The First Stage of Star Formation: From Cores to Disks

Neal J. Evans II

with much help from

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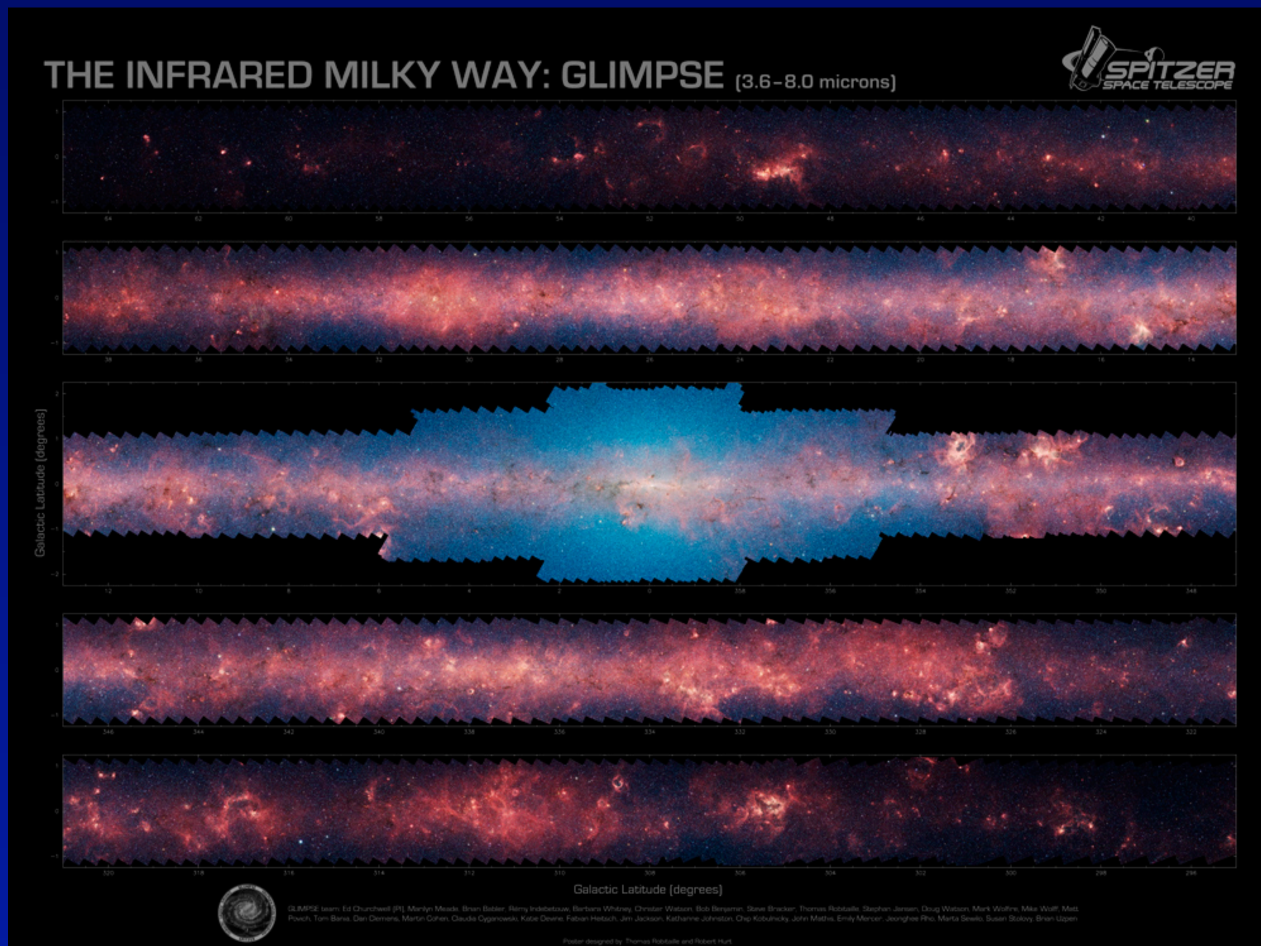
Gould's Belt

Some Star Formation Surveys

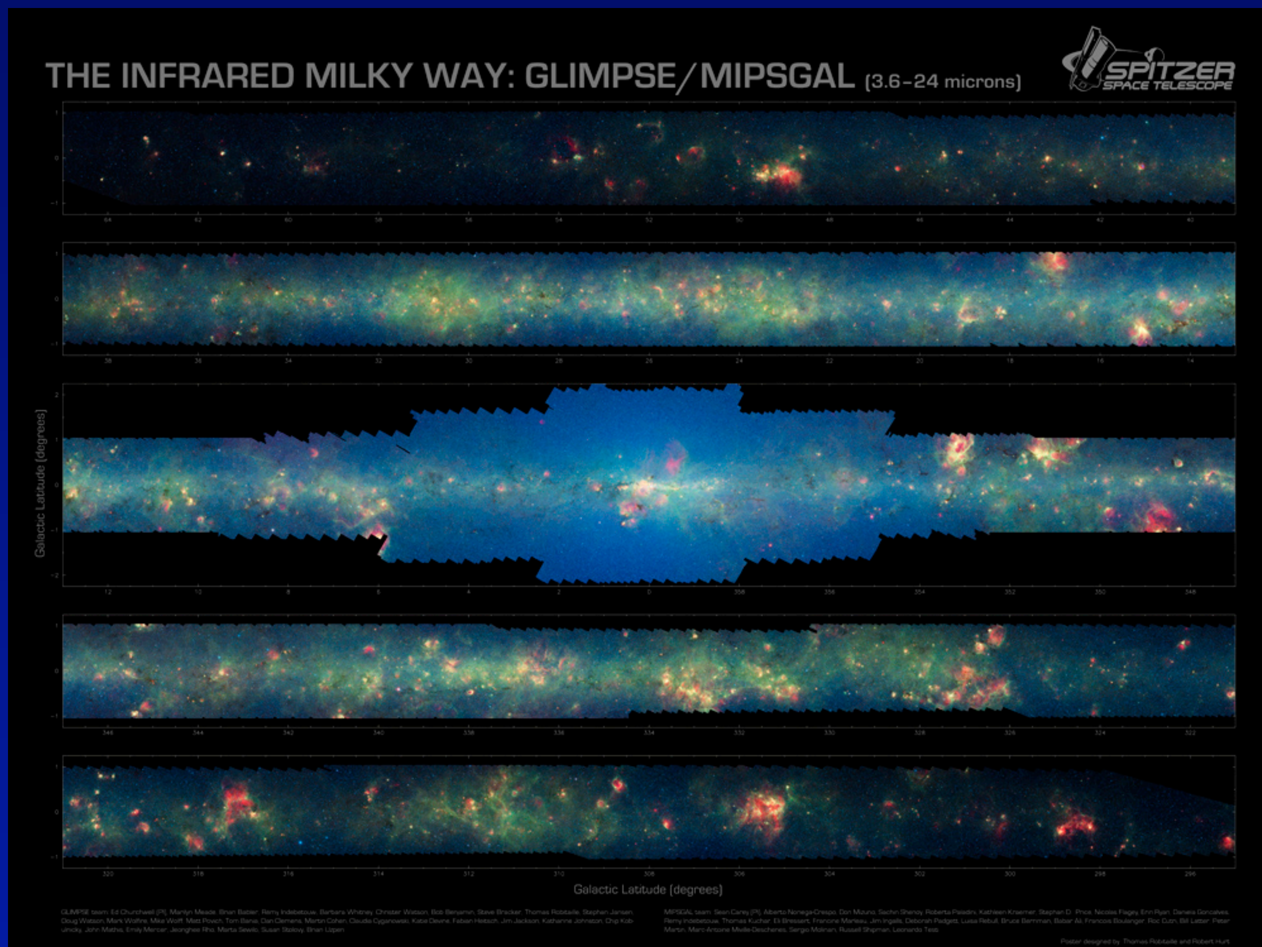
- GLIMPSE Legacy survey of Milky Way
  - Combine with other surveys, such as BGPS
- MIPSGAL Legacy survey of Milky Way
- GTO, GO studies of clusters, near and far
  - Orion, nearby clusters, W5, Cyg-X, …
- Taurus Legacy project
  - Nearly complete survey of Taurus
- Cores to Disks (c2d) Legacy Project
  - Surveys of 7 nearby "large" clouds and many small ones
  - Complementary molecular line and dust continuum maps
- Gould Belt Legacy Project
  - Surveys of 12 nearby "large" clouds to complete census

GLIMPSE: The Big Picture



Blue is 3.6 microns, green is 4.5 microns, red is 8 microns

MIPSGAL+GLIMPSE



Blue is 3.6, green is 8 microns, and red is 24 microns

Bubbles, EGOs, and Reds

G28.83-0.25 (N49)
8(R), 4.5(G), 3.6(B) μm

D=5.7±0.6 kpc

$N_{UV} \geq 7.8 \times 10^{48}$ s^{-1}

=>O6V or hotter

Diam~5 pc

1. Bubbles all over plane, esp. seen at 8 microns.
2. Extended Green Objects (EGOs): 300 cataloged
3. Warm dust inside bubbles
4. Embedded Red Sources

E. Churchwell: GLIMPSE+MIPSGAL

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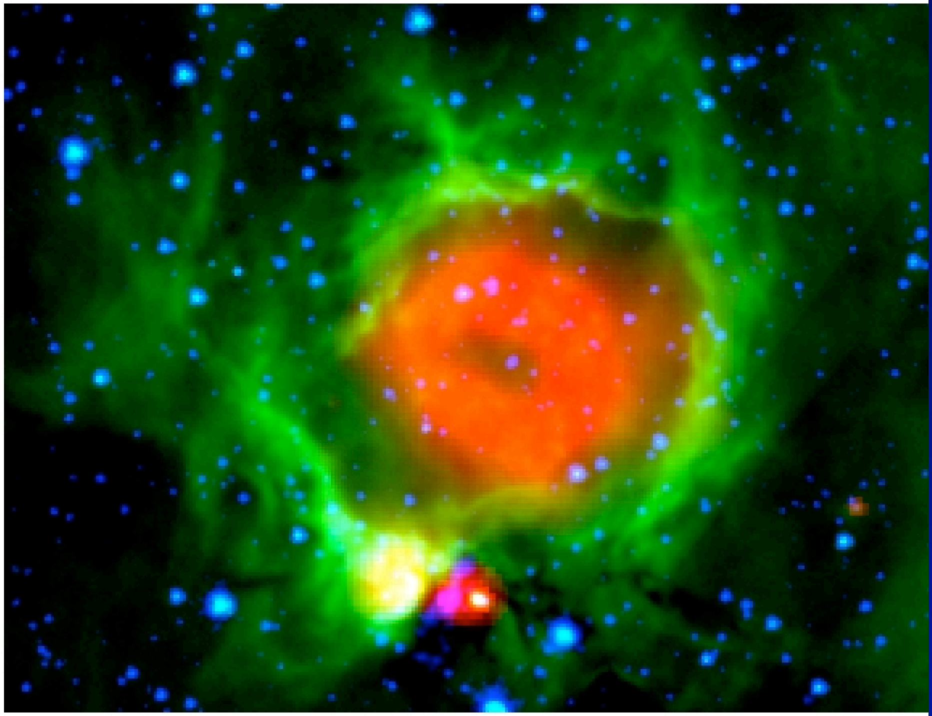

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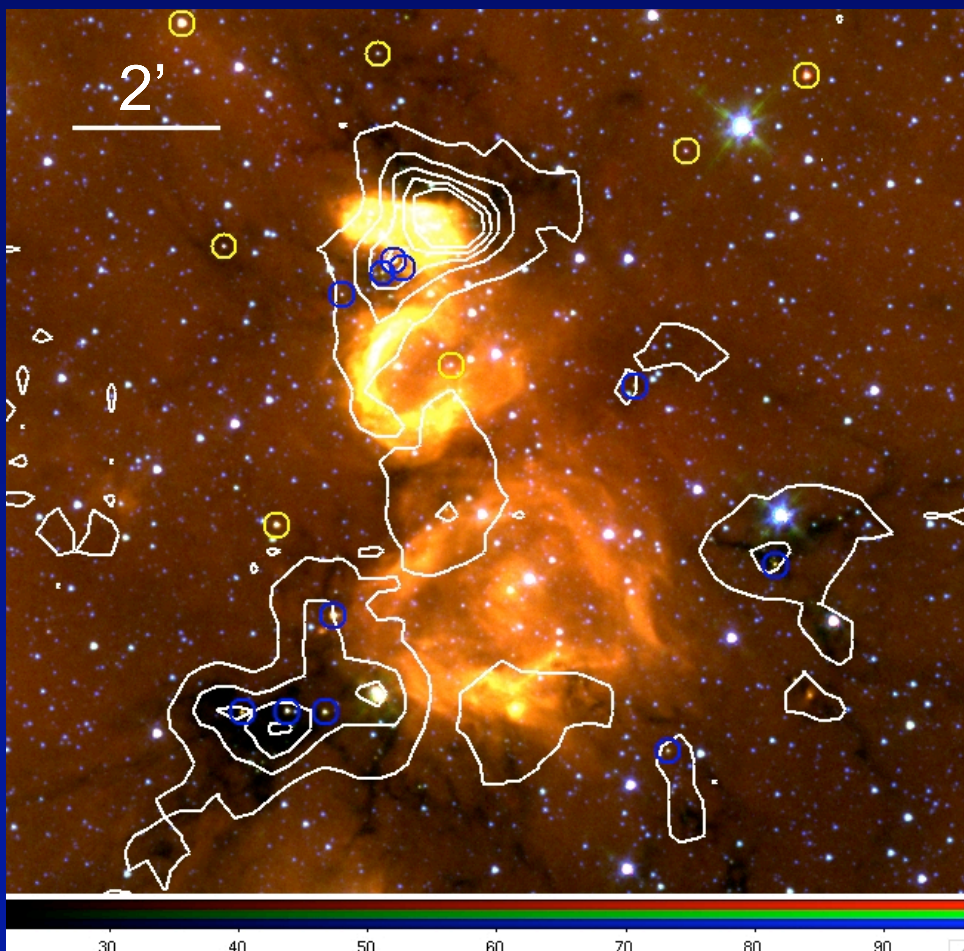
E. Churchwell: GLIMPSE+MIPSGAL

Red Sources and Dense Clumps



M. K. Dunham and T. Robitaille, in prep.

GLIMPSE:
Blue (3.6 μm),
Green (5.8 μm),
Red (8 μm)

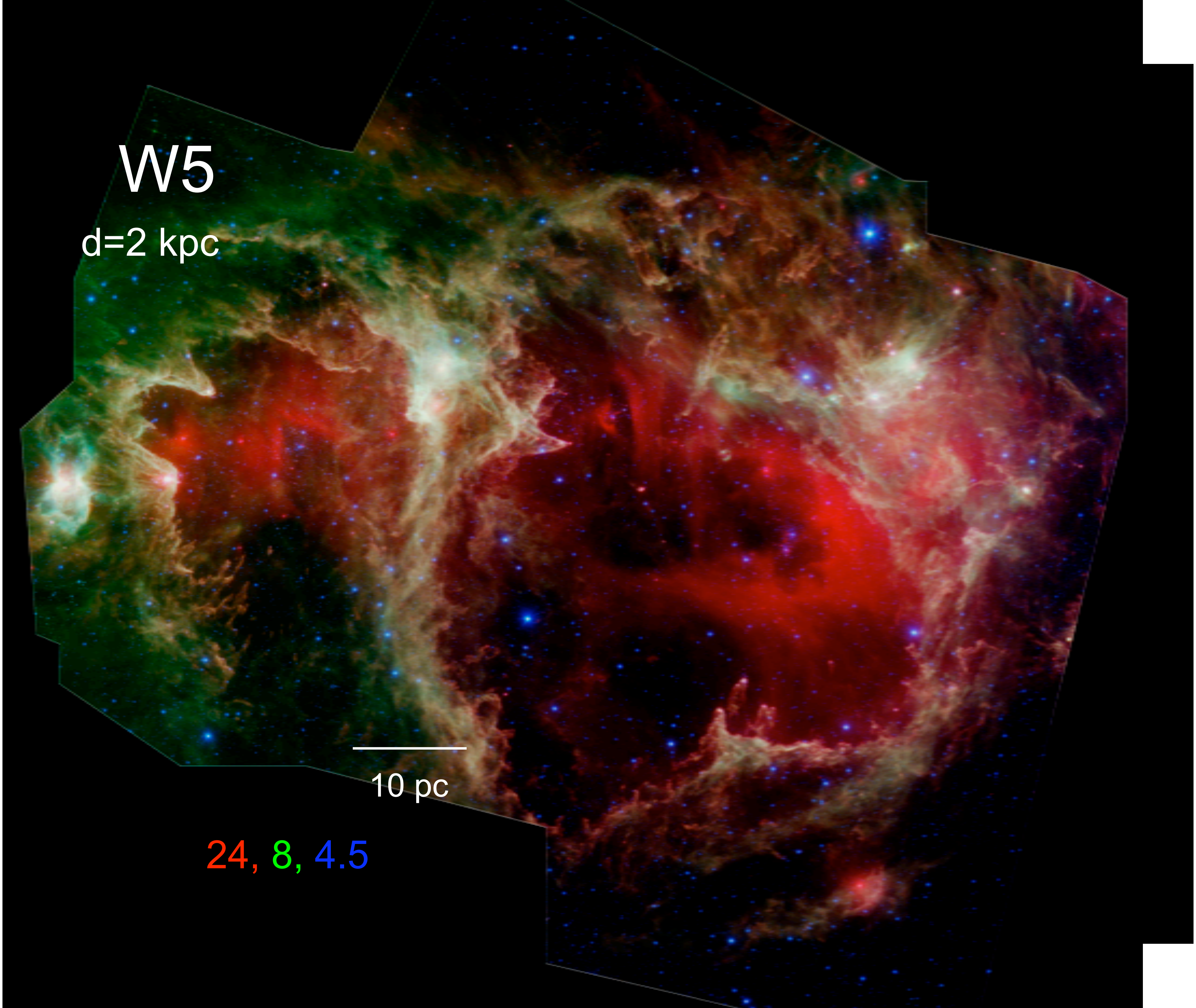
Bolocam Galactic Plane Survey (BGPS) of 1mm continuum (Contours)

Blue circles: Red sources associated with BGPS sources

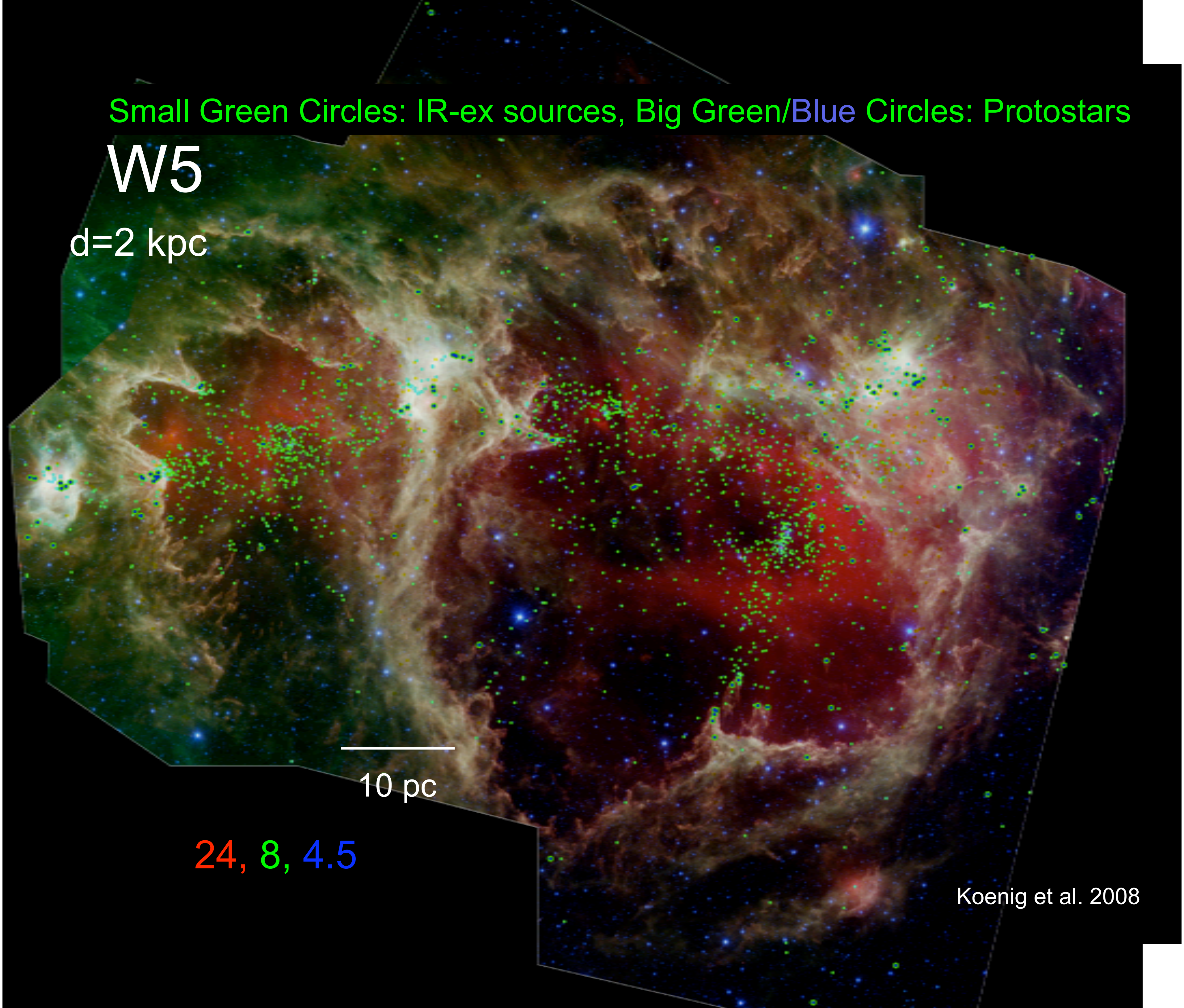
Yellow: not associated

GTO and GO Studies of Clusters

- **GTO Clusters (P. Myers)**
- **Cep OB3, Mon R2 (R. Gutermuth, J. Pipher)**
- **W5 (X. Koenig, L. Allen)**
- **Orion (T. Megeath)**
- **Bright Rimmed Clouds (L. Allen)**



W5
d=2 kpc
10 pc
24, 8, 4.5


Small Green Circles: IR-ex sources, Big Green/Blue Circles: Protostars
W5
d=2 kpc
10 pc
24, 8, 4.5
Koenig et al. 2008

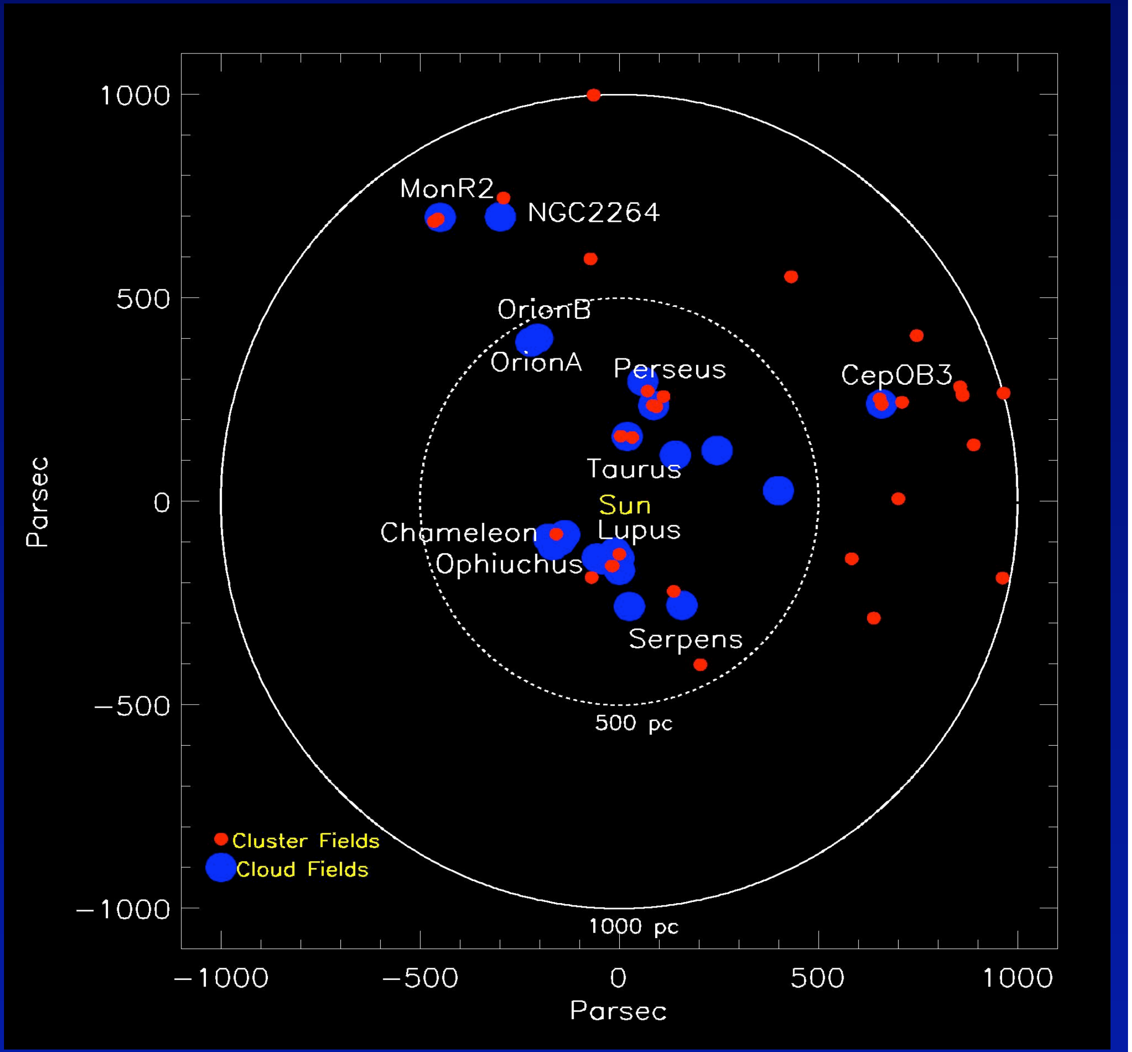
Surveys of Nearby Clouds and Clusters

20 nearby molecular clouds (blue circles)

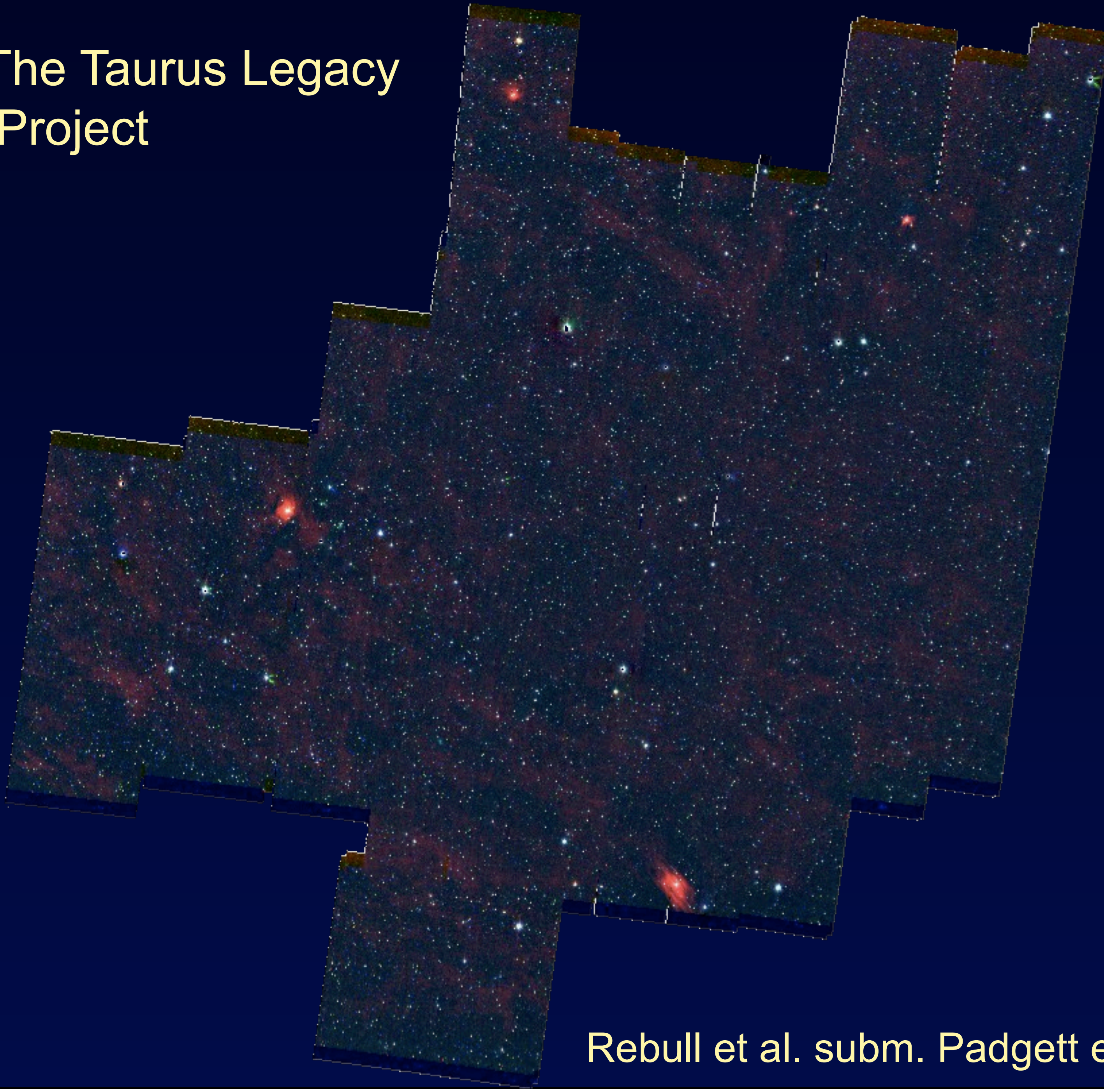
35 young stellar clusters (red circles)

90% of known stellar groups and clusters *within 1 kpc* (complete to ~ 0.1 M_{Sun})

+ Several massive sf complexes at 2-3 kpc (complete to ~1.0 M_{Sun})



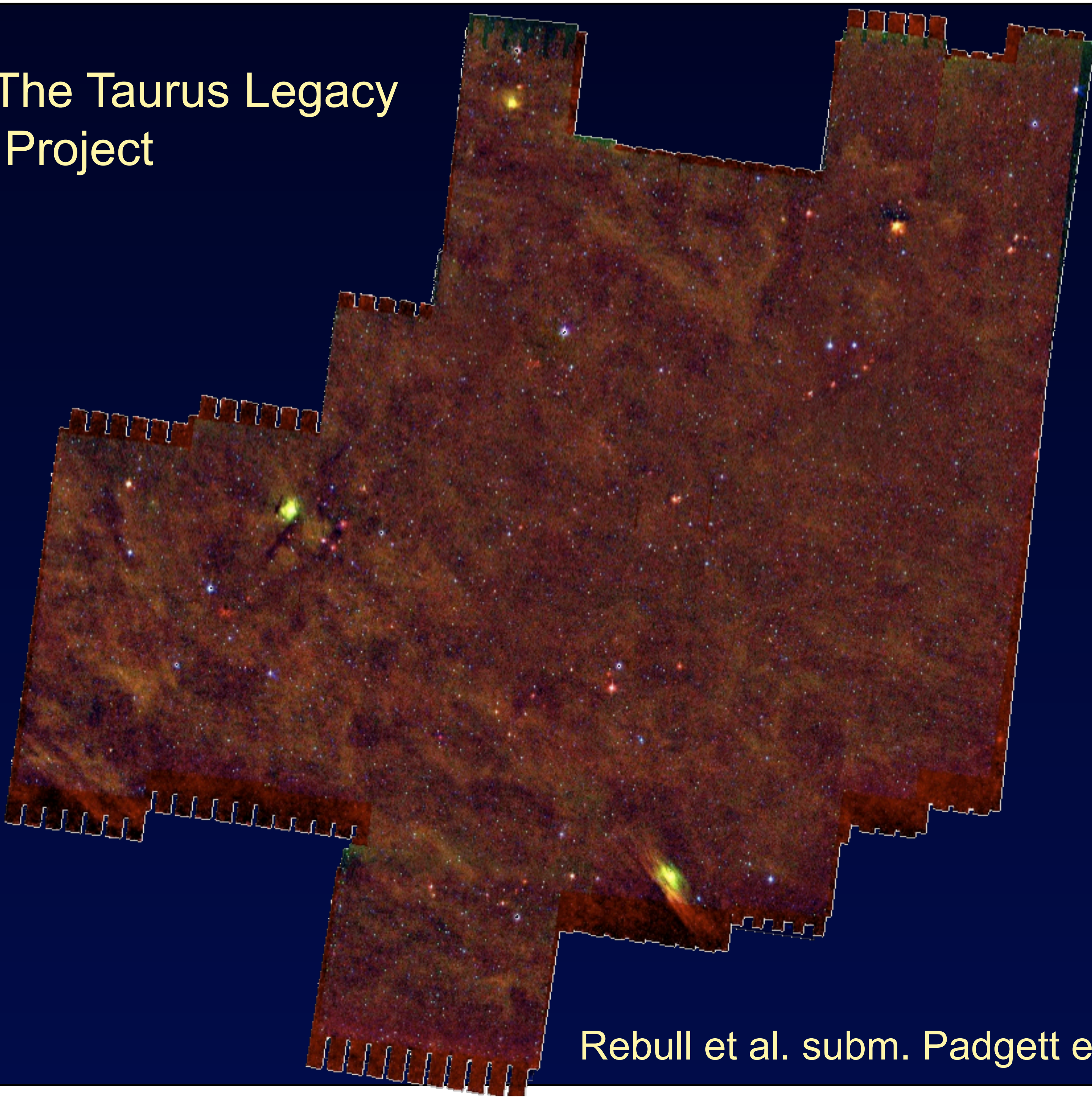
The Taurus Legacy Project



44 sq. deg. IRAC 3.6 (blue), 4.5 (green), and 8 μm (red) image of Taurus

Rebull et al. subm. Padgett et al. in prep

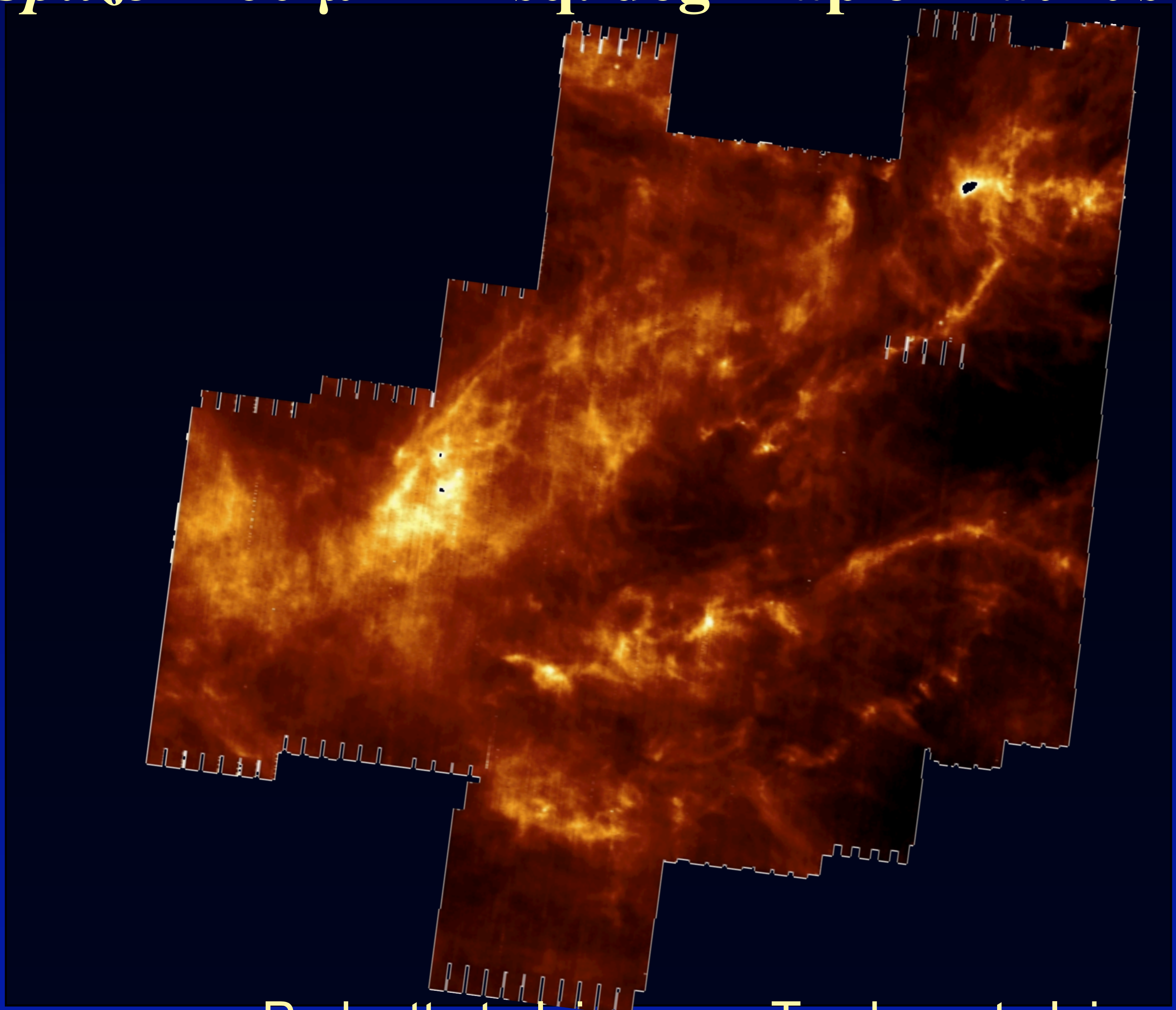
The Taurus Legacy Project



44 sq. deg IRAC 4.5 (blue), 8 (green), and 24 μm (red) image of Taurus Spitzer survey

Rebull et al. subm. Padgett et al. in prep

Spitzer 160 µm 44 sq. deg Map of Taurus



Padgett et al. in prep., Terebey et al. in prep.

New Taurus Objects

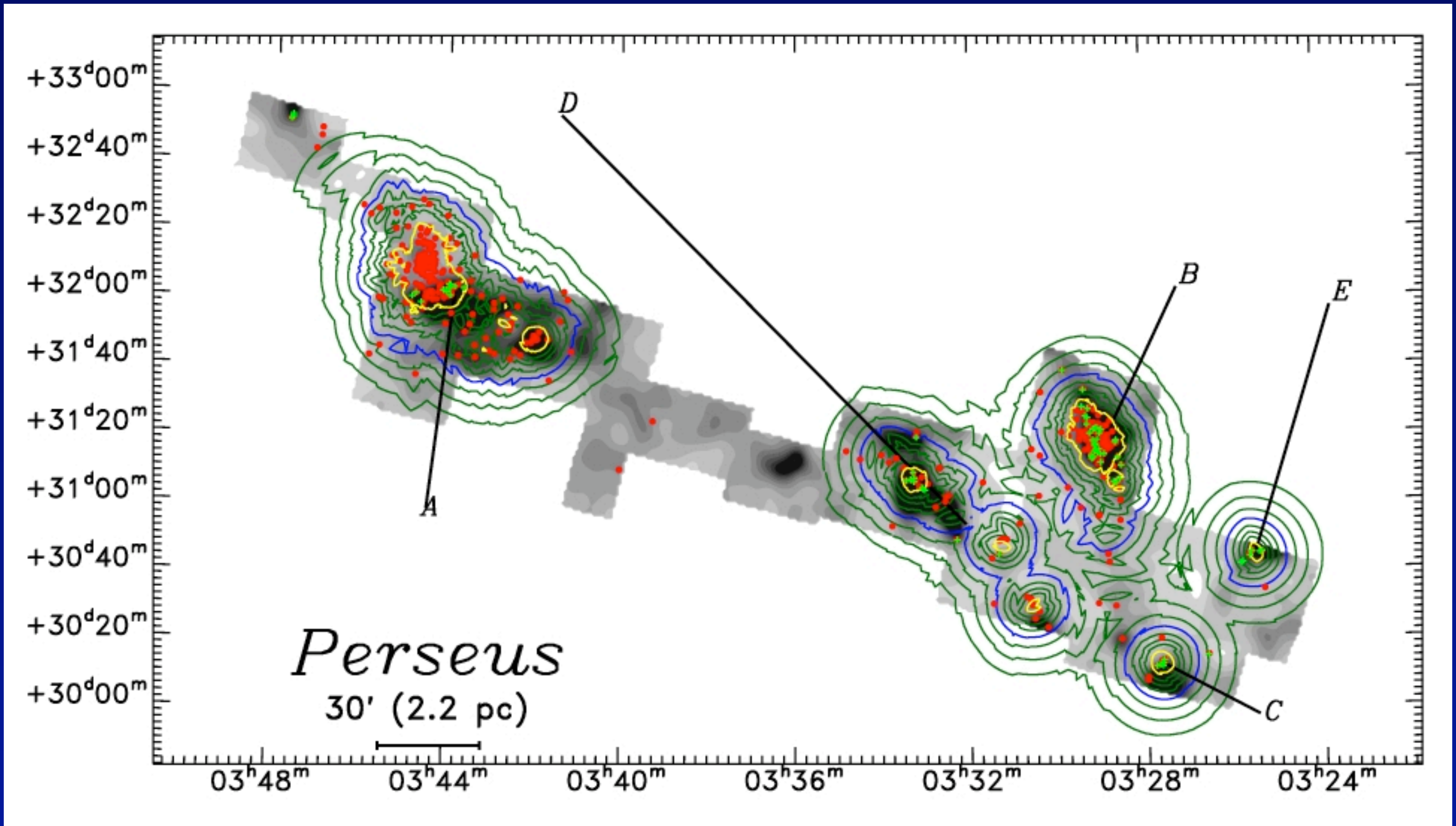
- 148 new potential Taurus members.
- Spectroscopy on about half the sample :
  - 34 new members, +4 probable new members, +9 possible new members = 47 new (with various shades of confidence)
  - 7 extragalactic
  - 1 background Be star(!)
  - 60 stars needing more follow-up, +33 needing any follow-up
- Increase of ~20% in Taurus membership in our mapped region, and still more could be confirmed.
- Most new members are Class II M stars, in close (projected) proximity to the previously-identified Taurus members.
- Also found planetary nebulae, background giants, carbon stars, galaxies, and AGN with colors like YSOs.

Rebull et al. subm.

Star Formation Questions

- Where do stars form in large molecular clouds?
- What determines the IMF?
- How long do various stages of the process take?
- Do any theories explain the data?
- How efficient is star formation?
- Do exgal prescriptions work on small scale?
- The key is to have a large, uniform sample
  - Survey large, nearby clouds with Spitzer
    - c2d+Gould Belt (19 clouds with identical procedures)
  - Taurus, nearby clusters (not identical)

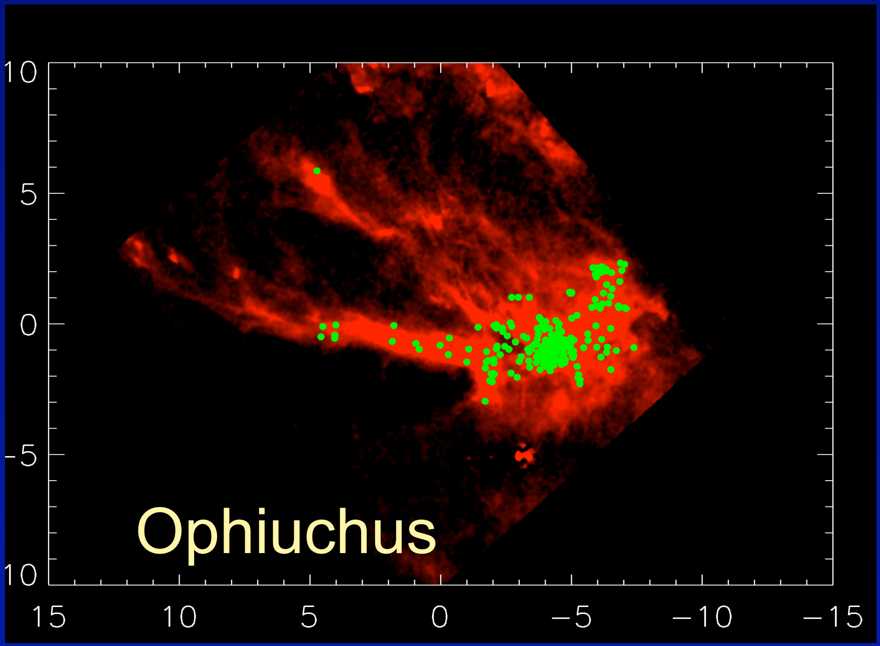
Where do Stars Form?

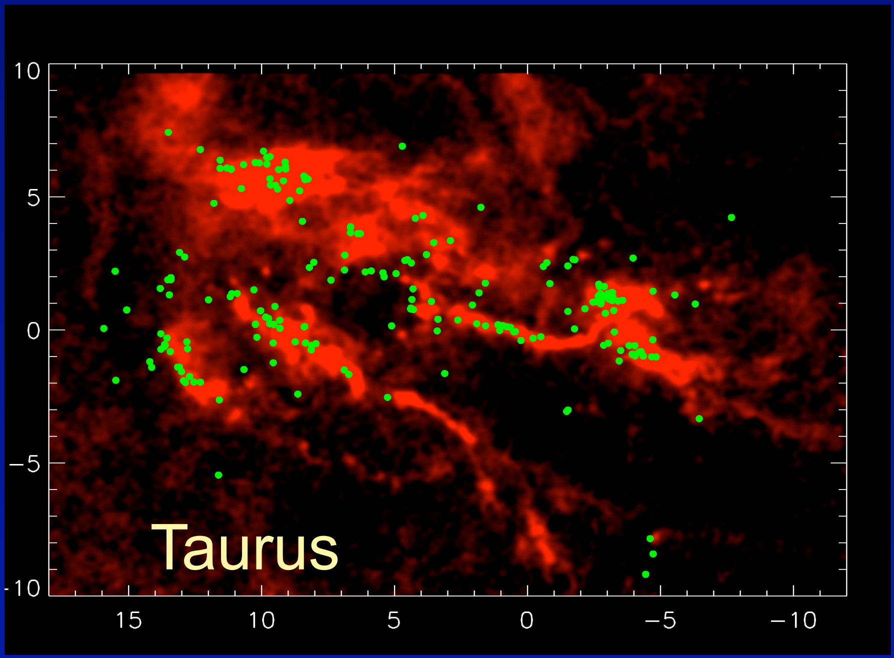


Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

Degree of Clustering Varies

T. Megeath et al. in prep.





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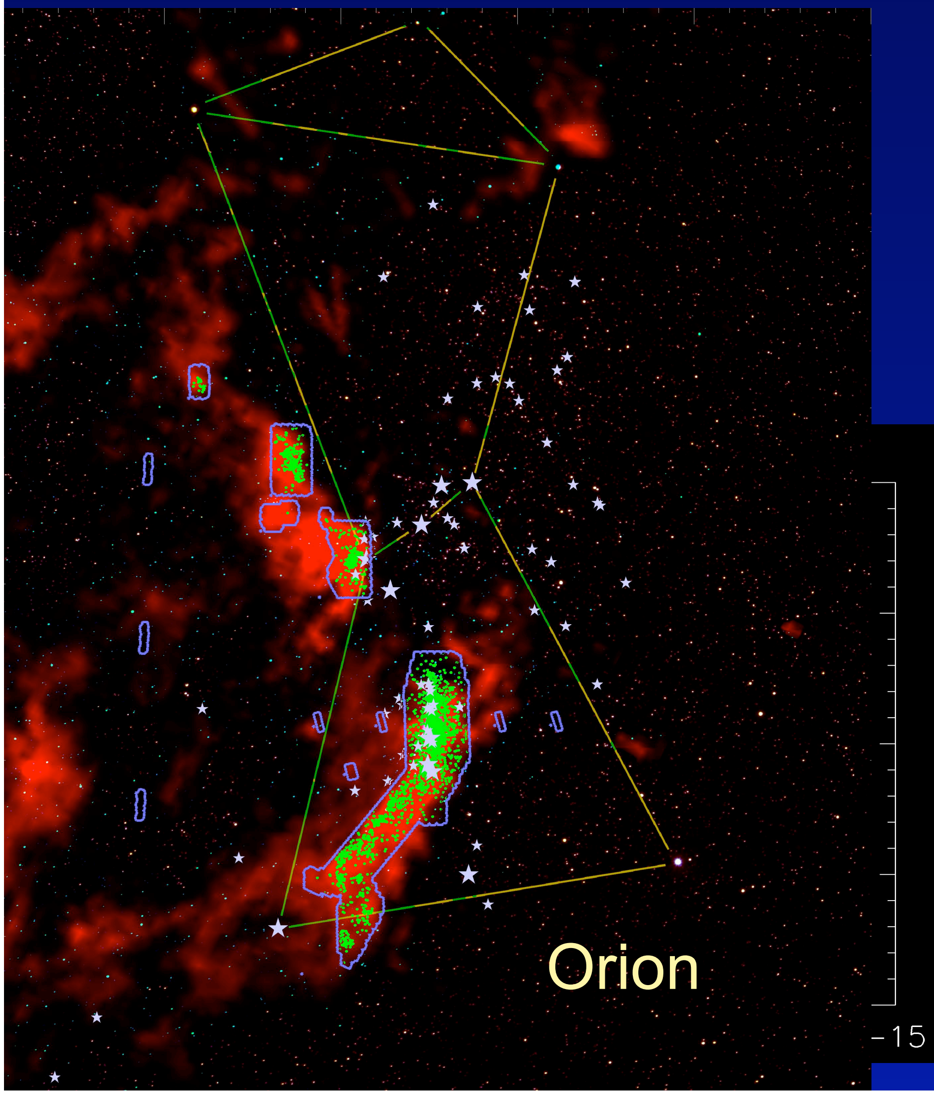
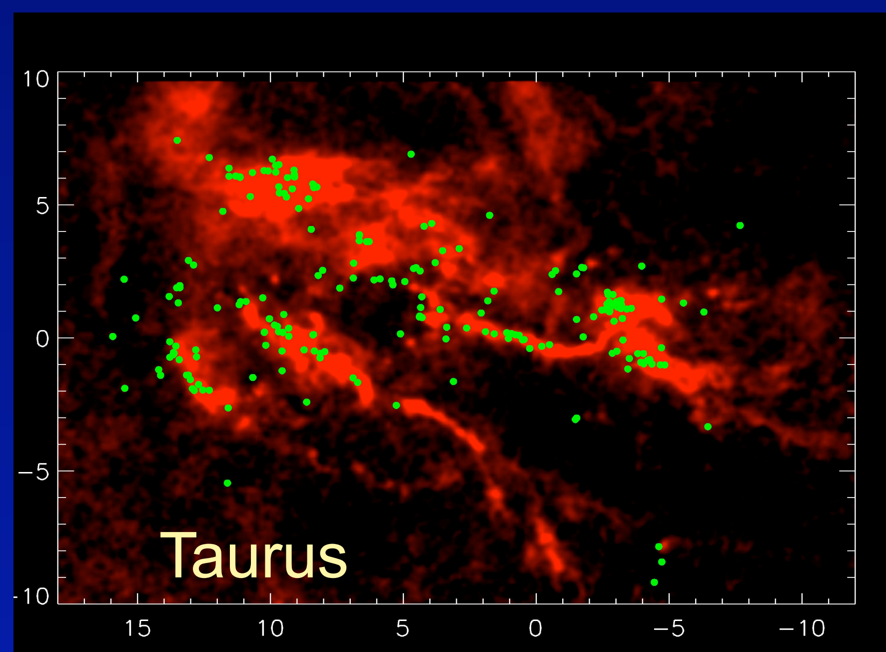
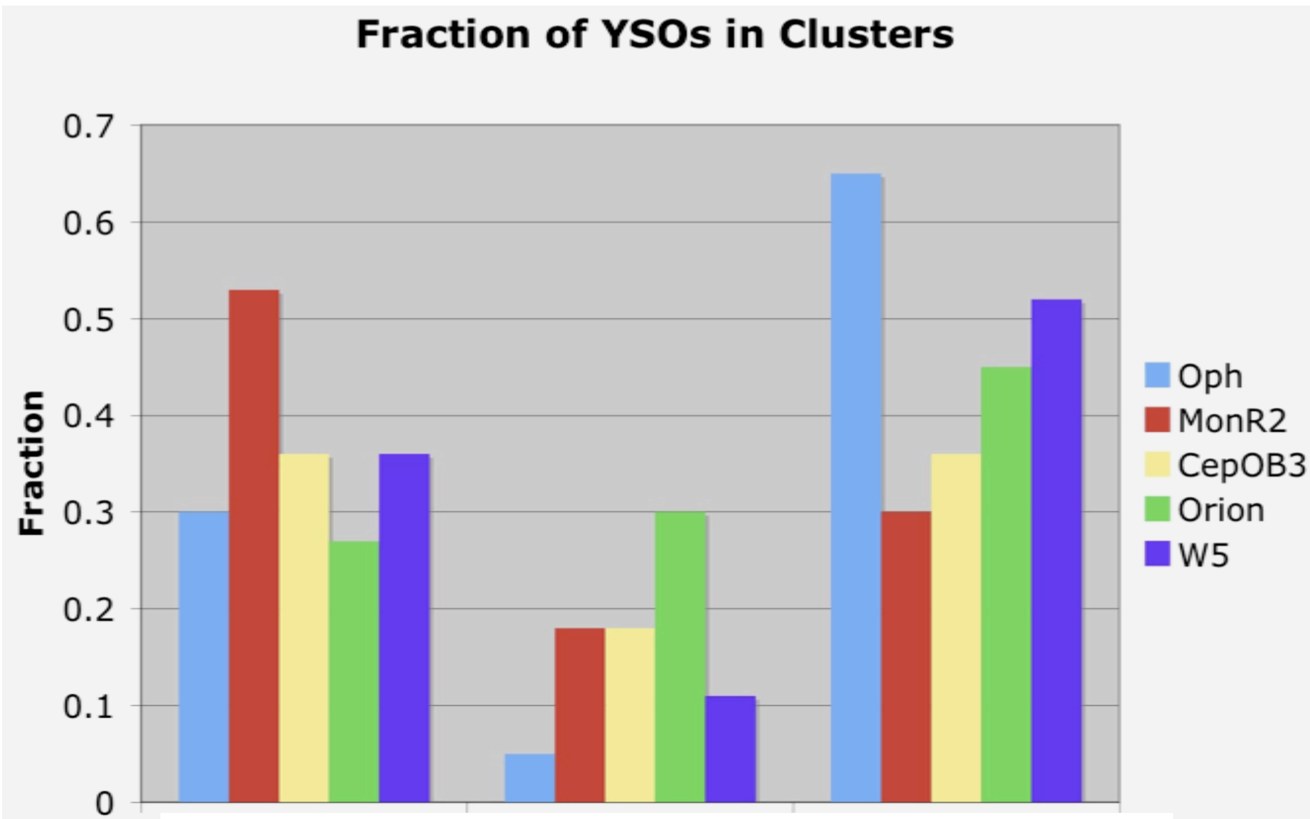




YSOs, Dense Cores are Clustered

- Only 9% of YSOs in c2d outside contour of 1 M_{sun} pc^{-3}
- Distributed YSOs are more evolved
- Distributed population could come from dispersed clusters [t_{cross} ~ t(ClassII) ~ 2 Myr]
- Densities of YSOs are high in clusters
  - But < 0.1 that in Orion, …
- Dense cores are even more clustered than YSOs

About Half are in Large Clusters



N<10	10<N<100	N>100
33%	19%	48%

L. Allen

The Initial Mass Function

- Distribution of Stars over mass
  - The “Initial Mass Function” (IMF)
  - For high masses, $dN/dM \sim M^{-2.4}$
  - Flattens and rolls over below 1 M_{sun}
- We can constrain Core Mass Function
  - 3 Clouds with Bolocam maps
  - Starless cores only
  - Masses from 1 mm dust
  - Absolute uncertainties substantial
  - But shape is not as sensitive

Combined starless core mass distribution

Masses:

$T_D = 10K$

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

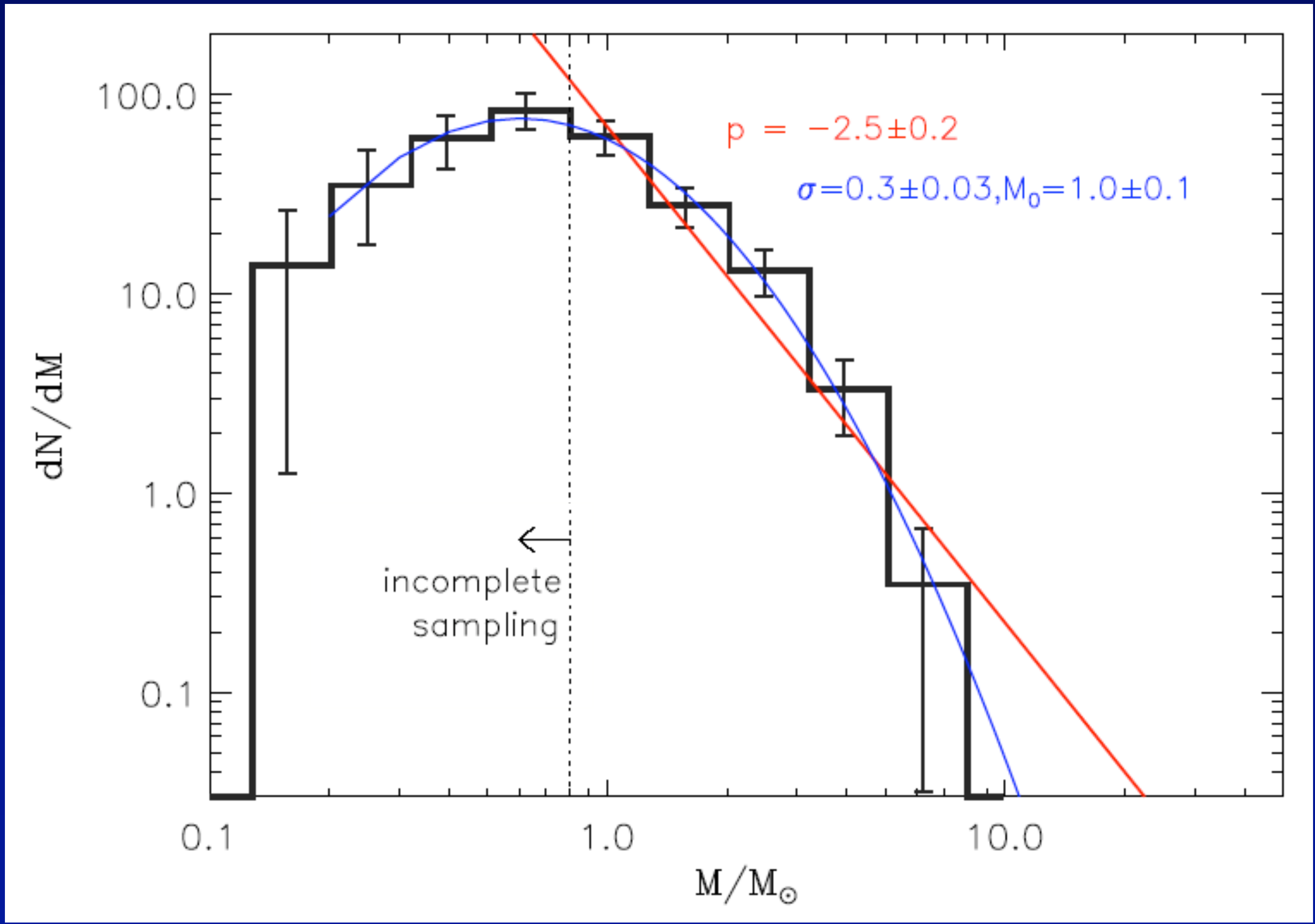
- Best fit power law: p ~ 2.5 or Lognormal

- 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. If so, >25% goes into star.

Enoch et al. 2008

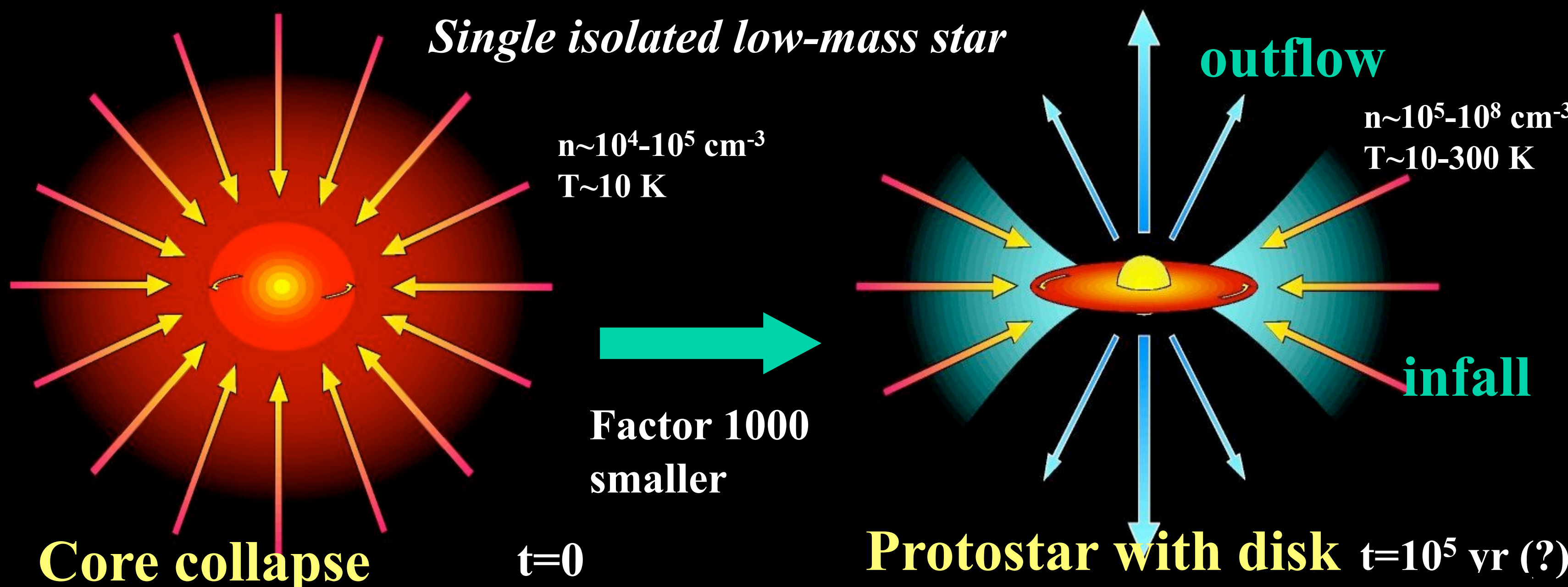
Evolution

- Various Stages in the evolution
  - Associated with Classes based on SED
- Durations in Classes inferred from numbers
- Previous studies based on small numbers
  - Typically 50 to 100 objects

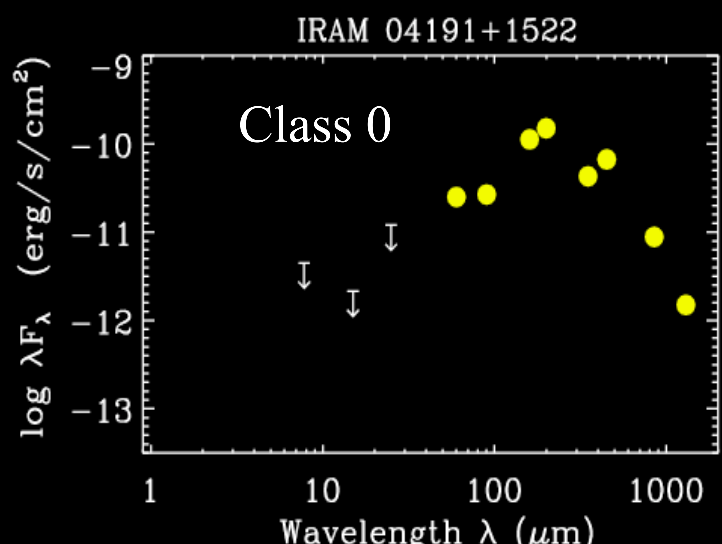
Standard Evolutionary Scenario

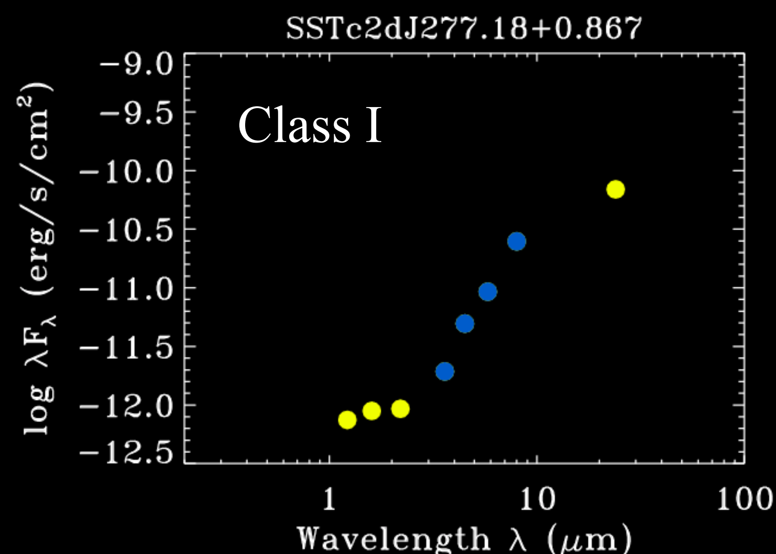
Single isolated low-mass star

Stages



Classes



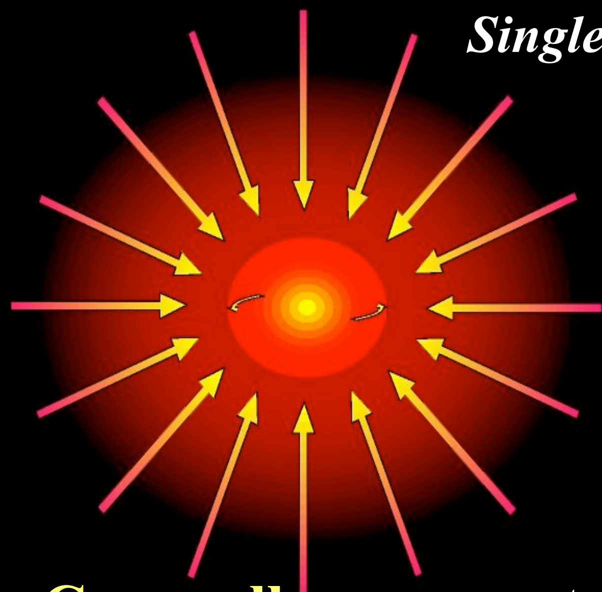


Note axis change!

Standard Evolutionary Scenario

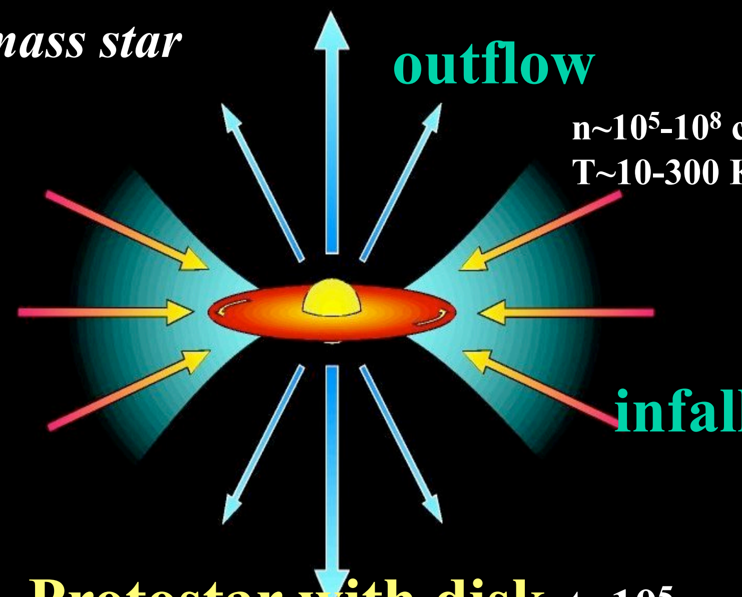
Single isolated low-mass star

Stages



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

Factor 1000 smaller

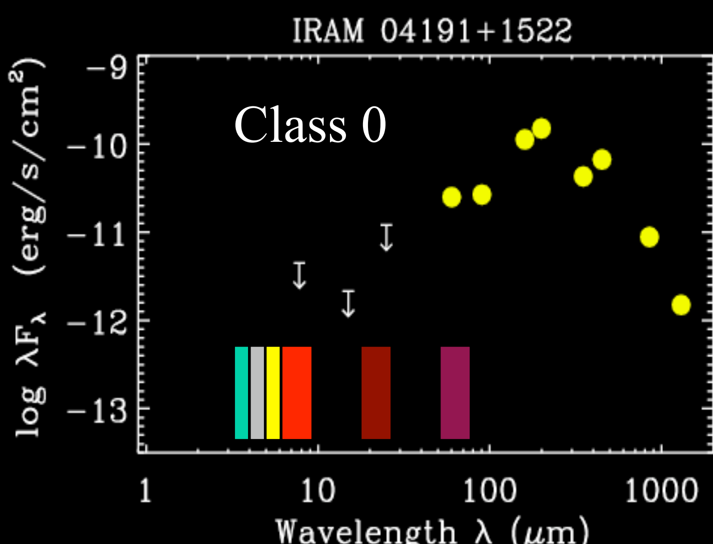


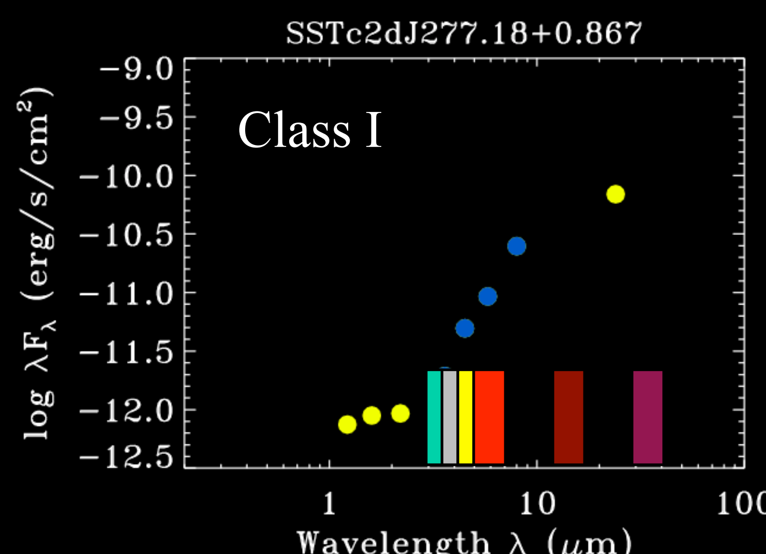
n~10^5-10^8 cm^{-3}
T~10-300 K

Core collapse t=0

Protostar with disk t=10^5 yr (?)

Classes





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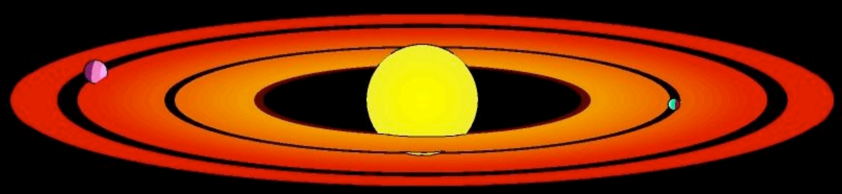
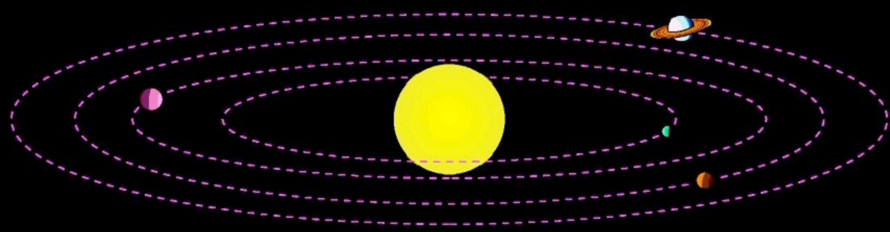
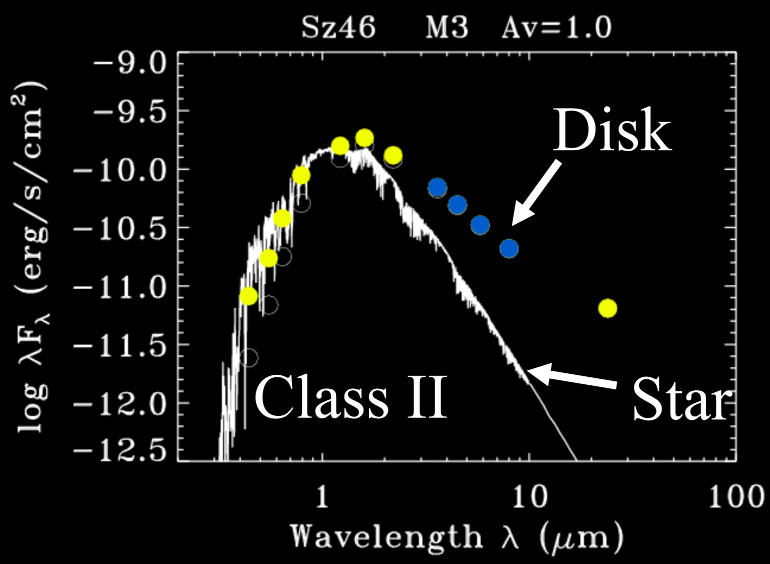
Scenario for star- and planet formation

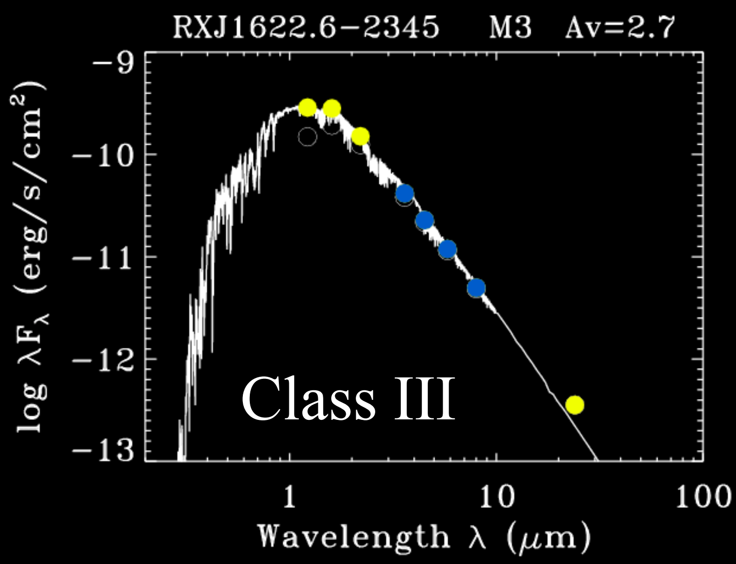




Formation planets $t=10^6$-10^7 yr

Solar system $t>10^8$ yr (?)





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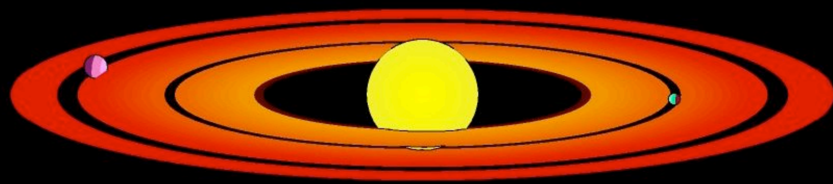

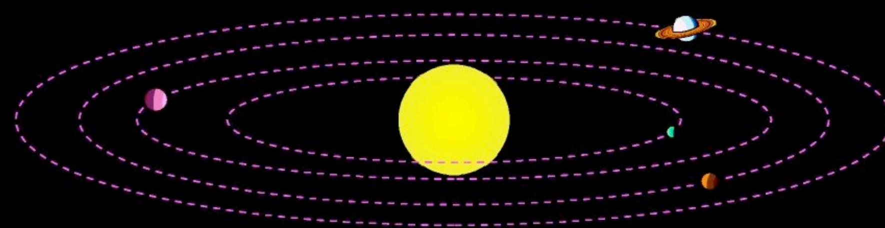

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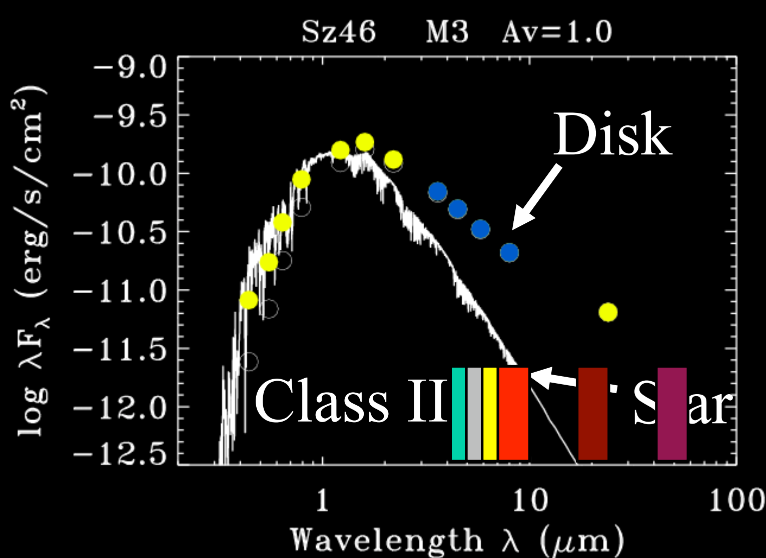
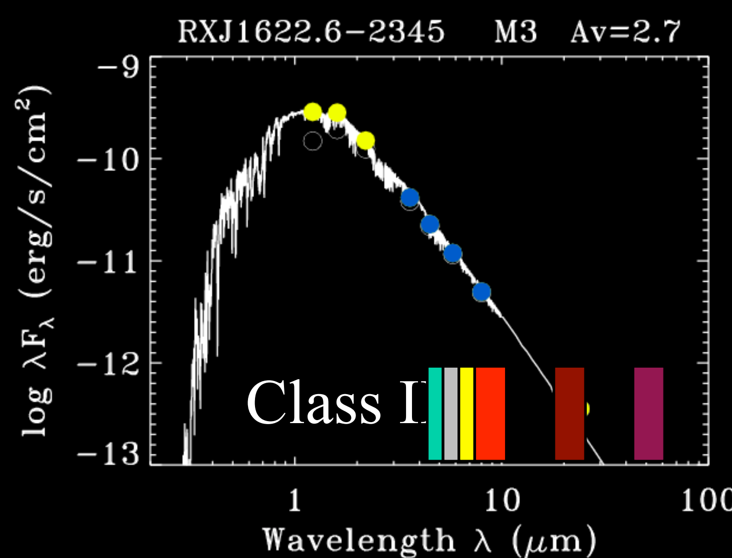
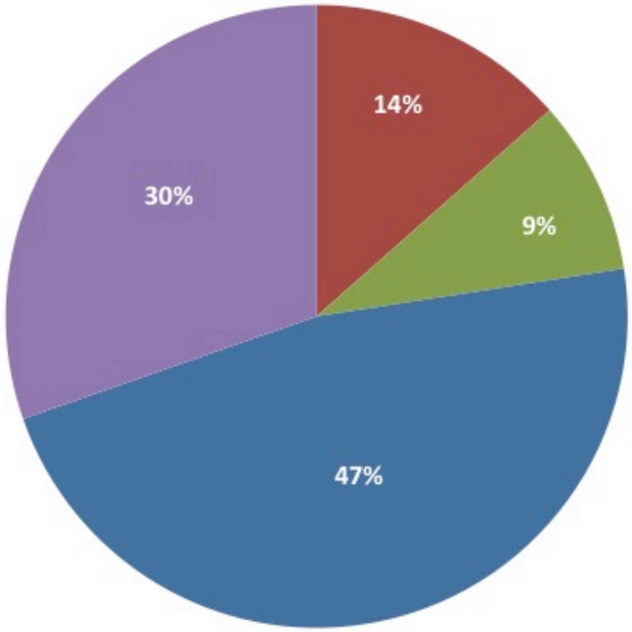




Previous Work

- 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)
  - t(0) ~ 0.01 Myr (Andre, Oph) Rapid early accretion
  - Or t(0) ~ 0.1 Myr (Visser, larger sample)
  - Issues
    - Small number statistics!
    - Differences between clouds!

19 clouds, 3158 YSO



I:	$\alpha \geq 0.3$	14%
Flat:	$-0.3 \leq \alpha < 0.3$	9%
II:	$-1.6 \leq \alpha < -0.3$	47%
III:	$\alpha < -1.6$	30%

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

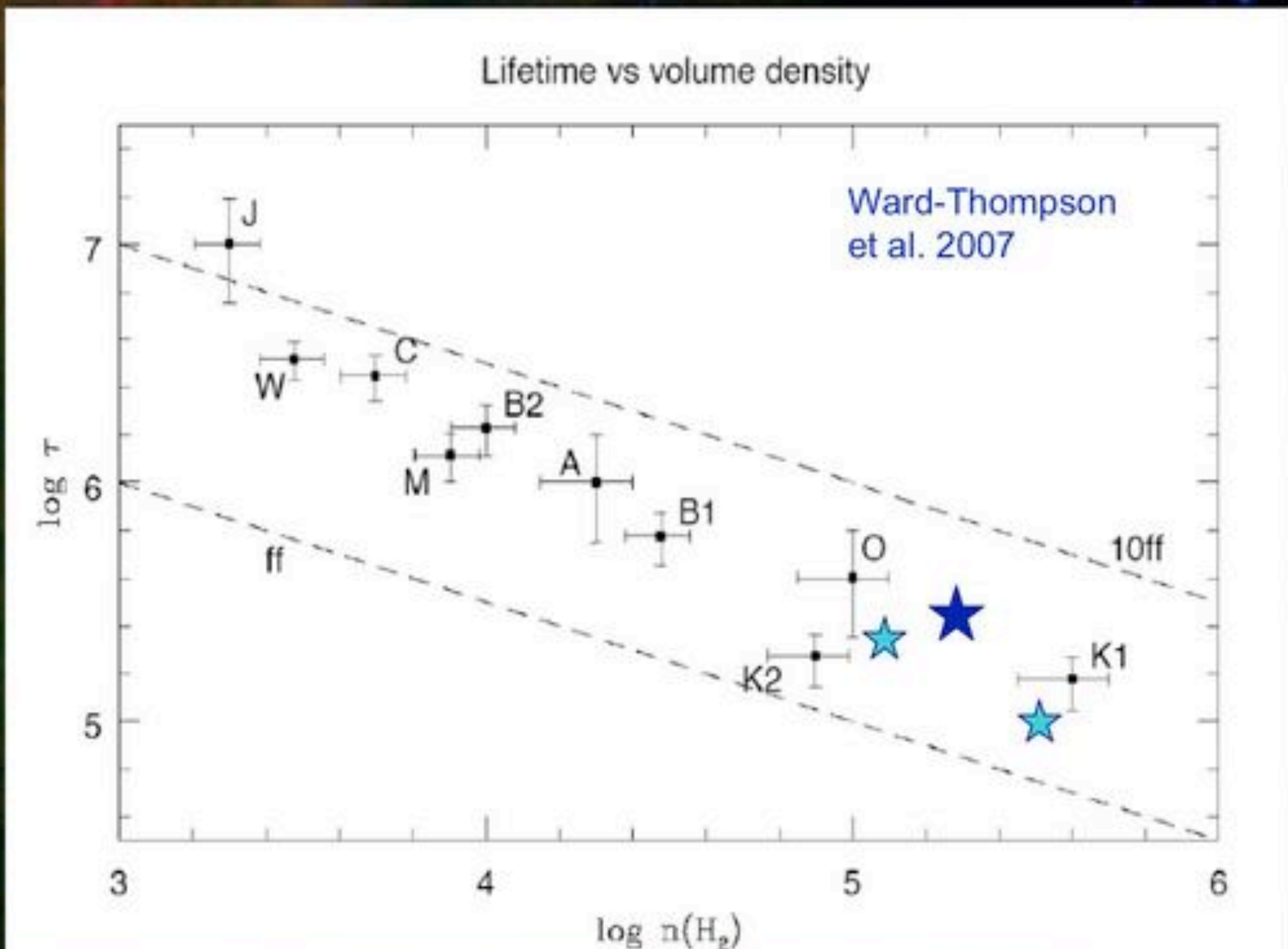
Class I lasts 0.57 Myr
Flat lasts 0.38 Myr
(longer than most previous estimates)

Caveats:
GB clouds extincted
(decrease by ~0.1 Myr)
Class III census incomplete
Class III not included in timescale
Depends on *how* α is calculated
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 say starless
  - 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



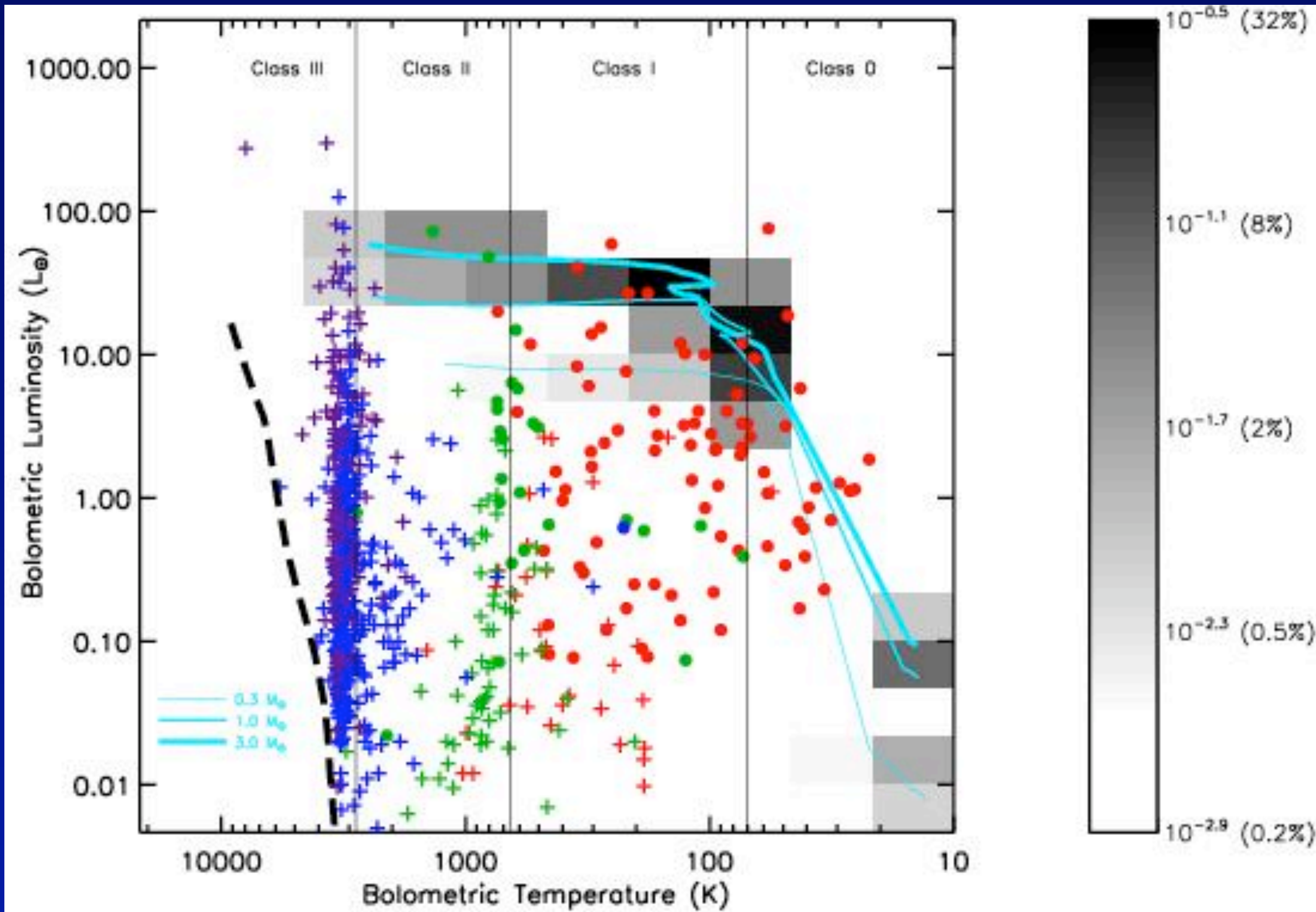
- $n(H_2)$ measured in 10^4 AU aperture
- Estimated τ
  - ⇒ Cores not in free-fall
  - ⇒ Not highly subcritical
- Lifetime decreases at higher densities

Enoch et al. 2008

Comparison to Shu model

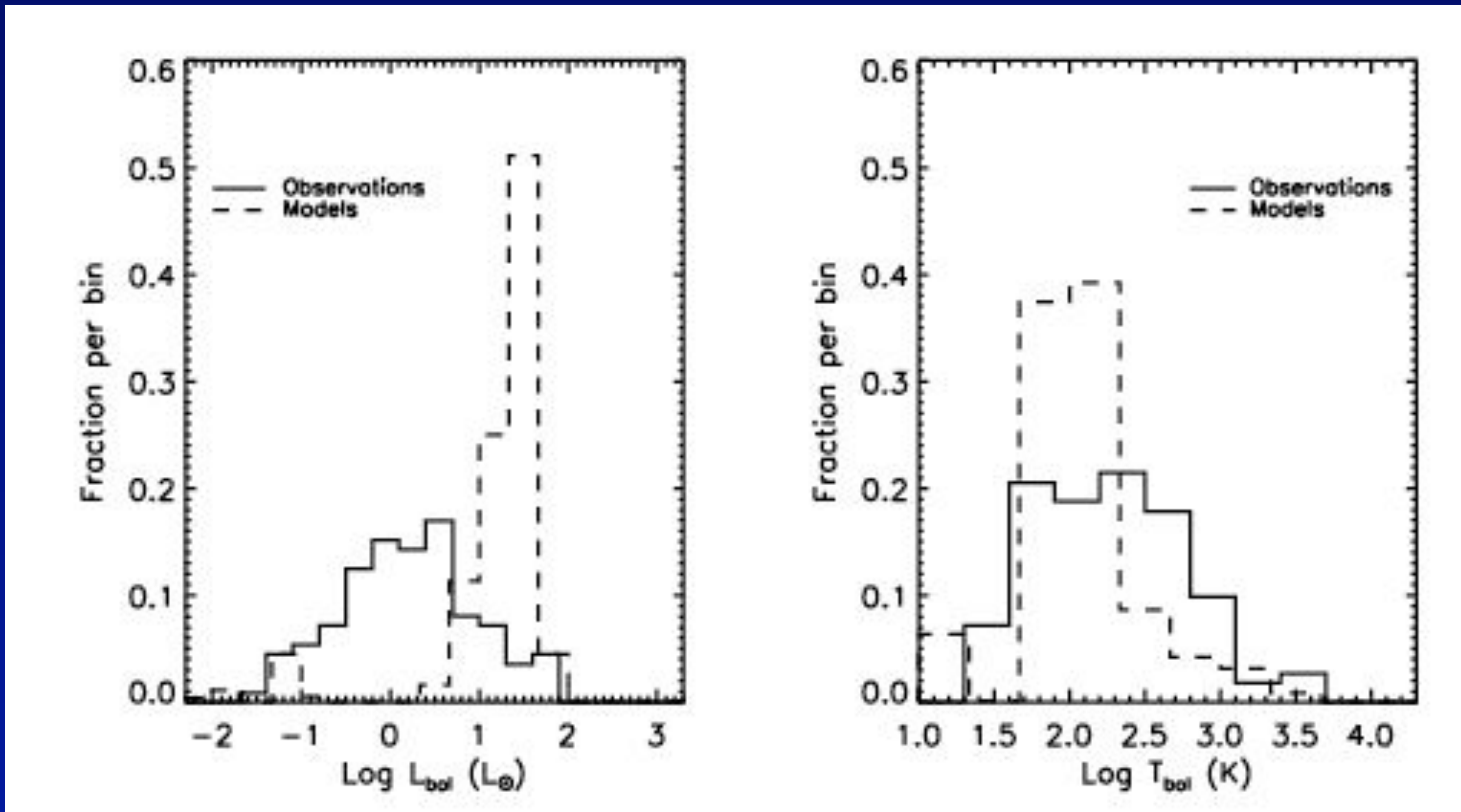
- Assume inside-out collapse at 0.19 km/s
  - Sound speed at 10 K
- In 0.57/2 Myr, $r_{inf} = 0.057$ pc
  - Consistent with some sizes
  - Mean separation in clusters 0.072 pc (Gutermuth)
- At $dM/dt = 1.6 \times 10^{-6}\ M_{sun}/yr$, $M_* \sim f\ 0.90\ M_{sun}$
  - If $f \sim 0.3$, get $0.27\ M_{sun}$ ~ modal mass
- Consistent with assumptions, most data
- Picture holds together, except…

The Luminosity Problem!



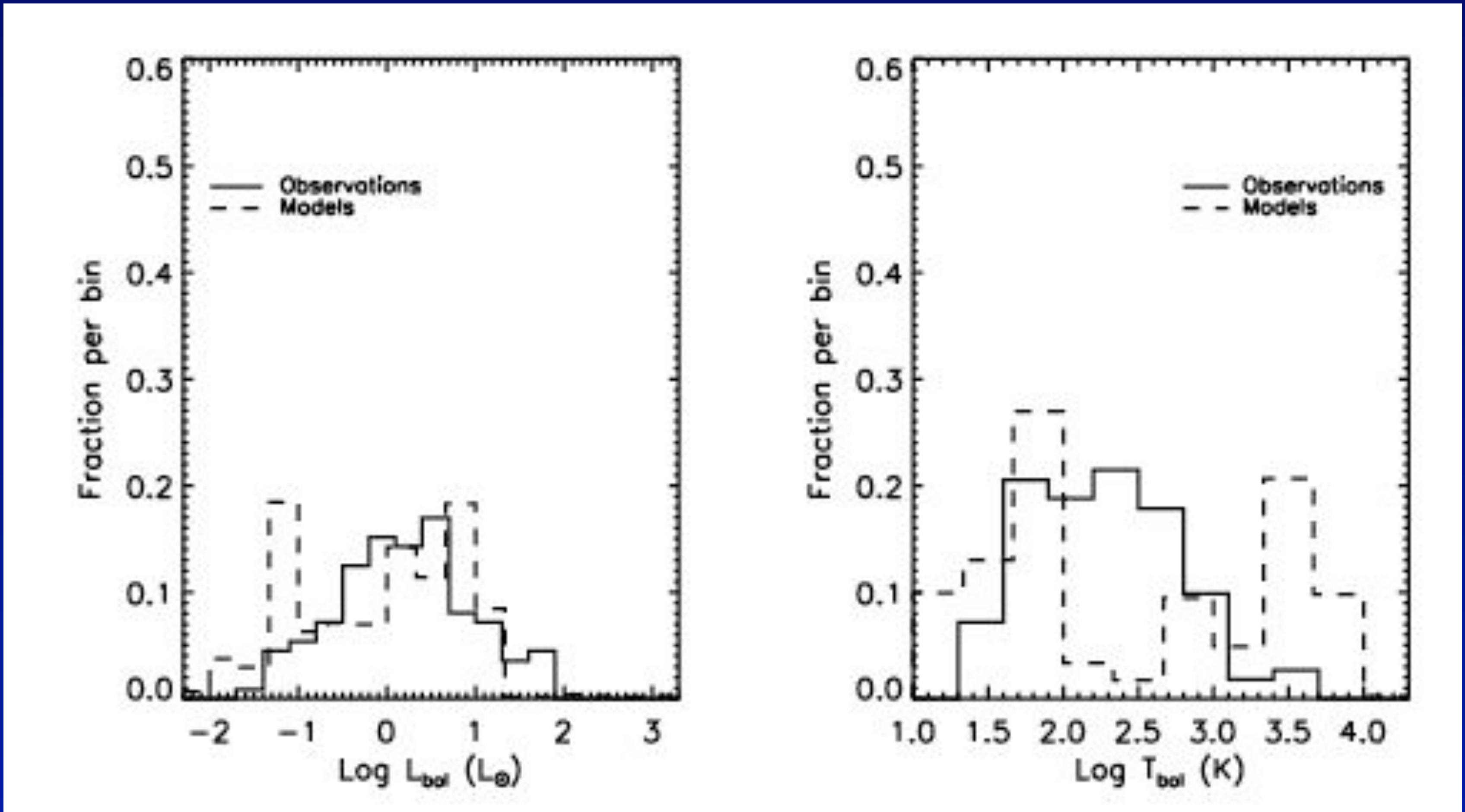
M. M. Dunham et al. in prep.

Many are under-luminous



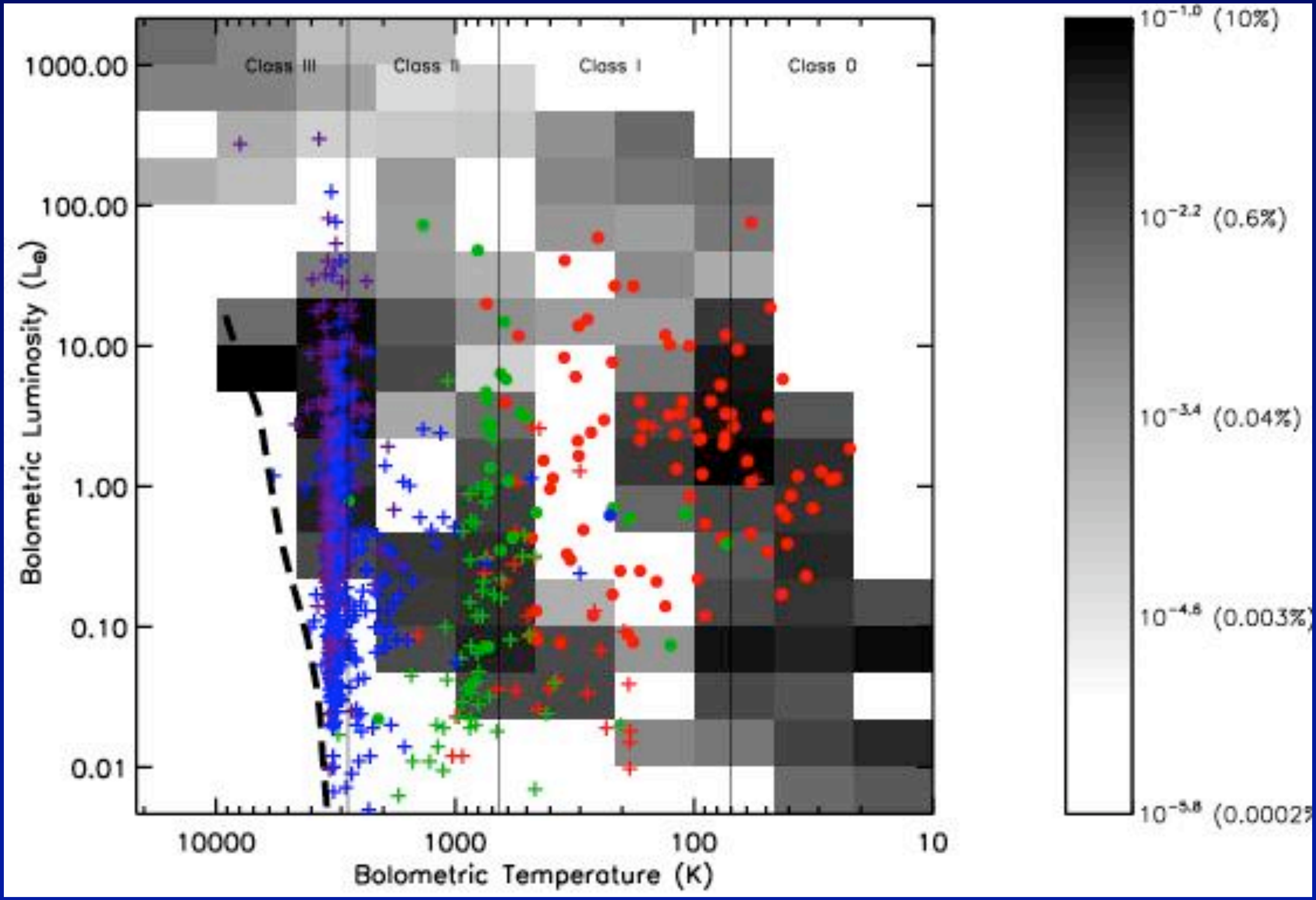
Predicted L = GM(dM/dt)/R= 1.6 L_{sun} for standard (Shu) accretion onto M = 0.08 M_{sun}, R = 3 R_{sun}. Most (59%) are below this. M. M. Dunham et al. in prep

With 2D, Outflows, Episodic Accretion



M. M. Dunham et al. in prep.

and the BLT



M. M. Dunham et al. in prep

Estimating Star Formation Efficiency

- Much more complete sample, uniform analysis
- Complete (90%) down to about 0.05 L_{sun}
- $M_* = N(YSOs)*0.5\ M_{sun}$
  - $SFR = M_*/2$ Myr (largest uncertainty)
- M_{cloud} from extinction of background stars
  - $\Sigma_{gas} = M_{cloud}/Area$
- M_{dense} from dust emission at millimeter
- Caveats
  - Miss more evolved PMS (no significant IR excess)
  - Results apply to last 2 Myr

How "Efficient" is Star Formation?

- Not very for the cloud as a whole
  - 2% to 5% of mass with $A_V > 2$ is in dense cores
    - (Enoch et al. 2007)
  - 3% to 6% is in stars
- Large variations in SF rate
  - Serpens is 360 times more productive than Cha III
  - Normalized to area, Serpens is 100 times Cha III
- Quite efficient in dense gas
  - Current TOTAL M_* similar to M_{dense}
  - Depletion time is 0.6 to 2.9 Myr

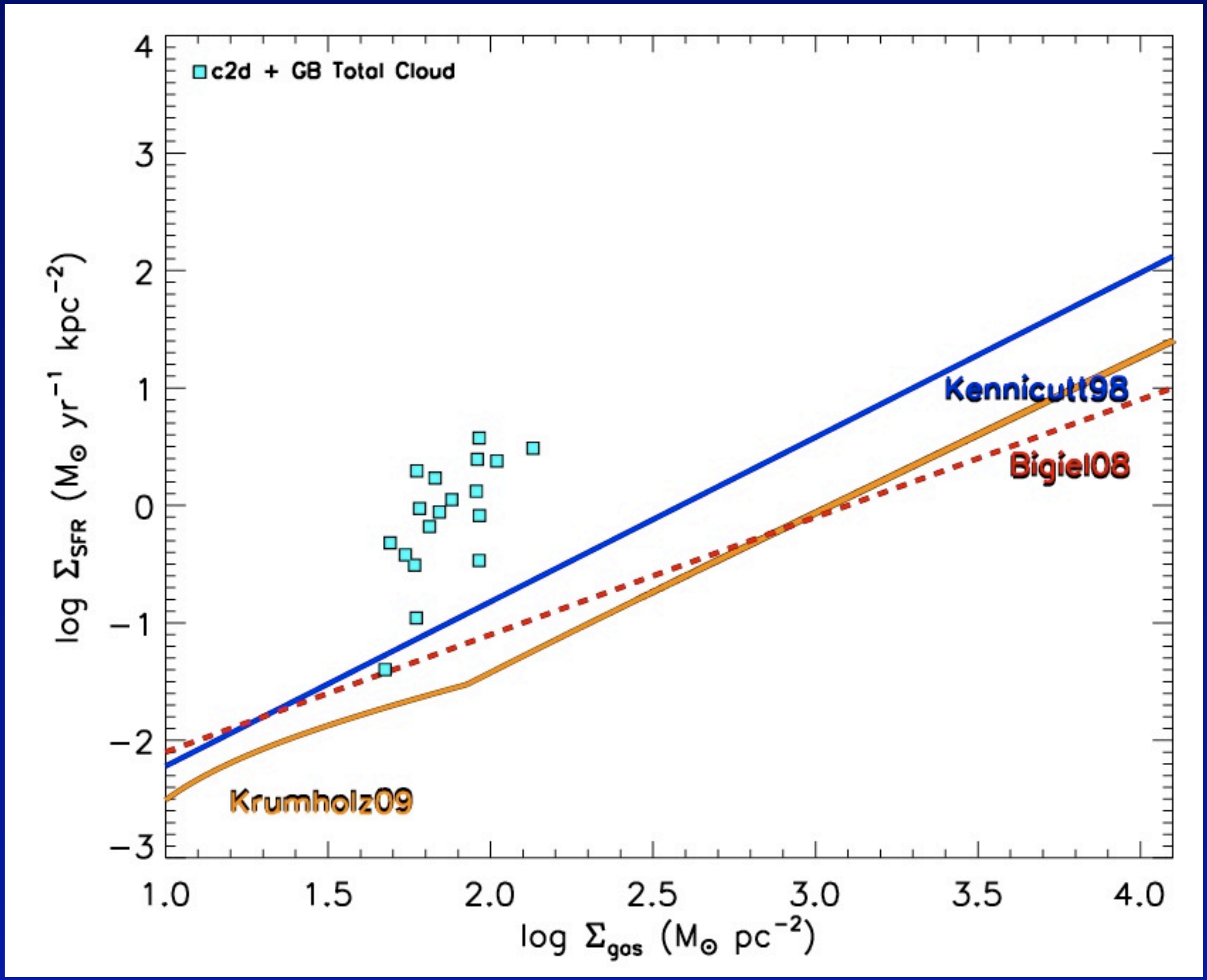
Ex-Gal Star Formation Prescriptions

- **Kennicutt (1998)**
  - $\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 2.5x10^{-4}\ \Sigma^{1.4}{}_{gas}(M_{sun}\ pc^{-2})$
  - $\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 6.3x10^{-3}\ \Sigma^{1.4}{}_{gas}(10\ M_{sun}\ pc^{-2})$
- **Bigiel et al. (2008)**
  - $\Sigma_{SFR}(M_{sun}\ yr^{-1}\ kpc^{-2}) = 7.9x10^{-3}\ \Sigma^{1.0}{}_{mol}(10\ M_{sun}\ pc^{-2})$
- **Krumholz et al. (2009)**
  - $\Sigma_{SFR} = f(\Sigma_{gas}, f(H_2), Z, \text{clumping})$
  - Nearly linear with Σ_{mol} below ~ 100 $M_{sun}\ pc^{-2}$
  - Steepens above 100 $M_{sun}\ pc^{-2}$

Testing Locally

- Observing Clouds in the Milky Way
  - Advantage is good resolution
    - Ability to count stars
    - Not extrapolating from massive stars ($H\alpha$)
  - Disadvantage is good resolution
    - Hard to compare on scales ~ galaxies
    - Progress from large surveys with Spitzer, Herschel, mm telescopes

Averaged Over Whole Clouds



c2d and GB clouds, Heiderman et al. in prep.

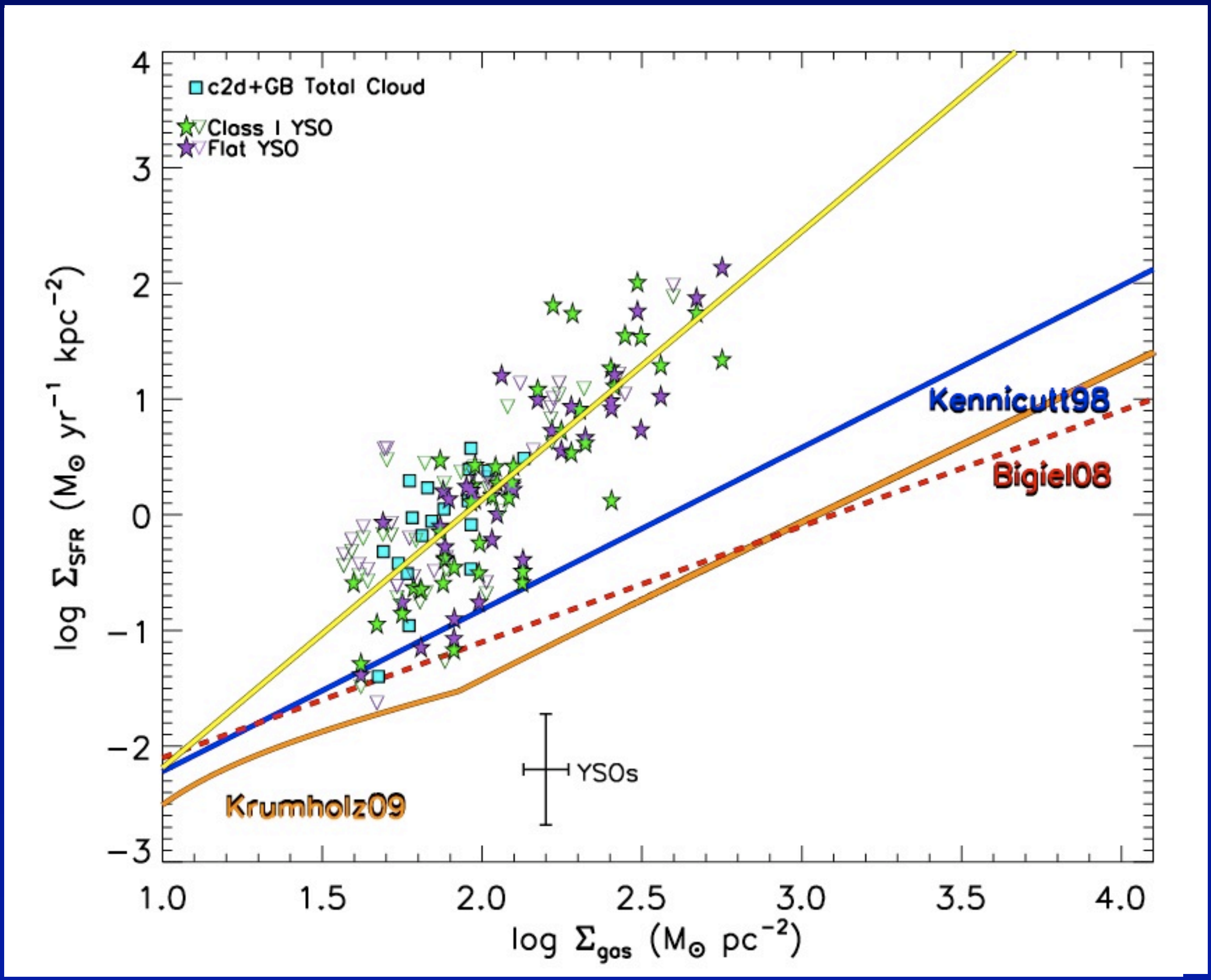
Test on Smaller Scales?

Star formation mostly at high extinction

Cloud average biased toward lower Σ_{gas}

- **Count YSOs in contours of A_V**
- **YSOs can wander out of formation region**
- **Count only Class I, Flat**
  - **Use suitable lifetimes (~0.5 Myr each)**
- **Checking for fakes at low A_V**

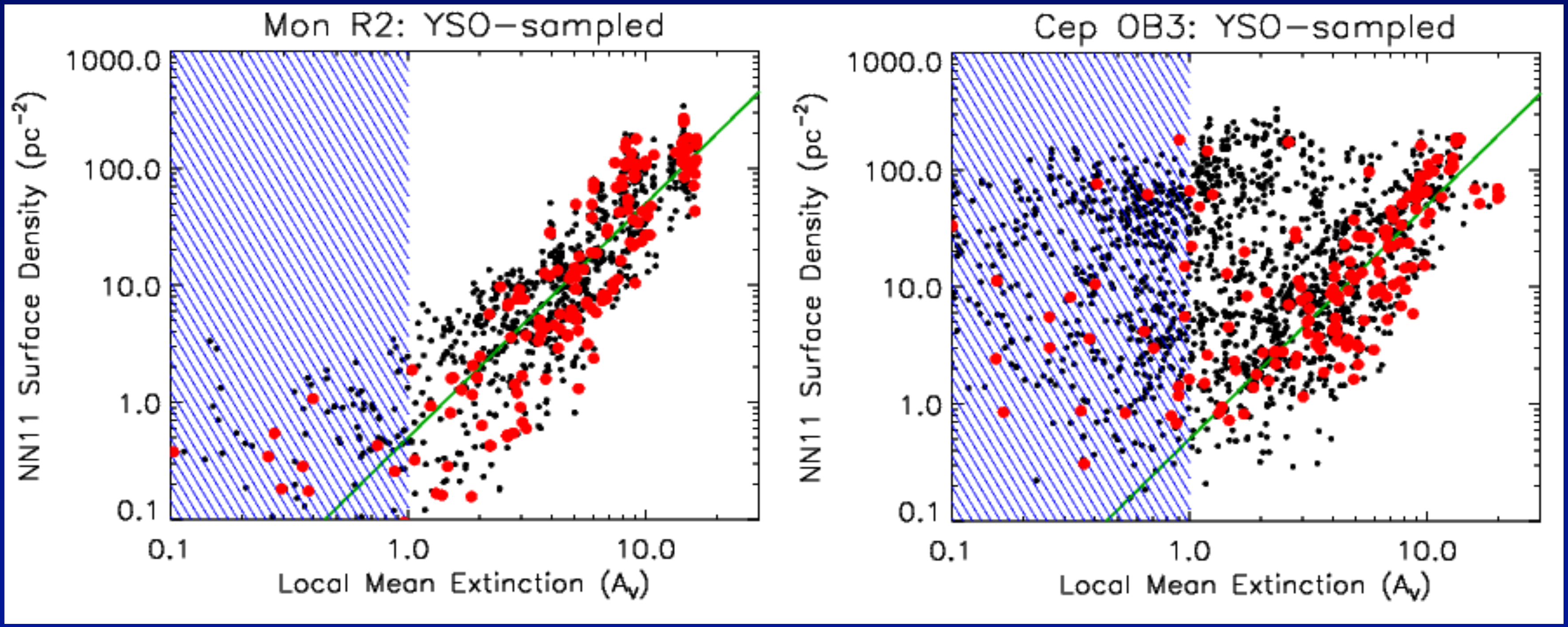
Within Each Cloud



Best fit,
including upper limits:
Slope = 2.3

Heiderman et al. in prep.

Similar Relation in Regions forming High Mass Stars



Green line is Σ(YSOs) ~ Σ^2 (gas) Red points are Class I
(more likely to be in formation region)
Gutermuth et al. in prep.

Lessons from Nearby Clouds

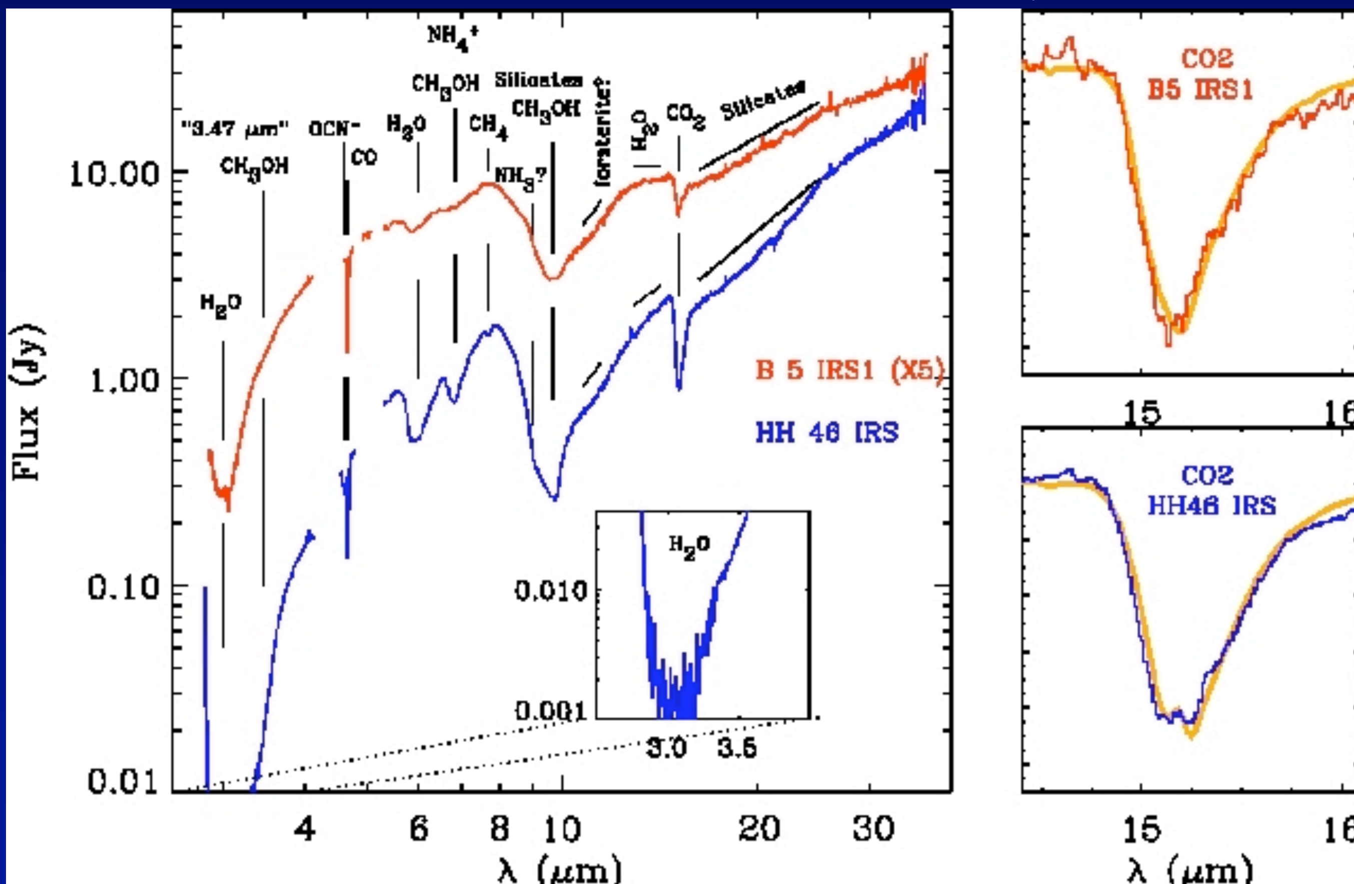
- Σ_{SFR} ~ 10 times prediction of relations for galaxies on average
- Variations from cloud to cloud factor of 100
- These regions are forming only low mass stars
  - Would not even be seen in most exgal SFR tracers
- On scales where SF actually happens…
  - Dependence on S_{mol} may be very strong
- SFR determined on sub-pc scales << exgal resolution

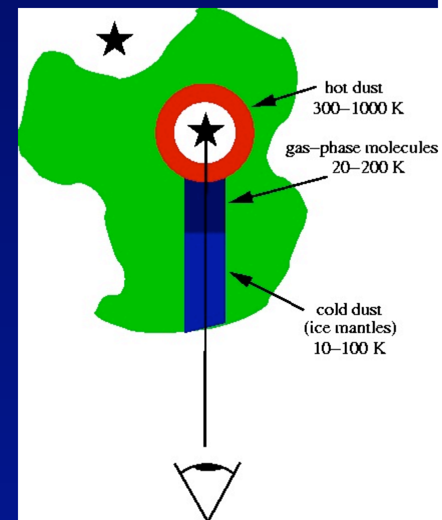
Summary

- Stars form mostly in clustered environments
  - Regions of high extinction, dense gas
  - About half in large (N>100) clusters
- Mass function may trace IMF of stars
- Timescales for Class 0 and I longer
- Shu inside-out collapse consistent, except
  - Luminosities imply accretion is episodic
- Efficiencies in clouds are low (3-6%)
  - Efficiencies in dense cores are high (>25%)
- Exgal prescriptions do not work locally

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**