# ***X-ray studies of star and planet formation***

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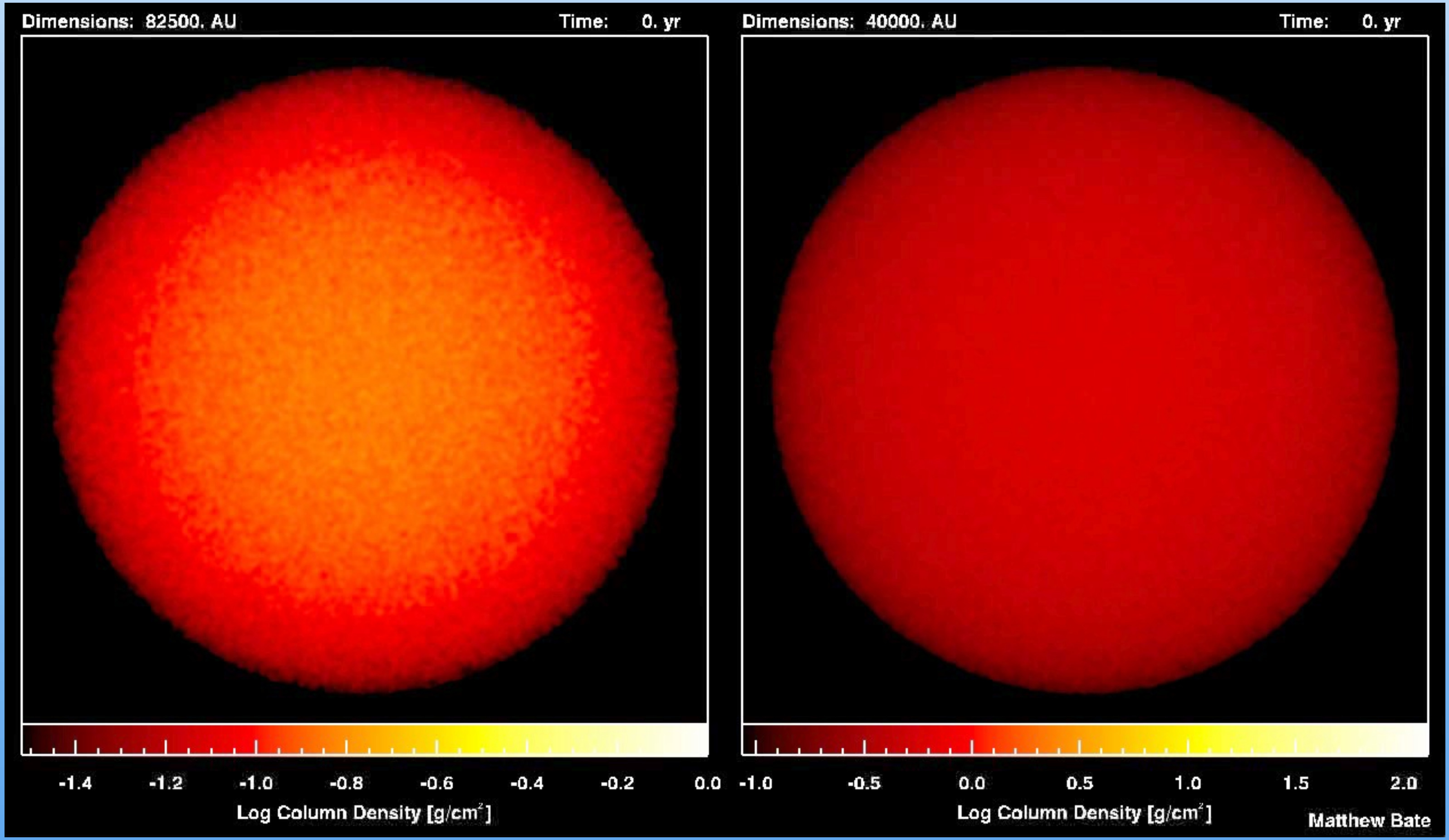
**Chandra Decade of Discovery 20**

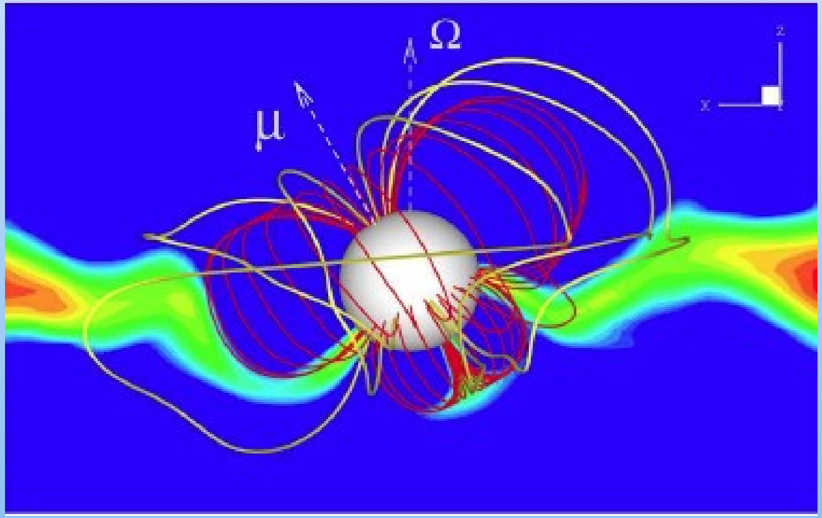
# Growing insights into the processes of star formation




**Bate et al. 2003**

Stars generally form in groups & clusters with an Initial Mass Function from brown dwarfs to OB stars.

Gravitational collapse is not simple, mediated by thermal pressure, angular momentum, $B^2/8\pi$, and MHD turbulence



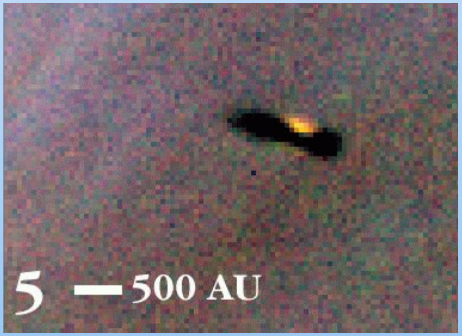

Young stars are very complex with accretion from protoplanetary disks, and ejection of collimated winds (Herbig-Haro objects), all mediated by the multipolar stellar magnetic field

**Long et al. 2007**

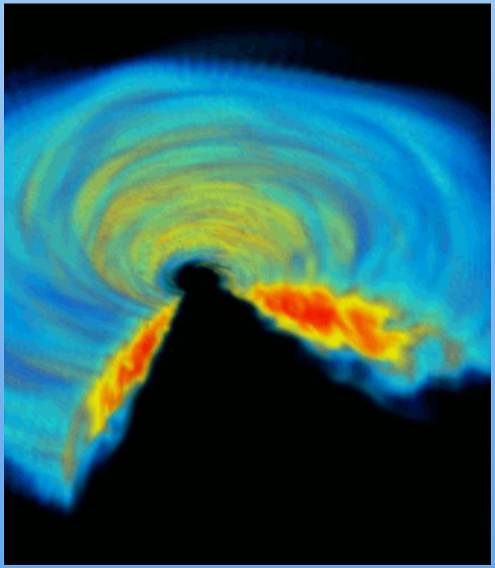
***Some major issues of star formation:***

- ***how do massive OB stars form?***
- ***how do OB stars affect their natal clouds?***
- ***do PMS stellar outflows affect their natal clouds?***
- ***how is the stellar IMF established?***
- ***more?***

# Growing insights into the processes of planet formation




Infrared studies of protoplanetary disks and exoplanet discoveries verify traditional concept of growth of solids from dust → pebbles→ planetesimals → planets.



*But there are many mysteries of planet formation:*

- role of stellar irradiation
- presence of MHD turbulence
- role of gravitational instability
- non-equilibrium chemistry
- isotopic anomalies
- suppression of migration
- more?

PPDs are irradiated by star light, and the gas is slightly ionized and maybe turbulent. Protoplanets interact with the gas in complex ways (e.g. migration).

# High energy processes in star/planet formation

Star and planet formation are vibrant fields of astronomical & astrophysical research. But why is Chandra relevant? Formation environments have meV energies, while X-rays reveal keV energies.

High energy radiation is indeed present in these environments at modest levels, $L_x/L_{bol} \sim 10^{-4}$ for low mass stars and $\sim 10^{-7}$ for OB stars. Several causes: magnetic reconnection flaring; accretion shocks; OB wind shocks on several scales, SNRs

*Question 1: Does X-ray emission affect the physical processes of star & planet formation?*

*My opinion:*

Probably not much for stars,
but quite likely important for planets

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*Question 2: Can X-ray studies elucidate open issues & mysteries in star & planet formation?*

*My opinion:*

Definitely yes! They address:
stellar populations (IMF, triggering),
OB winds and HII region physics,
origin & evolution of OB stars and clusters,
ionizing and particle irradiation of disks,
and more

# Star forming regions imaged by Chandra

**D < 500 pc**

Taurus & Oph
Cha I, L1448, CrA
HAeBe's, **TW Hya**, Sco-Cen
NGC 1333, IC 348, Serpens
NGC 2264
**ONC (COUP)**, **Orion A**, other OMC
HH objects

**0.5 < D < 3 kpc**

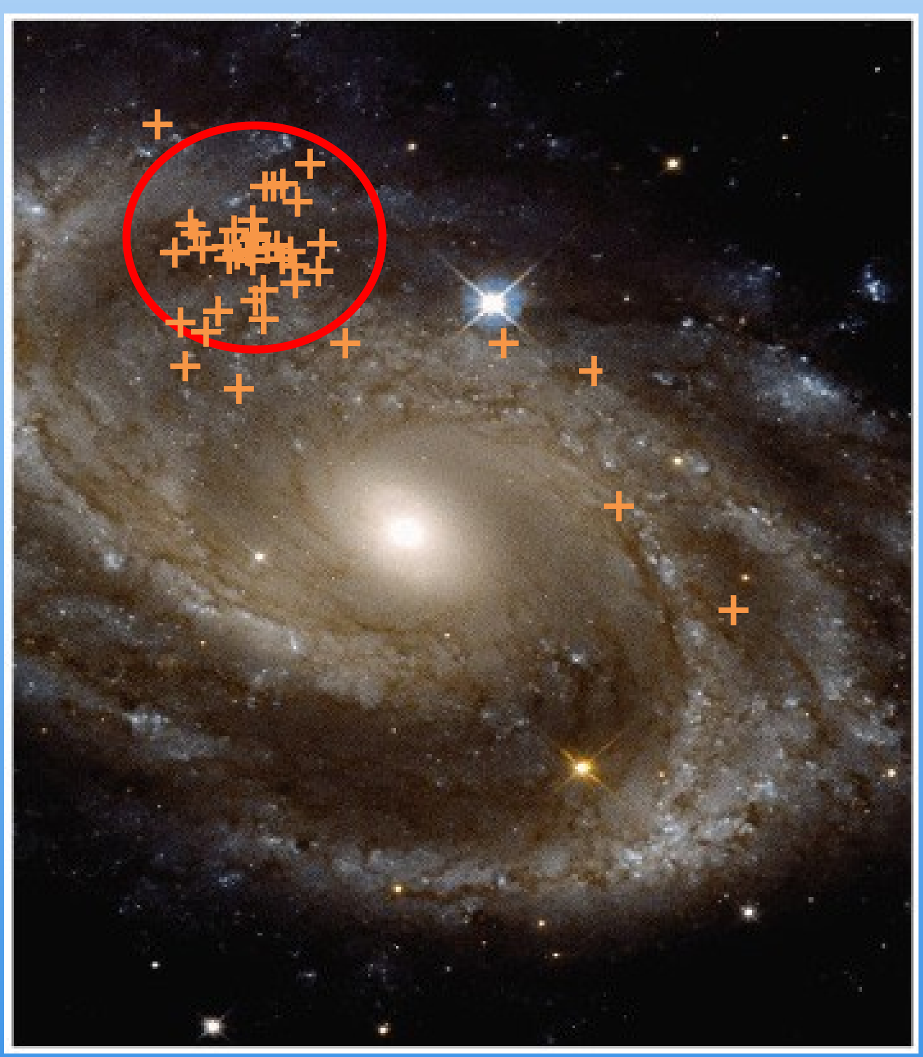
**W 3**, 4, 5, 40
**Carina**
M 8, 16, **17**
NGC 3576, 6334, 6357,7538
Trifid, Rosette, IC 1396
RCW 36, 38, 49, 108 & LkHa 101
Cyg OB2, Cep A & B
Isolated OB/WR

**D > 3 kpc**

**Gal Cen**, Sgr B2, Arches, Quintuplet
Wd 1, Wd 2, NGC 3603
W 49, 51
**NGC 1893**

**Bold** = Large Project

# Chandra has examined most of the young stellar clusters and active star formation regions in the nearby Galaxy



Star formation and young star observations occupy several percent of Chandra’s time and include 7 Large Projects and 1 Very Large Project

# X-ray insights into star and planet formation issues

1. Discovering X-rays from protostellar outflow shocks
2. Characterizing magnetic activity in pre-main sequence stars
3. X-rays from the very youngest stars
4. Characterizing accretion shocks in PMS stars (Brickhouse)
5. Establishing the stellar Initial Mass Function
6. Discovering the fate of OB stellar winds
7. Investigating triggered star formation around HII regions
8. Uncovering the structure of young stellar clusters
9. Studying local templates for starburst galaxies (Townsley)

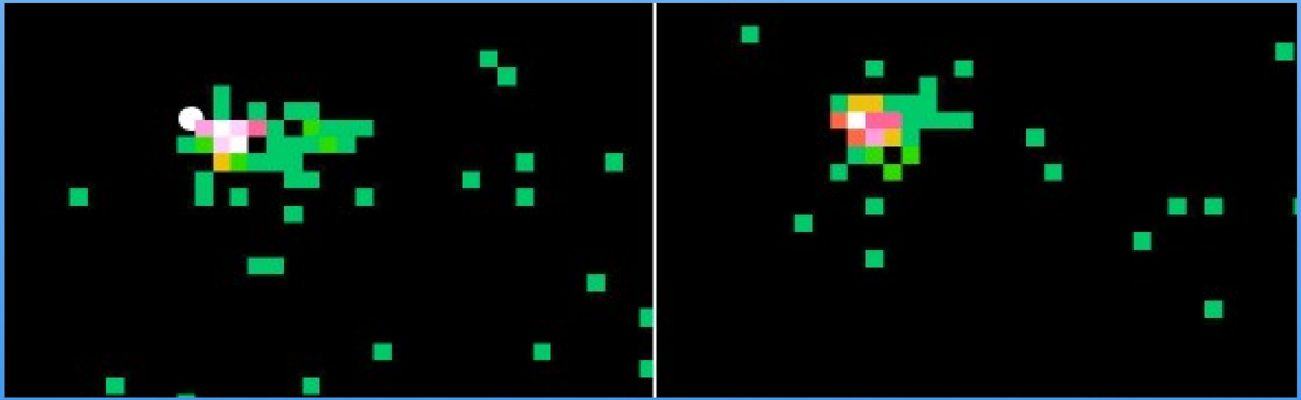
11. Examining X-ray irradiation of protoplanetary disks
12. X-ray flares and the mysteries of ancient meteorites

# 1. Discovering X-rays from protostellar outflow shocks

HH 2 Pravdo et al. 2001

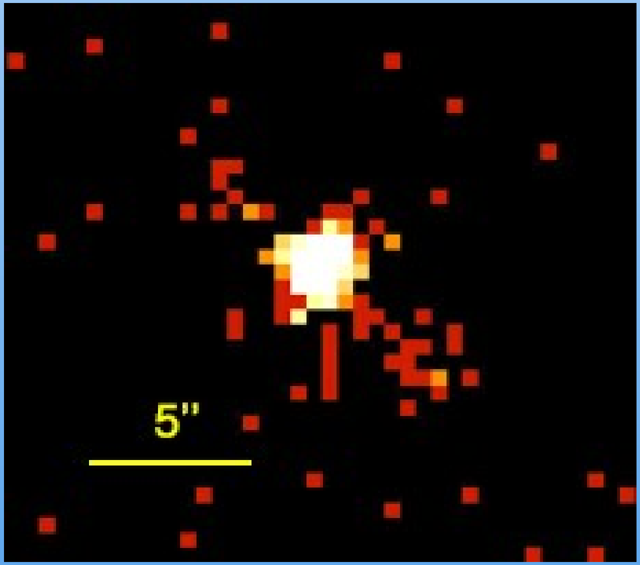
Faint, soft, resolved X-ray structures seen from a few high-velocity Herbig-Haro objects. Two types:

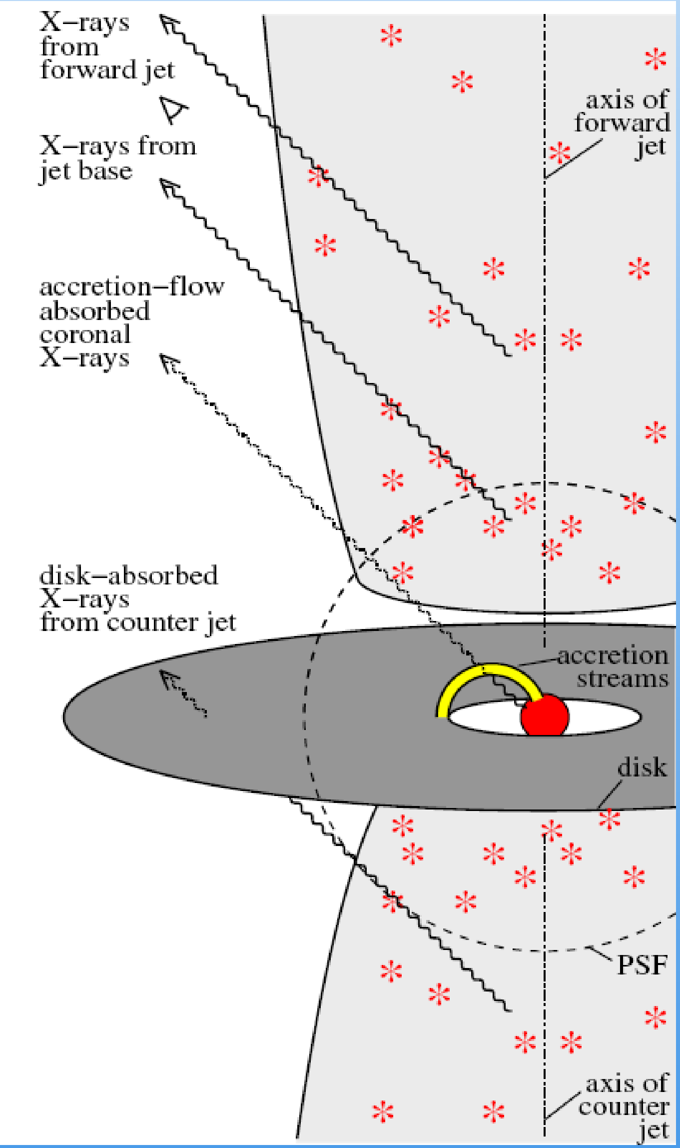
- terminal shocks far from star
- shocks near base of outflow



HH 154 in 2005 in 2001 Favata et al. 2006

## The dual jets of DG Tau



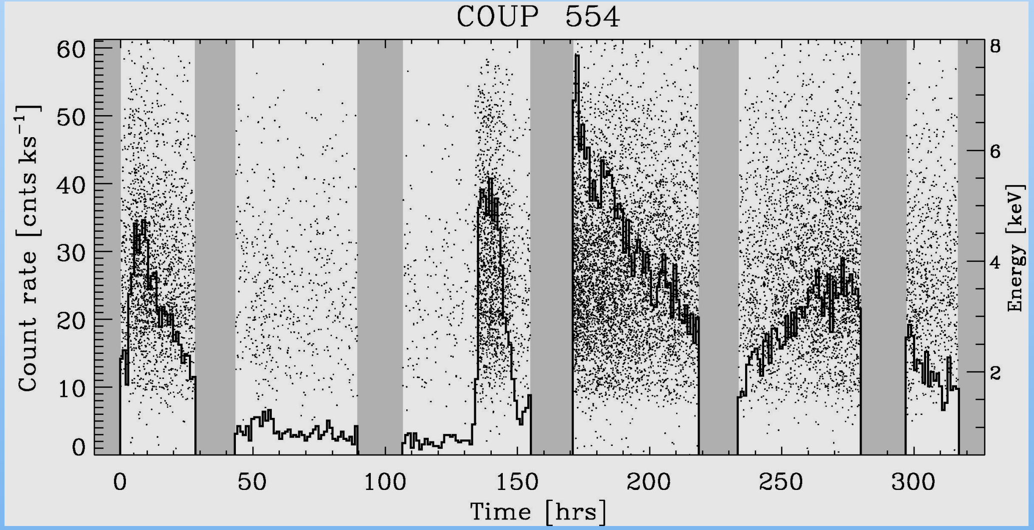

Gudel et al. 2008

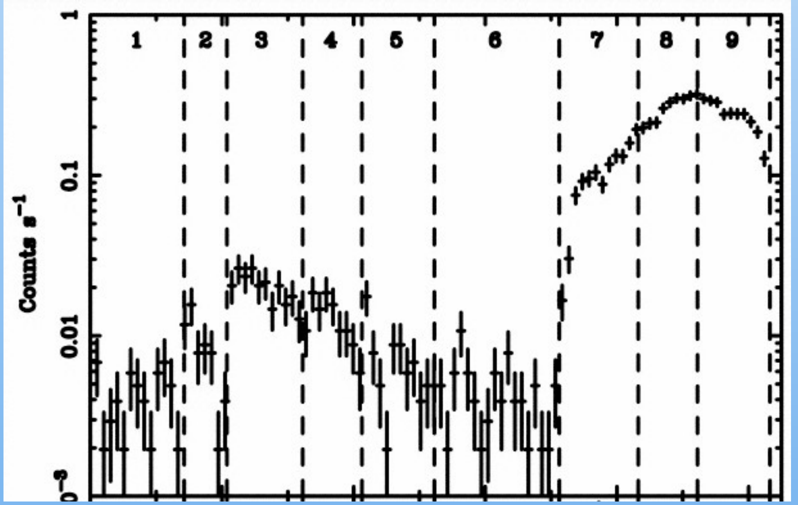
# 2. Characterizing magnetic activity in PMS stars

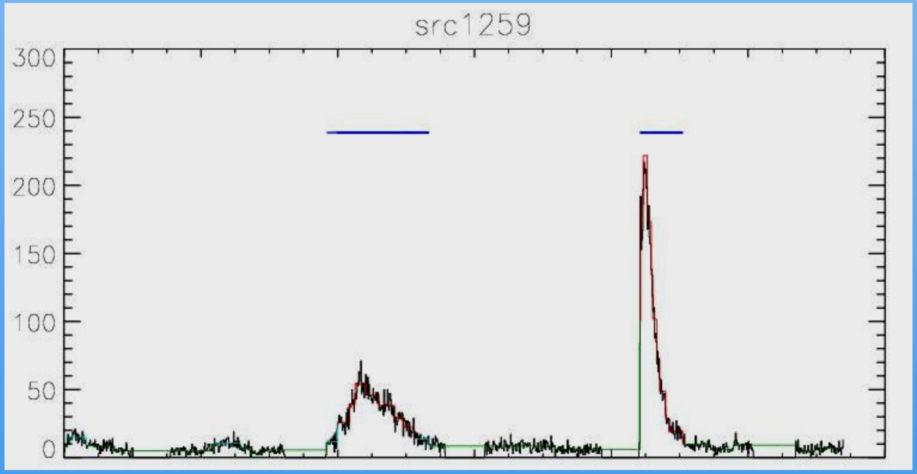
The COUP movie (Chandra Orion Ultradeep Project)

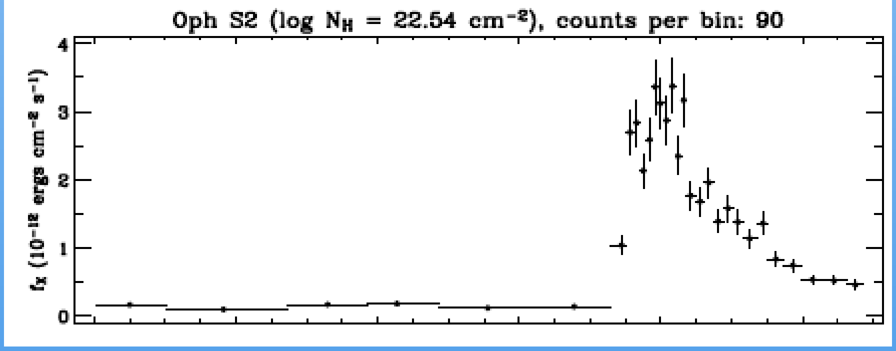
Getman et al. 2005, Feigelson et al. 2005

# Extraordinary flares in pre-main sequence stars



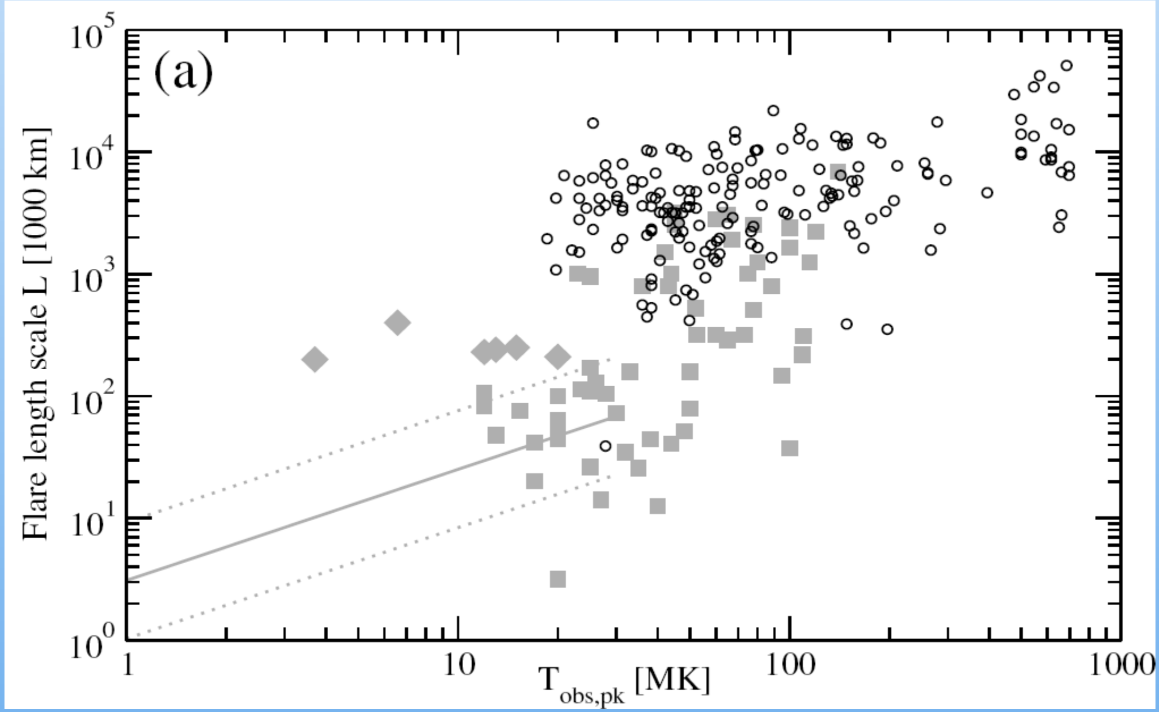



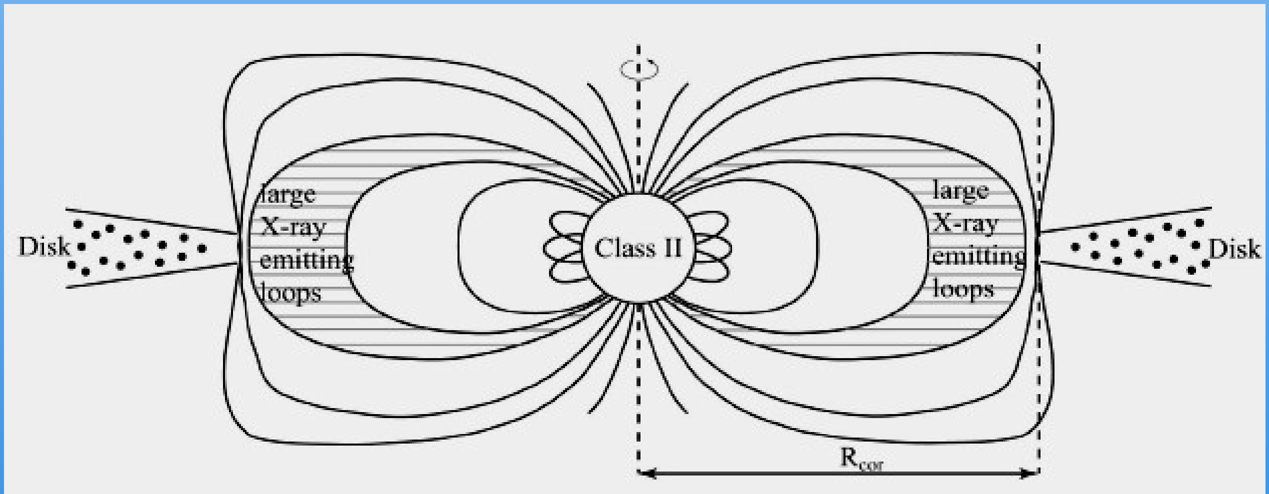

Imanishi et al. 2001 Gagne et al. 2004

Grosso et al. 2005 Wolk et al. 2005




PMS flares are:
~$10^2$ more powerful
~$10^2$ more frequent
~$10^1$ hotter
than the biggest solar flares

What is the relationship between flaring magnetic loops and accreting field lines?




Favata et al. 2005
Getman et al. 2008a & b

# 3. X-rays from the very youngest stars

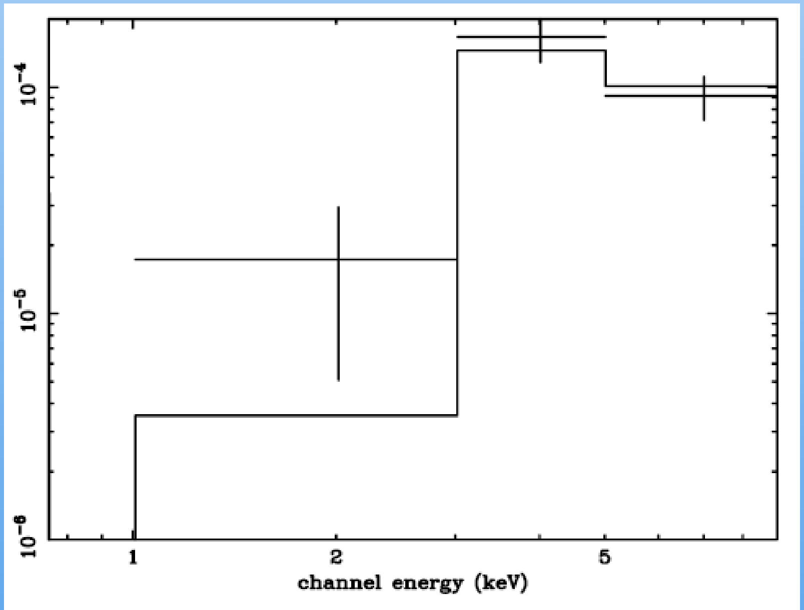
Are X-rays present at the very onset of star formation (Class 0 protostars, age~$10^4$ yrs)?

This is essential if X-ray ionization is responsible for the coupling between the disk magnetic field and bipolar outflow in models of jet magnetocentrifugal acceleration.

Result to date

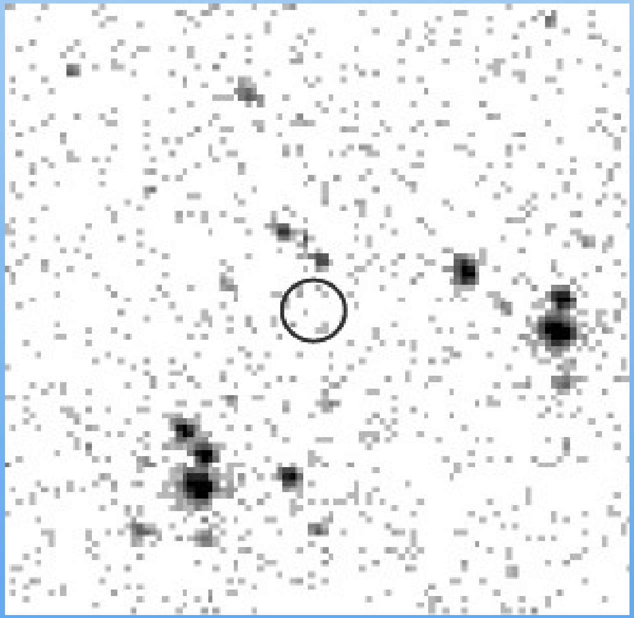
The answer is still not clear. Class 0 stars suffer $N_H > 10^{24}$ $cm^{-2}$ absorption from their infalling envelopes, but Chandra can penetrate only $N_H \sim 10^{23}$ for the hardest PMS sprectra.

Chandra/XMM detection of
IRS 7 = VLA 10W in R CrA cloud
Class 0/I, $\log N_H \sim 23.5\ cm^{-2}$



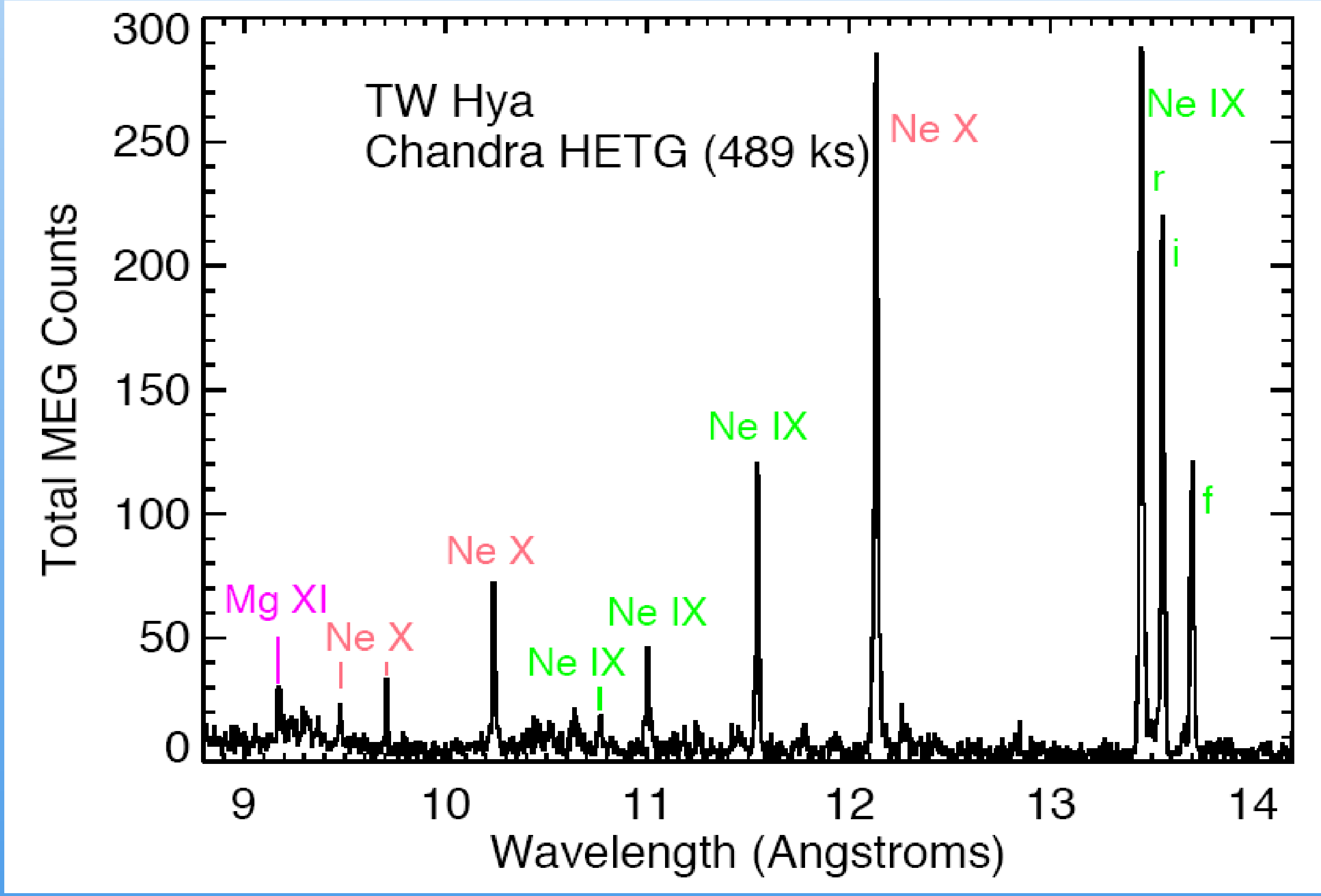

Hamaguchi et al. 2005

Failure to detect Class 0
source in Serpens cloud



Giardano et al. 2007

# 4. Characterizing PMS accretion shocks




In addition to hard variable emission from flares, a softer constant X-ray component is produced by the accretion shocks

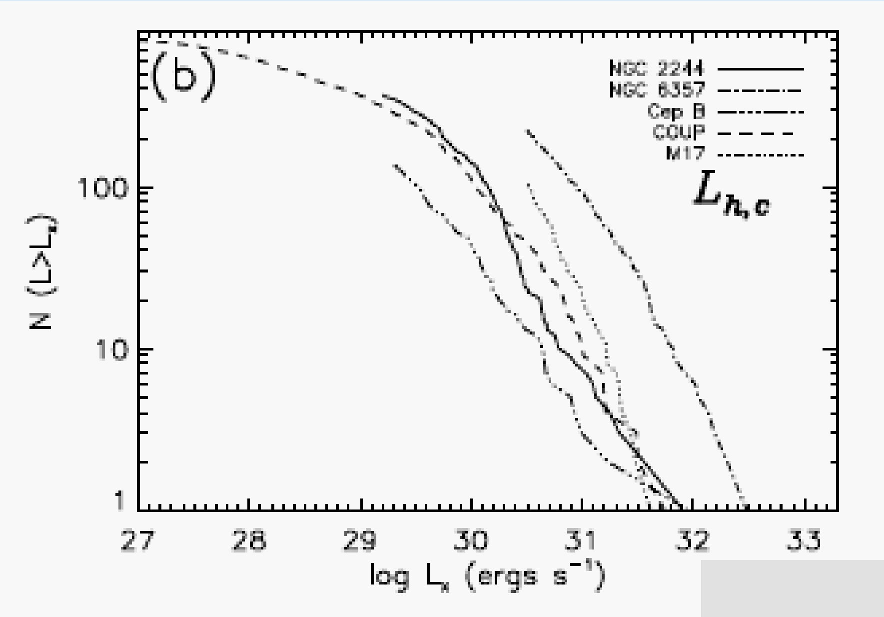
TW Hya Chandra Large Project

Talk by Nancy Brickhouse

# 5. Establishing the stellar Initial Mass Function

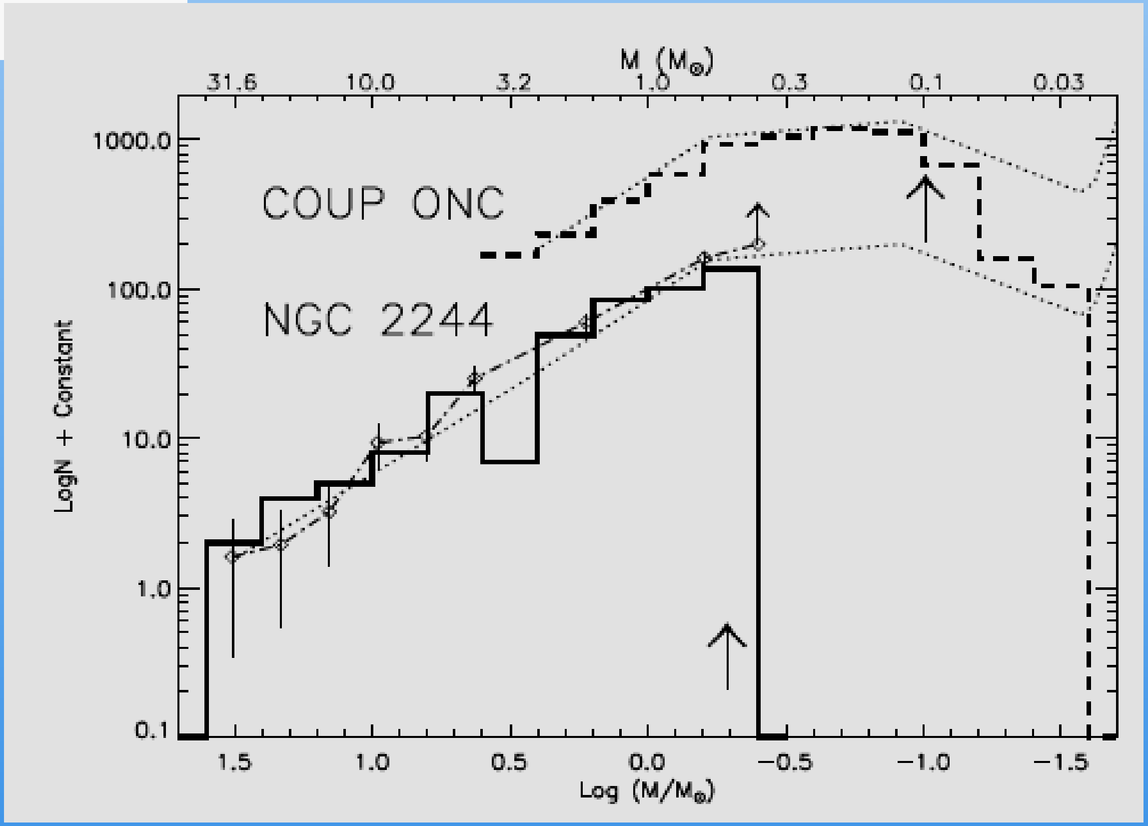
Near- and mid-infrared surveys can readily detect photospheres of the full IMF, including proto-brown dwarfs, out to 1-2 kpc.  But, except in the closest star forming regions (e.g. Taurus, Orion), the fields are very badly (factors ~ few-100) contaminated by Galactic field stars.

Chandra is typically sensitive only to masses >0.3-1 $M_\odot$ (depending on exposure), but suffers only ~5-25% contamination from older stars and quasars (!).   Chandra thus provides the best cluster membership samples, and serves as a `finder telescope' for further opt/IR study.




## Result to date

X-ray luminosity functions (left) are very similar to each other in different young stellar clusters, and XLFs map reliably to IMF (below).




Rosette Nebula cluster
Wang et al. 2008

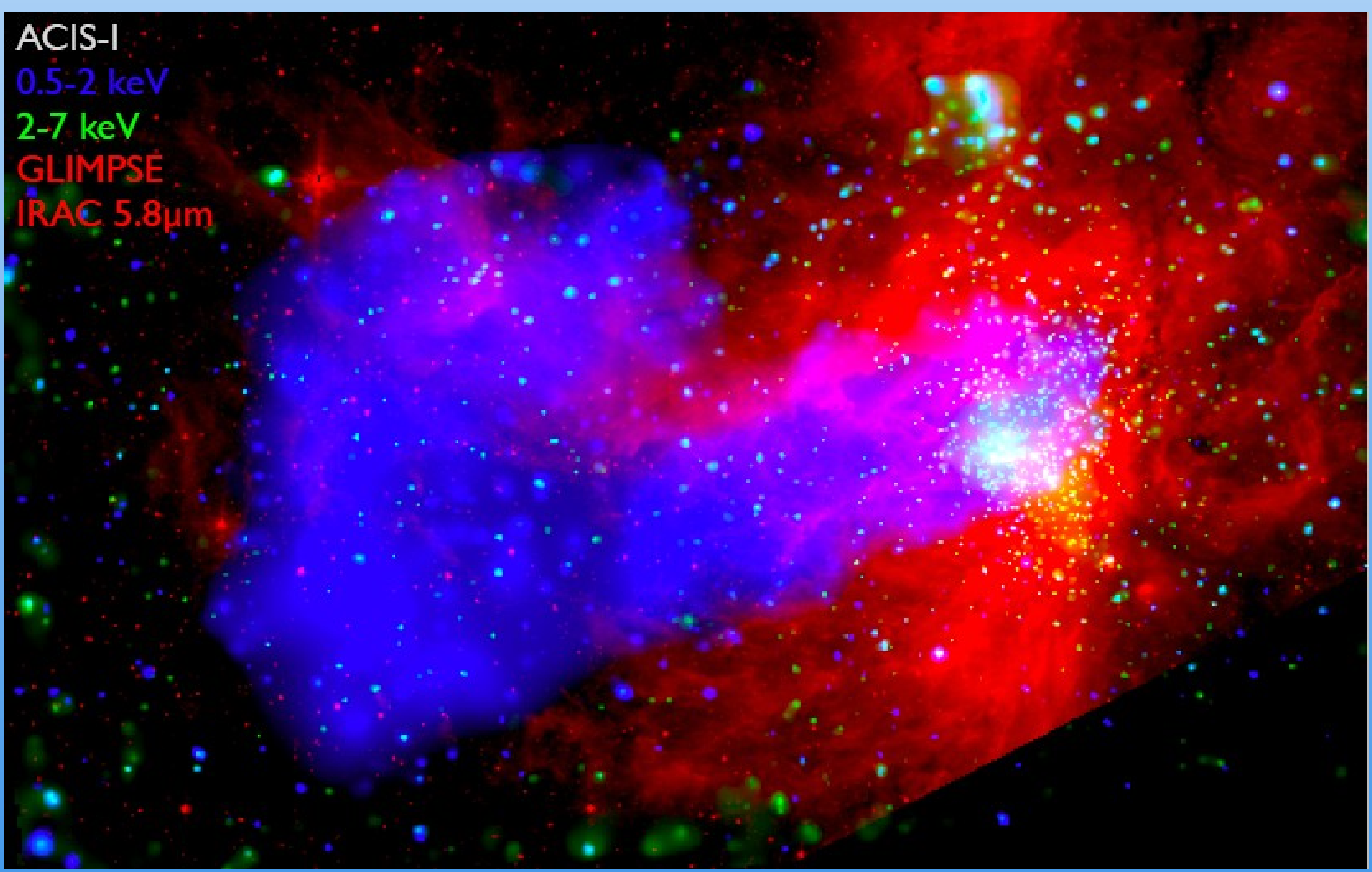
# 6. Discovering the fate of OB stellar winds

OB winds are radiatively acceleration near the stellar surface where they are studied with UV and X-ray emission lines. But the fate of the winds on parsec scales was unknown … predicted to produce strong X-rays in shock against molecular cloud (Weaver/McCray 1977), and to enrich/energize the Galactic ISM.

Chandra discovered the shocked OB winds in M 17 and a few other clusters (Townsley et al. 2003; Wolk et al. 2004). Emission is $10^2$ below predictions, and is entirely missing in the youngest systems (UCHIIs). Practical difficulty in distinguishing diffuse plasma emission from integrated emission from thousands of low-mass PMS stars.

Results to date

Smooth shocked OB wind plasma detected, but much fainter than expected. X-ray morphology shows confinement by molecular cloud. Major revision needed in HII region shock physics.




Broos et al. 2007, Townsley et al., in prep

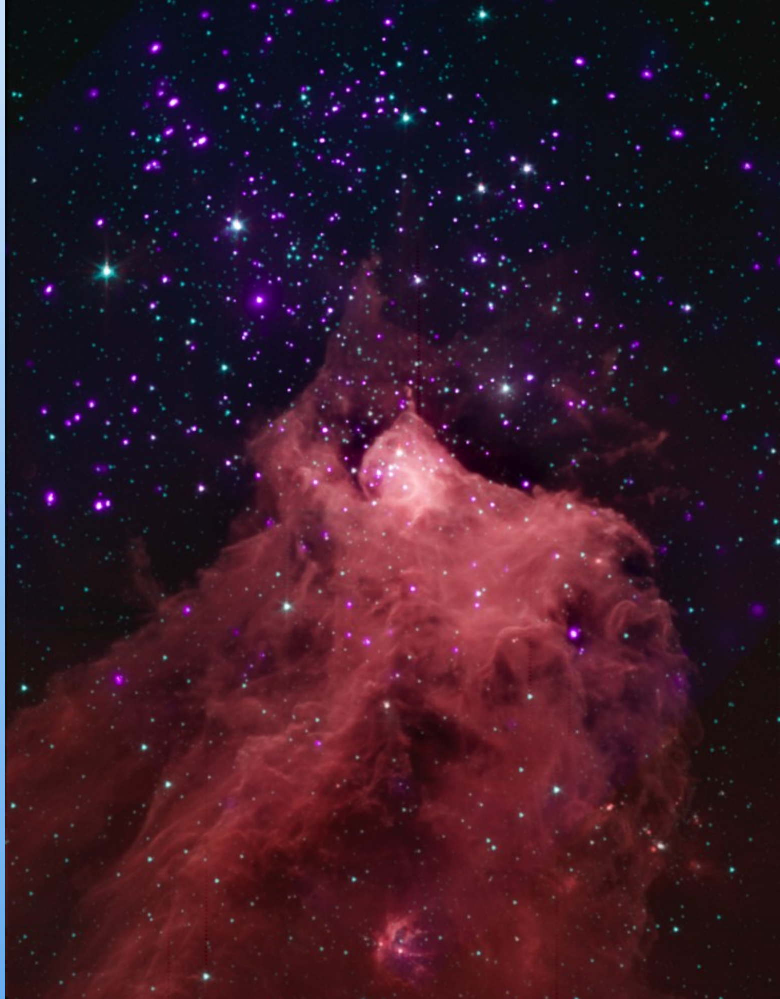
# 7. Investigating triggered star formation

The expanding HII region around OB stars will shock and compress molecular cloud material, triggering a new generation of star formation. Few stellar samples are available to test the models (`collect-and-collapse' and `radiative driven implosion').

Chandra is providing larger samples of triggered SF around several HII regions than available from IR studies due to non-accreting Class III systems (Getman et al. 2006).

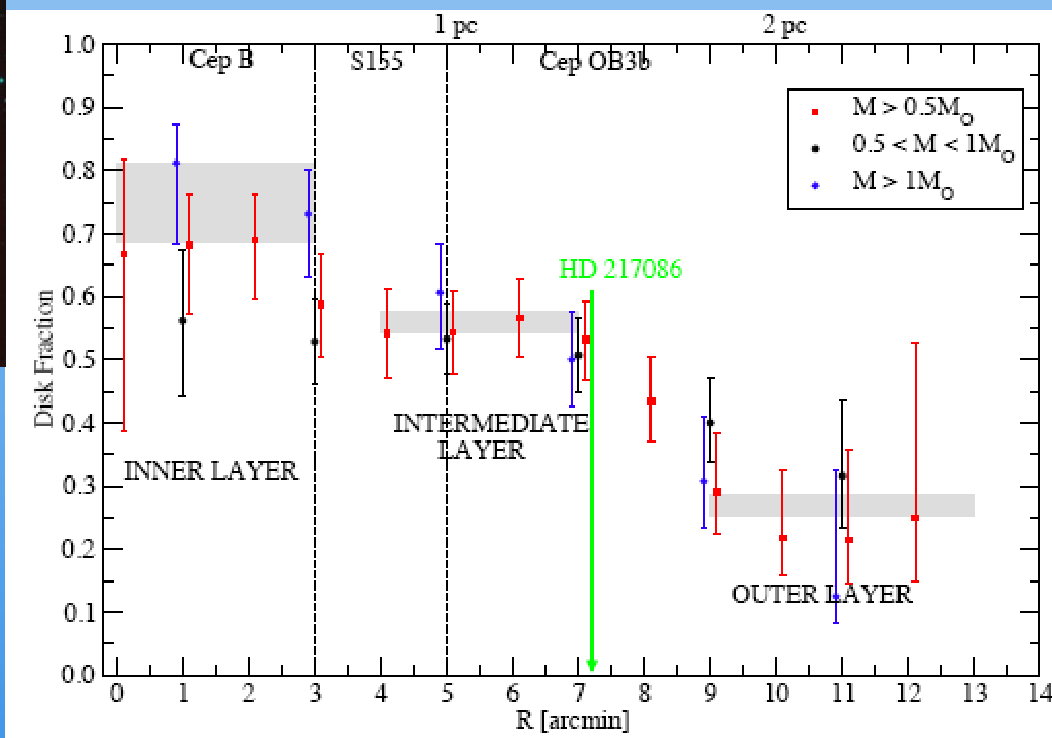
Results to date

Triggering concept and RDI model are confirmed, but duration of triggering found to persist for millions of years suggesting it may be responsible for many stars.



Chandra sample of ~400 PMS stars, with ~200 more from Spitzer, gives nearly complete sample of Cep B region (left).

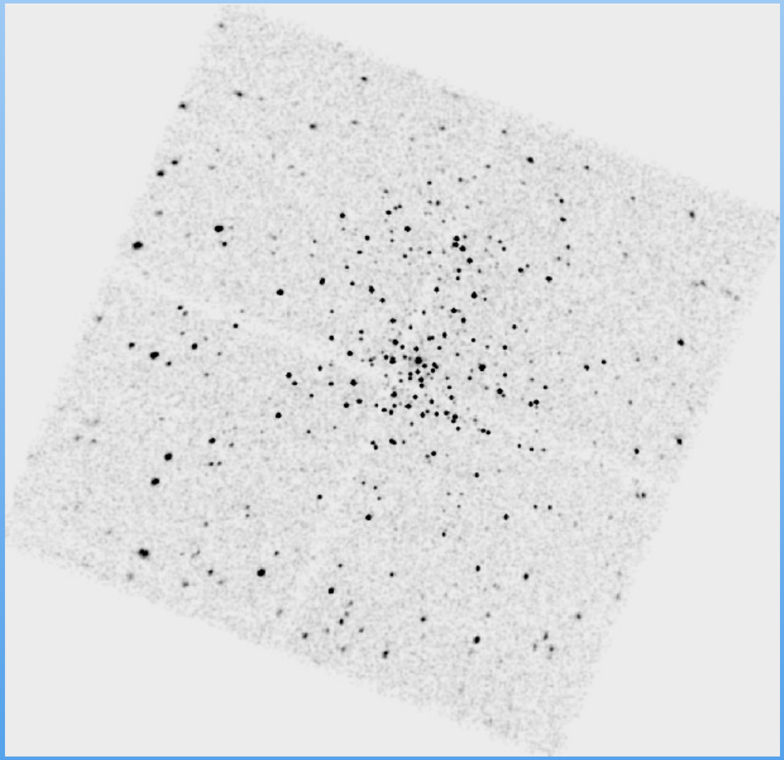
Age gradient demonstrated by disk Fraction gradient (below) supports triggering process with shock propagation at ~1 km/s.



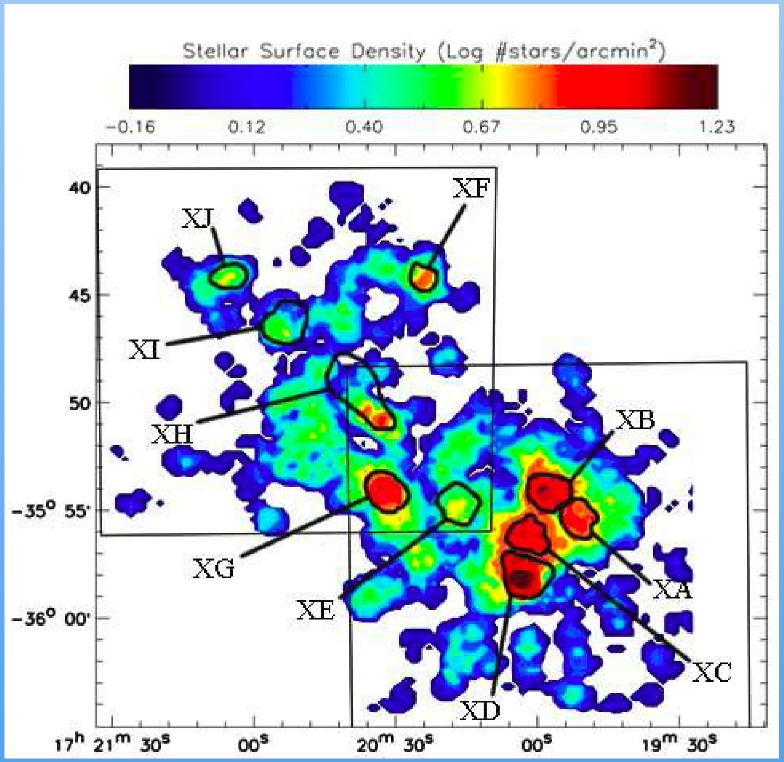

Getman et al. 2009

# 8. The structure of young stellar clusters

Some clusters are simple spheres …. while others have complex structure

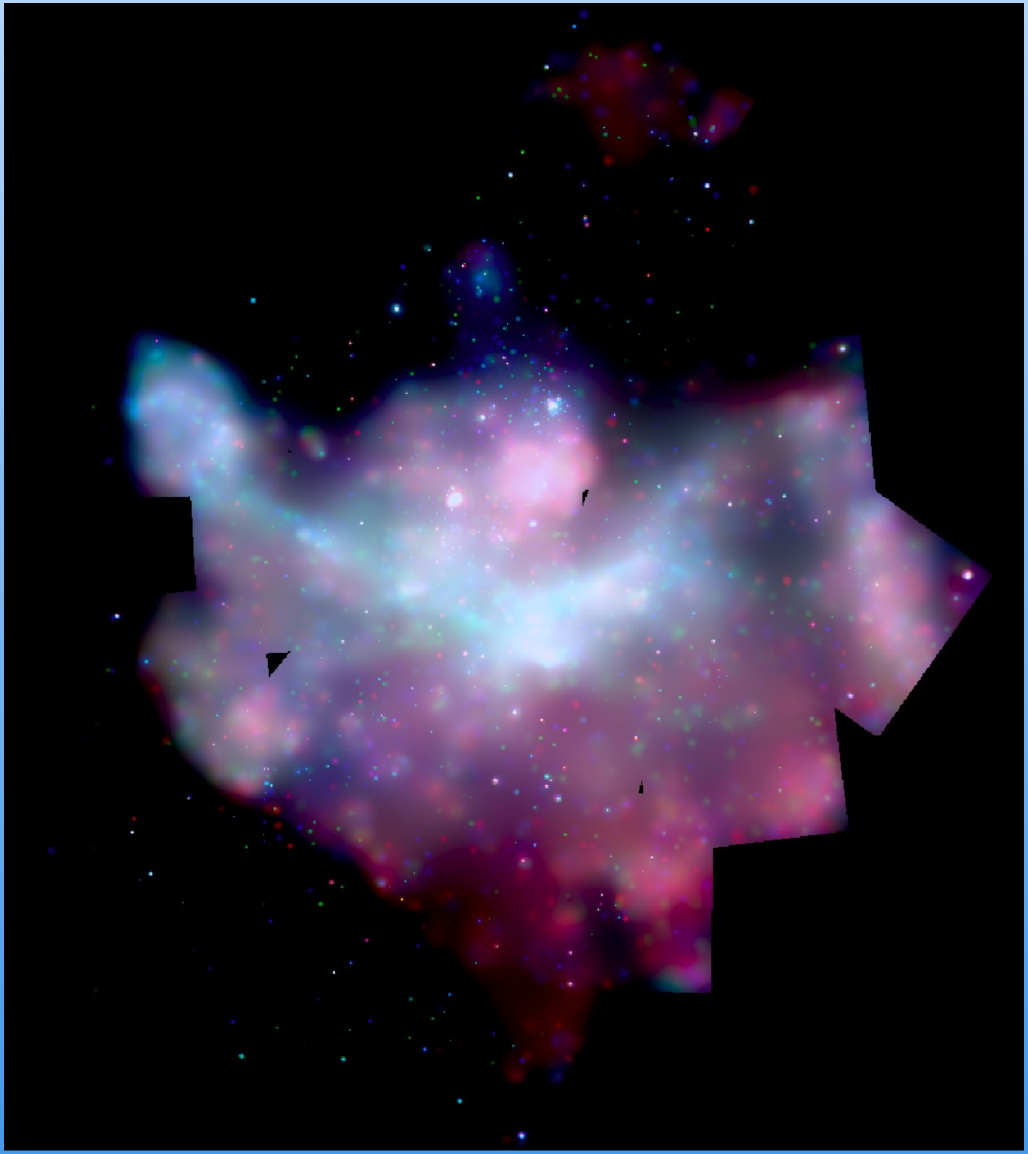


NGC 2362 Damiani et al. 2006




NGC 6634 Feigelson et al. 2009

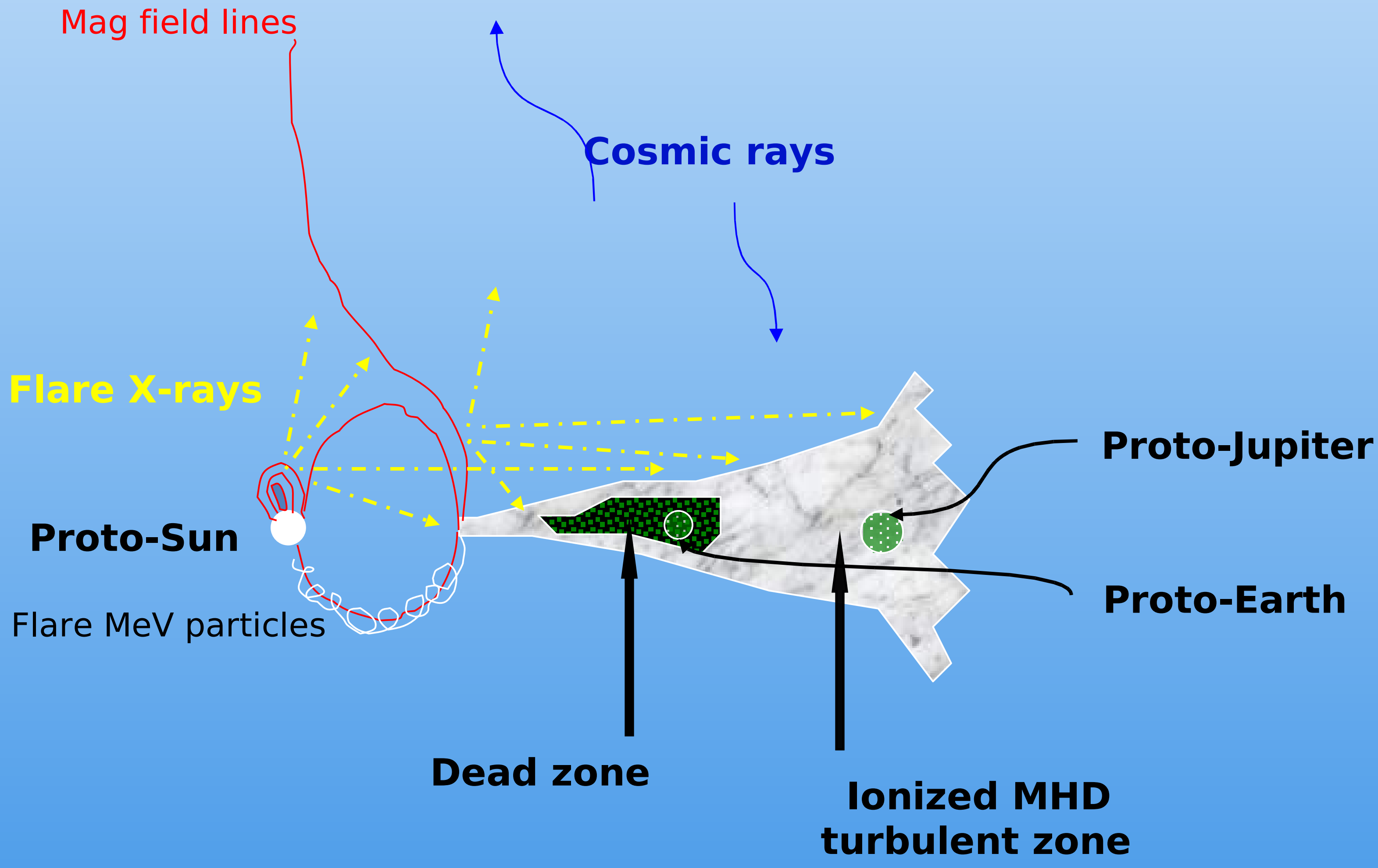
# 9. Studying local templates for starburst galaxies



The Chandra Carina Very Large Project

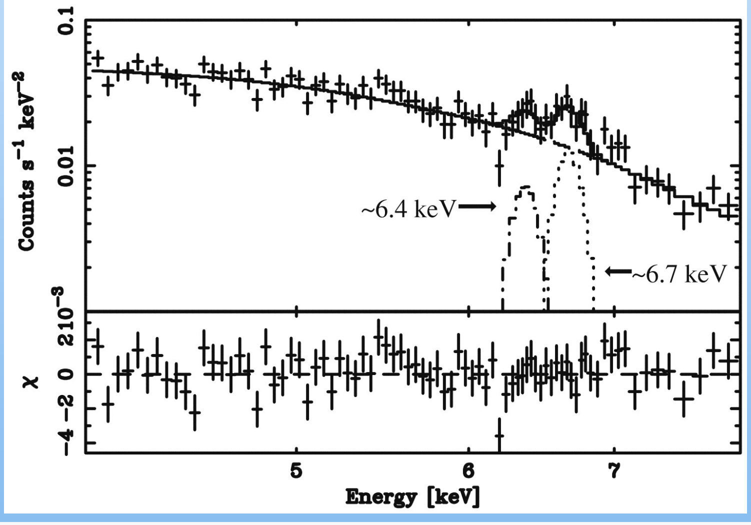
Talk by Leisa Townsley

# 10. Examining X-ray irradiation of protoplanetary disks



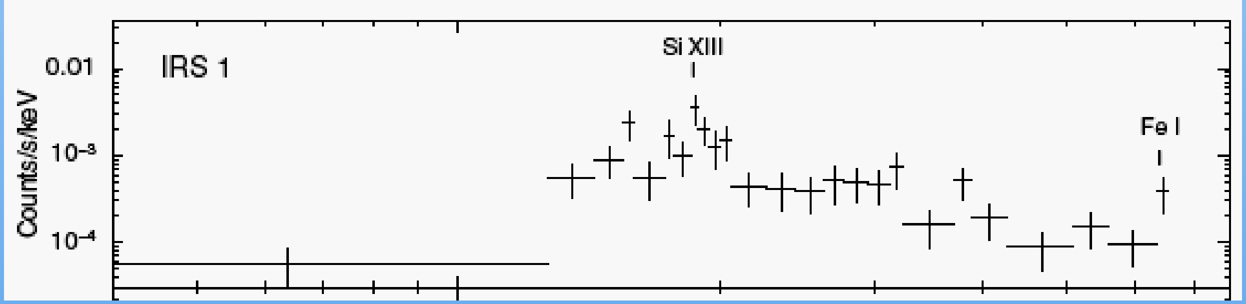

Feigelson 2003, 2005, 2007

# Evidence for disk irradiation by X-rays

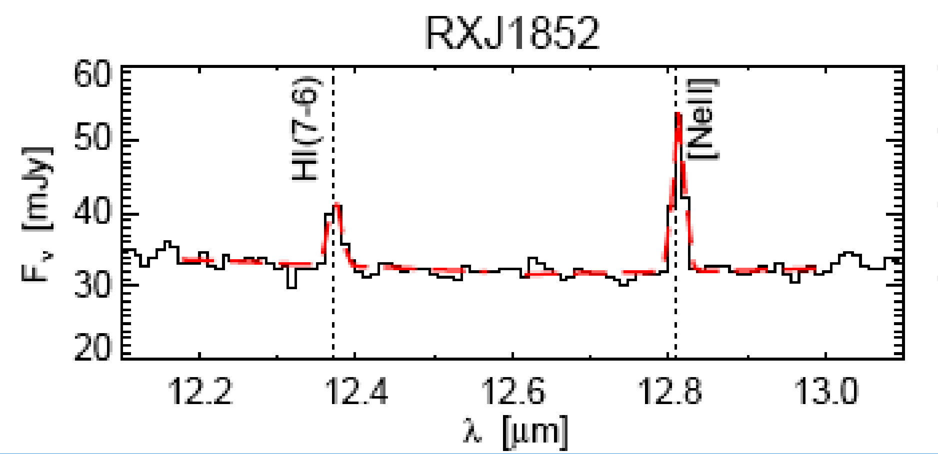



The 6.4 keV fluorescent iron line Is seen in several PMS stars with heavy disks.

Protostar YLW 16A in Oph cloud
Imanishi et al. 2001




IRS 1 in NGC 2071
Skinner et al. 2009

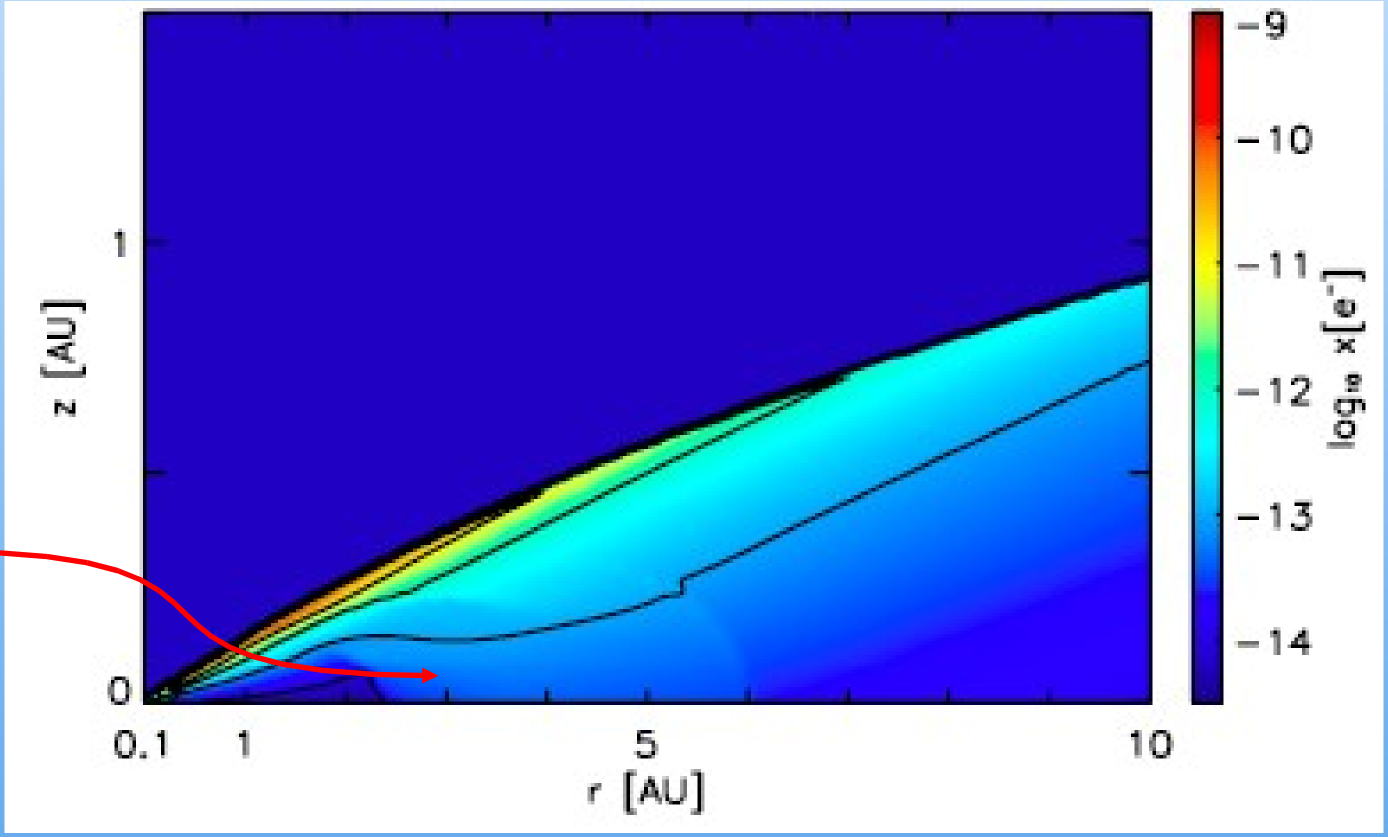



[Ne II] 12.8 μm line from ionized outer disk layers detected with Spitzer and Keck

Glassgold et al. 2006 prediction
Pascucci et al. 2007 discovery

# X-ray ionization of outer & mid disk layers

Dead Zone




Ilgner & Nelson 2006c

Active Zone (turbulent, viscous flow) is essential for accretion.
Dead Zone extent may be regulated by variable hard X-ray emission.
Growth processes from dust to planetesimals differ in these regions.

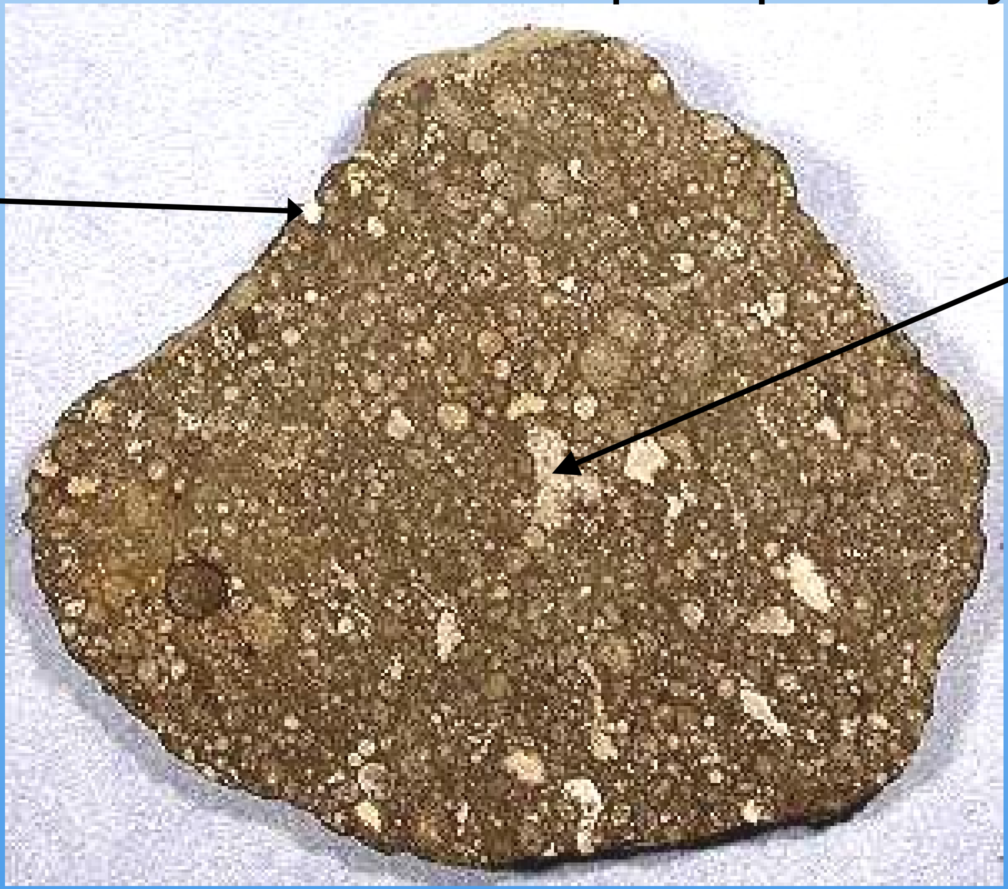
~ 100 theory papers (most since 2004) discuss physics, chemistry, planet formation and evolution in X-ray ionized disks.

# 11. X-ray flares and the mysteries of ancient meteorites

Carbonaceous chondrites:
Pristine relics of the solar protoplanetary disk

**Chondrule**

What flash-melted the chondrules?



**Calcium-aluminum-rich inclusion (CAI)**

What produced the short-lived radio-nuclides in CAIs?

**Allende meteorite** **Age = 4567 Myr**

# Conclusions

Chandra has provided a wealth of phenomenology on X-ray emission from young stars and the role of high energy processes in the thermodynamically cold environments of stars/planet formation.

To an extent unforeseen prior to its launch, Chandra is now addressing many astrophysical issues: pre-main sequence stellar flares and magnetospheres, accretion and outflows, stellar IMF, triggered SF, star cluster structure, OB winds, starburst astrophysics, protoplanetary disk physics, and meteoritic mysteries.

The next decade of Chandra will involve longer exposures of important targets to give uniquely valuable PMS samples, penetrate deeper into molecular clouds and the Galactic Plane, and address specifical astrophysical issues.