

University
of
St Andrews



SED modeling of young massive stars

Thomas Robitaille
University of St Andrews, UK

GLIMPSE/SAGE teams, including Barb Whitney (SSI), Remy Indebetouw (Virginia), Matt Povich (UW), Marta Sewilo (STScI), Christer Watson (Manchester)

Kenny Wood, Katharine Johnston & Chris Poulton (St Andrews), Deb Shepherd (NRAO),
Joe Mottram & Melvin Hoare (Leeds)

And many others!



A GLIMPSE of the Galactic mid-plane

Techniques developed to analyze YSO SEDs

- Grid of SED models
- SED fitting using pre-computed models

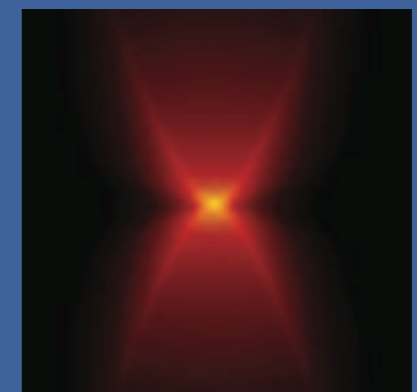
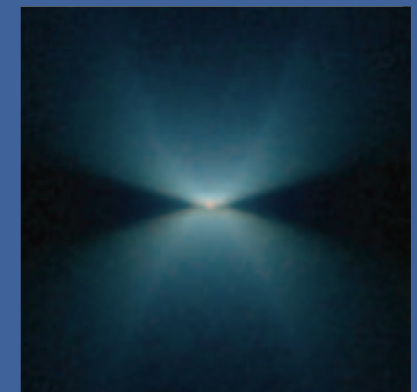
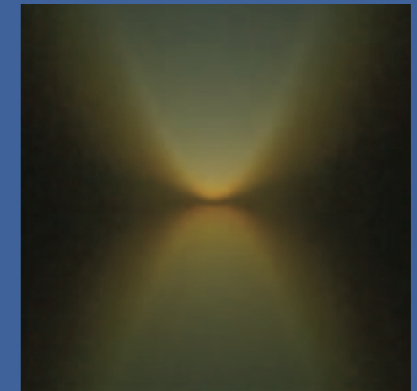
Applications and caveats for MYSOs

Modeling large numbers of YSOs in GLIMPSE

- Catalog of ~25,000 IR excess sources

The Radiation Transfer Code

- Developed by Whitney et al.
- 3D Monte-Carlo code
- Computes SEDs, images, polarization maps
- For this grid of models, assume an axisymmetric dust density distribution



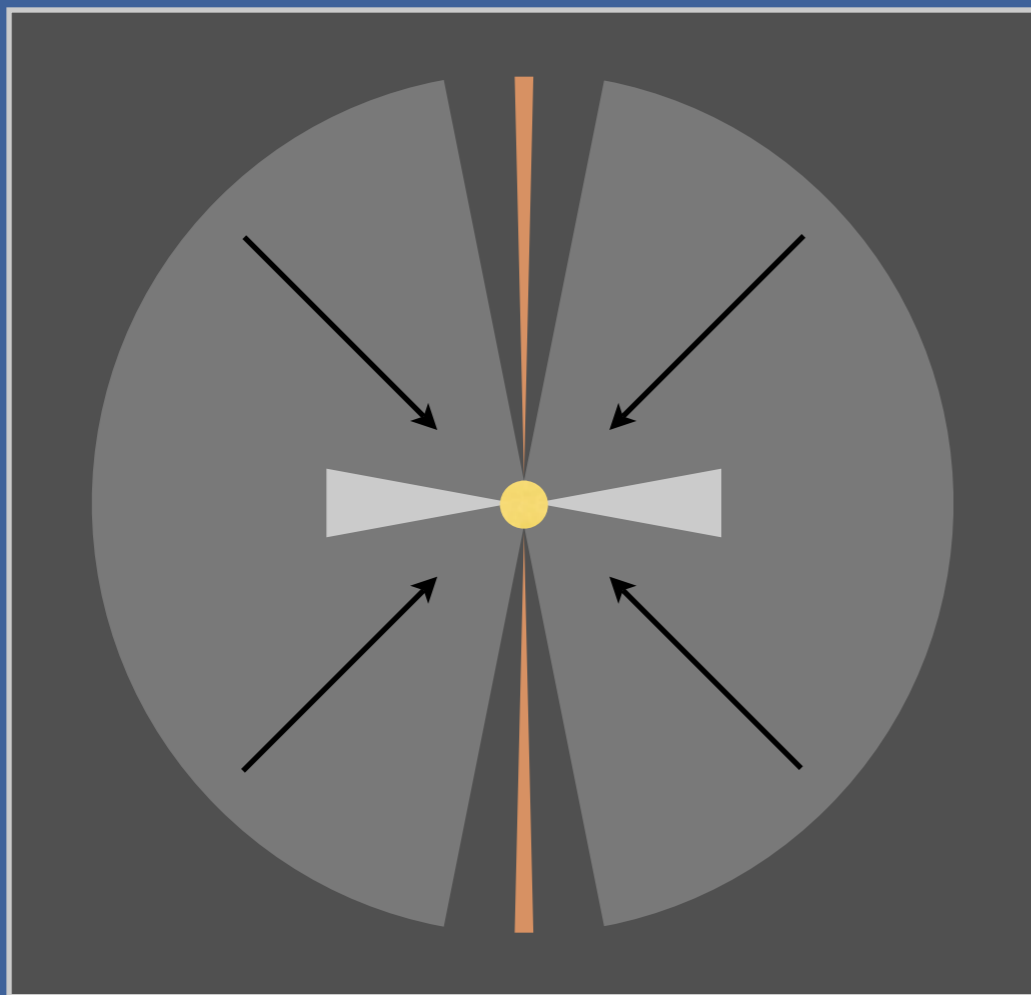
Whitney et al. (2003)

Grid of YSO SED models

- Aim is to learn about the physical conditions in thousands of YSOs
- 20,000 RT models (65,000 CPU hours)
- Large range of stellar masses ($0.1-50 M_{\text{sol}}$) and evolutionary stages (embedded protostars to dispersing disks)
- Each model predicts an emergent SED at 10 viewing angles
- 200,000 SEDs in total

Grid of YSO SED models

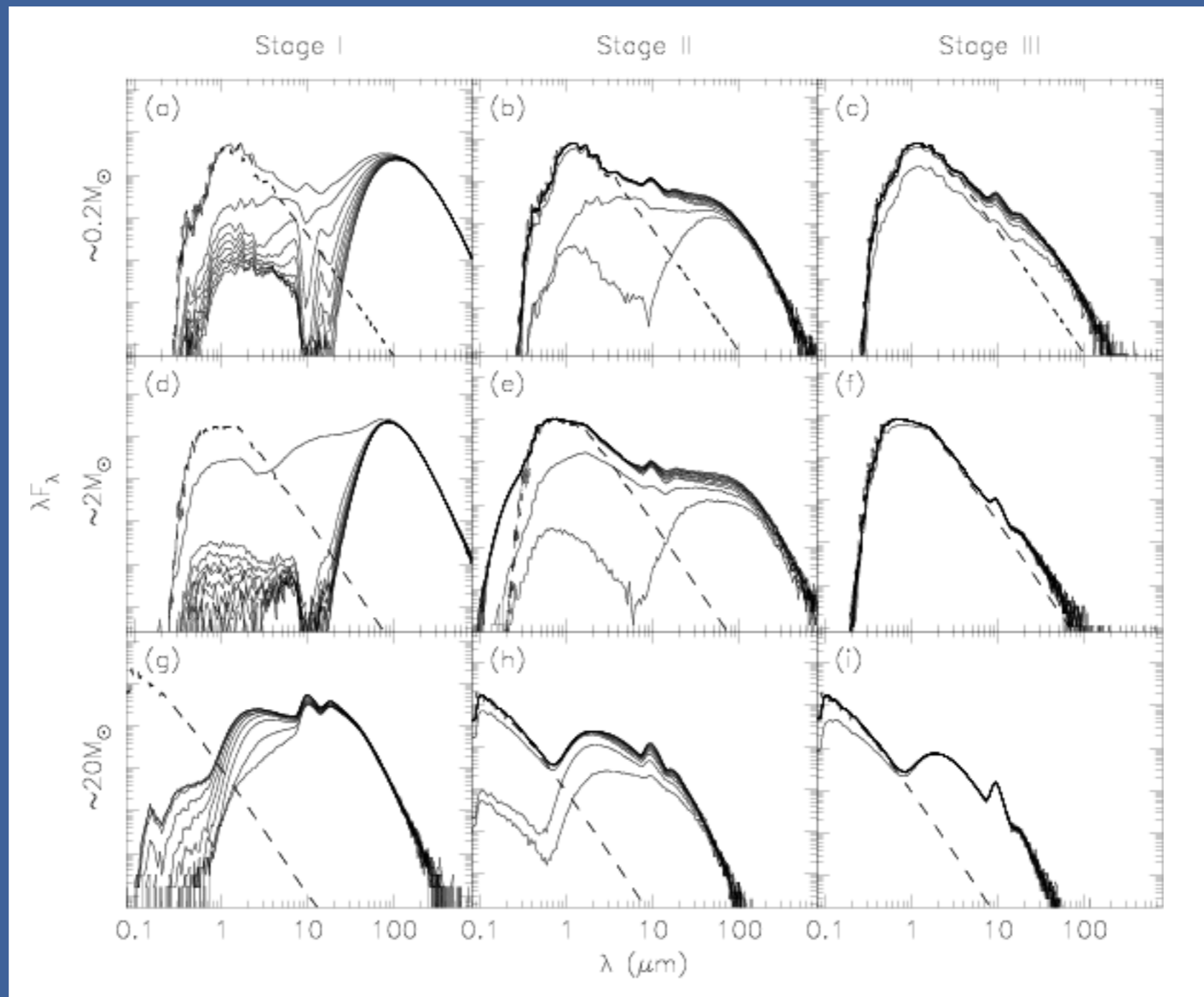
14 parameters - not all important at all stages of evolution



- Ingredients:
 - Pre-main sequence star
 - Disk
 - Infalling envelope
 - Bipolar cavities
- Sampling of parameter space includes previously observed or predicted geometries

For more details, see Robitaille et al. (2006)

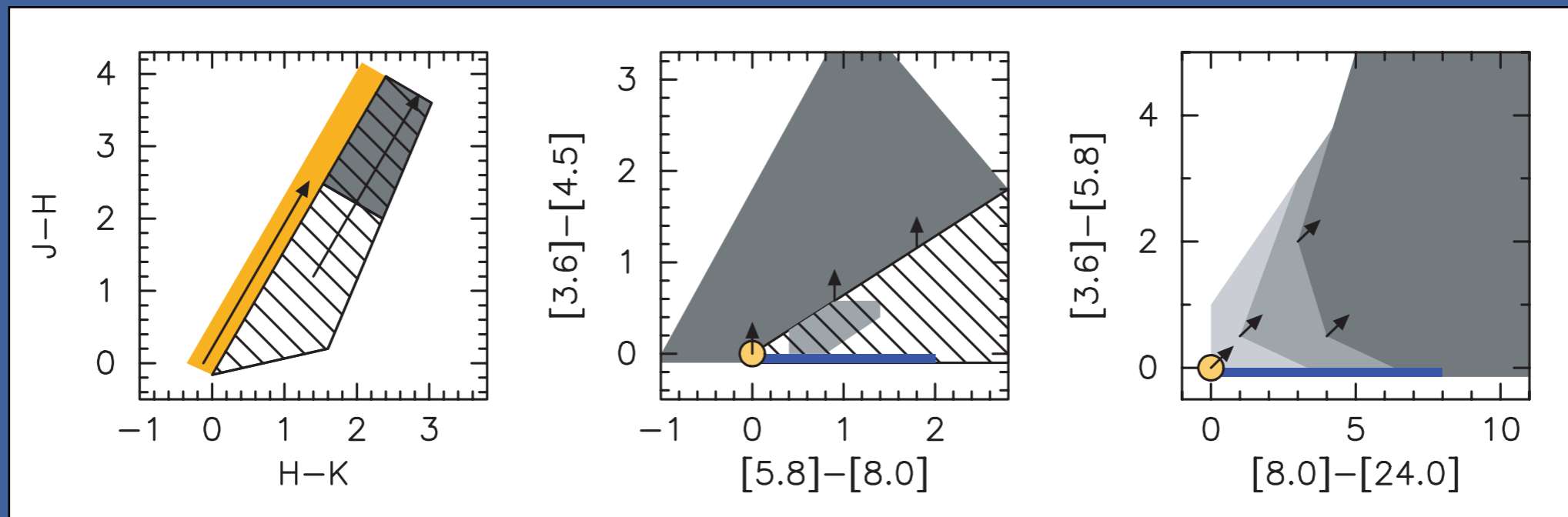
Example SEDs



Robitaille et al. (2006)

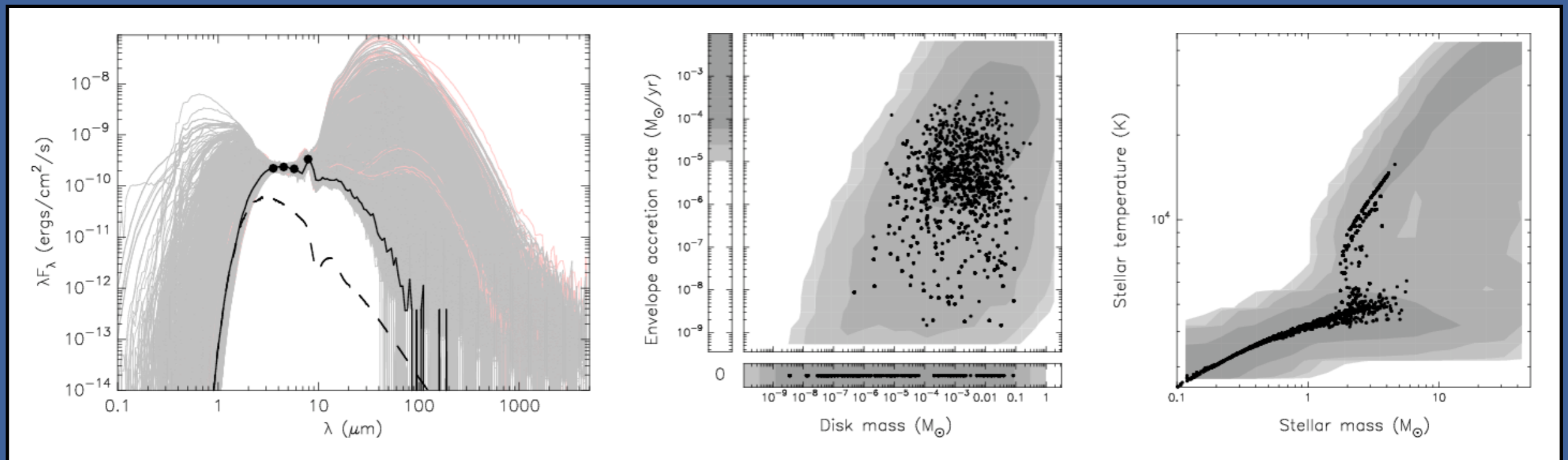
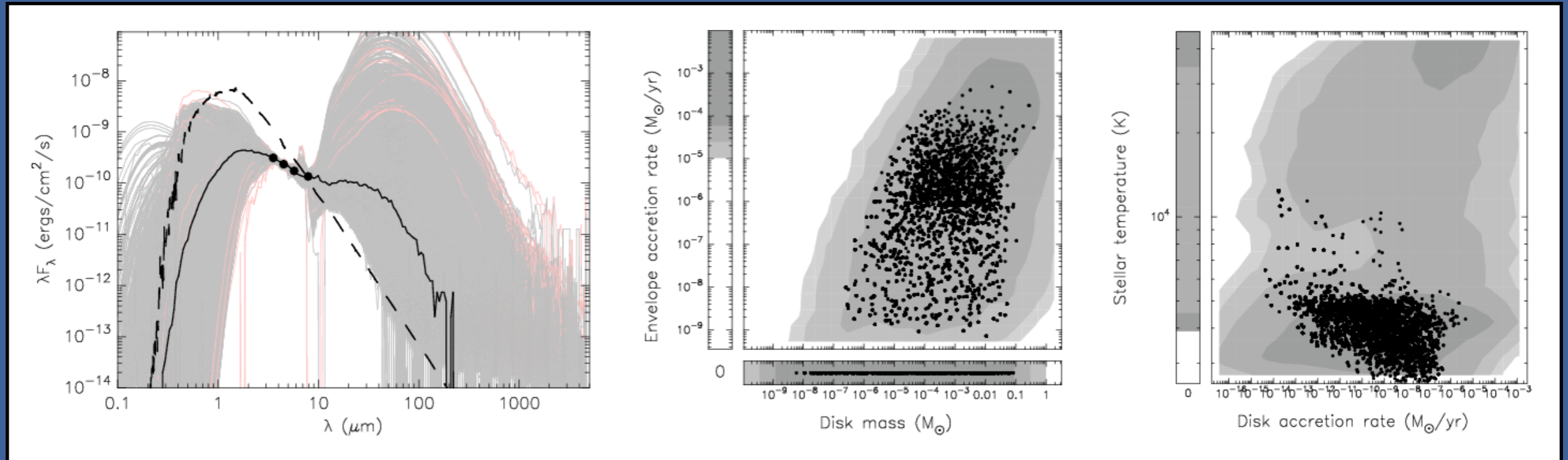
Results

- The near-IR and mid-IR colors of disk-only sources are mainly sensitive to the stellar temperature, disk inner radius, and disk scaleheight (e.g. $h_{100\text{AU}}$)
- Embedded sources can have a very large range of mid-IR colors, overlapping with disk colors. Very blue colors are possible in IRAC wavelengths due to scattering in bipolar cavities
- Data beyond $20\mu\text{m}$ crucial to reliably estimating evolutionary stages

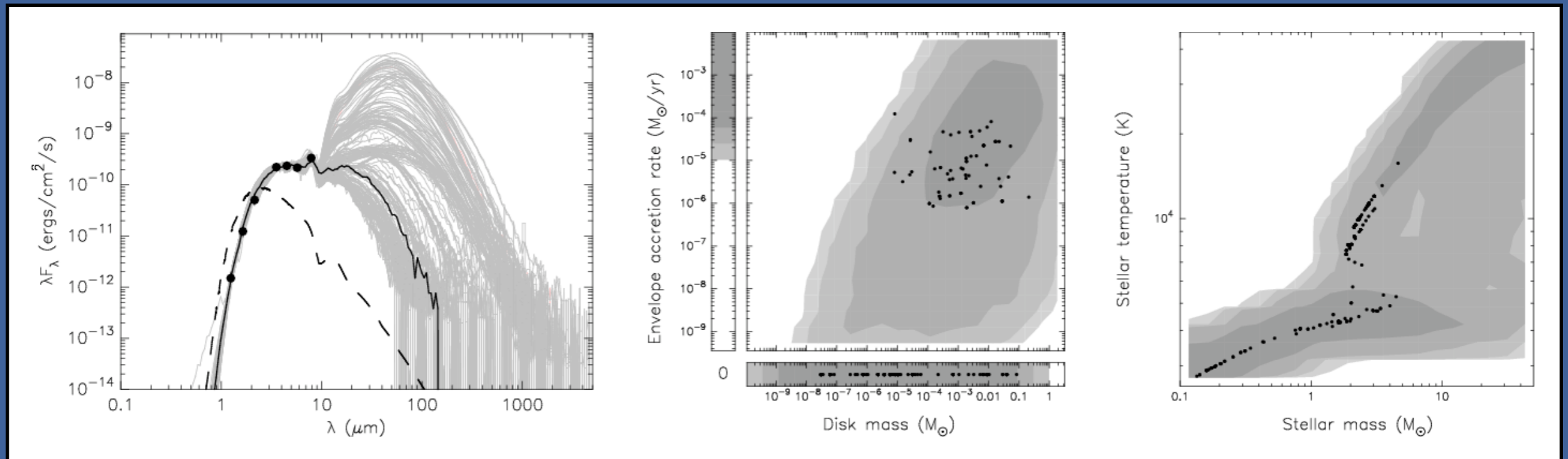
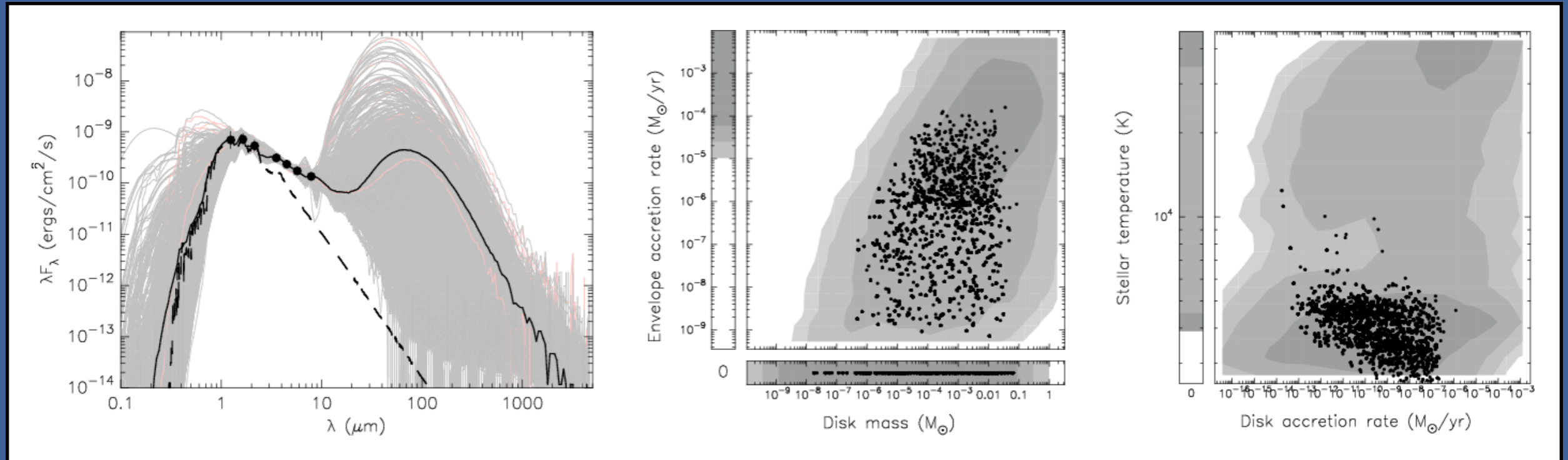


Robitaille et al. (2006)

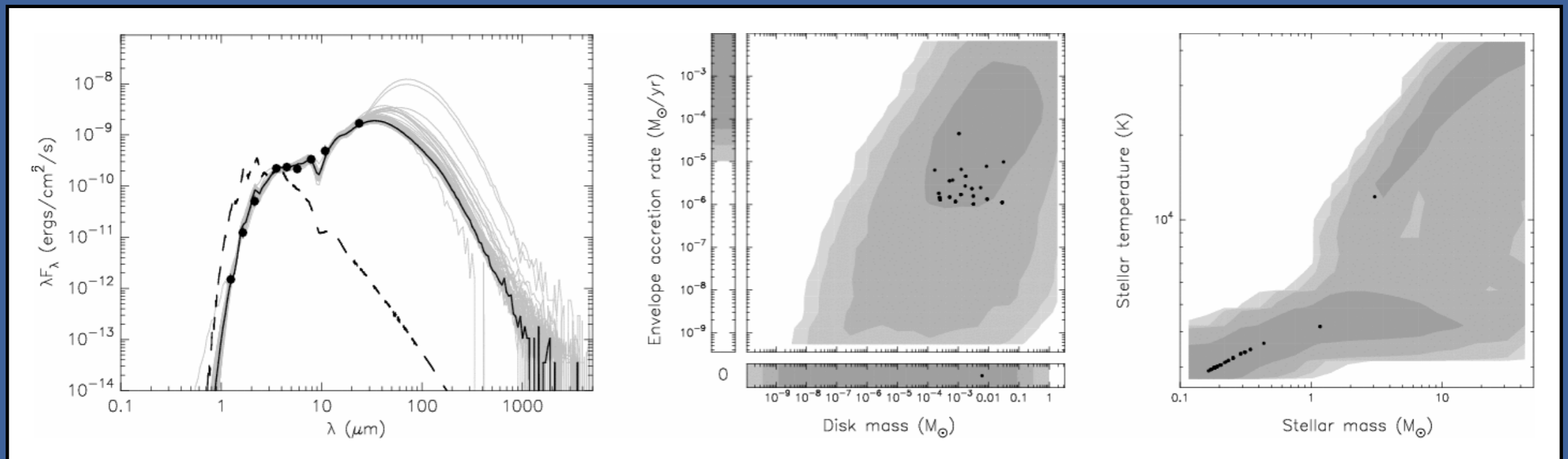
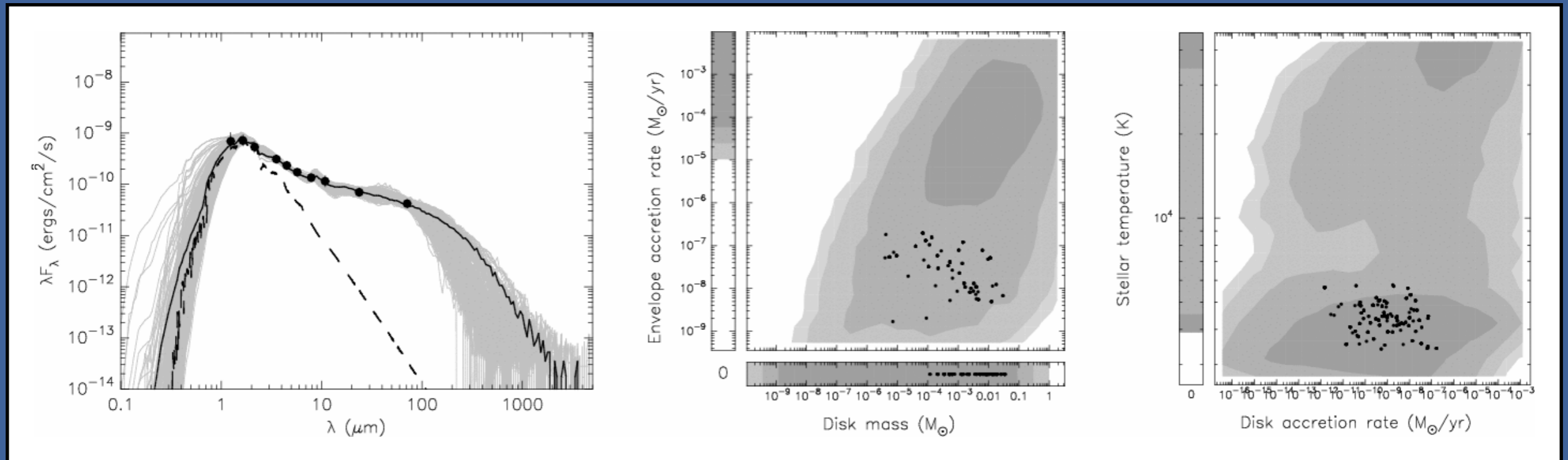
Constraining parameters



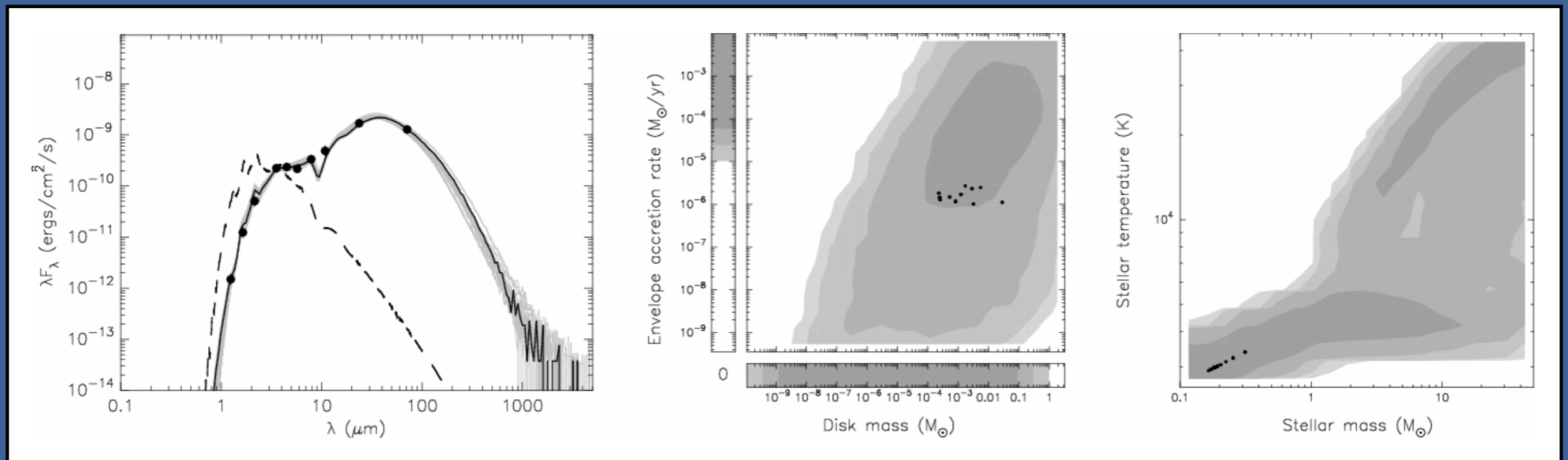
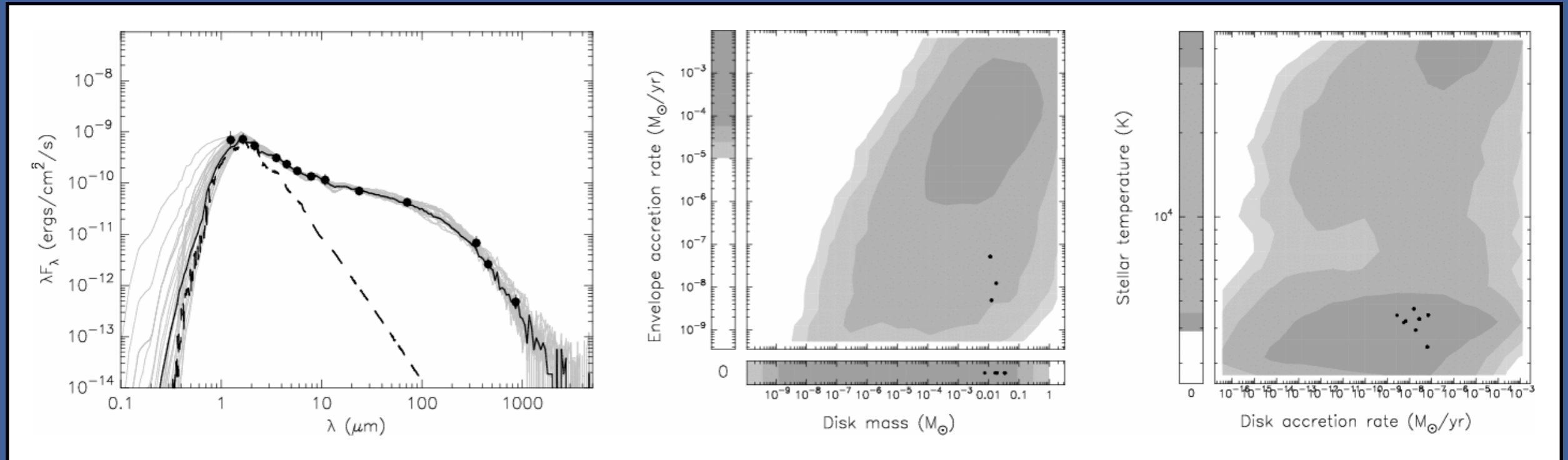
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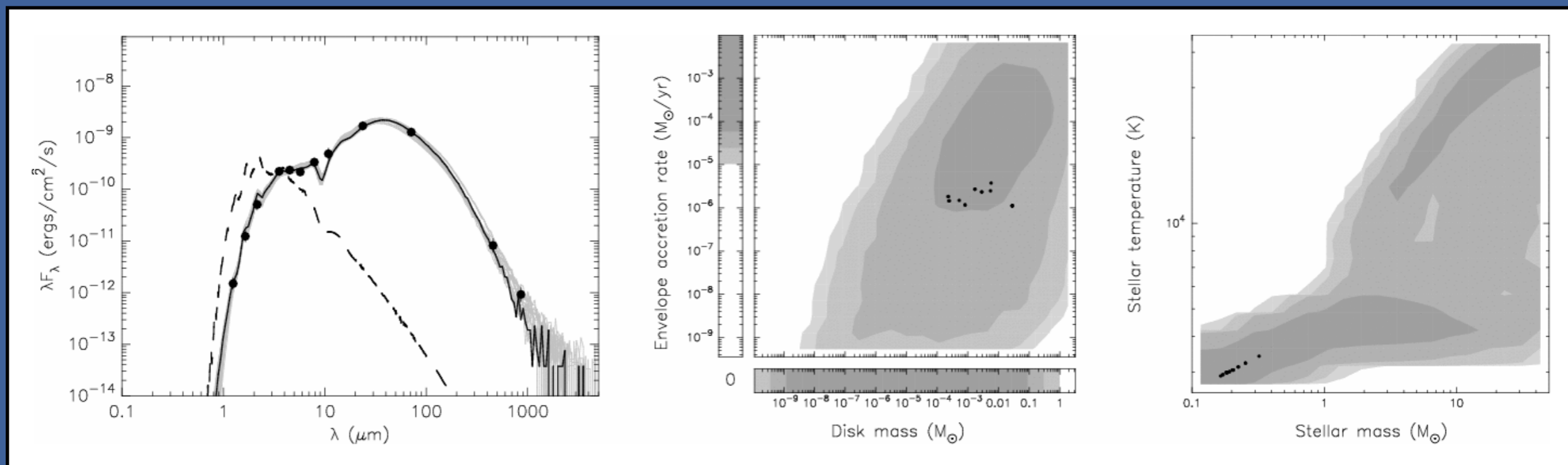
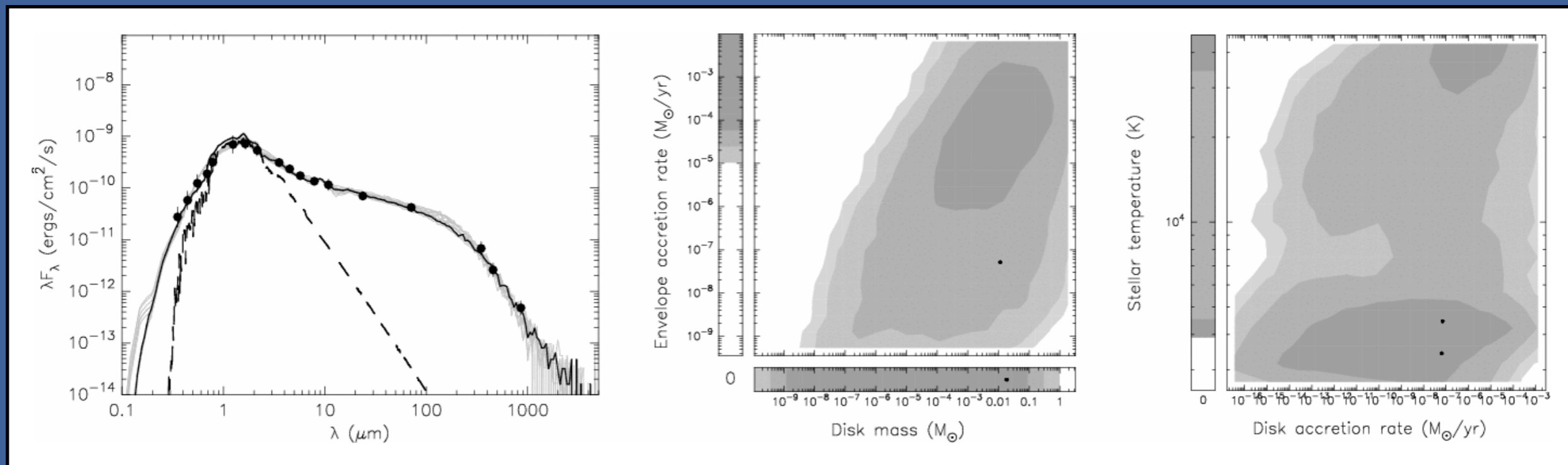
Constraining parameters



Constraining parameters



Constraining parameters



Techniques developed to analyze YSO SEDs

- Grid of SED models
- SED fitting using pre-computed models

Applications and caveats for MYSOs

Modeling large numbers of YSOs in GLIMPSE

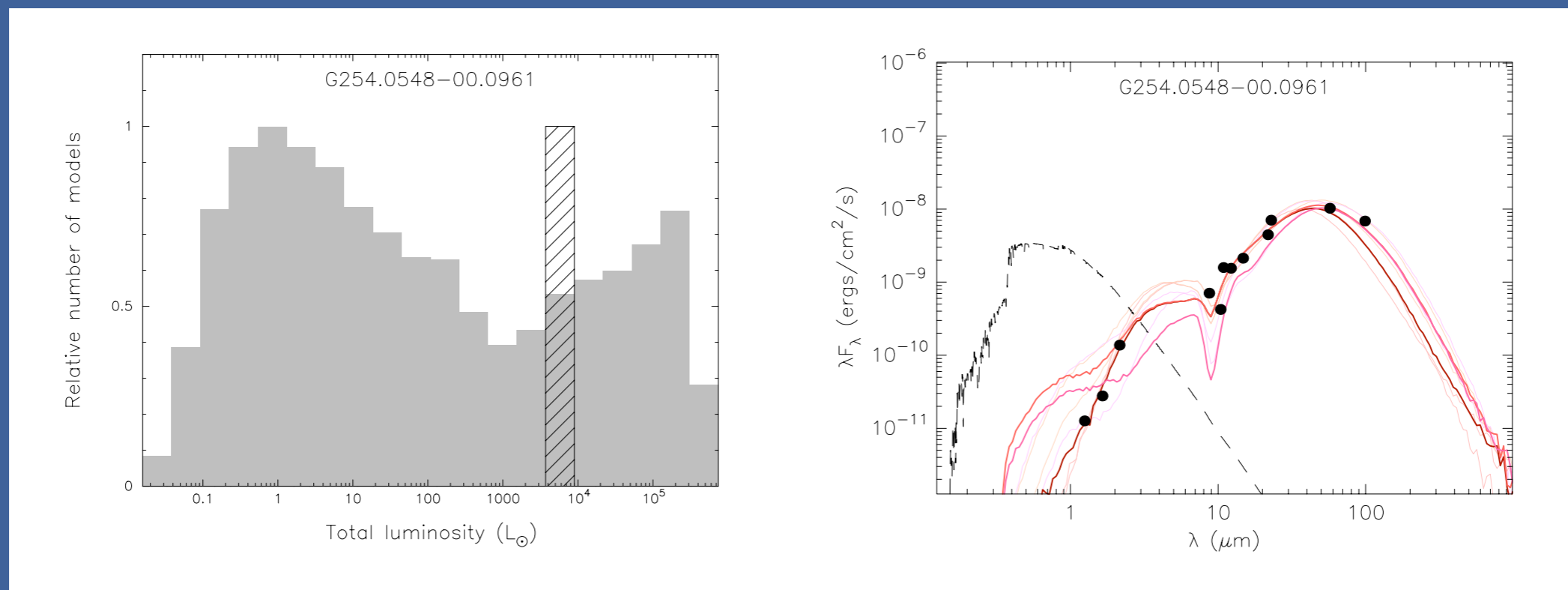
- Catalog of ~25,000 IR excess sources

Modeling Massive YSOs

- Many MYSOs, for which near- to far-IR data are available (e.g. in the GLIMPSE and SAGE surveys)
- We can model their SEDs in order to determine some of the physical properties **but** we need to keep in mind the assumptions we make for the models (e.g. axisymmetry, single source, scaling up)

The RMS survey

- SED fitting tool is being used to determine luminosities of sources in the RMS survey (Hoare et al.)
- See poster by Mottram et al. (#71)

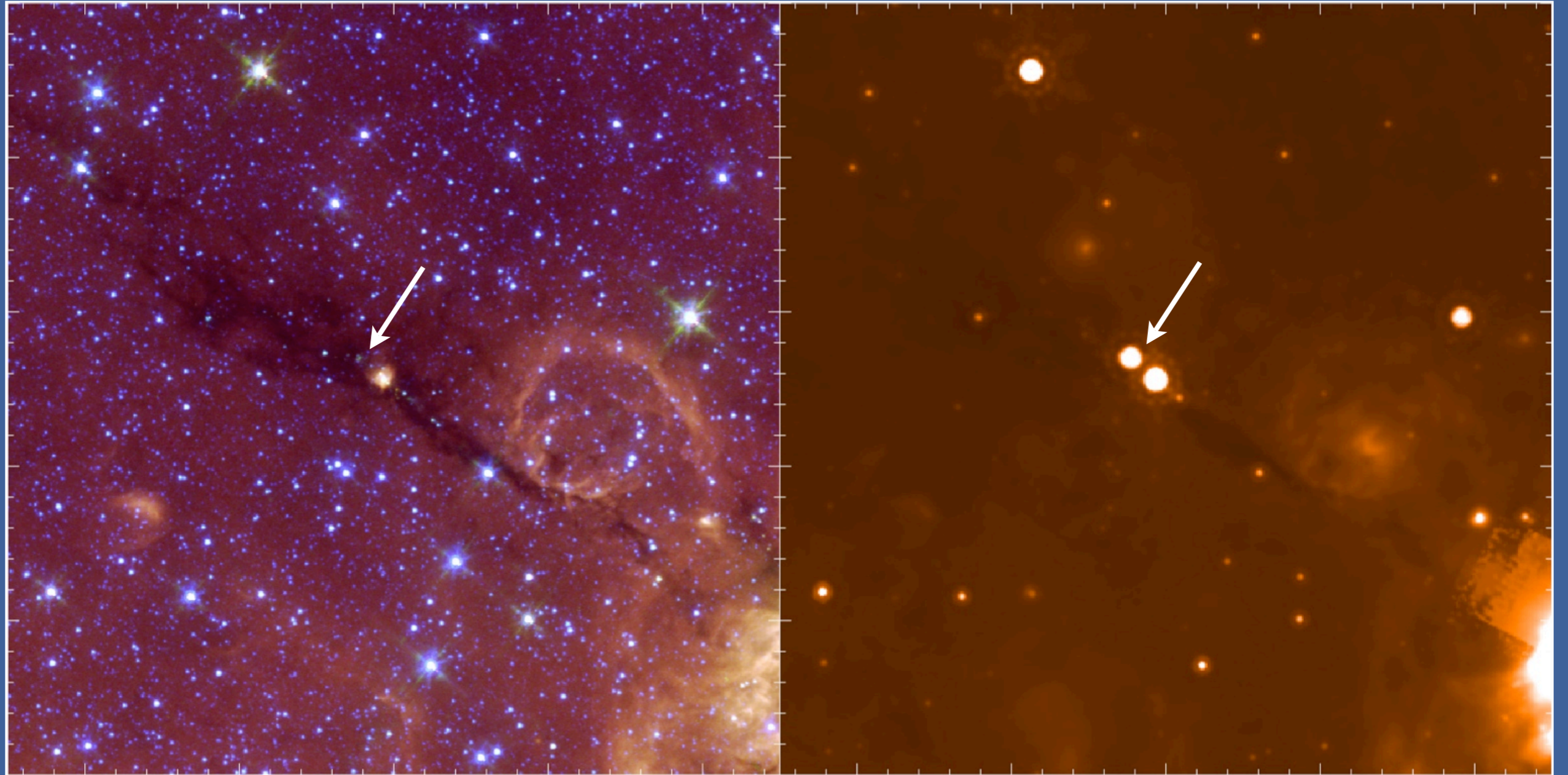


G254.0548-00.0961 - $L_{\text{bol}} \sim 10^4 L_{\text{sun}}$

G34.4MM

IRAC 3.6 μ m (B), 5.8 μ m (G), 8.0 μ m (R)

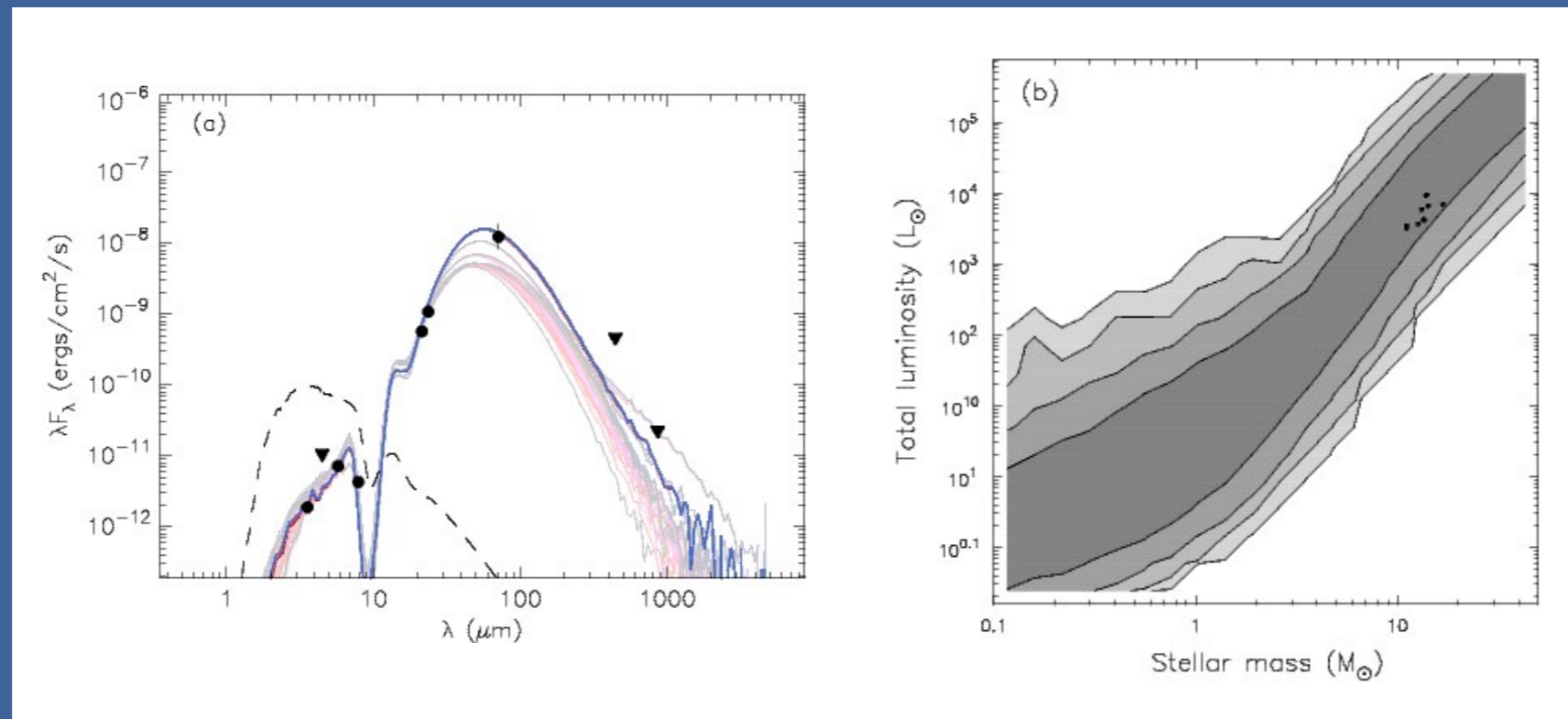
MIPS 24 μ m



G34.4MM

This source appears can be well-fit by embedded models with $M \sim 10 M_{\text{sol}}$.

We can explain the presence of IRAC emission by scattered light in a bipolar cavity.



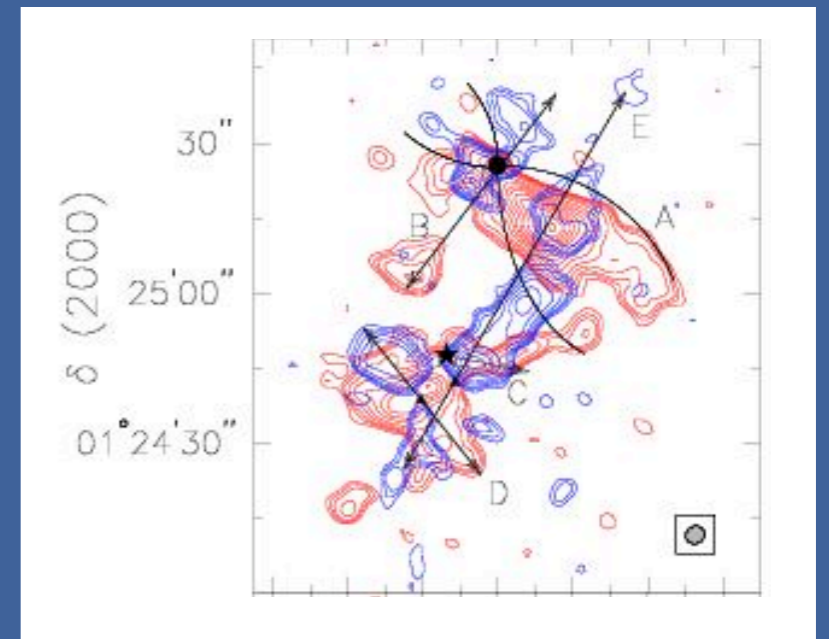
Shepherd et al., 2007

G34.4MM - *Caveats*

Underlying assumption is that only one source is present.

But CO observations reveal outflows from *at least two* different sources in G34.4MM

However, *if one source dominates the SED at all wavelengths*, modeling results are still likely to be relevant.

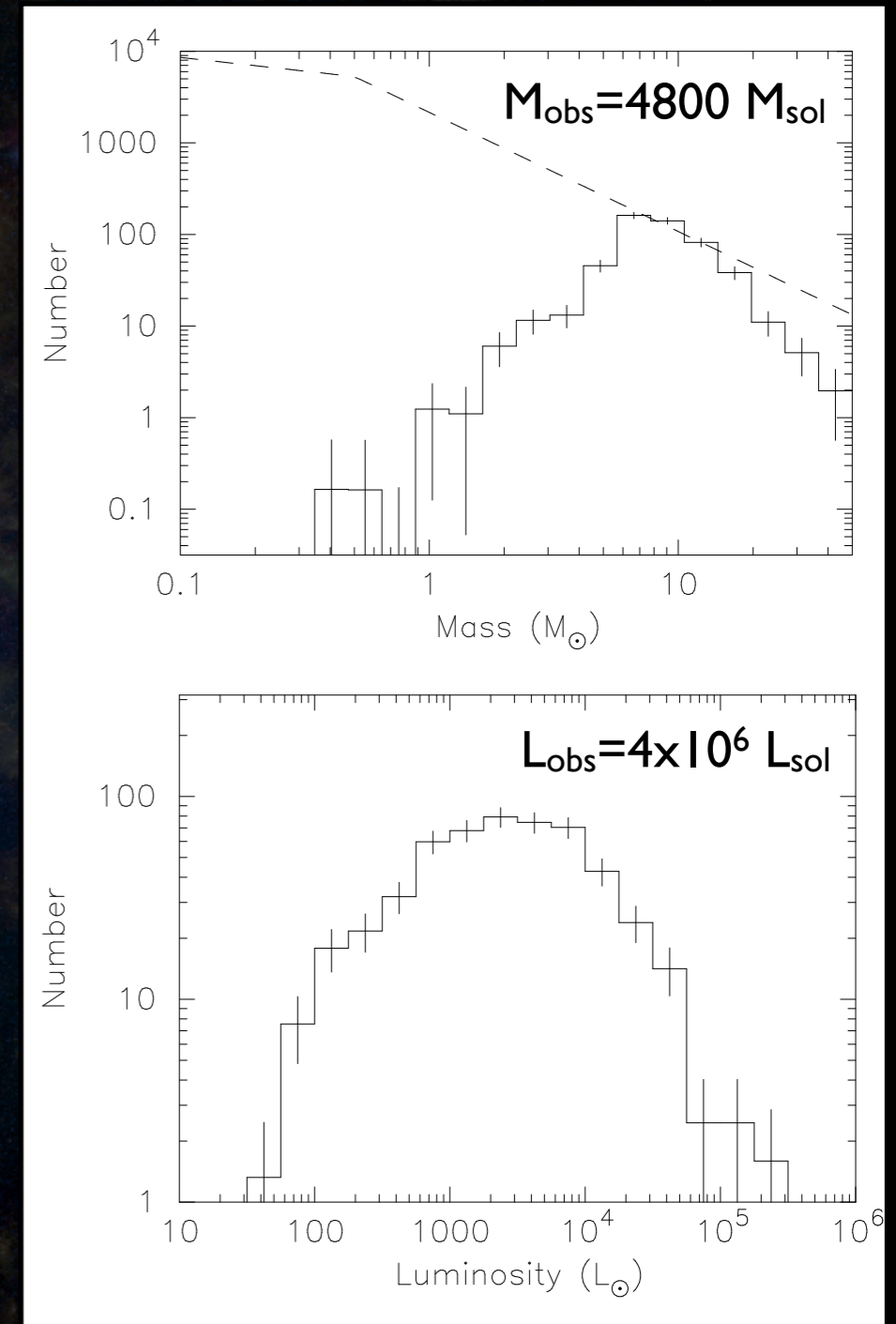


Shepherd et al., 2007



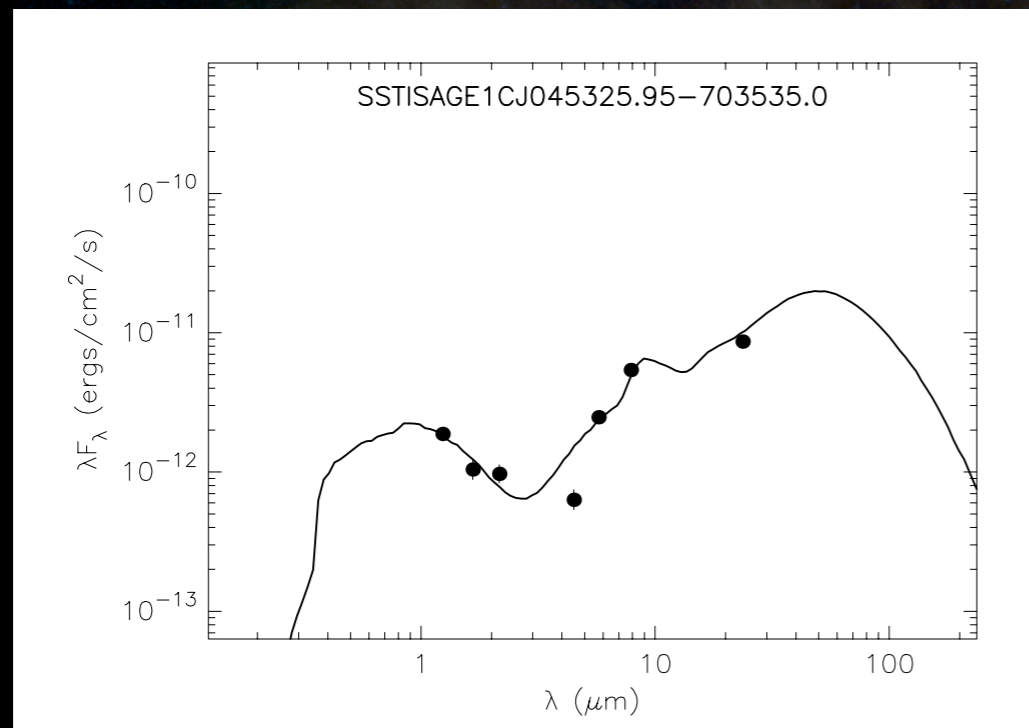
The Large Magellanic Cloud - Results

- >1000 sources have colors consistent with intermediate and high-mass YSOs based on color-magnitude selection (Whitney et al., submitted)
- Estimated SFR is $0.1 M_{\text{sol}} / \text{yr}$
 - Value from UV, H_{α} and IR fluxes is 0.1 to $0.25 M_{\text{sol}} / \text{yr}$
- See poster by Sewilo et al. (#110)



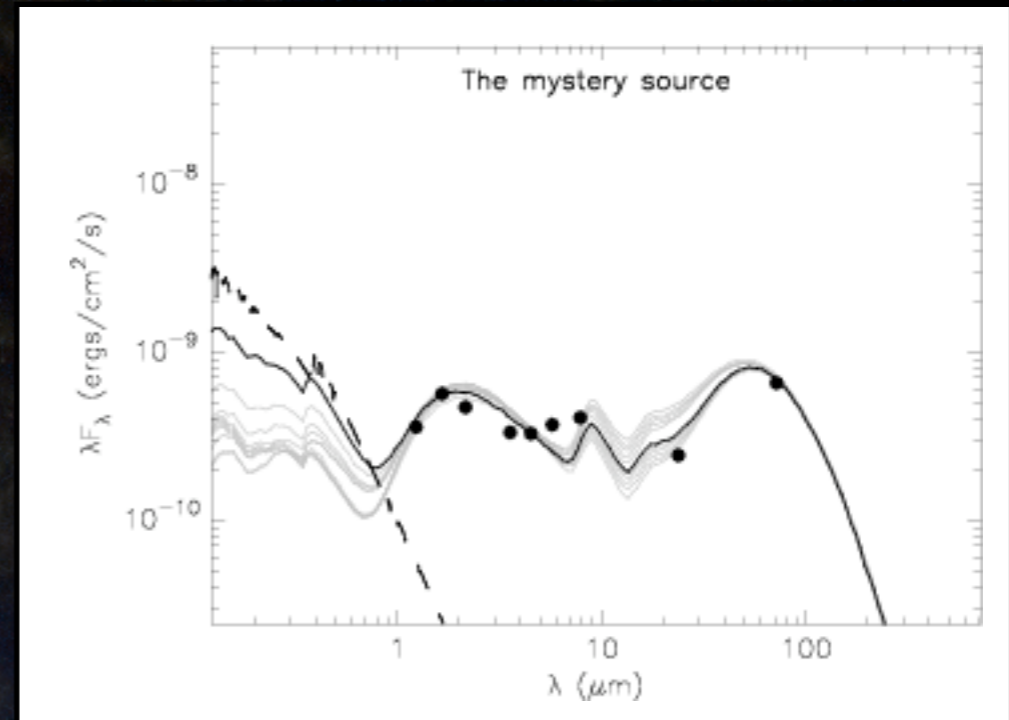
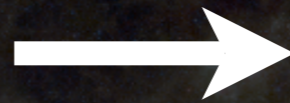
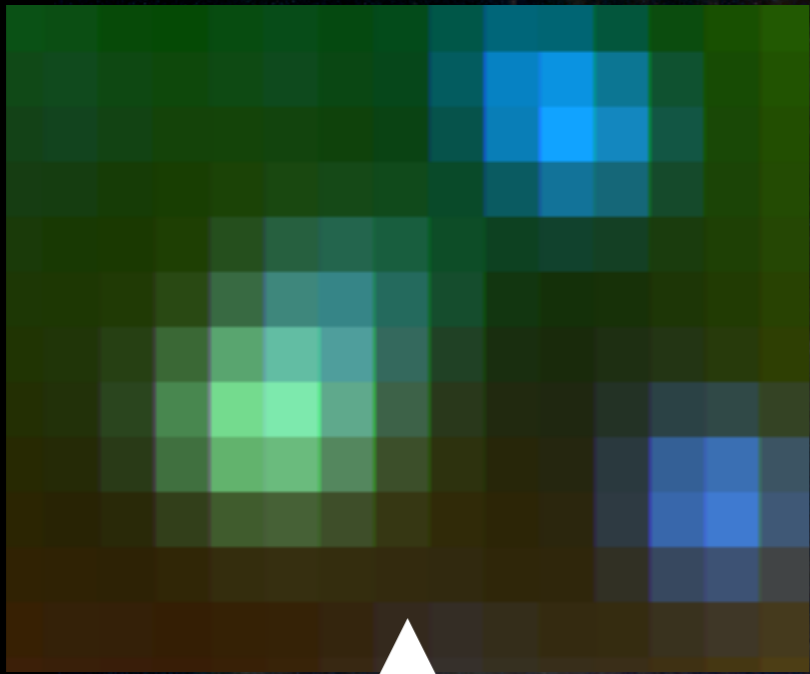
The Large Magellanic Cloud - *Caveats*

At 50kpc, 6" (\sim MIPS 24 μ m) = 3pc



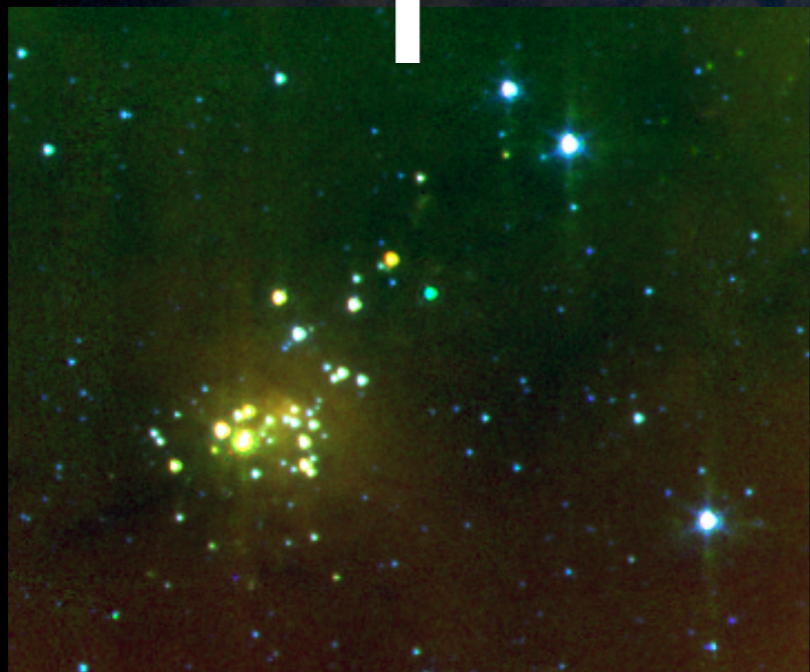
Much more likely to be a proto-cluster than a single MYSO with a strange SED. In this case, different sources might dominate at different wavelengths.

The Large Magellanic Cloud - *Caveats*



$$M_{\text{obs}} = 8-10 M_{\text{sol}}$$

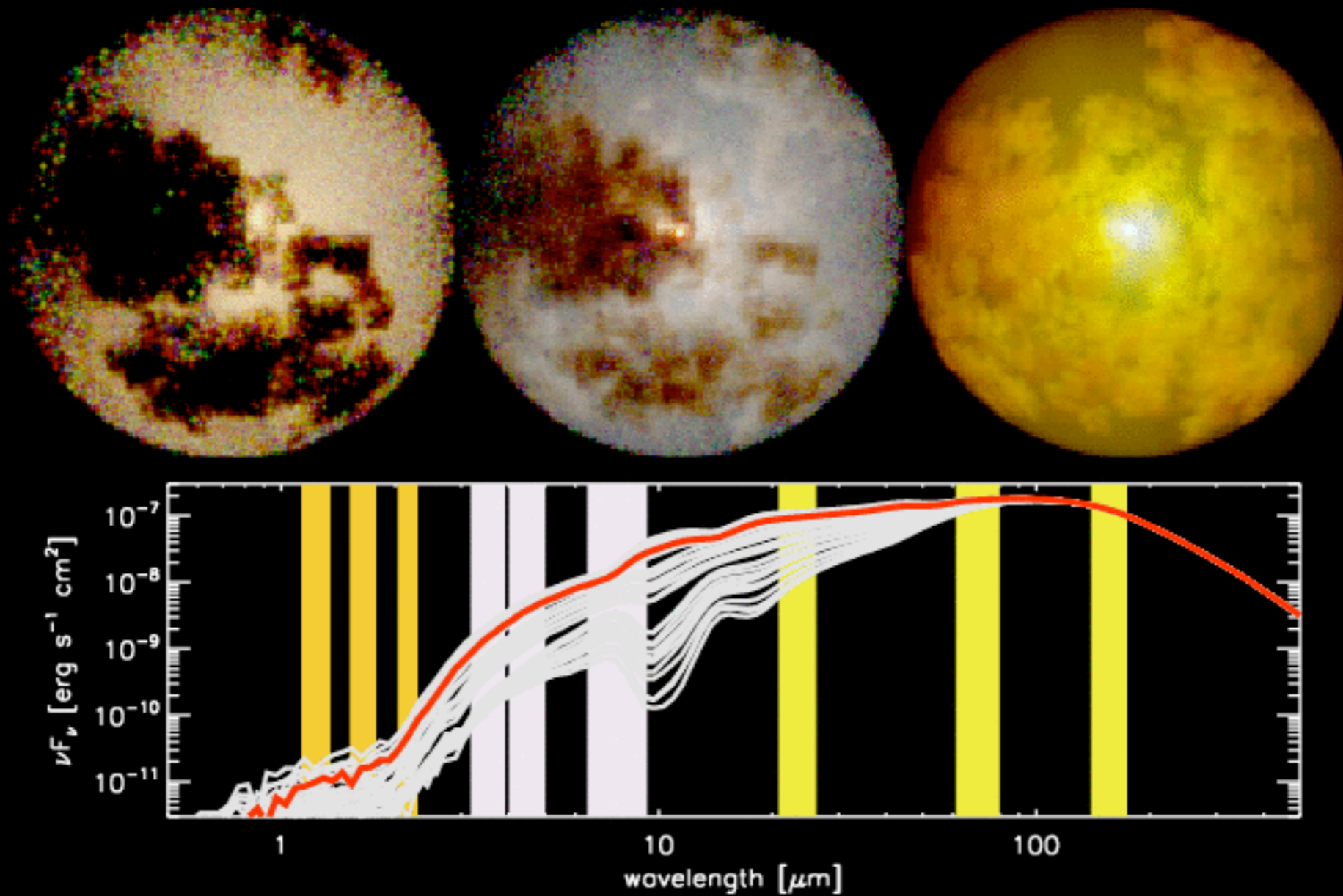
$$L_{\text{obs}} = 1000-2000 L_{\text{sol}}$$



The 'scaling up' caveat

- The massive YSO models are scaled-up versions of the low-mass picture of star formation
- Above $20 M_{\text{sol}}$, geometries assumed in the grid of models may no longer be appropriate
- Fitting a MYSO well with one of these SEDs is not *proof* that the source is indeed forming in a scale-up fashion, simply that its SED is *consistent* with that interpretation
- In future we plan to include models with alternative dust geometries, e.g. stars embedded in clumpy envelopes

Clumpy models : example



Indebetouw et al., 2005

Techniques developed to analyze YSO SEDs

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Applications and caveats for MYSOs

Modeling large numbers of YSOs in GLIMPSE

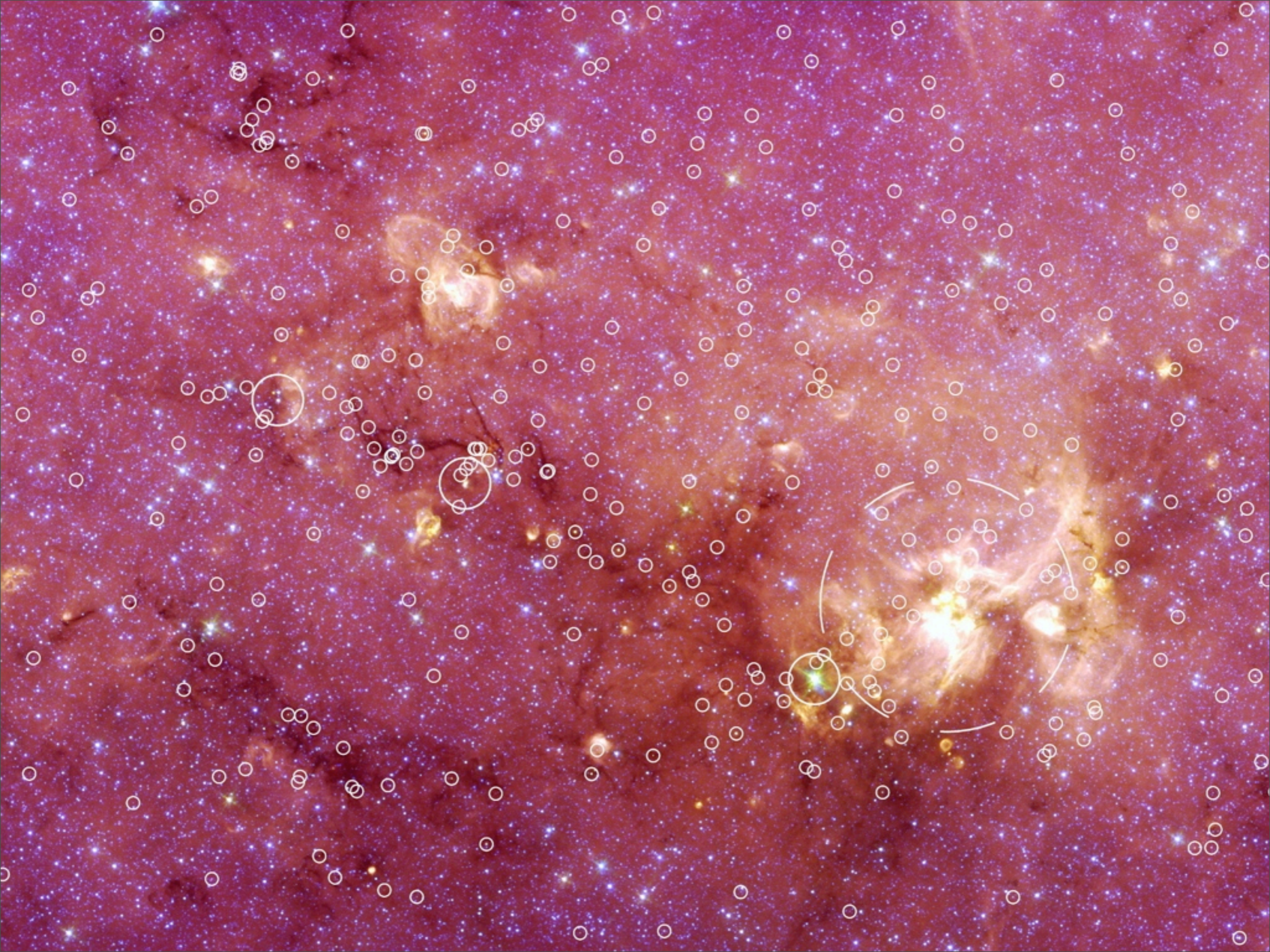
- **Catalog of ~25,000 IR excess sources**

The environments of MYSOs

- We can model not only MYSOs, but also lower mass YSOs in their vicinity
- Aim is to find out more about the environments in which massive stars form (clustering, triggering,...)
- We are compiling a highly reliable catalog of IR excess sources in GLIMPSE (~25,000 sources) based on the publicly available catalogs.
- Aside from modeling their SEDs, we will look for spatial correlations with e.g. dark clouds and bubbles

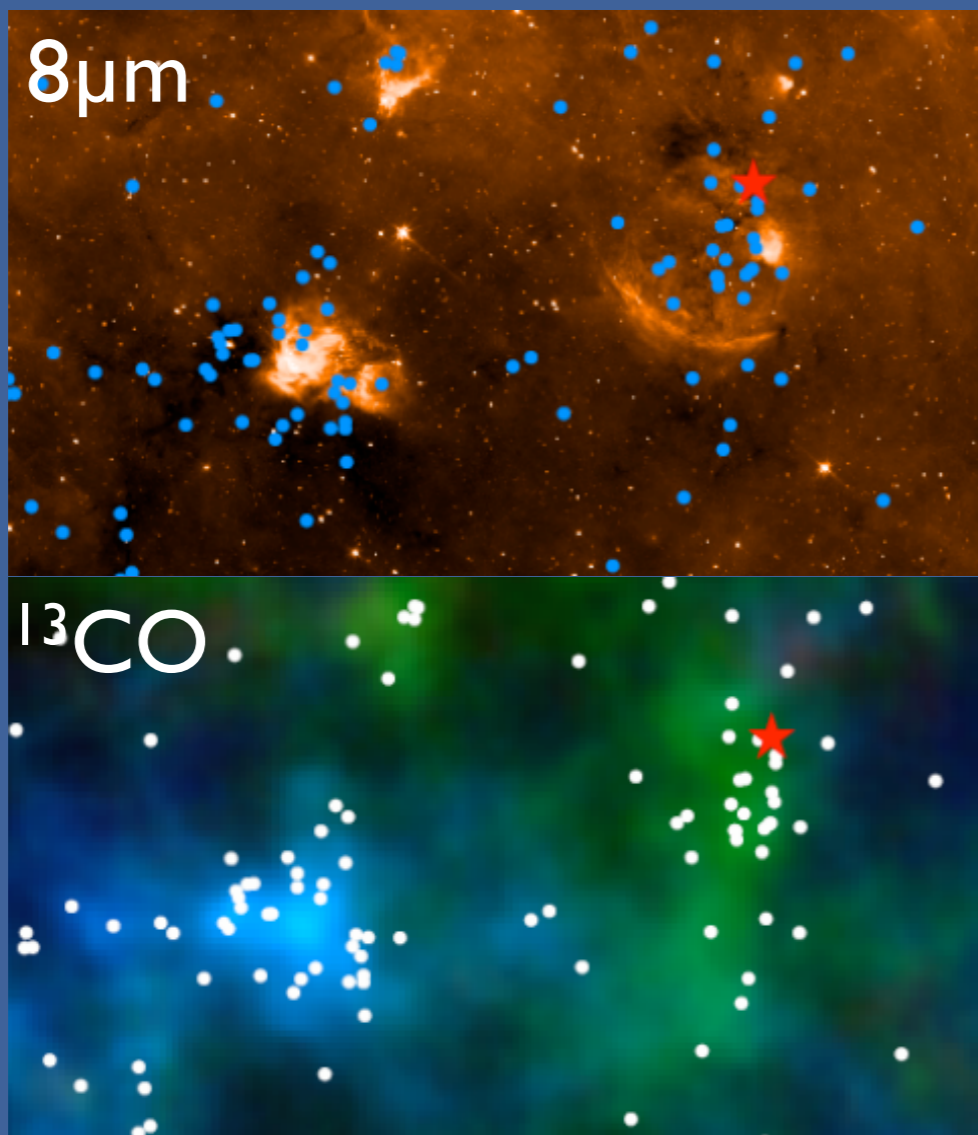






IR excess sources in GLIMPSE

For more information see poster by Robitaille et al. (#91)



A GLIMPSE of star formation in the Galactic plane

Thomas P. Robitaille, Barbara A. Whitney, Marilyn Meade, Brian Babler, Remy Indebetow, Ed Churchwell

The IR excess source catalog

I - Introduction

The *Spitzer*/GLIMPSE I and II surveys provide a spatially complete coverage of the Galactic plane at mid-IR wavelengths, extending $\sim 1^\circ$ in Galactic Longitude on either side of the Galactic Center, and at least 10° in Galactic Latitude. The publicly available Point Source Catalogue from the GLIMPSE I and II surveys contain over 45,000,000 sources. We use these catalogs that we are selecting IR excess sources.

The surveys include many well studied sites of star formation, such as MW and M17, and many known massive Young Stellar Clusters (YSCs). However, the increased sensitivity of *Spitzer* also allows us to see intermediate mass YSCs, and more distant massive YSCs than were previously seen.

We are in the process of compiling a highly reliable catalog of mid-IR excess sources which will be made available to the community. This catalog should include nearby intermediate mass YSCs and AOB stars.

II - The need for a highly reliable catalog

Due to the difficulty to perform a automated photometry in regions of complex backgrounds, a very small fraction of sources in the GLIMPSE Catalogs are likely to have incorrect flux densities at 5.8 and 8.0 μ m. In addition, we expect bad data at any wavelength for sources with low signal-to-noise, and sources in crowded regions. However, most of these only represent a small fraction of the total number of sources, we need to carefully construct them when compiling a catalog of sources with non-linear colors, because bad data (e.g. a too high flux density at 5.0 μ m) will often cause a source to be classified as an AOB star.

III - Source selection

In order to produce a flux-limited, complete (within the flux limits and color selection), and highly reliable catalog, we proceed as follows:

- we require IRAC 3.6 & 4.5 μ m fluxes to be greater than 1 mJy for a detection, and the IRAC 5.8 & 8.0 μ m fluxes to be greater than 0.5 mJy;
- we remove origin detections (as GLIMPSE areas were observed at least twice);
- we require detections in all IRAC bands;
- we require $(J-K_s) > 0.25$, $(K_s-H) > 0.25$, and $(H-K_s) > 0.25$.

Using these criteria, we obtain $\sim 30,000$ sources. However, even these stringent criteria cannot guarantee a 100% reliability as we visually inspect every source in each band, and remove any bad subpixels. So far, we have found that for around 10-15% of the $\sim 30,000$ sources, the photometry is not reliable in at least one band. We expect the final catalog to contain $\sim 25,000$ sources.

A GLIMPSE at the catalog

Below, three color-maps show the Galactic plane from $l=0^\circ$ to $l=1^\circ$, and from $b=1^\circ$ to $b=1^\circ$. The top panel shows a *Spitzer*/GLIMPSE 8.0 μ m image, and the bottom panel shows a ^{13}CO J=1-0 integrated intensity image using emission between 160 and 170 GHz. The color in the ^{13}CO image shows different velocities: 3 m/s (blue), 10 m/s (green), 20 m/s (yellow), and 30 m/s (red). The color and white points show the location of the mid-IR excess sources in our catalog, and the red dots show the location of YSCs from the Best IRDC Source Catalog (Remy Indebetow, Meade et al., 2005).

Many small clusters are seen to be aligned with clumps in ^{13}CO , some of which also contain massive YSCs from the IRDC Catalog. A large number of IR excess sources and massive YSCs from the IRDC Catalog are seen towards the Scutum Spiral arm. Below these three panels is a detailed visualization of sources which contain AOB stars, showing the strong correlation between many IR excess sources, massive YSCs from the IRDC Catalog, and the ^{13}CO intensity towards that region from the IRDC catalog and IRDC YSCs.

Left: Number of sources in the GLIMPSE catalog, and in our IR excess source catalog, versus the ^{13}CO J=1-0 intensity (intensity for the entire region).

Right: The IR excess sources are clearly concentrated in the ^{13}CO J=1-0 intensity, showing that a significant number of the mid-IR excess sources are indeed young stellar populations (YSCs). The correlation can clearly be seen in the bottom panels, with small clusters of sources aligned with ^{13}CO clumps.

Left: The two-panel correlation function plot (upper and lower panels) and the nearest neighbor correlation function for the sources in the above region.

Right: The two-panel correlation function plot (upper and lower panels) and the nearest neighbor correlation function for the sources in the above region.

Summary

We are in the process of compiling a catalog of IR excess sources using the GLIMPSE I and II surveys, with the aim of providing a highly reliable catalog of mid-IR excess sources. This catalog should include nearby intermediate mass YSCs and AOB stars. The catalog will be made available to the community.

We expect to see the catalog to have a higher completeness of the entire high and intermediate mass stars from the Galactic plane. The catalog will also include the sources in the Scutum spiral arm, and other sources in the Galactic plane. We hope that this catalog will also serve as a basis for future observations.

This poster makes use of the Best IRDC Source Survey catalog (Meade et al., 2005), MAO5 Survey (2007, 2010), and makes use of molecular line data from the Boston University FOMM Survey (Meade et al., 2005). The MAO5 is a joint project of Boston University and the College Park Radio Astronomy Observatory, funded by the National Science Foundation under grants AST-0000008, AST-0000009, AST-0000010, and AST-0000011.

Summary

- We have developed a grid of models which we can fit to observed SEDs to determine parameter constraints. The grid and a fitting tool are available online.
- We can apply this technique to MYSOs, **but** need to be aware of where assumptions break down.
- We are compiling a catalog of IR excess sources in GLIMPSE I & II, focusing on a high reliability.

Future work

- Improved grid of YSO models
 - ➔ e.g. unbiased gridding
 - ➔ images, visibilities, polarization maps
 - ➔ feedback/suggestions for improving our high-mass models welcome!
- Study the effects of multiplicity/clustering on SEDs
- Analysis/Follow-up of sources in the GLIMPSE IR excess source catalog

See also

- Poster #71 - Mottram et al. (RMS survey)
- Poster #91 - Robitaille et al. (IR excess sources)
- Poster #110 - Sewilo et al. (YSOs in the LMC)
- Poster #139 - Watson et al. (GLIMPSE bubbles)

- Model grid and SED fitting tool:

<http://www.astro.wisc.edu/protostars>