Results from Cores to Disks: I. Rates and Timescales

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and

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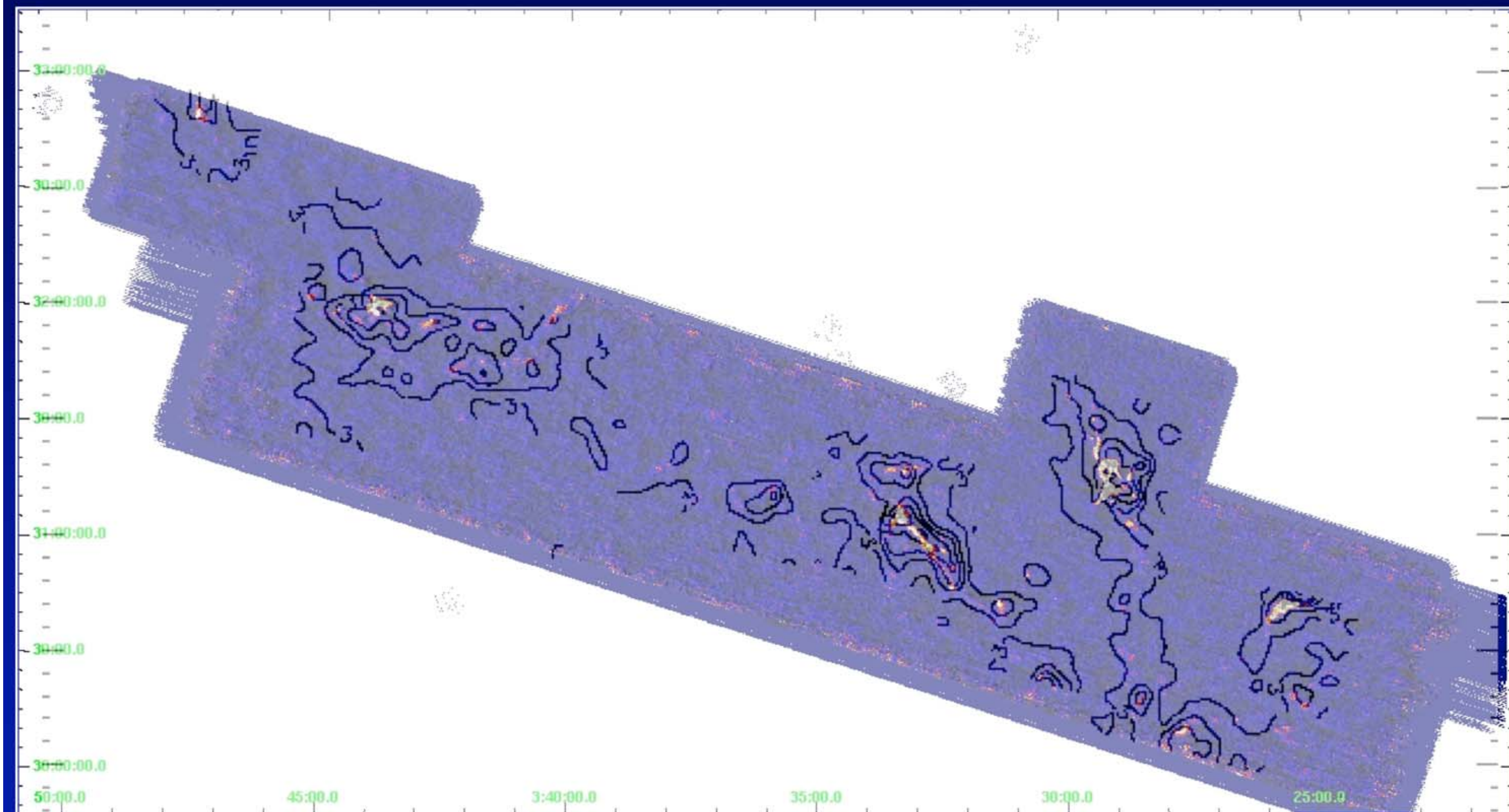
Star Formation in Larger Clouds

- **Where do stars form in large molecular clouds?**
  - **Large cloud surveys with c2d, Bolocam, and COMPLETE**
  - **Will focus on Perseus and Serpens as examples**
- **How efficient is star formation?**
- **What is distribution over traditional classes for a complete, unbiased sample?**
- **Modifications to traditional classes?**

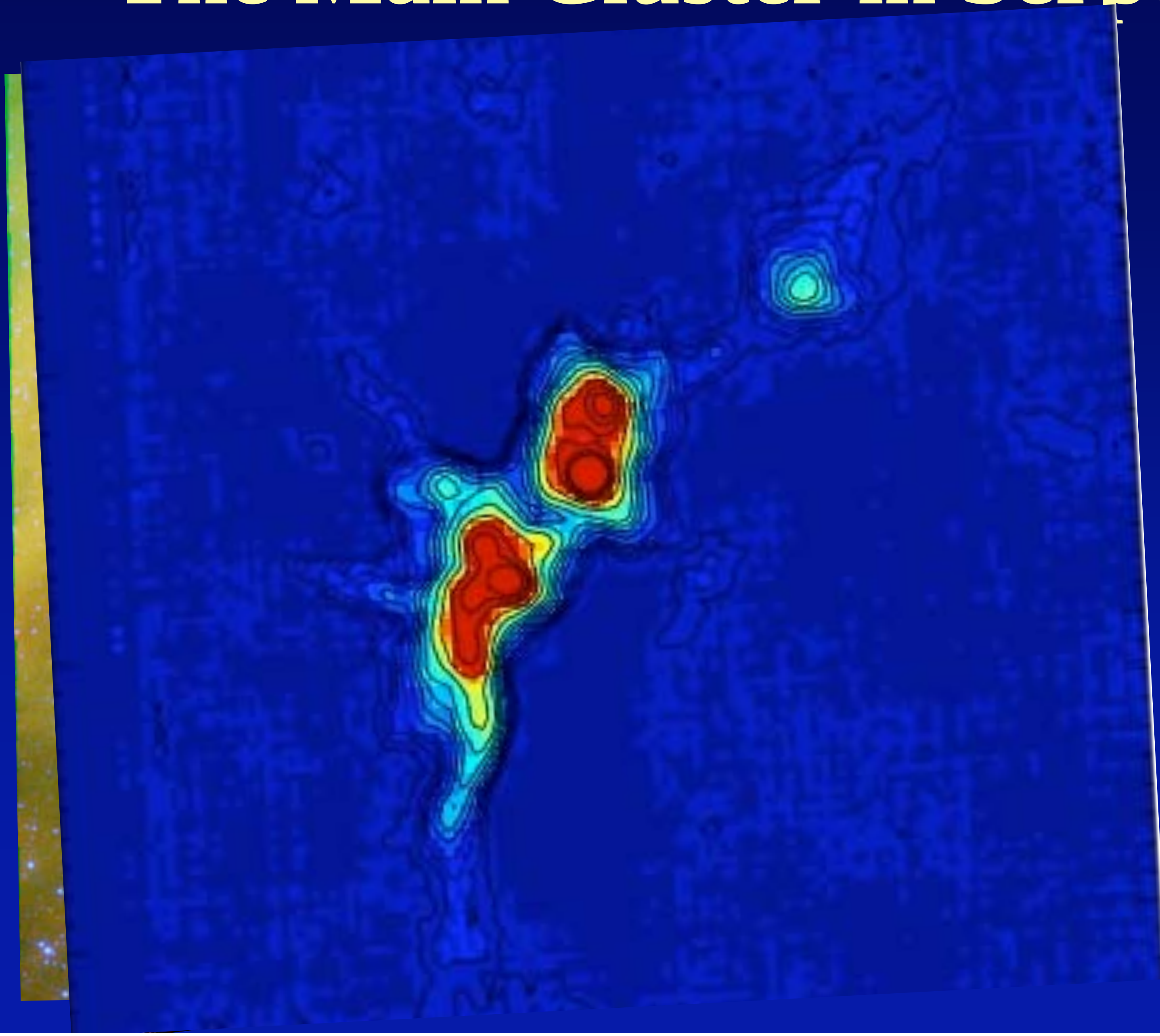
Perseus Molecular Cloud



10 pc

CO, ^{13}CO, 1 mm dust continuum, A_V
Ridge et al. (2006); Enoch et al. (2006)

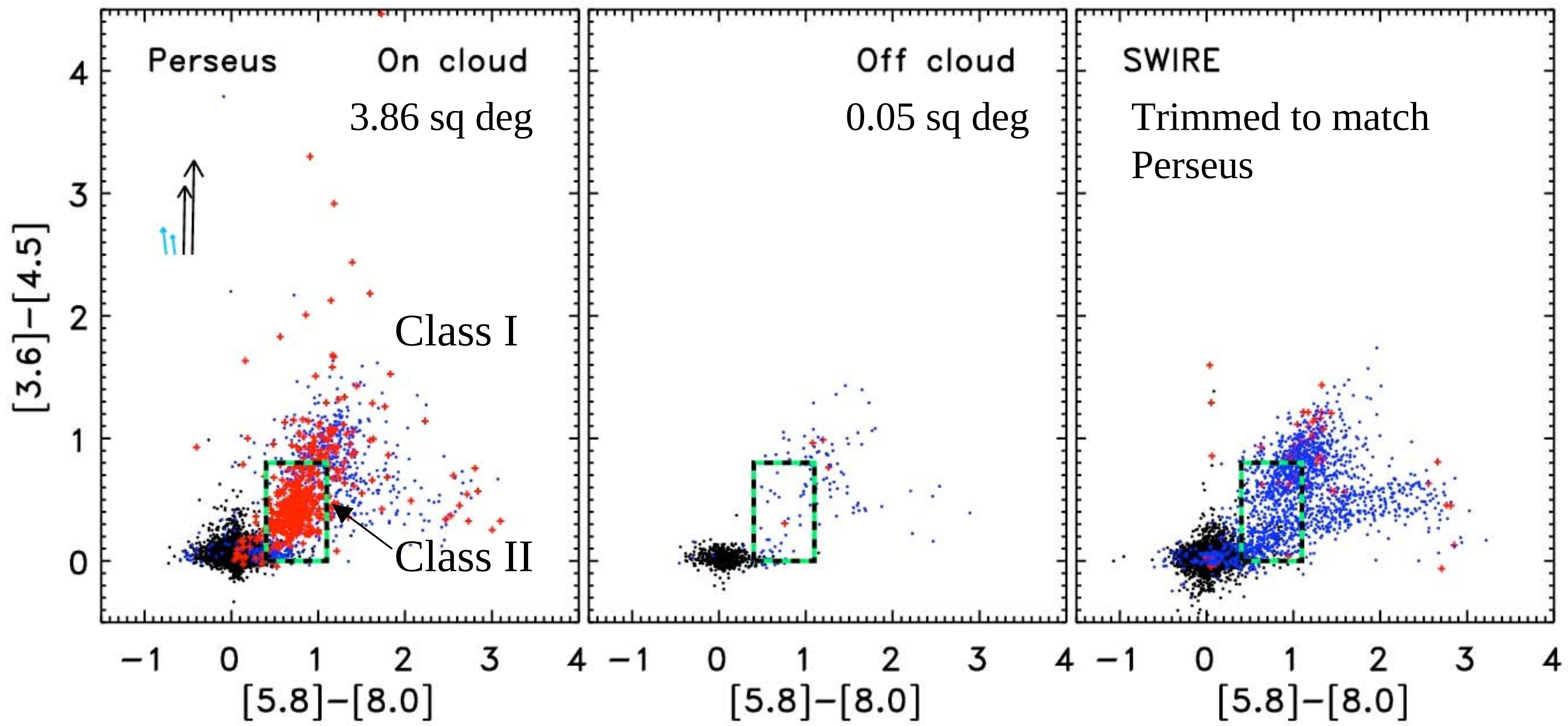
The Main Cluster in Serpens



A Rich, but Contaminated, Sample

- Serpens as example (0.85 sq deg)
  - 377,456 total sources
  - 104,099 in High Reliability Catalog
  - 91,555 with at least 3 bands (2MASS-MIPS)
    - 57,784 stars
    - 208 candidate star forming galaxies
    - 262 candidate YSOs (0.3%)
    - 235 (90%) certified YSOs by human examination

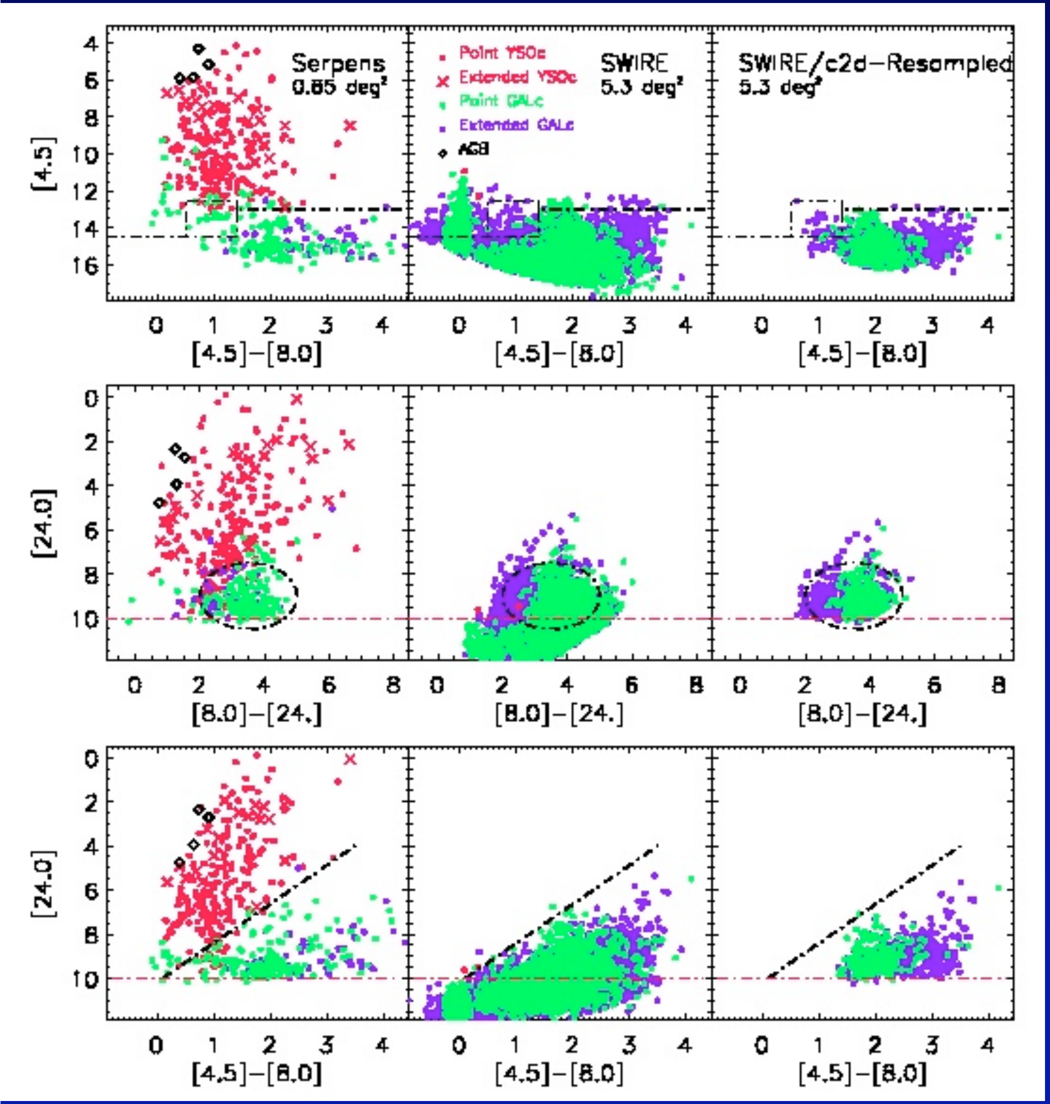
Colors Separate Stars



Joergensen et al. 2006

But note that we miss PMS stars without IR excess
And galaxies can have similar colors to YSOs

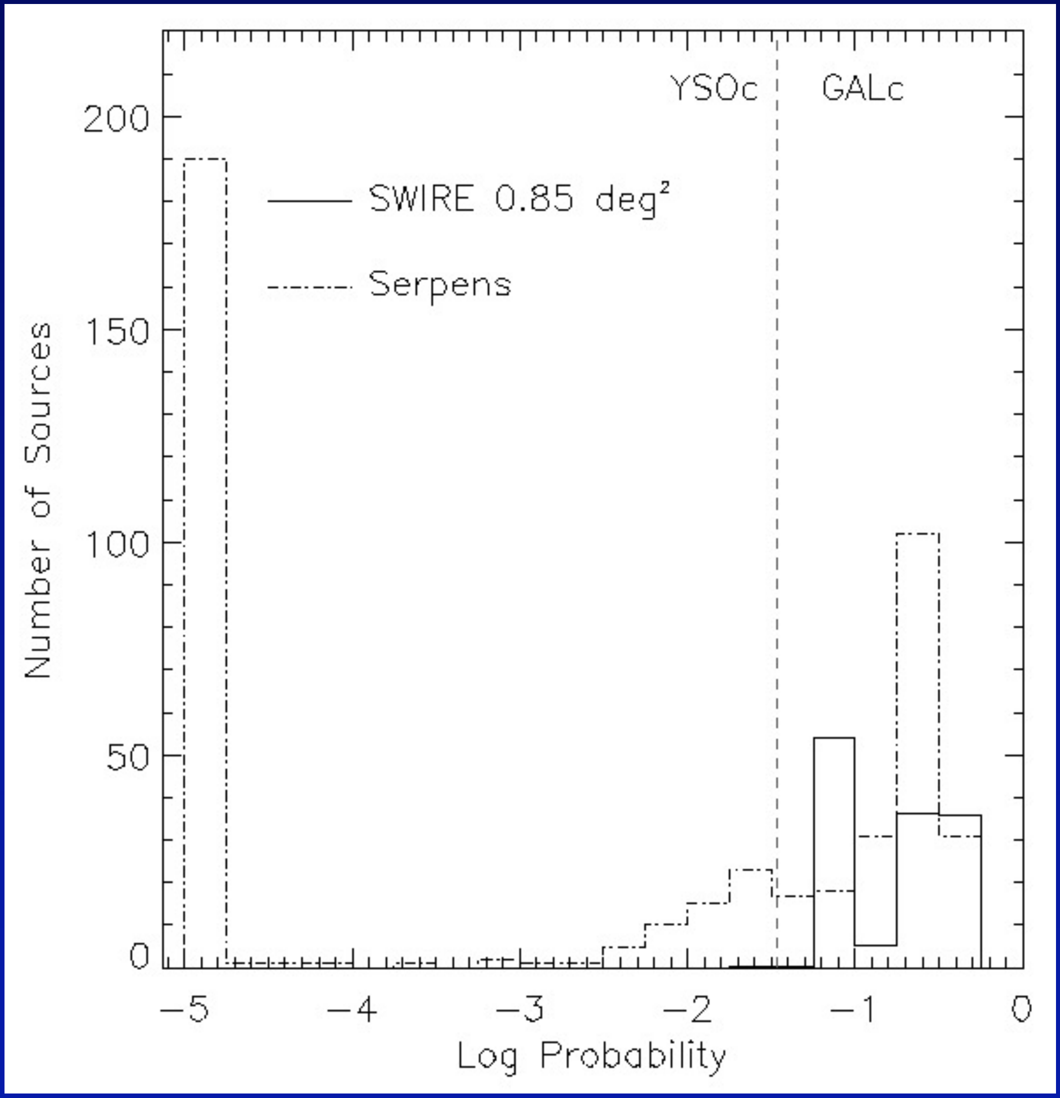
Eradicating galaxies



New set of criteria to remove exgal vermin (P. Harvey) Applied to full 5.3 sq. deg. of SWIRE ELAIS-N1. Only 2 false YSOs! If extincted and resampled to match Serpens, no false YSOs. More generally, predicts 0 to 1 per sq. deg.

YSO candidates
Point-like galaxies
Blue are extended galaxies
Stars removed already
AGB stars

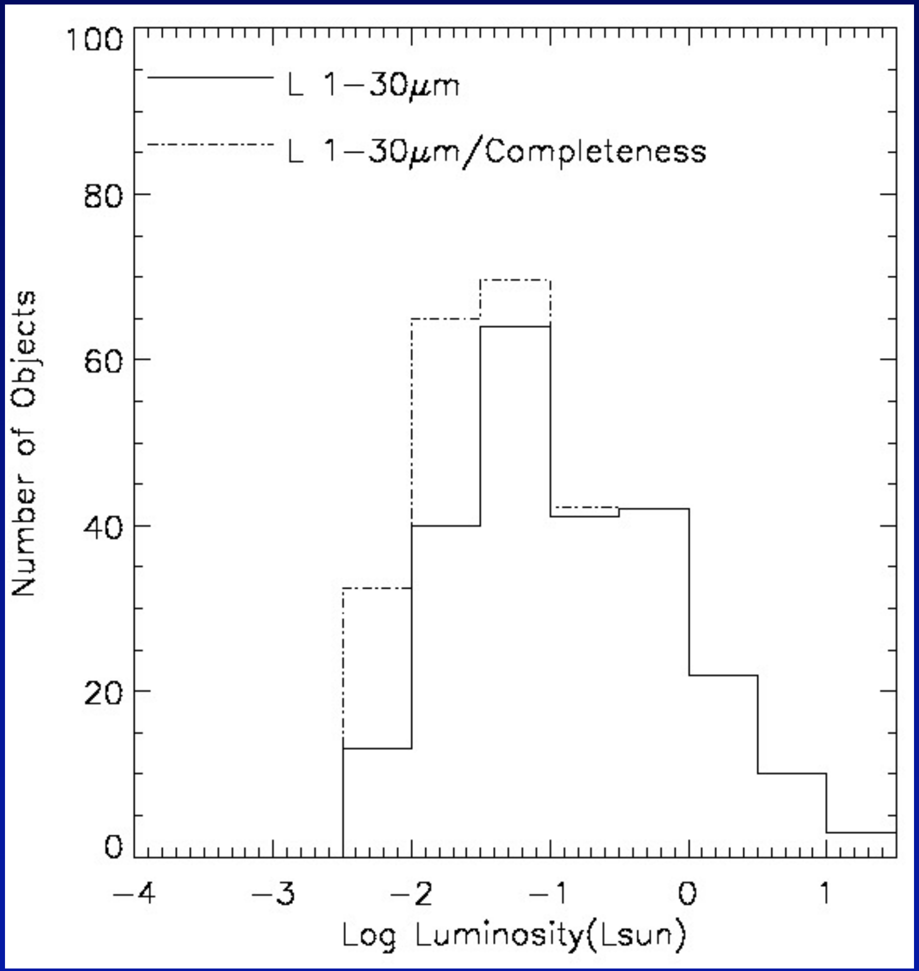
Most YSOs Separate Well



"Probability" that source is a galaxy, based on location in cc, cm diagrams. Purely empirical. Most Serpens YSOs separate well, but there is a tail of ambiguous sources in Serpens.

Harvey et al. 2007

How Low in Luminosity?



Completeness assessed by comparing full SWIRE and SWIRE resampled to Serpens extinction and sensitivity. Dotted line shows corrections. Note: $L = 10^{-2}$ is L expected for H-burn limit at age of 2 Myr

Luminosity Function for YSOs in Serpens, with and without completeness corrections.

Harvey et al. 2007

How Low do they Go?

- Completeness
  - Secure YSOs down to L(1-30 micron) ~ 10^{-2} L_{sun}
  - Possible YSOs to 10^{-3} L_{sun}
  - Estimate 90% complete to 0.05 L_{sun}
  - Search for low L embedded objects confirms (Dunham)
- For lowest mass objects
  - Need to add other wavebands
  - Complementary project by Allers, Jaffe

Efficiencies

- Much more complete sample
- Uniform photometry
- Caveats
  - Ophiuchus has not been hand-checked
    - Final counts will change, but not much
  - We may be missing:
    - More evolved PMS (no significant IR excess)

Overall Star Formation Rates

	Cha II	Lupus	Perseus	Serpens	Ophiuchus
SFR (M_{sun}/Myr)	6.5	24	91	59	71
SFR/Area (M_{sun}/Myr-pc^2)	0.65	0.83	1.2	3.4	2.2
$\frac{M_*}{M_{cloud}}$	0.019	0.031	0.025	0.042	0.040

SFR assumes $<M_*> = 0.5\ M_{sun}$; $t_{SF} = 2$ Myr

Comparison to Dense Gas

Cloud	Perseus	Serpens	Ophiuchus
M_*(tot)	182	118	141
M_{dense}	278	92	44
t_{dep} (Myr)	3.1	1.6	0.6

M_*(tot) assumes <M_*> = 0.5 M_{sun}; Depletion time: $t_{dep} = M_{dense}/SFR$
M_{dense} is total mass in dense cores from 1 mm maps.

How “Efficient” is Star Formation?

- **Not very for the cloud as a whole**
  - **1% to 4% of mass with A_V > 2 is in dense cores**
    - **(Enoch et al. 2007)**
  - **2% to 4% is in stars (assume $\langle M_* \rangle = 0.5\ M_{sun}$)**
- **Large variations in SF rate**
  - **Perseus is 14 times more productive than Cha II**
  - **Normalized to area, Serpens is 5 times Cha II**
- **Quite efficient in dense gas**
  - **Current TOTAL M_* similar to M_{dense}**
  - **Depletion time is 0.6 to 3.1 Myr**

What would Kennicutt Predict?

- Quick calculation, may be wrong…
- Sum over all clouds
  - Σ(gas) = 84 M_{sun} pc^{-2}
  - K98 predicts Σ(SFR) = 0.12 M_{sun} Myr^{-1} pc^{-2}
  - We see 1.6 M_{sun} Myr^{-1} pc^{-2}
  - Averaging scale > molecular clouds

Mass Functions

- Need more information to get IMF
  - Spectral types, extinction, sort out low L,…
  - Work is underway
- We can constrain Core Mass Function
  - 3 Clouds with Bolocam maps
  - Starless cores and protostellar cores separately
  - Masses from 1 mm dust
  - Absolute uncertainties substantial
  - But shape is not as sensitive

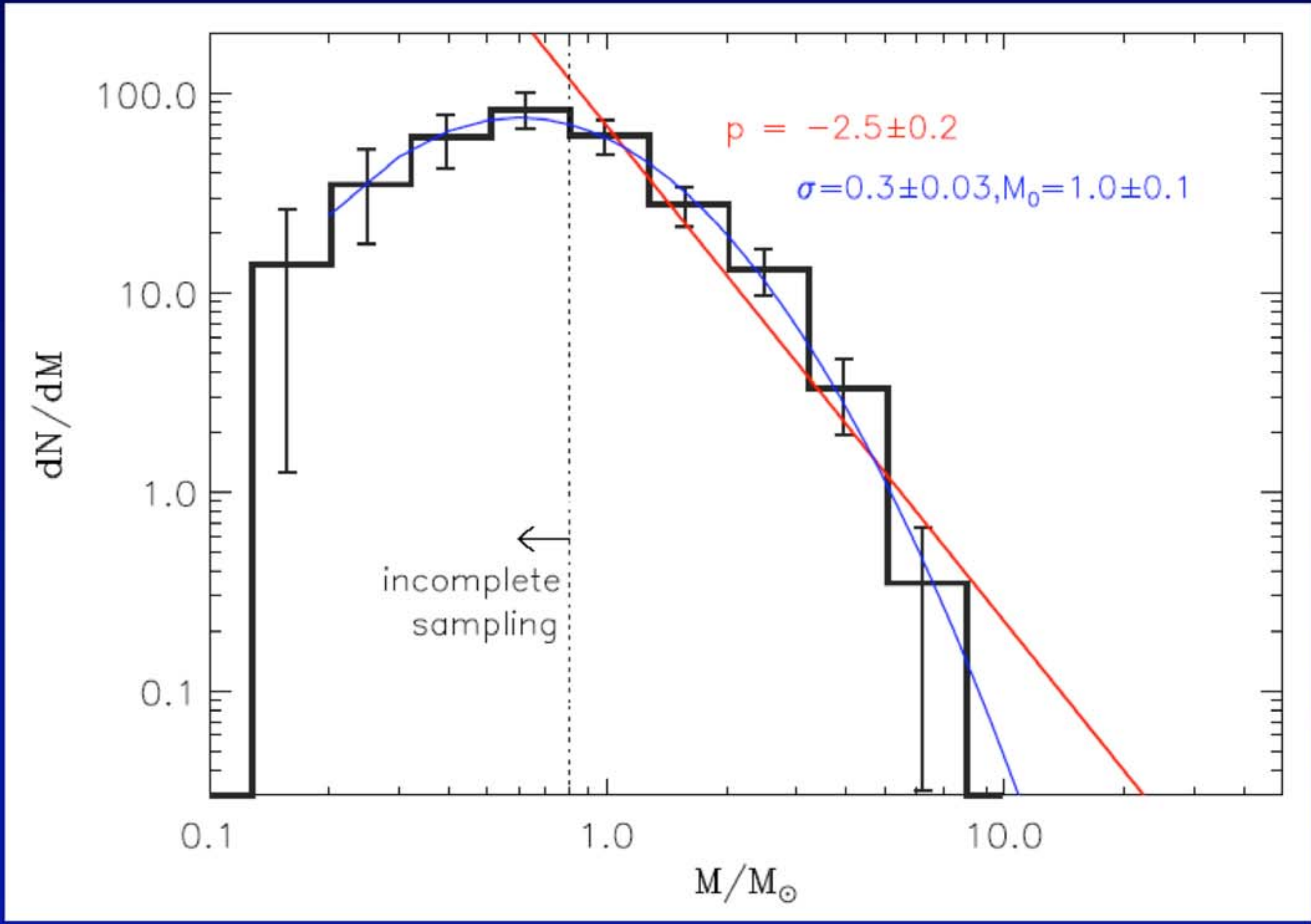
Combined starless core mass distribution

Masses:

$T_D = 10K$

$\kappa_\nu = 0.0114\ cm^2/g$

- Best fit power law: p ~ 2.5 or Lognormal
- IMF:
  Salpeter (p~2.4)
  Chabrier 03
  (p~2.7 M>1$M_\odot$)



⇒ "Not inconsistent" with a scenario in which stellar masses are determined during core formation

Enoch et al. 2007

Wait til Tomorrow…

Evolution:
Tales from 1001 YSOs

- First based on traditional class system
- Previous studies based on small numbers
  - Typically 50 to 100 objects
- Combining all our large clouds yields 1001 YSOs

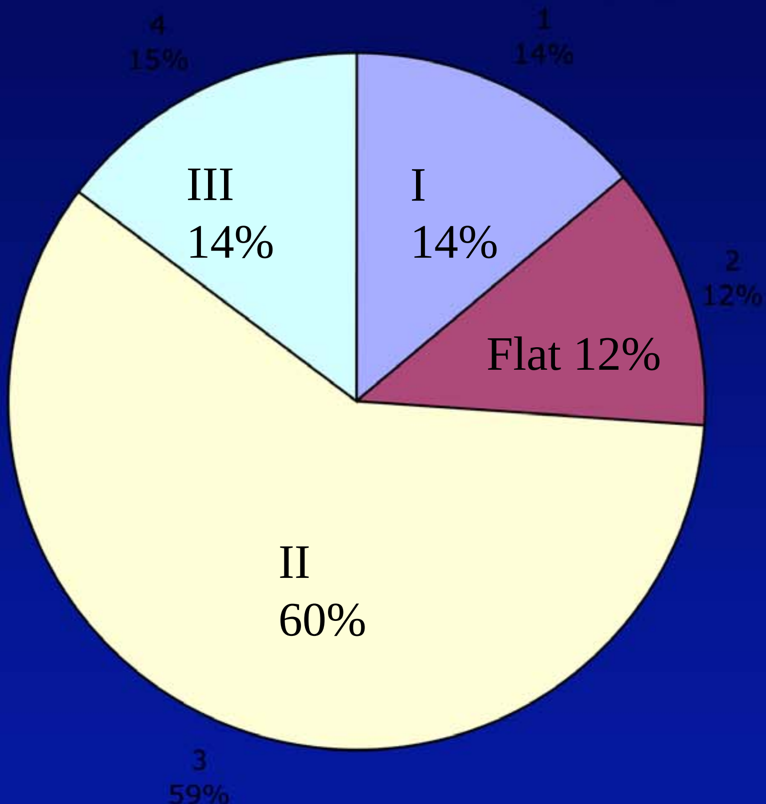
Previous Work

- Previous estimates for timescales
  - t(I) ~ t(II) ~ 0.4 Myr
    - In Ophiuchus (Wilking et al. 1989)
  - t(I) ~ t(flat) ~ 0.1 -0.2 Myr; Class II 1-2 Myr
    - In Taurus (Kenyon and Hartmann 1995)
    - Note t(II) ~ 10 t(I)
  - Issues
    - Small number statistics!
    - Differences between clouds!

Our Results

- Based on "Lada class" as extended by Greene et al.: α based on slope of νS_ν
- Fit to any photometry between 2 and 24 microns
- Not quite final!
- Averages over different situations
  - Five clouds, very different environments
  - Clusters, aggregates, and distributed

Overall Stats



I: $\alpha \geq 0.3$

Flat: $-0.3 \leq \alpha < 0.3$

II: $-1.6 \leq \alpha < -0.3$

III: $\alpha < -1.6$

IF Class II lasts 2 Myr,
AND
IF star formation continuous
AND
IF Time is the only variable
THEN
Class I lasts 0.46 Myr
Flat lasts 0.42 Myr

Notes:
Results depend a bit on how α is calculated
Class III under-represented
Class 0 mixed with Class I

Consequences

- Assume inside-out collapse at 0.19 km/s
  - Sound speed at 10 K
- In 0.46 Myr, r_{inf} = 0.092 pc (or 0.046 pc)
  - Consistent with some sizes, but large in clusters
- At $dM/dt = 1.6 \times 10^{-6}\ M_{sun}/yr$, $M_* \sim f\ 0.74\ M_{sun}$
  - If $f \sim 0.3$, get $0.2\ M_{sun}$
- Consistent with assumptions, most data
- Picture holds together
- Remember this tomorrow…

Clusters vs. Distributed: Serpens

Region	Cluster A	Cluster B	Rest of cloud	Total
N(YSO)	44	17	174	235
N/Vol (pc^{-3})	500	315	2.5	3.2
M(dense) (M_{sun})	40	9	44	92
t_{dep}(dense) (Myr)	3.6	2.1	1.0	1.6

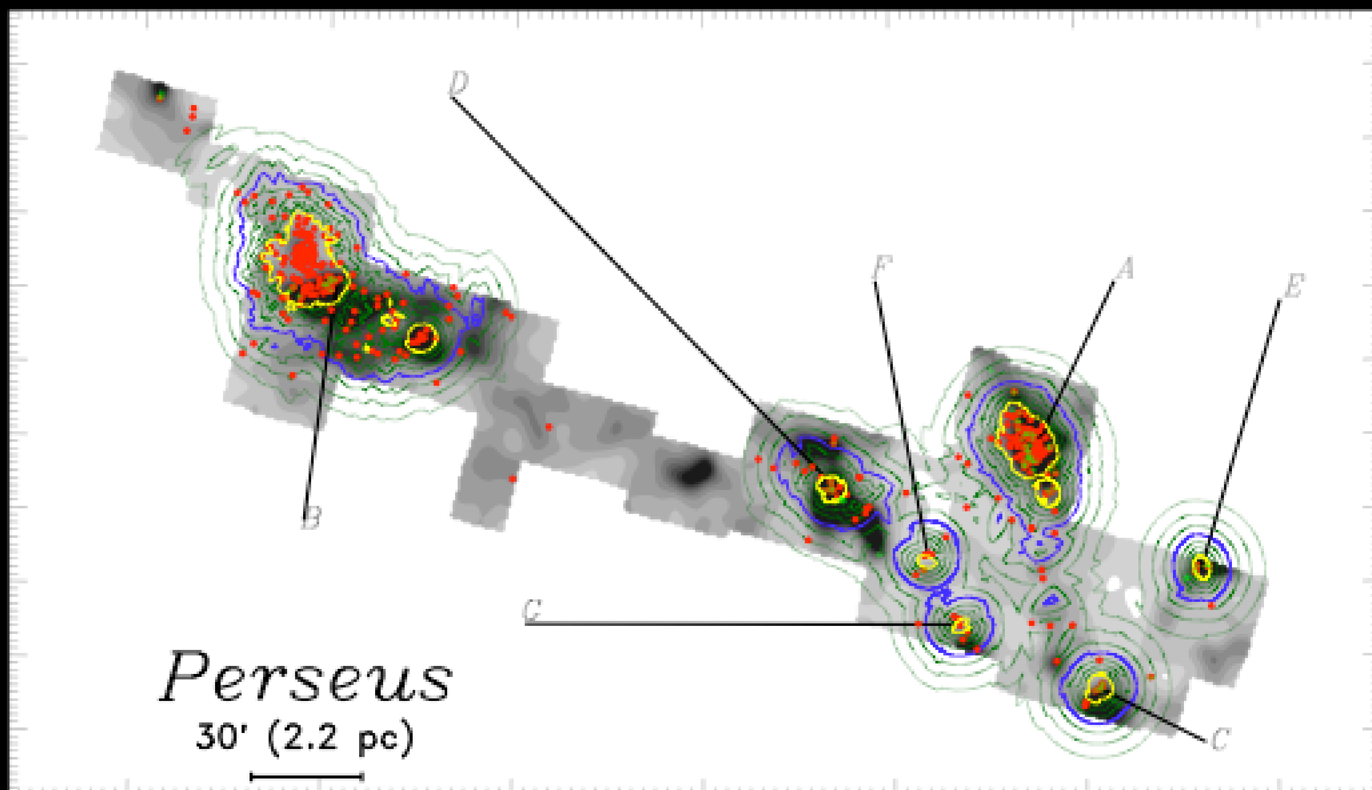
Cluster boundary defined by A_V = 20 contour. Dense gas mass from 1 mm continuum emission. Depletion time: $t_{dep} = M_{dense}/SFR$; **assumes** $\langle M_* \rangle = 0.5\ M_{sun}$; t_{SF} = 2 Myr

More Comparisons

Region	Cluster A	Cluster B	Rest	Total
<u>I+F</u> II+III	3.0	1.4	0.14	0.37
t_{cross} (Myr)	0.45	0.38	4.1	4.2
t_{coll} (Myr)	3.1	4.8	1200	

$t_{cross} = A^{0.5}/v$, $v = 1$ km/s; $t_{coll} = (n\ \pi r^2\ v)^{-1}$, $r = 0.03$ pc, $v = 1$ km/s
$n = N(\text{cores})/\text{Volume}$. t_{coll} is the time between core collisions.

Clustering in Perseus



Blue contours are 1 M_{sun} pc^{-2}; yellow 15 M_{sun} pc^{-2}

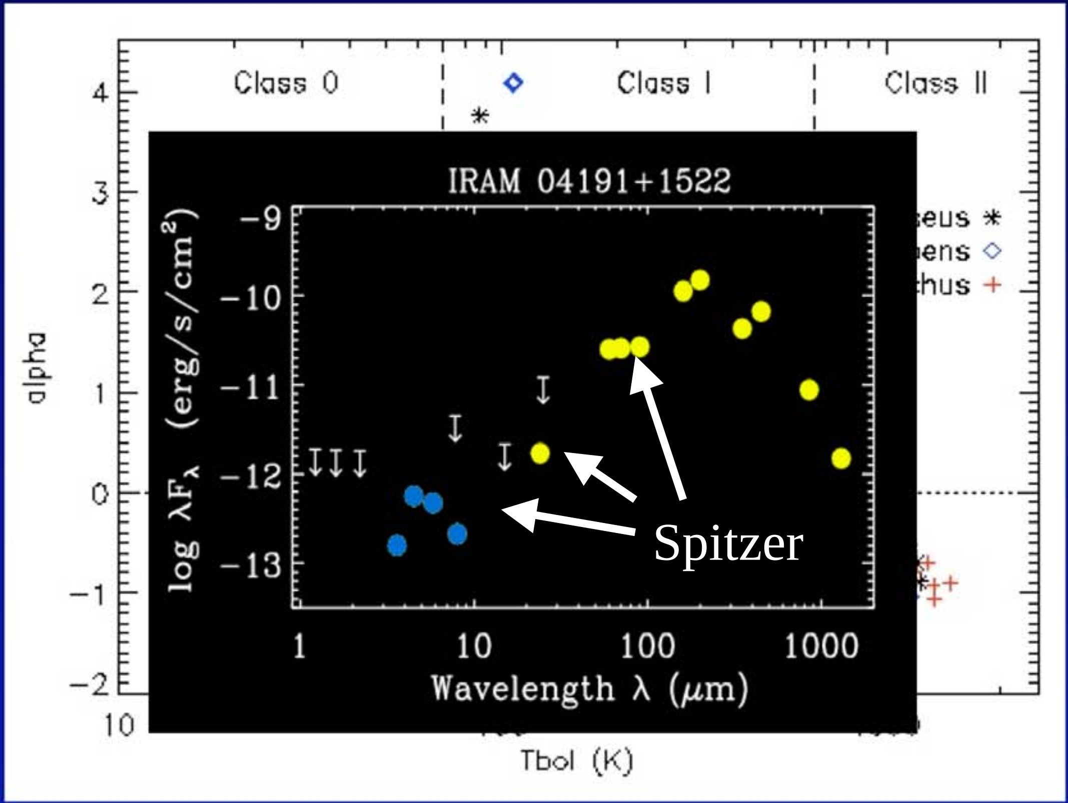
Clusters vs. Distributed

- Densities high in clusters
  - But < 0.1 that in Orion, …
- Dense cores are more clustered than YSOs
- Clusters are younger
- Distributed population could come from dispersed clusters [t_{cross} ~ t(ClassII)]
- Core collisions not common at present
  - [t_{coll} ~ 10 x t(ClassI)]
- Range of v_{LSR} ~ 1.4 km/s in Serpens core
    - Williams and Myers (2000)

Adding Diversity to the Class System

- **The Class system has provided the framework for 20 years**
- **Class 0 sources could not be seen in NIR/MIR**
  - **T_{bol} was introduced**
  - **Can we see them now? (tomorrow…)**
- **Does Class II to Class III capture late evolution?**

Separating Class 0 from I



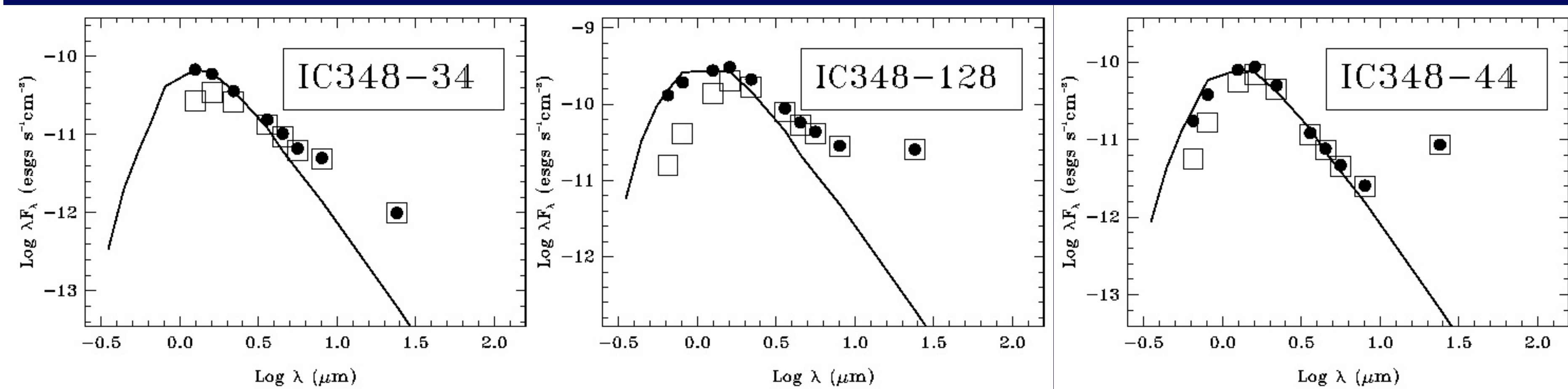
Enoch et al. In prep.

Use T_{bol} to separate.
Using α was not possible before for Class 0, but Spitzer can see many Class 0 in MIR.

α versus T_{bol}.
Good agreement for $T_{bol} > 300$, but poor for $T_{bol} < 300$.

Class 0 can have large range of α and not monotonic.

Diversity in disk SEDs

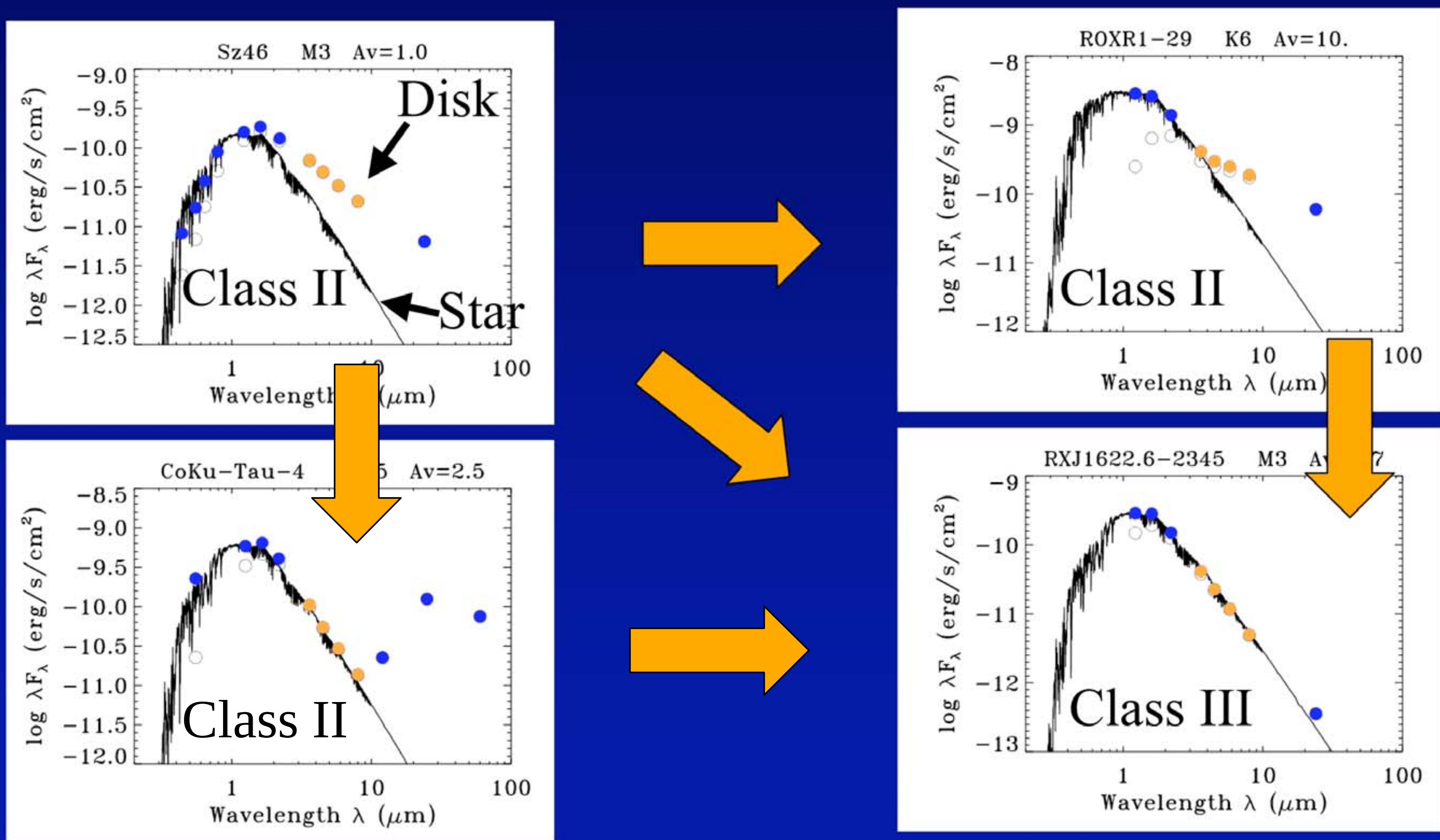


Traditional III | III, then flat | III, then rising

Some excesses start only at long wavelengths but are substantial: We call these cold disks; others call them “transitional” disks. The traditional transition from II to III does not capture the diversity seen in disk SEDs.

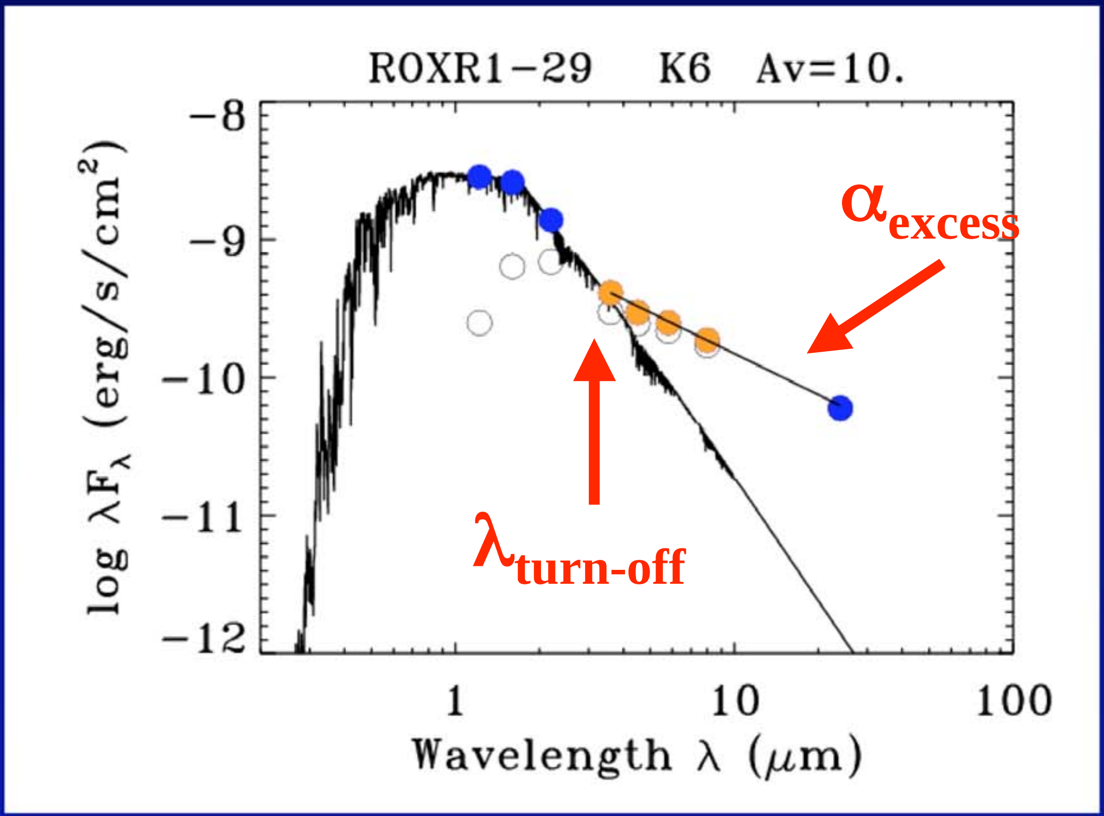
Disk evolution

There are multiple paths from thick to thin disks.



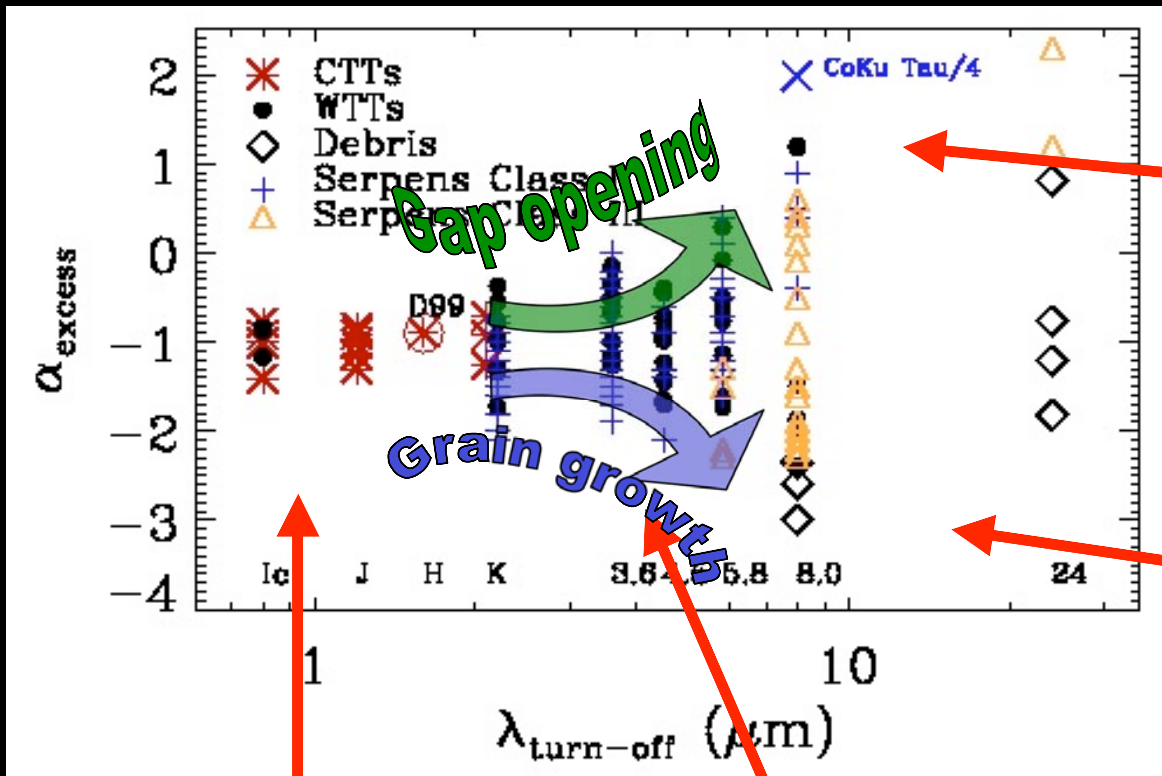
New 2D classification scheme

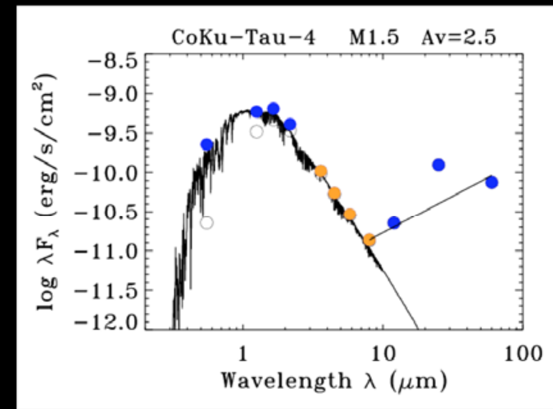
Two parameters needed

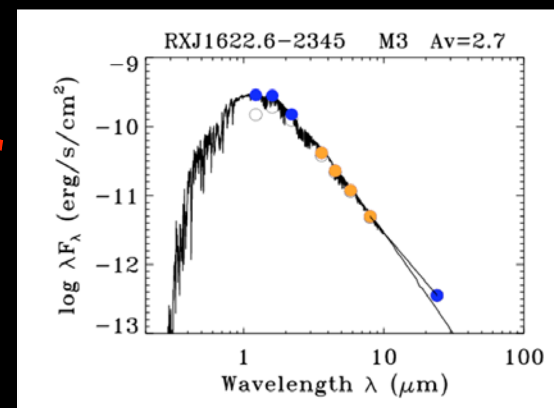


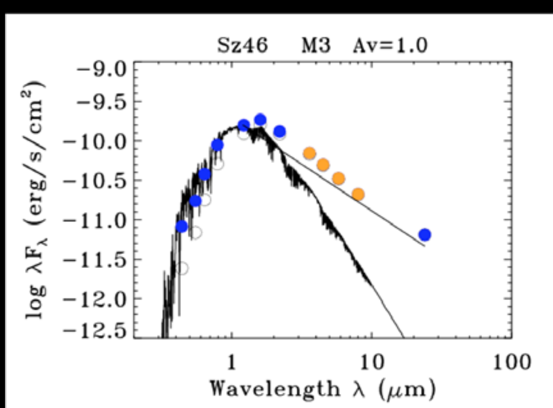
$\lambda_{turn\text{-}off}$: last wavelength without excess

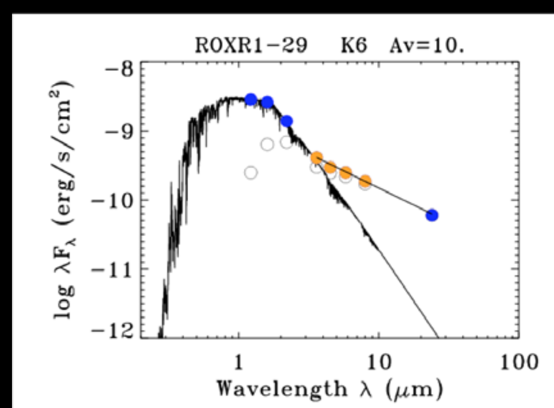
α_{excess}: SED slope for $\lambda > \lambda_{turn\text{-}off}$











cTTs: $\lambda_{turn-off} < 2\ \mu m$;
$\alpha_{excess} \sim -1$

wTTS: $\lambda_{turn-off} > 2\ \mu m$;
α_{excess} −3 to 1

From Classes to Stages

- **Conflation of physical stage with SED**
  - **Time to reexamine**
  - **Identify physical Stages:**
    - **Prestellar (no central object)**
    - **Stage 0 ($M_{env} > M_* + M_{disk}$)**
    - **Stage I ($M_{env} > 0.1\ M_{sun}$)**
    - **Stage II ($M_{env} < 0.1\ M_{sun}$ and M_{disk} "not small"**
    - **Stage III Debris disk or nothing?**

How do Classes map to Stages?

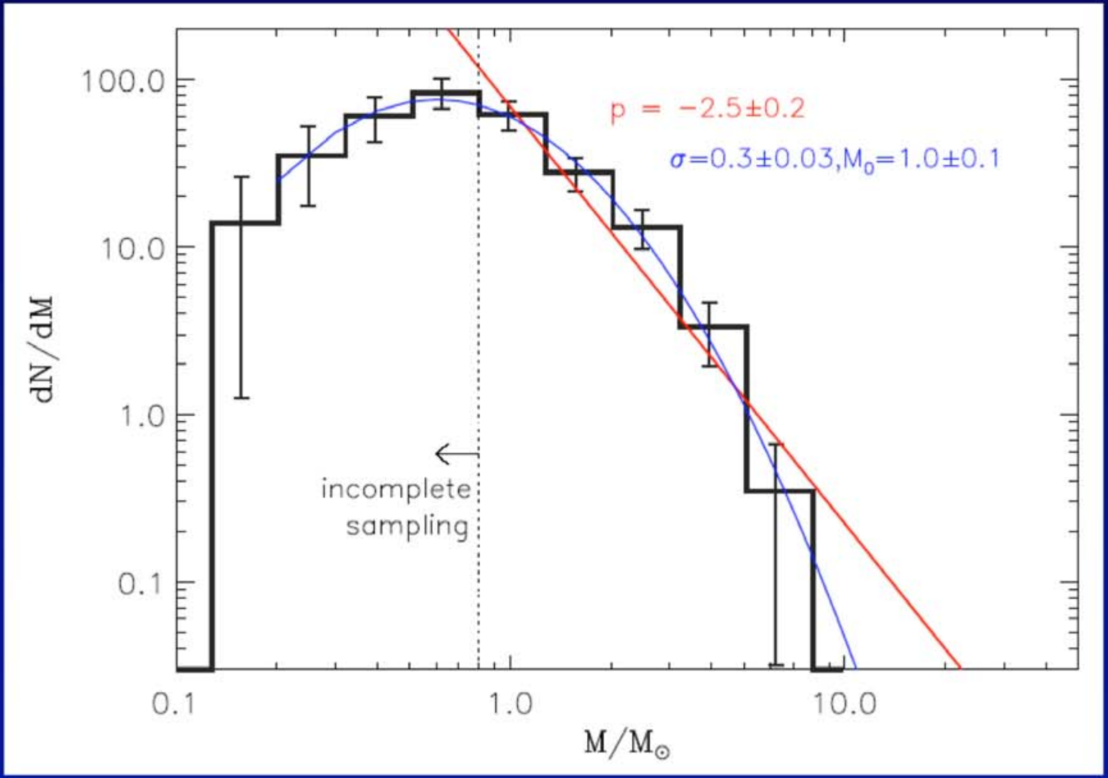
- Class 0 requires T_{bol}
- No Flat SED class in T_{bol}
- Where do Flat SED sources go?
  - About half to I, half to II (Classes)
    - From observations (Enoch)
  - Nearly all can be edge-on Stage II
    - From Models, Crapsi et al. 2007
- Can Class I be Stage II?
  - Yes, up to half of them (Crapsi et al. 2007)
  - Would shorten infall time

Summary

- Efficiencies in clouds are low
  - For making dense cores or YSOs
- Efficiencies in dense cores are high
- With assumptions, can constrain t(Class)
  - t(I) ~ 0.46 Myr, longer than previous
    - Mostly consistent
    - Stage I may be about half this.
- But we need to add diversity…

Combined starless core mass distribution

110 Starless cores
All three clouds
Vertical line is 50% in Perseus (worst one)
Power law fit to $M>0.8\ M_{sun}$
Lognormal to $M>0.2\ M_{sun}$ (so includes incomplete bins)
Reduced chi-sq = 3.6 (PL); 0.7 (LN)
Mean size 1.4×10^3 AU
Mean density $3 \times 10^5\ cm^{-3}$



Enoch et al. 2007