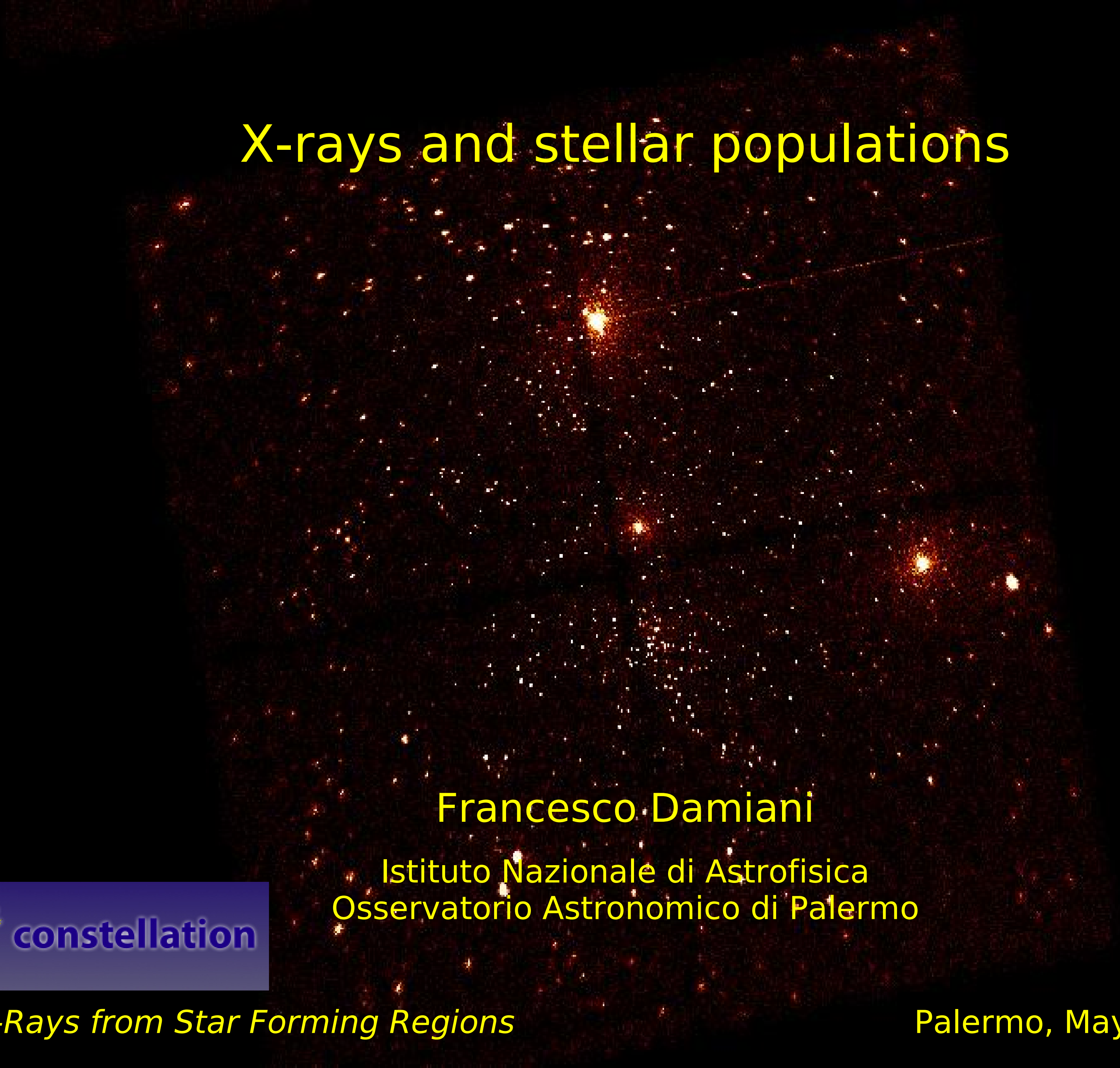

X-rays and stellar populations

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X-Rays from Star Forming Regions

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Outline

Early X-ray observations of clusters: the *Einstein* Observatory

X-ray images of star-forming regions and serendipitous discovery of pre-main-sequence stars with *no strong emission lines* (WTTS). Emerging trends: younger clusters are *X-ray brighter*; younger stars are *strongly variable in X-rays*.

ROSAT and the first All-Sky X-ray survey (RASS) in soft X-rays

Bright X-ray sources far from star-forming regions as post-T Tauri or runaway T Tauri star candidates? More WTTS candidates in other regions, all nearby.

XMM and Chandra: reaching farther away

...and probing a much larger cluster “parameter space”, up to massive SFRs with Chandra. Identifications and follow-ups; X-ray selection efficiency compared to other selection methods. Detection of cluster members over a factor ~ 100 in mass.

Some results

Cluster morphologies; age spreads and sequences; mass segregation; cluster stellar initial mass function; disk frequency vs. age and environment.

Einstein observations of SFR:

X-ray images of *Tau-Aur, Oph, CrA, Cha I* fields (all within 160 pc) yielded detection of tens of known T Tauri stars.

A higher-than-elsewhere density of X-ray sources was noted, often identified with uncatalogued stars.

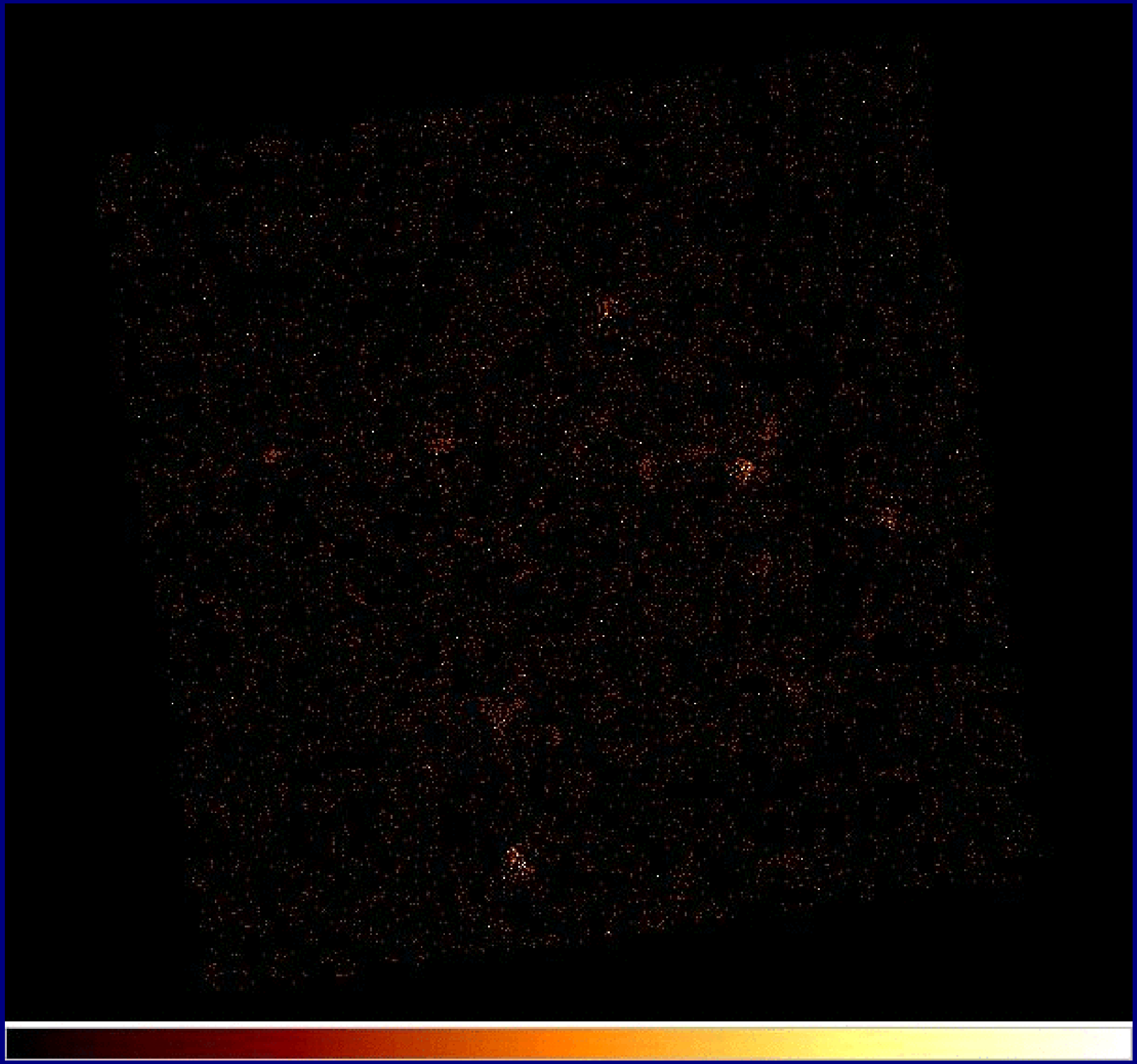
Optical follow-ups resulted in finding many tens new PMS stars in each region, showing the same high X-ray activity level as already known “classical” T Tauri Stars (CTTS), but much less (or absent) optical emission lines and IR/UV excesses: these were called *weak-line T Tauri stars* (WTTS).

The number of WTTS was found ~ that of CTTS, or even larger:
a substantial part of the PMS population in each SFR!

On average, WTTS tend to be less spatially concentrated than CTTS, and slightly older (but age overlap with CTTS is substantial).

A few original papers:
Gahm (1980); Feigelson and Decampli (1981); Feigelson and Kriss (1981); Walter and Kuhi (1981); Feigelson and Kriss (1983); Montmerle et al. (1983); Mundt et al. (1983); Walter and Kuhi (1984); Herbig, Vrba and Rydgren (1986); Walter (1986); Walter et al. (1987); Feigelson et al. (1987); Walter et al. (1988); Feigelson and Kriss (1989); Damiani et al. (1990); Walter (1992);Walter et al. (1994);Walter et al. (1997).

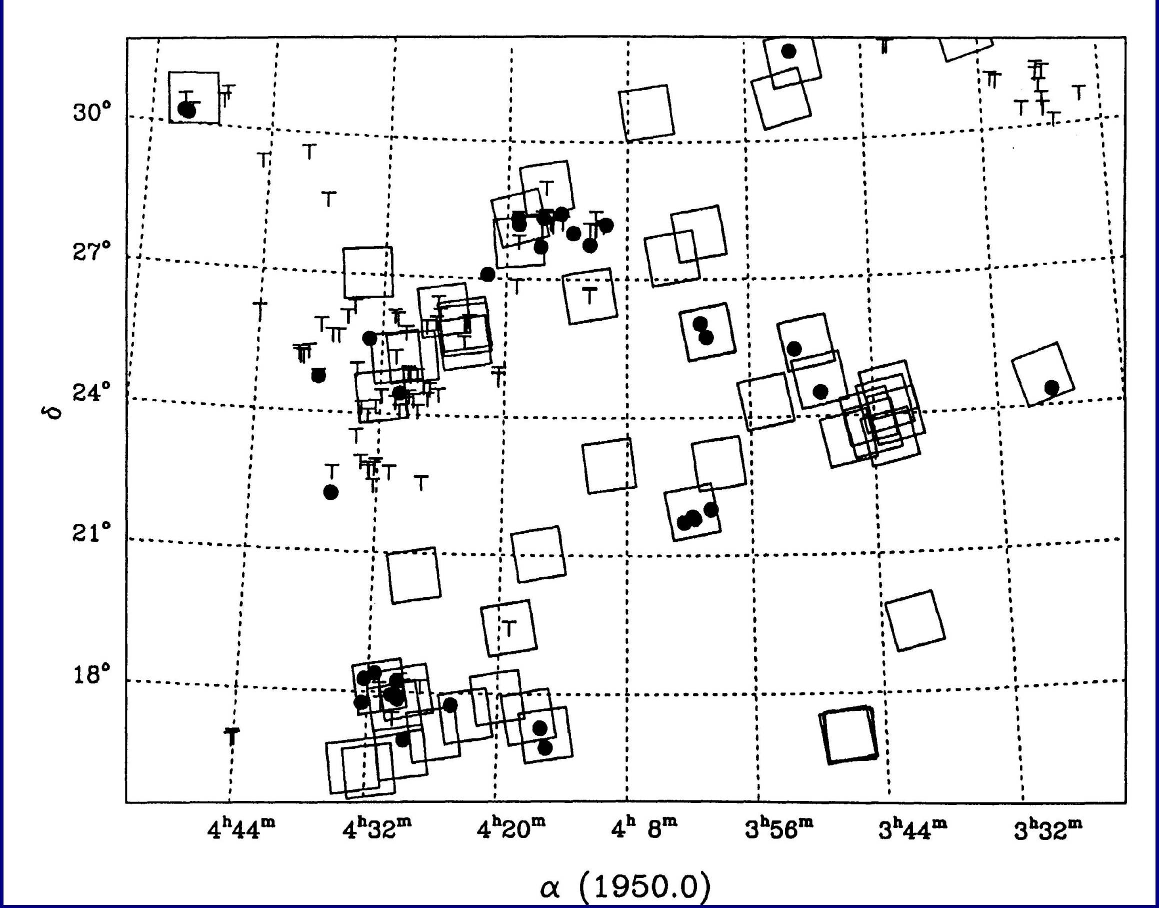
ρ **Oph: an "X-ray Christmas tree"** (Montmerle et al. 1983, *Einstein IPC* data):



→ Strong X-ray variability may lead to non-detection in single-epoch observations of CTTS

Einstein IPC fields in Taurus-Auriga (from Walter et al. 1998):

T: CTTS
●: WTTS



A few WTTS also selected from Ca II (Herbig et al. 1986)

For all WTTS, *Lithium+ radial-velocity* tests confirmed youth and cluster membership. Some WTTS also have emission lines, but usually with EW(Hα)<10Å

Incomplete spatial coverage!

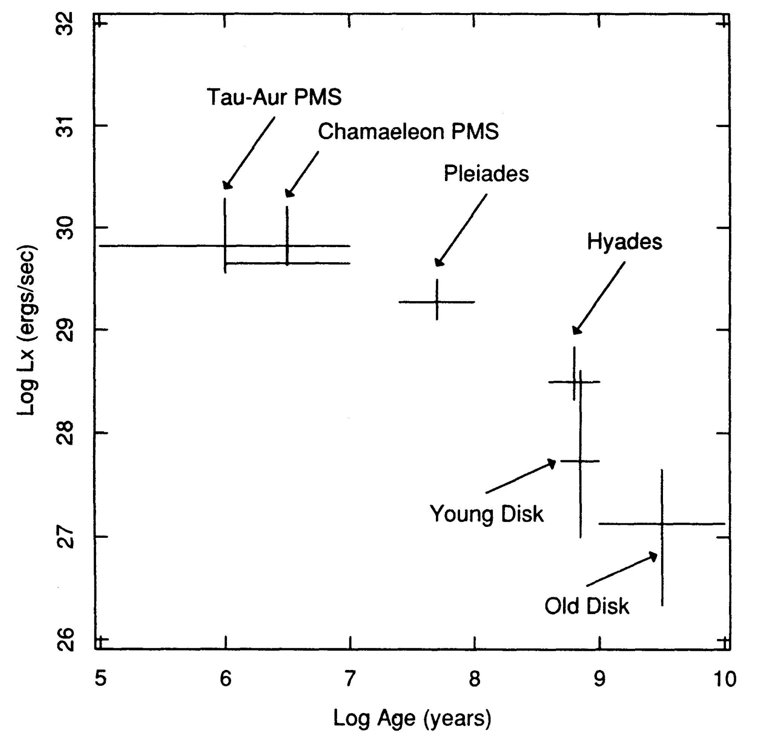
Why X-rays?

X-ray emission from normal (non-degenerate) stars found to decrease with stellar age (figure from Damiani et al. 1995):

More recent, deeper X-ray data have lowered mean Lx of some groups, but the decrease is still there.

→ *TTS (esp. WTTS) stand out in X-ray images w.r.t. older field stars, which are ~1000 times less bright.*

On average Lx (CTTS) ~ 0.1 Lx (WTTS) (Stelzer and Neuhäuser 2001).



The first soft X-ray All-Sky Survey (RASS) with ROSAT

Lots of new candidate WTTS *all around* SFRs (Tau-Aur, Wichmann et al. 1995), but also Oph, Cha, CrA, Orion...outnumbering CTTS by 6-8 times!

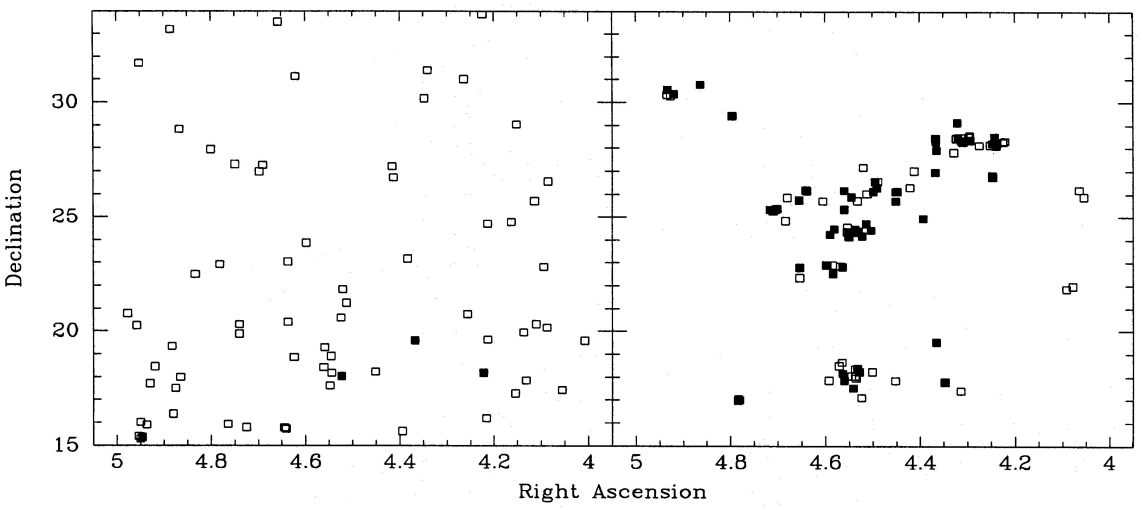


Fig. 3. Spatial distribution of our sample of new RASS-detected TTS (left panel) and the TTS known prior to ROSAT in the study region (right panel). Open squares denote WTTS, filled squares CTTS.

Are these post-T Tauri stars (Herbig 1962)? Run-away T Tauri stars?
Perhaps too much enthousiasm...many of them equally good candidates as *Pleiades-age young MS stars* (Favata et al. 1997)...so *no TTS at all*!
Also remember the high “infant mortality” of embedded clusters (Lada & Lada 2003): all those young stars soon end up in the field!

ROSAT pointed observations: expanding the accessible cluster list

Much deeper/higher resolution than the RASS, they led to solid detection of new *clustered* members of known PMS/ZAMS *low-mass clusters*:

Tau-Aur, Cha, Oph, Lup, CrA, Upper Sco-Cen, IC348, IC2391, IC2602

And also *high-mass clusters* were studied in X-rays, with analogous results:

Orion Nebula Cluster, NGC2264, Lambda Ori, Sigma Ori

...but source confusion in the ROSAT images was a serious obstacle for the analysis of data on massive clusters *farther away than 1 kpc:*

NGC2244 (Rosette), h/χ Per, M20/NGC6514, NGC2362, Cyg OB2, ...

By the late '90, higher spatial resolution and sensitivity was really needed to advance in X-ray cluster studies...

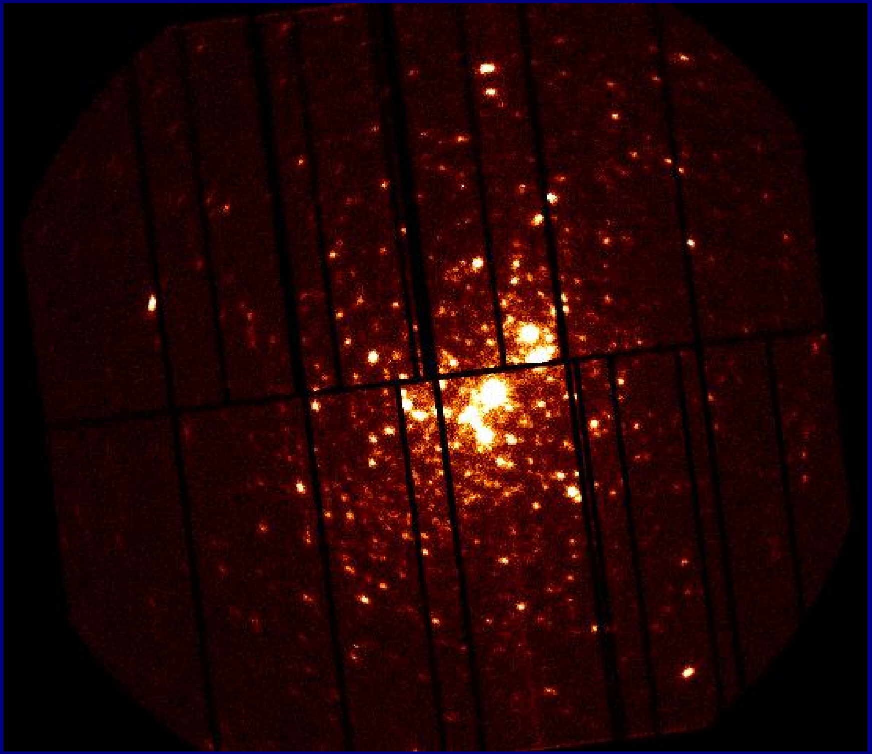
...and in 1999-2000 both *XMM-Newton* and *Chandra* observatories started operating! And many, many clusters were studied for the first time in X-rays:

XMM-Newton observations of young clusters

Taurus-Auriga	(many pointings and papers, e.g. Favata et al. 2003, XEST project: new members in Scelsi et al. 2008)
ρ Oph	(Ozawa et al. 2005, Giardino et al. 2007)
Lupus	(Gondoin 2006)
Upper Sco-Cen	(Argiroffi et al. 2006)
Cha I	(Stelzer et al. 2004, Robrade and Schmitt 2007)
TW Hya	(Stelzer and Schmitt 2004, Argiroffi et al. 2005)
CrA	(Hamaguchi et al. 2005, Forbrich et al. 2006)
NGC1333	(Preibisch 2003)
IC 348	(Preibisch and Zinnecker 2004)
IC2391	(Marino et al. 2005)
IC2602	-----
NGC2547	(Jeffries et al. 2006)
Serpens	(Preibisch 2004)
25 Ori	-----
Barnard 30	-----
Barnard 35	-----
Barnard 335	-----
OMC 2/3	-----
Sigma Ori	(Franciosini et al. 2006)
Lambda Ori	-----
NGC2024	-----
NGC2023	-----
NGC2071	(Skinner et al. 2007)
NGC2264	(Simon et al. 2005, 2007)
IC 5146	(Skinner et al. 2009)

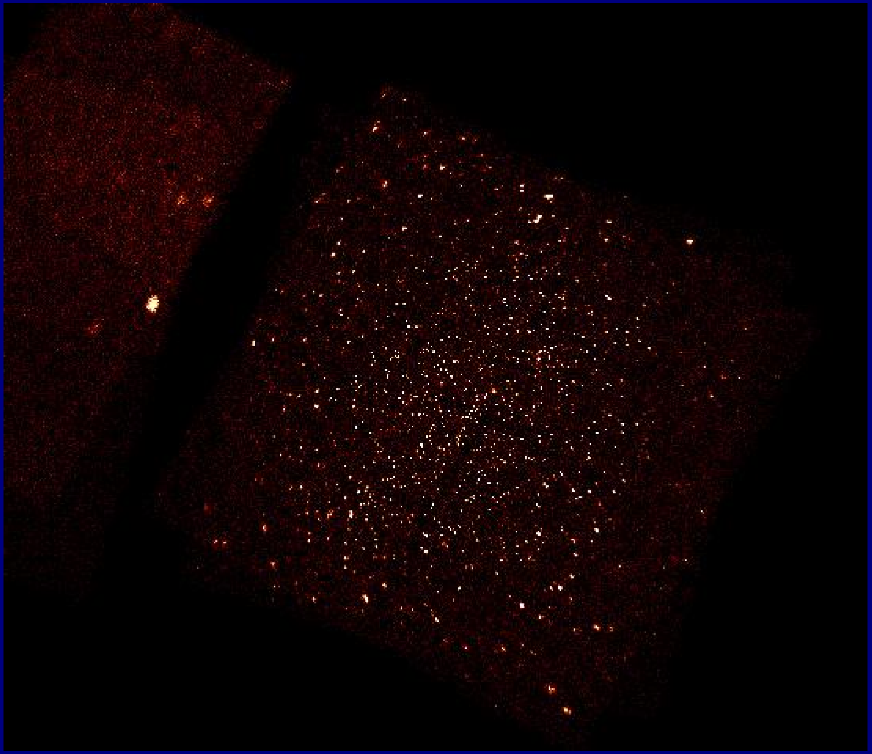
XMM-Newton observations of young clusters (continued)

Gamma2 Vel	(Raassen et al. 2004)
NGC2362	-----
NGC6530	(Rauw et al. 2002)
NGC6231	(Sana et al. 2006, 2007)
M17	-----
Cyg OB2	(Linder et al. 2009)
χ Per (NGC884)	-----
Tr16/14/Car OB1	(Albacete-Colombo et al. 2003, Antokhin et al. 2008)
Westerlund 1	(Muno et al. 2007)



Source confusion for rich, massive, distant (>1 kpc) clusters: e.g. NGC6231 (1250 pc)
EPIC-pn image (170 ks), ~800 sources

Chandra really needed...



Chandra ACIS-I image, same field, 120 ksec, ~1500 sources

Chandra observations of young clusters

Taurus-Auriga	(too many pointings and papers...)
Eta Cha	(Evans et al. 2003, 2004)
Epsilon Cha	(Feigelson, Lawson, Garmire 2003, Testa et al. 2008)
Cha I	(Feigelson and Lawson 2004)
CrA + Coronet cluster	(Hamaguchi et al. 2005, 2008, Forbrich et al. 2007)
ρ Oph	(Imanishi et al. 2001, 2002, 2003, Flaccomio et al. 2003, Gagne' et al. 2004)
TW Hya association	(Gizis et al. 2004)
NGC1333	(Getman et al. 2002)
IC 348	(Preibisch and Zinnecker 2001, 2002)
L1251B	(Simon 2009)
L1448N-A	(Tsujimoto et al. 2005)
L1415	------
L1527	------
LkHa 101	(Osten and Wolk 2009)
Orion Nebula Cluster	(Garmire et al 2000, Schulz et al. 2001, Flaccomio et al. 2003a,b, Feigelson et al. 2003; COUP project: many authors, ApJS 160)
Orion flanking fields	(Ramirez et al. 2004, Rebull et al. 2006)
M78/NGC2068	(Grosso et al. 2004)
NGC2071	------
NGC2024	(Skinner et al. 2003, Ezoe et al. 2006)
OMC 2-3	(Tsuboi et al. 2001, Tsujimoto et al. 2002)
Lambda Ori	------
Sigma Ori	(Skinner et al. 2008)

Chandra observations of young clusters (continued)

L1630 (HH 24-26)	(Simon et al. 2004)
Mon R2	(Kohno et al. 2002, Nakajima et al. 2003)
NGC2244 (Rosette) + new cluster	(Townsley et al. 2003, Wang et al. 2008, 2009)
NGC2264 (North/South)	(Ramirez et al. 2004, Rebull et al. 2006, Flaccomio et al. 2006)
NGC2362	(Damiani et al. 2006, Delgado et al. 2006)
IC 1396-N	(Getman et al. 2007)
CG12	(Getman et al. 2008)
h Per	(Currie et al. 2009)
DB2001CL-123	-----
NGC281	-----
Cep B	(Getman et al. 2006)
M8/NGC6530	(Damiani et al. 2004)
M20/NGC6514	(Rho et al. 2004)
M16/NGC6611	(Linsky et al. 2007, Guarcello et al. 2007)
M17/NGC6618	(Townsley et al. 2003, Broos et al. 2007)
NGC6231	(Damiani et al. 2009)
NGC6334	(Ezoe et al. 2006, Feigelson et al. 2009)
NGC6357	(Wang et al. 2007)
RCW 38	(Wolk et al. 2006)
W3	(Hofner et al. 2002, Feigelson and Townsley 2008)
W51	(Koo et al. 2005)
Cyg OB2	(Albacete-Colombo et al. 2007)
S106	(Giardino et al. 2004)
Berkeley 87	-----
Serpens	(Giardino et al. 2007, Winston et al. 2007)

Chandra observations of young clusters (continued)

RCW 36	-----
W49A	(Tsujimoto et al. 2006)
NGC7538	-----
IC 1805	-----
Sh2-187	-----
NGC1893	(Caramazza et al. 2008)
DR21	-----
W75N	-----
GGD 27	(Pravdo et al. 2009)
W3 (Main IRS5/North/OH)	(Feigelson, Townsley 2008)
RCW 108/NGC6193	(Skinner et al. 2005, Wolk et al. 2008)
Trumpler 14	(Townsley 2006)
Trumpler 16	(Evans et al. 2004, Albacete-Colombo et al. 2008)
Carina complex	-----
NGC3576	(Townsley 2006)
NGC3603	(Moffat et al. 2002, Poteet et al. 2004)
Westerlund 1	(Skinner et al. 2006, Clark et al. 2008)
RCW 49 (Westerlund 2)	(Tsujimoto et al. 2007, Naze' et al. 2008)
Sgr B2	(Takagi et al. 2002)
Arches	(Yusef-Zadeh et al. 2002, Wang et al. 2006)
RSG2	-----

Many more massive clusters than observed with XMM-Newton, and richer low-mass populations detected.

In this list, observations of small PMS star groups (e.g. near Herbig Ae/Be stars) are missing, as well as observations of individual PMS stars.

High-mass clusters

Massive stars spend little or no time in their PMS phases;
They live so shortly (few Myrs), however, that *low-mass stars* coeval with them are still found *in their PMS phase*.
Massive clusters may not be *star-forming* clusters today, if formation has stopped once massive stars have formed, *but* are definitely *very young clusters* containing (many) *low-mass PMS stars*. Or star formation may continue, perhaps triggered by OB stars themselves; in either case we have...

Chandra: good X-ray selected populations

...of low-mass stars, even in populous, massive clusters.
Importance of high spatial resolution: little/no confusion, reliable optical/IR identifications with very few (<1%) ambiguous cases.

Follow-ups

Deep photometry/spectroscopy to place stars in HR diagram, find any photometrically peculiar objects (non-stellar emissions), confirm candidates from Lithium/radial velocity (but beware of SB1 observed only once...)

X-rays vs. other selection methods

X-rays: up to 90% success rate (for Class I-III stars).

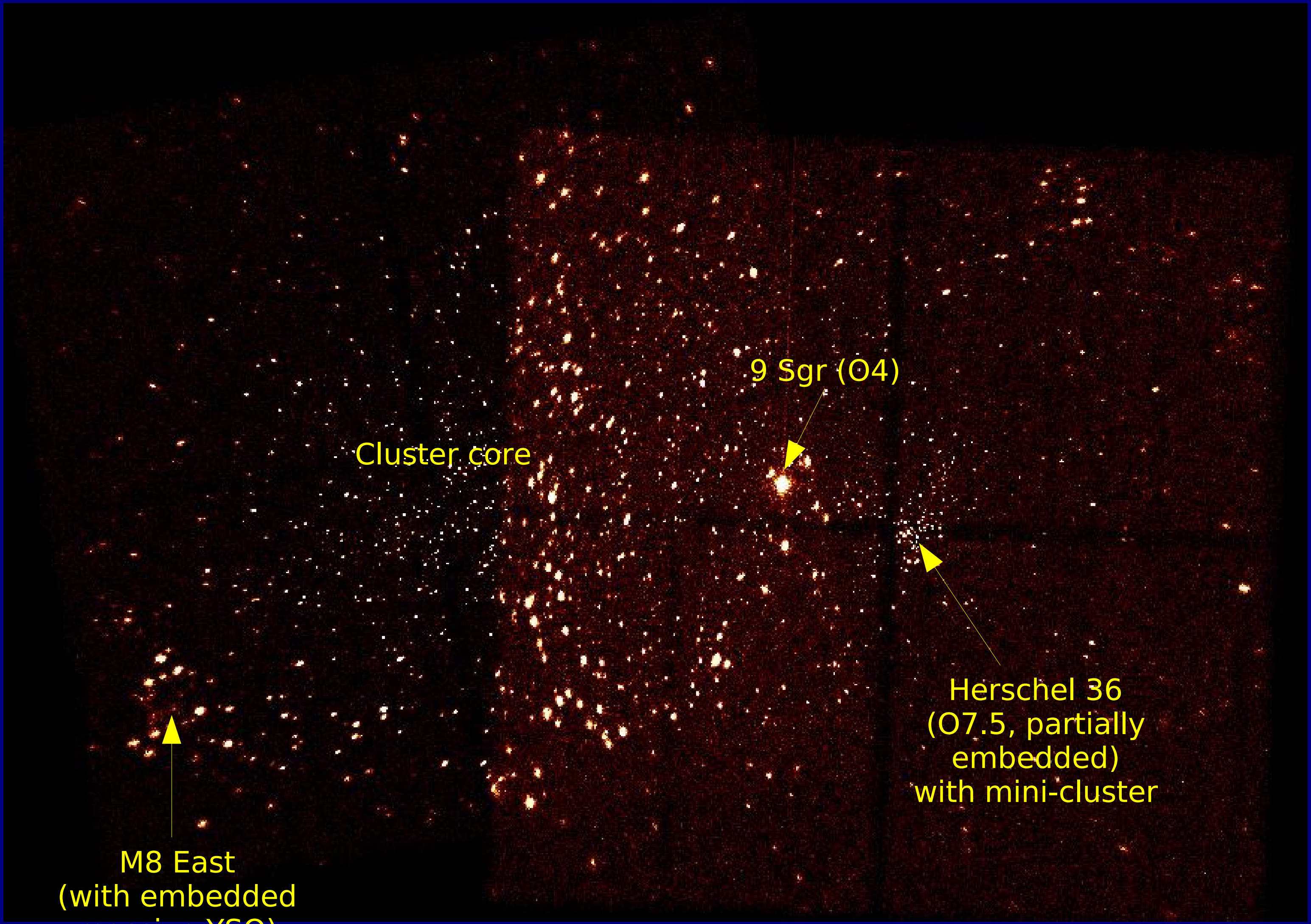
IR/Hα emission: 5-70% success rate (Class I-II only).

Proper motion: in principle, a better membership indicator, but available only for few stars in nearby clusters!

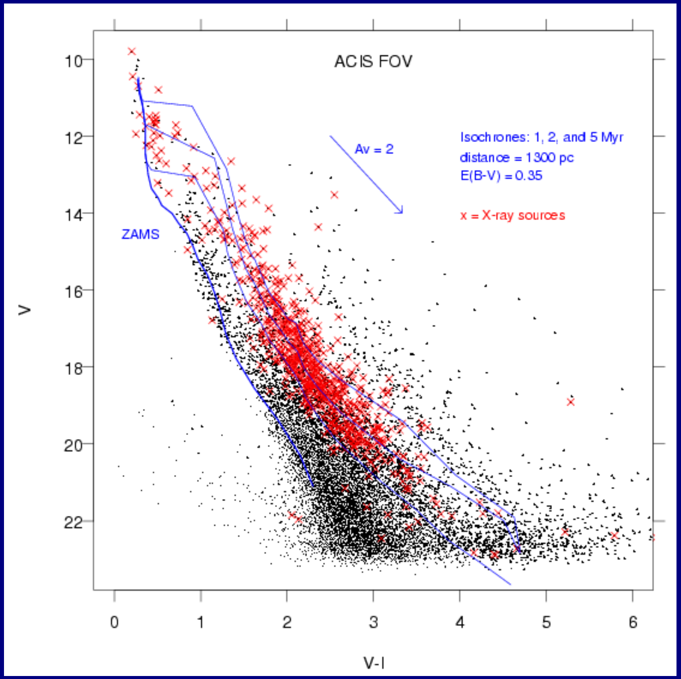
Lithium test: another kind of “definitive” test, but observing with high-enough spectral resolution over 10000 stars in a Galactic plane 20'x20' field down to V=20 takes forever...

But **beware:** take a 100 ksec X-ray image on the Galactic Plane, you'll probably get ~100-150 sources, slightly concentrated to center of FOV: *this is likely **not** a cluster* (unless follow-up proves it), but normal field stars. X-ray membership works better for rich clusters (say >300 sources, there are plenty!)

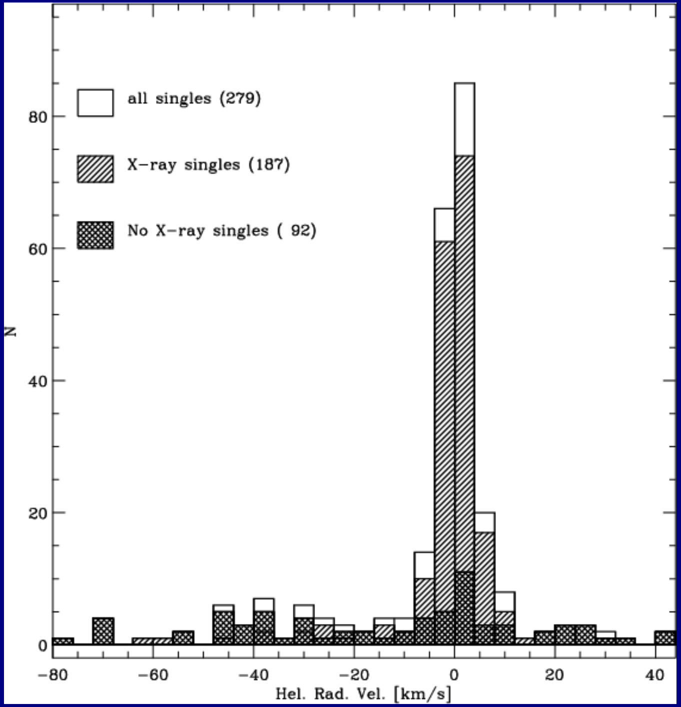
Example: *NGC6530 and M8*, Chandra ACIS mosaic (~20'x30'), ~1500 X-ray sources (central/eastern part studied by Damiani et al. 2004); a complex structure.



Deep BVI photometry (WIFI@ESO 2.2m) and CMD of NGC6530 X-ray sources (Prisinzano et al. 2005)



...used also to compute ages, masses and the IMF (see later)

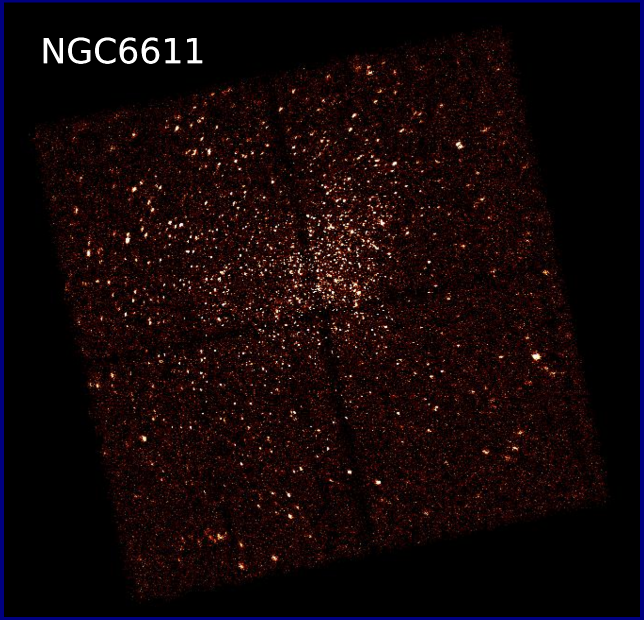


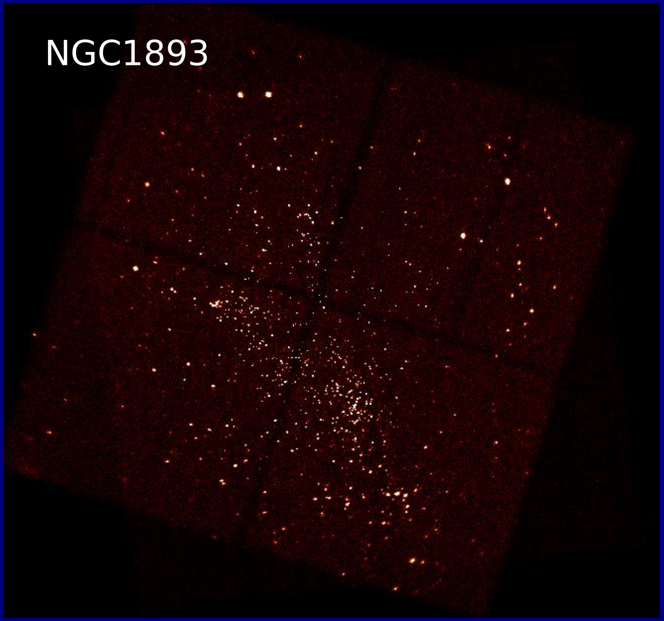
VLT/Giraffe spectroscopic study of Radial velocity/Lithium (Prisinzano et al. 2007) yielded an *X-ray selection completeness of ~90%* down to V=18.2

Cluster morphologies

Detection of sizable population of a cluster permits to study its *morphology,* which gives clues to the cluster dynamical state

- Quasi-spherical (relaxed?): e.g. *ONC, NGC2362, NGC6231, NGC6611*
- Multiple star-forming sites: e.g. *NGC6530/M8, Cyg OB2, NGC6334, NGC1893*



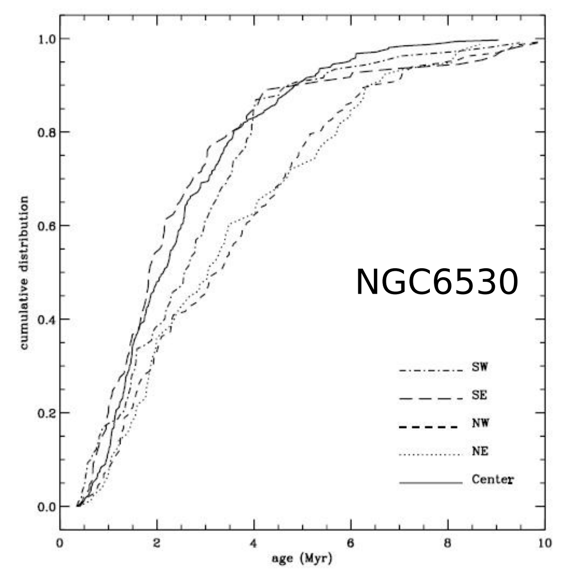


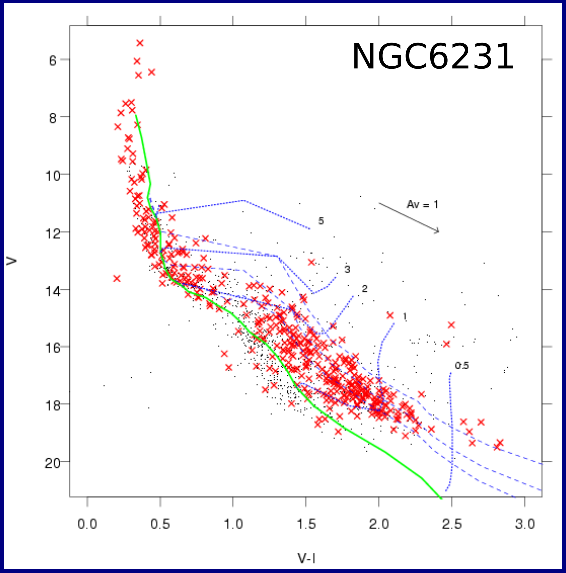
Low-mass star density peaks usually around the OB stars. Sometimes O stars off density peaks: η Car in *Trumpler 16*, 9 Sgr in *NGC6530*, HD 46223 in *NGC2244* *dynamical evolution/runaway stars, or a different mode for star formation?*

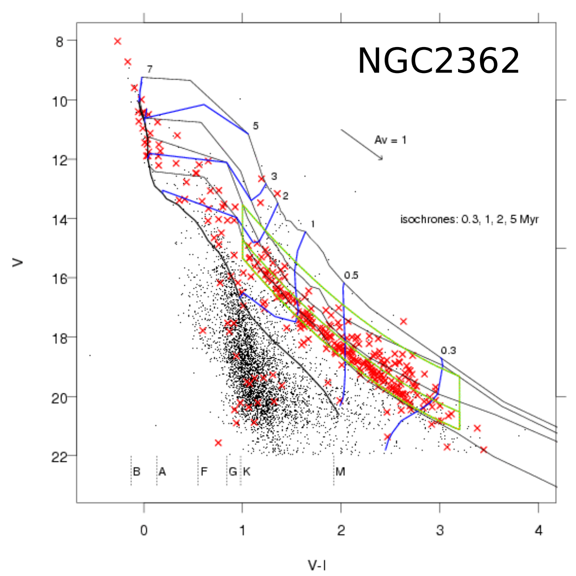
Age spread/sequences

Differences in star-formation histories between clusters, from X-ray selected populations.

- Formation during extended period of time (5-10 Myr): NGC6530, NGC6231
- Nearly simultaneous formation (within ~1 Myr): NGC2362
- Formation through *spatial sequences*: NGC6530 (core → Hourglass → M8 East)
- Formation along *mass sequences*: NGC6231 (low-mass stars 10 Myr ago, massive stars 2 Myr ago)







Initial Mass Function

...is really initial? Likely *yes,* since little dynamical evolution is expected at clusters ages (<10 Myr) under consideration.

Questions:

Is the IMF universal?
If not, how it depends on ambient conditions?
Are there clusters with top-heavy IMF?

Method:

Find optical counterparts to X-ray sources (esp. low-mass: massive stars have better characterized membership...), derive their masses from position in CMD and PMS evolutionary models, and make a mass histogram. But...

Initial Mass Function

Warnings:

(1) this must be complemented by estimates of *X-ray (in)completeness*, especially in lowest-mass bins.

(2) if many cluster stars have *IR excesses*, photometrically derived masses are likely inaccurate, must resort to spectroscopy.

(3) if many optically/IR *unidentified X-ray sources* remain (with spatial clustering) try to include them, by deriving *star masses* from $L_{x,}$, via $L_x \sim 10^{-3} L_{bol}$ and the L_{bol}-*mass* relation appropriate to the cluster age/reddening.

(4) Optically, glare from OB stars may prevent finding faint, low-mass stars: much less so in X-rays, since $L_x/L_{bol} \sim 10^{-3} L_{bol}$ (low mass), but $L_x/L_{bol} \sim 10^{-7} L_{bol}$ (OB stars)
→ contrast reduced from ~10^6 to 10^2-10^3 by using X-rays!

Initial Mass Function

Results on cluster IMFs:

- For many clusters, first IMF determination ranging down to solar-mass stars: up to 2 orders of magnitude in mass are covered!
  Comparison between IMFs of many clusters: Maggio et al. (2008, meeting “From Taurus to the Antennae”).

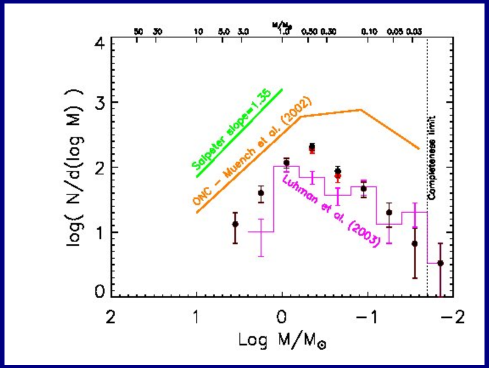
- Upper part generally consistent with Salpeter IMF.

- Turn-off at some mass, *generally* sub-solar (but NGC2362 possible exception with turn-off at higher mass), however turn-off mass slightly different from cluster to cluster.

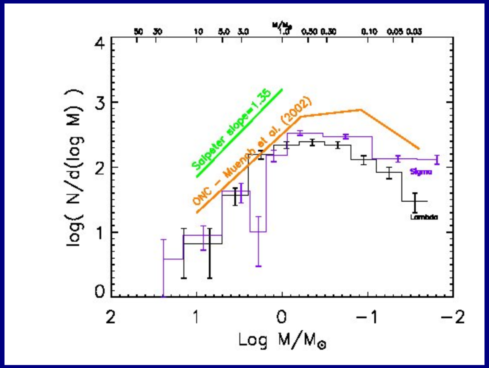
- Apparently, IMF shape independent from place in the Galaxy (NGC1893).

- Comparison with a previous optical/Hα determination (e.g. NGC6231) shows the incompleteness of this latter: it missed WTTS entirely (90% of low-mass stars in this particular case).

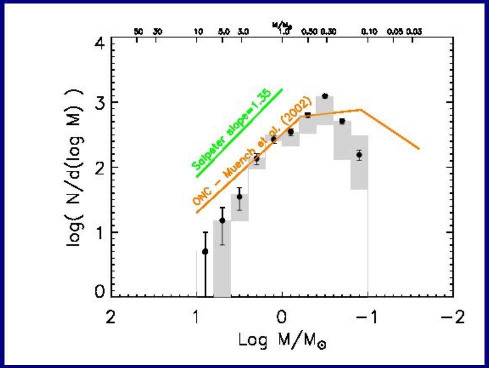
Taurus-Auriga



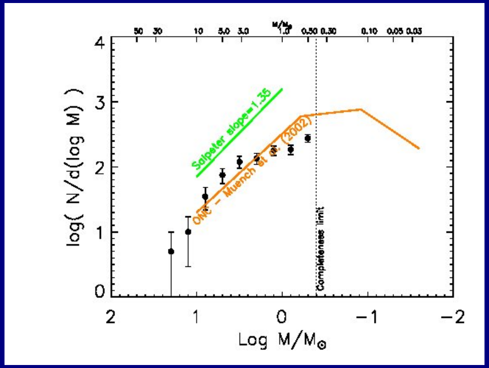
λ and σ Ori clusters



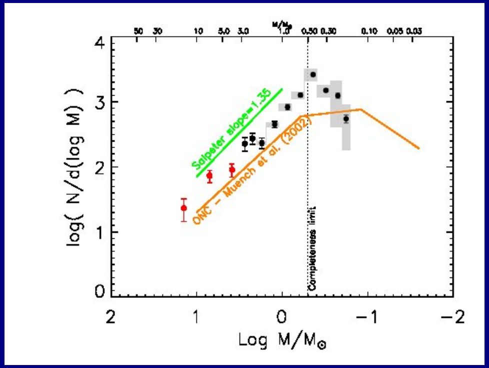
NGC 2264



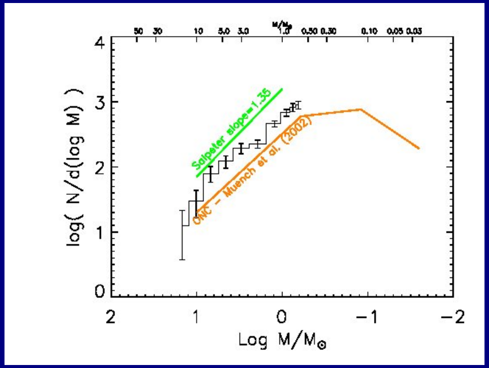
NGC 2362



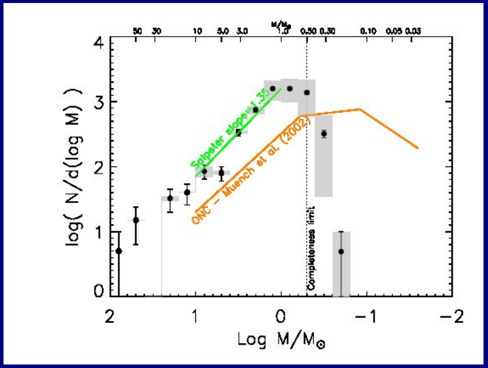
NGC 6530



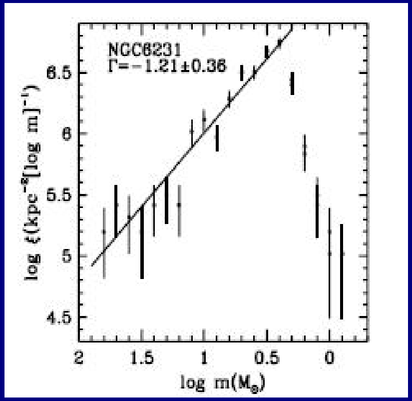
NGC 1893



NGC 6231...



...and its IMF from optical alone (Sung et al. 1998):



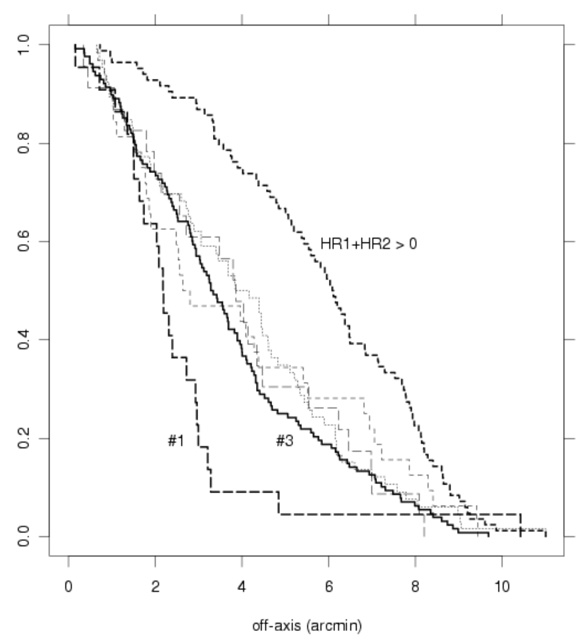
Mass segregation

Do low-mass stars concentrate less than massive stars towards cluster center?
(...well, as long as a center may be defined! Not always the case)
If a meaningful “center” exists, the X-ray traced low-mass population can be compared to the massive one.

Warning: beware of radial *sensitivity variations* (always there) in X-ray images! Or you end up with wrong characteristic sizes.

Positive answer in a few cases (e.g. *NGC6231, NGC2362 – see picture, from Damiani et al. 2006),*
negative in others (e.g. *NGC2244*).

Since no dynamical evolution is expected, this is likely primordial.



Disk frequency vs. age and environment

Various diagnostics of T Tauri disks exist (inner disk from *near IR*, outer disk from *far IR*...), or of CTTS status (accretion through *Hα*, optical/UV *veiling*...).

→ difficulty of obtaining a *uniform disk/accretion* indicator for many/all clusters!

In any case, need of a *WTTS-status* indicator: *X-rays*! (what else?...)

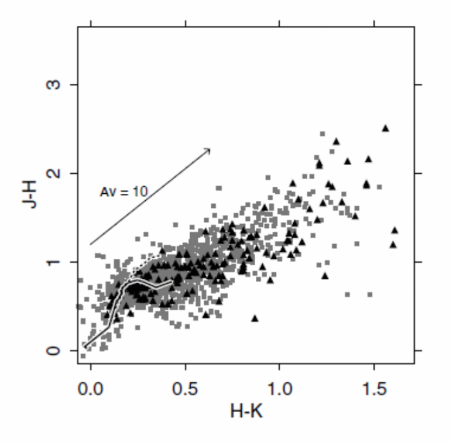
→ meaningful comparisons of CTTS/WTTS populations.

From X-ray selection and various disk/accretion indicators, we obtain the *circumstellar disk frequency* for several clusters:

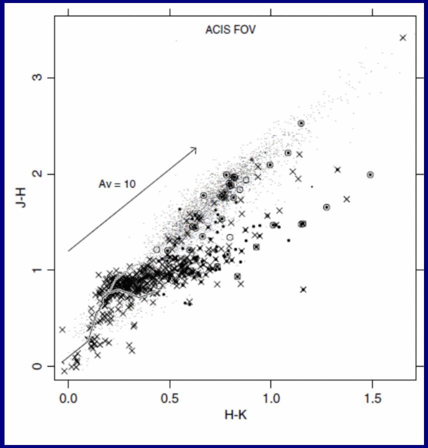
ONC:	(1 Myr)	near-IR, M>1 M⊙	20.6%	(becomes higher using more indicators/larger mass range)
Cyg OB2:	(2 Myr)	near-IR, M>1 M⊙	4.4%	→ *very low!*
NGC2264:	(3 Myr)	Hα	42%	
NGC1893:	(3-4 Myr)	Spitzer SED	67%	
NGC2362:	(5 Myr)	Hα	5%	(IR: 12%)
NGC6530:	(2-3 Myr)	near-IR, M>0.5 M⊙	20%	
NGC6611:	(1 Myr)	near-IR, M>0.5 M⊙	20%	
Tr 16:	(3 Myr)	near-IR, M>0.5-1 M⊙	15%	
NGC6231:	(5-7 Myr)	near-IR, M>1 M⊙	4%	→ *very low!*

Disk frequency vs. age and environment

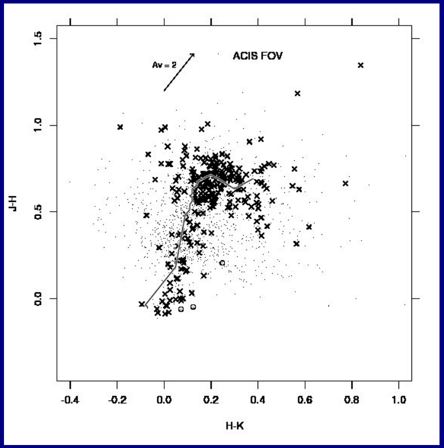
Taurus (black) & ONC (grey)



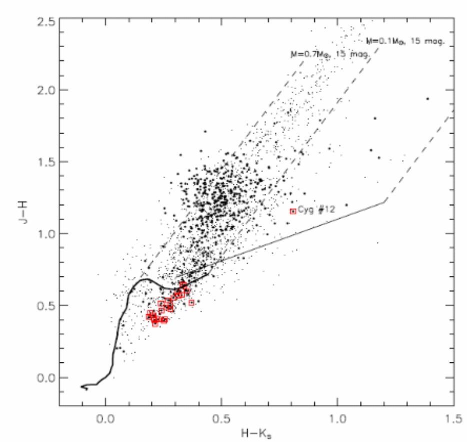
NGC6530



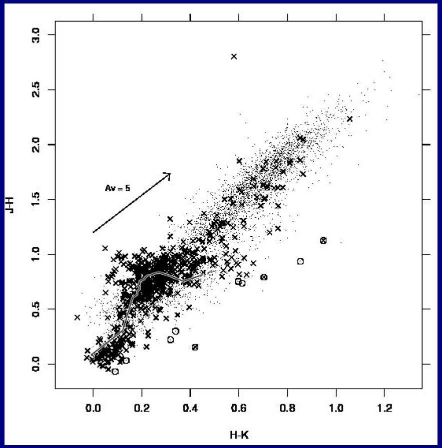
NGC2362



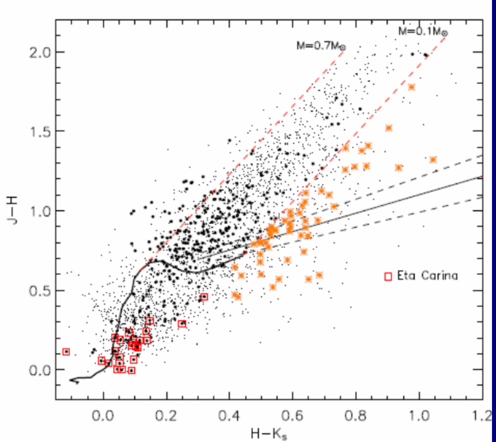
Cyg OB2



NGC6231



Trumpler 16



Disk frequency vs. age and environment

Possibly, low disk frequency (in *Cyg OB2* and *NGC6231*) caused by fast disk evolution under the effect of the radiation field of OB stars (*photoevaporation*).

Another clue to the same effect in *NGC6611*:

Disks are less frequent where OB stars' summed UV flux is larger!
(Guarcello et al. 2007)

→ age is not the only relevant parameter for disk evolution.