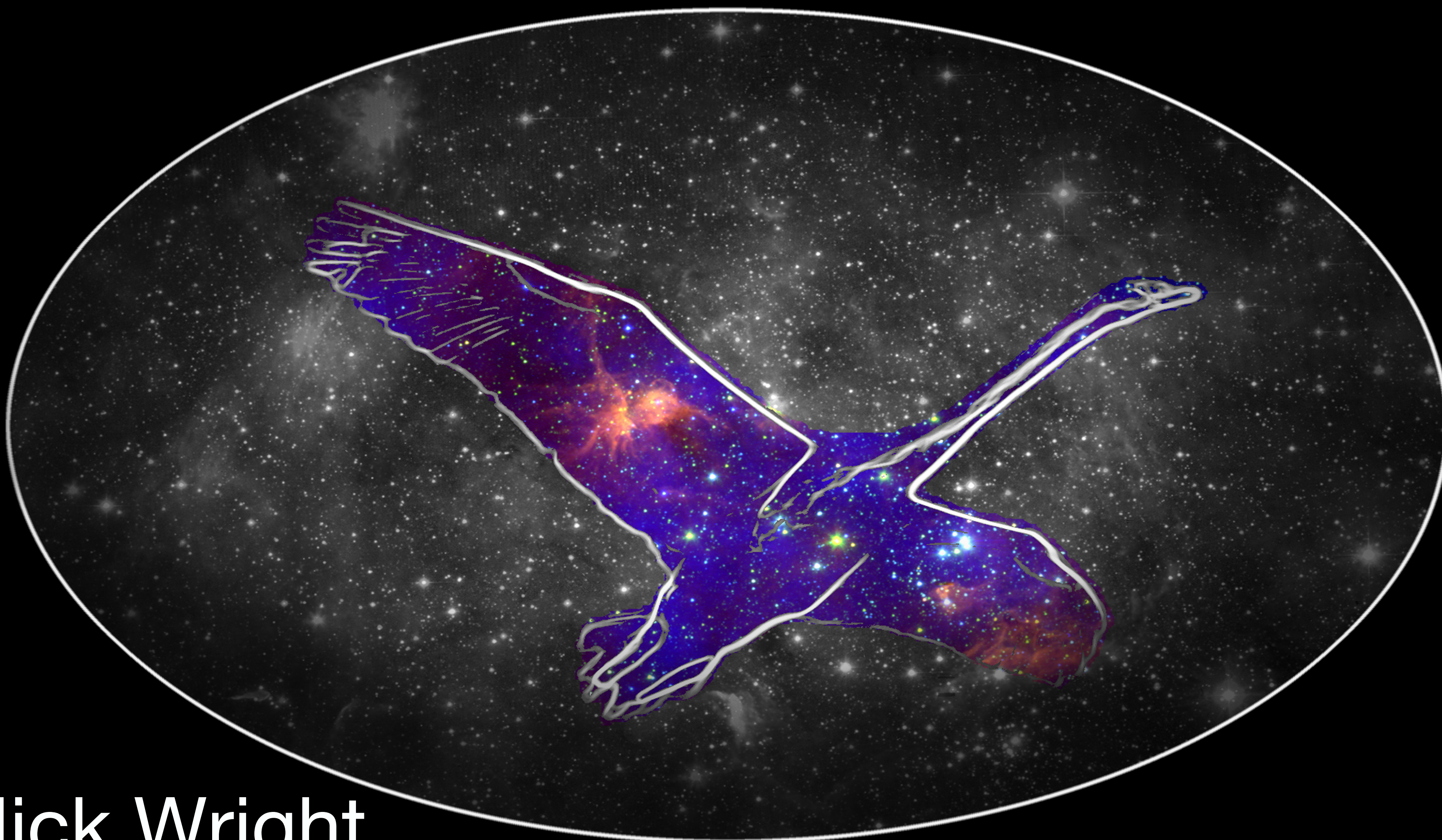
The Chandra Legacy Survey of Cygnus OB2

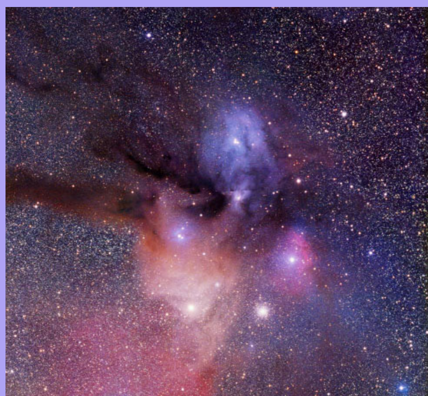


Nick Wright

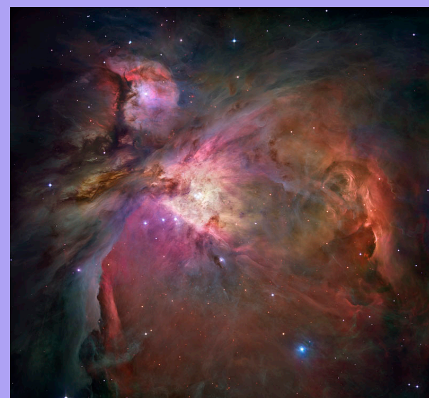
Harvard-Smithsonian Center for Astrophysics

Jeremy Drake, Mario Guarcello, Tom Aldcroft, Vinay Kashyap, Janet Drew, Ettore Flaccomio, Erik van der Veen, Jorick Vink, Francesco Damiani

Demographics of Star Formation



Ophiuchus
no O stars
0-5 Myr old
$M_\star \sim 100\ M_\odot$
$d \sim 130$ pc
(Wilking et al. 2008)

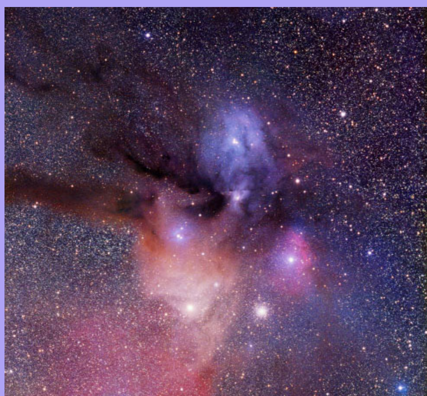


Orion
1 O star (20 OBs)
0-2 Myr old
$M_\star \sim 2{,}000\ M_\odot$
$d \sim 400$ pc
(Hillenbrand 1997, Muench et al. 2008)

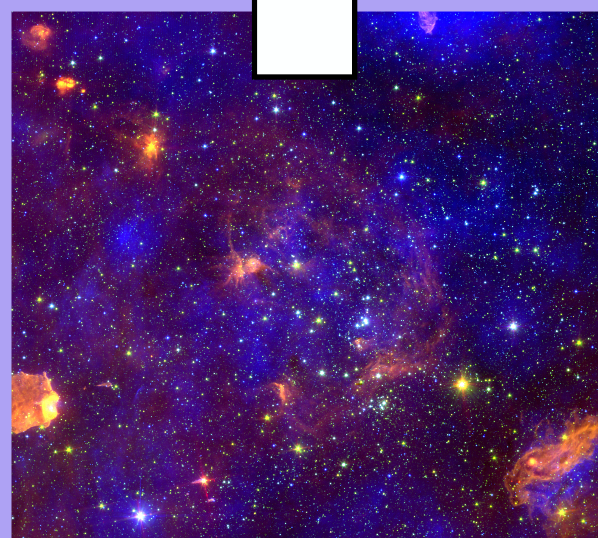
Westerlund 1
~140 O stars
2-3 Myr old
$M_\star \sim 50{,}000\ M_\odot$
$d \sim 4$ kpc
(Clark et al. 2005, Brandner et al 2008)

R 136 (30 Dor)
> 300 O stars
2-5 Myr old
$M_\star > 10^5\ M_\odot$
$d \sim 50$ kpc
(Brandl et al. 2007, Crowther et al 2010)

Demographics of star formation



Ophiuchus	Orion	Westerlund 1	R 136
no O stars	1 O star	~140 O stars	> 300 O stars
~ 100 $M_\odot$	~ 2,000 $M_\odot$	~ 5×10^4 $M_\odot$	> 10^5 $M_\odot$
d ~ 130 pc	d ~ 400 pc	d ~ 4 kpc	d ~ 50 kpc



Cygnus OB2

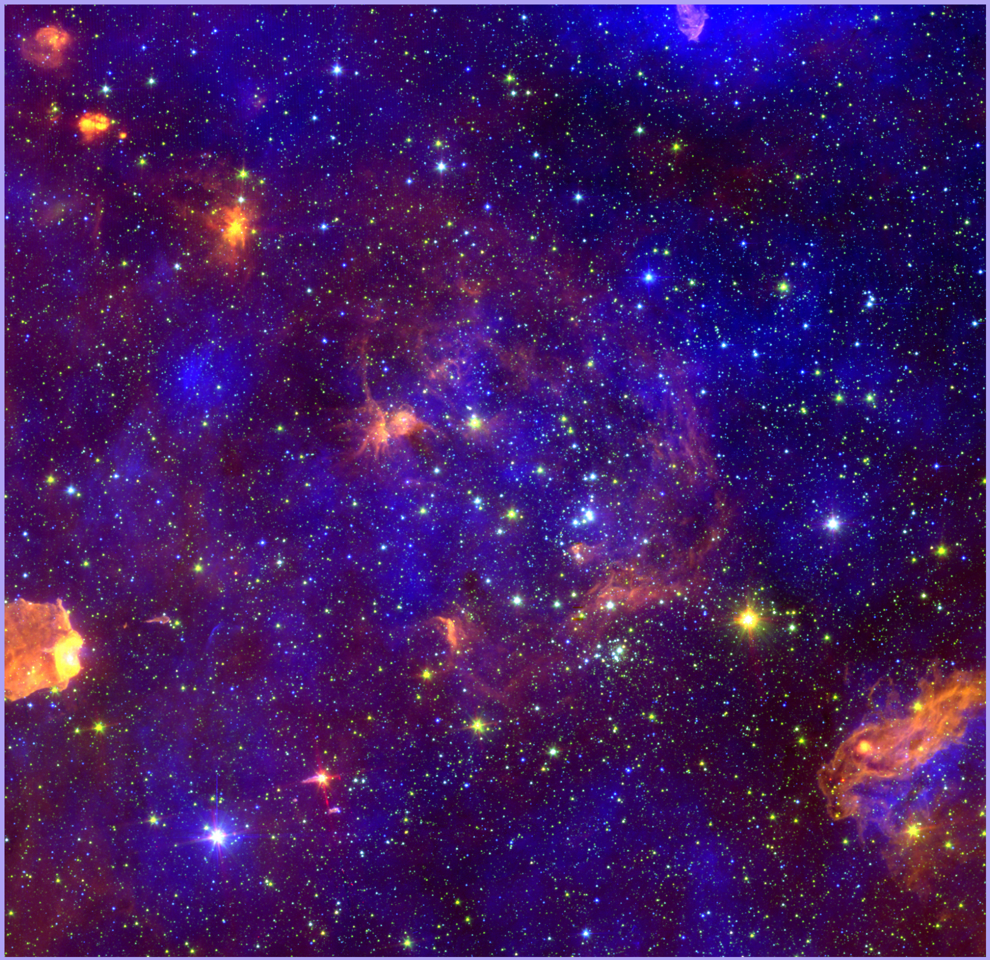
65 O stars

$M_\star \sim 10^4\text{-}10^5\ M_\odot$

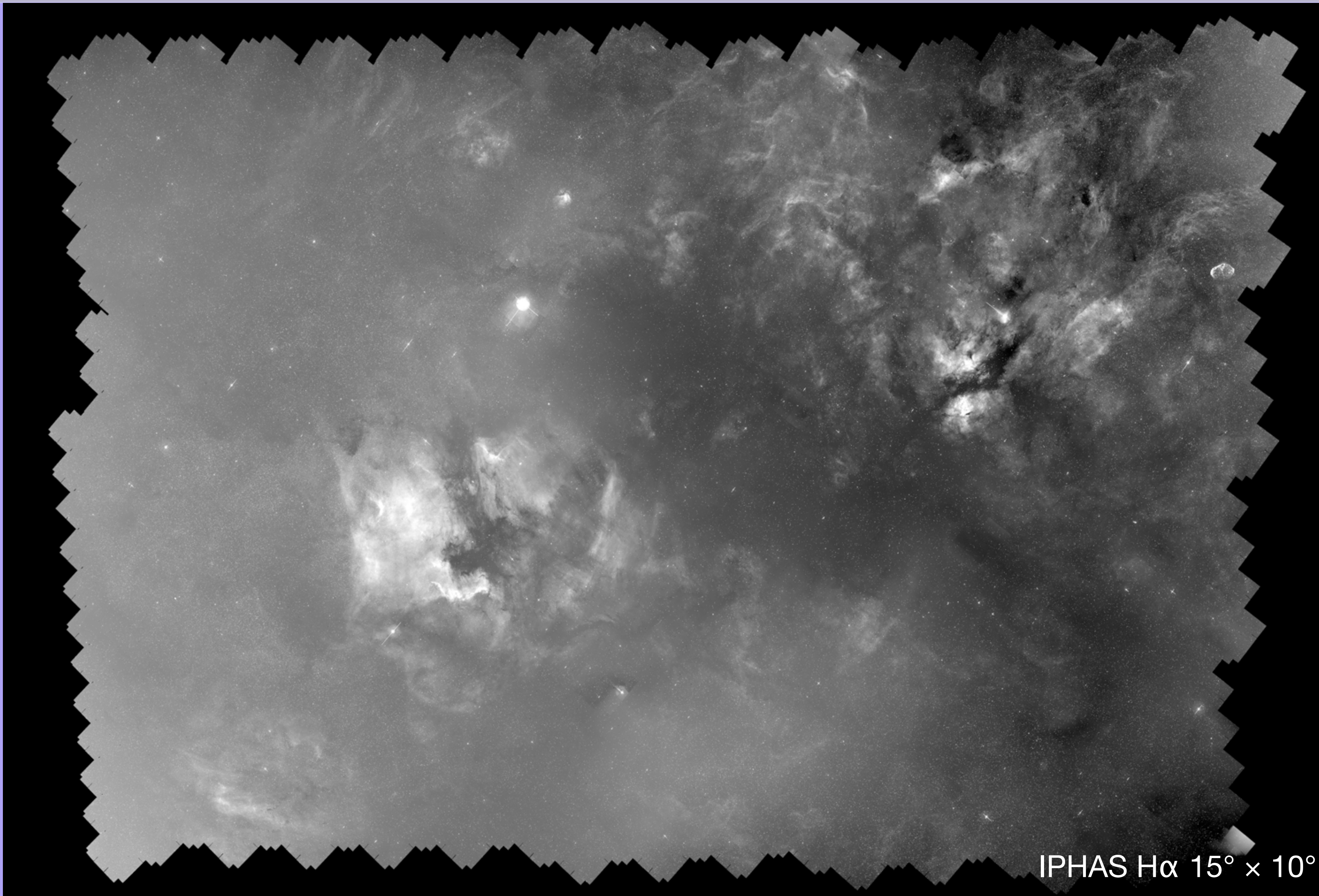
d ~ 1.5 kpc

Cygnus OB2

- Largest young cluster in the northern hemisphere, total mass ~ (4-10) × 10^4 $M_\odot$ (Knödlseder 2000)
- Center of the Cygnus X GMC
- d ~ 1.5 kpc (Hanson 2003)
- Age ~ 1-3 Myrs (Hanson 2003), but also evidence for older population (Drew et al. 2008)
- 65 O-type stars (inc. 2xO3), hundreds of B-type stars.
- Largest group of young stars within 2 kpc!



IPHAS Hα + Spitzer IRAC 4.5μm, 5.6μm


IPHAS Hα 15° × 10°


MSX 8μm 14° × 10°

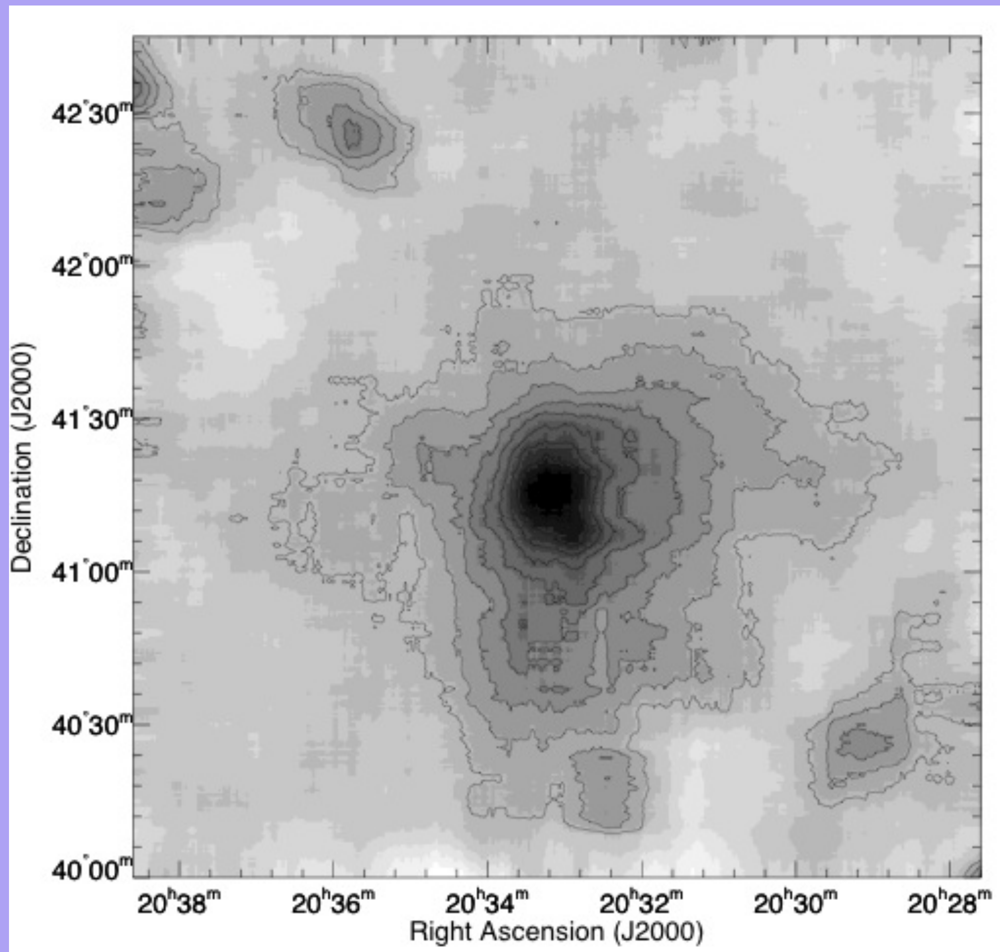
Problems Studying Cygnus OB2

- High extinction: A_V ~ 5-10 (varies over the region)
- Large area on the sky:

  Size ~ 2° diameter

  r_{hl} = 13' (5 pc)

  (Knödlseder 2000)
- Contaminants: Large population of foreground and background field stars.
- Low mass population can't be confidently identified using optical or infrared photometry alone!



Knödlseder 2000

X-rays from stars

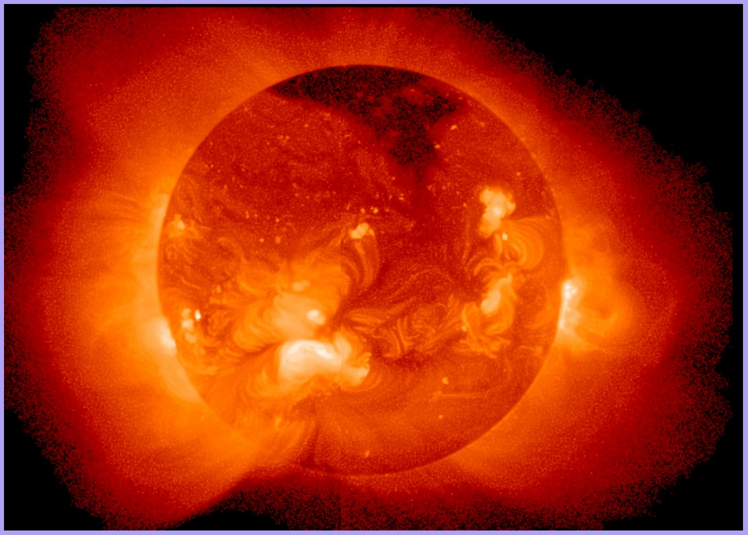
Nearly all stars emit X-rays:

- High mass stars via shocks in radiatively-driven stellar winds

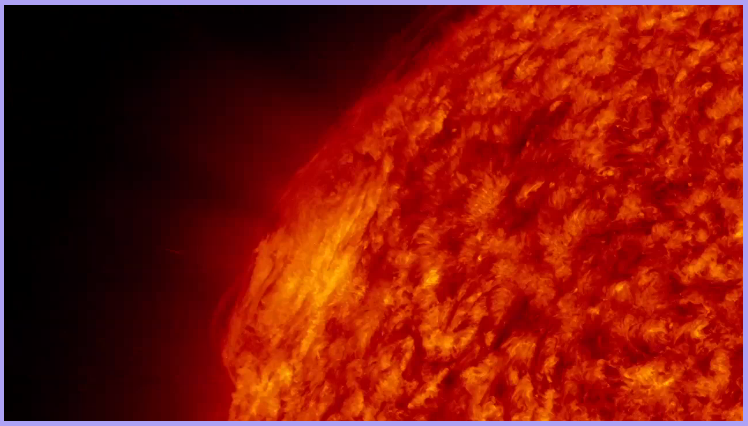
  (e.g. Seward 1979, Berghoefer et al. 1997).

- Low mass stars via flares in a magnetically-confined plasma

  (e.g. Wilson et al. 1966, Vaiana et al. 1981).



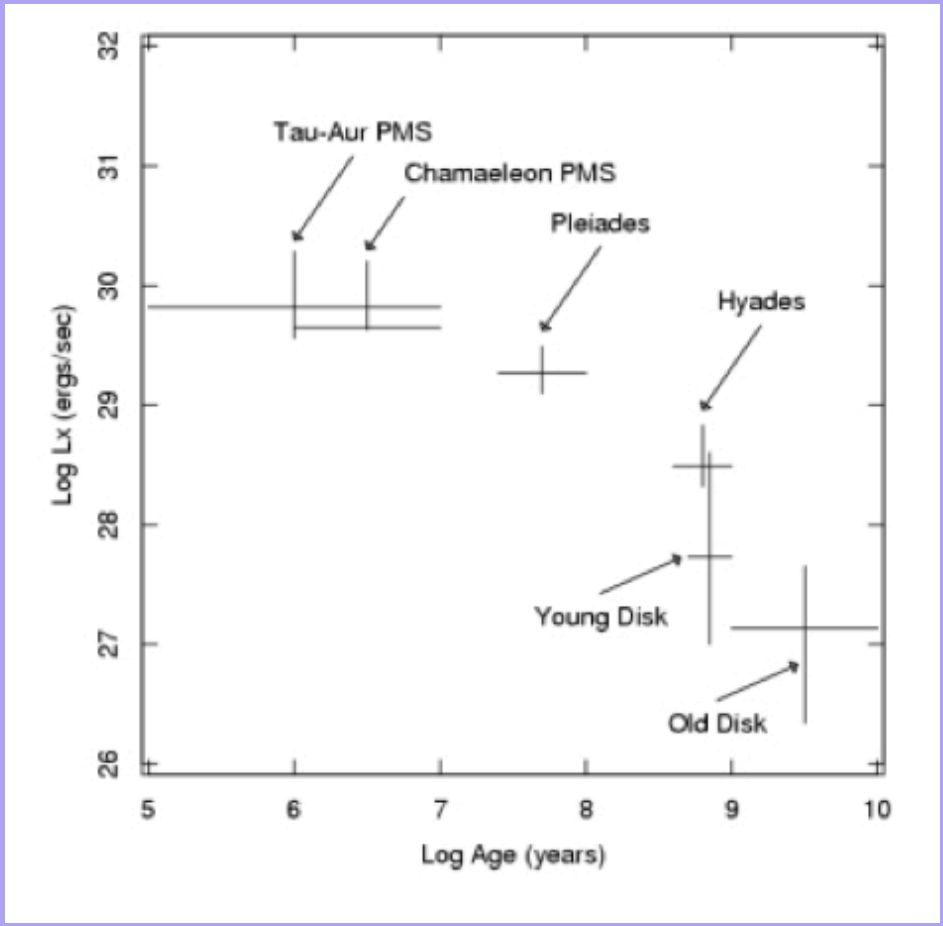
YOHKOH SXT 0.25-4.0 keV



SDO AIA 0.041 keV

X-rays as a Diagnostic of Youth

- Young stars more X-ray luminous than older stars.
- Corona powered by a dynamo driven by stellar rotation.
- Stars spin-down as they age, therefore dynamo and X-ray emission weakens.
- X-rays efficiently separate young stars from older field stars without biases.



Micela 2003

X-ray observations of Cygnus OB2

Two Chandra observations of Cygnus OB2 in 2004:

- Butt et al. 2006
- Albacete Colombo et al. 2007
- Wright & Drake 2009
- Wright et al. 2010

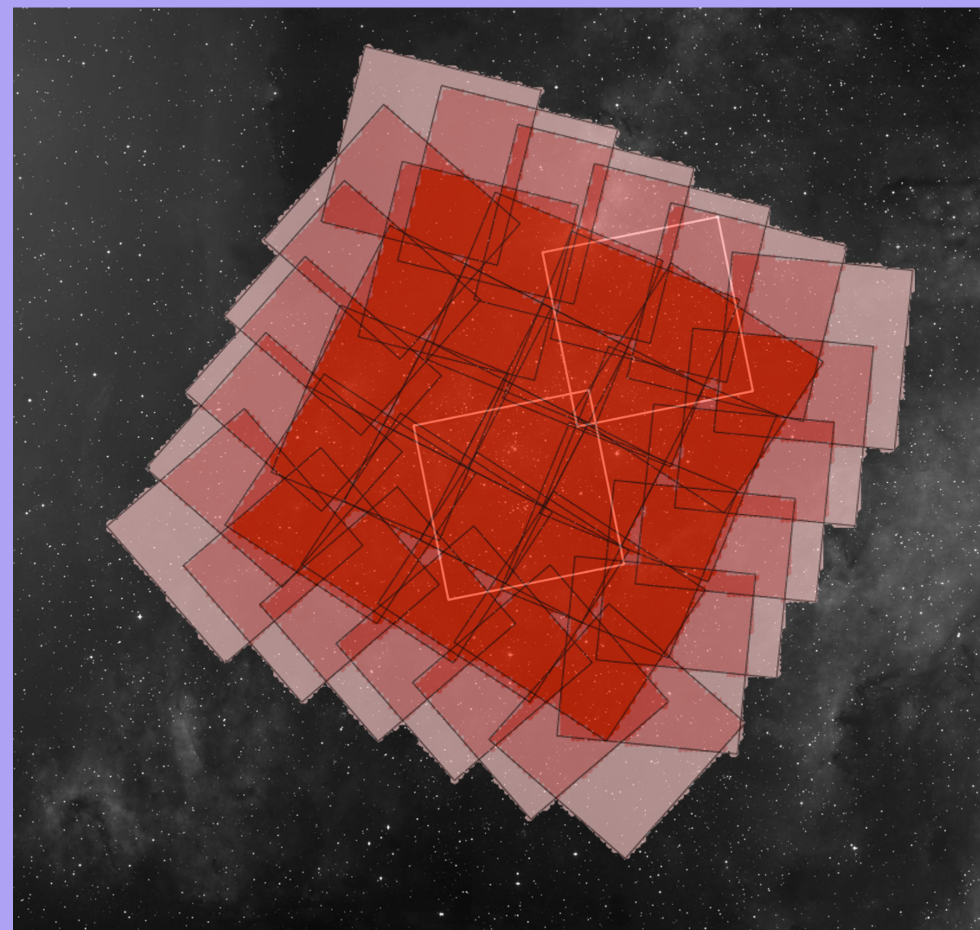
X-ray + IPHAS + UKIDSS:

- 1700 X-ray sources detected
- Optical / near-IR associations for ~1500 sources (~90%)
- First Cygnus OB2 study complete to ~1 $M_\odot$

Wright & Drake 2009

Cygnus OB2 Chandra Legacy Survey

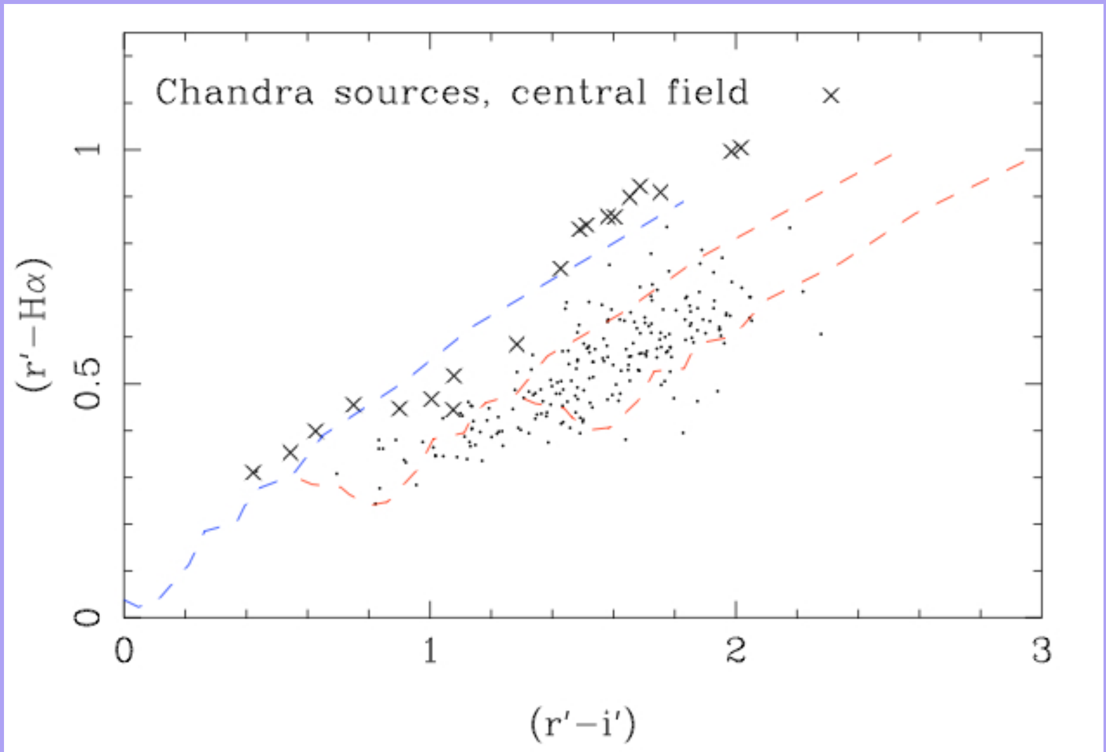
- Grid of 36 Chandra ACIS-I pointings, each 30ks
- Total survey area ~1 sq. deg.
- Central 0.5 sq. deg. imaged 4 times, total exposure ~120ks
  - >95% complete at 1 $M_\odot$
  - >50% complete at 0.5 $M_\odot$
- Complementary data:
  - IPHAS + GTC/OSIRIS optical
  - 2MASS + UKIDSS near-IR
  - Spitzer IRAC + MIPS mid-IR
  - Herschel, VLA, e-Merlin, INTEGRAL, IRAM, KOSMA



Current Survey Status

- All 36 observations performed January – March 2010.
- X-ray source detection on individual and combined observations performed ~15,000 sources detected.
- Visual inspection, X-ray photon extraction and comparison with other catalogs follows.
- Source list converging to ~10,000 sources – vast majority have optical, near- and mid-IR photometry!

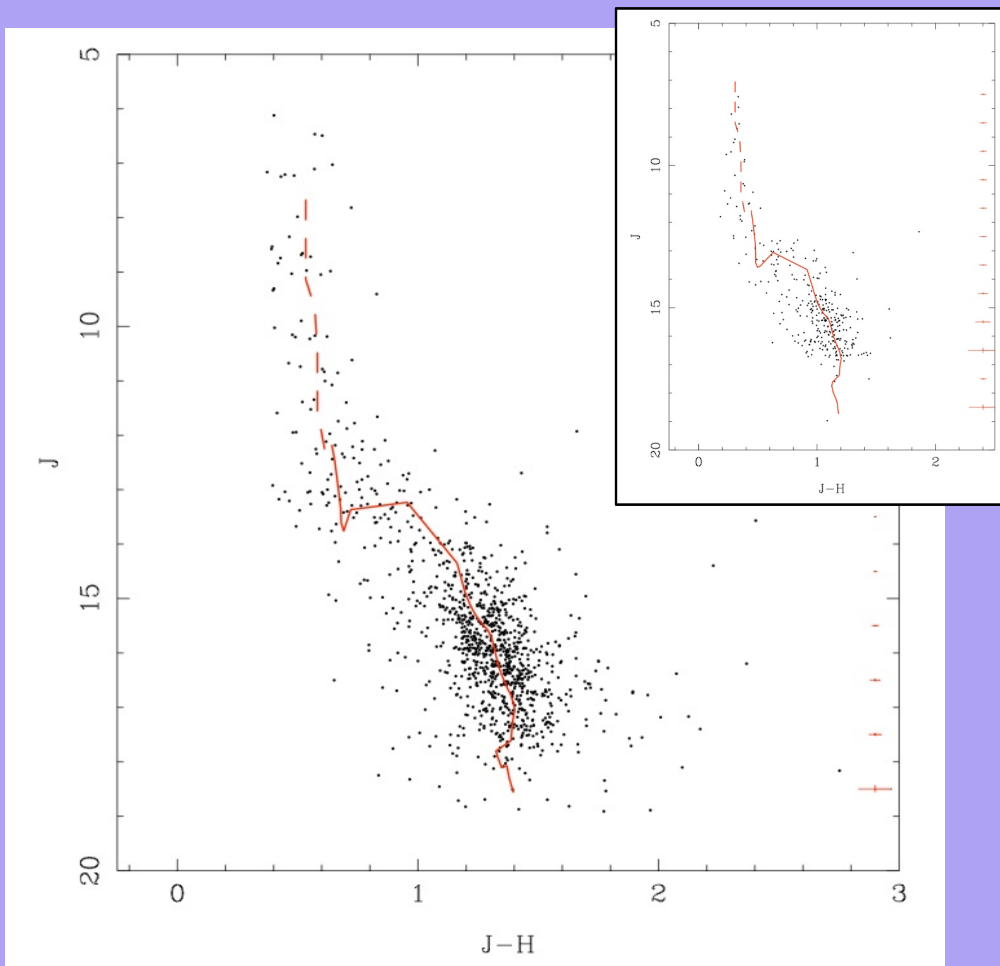
Foreground Sources



Wright et al. 2010

- Foreground stellar X-ray population removed using IPHAS color-color diagram (Drew et al. 2005, Sale et al. 2009)
- Differently-reddened populations can be separated
- ~10% of Chandra-IPHAS sources found to foreground contaminants

Stellar ages from the near-IR CMD



Wright et al. 2010

Ages from near-IR CMD and pre-MS isochrones:

- Central field ~ 3.5 ± 1 Myr
- Northern field ~ 5.25 ± 1.5 Myr

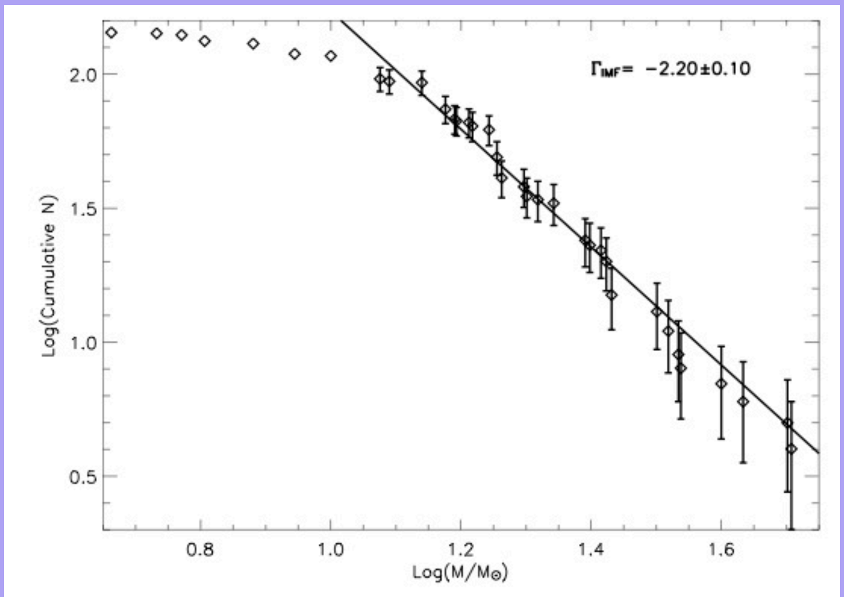
Age difference between fields?

Better age estimates from optical CMD (coming soon!)

Large Age Spreads in Massive Clusters

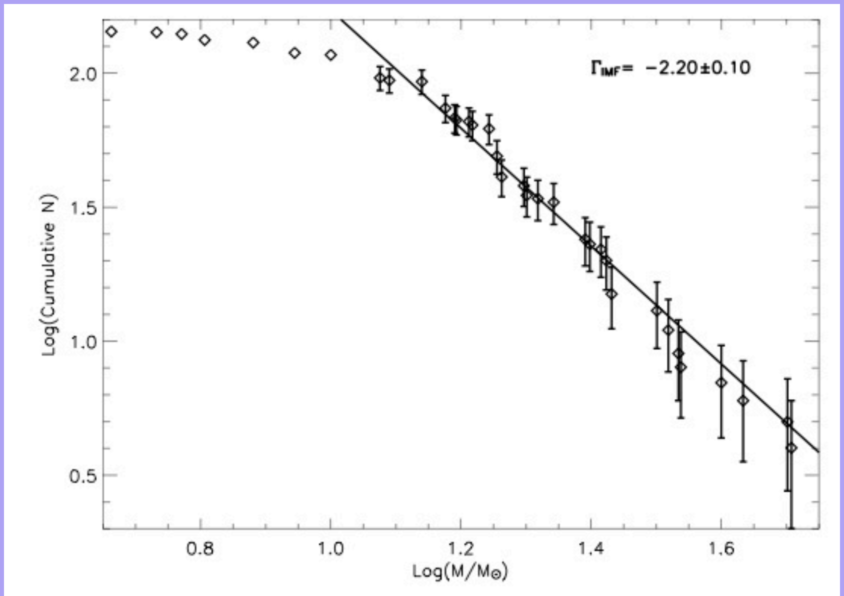
- Cygnus OB2
  - Wider population of older massive stars (Hanson 2003, Comerón et al. 2008)
  - 5-7 Myr population of A-type stars to the south (Drew et al. 2008)
  - Low-mass stars aged 5+ Myrs to the north-west (Wright et al. 2010)
- The Carina Nebula:
  - Distributed population of X-ray sources, likely older (Feigelson et al. 2011)
- 30 Doradus:
  - Star formation spread over 10+ Myrs, with spatial evolution over the cluster (De Marchi et al. 2011)

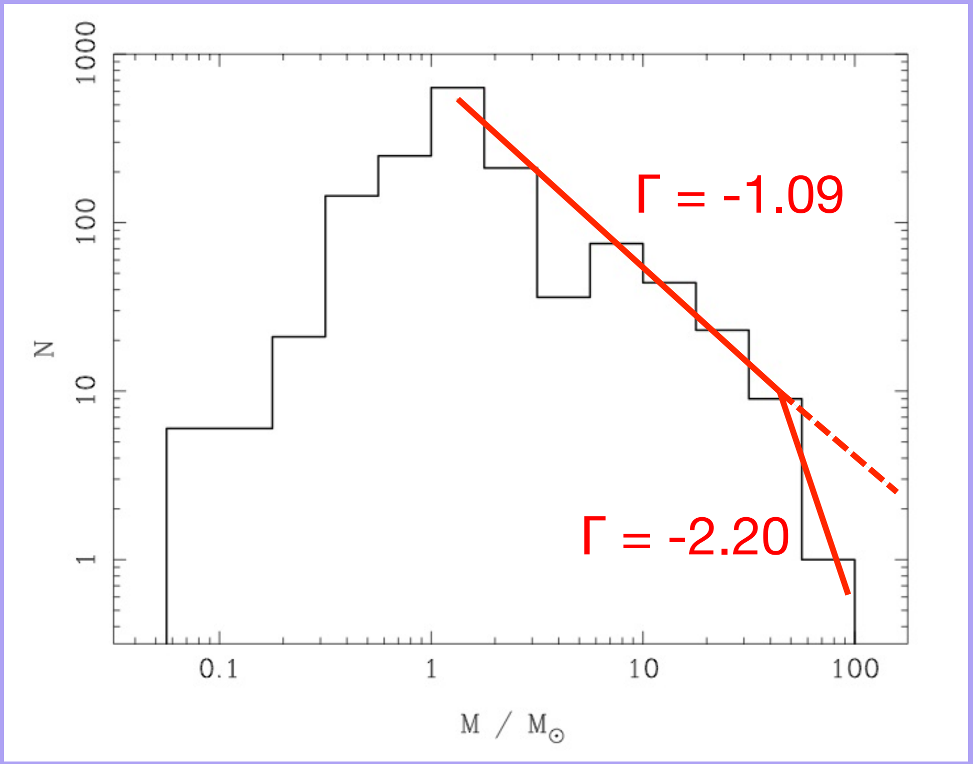
Initial Mass Function



Kiminki et al. 2007

(Initial?) Mass Function





Wright et al. 2010

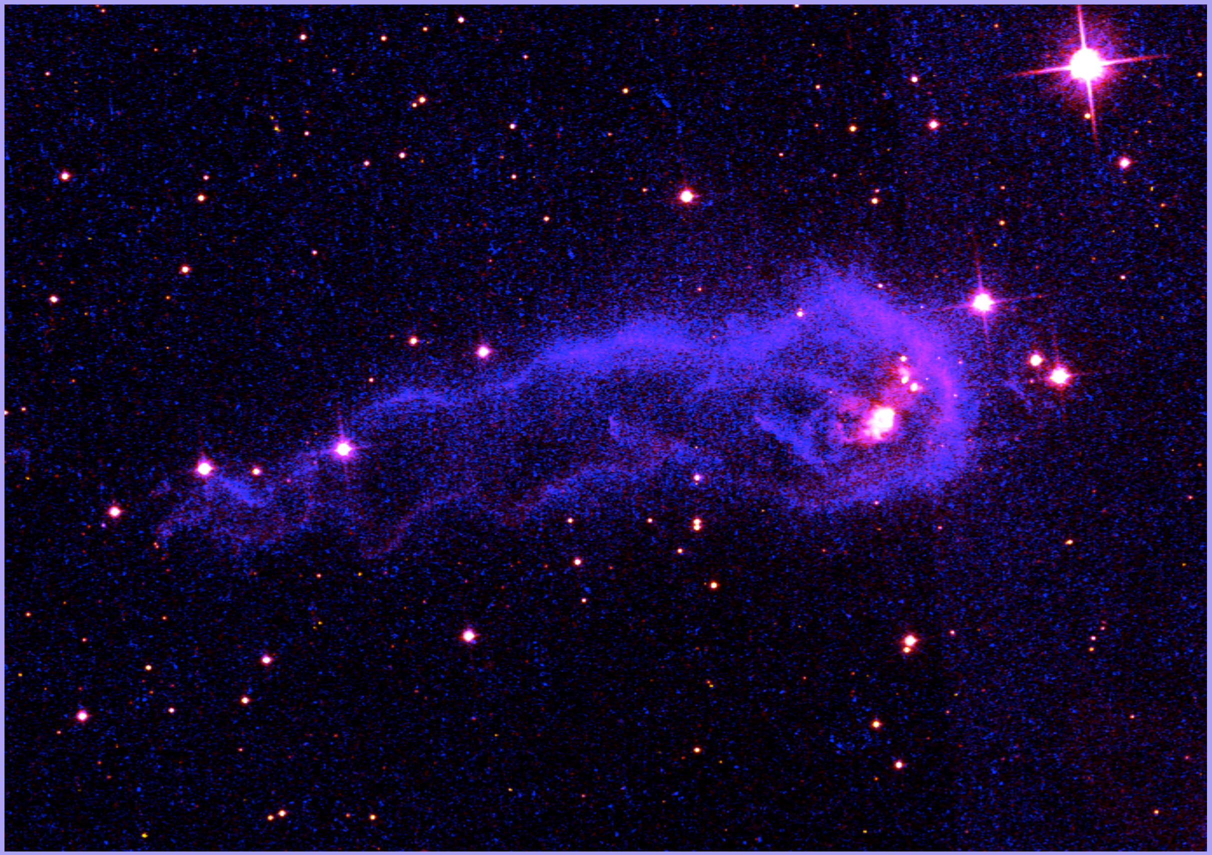
Masses from CMD / spectra:

- Complete to ~ 1 $M_\odot$ (exc. A/B stars)
- Salpeter-like slope Γ = -1.09
- Steepens at high-masses (age-steepening?)

Impact of Massive Stars in Cygnus OB2

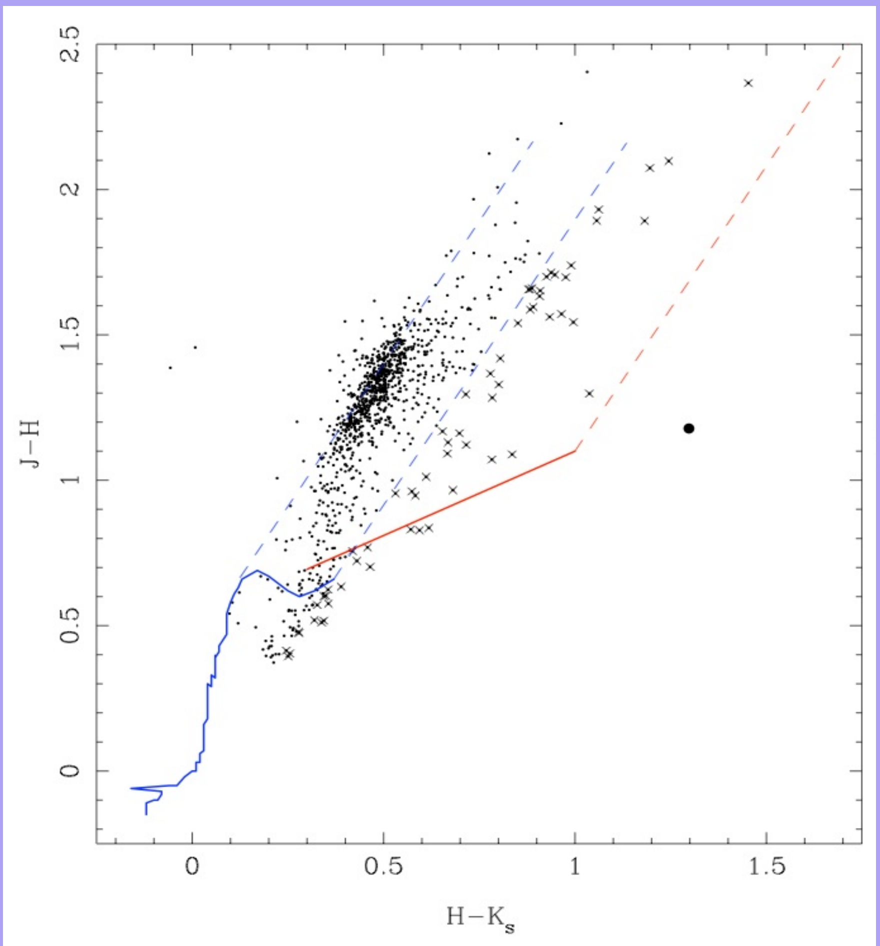
IPHAS INT/WFC (Hα)

IPHAS INT/WFC (Hα)



HST/ACS (F606W / F814W filters)

Erosion of Proto-planetary Disks

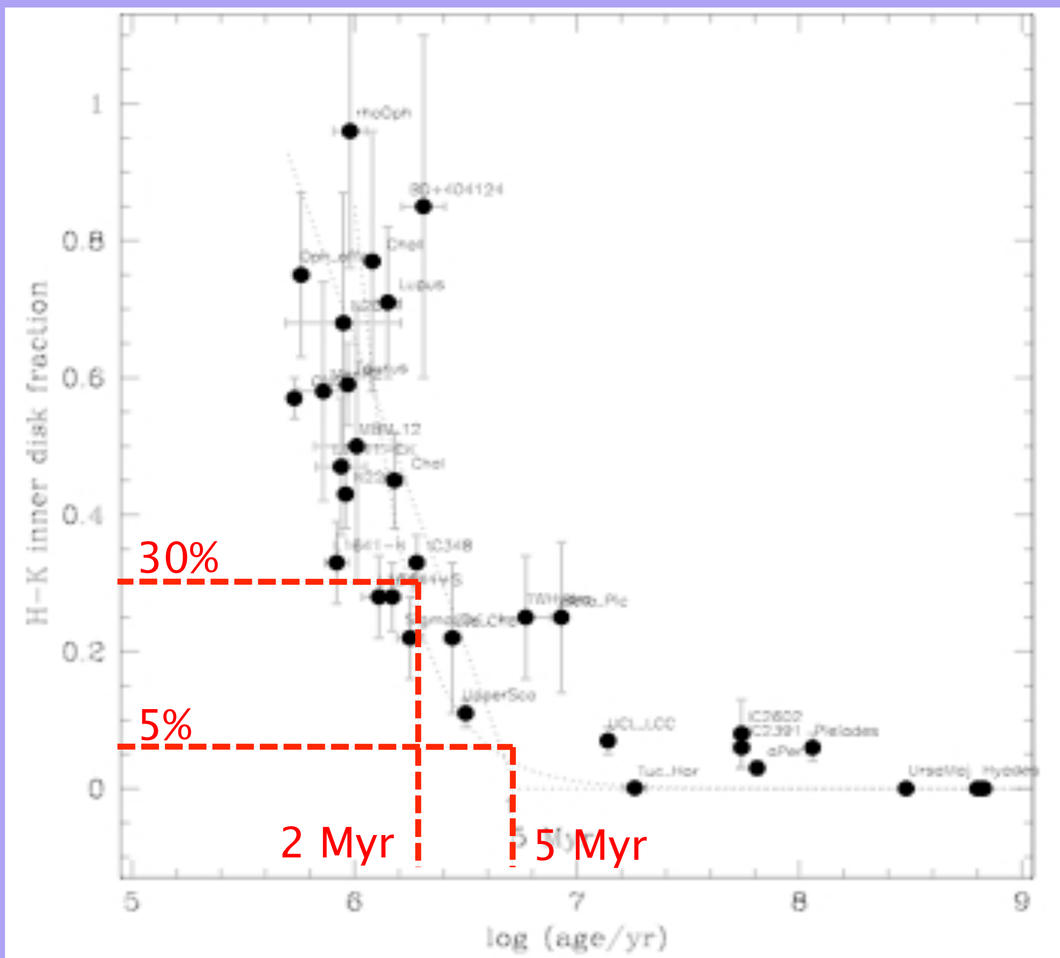


Wright et al. 2010

Low fraction of JHK excess stars (Albacete-Colombo et al. 2007, Wright et al. 2010):

- H-K inner disk fractions ~ 6-8%
- Low compared to other regions (typical 20-40% for 2 Myr population, e.g. Hillenbrand 2005)
- Evidence for disk photoevaporation by OB stars?

Another Interpretation: Stars are Older

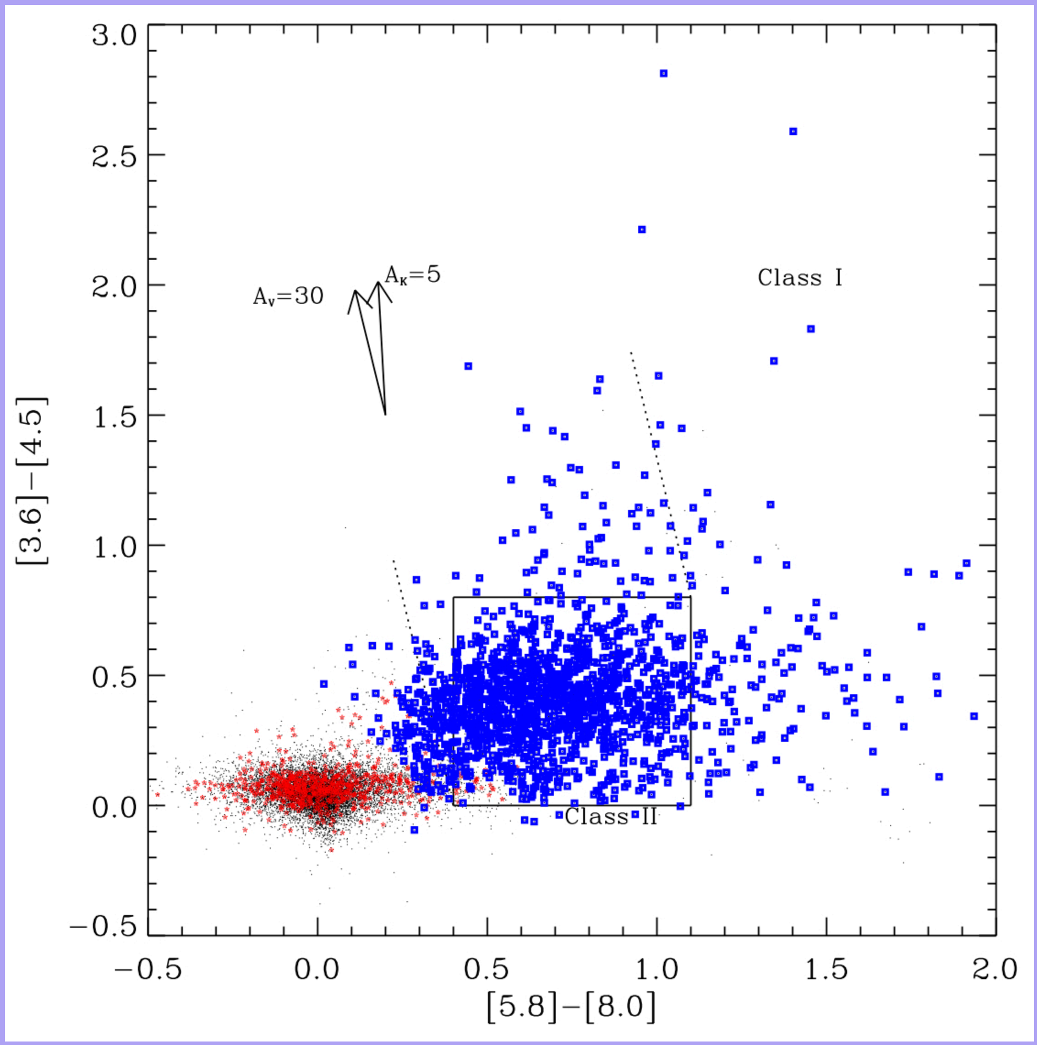


Hillenbrand 2005

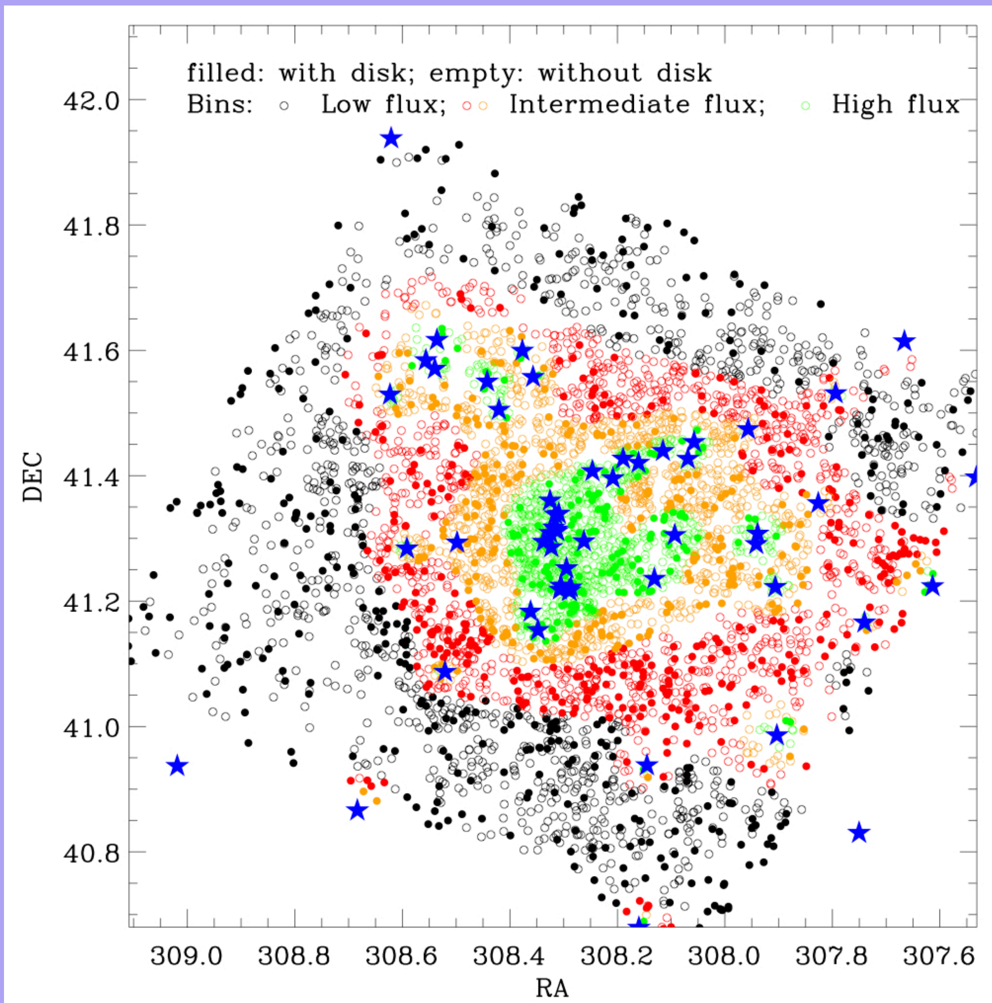
- Inner disk fraction of ~5% appropriate for a 5 Myr population (Wright et al. 2010).
- Highlights risk of interpreting results without fully understanding region being studied.

Identifying Proto-planetary Disks

- Mid-IR photometry a better probe of circumstellar disks.
- X-ray + Spitzer allows pre-MS stars with and without disks to be identified:
    - 2122 stars with disks
    - 5080 stars without disks
- Mid-IR disk fraction ~30%

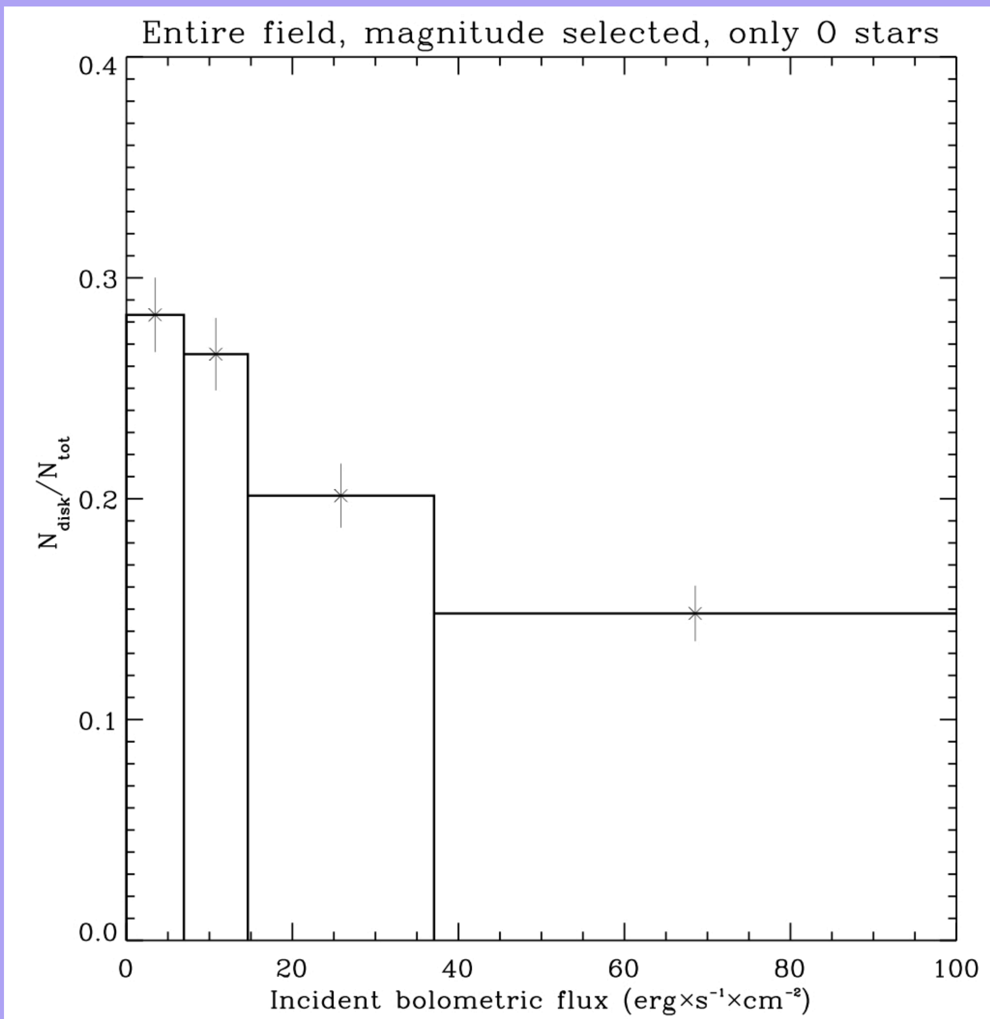


Disk fractions from Spitzer/IRAC



- X-ray + Spitzer distribution of stars with and without disks in Cygnus OB2.
- Compared to positions of known O-type stars.
- Color-coded based on their projected exposure to UV flux:
  - Green = Very high UV flux
  - Orange = High UV flux
  - Red = Moderate UV flux
  - Black = Low UV flux

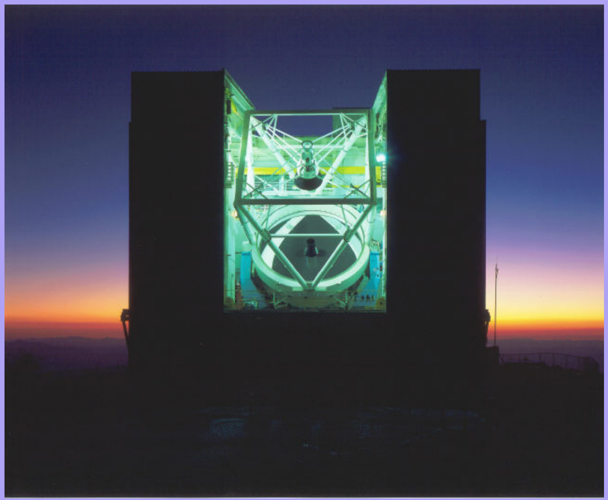
Disk Photoevaporation

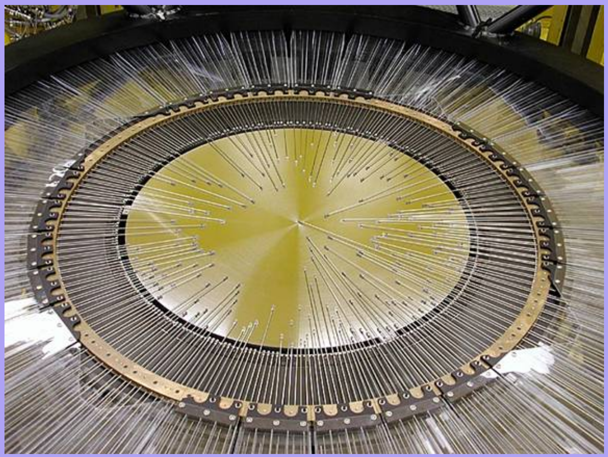


- Disk fraction decreases as UV bolometric flux increases.
- Factor of ~2 difference in disk fraction between high and low UV 'dose'.
- Cannot be explained by known age differences.
- Shortened disk lifetimes must affect planet formation!

Dynamical Survey of Cygnus OB2

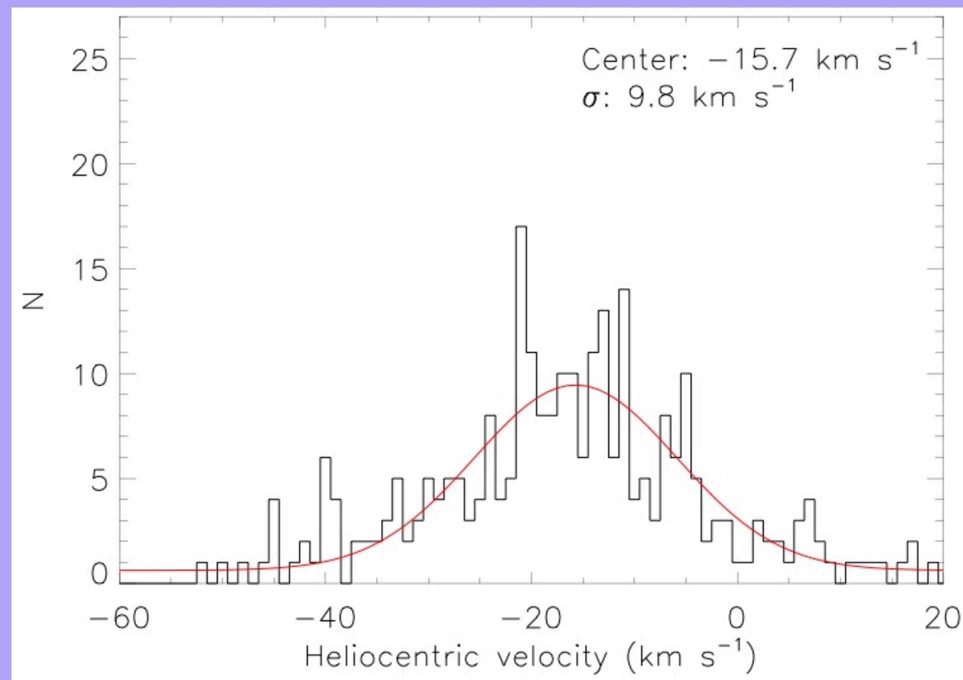
- Radial velocity survey using MMT/Hectospec multi-fiber optical spectrograph.
- Spectra for all X-ray members of CygOB2 above $1M_{\odot}$ ~ 5000 stars to i=20 mag
- Radial velocities measured from Ca II triplet (σ_{RV} ~ 3-5 km/s).
- Proper motions from multi-epoch wide-field surveys (e.g. IPHAS, UKIDSS) spanning ~5-8 years: σ_{PM} = 0.4 mas/yr = 3 km/s (at 1.5 kpc).





Initial Dynamics Results

- Radial velocity survey of 2004 Chandra data ~ 500 sources.
- Velocities match those from massive stars (Kiminki et al. 2007).
- No energy equipartition (dynamical mass segregation), yet mass segregation exists.
- Cluster is globally unbound, but dense low-velocity cores exist.



Conclusions

- Cygnus OB2 an excellent region to study how star formation differs in extreme environments.
- Chandra X-ray observations + deep optical, near- & mid-IR photometry provides excellent census of YSOs.
- Ages, steepened IMF, and disk fractions implies generation of older stars exists alongside current 2 Myr population – large age spreads exist in massive clusters.
- Proto-planetary disk fraction inversely proportional to UV flux exposure - massive stars shorten the lives of disks (implications for planet formation).
- Dynamical survey suggests the association is unbound, but bound cores may survive.