Chandra studies of stars and exoplanets: The next ten years

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Several colleagues have kindly provided inputs (N. Brickhouse, E. Flaccomio, E. Feigelson, M. Guarcello, D. Huenemoerder, J. Kastner, M. Agüeros, L. Oskinova, I. Pillitteri, B. Stelzer, S. Wolk).

All mistakes and misquotations are mine

Disclaimer: NOT a "formal" review but mostly my views on some good use of Chandra in the coming years.

X-rays and Exoplanetary Studies (cf. S. Wolk's talk)

- Effects of the EUV/X-ray stellar emission on planet atmosphere size, mass loss and chemistry → unique insights into the atmospheric history of the potentially habitable rocky planets. [eg. Sanz-Forcada et al. 2011, Cezla et al. 2016] ….

Available X-ray Data probably good enough

- Magnetic entaglement, e.g. Star-Planet Interaction traced by enhanced emission seen in X-rays (and FUV). In highly eccentric systems @periastron host star X-ray and particle incident flux 2-3 order of magnitude higher than for Saturn and Jupiter → major effects expected (still to be properly modeled) …

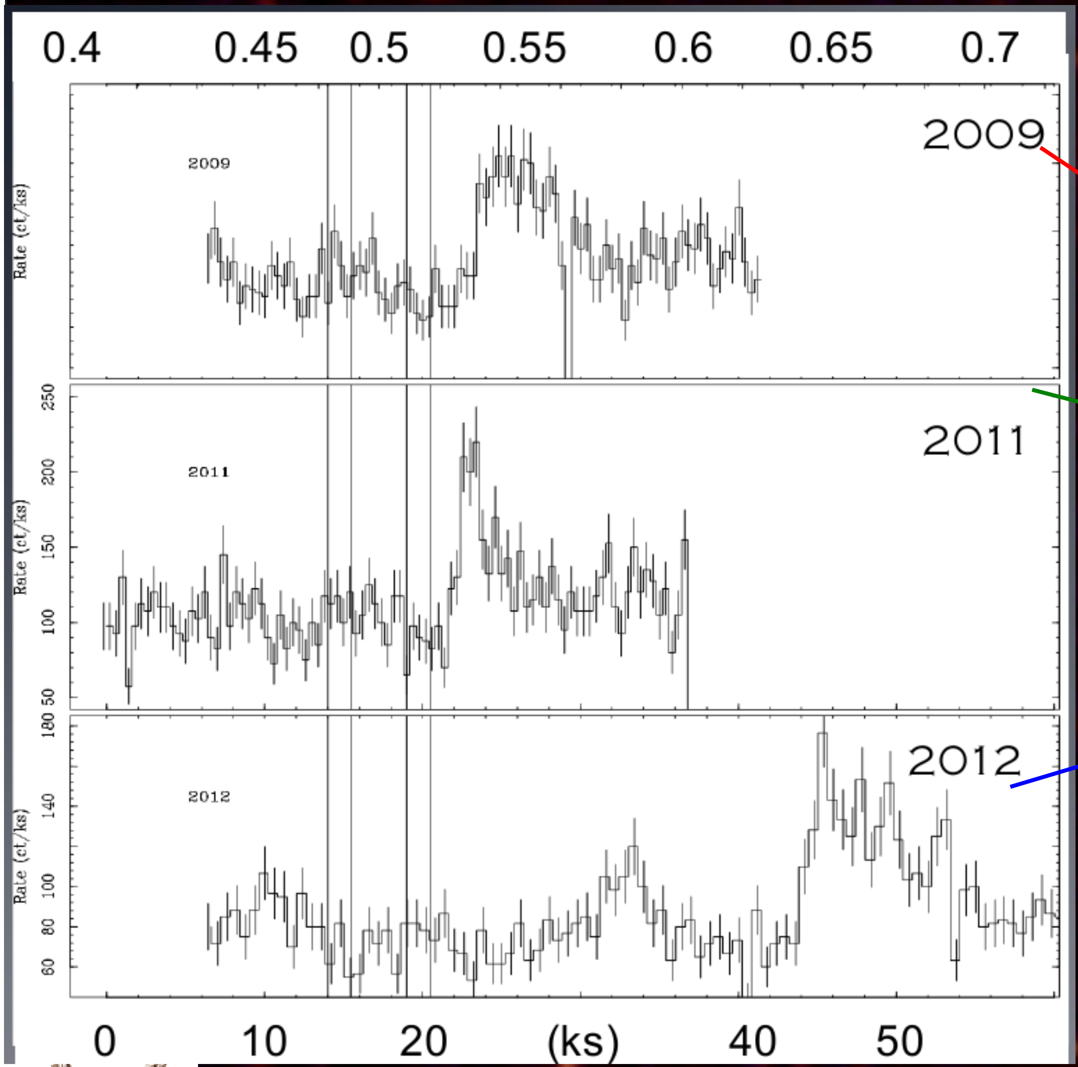
New Data needed, Chandra can do it for the "stronger" sources

- For transiting hot Jupiter planets look for transit in X-rays and possibly characterize planet atmosphere with an X-ray shadowgraph

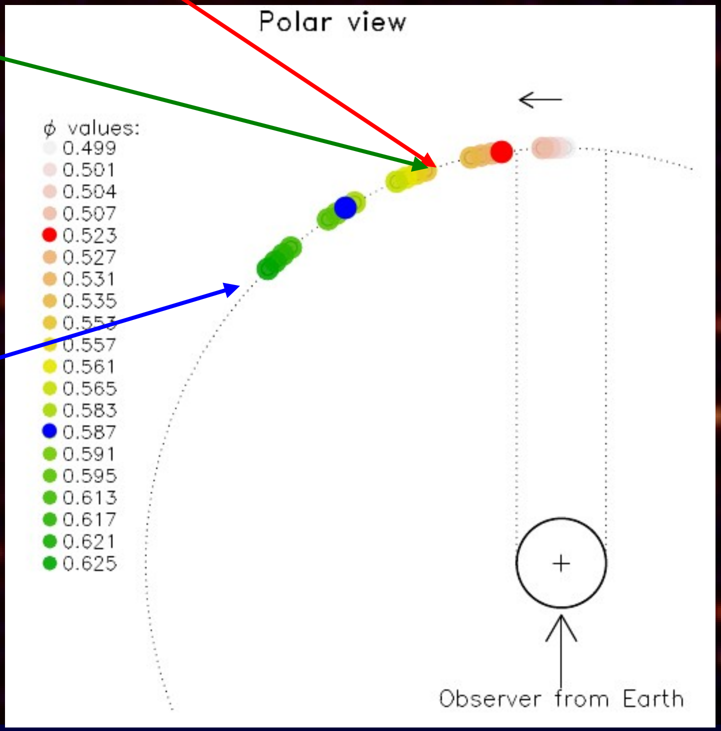
New Data needed, challenging with current X-ray observatories

Star-Planet Interaction - 1

HD189378 is a widely studied star hosting a transiting hot-Jupiter with M ~ 1.16 Mjup, R ~ 1.138 Rjup, orbiting in ~2.22 days at ~0.031 AU.

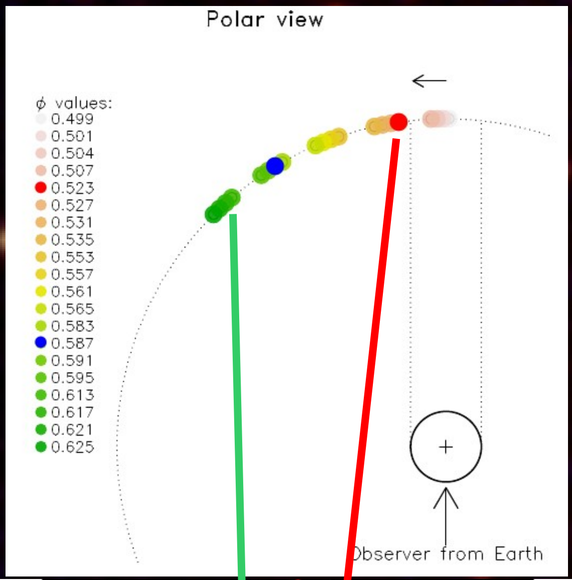


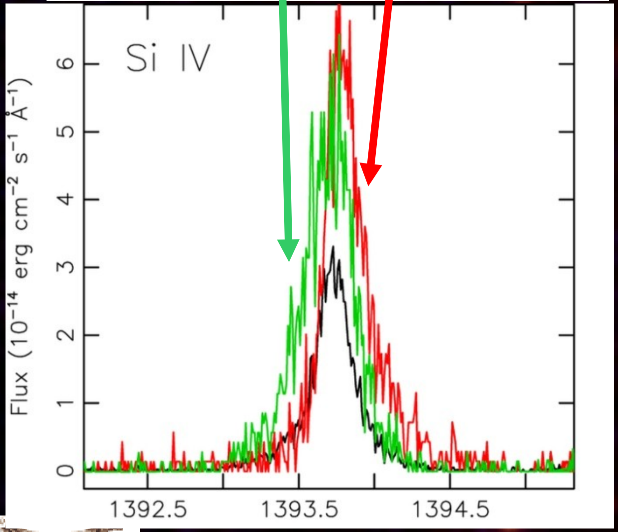
→ Evidence of recurrent X-ray "flaring" at ~ a given orbital phase & HST FUV spectral data (Pillitteri et al. 2010, 2011. 2014, 2015a)

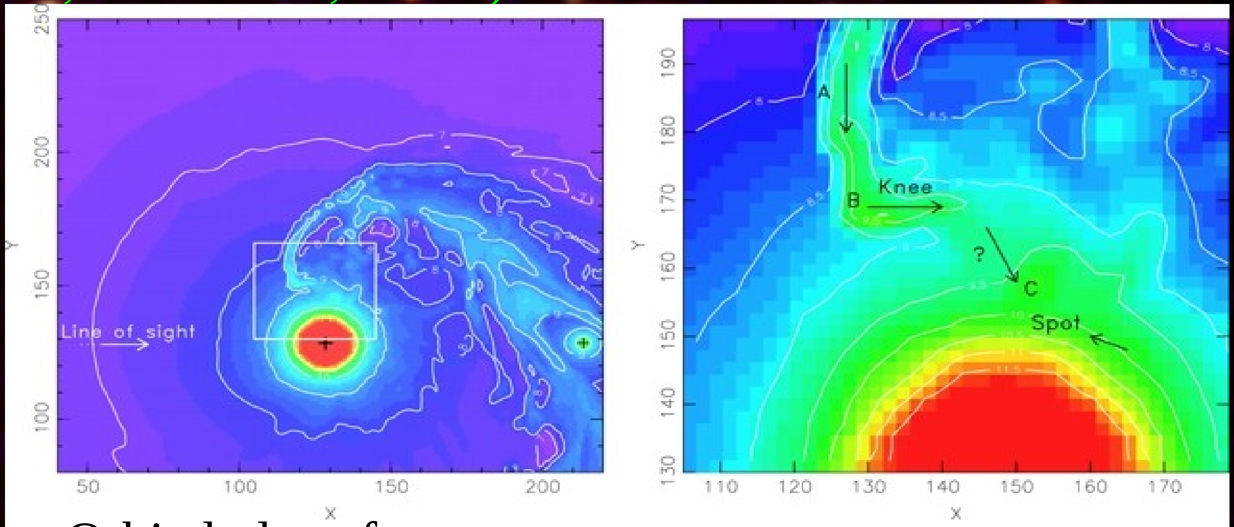


Star-Planet Interaction - 2

HD189378 – evidence of recurrent phased X-ray & HST FUV flaring (Pillitteri et al. 2010, 2011. 2014, 2015a)

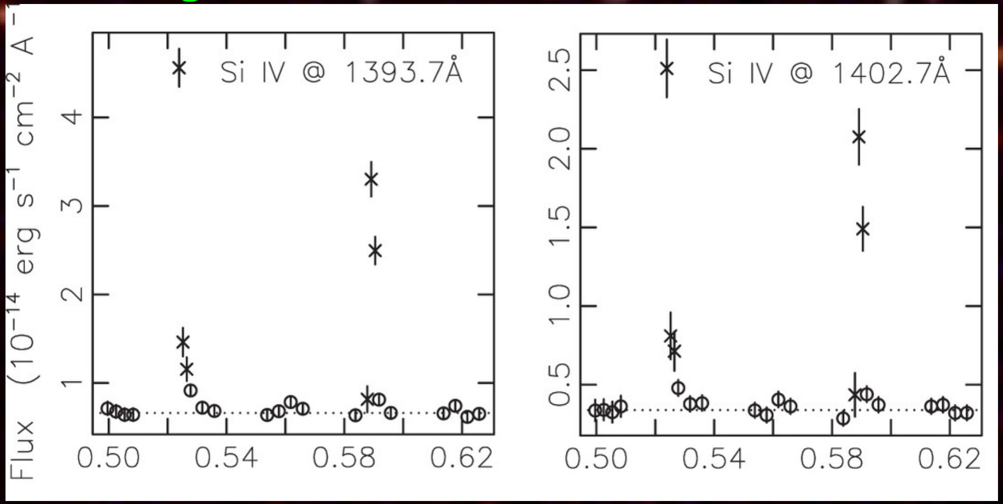






Orbital plane face-on

Flaring events seen in SiIV, and NV, but not in CII

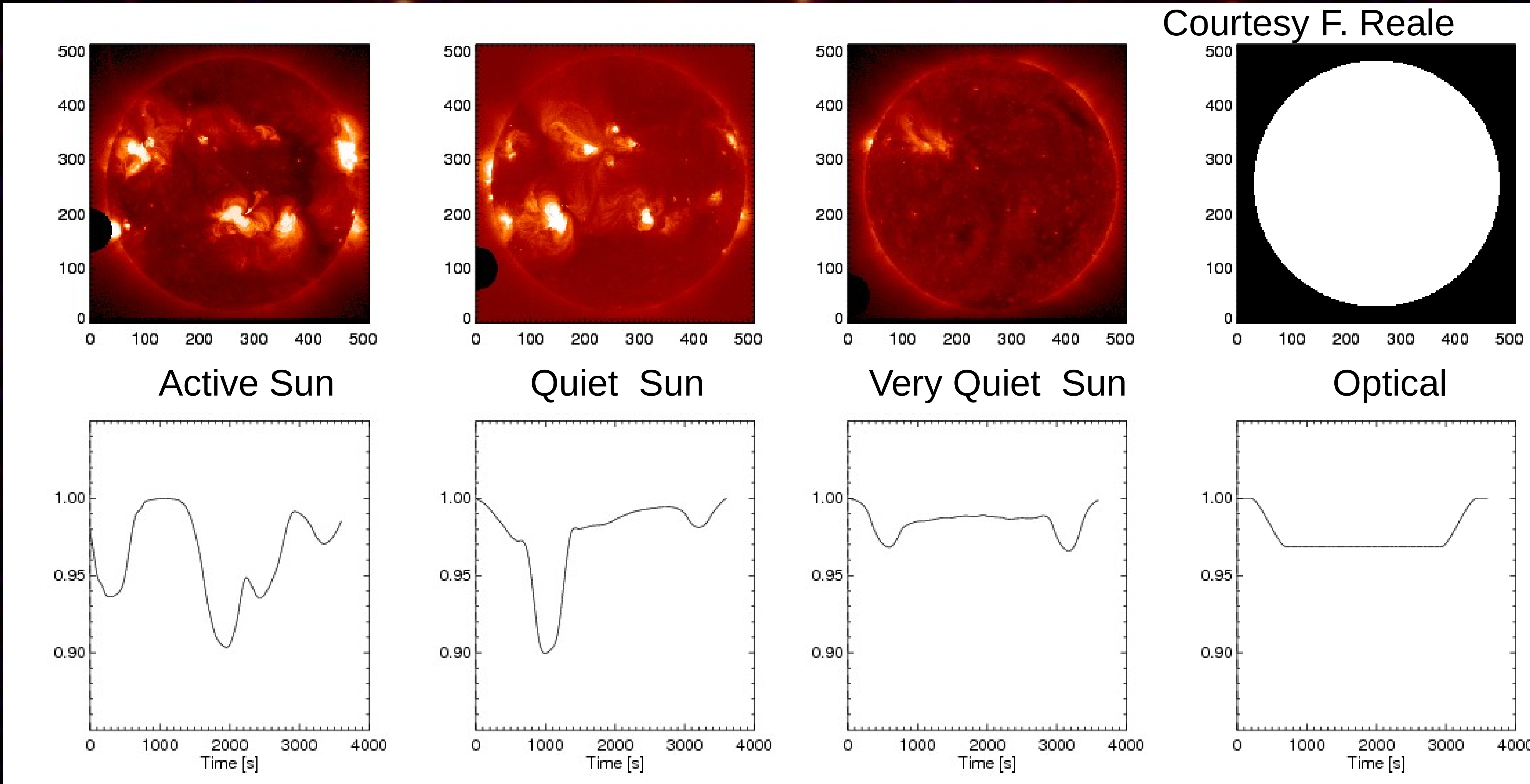


Star-Planet Interaction - 3

WASP-18 – no X-ray emission contrary to expectation for spectral type and evolutionary stage. SPI likely affects structure of convective zone and resulting dynamo action (Pillitteri et al. 2015b)

HD 17156 – highly eccentricity system, SPI expected to vary with orbital phase. Higher X-ray emission and R_{HK} chromospheric index found at periastron only (Maggio et al 2015). An impossible experiment with Chandra, and nearly impossible with XMM … only 3 known systems and (2) 1 observable

X-ray and transit study



Uncertain Prediction: Extent, latitude, etc. of coronal structures not firmly known

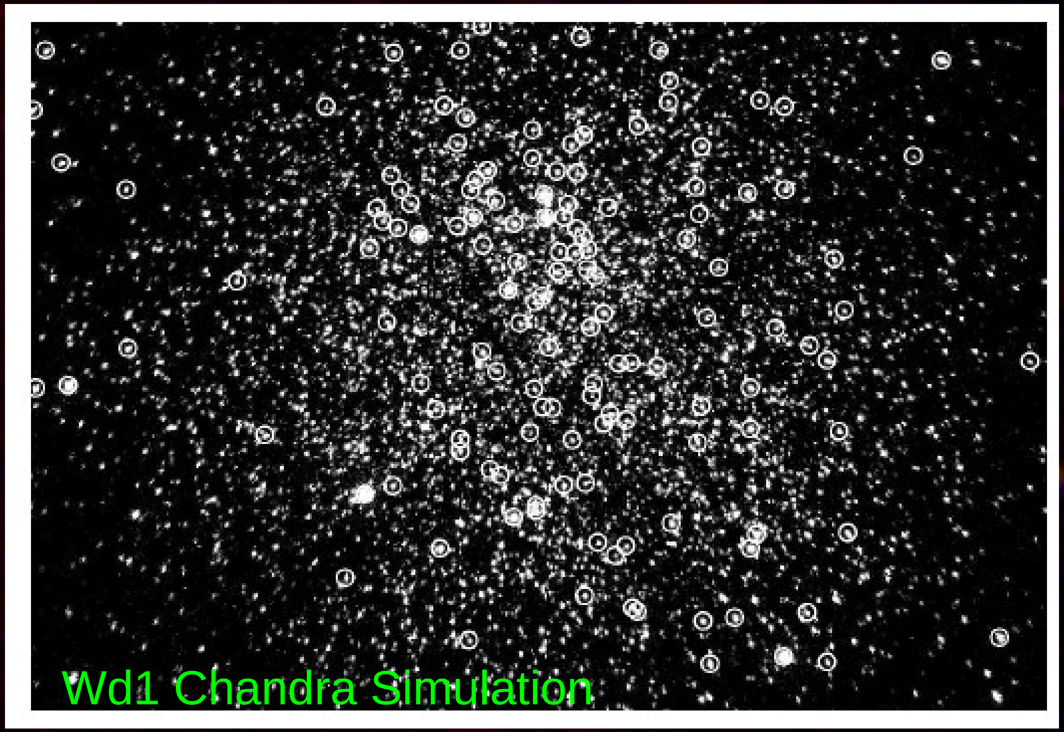
Many repeated observations needed. Challenging with today X-ray observatories and known targets. TESS may discover new accessible targets.

Interesting Stellar Science

-> [Very] Deep Pointings & Multi-Wavelength Opt/IR Studies
-X-ray effects on Star formation (e.g. Disk Lifetime of YSOs, etc.) in **extreme star formation environment**
-Origin of the X-ray emission from UCDs
-Magnetospheric structure and variability phenomena in YSOs
-Dinamo evolution as the radiative core grow: survey of nearby 10-60 Myr old Post-T-Tauri star. Big sample needed: Lx depends on mass, age, rotation. Synergy with GAIA
-Population studies of 5-15 kpc far-away SFRs: with ~ 300 ks **only Chandra can see the stars** and not just the dust/gas in distant region across the Galaxy
-> Long term monitoring
-Coronal Cycles
-> [Time resolved] X-ray spectroscopy
-Accretion studies in YSOs and young UCDs
-Excitation mechanism of the Fe Ka emission in YSOs
-(Extreme) flare dynamics
-Wind and Mass Loss in Massive stars (OB-stars, WR-stars)

Ultra deep (1-2 Ms) "Imaging"

The Chandra esquisite angular resolution has allowed to study many SFRs, Open Clusters, OB Associations and numerous astrophysical questions addressed (eg. COUP, Cyg-OB2, NGC2264, NGC6611, NGC6530 surveys …cf. original and MYStiX papers)

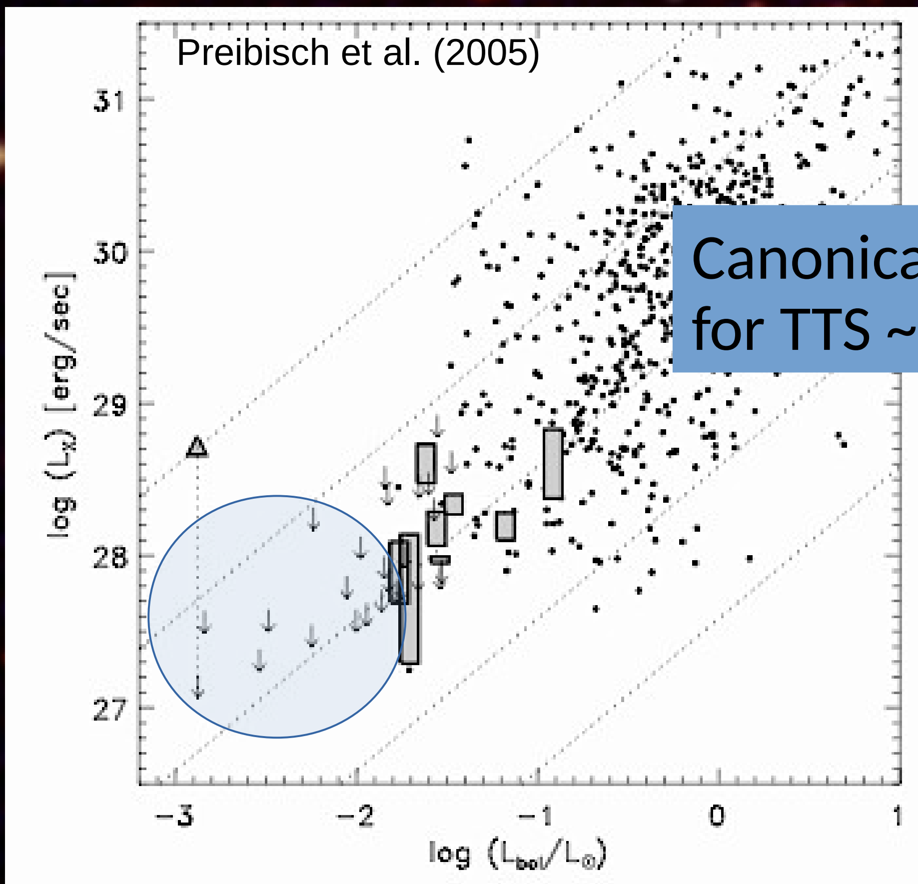


Most of parameter space explored including metallicity (cf. NGC602 in SMC, Oskinova et al. 2013), still some "extreme" conditions worth to be explored, e.g. starbust cluster hosting thousands stars and being the most extreme star formation environment in the Galaxy (Wd1, RCW 38 or NGC3603). **Only Chandra can do this !!**

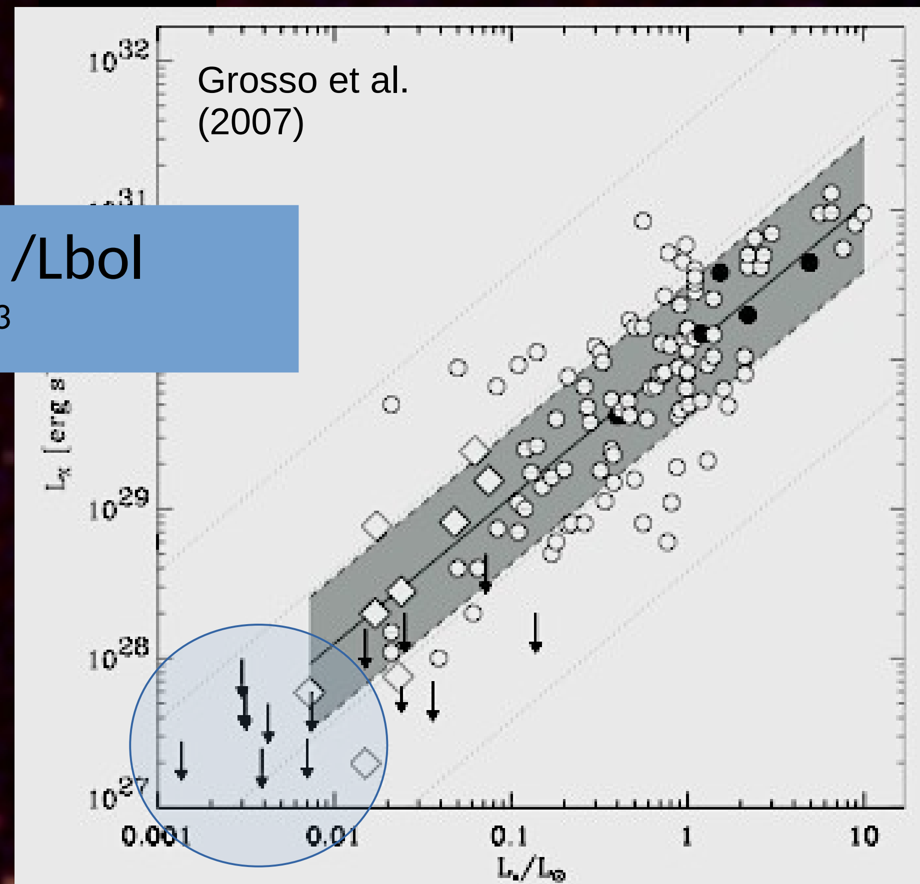
Ultra Cool Dwarfs (SpT > M7)

Dynamo in the substellar regime compared to TTS?
From a coronal to a planetary-like emission ? At what mass (& age) ?

COUP (ONC) -- 1 field for 850ks Chandra



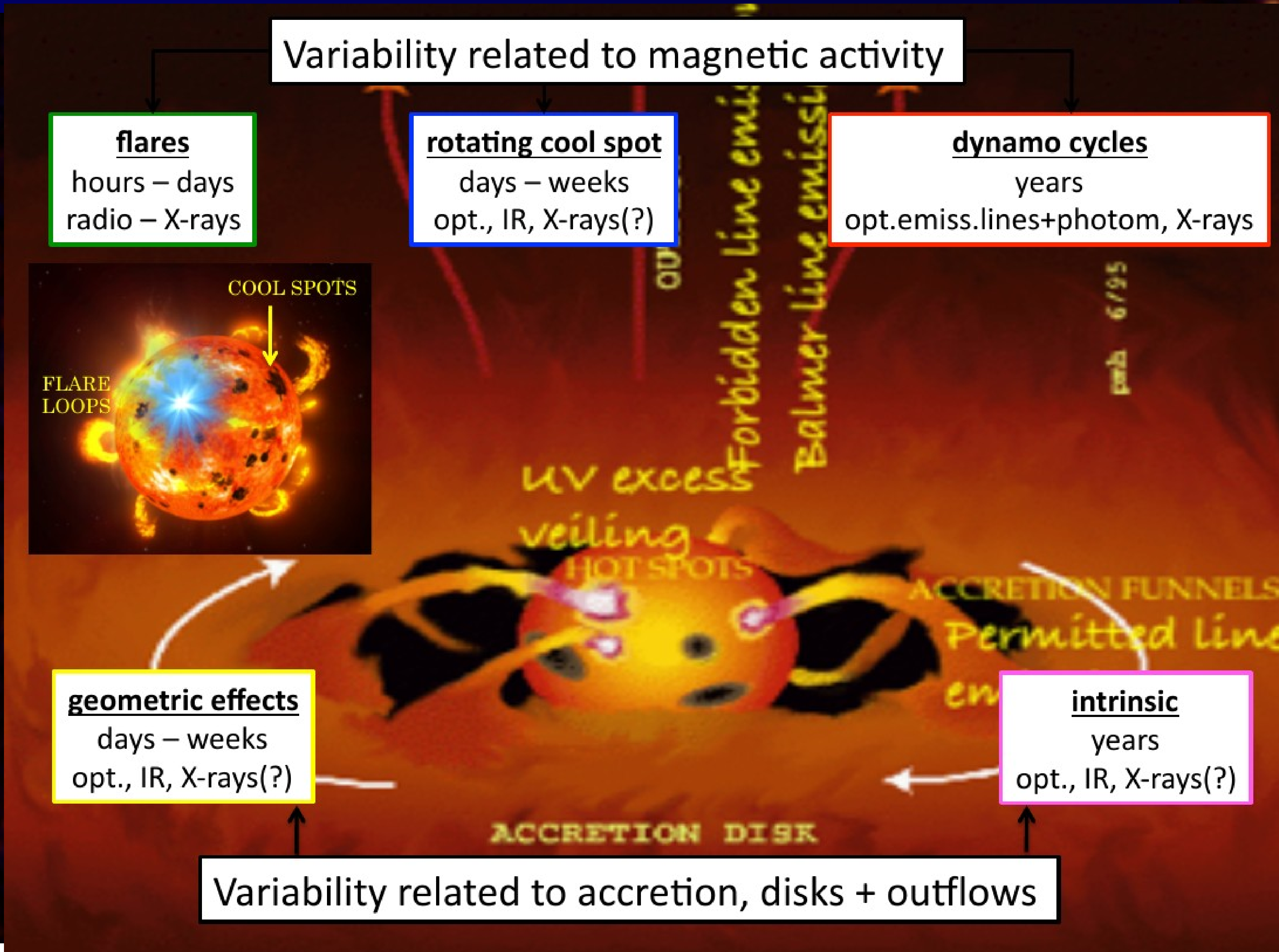
XEST (TMC) -- 19 fields for 30 ks XMM



Canonical Lx /Lbol for TTS ~ 10^{-3}

Is Lx / Lbol of BDs in SFRs comparable to higher-mass stars or lower ?
Too few detected BDs for a firm conclusion

Tracing Physical Processes in YSOs

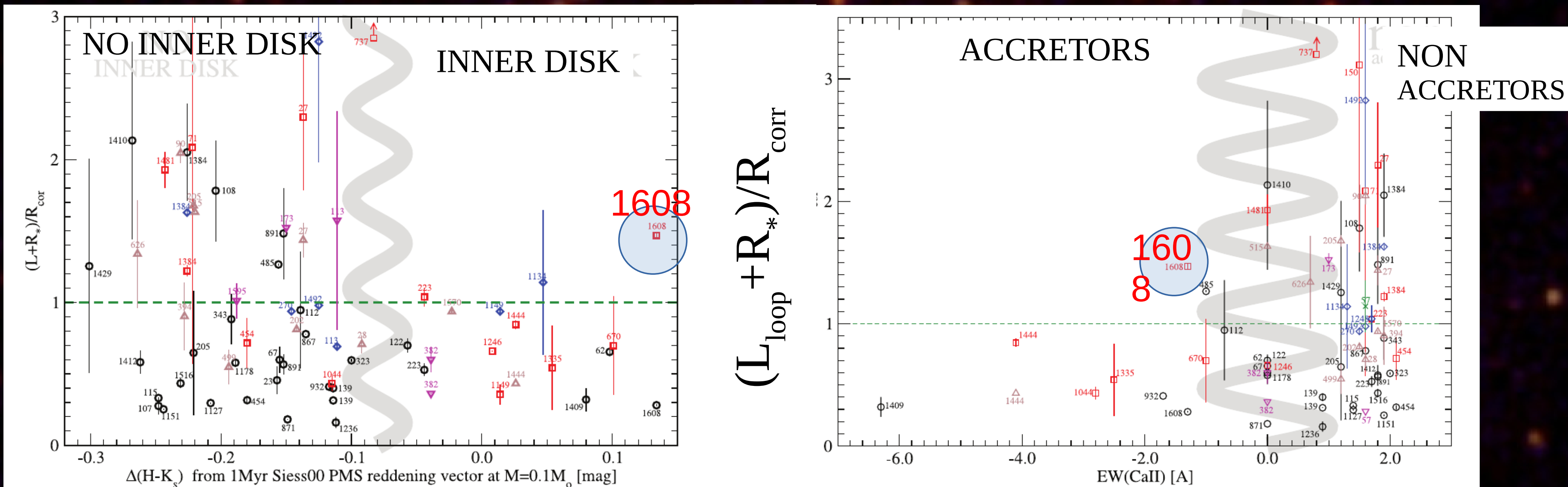


Courtesy B. Stelzer

Long Pointings enable Flare studies

Controversial Magnetospheric structure (eg. Favata et al 2005, Getman et al. 2008):

- Closed vs Open loops vs. Loops connected to the disk



Getman et al. (2008) conclusions:

- Disks have no effect on Flare Morphology
- Disks are unrelated to Flare Energetics
- Disks may truncate PMS magnetospheres alias no star-disk interconnecting flaring loop BUT COUP 1608 …. (& COUP 332)
- Superhot (> 100 MK) "non-standad" flares found in accreting stars

Again using COUP data → disk-bearing stars more X-ray variable than disk-less ones → time-variable absorption by warped disk is a likely explanation (Flaccomio et al. 2012)

Coordinated Simultaneous MultiWavelenght Observations

A very interesting territory, but with little explorations

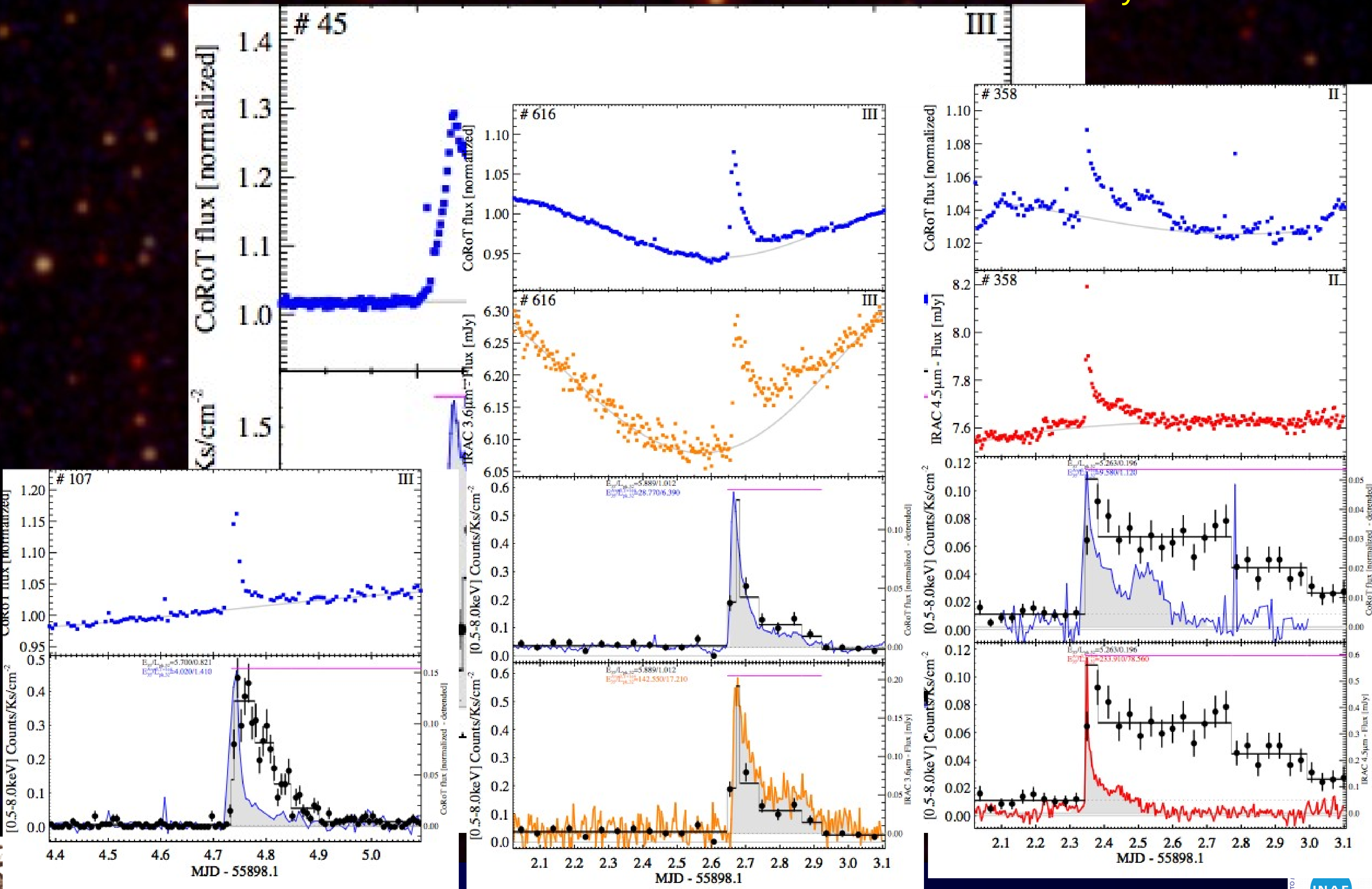
- CSI (Coordinated Synoptic Investigation) of NGC 2264 based on COROT, Chandra & Spitzer simultaneous observations

- Kepler/Chandra on the Pleiades

- Few more selected interesting sources (e.g. AB Dor, V4046 Sgr, V2129 Oph, ...)

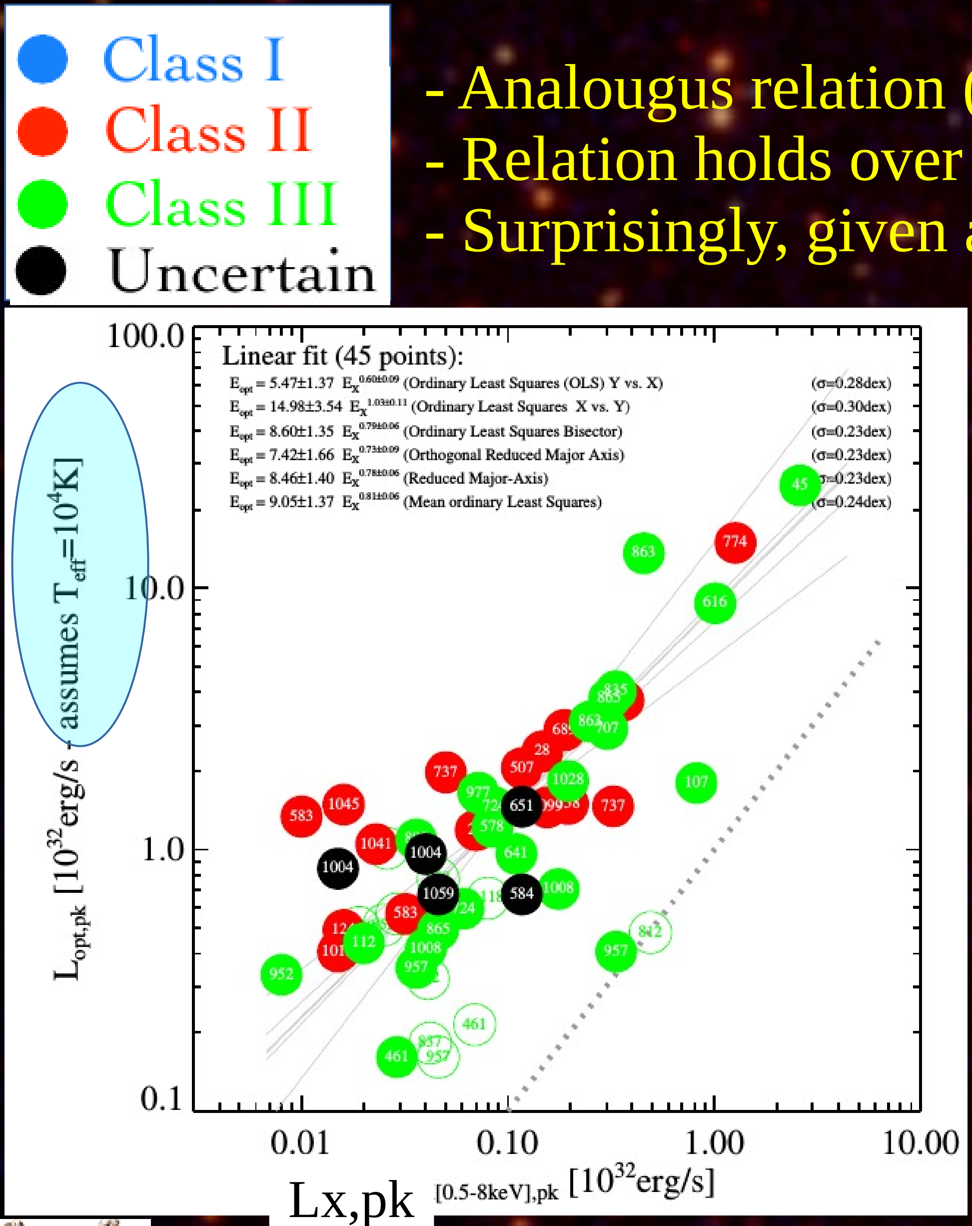
CSI – MW Flare Examples

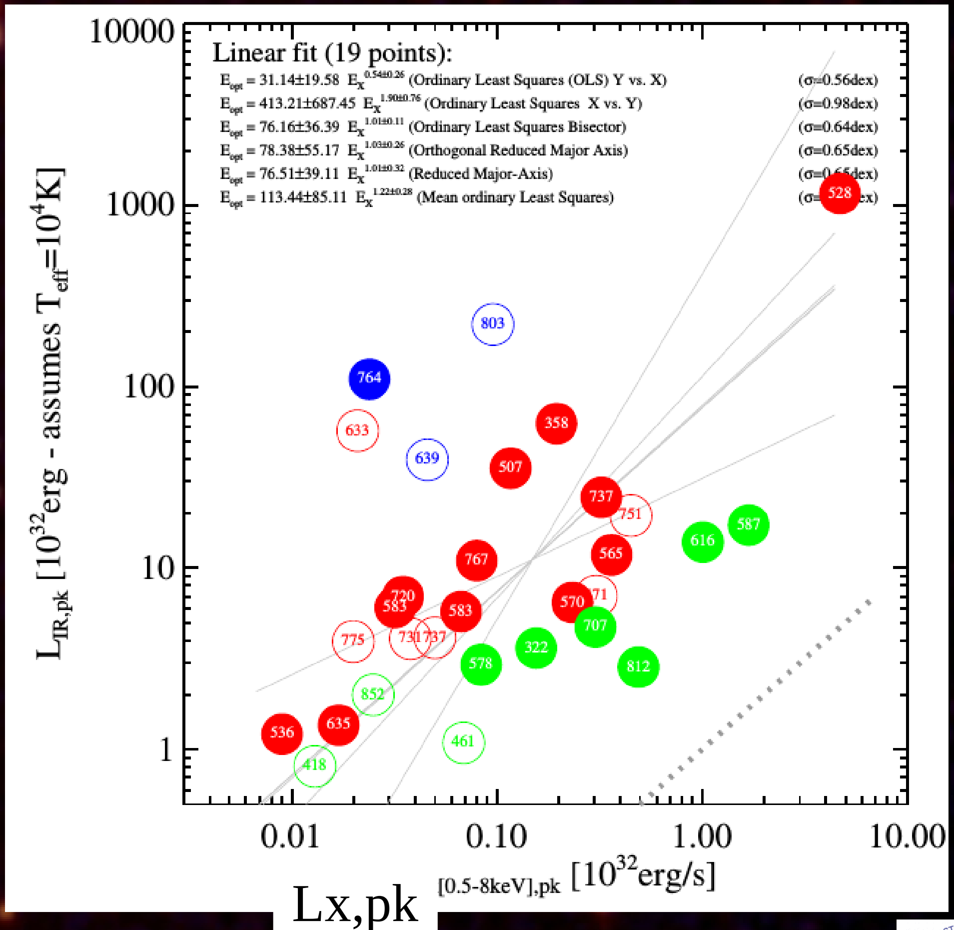
Courtesy of E. Flaccomio



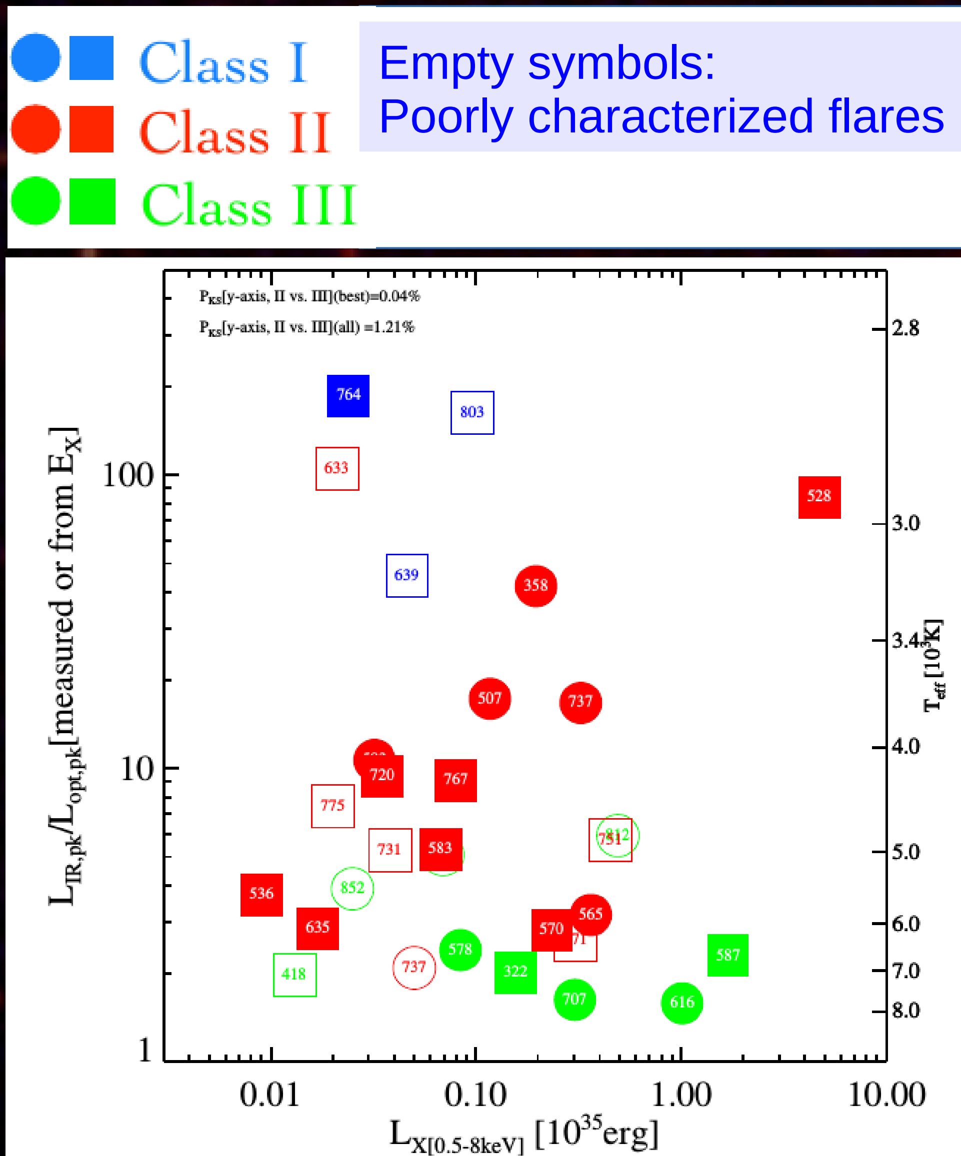
Optical/IR vs. X-ray: peak luminosities

- Analougus relation (& scatter) holds for the total Flare Energy
- Relation holds over more than 3 dex with little (.3 dex) scatter
- Surprisingly, given available data and analysis assumptions





IR/Optical vs. X-ray

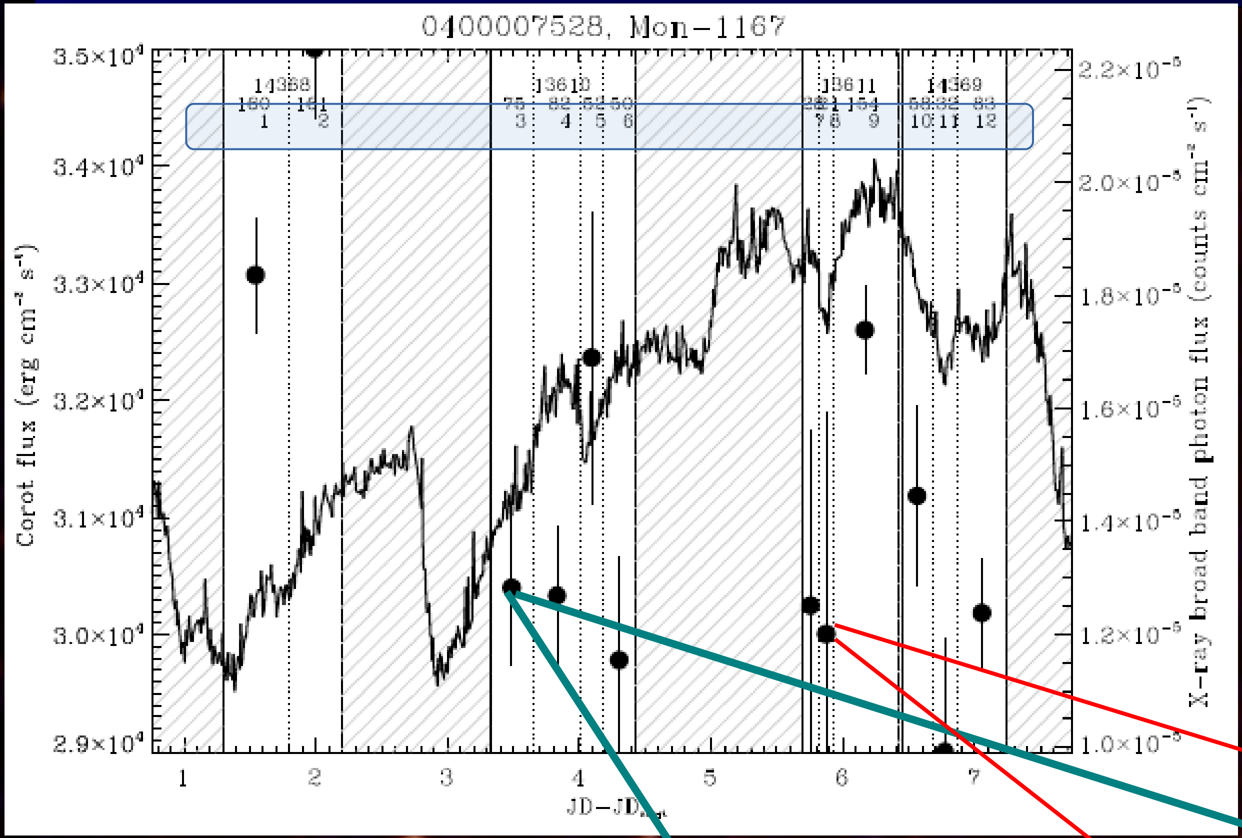


The peak luminosity & energy emitted in the optical and X-ray bands are tightly correlated, with a small scatter

Emitted energies up to ~5 dex higher than for the brightest solar flares: Solar flares not necessarily a good model. Flare photosheric T < 10^4 K, typical solar value

Strong IR excesses for flares in stars with circumstellar disks: likely the direct response (heating) of the inner disk to the optical/X-ray flare

CSI optical dips ↔ n_H increases (from X-rays)



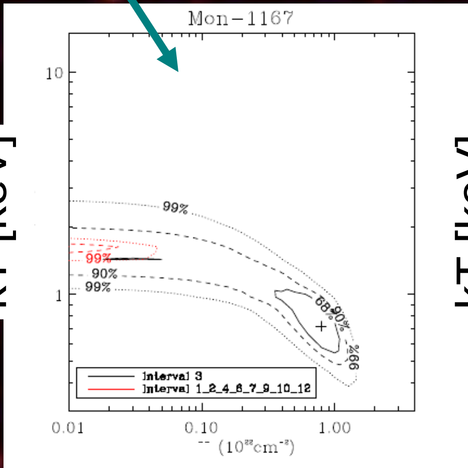
cf. POSTER by Guarcello et al

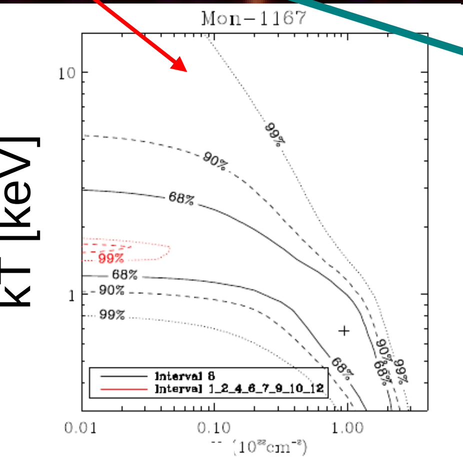
Signature of absorption by matter in streams or in a warped disk

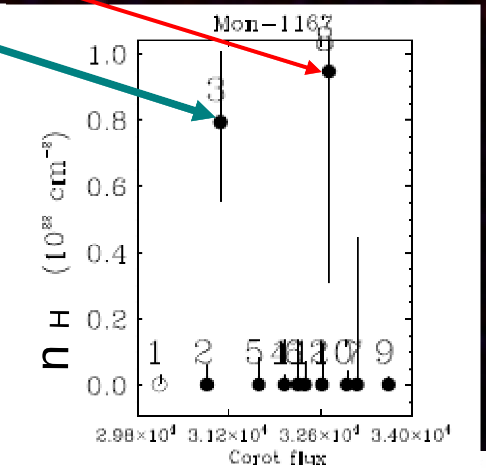
n_H increases in 9 out of 33 stars with Dips.

Not surprising because of line of sight (geometrical) effetcs

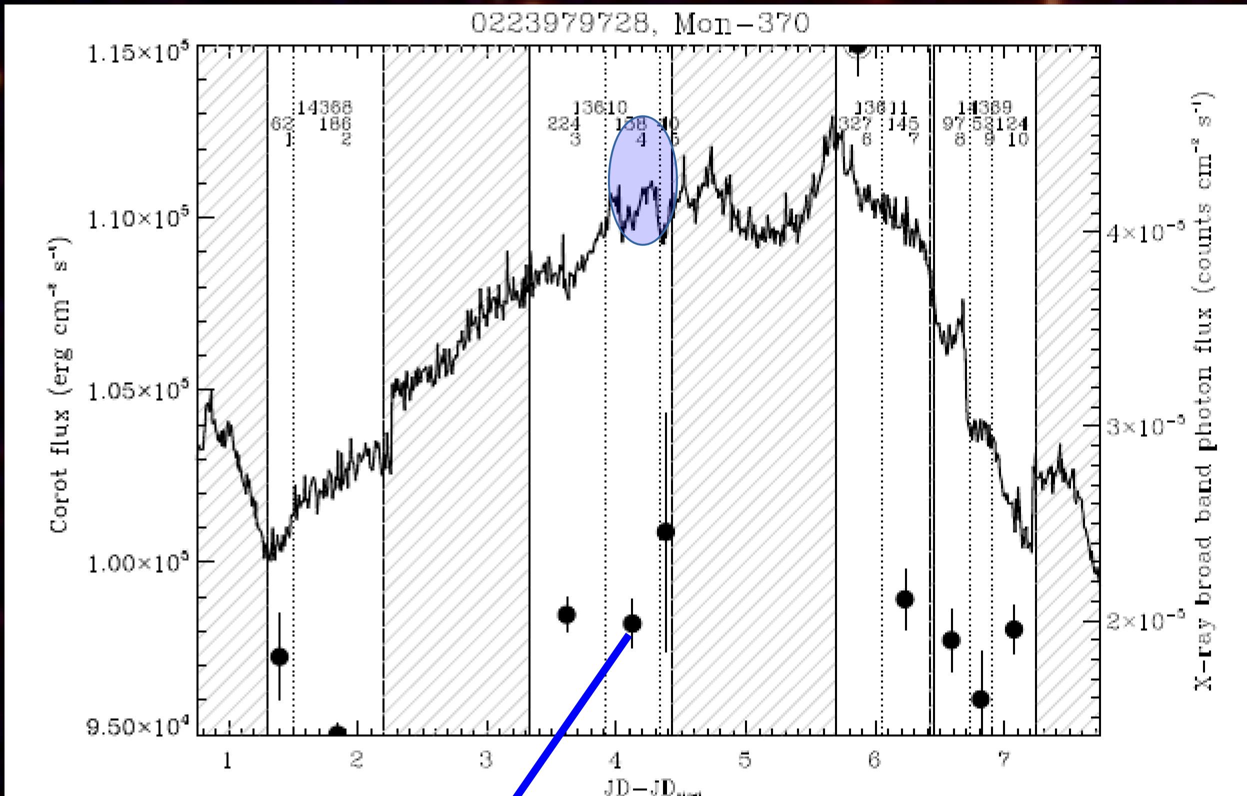
Nh increases > 68% confidence level
Red outside the Dips
Black in the Dips

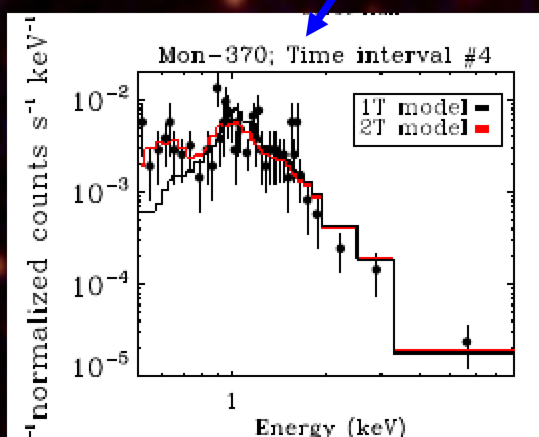






CSI: Soft X-ray excess during optical bursts





Soft excesses in 5 out of 27 stars with optical bursts

Soft X-ray excess likely due to the emission from accretion shocks.

In 2 stars $R_{\text{free-fall}} < R_{\text{co-rotation}} \rightarrow$

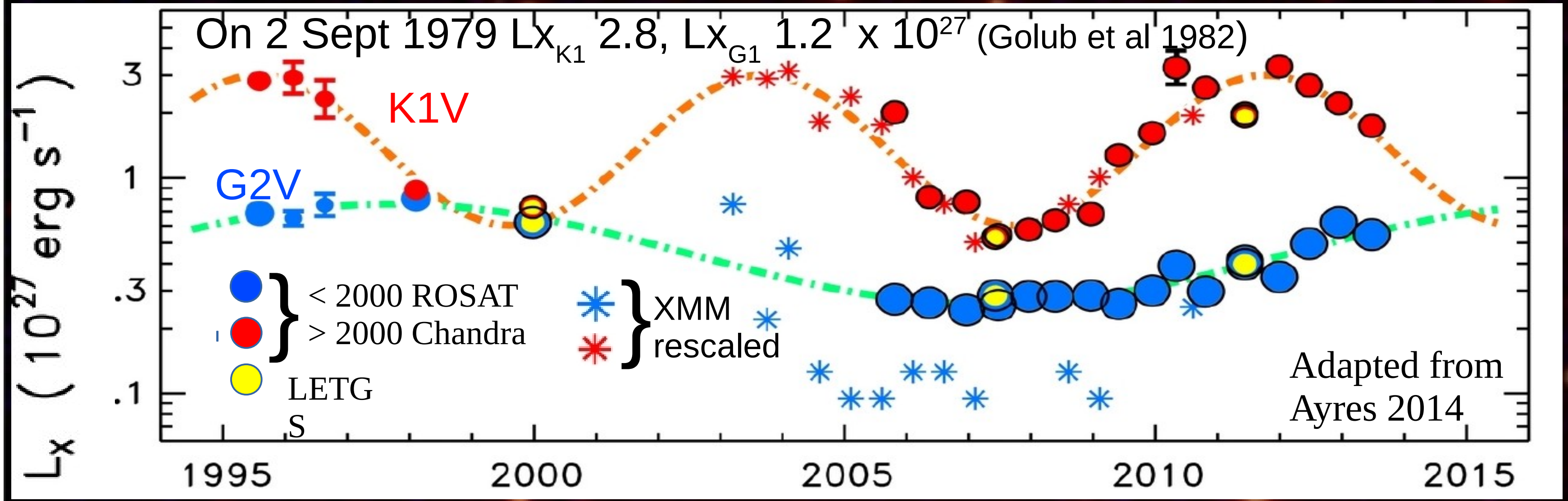
unstable accretion seems to be more likely.

Photometric monitoring facilities in the next decade

Facility	Operation Time Frame	Target V magnitude	Lenght of lightcurves
K2	2014-2019	> 4 (> 11)	~ 80 days
SPITER	2003-2019	….	….
TESS	2017-2018+	8-12	27+ days
LSST	2022-2032	>16	10yr (200 points)
PLATO	2024-2027	4-11	2-3 yr

Joint observations with Chandra are definitively worth to be pursued

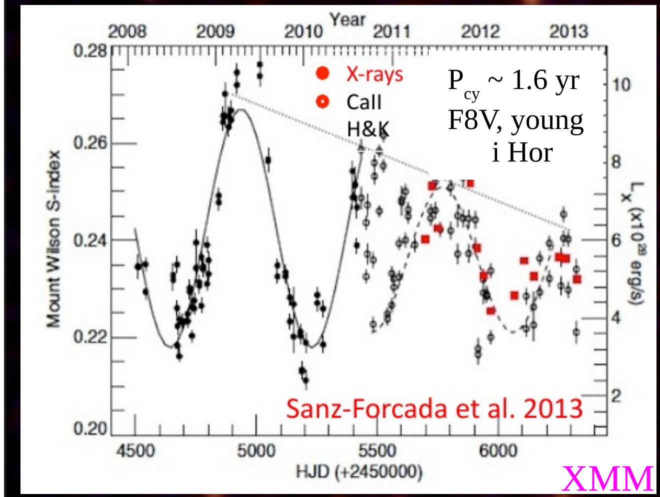
Long Term Monitoring: X-ray Cycles

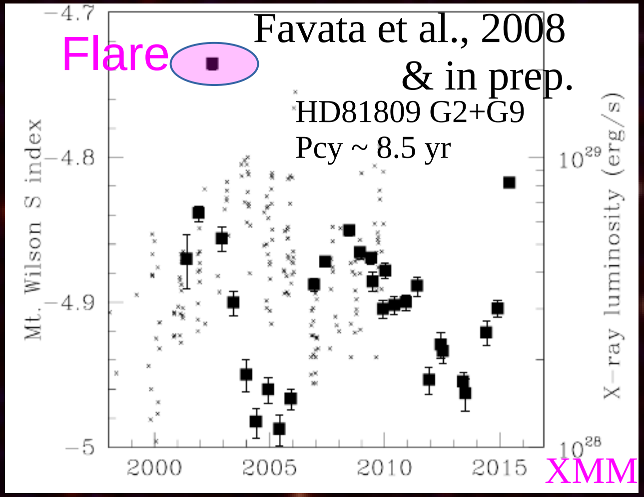


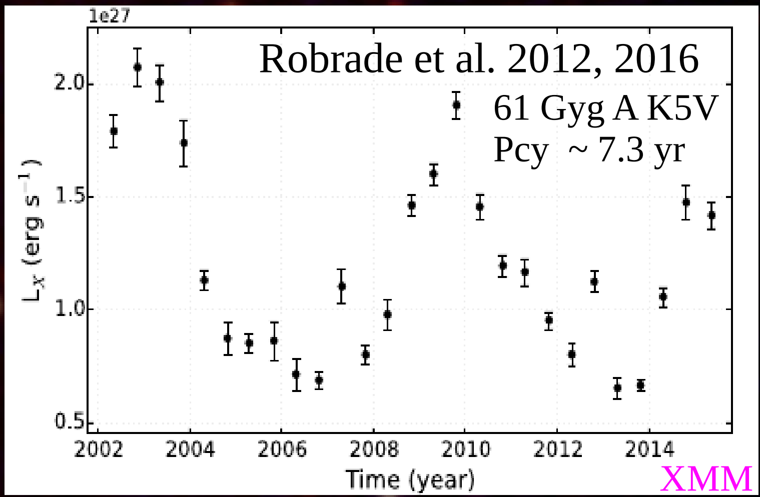
$P_{cy,K1}$ =9.1±0.2 yr

$P_{cy,G1}$=19.2±0.7yr

2004-2011 Maunder Min ?







- Only 4 X-ray Cycles known to date … more data really needed !!
- Clue to stellar dynamo mechanism
- Influence on planet atmospheres

Too little devoted Chandra time ?

(Time Resolved) High Resolution Spectroscopy

Chandra grating resolution & medium/long observations have been instrumental for new discoveries, e.g.:

- Accretion on YSOs, like TW Hya (Kastner et al. 2002; Brickhouse et al. 2012)
- Physical processes in single and binary early type stars, like Delta Ori (Corcoran et al. 2015, Shenar et al. 2015), θ1 Orionis C (Gagne et al. 2005), Zeta Pup and more (Waldron & Cassinelli 2007) ... (cf. also Toala and Oskinova talks)

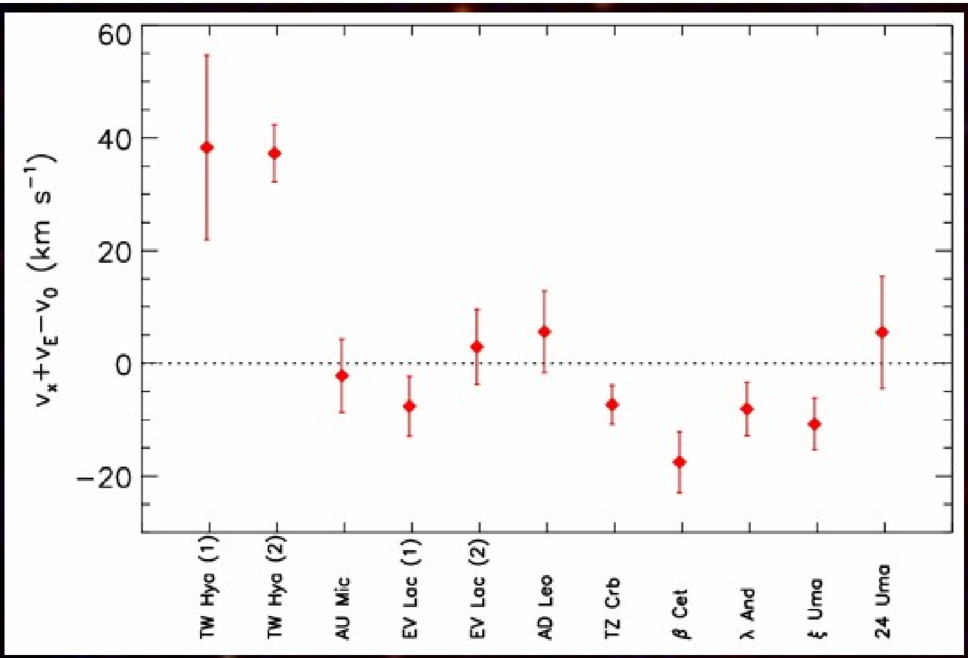
Chandra Grating area is "small" → Tracing time variability of spectral features (e.g. flares on YSO and cool stars, colliding wind variability in massive binaries, etc.) is challenging.
Most of accessible sources already observed; for fainter ones only time averaged spectra can be obtained preventing the "fast" variability studies. Given the sad loss of Hitomi those studies are in hold . In the coming future ATHENA will allow them.

High Resolution Spectroscopy in accreting YSOs

Near the limit of Chandra capability! Doppler shift determination of radial velocity of accreting cool emitting plasma (cf. Argiroffi et al poster)

Star	Chandra Obs Id	v_X (km s^{-1})	v_E (km s^{-1})	v_0 (km s^{-1})	$(v_X+v_E)-v_0$ (km s^{-1})	$n\sigma$
TW Hya (1)	**5**	**73.1 +/- 16.4**	**-21.3**	**13.4**	**38.3 +/-16.4**	**2.3**
TW Hya (2)	**7435+7436+7437**	**38.9 +/- 5.1**	**11.8**	**13.4**	**37.3 +/- 5.1**	**7.3**

Short observation
Long observation



V_X = plasma velocity (average on many lines)
V_E = earth intrinsic velocity toward target
V_0 = predicted radial velocity of target

Only TW Hya shows a significant Doppler shift velocity respect to stellar photosphere of about ~35-40 km/s

Infalling material velocity, Vpre ~ 300-500 km/s

Post-shock X-ray emission → Bulk inward velocity ,Vpost = Vpre/4 ~ 100 km/sec

TW Hya is observed from the pole: 100 km/s → 35 km/s ==> emitting spot at low latitude (~ 25º)

Conclusions

There are several science subjects in which Chandra can provide really unique data in the field of normal stars and their exoplanets.

Most of them require Medium or Long or even Very Long Observations. The typical “minimum” observation lenght should be of ~ 100 ks.

Needless to say for all the research areas requiring very good angular resolution (and I have mentioned a few) Chandra is the “perfect” companion.

While probably Chandra ageing makes this not simple, attention should be devoted to joint simultaneous multiwavelenghts studies and monitoring studies. There only few of them and those few have provided interesting results “per se” and are opening, in my opinion, quite interesting perspective for the future.

Imaging Survey (100-500 Ks)

- Tracing star formation regions at distance 5-15 kpc: with 300 ks exposure Chandra is the only telescope that can see the stars rather than dust/gas in distant SFR accross the Galaxy.

- Nearby Post-T Tauri Star (10-60 Myr) surveys [in ScoCen, TW Hya, Tuc-Hor, AB Dor groups]: Dinamo evolution as the radiative core grows. A big sample is required since Lx depends on mass, rotation & age. Huge synergy with GAIA.

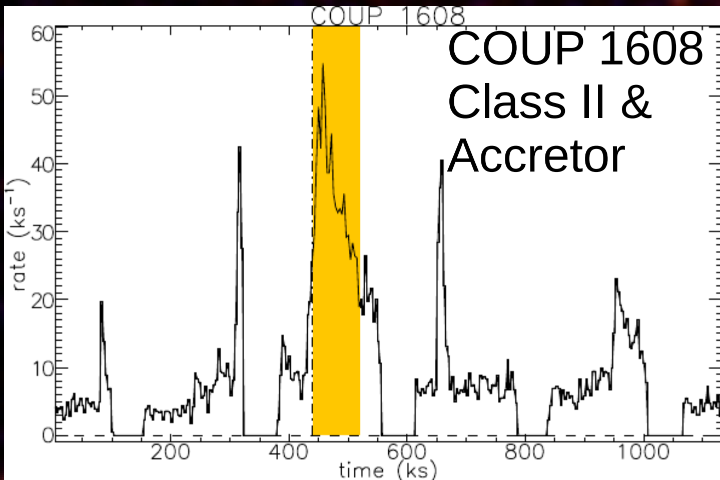
- Long Observations for flare studies (more in the following)

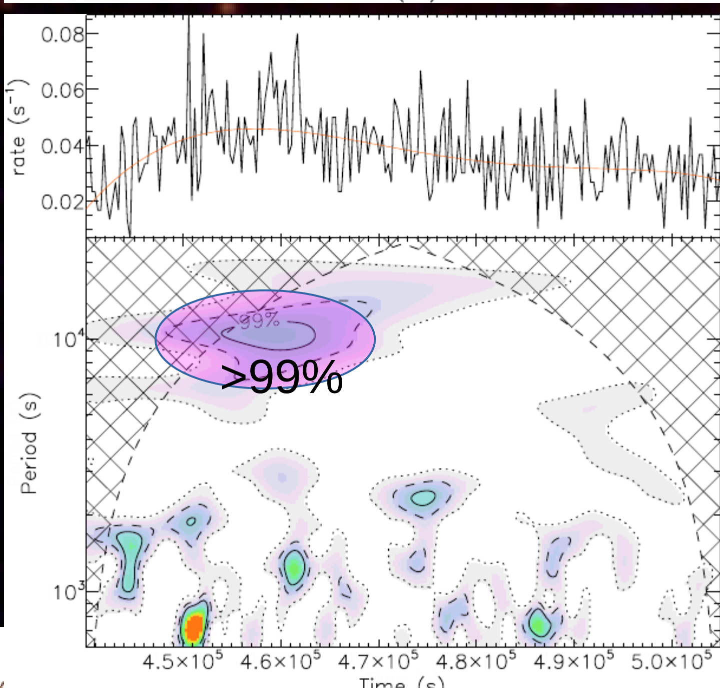
- Chandra has provided a huge list of candidate OB stars and protostars and class III within 3 kpc. Notable the thousands new young stars in Carina (at 2 kpc). Additional IR follow-up needed.

Long Pointings enable Flare studies

Controversial Magnetospheric structure (cf. Favata et al 2005, Getman et al. 2008):

- Closed vs Open loops vs. Loops connected to the disk





Wavelet Analysys of COUP data, very robust (Lopes-Santiago et al. 2016)

$P_{obs} \rightarrow L_{loop}$

COUP 1608 (OW Ori)

P_{obs} ~ 10 ksec

L_{loop} ~ 1.8+-0.2 10^12 cm

R_{cor} ~ 0.60 10^12 cm

R_{dust} ~ 0.75 10^12 cm

COUP 332 (2MASS J05350934-0521415)

P_{obs} ~ 9 ksec

L_{loop} ~ 1.0+-0.1 10^12 cm

R_{cor} ~ ….

R_{dust} ~ 0.56 10^12 cm