IRAC

From Conception to Successful Maturity

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Giovanni Fazio, and the IRAC Vision

In the early 1970s Giovanni began far-IR ballooning, working on the Spacelab-2 InfraRed Telescope, and obtaining ground-based observations with the GSFC mid-IR array camera.

By 1983 (time of the SIRTF proposal), Giovanni knew first-hand the promise of the areal arrays just becoming available, the advantages of space, and the power of the IR for addressing astrophysical problems.

Giovanni was the ideal astrophysicist to envision what IRAC could accomplish on SIRTF (S = shuttle or space!).

The IRAC Proposal November 1983

- IRAC - as originally conceived by Giovanni
  - Wide-field (5′ x 5′) and diffraction-limited cameras (1.25′ x 1.25′)
  - InSb, Si:Ga, and Si:Sb photoconductive detector arrays covering 2-30 μm (128 x128 and 64x64 formats proposed)
  - Simultaneous observations of the same FOV, and 3 filter wheels giving spectral resolutions of $\lambda/\Delta\lambda$ = 0.01 – 100

- Descopes a decade later, and other considerations led to
  - Wide field camera only
  - InSb and Si:As IBC arrays covering 3.26-9.5 μm
  - Fixed filters ($\lambda/\Delta\lambda$ =2.7 to 5) for each array
  - No moving parts

Astronomical array images in the IRAC proposal
So much to achieve before launch!

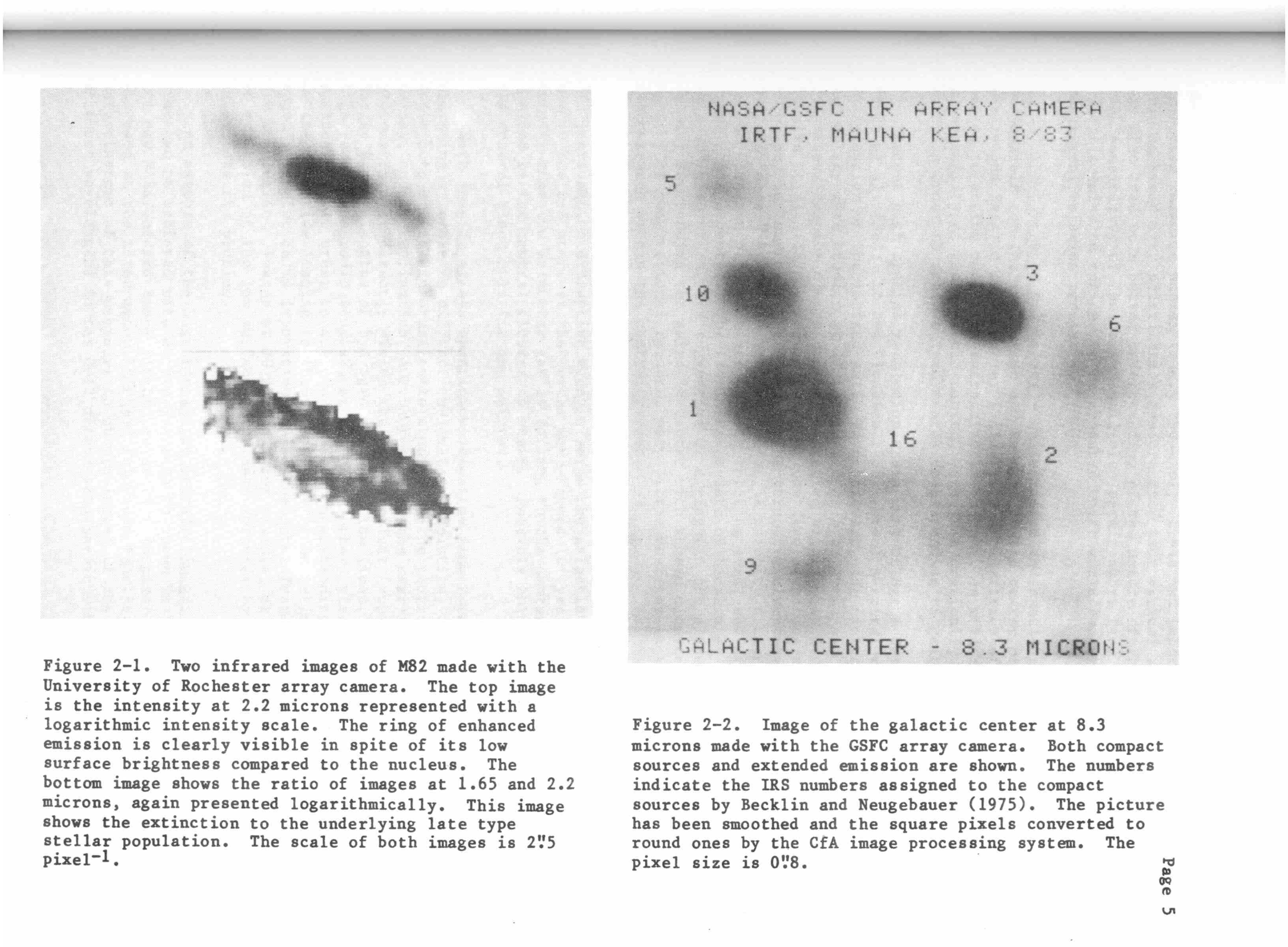


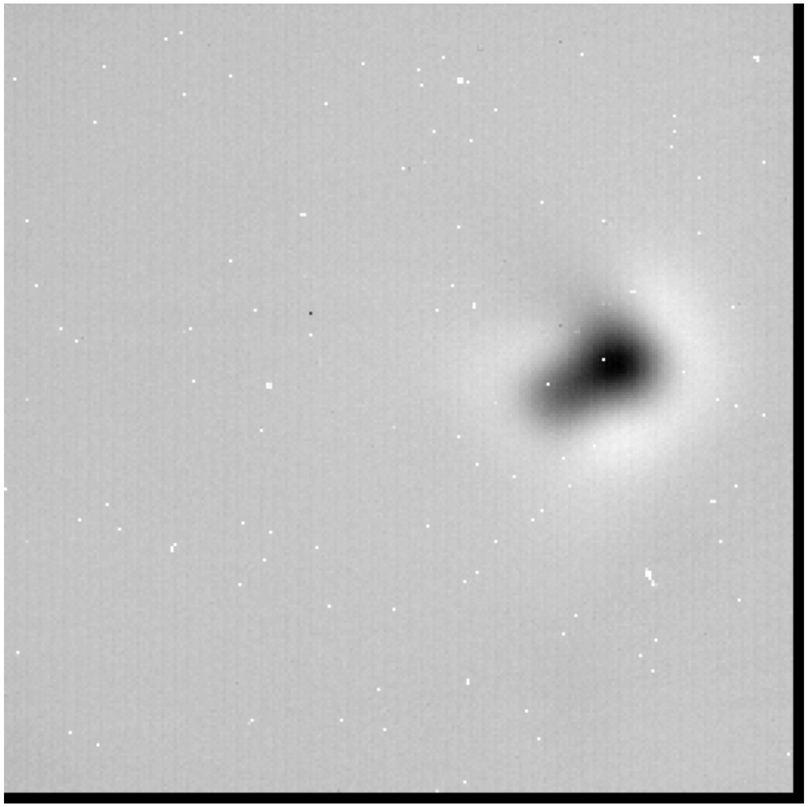
Figure 2-1. Two infrared images of M82 made with the University of Rochester array camera. The top image is the intensity at 2.2 microns represented with a logarithmic intensity scale. The ring of enhanced emission is clearly visible in spite of its low surface brightness compared to the nucleus. The bottom image shows the ratio of images at 1.65 and 2.2 microns, again presented logarithmically. This image shows the extinction to the underlying late type stellar population. The scale of both images is 2″5 pixel^{-1}.

Figure 2-2. Image of the galactic center at 8.3 microns made with the GSFC array camera. Both compact sources and extended emission are shown. The numbers indicate the IRS numbers assigned to the compact sources by Becklin and Neugebauer (1975). The picture has been smoothed and the square pixels converted to round ones by the CfA image processing system. The pixel size is 0″8.

Giovanni had faith that IR Detector Arrays, would achieve the desired performance!

Then (1st NASA Ames Detector Conference)	Now
InSb 32 x 32 CCD	InSb 256 x 256 SFD
QE 0.65	QE > 0.8
DC 3000 e-/s	DC < 1 e-/s
Noise 1000 e-	Noise 50 e- Fowler 2
Si:Bi 16 x 16 CID	Si:As 256 x 256 SFD
QE 0.05	QE 0.5
DC 200 e-/s	DC 10 e-/s
Noise Background limited	Noise 50 e- Fowler 2

10+ years post-proposal fraught with issues: Giovanni continued to keep the faith



- Budget considerations
  - Scope of SIRTF
  - Launch vehicle, orbit
  - Explore IRAC on Japanese satellite
  - Instrument descopes
- Detector development issues
  - (e.g. “black holes” – IRAC maintained focal plane temperature stability avoiding black holes)

SIRTF IRAC Arrays - Pune, India IUCCA 1994

Bill Forrest demonstrated real-time SIRTF array performance over the internet to participants

IRAC invitees: Bill Forrest, Craig McCreight, Giovanni Fazio

IRAC Science Objectives in 1983 Proposal (most have been executed!)

Galaxy formation in early stages of the Universe

Search for cool stars in galactic haloes

Energy sources in AGN/Starburst galaxies

The center of our Galaxy

Large scale star formation in external galaxies

Properties of clusters of galaxies

Dust around stars

Physical properties of star formation and evolution in the Galaxy

(Heavy element abundances IRS)

Dust in comets

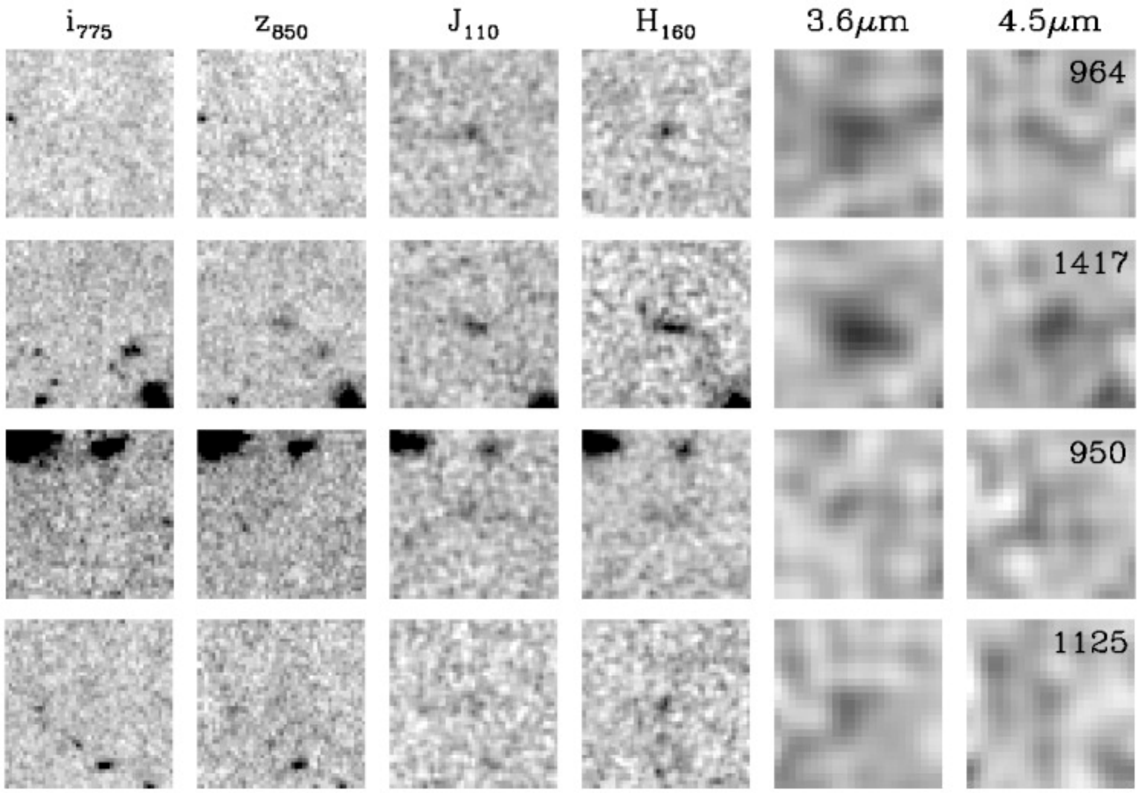
A few representative IRAC results

Search for cool stars in dark matter haloes

Ashby et al.(2009) find no evidence for halo – no significant emission > 10 kpc from midplane, nor is thick disk required

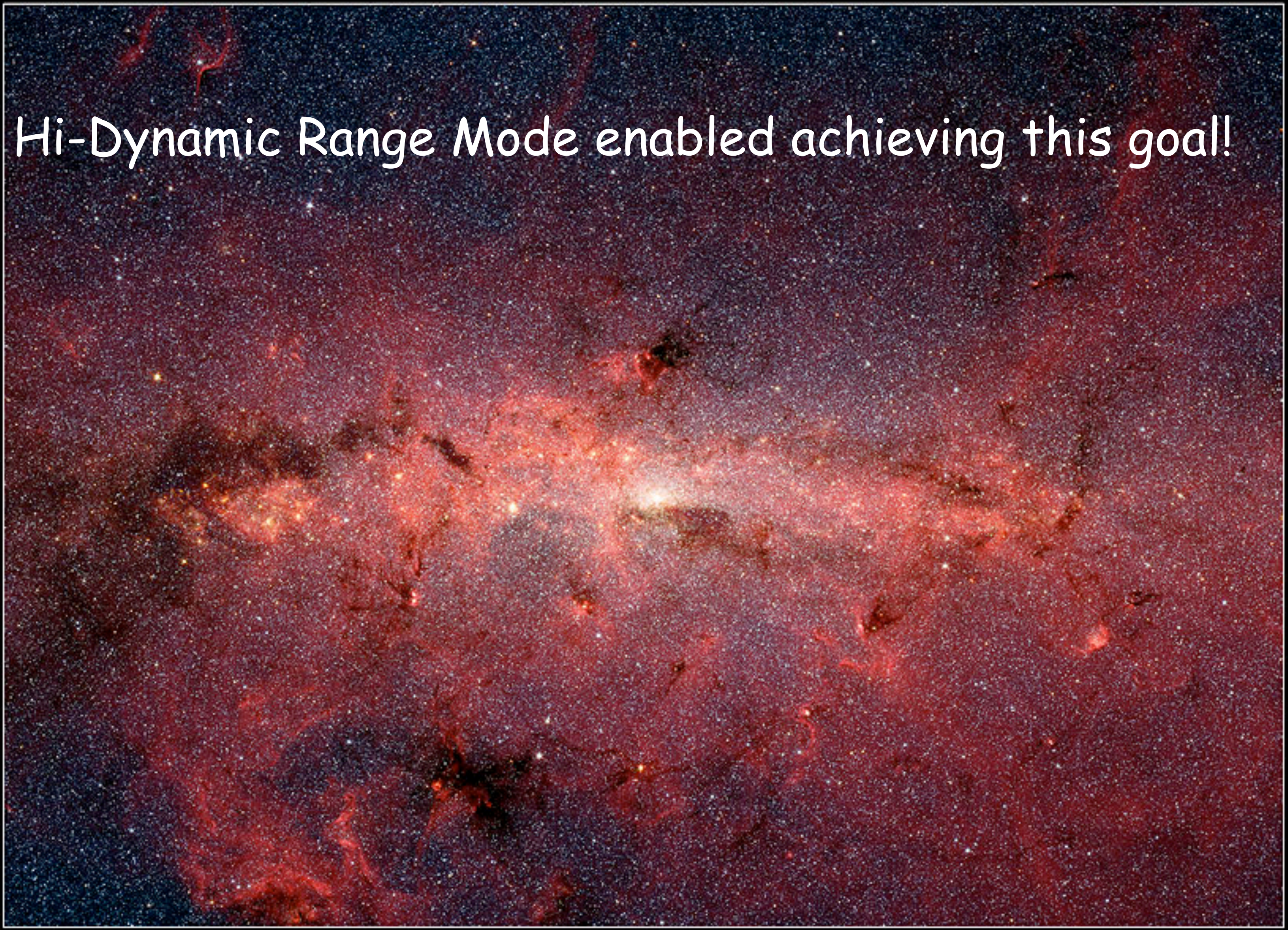
Galaxy Formation in the Early Universe

i/z dropout galaxies detected at 3.6, 4.5 μm in Hubble Ultra-Deep Field



Labbe et al. (2006) interpret these two good detections as z ~ 7 galaxies (t ~ 750 Myr) using photometric redshifts determined from stellar population model fits to the SEDs

Hi-Dynamic Range Mode enabled achieving this goal!



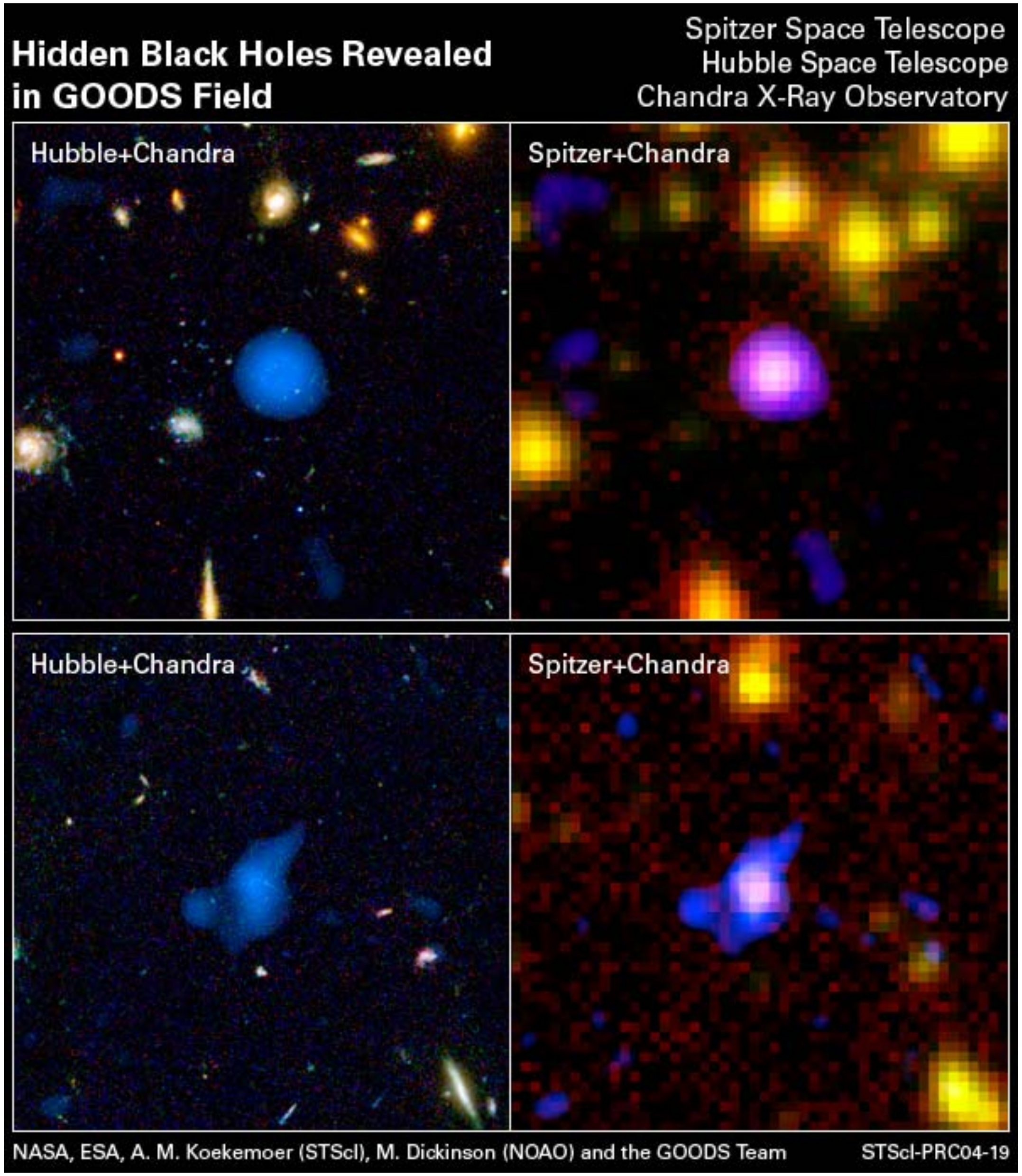
The Center of the Milky Way Galaxy

NASA / JPL-Caltech / S. Stolovy (Spitzer Science Center/Caltech)

Spitzer Space Telescope • IRAC

ssc2006-02a

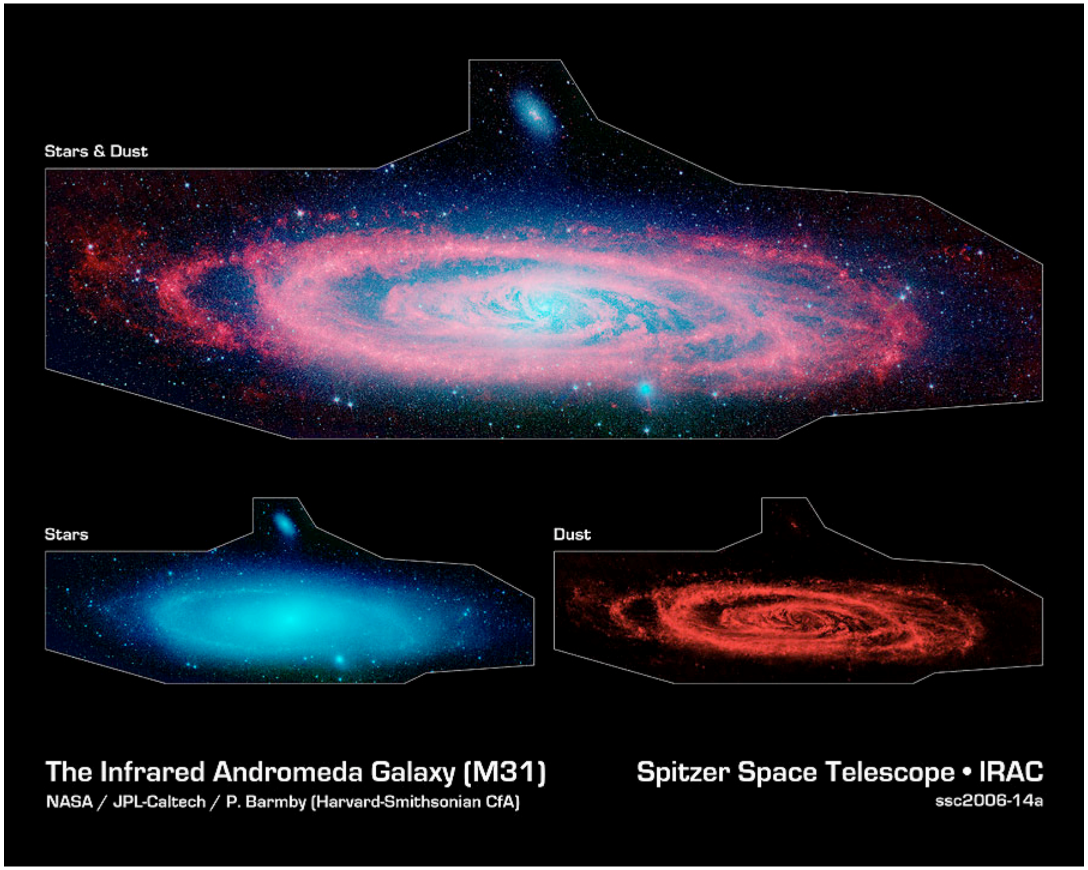
Explore energy sources in AGN



NASA, ESA, A. M. Koekemoer (STScI), M. Dickinson (NOAO) and the GOODS Team STScI-PRC04-19

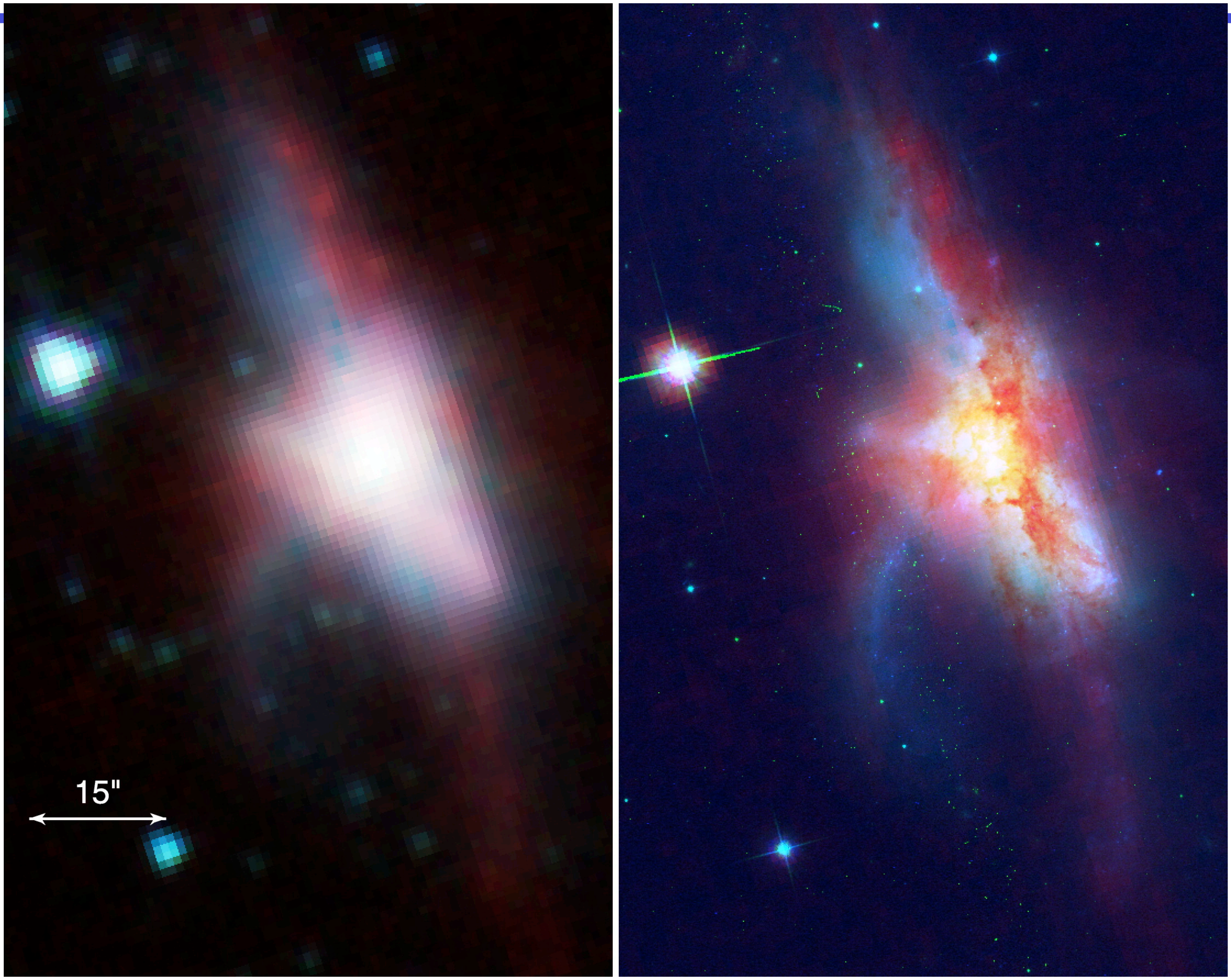
- Koekemoer et al. (2006) explore extreme X-ray detected AGNs with no optical counter-parts (IRAC 5.8 μm shown)
- SEDs including optical limits constrain AGN at z ~ 7
- Evolution of AGN luminosity function , co-evolution of galaxies and central black holes

Large scale star formation in external galaxies



M31 – Barmby et al. - oldest stars in disk and bulge (3.6, 4.5), PAH dust associated with star forming regions (8). No IR-bright nucleus.

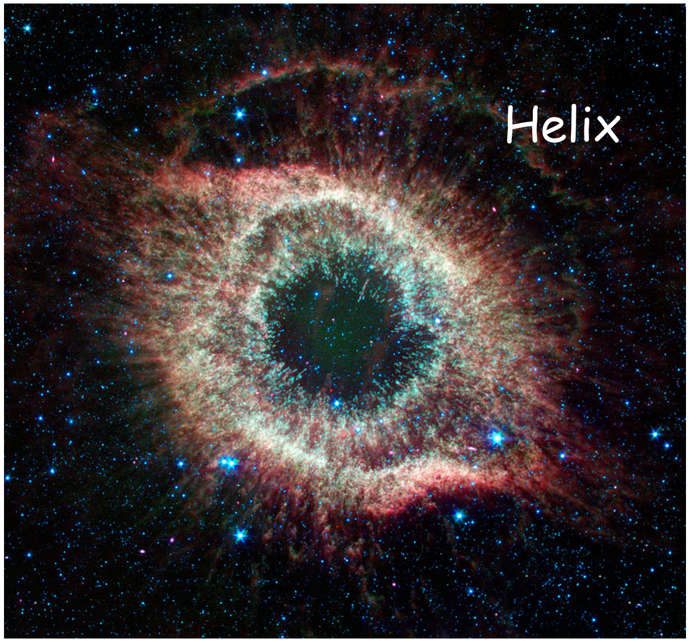
ACS B-Band and IRAC 3-Color of NGC 6240

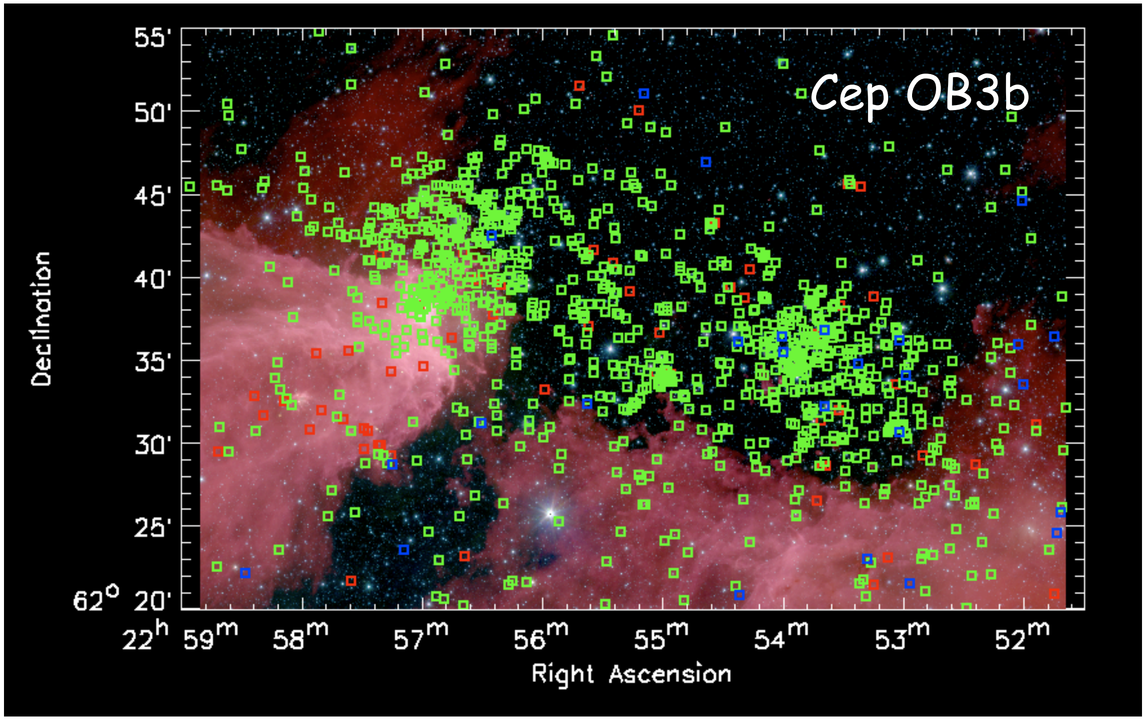


Bush et al. (2008) 3.6 4.5 8 (PRF subtracted) B I 8 (PRF subtracted)

Transition between merger, spheroid. IRAC focuses on distribution of dust and stars, dependent on merger

Dust around stars – then and now





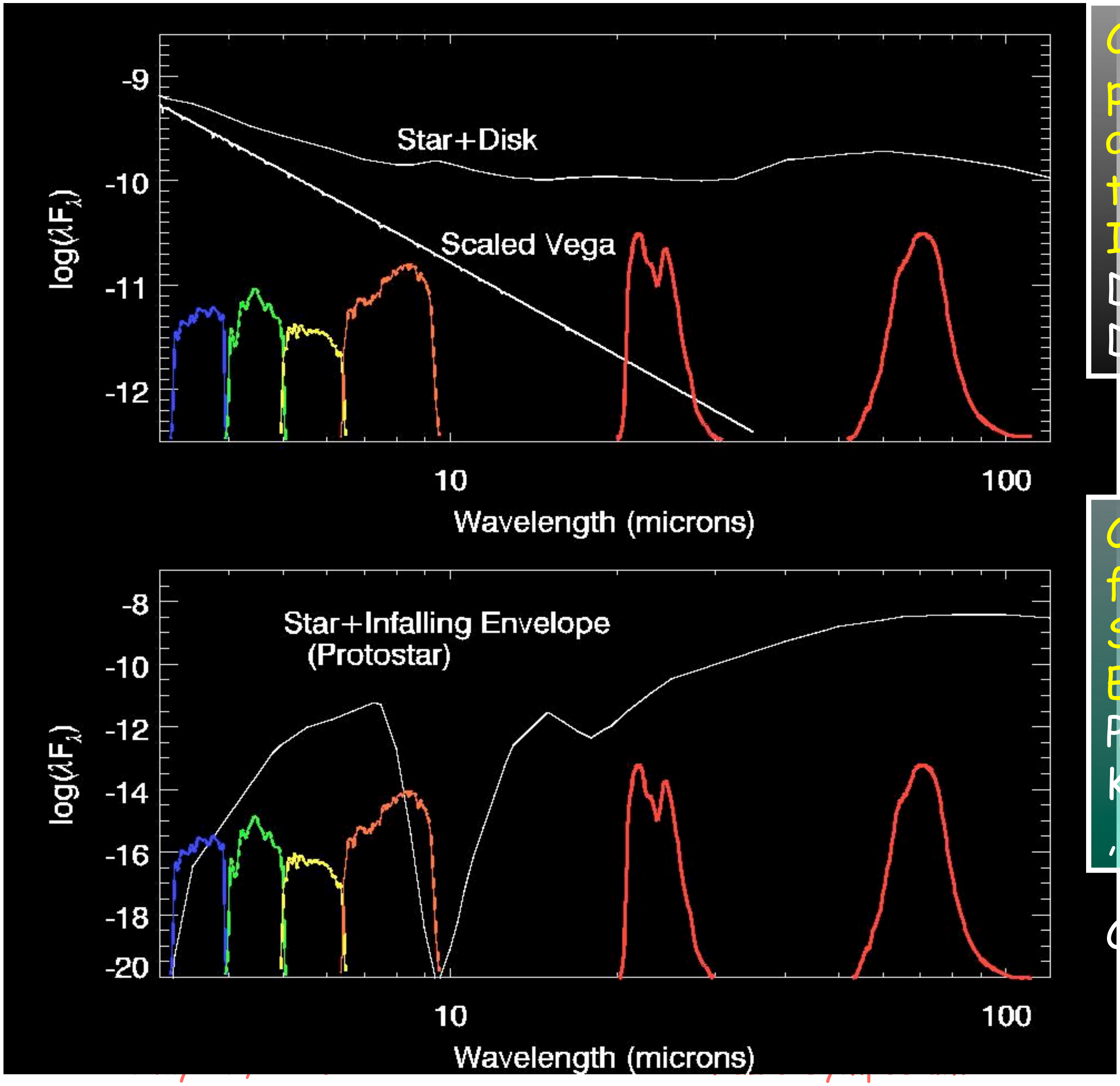
In 1983, only bright, compact young planetary nebulae could be imaged at 8 μm from the ground.

Hora et al. have observed many extended, faint PNe (Helix). IRAC images 3.6, 4.5, 8.0

Circumstellar disks around T Tauri stars *identified* (Cohen 1983), but ubiquity (IRAS) in 1985

T.Allen et al.(2009) identify 1000 class II objects (classical T Tauri stars) in Cep OB3b cluster, as well as Protostars and transition objects

Classify Stars with Disks and Protostars via IR Excess



Class II: Disk and photosphere comparable at 2 μm, disks brighter than photospheres in IRAC & MIPS bands.

Disk models from D'Alessio et al. (2004)

Class I: Protostars show flat or rising
S
ED between 4.5 & 24 μm.

Protostar models generated using method of Kenyon

Physical processes of star formation and evolution in the galaxy*

IRAC GTO Young Clusters Survey = YCS

(Myers, Megeath, Gutermuth among others)

Embedded Young Clusters

- Survey of 36 young clusters within 1 kpc – size, membership, shape

Examine Spatial Configuration of IR excess objects

- Effect of environment on configuration & evolution
- Clustered vs. distributed star formation

Disk Evolution

- Age
- Destruction

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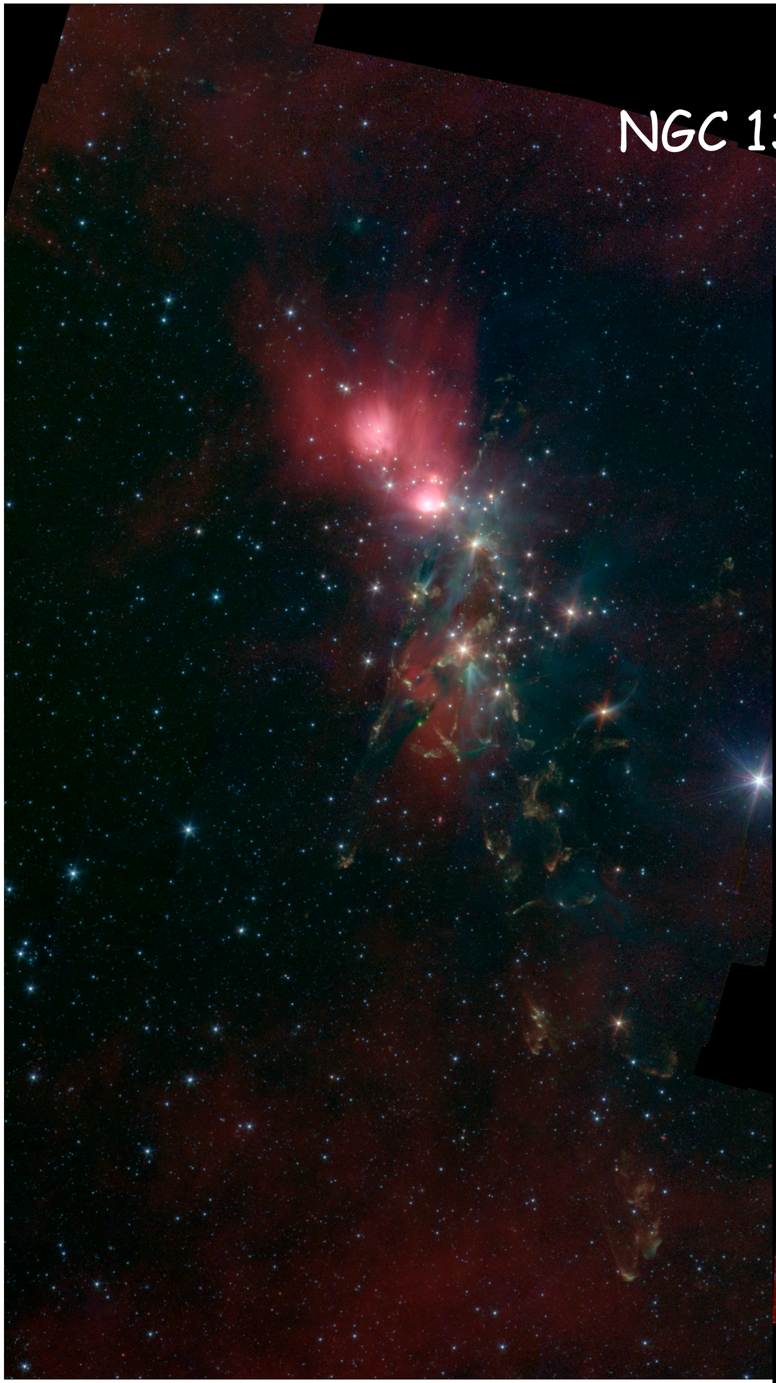
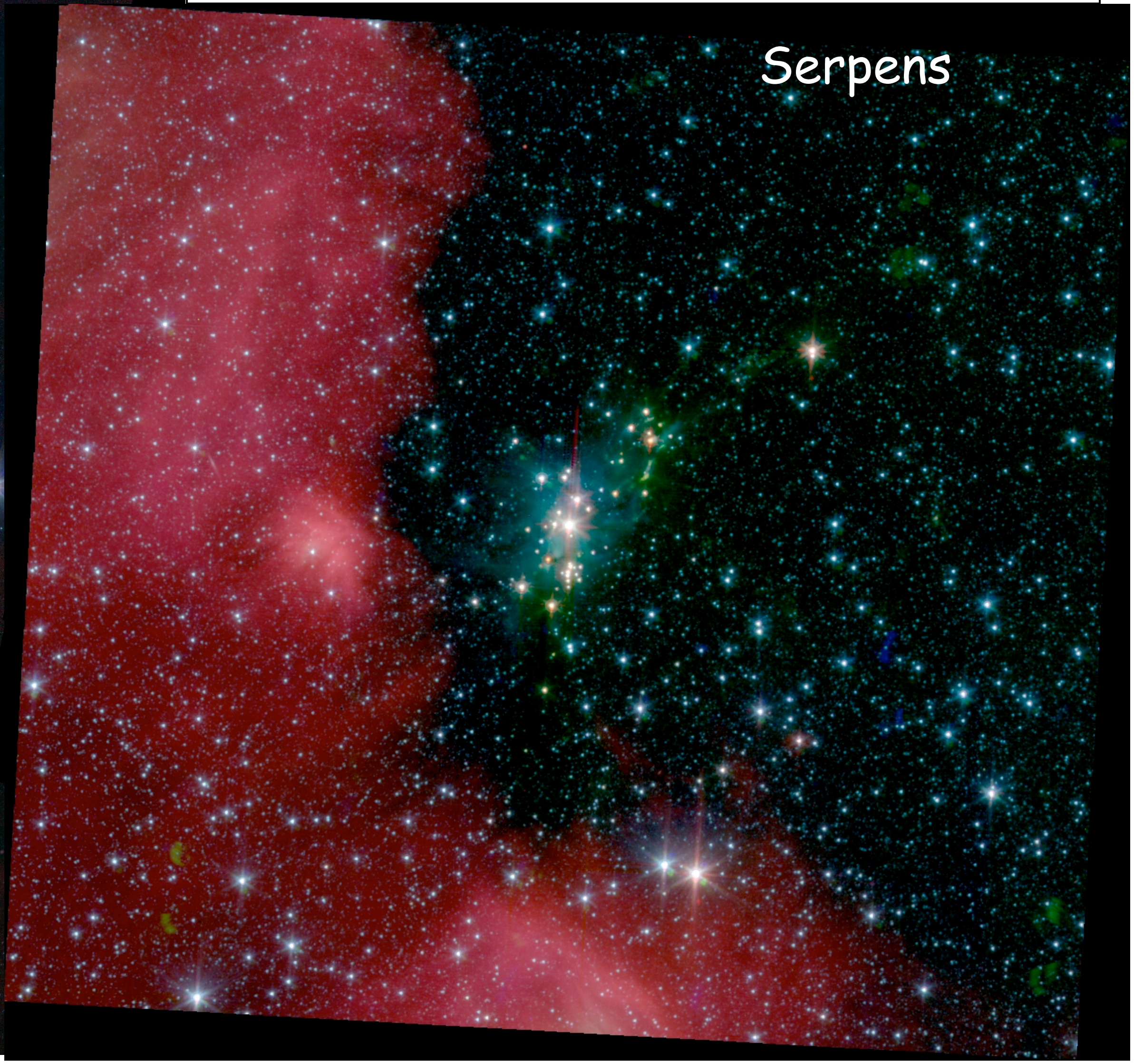
*(YCS, c2d, Orion Survey, Goulds Belt survey, GLIMPSE, and other surveys, as well as pointed observations)

A few examples from YCS

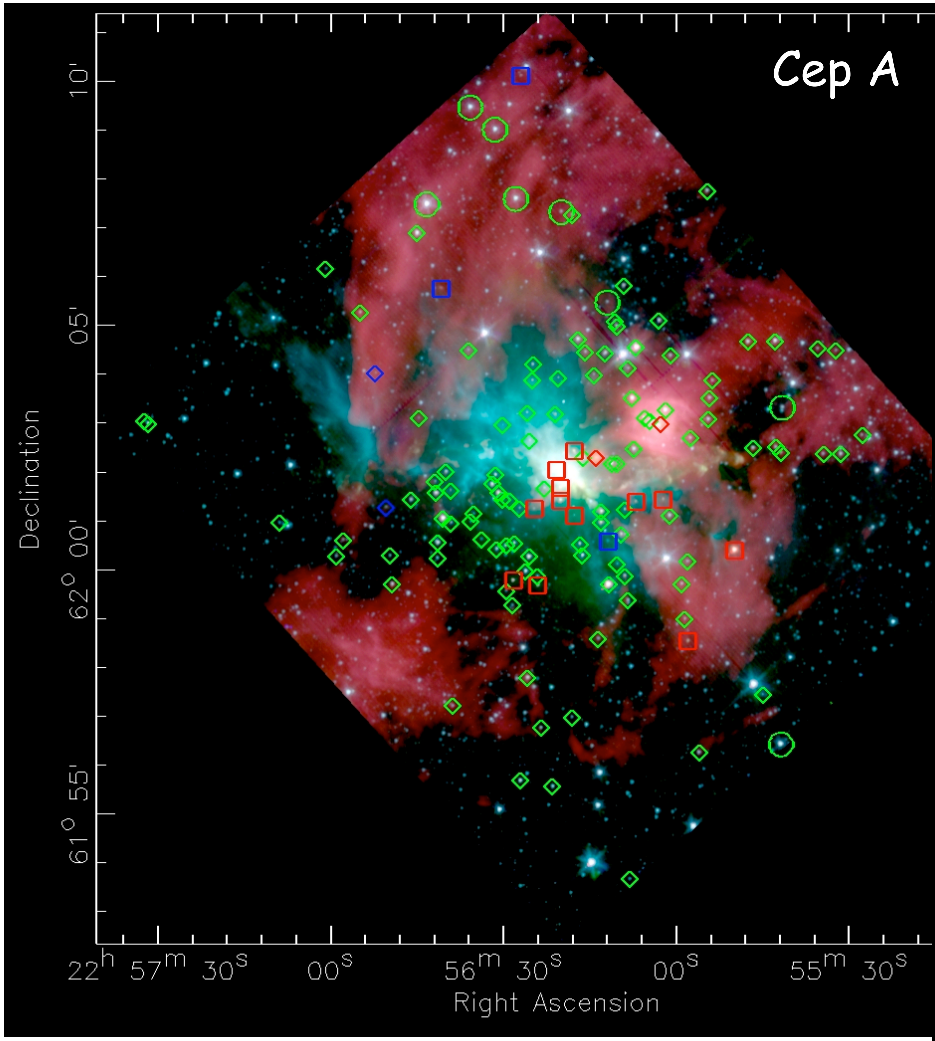
3.6, 4.5, 8.0

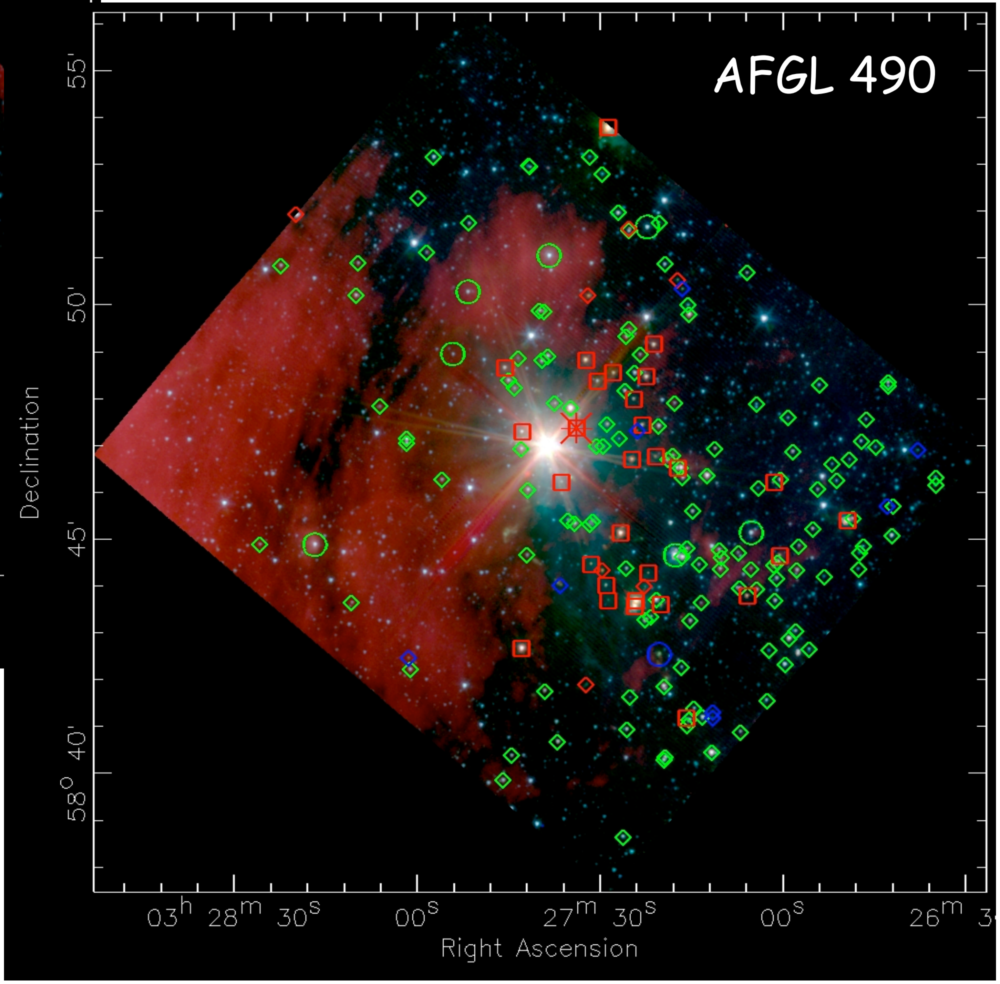




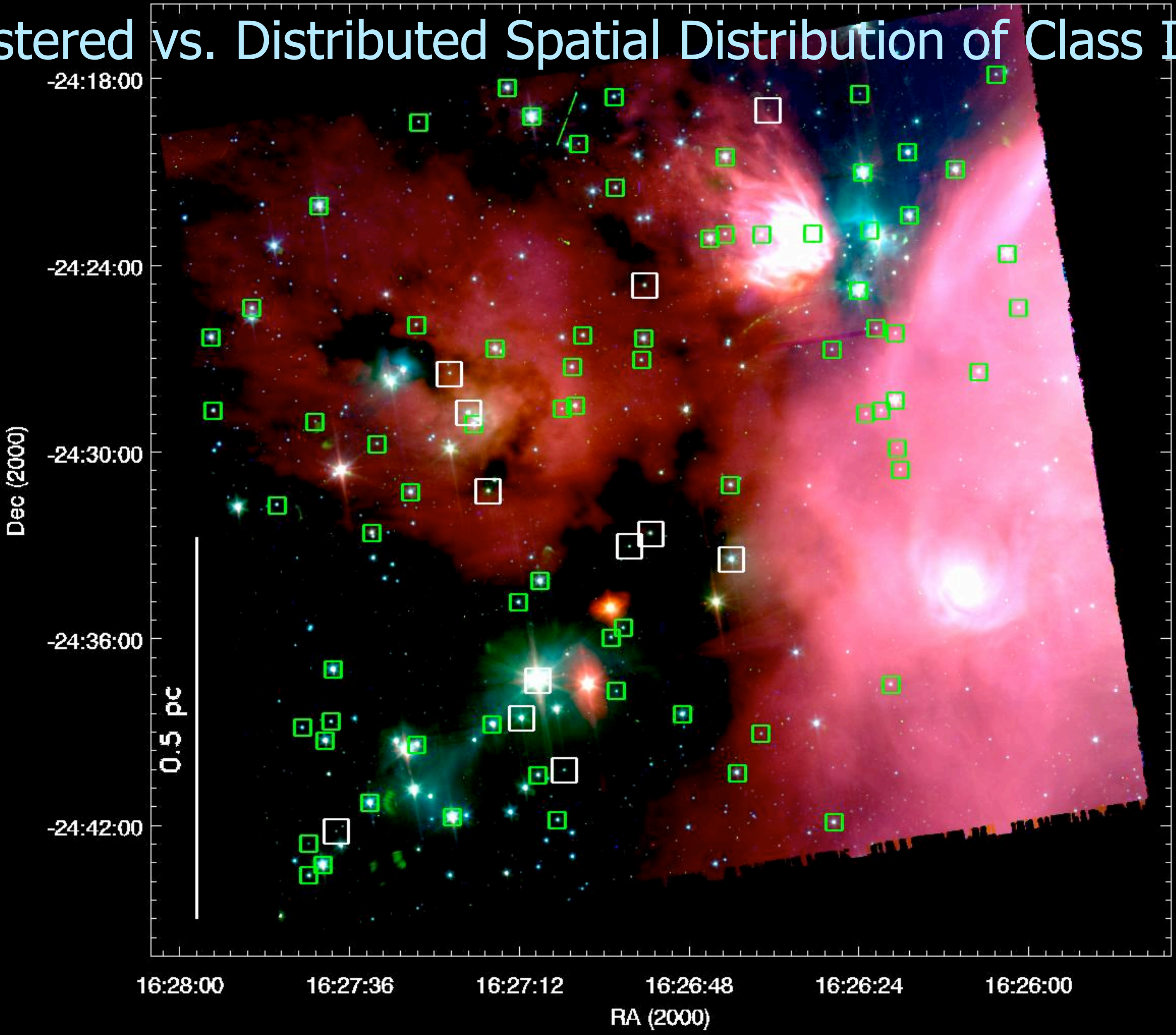
Examples with YSO Distributions Overplotted

Class II Class I

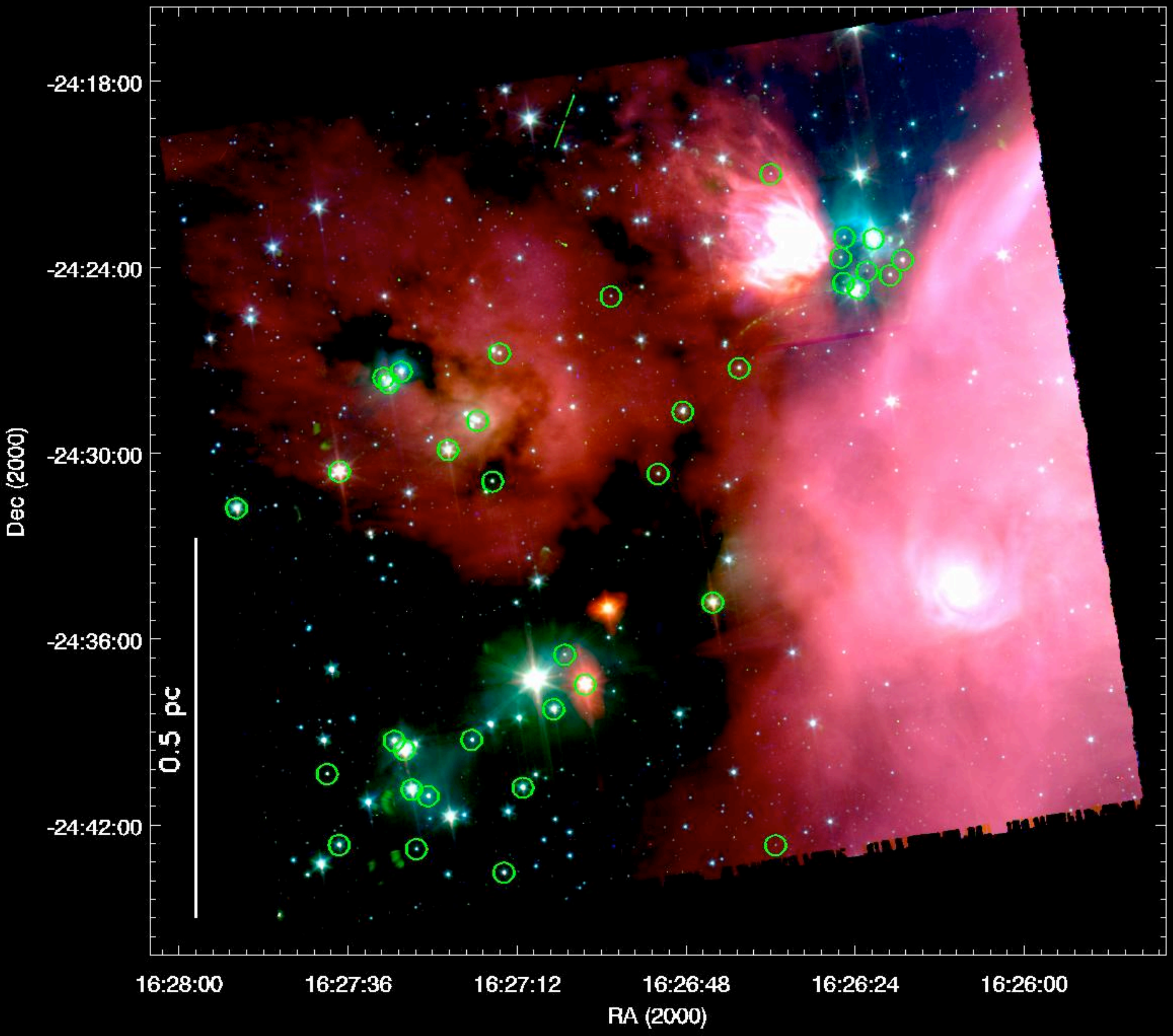


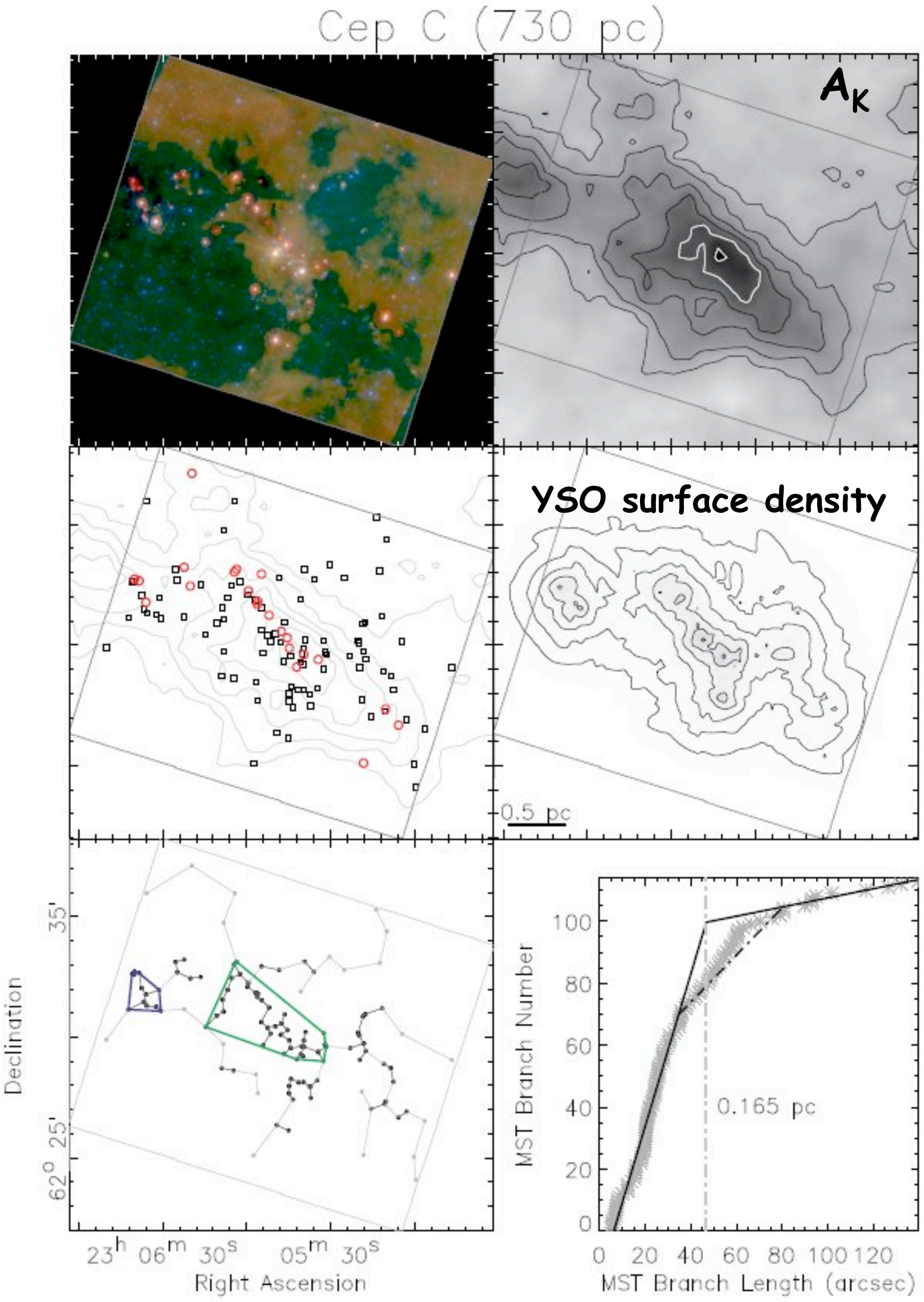


L1688 Class II Stars with Disks
Clustered vs. Distributed Spatial Distribution of Class IIs



L1688 Class I Protostars – concentrated along dust lane





MST Analysis Cep C

to isolate local surface overdensities (Gutermuth et al. 2009)

Minimum spanning tree – network of branches minimizing length of all connections

Branches are GREY if longer than the critical length and BLACK if shorter than the critical length.

Still connected sources with ≥ 10 members defined as a cluster.

Entire GMCs associated with OB associations

- Examples are Orion, Cep OB3, MonR2, W5 GMCs
  - Most low mass stars within 1 kpc have formed in GMCs associated with OB associations
  - EUV and FUV radiation from OB stars not only disperse/ ionize the gas, but may destroy disks over time
    - Compare Orion < 2 Myr with Cep OB3b 4 Myr
  - 30-40% of the young stars associated with cluster overdensities, remainder distributed

Most YSOs found in GMCs near OB Clusters at d < 500 pc (from Tom Megeath)

Ophiuchus & Perseus

A_v cloud map: Complete

YSOs: IR-excess from Spitzer c2d

Taurus

A_v cloud map: Lombardi & Alves

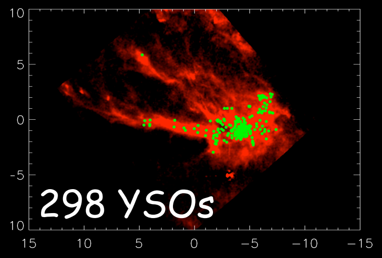
YSOs: all known from K Luhman

Orion

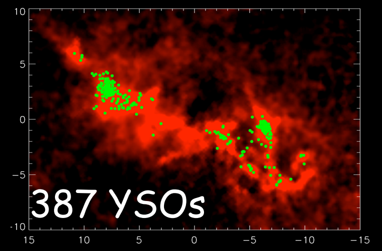
A_v cloud map: R. Gutermuth

YSOs: IR-excess from Spitzer Megeath in prep.

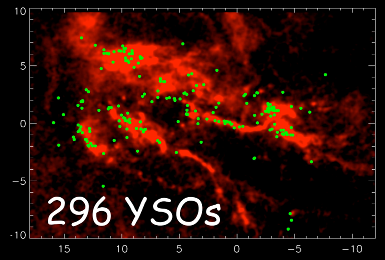
Ophiuchus

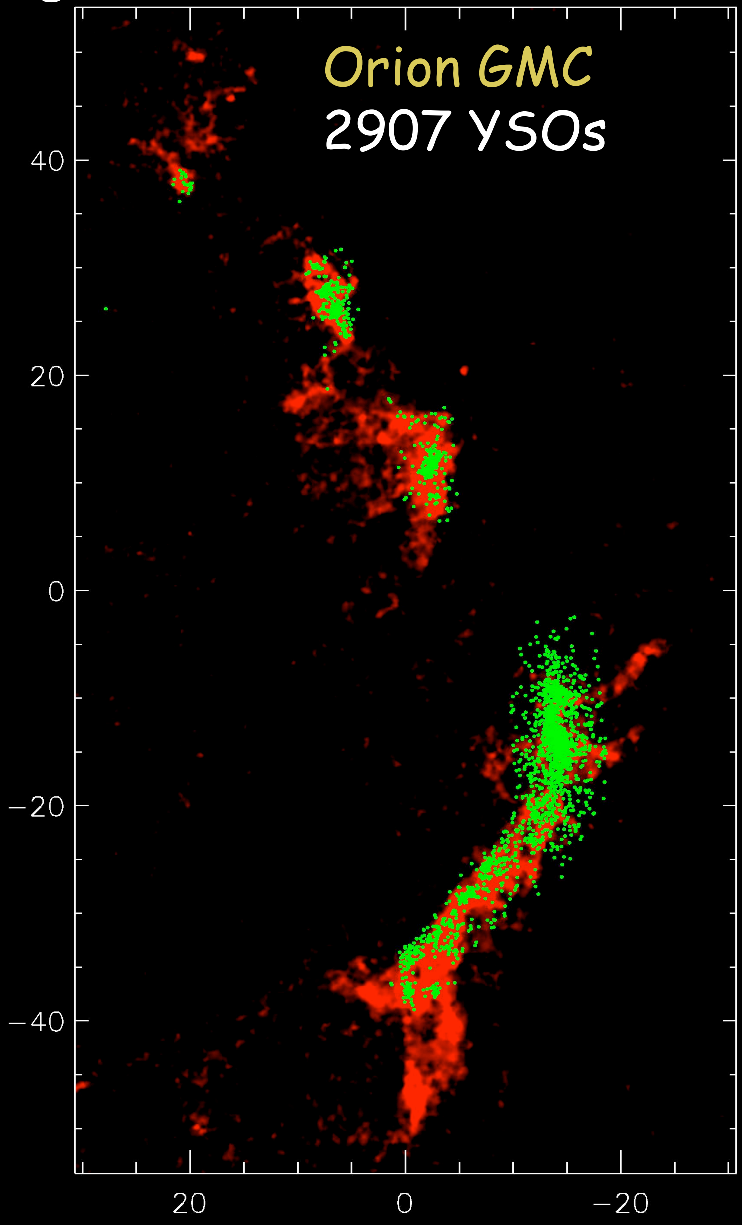


Perseus

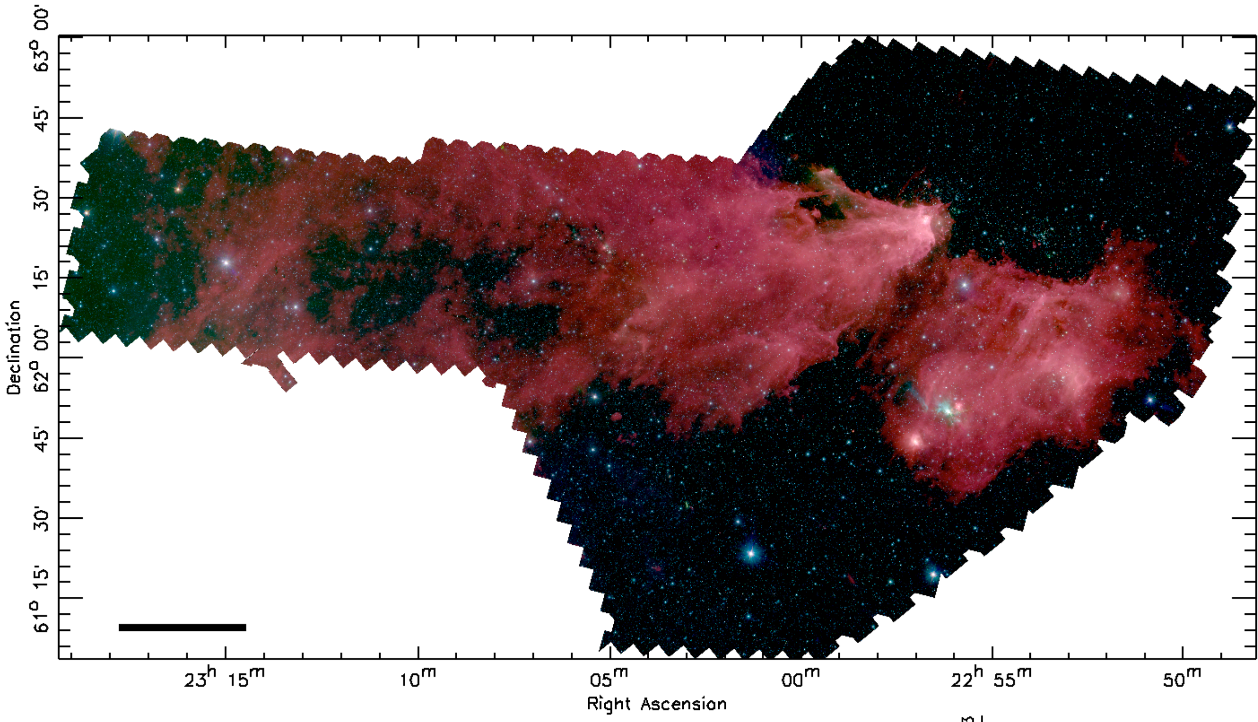


Taurus

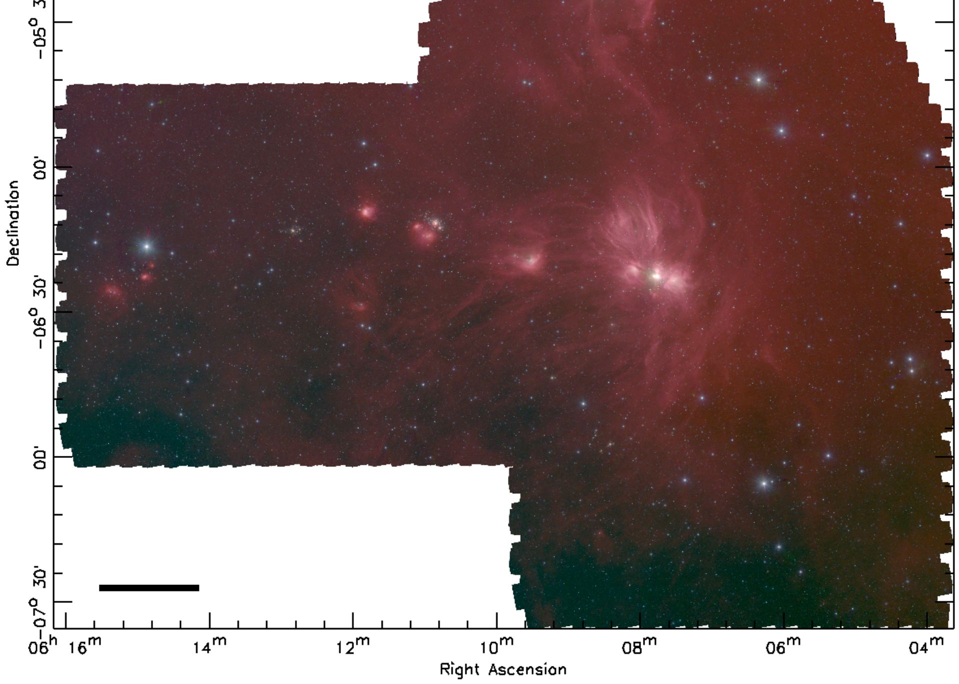




Clustered vs. Distributed Star Formation



Cep OB3
712 pc

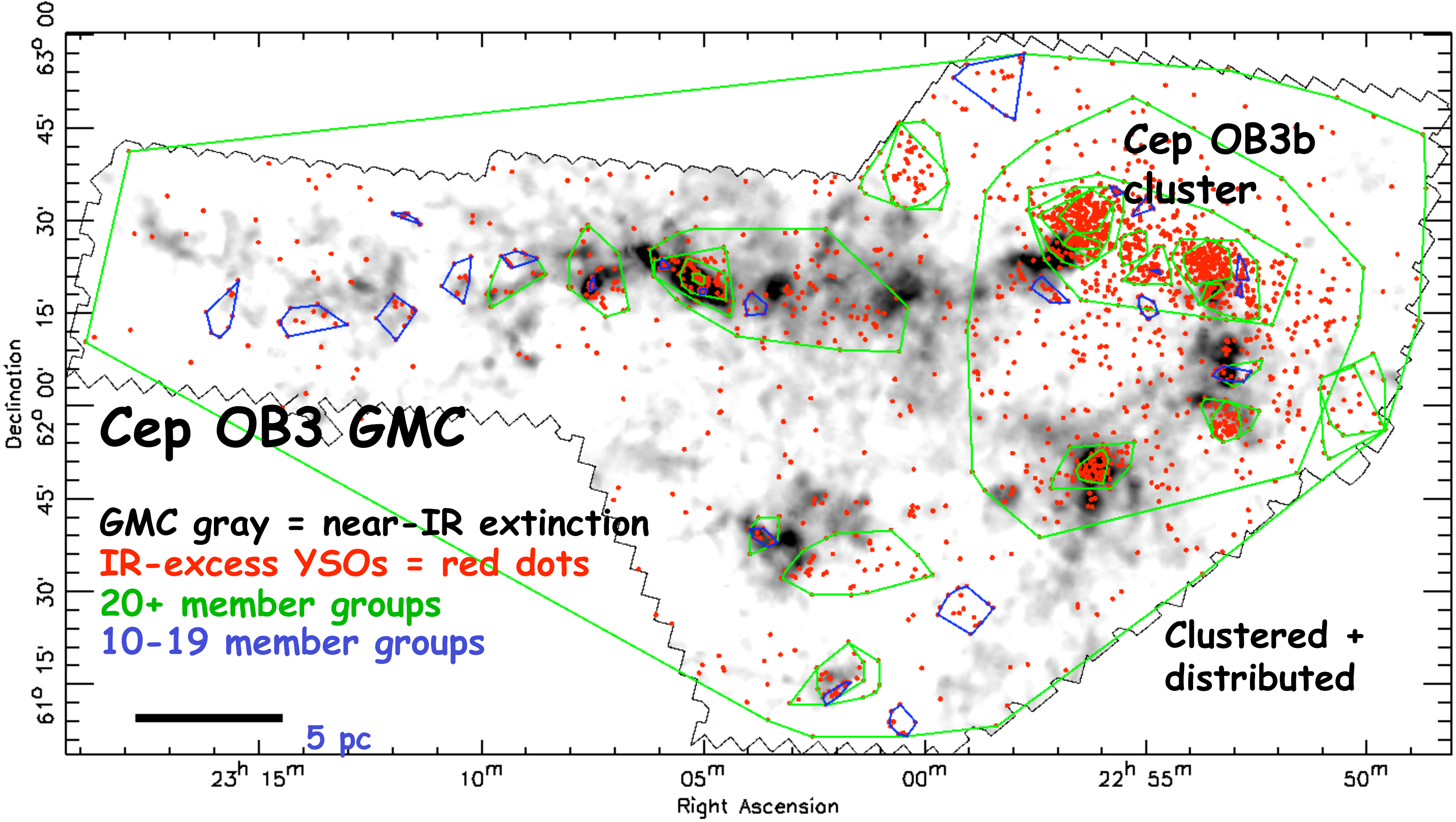


Mon R2
830 pc

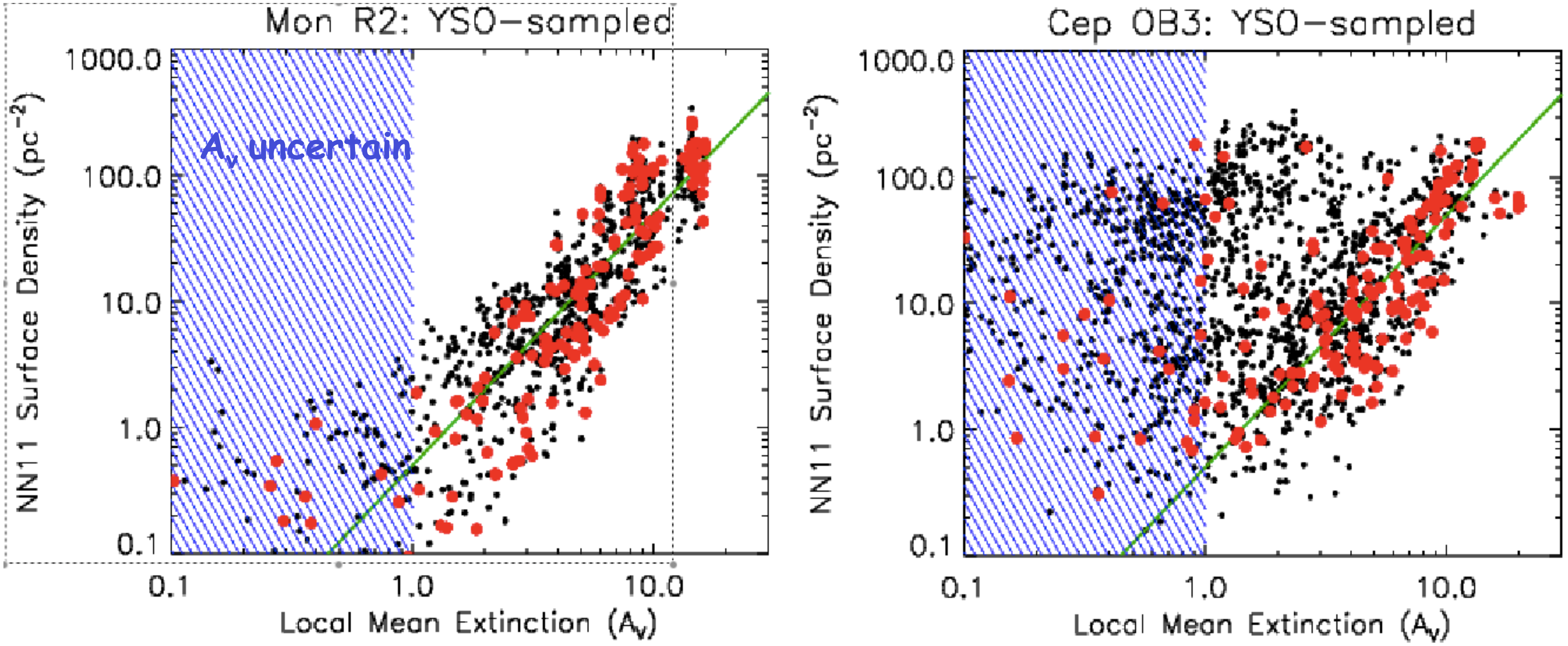
RGB = 8.0, 4.5, 3.6 μm

Minimum spanning tree to estimate overdensities

See "clusters" as peaks in the stellar density distribution: Clusters inside the GMC primarily associated with molecular clumps (from Gutermuth et al. 2009b)



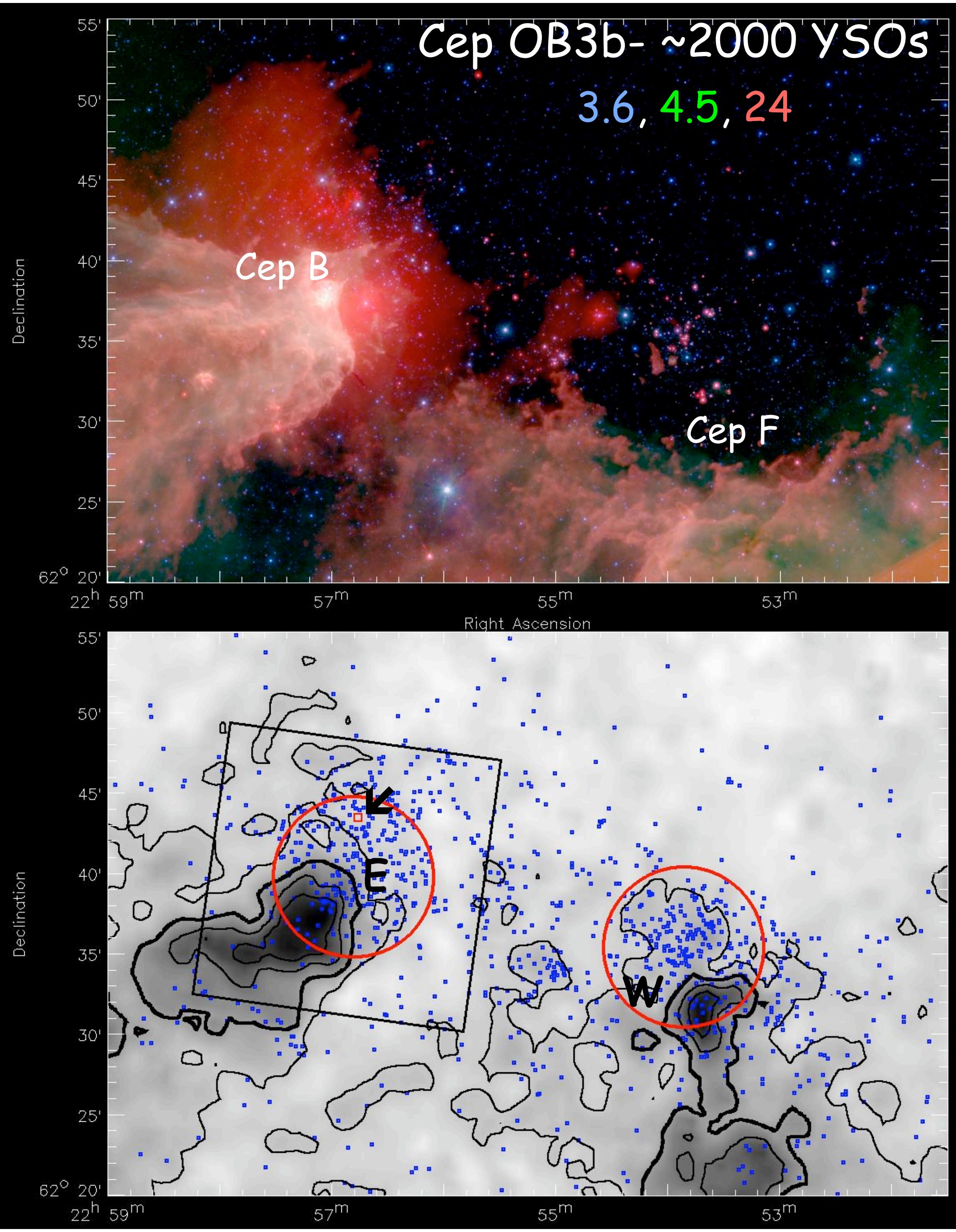
Column Density of Gas vs. Surface Density of Young Stellar Objects



Surface density of YSOs increases as *square of the column density* of gas interior to GMCs

Cep OB3b cluster in region of low extinction (gas dispersed by OB stars)

(Gutermuth et al. in prep. See poster by Gutermuth)



Disk Destruction due to nearby O star?

(T. Allen et al. 2009)

YSOs in excavated cavity near molecular clumps Cep B and F: very large young cluster

Disk fraction in E (near Cep B and O star) only 45%, typical of 4 Myr cluster, while in W near Cep F 79%, typical of <2 Myr cluster – BUT optical data indicate no age difference

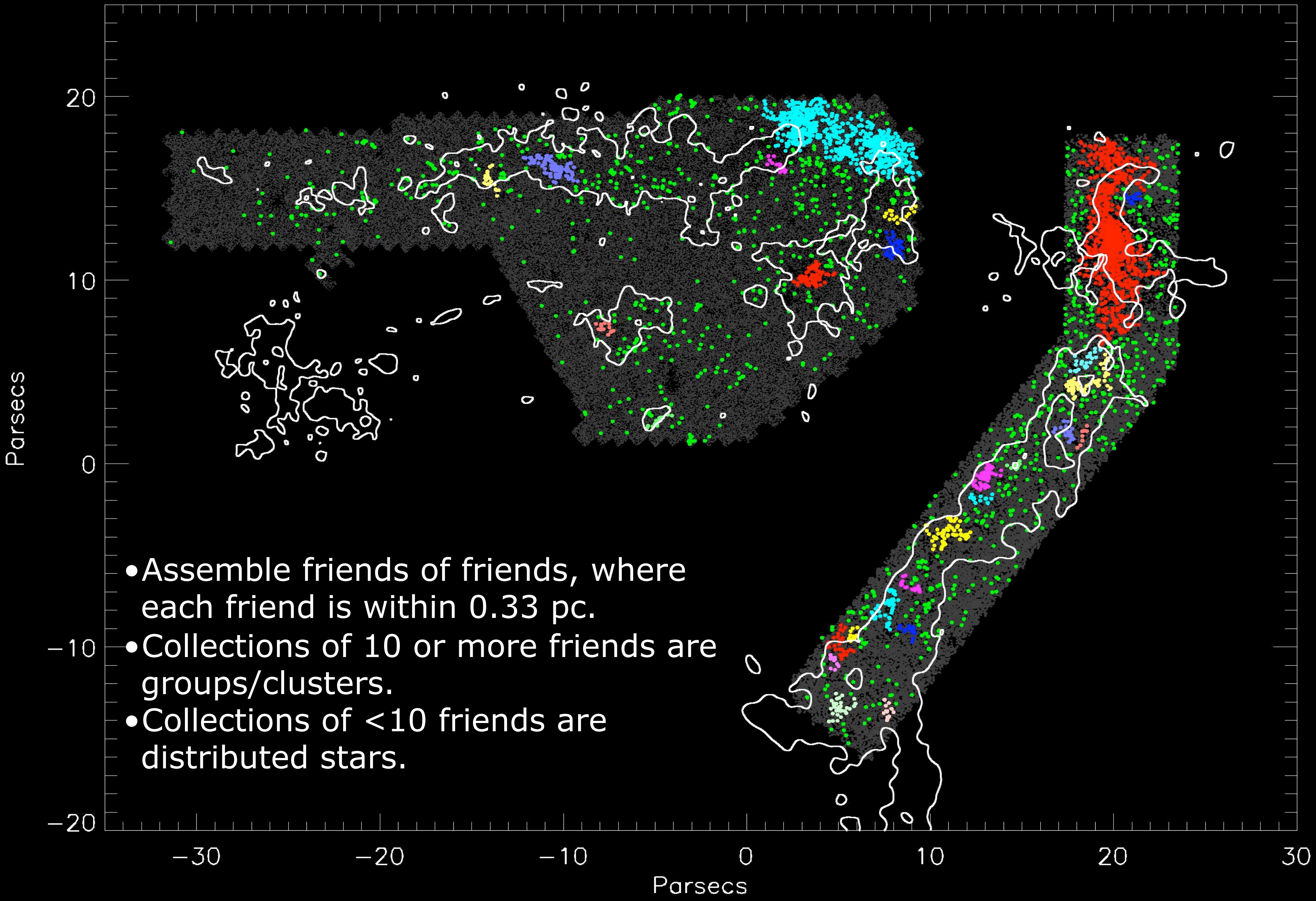
Orion 420 pc

Largest young cluster within 1 kpc
> 2000 YSOs

0.5 0.75 3.6 4.5

Megeath et al. (2009) Orion Survey

Large Clusters in GMCS Cep OB3 and Orion



- Assemble friends of friends, where each friend is within 0.33 pc.
- Collections of 10 or more friends are groups/clusters.
- Collections of <10 friends are distributed stars.

W5

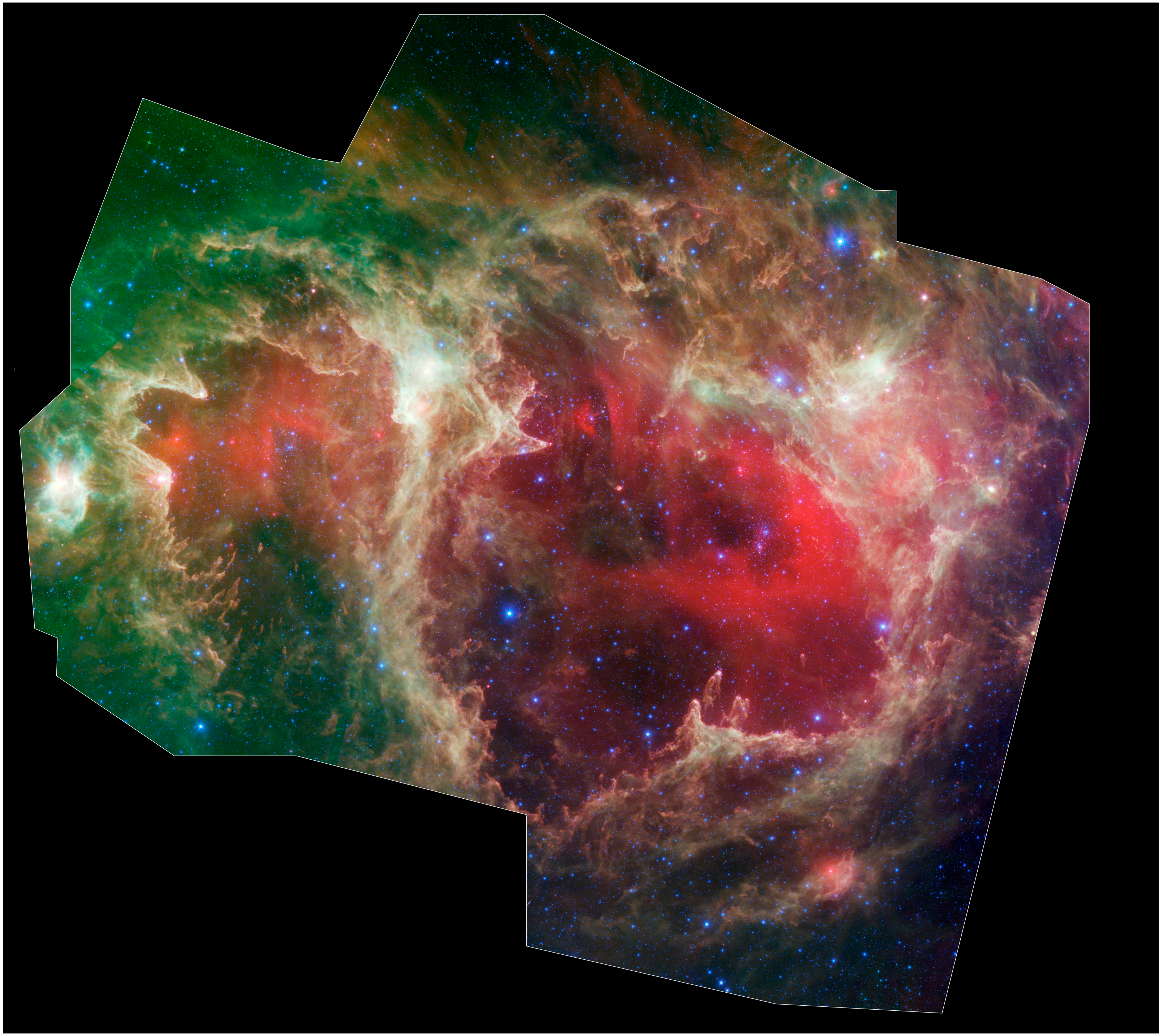
(Koenig, L.Allen et al.2008)

Molecular clouds surrounding bubbles driven by OB stars

Star formation triggered in pillars

24 8 3.6

May 27, 2009



Success in Maturity

Giovanni's IRAC has proved a grand success, as seen from these few examples

As of May 15, the cryogen has run out, but the IRAC warm mission is starting

Thanks Giovanni – from IRAC's conception to the present, and into the future – you have been our guiding light and an inspiration!