X-RAY EMISSION FROM STAR FORMING REGIONS

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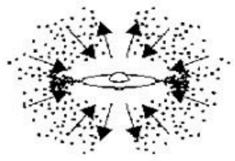
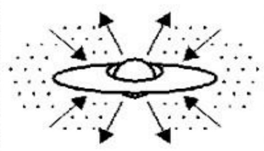
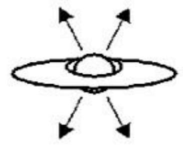
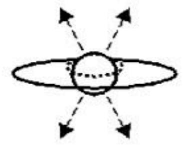
A quick tour of PMS stars

Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
Age (years)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Adapted from Feigelson & Montmerle, ARA&A, 1999

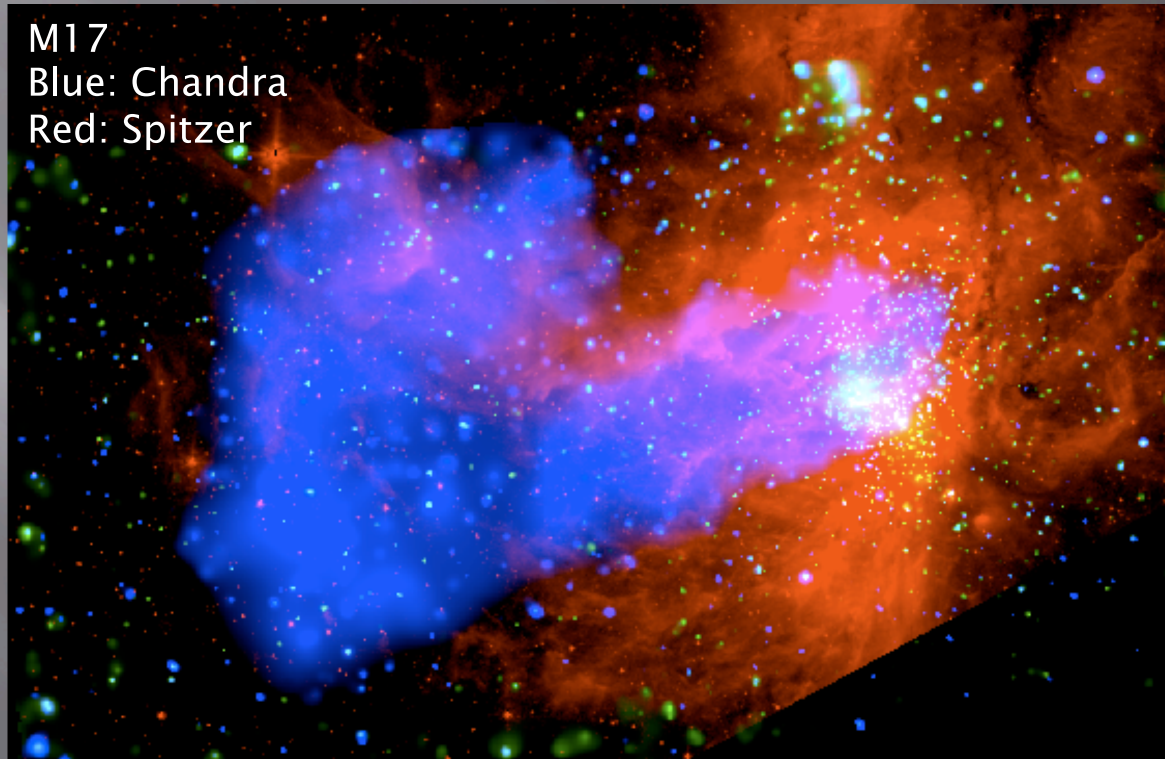
Outline

1. Diffuse X-ray emission from star forming clouds
2. X-ray emission from low mass PMS stars
   - **Coronae** (Results from COUP, XEST, DROXO)
   - Accretion
   - Jets
3. Effects of X-rays on circumstellar disks

Diffuse X-ray emission

Found in high mass SFR:

Orion (Guedel et al. 2008),
NGC2024 (Ezoe et al. 2006),
M17 (Townsley et al. 2003),
Rosette (Wang et al. 2009),
Westerlund 1 (Muno et al. 2006),
Carina Nebula (Ezoe et al. 2009),
RCW38 (Wolk et al. 2002, 2006),
NGC6334 (Ezoe et al. 2006),
30 Dor (LMC; Townsley et al. 2006)



Townsley et al. (2003)

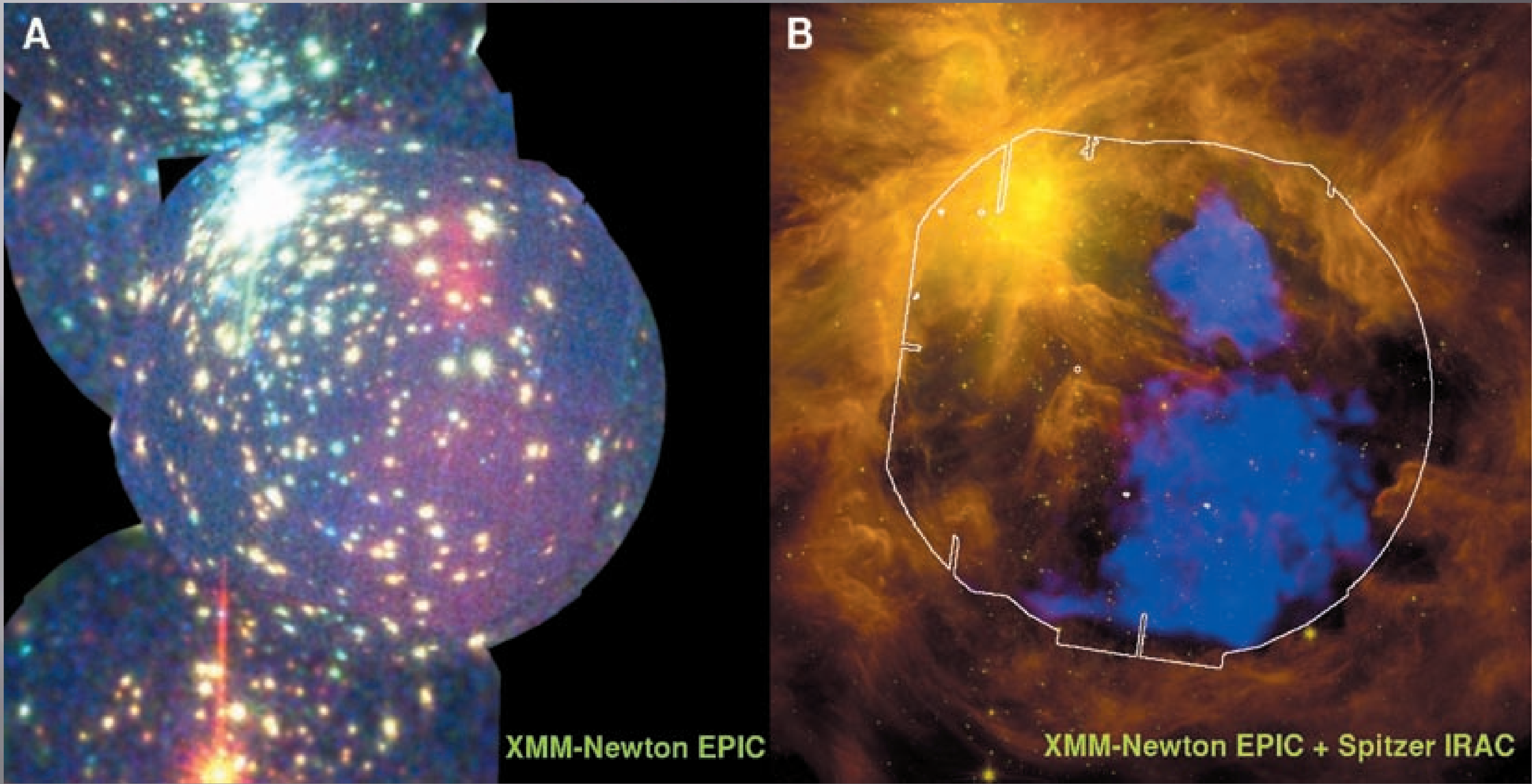
T ~ 1-10 MK

$L_X = 3.4\ 10^{33}$ ergs/s

Wind-wind, wind-cloud collision

Orion Nebula Cluster

Guedel et al. (2008)



T ~ 2MK

L_X = 5.5 10^{31} ergs/s

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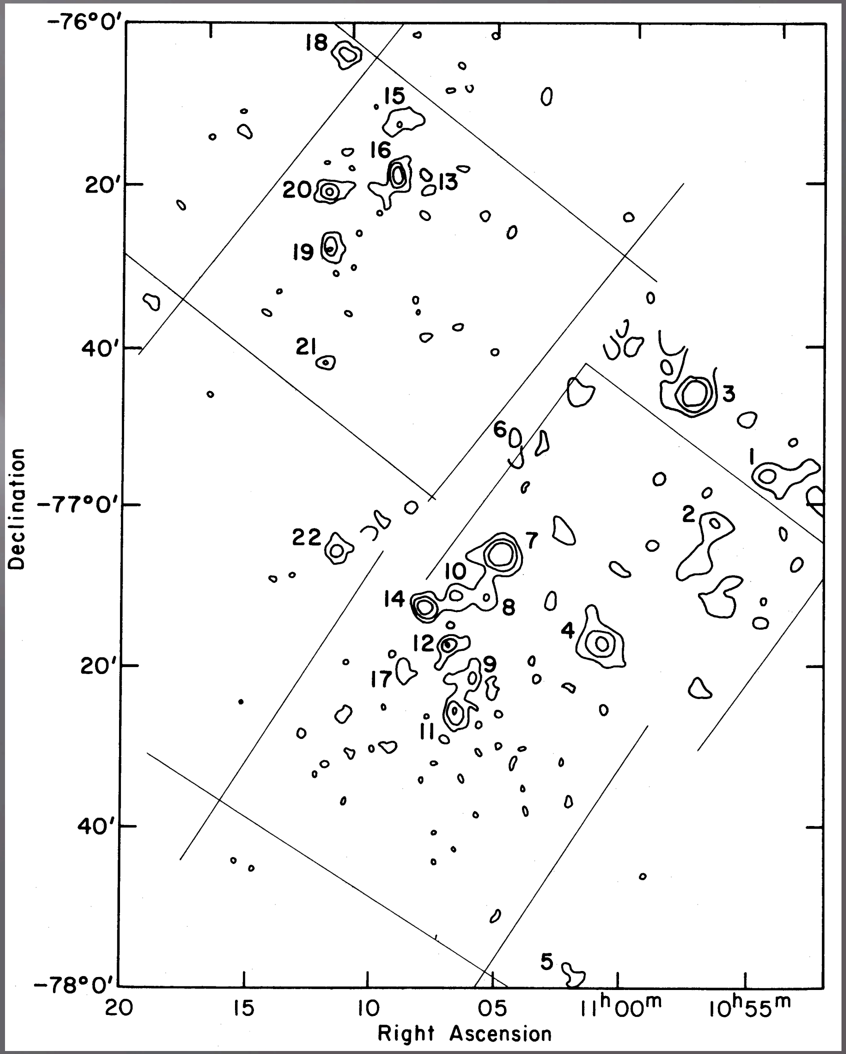
First Observations with Einstein (~1980)

E.g." Tautus-Aurigae, Ophiucus, Corona Australis, Chamaeleon

- Known T Tauri stars bright X-ray sources
  $L_X \sim 10^{30}$ ergs s^{-1}
- A number of other other X-ray sources also detected: Weak line T-Tauri Stars (WTTS)

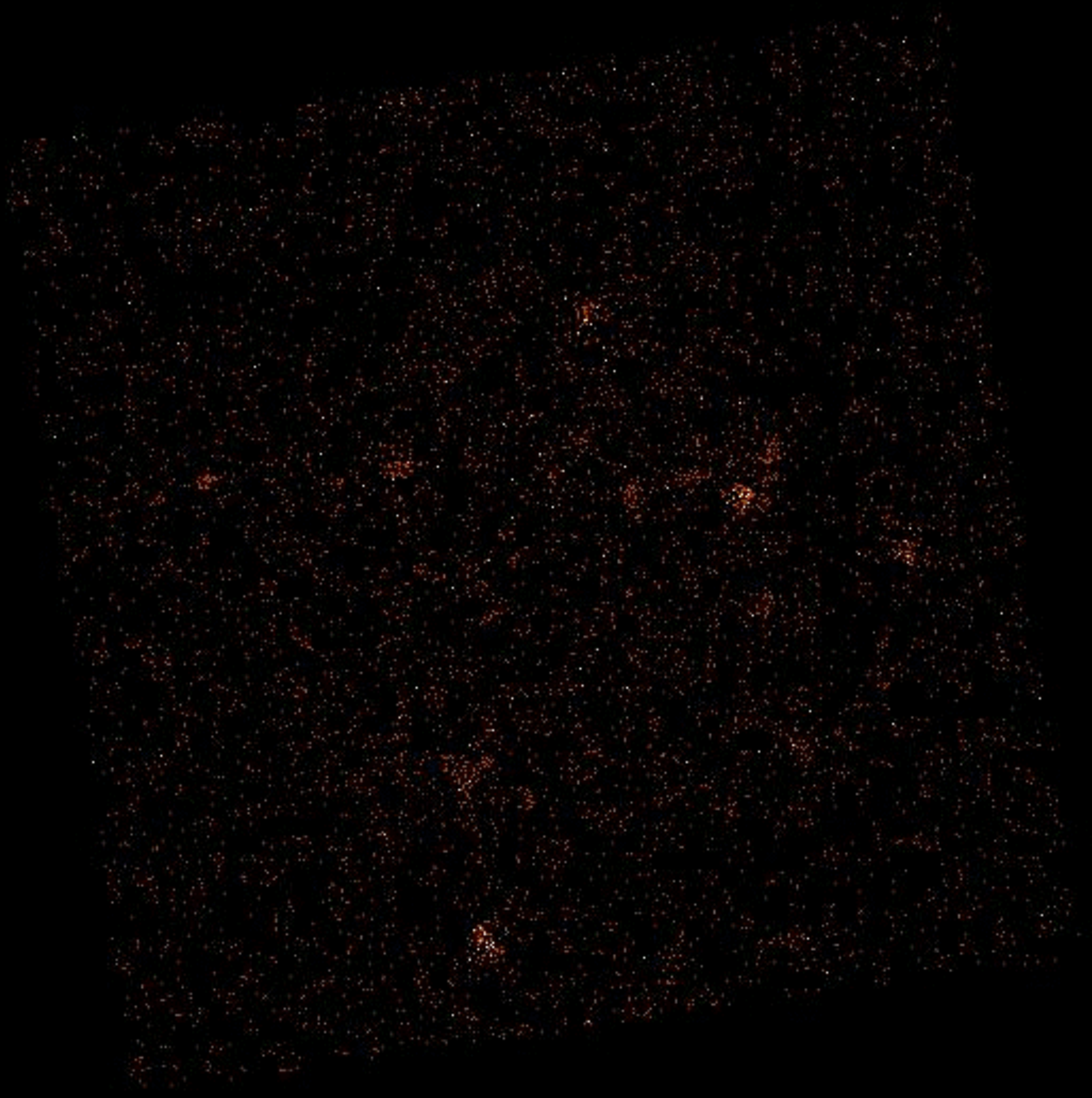
Gahm (1980); Feigelson and Decampli (1981); Feigelson and Kriss (1981); Walter and Kuhi (1981); Feigelson and Kriss (1983); Montmerle et al. (1983); Mundt et al. (1983); Walter and Kuhi (1984); Herbig, Vrba and Rydgren (1986); Walter (1986); Walter et al. (1987); Feigelson et al. (1987); Walter et al.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



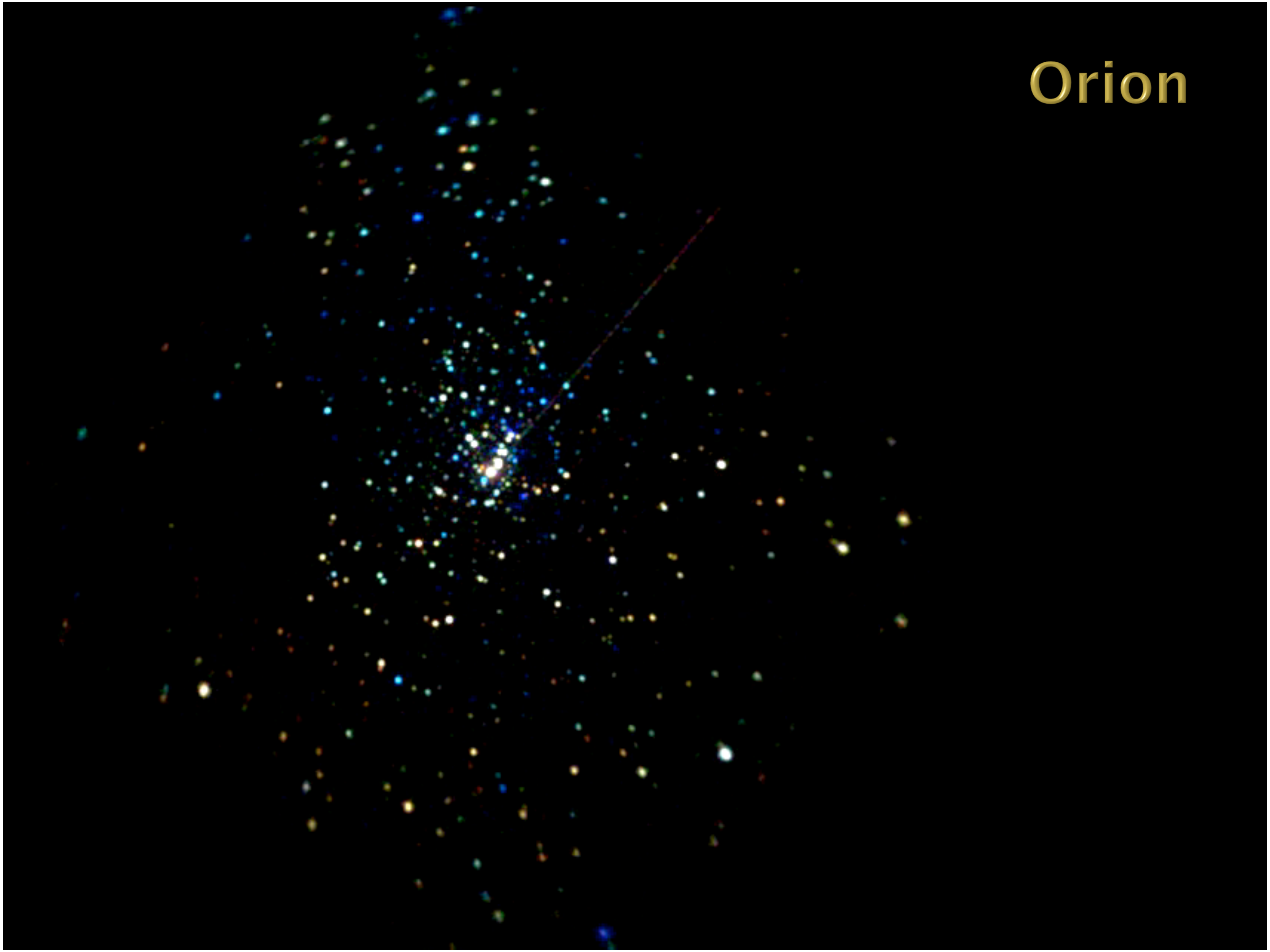
Feigelson & Kriss (1989)

ρ Ophiuchi: an "X-ray Christmas tree"

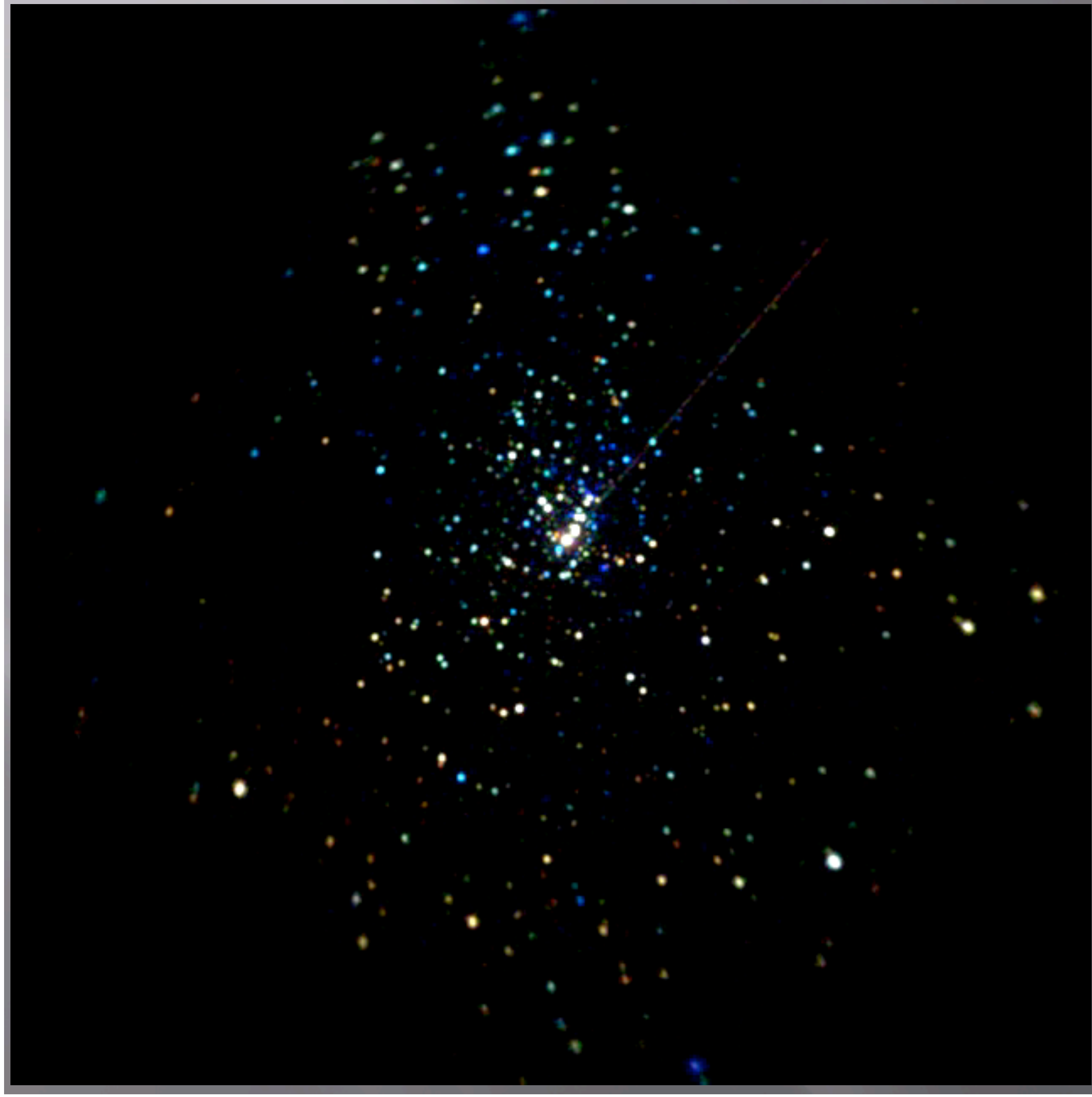
Montmerle et al. 1983 (*Einstein IPC* data)



Orion



Chandra Orion Ultradeep Project (COUP)



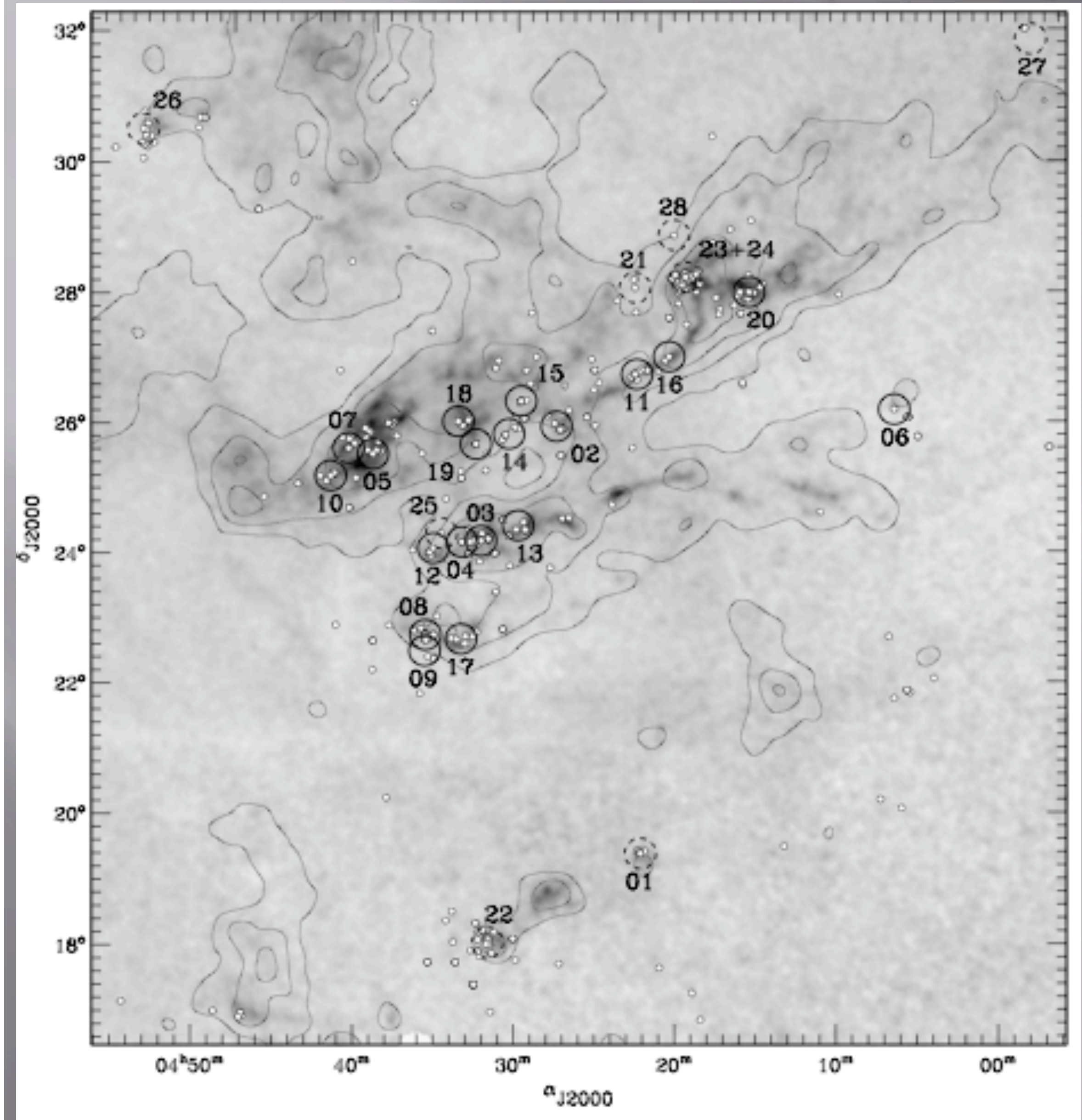
850 ks Chandra
on Orion Nebula Cluster (~ 1Myr)

PI: E. Feigelson

13 papers in ApJS Special Issue 160
and several others

1616 X-ray sources
of which >1300 cloud members

XMM-Newton Extended Survey in Taurus (XEST)



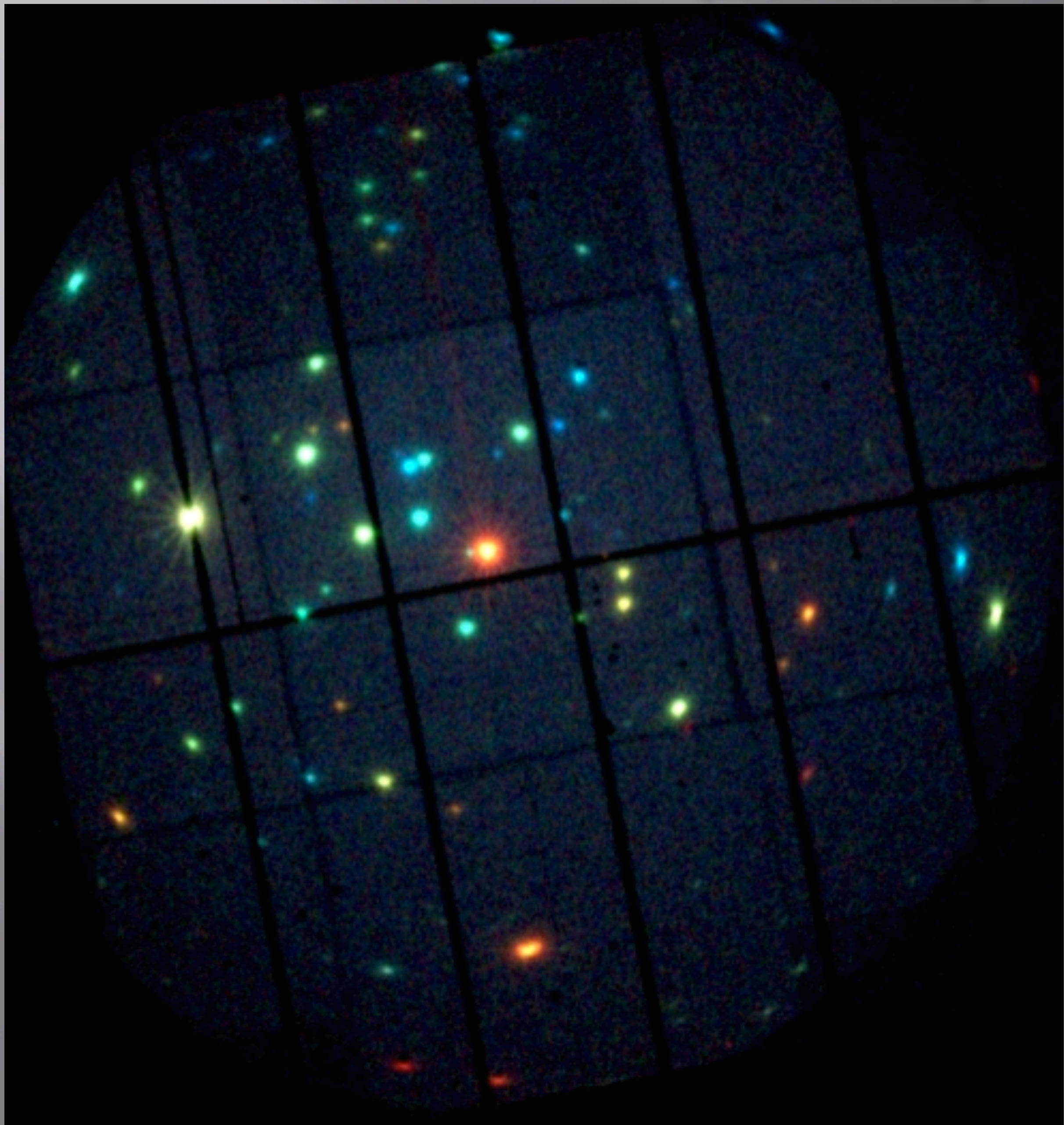
19 x 30 ks XMM-Newton
in Taurus Molecular cloud
(+ 9 XMM-Newton fields
in Taurus from archive)

PI: M. Guedel

15 papers in A&A Special Issue 468

126 cloud members detected,
33 cloud members undetected

Deep Rho Ophiuchi XMM-Newton Observation (DROXO)



500 ks XMM-Newton
on ρ Oph core F

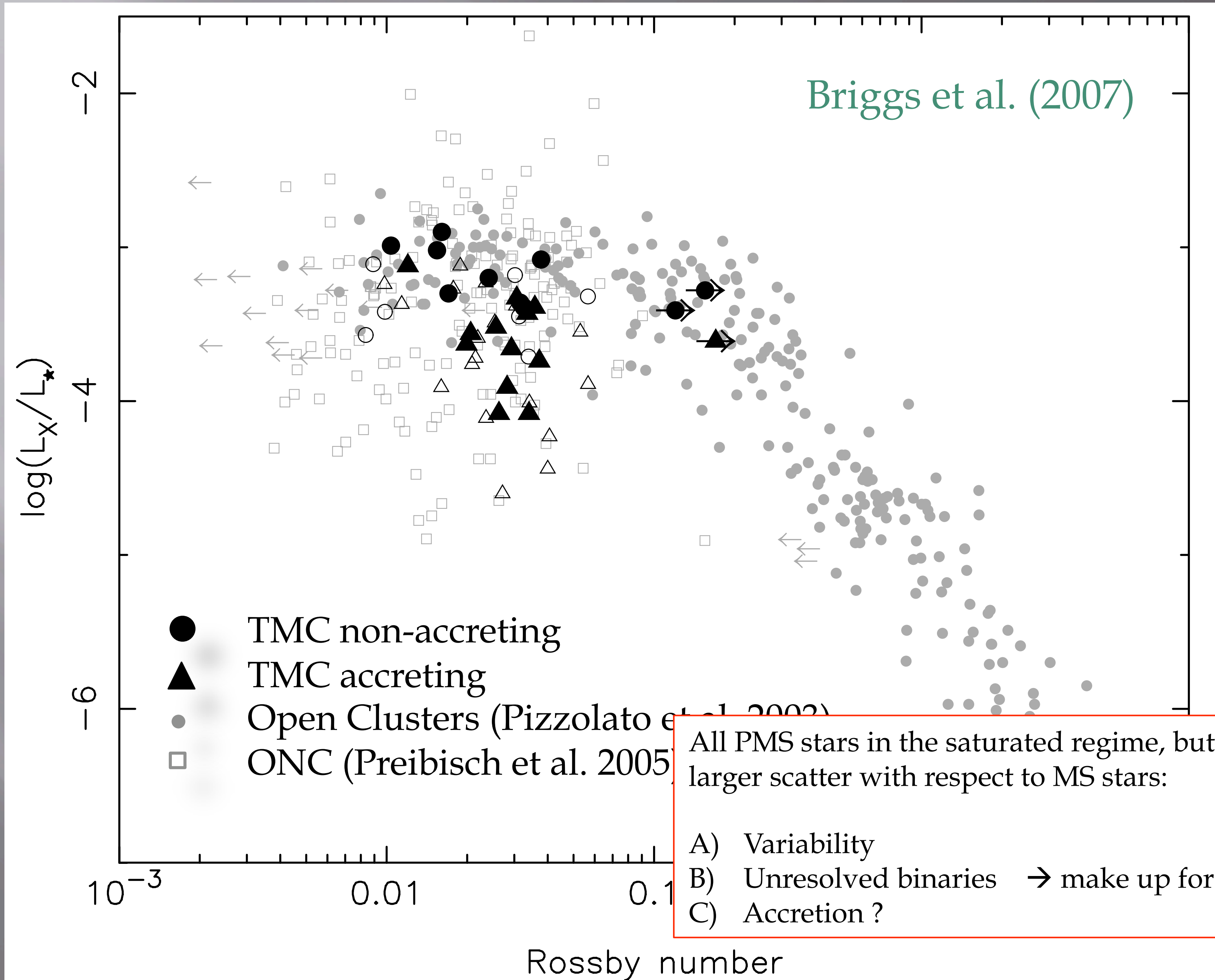
PI: S. Sciortino

2 paper published,
several others in prep.

111 X-ray sources

~ 0.5 Myr PMS stars

PMS stars (Taurus / XEST, ONC / COUP)

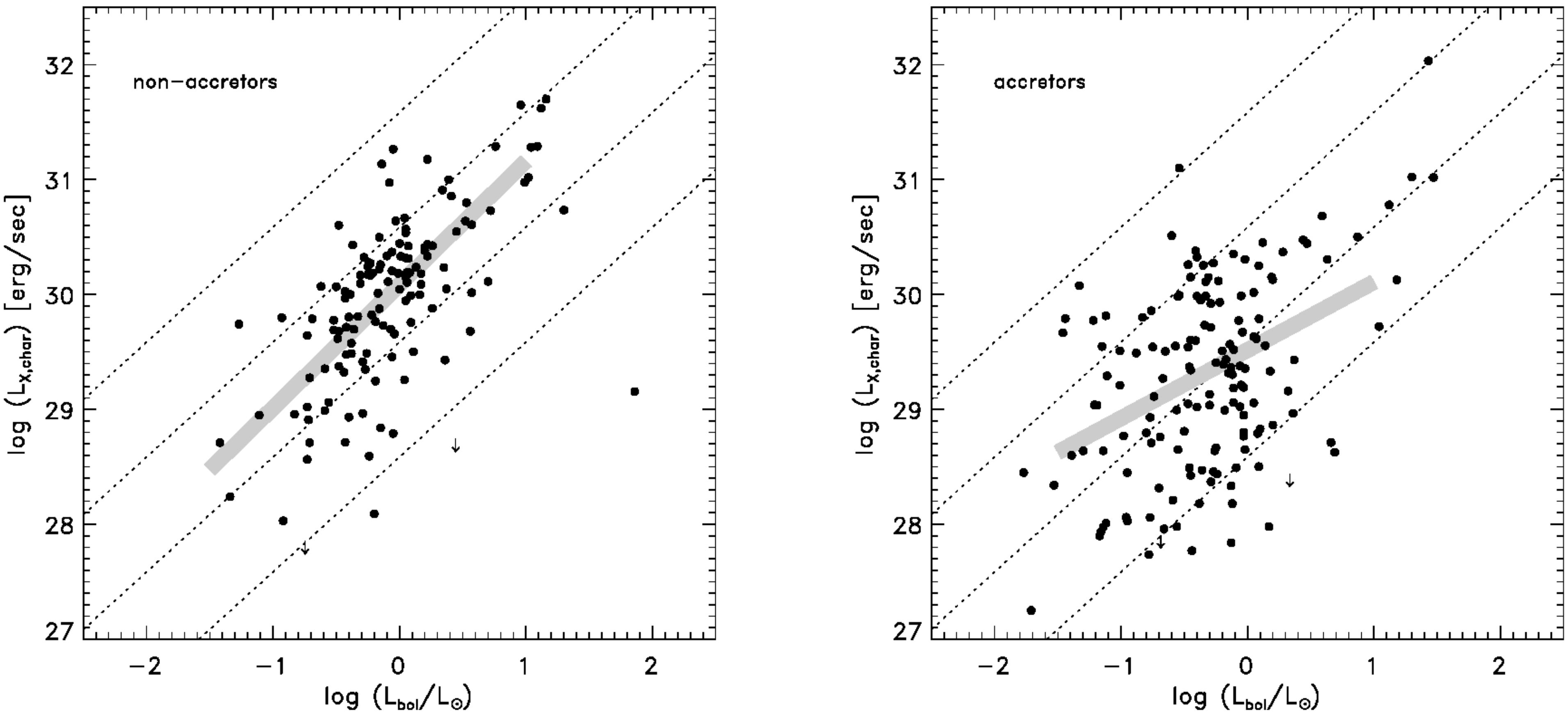


All PMS stars in the saturated regime, but much larger scatter with respect to MS stars:

A) Variability
B) Unresolved binaries → make up for <0.5 dex
C) Accretion ?

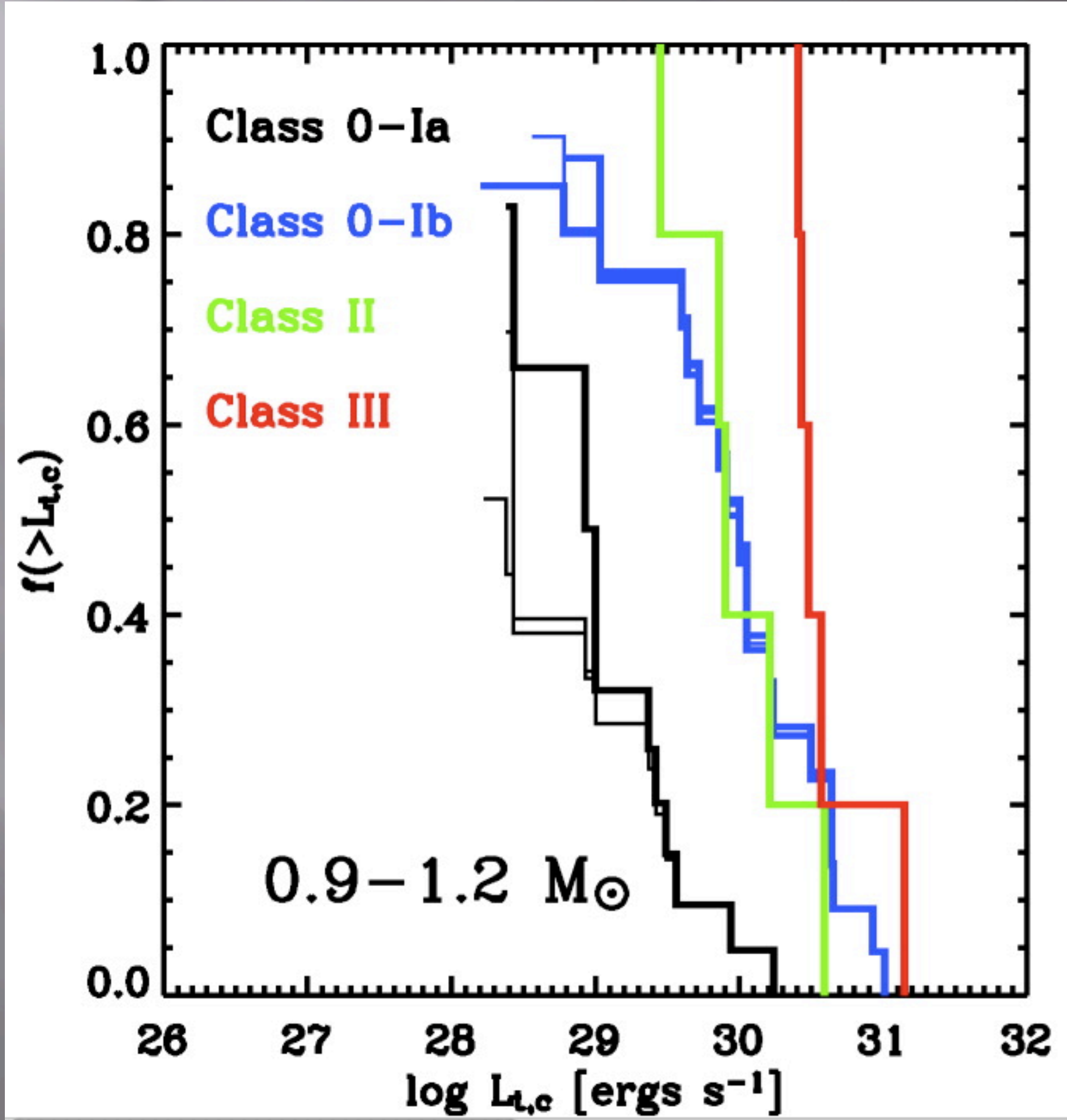
X-ray activity and accretion

Preibisch et al. (2005)



Accretion disks affect (depress) activity?

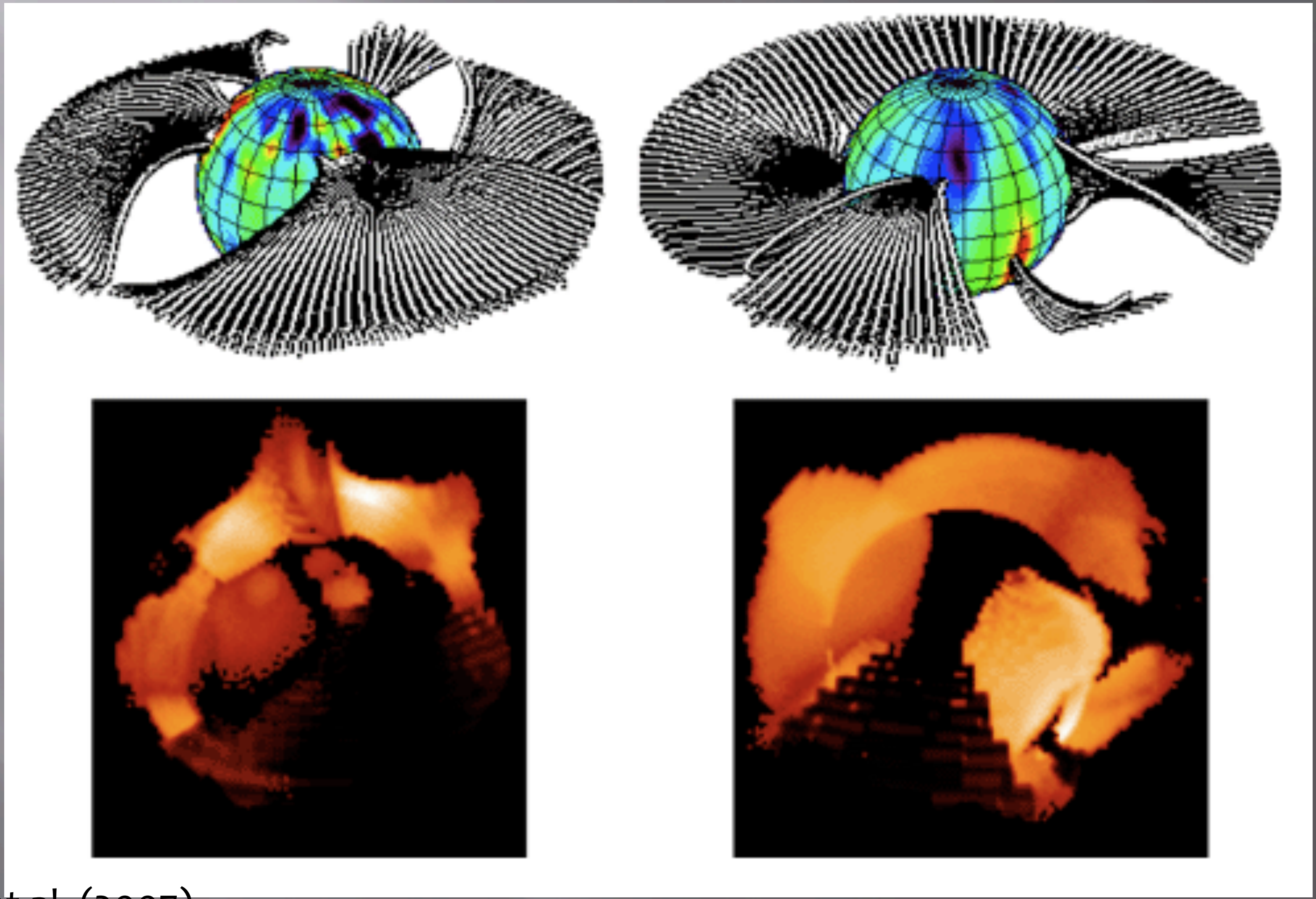
X-ray luminosities of Class I objects (ONC / COUP)



Prisinzano et al. (2008)

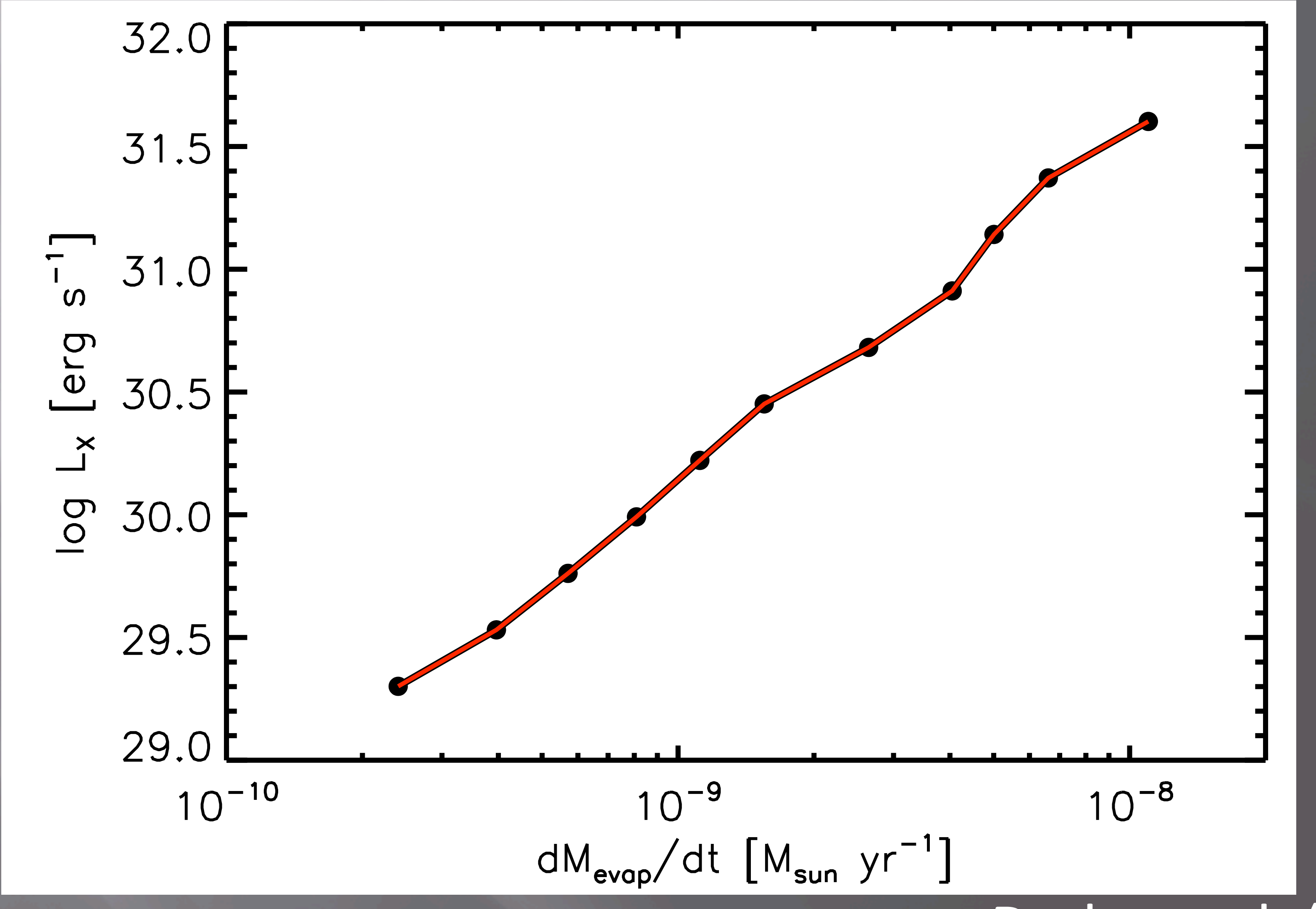
Possible explanation for lower L_x of accretors:

- Higher density → less efficient heating
- X-ray emission obscured by accretion streams



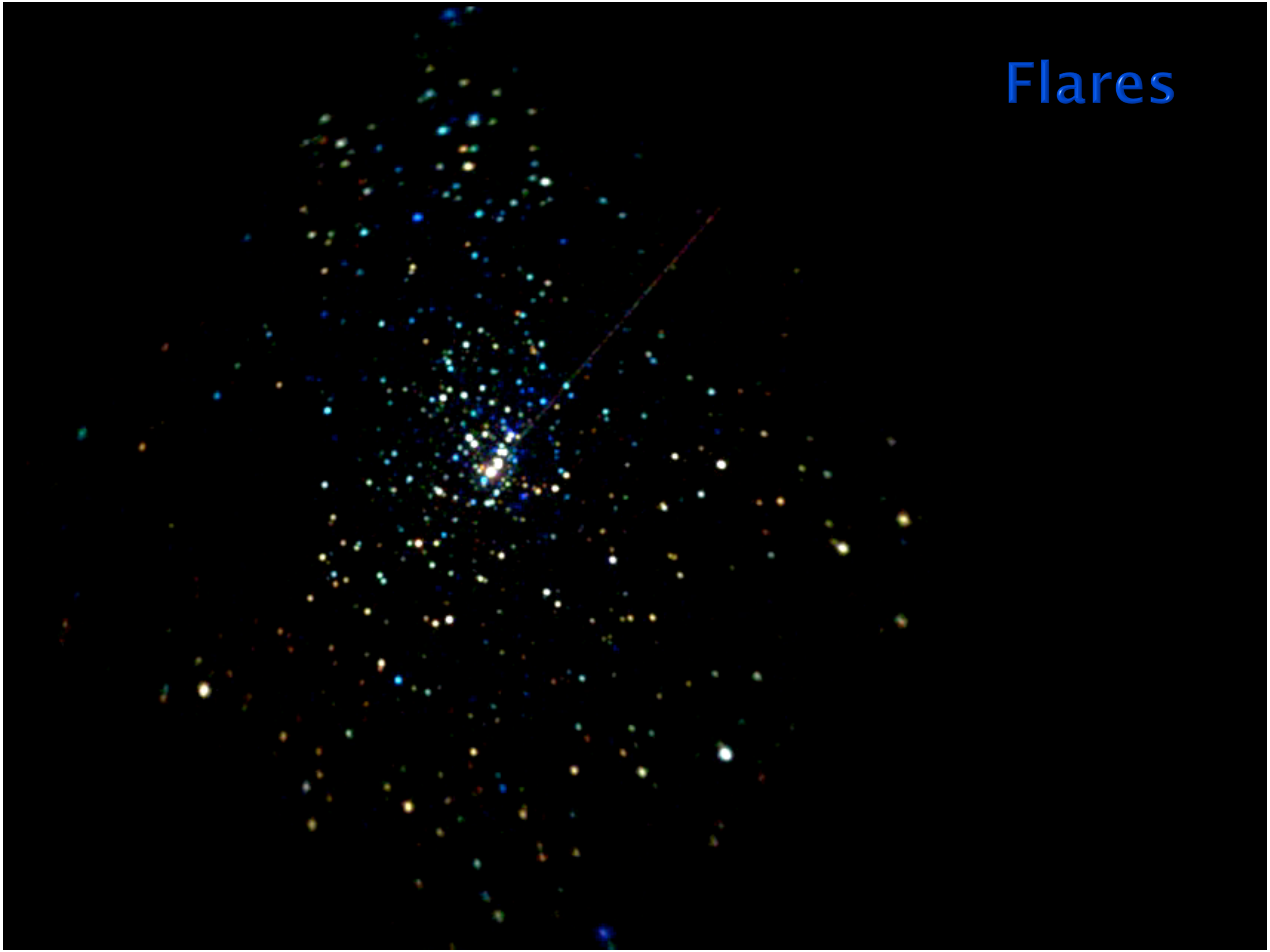
Gregory et al. (2007)

X-ray photoevaporation of accretion disks?



Drake et al. (2009)

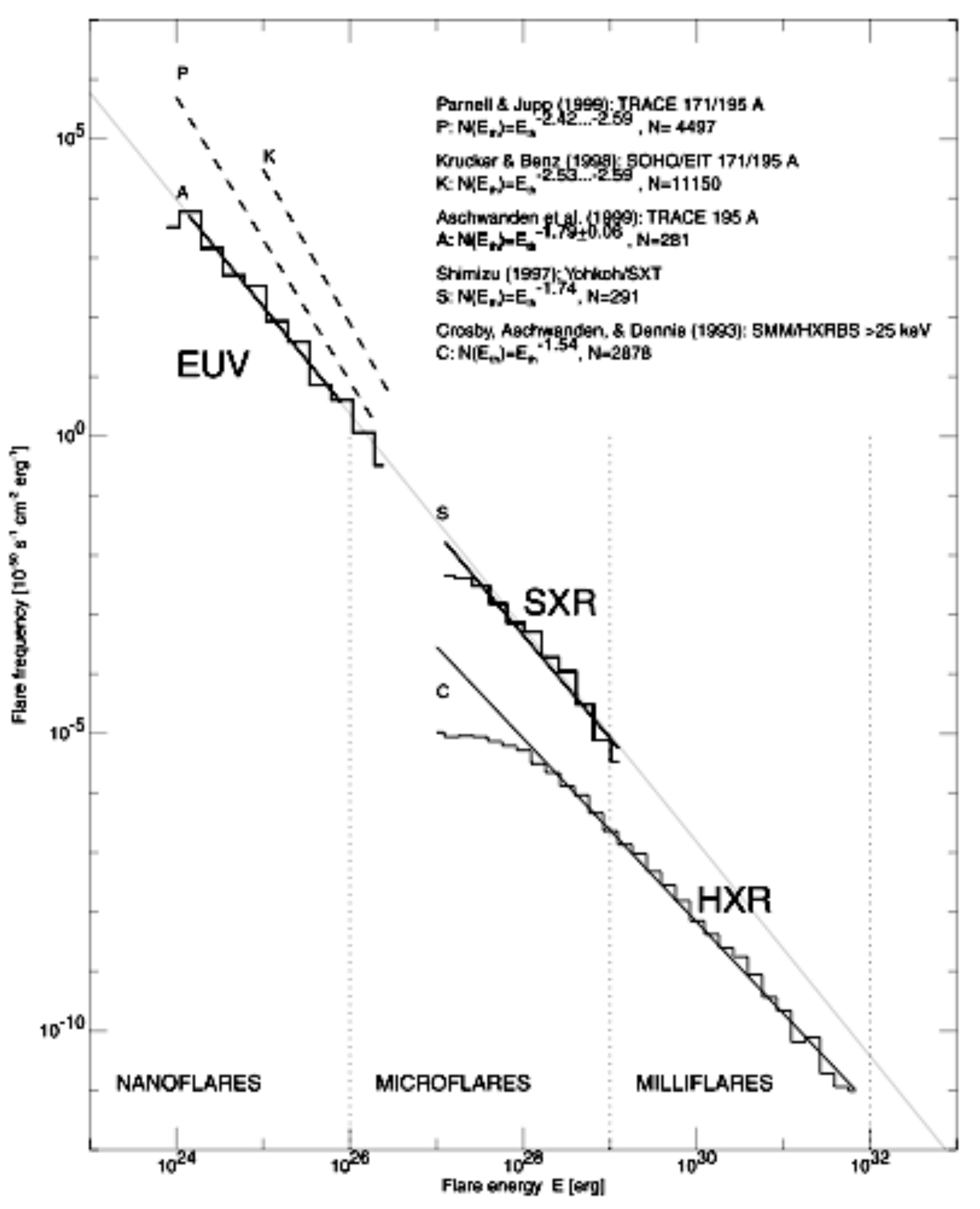
Flares



Flare energy distribution
Nanoflare heating?

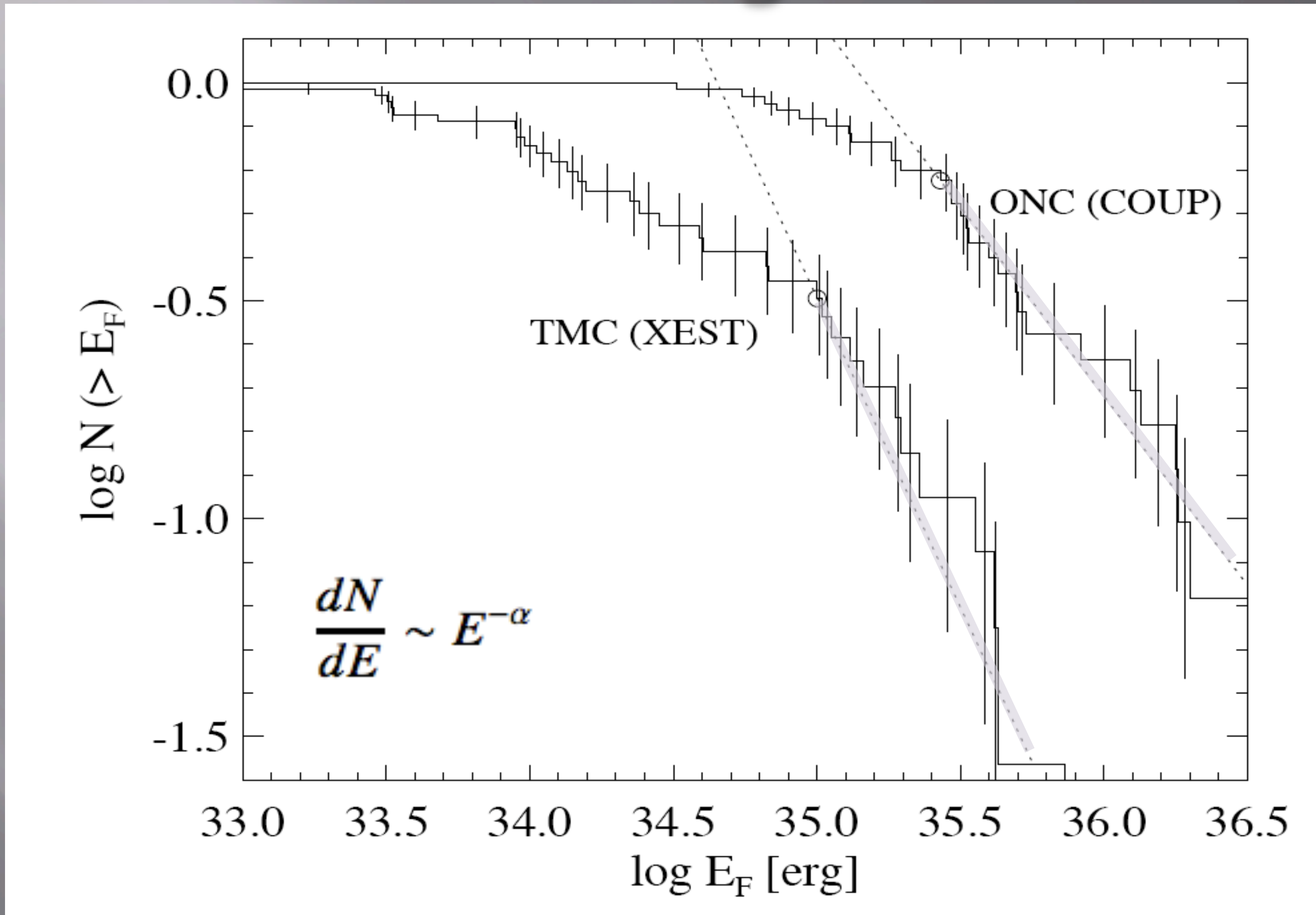
$$\frac{dN}{dE} \sim E^{-\alpha}$$

If $\alpha > 2$ the integral diverges for $E_{min} \rightarrow 0$
infinite amount of energy in nano-flares



Aschwanden et al. (2000)

Flare number energy distribution COUP solar-analogs + XEST stars



Stelzer et al. (2007)

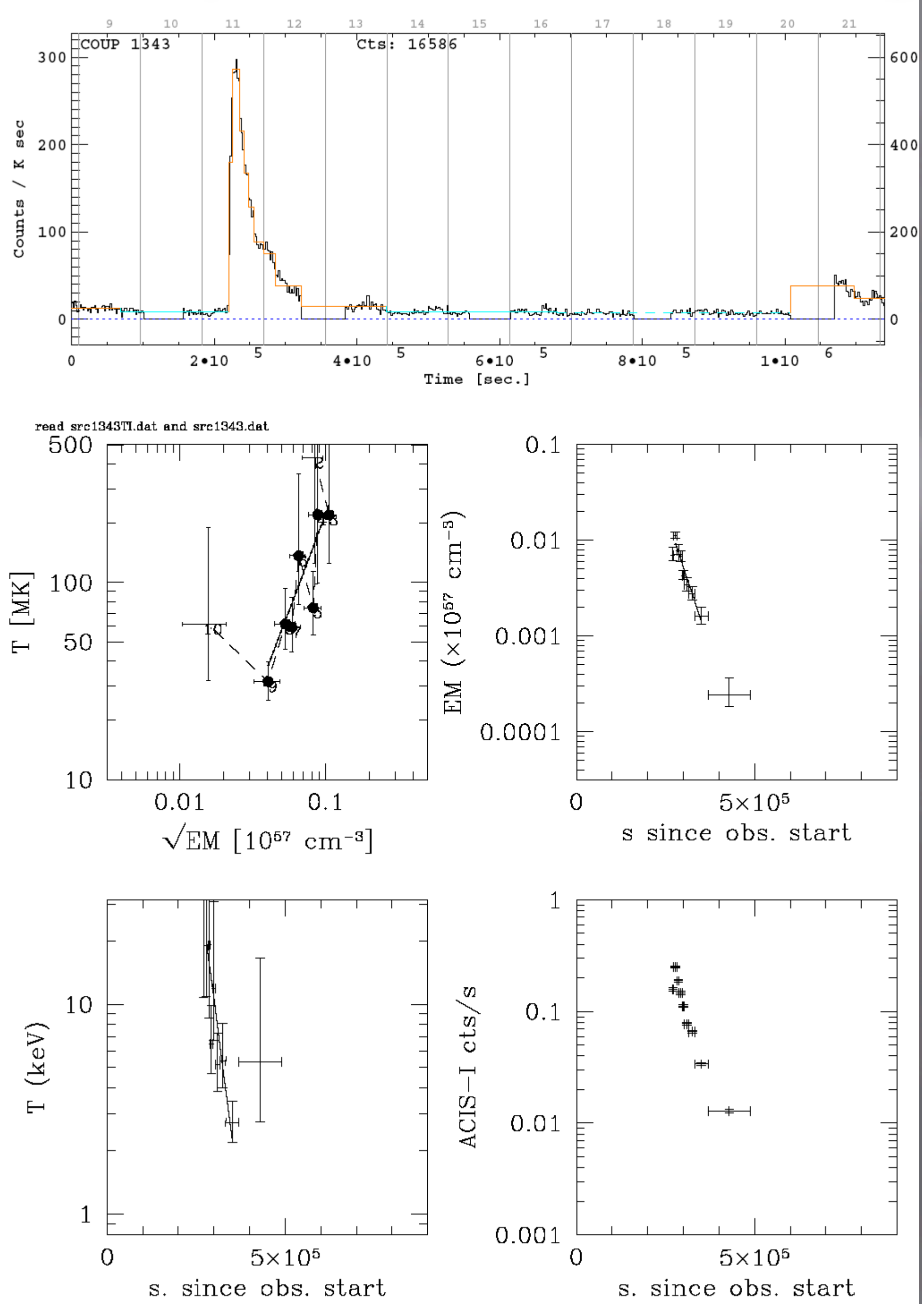
Flare energy distribution
Various star forming regions

	Log E_{cut}	α	F_{fl} with E> E_{cut}	Exp.T [ks]	N_{stars}
COUP solar analogs	35.3	1.9 +- 0.3	1 / 1150 ks	850	28
COUP very low-mass	-	2.2 +- 0.2	-	850	165
COUP all	35.6	2.05 +- 0.15	1 / 5542 ks	850	
XEST all	34.9	2.4 +- 0.5	1 / 770 ks	30	22
CygOB2 low mass	35.1	2.1 +- 0.1	1 / 1320 ks	100	1003

Wolk et al. (2005), Caramazza et al. (2007), Stelzer et al. (2007), Albacete Colombo et al. (2007)

Flare energy distributions in all Pre-MS samples support nano-flare heating, but completeness limits for energy are high

Physical modelling of 32 bright flares



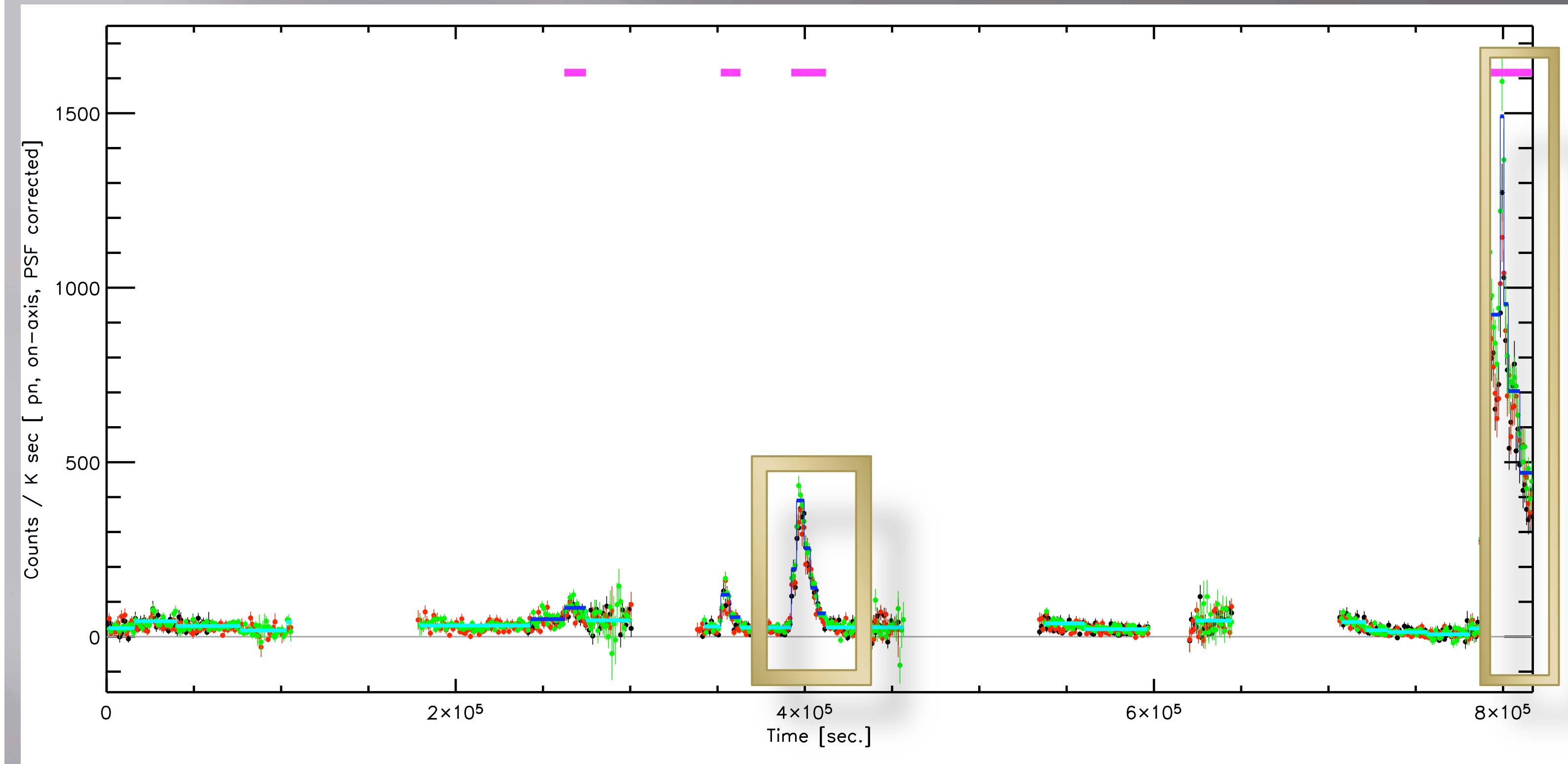
Favata et al. (2005)

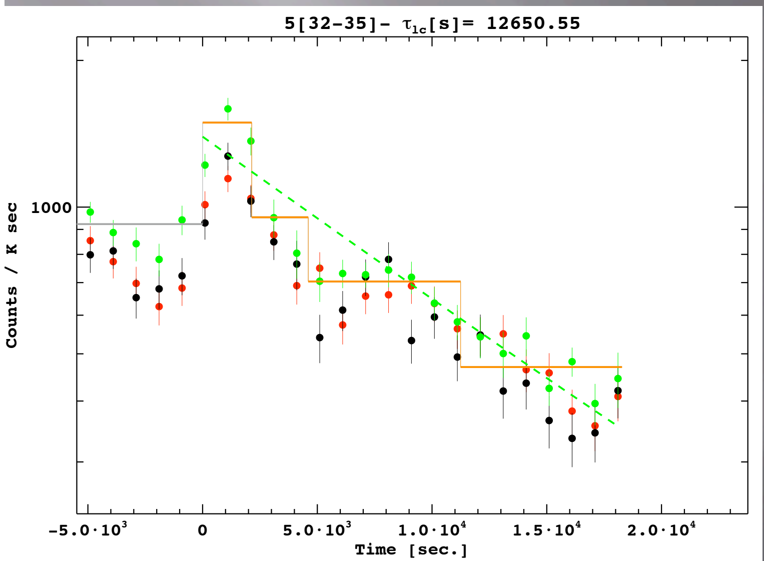
$$L = \frac{\tau_{lc}\sqrt{T_{pk}}}{3.7 \times 10^{-4} F(\zeta)}.$$

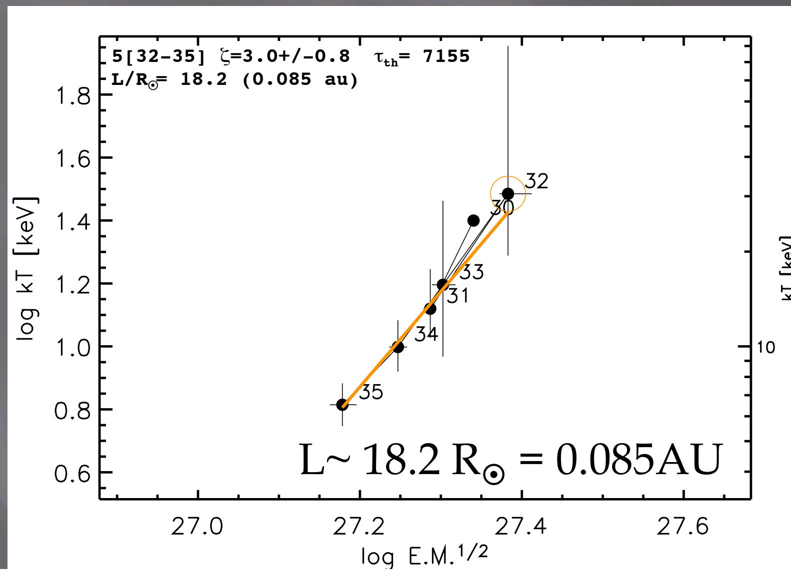
Reale et al. (1997)

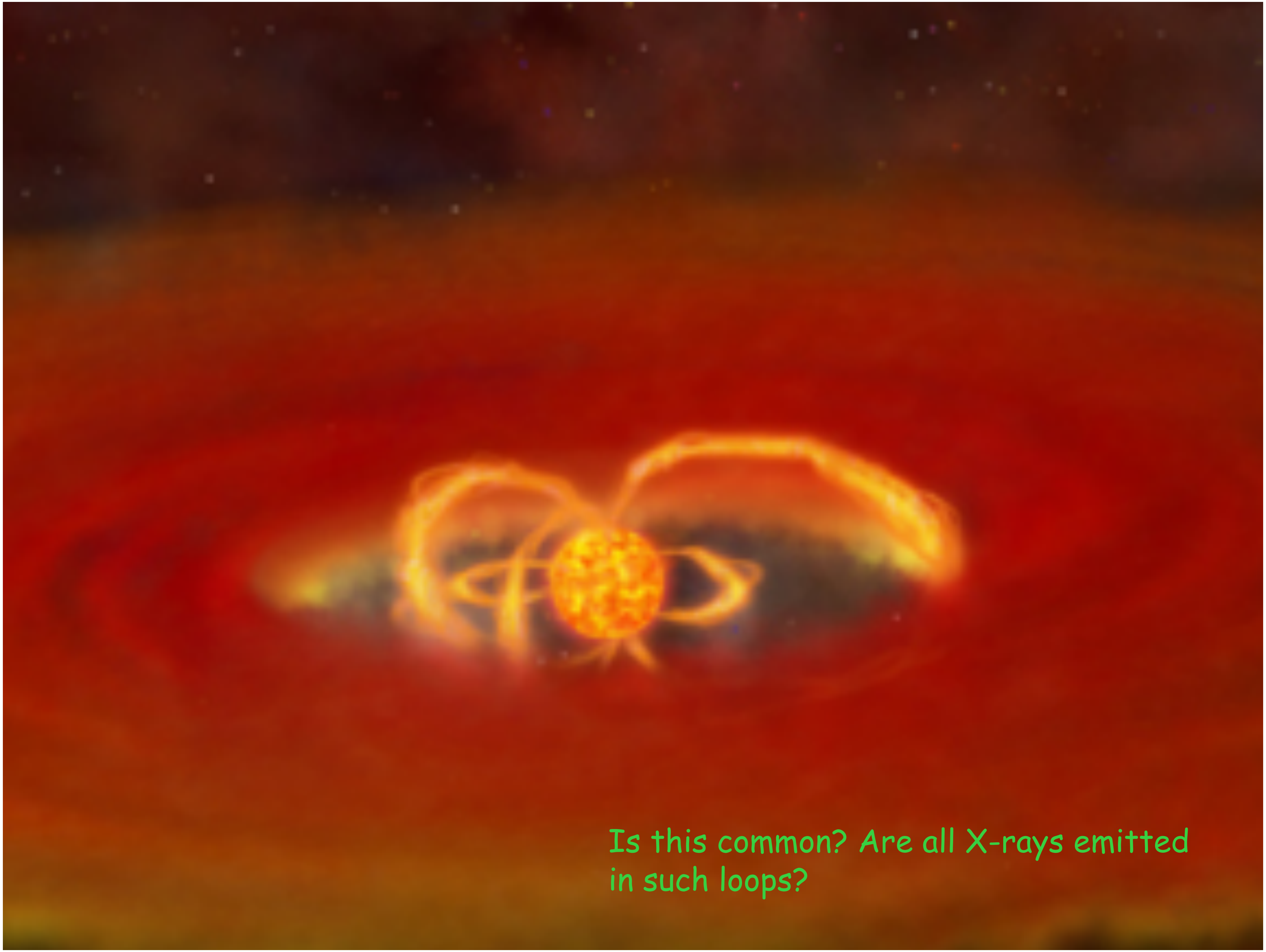
A sigificant number of flares (~10) imply loops longer than 5 $R_\star$

YLW 16A (class I)



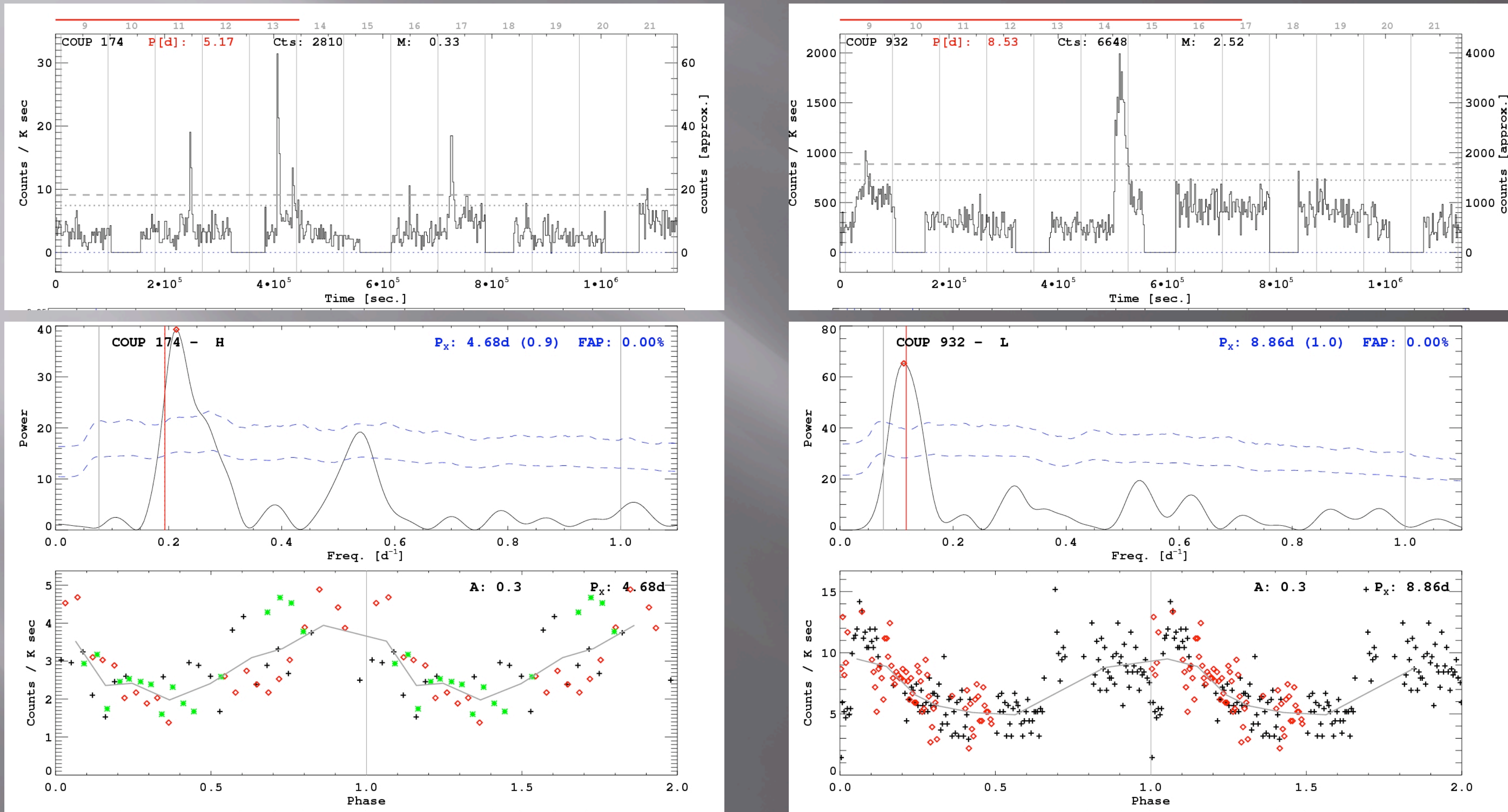





Is this common? Are all X-rays emitted
in such loops?

Rotational modulation of X-ray emission of ONC stars (COUP)

Flaccomio et al. (2005)



- ➢Rotational modulation is detected in >10% of the sample. Amplitudes: 20-70%
- ➢**X-ray emitting structures must be compact (< R*)**

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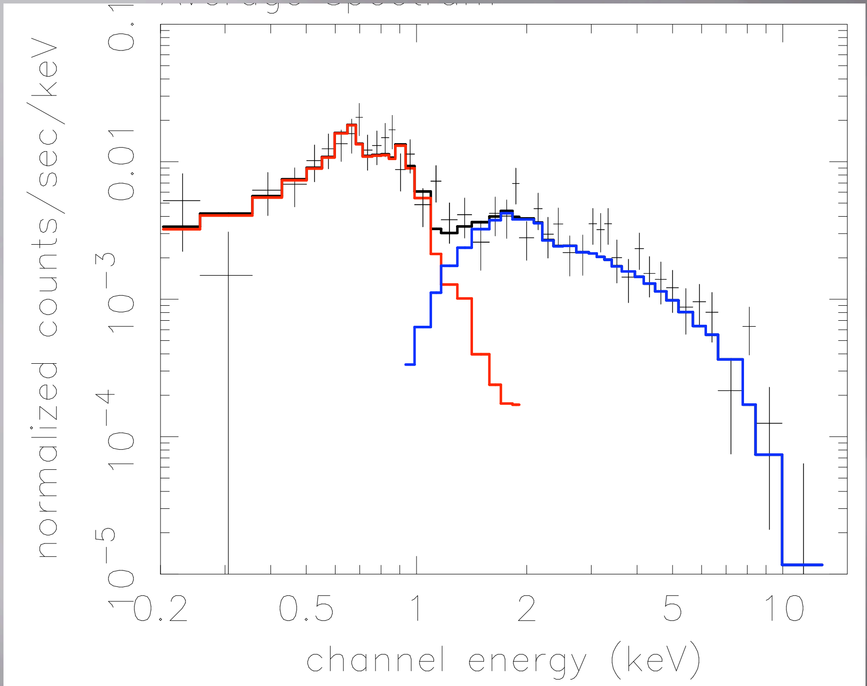
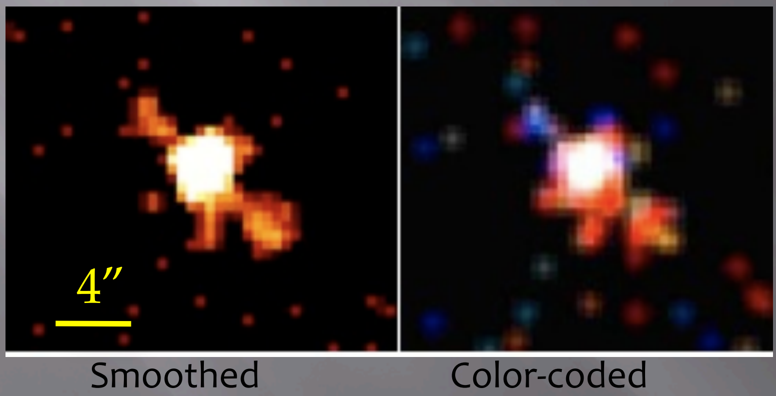
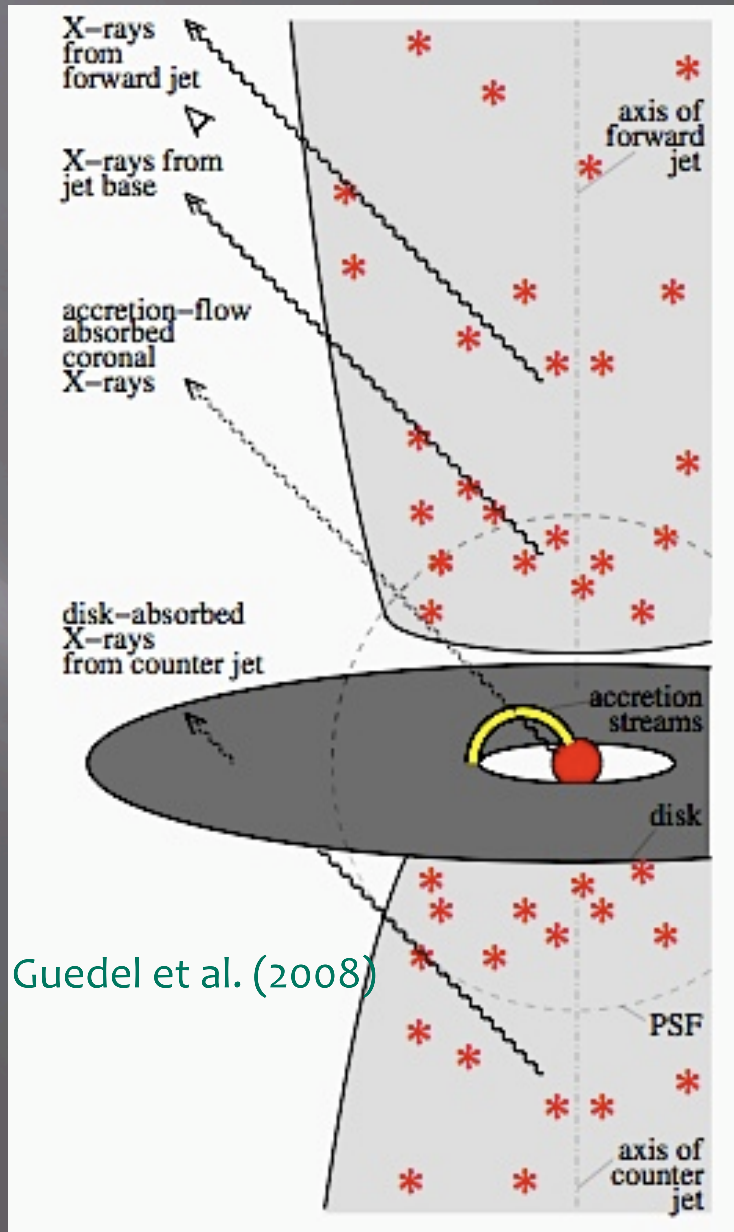
X-rays from protostellar and pre-MS jets



DG Tau - Guedel et al. (2007)



DG Tau - Guedel et al. (2008)



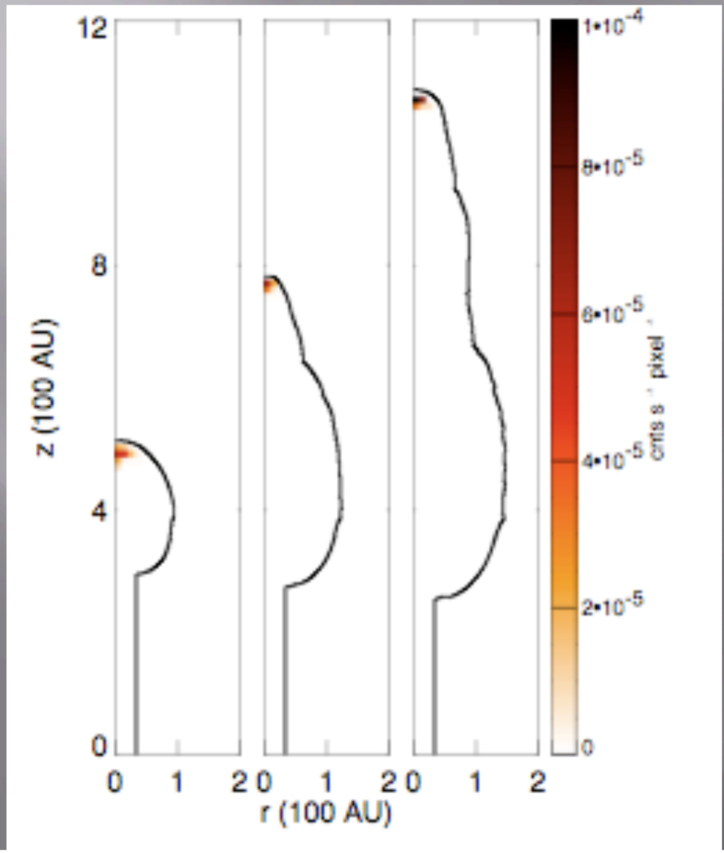
Guedel et al. (2008)

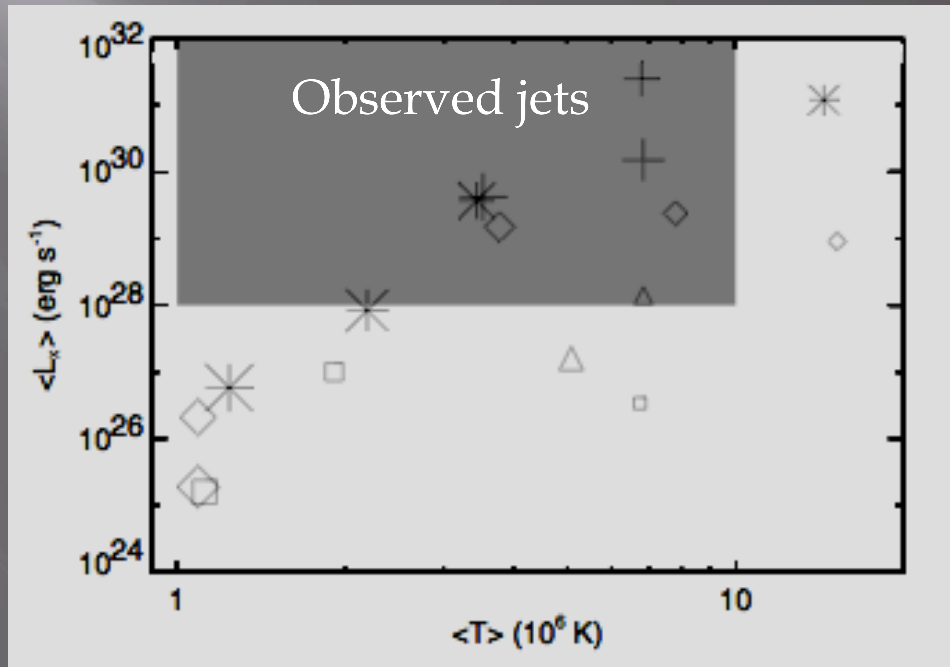
X-rays from protostellar and pre-MS jets

Object	L_X [10^{29} erg s^{-1}]	kT [keV]	N_H [10^{22} cm^{-2}]	v_{sh} [km s^{-1}]	D [pc]	$L_{bol}/L_{\odot}$	L_X/L_{bol}
HH 2	5.2	0.23	≤ 0.09	230	480	81^a	1.7×10^{-6}
HH 154	3.0	0.34	1.40	500	140	40^b	9.7×10^{-7}
HH 80/81	450	0.13	0.44	700	1700	2×10^{4c}	1.5×10^{-4}
HH 168	1.1	0.5	0.40	500	730	2.5×10^{4c}	3.6×10^{-7}
HH 210	10	0.07–0.33	0.80	130	450	–	–

Bonito et al. (2007)

Only a handful of pre-MS jet shocks have been detected in X-rays.





Calculations for jets with different Mach number (plotting symbols) and different medium/jet density contrast (size of symbols).

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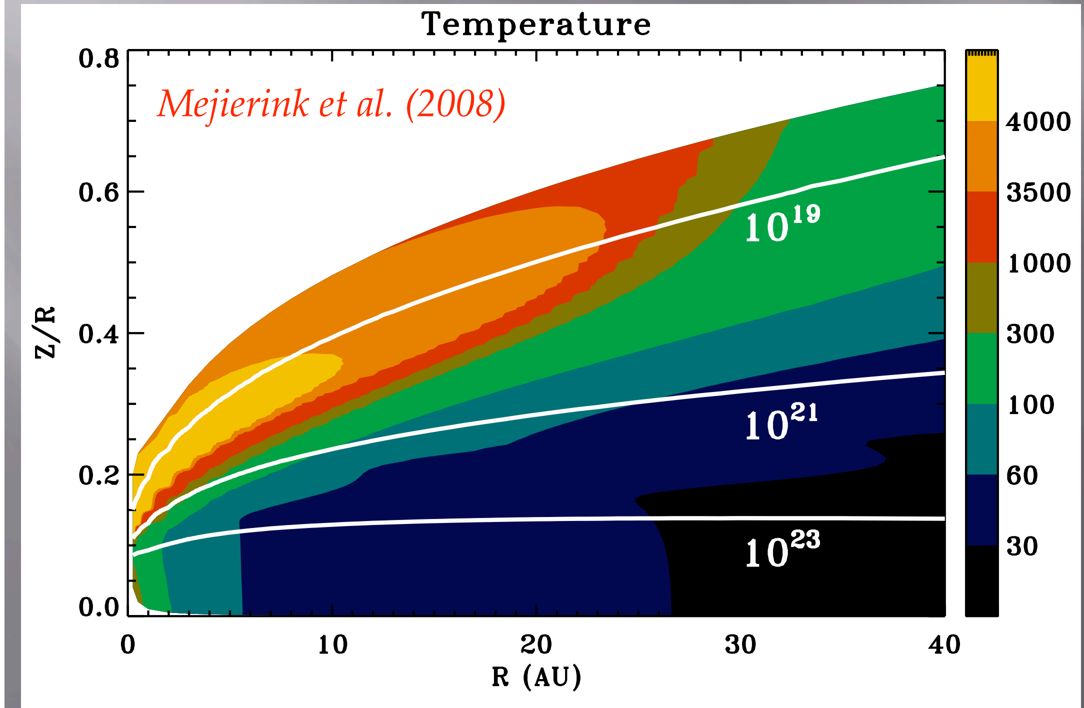
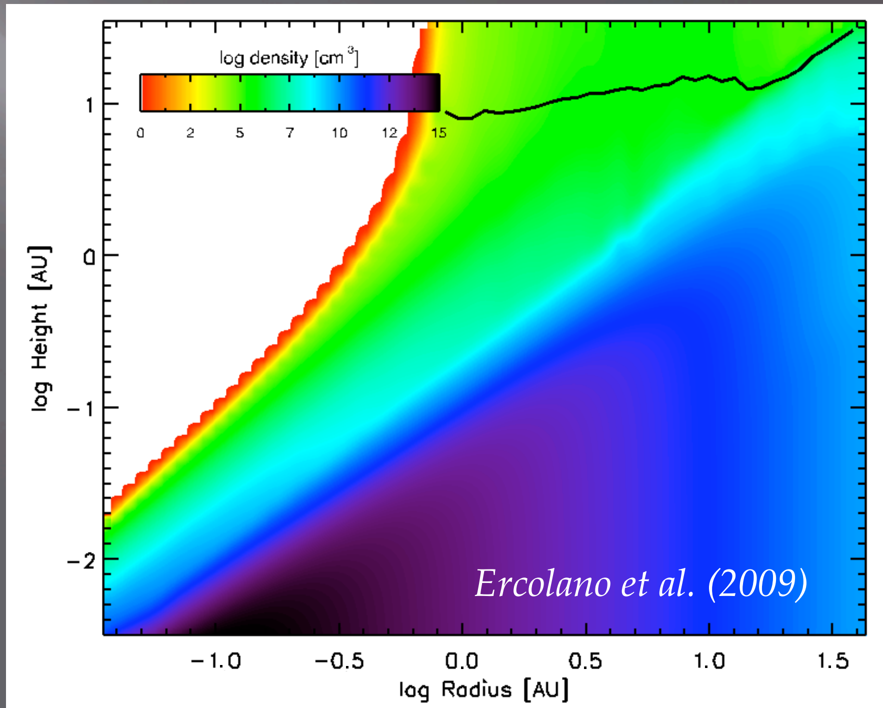
X-rays and circumstellar disk

- Stellar X-rays heat and ionize circumstellar disks (e.g. Igea & Glassgold 1999, Glassgold et al. 2004)
- Significant effects on disk structure/evolution and planet formation e.g.: viscosity, photoevaporation (>EUV)

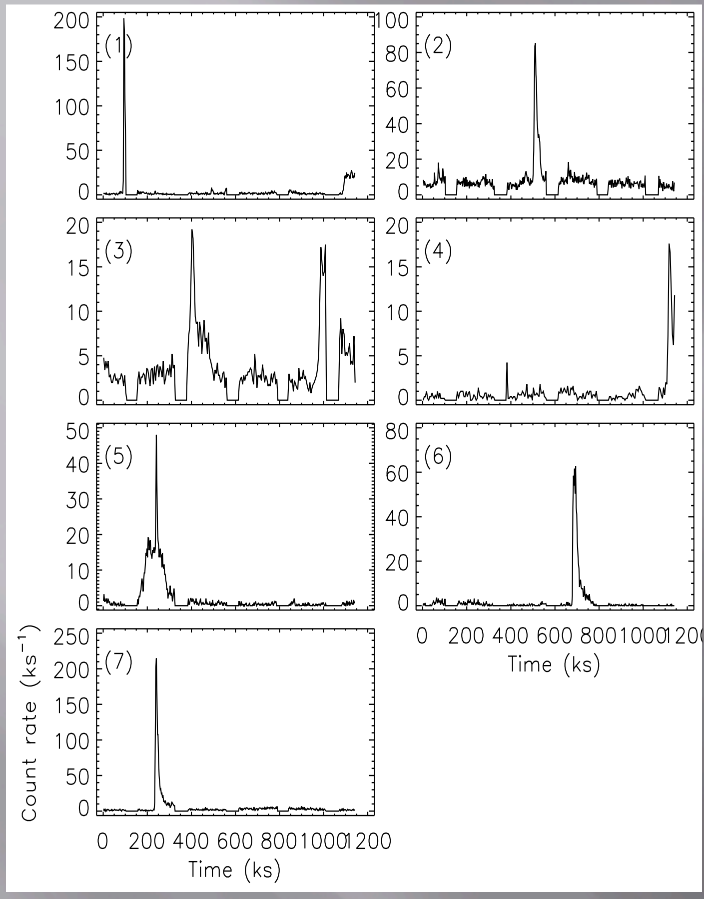


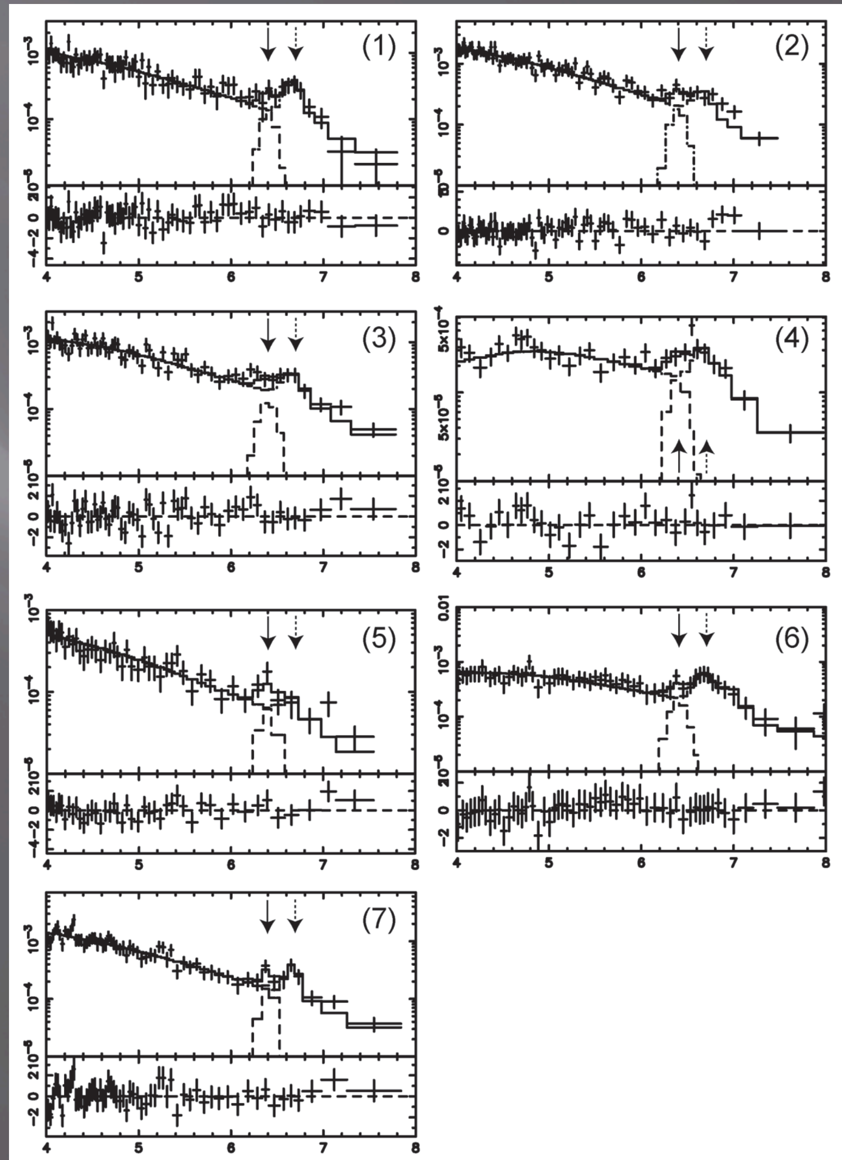


Glassgold et al. (2007), Mejierink et al. (2008), Gorti & Hollenback (2008), Ercolano et al. (2009)

Fe 6.4keV - COUP

Tsujimoto et al. (2005)

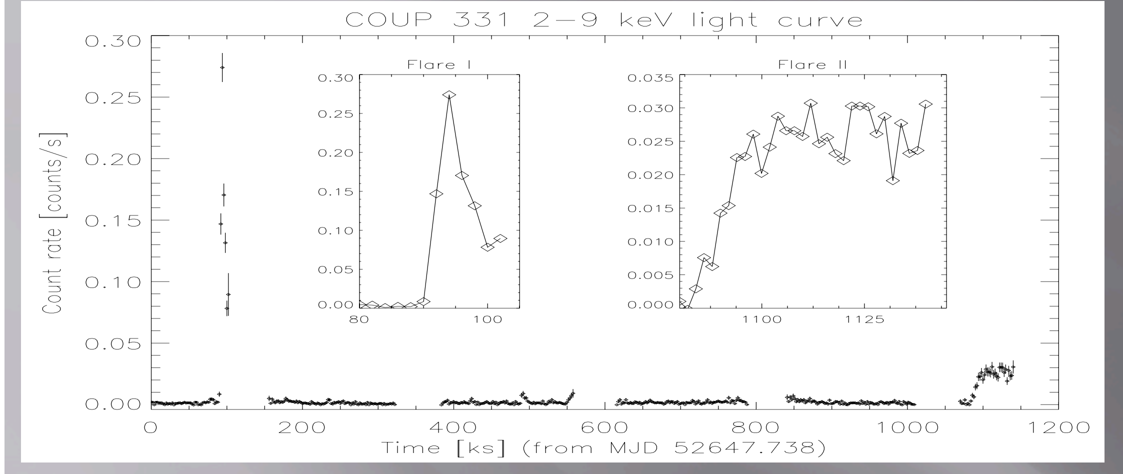


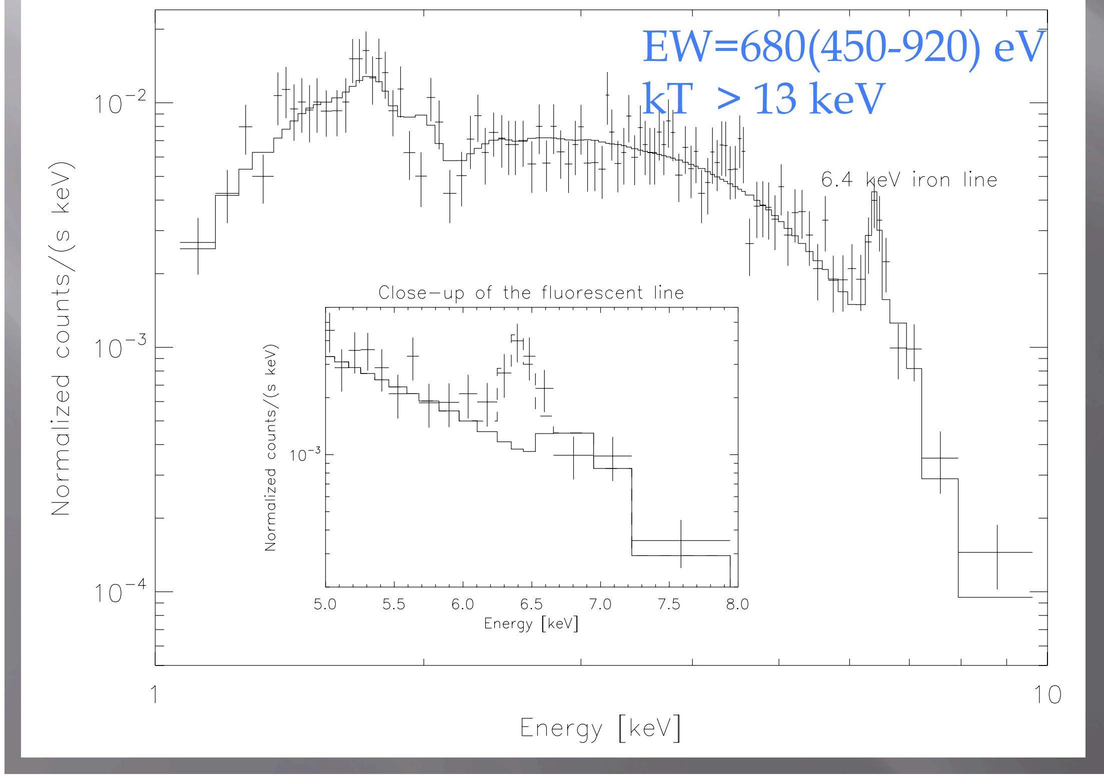


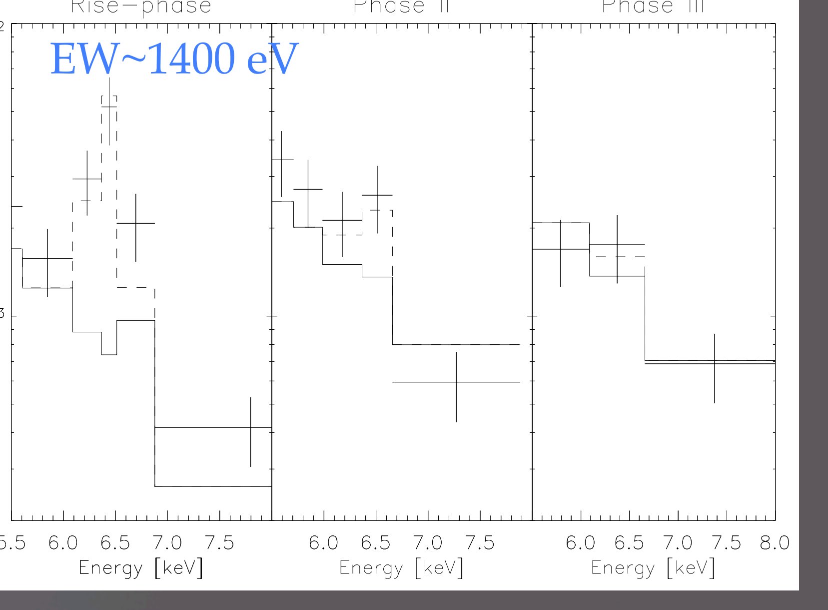
COUP[b] Sequence Number	k_BT [d, f] (keV)	L_X [d, f] (10^{30} ergs s^{-1})	$L_{X,\ peak}$ [g] (10^{31} ergs s^{-1})	$N_{K\alpha}$ [d, e] (10^{-7} cm^{-2} s^{-1})	$EW_{K\alpha}$ [e] (eV)
331	4.6 (4.3–5.6)	3.4 (2.7–3.9)	17	2.6 (0.1–4.6)	126
561	2.8 (2.6–2.9)	5.6 (5.8–6.1)	4.4	3.6 (1.1–7.3)	130
621	3.2 (2.9–3.4)	4.1 (3.4–4.8)	1.6	2.5 (0.5–3.9)	111
647	5.7 (4.7–8.1)	3.3 (2.9–4.1)	5.7	4.1 (1.9–6.2)	135
649	3.0 (2.6–3.1)	1.4 (1.0–1.7)	2.1	1.2 (0.3–2.2)	268
1030	9.4 (6.4–14)	11 (9.3–12)	45	17 (2.5–17)	111
1040	3.3 (3.0–3.5)	6.7 (6.2–7.2)	40	4.3 (1.5–6.6)	122

V1486 Ori (COUP #331)

Czesla & Schmitt (2007)

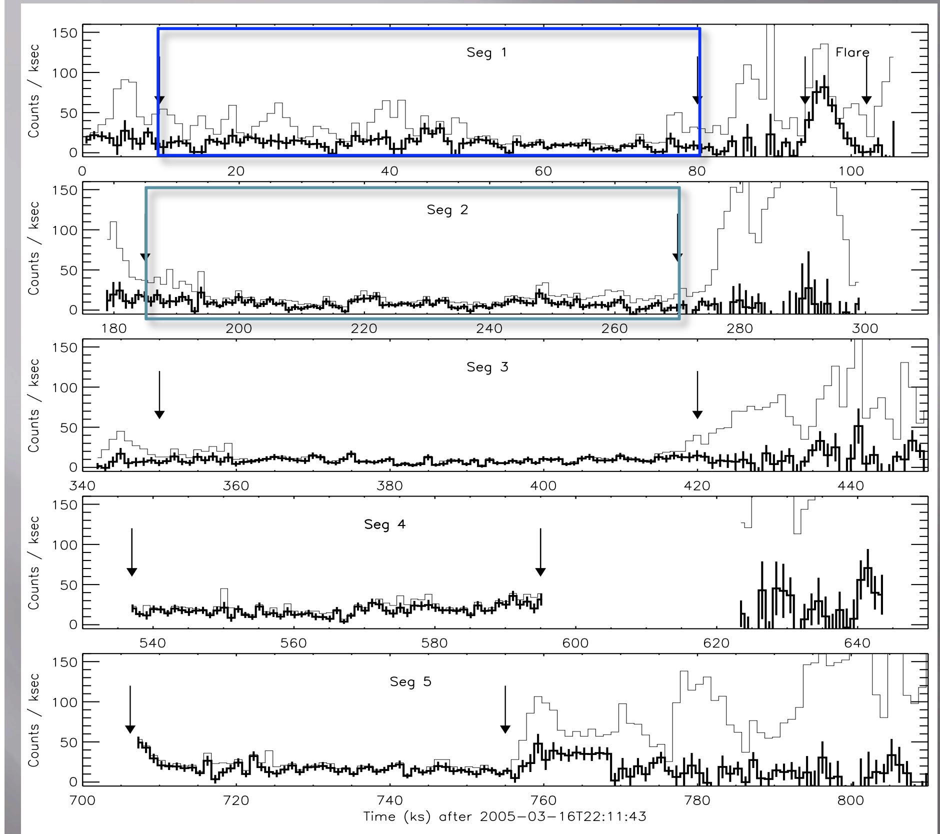


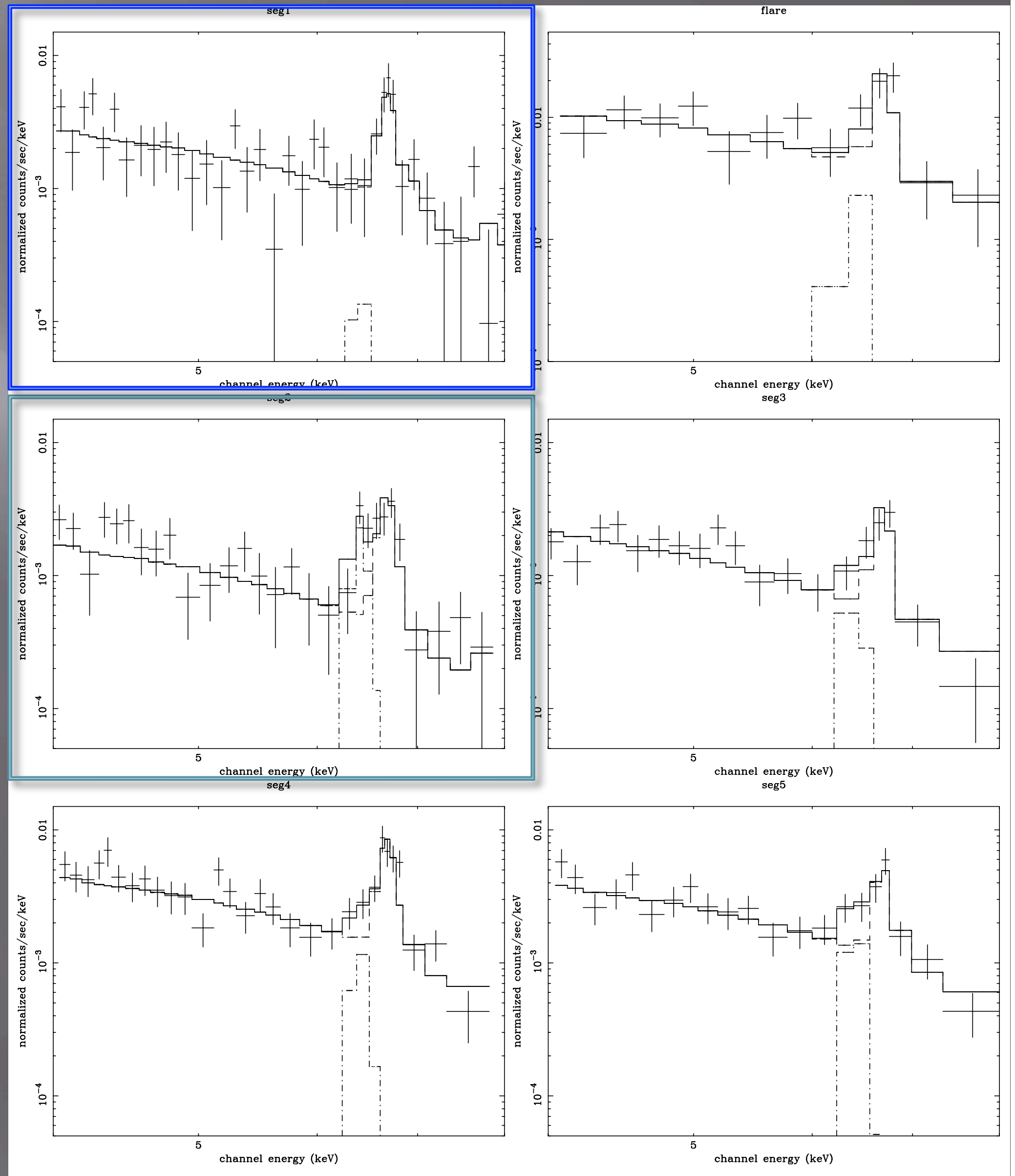




Elias 29 (DROXO)

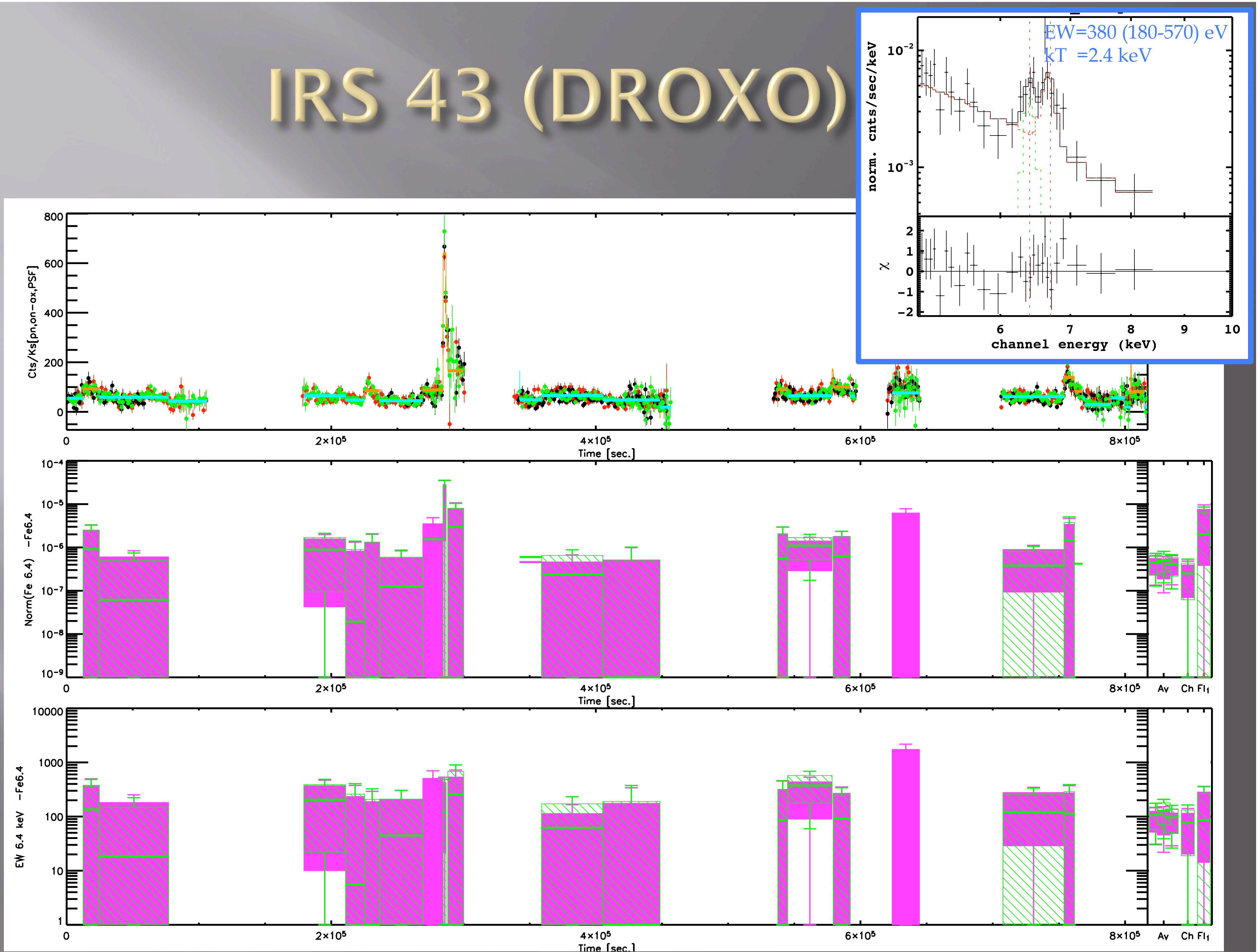
Giardino et al. (2007,2009); see also Favata et al. (2005)





Time interval	$N(\mathrm{H})$	kT	$f_{6.4\mathrm{keV}}$	$W_{6.4\ \mathrm{keV}}$
	N_{22}	keV	f_{-6}	eV
seg1	5.5 ± 0.7	4.8 ± 1.0	0.1 ± 0.7	34.8
flare	9.4 ± 2.0	3.9 ± 1.4	2.0 ± 5.9	162.0
seg2	8.2 ± 1.3	2.8 ± 0.6	1.1 ± 0.6	834.0
seg3	6.6 ± 0.8	3.3 ± 0.6	0.5 ± 0.5	270.0
seg4	7.6 ± 0.6	3.6 ± 0.4	0.7 ± 0.7	171.0
seg5	4.9 ± 0.4	4.5 ± 0.8	1.1 ± 0.8	335.0
seg3+seg4+seg5◊	6.4 ± 0.3	3.9 ± 0.3	1.0 ± 0.3	330.0

IRS 43 (DROXO)

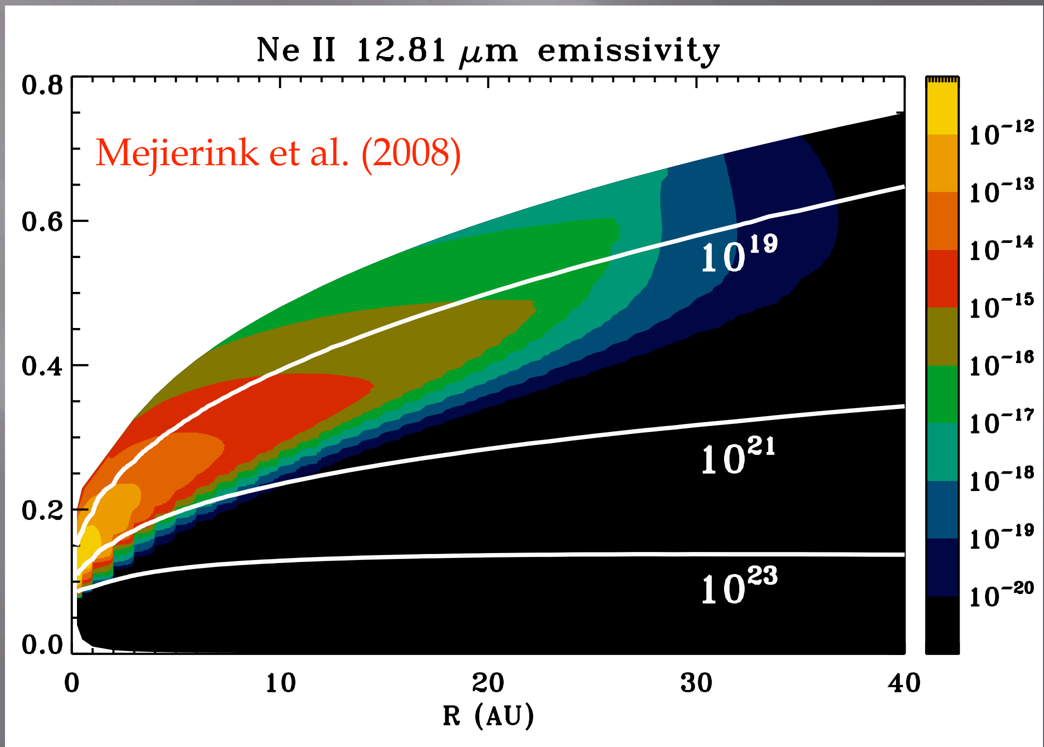


EW=380 (180-570) eV
kT =2.4 keV
norm. cnts/sec/keV
χ
channel energy (keV)
Cts/Ks[pn,on-ox,PSF]
Time [sec.]
Norm(Fe 6.4) -Fe6.4
EW 6.4 keV -Fe6.4
Av
Ch
Fl

The [Ne II] 12.81μm fine structure line: a tracer of disk gas and of its response to high energy radiation

- Ne 1st and 2nd ionization potentials: 21.56 and 41.0 eV

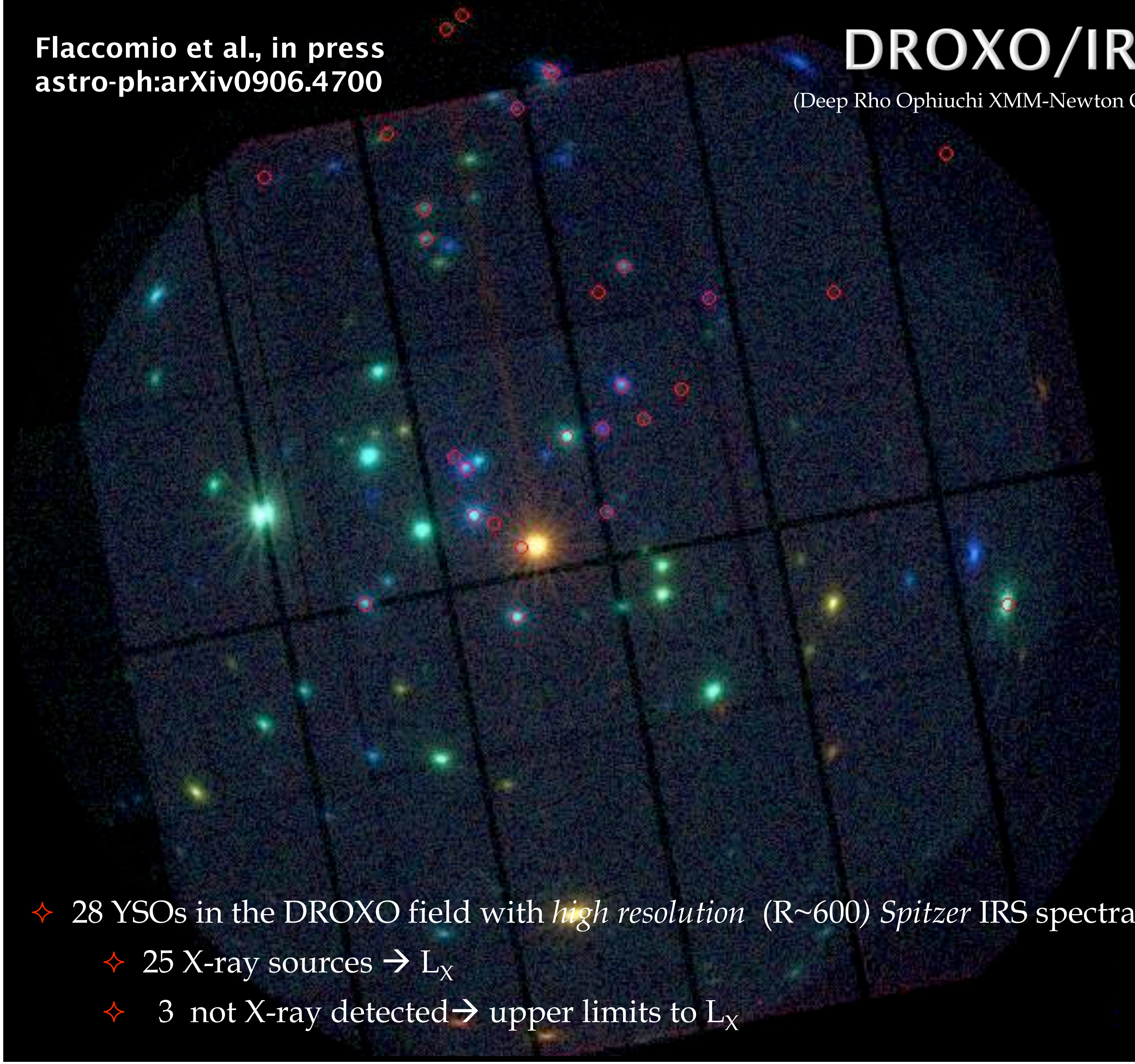
  Glassgold et al. (2007), Mejierink et al. (2008), Gorti & Hollenback (2008), Alexander(2008), Ercolano et al. (2009)



Flaccomio et al., in press
astro-ph:arXiv0906.4700

DROXO/IRS Sample

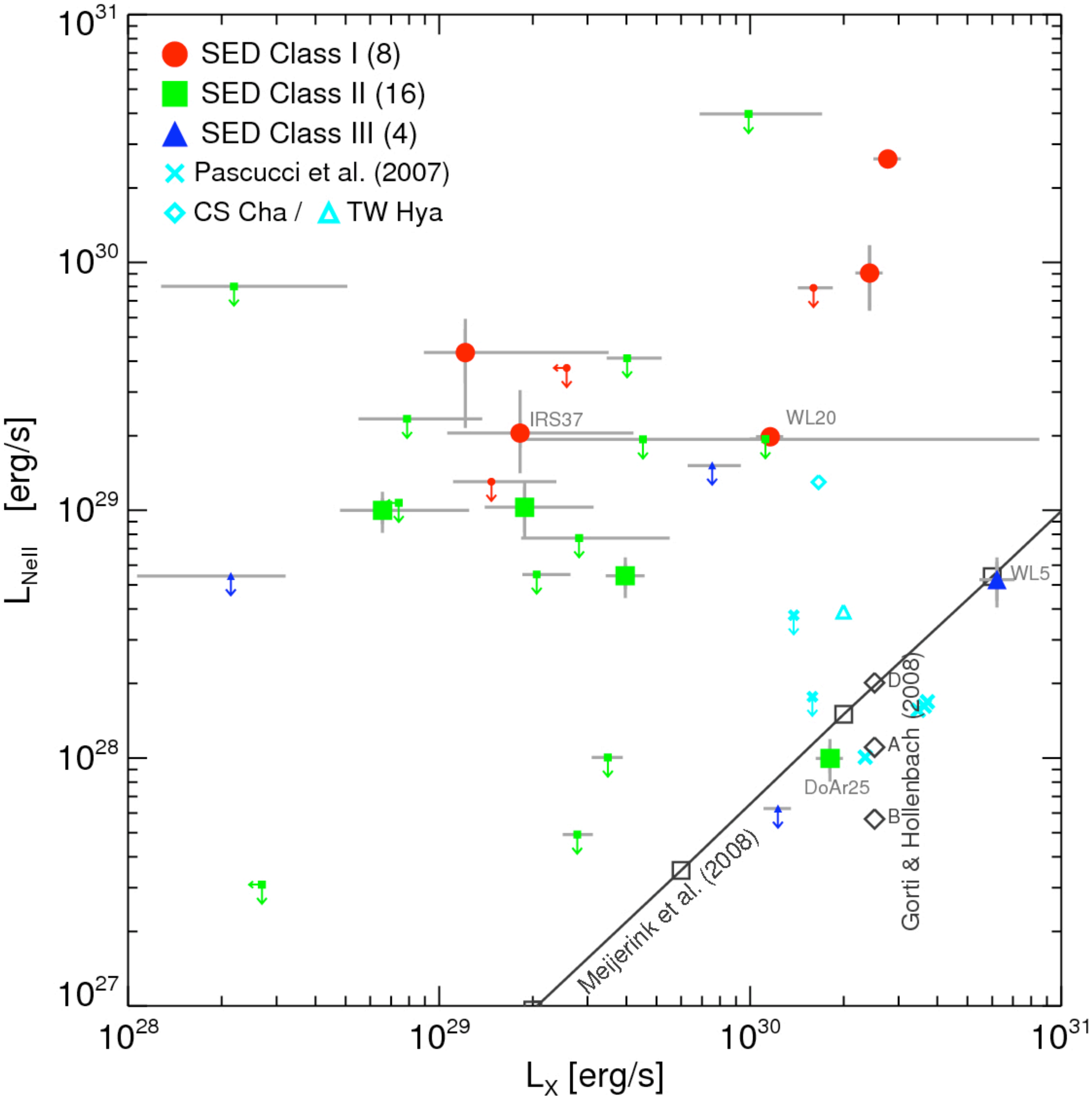
(Deep Rho Ophiuchi XMM-Newton Observation – PI: S. Sciortino)



DoAr25/GY17	II
IRS14/GY54	III
WL12/GY111	I
WL22/GY174	II
WL16/GY182	II
WL17/GY205	II
WL10/GY211	II
EL29/GY214	I
GY224	II
WL19/GY227	III
WL11/GY229	II
WL20/GY240	I
IRS37/GY244	I
WL5/GY246	III
IRS42/GY252	II
GY253	III
WL6/GY254	II
CRBR85	II
IRS43/GY265	I
IRS44/GY269	I
IRS45/GY273	II
IRS46/GY274	I
IRS47/GY279	II
GY289	II
GY291	II
IRS48/GY304	I
IRS51/GY315	II
IRS54/GY378	II

- 28 YSOs in the DROXO field with *high resolution* (R~600) *Spitzer* IRS spectra
  - 25 X-ray sources → L_X
  - 3 not X-ray detected → upper limits to L_X

$L_{[Ne\ II]}$ vs. L_X



SED Class I (8)
SED Class II (16)
SED Class III (4)
Pascucci et al. (2007)
CS Cha / TW Hya
IRS37
WL20
WL5
DoAr25
D
A
B
Meijerink et al. (2008)
Gorti & Hollenbach (2008)
L_{NeII} [erg/s]
L_X [erg/s]
10^{27}
10^{28}
10^{29}
10^{30}
10^{31}

Final remarks

- X-ray emission from SFRs is a complex multi-faceted phenomenon (cloud, coronae, accretion, jets)
- High energy phenomena now important for star formation and early stellar evolution
- In the past 10 years *Chandra* & *XMM-Newton* have indeed produced new exciting results
- **We have now reached the limits of current instrumentation, and progress will be painful (e.g. for flare analysis, Fe6.4 keV line)**