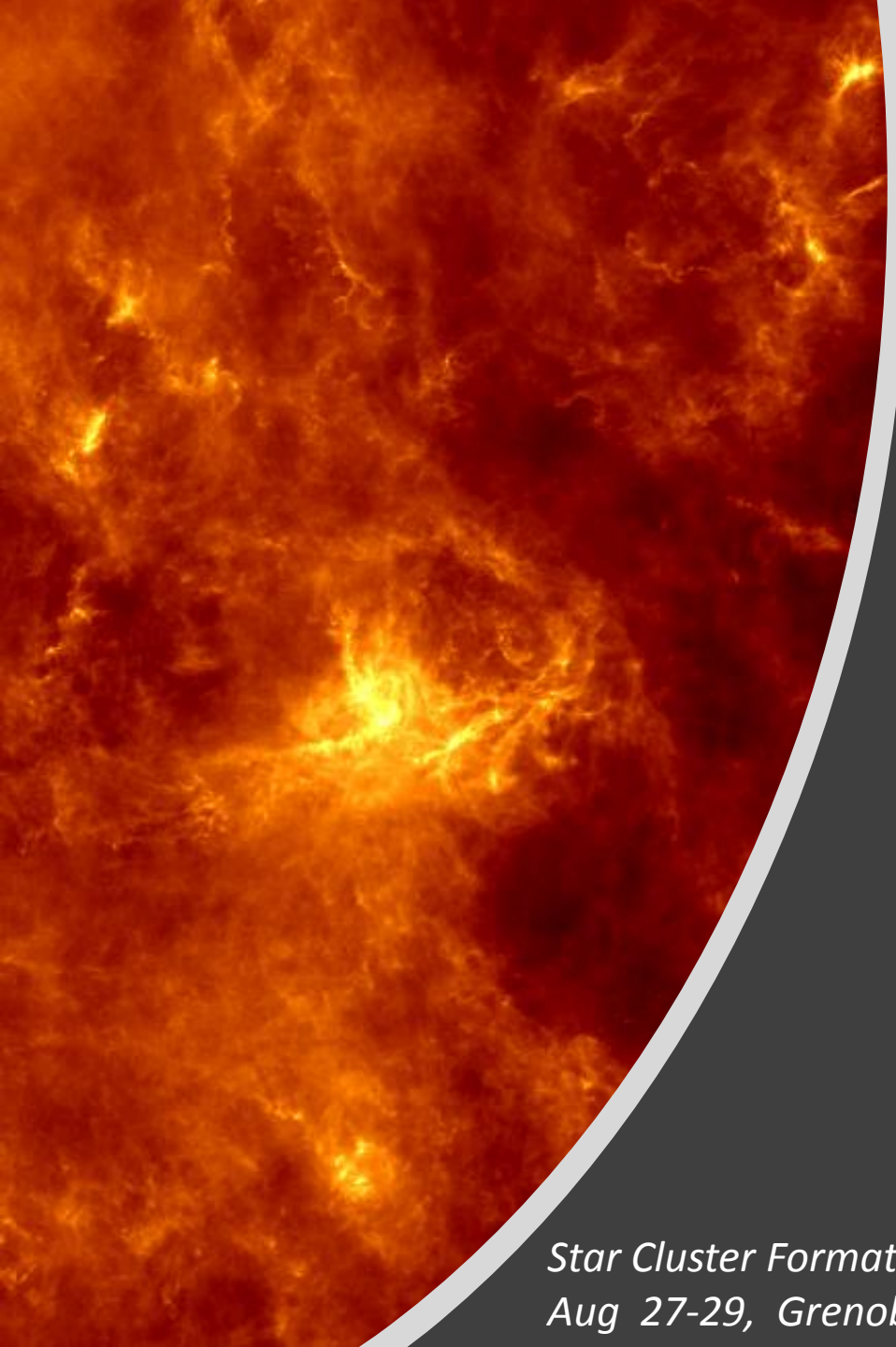


Clustered and Dispersed Star Formation Across the Serpens Molecular Complex

Marc Pound

Lee Mundy

Isabelle Joncour

Emma Schwarzman

Jacqueline Lydon

Star Cluster Formation: Mapping the first few Myrs
Aug 27-29, Grenoble, France

What are the Goals of this Study?

Measure
properties of star forming regions in one complex

- Clustering properties of YSOs
- YSOs evolutionary & dynamical status
- Relationship to gas
- Age and mass segregation

Test
against our expectations* from cluster origin theories

- Highly dynamic, “rapid”

  Bonnell+ 2003; Bate 2009; Vazquez-Semadeni+ 2017
- Quasi-equilibrium, “slow”

  Elmegreen+ 2000; Tan+2005; [Krumholz+ 2005]

* But our expectations may have changed based on yesterday’s discussions!

Expectations from Cluster Models

Feature	Model Prediction	
	Rapid	Slow
Degree of clustering	very high	low
Subcluster shape	elongated	round
Stellar hierarchy	inherited from gas	none
YSO Class content	mixed	segregated

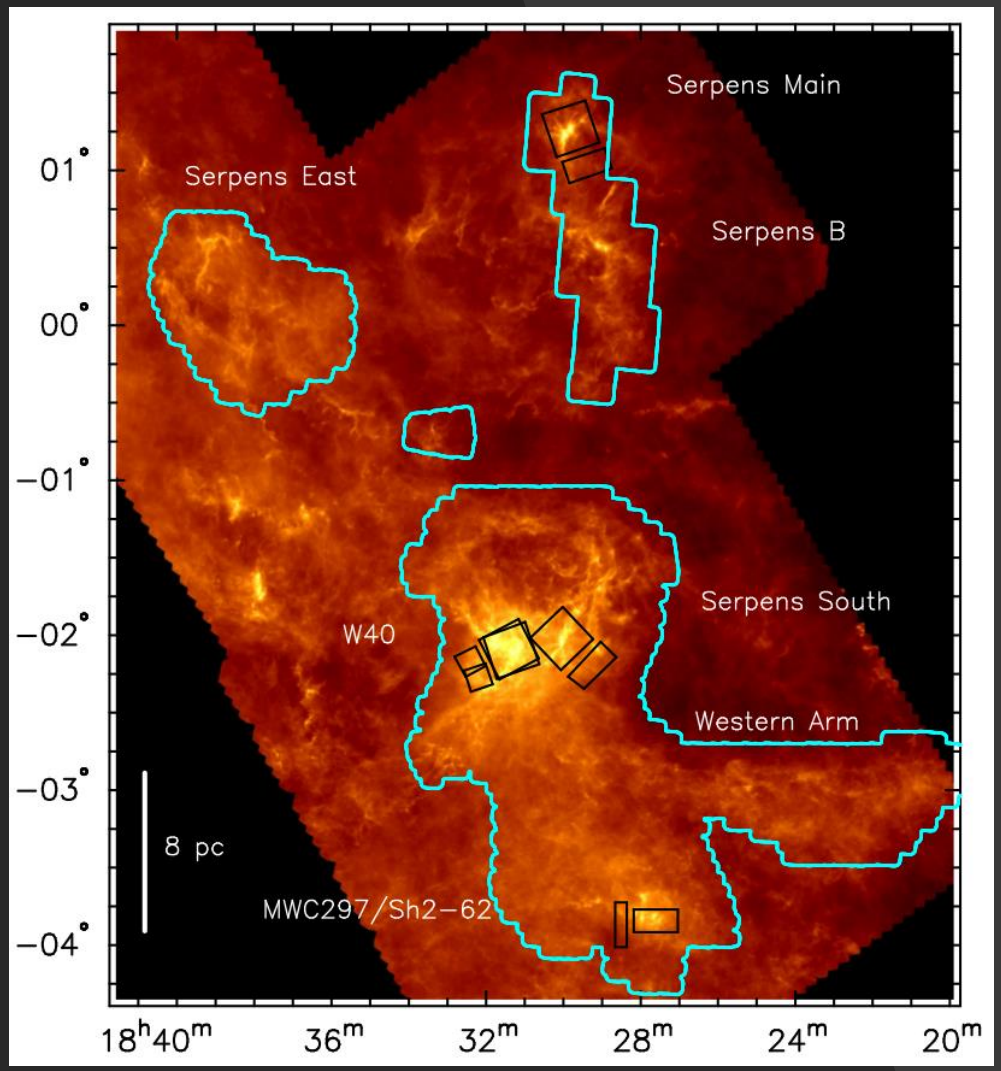
These features can be examined using our methods

Predictions from Cluster Models

Feature	Technique to be used
Clustering degree	correlation functions, dbscan extraction (FoF)
Subcluster shape	shape analysis
Stellar & gas hierarchies	hierarchical dbscan, dendrogams
YSO Class content	observed & fitted SEDs

Why Choose Serpens MC?

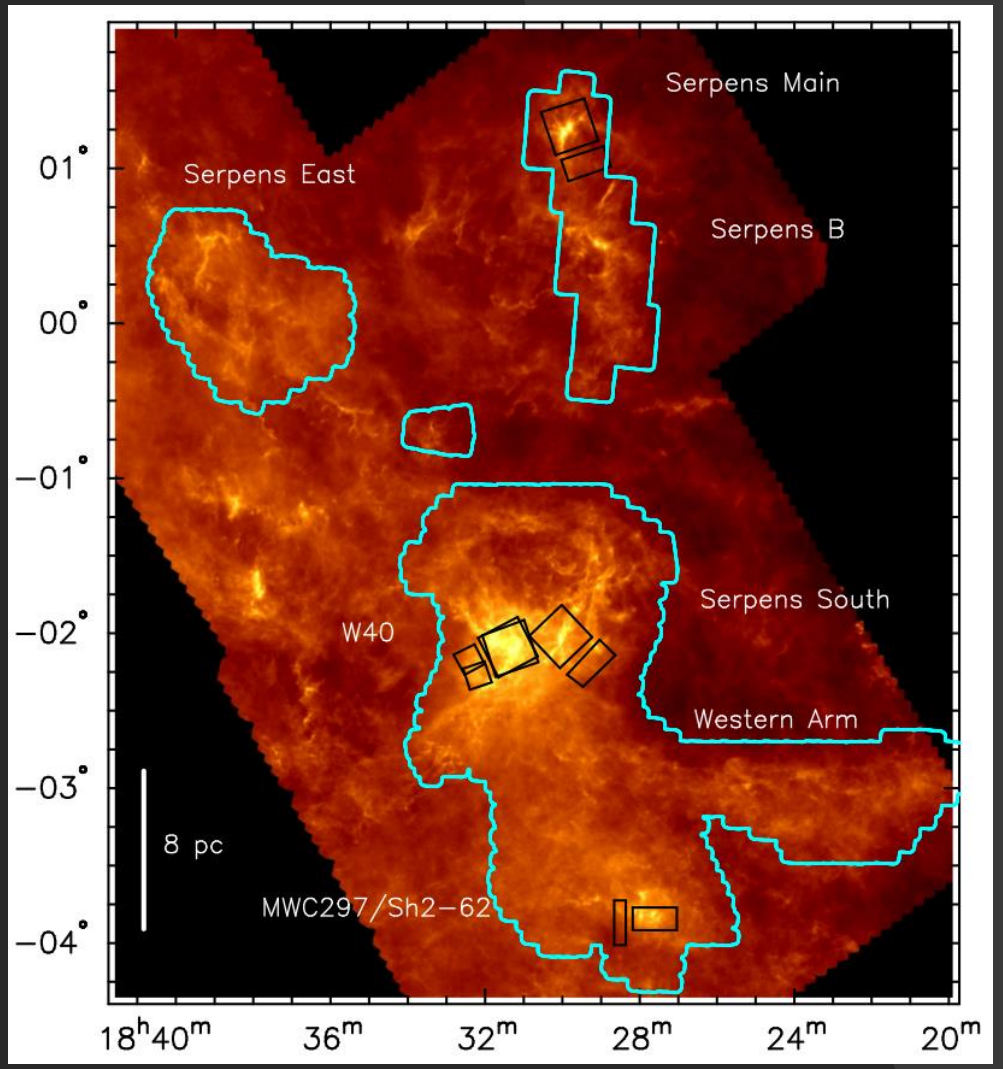
- Location, size, population
  - Large (384 sq pc), nearby (436 pc) region with several rich protostellar clusters and distributed star formation
- Large archival surveys
  - Spitzer, Herschel, 2MASS, VISTA, WISE, SDSS, CARMA CLASSY, Chandra
- GAIA now available
  - Photometry, distances, proper motions



Color: Herschel 350 micron, boxes: Chandra, outline: Sptizer c2d and GB

Why Is More Study Needed?

- No published uniform study covering entire region
- Existing studies have
  - Limited depth (c2d, GB)
  - Limited area (Getman+)
  - Conflicting YSO classifications
  - Known contamination
  - Have not looked at clustering substructure
  - Did not use photometry from visible bands
- GAIA now available



Color: Herschel 350 micron, boxes: Chandra, outline: Sptizer c2d and GB

Analysis Tools

YSO Identification

- Catalog matching: GAIA, c2d/GB, 2MASS, WISE, SDSS
- GAIA distances

YSO Classification

- Measurement of SED spectral power law α
- YSO models and fitting code (Robitaille 2017)

Spatial Clustering

- 1pt, 2pt correlation functions, Nearest neighbor statistics
- Hierarchical DBSCAN (Joncour+ 2018)

Dust Morphology

- Dendrograms – can compare with H-DBSCAN trees

Kinematics

- GAIA proper motions to help determine YSO membership
- Comparison with motions of local gas

Initial Results From…

- YSO Identification
  - Catalog matching: GAIA, c2d/GB, 2MASS, WISE, SDSS
  - GAIA distances
- YSO Classification
  - Measurement of SED spectral power law α
  - YSO models and fitting code (Robitaille 2017)
- Spatial Clustering
  - 1pt, 2pt correlation functions, Nearest neighbor statistics
  - Hierarchical DBSCAN (Joncour+ 2018)
- Dust Morphology
  - Dendrograms – can compare with HDBSCAN trees
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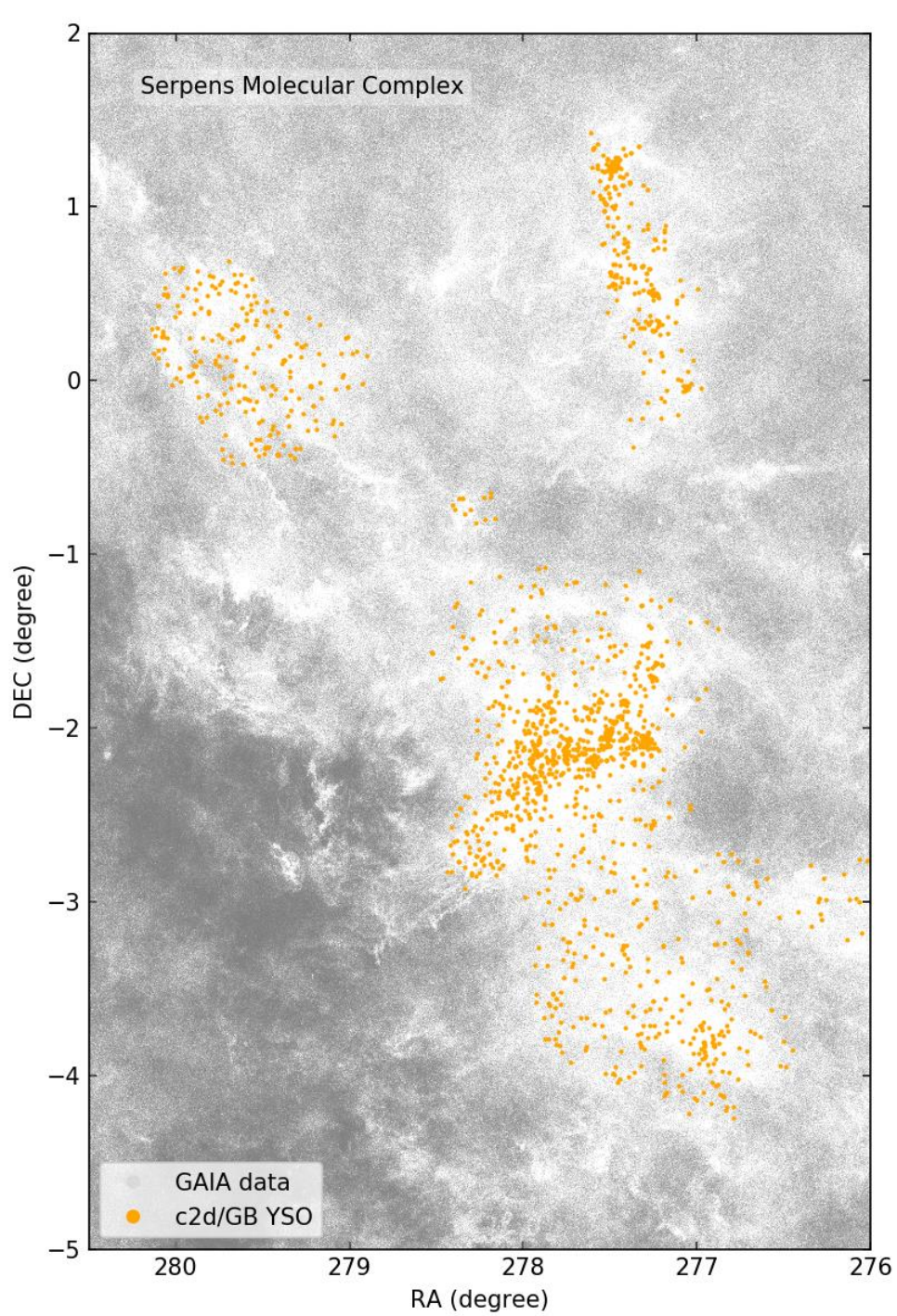
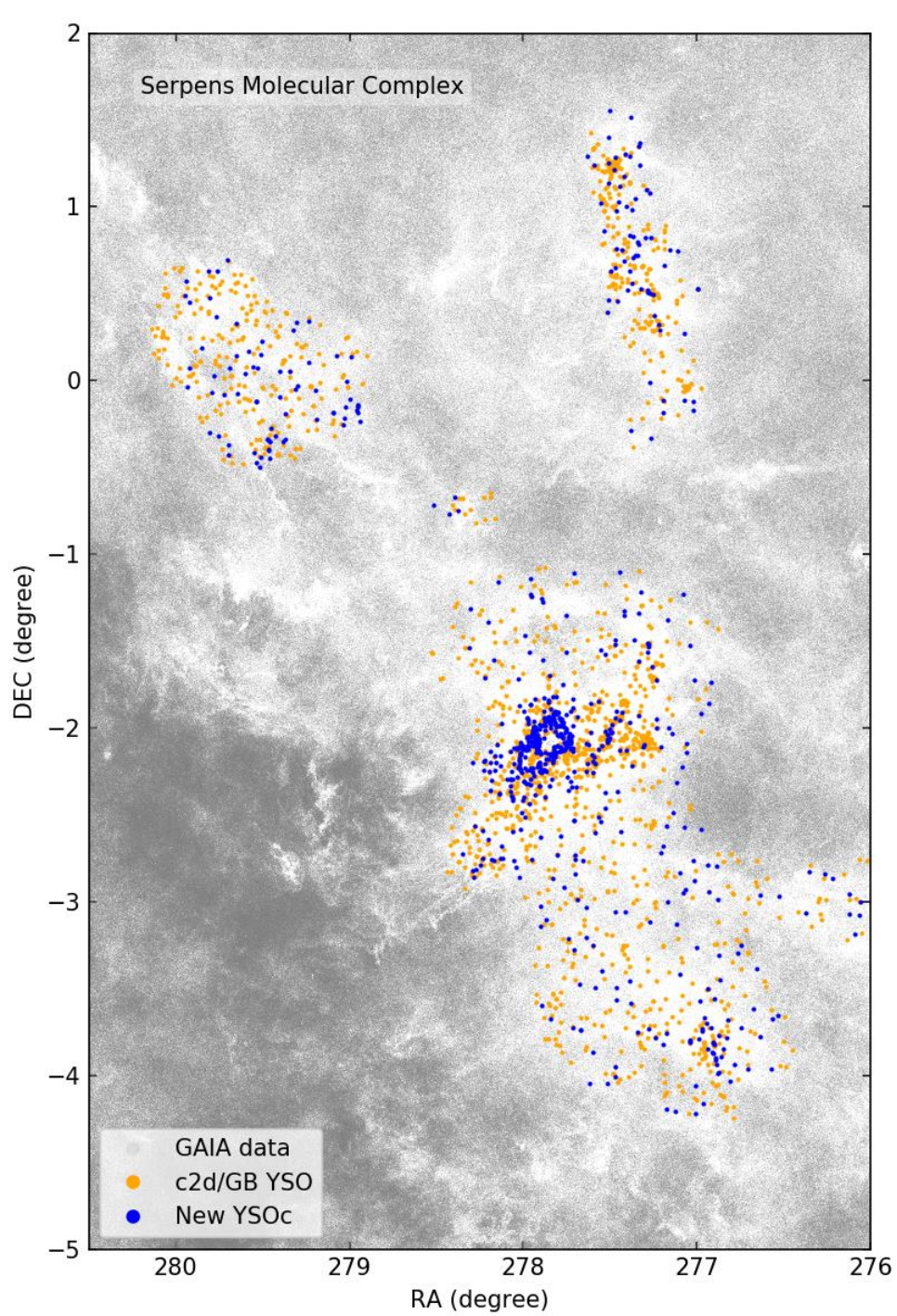
  - Comparison with motions of local gas



Buried Treasure!

Relaxing the c2d/GB "galaxy probability" criterion from 3% to 25% uncovers many **new YSO candidates** clustered around **catalogued YSO candidates**



Buried Treasure!

Relaxing the c2d/GB "galaxy probability" criterion from 3% to 25% uncovers many **new YSO candidates** clustered around **catalogued YSO candidates**

Perhaps **20%-40%** more

Revised Cluster Distances from GAIA

Source	# YSOs*	Distance (pc)	Dispersion (pc)
Serpens Main	80	437 ± 7	45
W40 and Serpens South	29	465 ± 5	59
Serpens East	21	484 ± 5	57
Western Arm	1	444	--
MWC 297	12	434 ± 4	8

* With Plx/ePlx $\geq$7

Clusters are at varying distances within complex and may have significant depth.

Physical Types of SED models

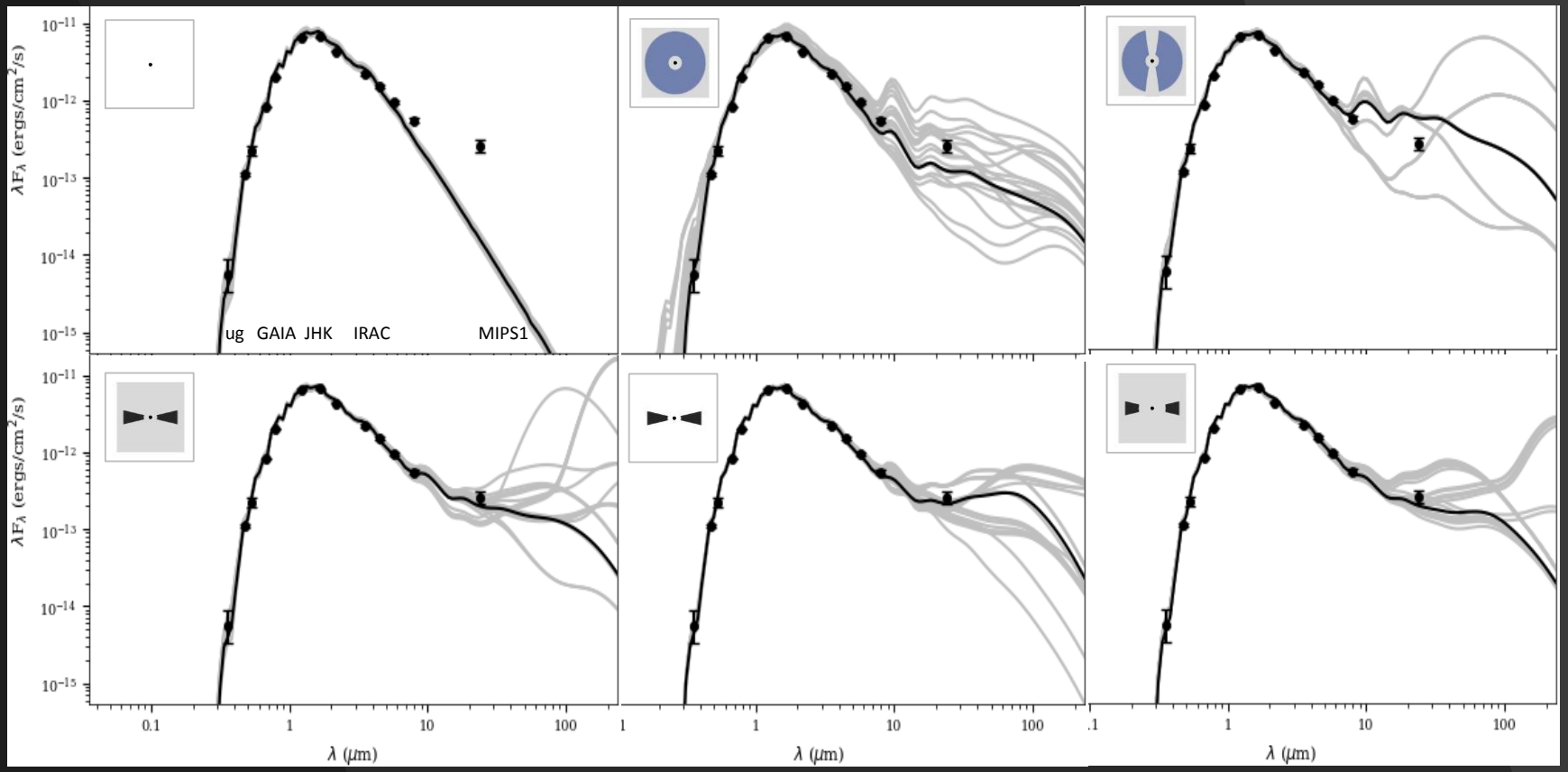
Icon	Star	Disk	Envelope	Cavity	Ambient	Inner radius
	yes	…	…	…	…	…
	yes	passive	…	…	…	$R_{\rm sub}$
	yes	passive	…	…	…	variable
	yes	…	…	…	yes	$R_{\rm sub}$
	yes	passive	…	…	yes	$R_{\rm sub}$
	yes	passive	…	…	yes	variable
	yes	…	power-law	…	yes	$R_{\rm sub}$
	yes	…	power-law	…	yes	variable
	yes	…	power-law	yes	yes	$R_{\rm sub}$
	yes	…	power-law	yes	yes	variable

+8 more

Robitaille (2017)

SED Fitting of YSO candidates

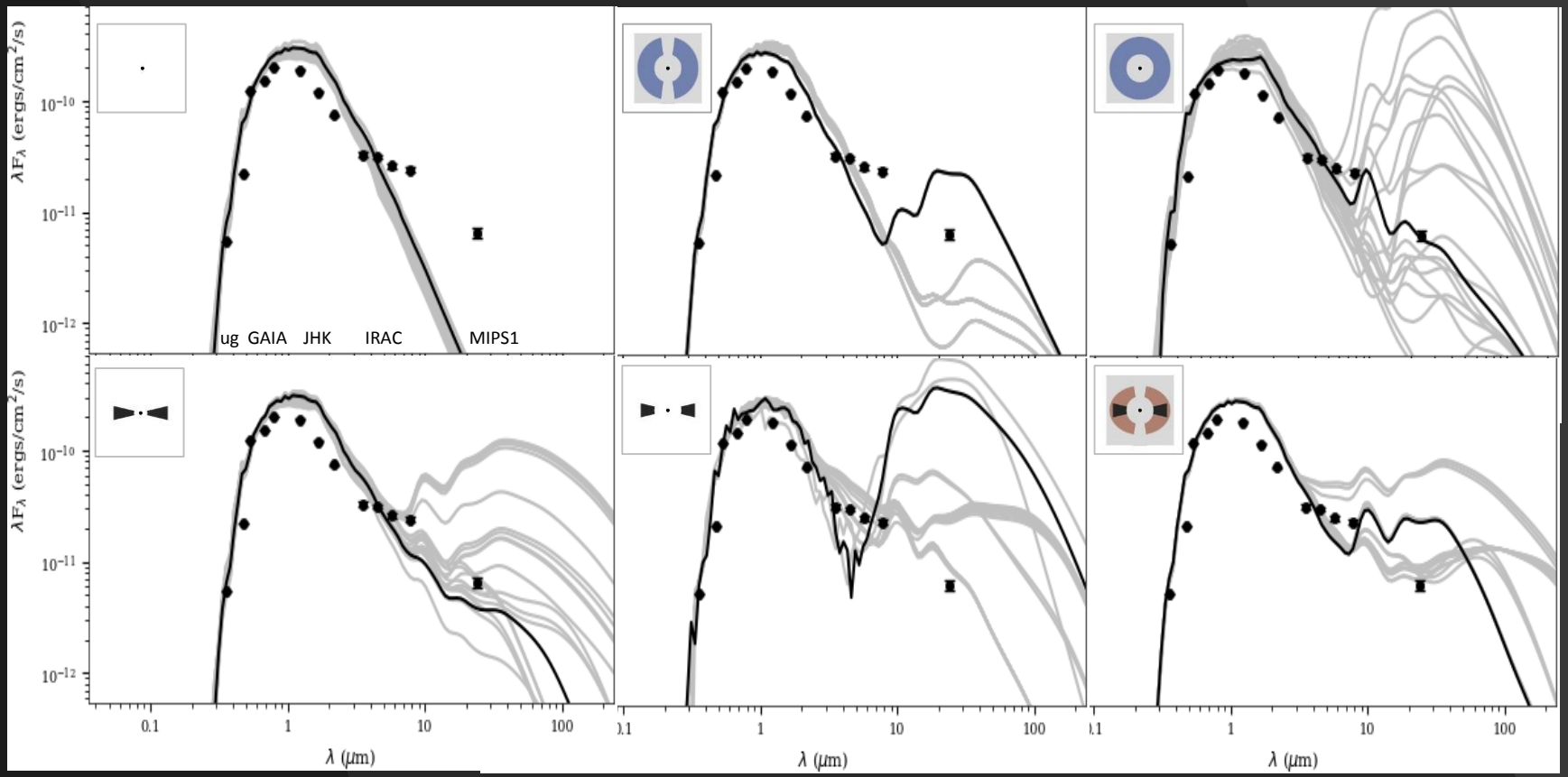
When it goes right….



Bare star or star with envelope clearly ruled out (top).
Star with passive disk fits very well (bottom).

SED Fitting of YSO candidates

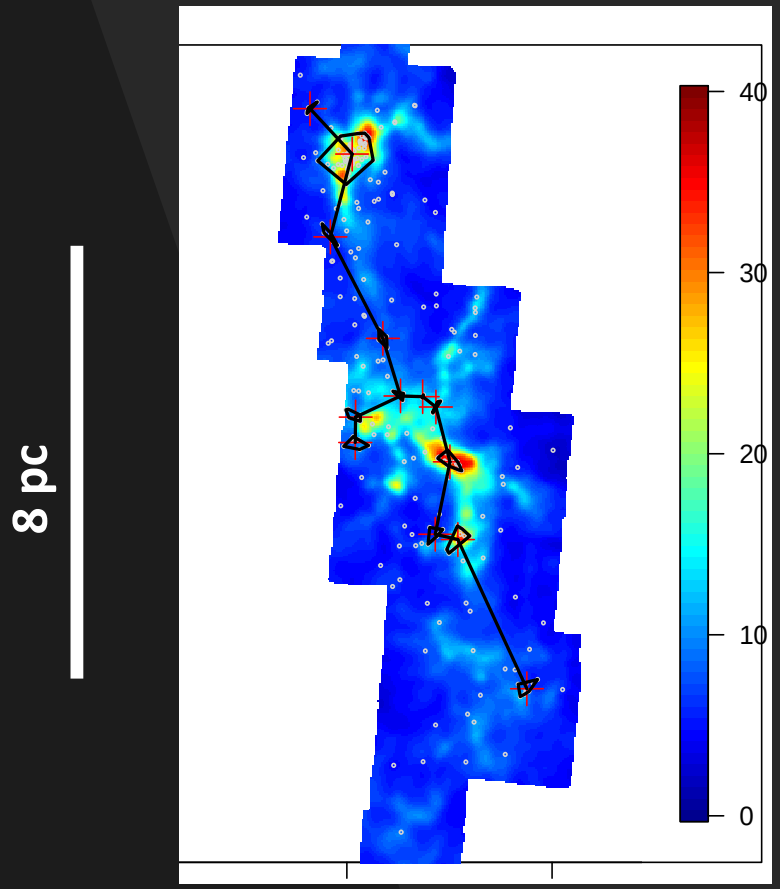
When nothing works…



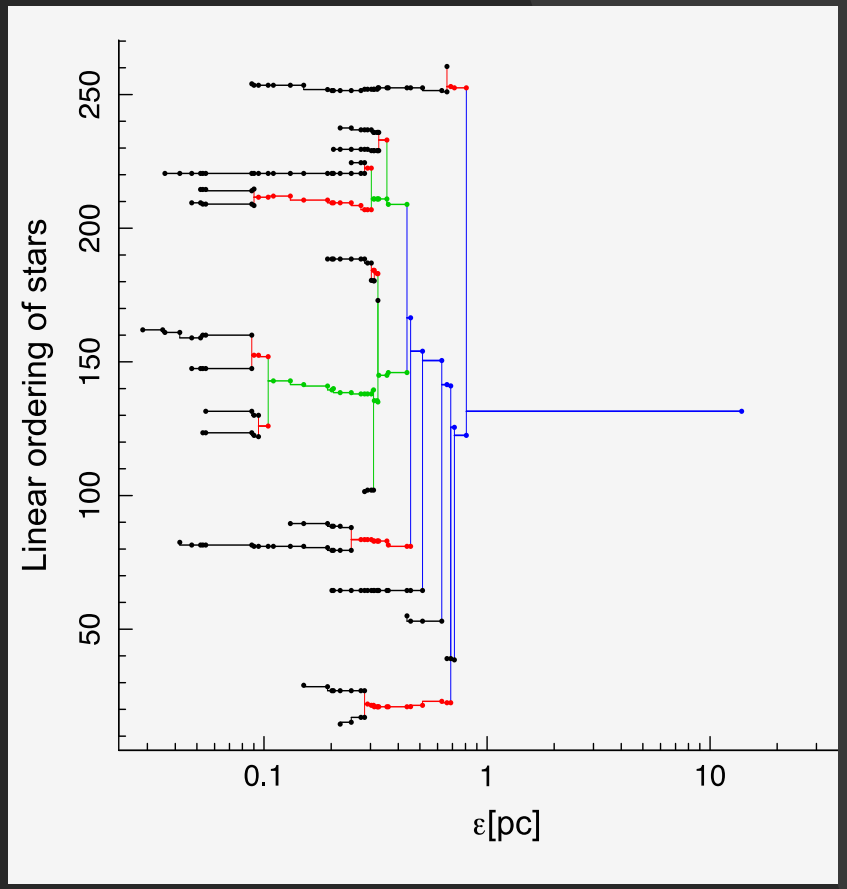
Cannot fit visible and infrared simultaneously.

Low errors on GAIA photometry challenge models.

Clustering Hierarchy – Serpens Main



Extinction map & Cluster sizes and locations



Clustering as a function of size scale

We find 19 subclusters and 4 levels of clustering hierarchy

Challenges

Data

Gould's Belt Catalog not as clean as c2d

- and even c2d has some false sources

SDSS Photometry

- *riz* is suspect, often o.o.m. off GAIA/UBV
- *ug* usually ok
- magnitude errors often extremely optimistic

Tools

Robitaille models

- defacto standard but BE CAREFUL!
- sensitive to total extinction & extinction law
- some underlying stellar models are "unphysical" (his word!)

We Will…

Create

A high-fidelity, uniform catalog of YSOs in Serpens
- Cross-matched with major catalogs
- Photometry from 0.25 to 70 micron.

Classify

- YSOs according to standard SED Classes
- YSO disk and envelope properties from model fits

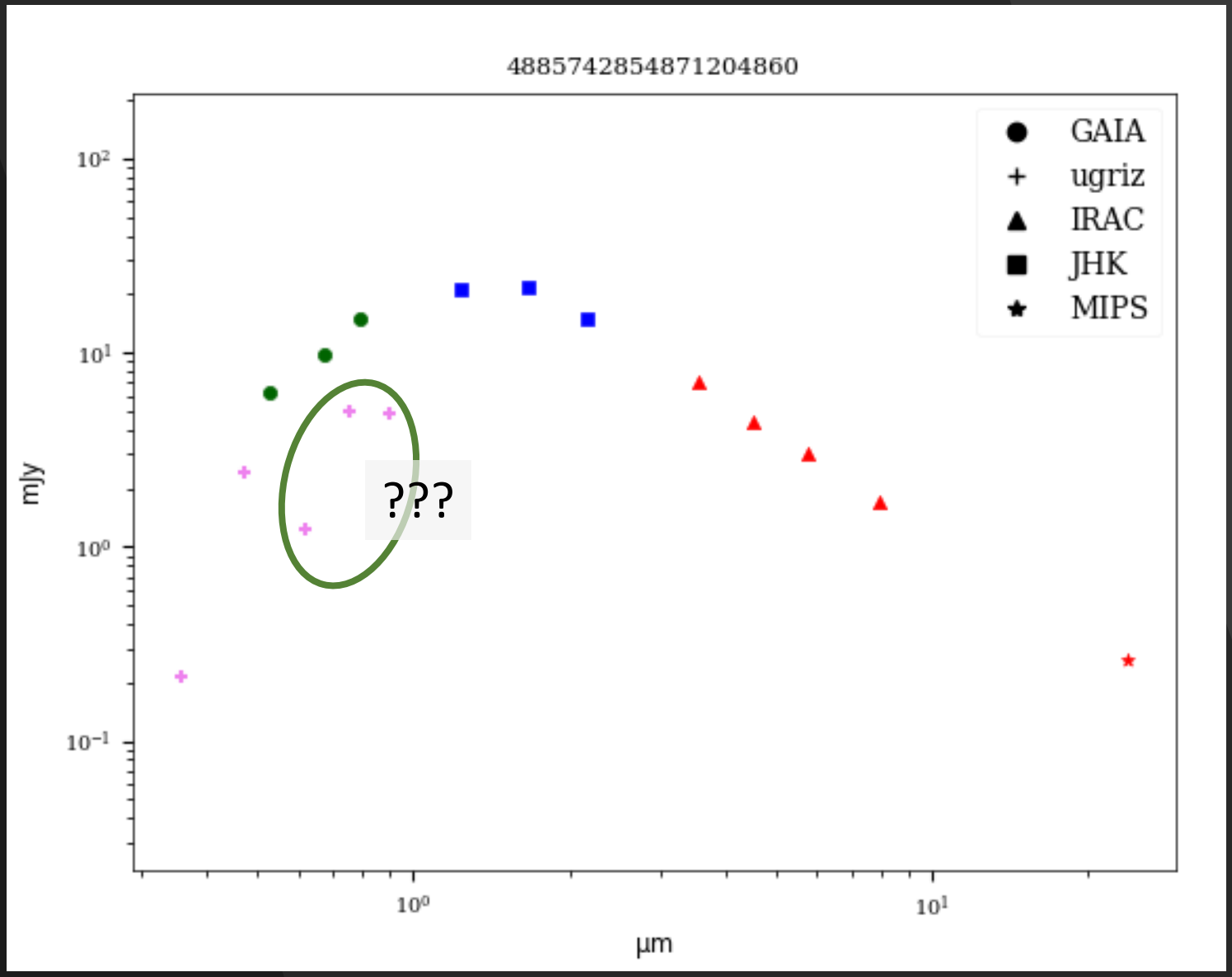
Correlate

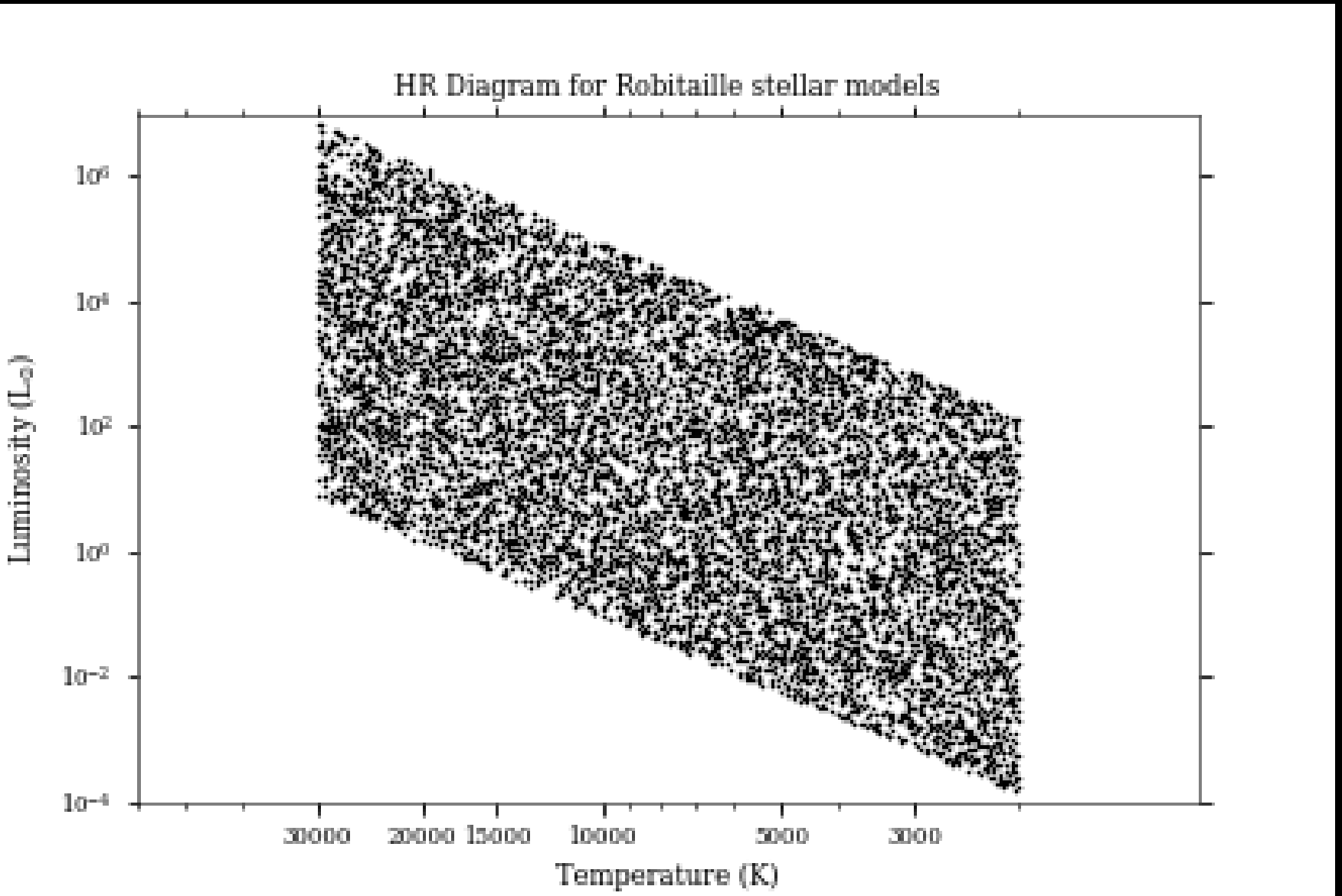
- YSO spatial clustering with individual properties
- YSO spatial clustering with dust morphology

Test

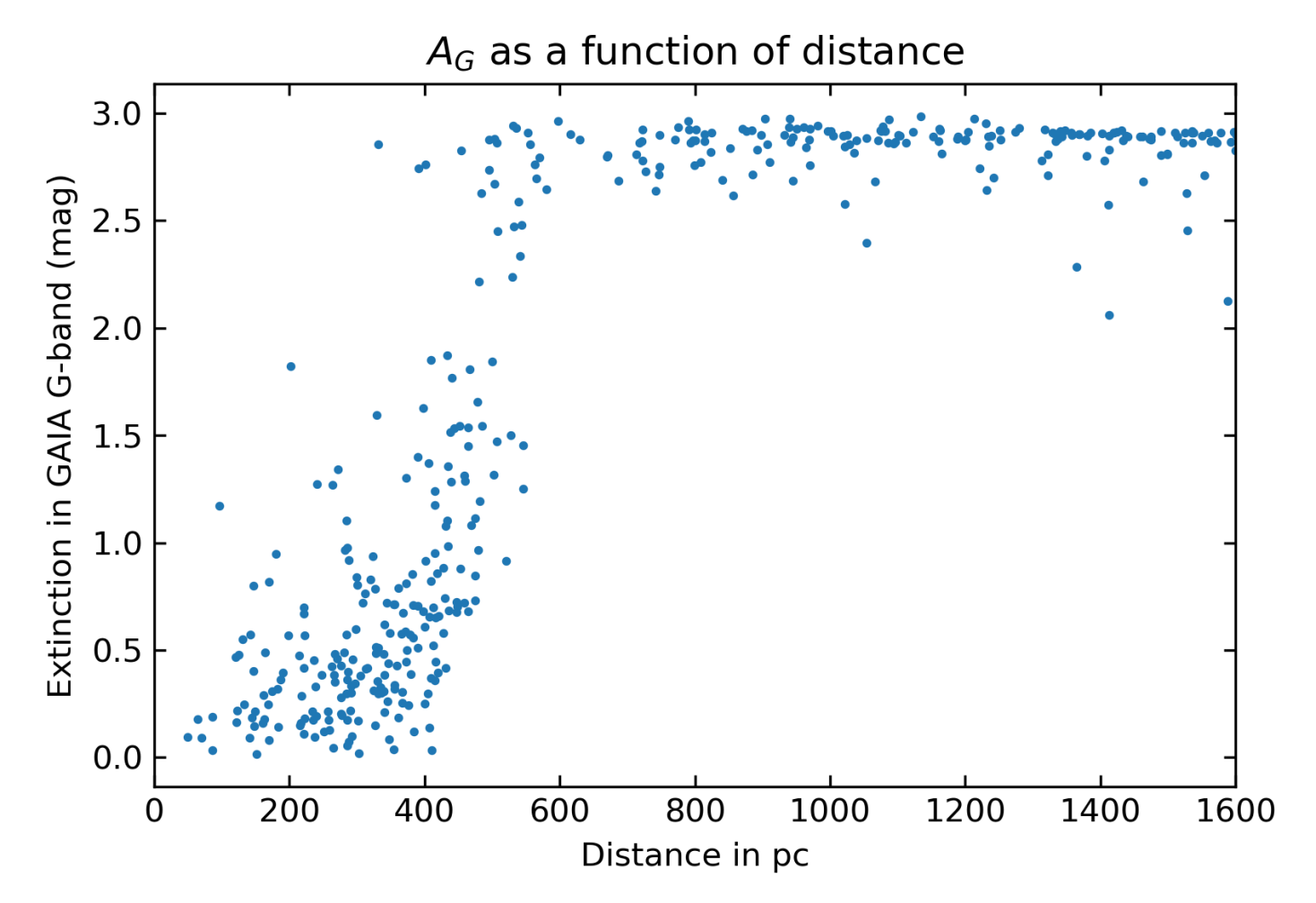
Measured properties against cluster formation models

Example of SDSS photometry of a star

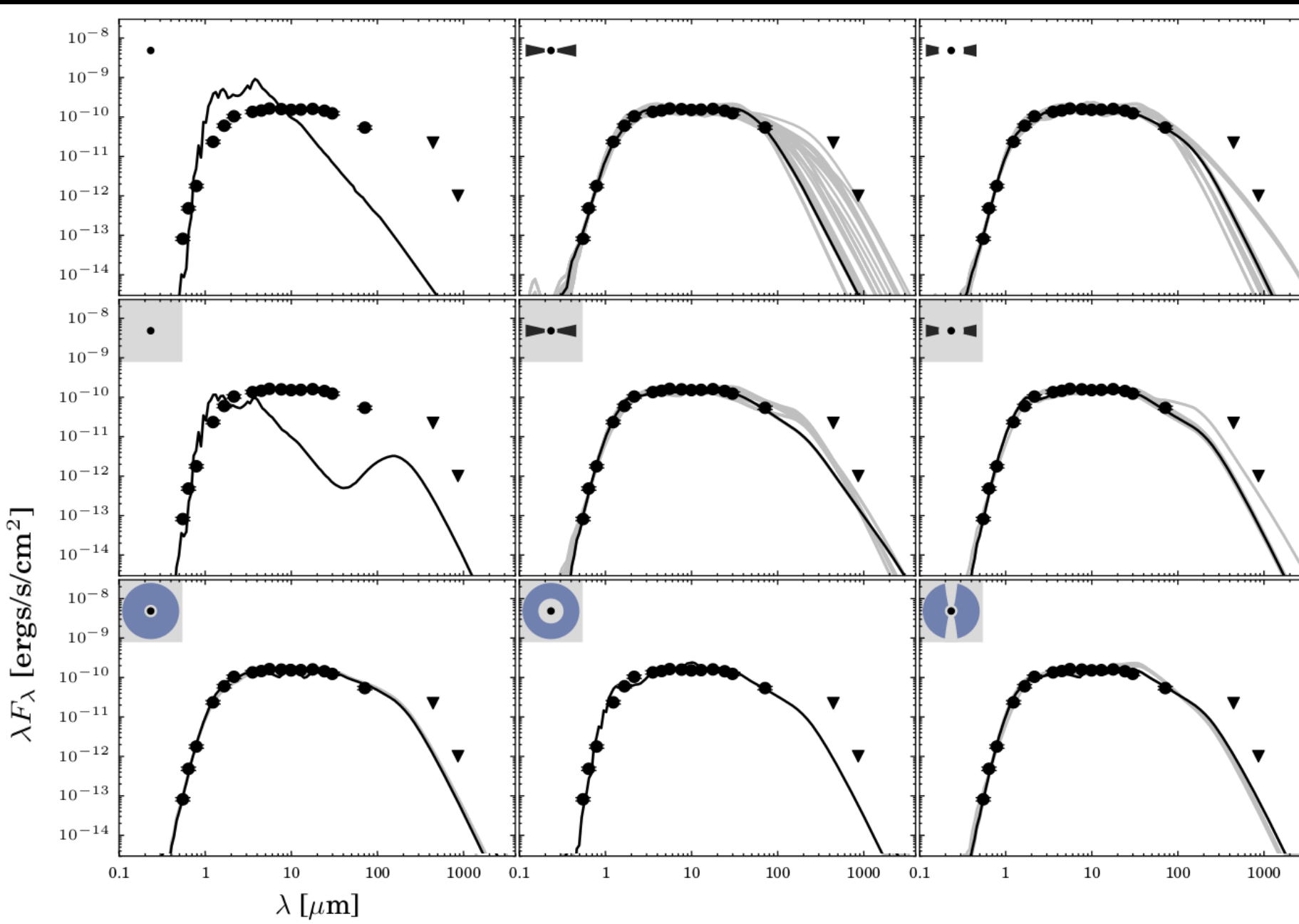



HR Diagram for Robitaille stellar models
Luminosity ($L_\odot$)
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
30000
20000
15000
10000
5000
3000
Temperature (K)

Rough Distances from A_G



Serpens East: 400 – 500 pc . But we can do better…


λF_λ [ergs/s/cm^2]
λ [μm]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.1
1
10
100
1000

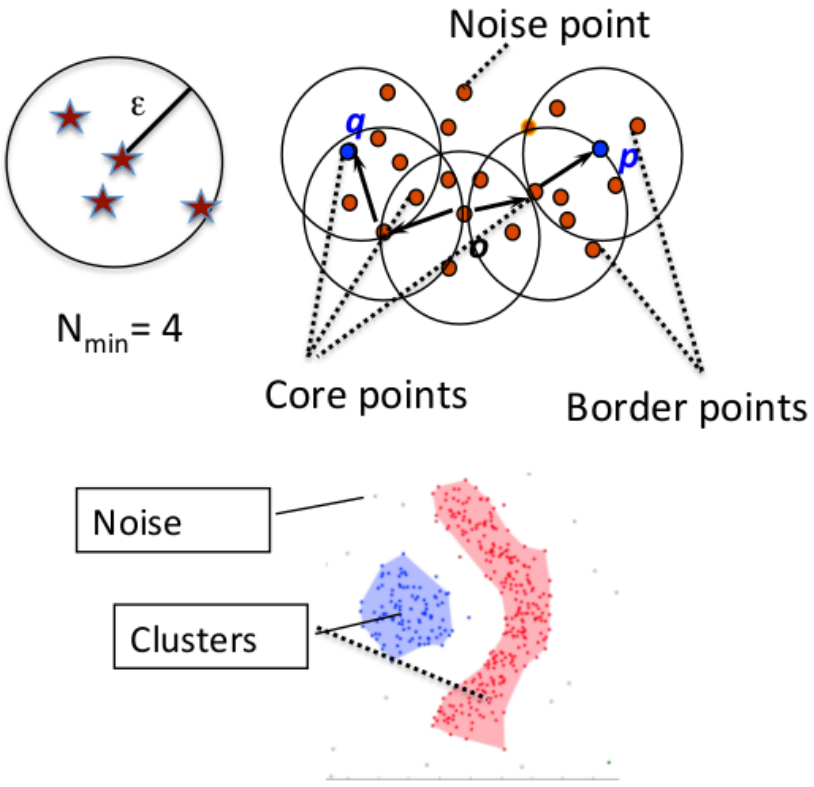


Figure 1 The DBSCAN algorithm (Ester et al. 1996). Two points are said to be *directly reachable* if they are separated by less than a given distance ϵ and they have at least the number of points N_{min} within a sphere of radius ϵ centered on them (upper left). Two points p and q are said to be *density-reachable* and belong to cluster if there is a path between these 2 points where each point along the path is directly reachable from the previous point. A point that is not reachable from any other point is called a *noise point*.