(Some things learned from)
Spitzer surveys of nearby molecular clouds

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With
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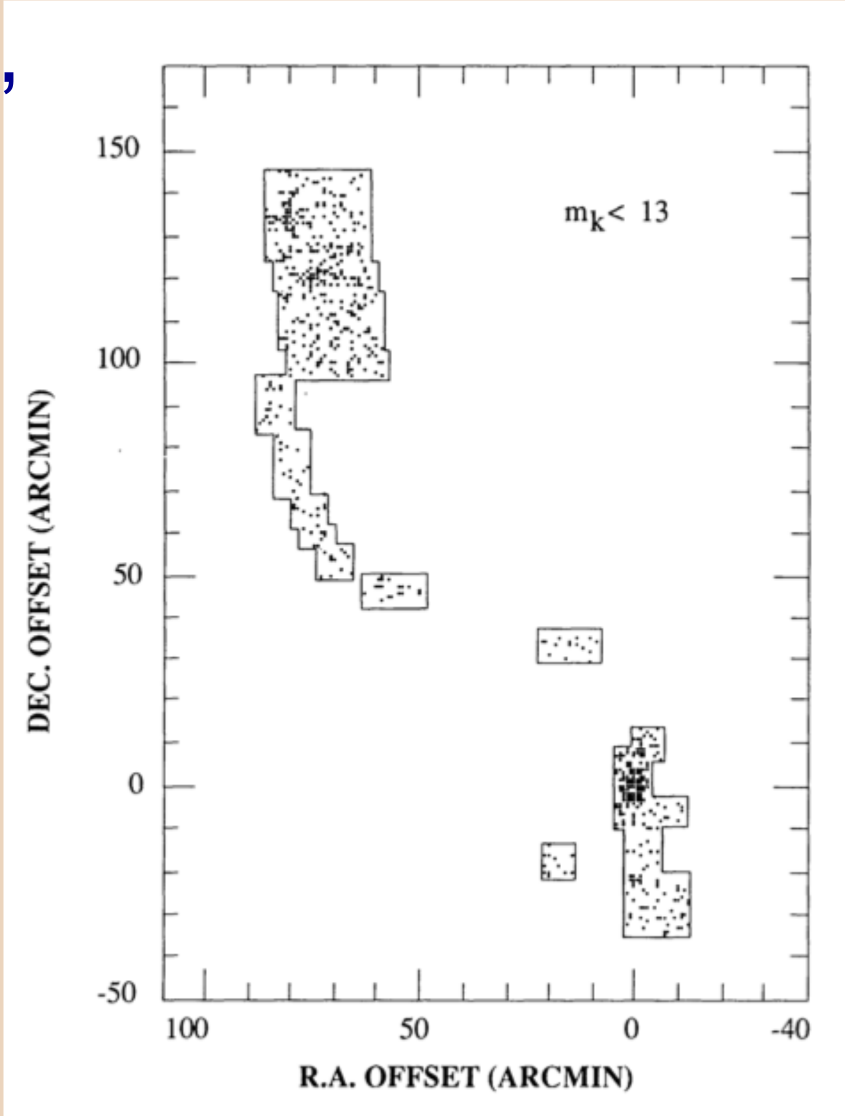
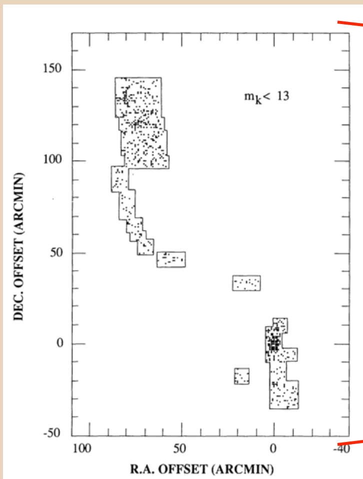
Mapping stellar distributions

Orion "then"

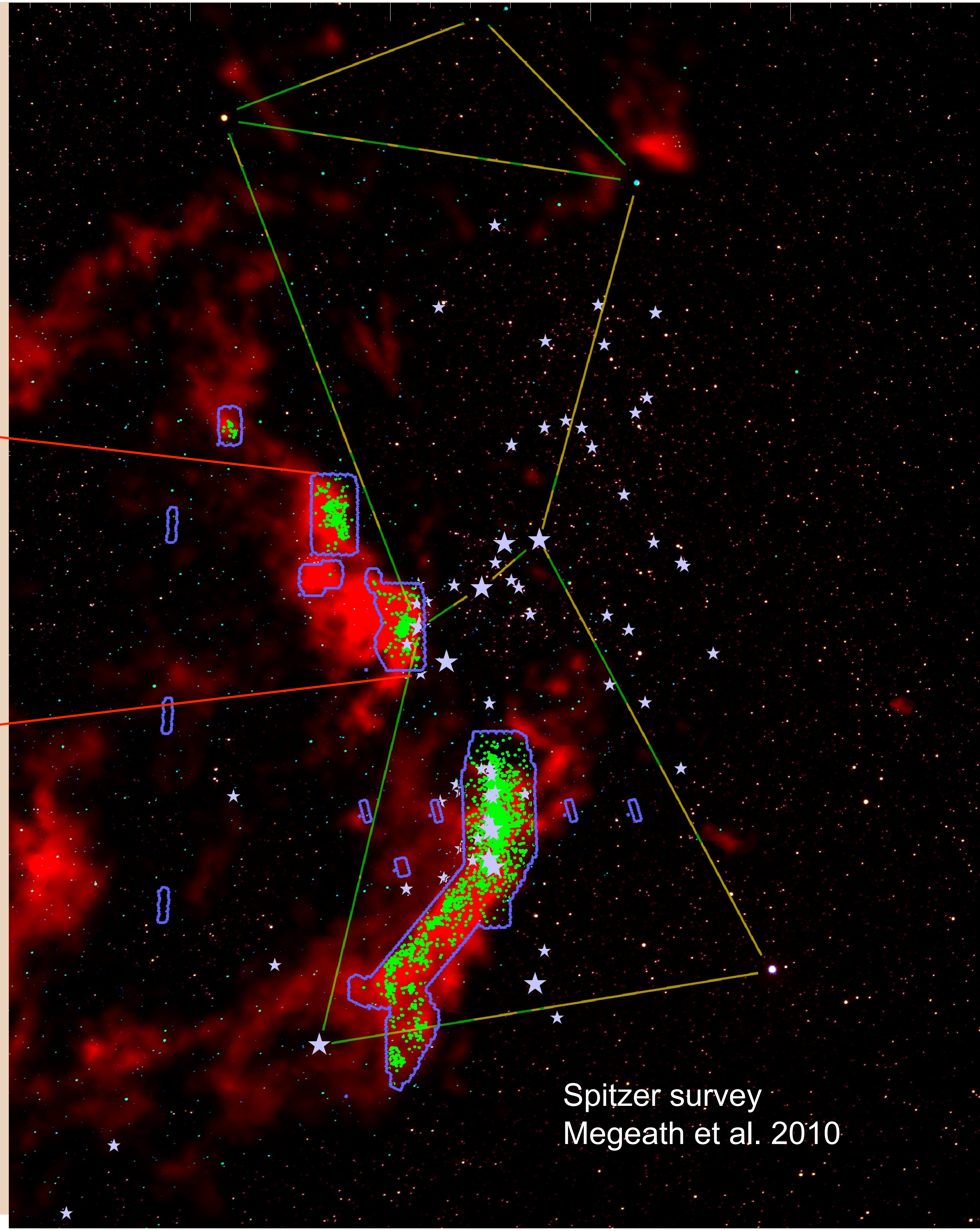


Near-IR imaging survey
E. Lada et al. 1991

and now

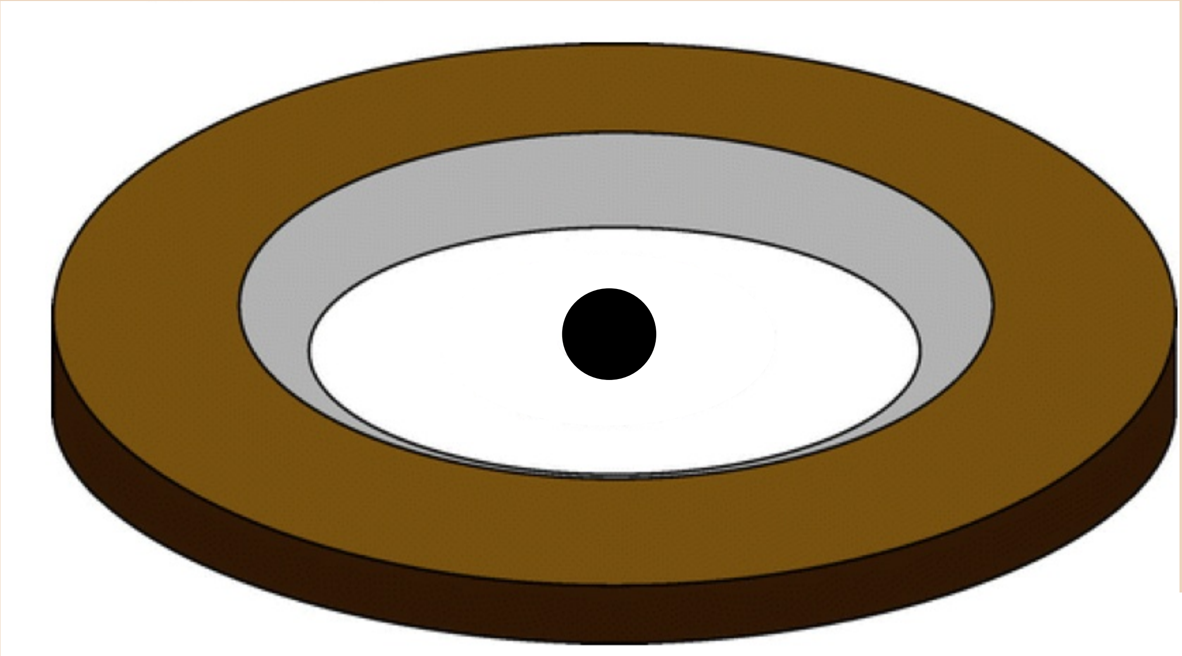


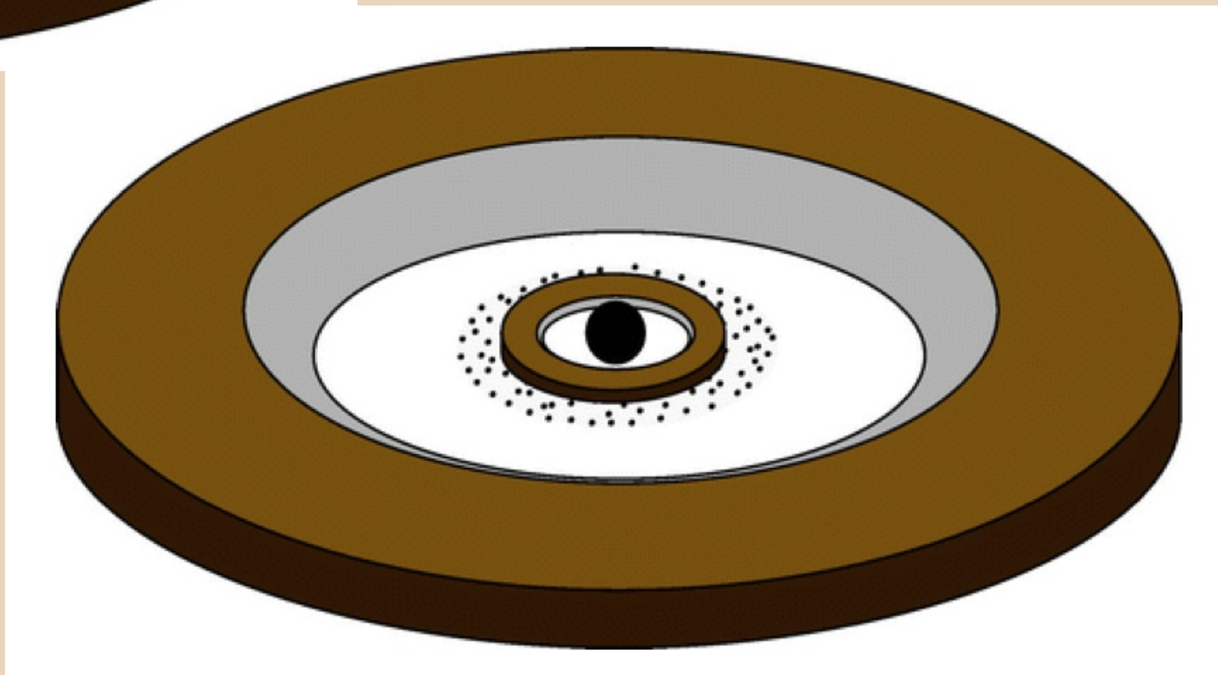
150
100
50
0
-50
100
50
0
-40
m_k < 13
DEC. OFFSET (ARCMIN)
R.A. OFFSET (ARCMIN)



Spitzer survey
Megeath et al. 2010

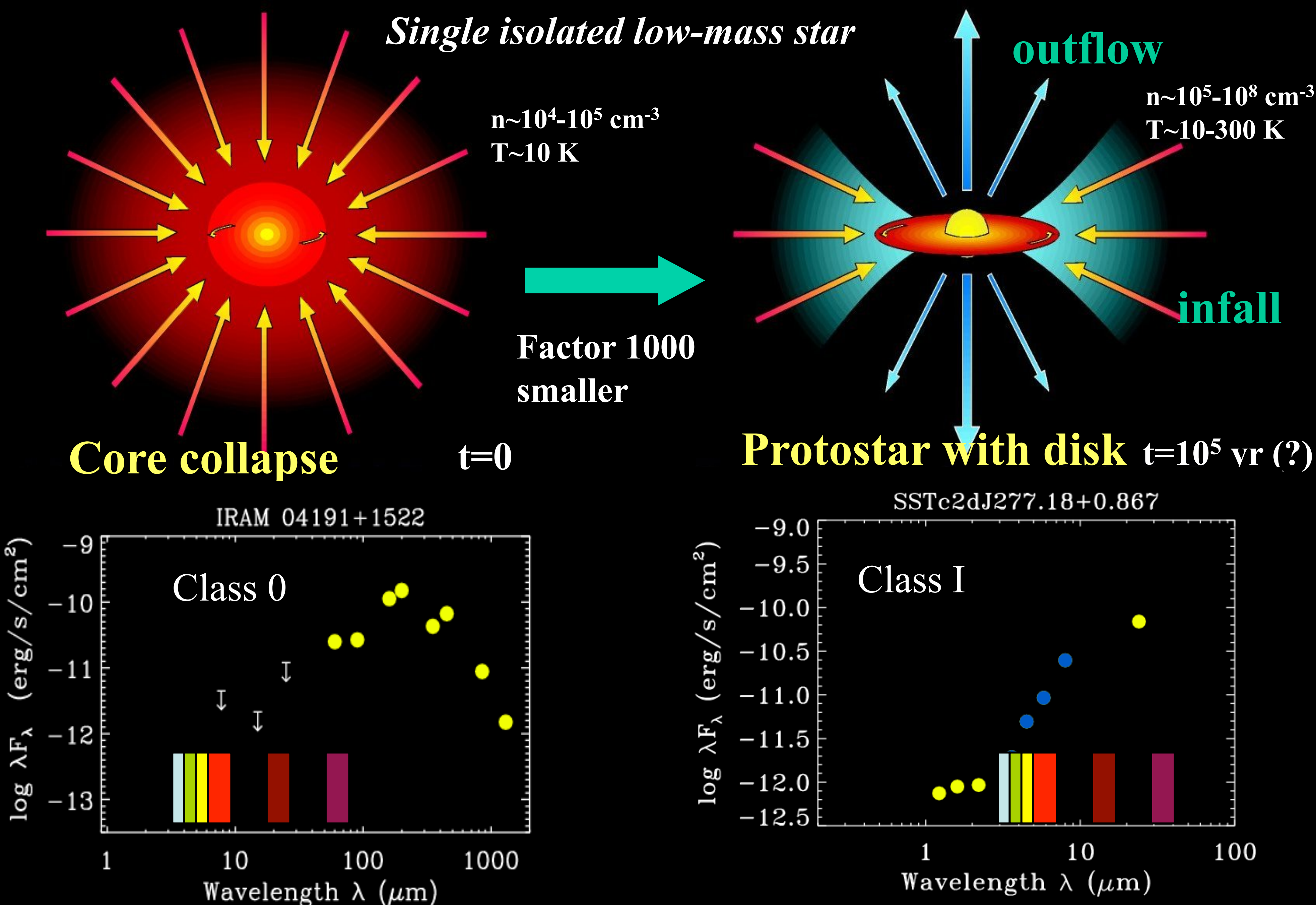
disk evolution





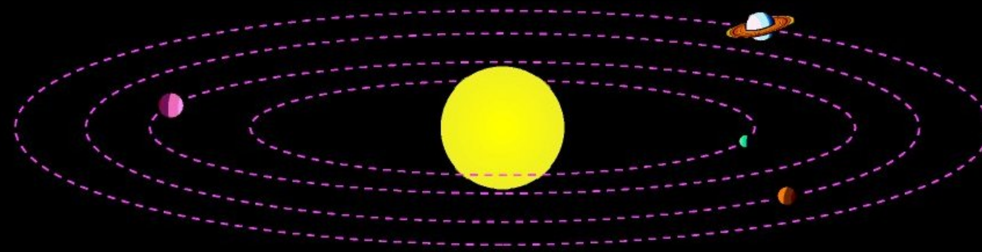
Espaillat et al. 2008

Standard Evolutionary Scenario



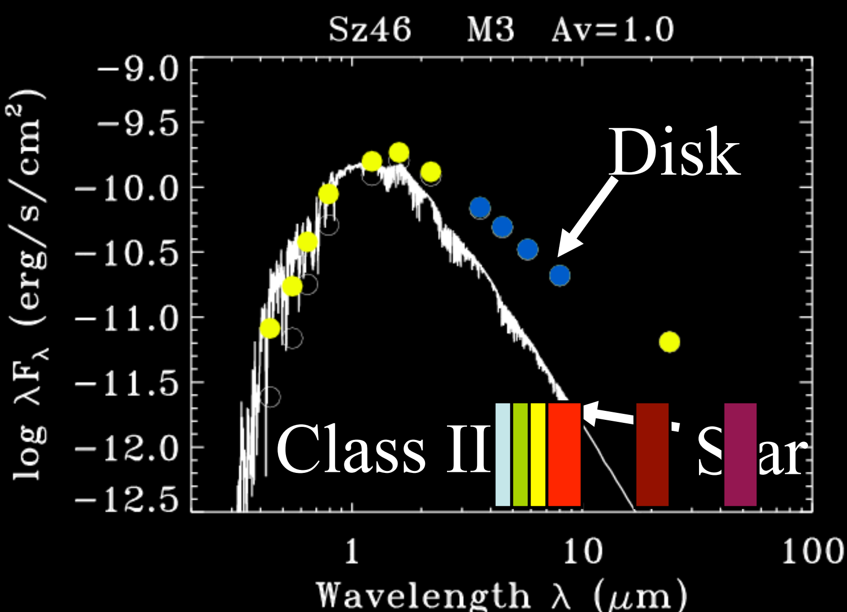
Note axis change!

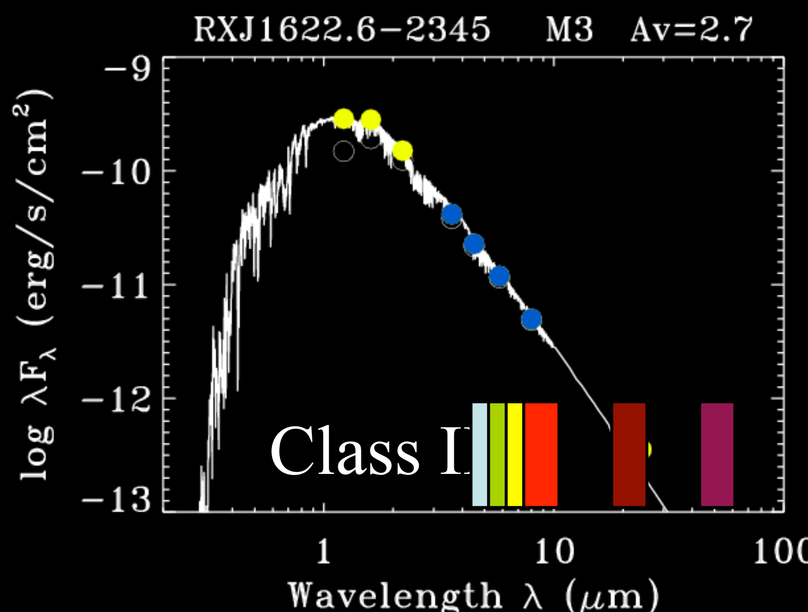
Scenario for star- and planet formation



Formation planets $t=10^6\text{-}10^7$ yr

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





Outline of talk

- Cloud-wide spatial distributions of young stars

  (see also Bressert talk tomorrow)

- Star formation rates and gas surface densities

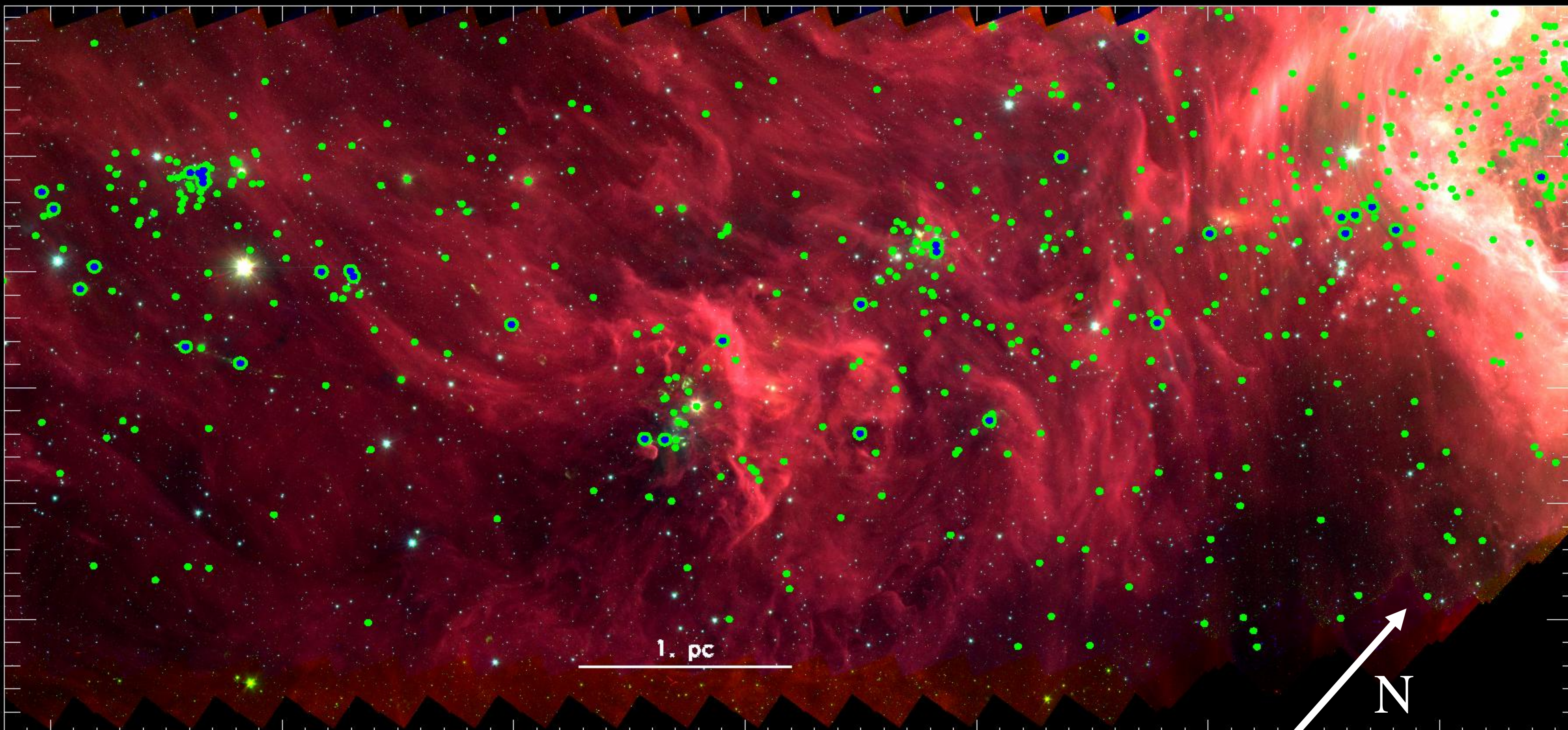
  (how the MW stacks up to other galaxies)

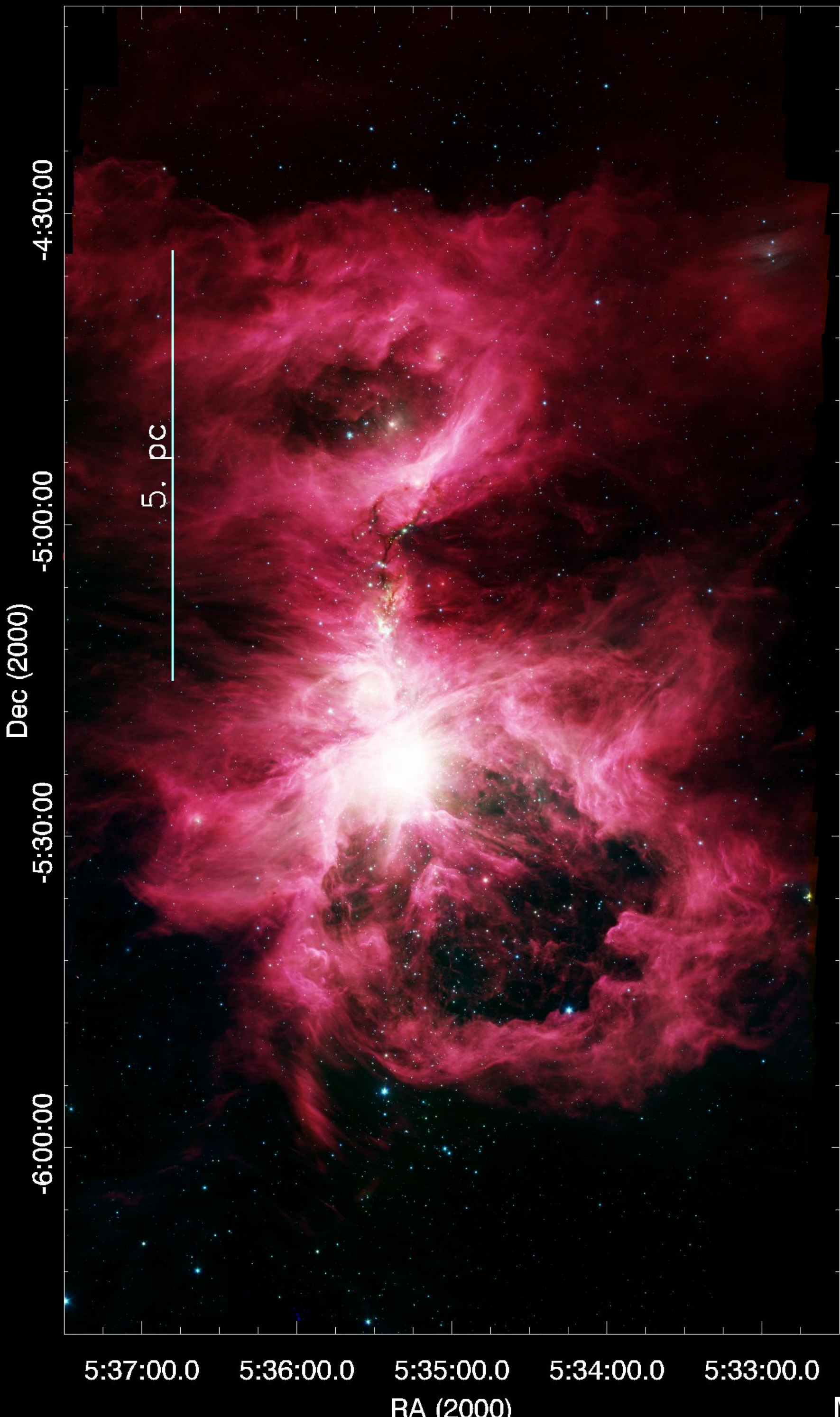
- Disk morphology and evolution

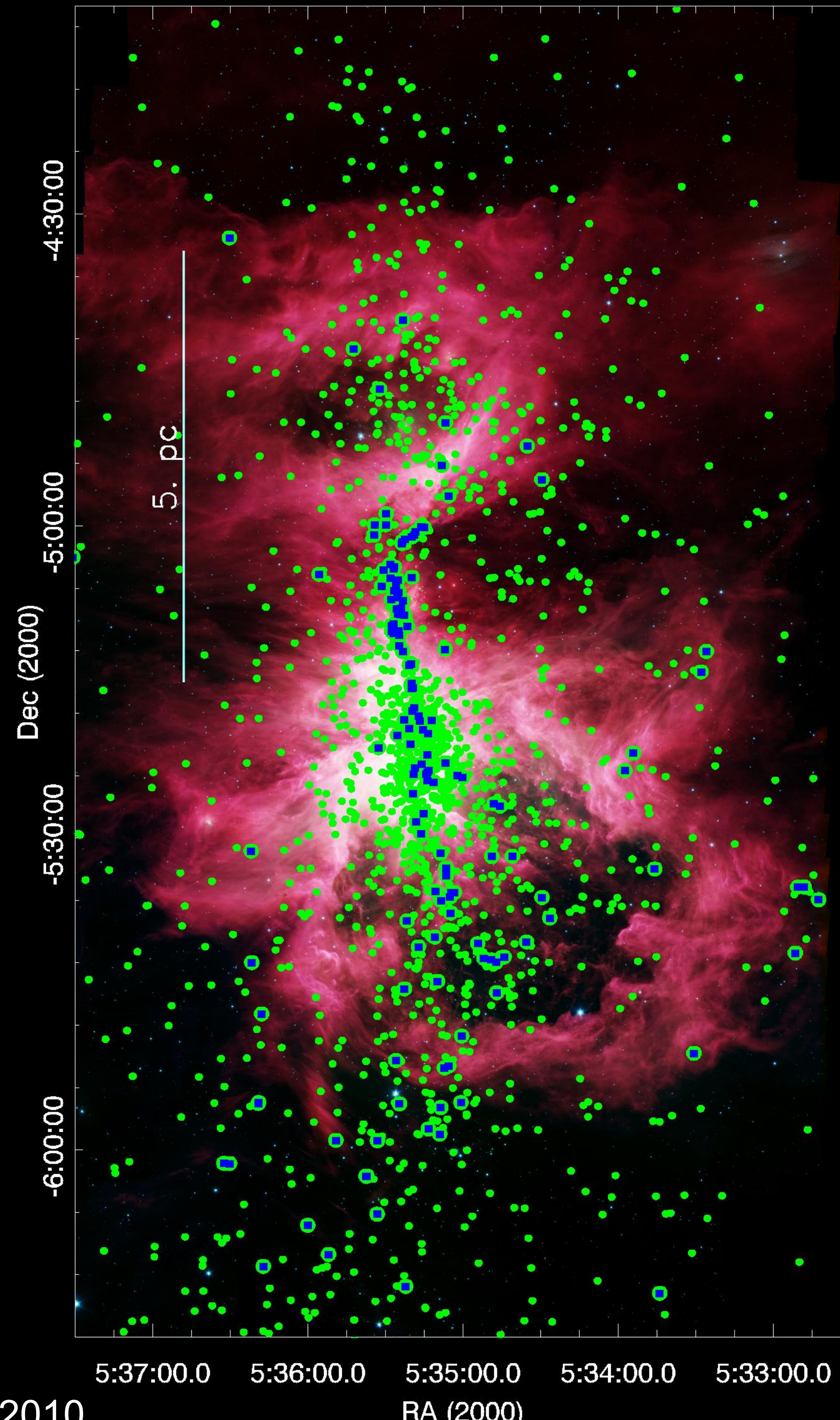
  (implications for planet formation)

L1641 in Orion A

Small Green Circles: IR-ex sources, Big Green/Blue Circles: Protostars

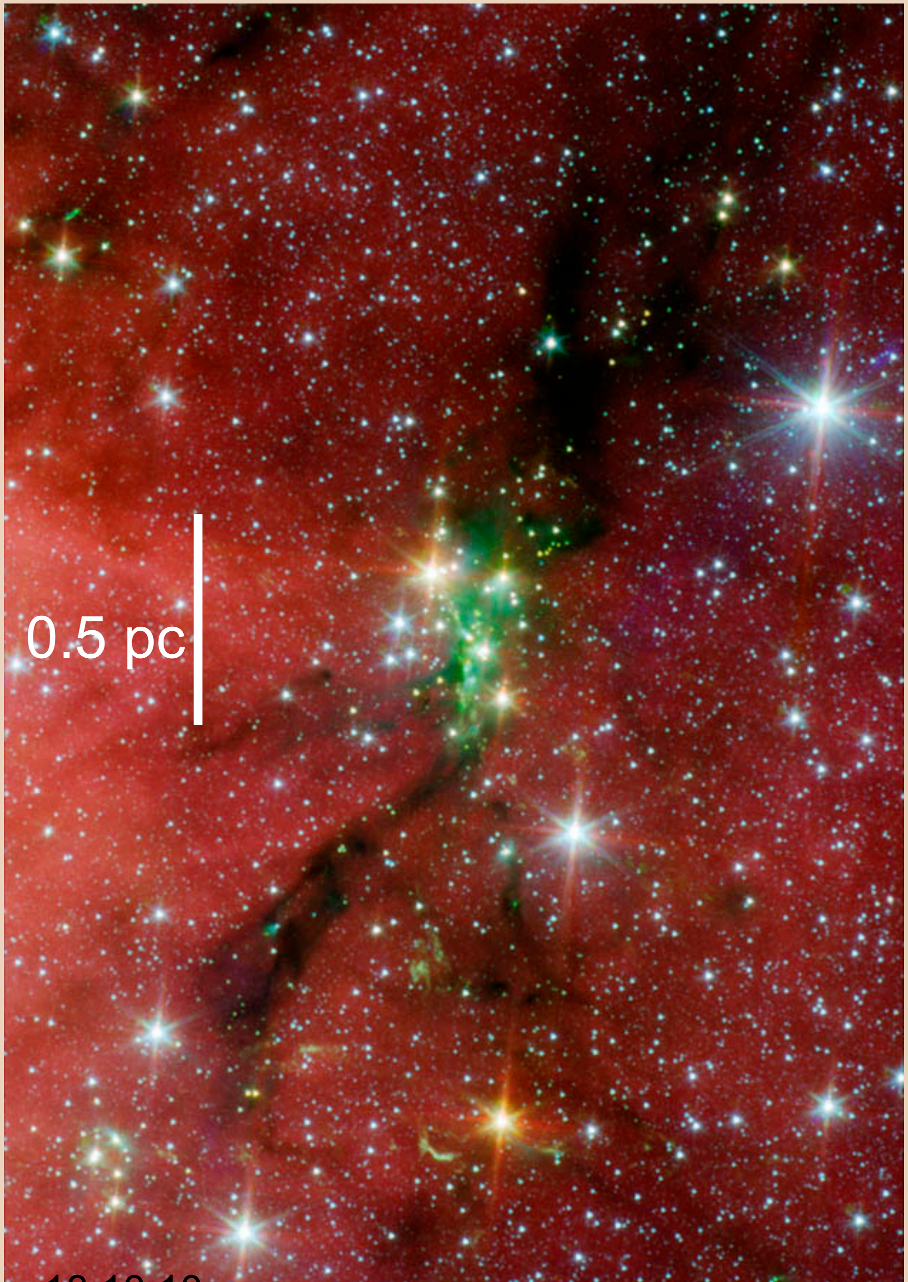




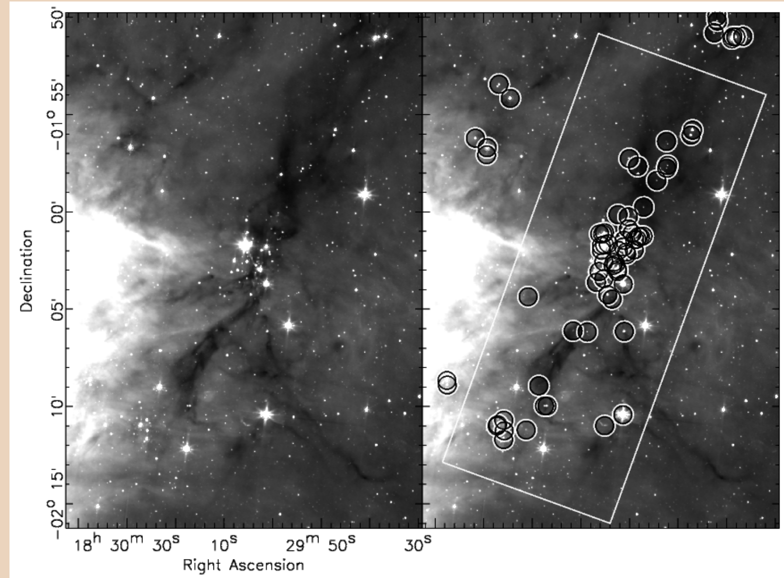


Megeath et al. 2010

Serpens South Young embedded cluster



Discovered by Gould Belt Legacy Survey



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

==> Likely probing primordial cluster structure.

(Gutermuth et al. 2008)

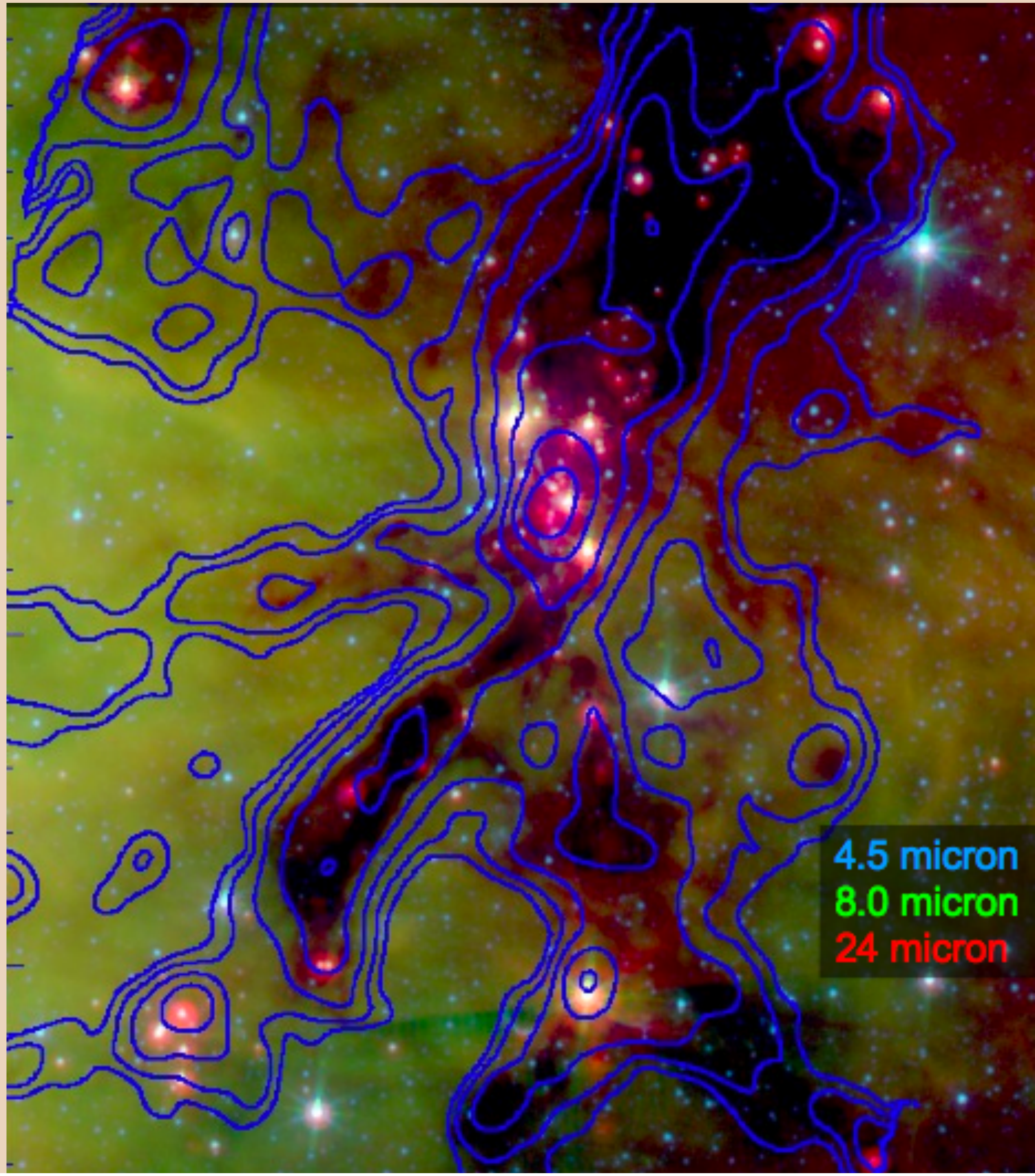
Serpens South

1.1mm continuum map (AzTEC/ASTE)

Contours: 30 mJy / bm
(x 2 per level)

Central peak ~4 Jy / bm

Millimeter emission follows absorption feature



Spitzer Surveys for nearby young stars

- Taurus Legacy project
  - Nearly complete survey of Taurus
- Cores to Disks (c2d) Legacy Project (d< 500 pc)
  - Surveys of 7 nearby "large" clouds and many small ones
  - Complementary molecular line and dust continuum maps
- Gould Belt Legacy Project (d < 500 pc)
  - Surveys of 13 nearby "large" clouds to complete census
- Regions of massive SF (400 pc – 2 kpc)
  - Orion (400 pc)
  - Cep OB3 (1 kpc)
  - W3/W4/W5 (2 kpc)

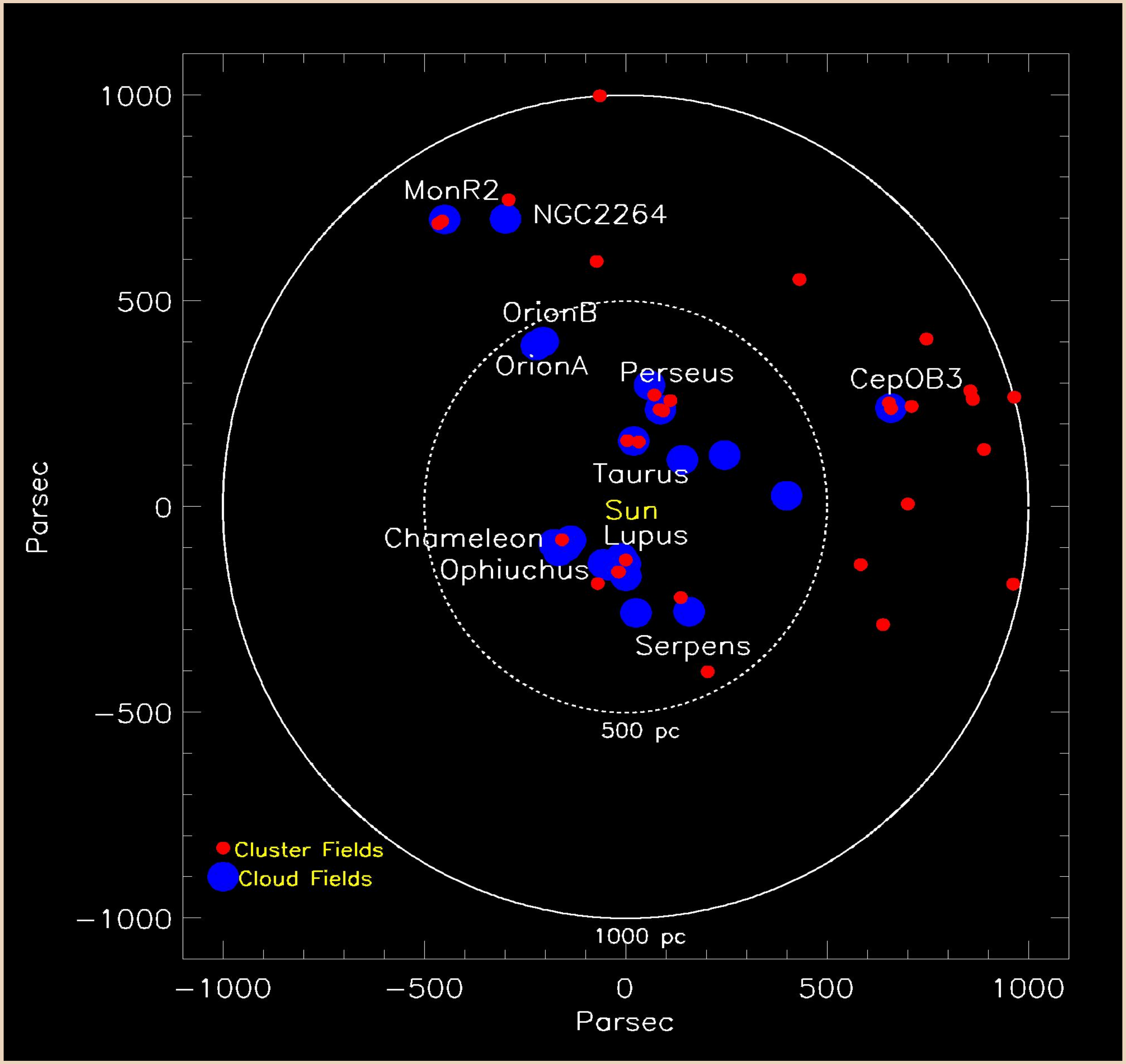
Spitzer Surveys of Nearby Clouds and Clusters

20 nearby molecular clouds

35 young stellar clusters

90% of known stellar groups and clusters *within 1 kpc* (complete to ~ 0.1 M_O)

+ Several massive sf complexes at 2-3 kpc (complete to ~1.0 M_O)

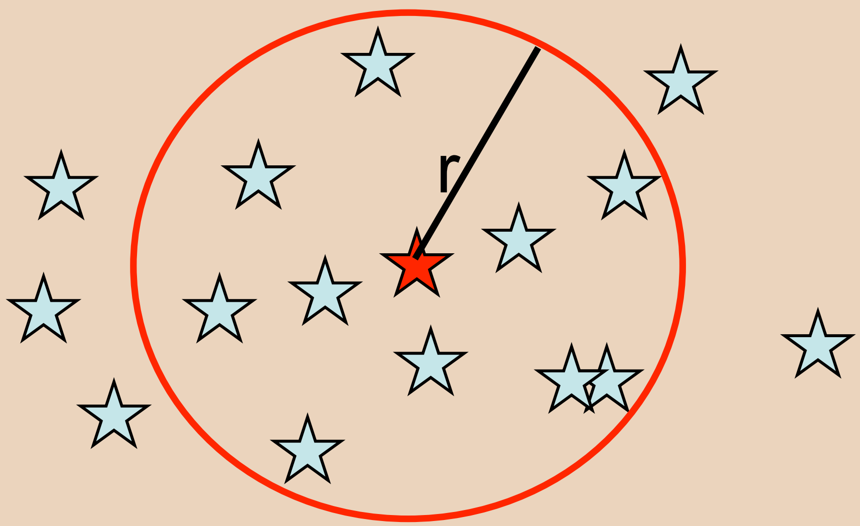


YSO10K

Spitzer surveys were used to identify more than 10000 YSO in 20 molecular clouds within a distance of 1 kpc.

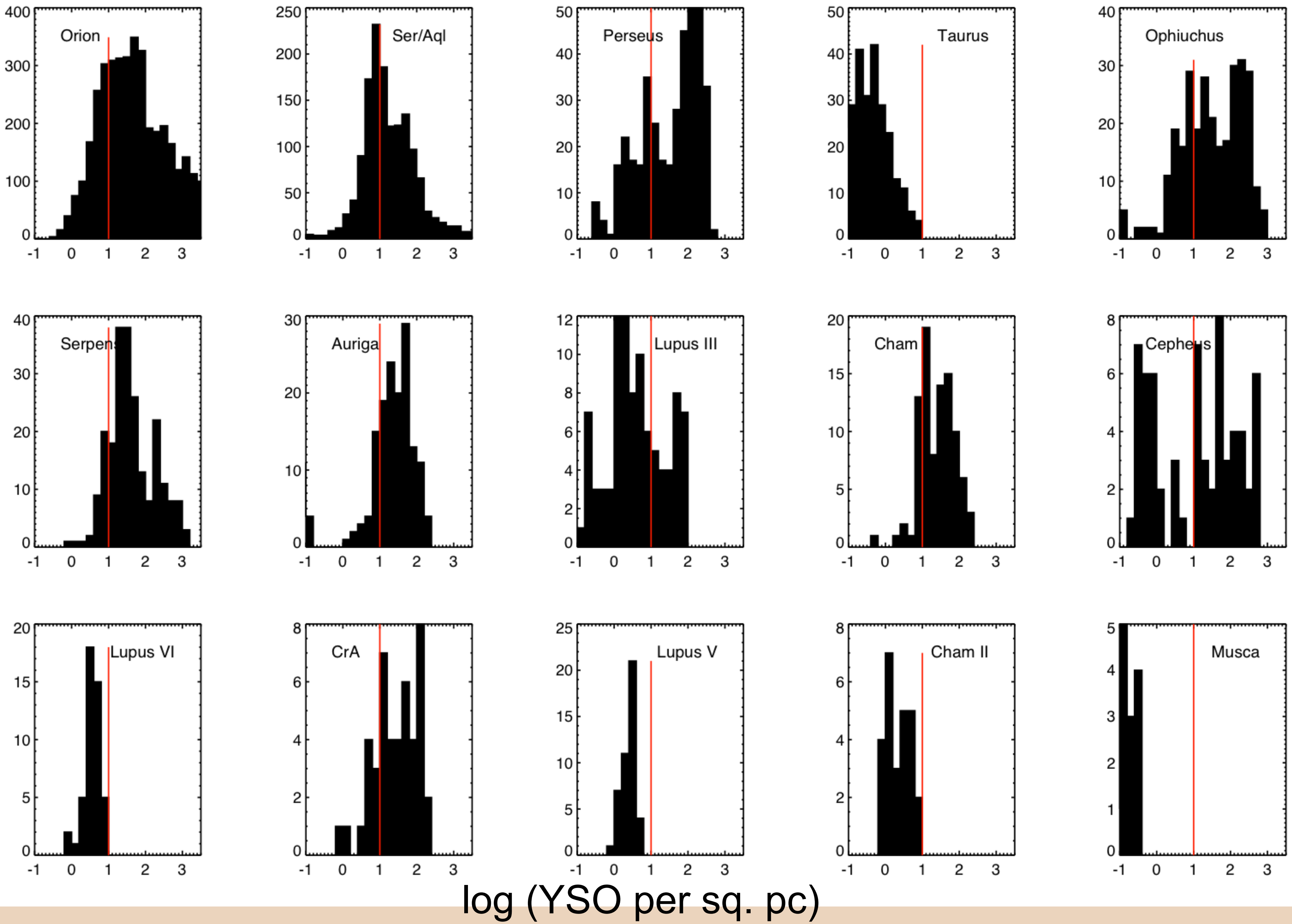
YSO surface densities were calculated using 10th nearest neighbor:

$$\Sigma(YSO) = 10/\pi r^2$$

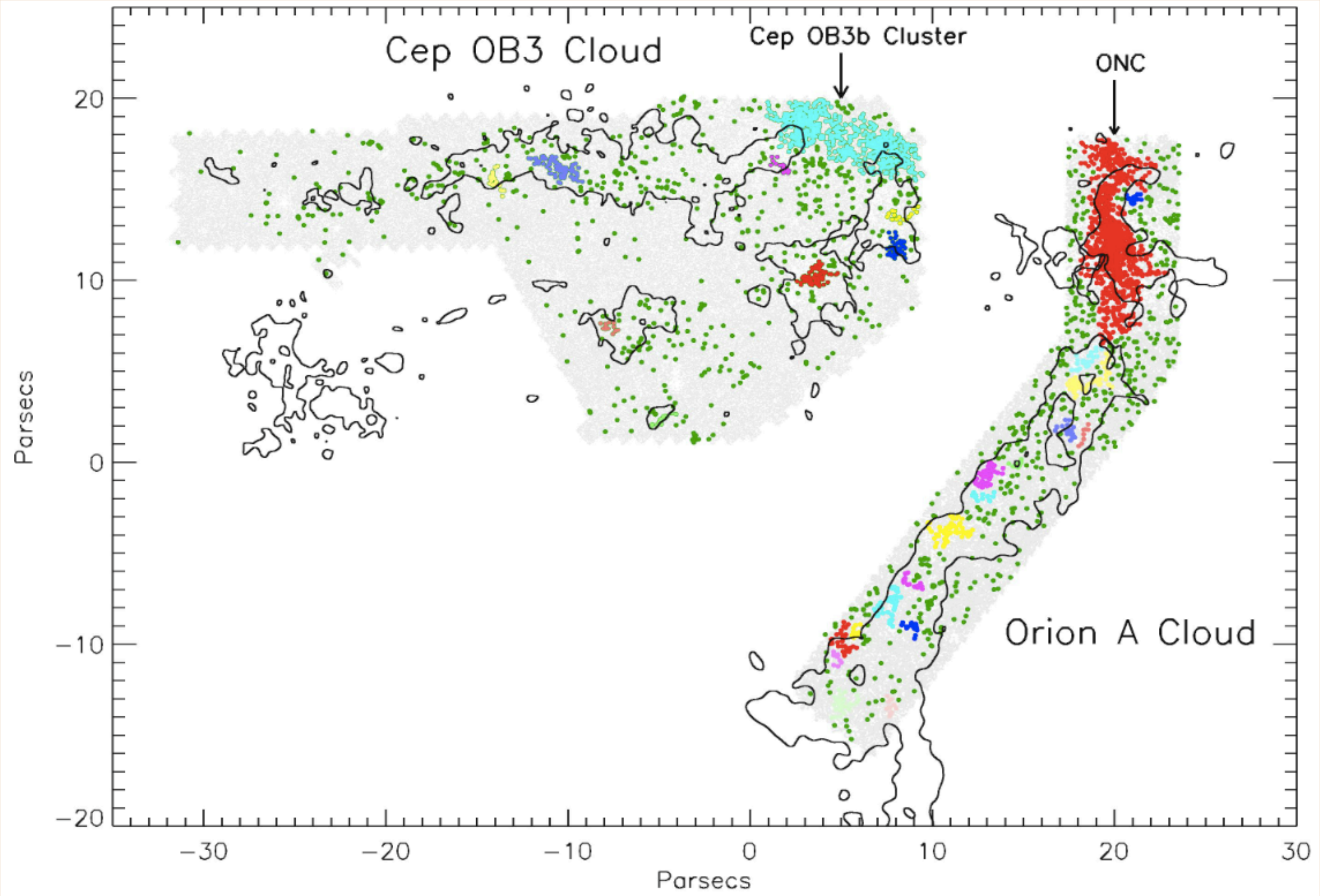


Cloud	N(YSO)
Orion	3845
CepOB3	2031
N. Am. Neb.	1505
Monoceros	925
Serpens/Aquila	739
S140	490
Perseus	353
Ophiuchus	256
Serpens	199
Auriga	161
Taurus	131
Chamaeleon I	85
Lupus	82
Cepheus	64
Cor. Australis	39
Chamaeleon II	22

Ordered by total number of YSO (high to low)



Identifying Clusters



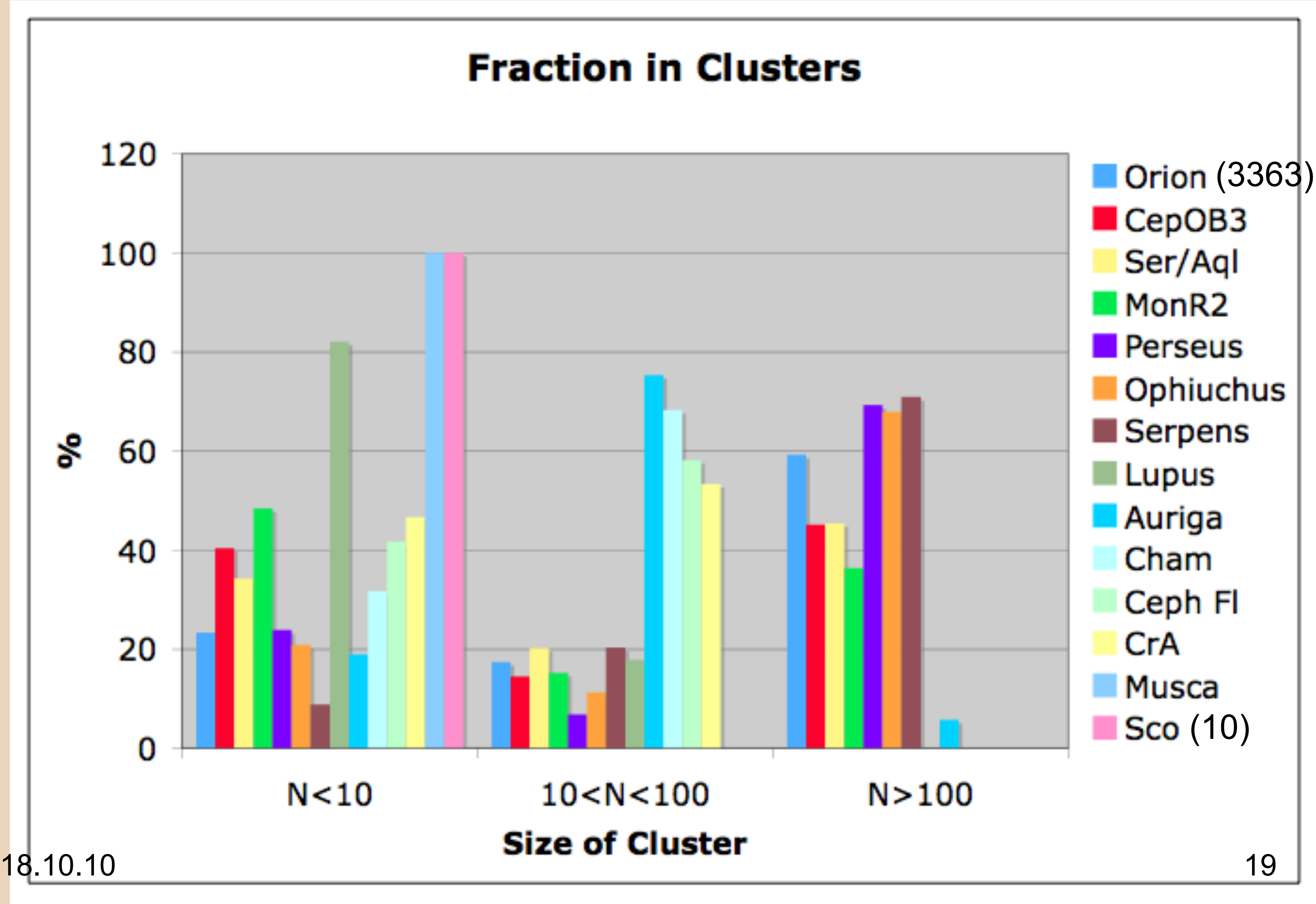
Census within 1 kpc :

14 cloud complexes, 20 clouds
> 10,000 YSO

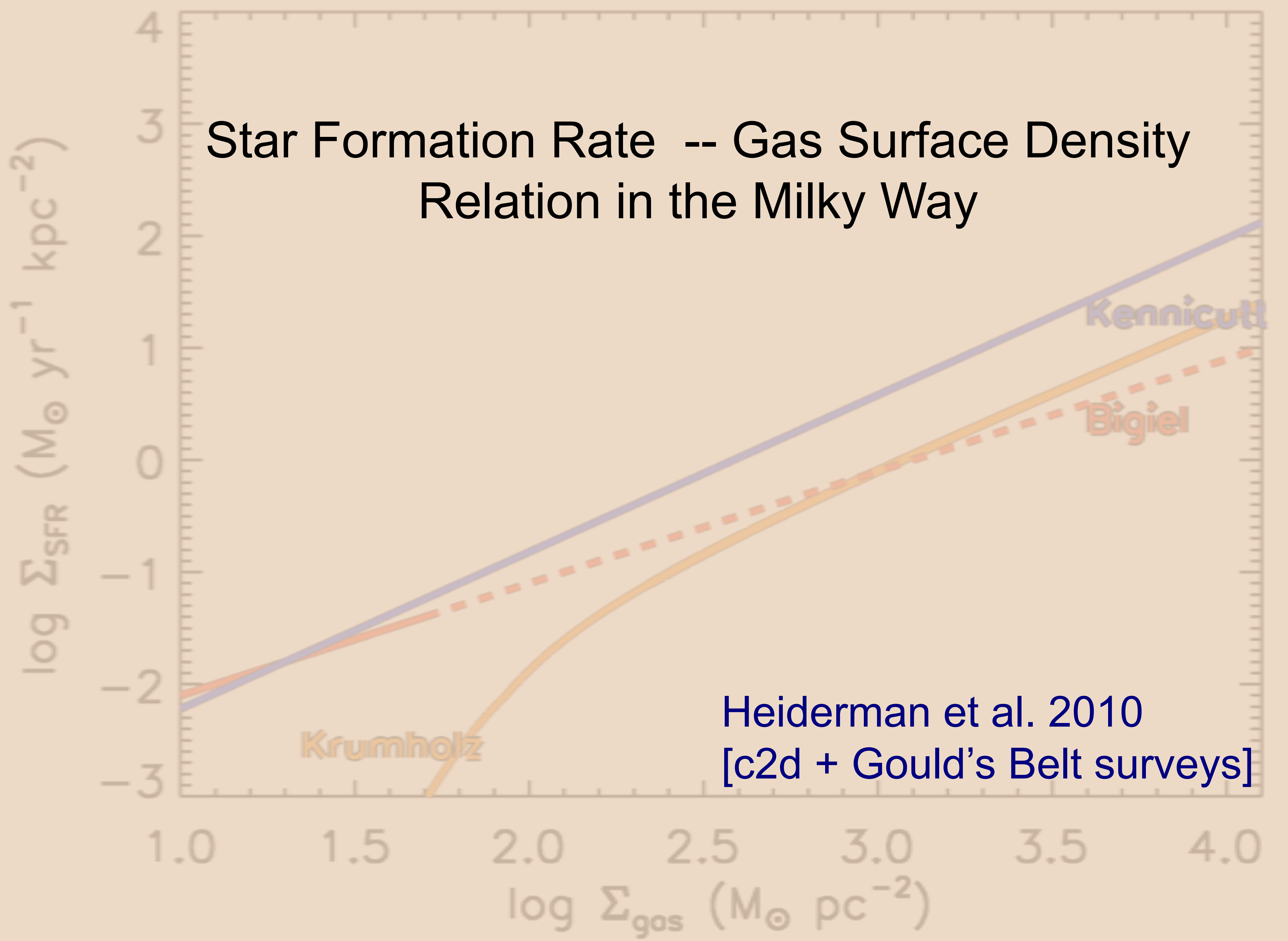
Fraction in clusters (N>10) = 67%
(N>100) = 10%

But varies greatly from cloud to cloud:
Fewer than half the nearby clouds contain clusters of N>100

For cloud complexes within 1 kpc, the fraction of young stars in clusters as a function of cluster size.



Star Formation Rate -- Gas Surface Density Relation in the Milky Way

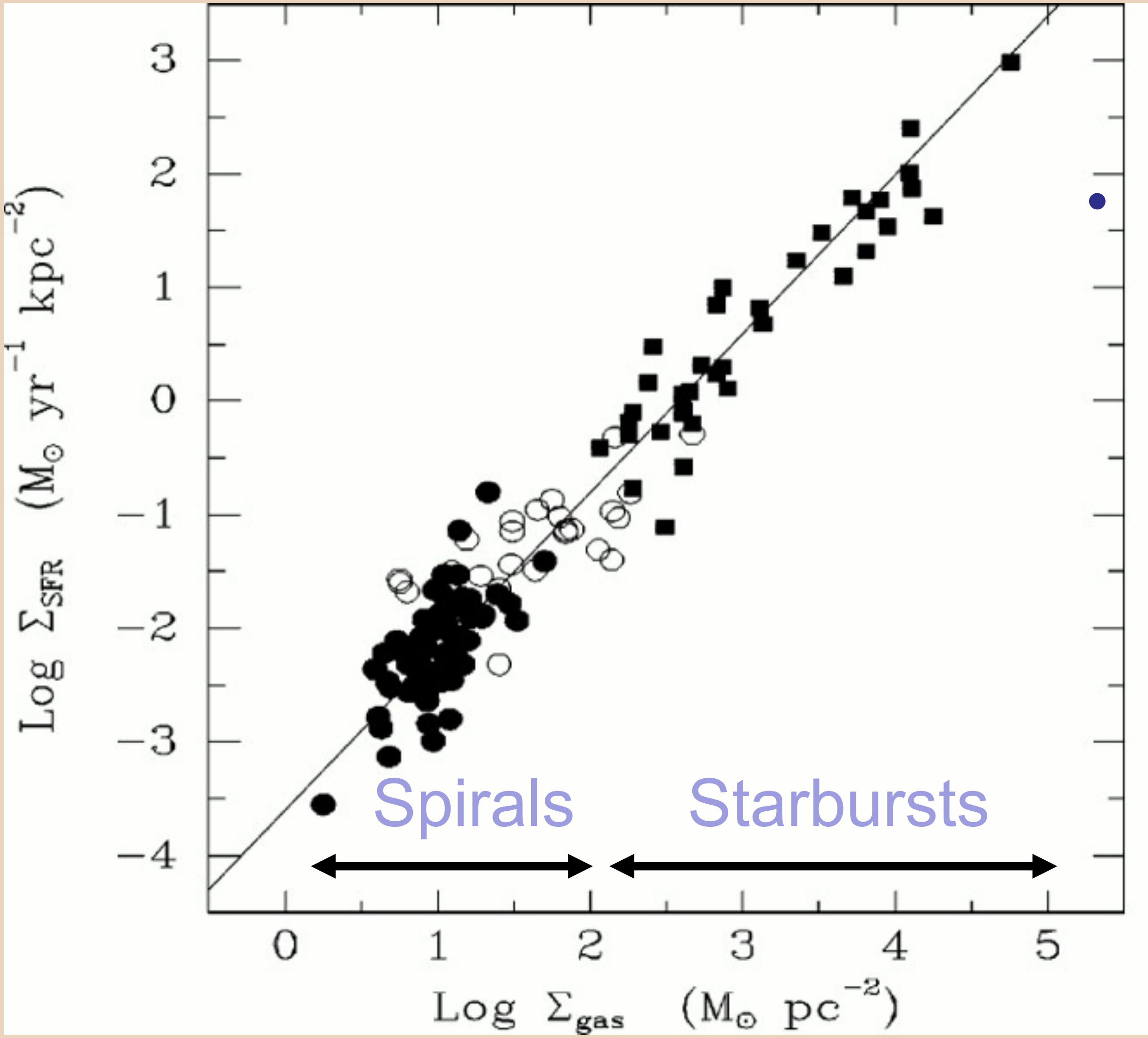


Heiderman et al. 2010
[c2d + Gould's Belt surveys]

Star Formation Relations

- **Schmidt 1959**:
  - SFR~ Σ^{N}_{gas}
- **Kennicutt 1998**:
  - $\Sigma_{SFR}(M_{\odot}\ yr^{-1}\ kpc^{-2}) = 2.5x10^{-4}\ \Sigma^{1.4}{}_{gas}(M_{\odot}\ pc^{-2})$
- **Bigiel 2008**:
  - $\Sigma_{SFR}(M_{\odot}\ yr^{-1}\ kpc^{-2}) = 7.9x10^{-3}\ \Sigma^{1.0}{}_{mol}(10\ M_{\odot}\ pc^{-2})$
- **Krumholz 2009 Prediction**:
  - $\Sigma_{SFR} = f(\Sigma_{gas}, f(H_2), Z, \text{clumping})$
  - linear $\Sigma_{gas} < 85\ M_{\odot}\ pc^{-2}$; steepens $\Sigma_{gas} > 85\ M_{\odot}\ pc^{-2}$

Star Formation Relations



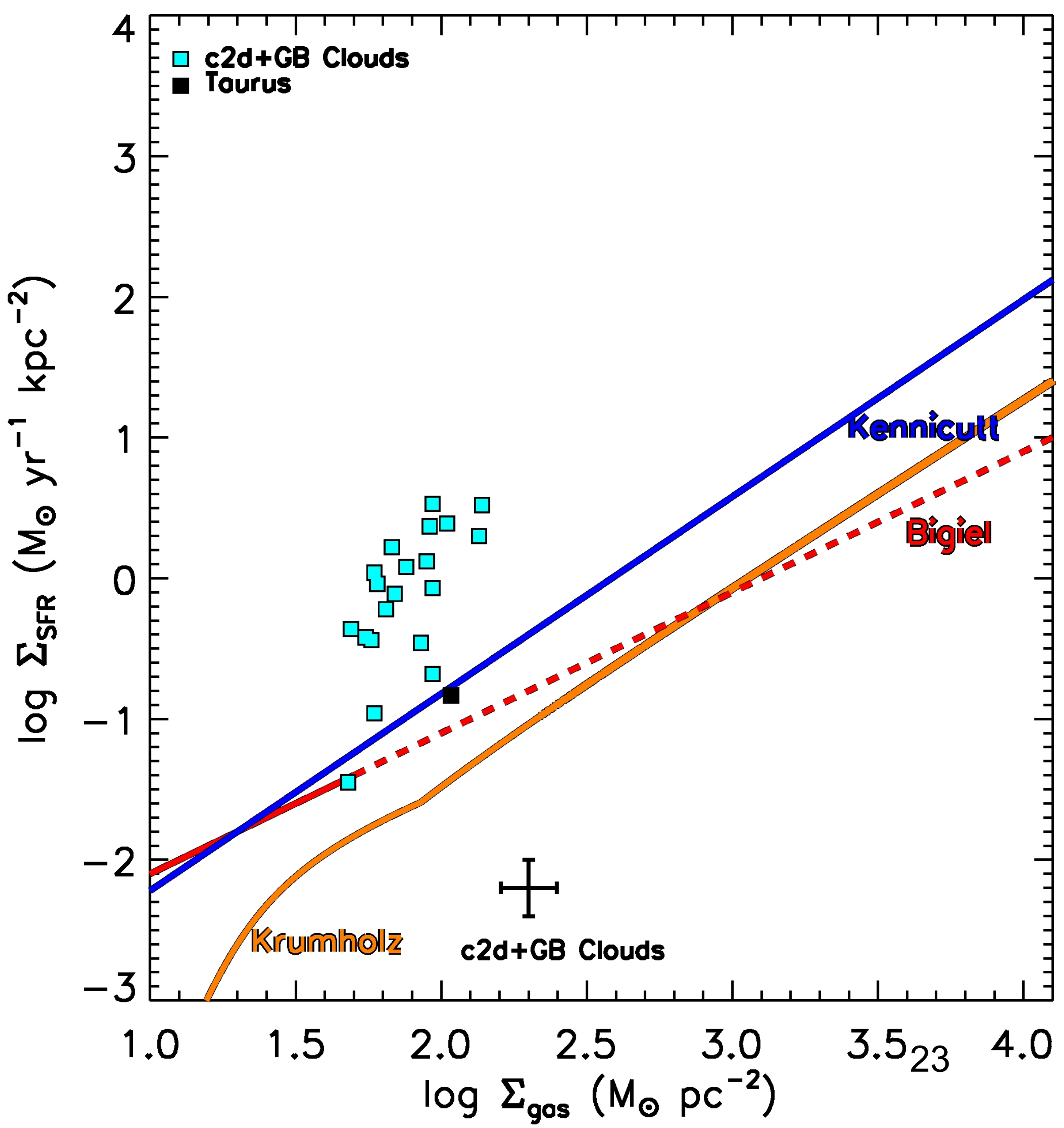
- Kennicutt 1998:

  $\Sigma_{SFR}(M_\odot\ yr^{-1}\ kpc^{-2}) =$

  $2.5\times10^{-4}\ \Sigma^{1.4}_{gas}(M_\odot\ pc^{-2})$

c2d+GB Clouds (Heiderman et al. 2010)

- 20 c2d+GB clouds and Taurus
- Clouds lie factor of 9-17 above exgal relations
- Average Σ_{gas} = 92 $M_\odot$ pc^{-2}
- Kennicutt-Schmidt relation predicts Σ_{SFR} ~0.13 $M_\odot$ yr^{-1} kpc^{-2}; average measured is Σ_{SFR} =1.2 $M_\odot$ yr^{-1} kpc^{-2}
- "inactive" clouds (Taurus, Cha III) lie near predictions



Possible Explanations

(1) Σ_{gas} from CO (exgal) ≠ Σ_{gas} from A_V

(2) Does Low-mass star formation behave different from high-mass star formation?

- Exgal tracers **only measure massive star formation**, missing low- mass star formation

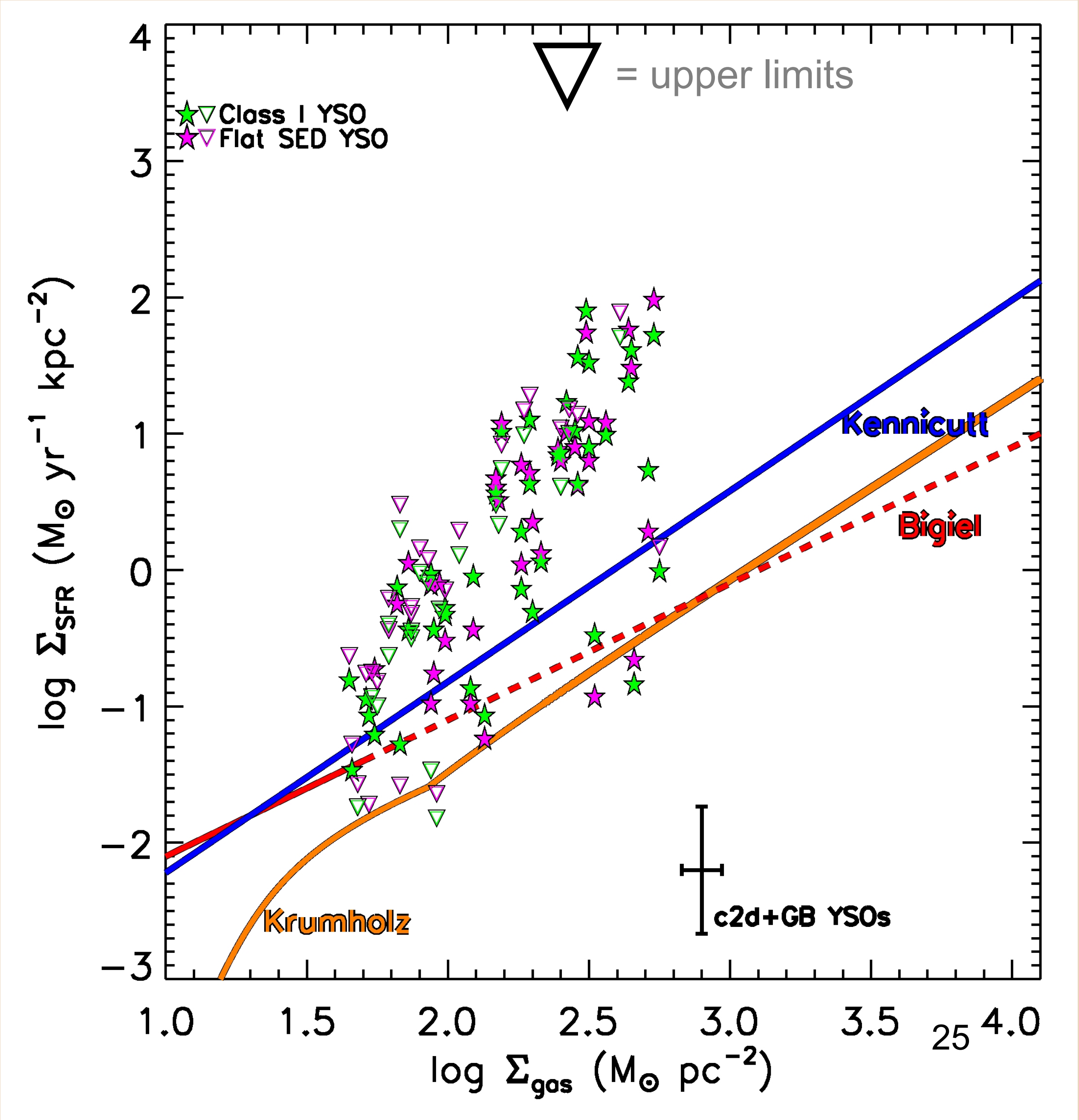
(3) Exgal measurements are highly beam-diluted

- **Most gas lies below a star forming threshold Σ_{gas}**

Youngest YSOs

- factor of 21-54 above exgal relations
- Average $\Sigma_{gas} = 225\ M_\odot\ pc^{-2}$
- Kennicutt-Schmidt relation predicts $\Sigma_{SFR} \sim 0.47\ M_\odot\ yr^{-1}\ kpc^{-2}$; average measured is $\Sigma_{SFR} = 9.7\ M_\odot\ yr^{-1}\ kpc^{-2}$

(Heiderman et al. 2010)



Star Forming Threshold

- Physical motivation for a threshold first proposed by Mouschovias & Spitzer (1976)
- Σ_{crit} above which interstellar B field can't support gas from self gravitational Collapse:

$$\Sigma_{crit} > 80\ (M_{\odot}\ pc^{-2})\ x\ B\ /\ (30\mu G)$$

- B ~20-40μG (Troland & Crutcher 2008)
- Σ_{crit} >50-110 $M_{\odot}$ pc^{-2}
- Similarly, many observational studies find

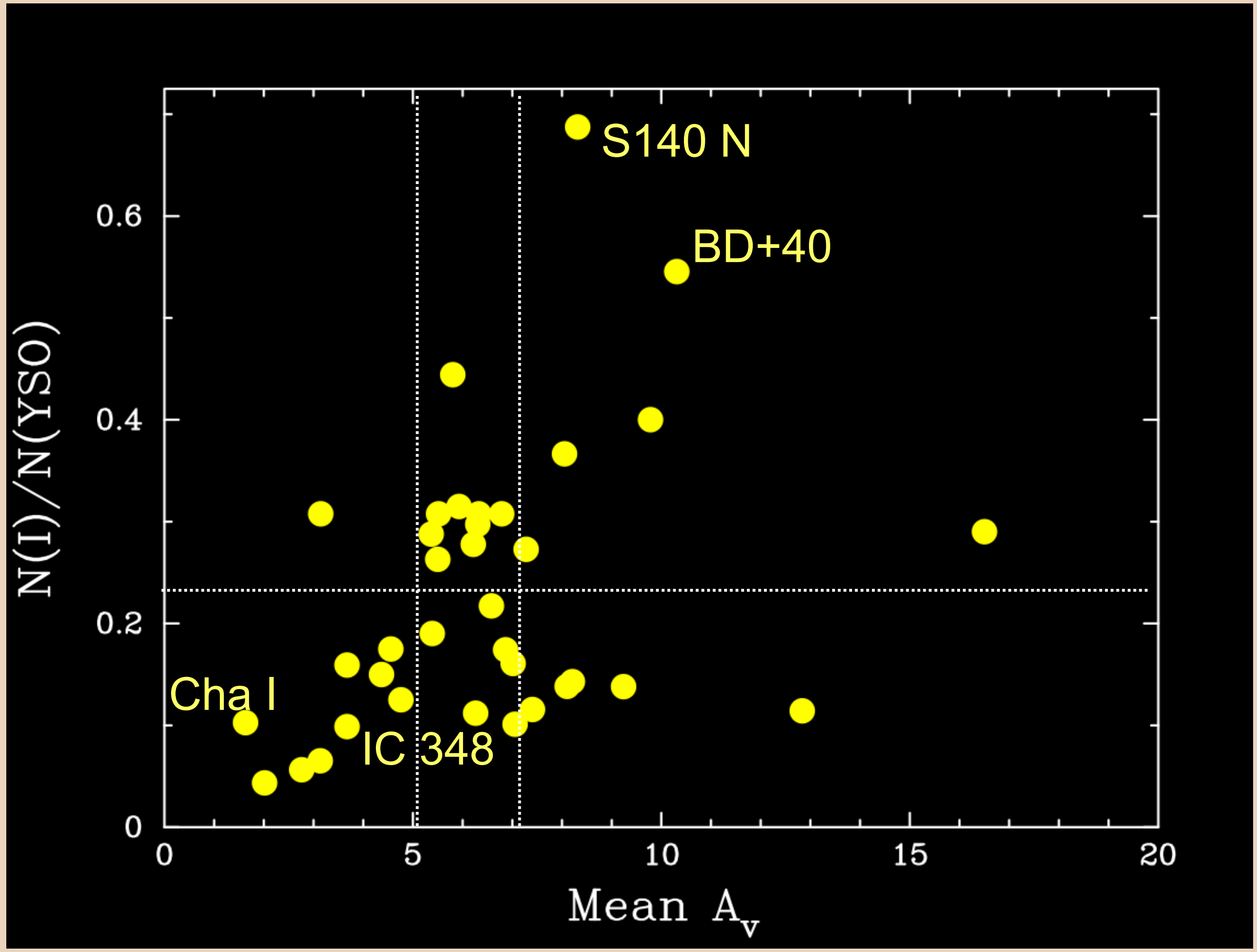
Σ_{th} ~120-150 $M_{\odot}$ pc^{-2}

(Onishi 1998; Johnstone 2004, Enoch 2007; Andre 2010; Lada 2010)

Extinction threshold for star formation

- Most active clusters contain multiple concentrations of protostars associated with high density gas and dust.

- Can group clusters according to SFR, spatial distributions of protostars, and gas column density.

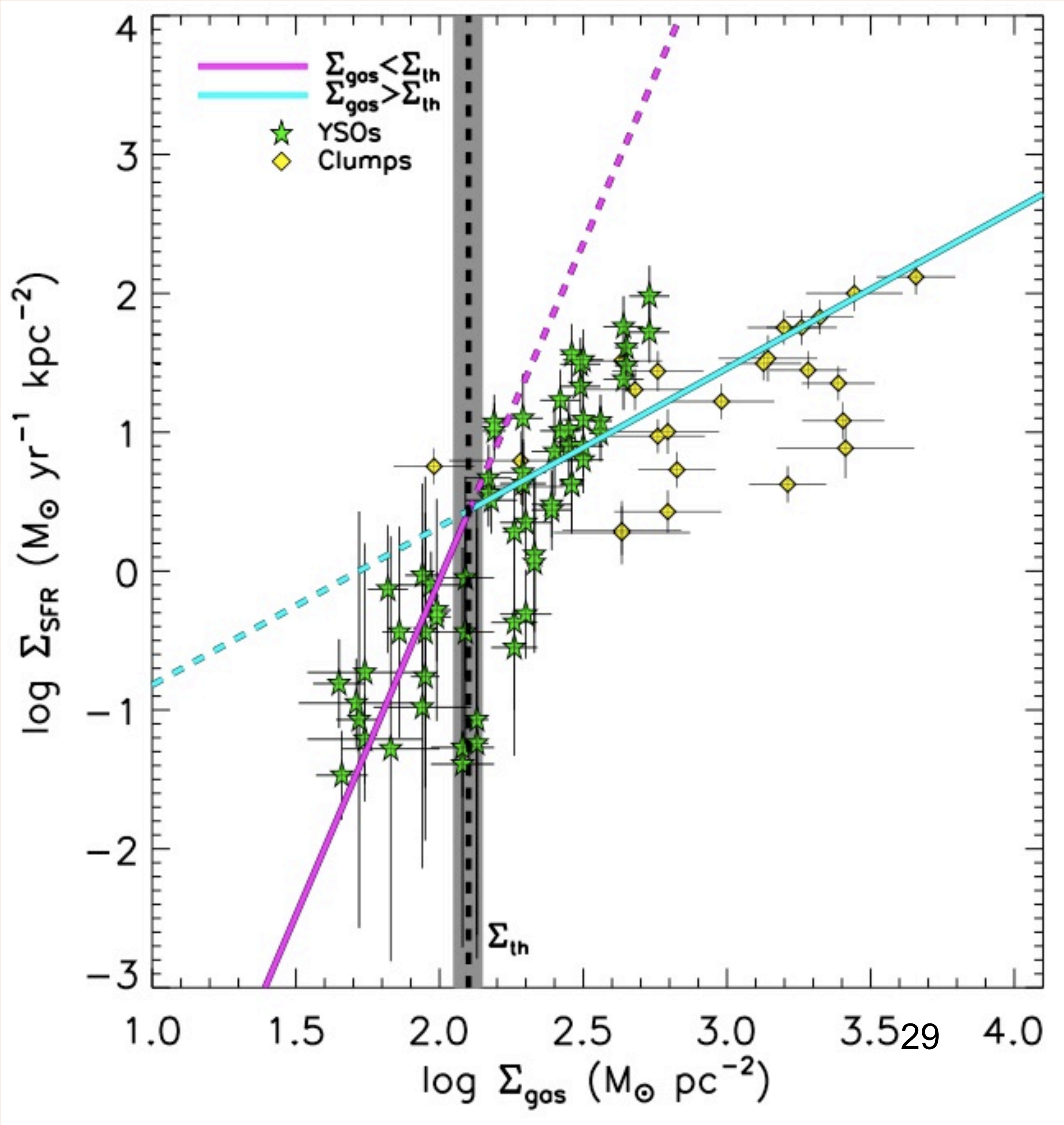


Extinction from 2MASS

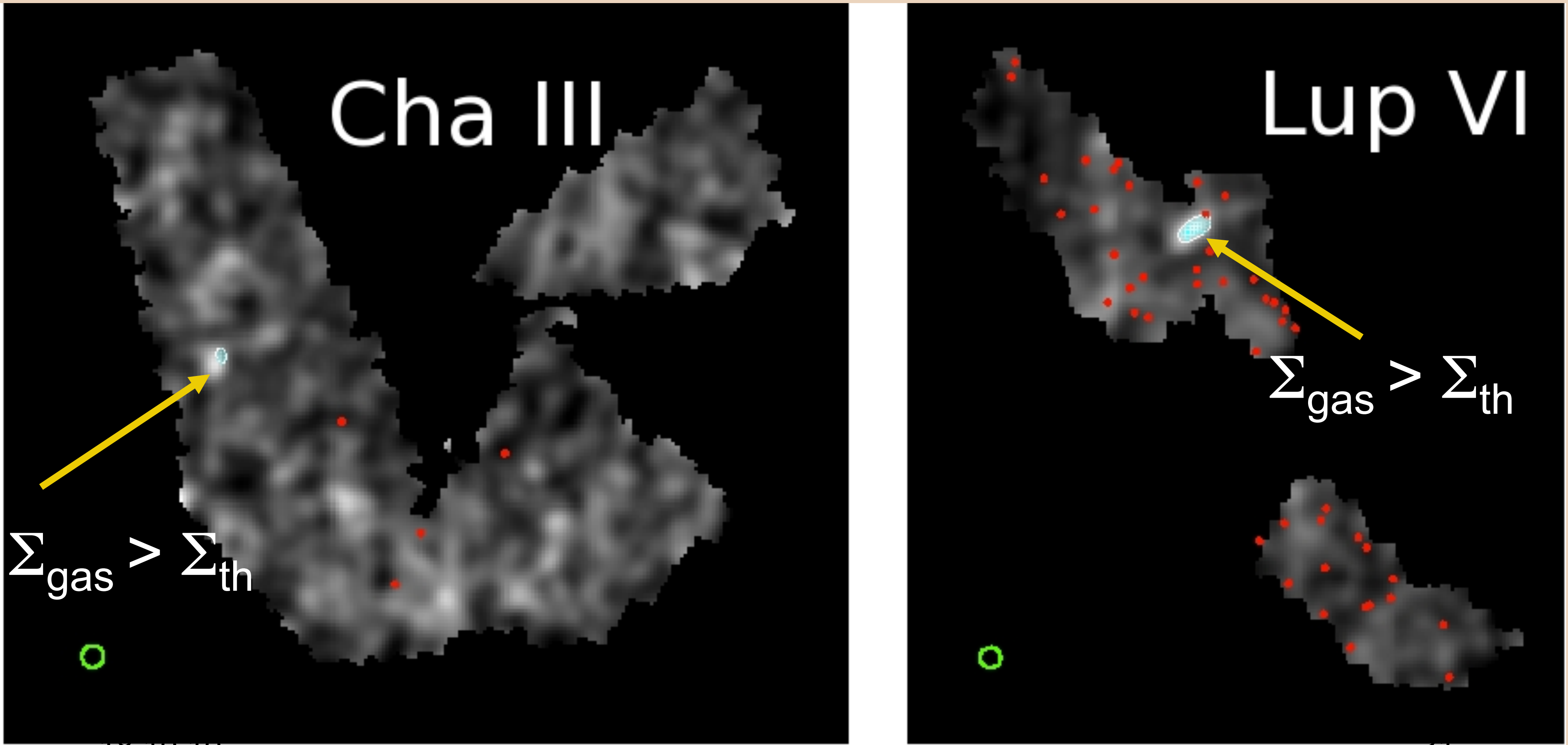
Star Formation Threshold (Σ_{th})

- broken power law fit to Class I & Flat YSO + clumps
- Σ_{th} = 129±14 $M_\odot$ pc^{-2}

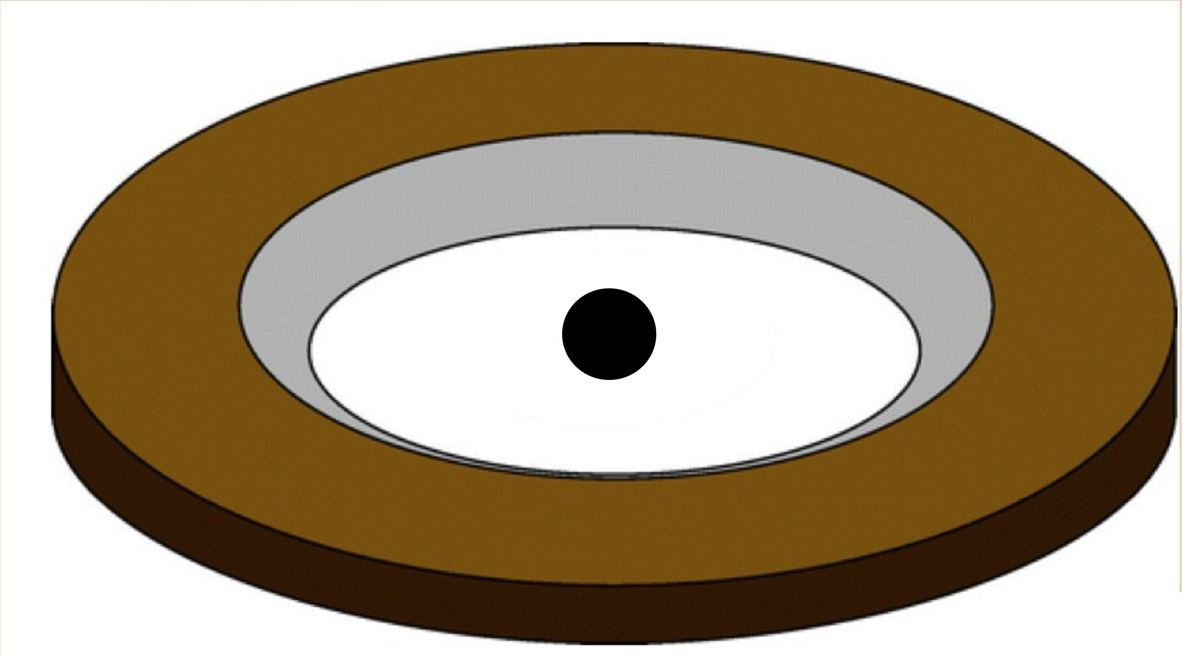
  (A_V ~ 8 mag)
- Linear (slope 1.1) $\Sigma_{gas} > \Sigma_{th}$

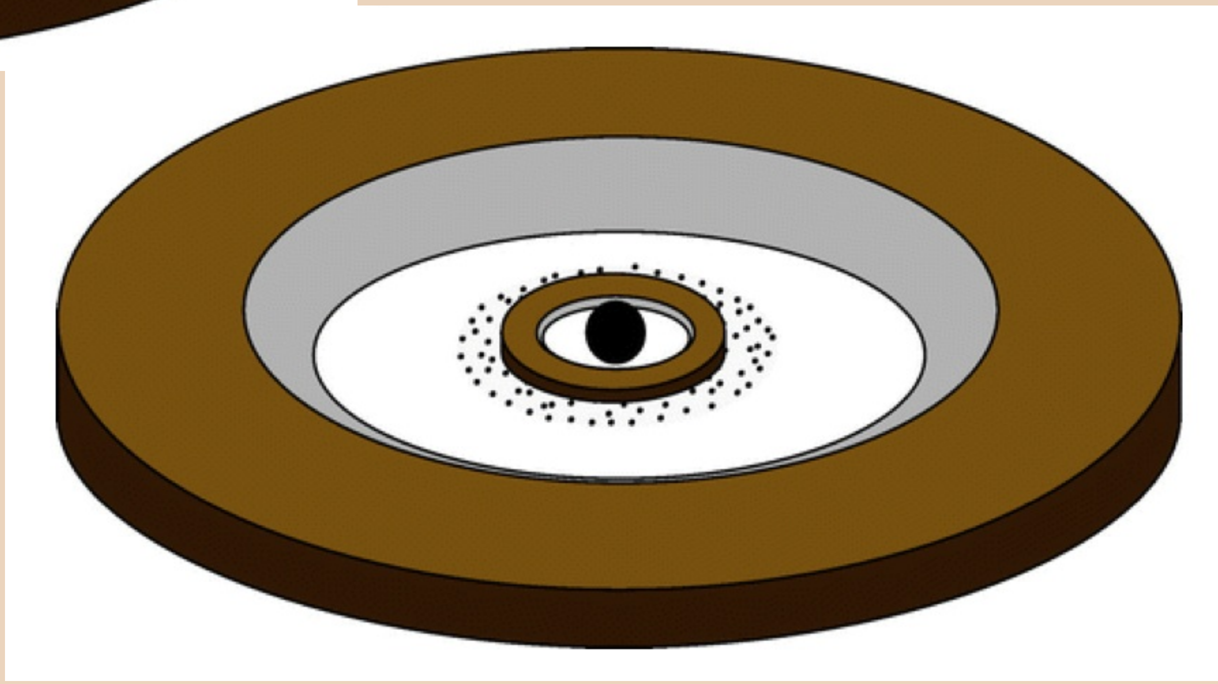


Evolved Clouds

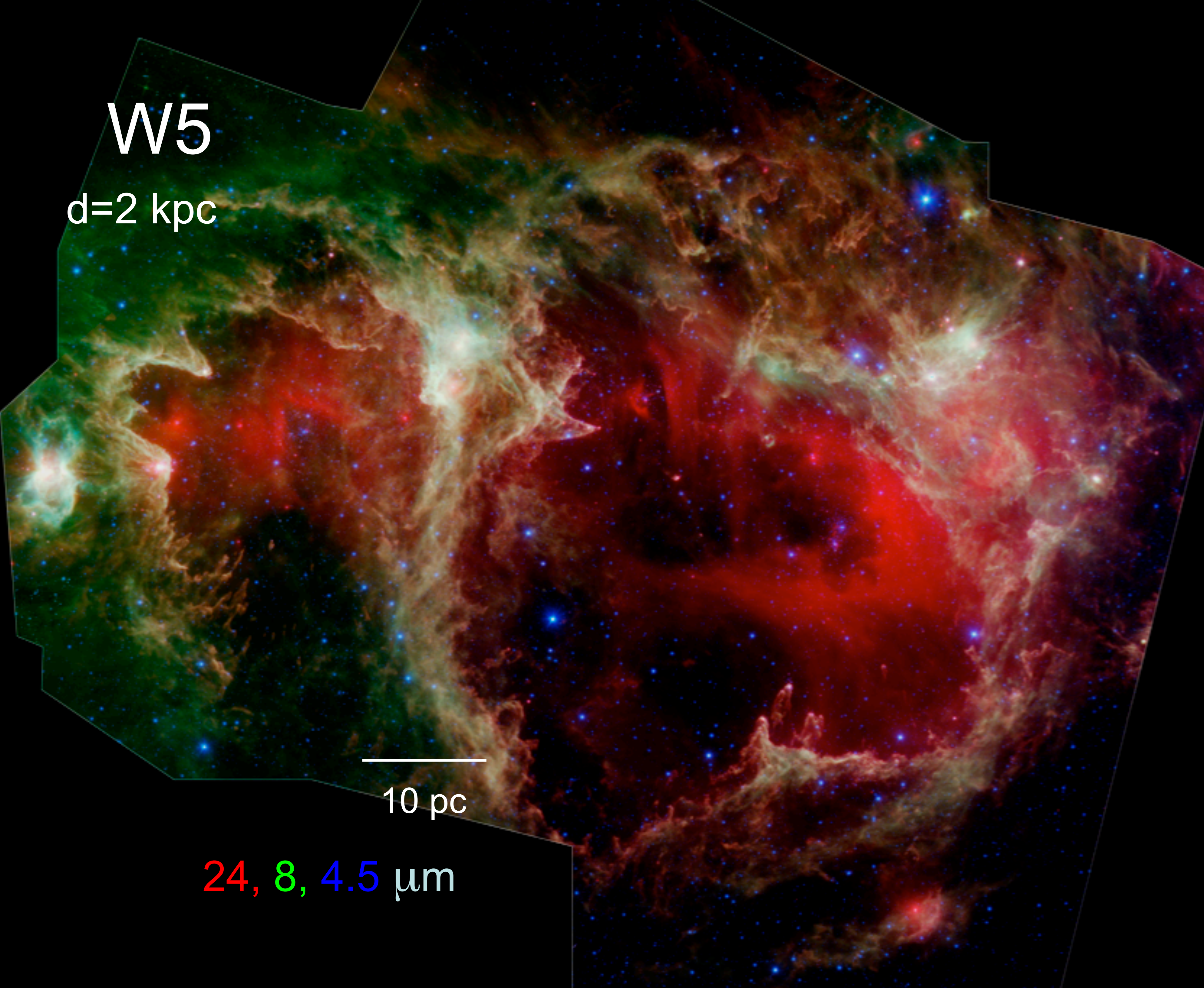


disk evolution

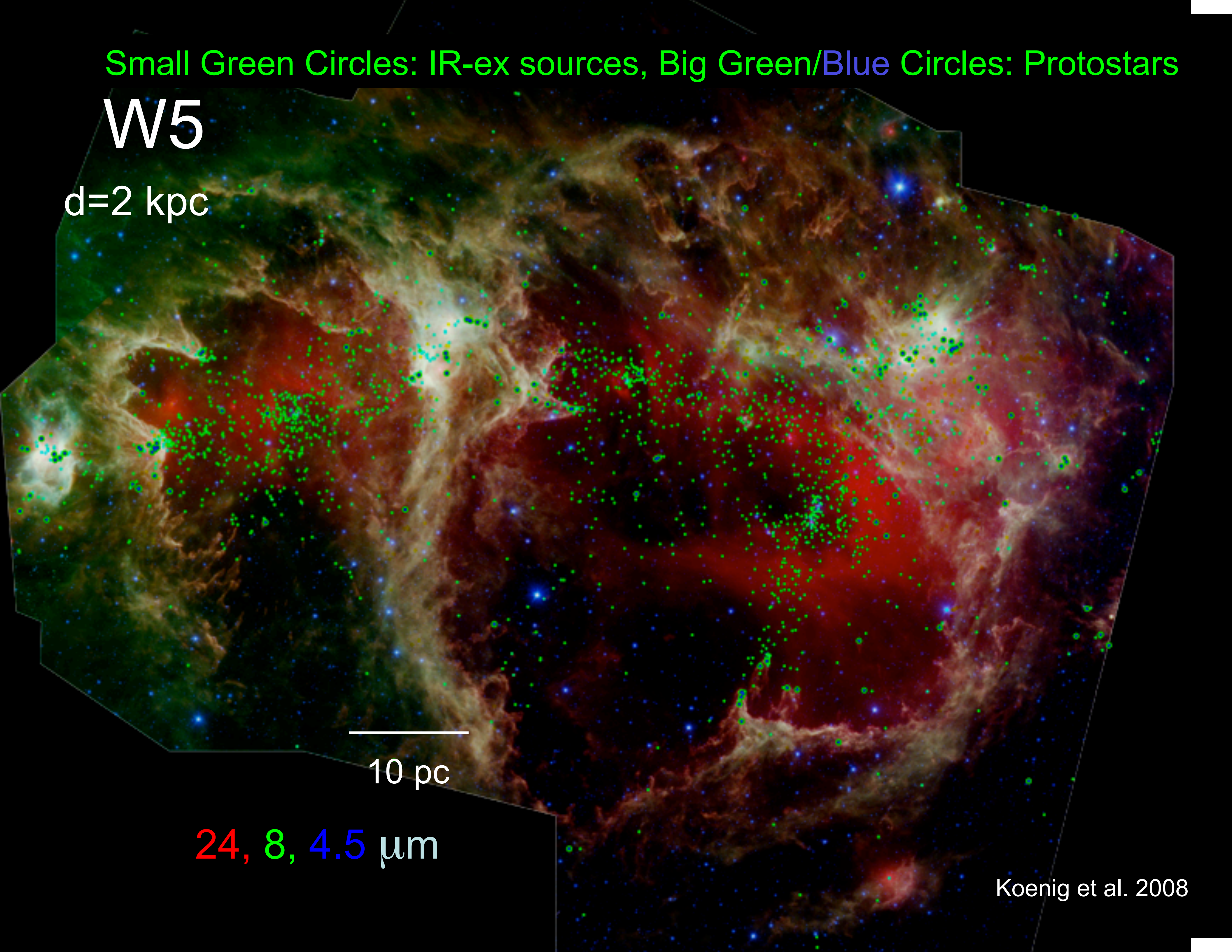




Espaillat et al. 2008



W5
d=2 kpc
10 pc
24, 8, 4.5 µm



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

Spitzer photometry + spectral types

Four distinct SED types that suggest:

a) Optically thick disks (2-24 μm) extending inward to the dust destruction radius

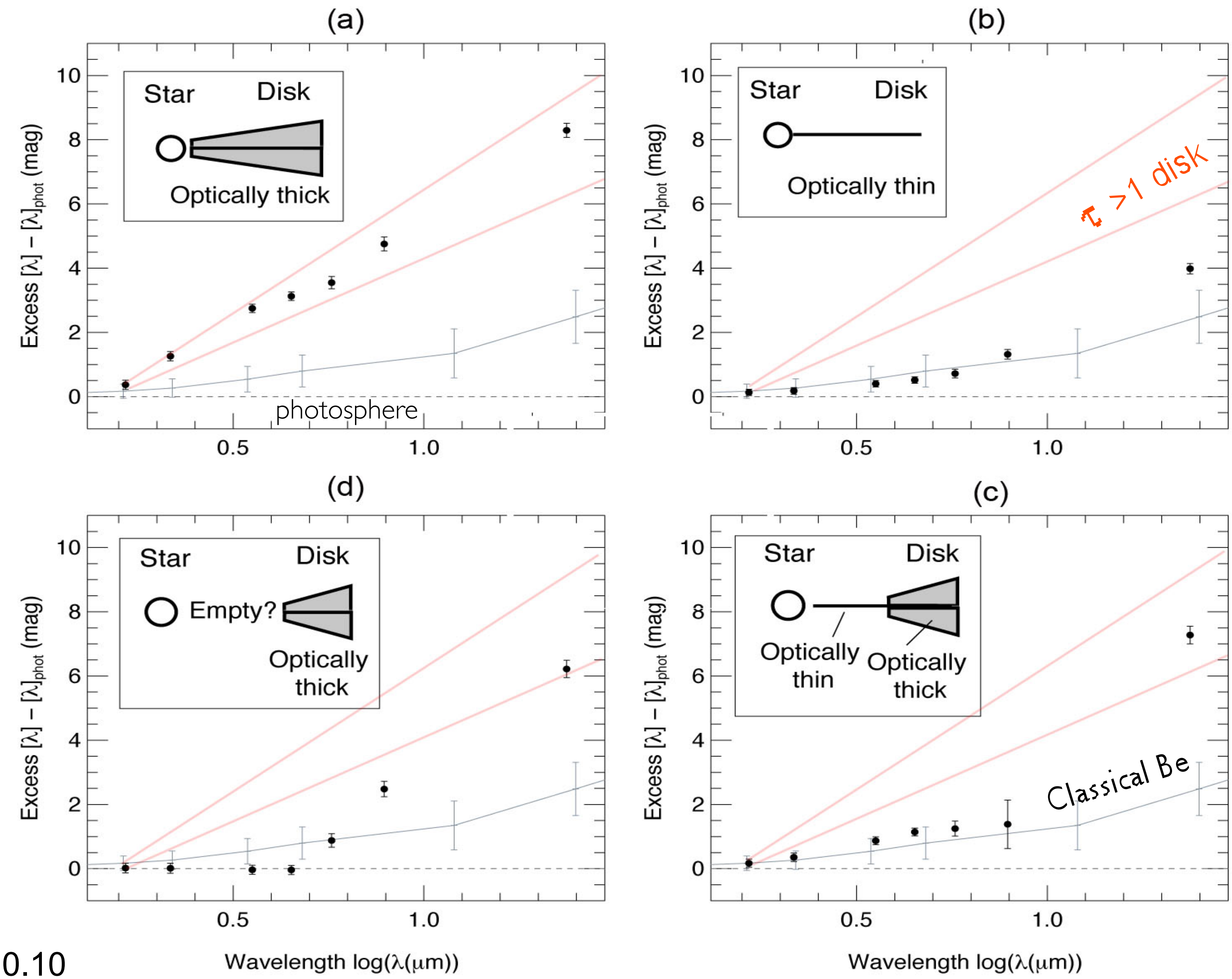
b) Optically thin disks (2-24 μm)

c) Optically thick outer disks (24 μm) and optically thin inner disks (2-8 μm)

d) Optically thick outer and empty inner disk

Ref: IC 348 Lada et al. 2006; Muzerolle et al. 2006; W5: Koenig et al. 2009; W4:Wolff et al. 2009

Range of SEDs



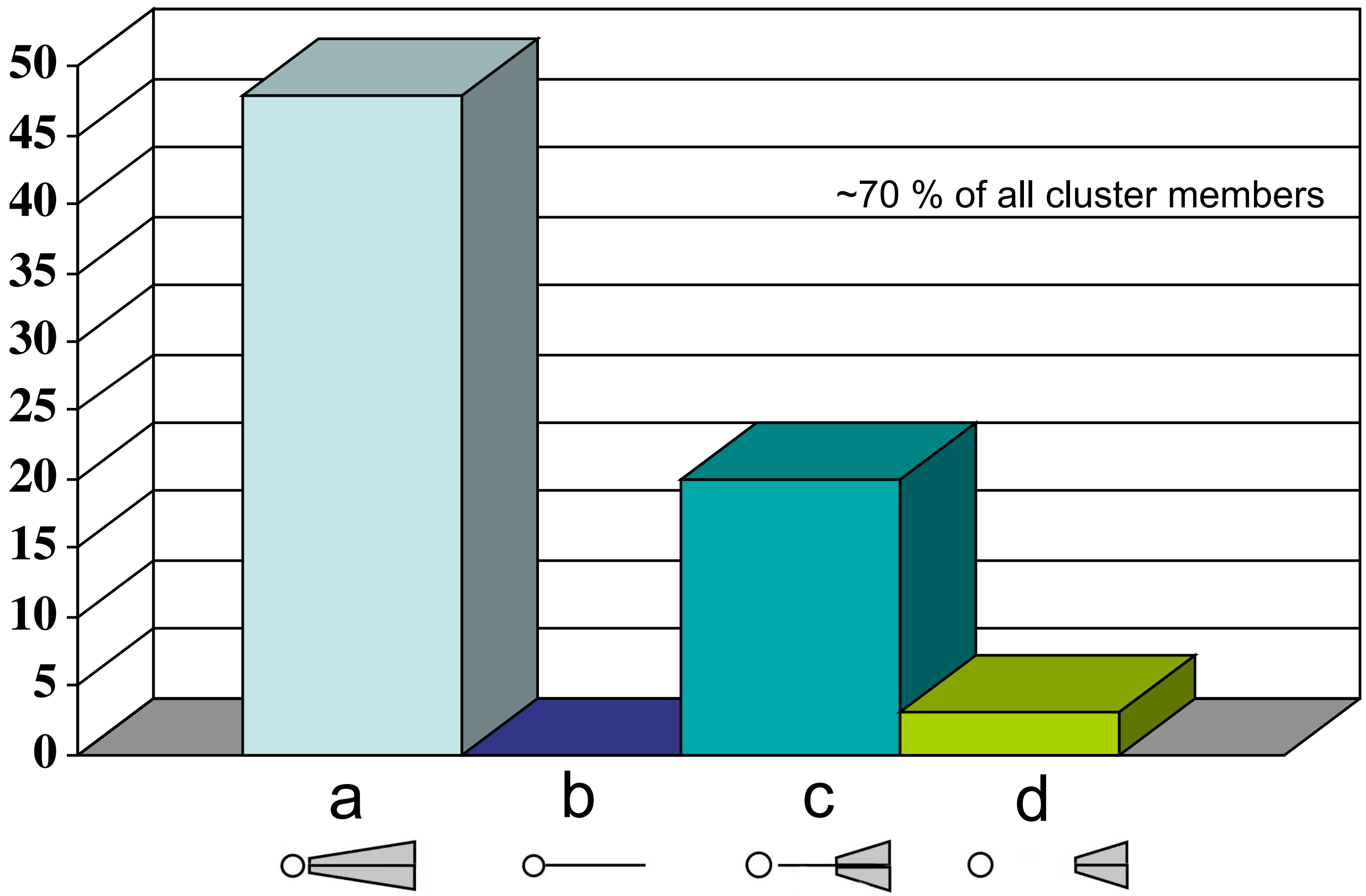
Koenig & Allen 2010

Agents of Disk Evolution

- Viscous spreading and draining of the disk
- Grain growth (settling in the midplane)
- Formation of planetesimals and planets
- Photoevaporation (X-rays, FUV & EUV photons)
- Initial conditions (disk masses, accretion rates)

Distribution of SED Types

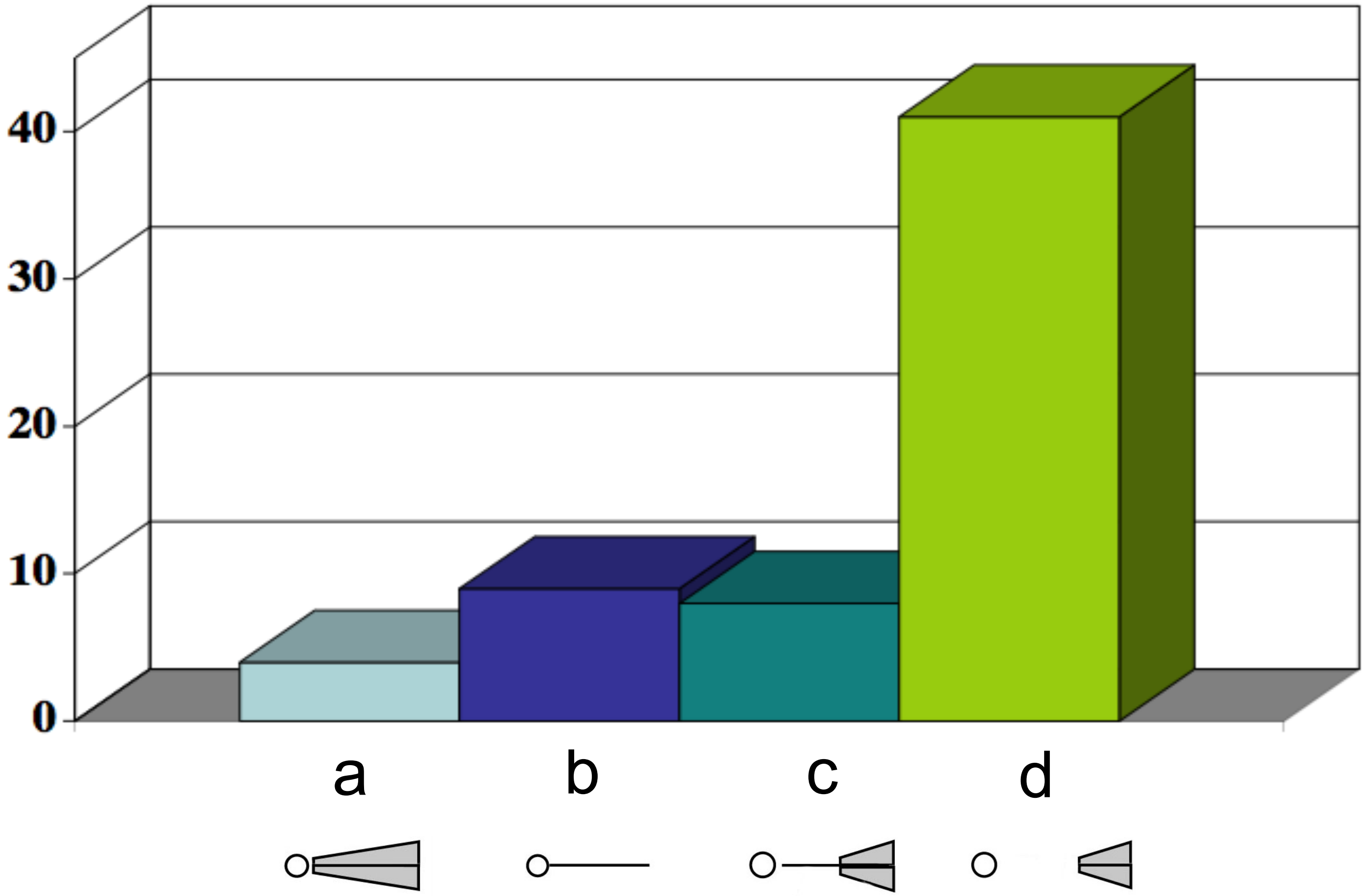
Taurus: Age ~1-2 Myr; Mass Range ~ 0.2-0.6 M_{sun}



Data from Furlan et al. 2006

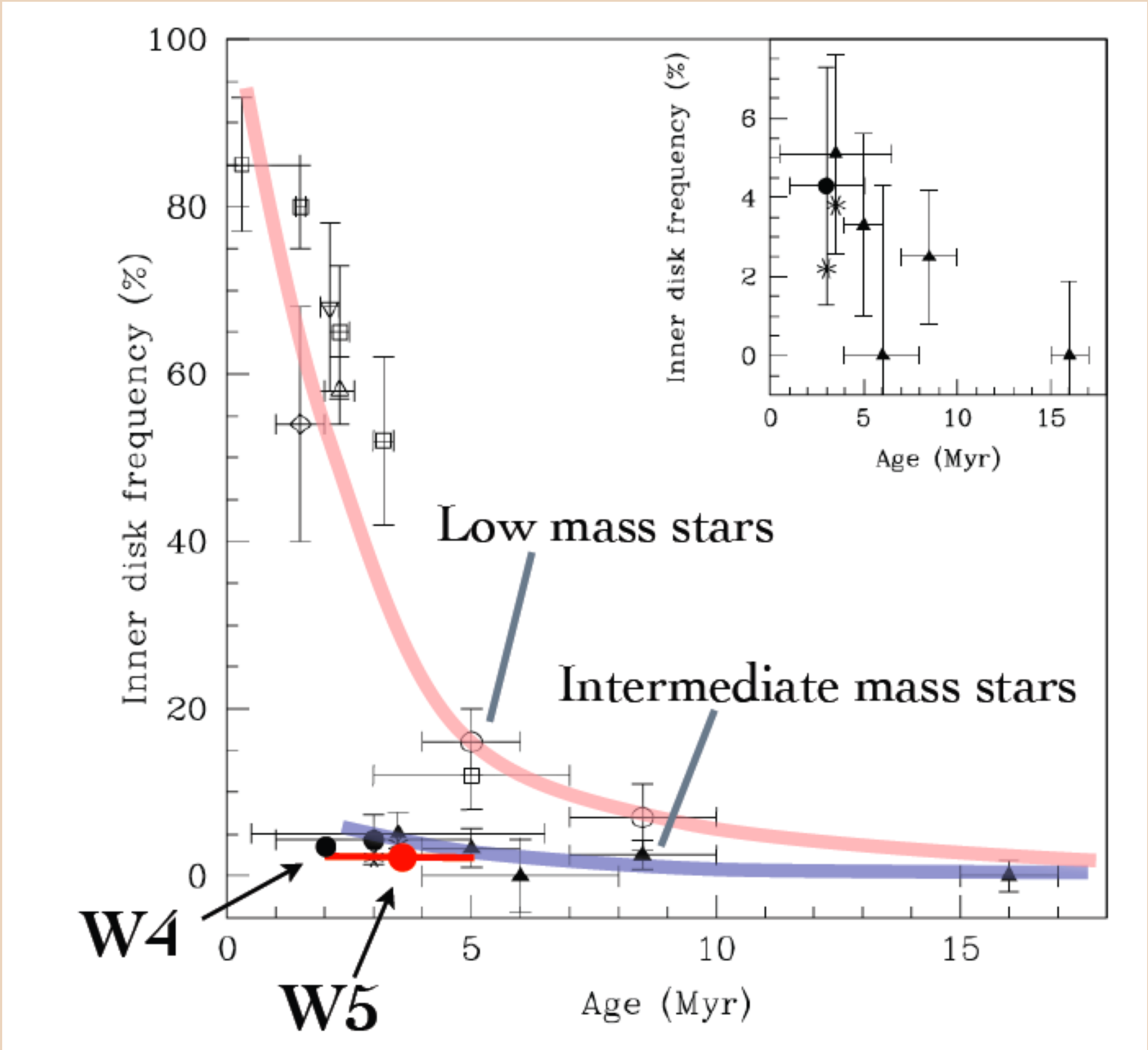
Distribution of SED Types

W5: Age ~2-5 Myr; Mass Range ~ 2- 4 M_{sun}

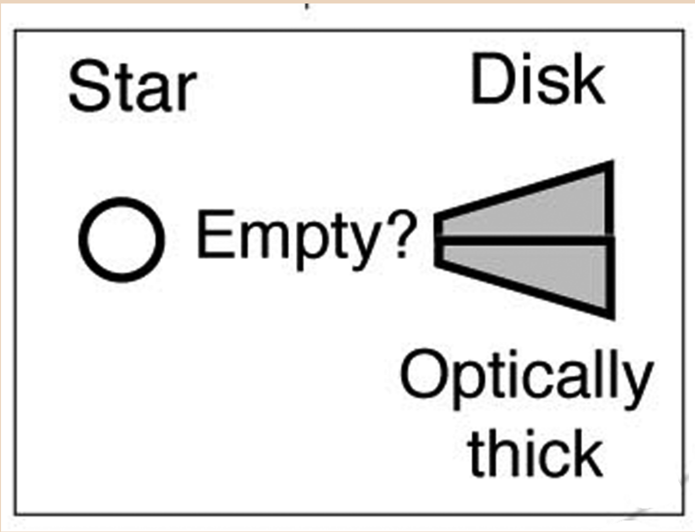


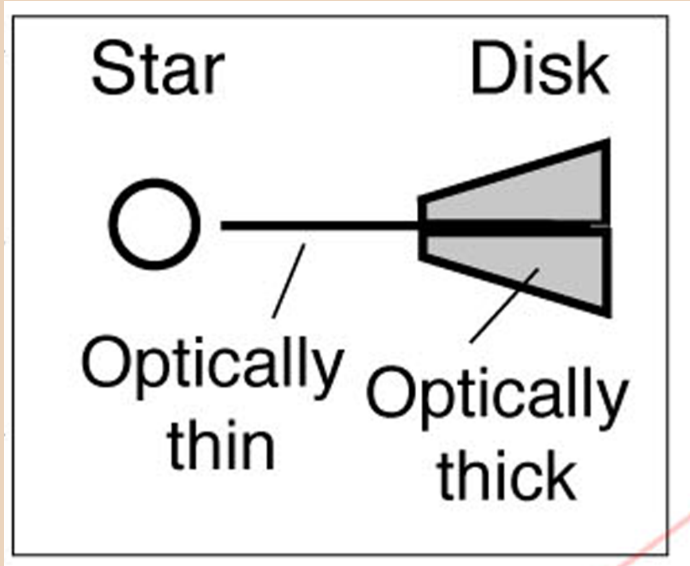
Data from Koenig et al. 2009

Intermediate-mass stars lose their inner disks faster than do low-mass stars



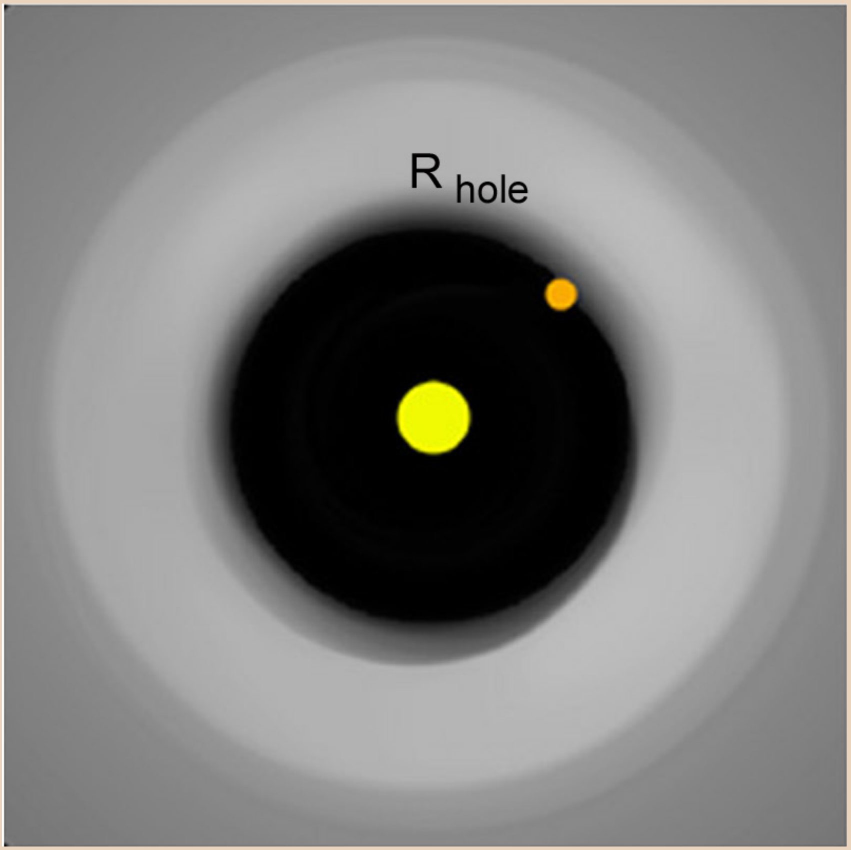
Let's tell a story….

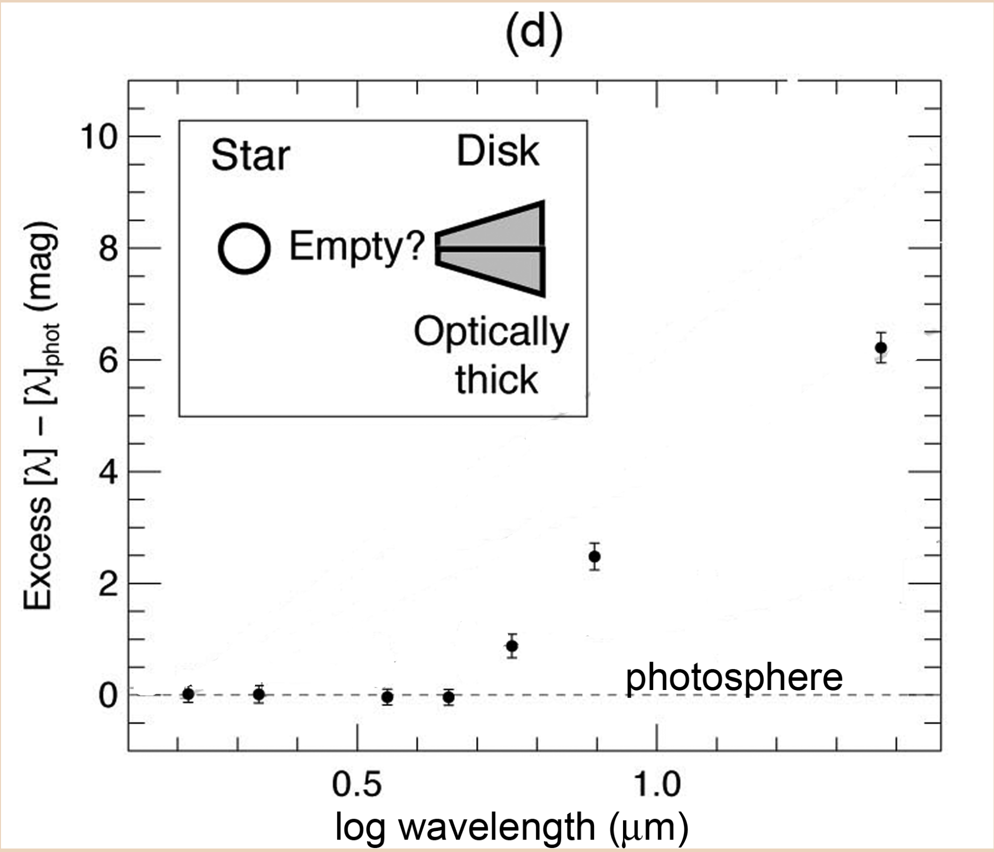




Thick Outer, Empty Inner Disk: d

Possibility (1); M >> M_{jup} companion forms; isolates inner disk

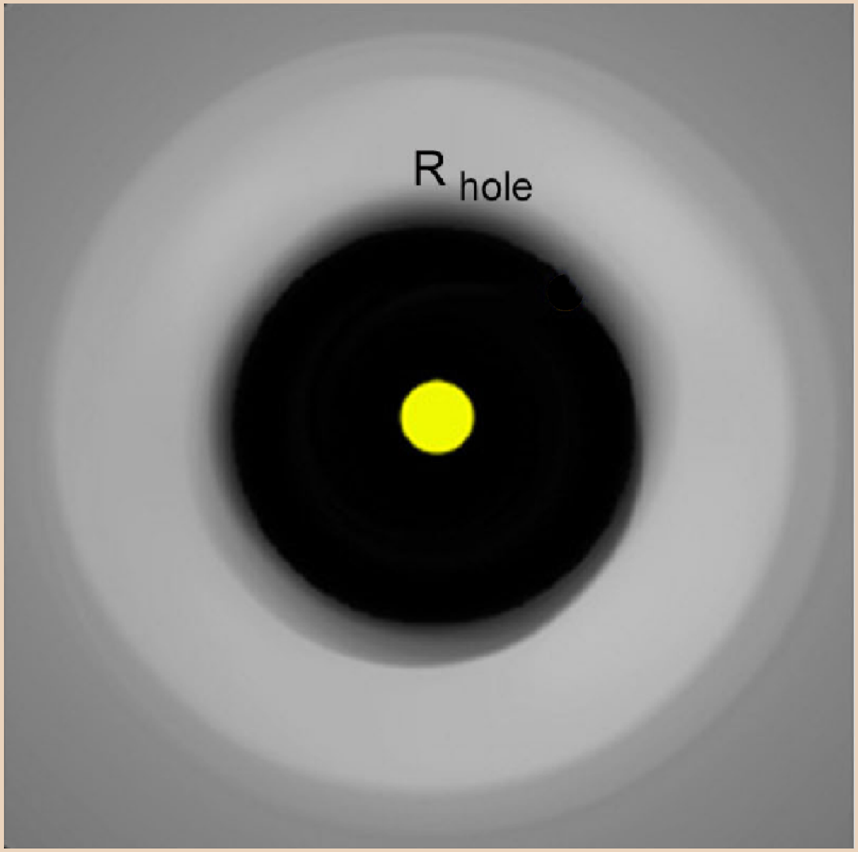


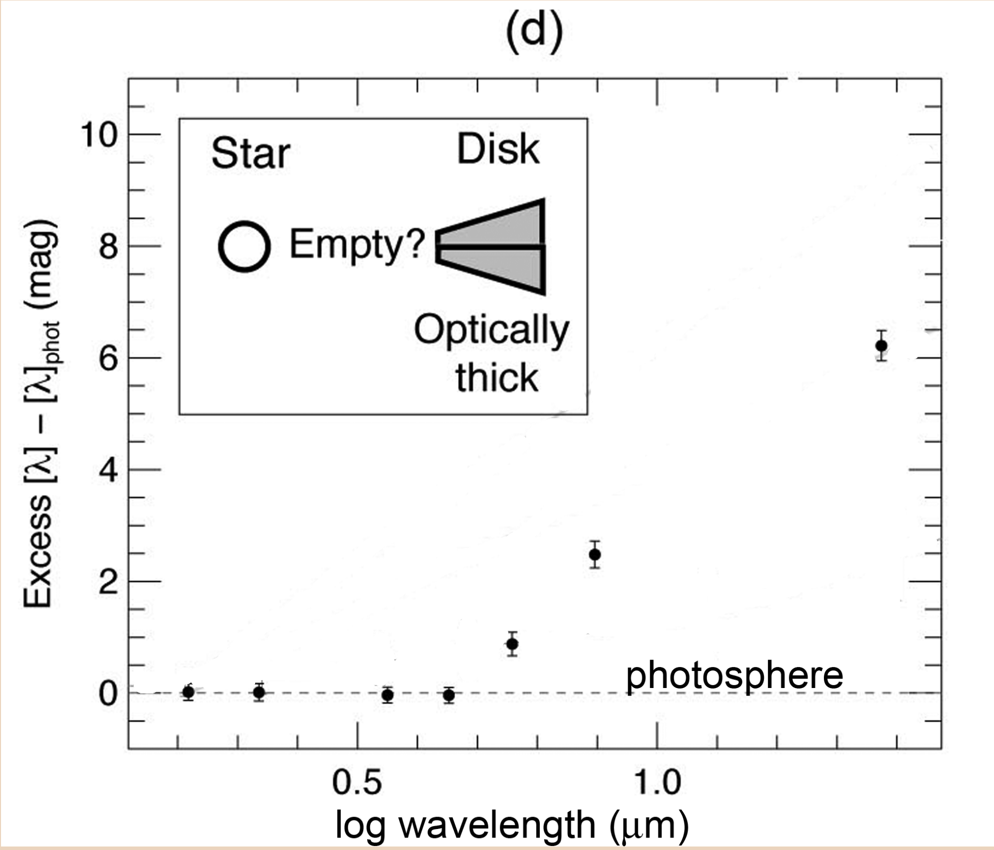


Such disks should show no inner disk gas and no evidence of gas accretion

Thick Outer, Empty Inner Disk: d

Possibility (2); $dM_{acc}/dt < dM(pe)/dt$; isolates inner disk

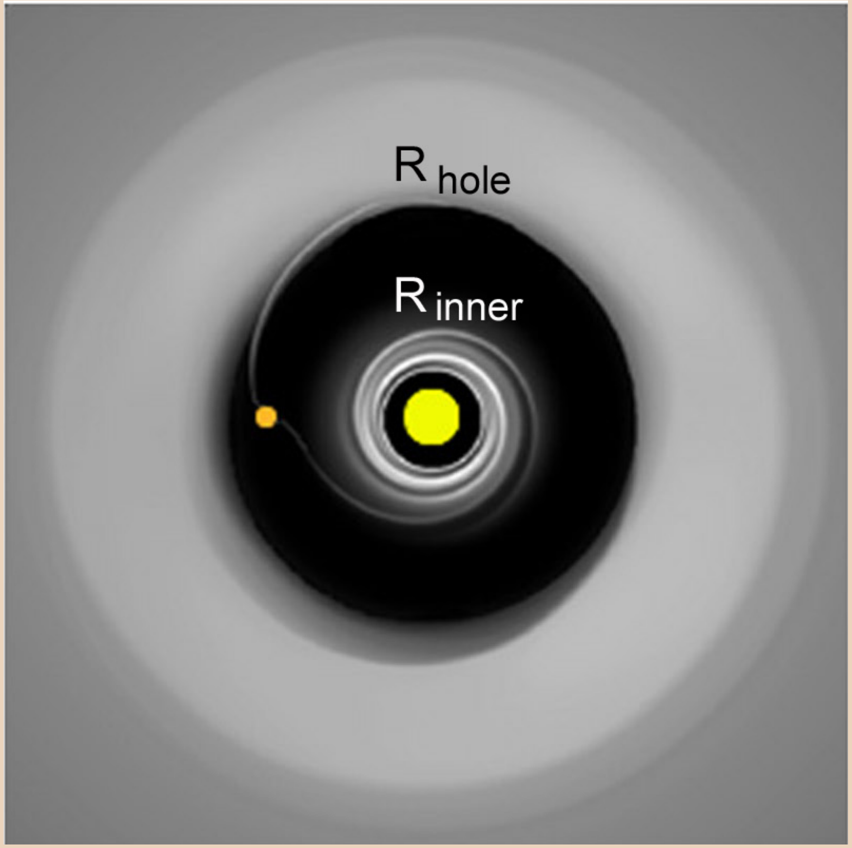


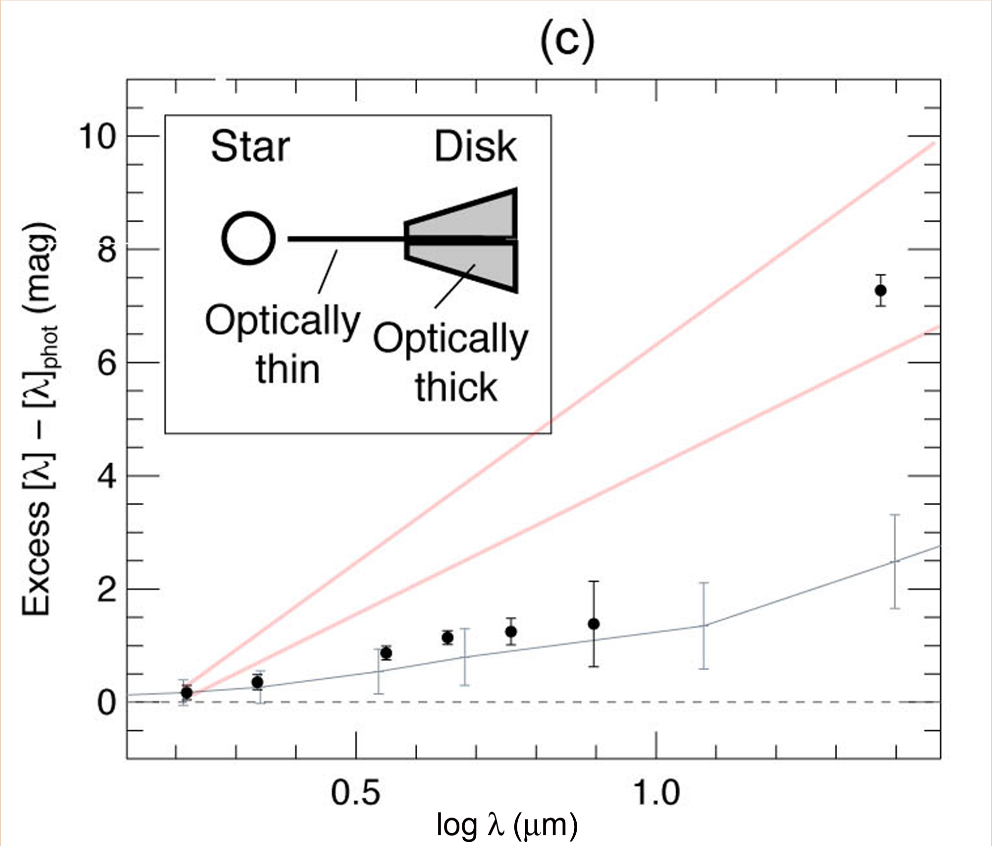


Such disks should show no inner disk gas and no evidence of gas accretion

Thick Outer; Thin Inner Disk: c

Possibility (1): A M_{jup} planet forms, creating a tidal gap



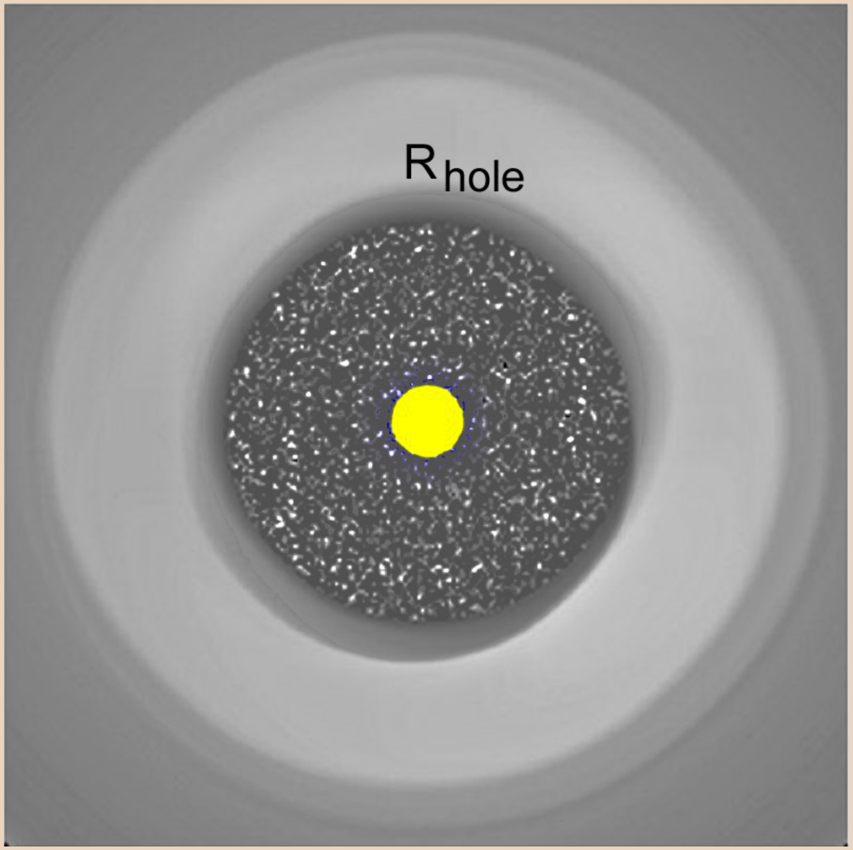


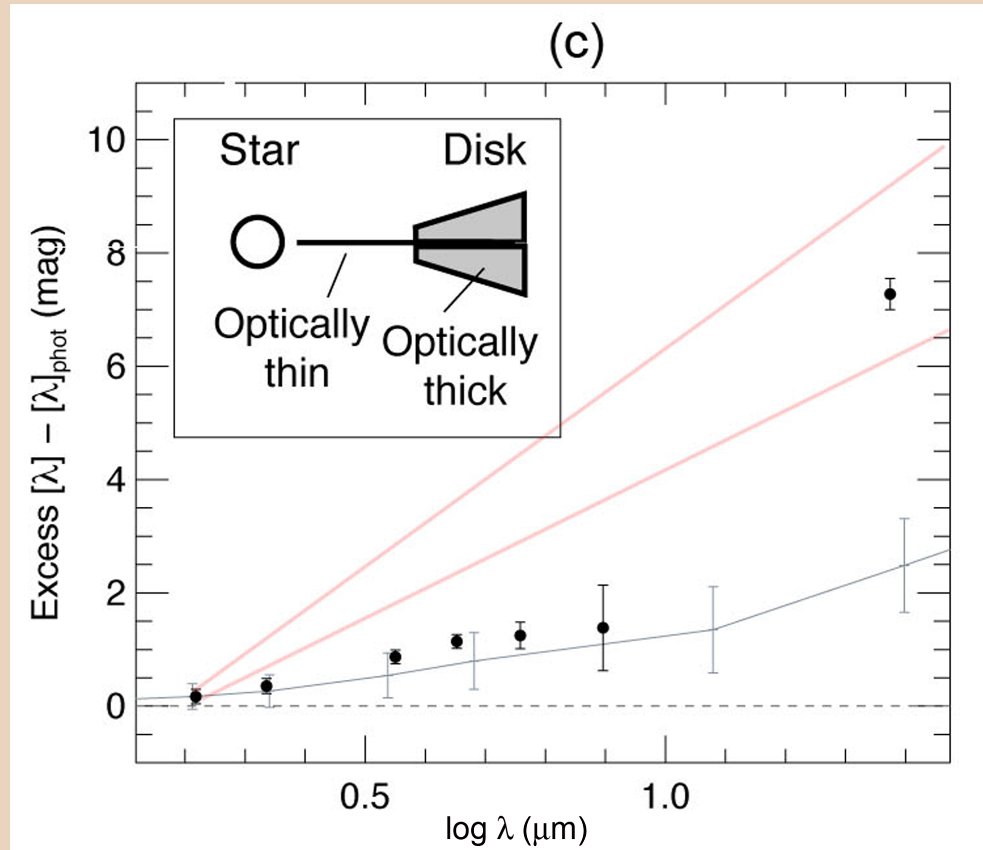
90% of the accreting gas winds up on the planet; 10% spirals into the star

Inner disk gas should exhibit a gap; accretion rate ~ 10% of accretion rate of optically thick disks

Thick Outer; Thin Inner Disk: c

Possibility (2): Planetesimal formation creates optically thin inner hole; gas still present





Gas present throughout disk; accretion rate ~ accretion rate typical of optically thick disks

Summary

10k young stars w/in 1 kpc

- Cloud-wide spatial distributions of young stars

  Surface density varies greatly within and among clouds
  ~70% of young stars in 1 kpc are in groups of 10 or more

- Star formation rates and gas surface densities

  Σ_{SFR} - Σ_{GAS} relation linear at high densities
  SF threshold ~ 8 A_V mag

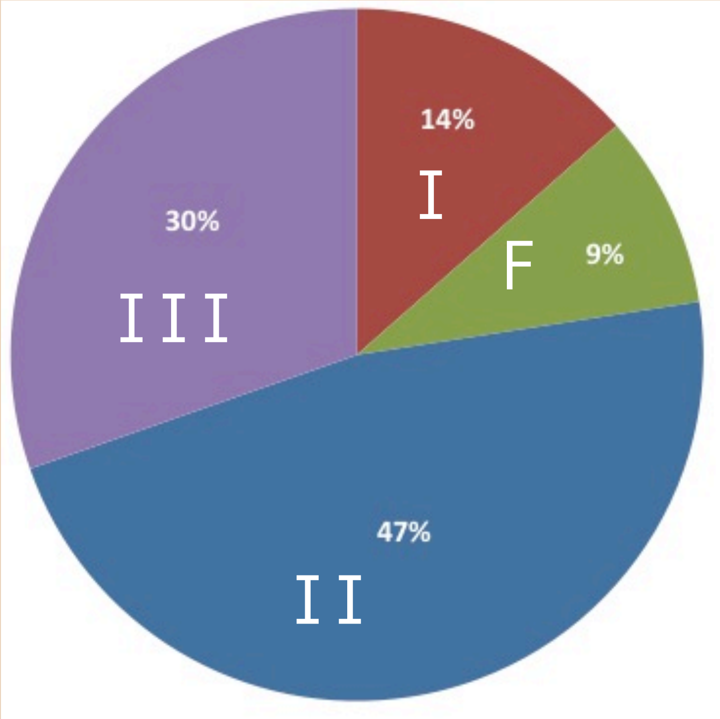
- Disk morphology and evolution

  Sort Class II+transition disks into 4 categories
  Inner disk clearing may be result of planet formation

Observational Diagnostics

SED Type	Physical State	Stellar dM_{acc}/dt	Gas Distribution Through Disk	Disk Mass
a	Accreting PMS star	~ cTTS & HAeBe	throughout	any
b	1: planetesimals 2: planetesimals with gas	1: zero 2- cTTS & HAeBe	1: none 2: throughout	1: 10^{-3} M_* 2: any
c	1: Jovian planet 2: planetesimals with gas	1: 10% cTTS/ HAeBe 2: cTTS/HAeBe	1: inner gap 2: throughout	1: 0.01 - 0.1 M_* 2: any
d	1: photoevaporation 2: supra-Jovian planet	1: zero 2: zero	1: outer only 2: outer only	1: 10^{-3} M_* 2: 10^{-1} M_*

20 clouds, 3124 YSO
c2d + GB surveys



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%

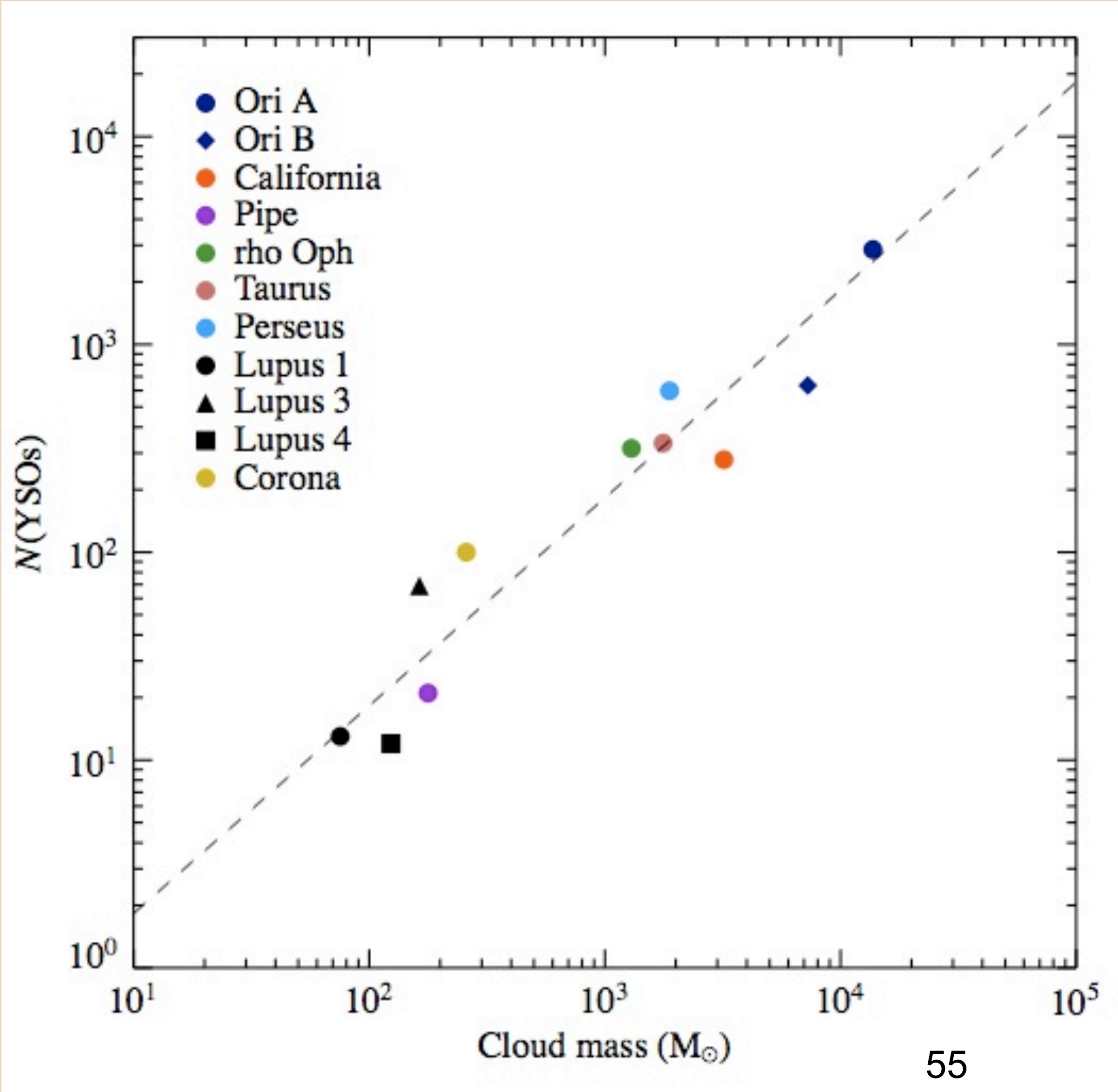
IF Time is the only variable
AND
IF star formation continuous
AND
IF Class II lasts 2 Myr (half-life)
THEN

Class I lasts 0.54 Myr
Flat lasts 0.35 Myr
(longer than most previous estimates)

<u>Caveats:</u>
Class III census incomplete; not included in timescale
Depends on *how* α is calculated
GB not corrected for extinction
Class 0 mixed with Class I

Star Forming Threshold

- Using different methods, Lada, Lombardi, & Alves (2010) found a threshold at ~116 $M_\odot$ pc^{-2} (A_V ~7.3)
- Measuring cloud mass above this threshold recovers a tight linear (slope =0.96) relation



Lack of Resolution in Exgal Studies?

- Exgal studies average over large areas, star forming regions unresolved
- Beam contains both diffuse & dense gas
- Assume underlying relation is what we observe: linear around Σ_{th} ~129 $M_{\odot}$ pc^{-2}
- To recover the Kennicutt relation averaged over large scales, fraction of dense gas:

assume: $\Sigma_{SFR} \propto <\Sigma_{gas}>^{1.4}$

if: $\Sigma_{SFR} \propto \Sigma_{dense}$ $(\Sigma_{gas} > \Sigma_{th})$

then: $\Sigma_{dense} \propto f_{dense} < \Sigma_{gas} > \propto \Sigma^{1.4}_{gas}$

or $f_{dense} \propto \Sigma^{0.4}_{gas}$

- At $<\Sigma_{gas}> \cong 300\ \Sigma_{th}$, $f_{dense} \sim 1$
- gas dense enough to form stars → maximal starburst

Local evidence for gas below Σ_{th}?

- No complete census of CO in all clouds within local 0.5 kpc
- Measure mass of gas using extinction maps above and below Σ_{th} (A_V~8)
- 16 clouds d< 500 pc, A_V down to 2 mag
- The ratio of total mass below the Σ_{th} to the total mass above is 4.6
- Factor of 5.1 more in Orion (Heyer, priv. com.)
- Goldsmith et al. 2008, Taurus, A_V <2, factor of 2 more mass
- 10 x more total molecular mass than mass above Σ_{th} is plausible
- most gas in 0.5 kpc is atomic (Evans 2008), including this gas below the threshold will yield agreement between local Σ_{SFR} and Kennicutt-Schmidt

=> exgal may lack resolution: measurements include a large amount of diffuse, non- star forming gas