Initial Conditions: The Transition From Cores to Disks

Neal J. Evans II

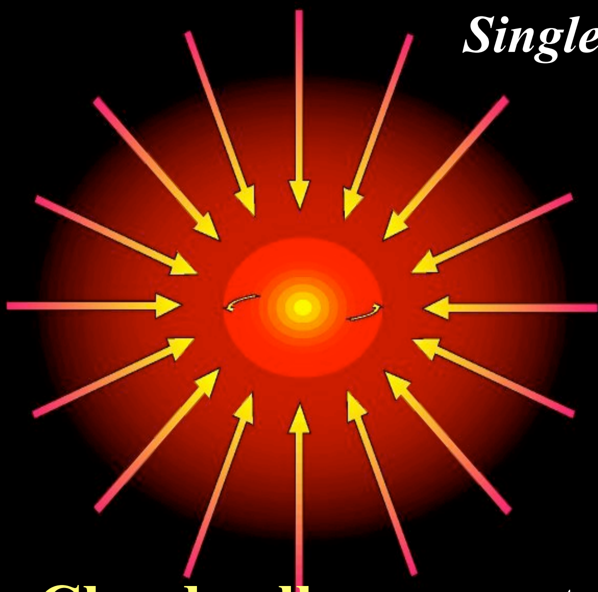
Why Should We Care?

- "Let there be a disk around a star"
  - Subsequent evolution is complex enough already
- Disks evolve in many different ways (B. Merin talk)
  - Many different structures
  - Different outcomes for planetary system architectures
- Maybe the outcome is affected by "initial" conditions
  - Variations in "initial" masses, composition
- Disks exist and evolve through the infall phase
  - More mass passes through the disk in that phase
  - "Initial" state of disk is final state of infall phase

Standard Evolutionary Scenario

Single isolated low-mass star

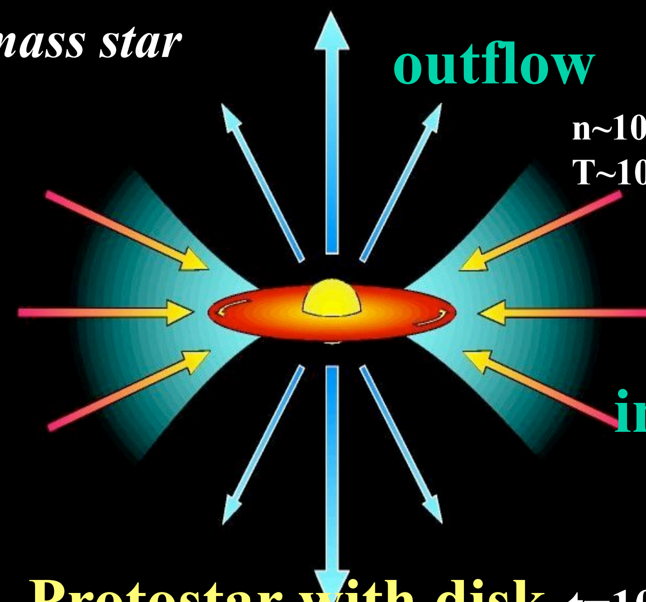
Stages



$n \sim 10^4$-10^5 cm^{-3}
T~10 K

Factor 1000 smaller

Cloud collapse t=0



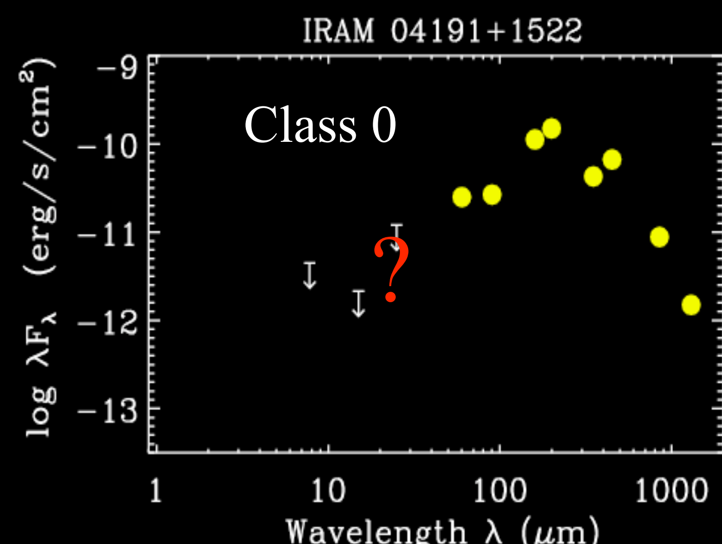
outflow

$n \sim 10^5$-10^8 cm^{-3}
T~10-300 K

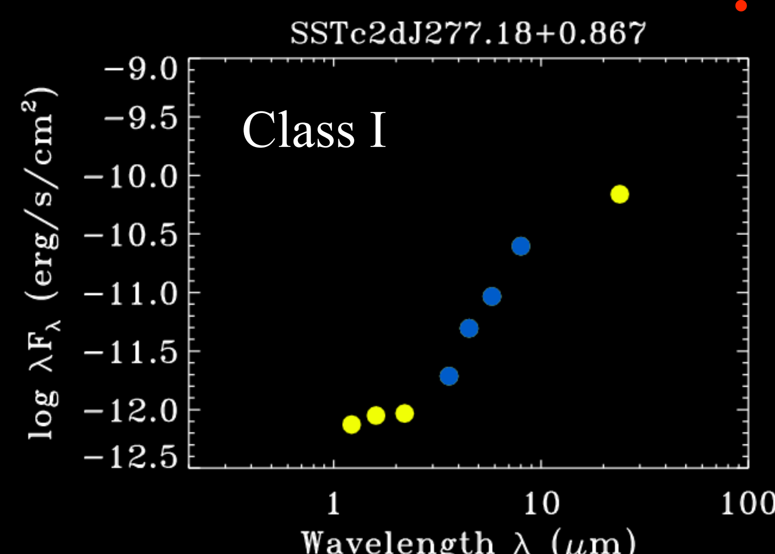
infall

Protostar with disk $t = 10^5$ yr ?

Classes

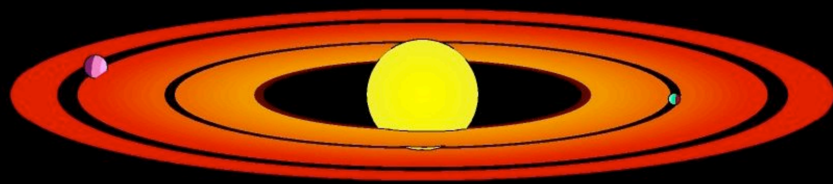


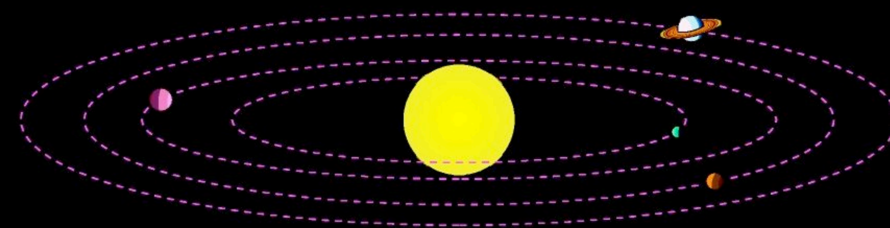
Between stages!



Note axis change!

Scenario for star- and planet formation

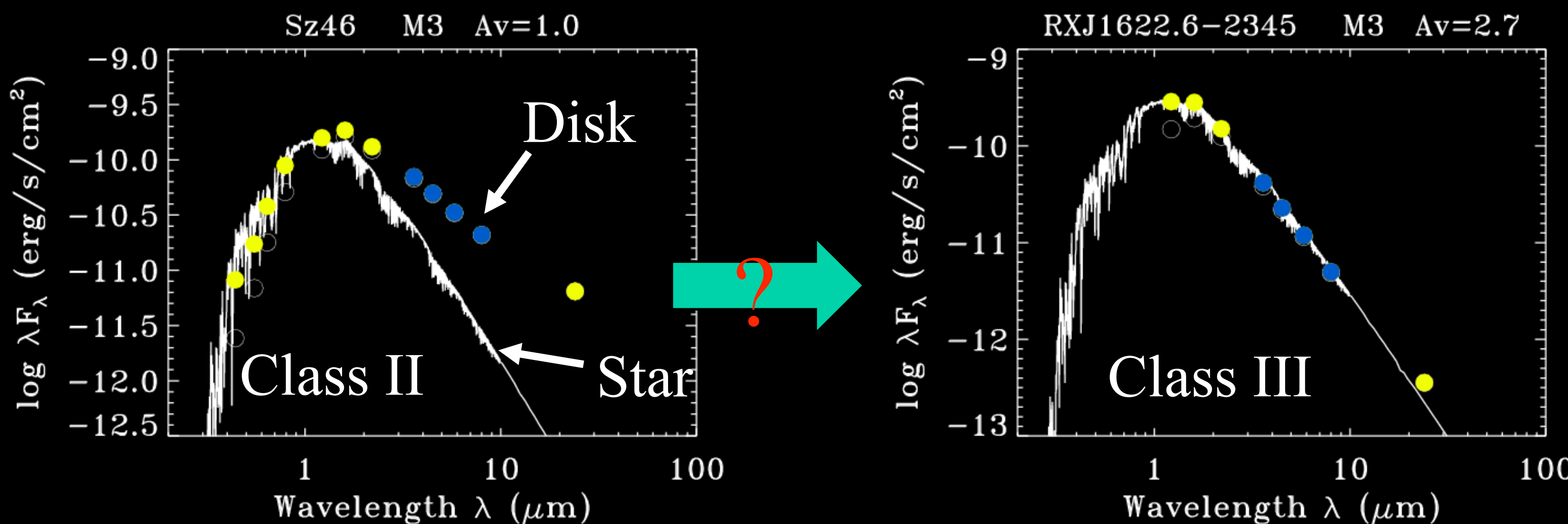




?

Formation planets t=10^6-10^7 yr

Solar system t>10^8 yr (?)



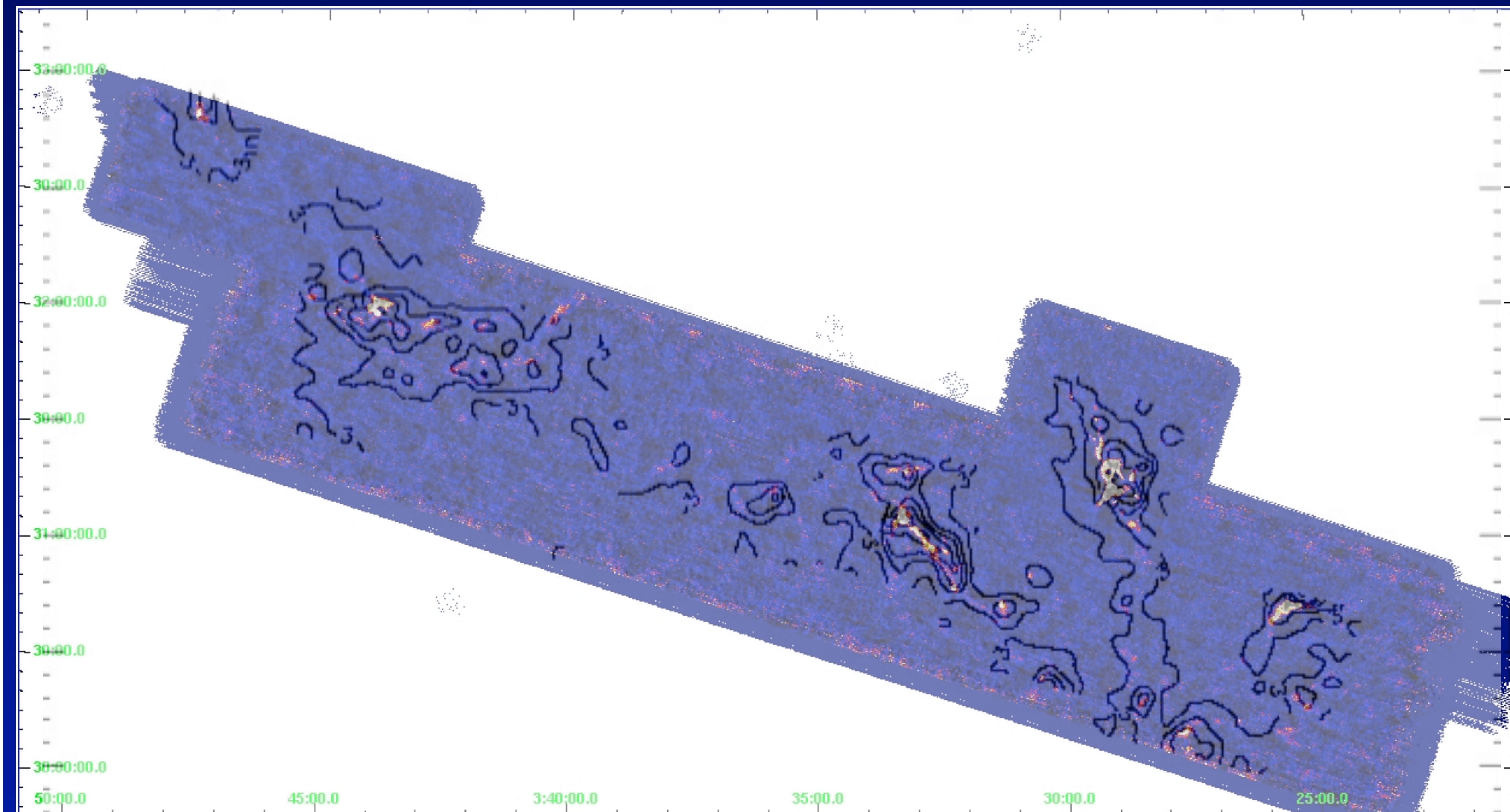
Issues to Address

- Environment: How much interaction?
- Timescales: How long in each stage?
- Events during embedded stages
- What do we know about disks then?
- Chemical evolution

Star Formation in Larger Clouds

- Where do stars form in large molecular clouds?
- What is distribution over traditional classes for a complete, unbiased sample?
- Timescales and Evolution
  - Survey 5 large clouds with Spitzer
  - Survey 3 of them with Bolocam, and COMPLETE
  - Will focus on Perseus and Serpens as examples

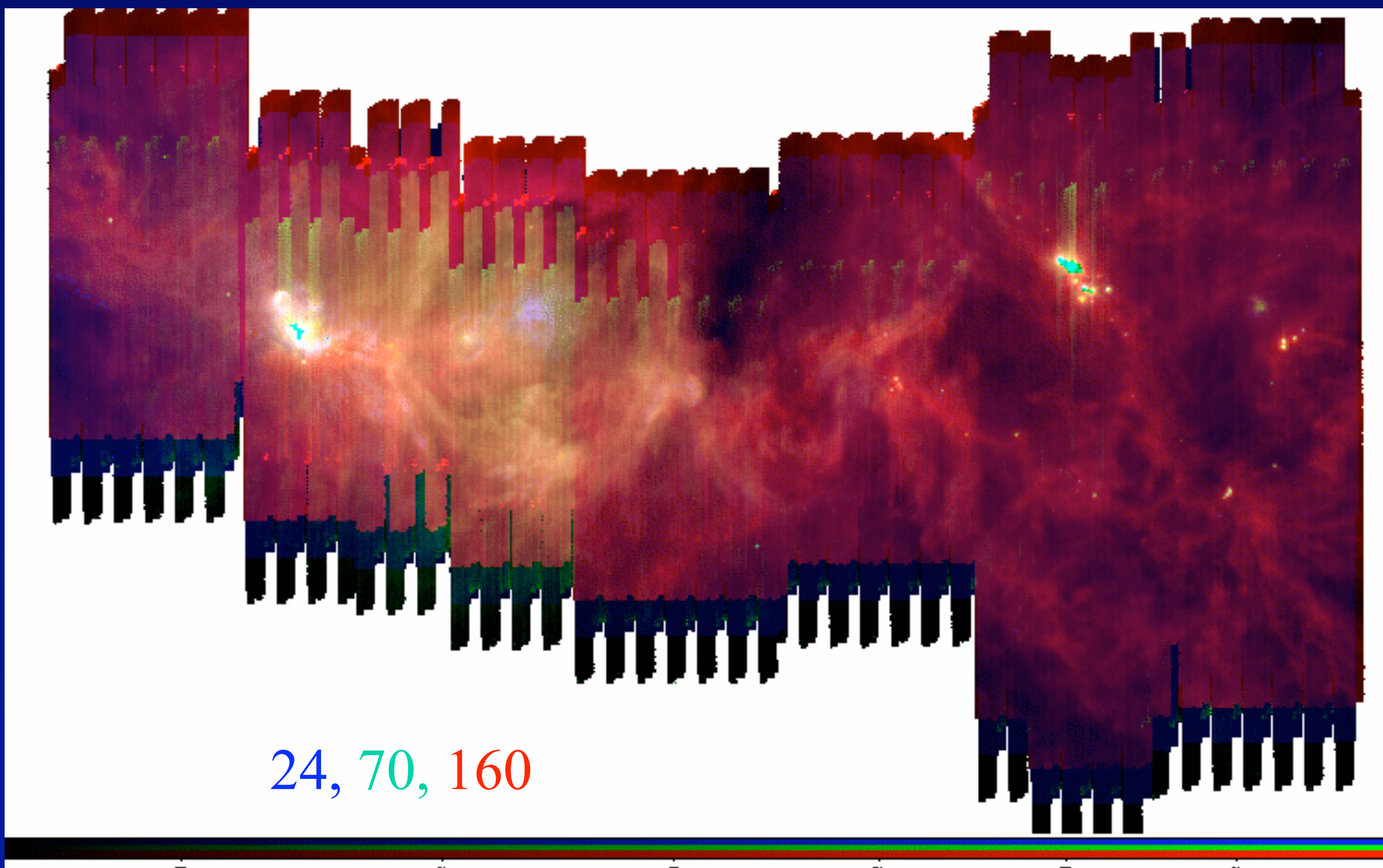
Perseus Molecular Cloud



10 pc

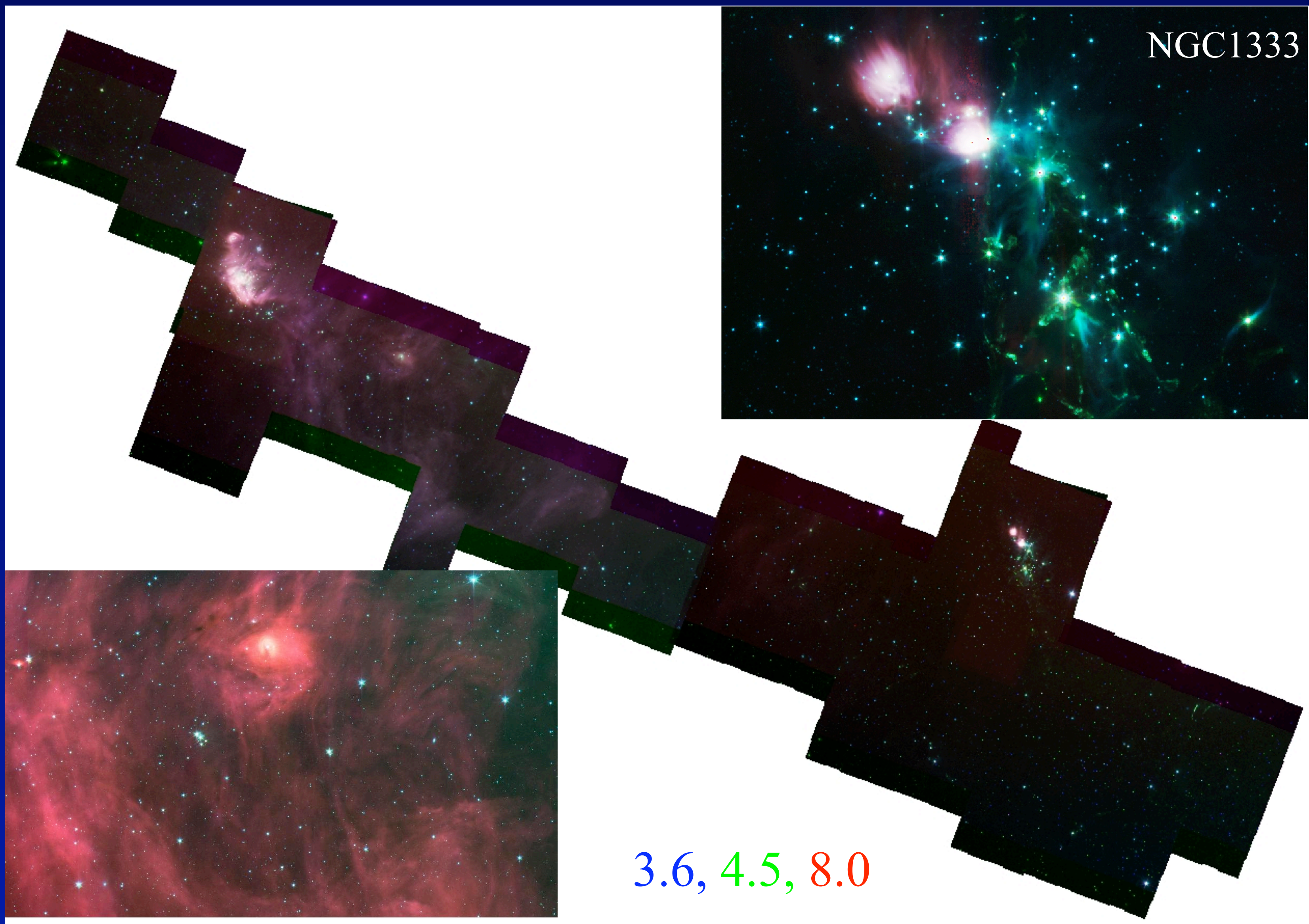
CO, ^{13}CO, 1 mm dust continuum, A_V
Ridge et al. (2006); Enoch et al. (2006)

Perseus as seen by MIPS



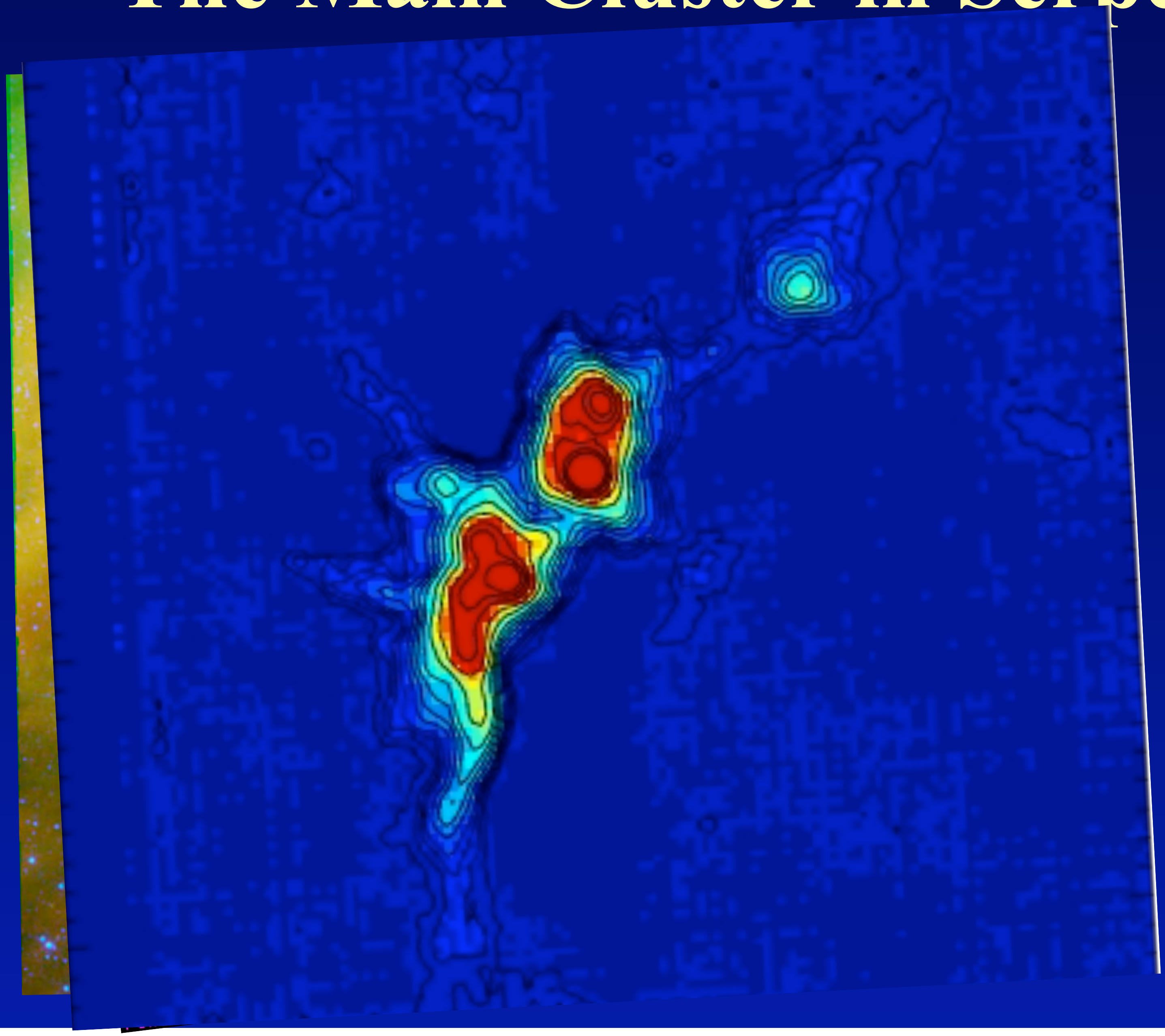
Rebull et al. 2006

Perseus as seen by IRAC



Joergensen et al. 2006

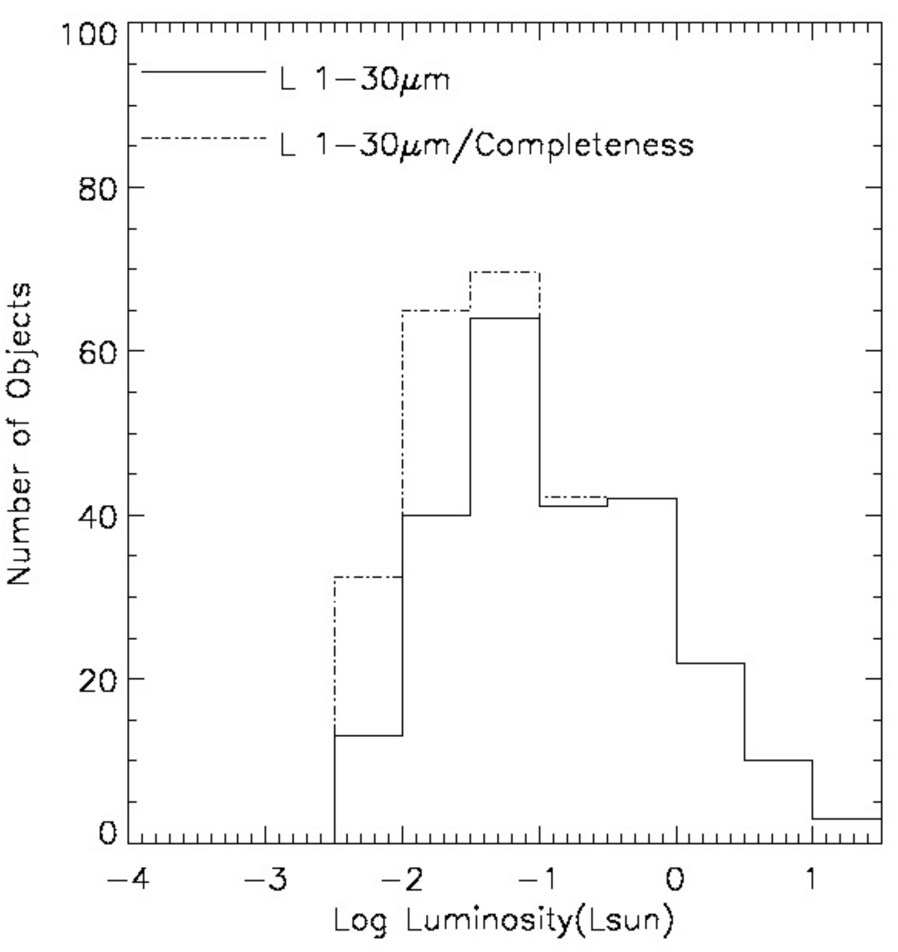
The Main Cluster in Serpens



Quantitative Results

- A large sample of YSOs in 5 clouds
  - 1024 YSOs (require IR excess)
    - Incomplete for PMS without IR (Class III)
  - Fairly complete in luminosity
    - 90% down to 0.05 L_{sun}, 50% to 0.01 L_{sun}
    - Similar across SED classes
    - Near stellar/brown dwarf boundary for 2 Myr
    - Miss some low mass brown dwarfs
      - We see them, but they are confused with galaxies

How Low in Luminosity?



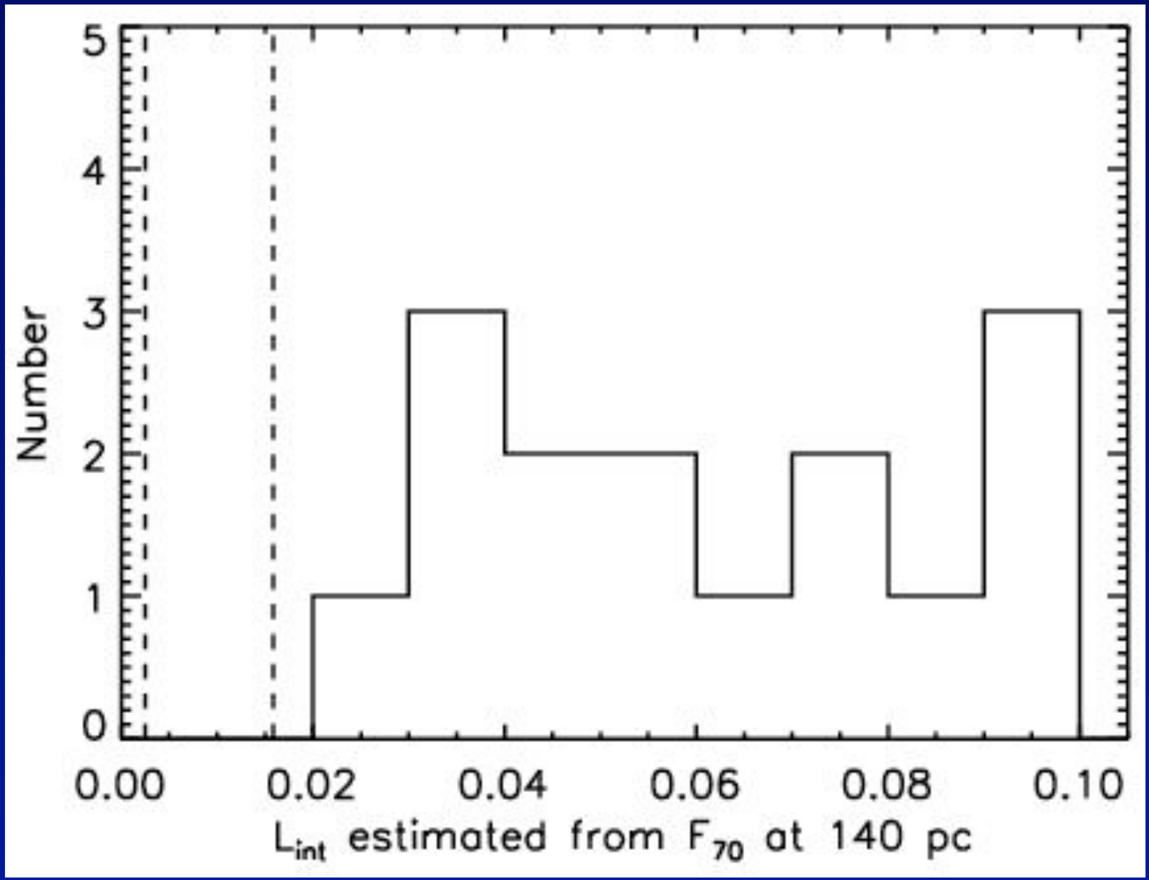
Completeness assessed by comparing full SWIRE and SWIRE resampled to Serpens extinction and sensitivity. Dotted line shows corrections.

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

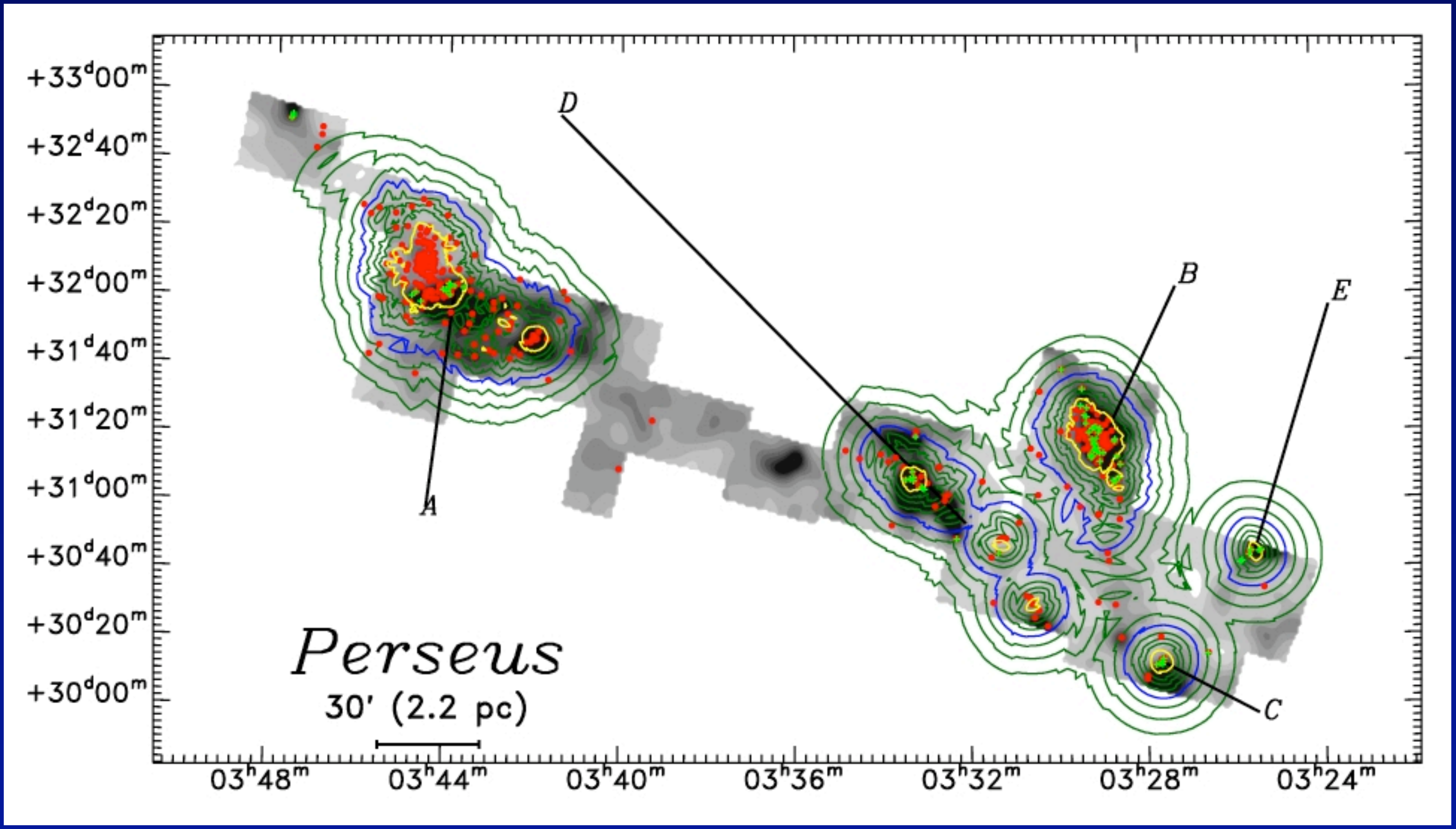
L_{int} Limit for Embedded Sources



Dunham et al. 2008

Embedded sources have L_{bol} ~ 0.1 L_{sun} from ISRF heating. Need models to get L_{int}. L(70) is good proxy.

What is the Environment?



Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

Overall Clustering

- Taking all clouds together
- Cluster (N >35 members)
  - 90% in loose ($1\ M_{sun}\ pc^{-3} < n_* < 25\ M_{sun}\ pc^{-3}$)
  - 54% in tight ($25\ M_{sun}\ pc^{-3} < n_*$)
- Groups (N < 35)
  - 7% are in loose groups
  - 13% are in tight groups
- 9% distributed
  - Distributed are "older" (fewer I and Flat)

Clusters vs. Distributed: Serpens

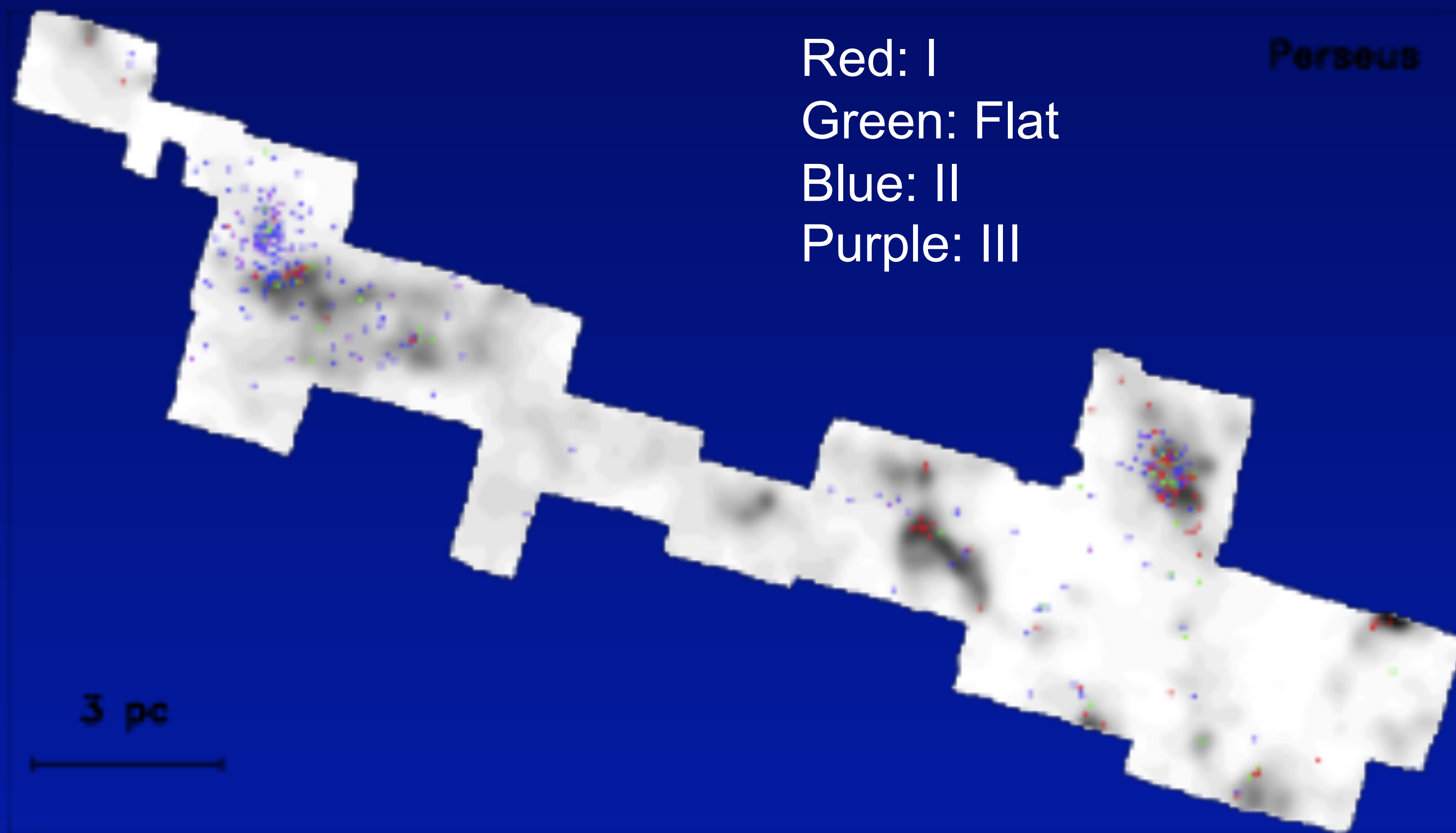
Region	Cluster A	Cluster B	Rest of cloud	Total
N(YSO)	44	17	166	227
N/Vol (pc^{-3})	500	315	2.5	3.2
M(dense) (M_{sun})	40	9	44	92
t_{dep}(dense) (Myr)	3.6	2.1	1.0	1.6

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

Clusters vs. Distributed

- Densities high in clusters
  - But < 0.1 that in Orion, …
- Clusters are younger (I+F)/(II+III)
- Cloud crossing times about 3-8 Myr
  - Assume dispersion from ^{13}CO linewidths
- Distributed population could come from dispersed clusters [$t_{cross} \sim t(\mathrm{ClassII})$]

Later Classes more distributed



Do They Interact?

- **For the densest clusters in c2d study**
  - About 50 cores pc^{-3}, 500 YSOs pc^{-3}
  - Collision time = $t_{coll} = (n\ \pi r^2\ v)^{-1}$
  - Velocity dispersion about 1 km/s
    - Williams and Myers (2000) for Serpens
    - Often less for cores (Walsh et al. 2004)
  - Assume r = 100 AU for disks, 0.03 pc for cores
  - For cores, $t_{coll} > 3$ Myr > t(I) ~ 0.5 Myr
    - See also Andre et al. (2007) for Ophiuchus
  - For disks, $t_{coll} > 8$ Gyr >> t(II) ~ 2 Myr

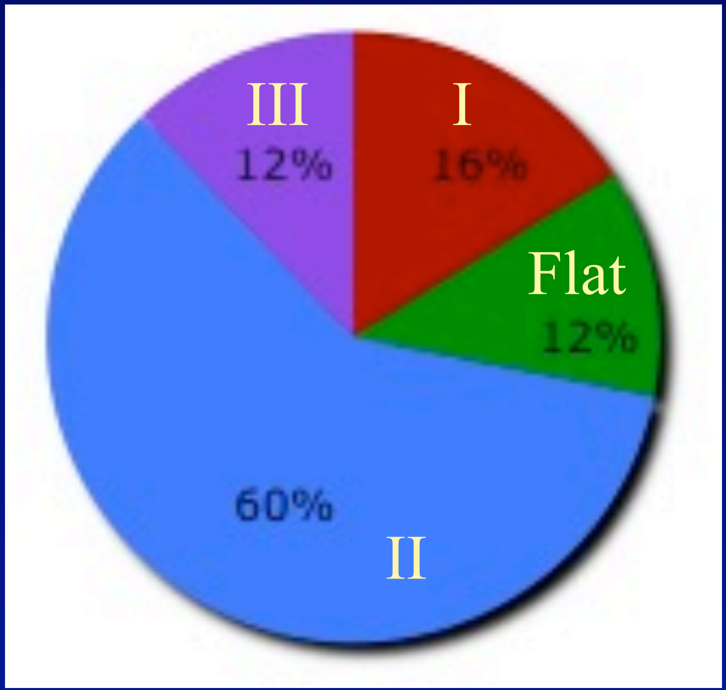
Evolution

- Classify using Greene et al. class system
- Previous studies based on small numbers
  - Typically 50 to 100 objects
  - Lifetimes differed by up to factor of 10
- Combining all our large clouds yields 1024 YSOs

Our Results

- α based on slope of νS_ν
- Fit to any photometry between 2 and 24 microns
- Averages over different situations
  - Five clouds, very different environments
  - Clusters, aggregates, and distributed
- Assume t(II) = 2 Myr (half life?)
  - L. Allen talk

Overall Statistics



IF Time is the only variable
AND
IF star formation continuous for t > t(II)
AND
IF Class II lasts 2 Myr,
THEN
Class I lasts 0.54 Myr
Flat lasts 0.40 Myr

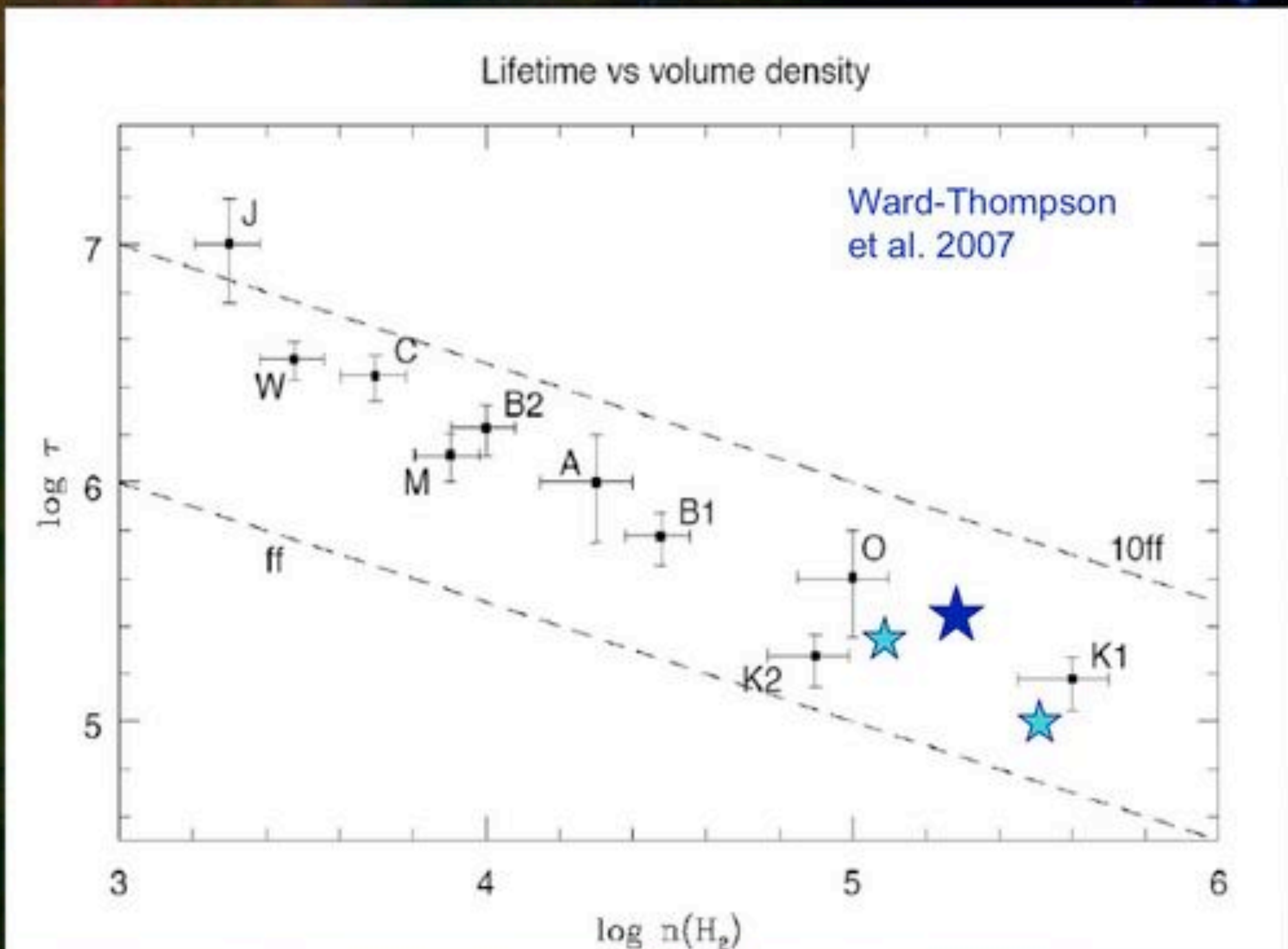
I: $\alpha \geq 0.3$
Flat: $-0.3 \leq \alpha < 0.3$
II: $-1.6 \leq \alpha < -0.3$
III: $\alpha < -1.6$

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

Timescales for earlier stages

- For 3 clouds with millimeter maps (Enoch08)
  - Use T_{bol} to separate Class 0 from I
  - Absence of IR source to identify starless cores
  - Largest sample to date: 200 cores
  - N(0) = 0.44N(I), so t(0) = 0.16 Myr
    - Not consistent with fast, early infall (Andre et al.)
    - Except Oph: 0.04 Myr, Oph was basis of low t(0)
      - Oph has faster evolution or not continuous
  - N(SL) = 0.8 N(0+I), so t(SL) ~ 0.46 Myr
    - After $\langle n \rangle > 2 \times 10^4$ cm^{-3}
    - t(SL) ~ 3 t_{ff}; between predictions of fast and slow

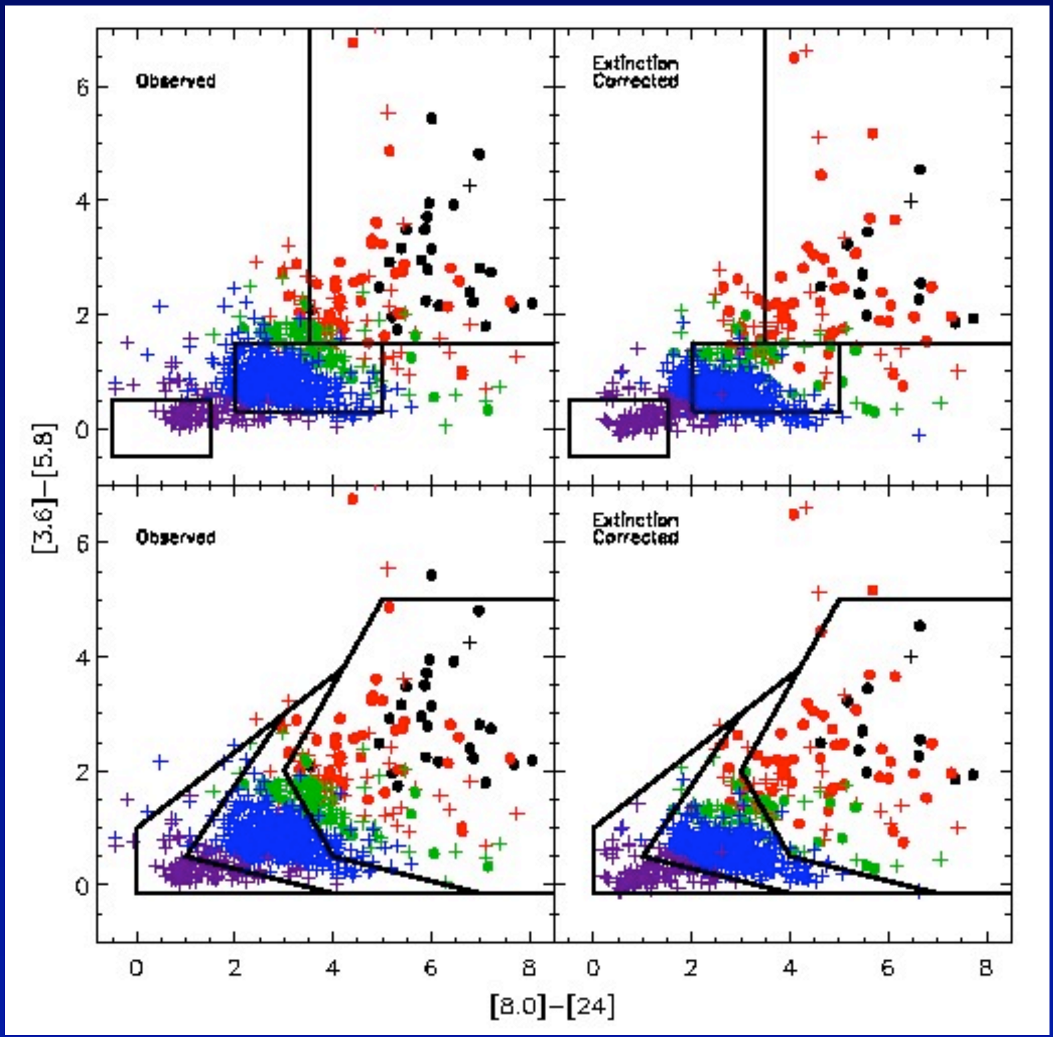
Prestellar core lifetime



- $n(H_2)$ measured in 10^4 AU aperture
- Estimated τ
  - ⇒ Cores not in free-fall
  - ⇒ Not highly subcritical
- Lifetime decreases at higher densities

Enoch et al. 2008

Classes and Stages



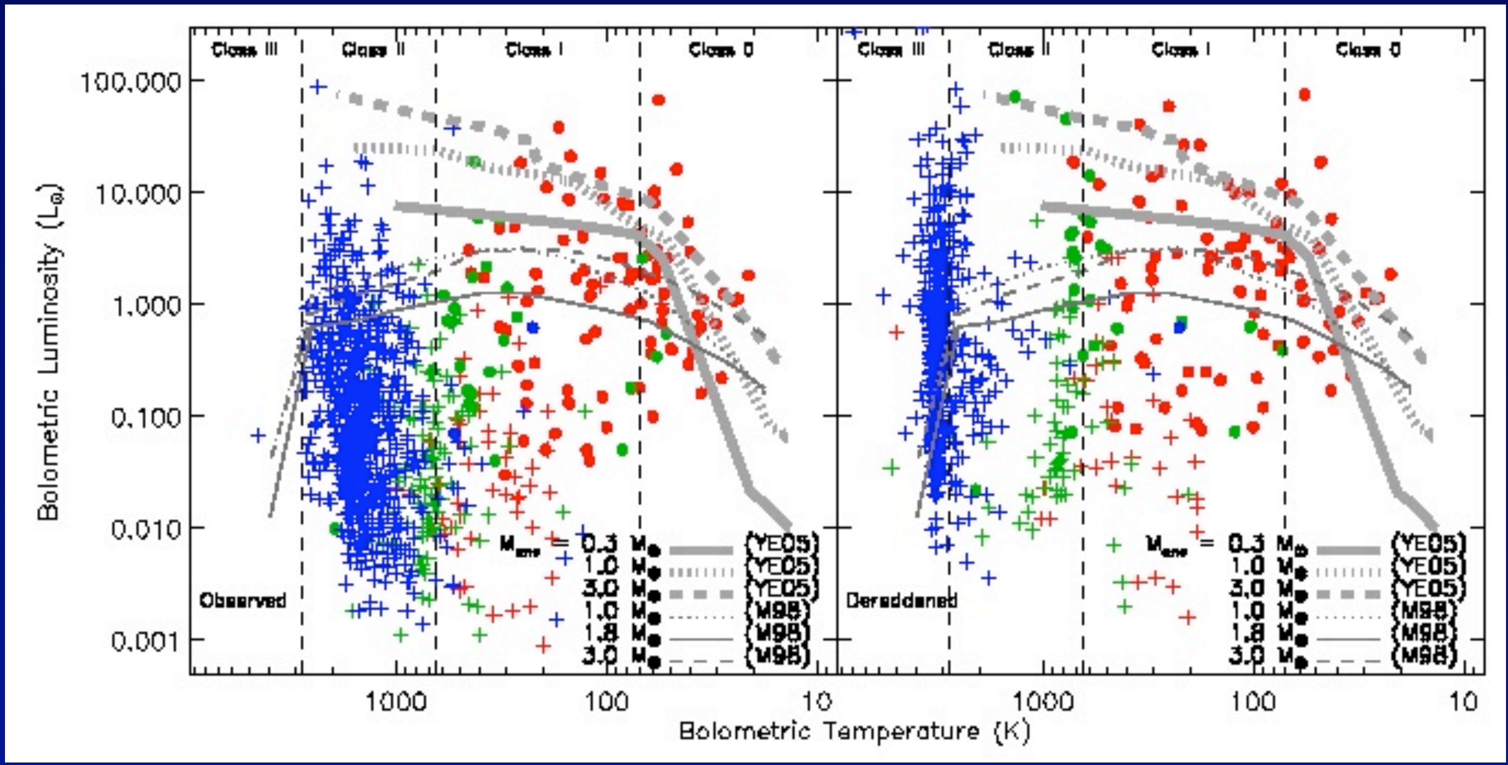
Boxes roughly separate classes, but could be cleaner. Black dots are Class 0, red are I, green are Flat, blue are II, purple are III

Division between stages from Robitaille et al. (2007) has better correspondence to classes.

Comparison to Shu model

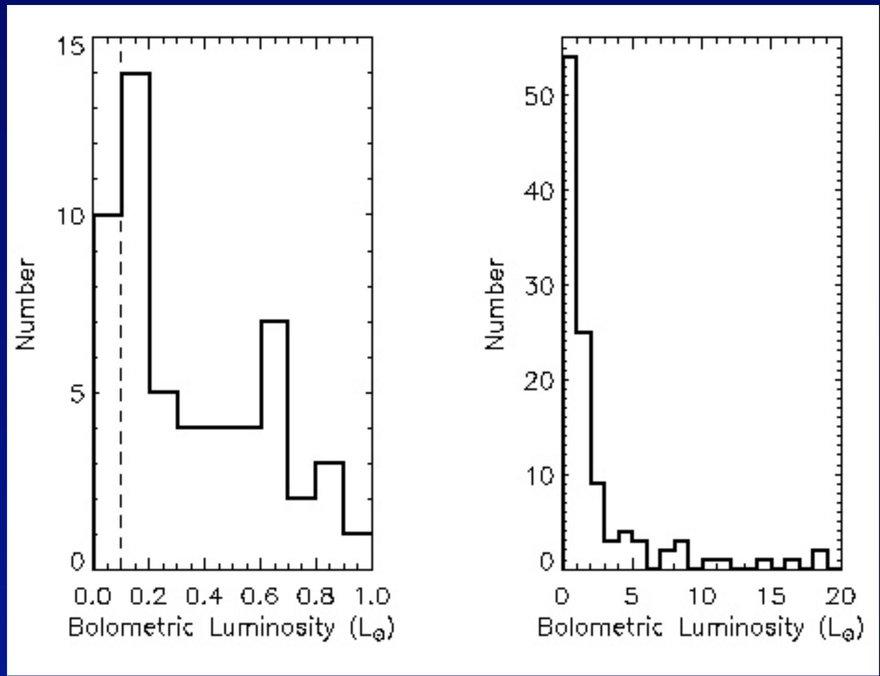
- Assume inside-out collapse at 0.19 km/s
  - Sound speed at 10 K
- In 0.54/2 Myr, r_{inf} = 0.054 pc
  - Consistent with some sizes, but large in clusters
- At dM/dt = 1.6 x 10^{-6} M_{sun}/yr, M_{*} ~ f 0.85 M_{sun}
  - If f ~ 0.3, get 0.25 M_{sun} ~ modal mass
- Consistent with assumptions, most data
- Picture holds together, except…

The Luminosity Problem!



Top curves show predicted evolution in Shu model with f = 1 for various masses (Young & Evans). Lower curves show exponentially decreasing accretion rate. Many current luminosities are very low compared to predicted values.

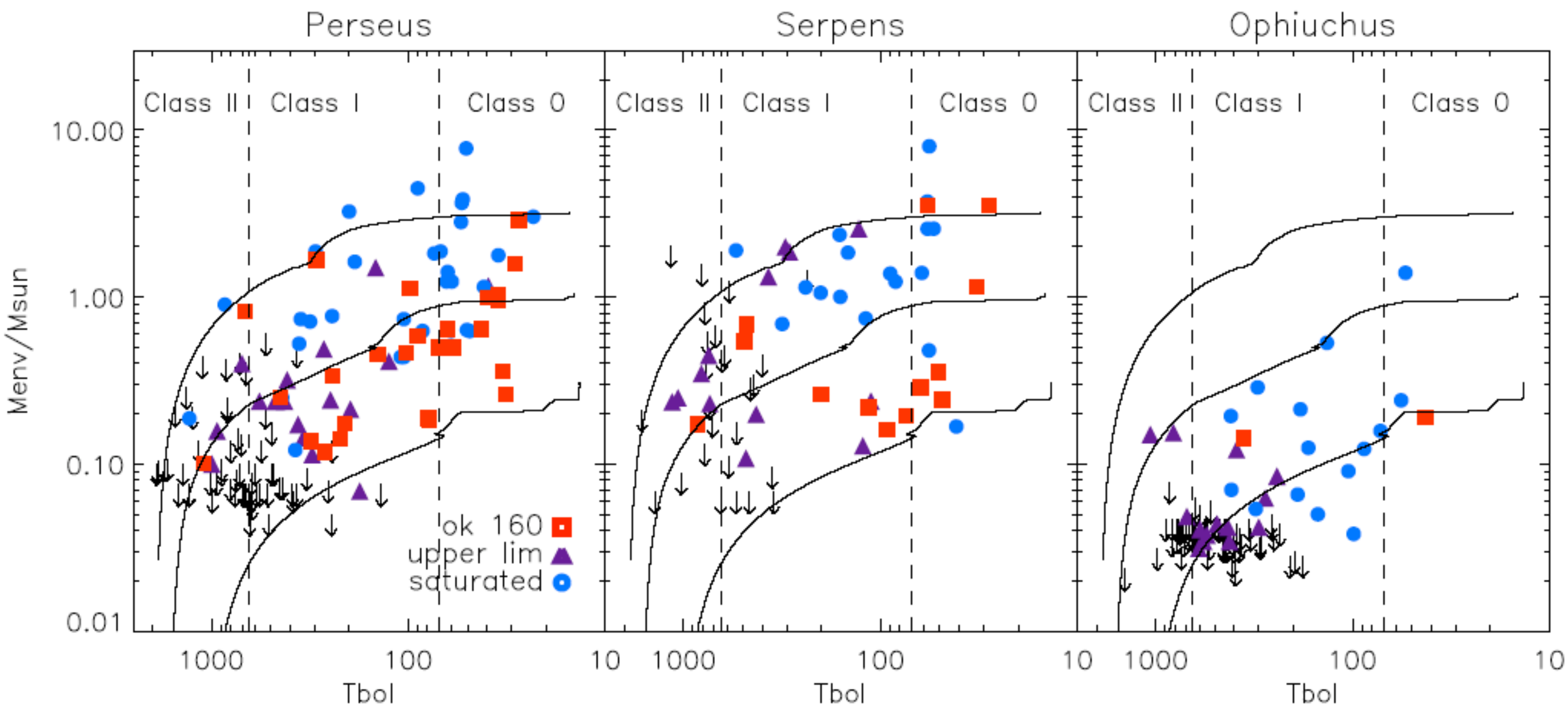
Luminosities of Embedded Sources



Histogram of luminosities of embedded (mm continuum) sources.
Blow-up of $L < 1\ L_{sun}$ on left. Three sources off scale on right up to $70\ L_{sun}$.
Predicted L = GM(dM/dt)/R= 1.6 L_{sun} for standard (Shu) accretion onto
M = 0.08 M_{sun}, R = 3 R_{sun}. Most (59%) are below this. Corrections for
extinction may increase L_{bol} by factor of two on average.

Points to episodic accretion.

Mass Leaves Envelope as Expected



Enoch et al. 2008

Episodic Accretion

- Suggests mass build-up in disk until unstable
  - Kenyon and Hartmann (1995)
- Toy Model
- Use distribution in L_{bol} to estimate mass accretion onto star and fraction of time at each accretion rate; add them up
- Can make 0.7 M_{sun} star even if, 80% of the time, they are accreting at < Shu rate
- Half the mass of star built in 7% of the Class I lifetime.

Stars form mostly when we are not looking…

Consequences

- If infall onto the disk is fairly steady,
- But accretion from disk to star is highly variable,
- The embedded disks cycle between
  - Maximal, unstable disks
  - Minimal, stable disks
- “Initial” conditions in disk could depend on phase of cycle when infall ends

Diversity in Disk Evolution

- We see a large range of disk SEDs (B. Merin)
- Study of wTTS provides constraints (Padgett 2006, Cieza 2006, talk by L. Allen)
  - Some wTTS have disks, but none older than 3-6 Myr
  - Some very young ones (0.8-1.5 Myr) are diskless
- Rotation studies indicate that ~30 to 50% of stars lost disk braking in < 1 Myr
  - Rebull et al. (2004) and (Cieza and Baliber 2007)

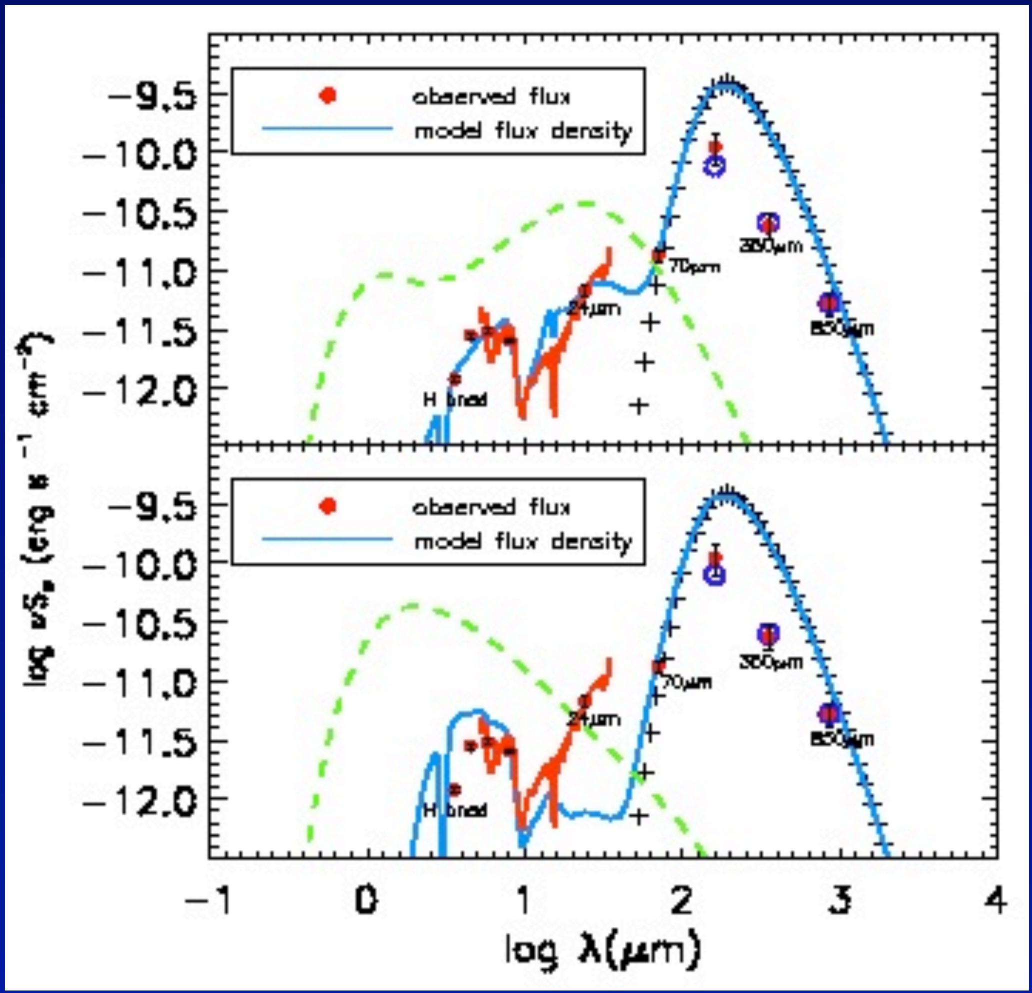
Speculation

- Stars that lose their disks within 1 Myr
  - Started with minimal disks
    - Infall ended just after a big accretion event
    - Or…
  - Started with maximal, unstable disk
    - Infall ended coincident with unstable disk
    - Disk instability leads to early loss of disk
    - Disk-braking fails, becomes fast rotator

Can We Observe Embedded Disks?

- Very difficult with millimeter data
  - The envelope is centrally peaked
  - Hard to separate a point source
  - Chiang et al. (2008) set limits ($M_{disk} < 0.1$ M_{sun}) in four Class 0 sources in Perseus
  - We will hear more from J. Joergensen

MIR Studies of Class 0 Objects



Spitzer's sensitivity allows detection of Class 0 objects in MIR and even IRS spectroscopy.

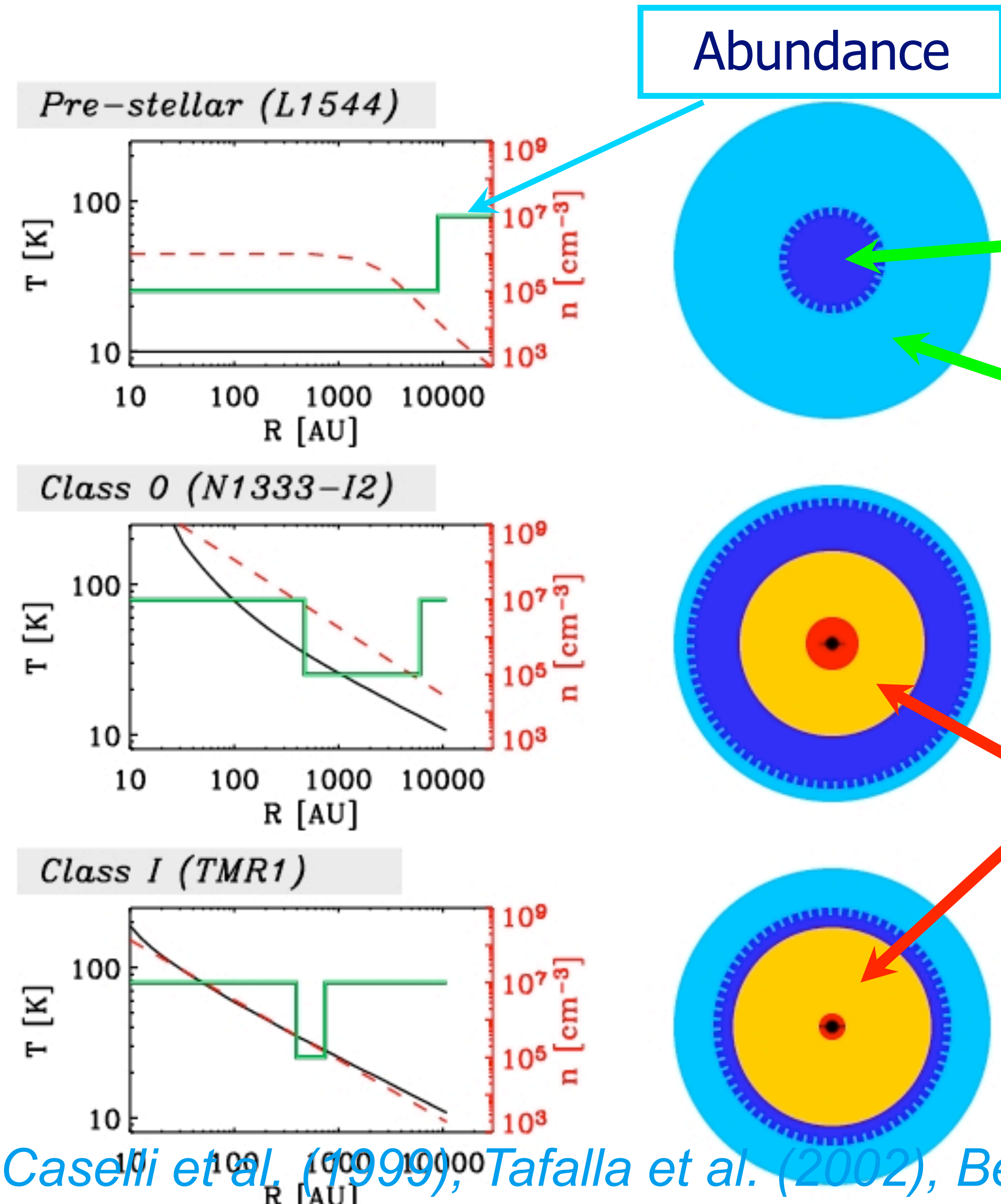
This region is extremely sensitive to nature of the disk.

But details of the transition from disk to envelope and deep ice features are also important.

Kim et al. 2009

Evolution of Dust, Ice, Gas

- Molecular lines show freeze-out of gas
- We see complex ices early in evolution
- Grain growth in the Class 0/I stage
- Further grain growth in disks



Pre-stellar core:

- Low temperature
- Depletion toward center (high density/short time)
- ...but not edge

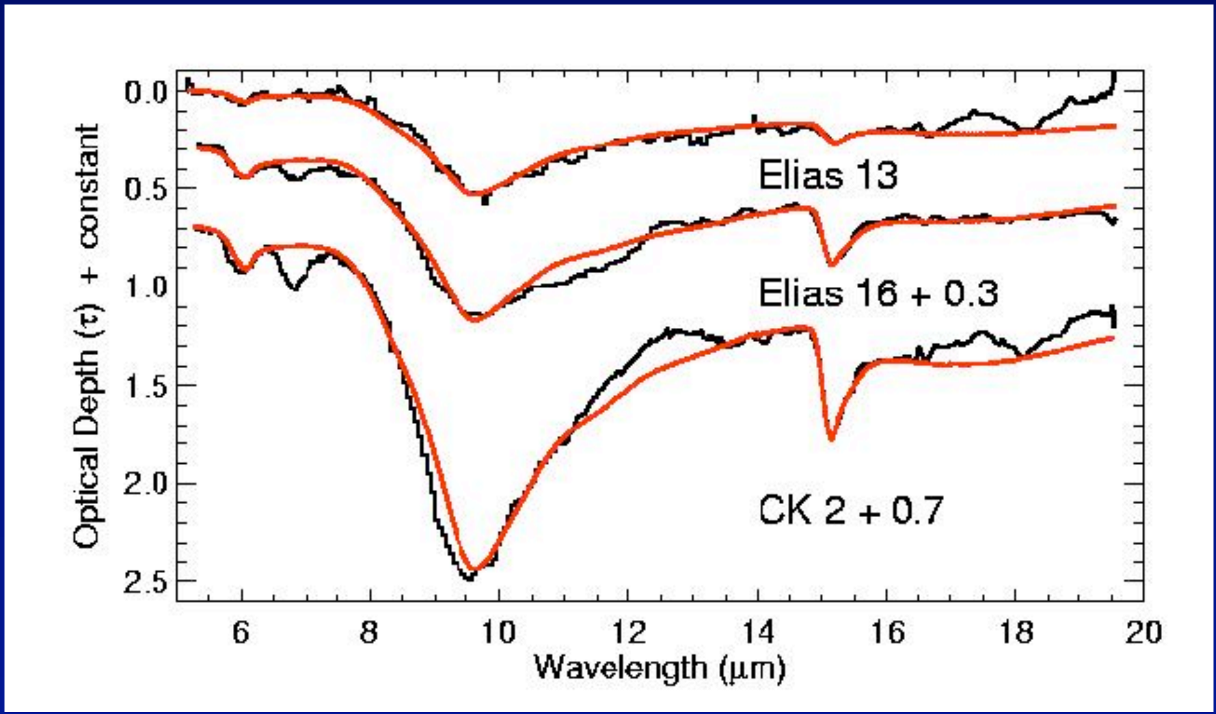
Protostellar core:

- Central heating ~ temperature gradient
- Thermal desorption toward center
- ...outside (low T): depletion/no depletion regions as in pre-stellar stages

Caselli et al. (1999), Tafalla et al. (2002), Bergin et al. (2002), Bacmann et al. (2002), Lee et al. (2003)...

Jørgensen, Schöier & van Dishoeck, 2005, A&A, 435, 177

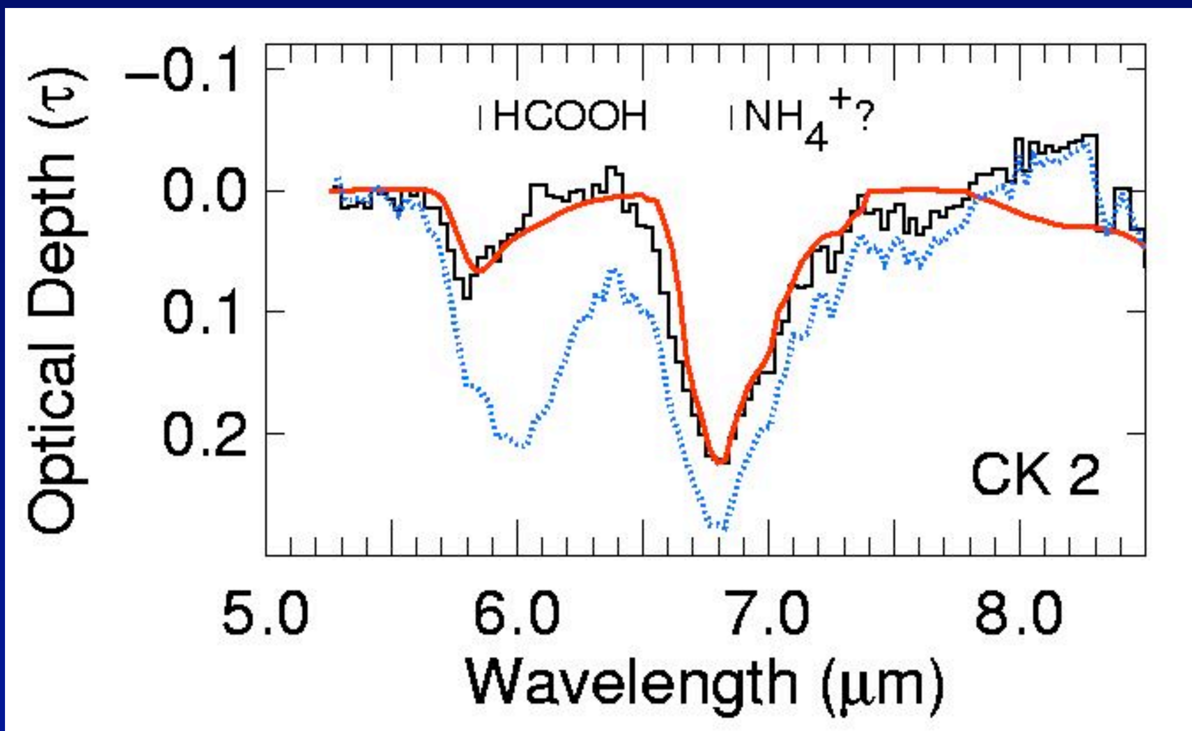
Ices form in molecular cloud



Probe ice composition **before** protostar formation.
Dependence on A_V, n, T
Large abundances of CO_2 relative to H_2O
CO_2 not crystallized, confirms pristine

Knez et al. 2005

Ices Can Be Complex Early



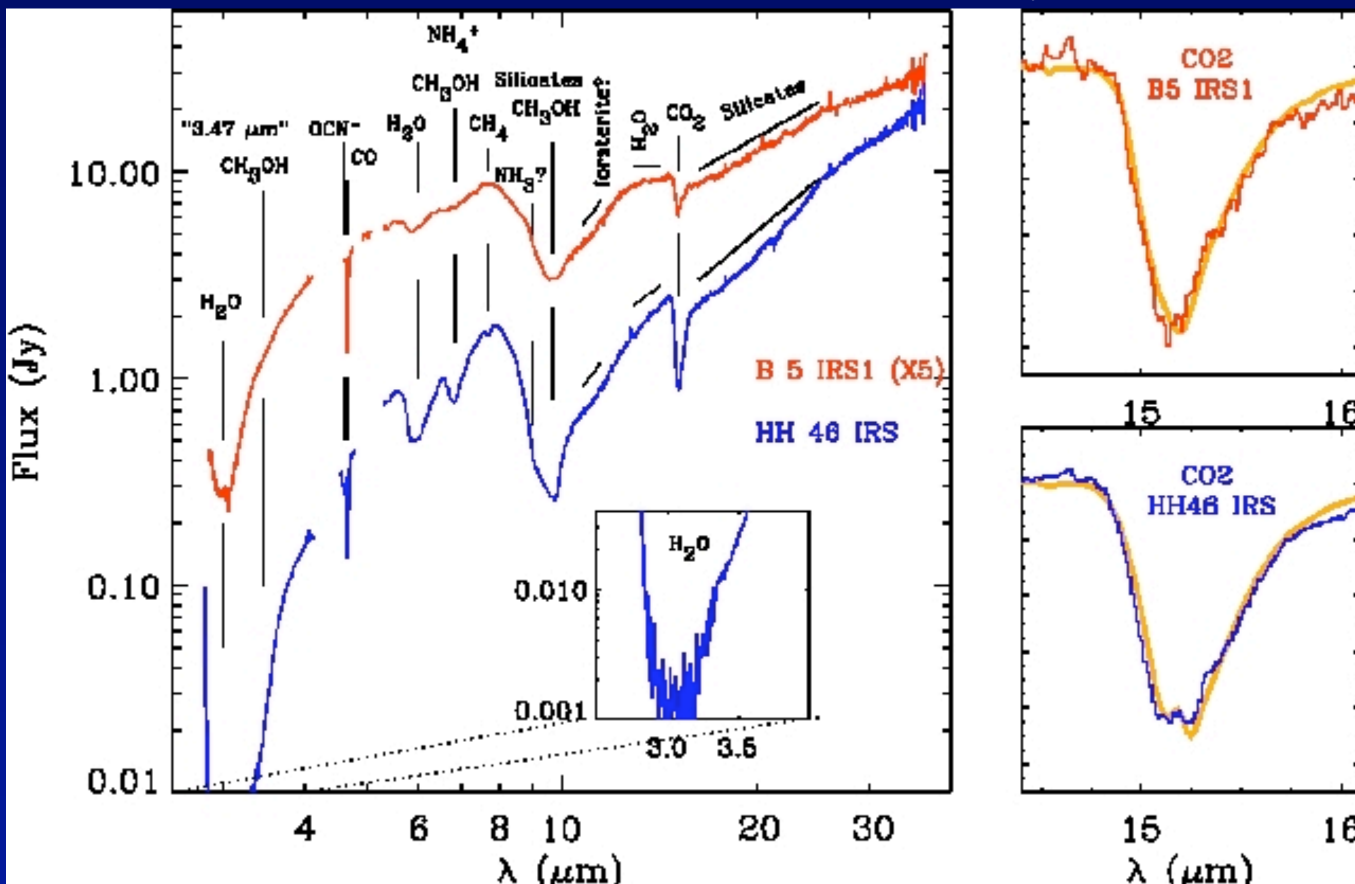
Knez et al. 2005

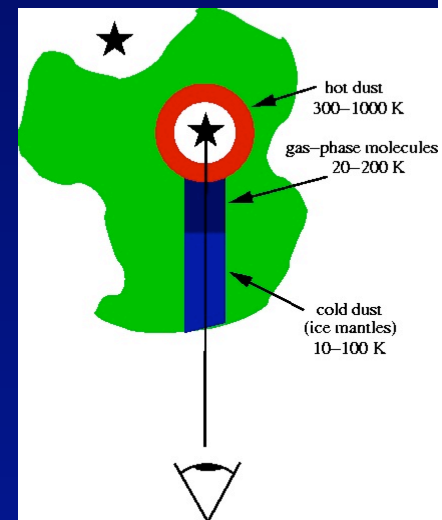
Minor species:
Blue: with silicate removed
Black: with H_2O ice also removed
Red: fit with HCOOH and 6.8 micron carrier

HCOOH present
6.8 micron (NH_4^+) present

Embedded low-mass protostars

Ice inventory

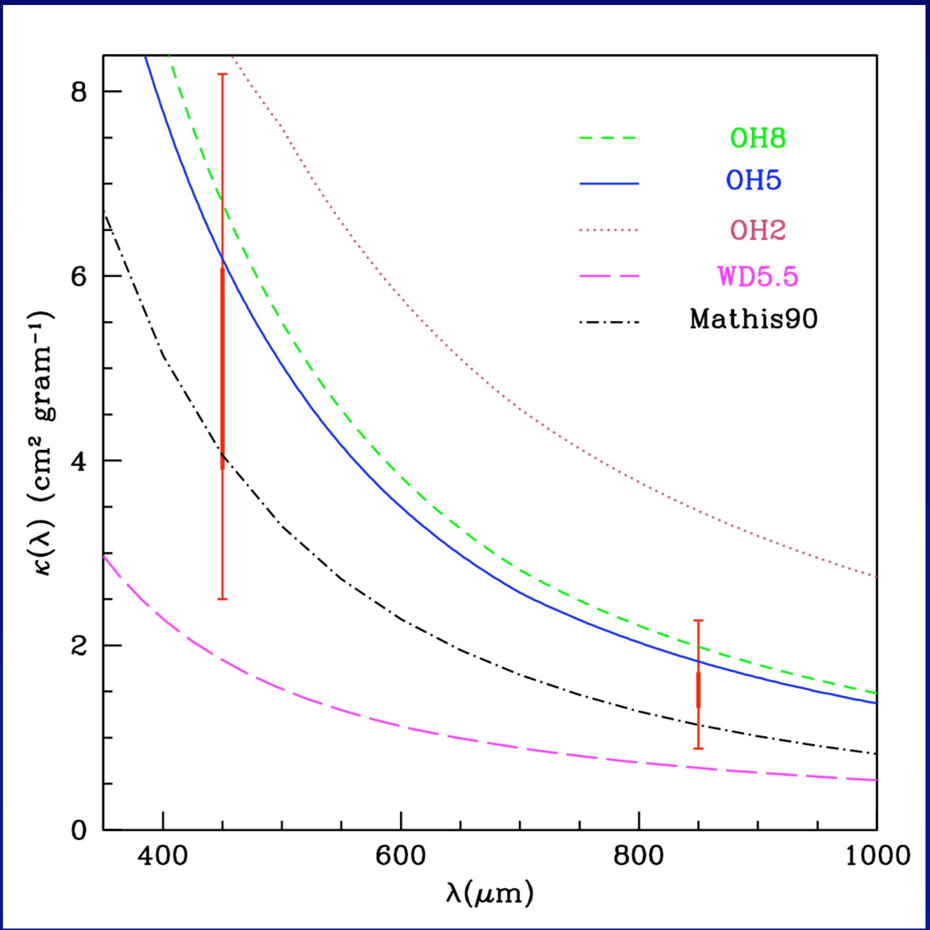




Boogert et al. 2004, 2007

- **Abundances of some species similar within factor of 2 (e.g., CO_2)**
- **Significant variations (>10) for other species (e.g., CH_3OH, NH_3, OCN^-)**
- **Evidence for NH_3 with high abundances (>10%) in some objects?**
- **First detection of CH_4 ice toward low-mass YSO's**

Grain growth in Class 0/I stage



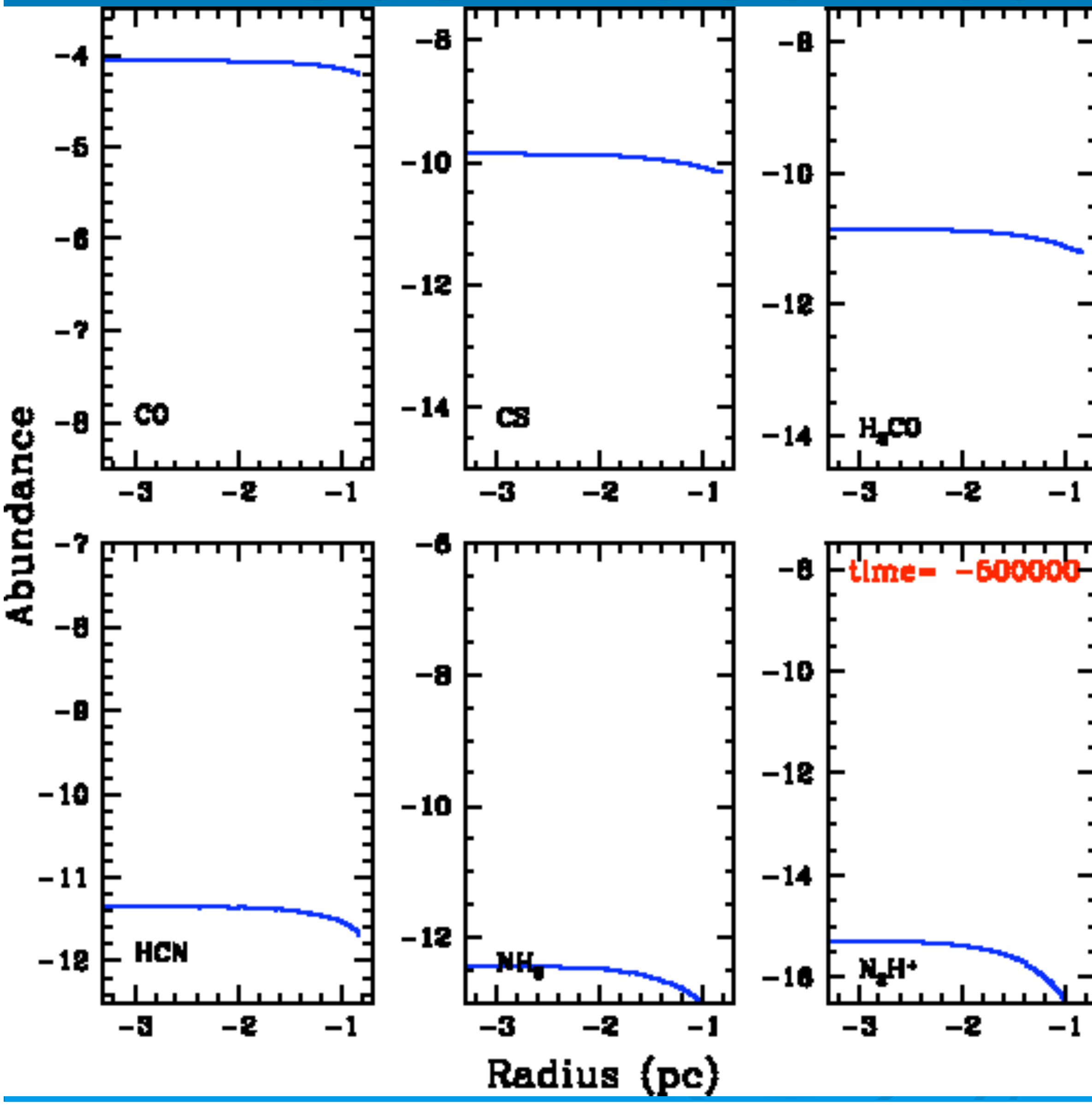
Comparing emission at submm from SCUBA with extinction at 2 microns to calibrate submm opacity.
Data fit models of dust that has grown and acquired ice mantles.
Best values about 75-90% of OH5, used to obtain core masses. Implies slightly larger masses from submm, but within errors.

Shirley and Huard 2008

What Kind of Material Reaches the Disk?

- Grains have grown, acquired ice mantles
- Further chemistry in the mantles
- Does this material reach the disk?
  - See Talk by D. Watson
- May depend on thermal history, luminosity evolution

Gas Phase Abundances

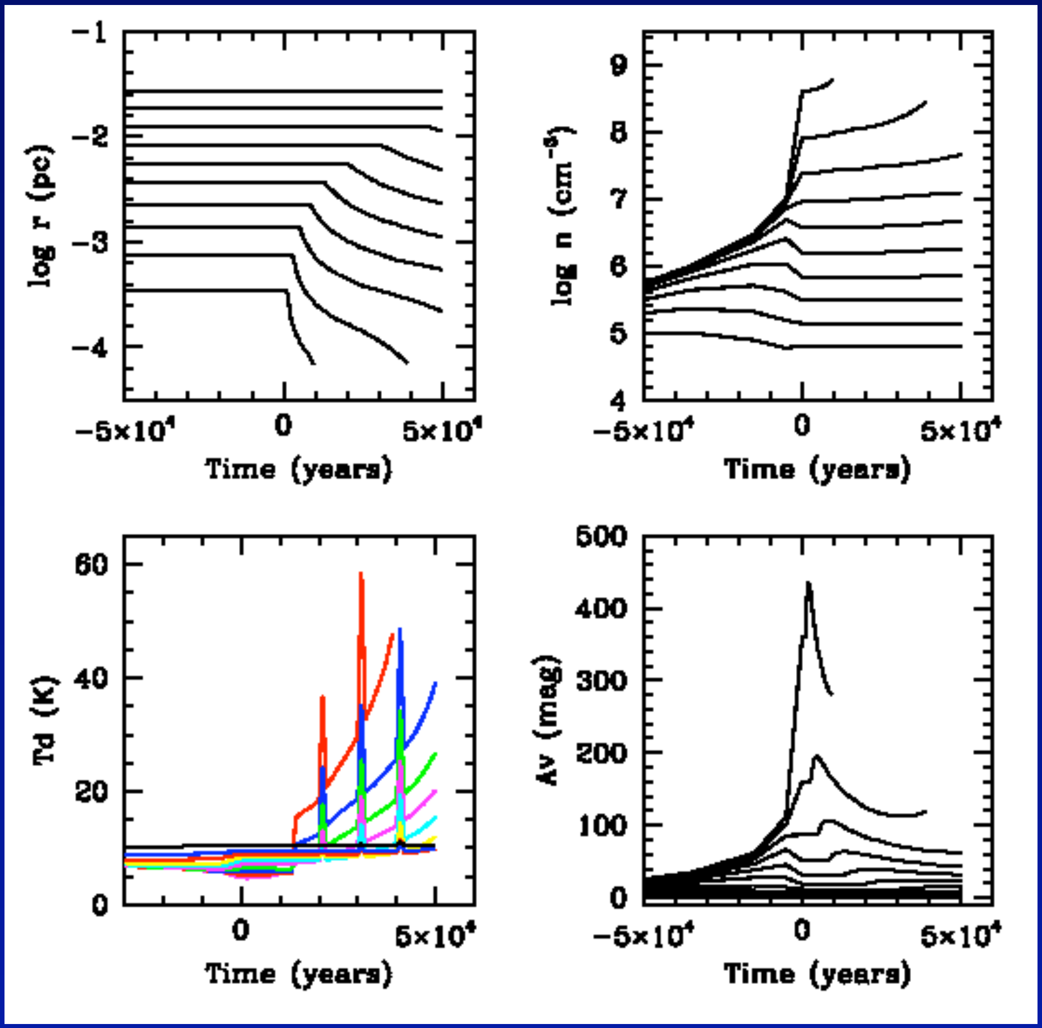


Chemical code by E. Bergin 198 time steps of varying length, depending on need. Medium sized network with 80 species, 800 reactions. Follows 512 gas parcels.

Includes freeze-out onto grains and desorption due to thermal, CR, photo effects. No reactions on grains. Assume binding energy on silicates for this case.

J. Lee et al. (2004)

Physical Effects of Episodic Accretion

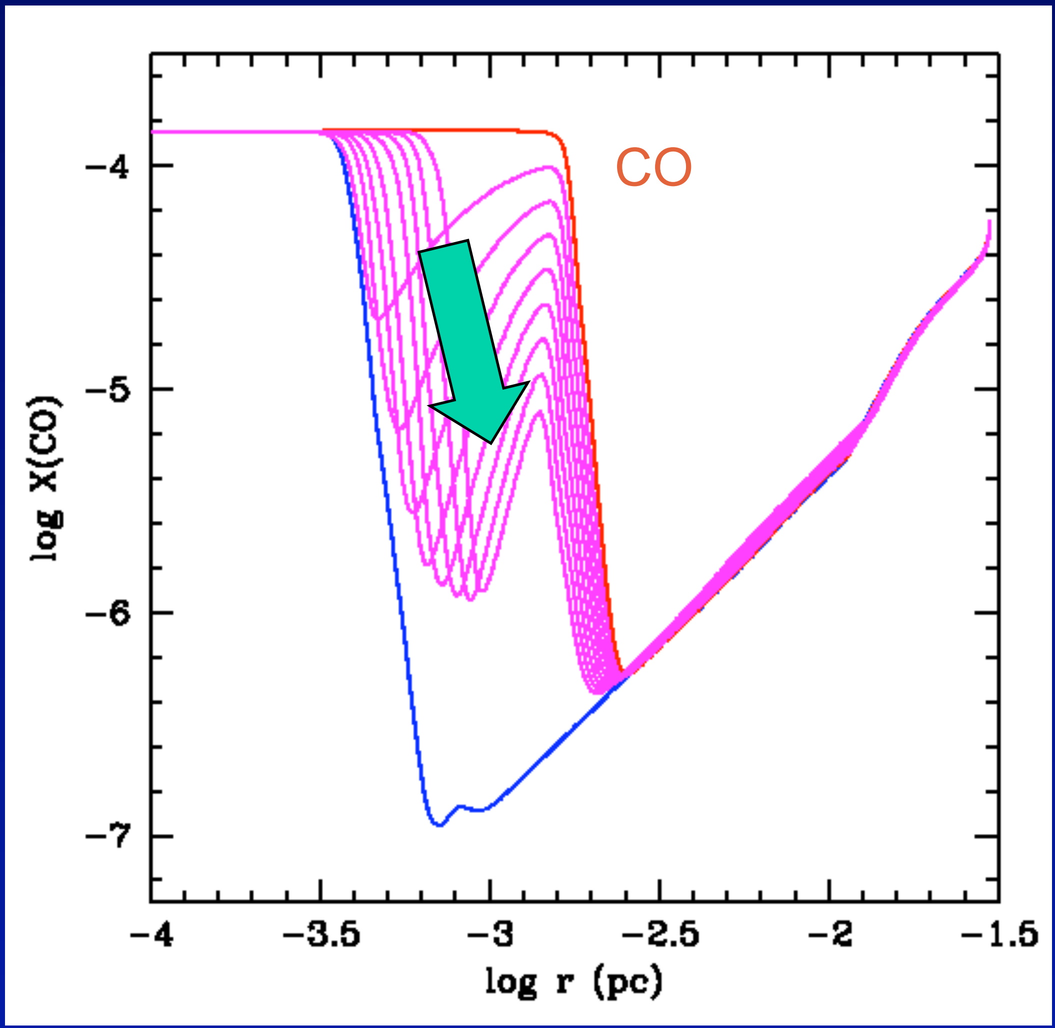


A simple model:
Starting at $2x10^4$ yr, increase L factor of 10 for $1x10^3$ yr every $1x10^4$ yr
L between flares is 10 times less than standard Shu model.
Calculation extends to $5x10^4$ yr, so includes 3 flares

Plots show r, n, T_D, A_V for 10 parcels of gas vs. time.

Lee, 2007, JKAS, 40, 83

Chemical Effects



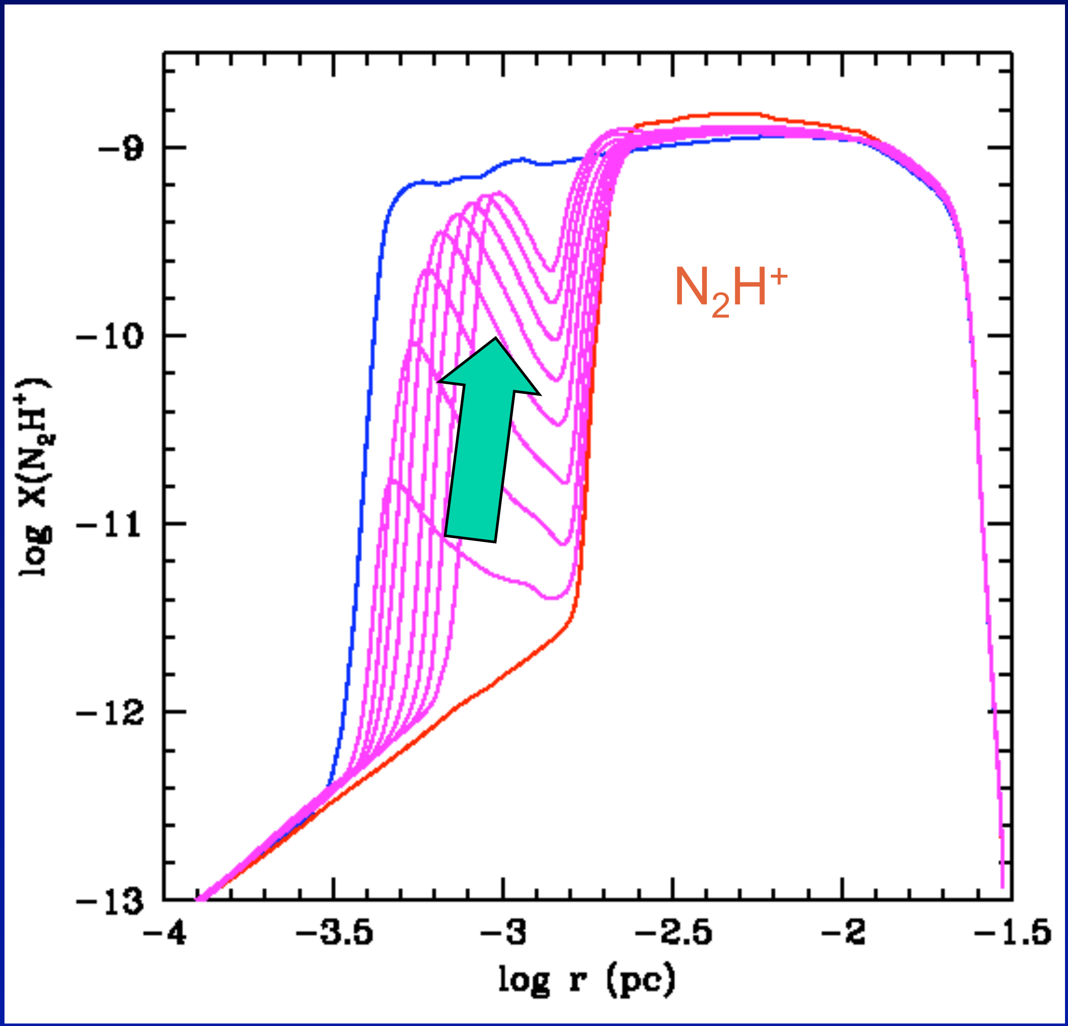
Blue line shows abundance at 4.1×10^4 yr, just before third flare and during flare (red line).

CO evaporation radius moves out.

Magenta lines show evolution every 1000 yr after third flare up to 5×10^4 yr.

Lee, 2007, JKAS, 40, 83

Chemical Effects



Blue line shows abundance at 4.1×10^4 yr, just before third flare and during flare (red line).

N_2H^+ destruction radius moves out.

Magenta lines show evolution every 1000 yr after third flare up to 5×10^4 yr.

Lee, 2007, JKAS, 40, 83

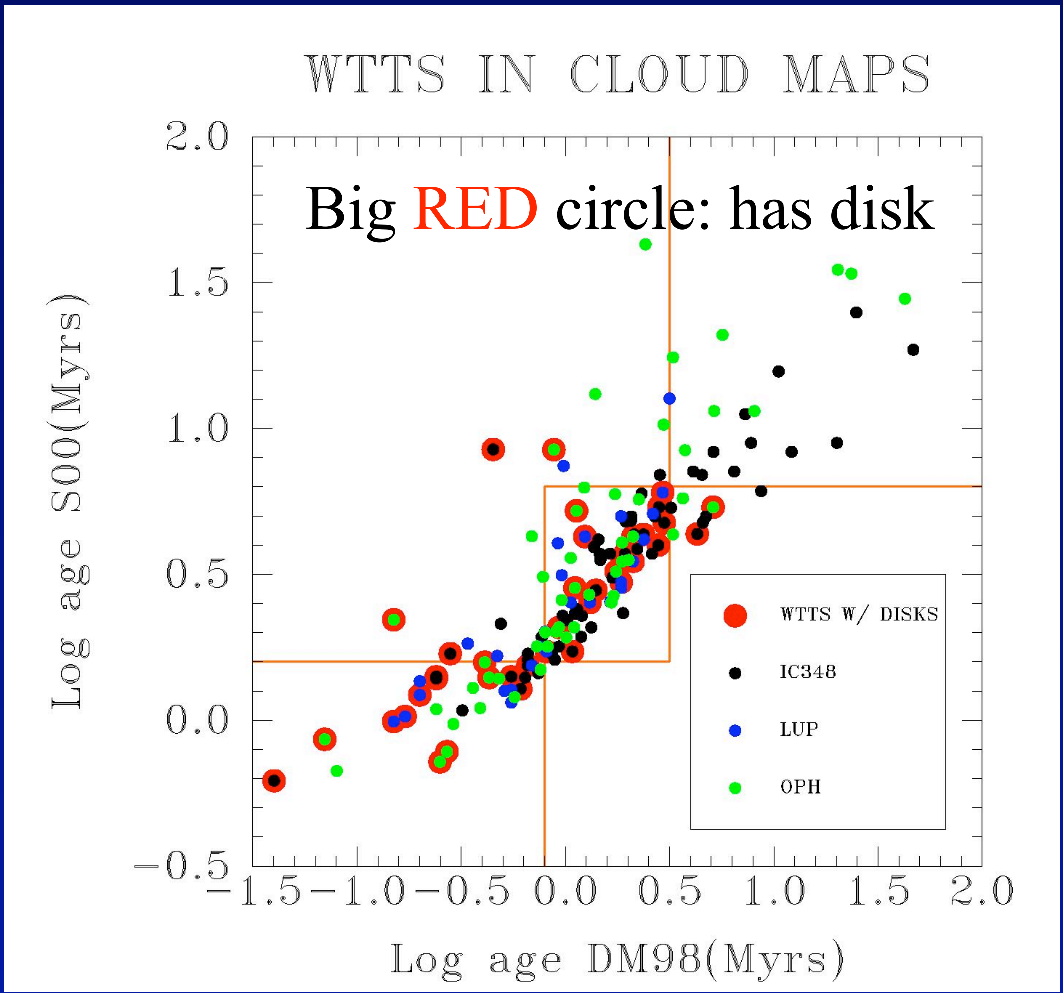
Chemical Memory

- A chemical abundance pattern inconsistent with current L is a clue to nature of episodic accretion
  - Irreversible changes in CO_2 ice features from heating events
- Understanding astrochemistry is crucial for understanding how stars are built
- … And conditions in planet forming disks

Summary

- Star formation highly clustered, but interactions unlikely in c2d clouds
- Timescale for embedded phases 1/4 to 1/2 of Stage II
- Episodic Accretion indicates cycling of disk states
  - Timing of end of accretion may affect disk evolution
- Dust, ice, gas evolve continuously
  - Molecular cloud, infalling envelope, disk

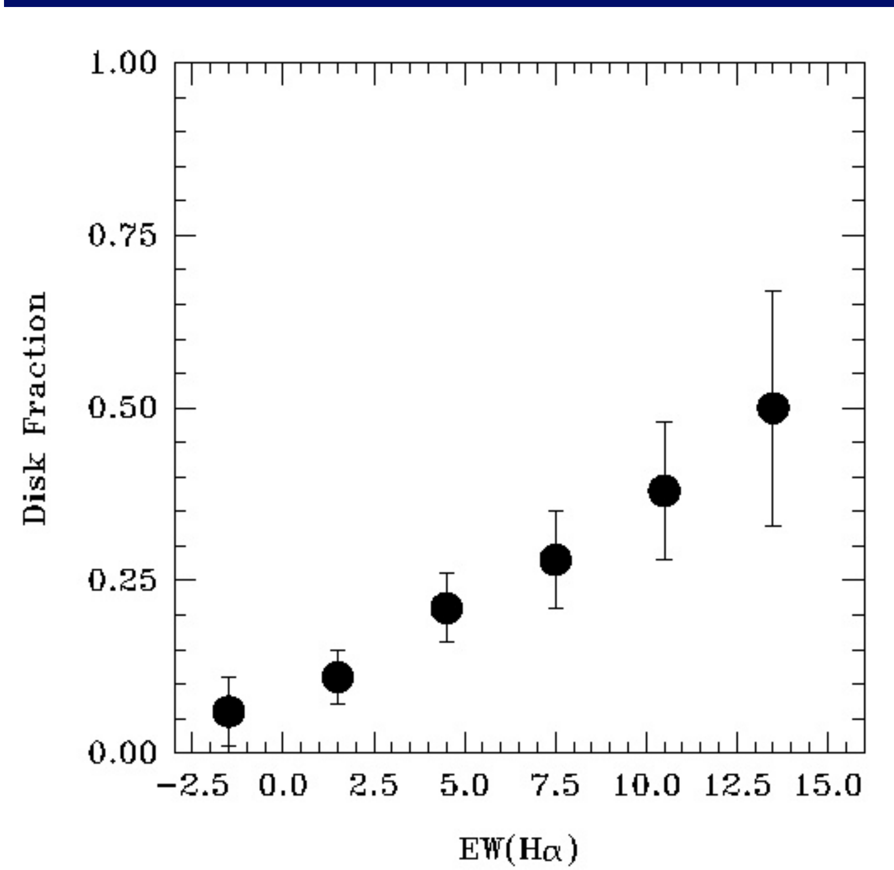
Disk Timescales

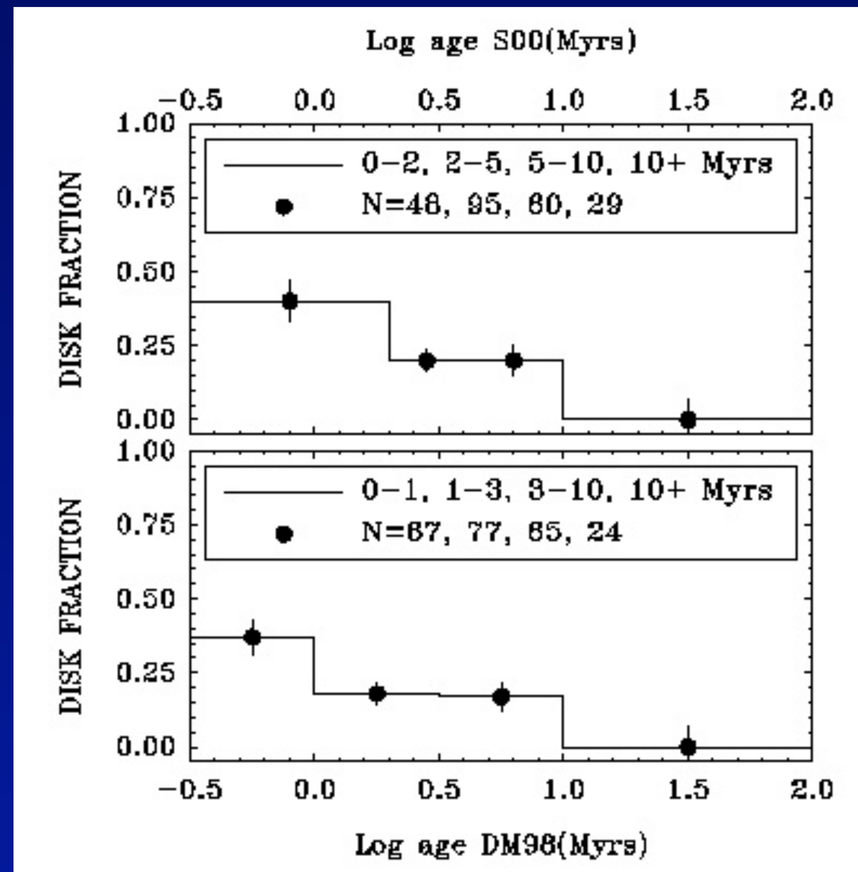


Some wTTs do have disks
Not seen before
But only the young ones
(age < 3 to 6 Myr)
Ages are uncertain due to models
Half the young ones lack disks (even at 0.8 to 1.5 Myr)
Time is NOT the only variable. Think of half-life.

Padgett et al., 2006; Cieza et al., 2006

Disk Fraction Correlations





For wTTs sample projected on clouds, disk fraction increases with Hα EW, declines with age.

Cieza et al. 2006

Conclusions wTTs

- Disk frequency *off* cloud ~6%
- Disk frequency *on* cloud ~22%
  - Off cloud sample contains older stars or closer by?
- Disk frequency highest among youngest stars ~1 Myr, but up to 50% of wTTs have lost disks by that time
  - None in this sample older than 10 Myr have detectable disks
- Transition timescale from optically thick to undetectable disks is ~0.4 Myr
- Disks exhibit a wide range of properties in terms of SED, inner radius, L_{disk}/L_{star} etc.