X-rays from pre-main sequence stars

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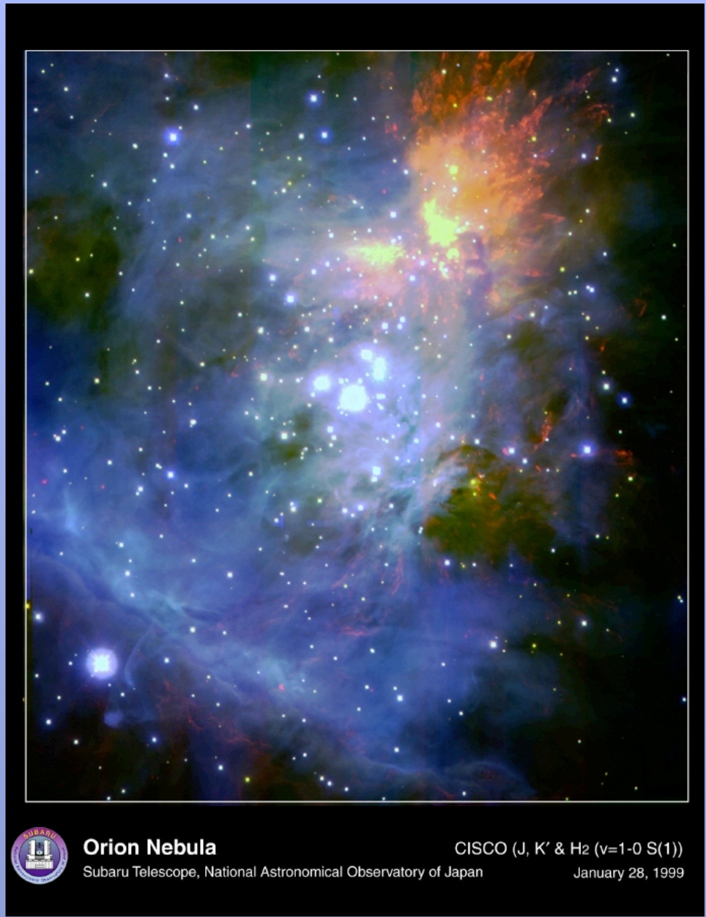
- **Introduction**

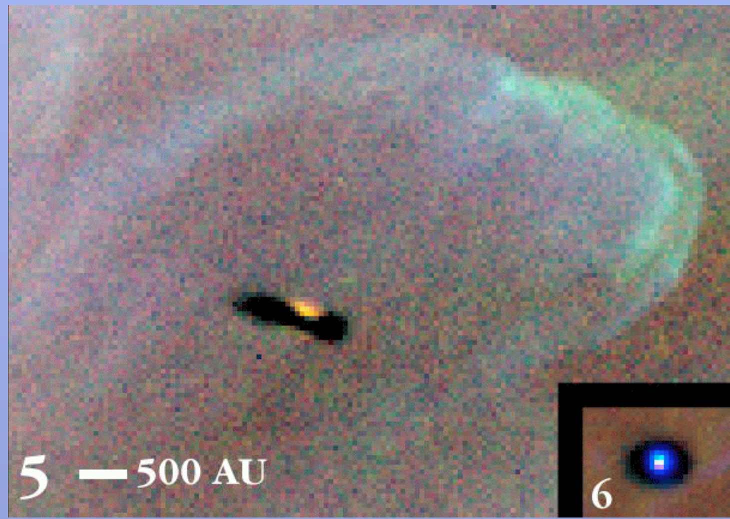
- **Flare phenomenology & modeling:**
  Flare statistics, loop models, plasma temperatures & abundances, dependences on stellar mass / rotation / age, radio emission

- **Accretion effects:**
  Suppression of flares, excess soft emission, abundances

CONSTELLATION School *X-rays from Star Forming Regions,* Palermo 2009



Orion Nebula cluster & proplyd



Star formation occurs in molecular clouds at T~10 K, and planet formation occurs in disks at T ~100-1000 K. This is neutral material (meV). But high energy radiation is present in star/planet formation environments: keV photons & MeV particles are produced in violent magnetic reconnection flares.

X-ray structures expected in a massive star forming region

\+ Protostars

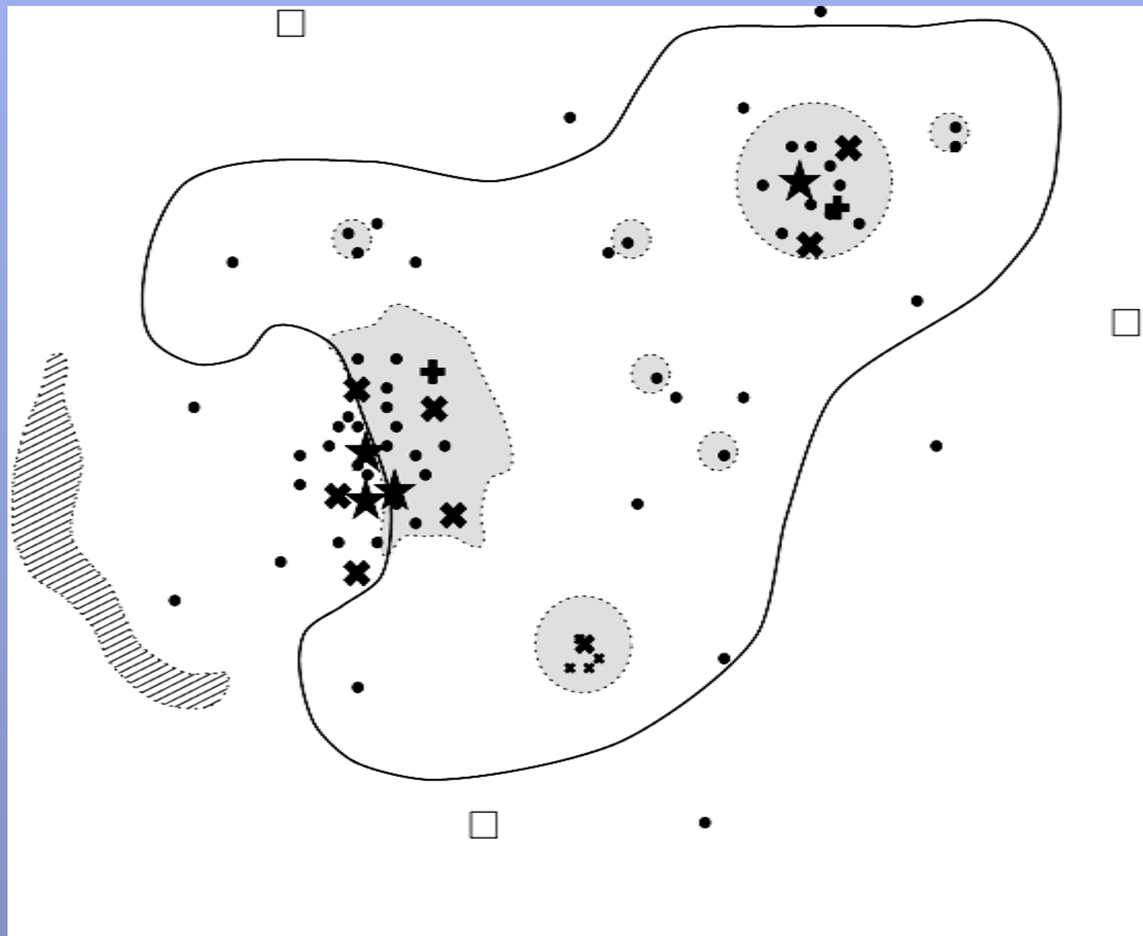
• T Tauri stars

* OB stars

OB wind shocks

Supernova remnants

X-ray binaries



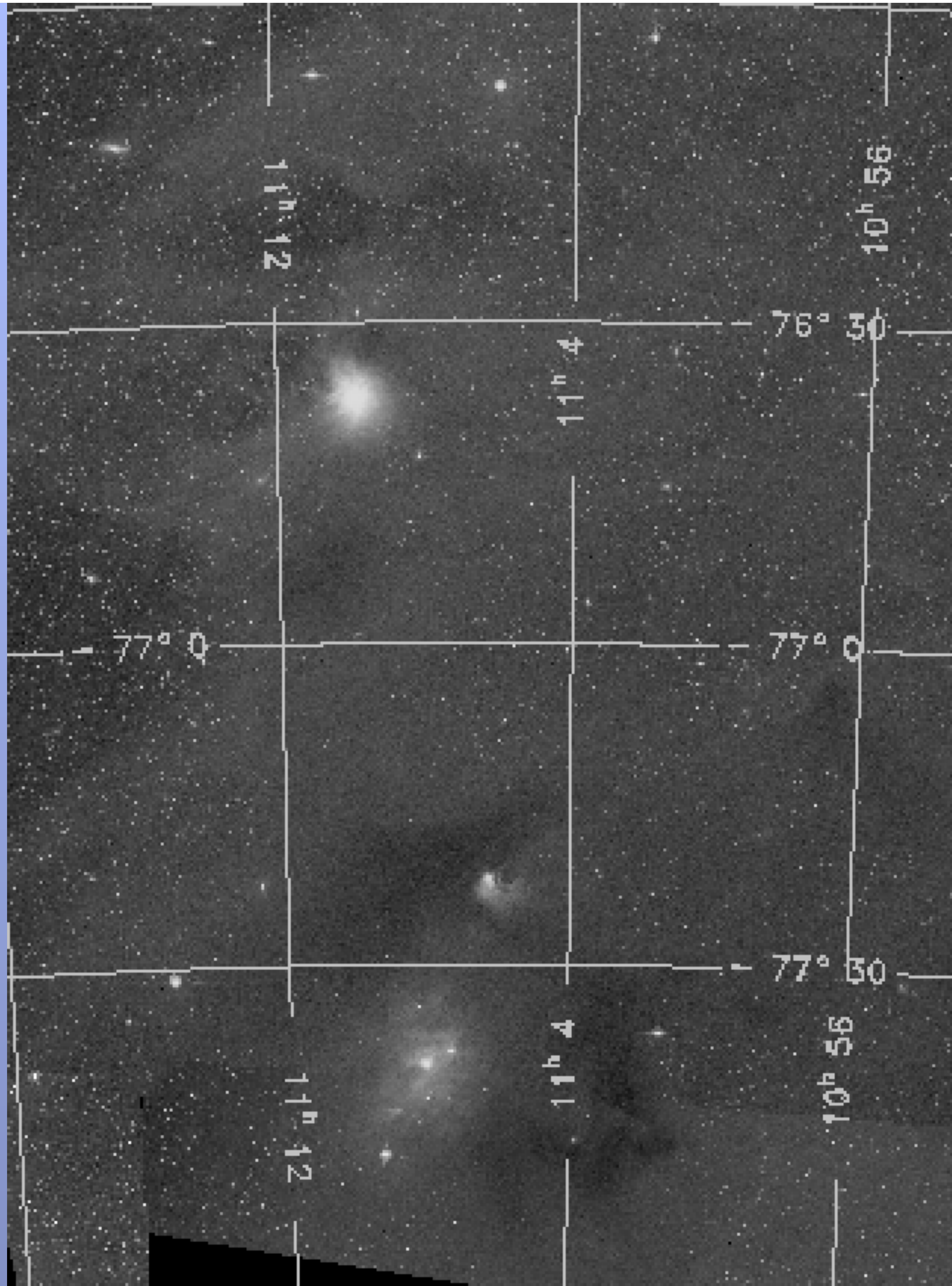
Feigelson 2001

Chamaeleon I

A typical nearby region of low mass star formation

D ~ 160 pc
Size ~ 3 pc
M_{gas} ~ 700 Mo

Known PMS population
~3 protostars
~50 CTT stars
~50 WTT stars

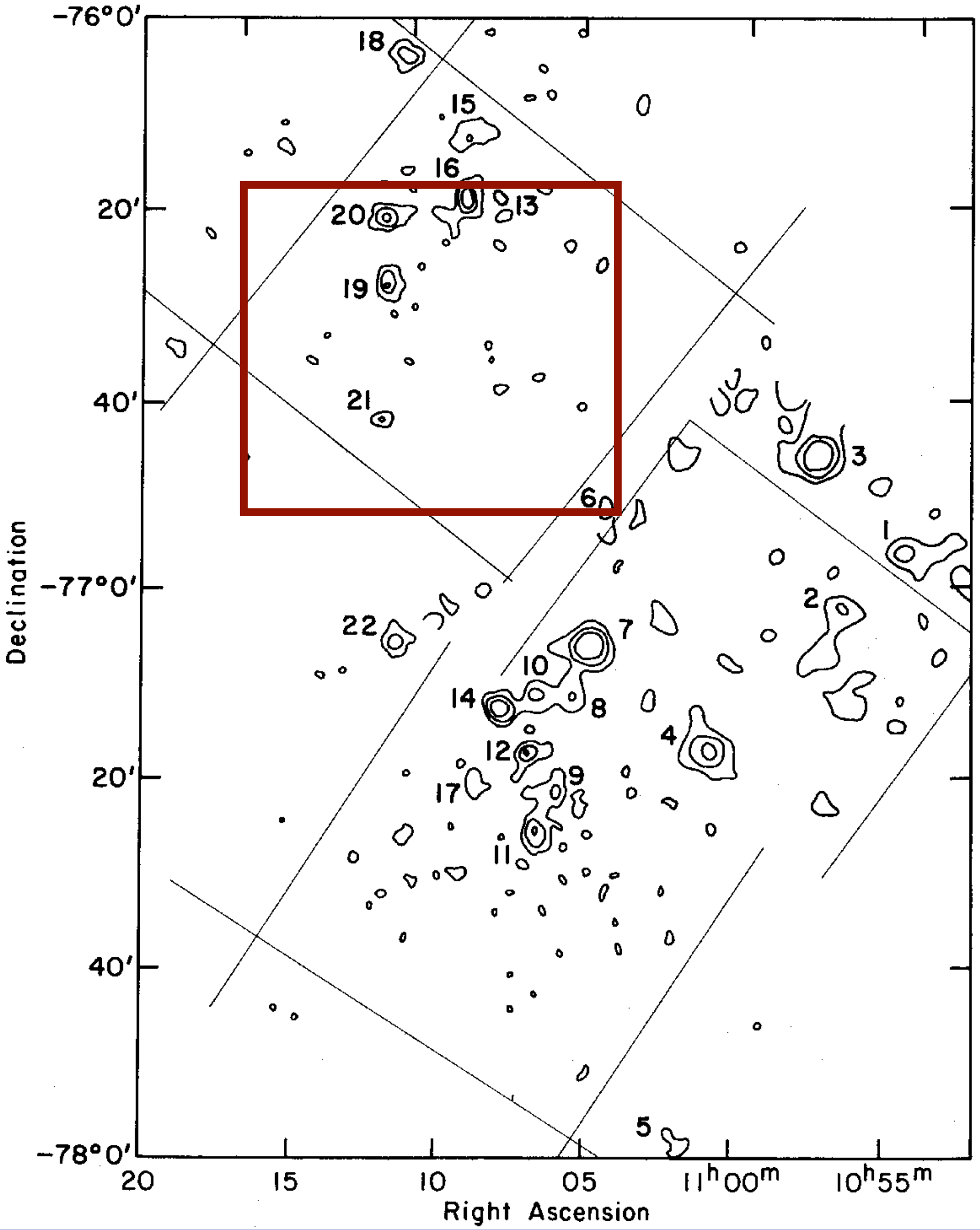


Digital Sky Survey

Einstein Observatory

1978-81

1’ resolution with Imaging Proportional Counter

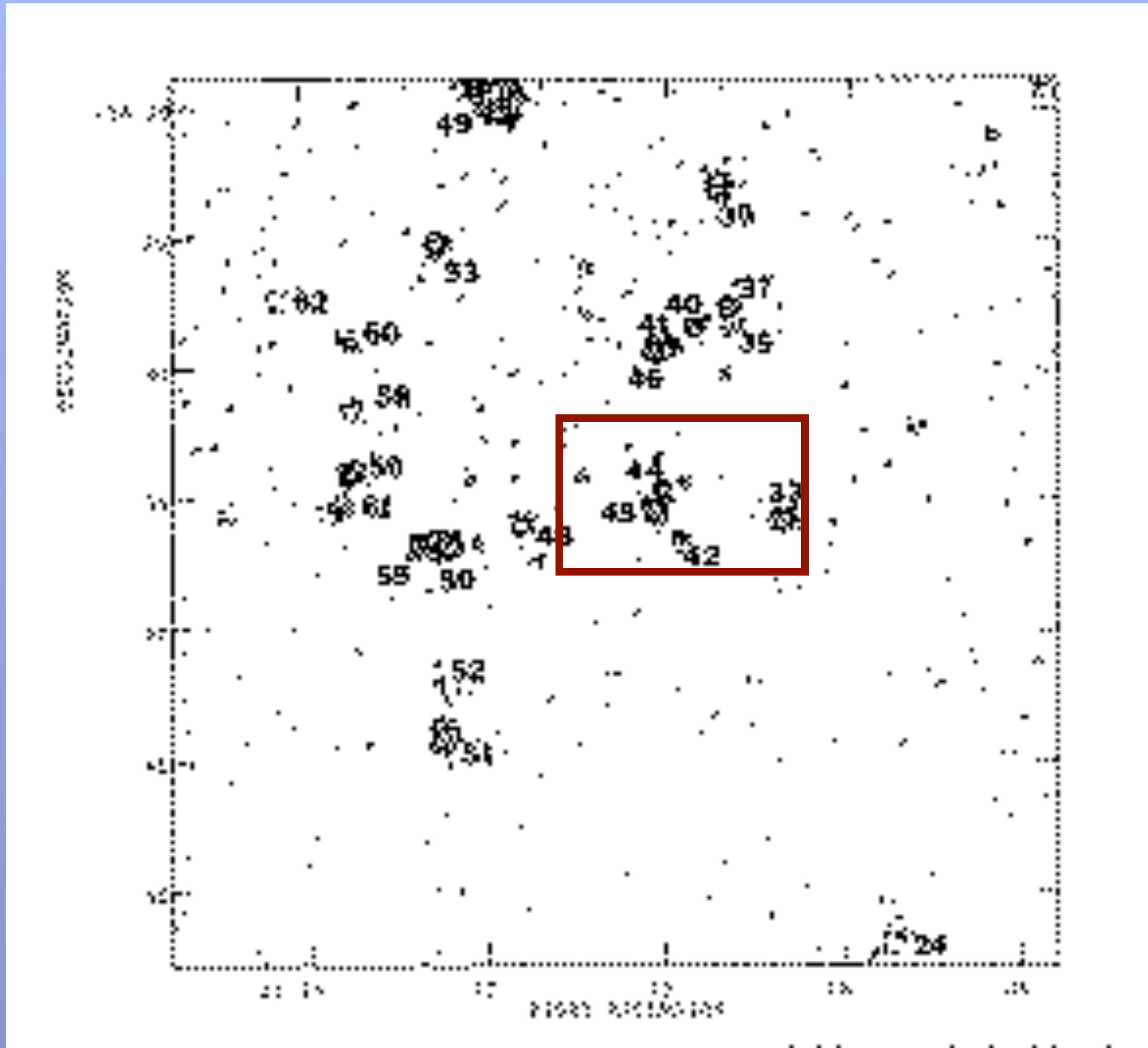


Feigelson & Kriss 1989

ROSAT

1990-99

20” resolution with Position Sensitive Proportional Counter

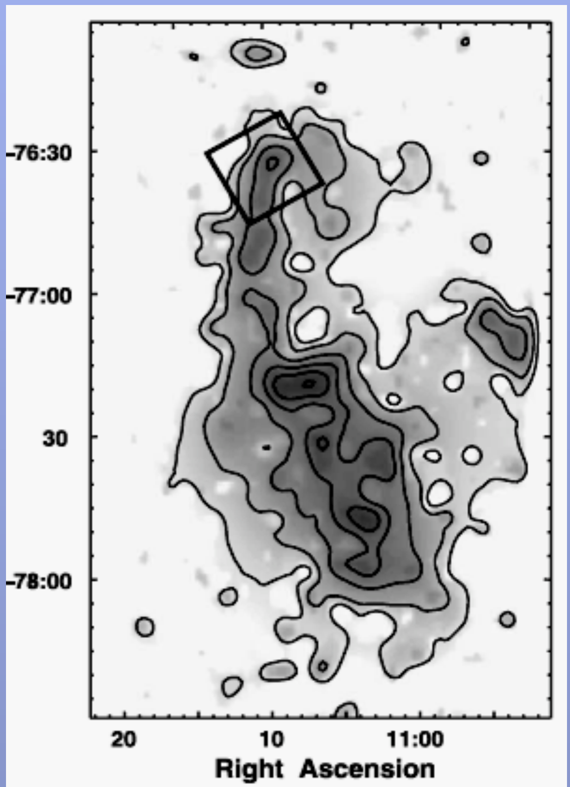


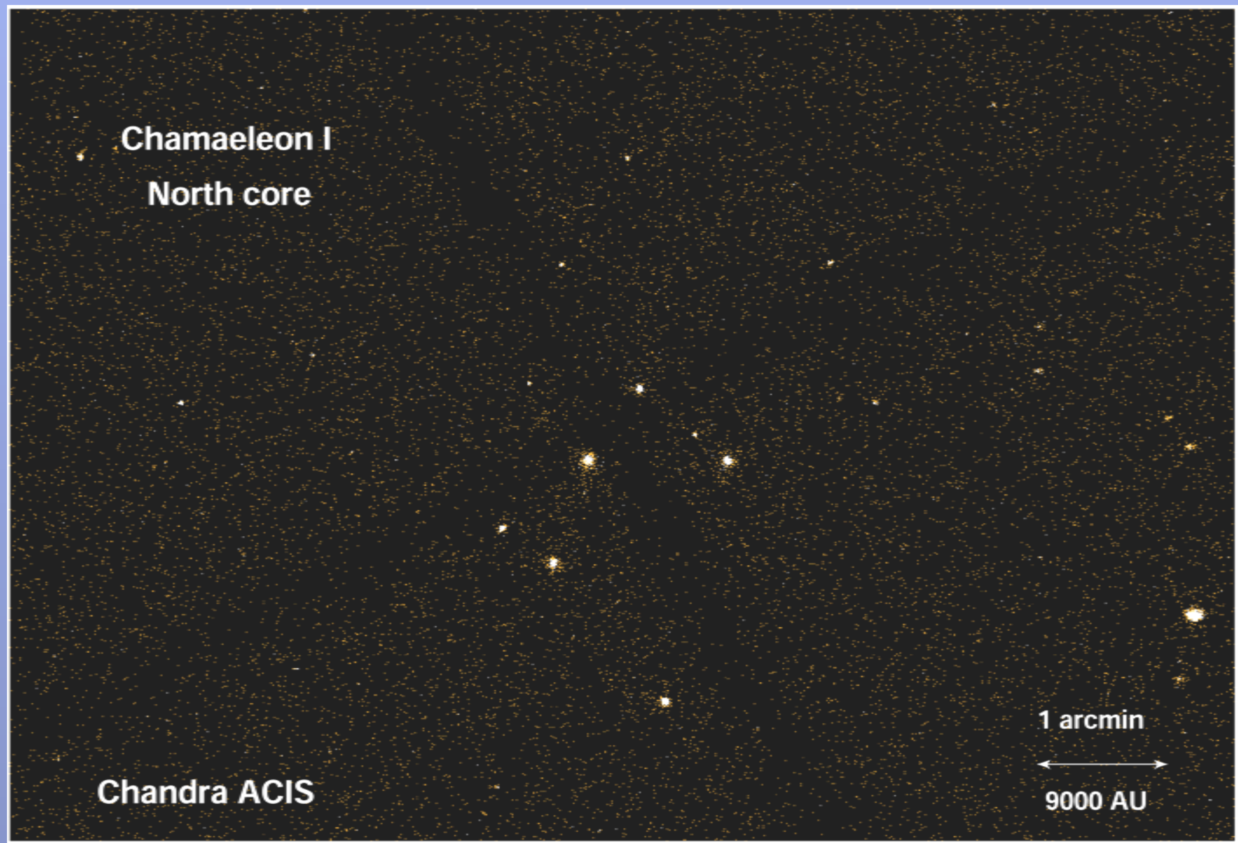
Feigelson et al. 1993

Chandra X-ray Observatory

1999—

<1” resolution Advanced CCD Imaging Spectrometer





Feigelson & Lawson 2004

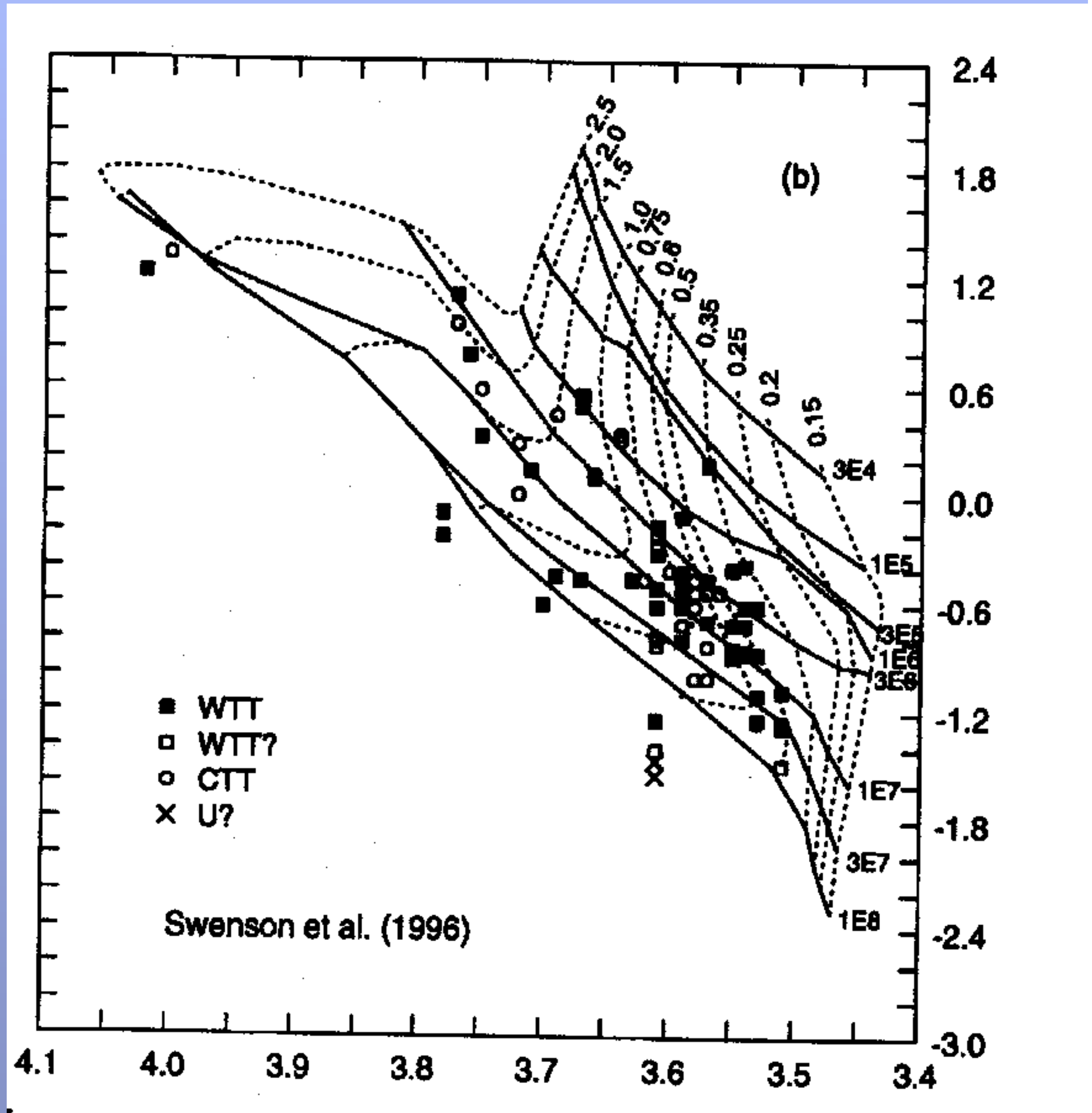
Cha I stellar population after ROSAT study:

Magnetic activity

Initial Mass Fn

SF history

Disk longevity

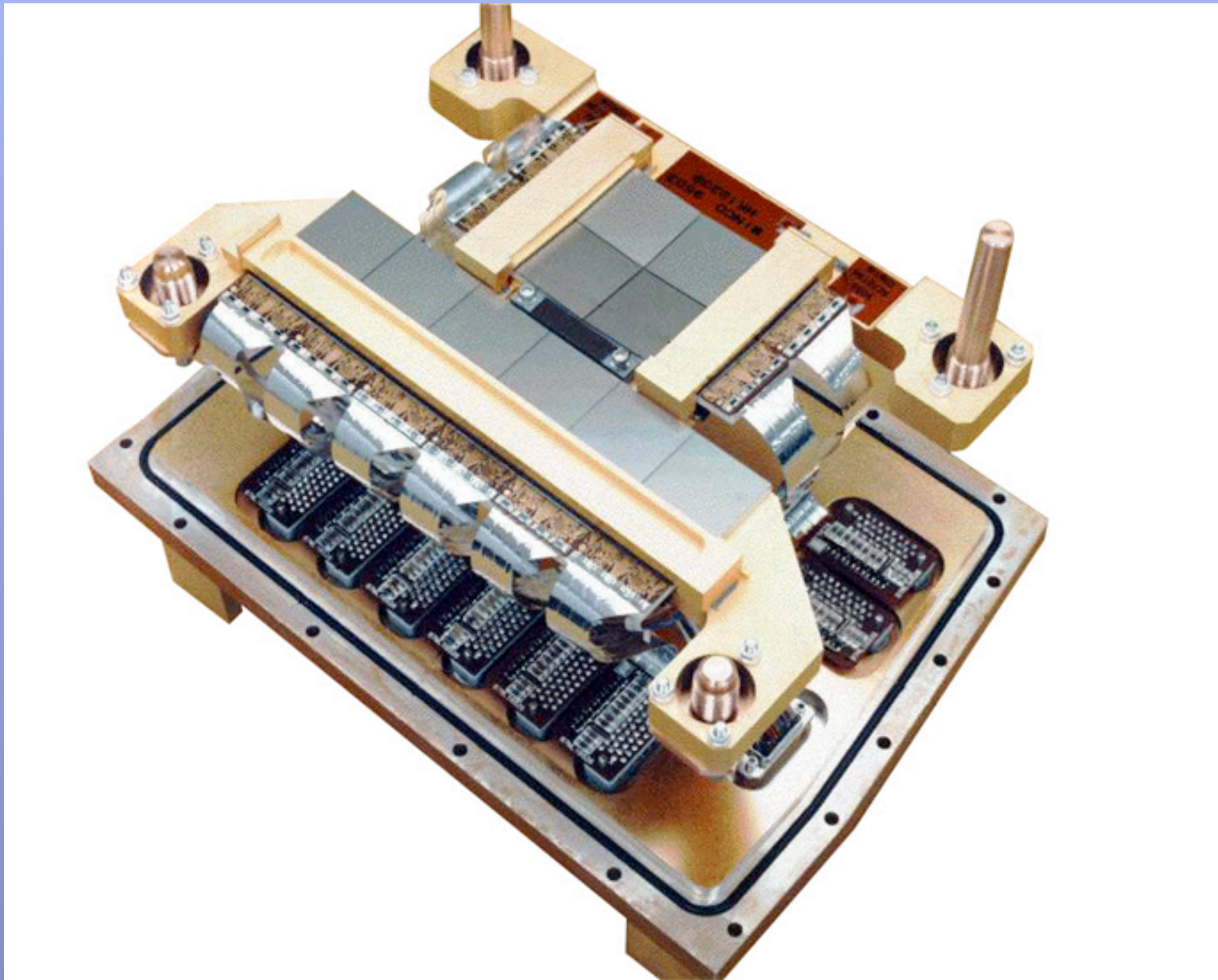


HR diagram *Lawson et al. 1996*

Chandra X-ray Observatory

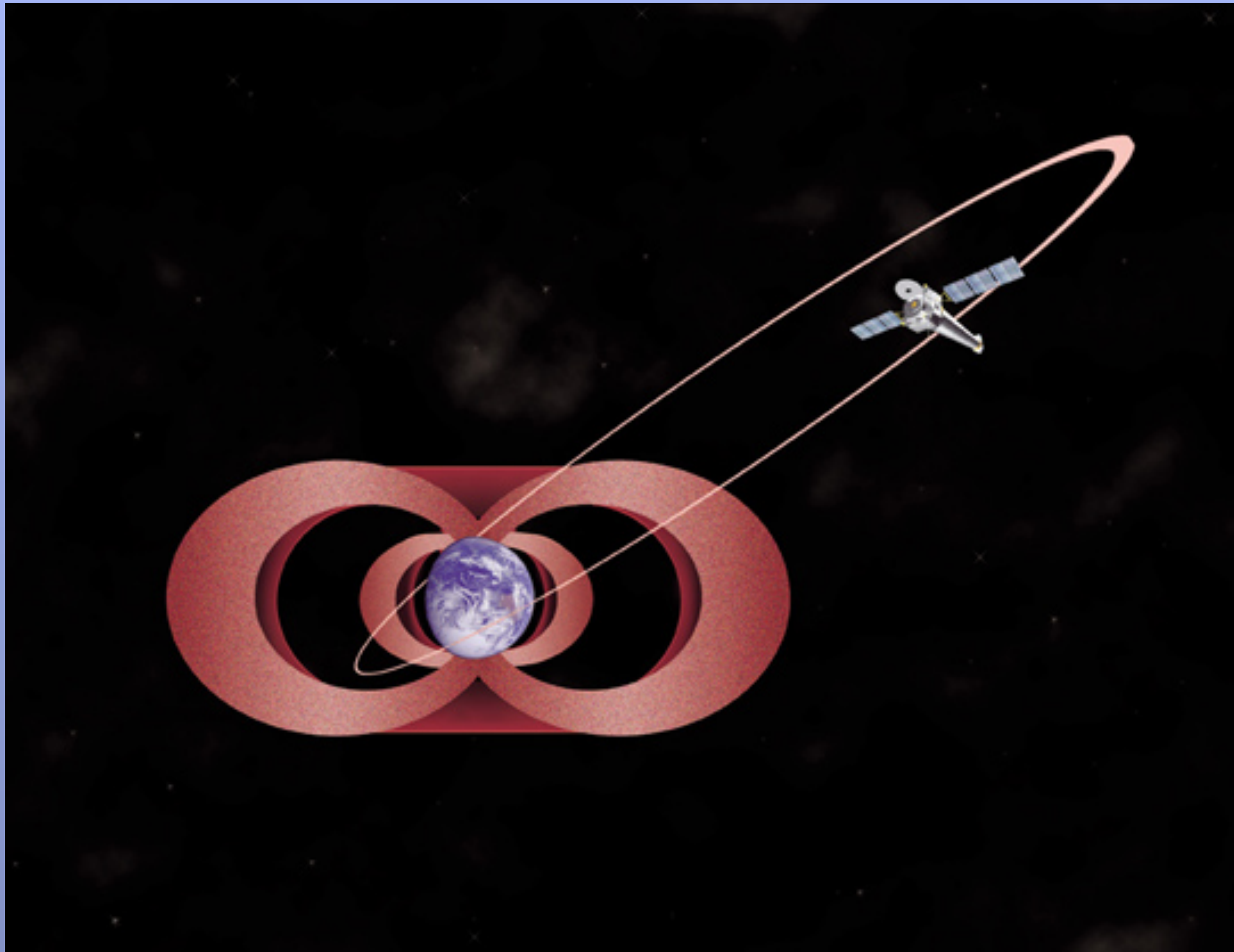
- NASA's 3rd Great Observatory (HST, GRO, CXO, SIRTF)
- Best mirrors ever produced in astronomy:
  <1" resolution on-axis, <0.3" astrometry
- Lead detector developed by Penn State & MIT:
  Advanced CCD Imaging Spectrometer (ACIS)
  4@1024x1024, high QE, ~ noiseless, $\Delta E/E \sim 20$
- Chandra is big (15m) with elliptical 2.3d orbit (1/3 to Moon).
  Operations are excellent.

Advanced CCD Imaging Spectrometer
(Penn State & MIT, G Garmire PI)



Chandra X-ray Observatory

Chandra in Orbit



Star forming regions imaged in X-rays

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

D > 3 kpc

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

0.5 < D < 3 kpc

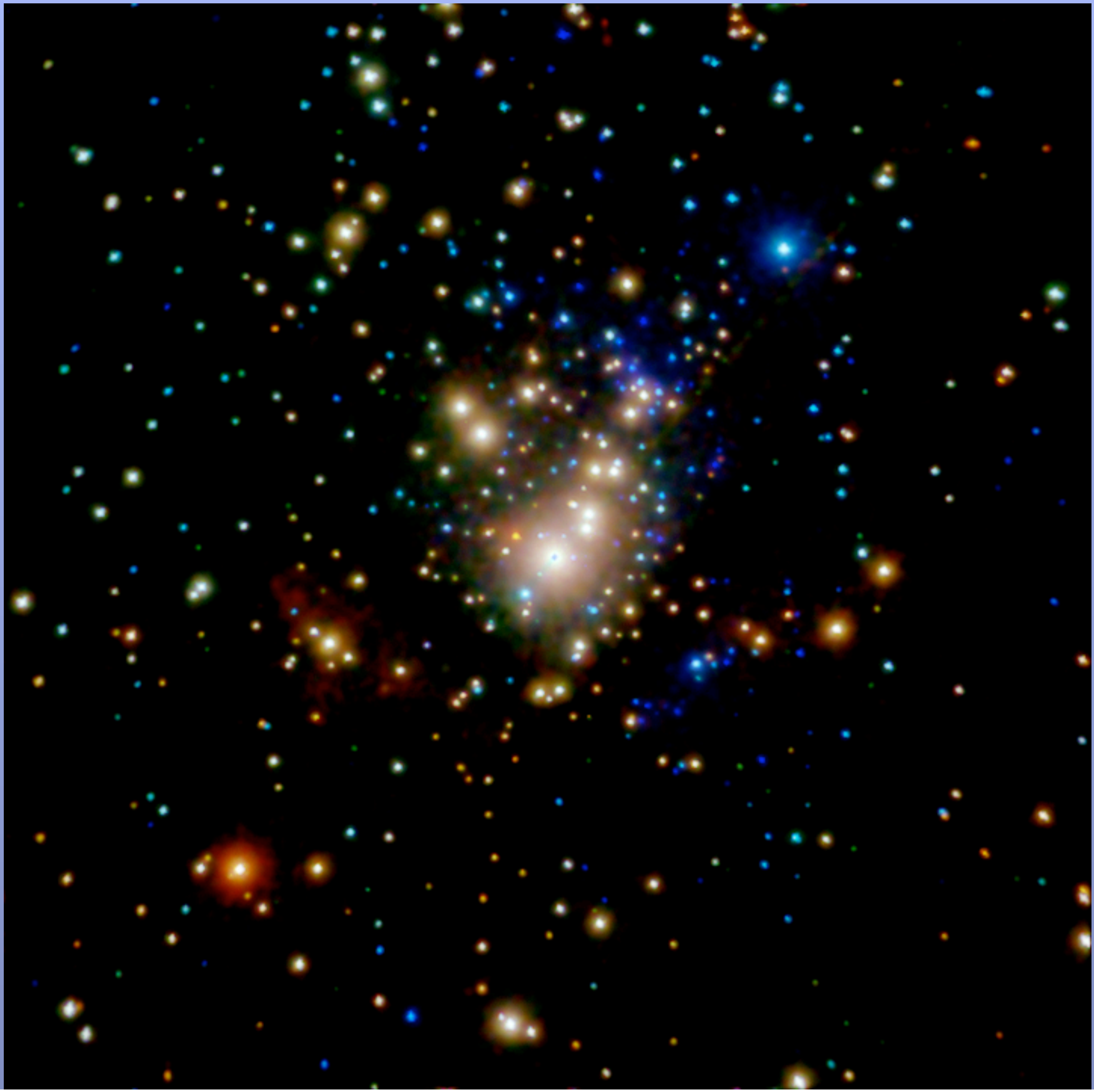
W3, 4, 5, 40
Carina
M8, 16, **17**
NGC 3576, 6334, 6357,7538
Trifid, Rosette, IC 1396,

RCW 36, 38, 49, 108 & LkHa 101
Cyg OB2, Cep OB3, Cep A

Bold = Large Project

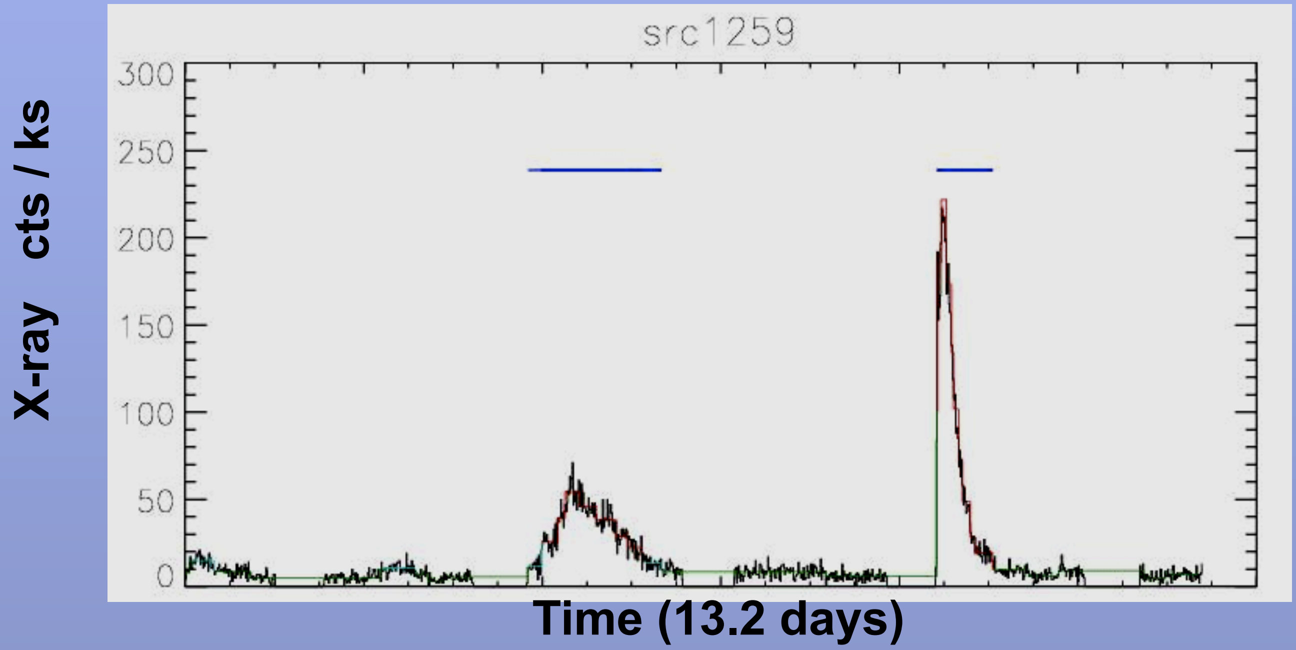
Red = Penn State

COUP: The Image



COUP: The Movie

Extraordinary flares in Orion pre-main sequence stars



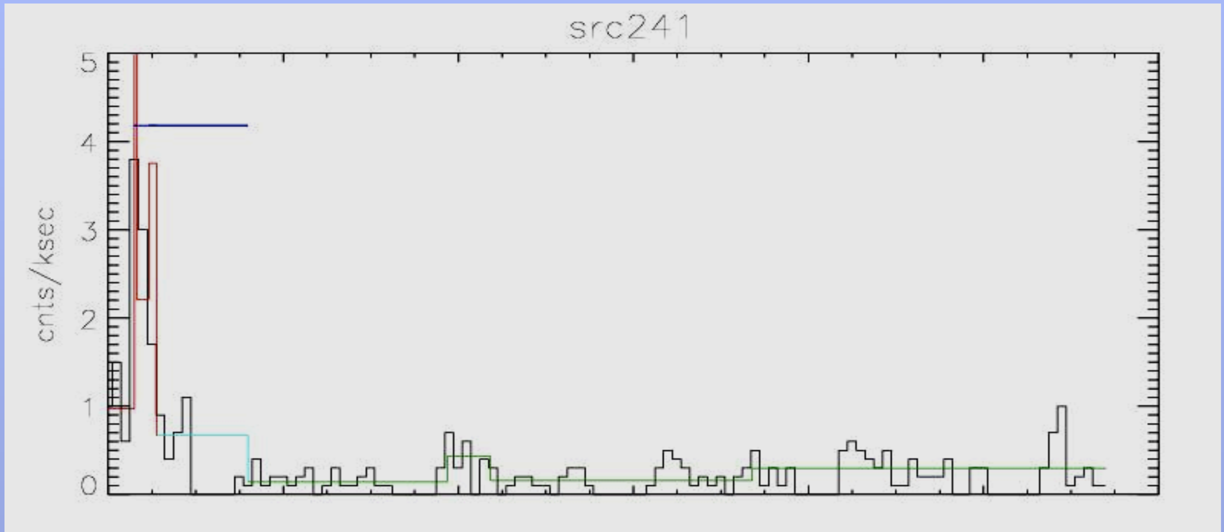
JW 738

K=10.5
Age ~ 10 Myr
Mass ~ 1 Mo

log Lp = 32.6 erg/s

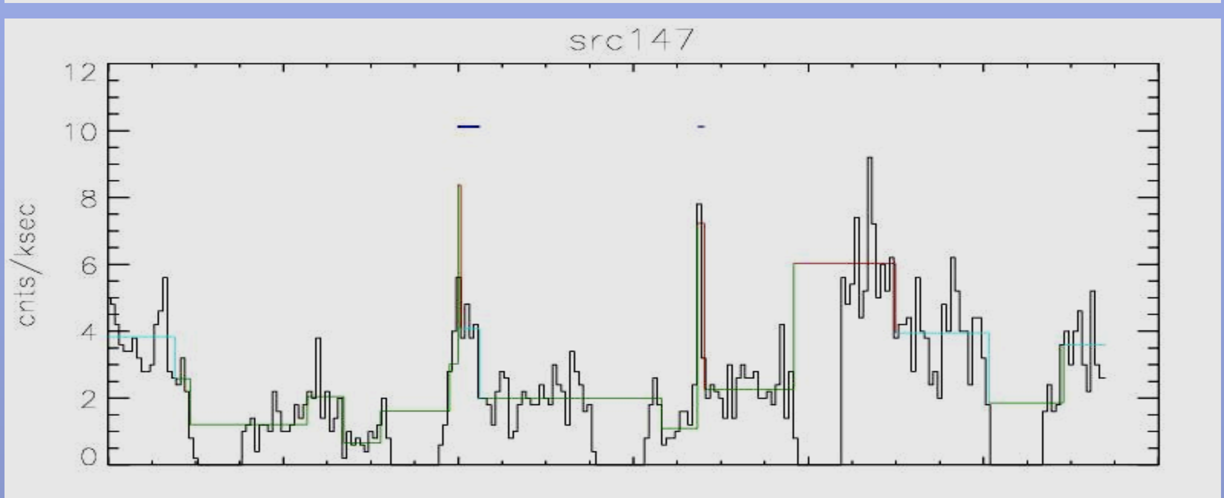
Wolk & 7 others 2005 COUP #6

Two weaker solar analogs



JW 268
K=10.8
Age=3 Myr

log Lp = 29.5 erg/s

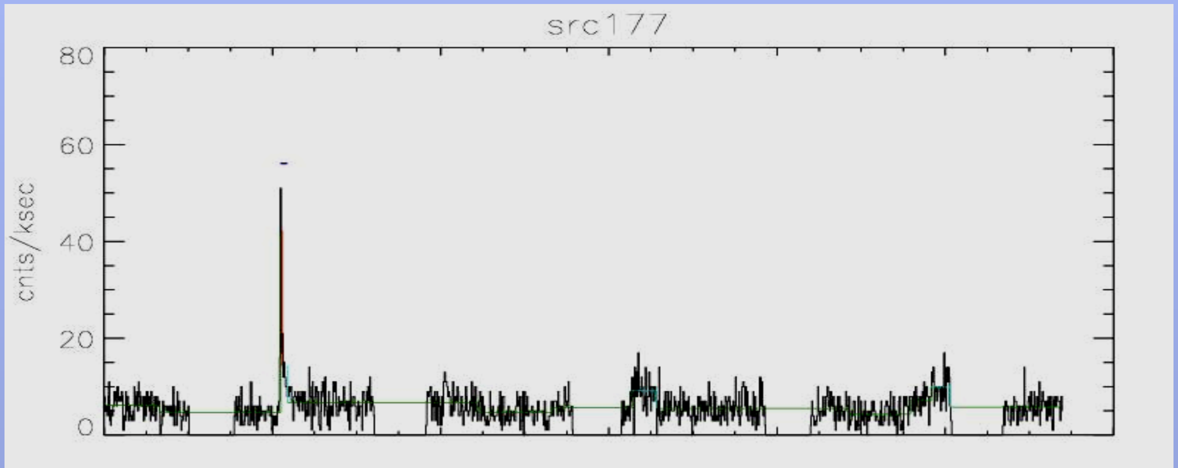


JW 198
K=10.4
Age=15 Myr
Proplyd, K excess

log Lp = 29.9 erg/s

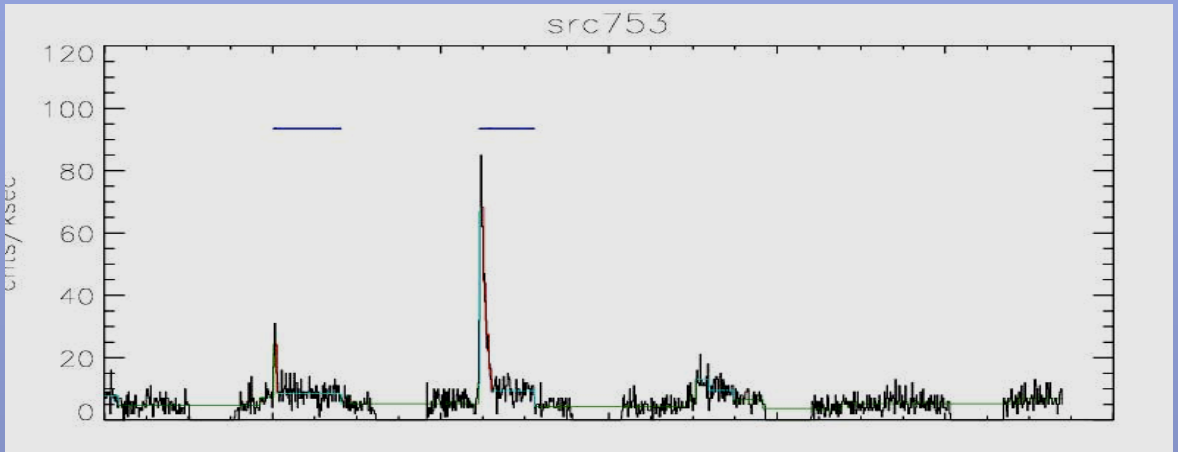
Even weak COUP flares are ~10x stronger than the most powerful flares from the contemporary Sun.

Short flares in solar analogs



JW 223a
V=16.1 K=10.1
Age=2 Myr
K excess

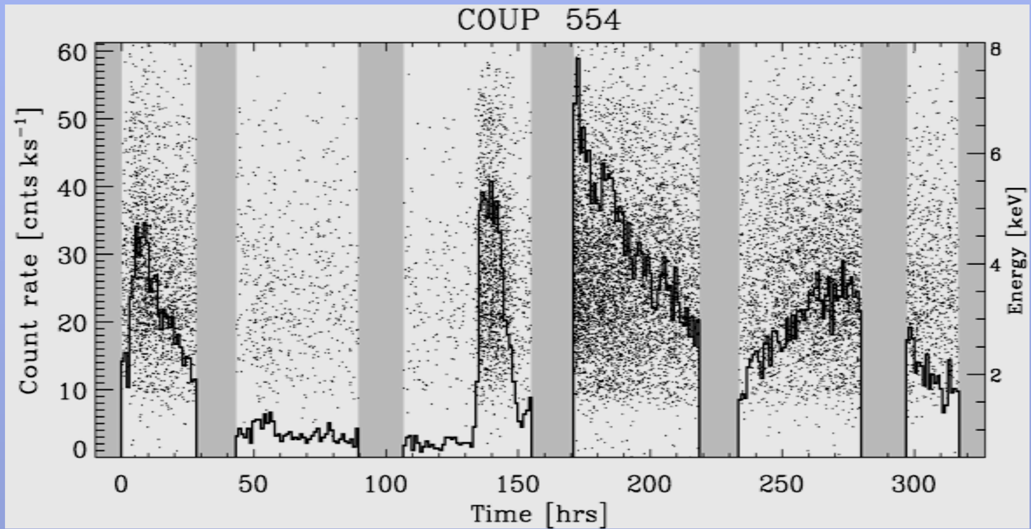
log Lc = 30.3 erg/s
log Lp = 31.2 erg/s

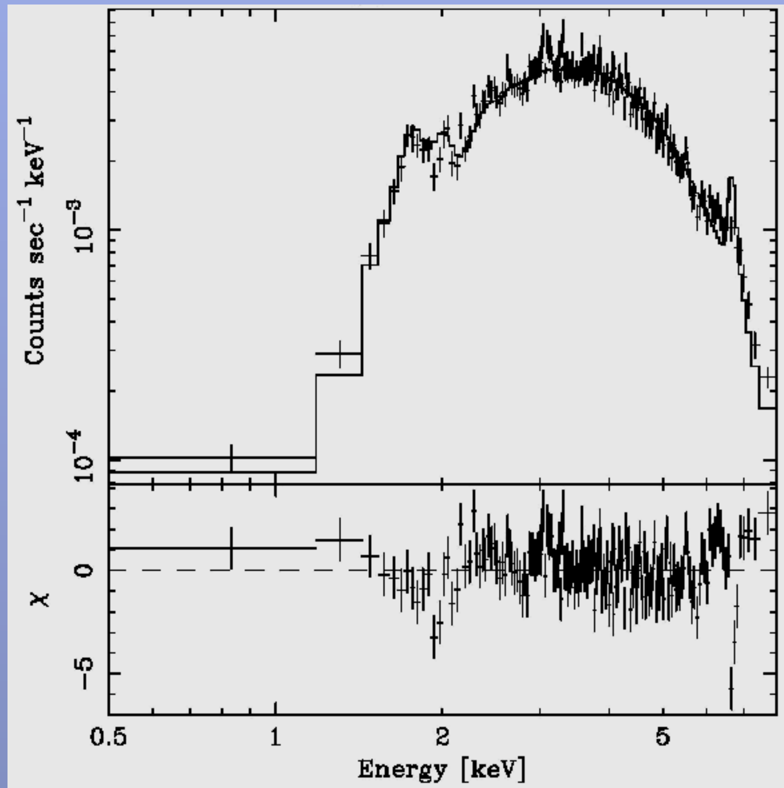


JW 487
V=14.6 K=10.3
Age=2 Myr

log Lc = 30.1 erg/s
log Lp = 31.4 erg/s

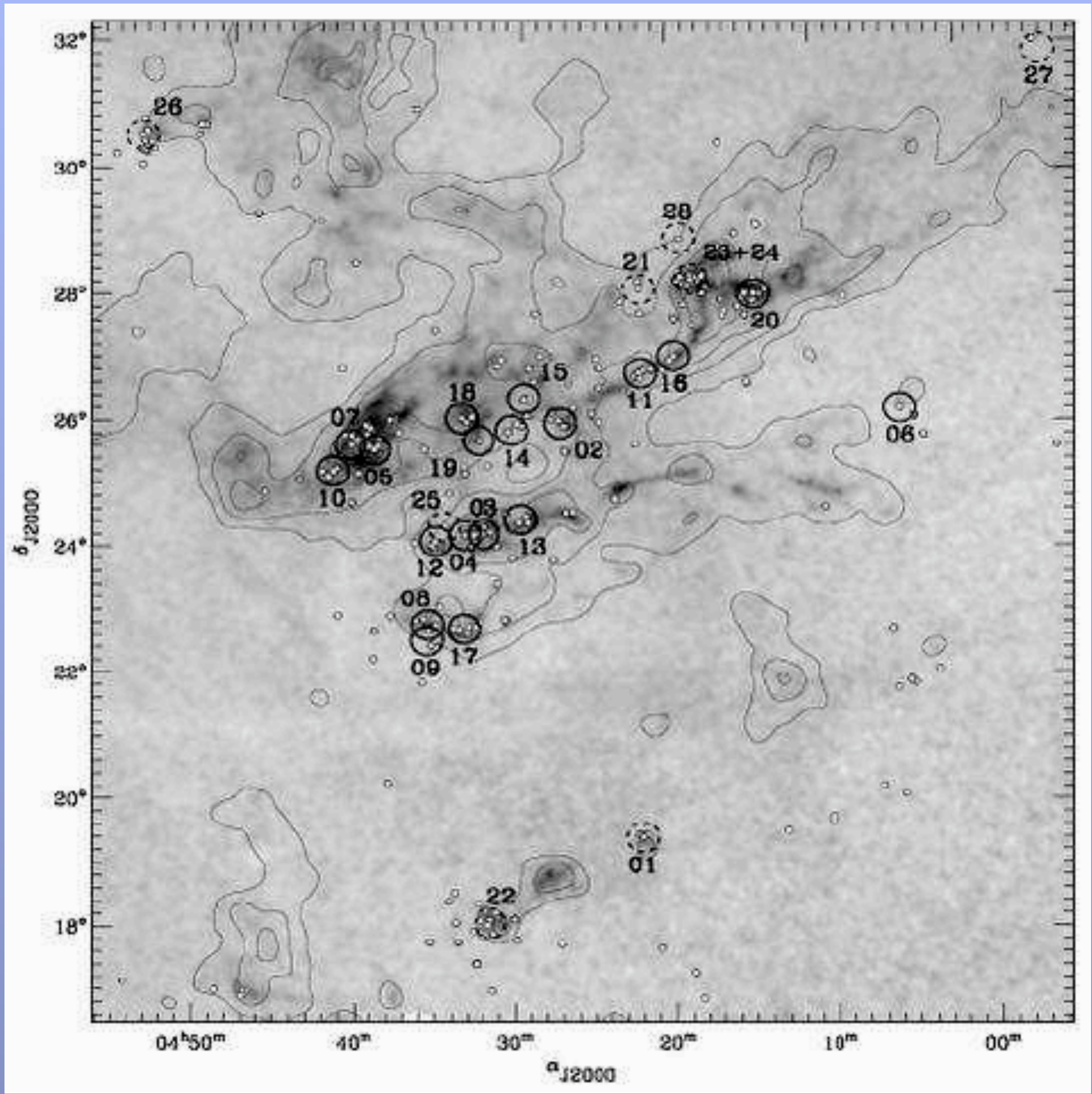
COUP lightcurve and spectrum of an embedded protostar in OMC 1-South





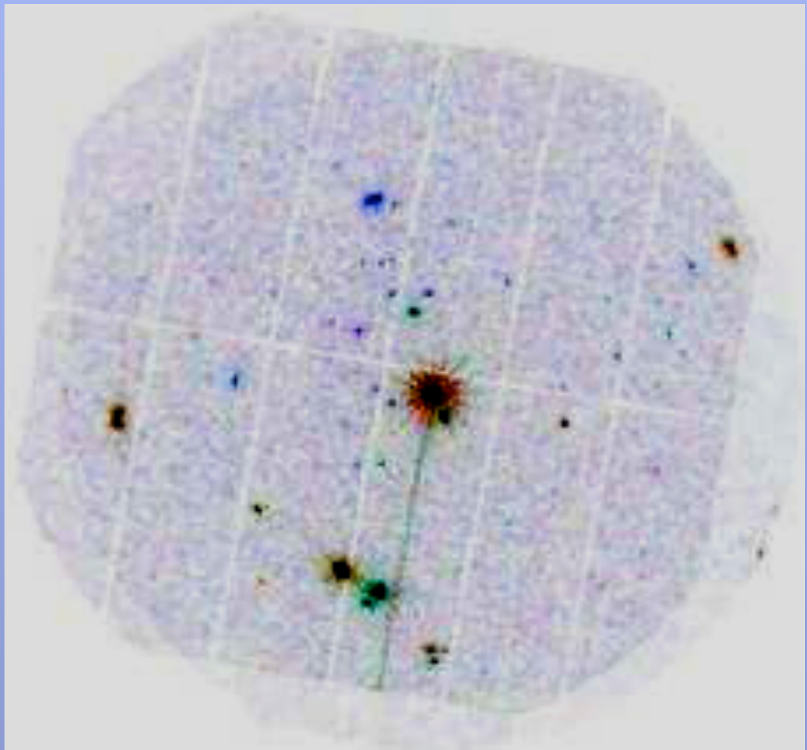
Grosso et al. 2005 COUP #11

XMM Extended Survey of Taurus (XEST)

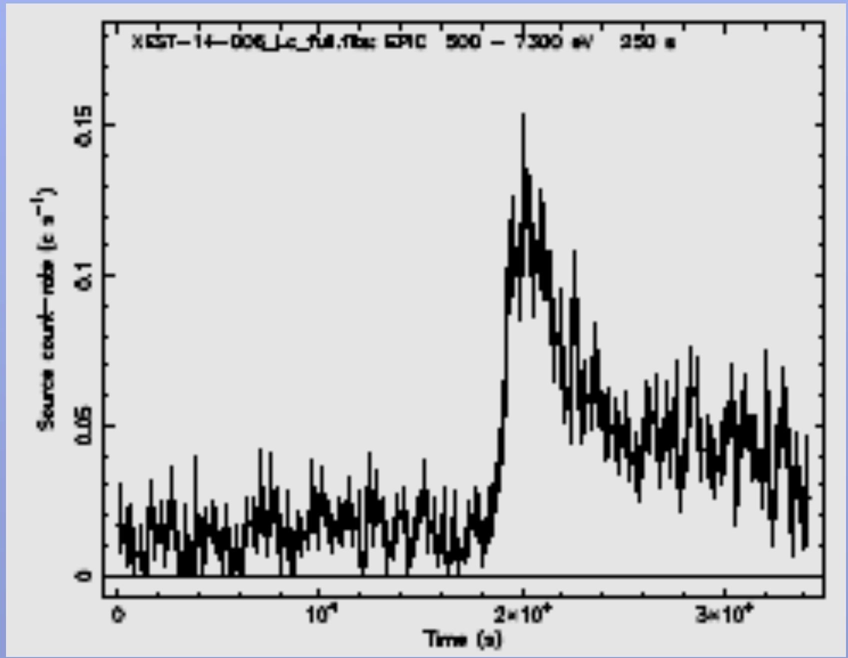


Guedel et al. 2007

XEST field of L1495 cloud

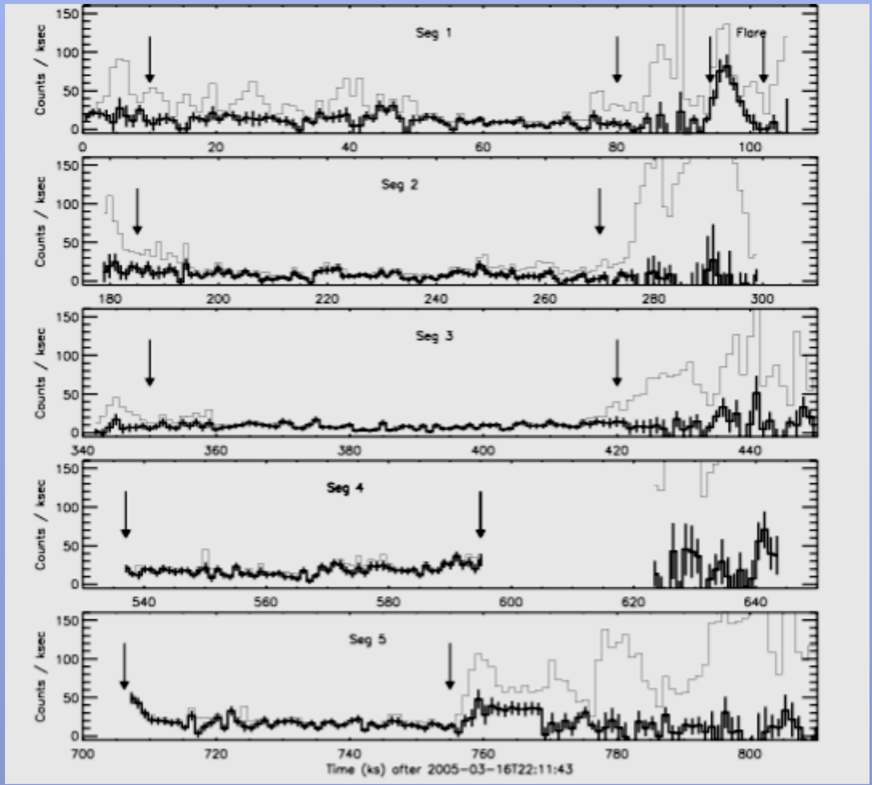


XEST flare of a classical TTS



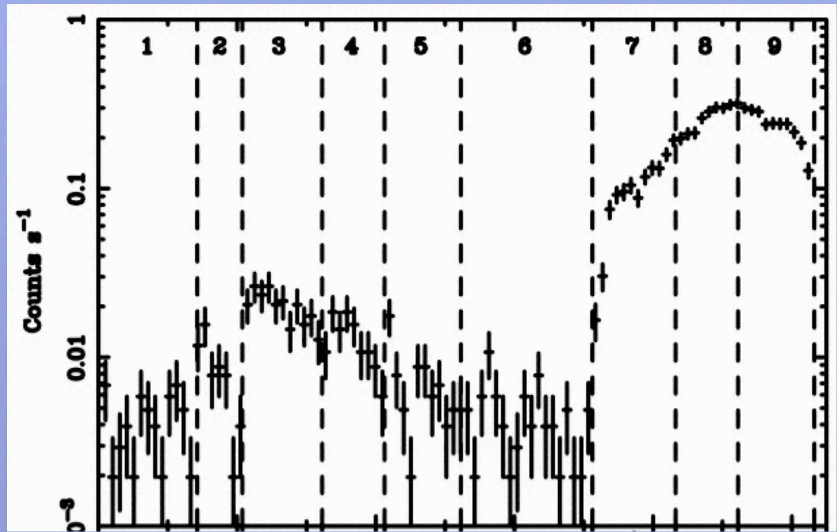
More examples of pre-main sequence X-ray lightcurves

Smaller flares on Class II star



XMM DROXO, 9 days   Giardino et al. 2007

Powerful Class I protostellar flare

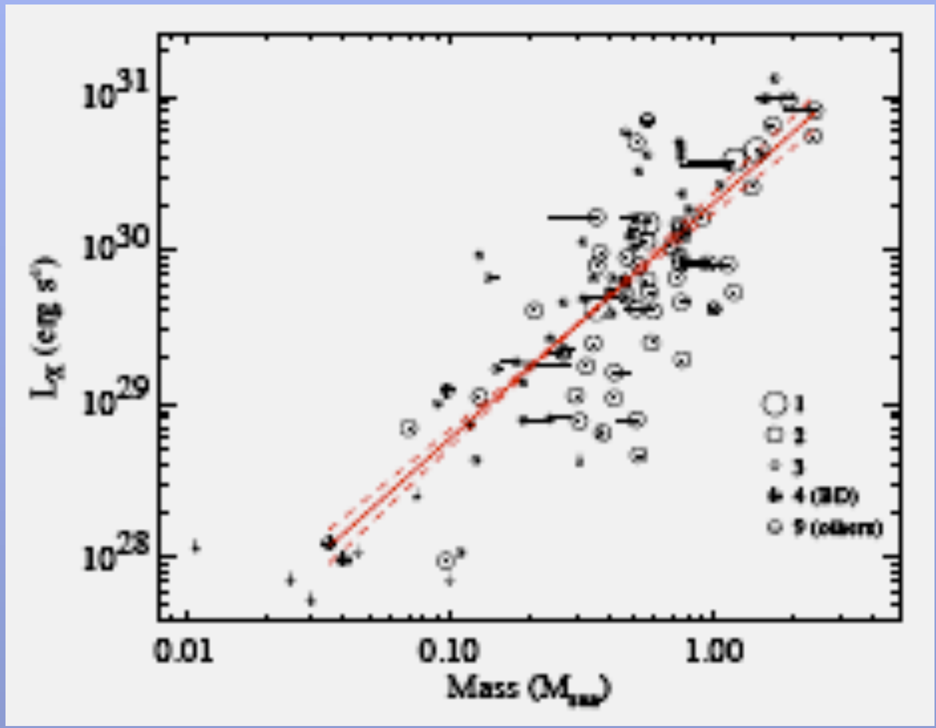


Chandra YLW 16A superflare, 1.2 days
Imanishi et al. 2001

X-ray characteristics of young stars

Powerful flares releasing up to 10^{36} erg in the 0.5-8 keV band occur every few days. Many weaker flares dominate the "quiescent" emission. Flares occur every few days and last ~2-20 hrs. Total flare irradiation is roughly 10^2 (intensity) x 10^2 (frequency) ~ 10^4 times Sun today.

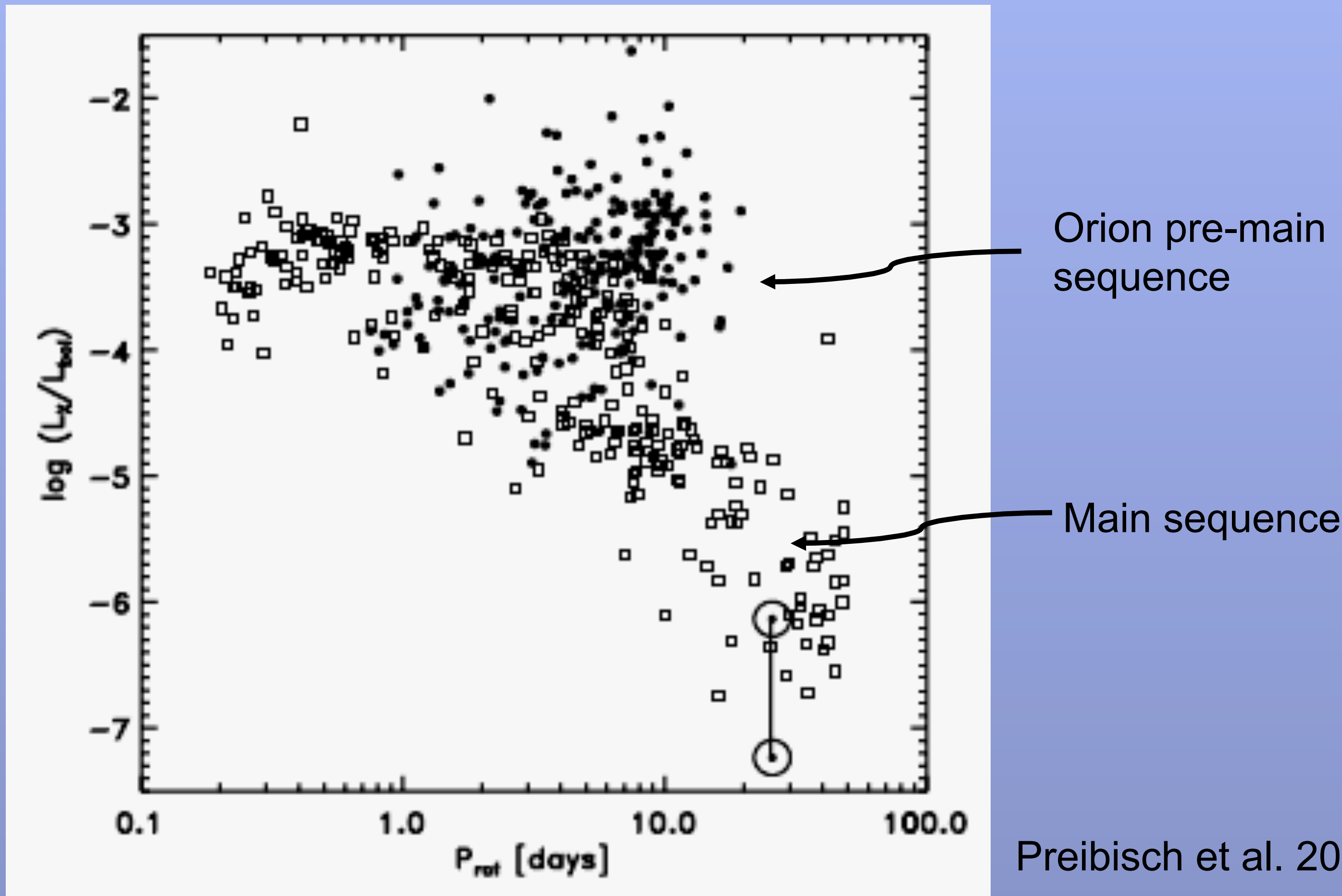
X-ray emission scales with stellar mass & volume. Reason unclear … probably related to magnetic dynamo processes in stellar interior.



Telleschi et al. 2007 XEST

Preibisch et al. 2005 COUP #4 Preibisch et al. 2005 COUP #5 Wolk et al. 2005 COUP #6 Favata et al. 2005 COUP #7 Flaccomio et al. 2005 COUP #8 Guedel et al. 2007 XEST #1 Maggio et al. 2007 COUP #17 Stelzer et al. 2007 XEST #5

Pre-main sequence X-rays do *not* show the dependence on stellar rotation seen in main sequence stars

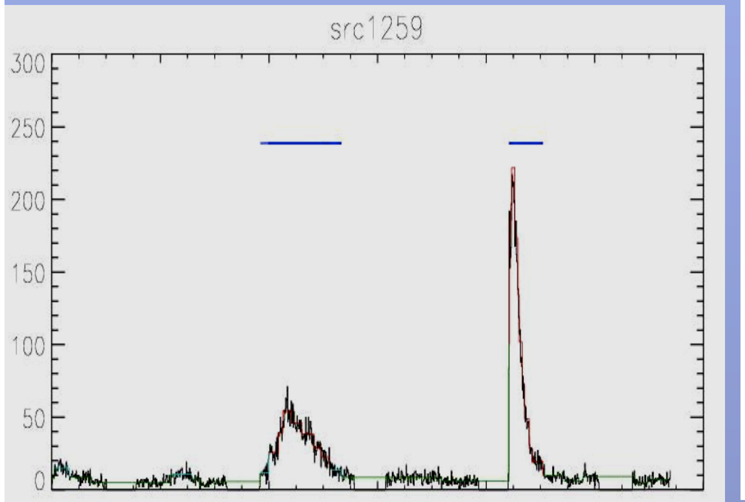


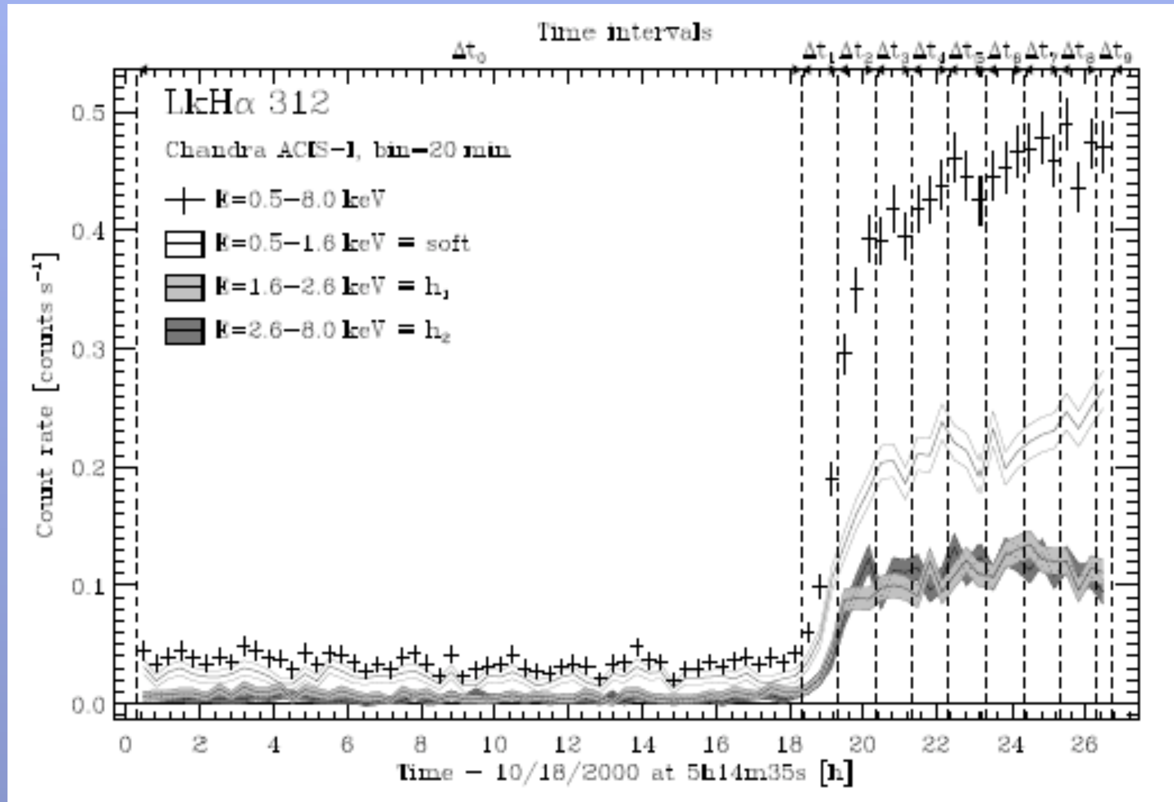
Preibisch et al. 2005

(suggests PMS stars have distributed convective dynamos)

What causes the slow-rise flares?

Unusual flare evolution in two older T Tauri stars



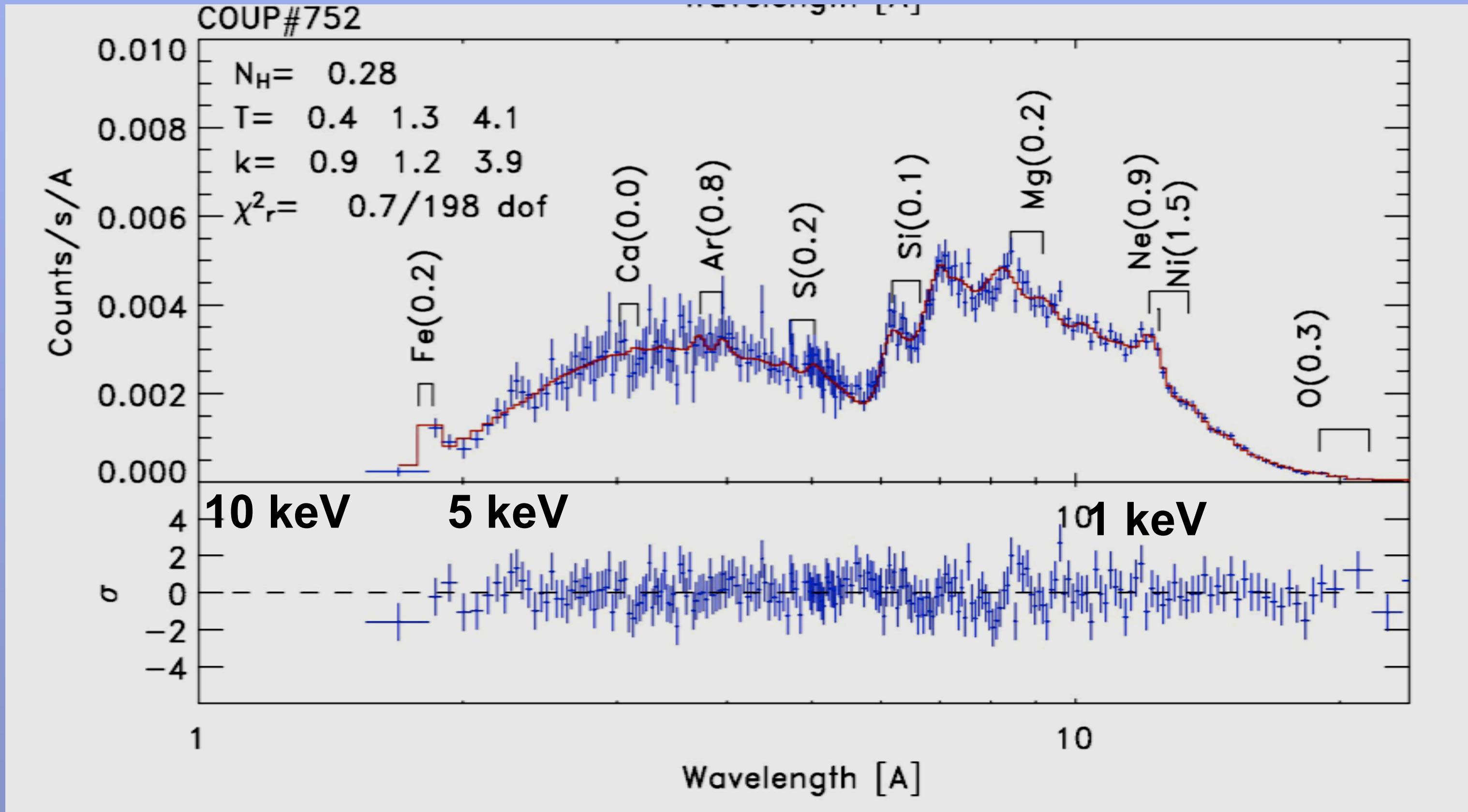


Wolk et al. 2005

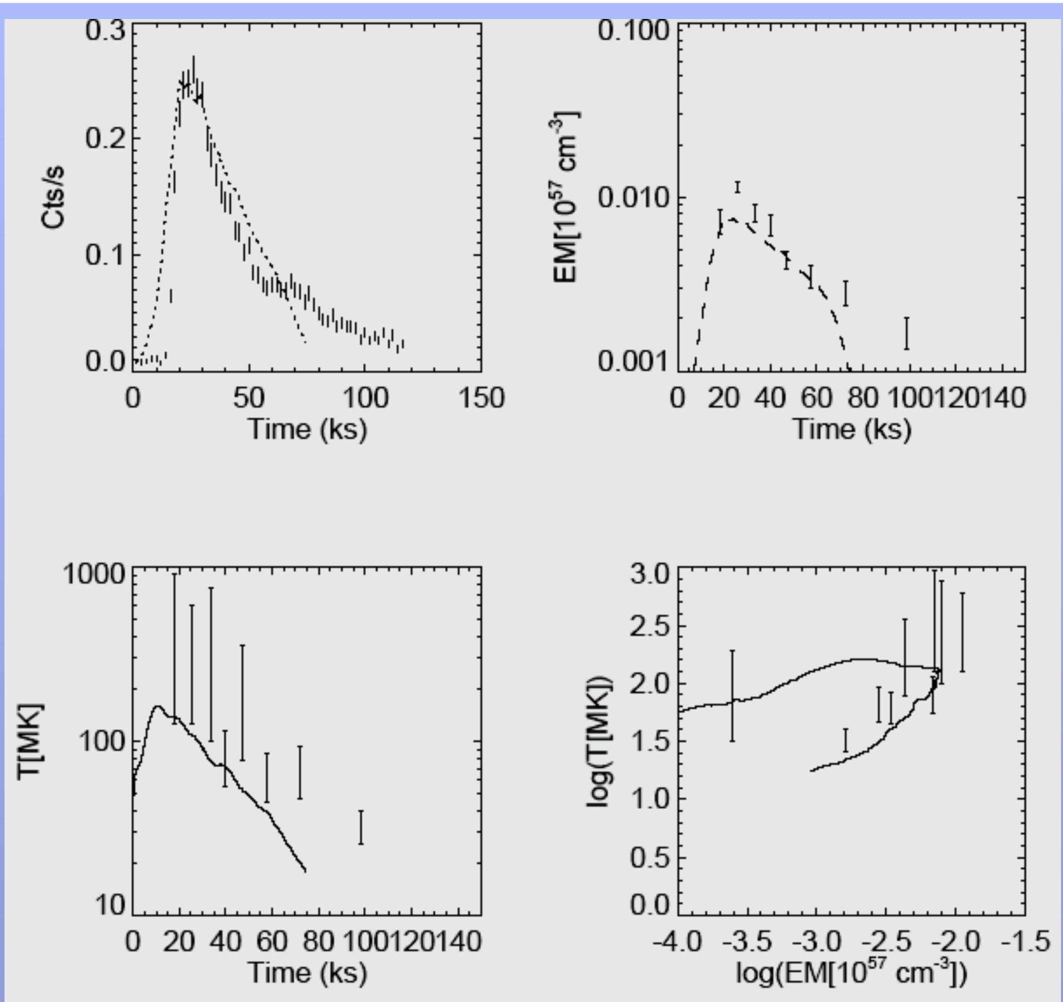
Grosso et al. 2004

X-ray spectra are modeled with a range of temperatures

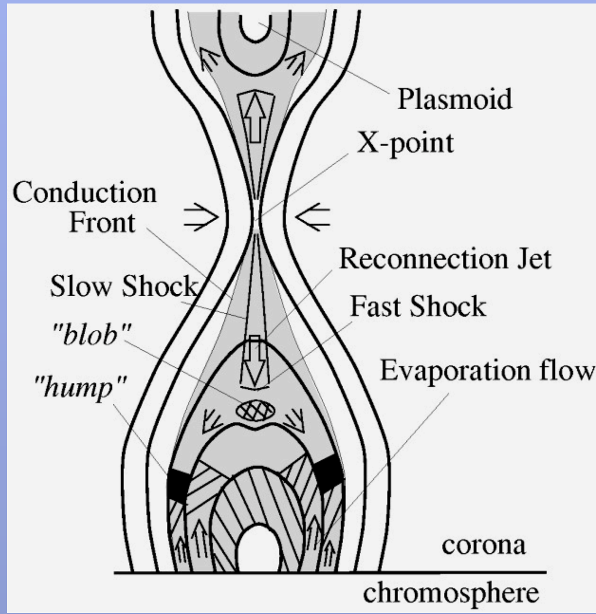
and with abundance anomalies similar to older flaring stars



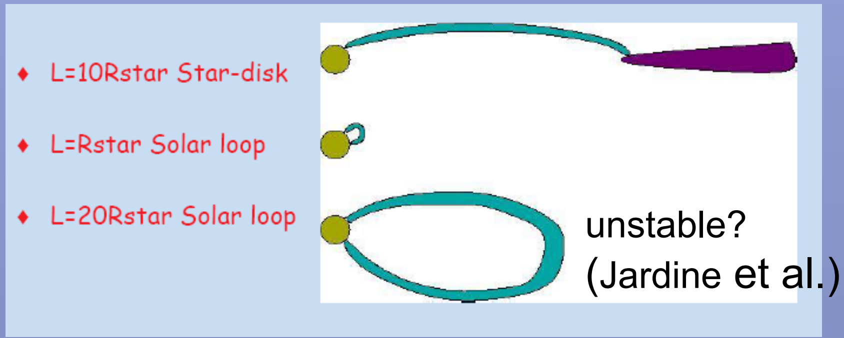
Maggio et al. 2007 COUP #17



The brightness/spectral evolution of COUP flares are well-fit by a simple solar plasma loop model (Reale et al. 1997)

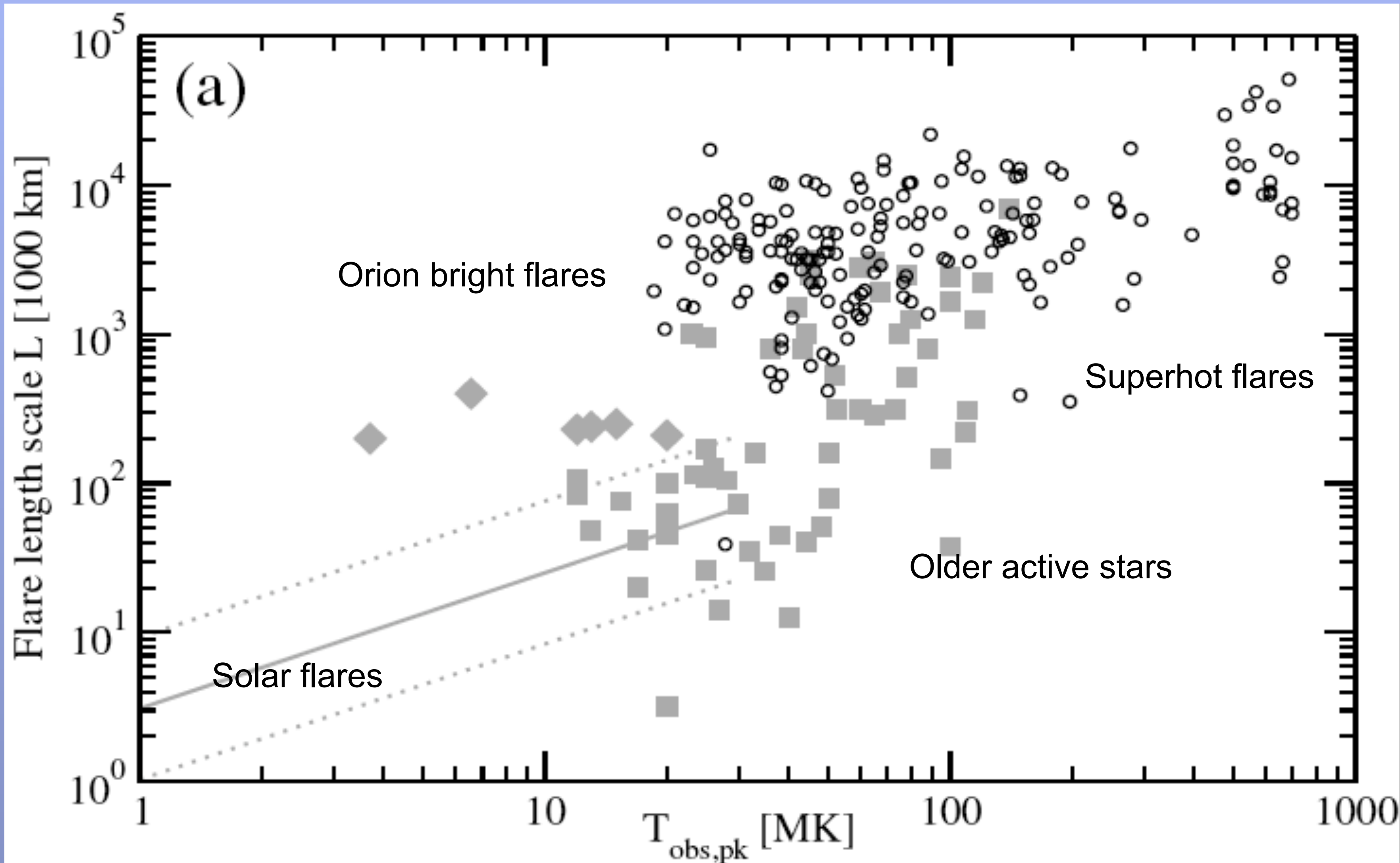


Brightest COUP flares require giant loops ~10 R_* ! Does this imply star/disk magnetic fields?



COUP flare modeling: Favata et al. 2005, Getman et al. 2008a

Some T Tauri flares are extraordinarily hot and arise in extraordinarily large loops



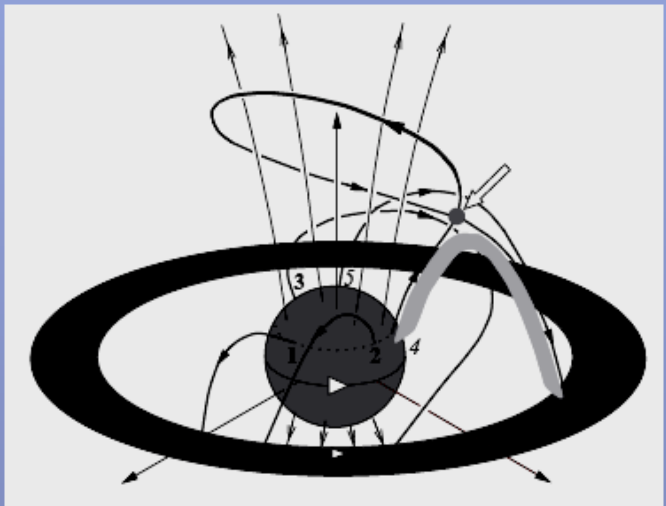
Getman et al. 2008a

Are the X-ray flares from star-disk fields?

Pro

Solar-type star-star magnetic loops may be centrifugally stripped in rapidly rotating stars (Jardine 2004)

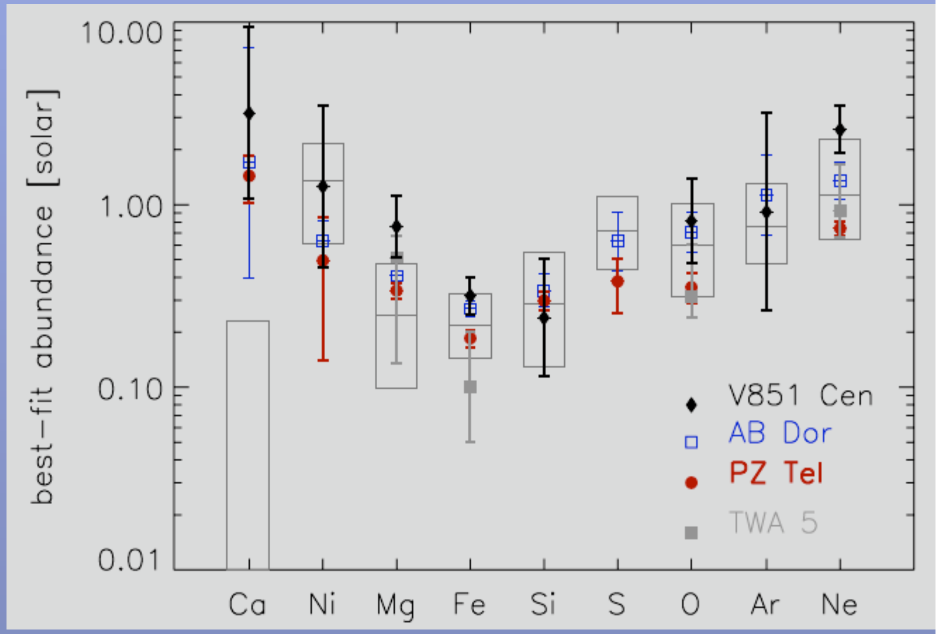
Star-disk field lines are plausibly twisted by differential rotation (Montmerle et al. 2000; Uzdensky et al. 2002ab)



Con

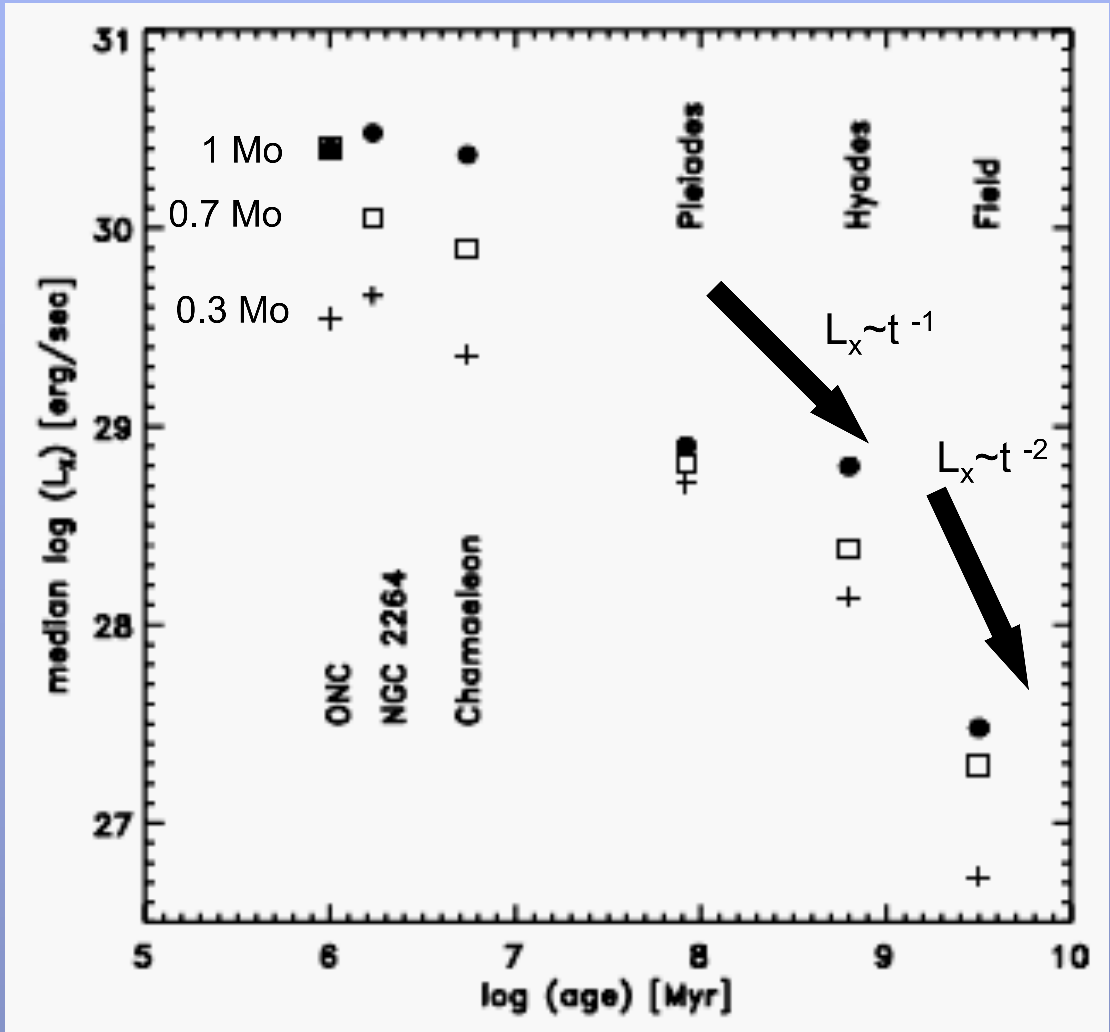
COUP flare properties strongly resemble solar/stellar flares: fast rise, cooling decay, power law energy distribution.

COUP flare plasmas also show FIP-related elemental abundances similar to older stars (Maggio et al. 2007)



Evolution of X-ray emission with stellar age

(0.5-8 keV band, mostly flares)



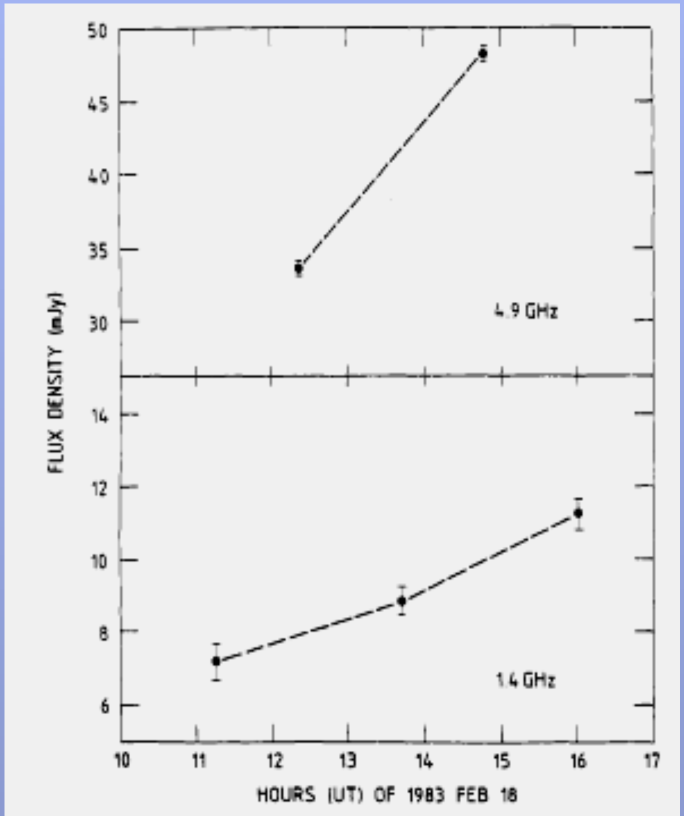
Preibisch & Feigelson 2005
Feigelson et al. 2004

MeV particles in young stellar flares

Solar flares produce MeV-GeV particles during the brief impulsive phase immediately following magnetic reconnection and later during coronal mass ejection. Radio gyrosynchrotron from $\Gamma \sim 1$ electrons spiralling in magnetic fields is produced with high amplitude variability and strong circular polarization.

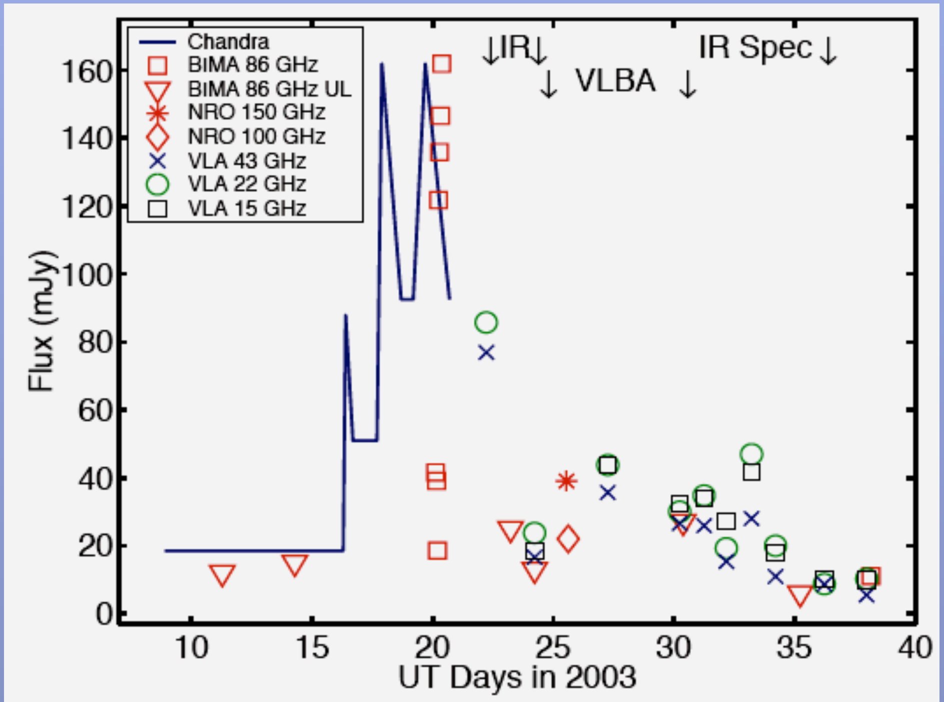
Radio gyrosynchrotron emission is seen in a variety of magnetically active stars: dMe flare stars, RS CVn binaries, and T Tauri stars. An empirical linear relationship Lx~Lr is seen over a range of ~108 from solar microflares to T Tauri superflares (Guedel & Benz 1993).

Centimeter flare from Class III star DoAr 21in Ophiuchus



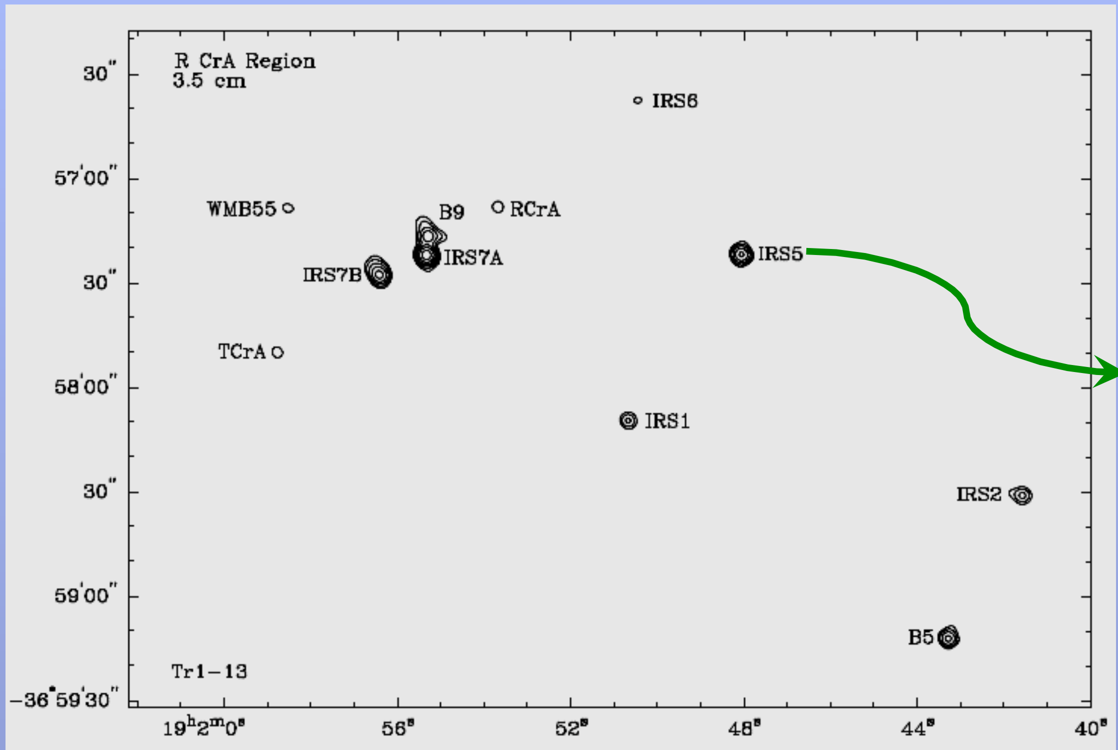
Feigelson & Montmerle 1986

Microwave flare from Class III star GMR-A on far side of Orion cloud

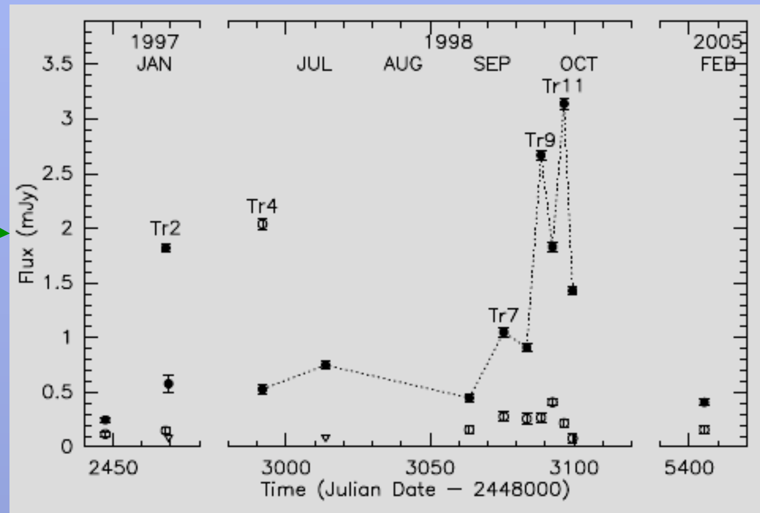


Bower et al. 2003

VLA radio continuum image of the R CrA cloud

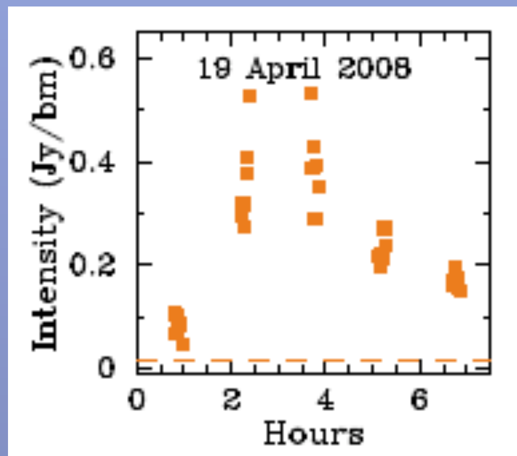


Flares from Class I binary IRS 5



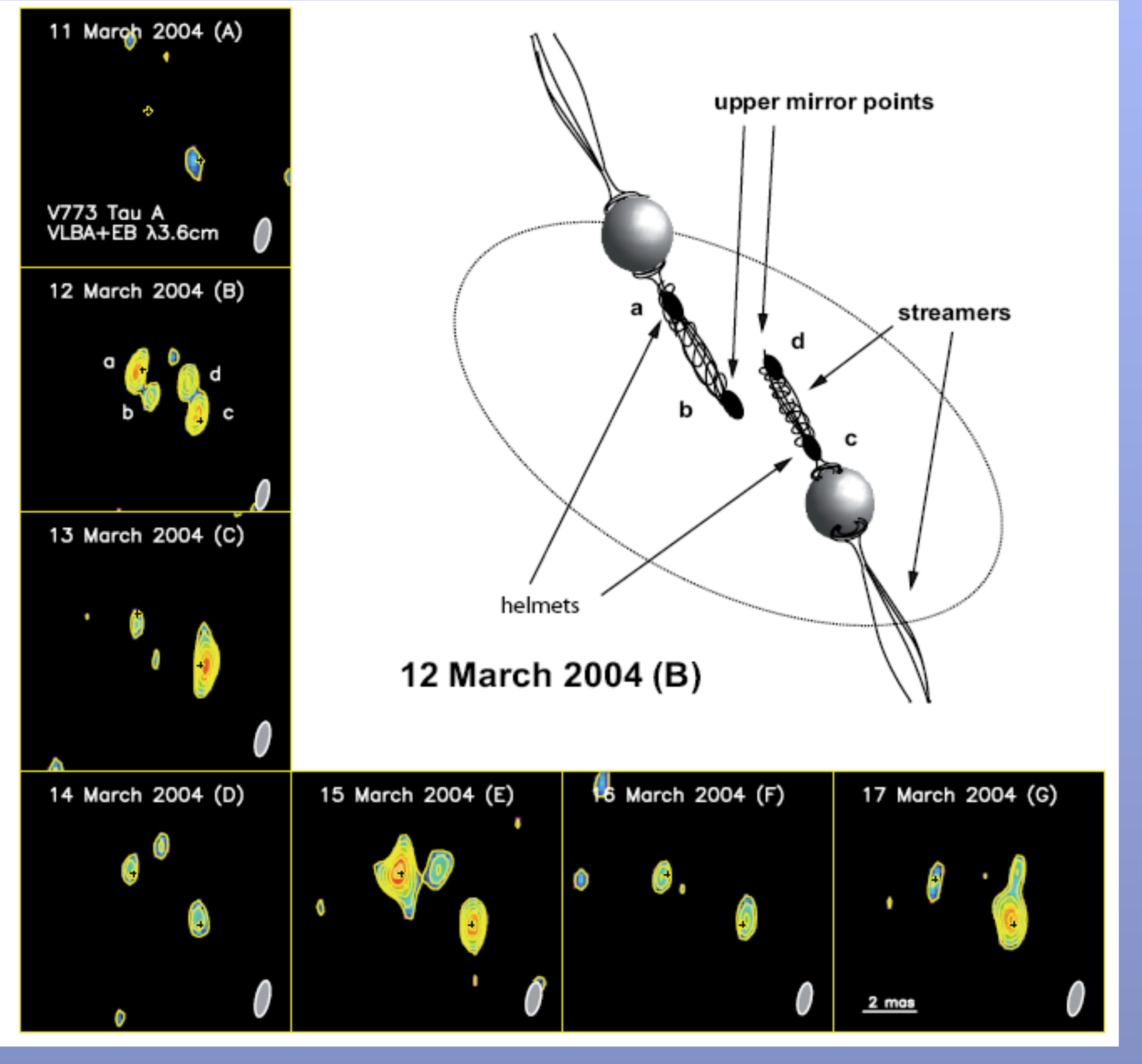
Choi et al. 2008

Radio flare from Class II binary DQ Tau



Salter et al. 2008

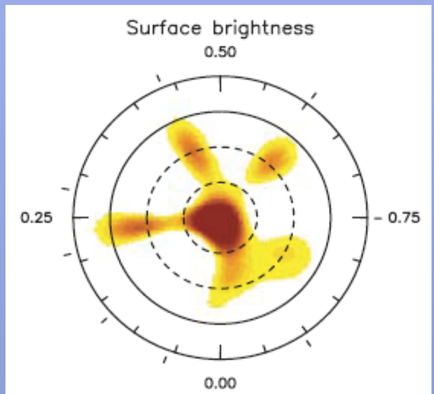
VLBI study of MeV electrons in large-scale magnetic structures in the Class III multiple V773 Tau

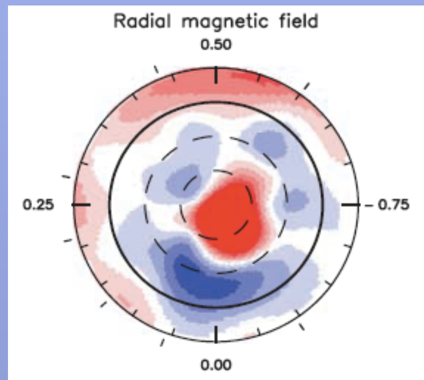


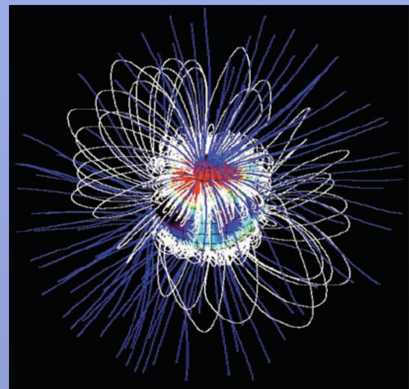
Massi et al. 2008

Other evidence for strong magnetic fields in T Tauri stars

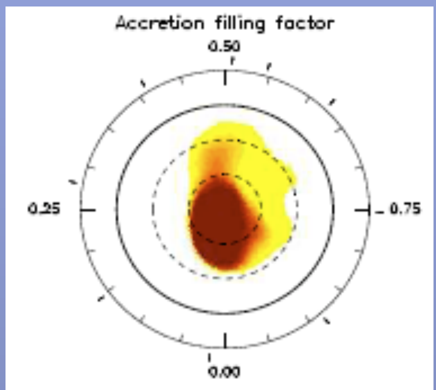
- Photometric modulation of huge cool star spots in Class III stars
- Zeeman splitting of photospheric lines, Bf~2 kG
- Doppler imaging of starspots
- Circular polarization & Zeeman Doppler imaging

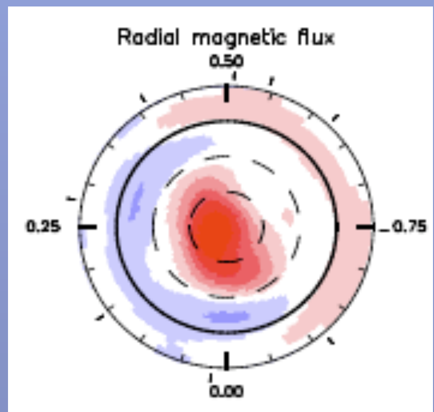


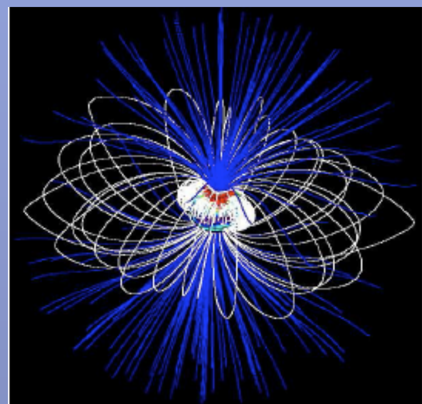




V2129 Oph







BP Tau

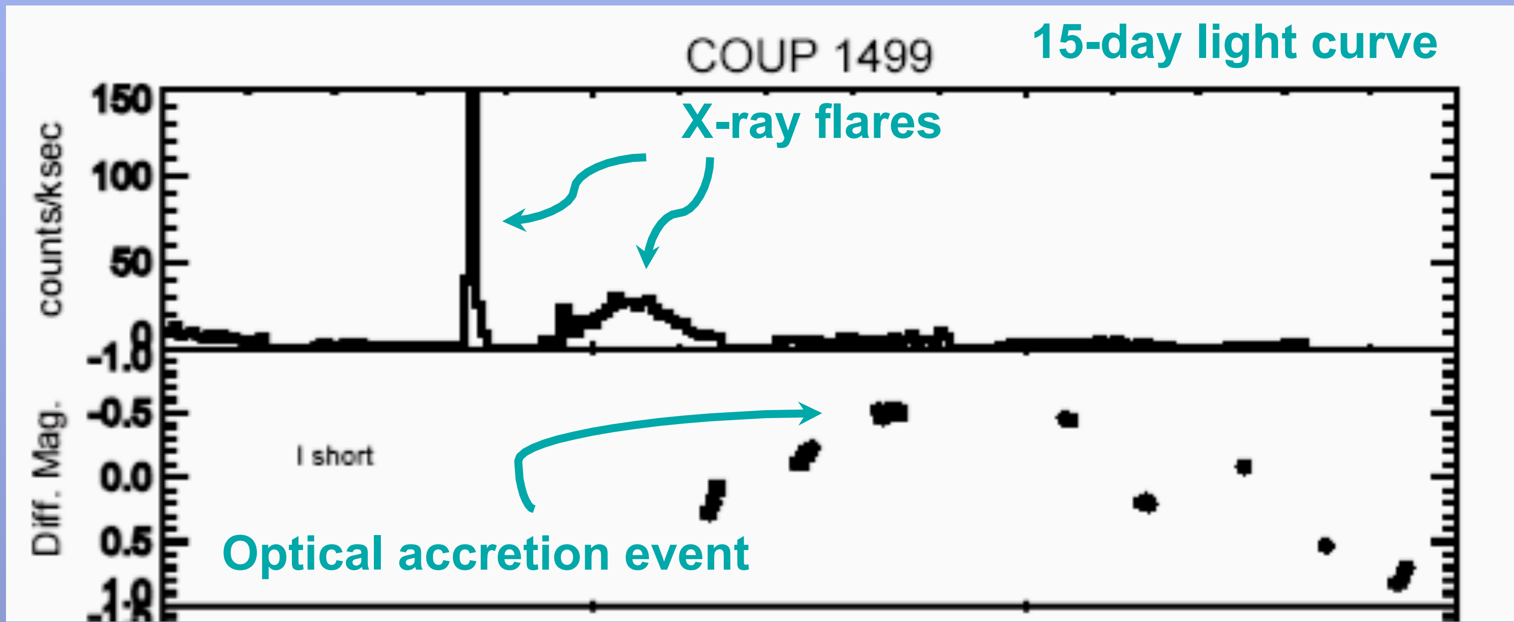
Donati et al. 2007, 2008

The enhanced magnetic activity model for pre-main sequence stars is strongly established

- Clear optical photometric/spectroscopic evidence for strong surface fields (progress with ESPADONS)
- X-ray flares are solar-like but orders of magnitude stronger and more frequent (progress with Chandra)
- Radio flares are sometimes seen, and giant magnetospheres occasionally imaged (progress with EVLA starting ~2011?)

- Questions regarding flare loop geometries: single-loops with ~10 R_*?
- Questions regarding internal magnetic dynamos

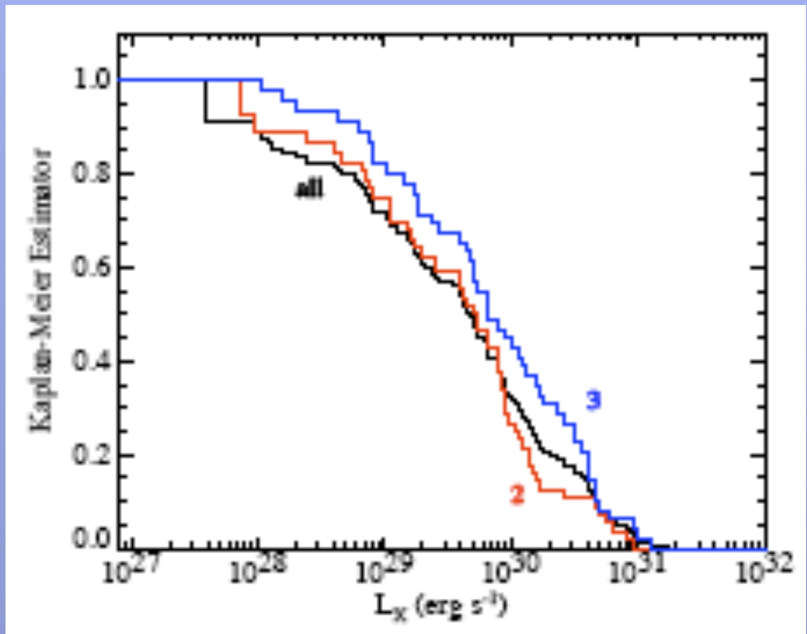
Pre-main sequence X-rays at E>1 keV are not produced by the accretion process

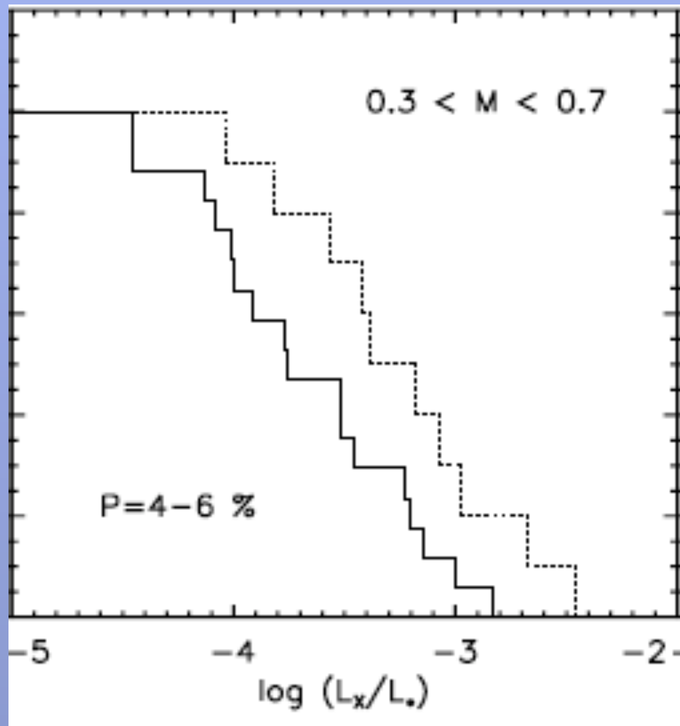


No relation seen between X-ray flares and accretion variations in ~800 simultaneously monitored Orion stars.

Stassun et al. 2006 (COUP)

Accreting T Tauri stars (CTTS, Class II) are factor ~2 fainter in X-ray flaring than non-accreting T Tauri stars (WTTS, Class III)

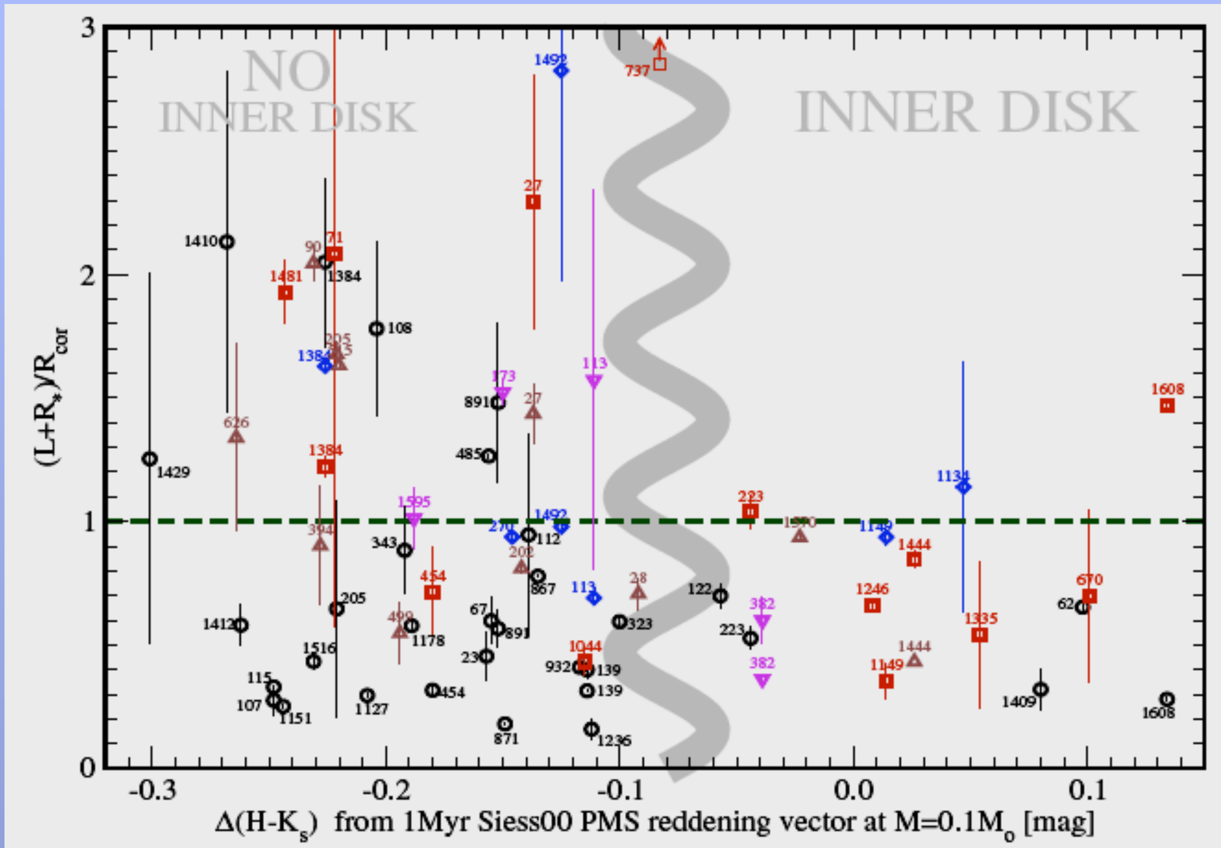




Effect discovered by Flaccomio et al. 2003

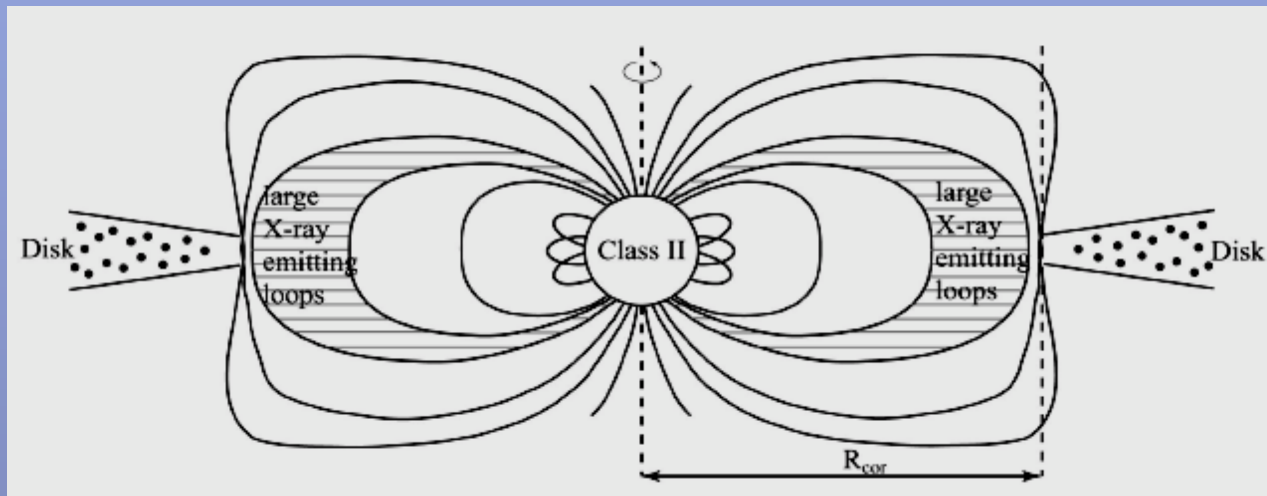
Telleschi et al. 2007 XEST

… but CTTS show an excess in soft X-ray emission



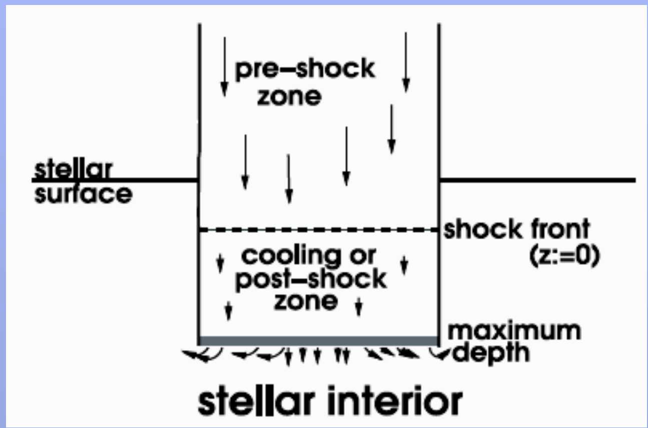
Evidence for magnetosphere confinement by disk

Star-disk corotation radius



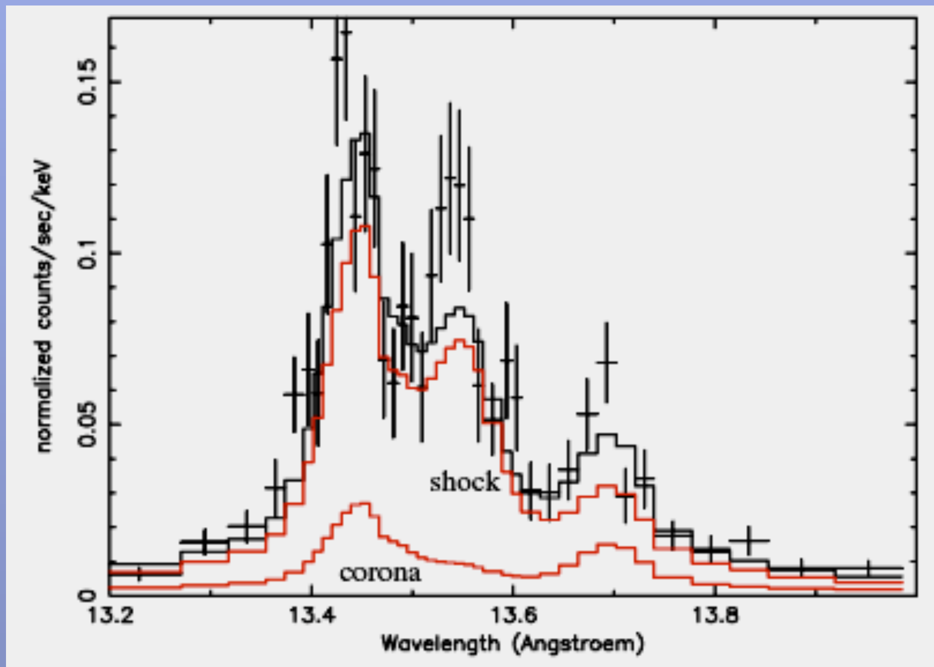
Getman et al. 2008b

Soft excess attributed to accretion shock (not magnetic flares)



Element	abundance	FIP [eV]
C	$0.20^{+0.03}_{-0.03}$	11.3
N	$0.51^{+0.05}_{-0.04}$	14.6
O	$0.25^{+0.01}_{-0.01}$	13.6
Ne	$2.46^{+0.06}_{-0.04}$	21.6
Mg	$0.37^{+0.10}_{-0.06}$	7.6
Si	$0.17^{+0.07}_{-0.07}$	8.1
S	0.02^{a}	10.4
Fe	$0.19^{+0.01}_{-0.01}$	7.9

[a] Formal 2σ limit.



The high densities in the accretion column explain the strong inter-combination line in the Ne IX triplet

However, this plasma arrives from the accretion disk and should not show FIP-related abundance anomalies.

Could this be a disk abundance effect due to planetesimal formation?

Kastner et al. 2002, Stelzer & Schmitt 2004, Drake et al. 2005, slides from Guenther et al. 2007

X-rays and accretion: A complicated situation

- X-ray luminosity does not show statistical link to K-excess disks
  (Feigelson et al. 2002, misleading)

- X-ray luminosity is statistically weaker in accreting systems
  (Flaccomio et al. 2003, confirmed repeatedly since)

- X-ray flares uncorrelated with optical accretional events
  (Stassun et al. 2006, 2007)

- X-ray flare statistics in accreting systems are similar to **(Stelzer et al. 2007 XEST)** or below **(Prisinzano et al. 2007 COUP)** flares in non-accreting systems

- X-ray spectra of accreting systems show soft component from dense plasma inconsistent with coronal loops and consistent with accretion column above stellar surface, but origin of abundances?
  (Kastner et al. 2003; Guedel & Telleschi 2007; Schmitt et al. 2005--)

Some useful references

- “X-rays from young stars & stellar clusters”
  Review article in Protostars & Planets V 2007
  Feigelson, Townsley, Guedel & Stassun

- 22 papers from Chandra Orion Ultradeep Project (COUP, Feigelson PI)
  ApJ Suppl Special Issue October 2005 + others 2006-08

- ~20 papers from XMM-Newton Extended Survey of the Taurus molecular cloud (XEST, Guedel PI)
  As&Ap Special Issue 2007