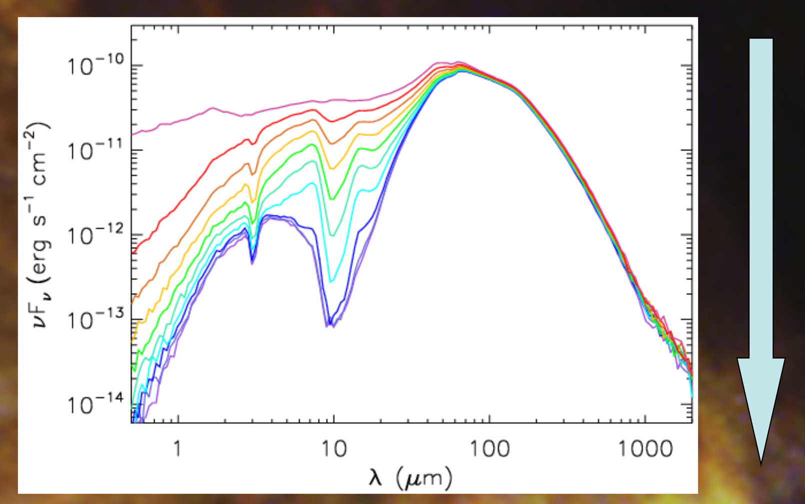


⇒ total of 3040 models

→ 30400 SEDs (10 SEDs per model, one for each inclination angle)



Two examples of model spectral energy distributions (SEDs)

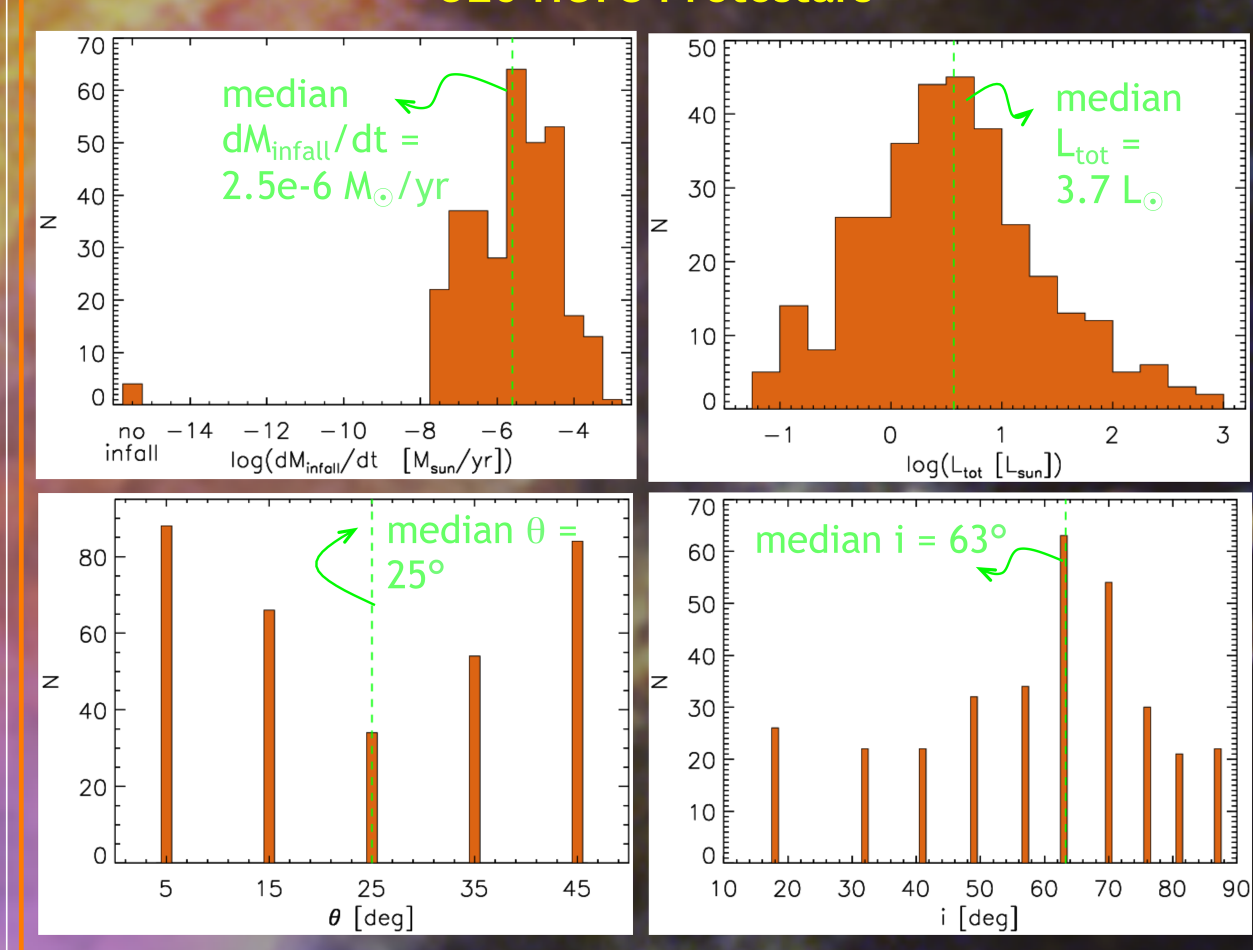


inclination angle increases from 18° to 87°

⇒ deeper silicate feature, steeper mid- to far-IR SED

Model with L_{tot}=1 $L_\odot$, L_{acc}=0.9 $L_\odot$, R_{disk}=5 AU, dM_{infall}/dt=5.0e-06 $M_\odot$/yr, θ=15°

Distribution of Model Parameters of 326 HOPS Protostars



- Our models yield estimates of protostellar parameters for the largest sample of protostars in one star-forming complex.
- We find a wide range for these parameters, implying effects of evolution and environment.