X-ray insights into the formation of young stellar clusters

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with

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KITP Star Formation Oct 2007

Outline

- Motivations & introduction
- X-ray surveys (ONC, M 17, RCW 49)
- XLFs --> IMFs & cluster pops (Rosette, NGC 6357, Cep OB3b)
- Cluster structures (NGC 6357, M 17, Rosette)
- Triggered populations (M 17, IC 1396N, CG 12)
- The remarkable case of W3

KITP cluster star formation
Big Questions addressed here

KITP SF BQ #4: What determines the IMF? (Does it vary with conditions?)
KITP SF BQ #5: How do massive stars form? (Cluster vs. isolation)
KITP SF BQ #6: How do star clusters form? (Origin of ICMF,
distribution of masses within cluster)

Bonnell: Cluster formation w/ infalling gas & competitive accretion
Inutsuka: HII region triggered SF
Krumholz: High-mass SF in cores (fragmentation, SFR)
Tan: Formation of clusters (smooth structure, broad age spread)

"Do we see a `concordance model' of star formation emerging? …
A concordance model must comply with observed properties of stellar clusters
(stellar masses, binarity, kinematics, spatial distribution)"
R. Klessen (KITP Discussion)

Other star formation questions addressed by the new X-ray data

GMC

Cloud star formation efficiency/history (WTT census)
X-ray ionization of cloud (ambipolar diffusion)

$\vec{B}$

Magnetic activity of pre-main sequence stars (saturated dynamos)
Flare astrophysics (B reconnection, PMS magnetospheric geom)
Evidence for star-disk magnetic fields (X-ray superflares)

Disk

Disk evolution (complete WTT samples give range of disk longevities)
X-ray effects on disks (heating/ionization, dead zone, disk MRI)
Flare effects on disks (meteoritic isotopic anomalies, chondrule melting)

OB

O star wind physics (magnetically confined wind shocks)
OBA star multiplicity (direct imaging, ultrahard O wind spectra)

HII

HII region astrophysics (Stromgren shell not sphere, X-ray gas hydrodyn)
Supernova remnant astrophysics (most expand into hot not cold medium)

Review of observations & some implications:
Feigelson, Townsley, Guedel, Stassun
X-ray properties of young stars and stellar clusters, Protostars & Planets V

Chandra X-ray Observatory

NASA's 3rd Great Observatory (HST, GRO, CXO, SSC)

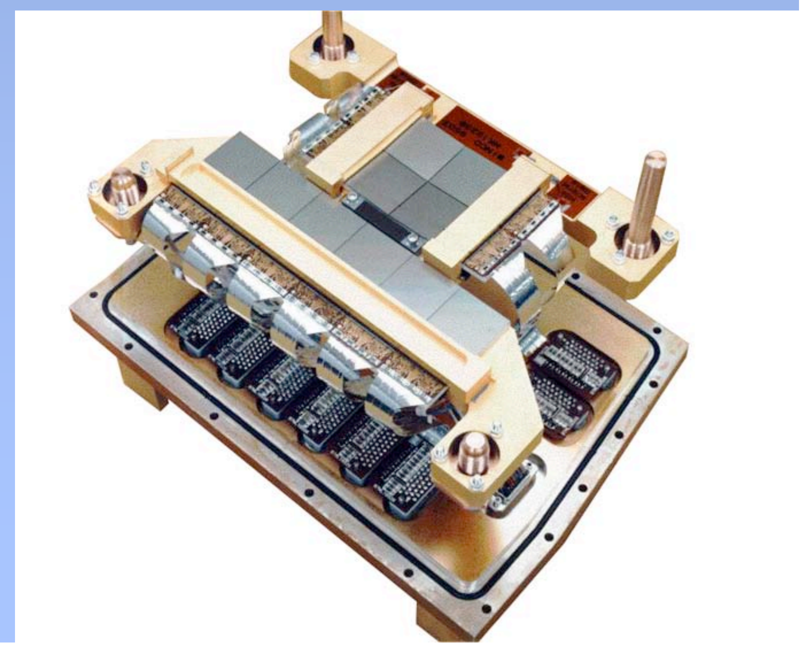
Best mirrors ever produced in astronomy:

<1" resolution on-axis, <0.3" astrometry

Lead detector developed by Penn State & MIT:

Advanced CCD Imaging Spectrometer (ACIS)

4@1024x1024, high QE, ~ noiseless, $\Delta E/E \sim 20$



Star forming regions imaged in X-rays

D < 500 pc
Tau-Aur (XEST project)
Oph, Cha I, L1448
Isolated: HAeBe's, **TW Hya**
NGC 1333, IC 348, Serpens
NGC 2264
ONC, **Orion A**, NGC 2024, 2071, 2078

D > 3 kpc
Gal Cen, Sgr B2, Arches, Quintuplet
W 49A, 51
NGC 1893
30 Dor & other LMC fields

0.5 < D < 3 kpc
W3, 4, 5, 40
Carina
M8, 16, **17**
NGC 3576, 6334, 6357,7538
Trifid, Rosette, IC 1396, Wd1
RCW 36, 38, 49, 108 & LkHa 101
Cyg OB2, Cep OB3, Cep A

Bold = Large Project

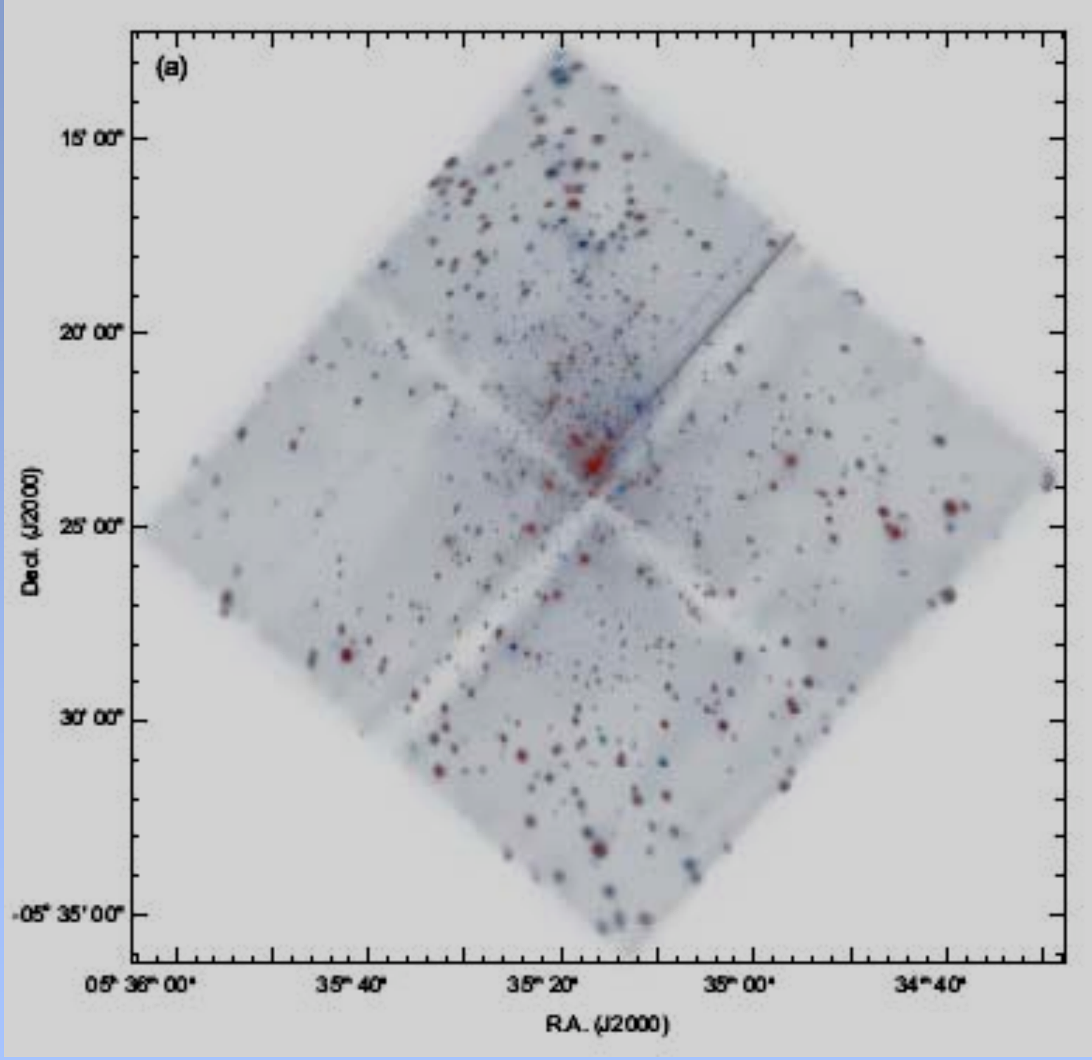
Red = Penn State

Chandra Orion Ultradeep Project

13-day observation of Orion Nebula in 2003

~20 papers 2005-7

1616 COUP sources:
849 low-N_H ONC stars
559 high-N_H stars, incl.
75 new members
16 foreground stars
159 probable AGN
23 uncertain

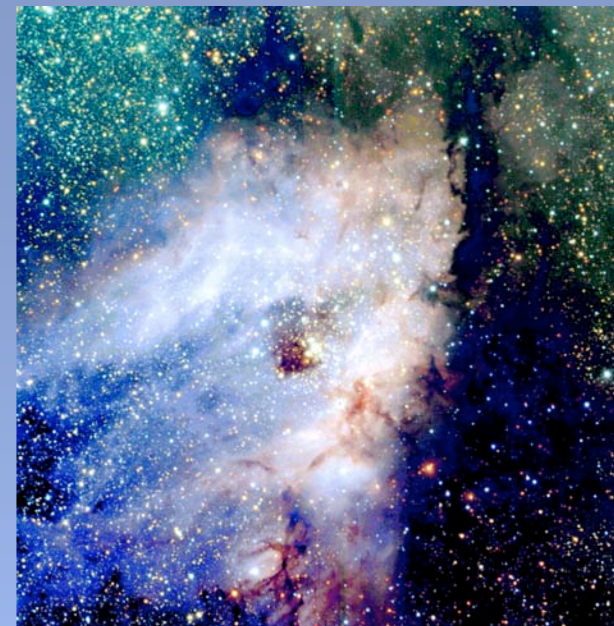


Getman & 22 others, ApJSuppl Oct 2005
(Feigelson, PI)

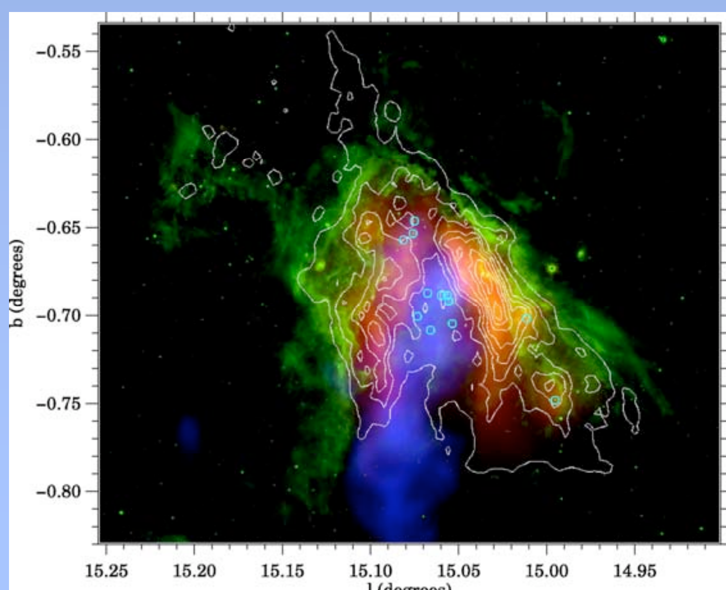
COUP: The Movie

M17 in the IR and optical bands

Hubble reveals ionized gas

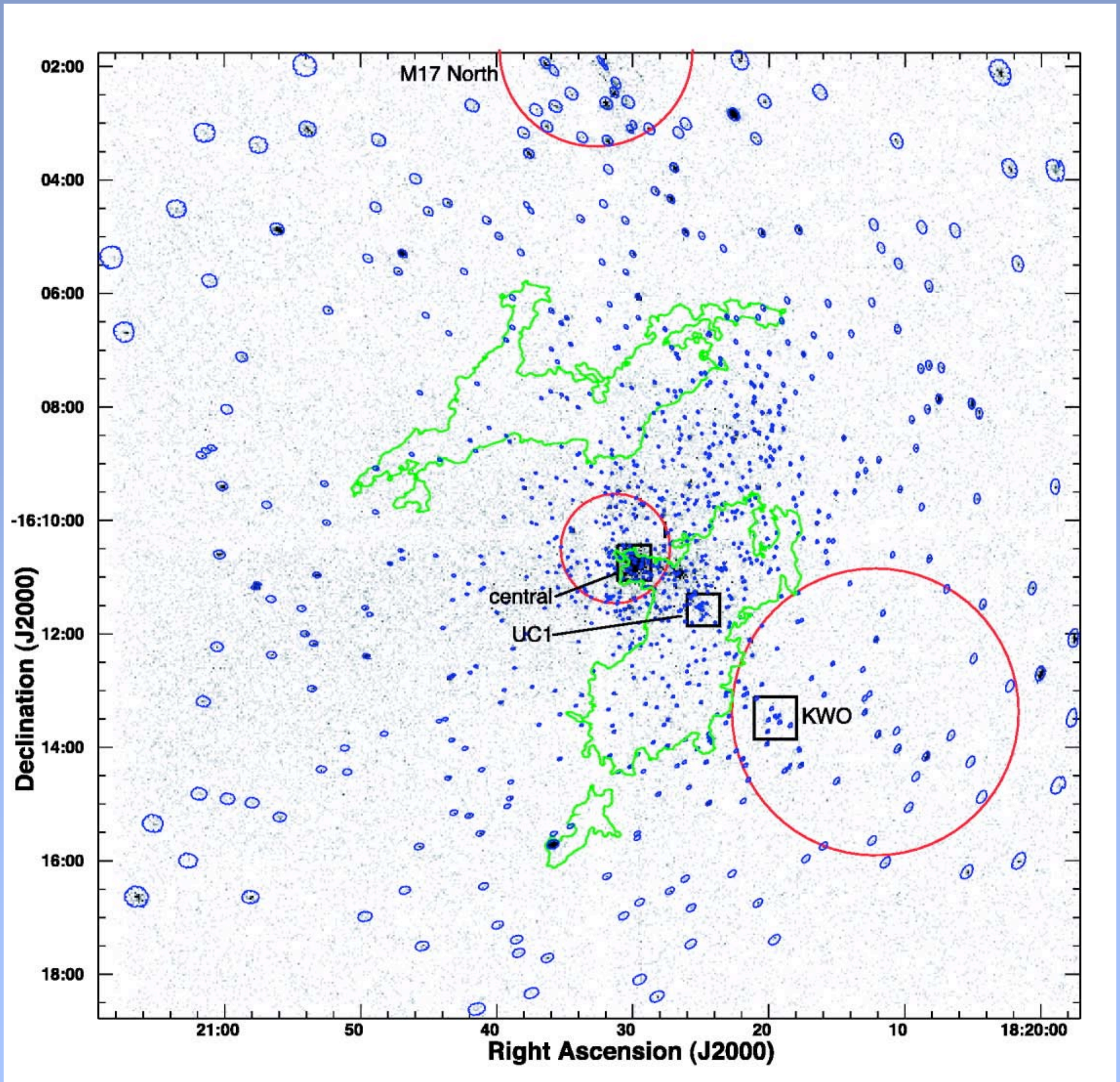


Spitzer reveals heated dust & disky stars
(Povich et al. 2007; blue from Chandra)



JHK reveals stars with heavy contamination by ionized gas and field stars
(Jiang et al. 2002)

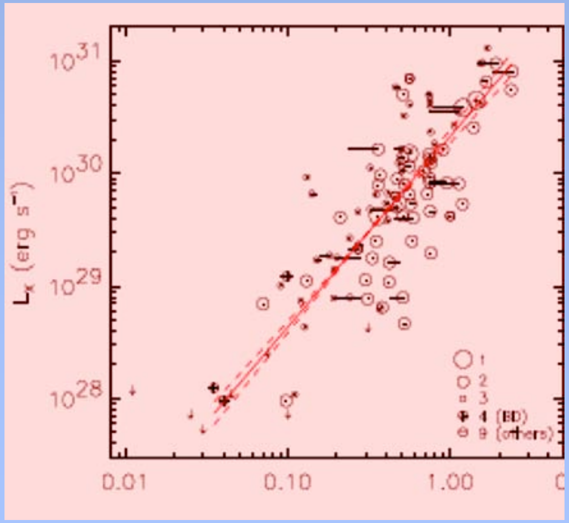
M17 in the X-ray band



Chandra reveals low mass stars, nearly complete to a mass limit, with only slight contamination

(Broos et al. 2007)

L_X-Mass relation in Taurus

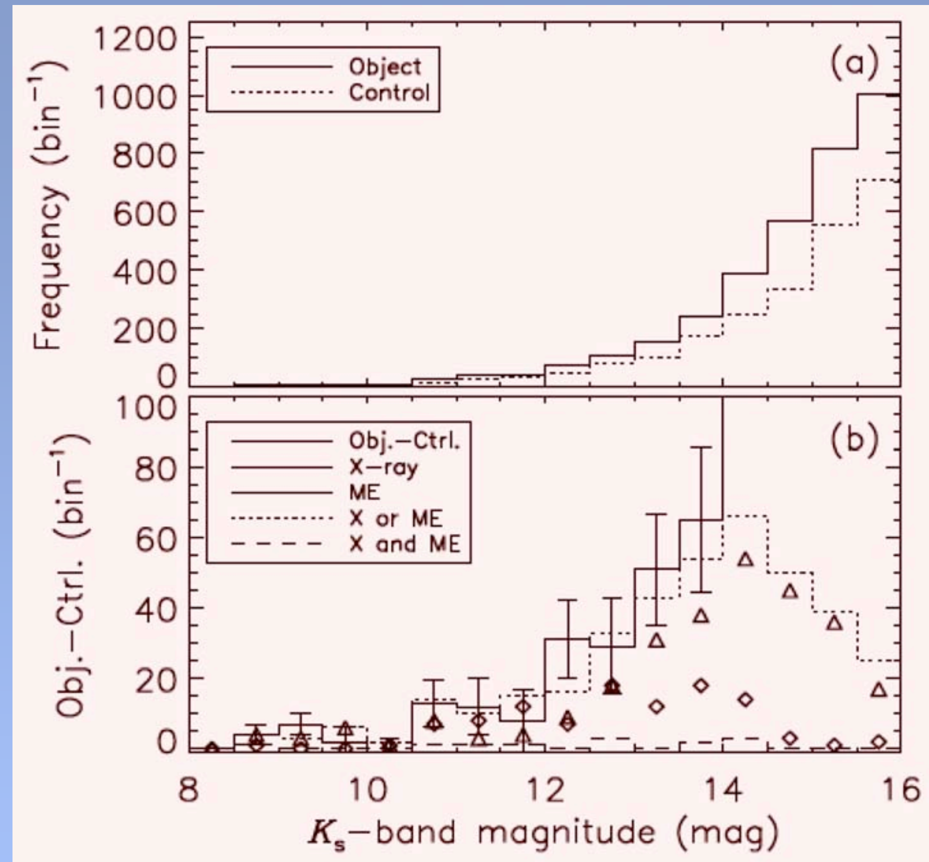


Telleschi et al. 2007 XEST

X-ray vs. infrared census of cluster members

X-ray selection is complete for M_{lim}<M<3 M_o where M_{lim}~0.2-1 M_o depending on sensitivity. Coverage is incomplete for 3<M<7 M_o and becomes complete again for B3 & earlier. Nearly insensitive to disks or accretion (Class I-III).

IR catalogs are often complete to brown dwarf regime, but are usually overwhelmed by field stars at D~2 kpc. IR-only selection limited to heavy-disk systems (Class 0-II).



RCW 49   X-ray/IR study   Tsujimoto et al. 2007

Example …   RCW 49 = Wd 2

10,540 JHK stars

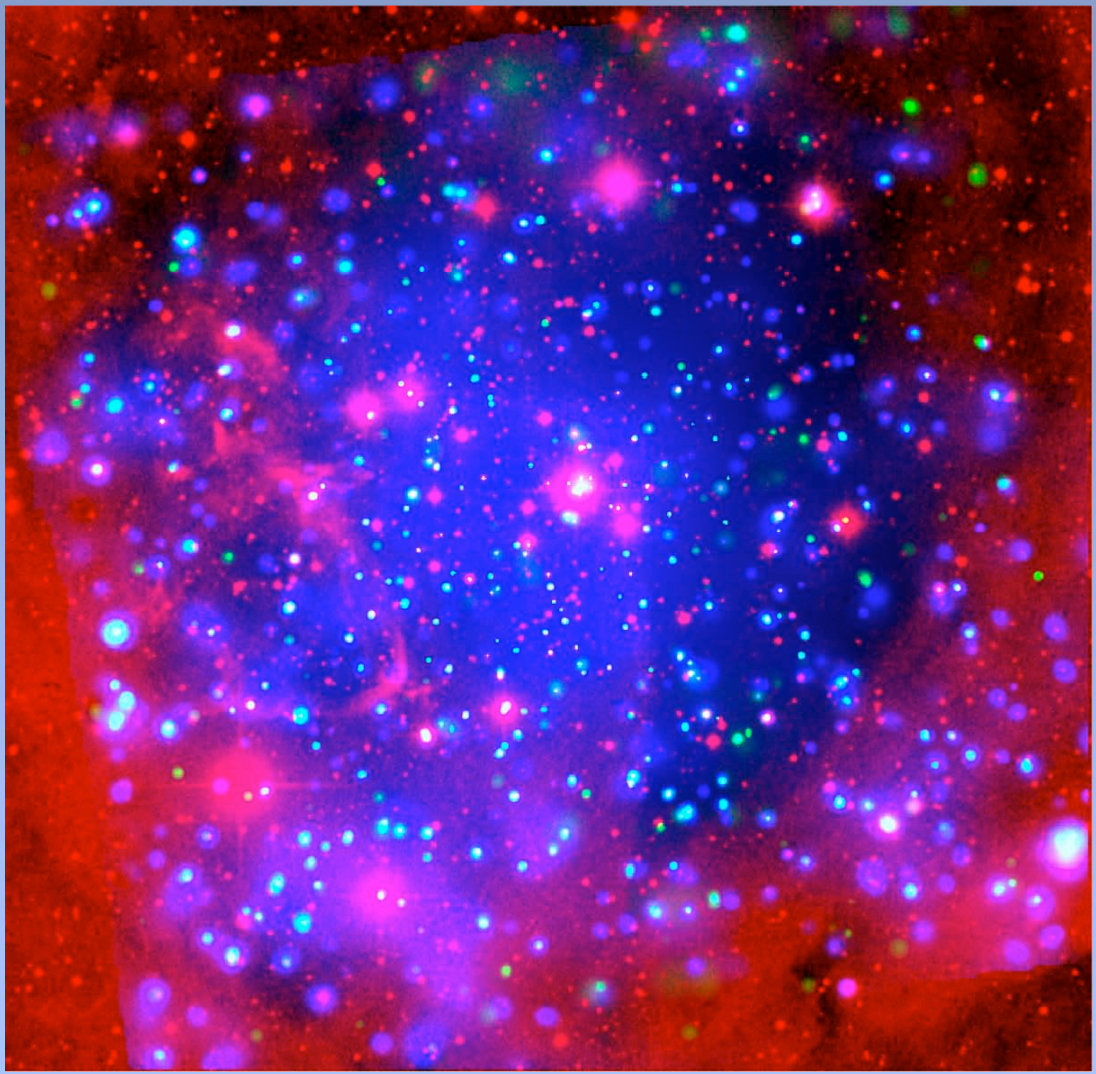
468 X-ray sources of which

379 have DSS, JHK, IRAC counterparts of which

37 have IR excess and 18 are previously studied

(Tsujimoto et al. 2007)

The Rosette Nebula & NGC 2244 cluster



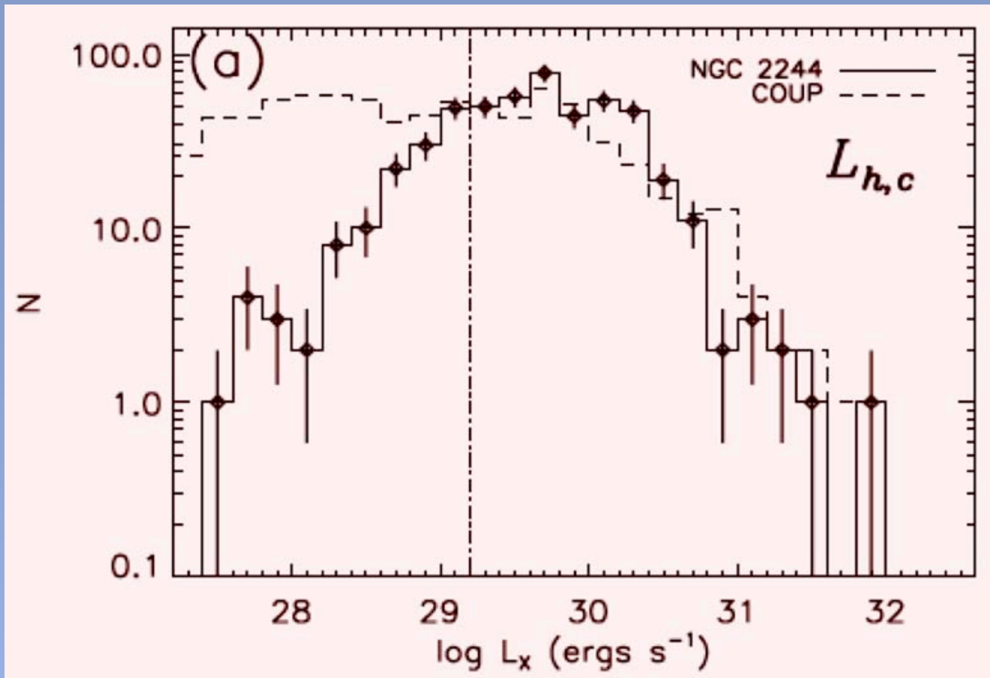
Blue = Chandra sources & diffuse emission Red = DSS stars & Hα

Annular HII region on edge of RMC

D~1.4 kpc

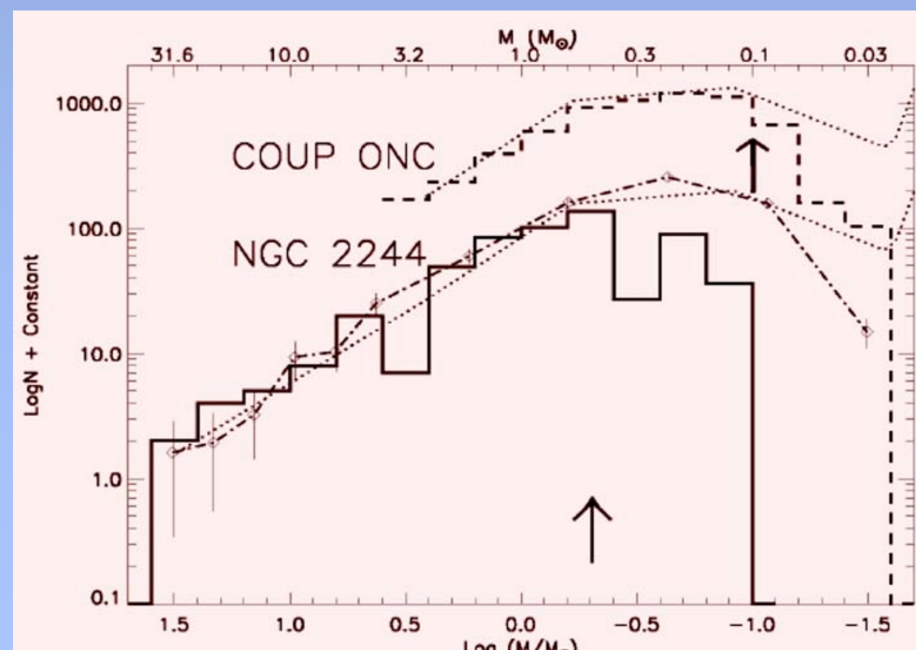
Mosaic of 5 Chandra fields

Four papers emerging in 2007 (Wang et al.)



Rosette XLF & IMF resembles ONC. Not top-heavy IMF, as previously reported.

NGC 2244 population = 1.2 x ONC
But with O4+O5 stars vs. O7 in ONC



X-ray sample --> KLF --> IMF (histogram) agrees with IMF from background-subtracted KLF (dot-dash). Orion cluster offset for comparison.

Wang et al. 2007b

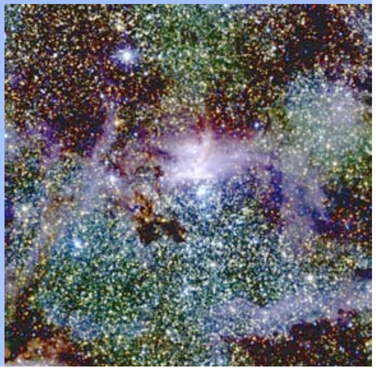
NGC 6357 and its cluster Pismis 24

Wang et al. 2007a   Red=MSX 8um   Blue=0.5-2 keV

Poorly studied massive YSC at d~2.5 kpc. Contains 5 of Galaxy's 15 known O3 stars.

Chandra reveals ~800 low-mass members & doubles OB population. Soft diffuse X-rays fills IR cavity.

Cluster off-center from HII region: 2 generations?

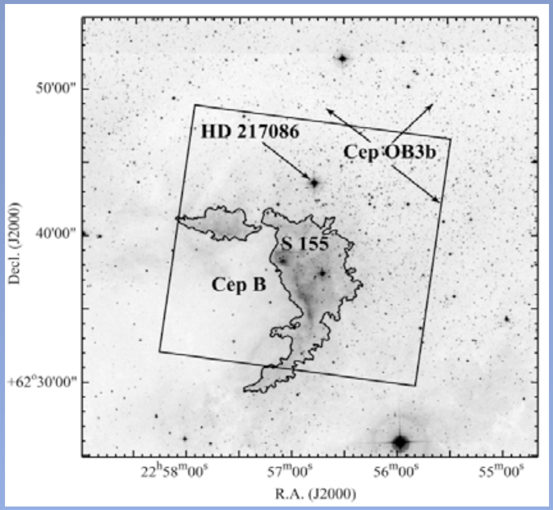


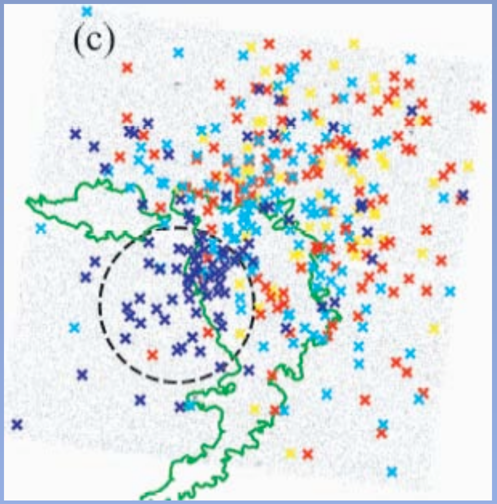
2MASS

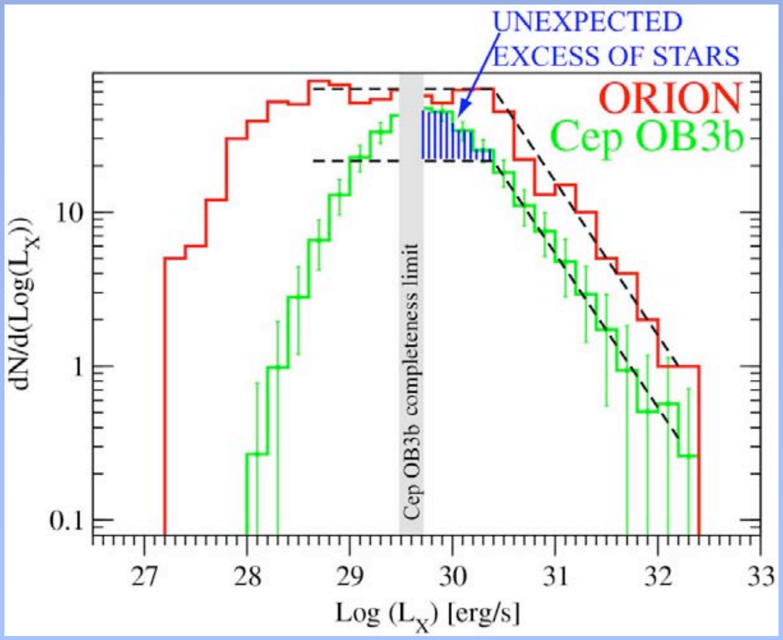
NGC 6357 XLF has same shape as ONC, implying same IMF
Stellar population is 5x ONC (10,000 stars)

Wang et al. 2007a

Cep OB3b: An anomalous IMF?





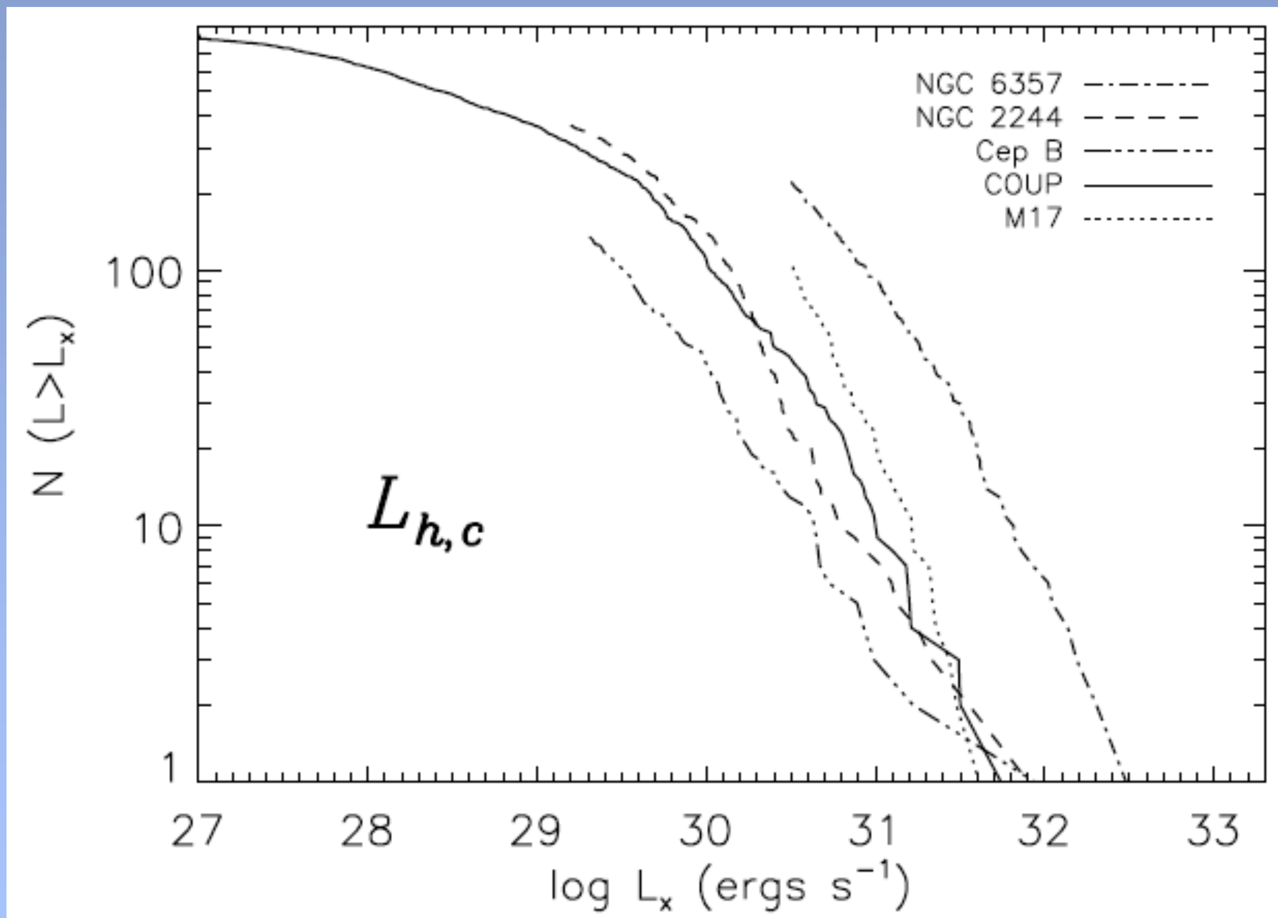


Does Cep OB3b have an excess of ~0.5 Mo stars?

Getman et al. 2006

XLF comparisons

(some clusters show subtle IMF differences?)

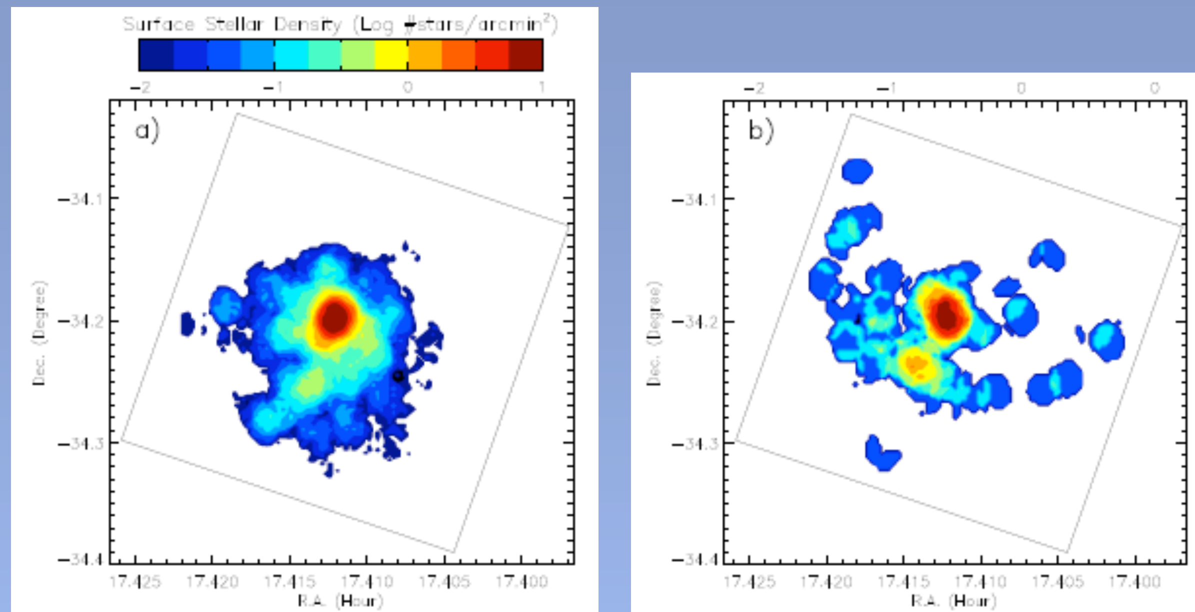


Getman et al. 2006
Wang et al. 2007b

Structure of NGC 6357

Main cluster is spherical
Secondary cluster at center of bubble?

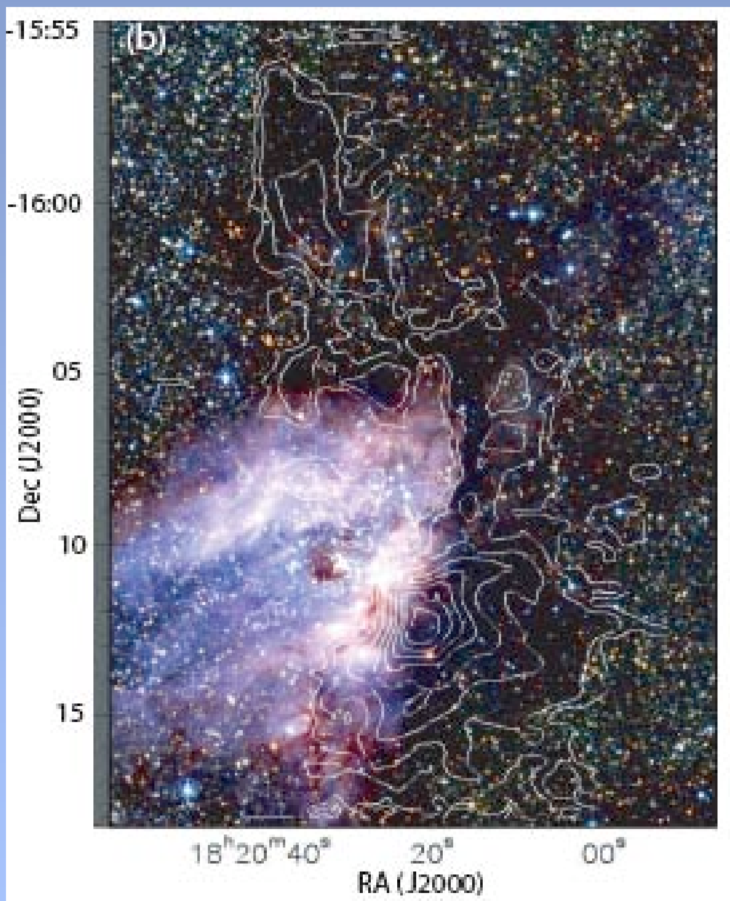
Stellar surface density (10^3 range)
Left: $A_V < 5$
Right: $A_V > 5$



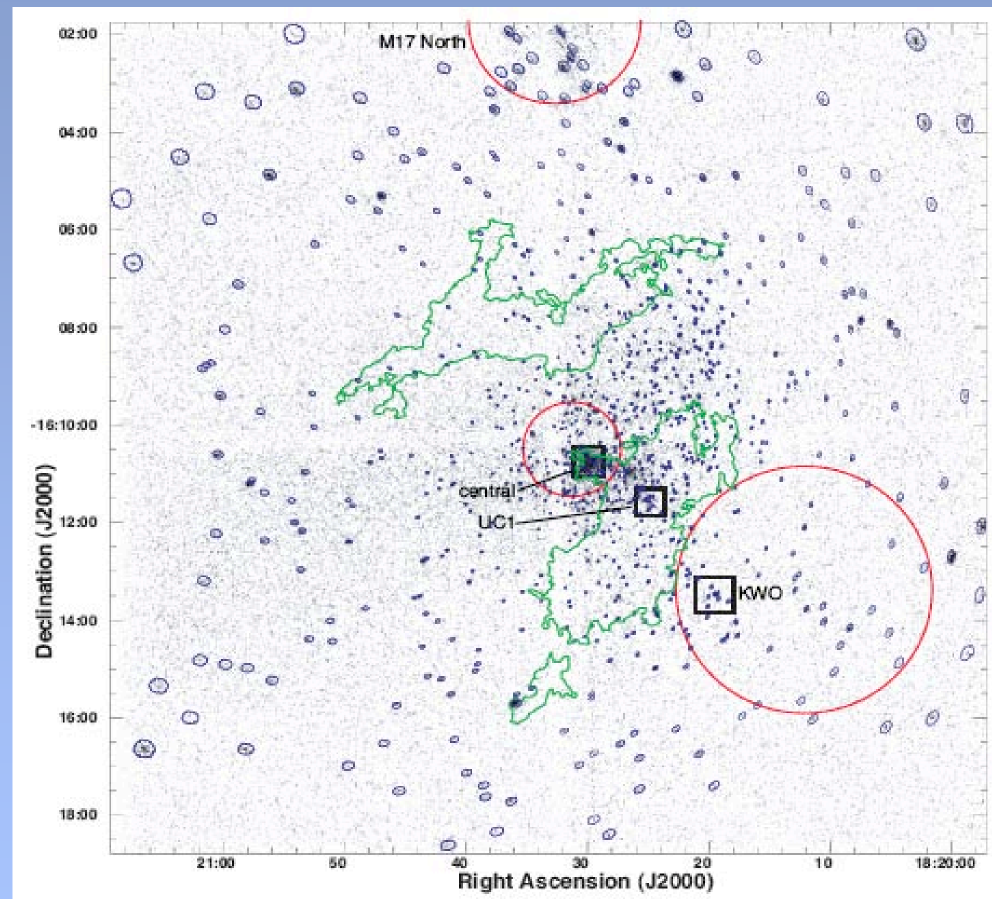
Radial profile shows cluster is much larger than ONC

Wang et al. 2007a

Messier 17 & its cluster NGC 6618



2MASS + CO contours

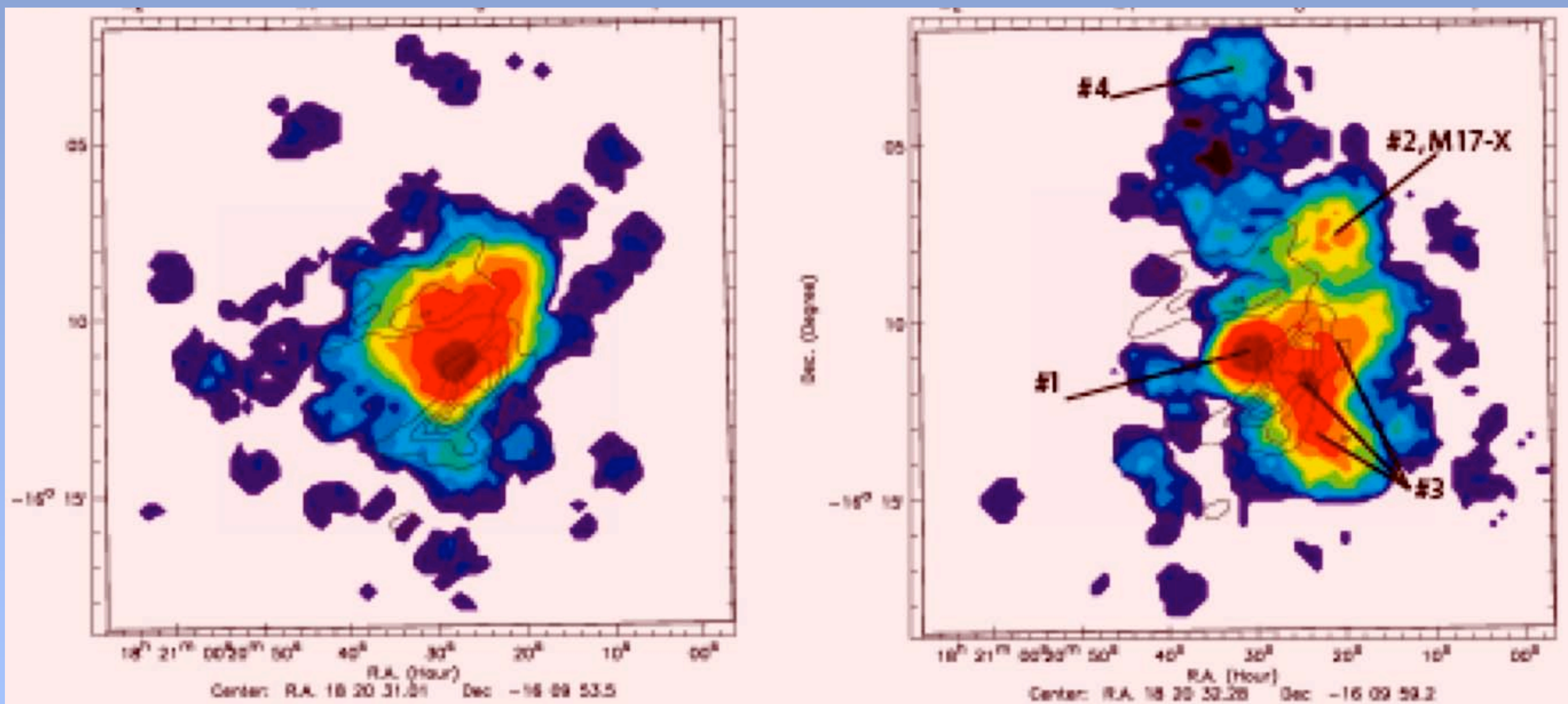


Chandra field & 886 sources

Broos et al. 2007

Lightly obscured central
NGC 6618 cluster
Is roughly spherical

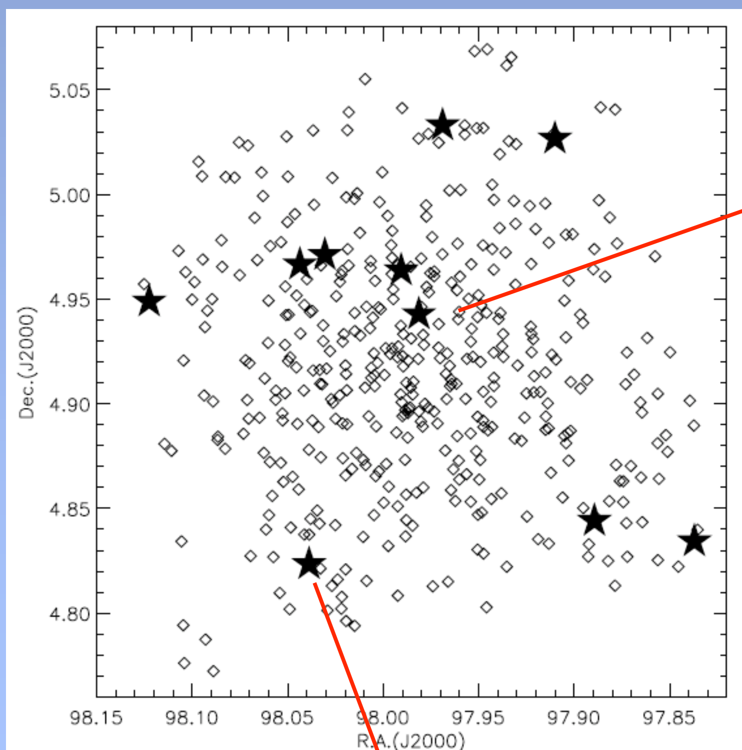
Complex heavily obscured structures:
#1 Central NGC 6618 cluster
#2 Newly identified embedded cluster?
#3 Triggered ridge of stars along SW bar
#4 M17-North cluster



Broos et al. 2007

The remarkable O stars in Rosette

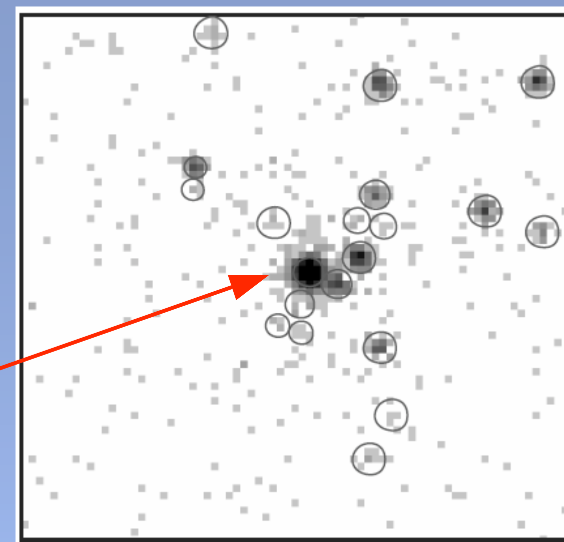
High-mass and low-mass spatial distributions are indistinguishable
No mass segregation !!



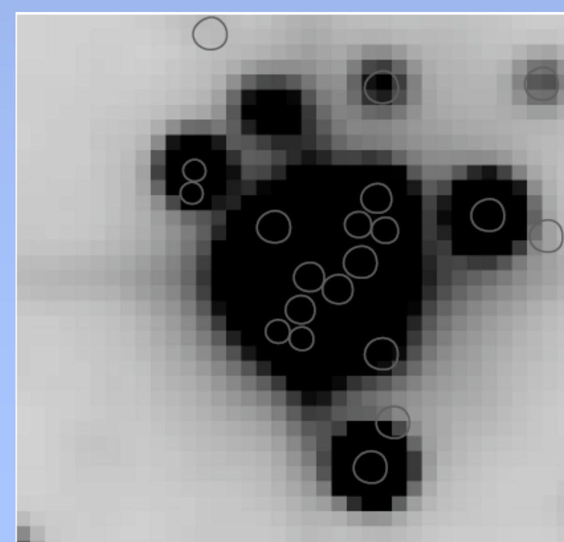
O4 star HD 46223 is isolated

Vicinity of O5 star HD 46150 has 50 star subcluster

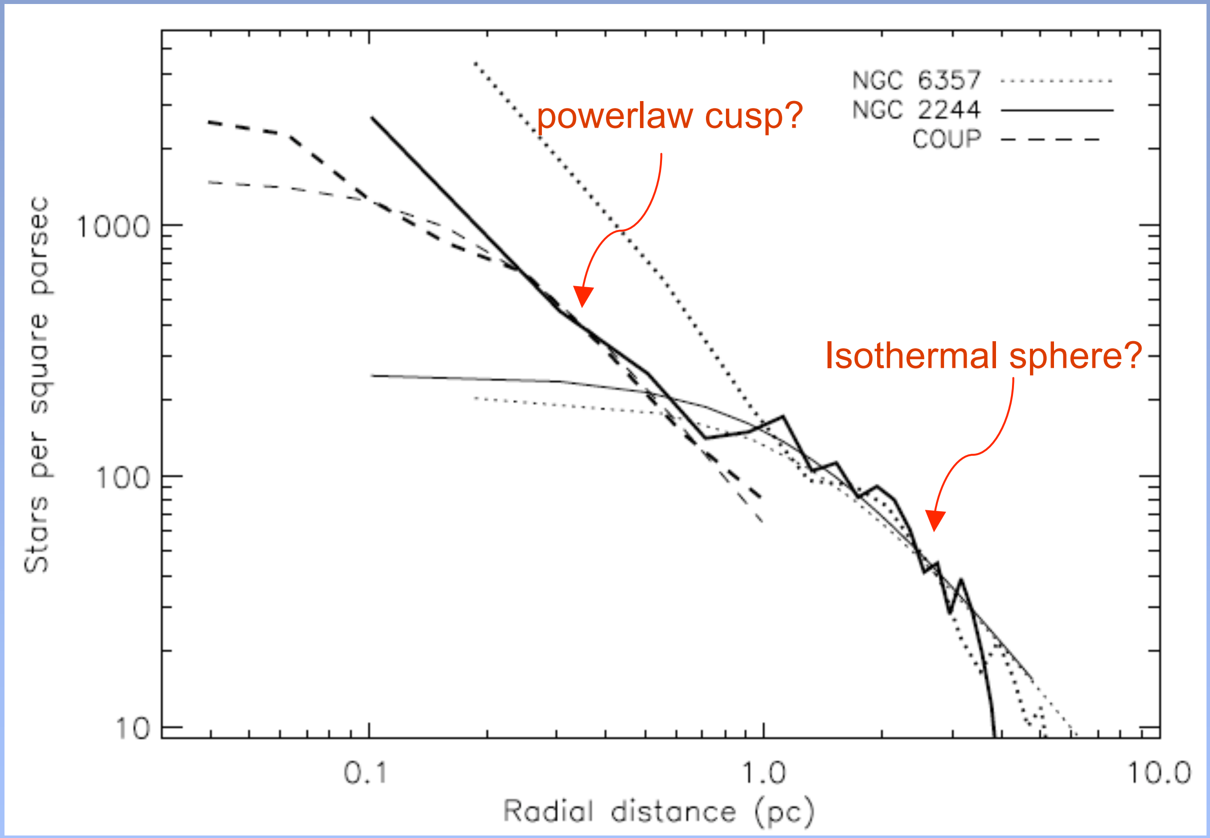
30” (0.2 pc) Chandra



2MASS



Two-component cluster structure?

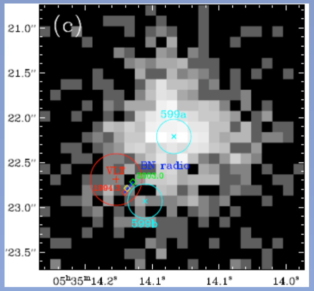


Wang et al. 2007b

X-ray windows into OB star multiplicity

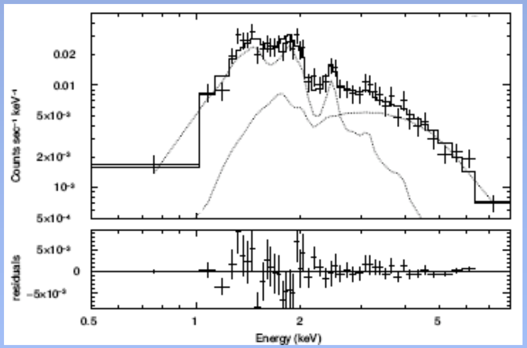
future clues to the dynamical origin of massive stars?

- Chandra effectively locates low mass stars near OB stars



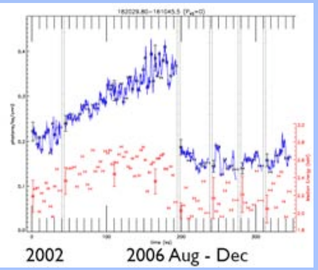
X-ray bright companion 1.1” (500 AU) from BN Object (Grosso et al. 2005)

- Unexpected ultra-hard X-ray spectrum seen in some very young O stars. Colliding wind binaries?

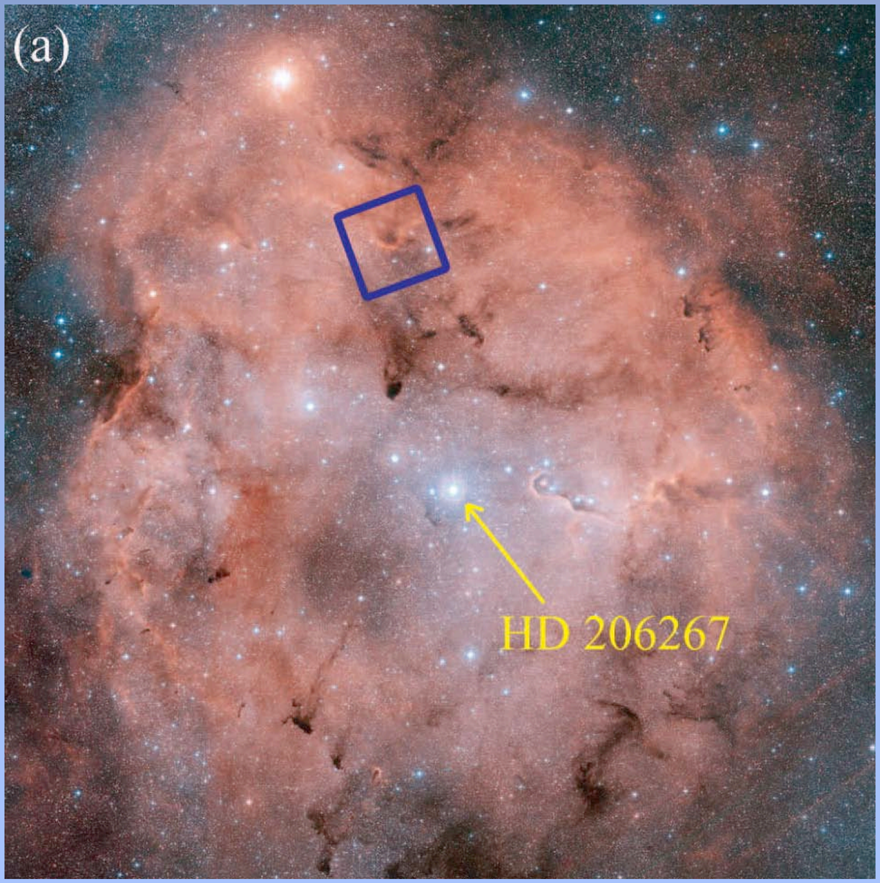


Spectrum (above) & lightcurve (below) of O4 star at center of M 17 (Townsley & Gagne, in prep)

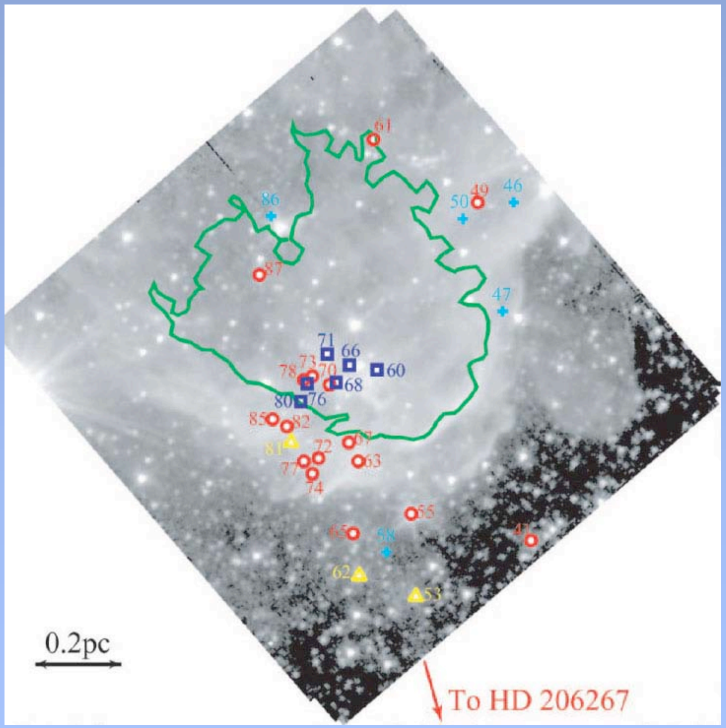
- Unexpected O star X-ray variability may indicate eccentric binary



Triggered populations
Bright-rimmed cloud IC 1396N



Yellow = Class III Red = Class II
Blue = Class 0/I

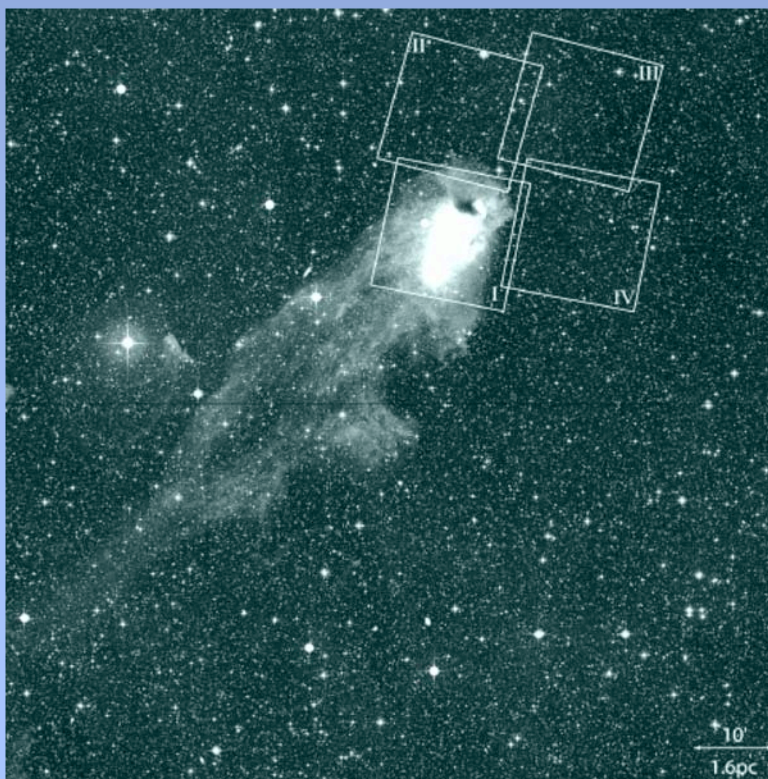


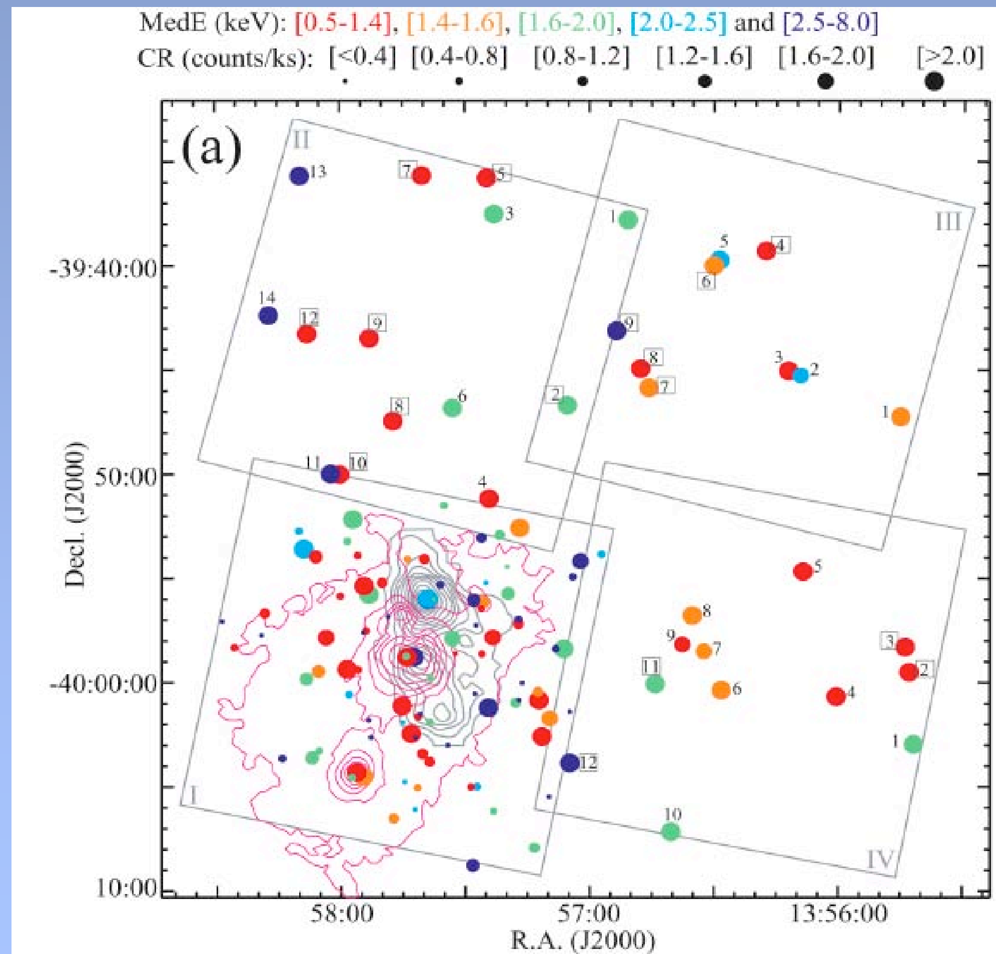
Spatial-age sequence agrees with radiation-driven
Implosion model for triggered SF in BRCs

Getman et al. 2007a

The mysterious high-latitude cometary globule CG 12

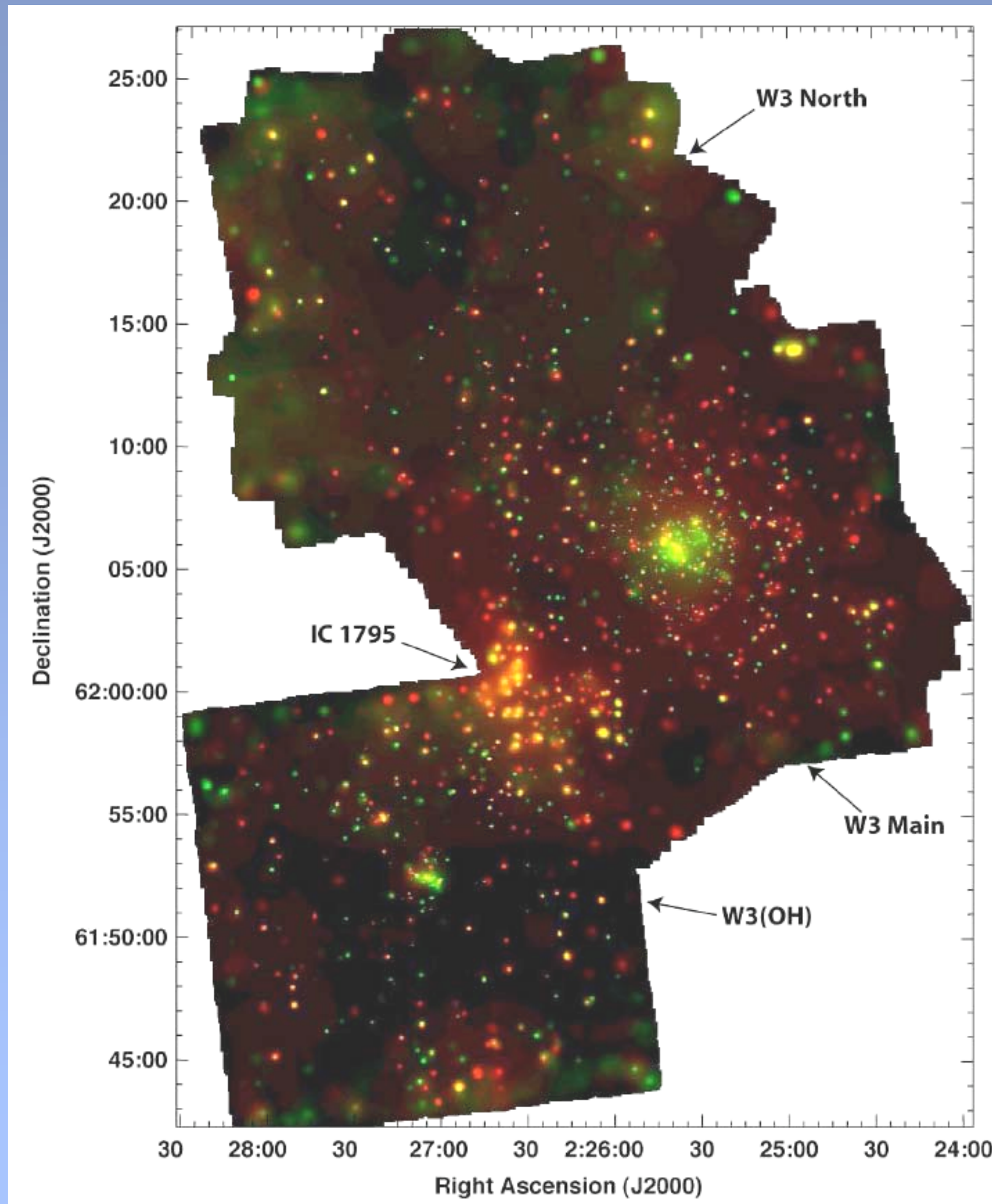
Chandra finds large, dispersed pre-main sequence population with wide age spread





Getman et al. 2007b

The remarkable case of Westerhout 3



Feigelson & Townsley 2007

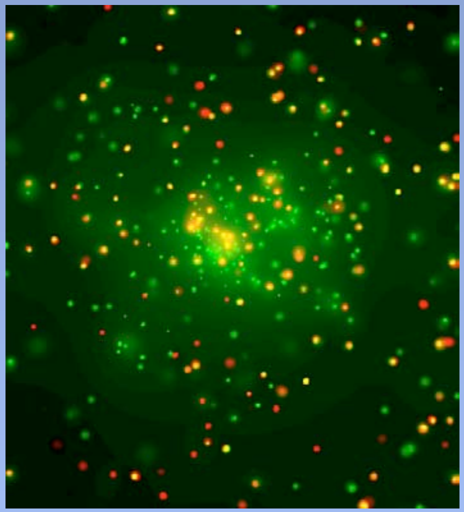
Chandra stars on the Spitzer map

ACIS Townsley et al., in prep

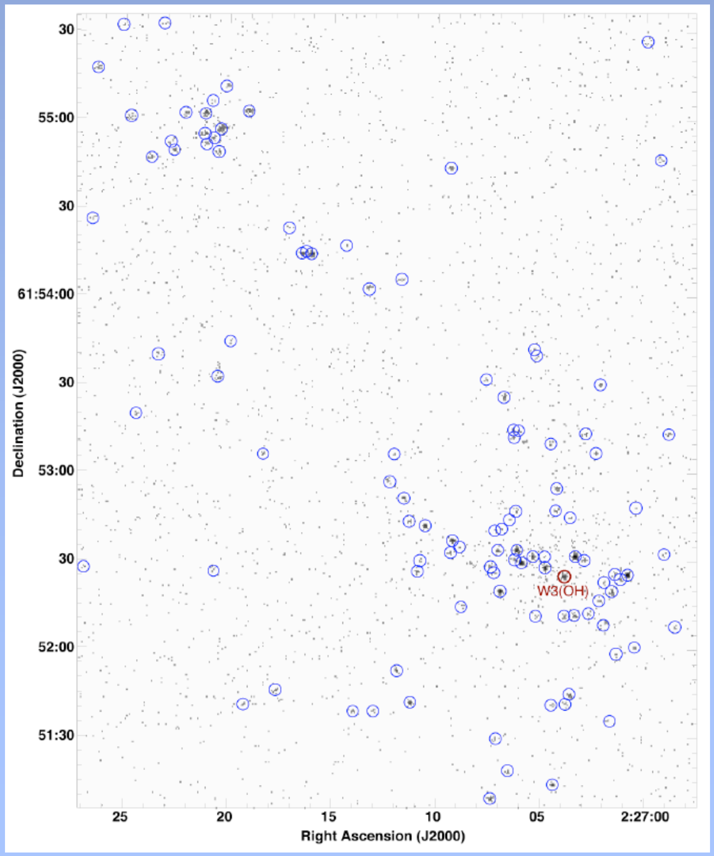
IRAC Ruch et al. 2007

The diverse populations of W3

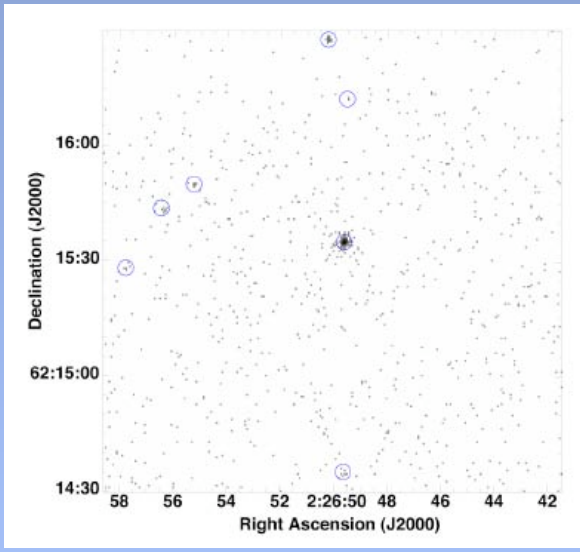
W3 Main
rich, ~900 stars
spherical



W3(OH)
sparse, ~70 stars
clumpy



W3 North
single O star
isolated



W3(OH) consistent with triggered SF from IC 1795 shocks (Oey et al. 2005)

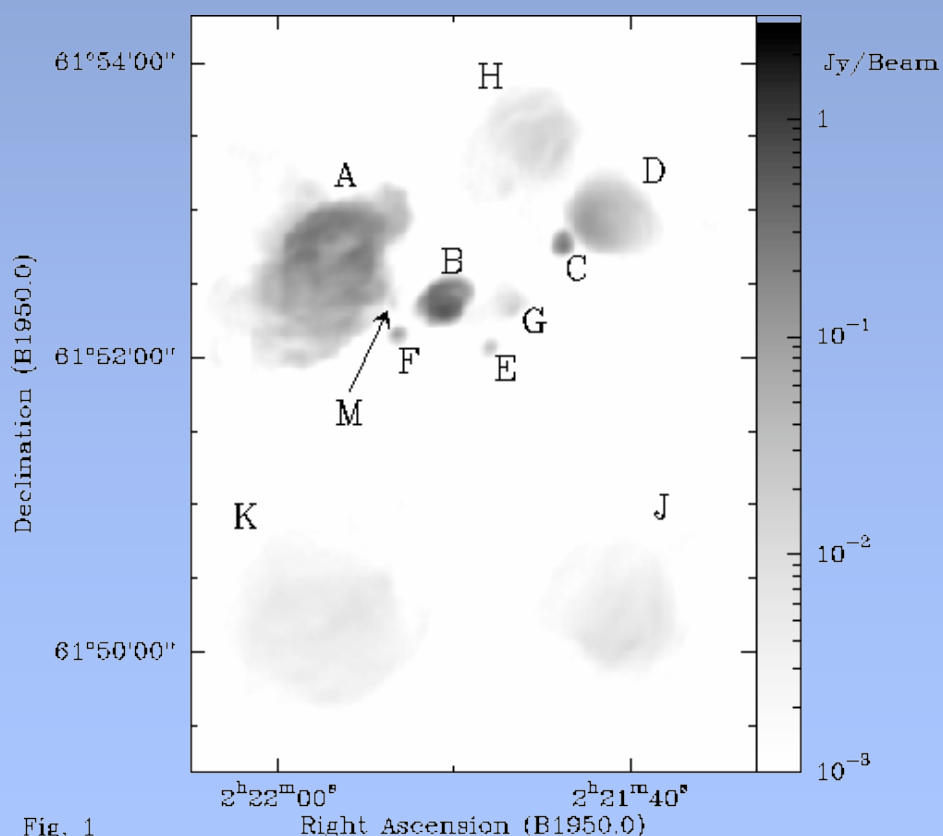
W3 North consistent with young runaway (t~10^5 yr): Not sparse cluster (Parker & Goodwin 2007)

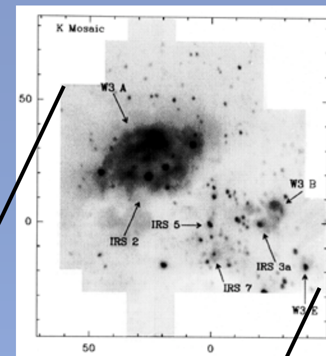
Feigelson & Townsley 2007

Multiwavelength views of W3 Main central region

0.5 pc

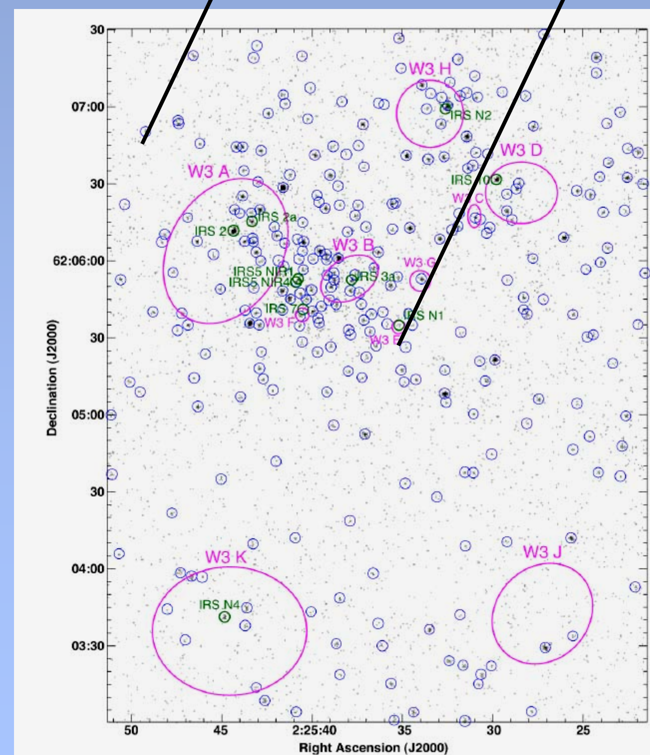
VLA radio Tieftrunk et al. 1997





K band

Megeath et al. 1996



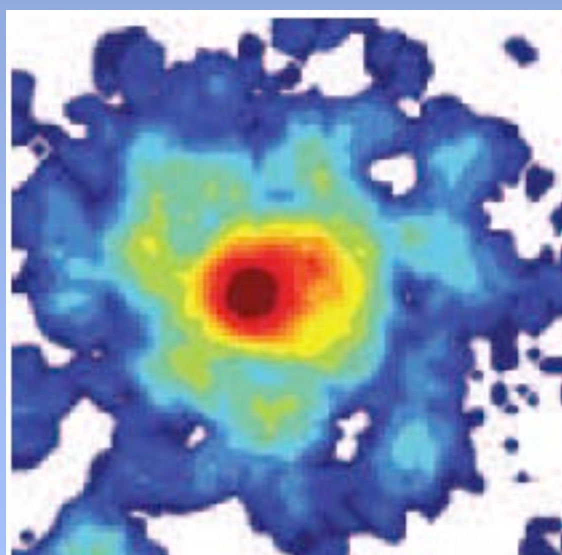
Chandra

Feigelson & Townsley 2007

Chandra constraints on the formation of W3 Main

Large-scale structure of W3 Main

smoothed Chandra source distribution



5 pc

• Large, spherical morphology of W3 Main does not support triggering from IC 1795 shock. Implies slow, extended cluster formation (Tan et al. 2006; Krumholz et al. 2007; Huff & Stahler 2007)

• UCHII OB stars in center must be much younger (10^{4-5} yr) than widely dispersed pre-MS stars (10^6 yr). <1% of Chandra stars are protostellar (Spitzer survey, Ruch et al. 2007). Range of HII sizes may indicate age spread among OB stars (VLA maps, Tieftrunk et al. 1997).

• Possible causes of delay: SF acceleration; stellar mergers, outflow turbulence, dynamics of subclumps, internal triggering (Palla & Stahler 2000; Bonnell et al 1998; Li & Nakamura 2004; McMillan et al. 2007; Tieftrunk et al. 1997)

X-ray insights into cluster formation

X-rays give an unexpectedly rich view of young stellar clusters
Complements IR studies

- IMFs of rich clusters in the 0.5-7 M_o regime generally agrees with ONC, though small deviations may be present
- Stellar population often dominated by a rich, spherical cluster. Mass segregation sometimes not present, central cusps, O runaways?
- Secondary asymmetrical triggered populations often present. Triggering in BRCs agrees with radiation-driven implosion model.
- The three components of W3 are totally different: rich cluster, triggered cluster, and isolated O star. W3 Main strong case for long-duration formation of low mass population followed by later rapid formation of central OB stars.

This research effort has just begun !