X-ray insights into young stellar clusters

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with

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CONSTELLATION school "X-rays from Star Forming Regions" 2009

Outline

- Motivations & introduction
- X-ray surveys (ONC, M 17, RCW 49)
- XLFs --> IMFs & cluster pops (Rosette, NGC 6357)
- Cluster structures (NGC 6357, M 17, Rosette, NGC 6334)
- Triggered populations (M 17, IC 1396N, CG 12)
- The remarkable case of W3

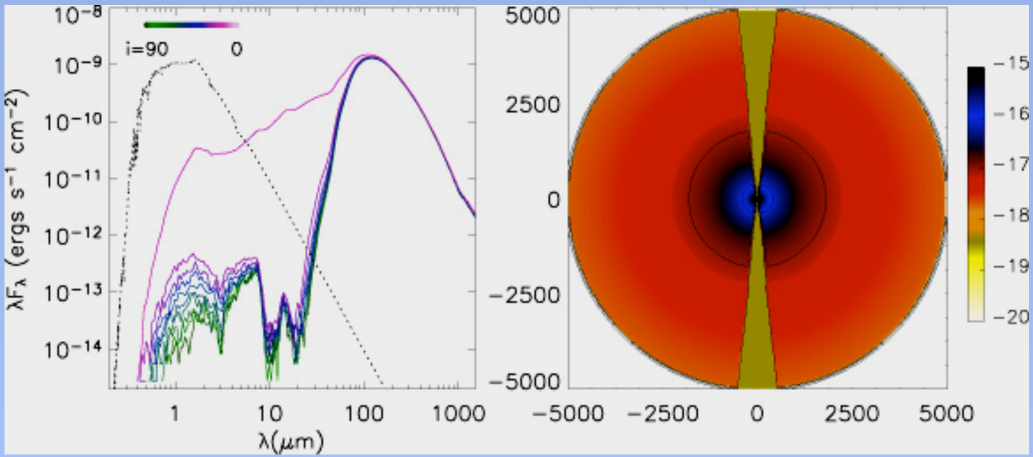
Formation processes of a single star are beginning to be understood

The formation and early stellar evolution of a single star in a small isolated star forming cloud involve: gravitational collapse, angular momentum & fragmentation, and magnetic fields combine to form a protostar with a protoplanetary disk, bipolar outflows and accretion.

Barnard 68: A pre-stellar core

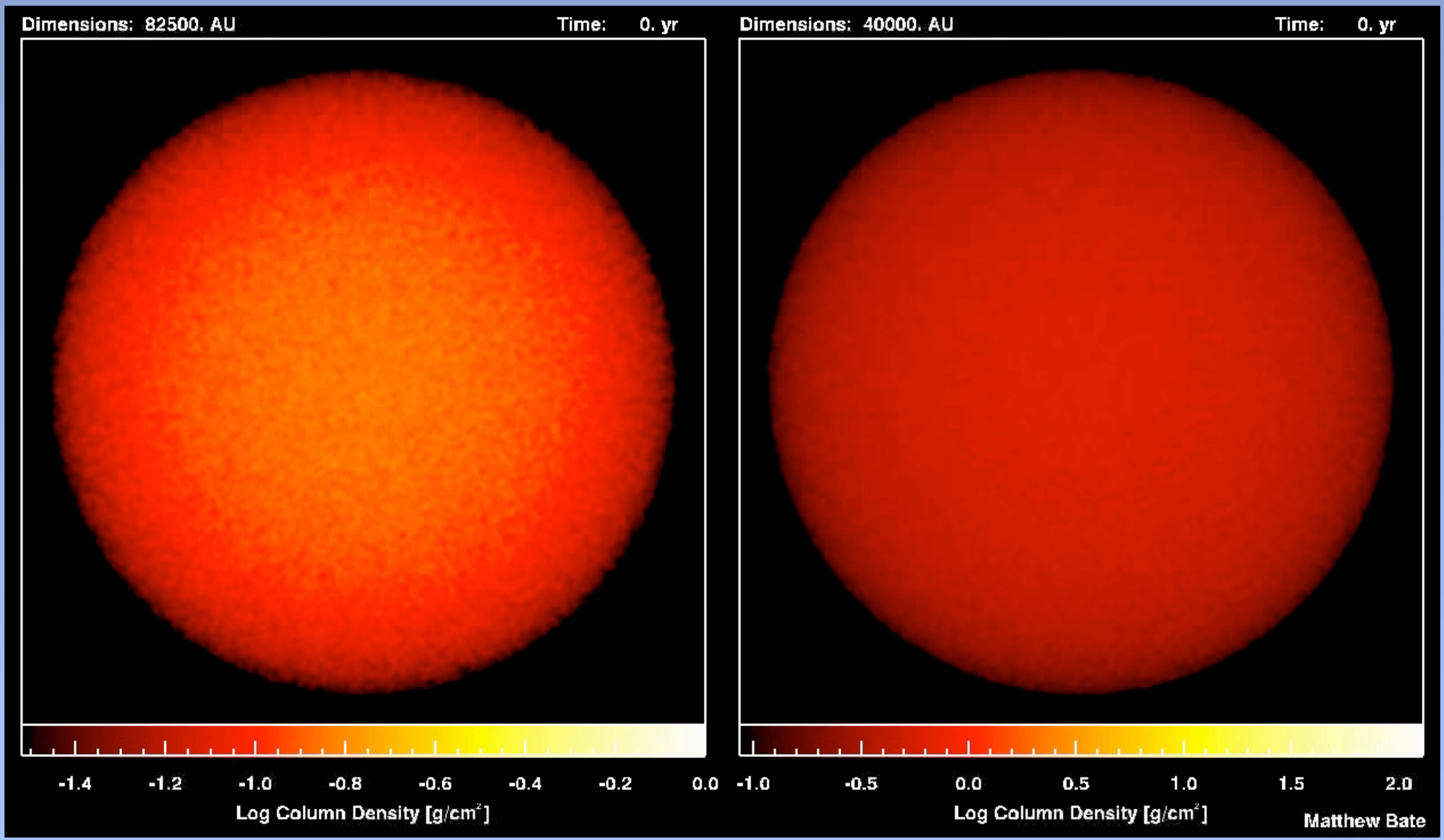
Alves et al. 2004

Spectral model of a Class 0 protostar



Whitney et al. 2004

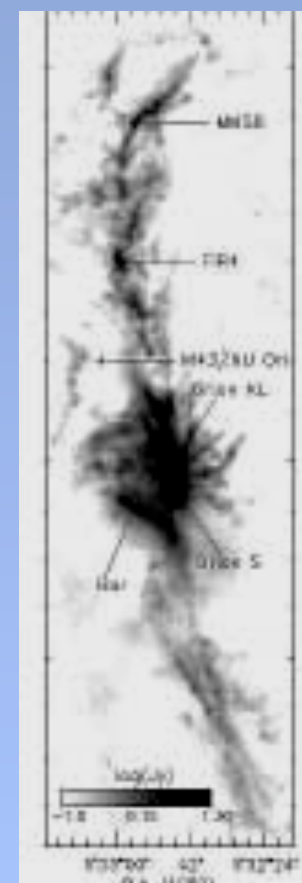
Growing insights from numerical simulations of small groups of stars



Bate et al. 2003

But most stars are born in rich stellar clusters within turbulent giant molecular clouds … and we do not understand these processes!

Portions of the Orion Molecular Cloud complex



Trumpler 14+16 clusters in the Carina Nebula

Hubble Space Telescope ACS mosaic, Nathan Smith

But these do not address many hotly debated issues:

- How do massive OB stars form (accretion or mergers)?
- What is the origin of the stellar Initial Mass Function?
- What causes mass segregation (primordial or dynamical)?
- Do clusters form rapidly or slowly?
- What fraction of stars are formed secondarily from triggering by expanding HII regions or supernova remnants?
- What is the interactions between OB winds and SNRs and the surrounding cold clouds?
- Can protoplanetary disks survive, and to planets form, in hostile HII regions?

Much of the difficulty arises because studies of rich stellar clusters in massive star forming regions are data-starved:

- Radio images show only the 10^4K gas around OB stars
- Near- and mid-infrared images show the heated gas and dust distributions, and cluster stars. But at d>1 kpc, these stellar samples are badly contaminated (factor >10) by Galactic field stars. IR-only cluster samples are limited to young stars with heavy disks, a biased subpopulation.
- Optical studies are contaminated by nebular emission and cannot penetrate into the cloud

The traditional long-wavelength approaches do not readily provide unbiased samples of the full cluster IMF, high-quality maps of the cluster structure, or knowledge of the OB winds on parsec scales.

These needed empirical findings
are now emerging from an
unexpected source:

X-ray images of young stellar clusters,
their surrounding HII regions and clouds

NASA's Chandra X-ray Observatory
is proving most valuable for
these studies

Star forming regions imaged by Chandra (1999-2009)

D < 500 pc

Tau-Aur (XEST)
Oph, Cha I, L1448
Isolated: HAeBe's, **TW Hya**
NGC 1333, IC 348, Serpens
NGC 2264
Wd1
ONC (COUP), **Orion A**, NGC 2024, 2071, 2078
LkHa 101

0.5 < D < 3 kpc

W3, 4, 5, 40
Carina
M8, 16, **17**
NGC 3576, 6334, 6357,7538
Trifid, Rosette, IC 1396,
RCW 36, 38, 49, 108 &
Cyg OB2, Cep OB3, Cep A

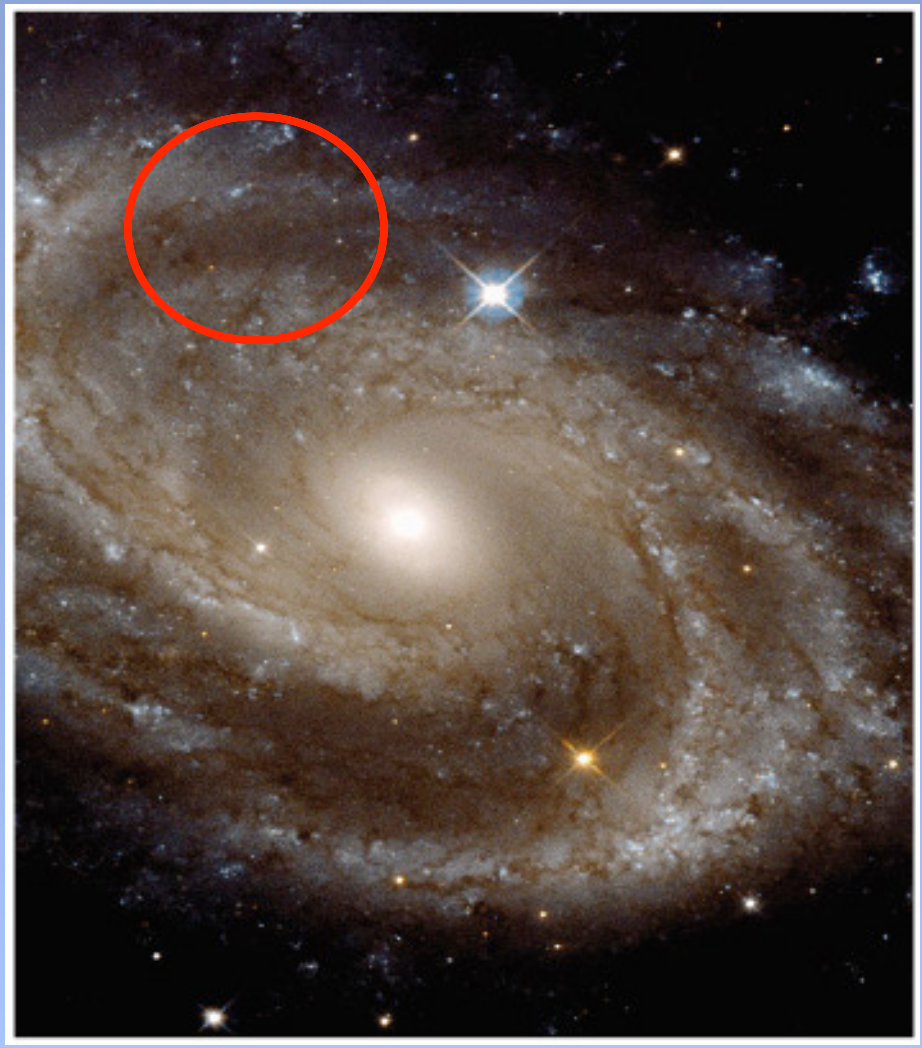
D > 3 kpc

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

Bold = Large Project

Red = Penn State

These clusters map most of the active star formation in the nearby Galaxy

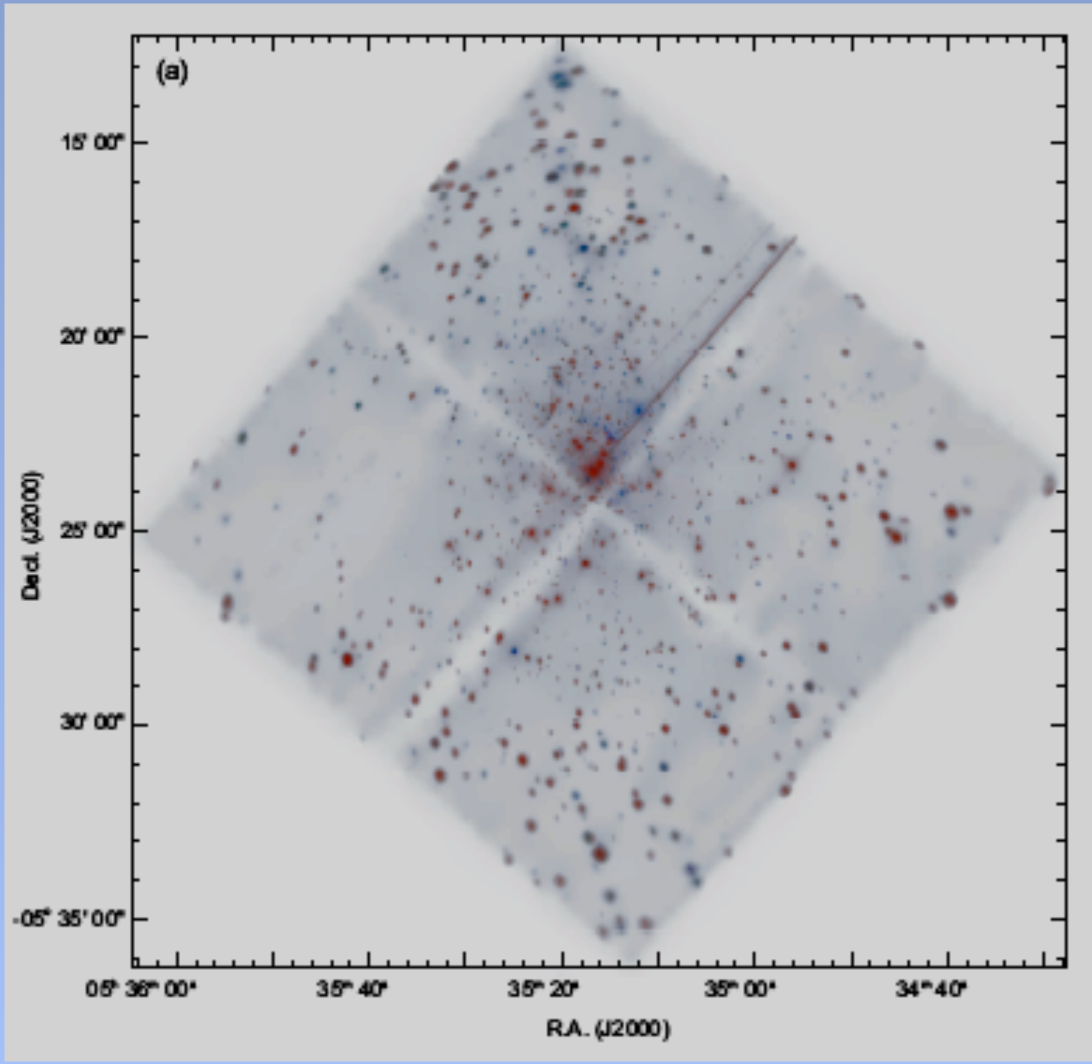


Chandra Orion Ultradeep Project

10-day observation of Orion Nebula Cluster in 2003

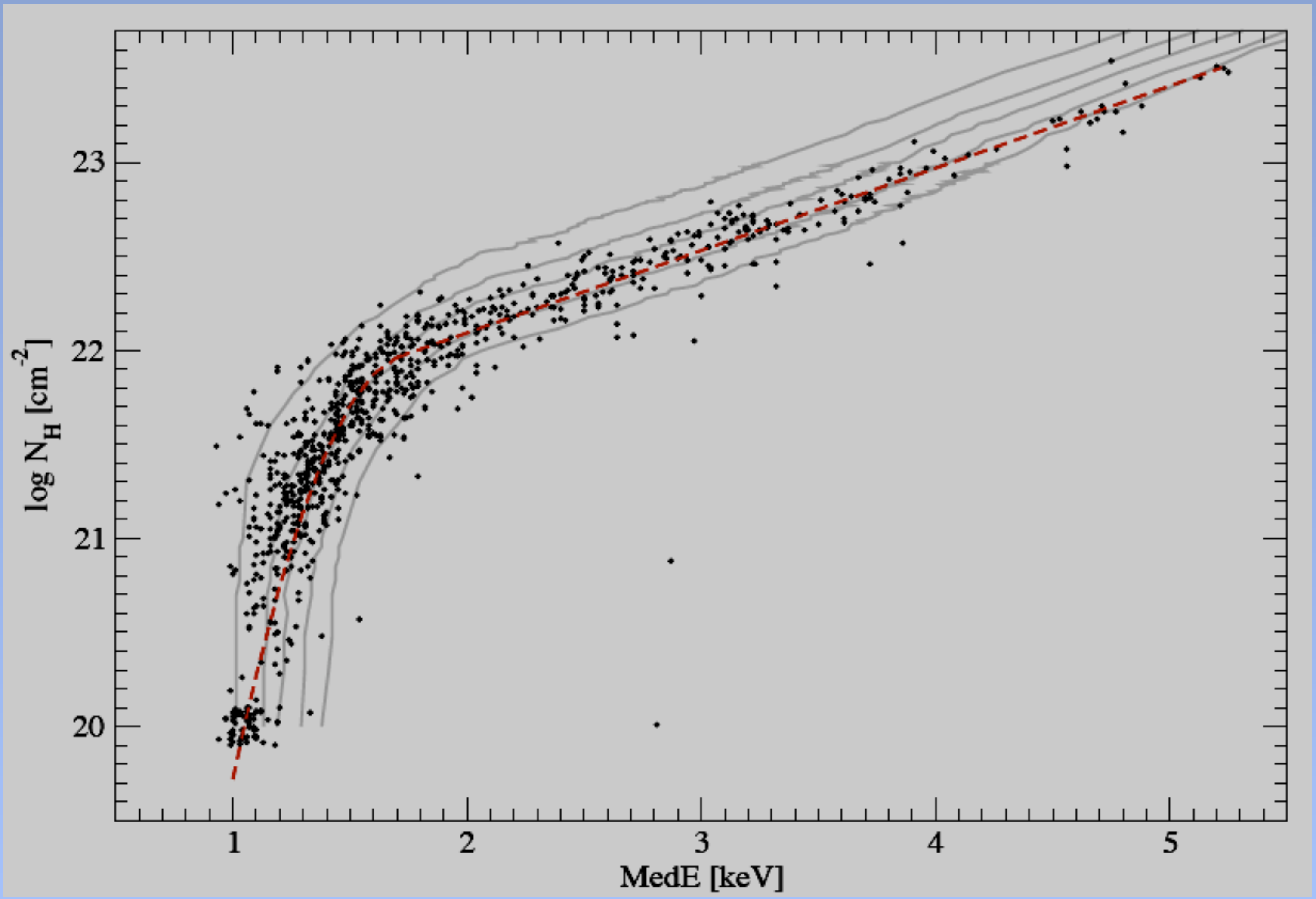
~20 papers 2005-7

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)

Median energy of extracted photons is an excellent measure of absorption in star forming regions



Dots:
COUP stars

Grey lines:
Simulated thermal spectra

Feigelson et al. 2005

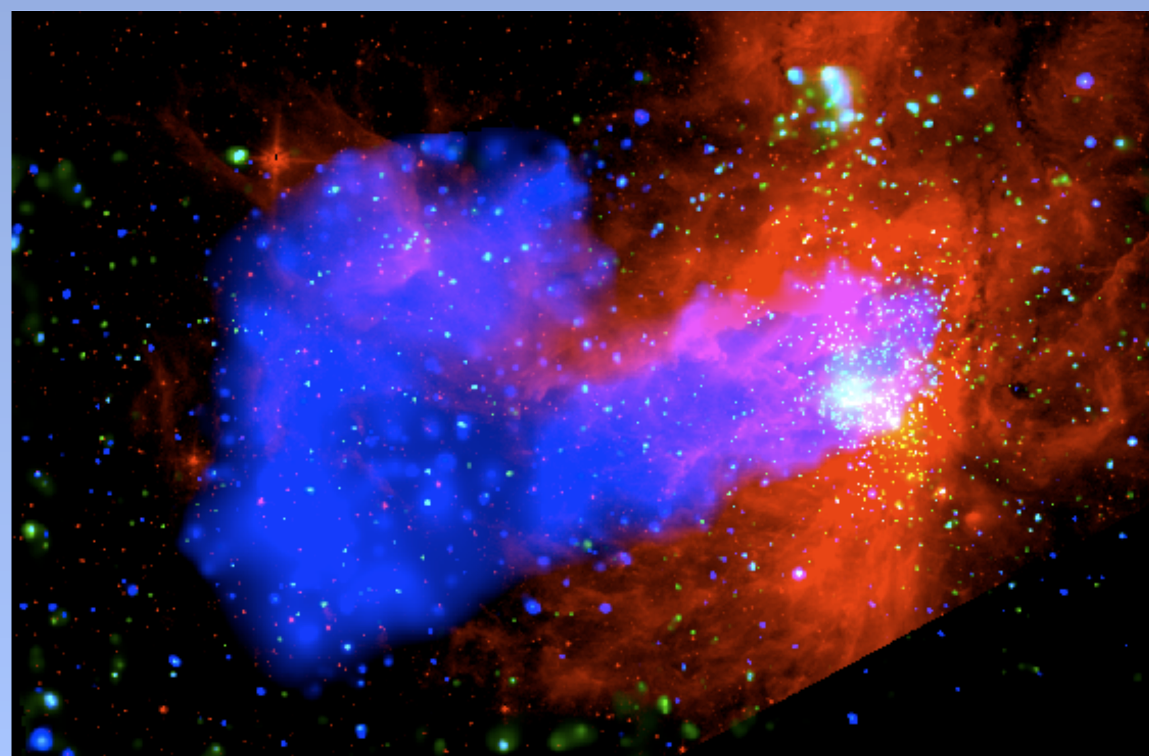
Recall $A_V = N_H / 1.6\text{-}2 \times 10^{21}$ $A_K = 0.1\ A_V$

Vuong et al. 2002

Messier 17: A nearby high mass star forming region

2MASS JHK shows stars & heated gas

Hubble Space Telescope reveals only heated gas



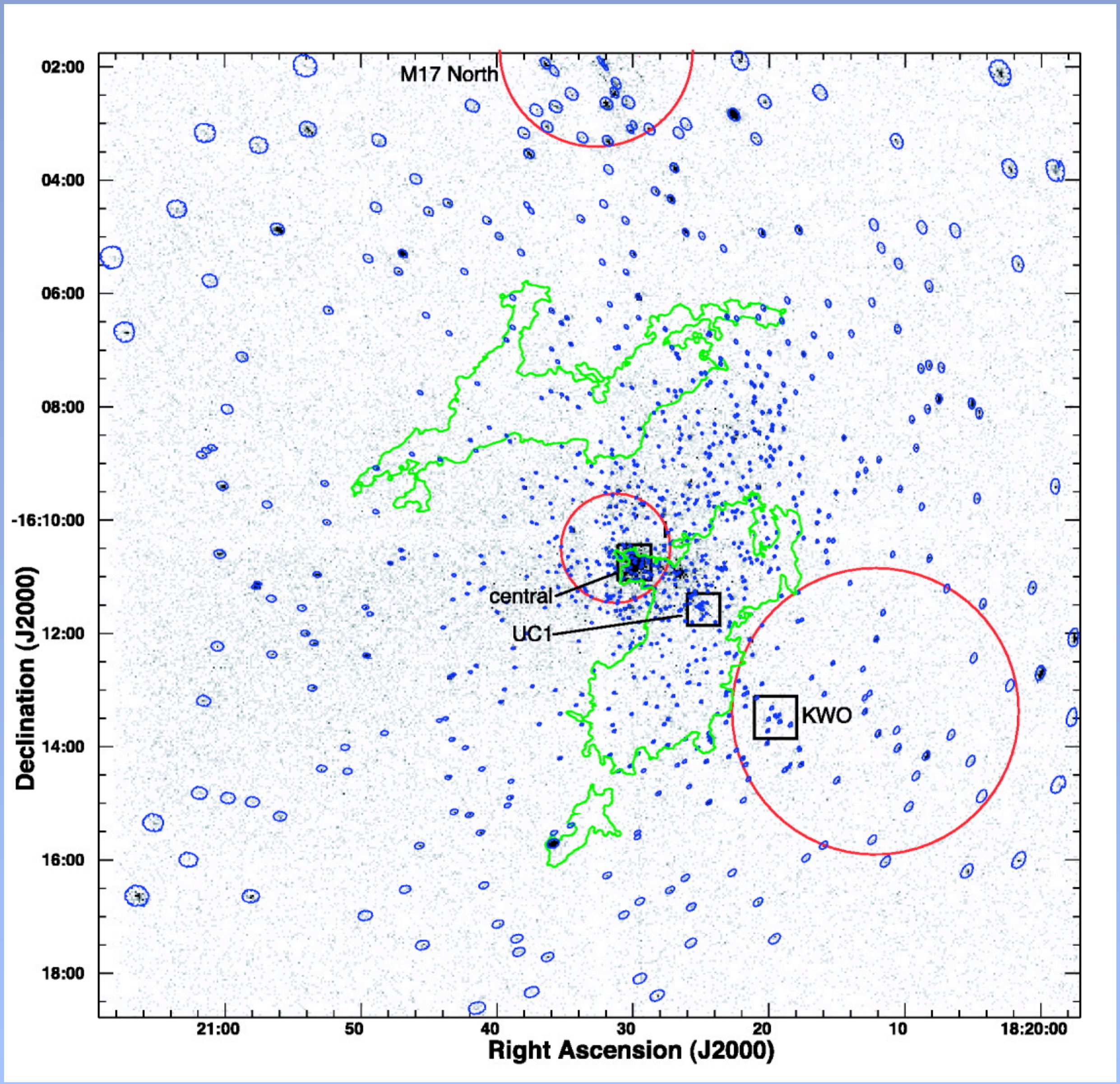
Red: Spitzer 8um shows heated dust & disky stars

Blue: Chandra 0.5-8 keV shows flaring stars & OB winds

Townsley et al. 2003

Broos et al. 2007

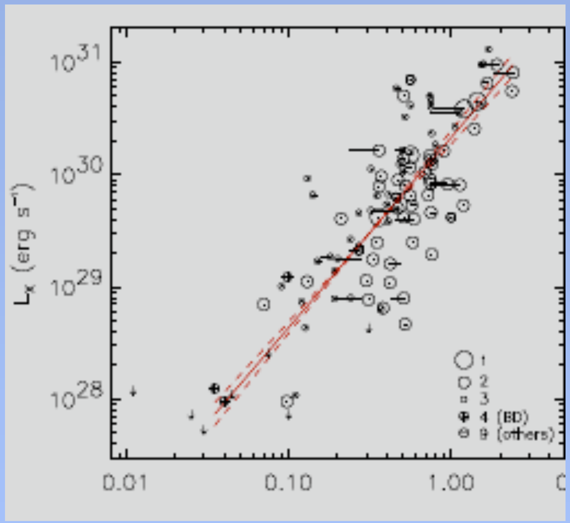
M17 in the X-ray band



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

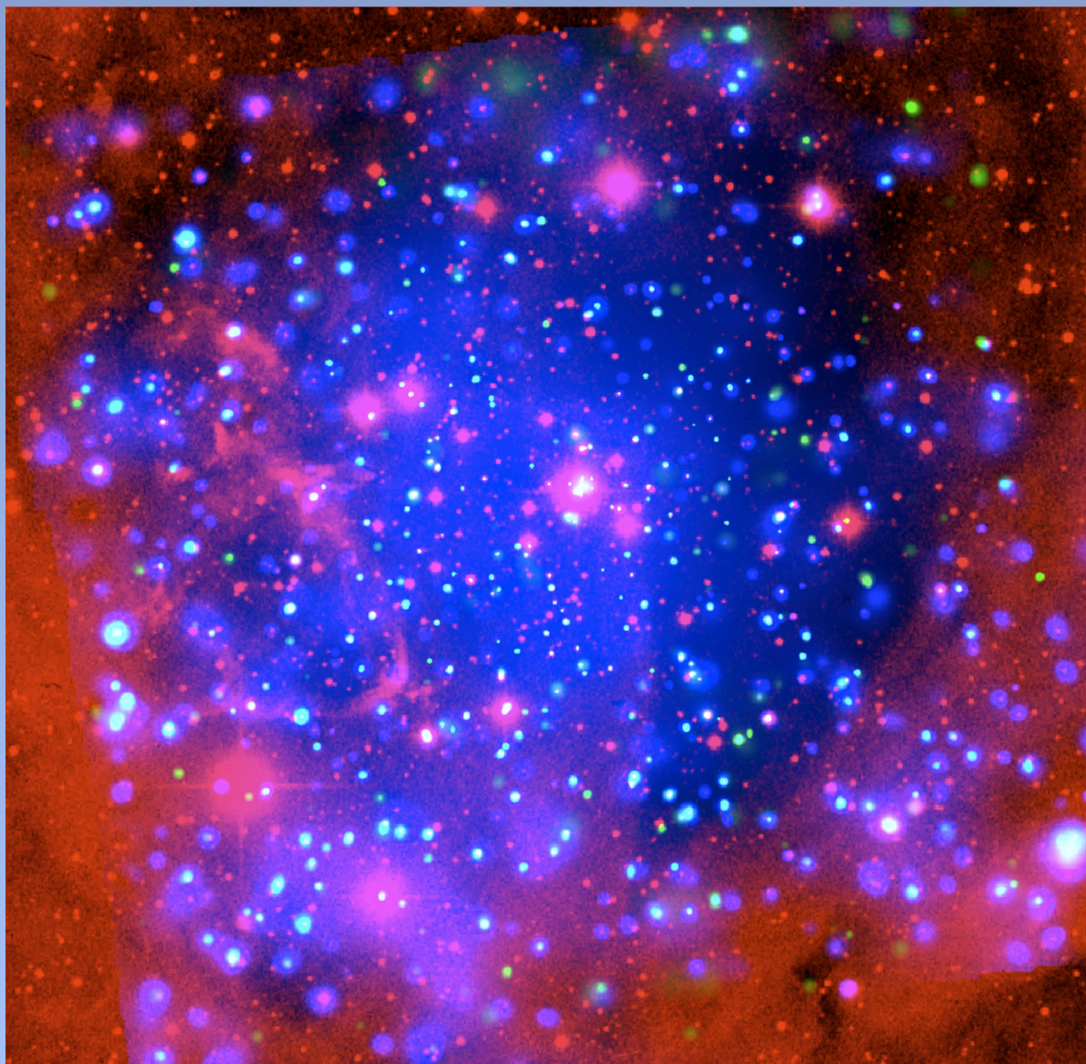
(Broos et al. 2007)

L_X-Mass relation in Taurus



Telleschi et al. 2007 XEST

The Rosette Nebula & NGC 2244 cluster



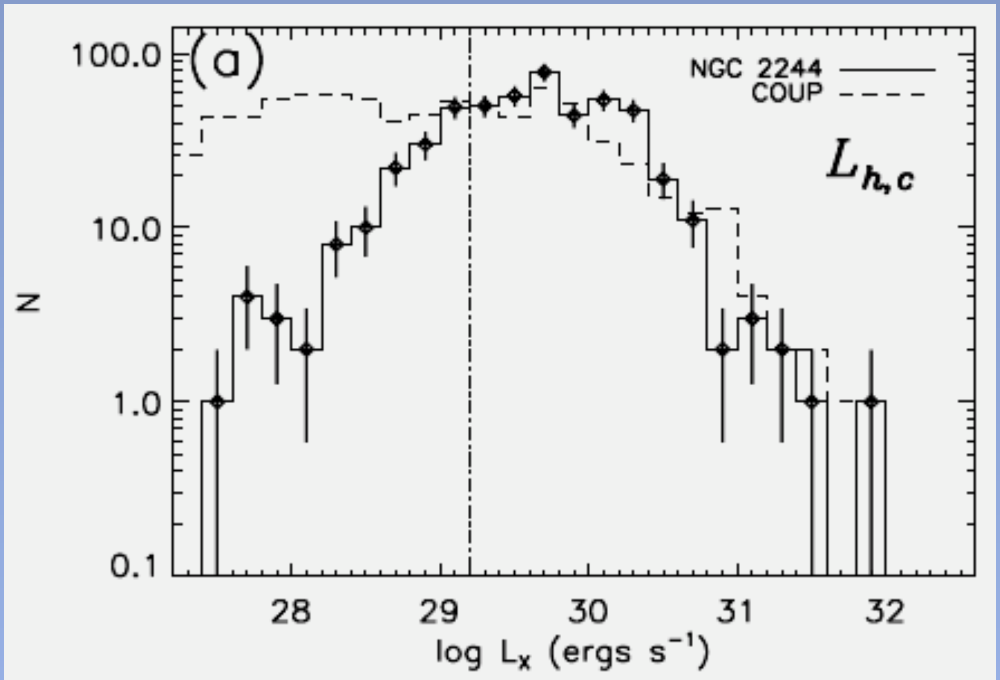
Annular HII region on edge of RMC

D~1.4 kpc

Mosaic of 5 Chandra fields

(Wang et al. 2008, 2009ab)

Blue = Chandra sources & diffuse emission Red = DSS stars & $H\alpha$

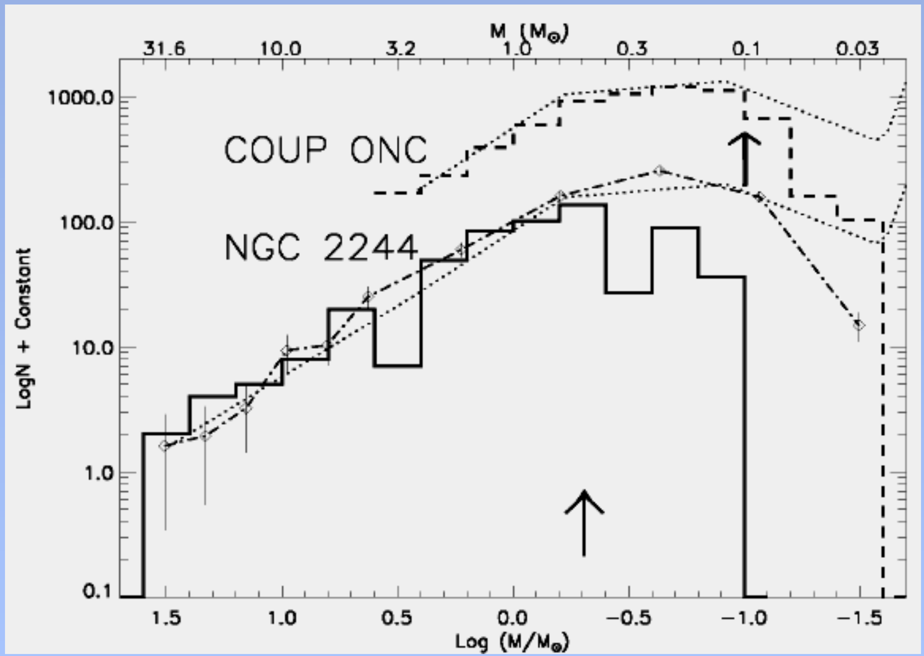


Rosette XLF & IMF resembles ONC. Not top-heavy IMF, as previously reported.

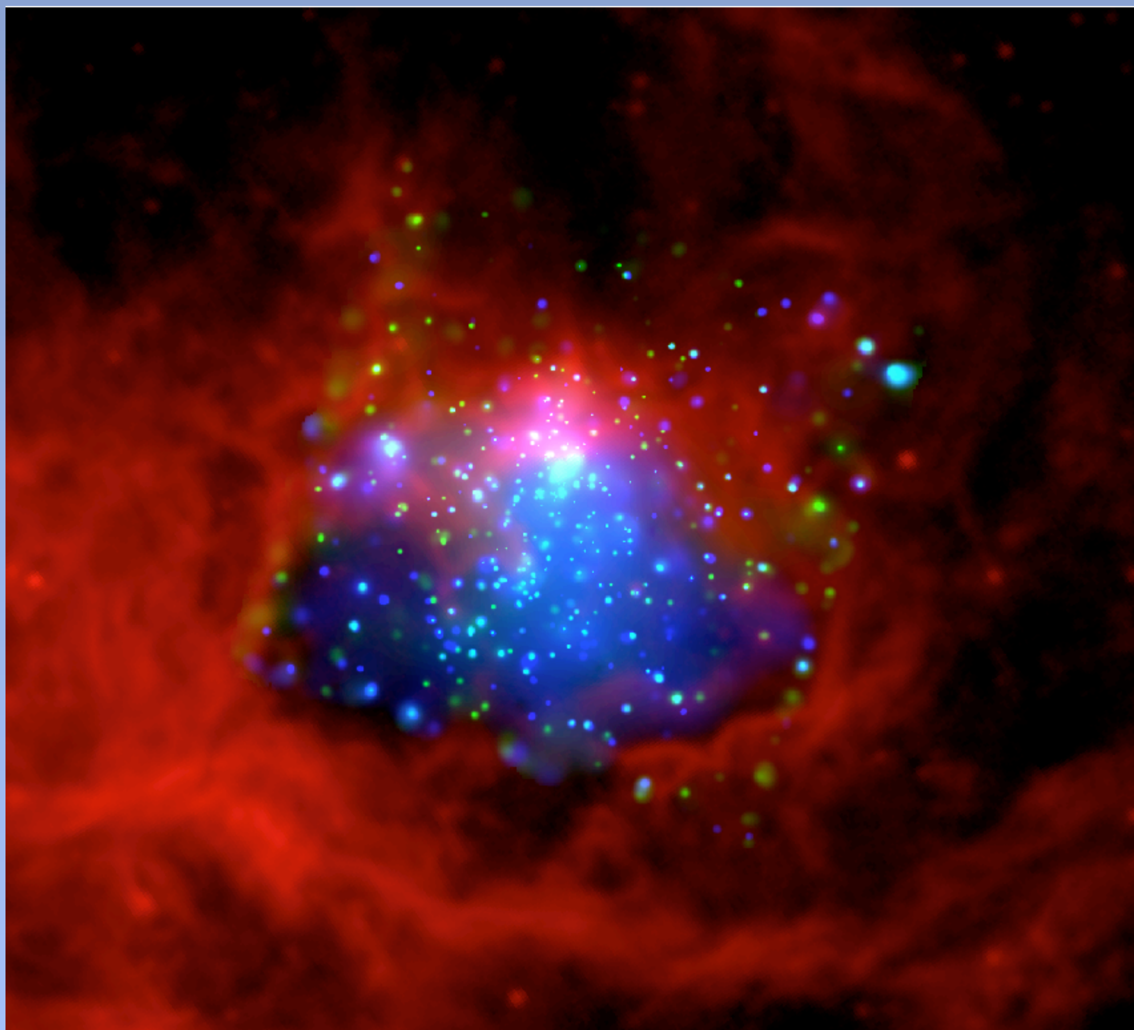
NGC 2244 population = 1.2 x ONC
But with O4+O5 stars vs. O7 in ONC

X-ray sample --> KLF --> IMF (histogram) agrees with IMF from background-subtracted KLF (dot-dash)

Wang et al. 2008



NGC 6357 and its cluster Pismis 24



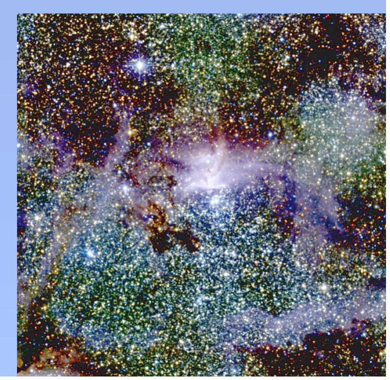
Wang et al. 2007 Red=MSX 8μm Blue=0.5-2 keV

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

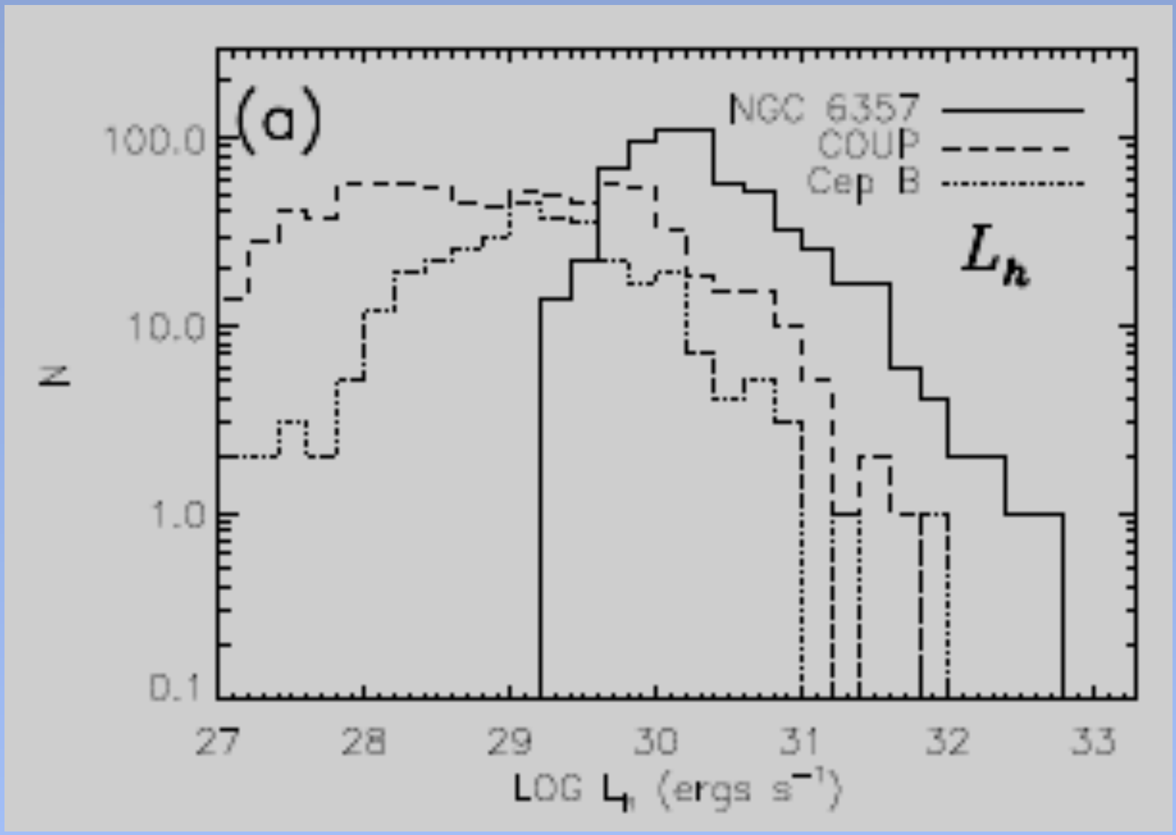
Chandra reveals ~800 low-mass members & doubles OB population. Soft diffuse X-rays fills IR cavity.

Cluster off-center from HII region: 2 generations?

2MASS



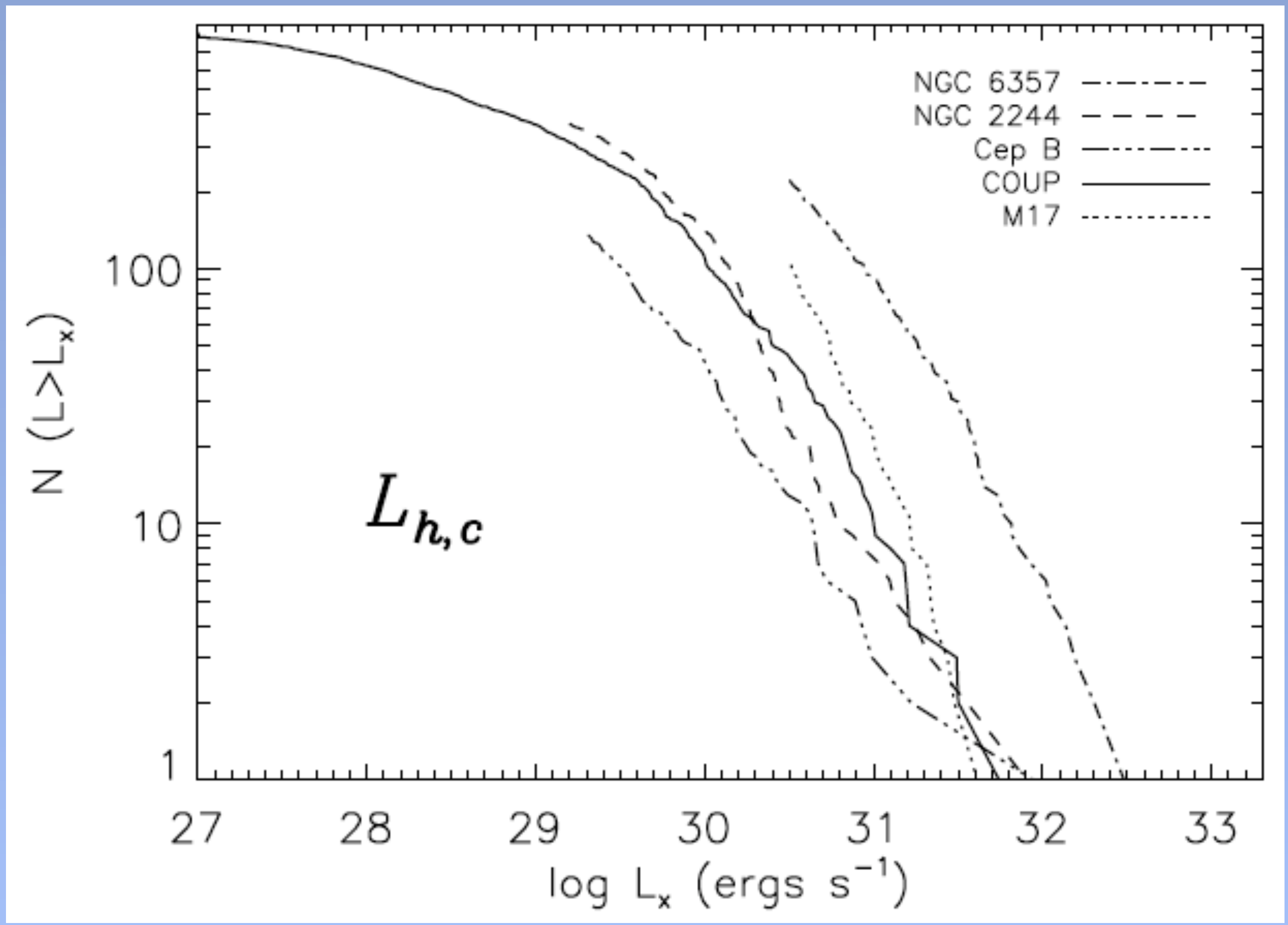
NGC 6357 XLF has same shape as ONC, implying same IMF
Stellar population is 5x ONC (10,000 stars)



Wang et al. 2007

XLF comparisons

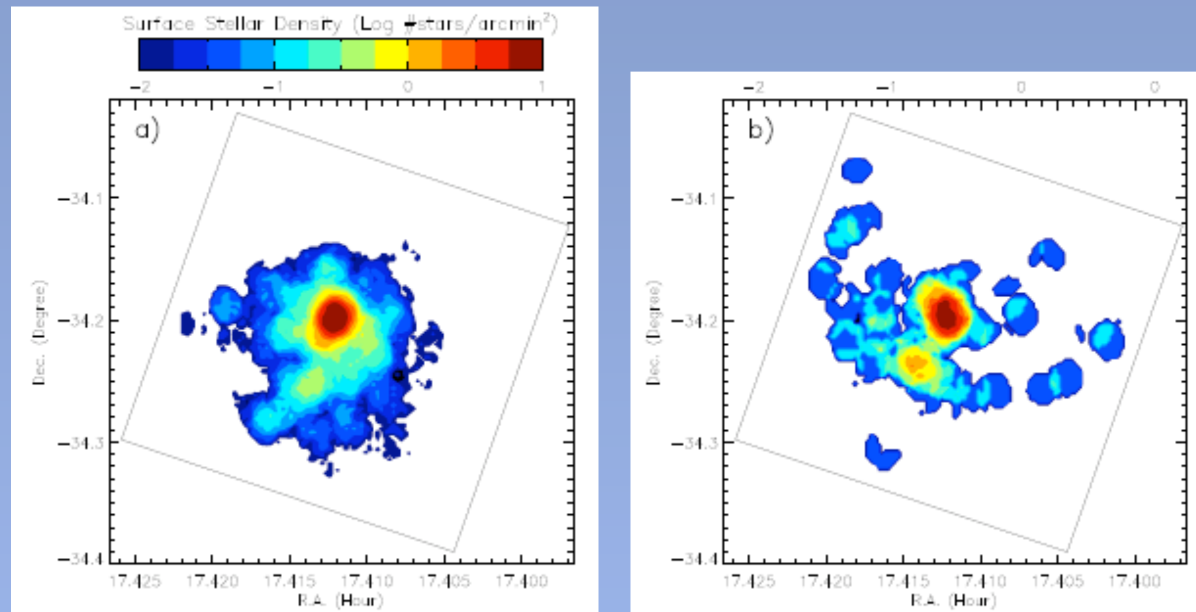
(some clusters show subtle IMF differences?)



Getman et al. 2006
Wang et al. 2008

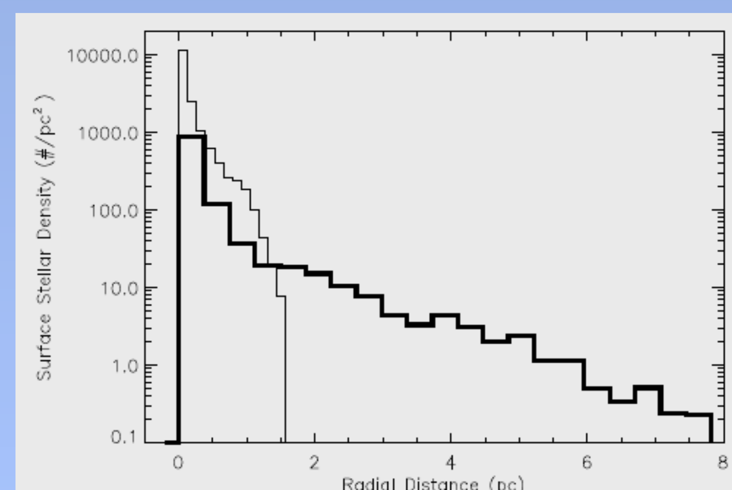
Structure of NGC 6357

Main cluster is spherical
Secondary cluster at center of bubble?



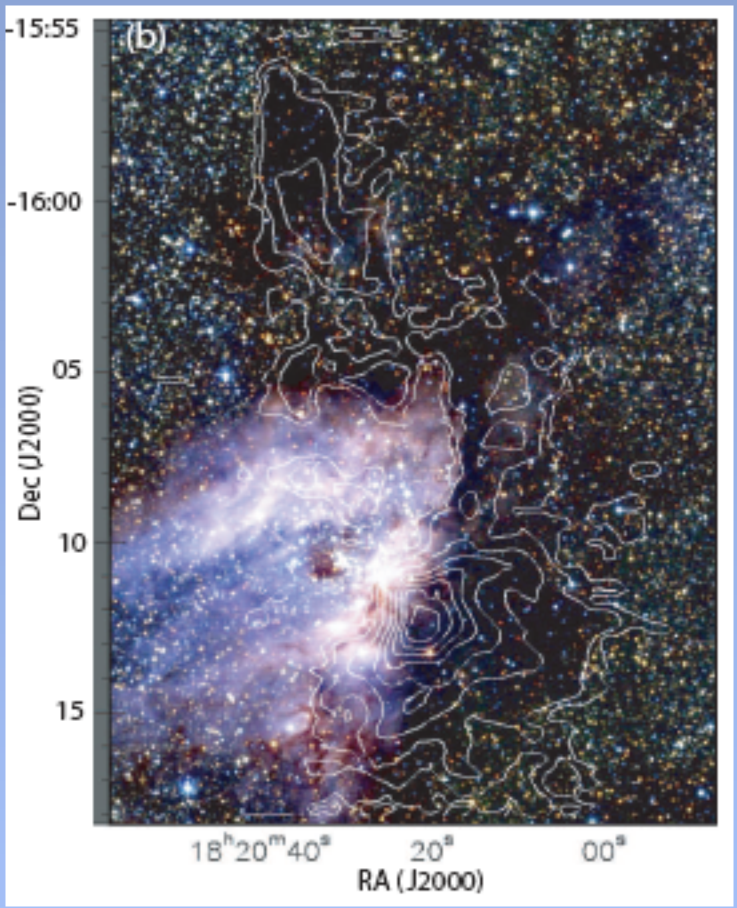
Stellar surface density
(10^3 range)
Left: $A_V < 5$
Right: $A_V > 5$

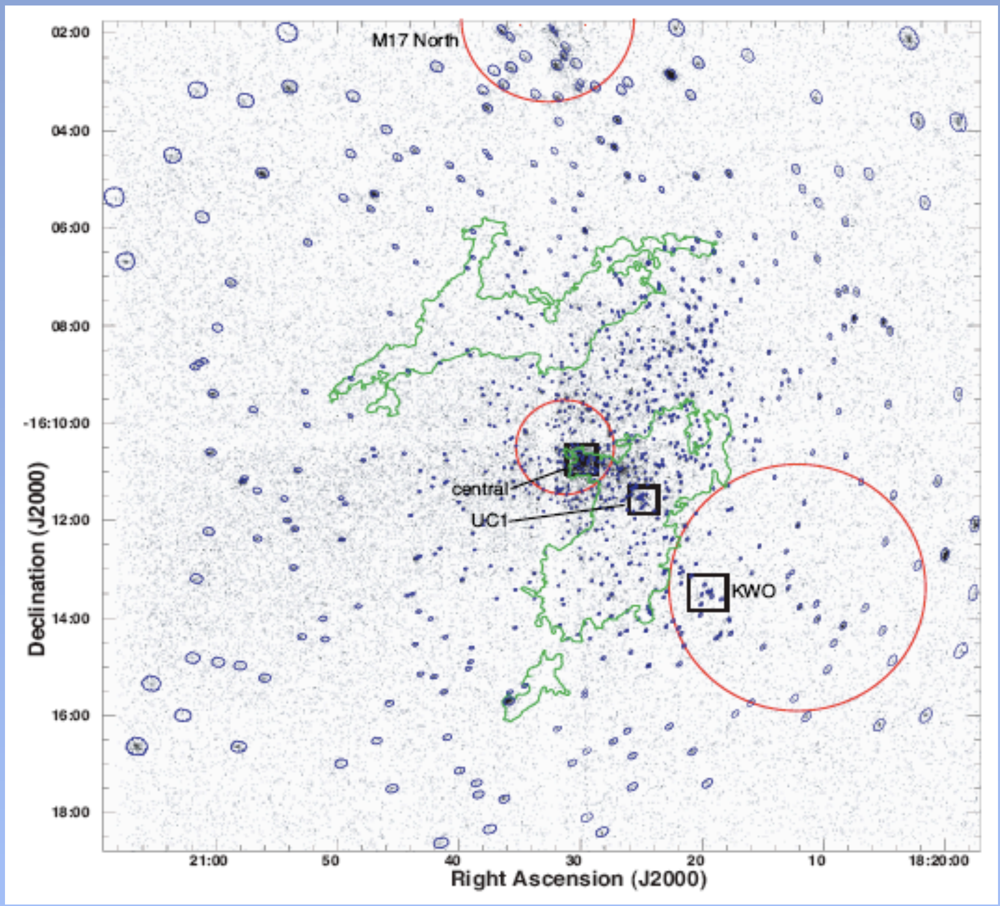
Radial profile shows cluster is much larger than ONC



Wang et al. 2007

Messier 17 & its cluster NGC 6618





2MASS + CO contours

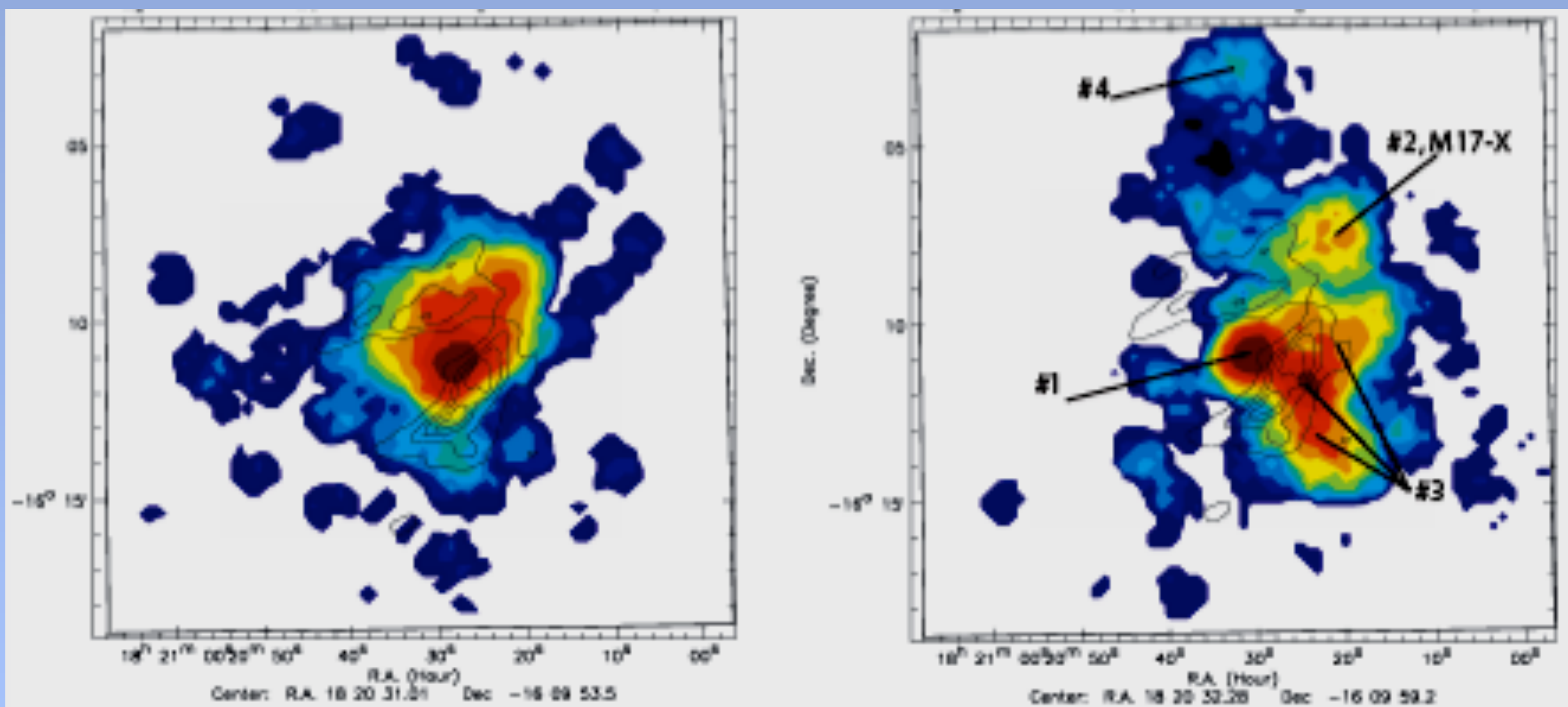
Chandra field & 886 sources

Broos et al. 2007

Embedded cluster substructure in M17

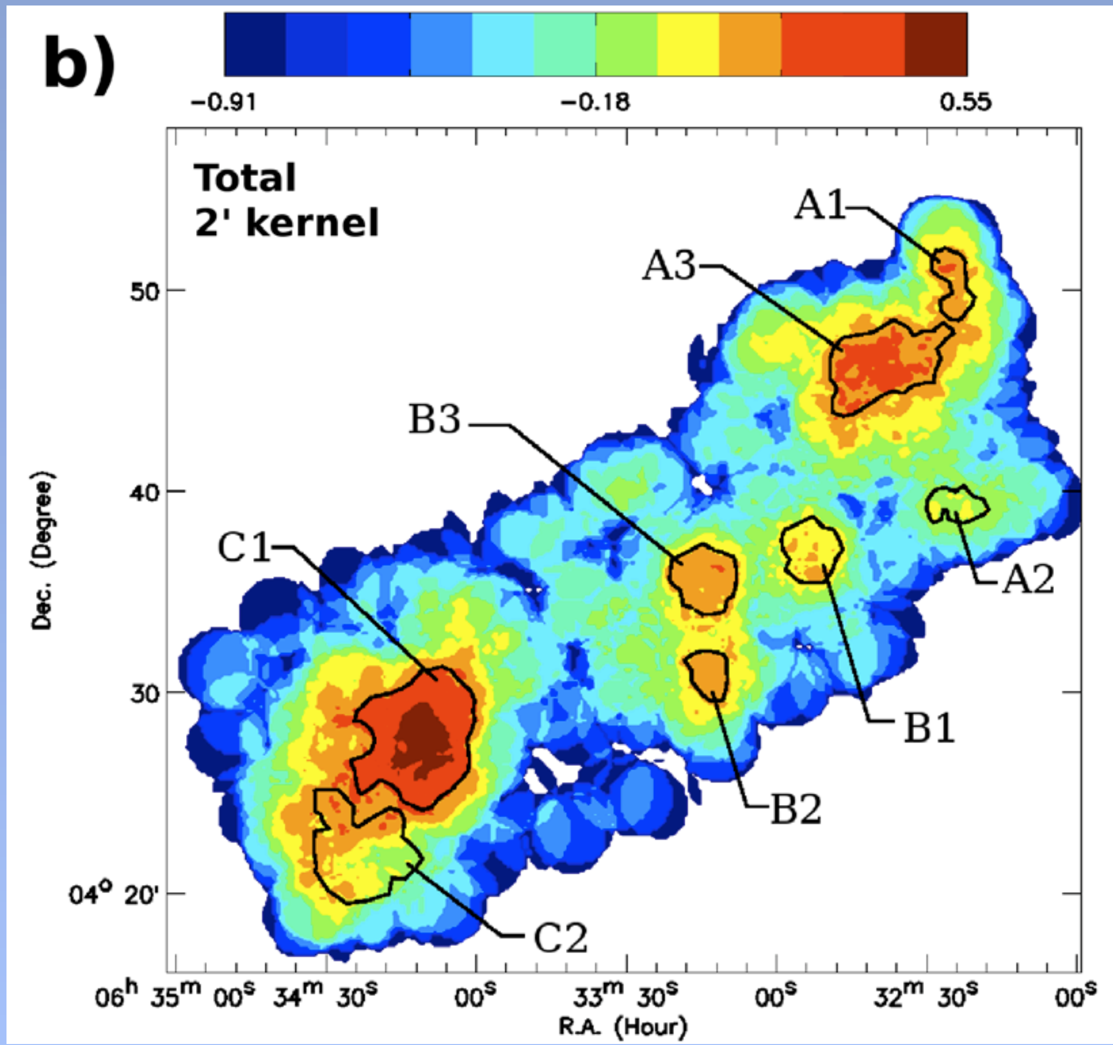
Lightly obscured central
NGC 6618 cluster
Is roughly spherical

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
No major clusters around embedded UCHIIs



Broos et al. 2007

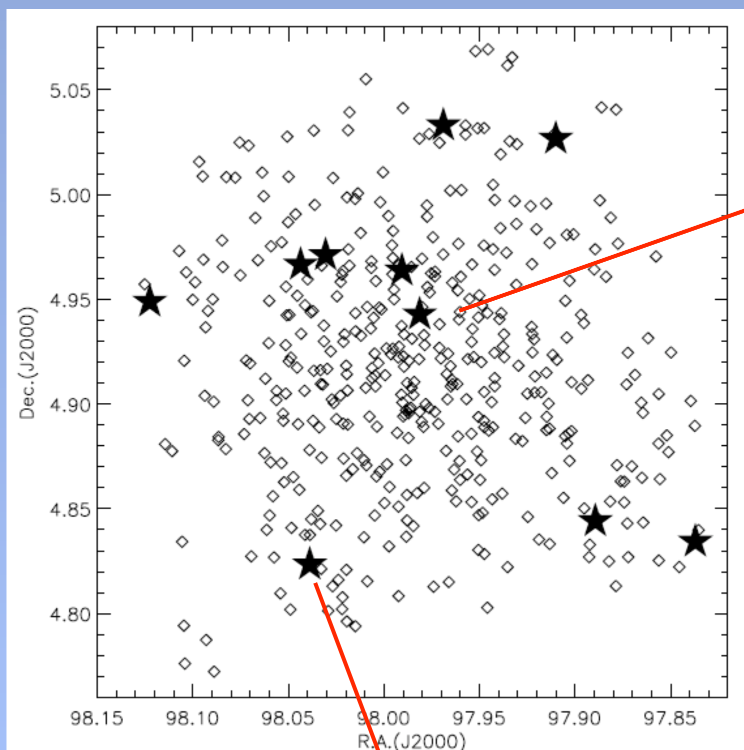
Stellar subclustering in the Rosette Molecular Cloud



Wang et al. 2009

The remarkable O stars in Rosette central cluster

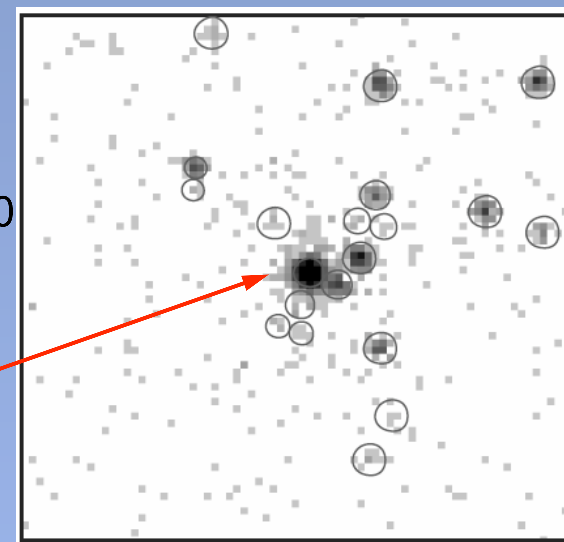
High-mass and low-mass spatial distributions are indistinguishable
No mass segregation !!



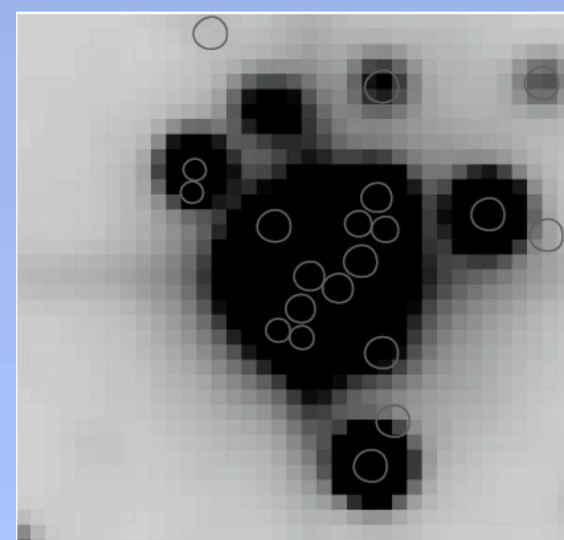
O4 star HD 46223 is isolated

Vicinity of O5 star HD 46150 has 50 star subcluster

30” (0.2 pc)
Chandra

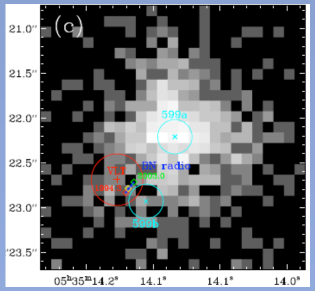


2MASS



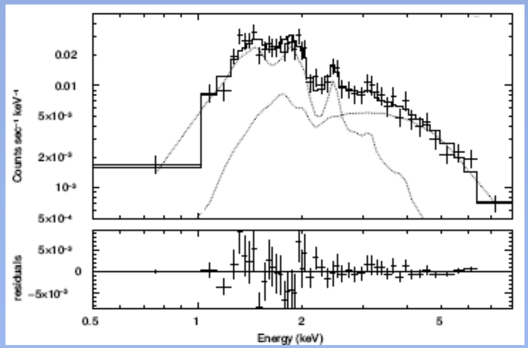
X-ray windows into OB star multiplicity
future clues to the dynamical origin of massive stars?

- Chandra effectively locates low mass stars near OB stars



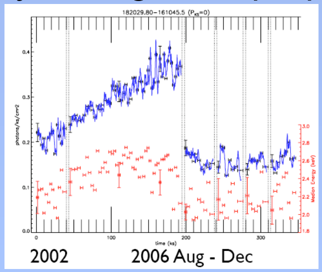
X-ray bright companion 1.1” (500 AU) from BN Object (Grosso et al. 2005)

- 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)

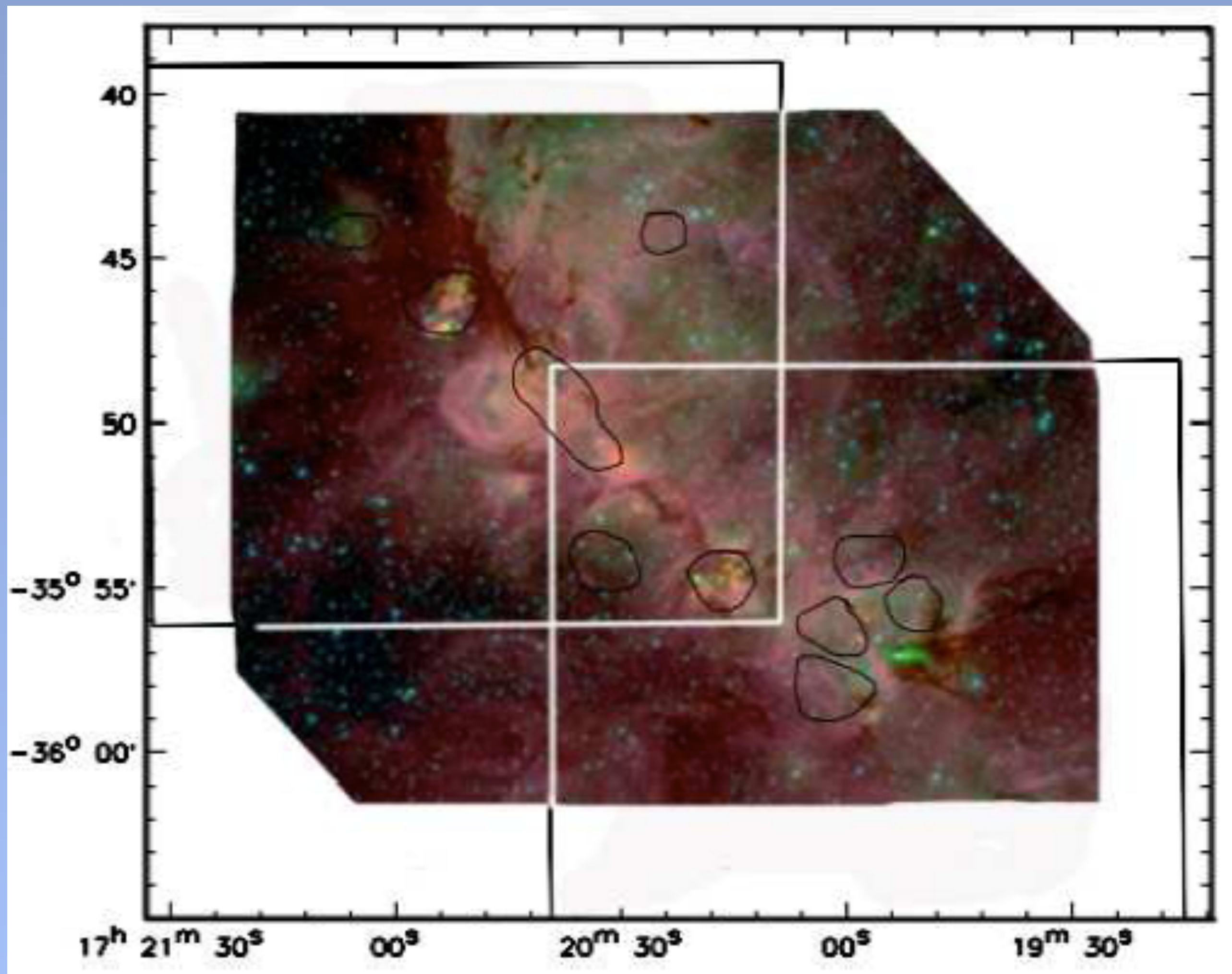
- Unexpected O star X-ray variability may indicate eccentric binary



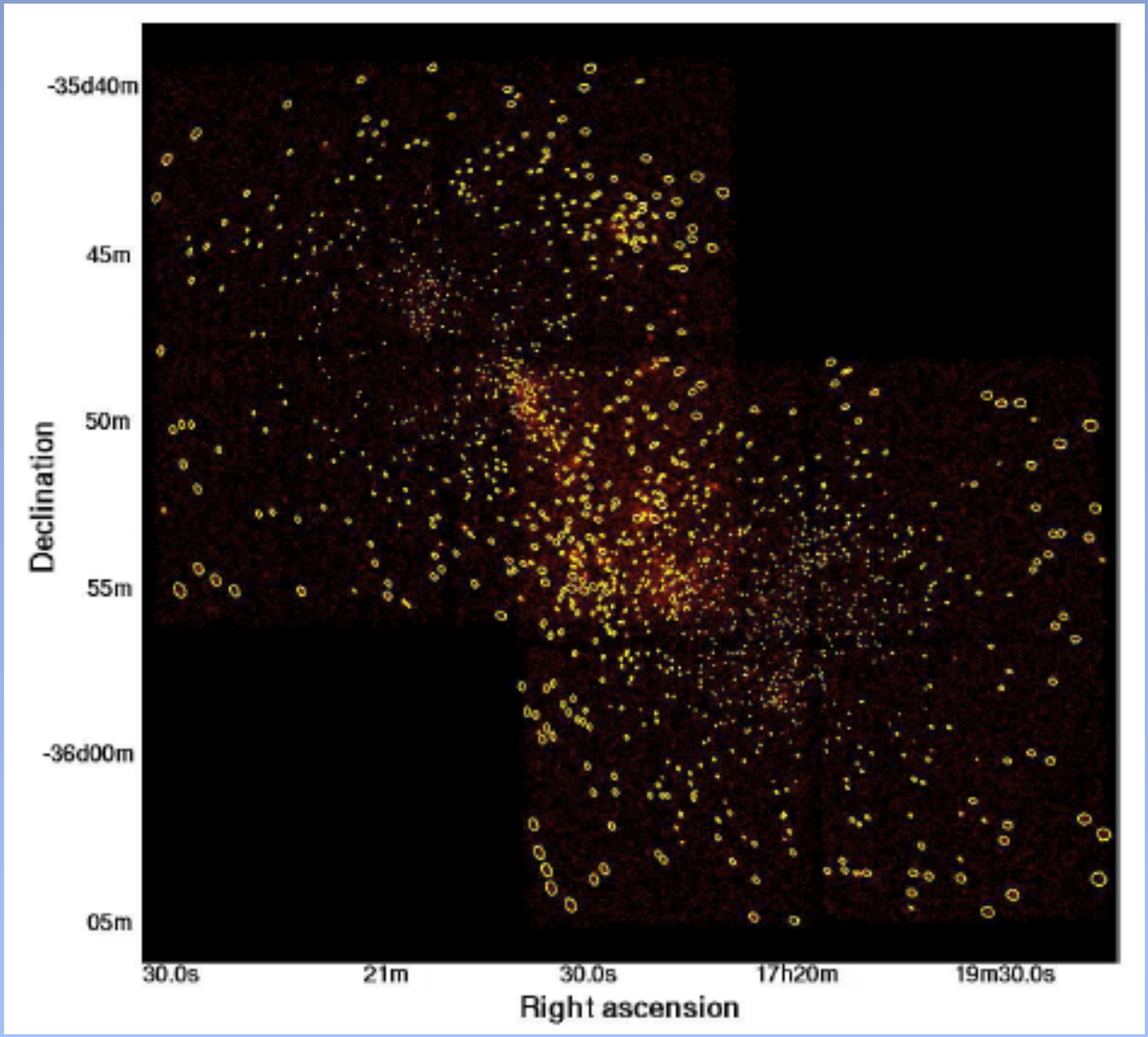
NGC 6334: A complex of very young SFRs

Map: Spitzer IRAC

Boxes: Chandra fields



Feigelson et al. 2009 (see also Ezoe et al. 2006)



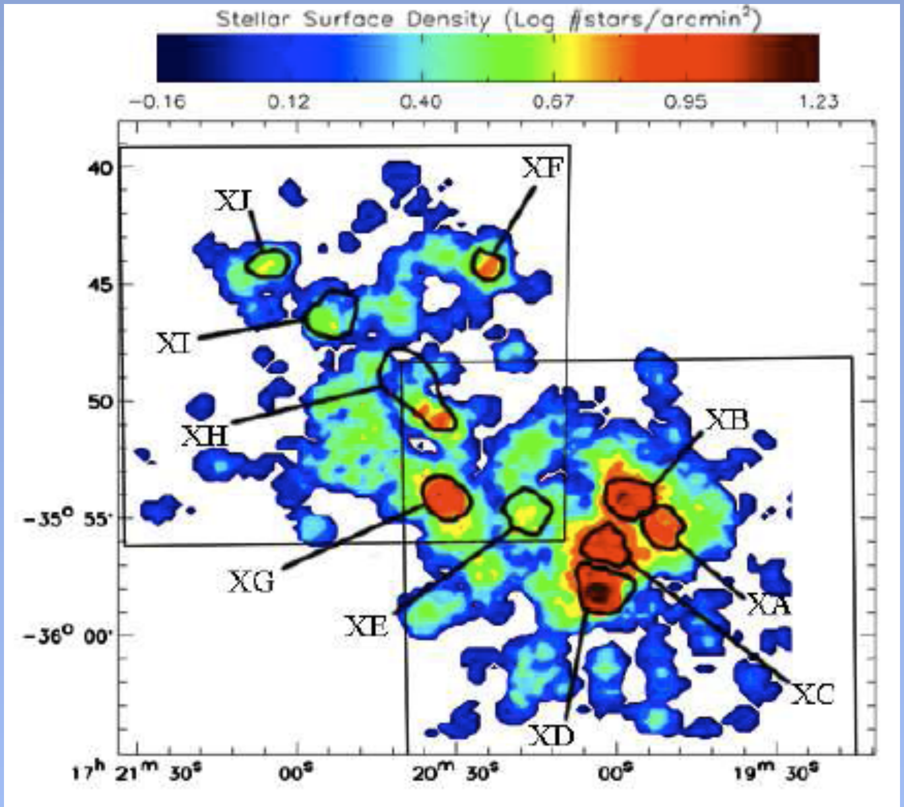
1607 X-ray sources found most with 3-10 counts

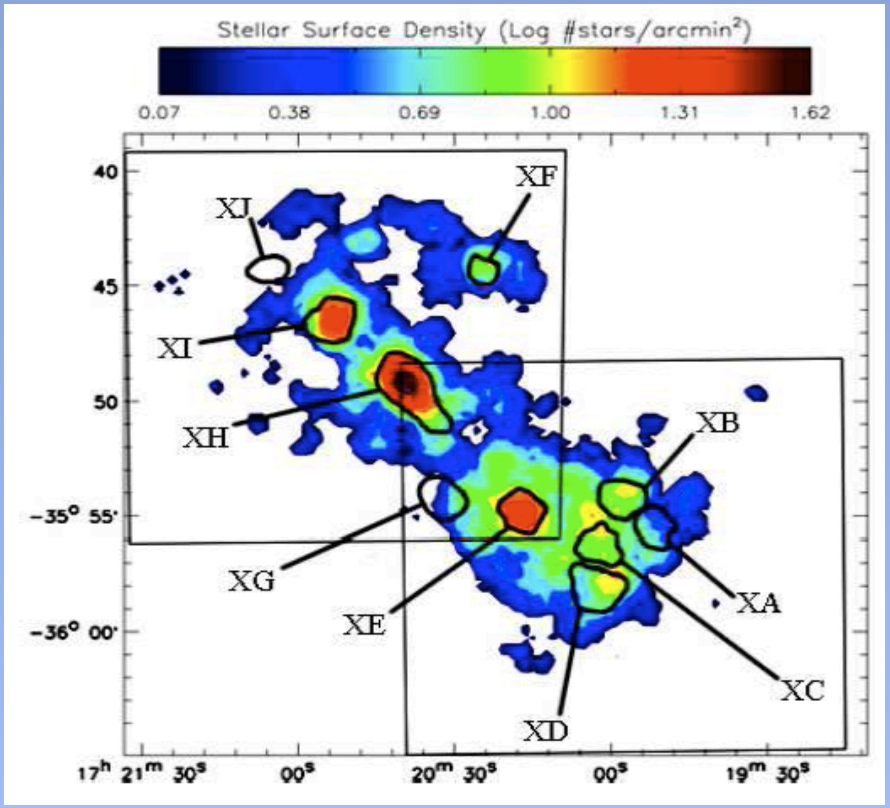
~5% expected contaminants

Some sources have extraordinary absorption, E_{med} ~ 6 keV

Feigelson et al. 2009

Distinct star clusters seen at low and high obscuration



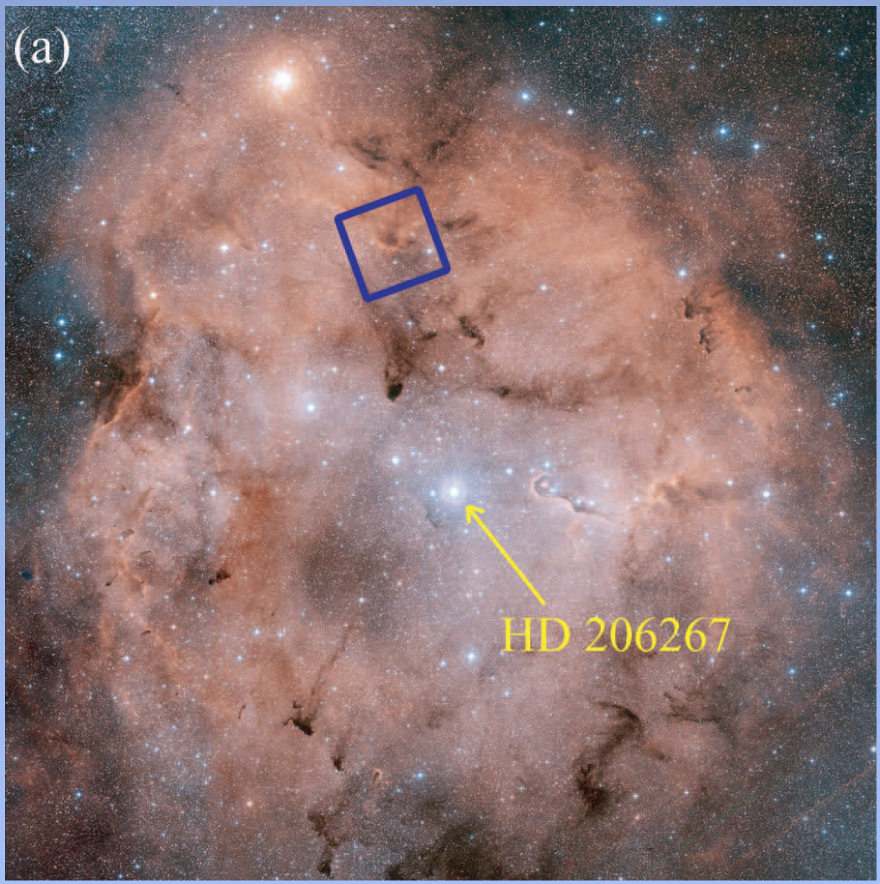


E_{med} < 2.5 keV **(A_V ~ 10 mag)** **E_{med} > 2.5 keV**

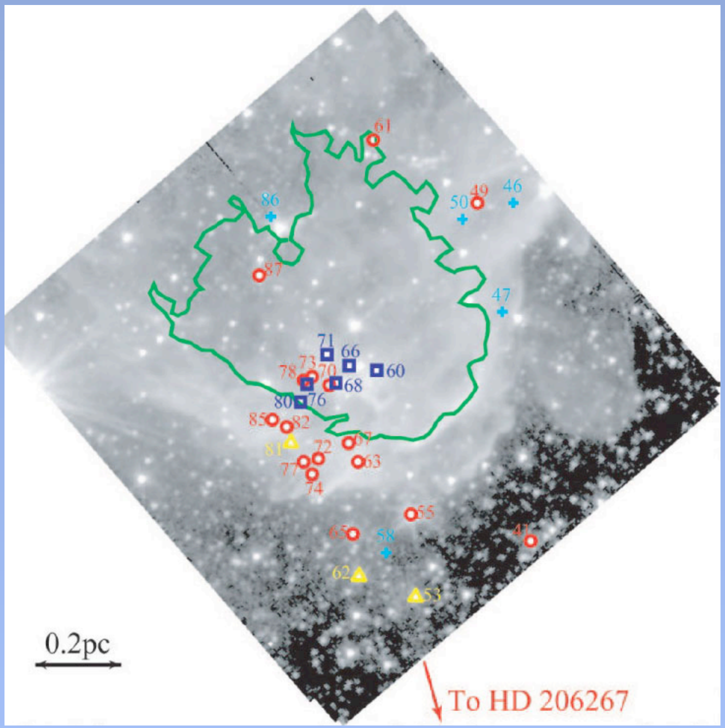
Feigelson et al. 2009

More triggered populations

Bright-rimmed cloud IC 1396N



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

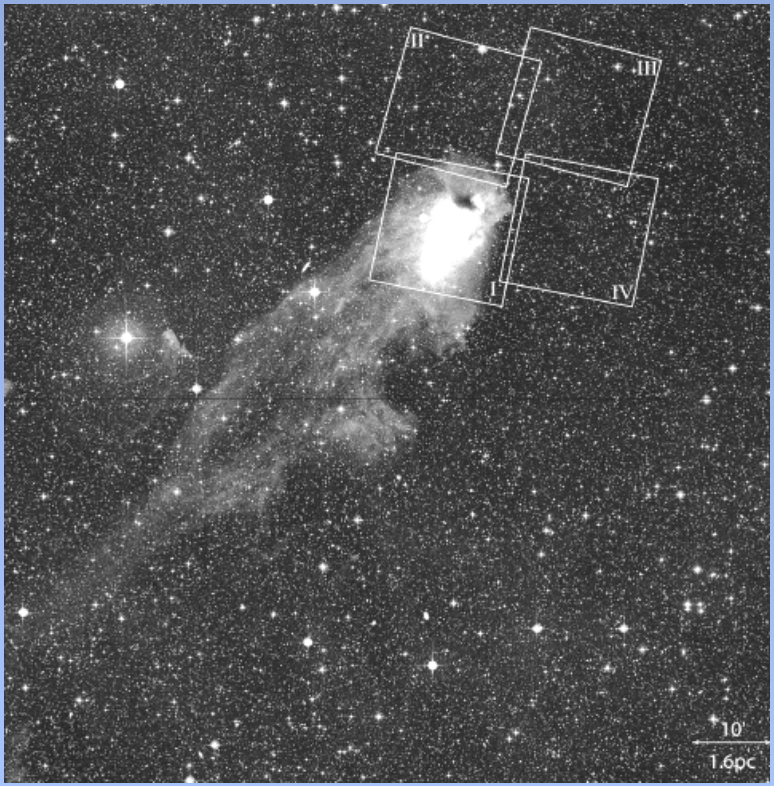


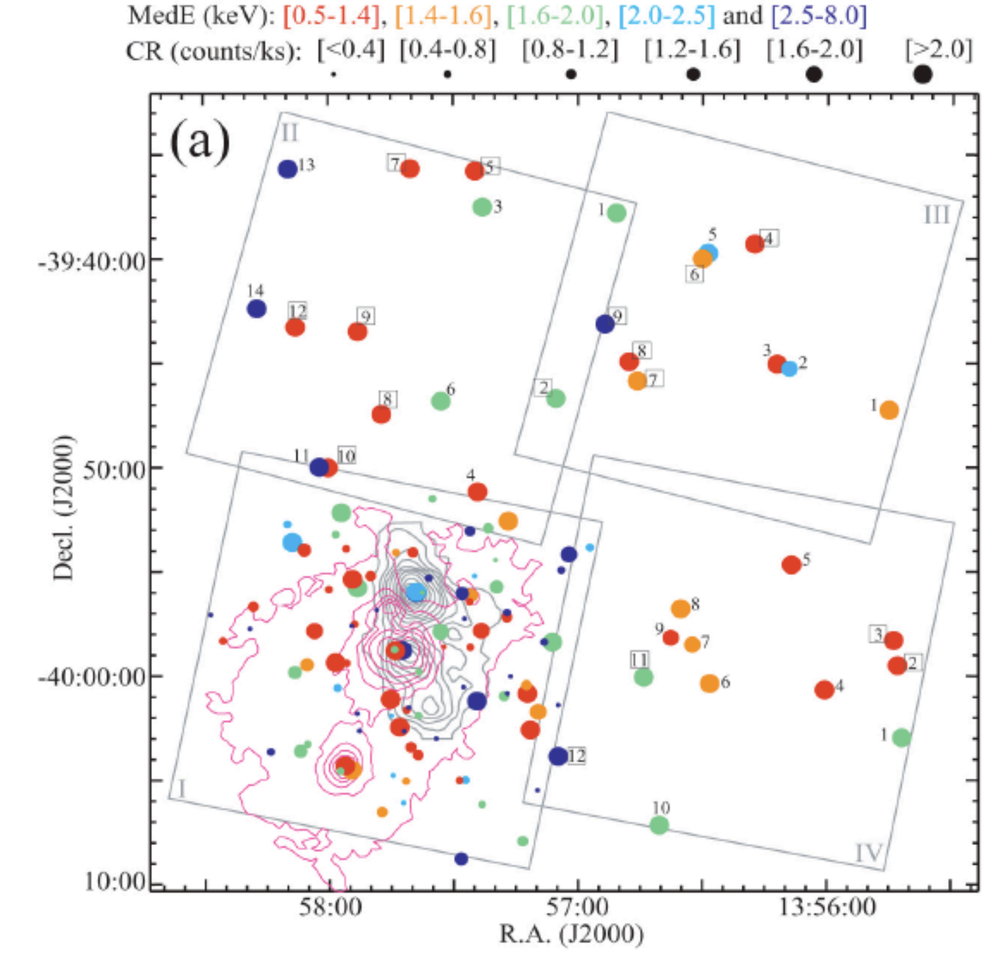
Spatial-age sequence agrees with radiation-driven Implosion model for triggered SF in BRCs

Getman et al. 2007a

The mysterious high-latitude cometary globule CG 12

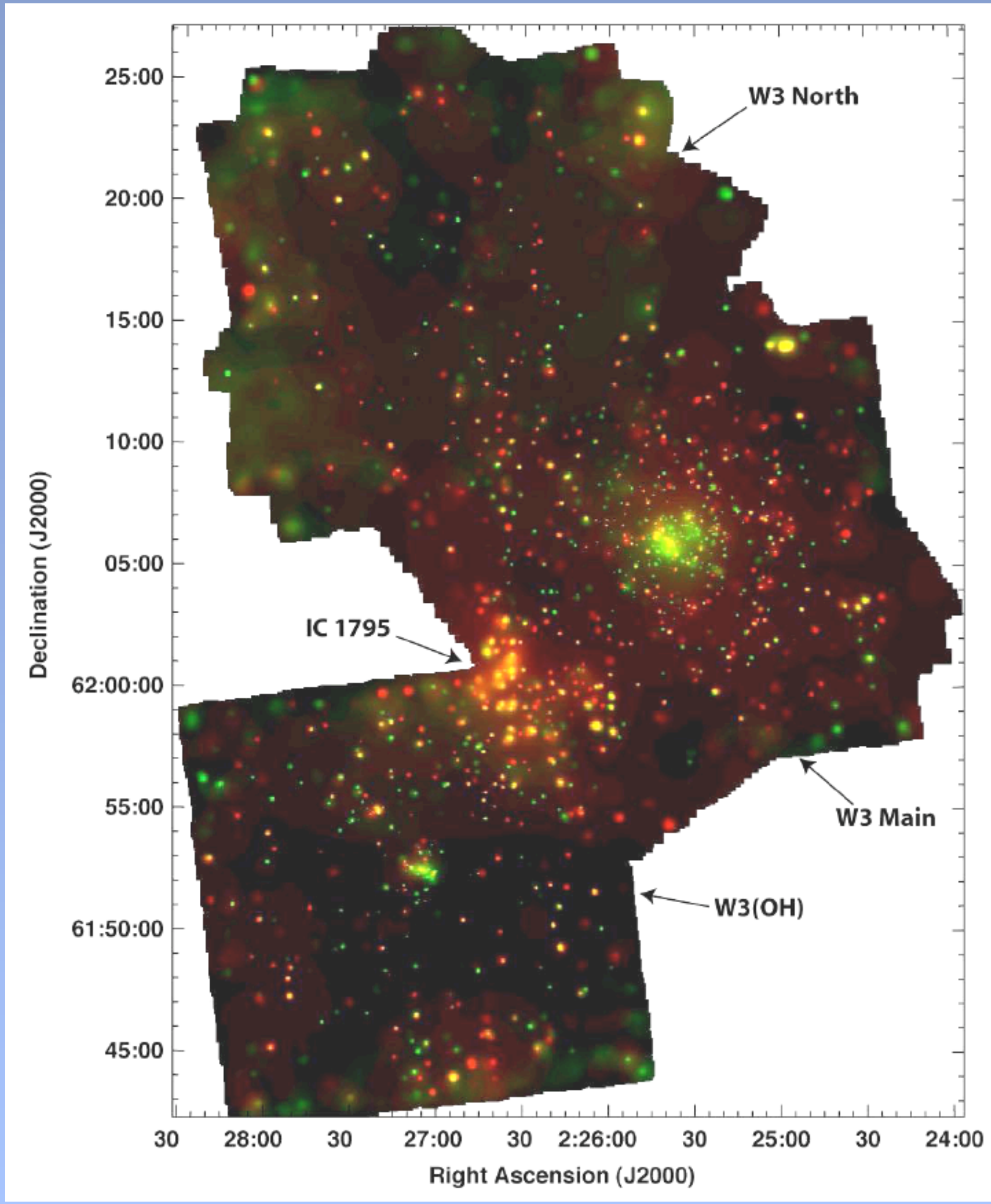
Chandra finds large, dispersed pre-main sequence population with wide age spread





Getman et al. 2007b

The remarkable case of Westerhout 3



Feigelson & Townsley 2007

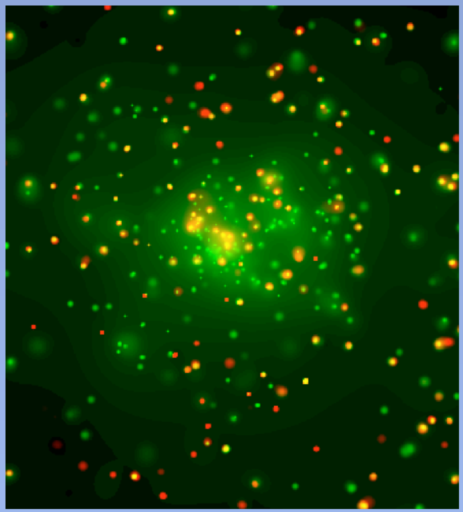
Chandra stars on the Spitzer map

ACIS Townsley et al., in prep

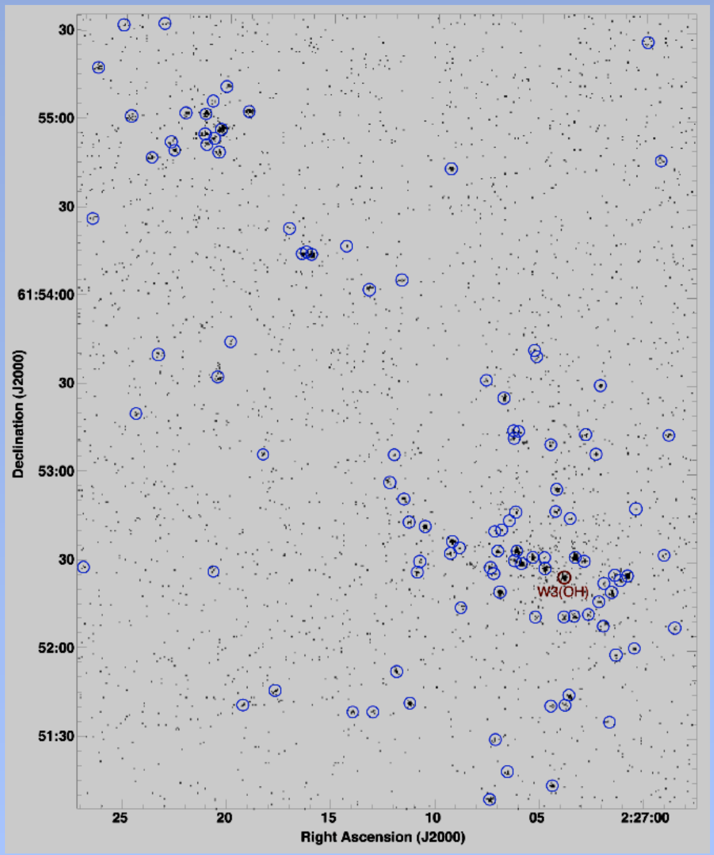
IRAC Ruch et al. 2007

The diverse populations of W3

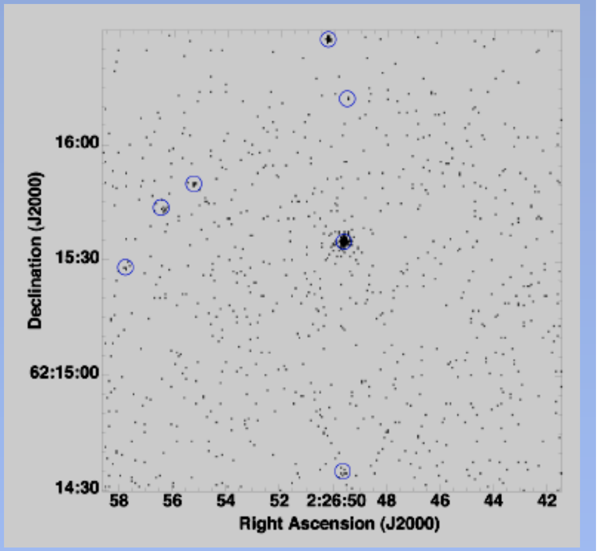
W3 Main
rich, ~900 stars
spherical



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)

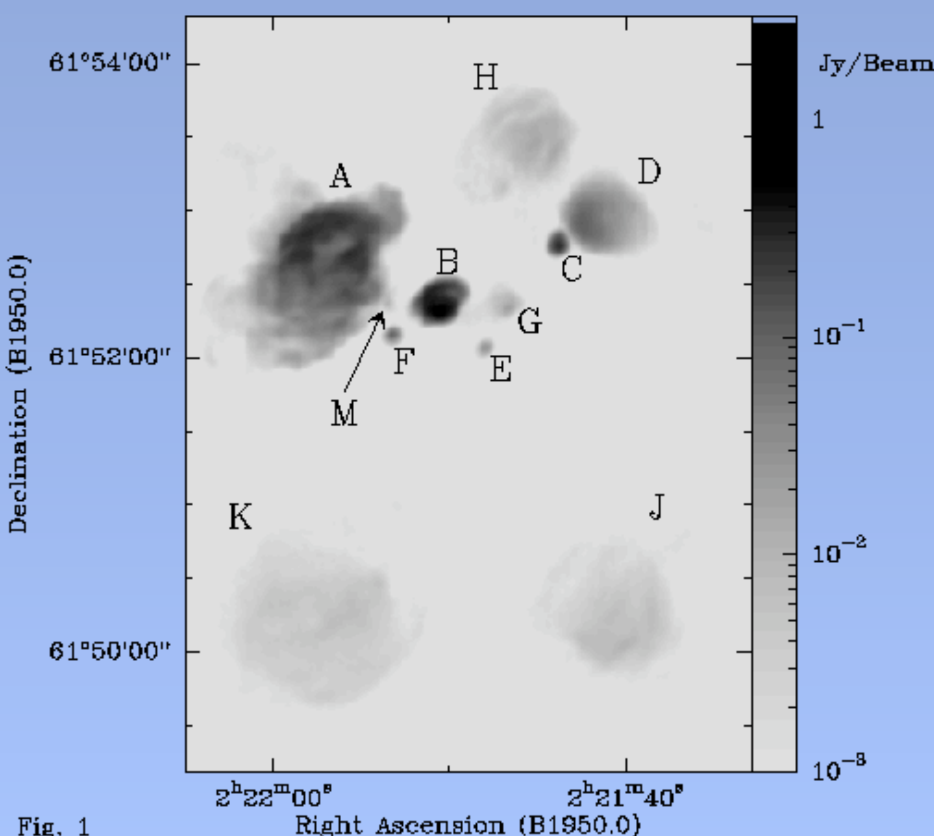
W3 North consistent with young runaway (t~10^5 yr): Not sparse cluster (Parker & Goodwin 2007)

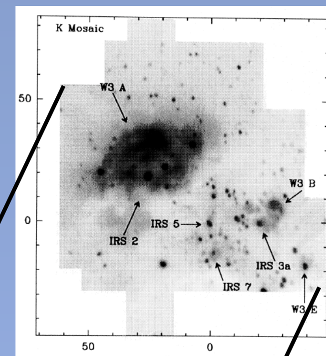
Feigelson & Townsley 2008

Multiwavelength views of W3 Main central region

0.5 pc

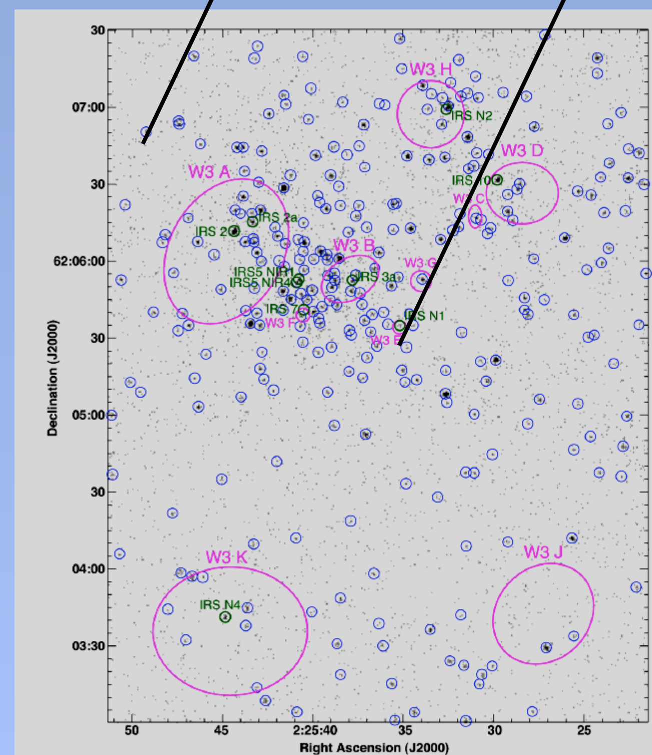
VLA radio   Tieftrunk et al. 1997





K band

Megeath et al. 1996



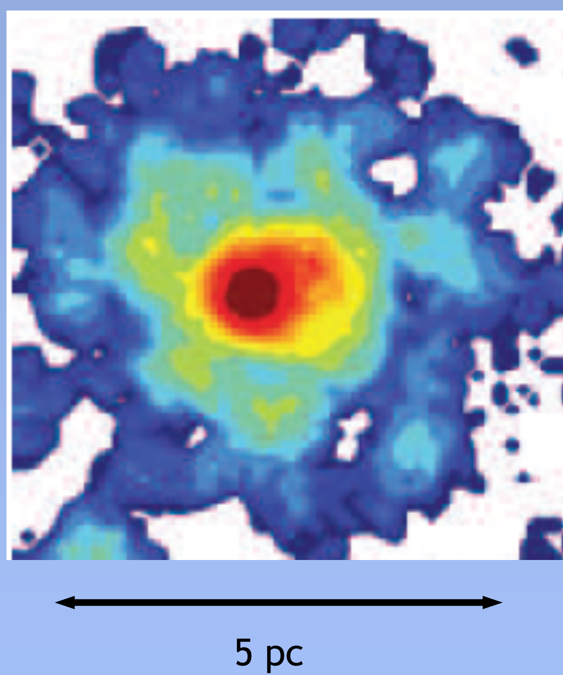
Chandra

Feigelson & Townsley 2008

Chandra constraints on the formation of W3 Main

Large-scale structure of W3 Main

smoothed Chandra source distribution



• Large, spherical morphology of W3 Main does not support triggering from IC 1795 shock. (Oey et al. 2005). Instead it implies slow 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 the 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-rays give an unexpectedly rich view of young stellar clusters, complementing 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 !

Chandra X-ray observations have been obtained for several dozen rich young stellar clusters with >20,000 PMS stars. Many should be reobserved with 10x original exposure.

High-quality Near-IR observations are needed for many clusters; 2MASS is inadequate beyond d~1 kpc. IR study is difficult due to field star and nebular contamination

Optical/NIR spectroscopic observations of X-ray/NIR stars needed for accurate masses, ages, velocities, accretion, …

Theory needed to explain spatial structures, mass segregation, OB star formation, HII region gas physics and triggering processes based on realistic star populations derived from X-ray surveys