Star Formation

Answering Fundamental Questions During the Spitzer Warm Mission Phase

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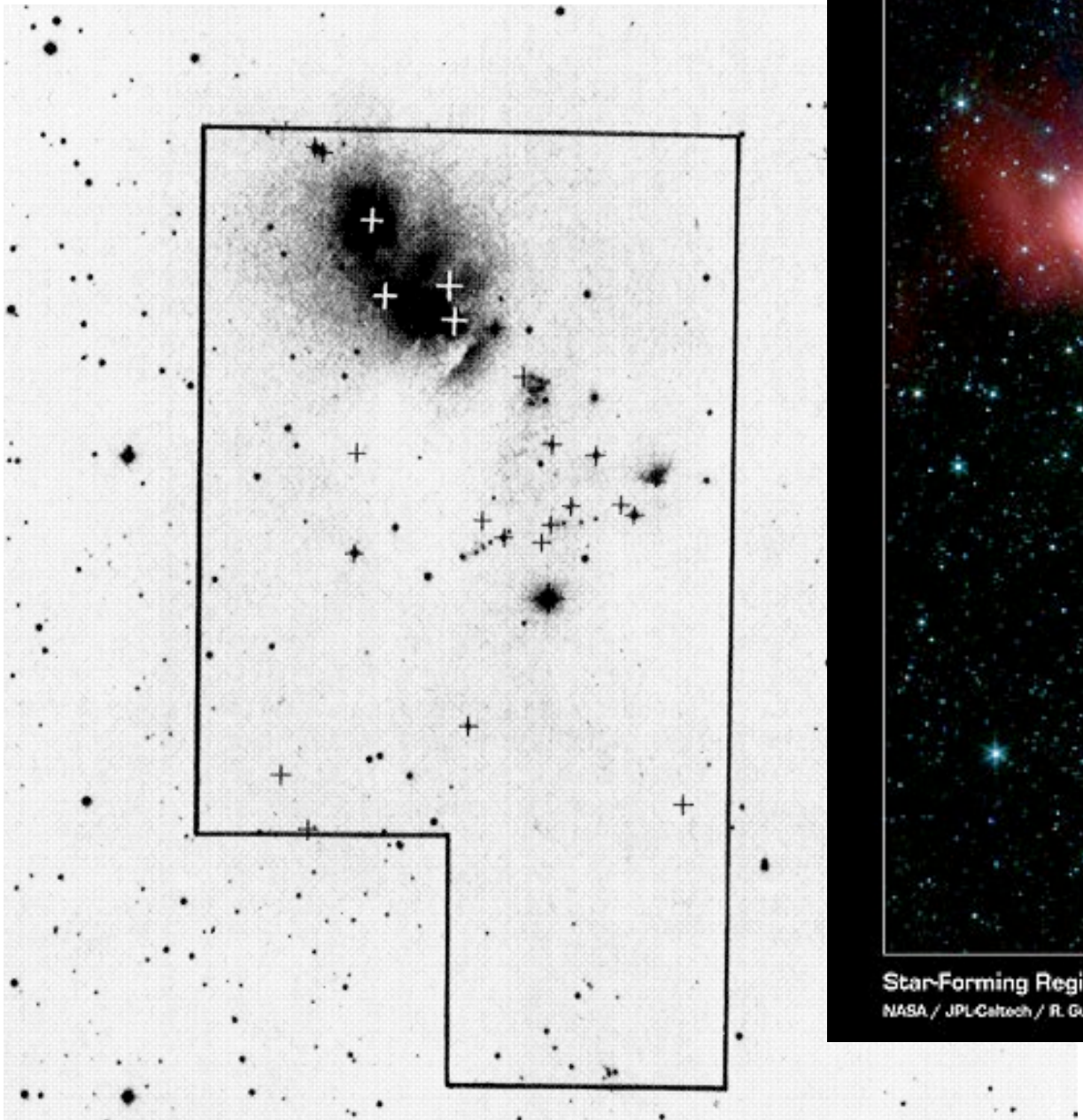
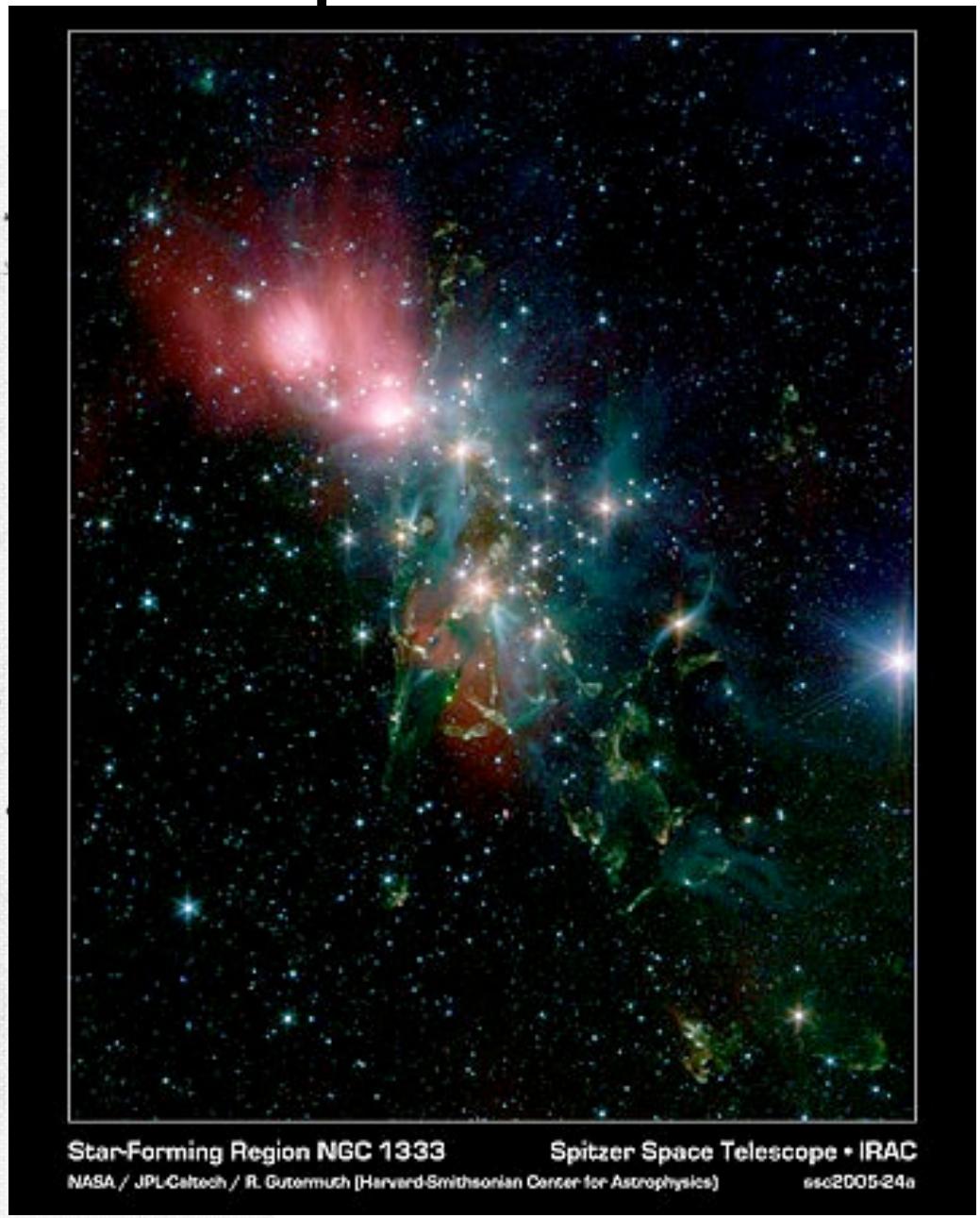
Progress: 1976 to Spitzer

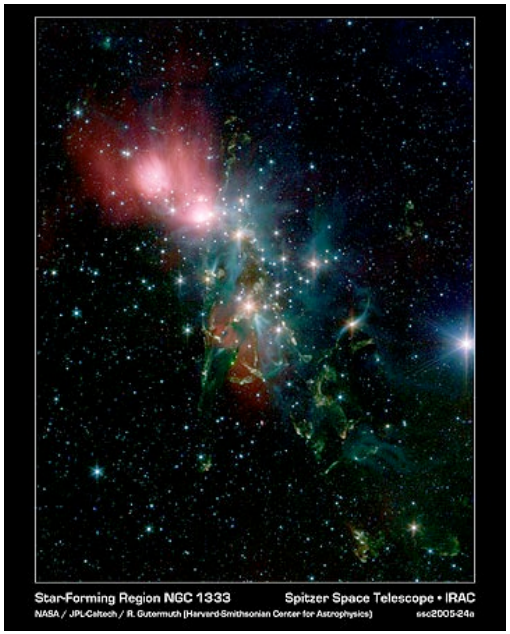
Strom, Vrba & Strom (1976)





Spitzer Key Contributions to Date

- Provide a census of forming stars in nearby molecular clouds
  - Sensitivity to ~ 10 $M_{Jupiter}$ for star-forming regions to distances d ~ 500 pc
  - Includes protostars and young stars surrounded by circumstellar disks at various evolutionary phases

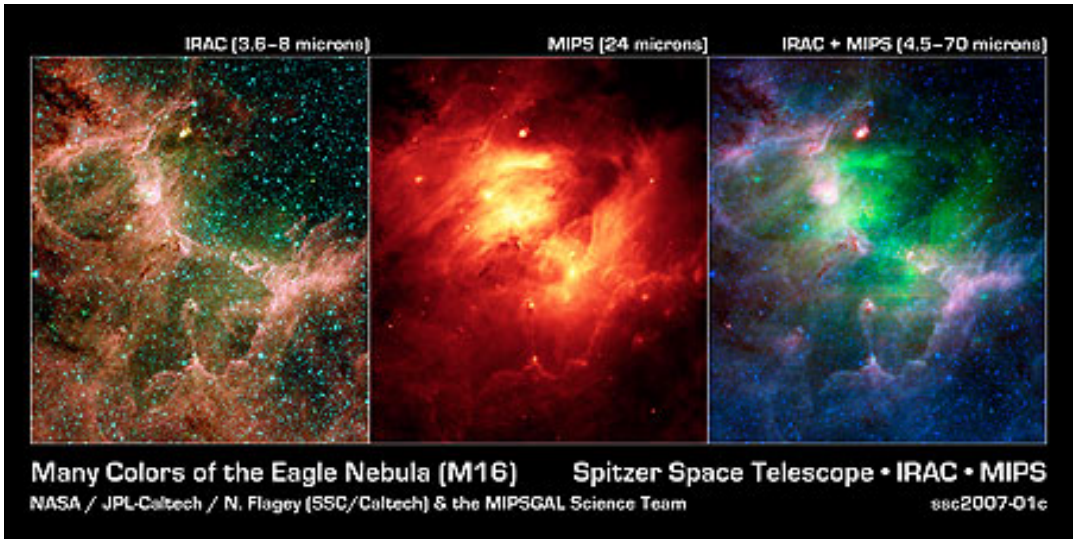


Spitzer Key Contributions to Date

- Provide basis for addressing key problems
  - How are initial core conditions related to outcome stellar properties?
  - What is the range of lifetimes for key evolutionary phases
    - Envelope-dominated
    - Accretion-disk-dominated
  - What is the range of lifetimes available for planet-formation?
  - Is there evidence for ongoing planet formation in disks?

Spitzer Key Contributions to Date

- Provide a census of stars surrounded by circumstellar accretion disks
  - Span ages from t < 1 Myr to t ~ 25 Myr
- Provide the basis for answering
  - What conditions in molecular clouds lead to cluster/distributed populations?
  - How important is propagating star formation in different regions?
  - How does the cloud environment affect disk evolution/lifetimes?



Spitzer Key Contributions to Date

- Provide direct evidence of accretion disk evolution

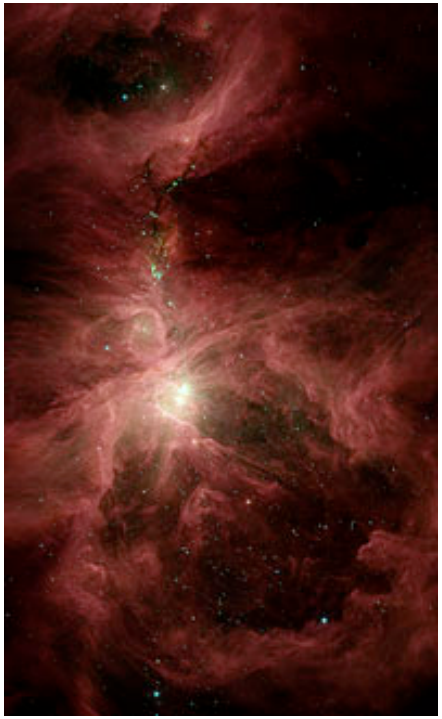
  - Grain settling to the midplane
  - Grain growth
  - Evolution in the nature and distribution of solid material in the inner disk
  - Initial surveys of the gaseous component of disks
    - Identify tracers of gas spanning a wide range of temperature; radii
    - Identify tracers of disk chemical structure
  - Provide the basis for answering
  - Timescales for key physical and chemical processes in disks
  - When, where and under what conditions planet-building may take place
  - Timescale(s) available for planet-building

Spitzer Key Contributions to Date

- Built a large and diverse international community working actively on a wide range of star/planet formation problems
  - This meeting is testimony to the vigor of that community
- Supported the research and launched the careers of a new generation of astronomers working on a frontier problem
- Provided observations of unparalled richness -- a database that will be mined and analyzed for more than a decade

Focus of Spitzer Observations to Date

- Deep observations of star-forming regions directly associated with well-known molecular clouds located within 500 pc of the sun



Focus of Spitzer Observations to Date

- Targeted observations of more distant regions located at 1-2 kpc
  - Generally focused on known centers of star formation or dense molecular gas

What Spitzer has yet to do

- Explore larger regions surrounding the active star-forming centers in nearby clouds
  - Environs of T- and OB- associations in which multiple episodes of star formation have taken place over timescales of 1-20 Myr
- Explore giant star-forming complexes found in the Carina & Perseus arms
  - Are sites of star-forming activity analogous to those in other galaxies
  - Provide evidence of the processes that initiate and propagate star formation

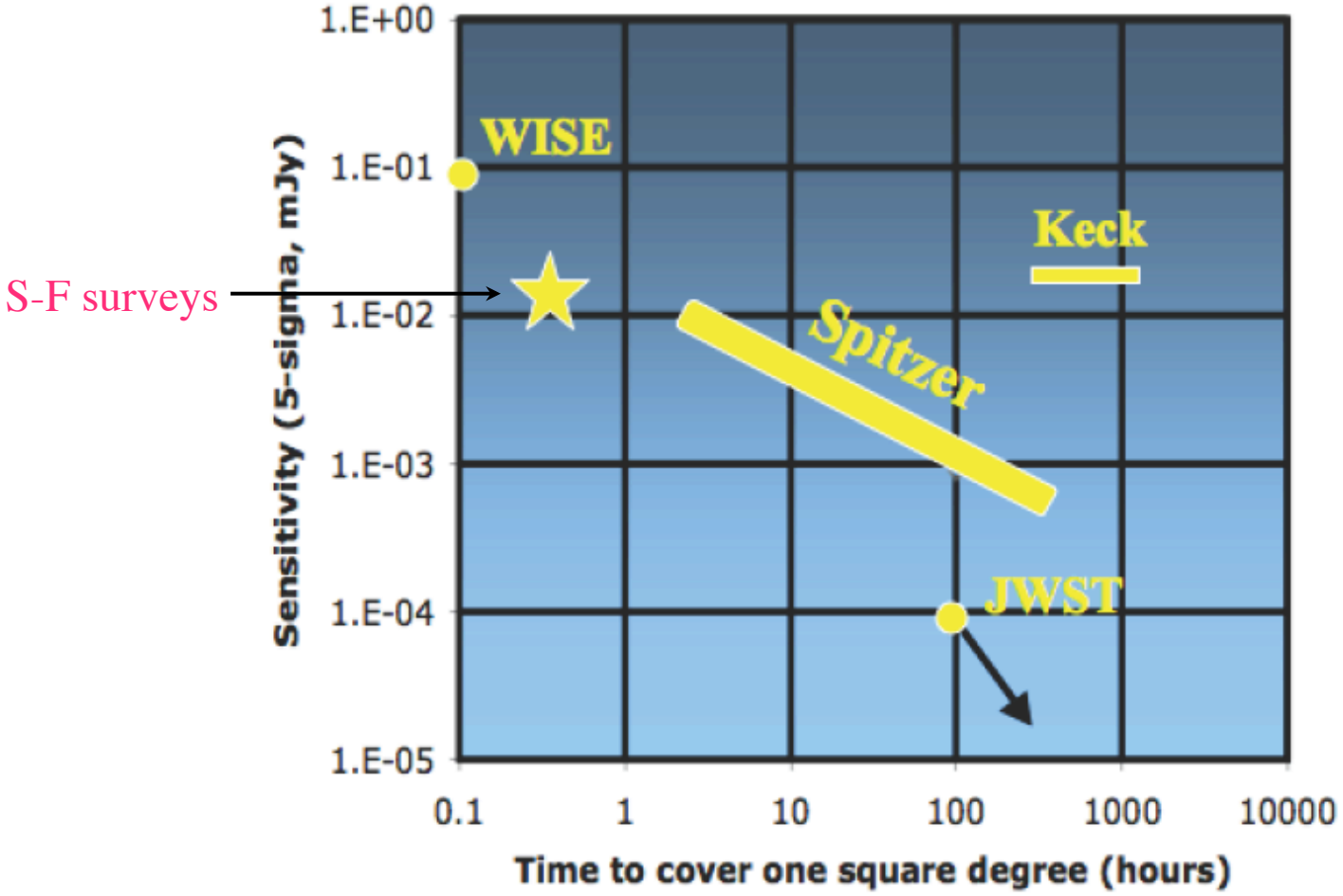
What Spitzer has yet to do

- Explore star-formation on the scale of a spiral arm
  - Understand how the stellar populations comprising galactic disks arise
- Explore variable sources at a variety of cadences and over long timescales
  - Gain insights into the fundamental physics of the accretion/stellar assembly process

The Power of Spitzer During the Warm Mission Phase

- Sensitivity sufficient to detect excess IR emission arising from protostars and young stars still surrounded by circumstellar accretion disks
  - Down to or below the HBL in nearby (d < 500 pc) OB- and T- associations
  - Down to ~ 0.3 M_{sun} in more distant (d ~ 2 kpc) clouds
- Ability to map several hundred square degrees in of order a thousand hours
- Angular resolution sufficient to
  - Resolve all but the densest regions of forming groups and clusters
  - Identify contaminating background galaxies whose colors mimic those of young stars

Spitzer Warm Mission: Comparison to Other Facilities



Spitzer Warm Mission: Three Proposed Programs

- Survey of Selected OB Associations
- Survey of Distant GMCs & a representative region of a spiral arm
- A Search for Variability Patterns among YSOs

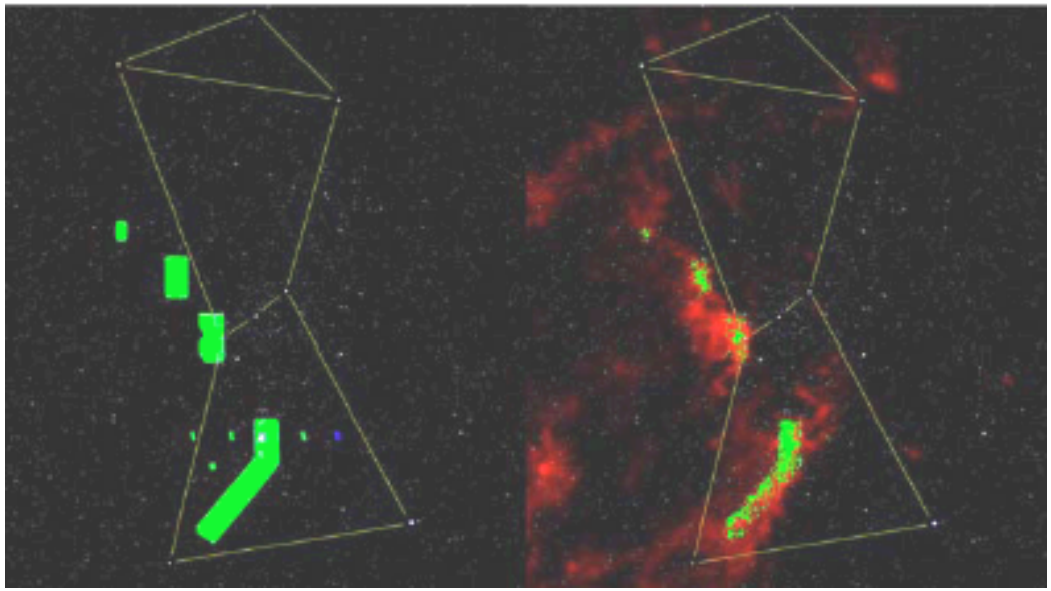
Spitzer Warm Mission: Survey of OB Associations

- Goals
  - Understand the number and spatial distribution of star-forming episodes
  - Understand the link of these patterns to initial conditions in molecular clouds
  - Determine the timescales for circumstellar disk evolution
    - Sample will include stars spanning a wide range of ages (up to 20 Myr) and masses

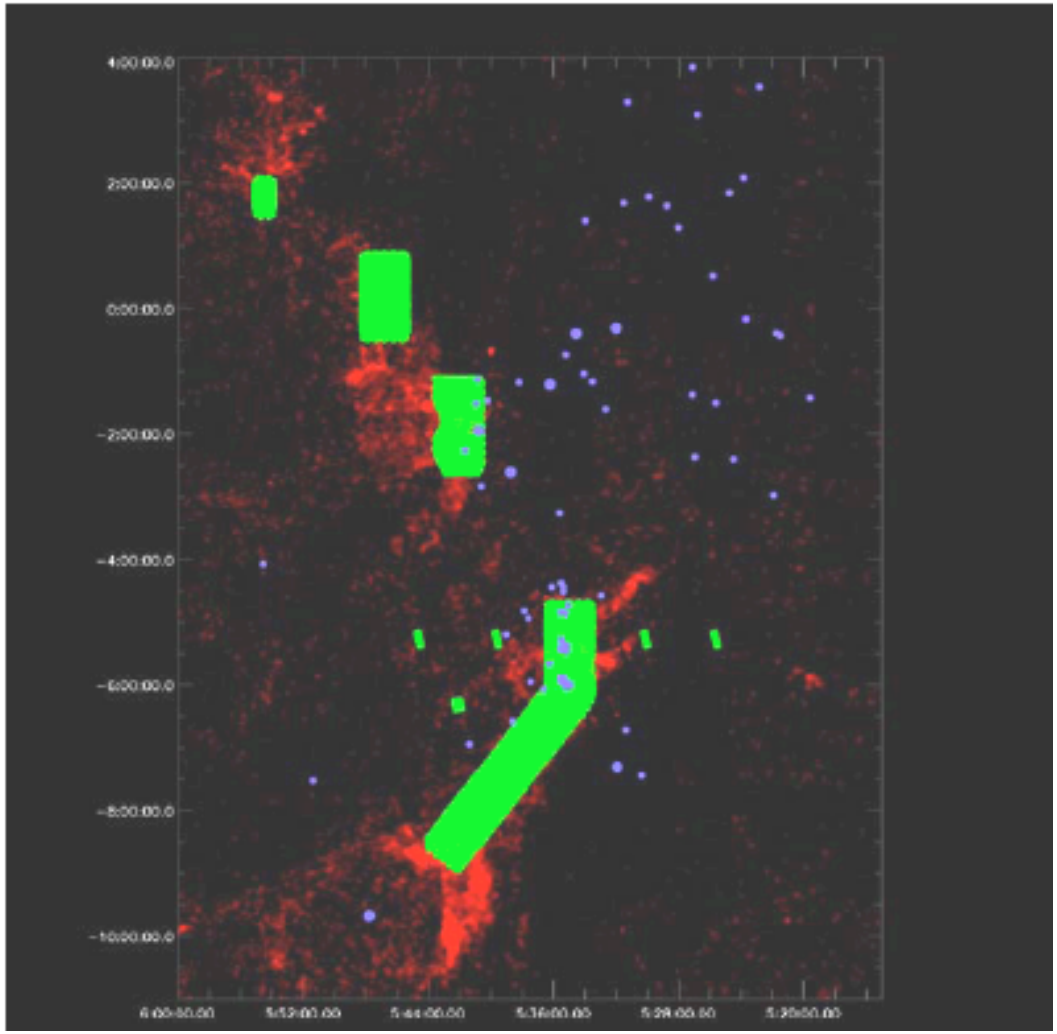
Spitzer Warm Mission: Survey of OB Associations

- Approach
  - Map areas of 50-200 square degrees of 3 representative OB associations
  - Survey depth: 12 μJy (IRAC 1) and 18 μJy (IRAC 2)
  - Will detect stars surrounded by accretion disks to masses ~ 0.08 Myr at ages t ~ 5 Myr
- Motivation for a Warm Mission Survey
  - Thus far, only selected regions (largely confined to dense molecular gas) have been mapped
  - Older star-forming episodes have largely been excluded
  - We lack information re the patterns of star-formation and timescales associated with each episode
  - Constraints on disk lifetimes as a function of mass and age are not yet robust
    - Samples are heavily biased toward regions younger than 5 Myr

Spitzer Warm Mission: Survey of OB Associations



Spitzer Warm Mission: Survey of OB Associations

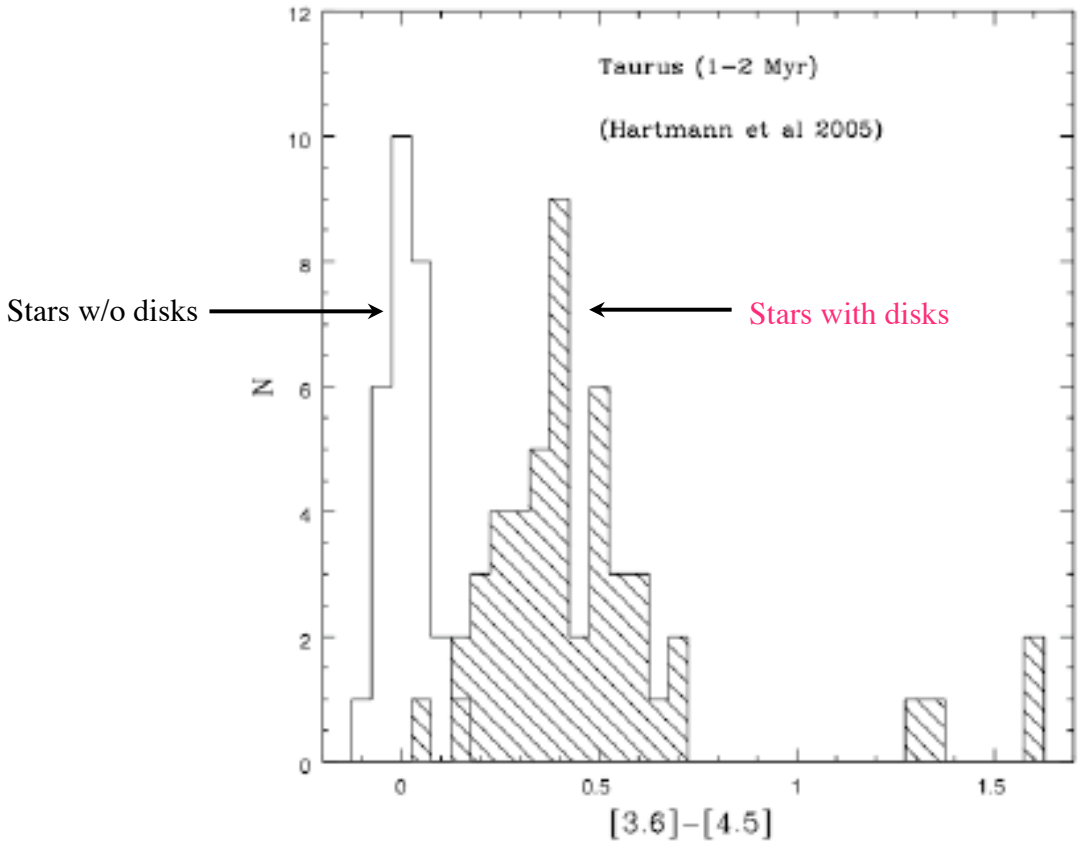


Spitzer Warm Mission: Survey of OB Associations

- Expected results
  - Complete surveys of protostars and stars surrounded by circumstellar accretion disks
  - Morphology will provide guide to sequence and possible triggers of star-forming events
  - Essential constraints on accretion disk evolutionary, and thus planet-building timescales
- Complementary ground-based observations motivated by Spitzer
  - Multi-epoch JHK imaging surveys
    - Detect young stars that lack disks via variability
    - Complementary tool for weeding out galaxies from candidate stars surrounded by disks or envelopes
  - High resolution spectroscopy
    - Kinematics of stellar population (key link to where and how stars formed and dispersed)
    - Accretion rate vs time and stellar mass
    - Infall rates in protostellar envelopes
  - ALMA observations of disk masses (dust continuum) + envelope properties

Spitzer Warm Mission: Survey of OB Associations

Value of Spitzer: Power to Identify Young Stars from IRAC colors



Spitzer Warm Mission: Survey of OB Associations

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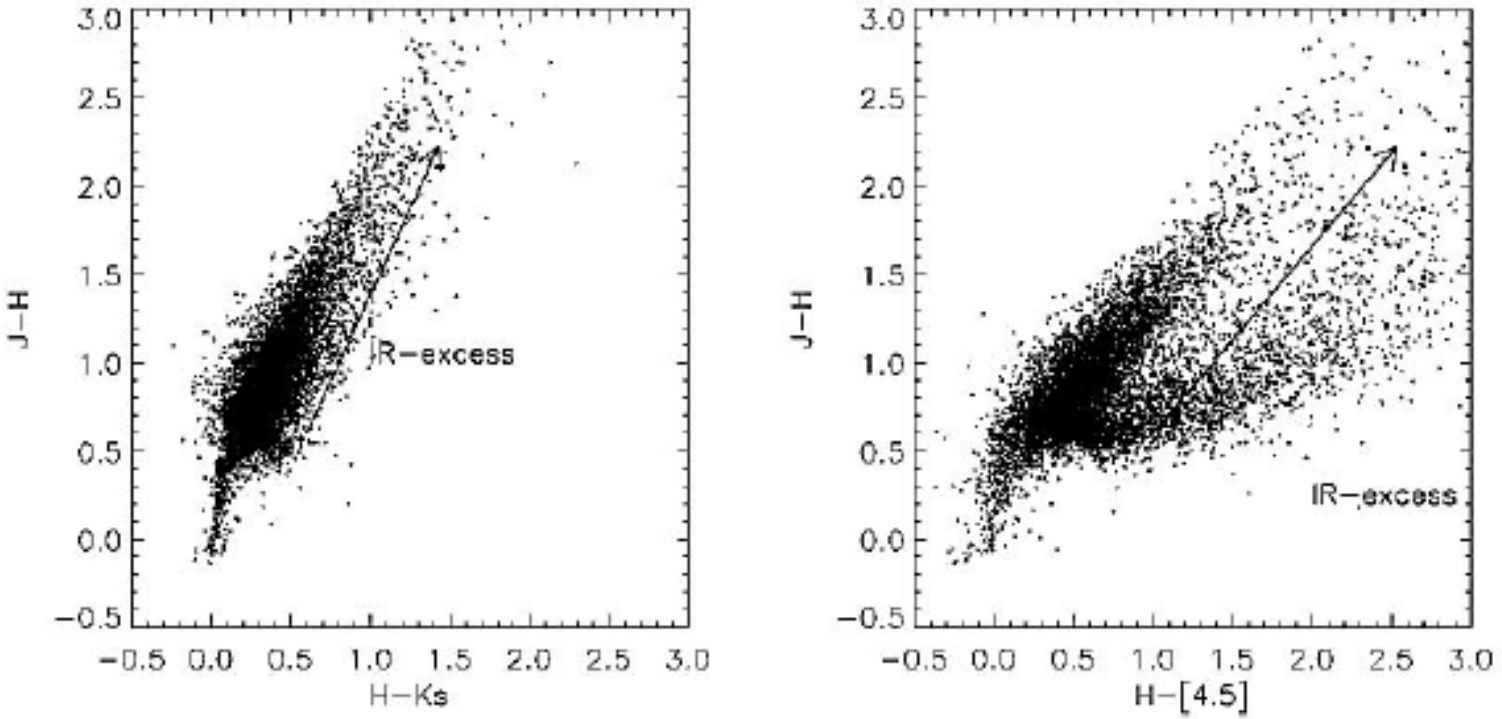


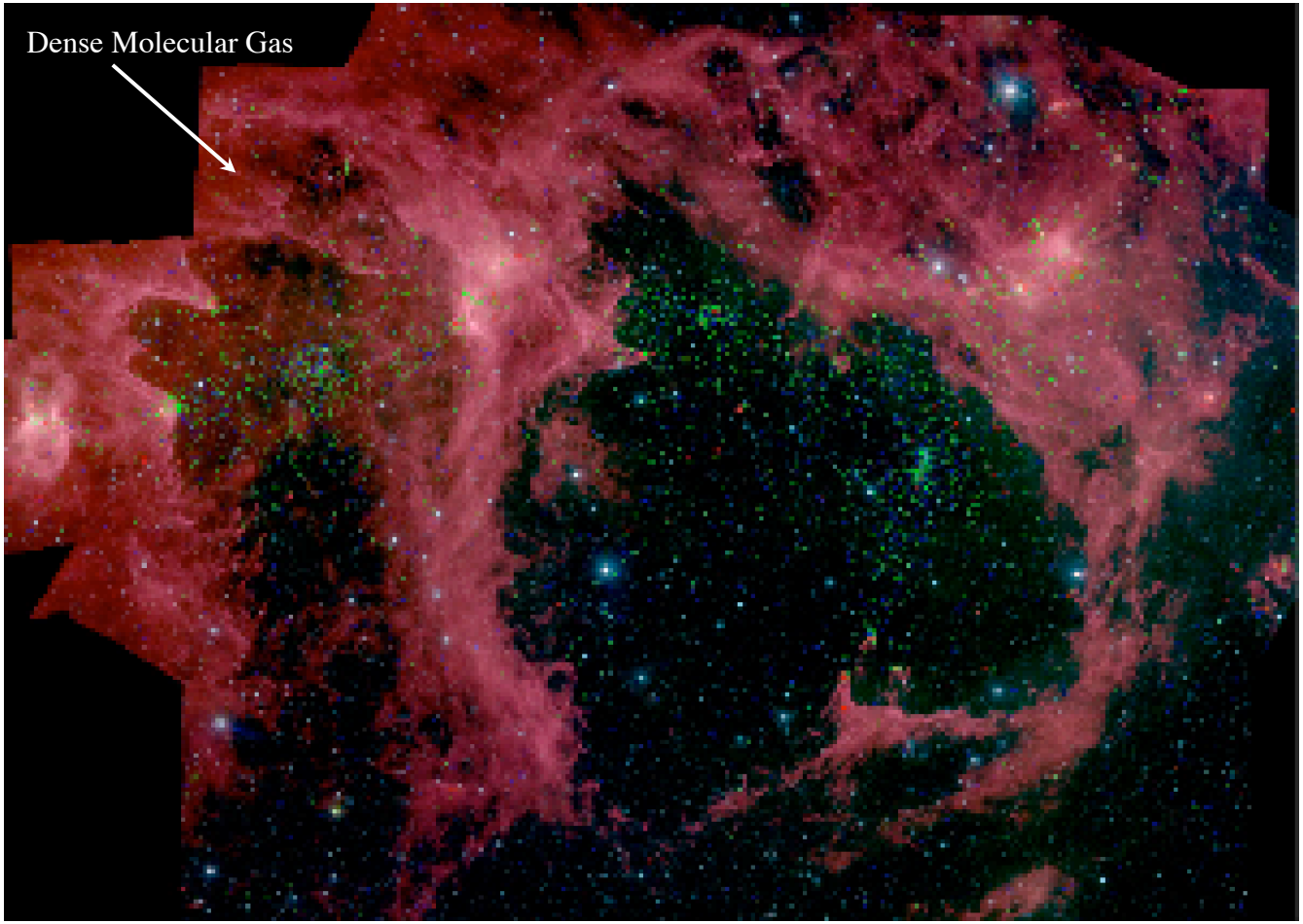
Spitzer Warm Mission: Survey of GMCs + Outer Galaxy Arm

- Goals
  - Examine star-formation in regions more analogous to those in other galaxies
    - Include clusters of richness and density far exceeding that of the Orion Nebula Cluster
  - Understand the pattern and timescales for star-forming events within GMCs
  - Understand the relationship between forming stars, propagating HII regions and superbubbles
  - Examine star-forming patterns on the scale of a spiral arm
    - Understand the extent of star-formation outside the boundaries of dense GMCs

Spitzer Warm Mission: Survey of GMCs + Outer Galaxy Arm

- Approach
  - Map area of ~300 square degrees of 5 representative GMCs (in Perseus and Carina arms)
  - Map area of ~300 square degrees in a relatively unconfused region of the Perseus arm
    - Chosen solely to lie within a fixed A_V contour; no bias toward known star-forming regions
  - Survey depth: 12 μJy (IRAC 1) and 18 μJy (IRAC 2)
  - Will detect stars surrounded by accretion disks to masses ~ 0.3 Myr at ages t ~ 5 Myr
- Motivation
  - To date, selected regions of GMCs have been mapped
    - focused on dense molecular gas and known signposts of star-formation
  - Large complexes analogous to those populating spiral arms in actively star-forming galaxies have not yet been mapped completely
  - Objective studies of star-formation on the scale of a spiral arm have been minimal

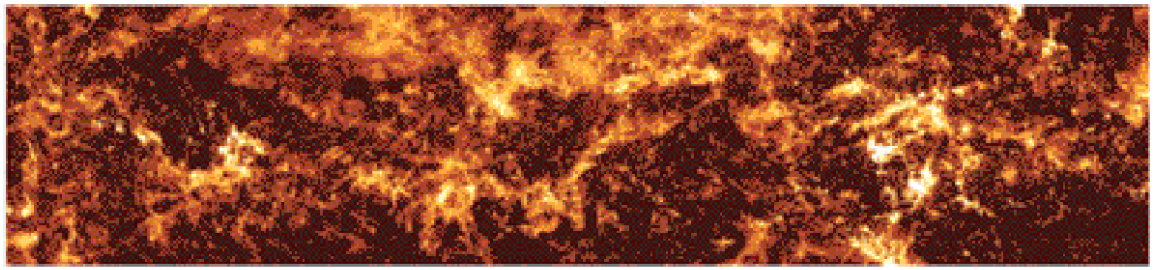
Spitzer Warm Mission:
Survey of GMCs + Outer Galaxy Arm



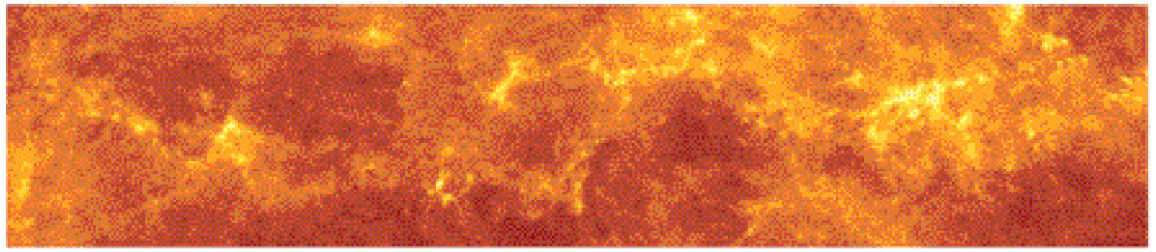
Multicolor IRAC Map of W5 (1.5 x 2°)

Spitzer Warm Mission: Survey of GMCs + Outer Galaxy Arm

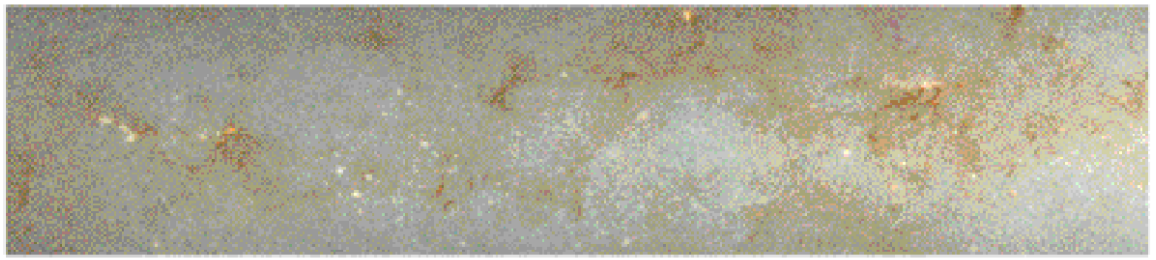
^{12}CO



2MASS A_V



2MASS Stellar Surface Density



10x30^o Region of the Outer Galaxy

Spitzer Warm Mission: Survey of GMCs + Outer Galaxy Arm

- Complementary ground- and space- based observations motivated by Spitzer
  - ALMA, CARMA, SMA and SCUBA-2 observations of
    - molecular cloud physical, chemical and kinematic properties (understand initial conditions)
    - Individual star-forming cores (understand relationship between core & outcome stellar properties)
  - High resolution near- and mid-IR spectroscopy
    - Determine conditions in the inner regions of star-forming cores
    - Determine stellar kinematics and relate to molecular cloud properties
  - Chandra, XMM and near-IR ground-based imaging surveys
    - Complete population survey in selected regions by locating young stars that have lost their disks
  - Moderate resolution ground-based spectroscopy (optical and near-IR)
    - Classification spectra needed to place stars in HRD: determine masses and ages
    - Determine sequence of star-formation
  - JWST imaging and spectroscopy in dense forming clusters
    - Determine stellar properties (e.g. IMF) in regions similar to dense clusters in other galaxies

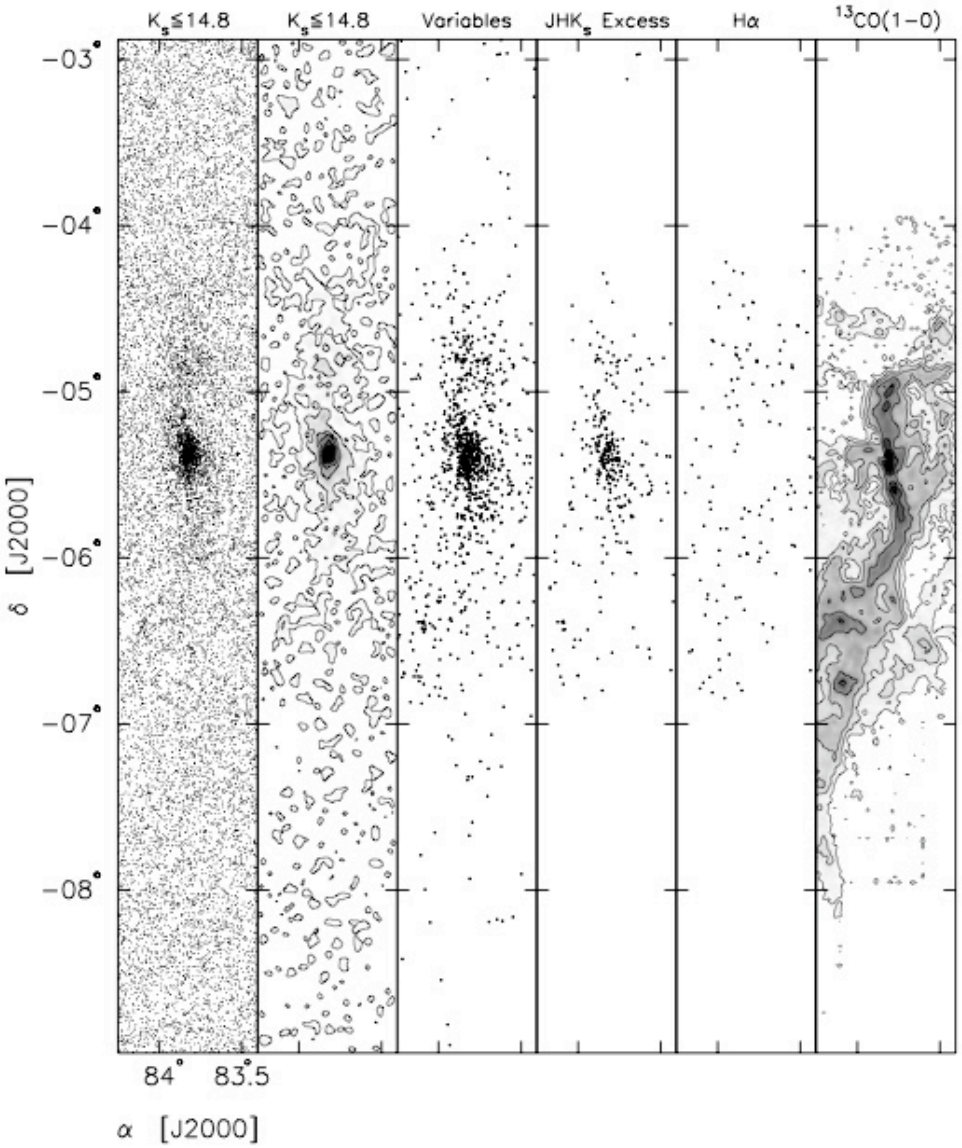
Spitzer Warm Mission: Variability Patterns among YSOs

- Goals:
  - Determine variability patterns among stars surrounded by protostellar cores and/or accretion disks
  - Diagnose source of variability
    - Warm or cool star spots
    - Variable obscuration by envelope/disk material
    - Variability driven by changes in accretion rate and heating in the inner disk
    - Variability driven by envelope/disk interactions

Spitzer Warm Mission: Variability Patterns among YSOs

- Approach (example program):
  - Monitor a 1x3 degree region centered on the Trapezium
  - Region can be mapped on four hour timescale
    - 400 non-overlapping IRAC frames
    - 12 sec integration HDR mode (yields 50σ at 4.5μm): sufficient to reach stars at the HBL
  - Repeat observations (a) six times per day for one 44 day visibility window of Orion, and then (b) repeat once per day for the next two visibility windows.
  - Total program time: ~ 1300 hours
- Motivation for a Spitzer Warm Mission Survey
  - 2MASS survey reveals variability among 100s of stars on timescales from hours to months
  - Spitzer has a unique combination of sensitivity, areal coverage & photometric precision
    - Ground-based L-band surveys map much smaller areas; precision limited to ~ 10%

Spitzer Warm Mission: Variability Patterns among YSOs



Spitzer Warm Mission: Variability Patterns among YSOs

- Possible results:
  - Understand factors that control variability in the inner (0.1-1 AU) disk regions
  - Understand variability during the infall phase
  - Understand the possible role of events driven by orbiting planets within accretion disk
- Complementary ground-based observations motivated by Spitzer
  - JHK imaging surveys aimed at sorting out stellar from disk-driven events
  - High resolution spectroscopy of selected objects to monitor emission line profile variability during same windows as IRAC photometry

Spitzer Warm Mission: Comparison to Other Facilities

- Conclusions
  - Large area surveys with JWST impractical
    - Small FOV and downlink data volume constraints
    - Reserve JWST for crowded/selected regions
  - Surveys from Keck cannot reach desired sensitivities in practical times
    - Keck AO may be important for selected sources
  - WISE lacks sensitivity to survey below HBL in nearby regions
  - WISE lacks angular resolution needed in more distant regions
  - Spitzer Warm hits a ‘sweet spot’ in sensitivity and angular resolution