Disk Statistics:
Infrared Surveys of Low and High Mass Star-Forming Regions

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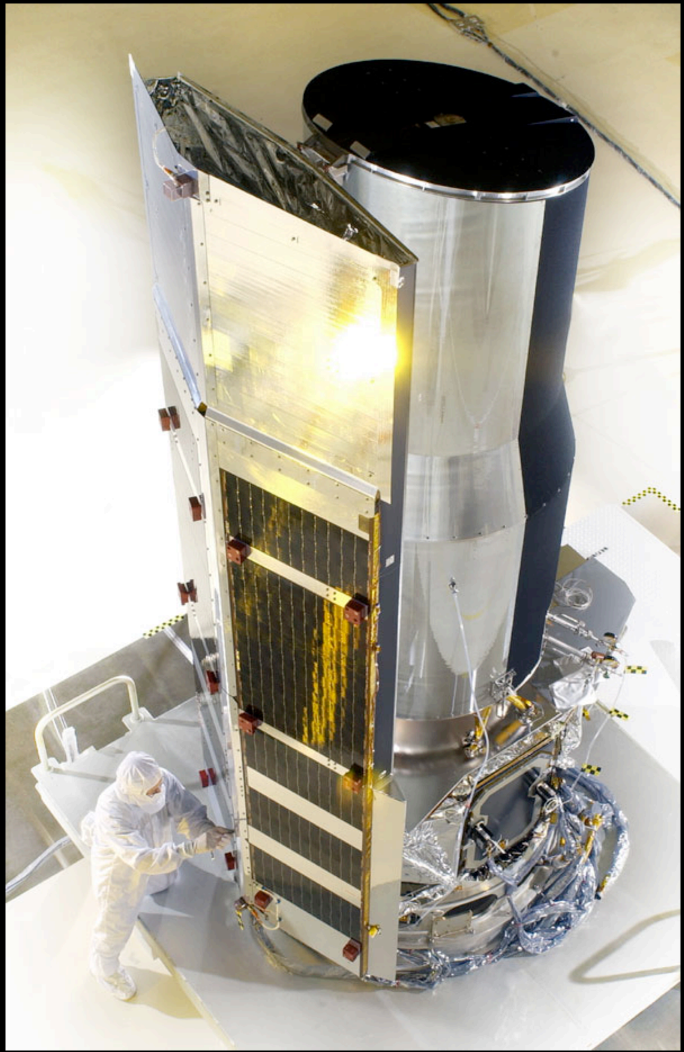
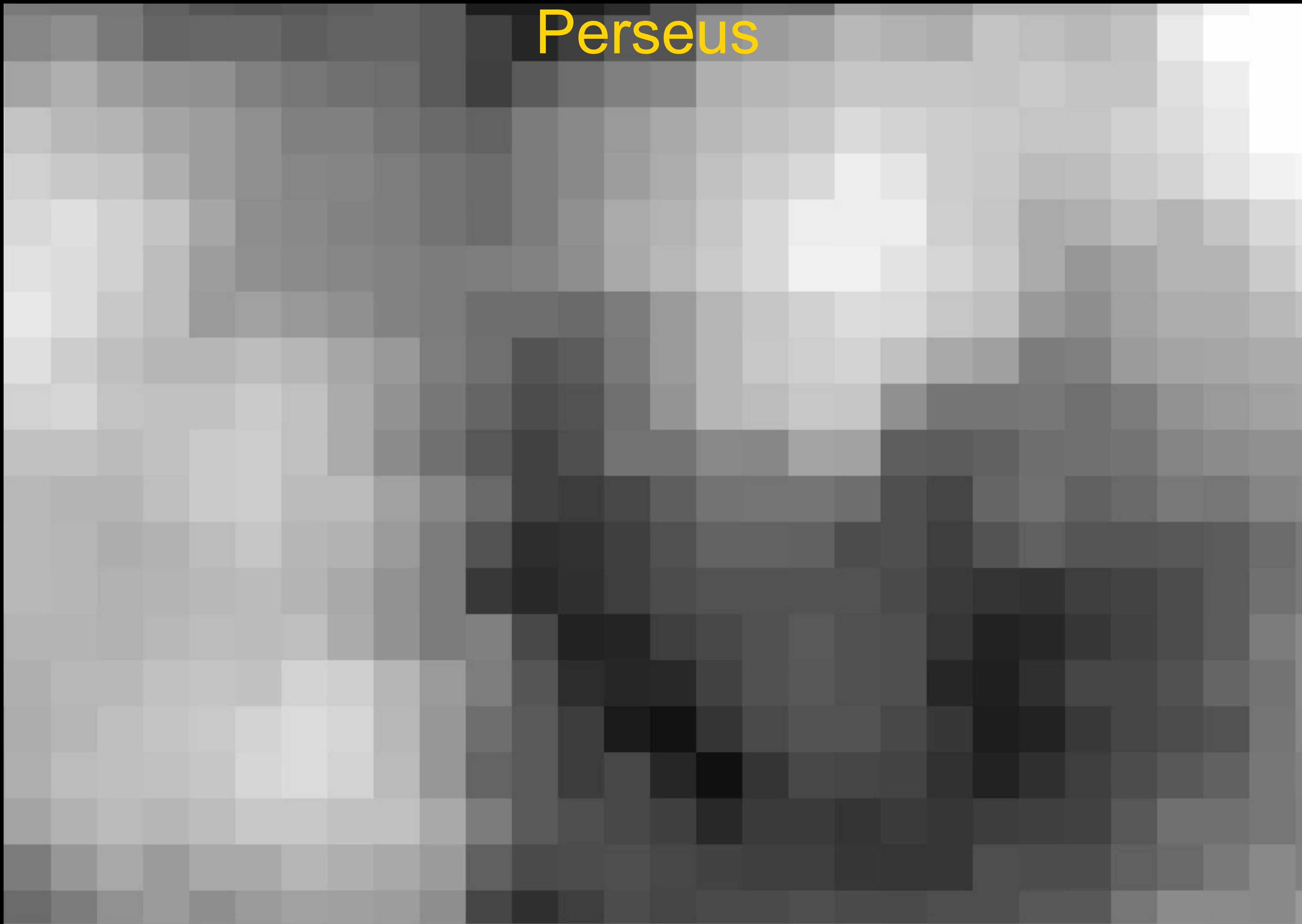
With thanks to Neal Evans, Tom Megeath,
Lori Allen, Sean Carey, Debbie Padgett

Spitzer Space Telescope

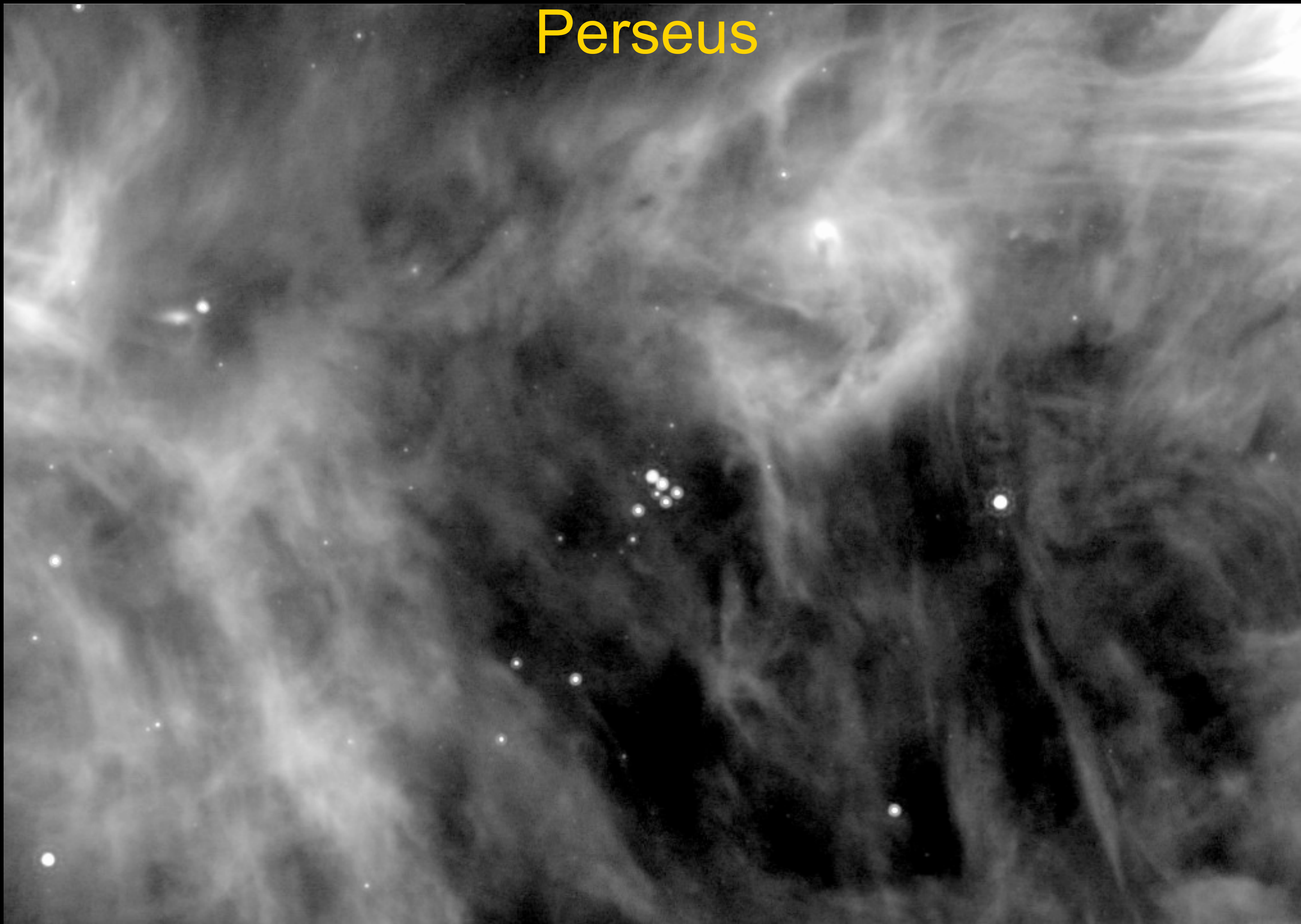


- Observatory has been in orbit for more than 6 years
- High observing efficiency equivalent to 13 yrs of HST
- More than 1,500 refereed publications to date; 500 in each of 2007 and 2008
- More than 700 astronomers from 24 different countries have been Spitzer PIs

Spitzer 24 μm vs. IRAS 25 μm in Perseus



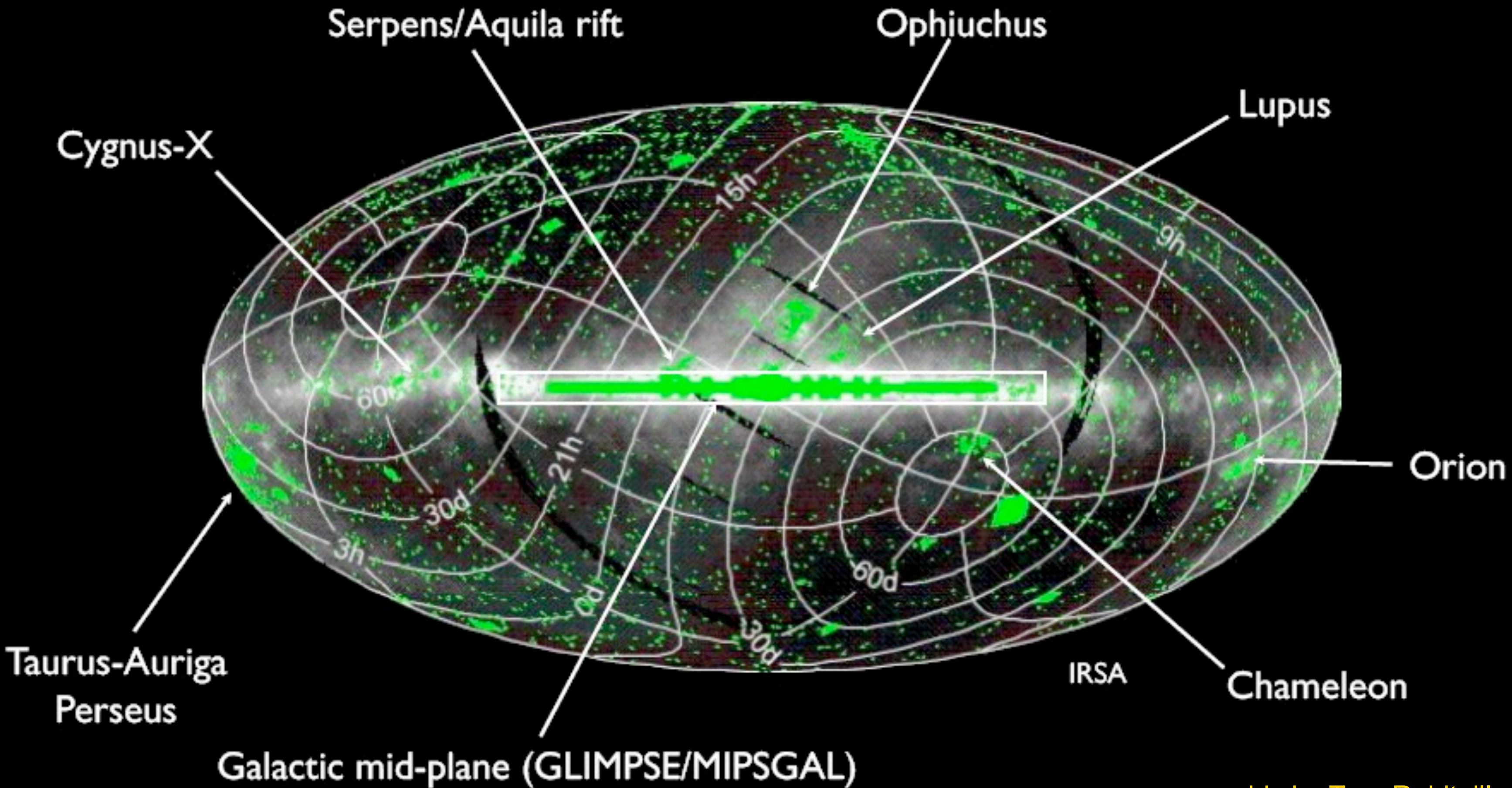
Spitzer 24 μm vs. IRAS 25 μm in Perseus



Spitzer Surveys of Local Star-Forming Regions:

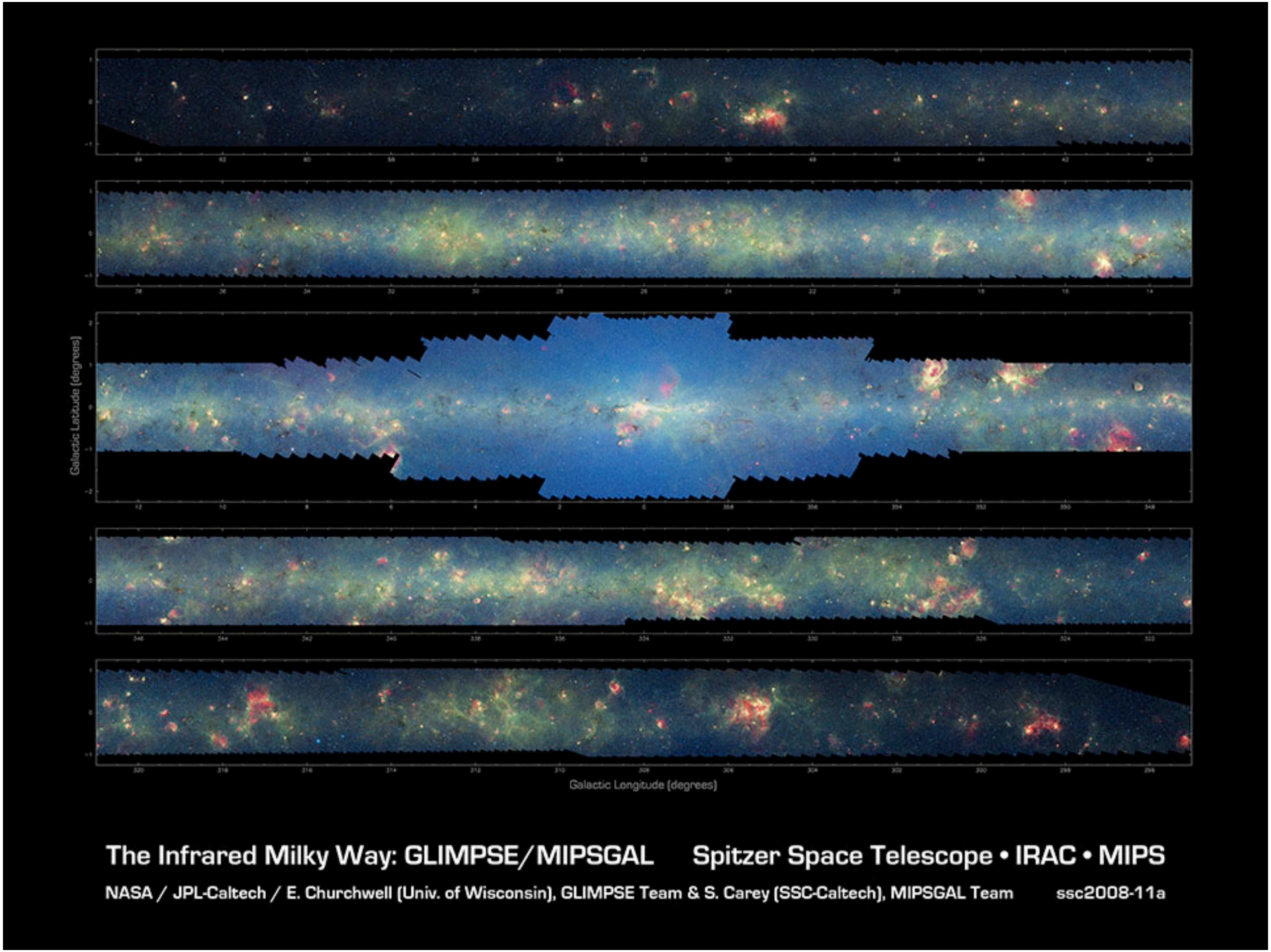
- Guaranteed Time Observer programs on young clusters
  - Orion et al. (Megeath, Gutermuth, Muzerolle)
- *Spitzer* Legacy surveys in star formation:
  - GLIMPSE/MIPSGAL (Churchwell, Carey): Galactic plane, 300+ deg^2
  - Cores to Disks "c2d" (N. Evans): 5 nearby clouds, 16 deg^2
  - Gould's Belt "GB" (L. Allen): c2d extension to 7 more clouds, 32 deg^2. See posters A10 (Bourke) and B43 (Vernazza) for new results
  - Taurus Spitzer Survey (D. Padgett): Taurus cloud, 44 deg^2
  - Cygnus-X (J. Hora): High mass SF region, 25 deg^2

Spitzer observations of SF regions

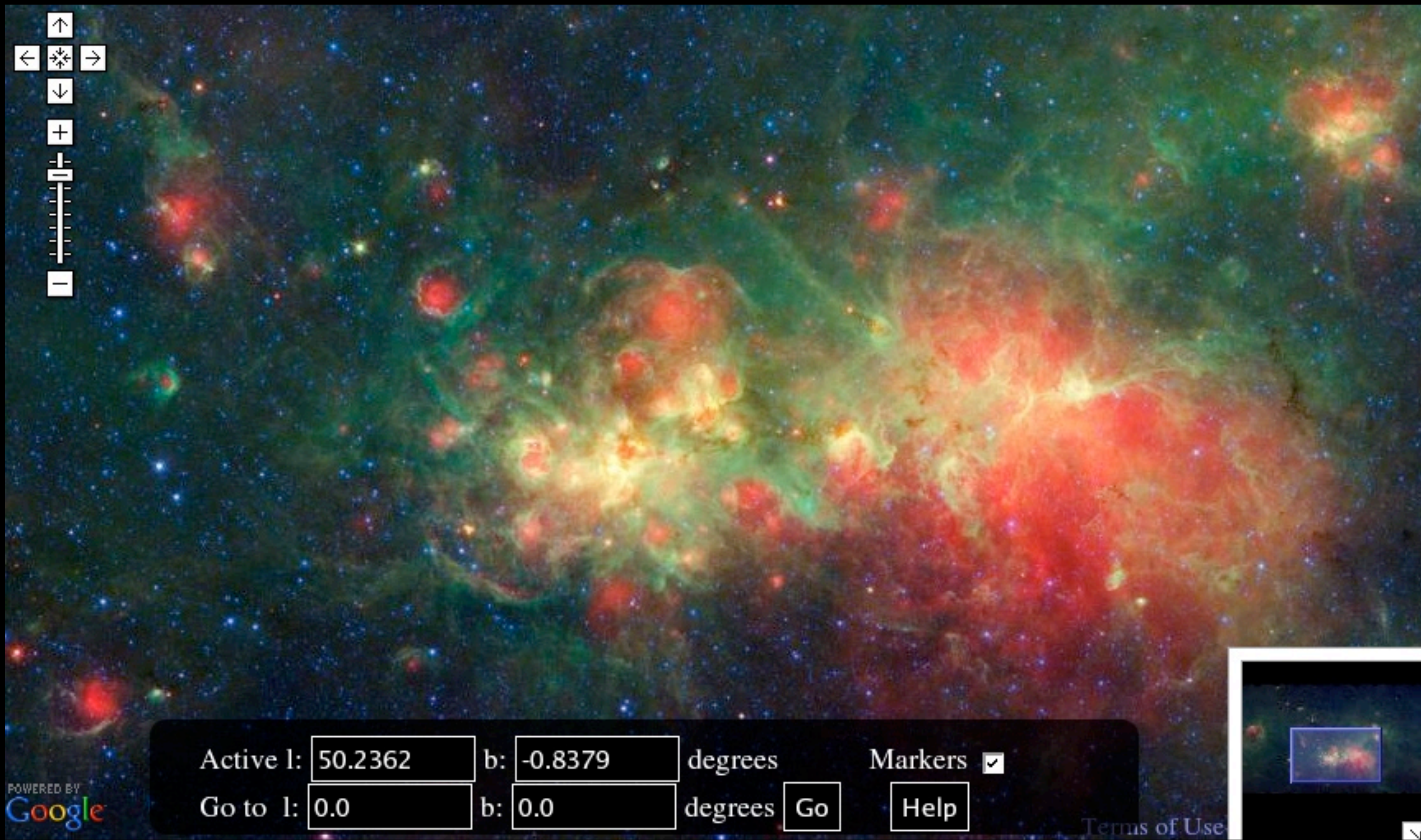


graphic by Tom Robitaille

90% of star-forming clouds & young clusters within 1 kpc have been done


Galactic Latitude (degrees)
Galactic Longitude (degrees)
The Infrared Milky Way: GLIMPSE/MIPSGAL
Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / E. Churchwell (Univ. of Wisconsin), GLIMPSE Team & S. Carey (SSC-Caltech), MIPSGAL Team
ssc2008-11a

Spitzer Galactic Plane map online at http://mipsgal.ipac.caltech.edu/iracmips_map.html



InfraRed Dark Clouds

- Thousands along the Galactic plane
- 70+% have embedded protostars
- Many opaque at 70 μm, seen in emission at 450/850 μm

Peak $N(H_2) \sim 2 \times 10^{23}$ cm^{-2} 8.0, 24, 70 μm

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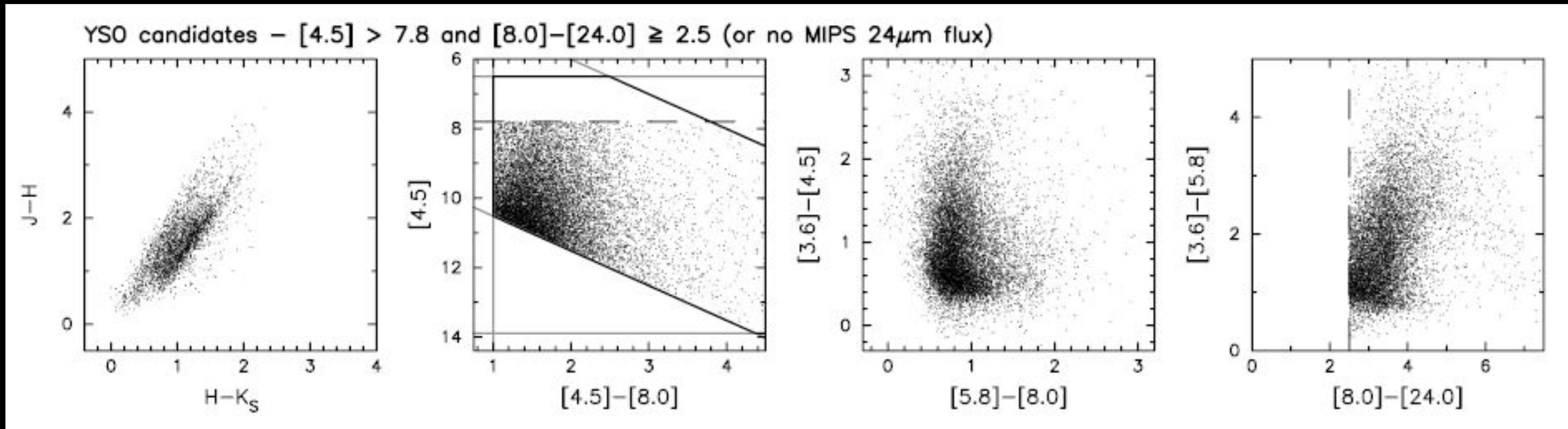
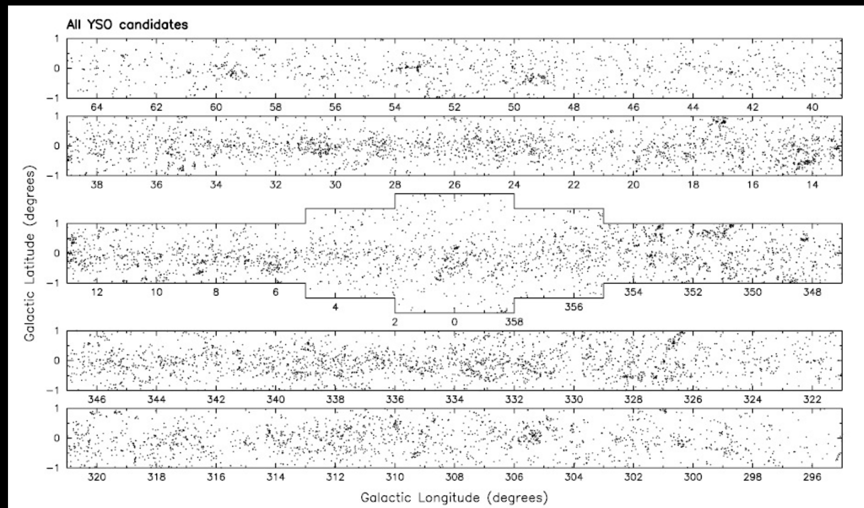
Peak $N(H_2) \sim 2 \times 10^{23}$ cm^{-2}

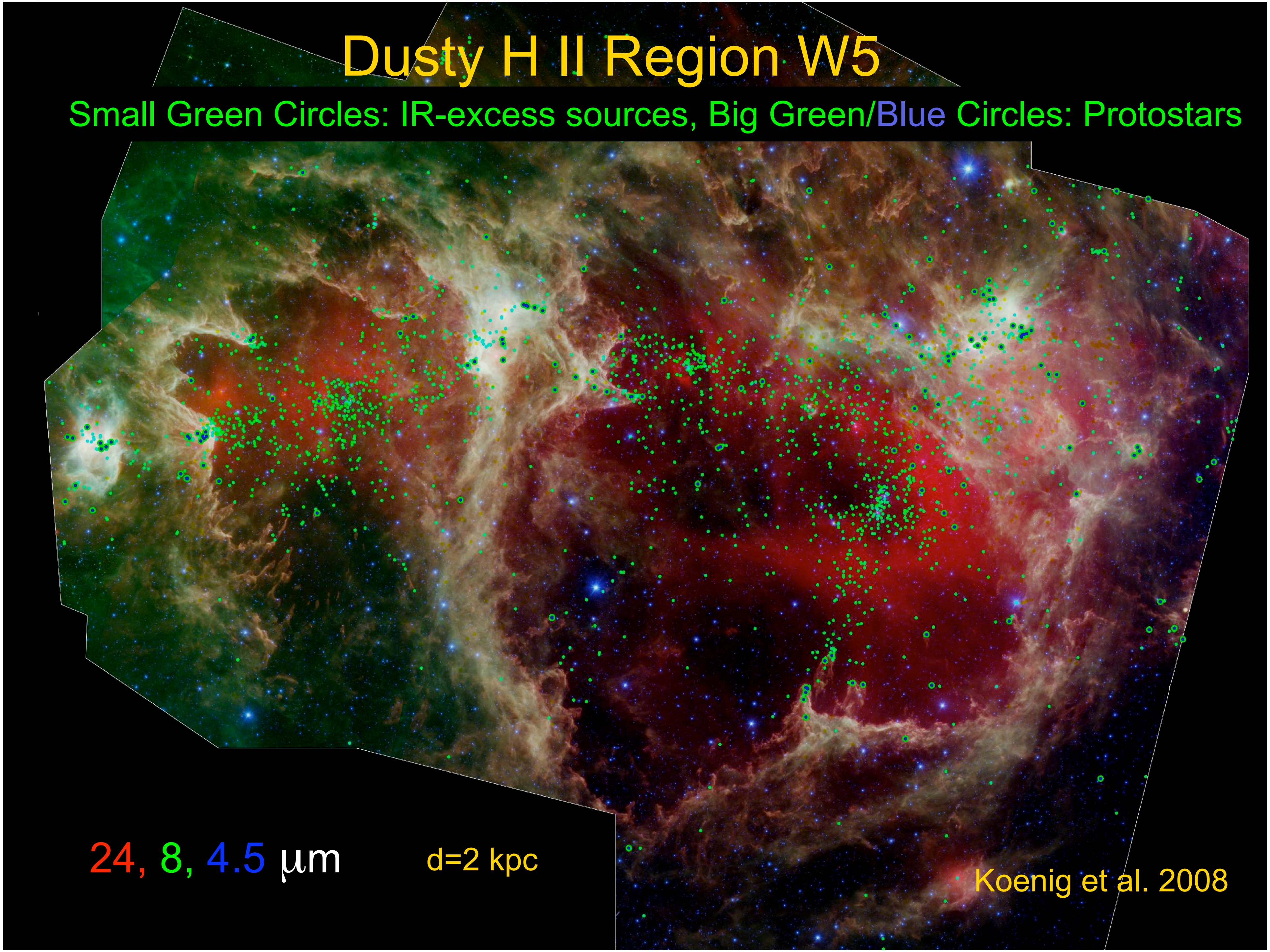
3.6, 8.0, 24 μm

11,000 YSO candidates along the galactic plane (Spitzer/GLIMPSE)



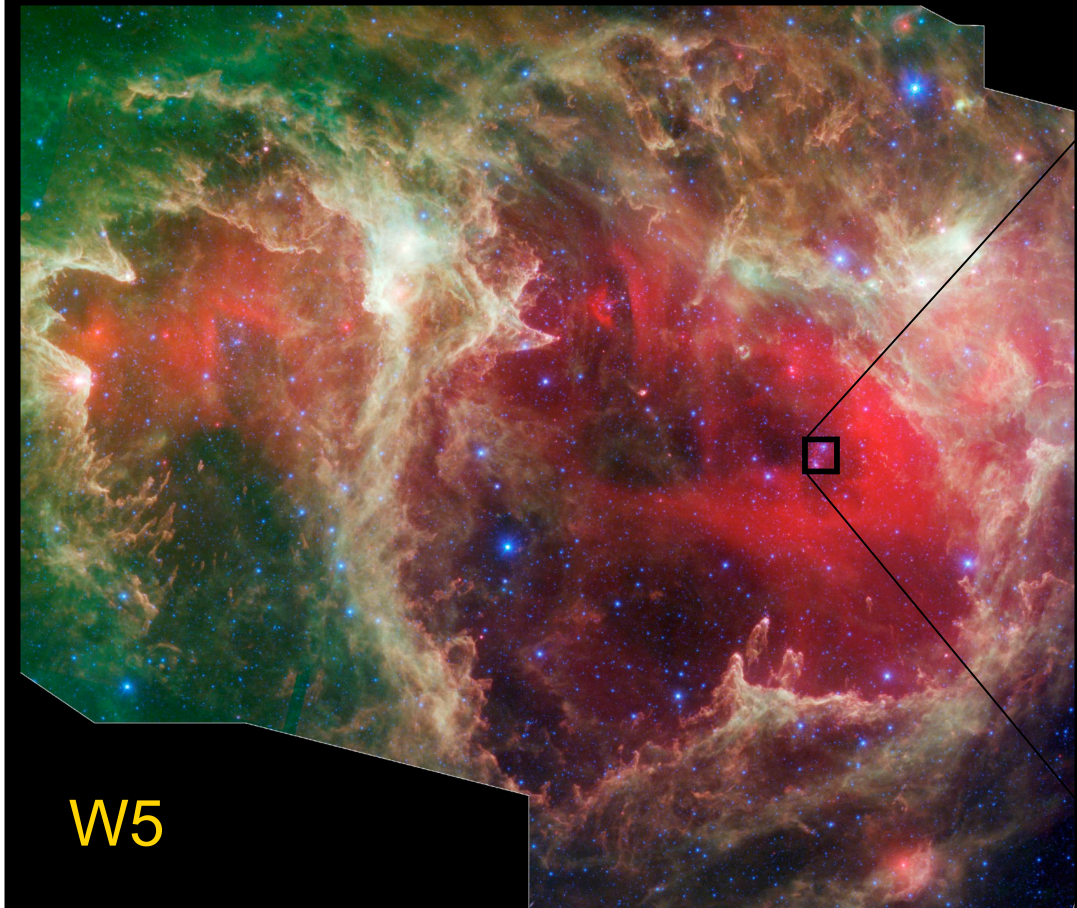


Intrinsically red sources selected; YSOs must be distinguished from AGB stars. Results are clustered as expected. Intermediate or high mass YSOs. Individual followup spectroscopy needed to confirm.
(Robitaille et al. 2008)


Dusty H II Region W5
Small Green Circles: IR-excess sources, Big Green/Blue Circles: Protostars
24, 8, 4.5 μm
d=2 kpc
Koenig et al. 2008

Destruction of dusty disks

Nearby O star blows away outer disk

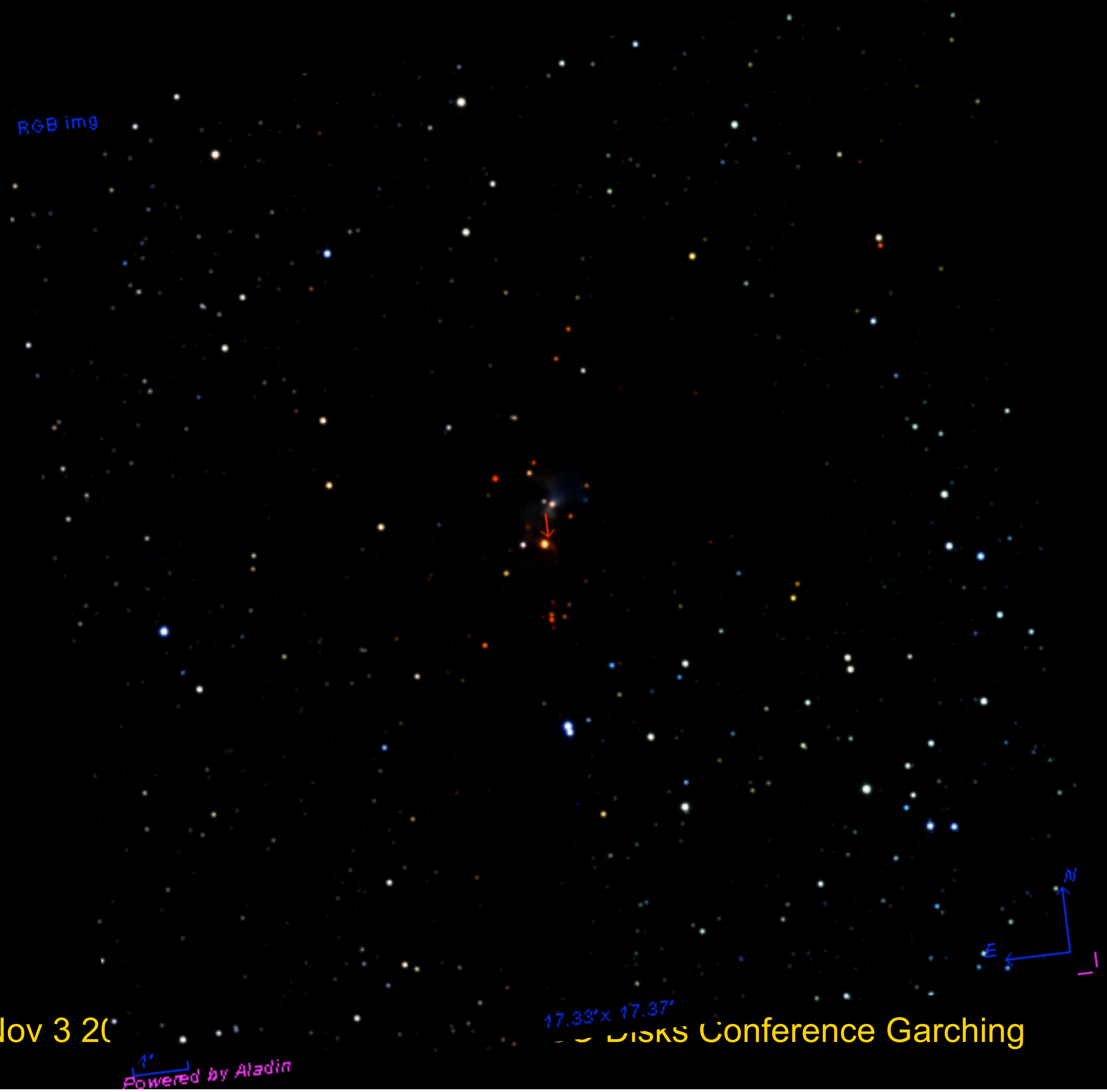


W5

Koenig et al. 2008; Balog et al. 2007

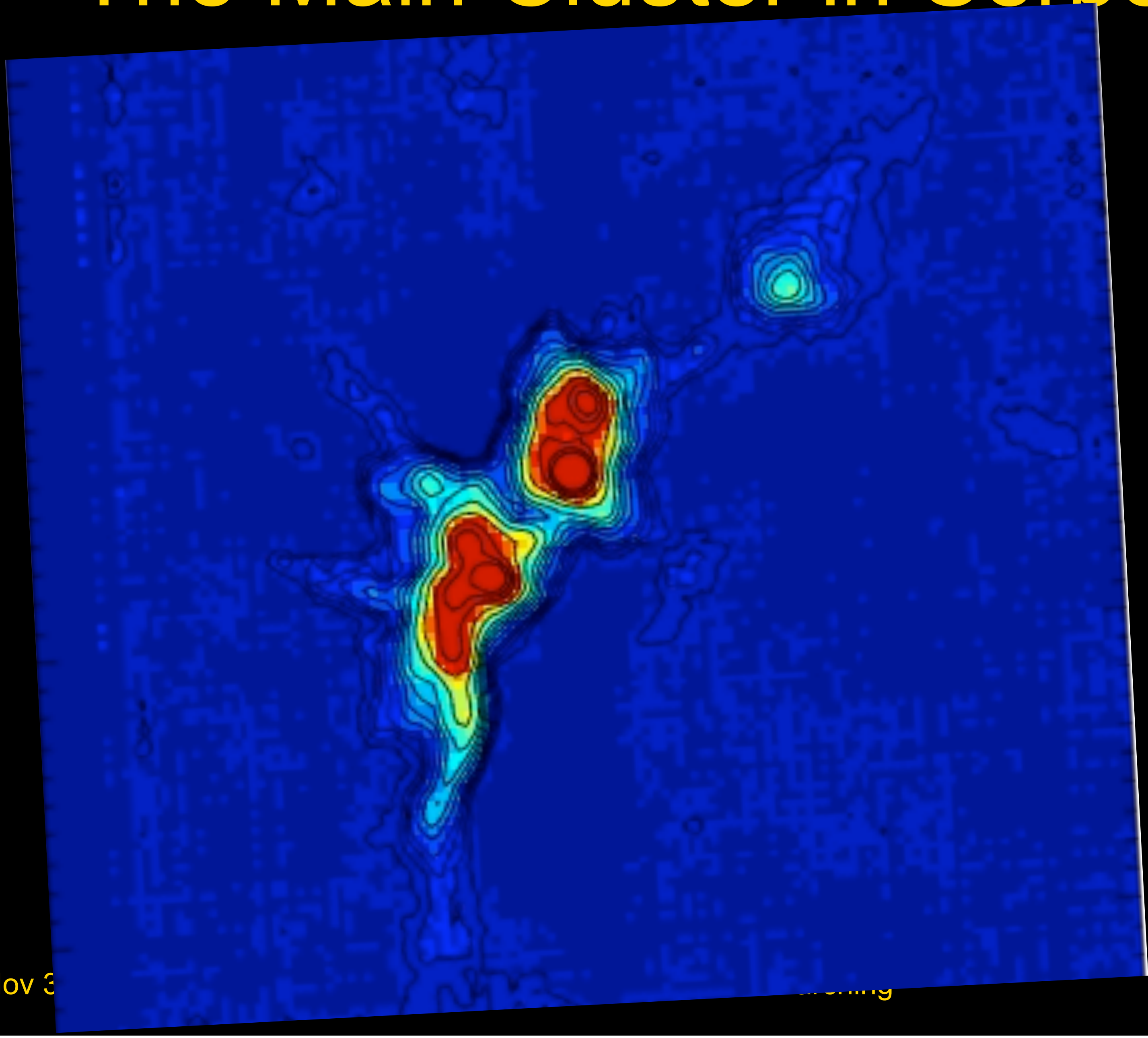
YSO clustering

The Main Cluster in Serpens

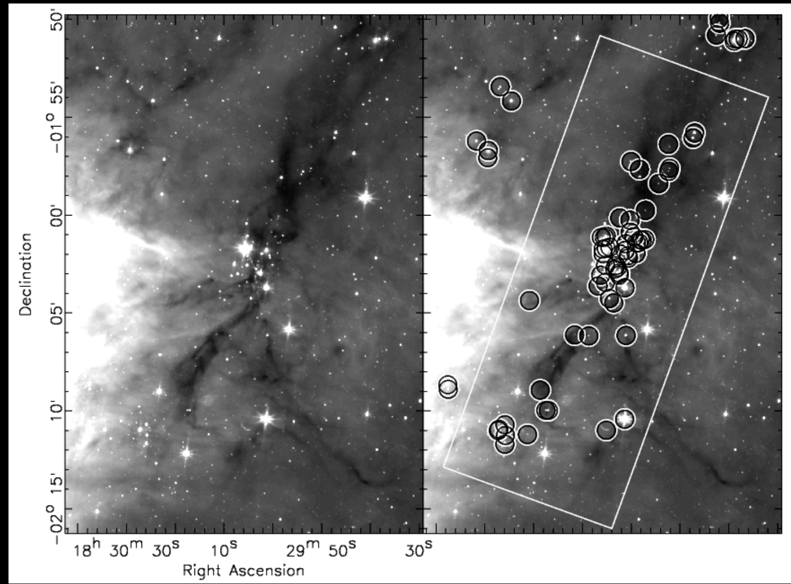


The Main Cluster in Serpens

The Main Cluster in Serpens



Serpens South Cluster: not a spherical structure



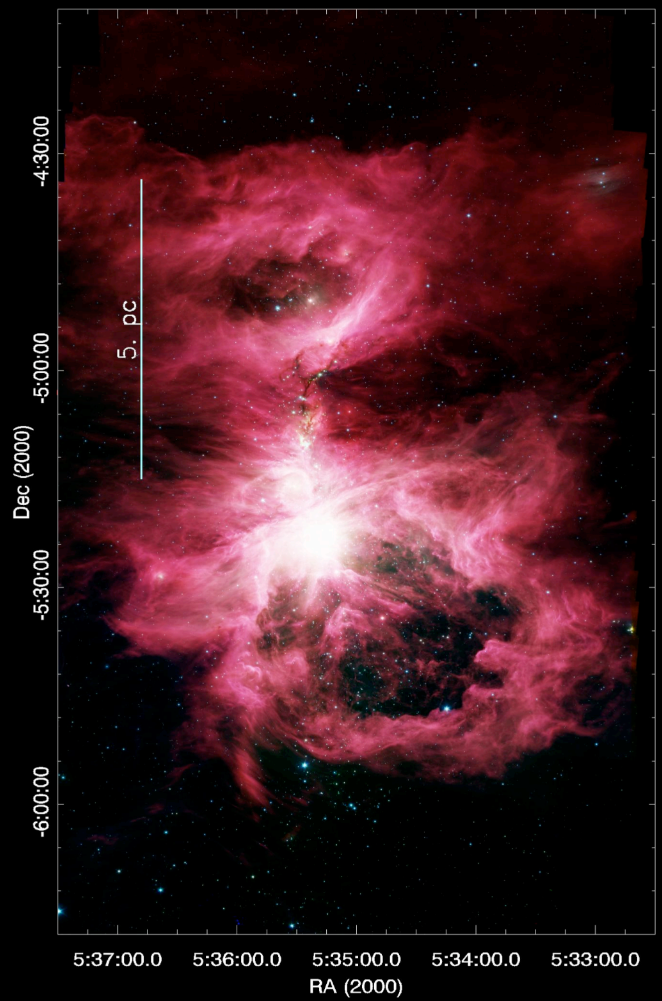
- Protostar-dominated cluster
- Follows dark filament
- High density (480 YSOs / sq. deg.)

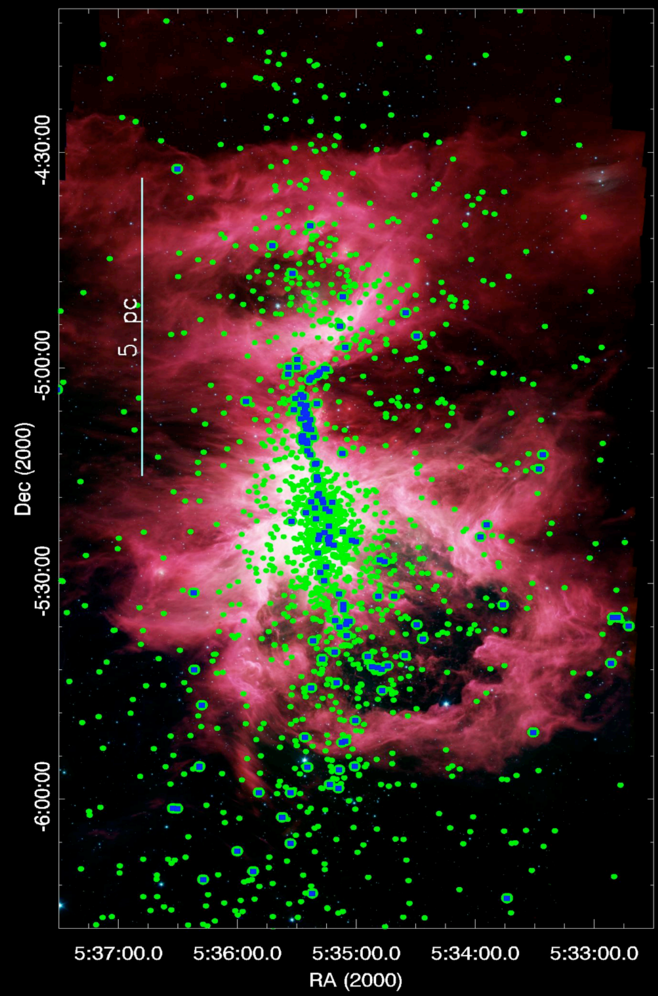
=> Likely probing primordial cluster structure

See also next talk (Teixeira) on this topic

(Gutermuth et al. 2008)

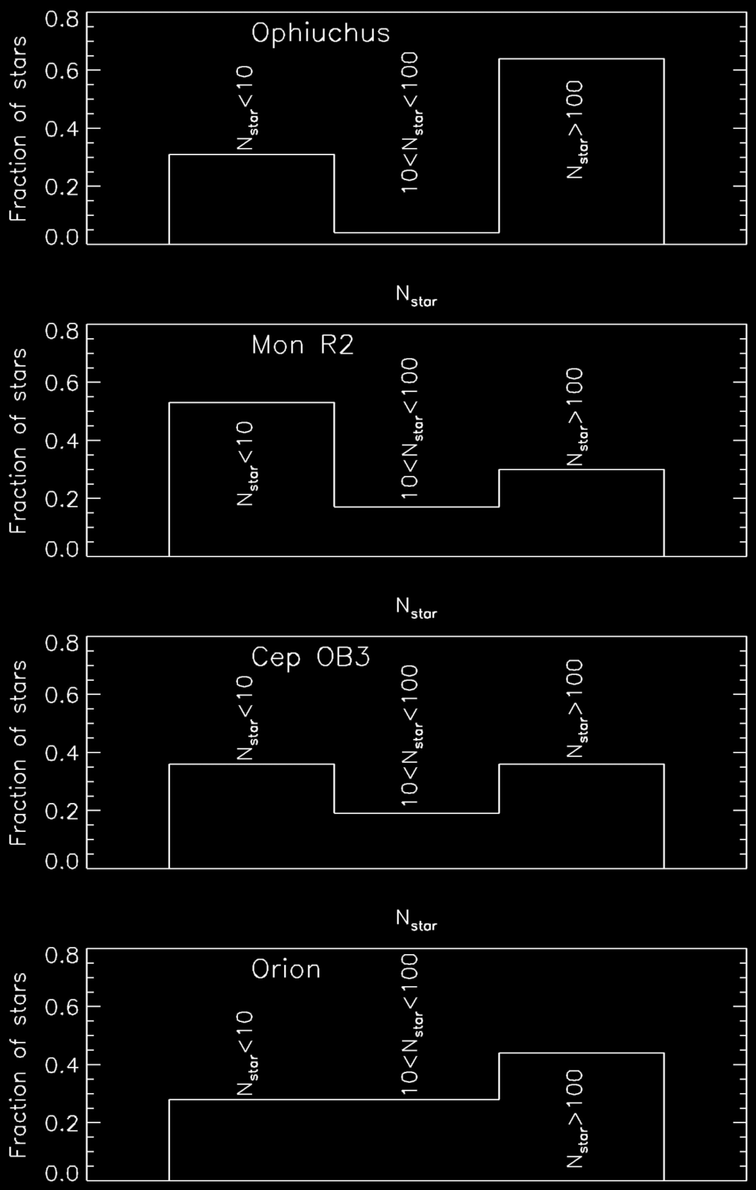
YSO distribution in Orion: Megeath et al. in prep





See also poster A29 (Fang)

Where do most stars form in molecular clouds?



Examine the relative fraction of stars in large clusters, small clusters, groups and relative isolation for three GMCs (and Ophiuchus).

Uncertainties include disk fraction, completeness in infrared bright emission, 3d effects.

Megeath et al. find that all three GMCs associated with massive stars contain large numbers of relatively isolated stars.

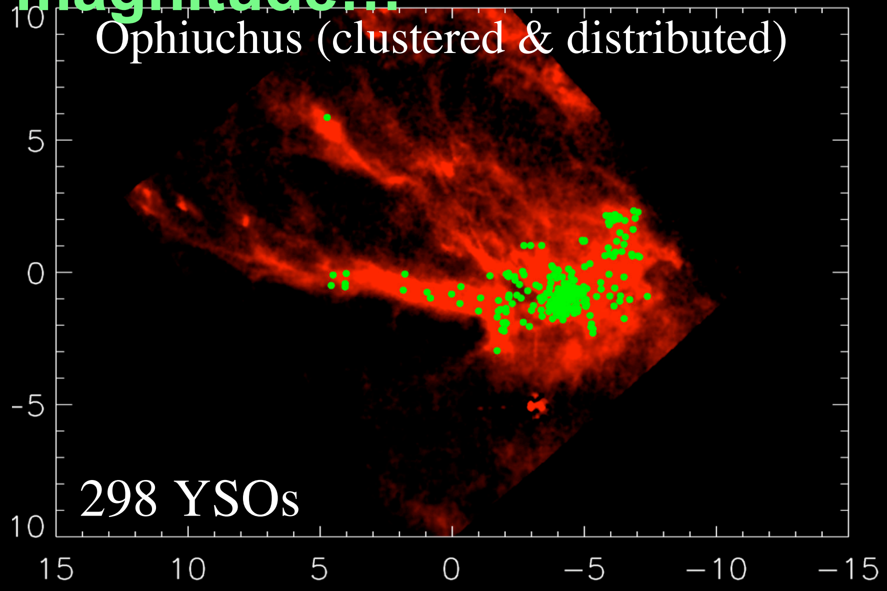
Even in GMCs containing young massive stars, many low mass stars are found in relative isolation, parsecs away from the hot OB stars.

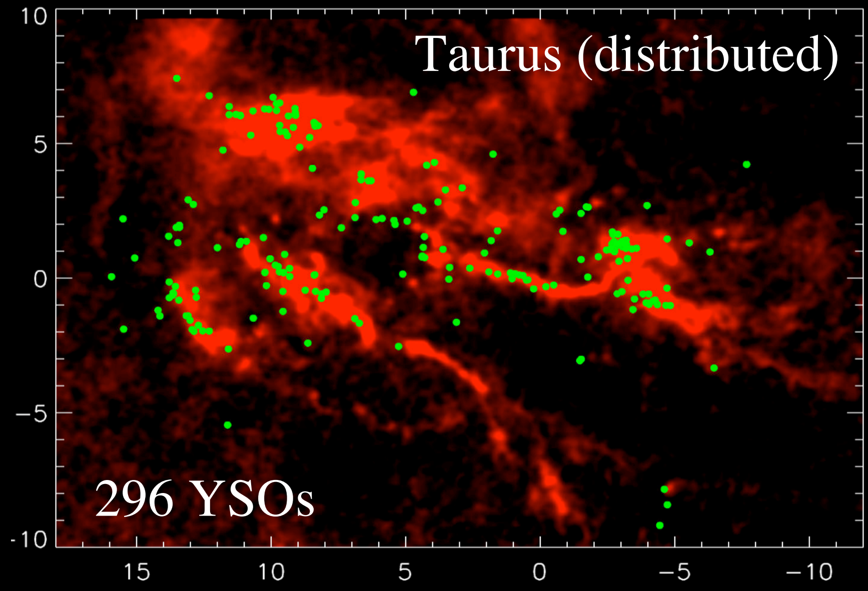
Surveys suggests two "modes" of organization:

clustered & distributed*, and *distributed

2. The observed mode is not just a function of the # of YSOs.

3. The density of stars varies over four orders of magnitude!!!

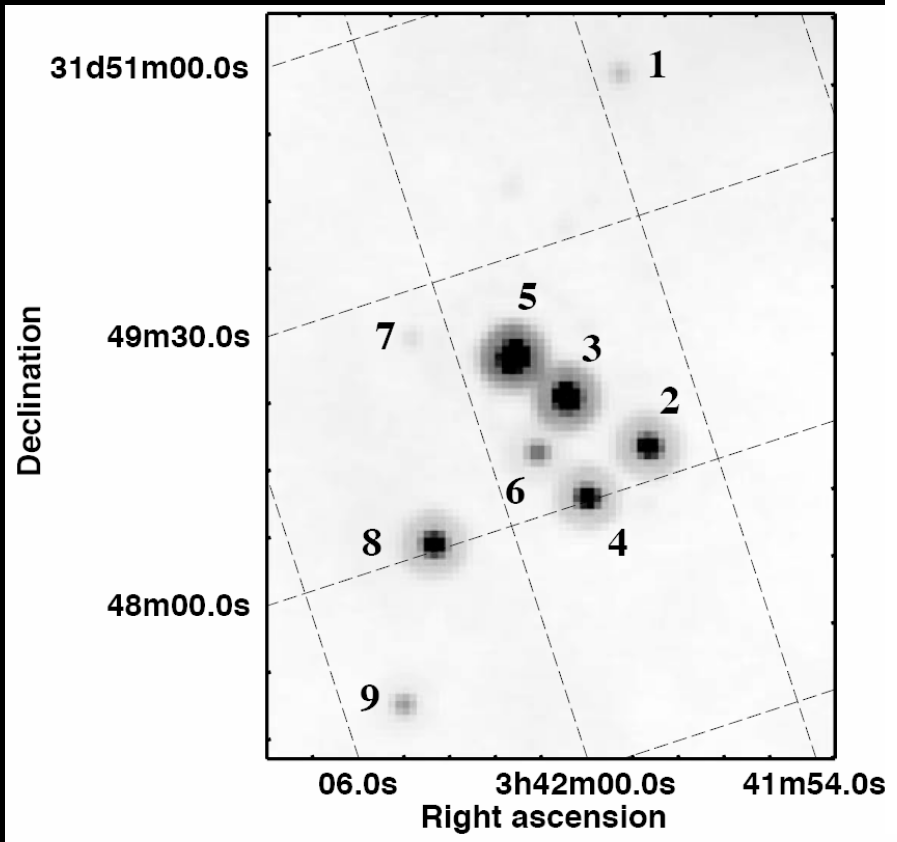


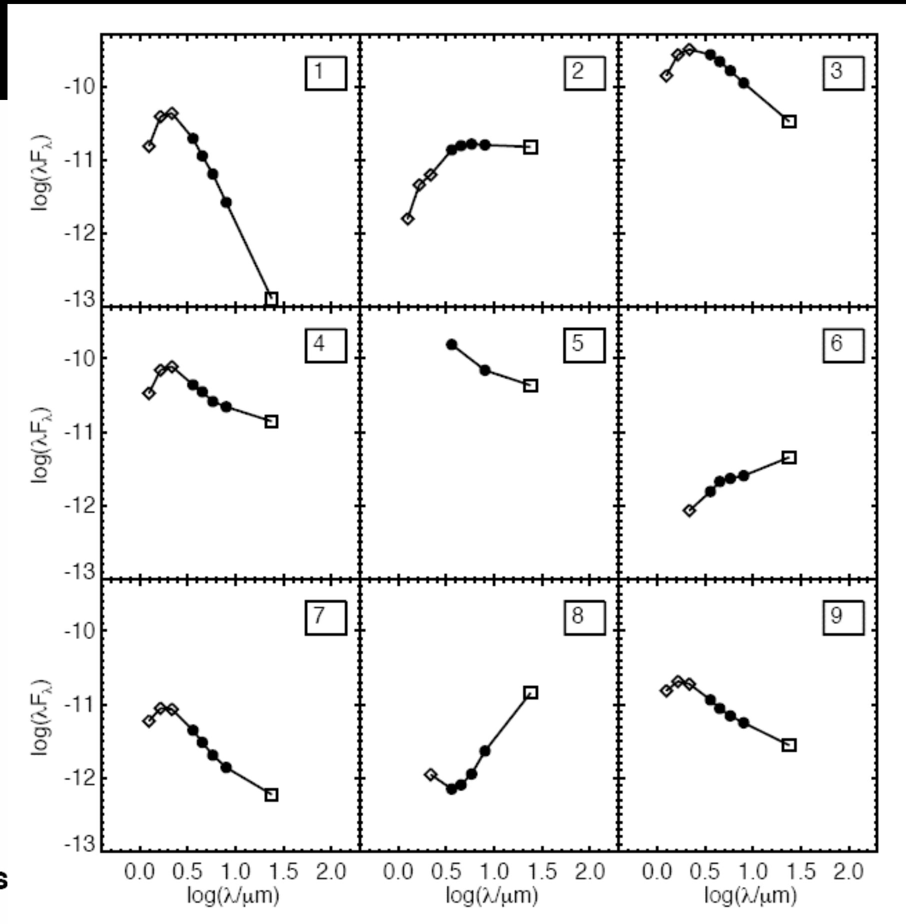


SED Diversity in Perseus aggregate IRAS 03388+3139

(Rebull et al. 2007)

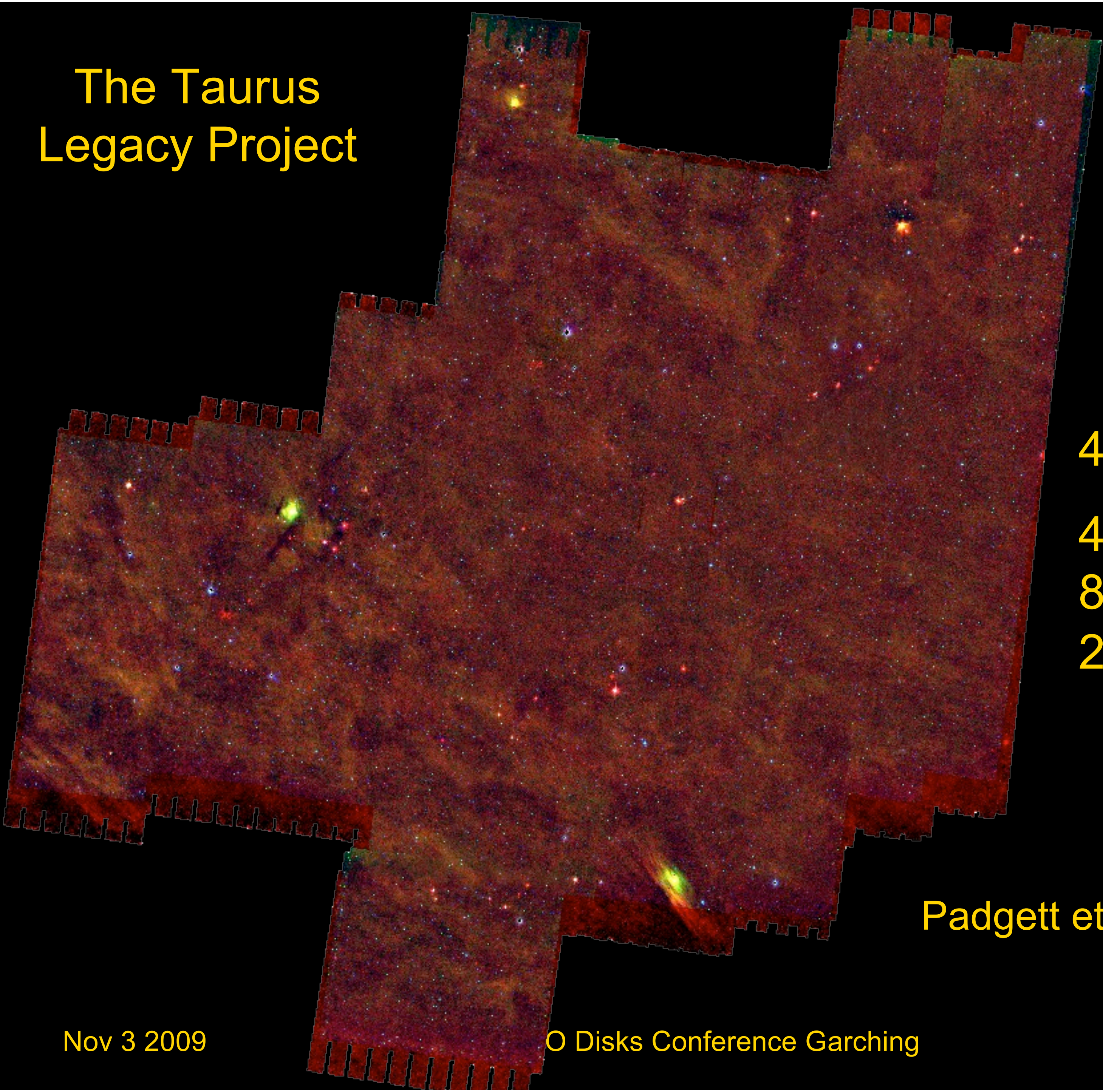
MIPS 24 μm image





Taurus Clouds

The Taurus Legacy Project

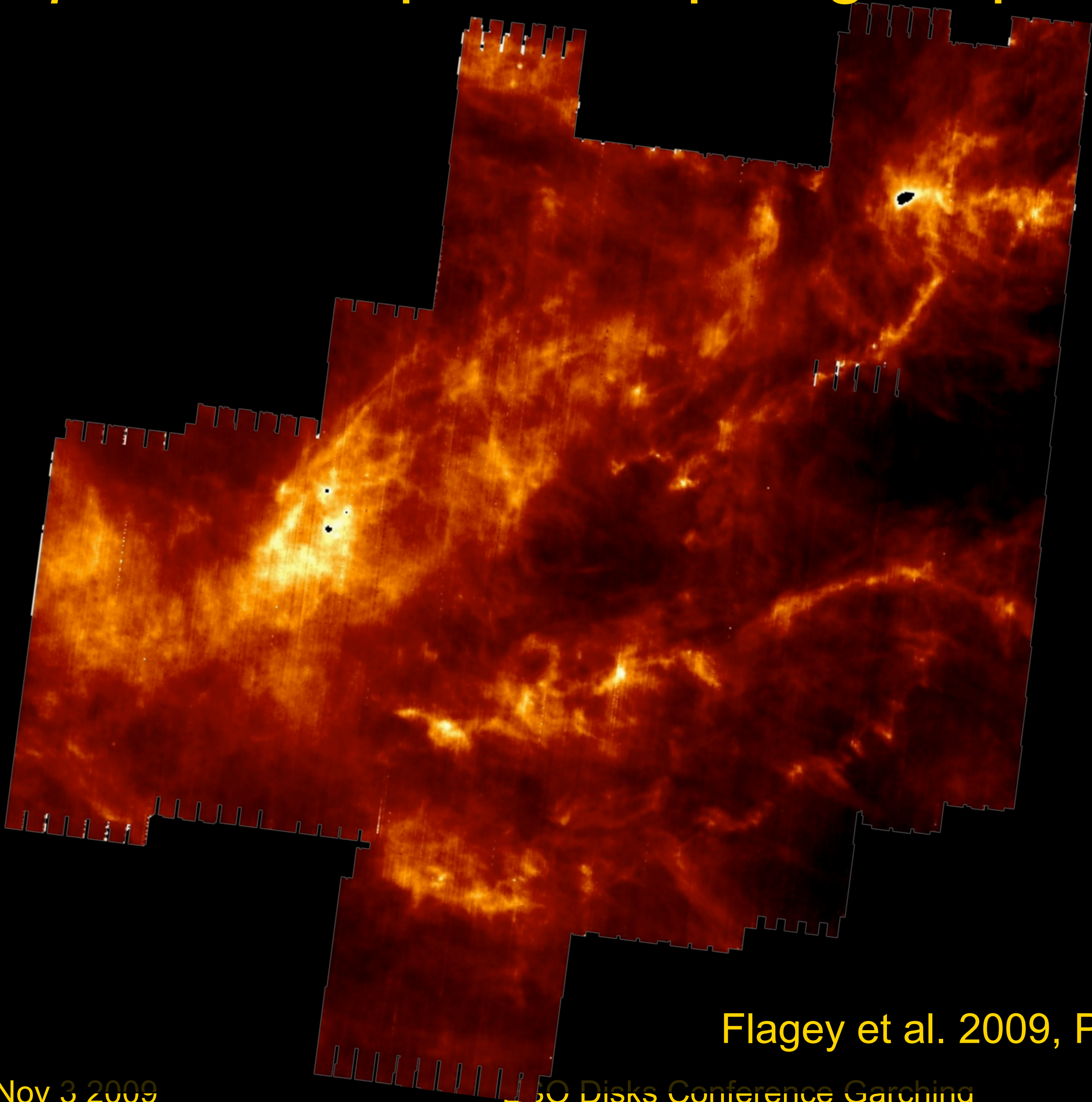


44 deg^2 map

4.5 μm (blue),
8 μm (green),
24 μm (red)

Padgett et al. in prep

Spitzer 160 µm 44 sq. deg Map of Taurus



Flagey et al. 2009, Padgett et al. in prep.

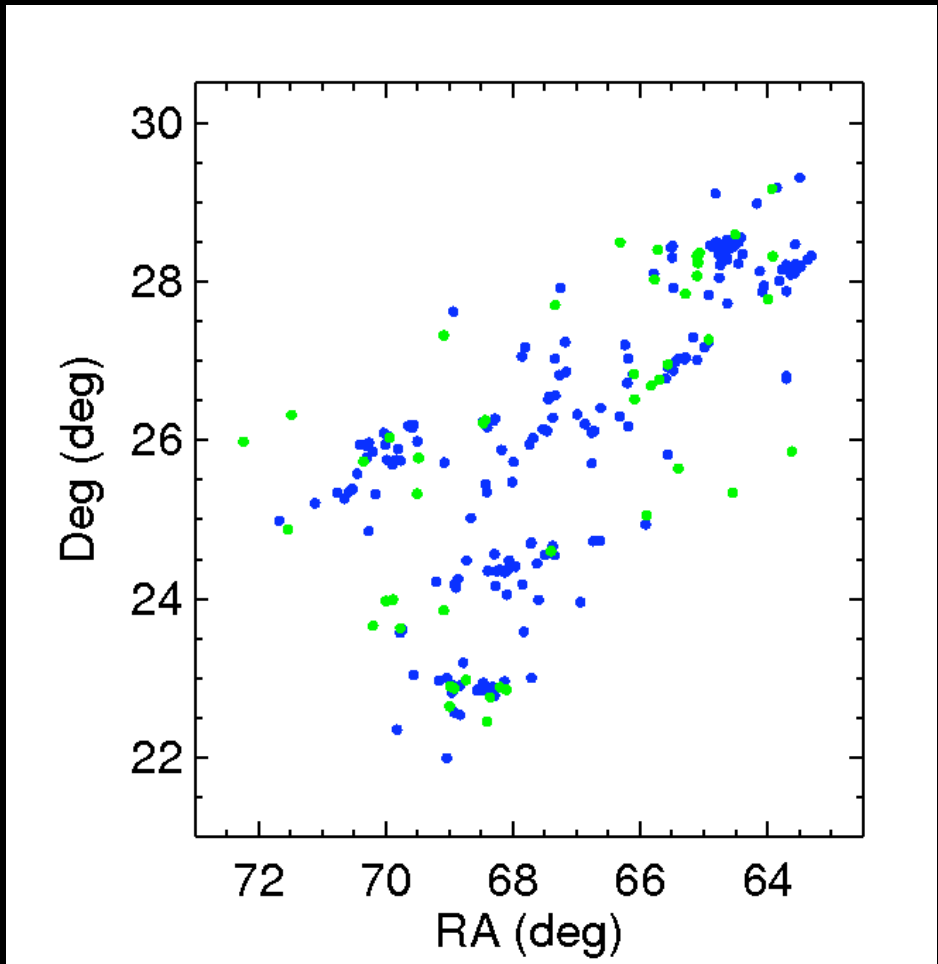
New Taurus Members

(Rebull et al. submitted)

- 148 candidates for new Taurus members, selected to have IR excess
- Optical or near-IR Spectroscopy has been done 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. Beware faint sources with PAH emission popup in IRAC band 4 !

Spatial distribution of new Taurus YSOs

(Rebull et al. submitted)



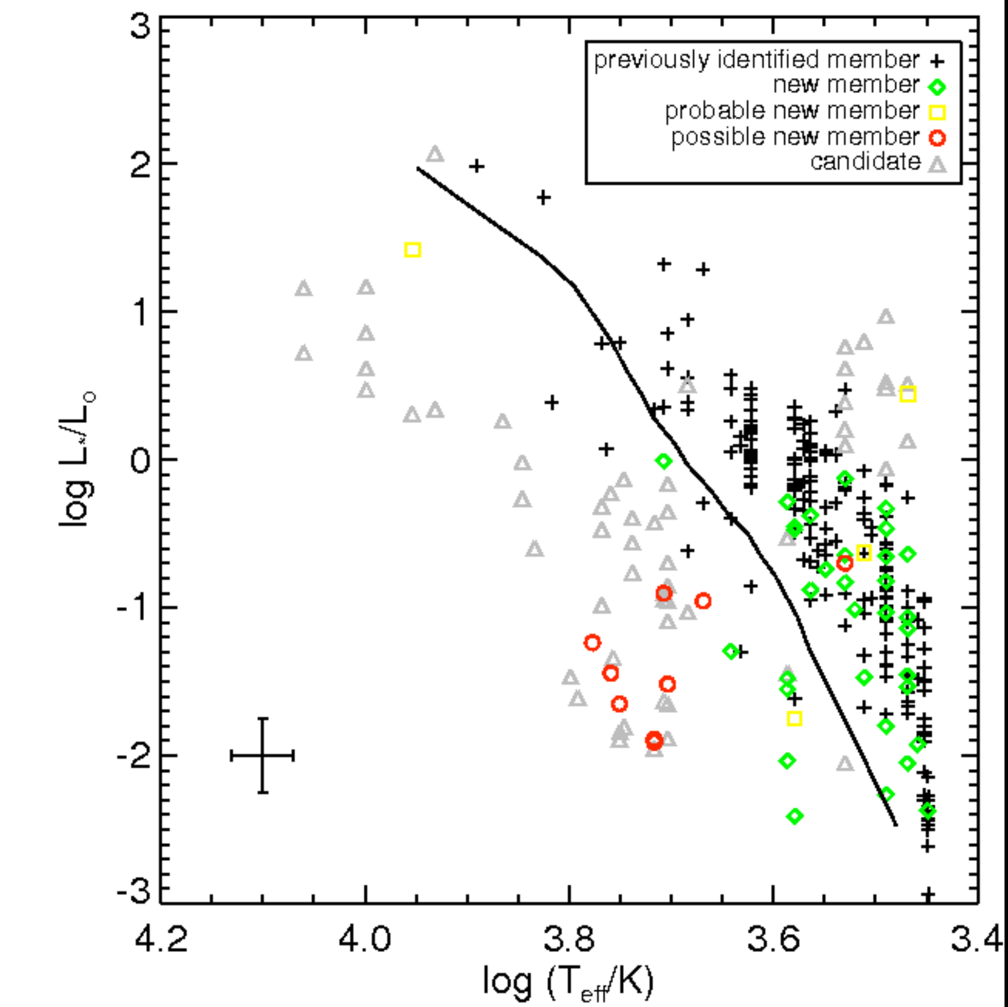
Known members

Confirmed new members

Confirmed new members tend to be found clustered among known members

Taurus YSO population

(Rebull et al. submitted)

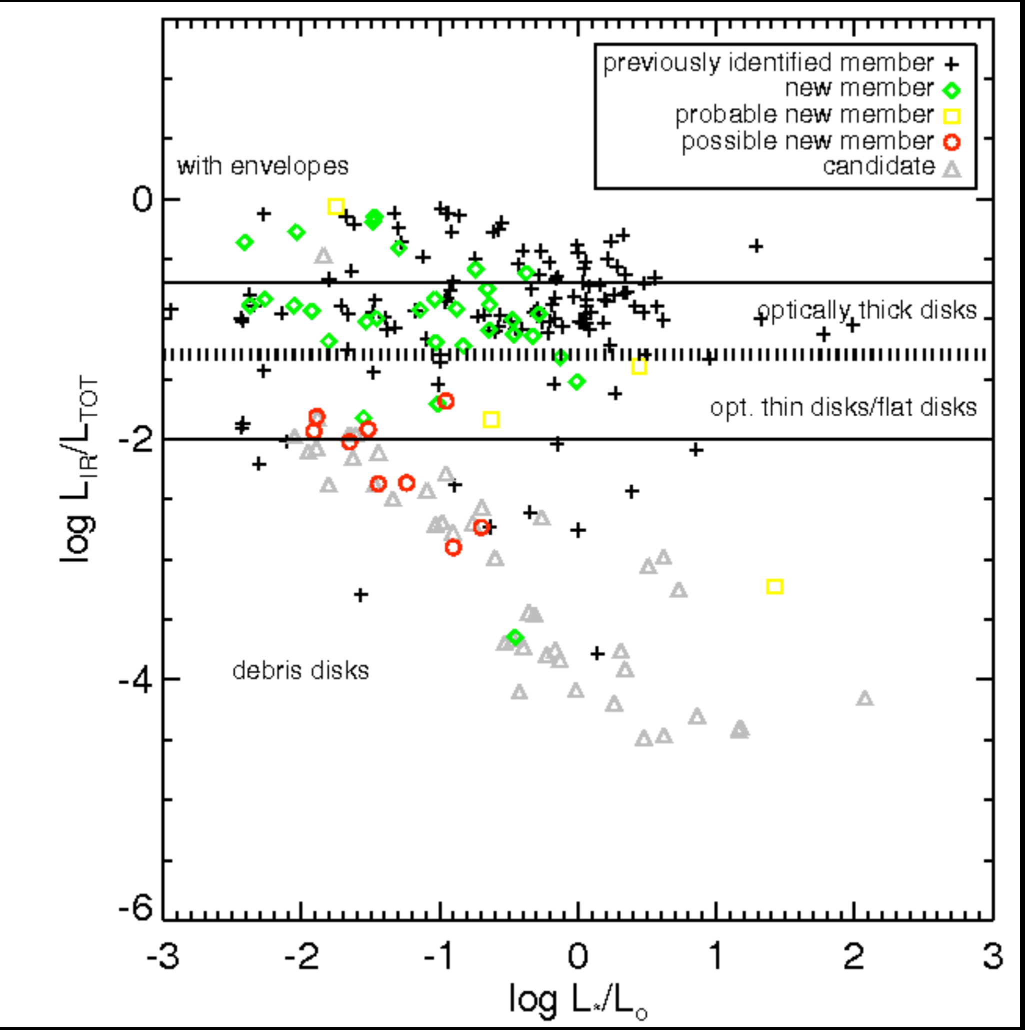


Most new members fall within region of the diagram populated by known members (i.e., where they should be).

Spectroscopic followup still pending for many objects

Taurus disk demographics

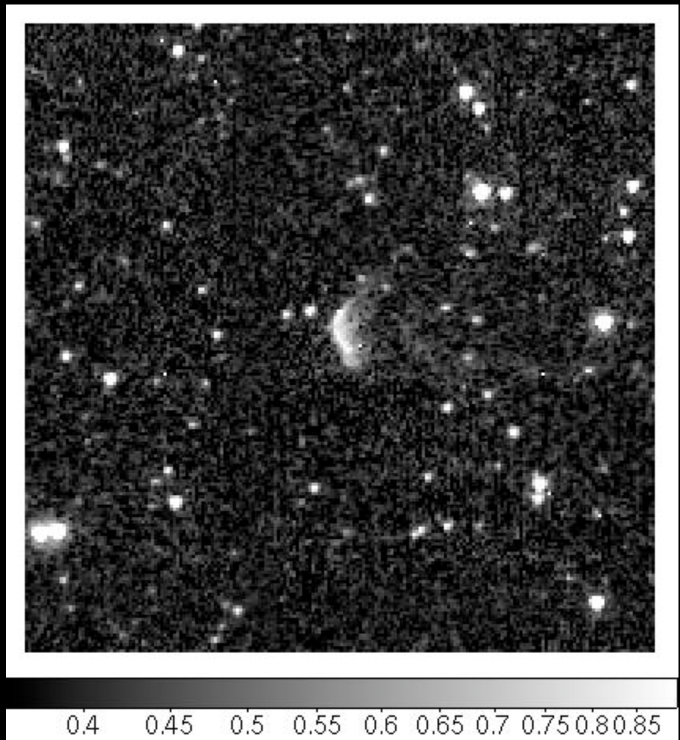
(Rebull et al. submitted)



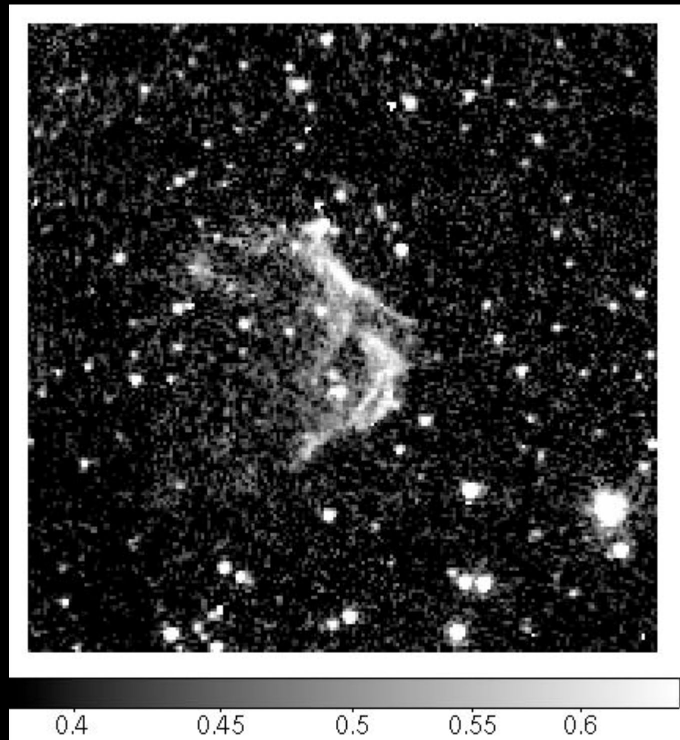
Fractional IR luminosity: Best measurement of overall disk evolutionary state.

Requires knowledge of spectral type & extinction, and good 70 μm data; so can't be calculated for all YSO populations.

New Giant Herbig-Haro flow in Taurus: IRAC 4.5 μm images



Stapelfeldt et al. in prep.



- Sharp edge; 25″ across

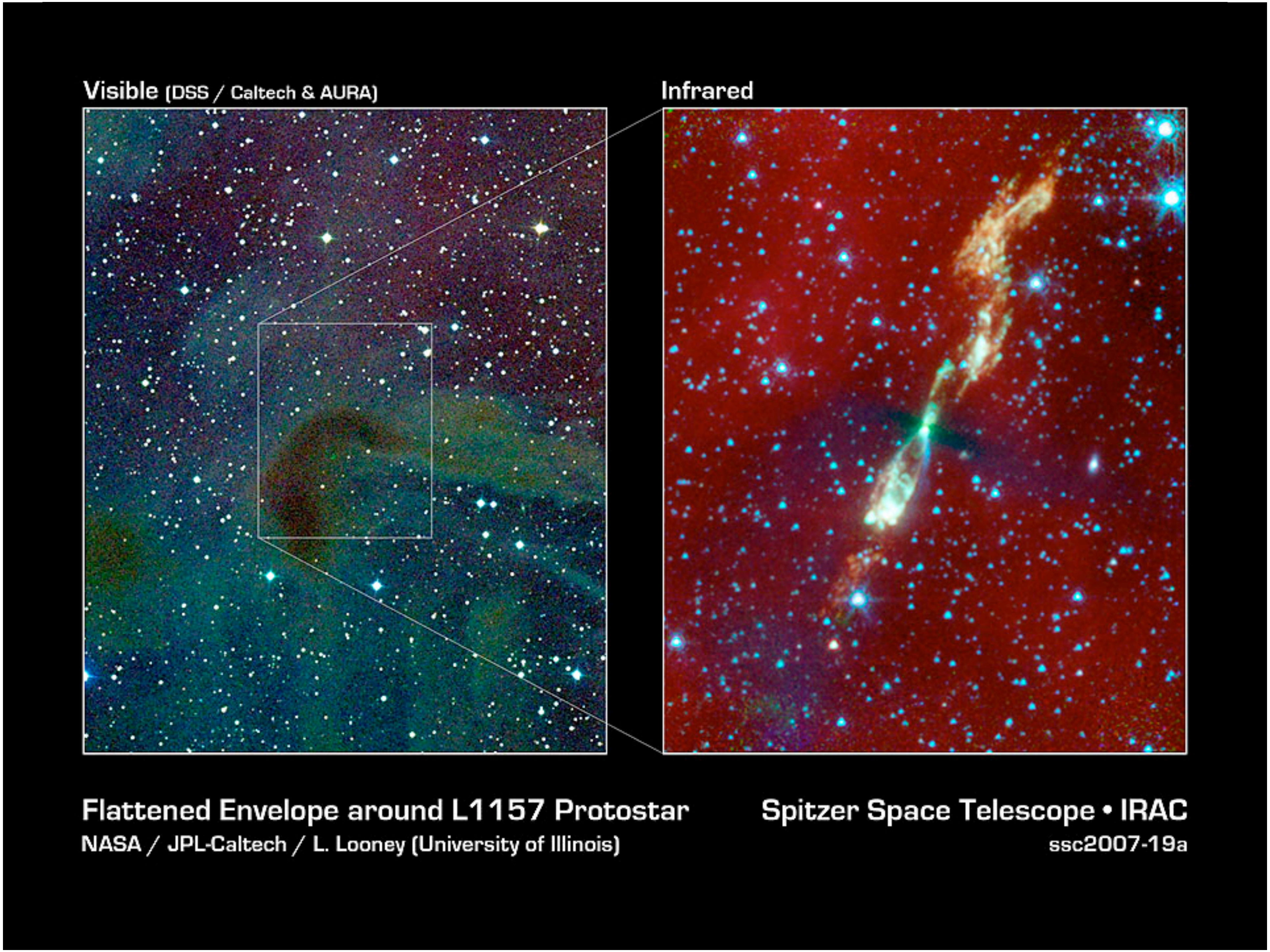
Spans 2.4 degrees = 5.9 pc !

- BIG: 80 arcsec across

15,000 yr ejection age

See poster A40 (Green) for more Spitzer outflow results

Cloud Populations

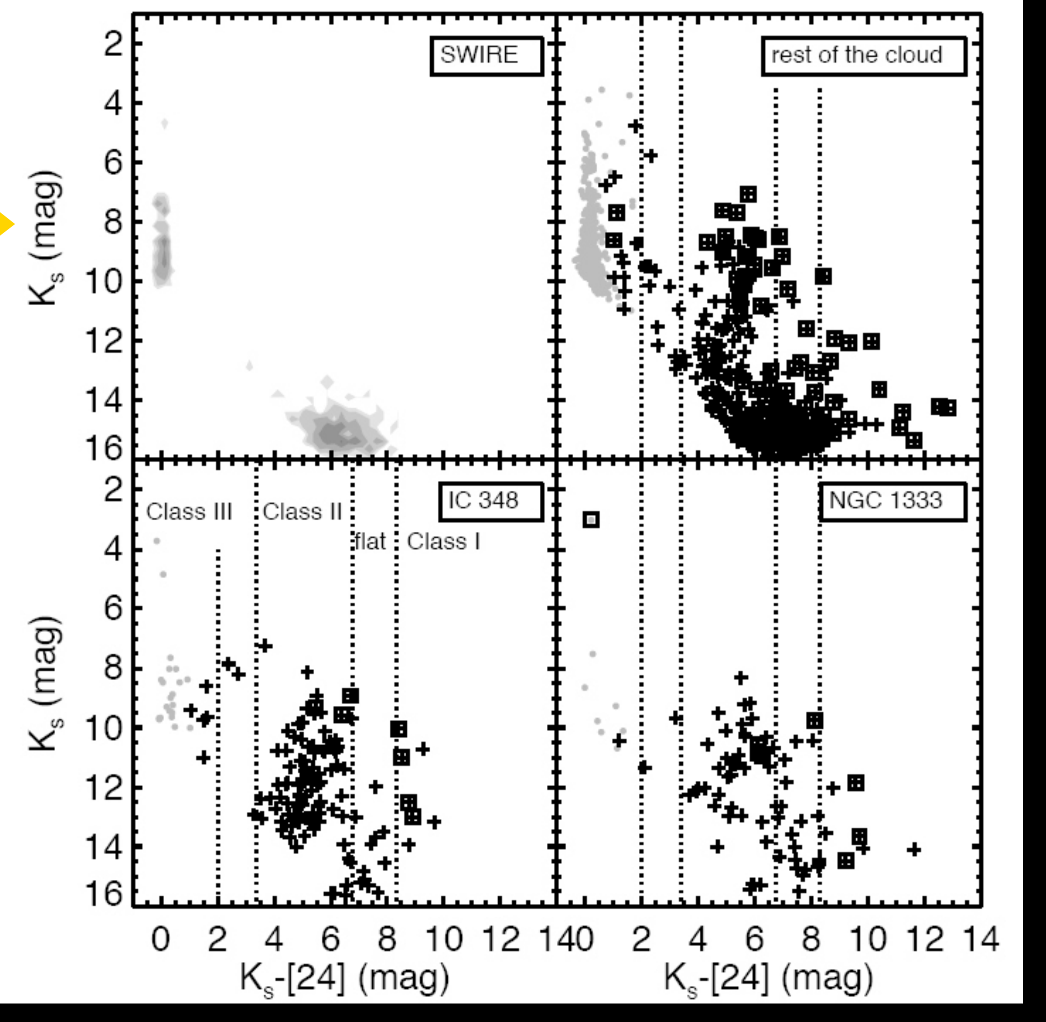

Visible (DSS / Caltech & AURA)
Infrared
Flattened Envelope around L1157 Protostar
NASA / JPL-Caltech / L. Looney (University of Illinois)
Spitzer Space Telescope • IRAC
ssc2007-19a

The c2d survey: A Rich, but contaminated sample

- In the combined catalog (5 clouds total):
  - 4.3×10^6 total sources
  - 6.1×10^5 in High Reliability Catalog
  - 6.8×10^5 with at least 3 bands (2MASS-MIPS)
    - 3.3×10^5 stars
    - 2.5×10^5 other (probably mostly galaxies)
    - 2965 candidate star forming galaxies
    - <u>1087 candidate YSOs (0.16%)</u>
    - 1035 (95%) certified YSOs by human examination

Distinguishing YSOs from background sources

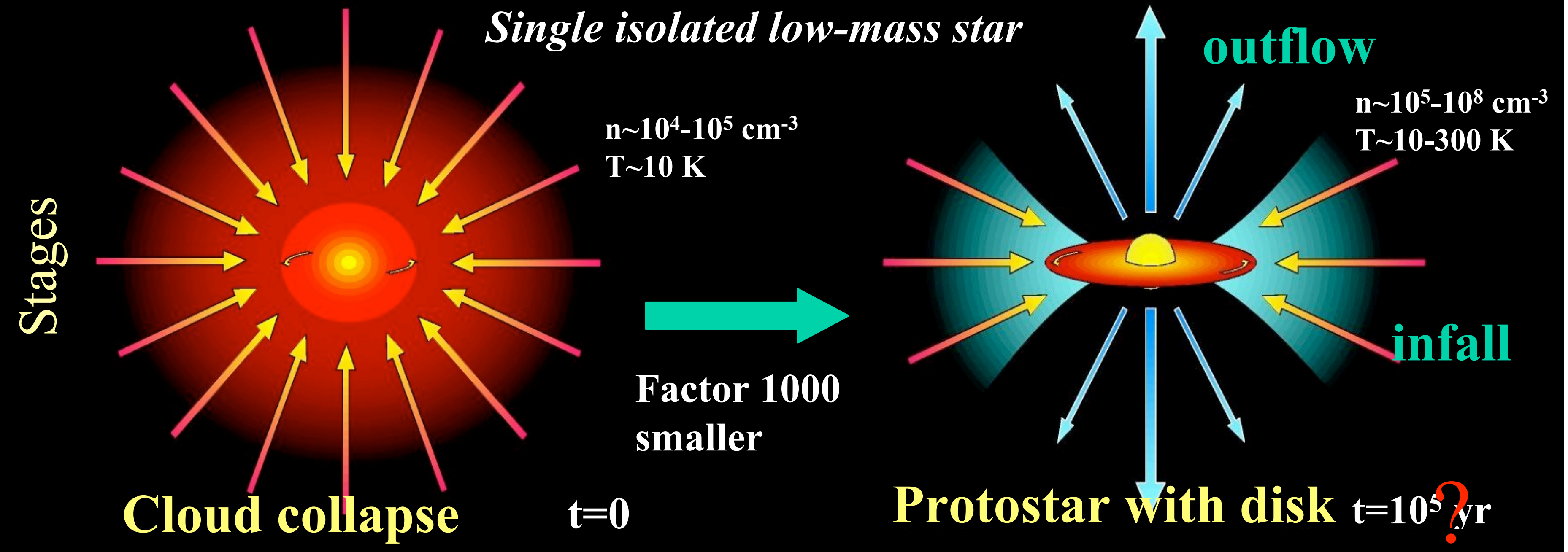
Extragalactic background



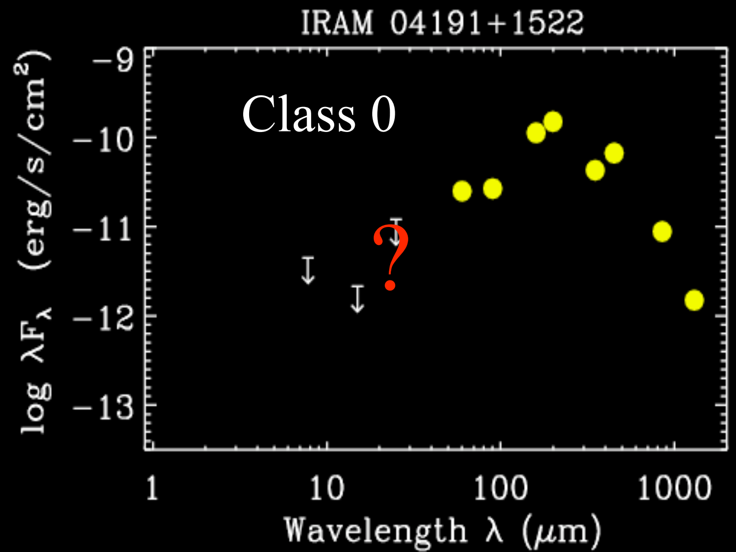
Rebull et al. 2007

Standard Evolutionary Scenario

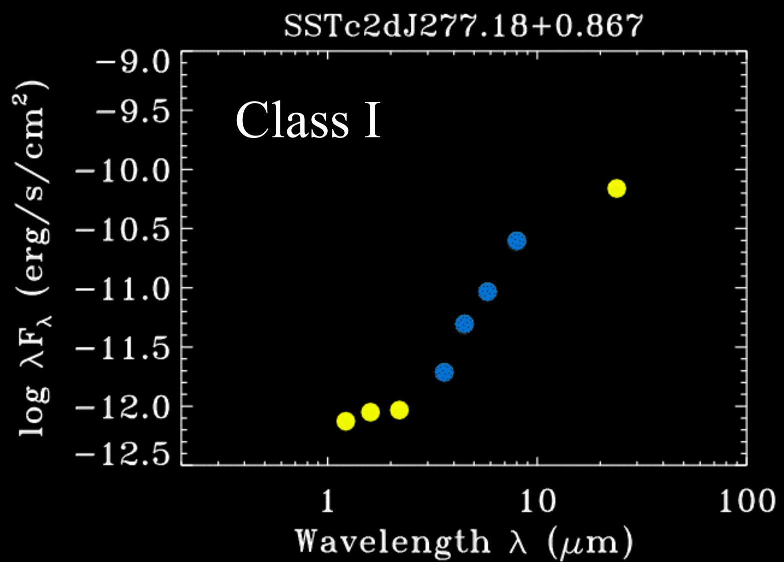
Single isolated low-mass star



Classes

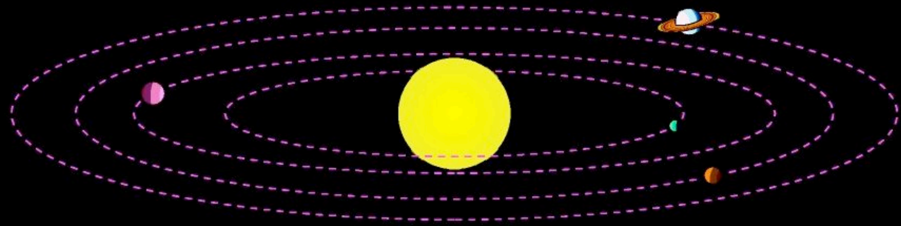


Between stages!



Note axis change!

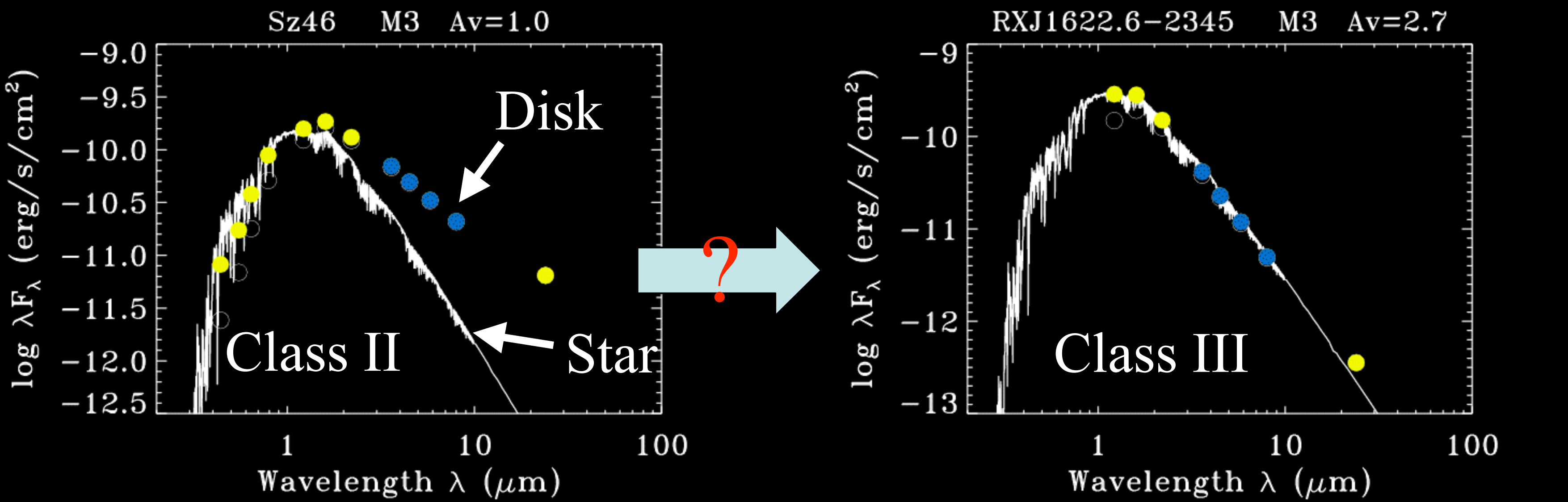
Scenario for star- and planet formation



?

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

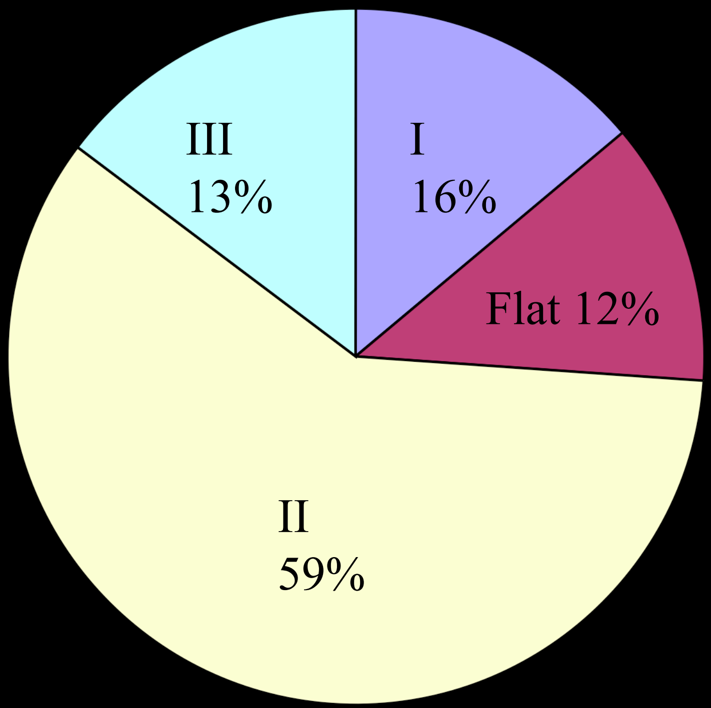
Solar system $t>10^8$ yr (?)



Previous Work

- Previous estimates for evolutionary timescales
  - t(Class I) ~ t(Class II) ~ 0.4 Myr
    - In Ophiuchus (Wilking et al. 1989)
  - t(Class I) ~ t(Flat) ~ 0.1 -0.2 Myr; Class II 1-2 Myr
    - In Taurus (Kenyon and Hartmann 1995)
    - Note t(Class II) ~ 10 x t(Class I)
  - t(Class 0) ~ 0.01 Myr (Andre, Oph)
    Rapid early accretion
  - Or t(Class 0) ~ 0.1 Myr (Visser, larger sample)
  - Issues
    - Small number statistics!
    - Differences between clouds!

Distribution of SED class for YSOs in five c2d clouds (Evans et al. 2009)



I: $\alpha \geq 0.3$

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

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

III: $\alpha < -1.6$

IF Time is the only variable

AND

IF star formation continuous for t > t(Class II)

AND

IF Class II lasts 2 Myr,

THEN

Class I lasts 0.54 Myr

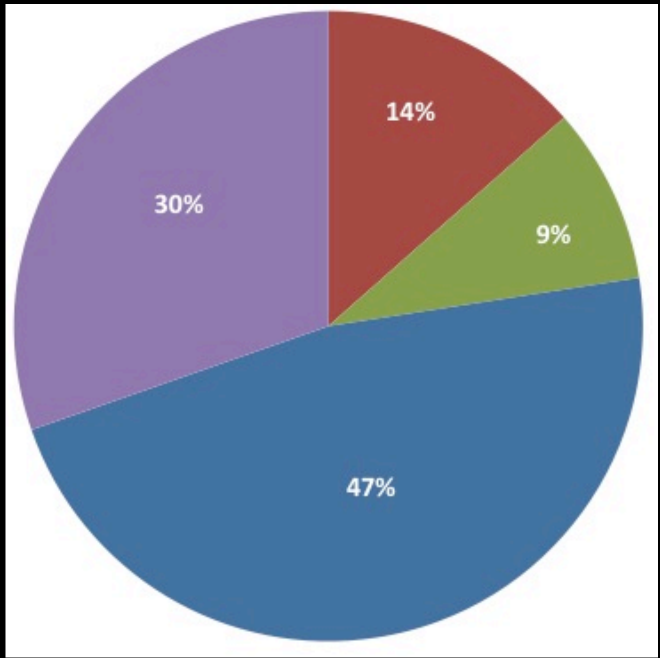
Flat lasts 0.40 Myr

Class III under-represented

Class 0 mixed with Class I

Combining c2d, Gould Belt, and GTO results for 19 nearby clouds hosting 3158 YSOs:

Evans, Allen et al. in prep



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%

For same assumptions as before:

Class I lasts 0.57 Myr

Flat lasts 0.38 Myr

(longer than most previous estimates)

<u>Caveats:</u>

GB clouds extincted
(decrease by ~0.1 Myr)

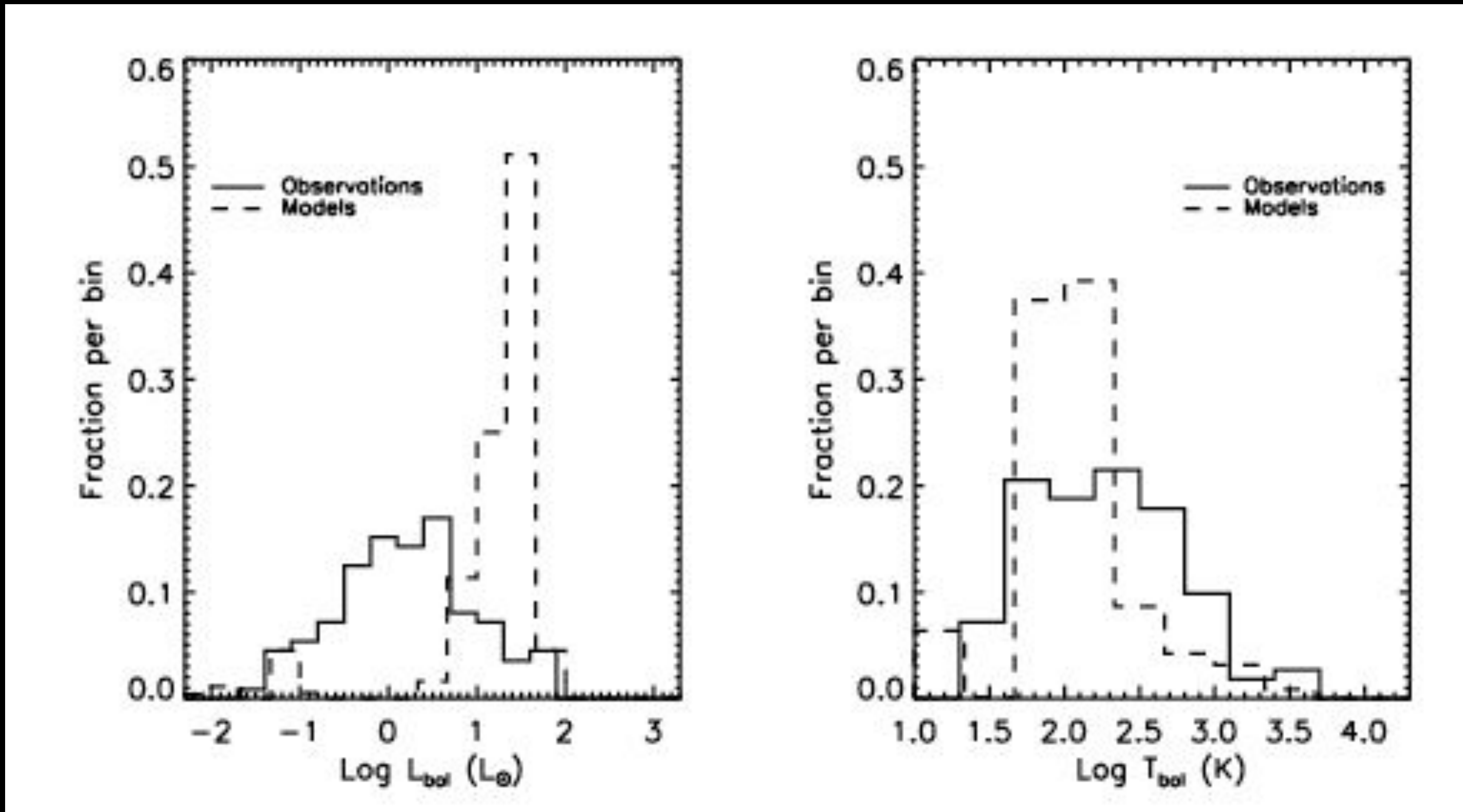
Class III census incomplete

Class III not included in timescale

Depends on *how* α is calculated

Class 0 mixed with Class I

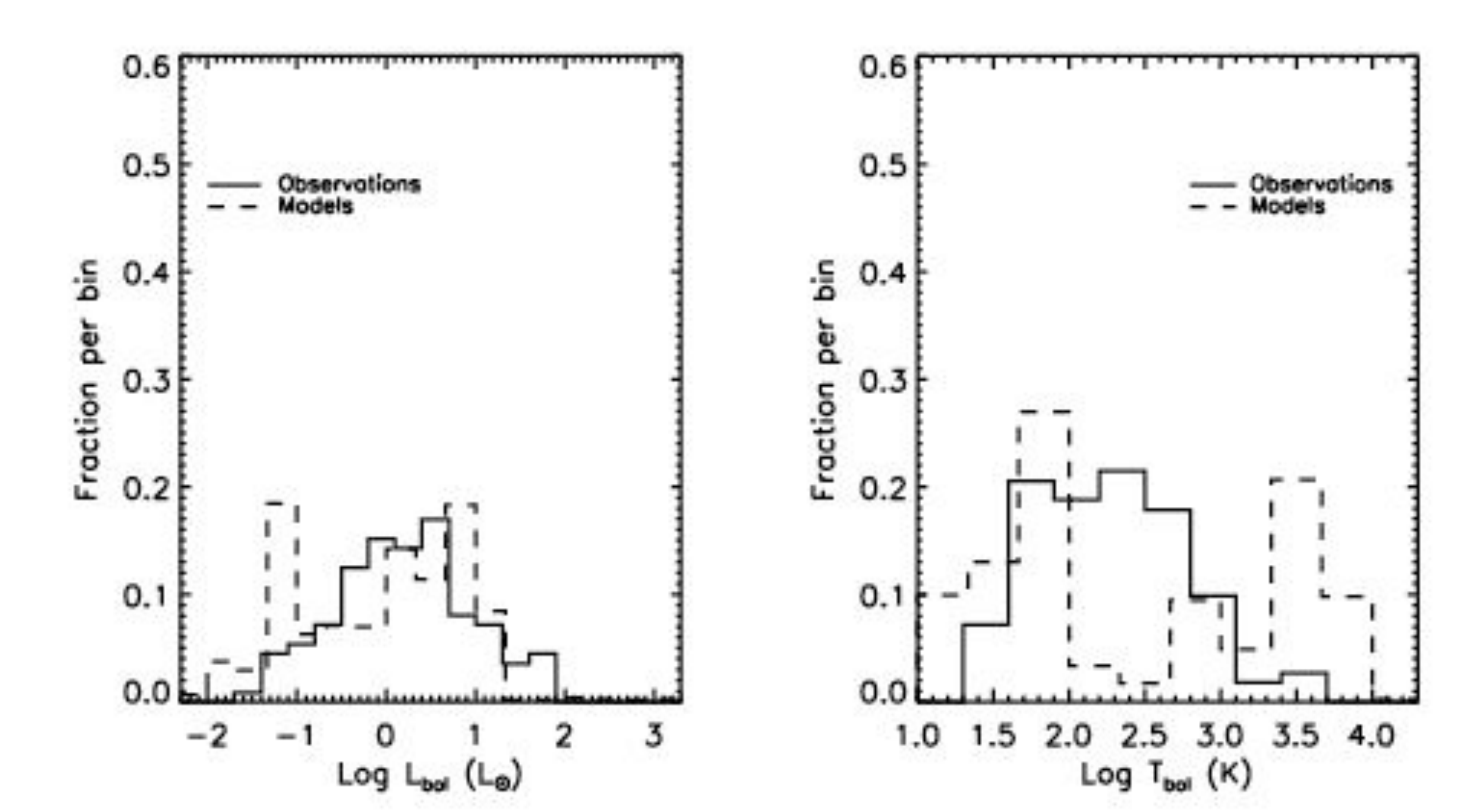
Many are under-luminous



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, and Episodic Accretion:

Stars form when we are not looking (Dunham et al. in prep)

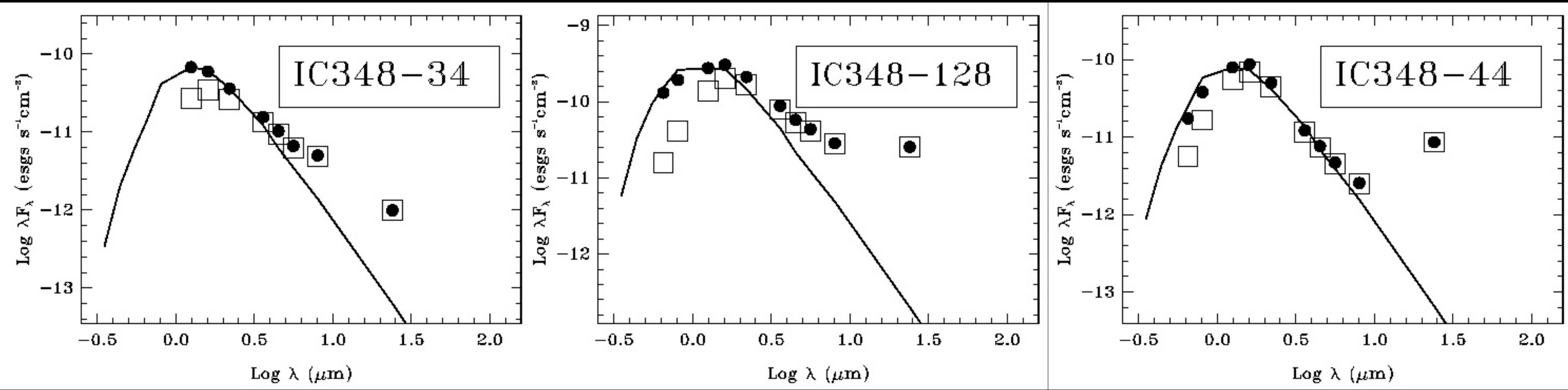


Disk Evolution

See also talks by Chen, Currie, and Meyer;

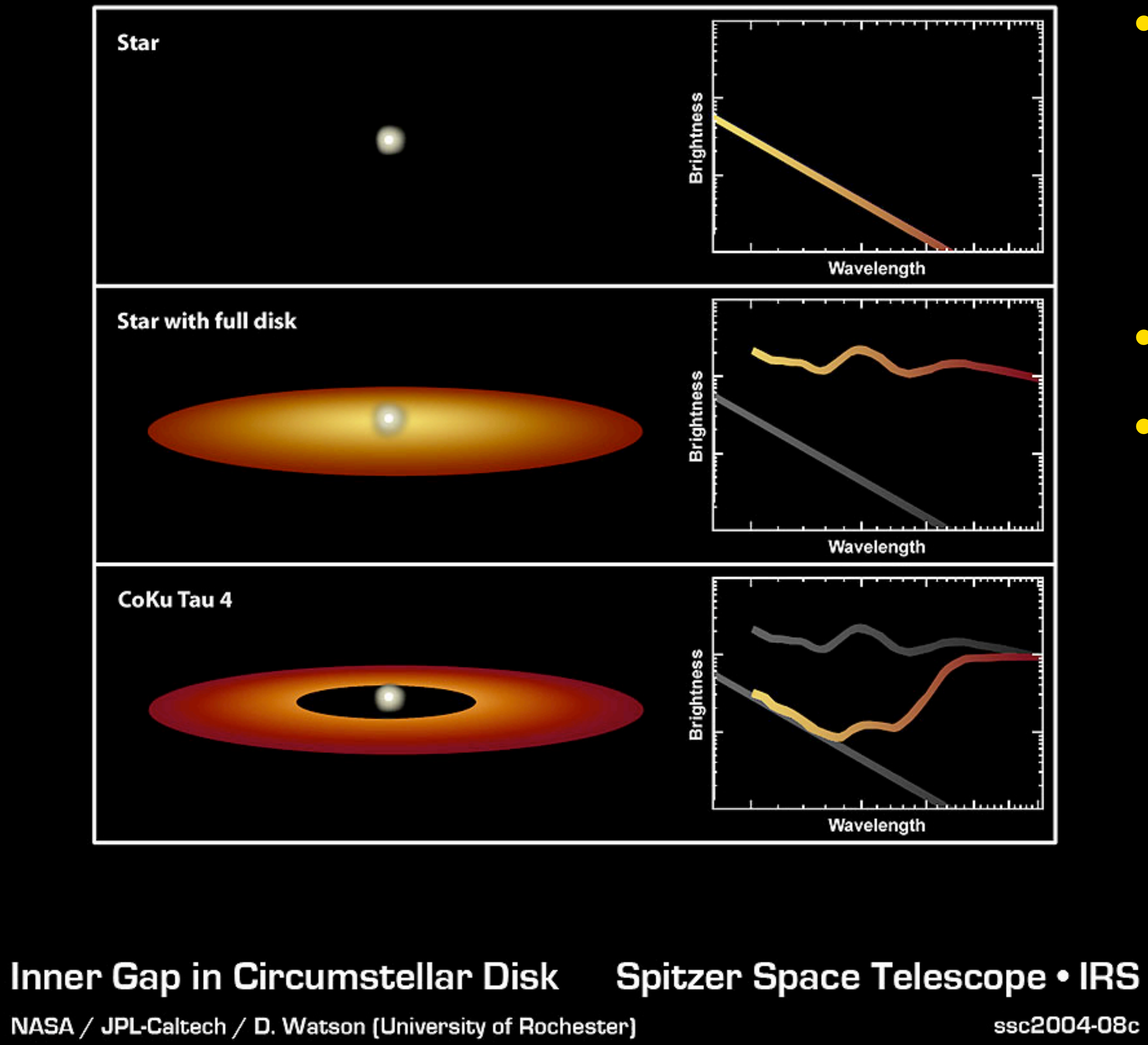
Posters A35 (Furlan) and B13 (Merin) with Spitzer work on this topic

Diversity in disk SEDs



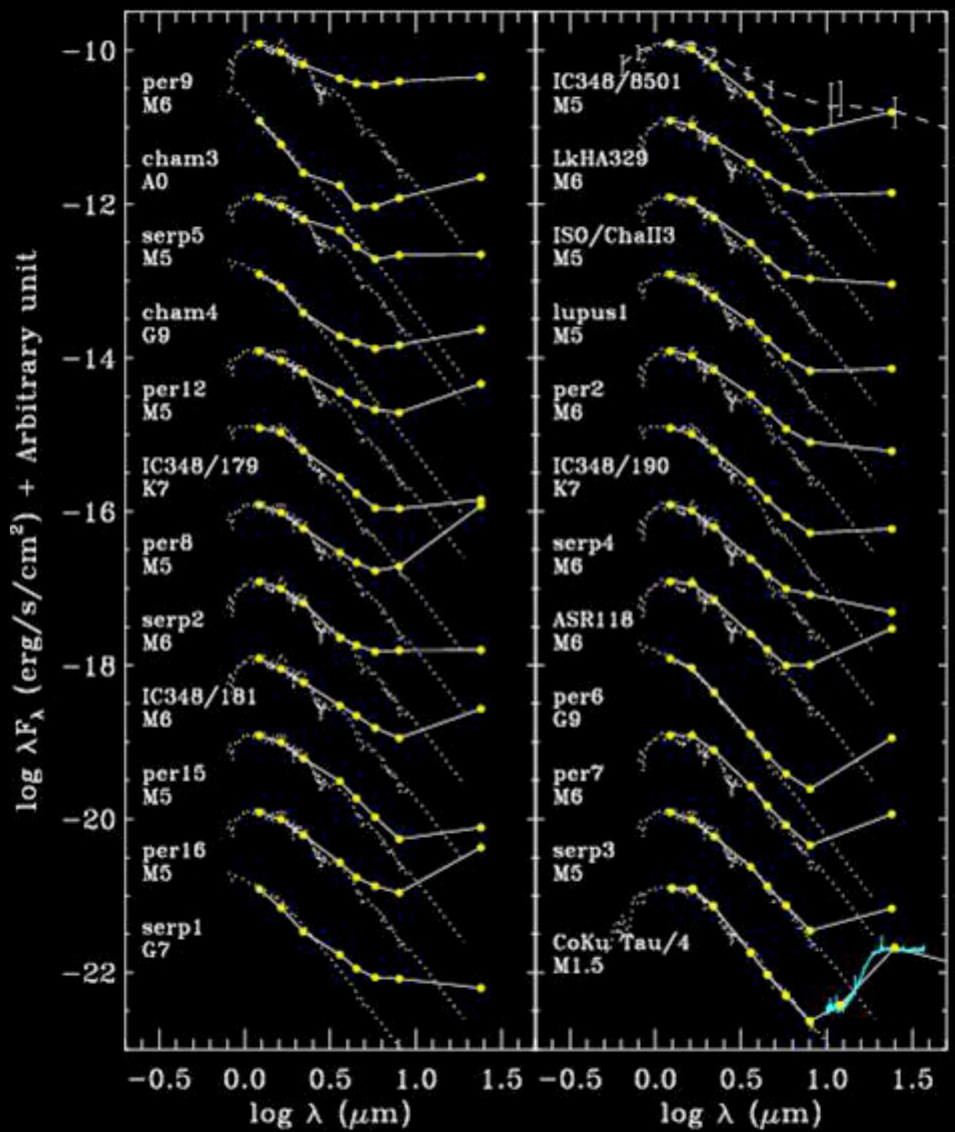
Traditional III | III, then flat | III, then rising

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



- Very young (1 Myr old) star has a central hole in its disk
- "Transition disk"
- What process has cleared dust from this inner region?
  - Agglomeration of dust into larger particles ?
  - Newborn Planet ?
  - Companion star ! See Kraus talk to follow

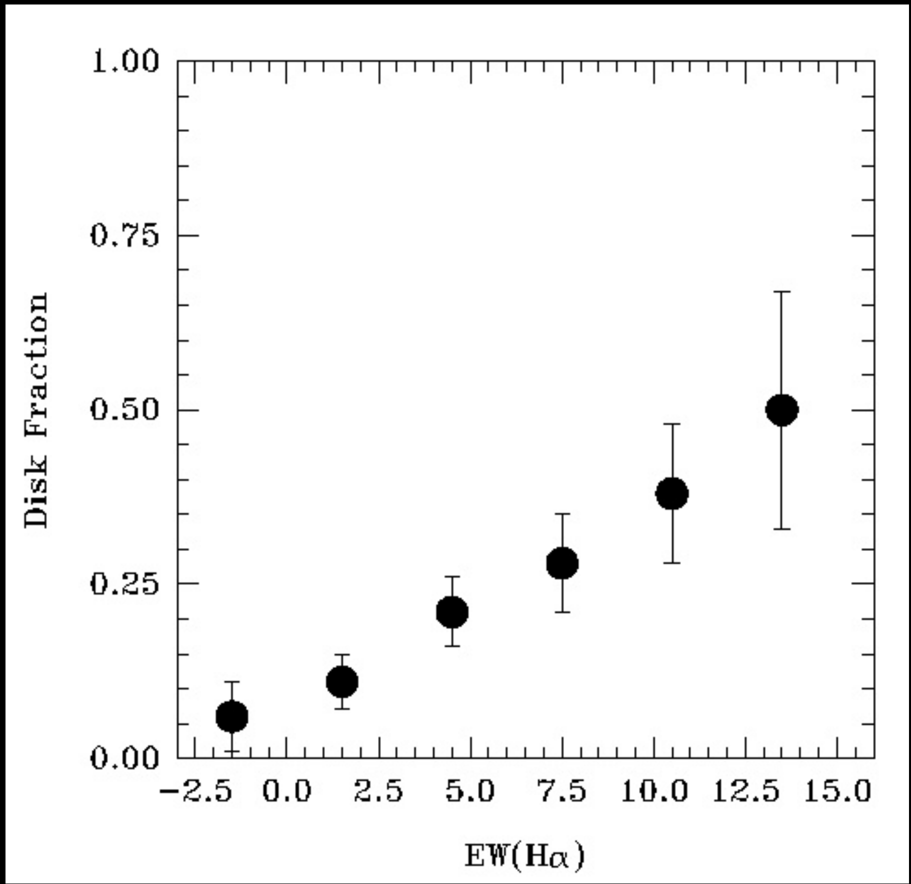
Cold disks ("transition disks" ?) in c2d

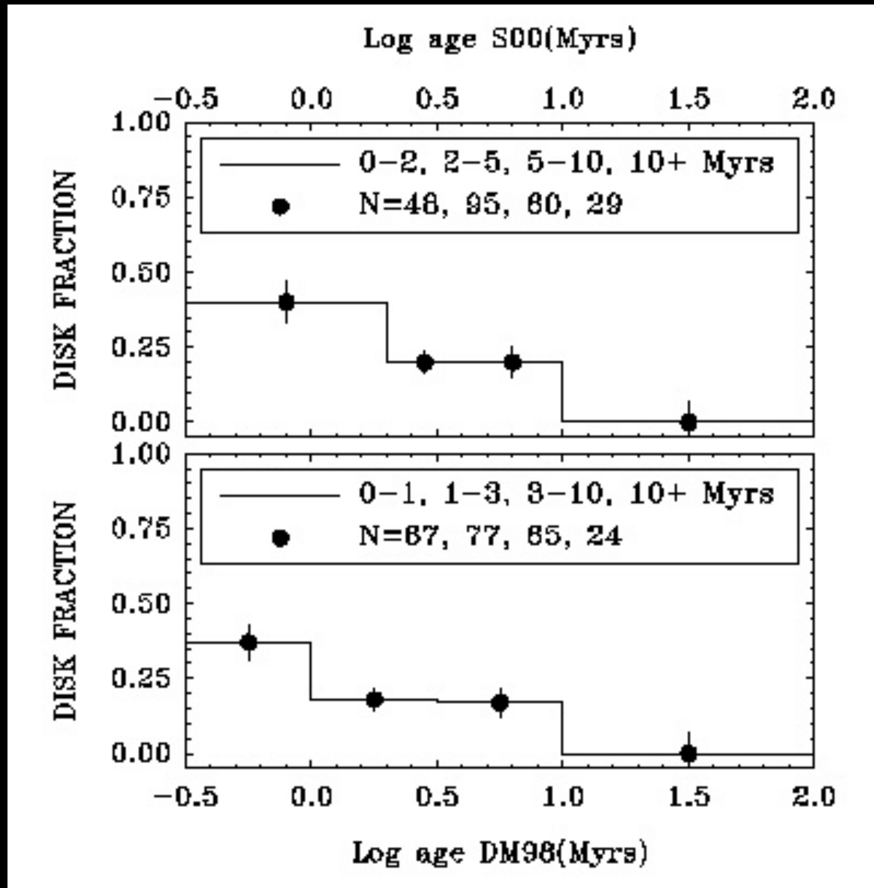


- **30 objects found with signs of having inner holes in their disks in the c2d mapped clouds (few % of disks => fast or rare?)**
- **Enlarges the sample of cold disks by a factor of 3.**
- **Large range in stellar parameters, hole sizes, dust mass in the hole, dust composition, and presence of gas.**

Merin et al. (in prep)

Tracking Disk Dissipation





Weak-line T Tauri stars projected against the clouds: disk fraction increases with Hα EW, declines with age. <u>But relative ages uncertain.</u>

Cieza et al. 2006

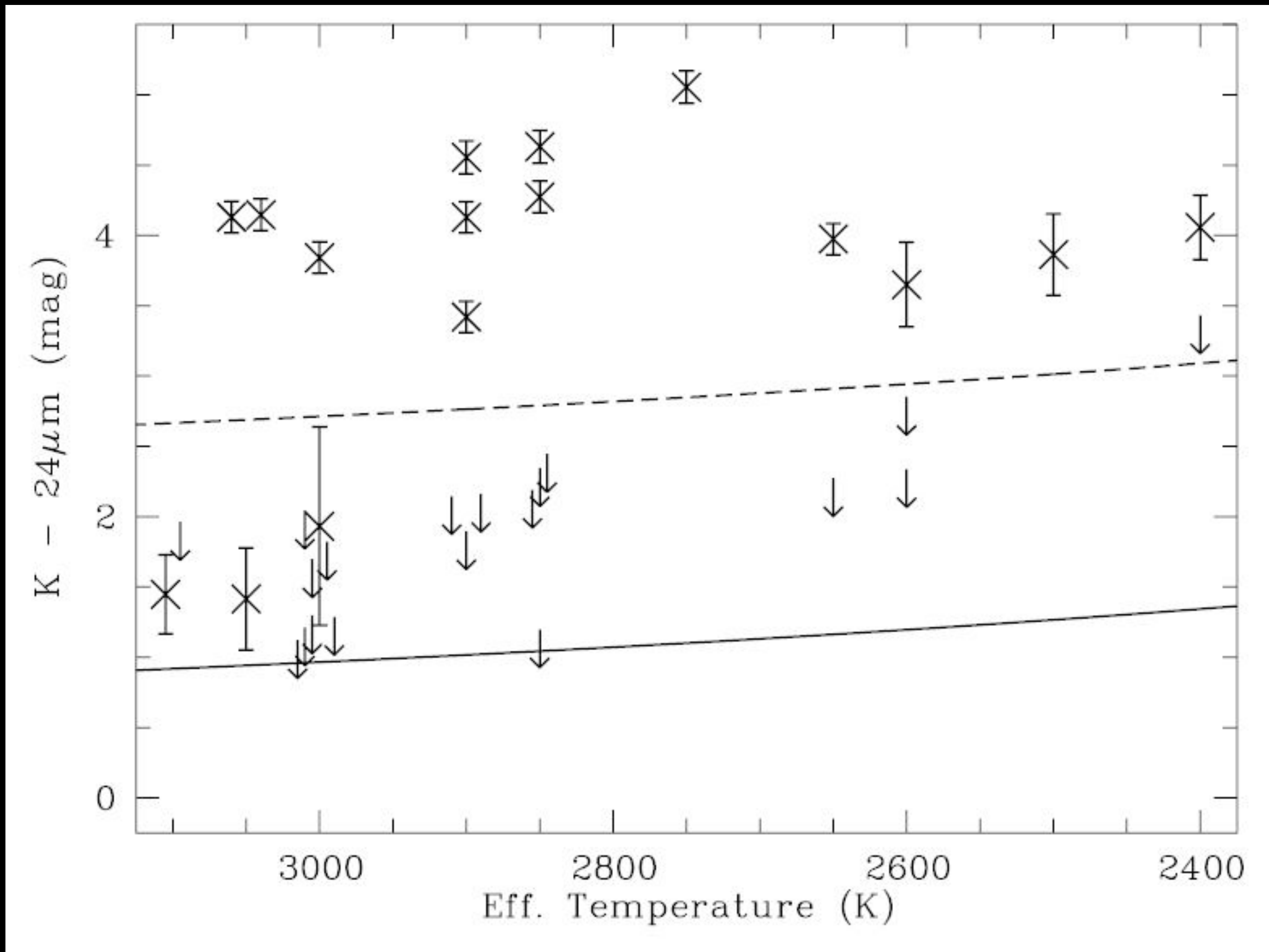
Depletion of primordial dust disks within 12 Myrs:

Young Association	24 µm excess frequency	70 µm excess frequency	MIPS inner hole frequency	Ld/L* range
eta Cha 8 Myrs Gautier et al. 2008	9/16= 56 ±18%	>5/15 = > 33±15%	0/5 Continuous disks	10^{-4} - 0.19 protoplanetary and debris disks
TW Hya 8 Myrs Low et al. 2005	7/23= 30 ±11%	>6/20 = > 30±10%	1/6 Mostly continuous disks	10^{-4} - 0.27 protoplanetary and debris disks
β Pic 12 Myrs Rebull et al. 2008	7/30= 23 ±9%	>11/30 = > 30±10%	4/11	10^{-4} –0.002 debris disks only

Disks in young Brown Dwarfs

Scholz et al. 2007

13/35 M5-M7 objects in Upper Scorpius possess circumsubstellar disks at age 5 Myrs



Star Formation Data Legacy of the Spitzer Cryogenic Mission

- Maps of ~300 square deg of the galactic plane, > 100 million sources
- Maps of ~70 square deg in nearby (d< 500 pc) star-forming regions: ~8 million total sources in Taurus, Ophiuchus, Perseus, Chamaeleon, Serpens, Auriga, Cepheus, Lupus, Orion clouds
- Access the data at http://archive.spitzer.caltech.edu/
- Access the mosaics and source catalogs at http://irsa.ipac.caltech.edu/

Key References

A combined total of >200 refereed papers so far from the two original Spitzer legacy projects in star formation. Recently published summary papers:

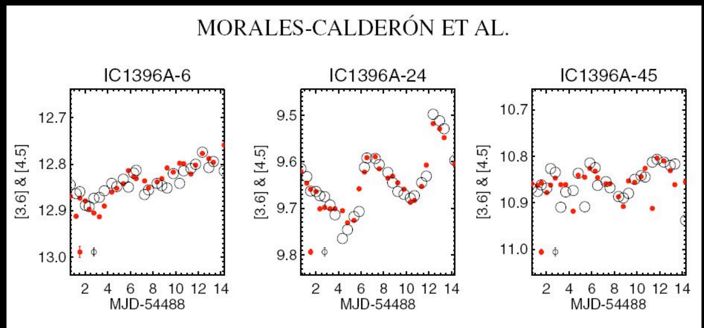
- GLIMPSE overview paper:
  Churchwell et al. 2009, P.A.S.P. 121 213
- c2d overview paper:
  Evans et al. 2009, Ap.J.Suppl. 181 321

The Spitzer Warm Mission

- Cryogen was exhausted 15 May 2009
- Telescope has equilibrated to 27 K passively
- Backup thruster system activated a week ago
- IRAC 3.6 and 4.5 μm channels operate as before; 120-1000x faster than VLT/Keck
- Cycle 6 programs started executing in July 2009
- Cycle 7 proposals tentative due date April 2010
- Spitzer Project will request funding for an additional 2 years of operations; decision will be made in mid-2010 by NASA senior review

Large YSO projects now executing in Spitzer Warm Mission

- GLIMPSE360: PI B. Whitney, 1980 hours. Nearly completes coverage of galactic plane in outer galaxy.
- YSOVAR: PI J. Stauffer, 550 hours. Timeseries monitoring of 11 clusters + Orion. 80 epochs will yield ultradeep fields.



See also posters
B1 (Juhasz) and
B3 (Kospal) for current
Spitzer YSO variability studies

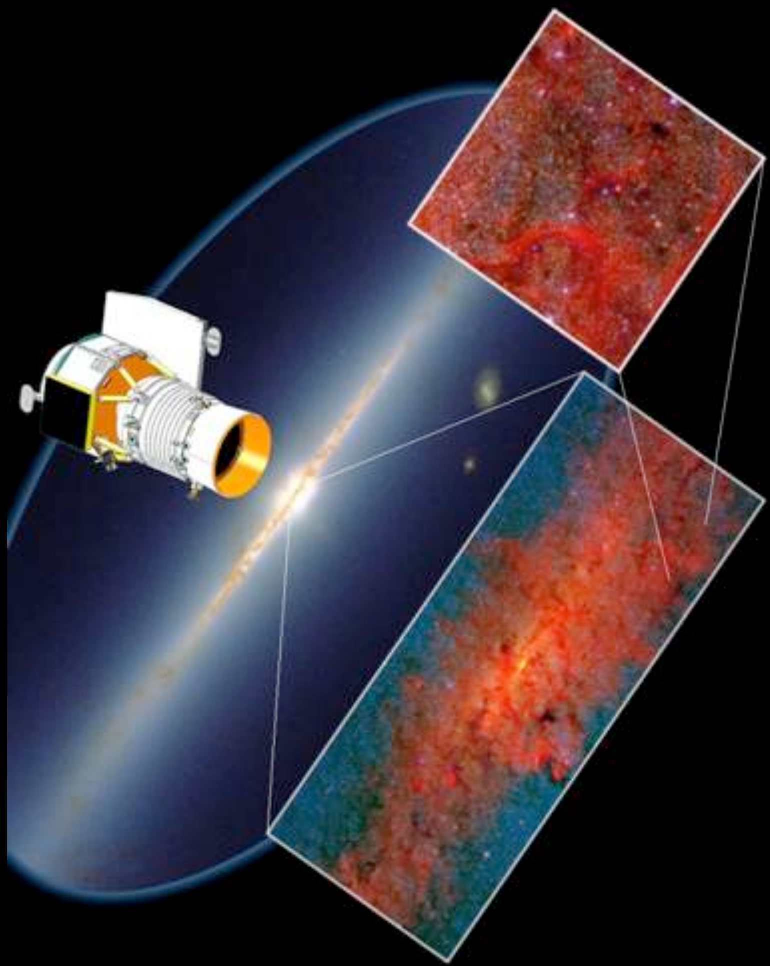
Akari

- Cryogenic 68.5 cm telescope
- Sun-synchronous orbit
- Variety of observing modes
  - All-sky MIR survey (sensitivity 50 mJy @ 9 μm, 120 mJy @ 18 μm; 9” resolution)
  - All-sky Far-IR scan mapping (1 Jy @ 65 μm, 0.2 Jy @ 90 μm, 1 Jy @ 140 μm, 2.5 Jy @ 160 μm)
  - NIR photometry and spectroscopy
- IC 4954 & 4955 results Ishihara et al. 2007. Numerous papers in press on bright objects.
- Spring 2010 initial public catalog release
- Currently in the midst of a “warm” mission at 40K

Wide Field Infrared Survey Explorer

Science

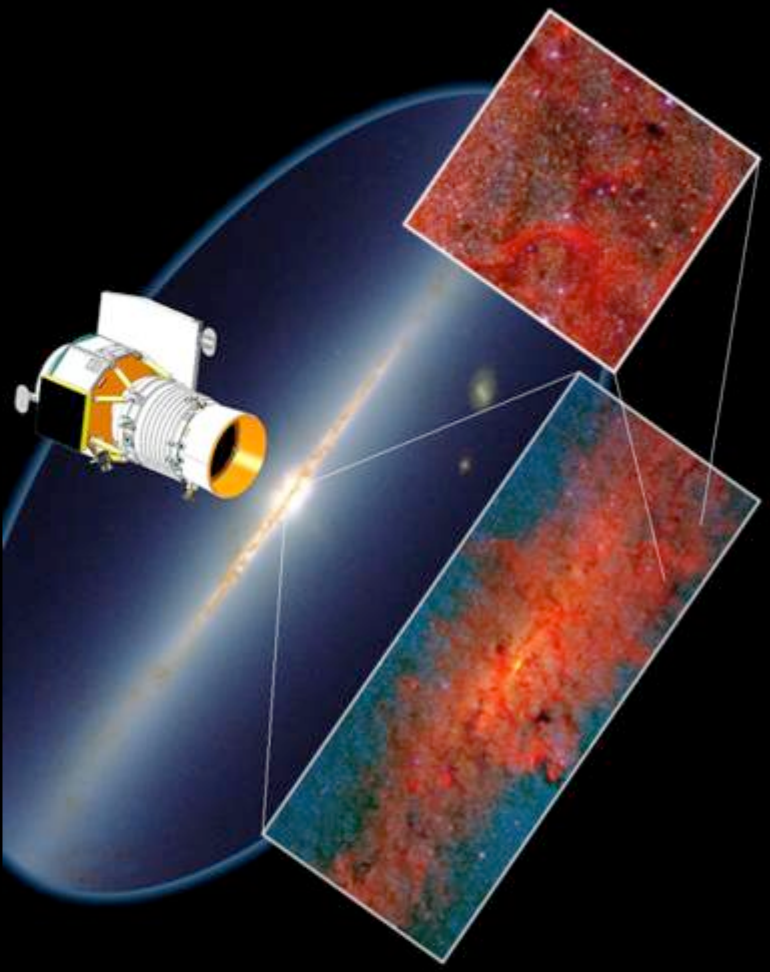
- *Find the most luminous galaxies in the universe*
- *Find nearest field brown dwarfs to the sun*
- *Catalog near-Earth asteroids*
- *Provide the essential reference star catalog for JWST*
- *Provide lasting research legacy as did IRAS*



Wide Field Infrared Survey Explorer

Salient Features

- *All-sky mid-IR survey in four bands using 1024x1024 arrays*
- *40 cm telescope operating at <17K; solid hydrogen cryostat*
- *Operational life: 10 months*
- *Sun-synchronous 6am/6pm 500km orbit*
- *Scan mirror provides efficient mapping.*
- *Each source detected 8x for redundancy*



More WISE details

- Launch currently scheduled for 07 Dec 2009
- Band centers 3.4, 4.6, 12 & 22 microns
- Sensitivity ~ 0.12, 0.16, 0.85 & 4 mJy
- Angular Resolution 6, 6, 6 & 12 arc-seconds
- Position accuracy 0.5 arc-seconds with respect to 2MASS reference frame
- Data release plans:
  - Preliminary release of 50% of the sky 6 months after last data taken; would be spring 2011
  - Final release 11 months later
- Data products include image atlas and point source catalog

WISE circumstellar disk science

- All-sky survey fills in edges/gaps in Spitzer maps of star-forming regions. Will cover isolated or high latitude clouds not mapped by Spitzer.
- Enables YSO variability studies vs. Spitzer archival data
- Should identify field stars with 22 μm excess $\rightarrow$ could lead to discovery of new young moving groups like TW Hya association

Conclusions

- With the success of Spitzer and Akari, the start of Herschel, and hopeful success of WISE, the decade 2003-2012 should stand out as a golden age for disk science with thermal infrared surveys.
- Follow up of these results should occupy the community for a long time (insert your favorite telescope here).
- Thanks to all who made this possible