

X-ray to radio

Multi-wavelength observations and variability of Young Stellar Objects

Jan Forbrich
Harvard-Smithsonian CfA



X-ray to radio

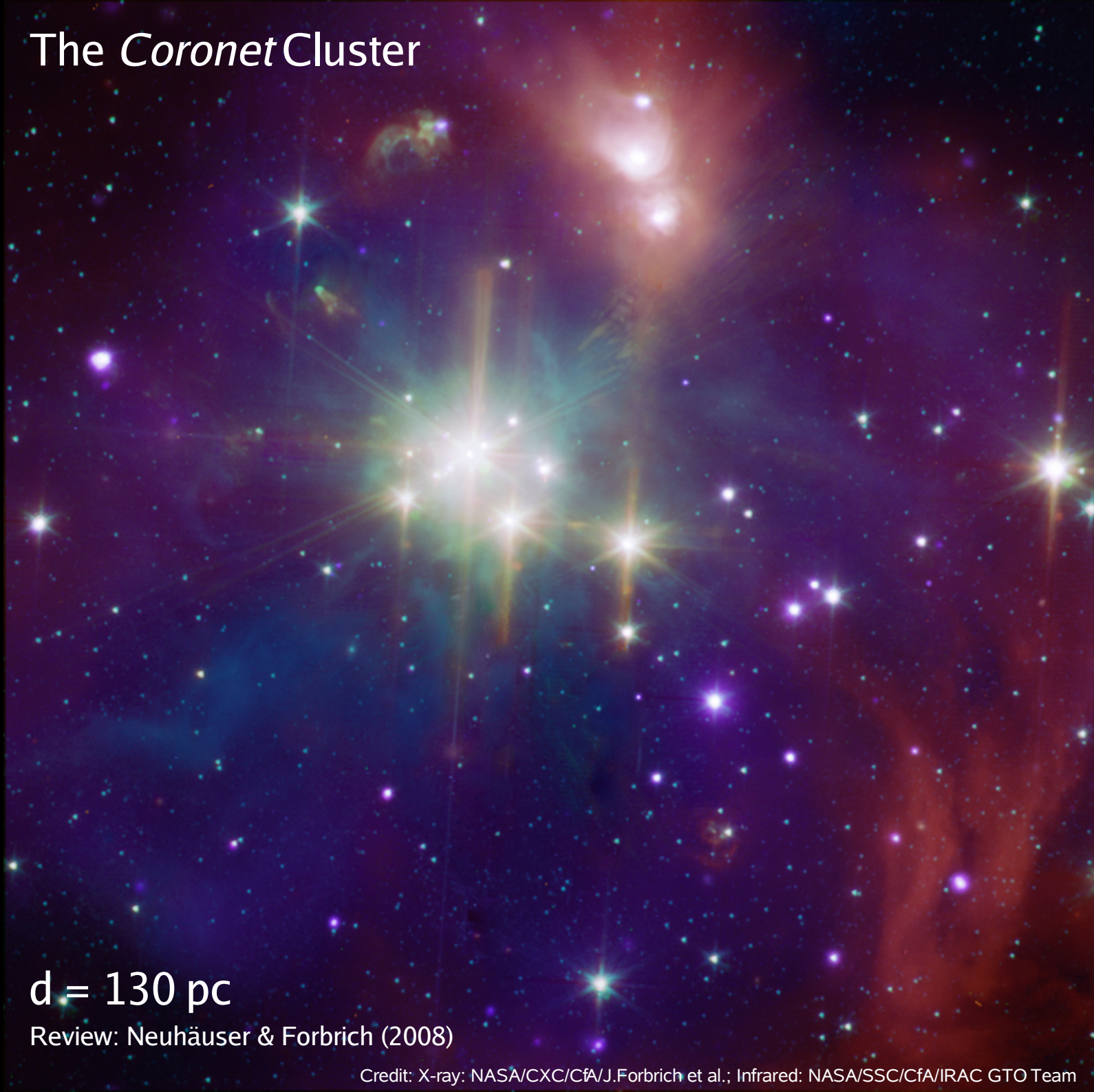
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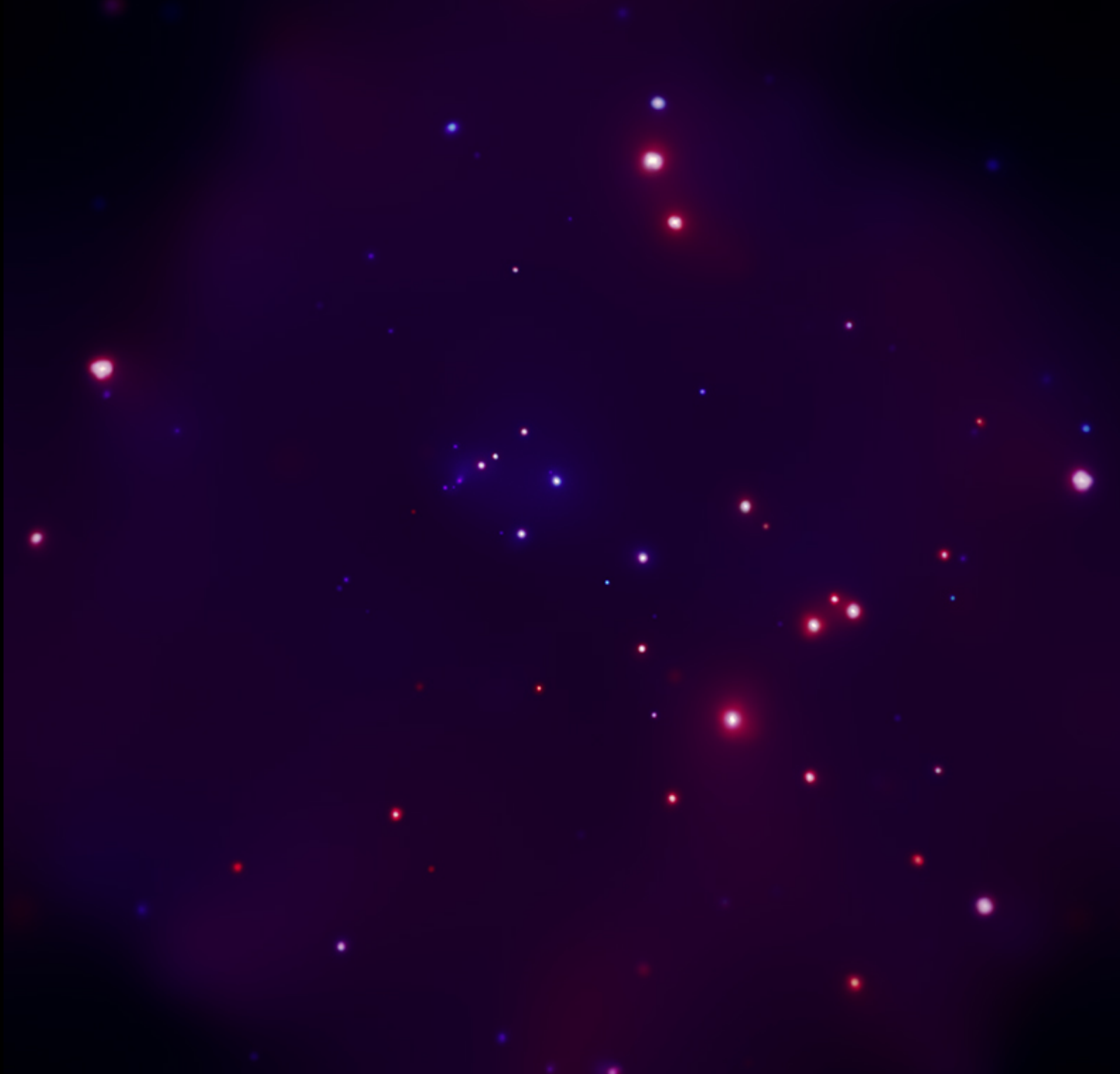
High-energy processes in YSOs
Simultaneous multi-wavelength observations
Radio observations of X-ray/infrared-selected YSOs
YSOs as transient radio sources?

The *Coronet* Cluster

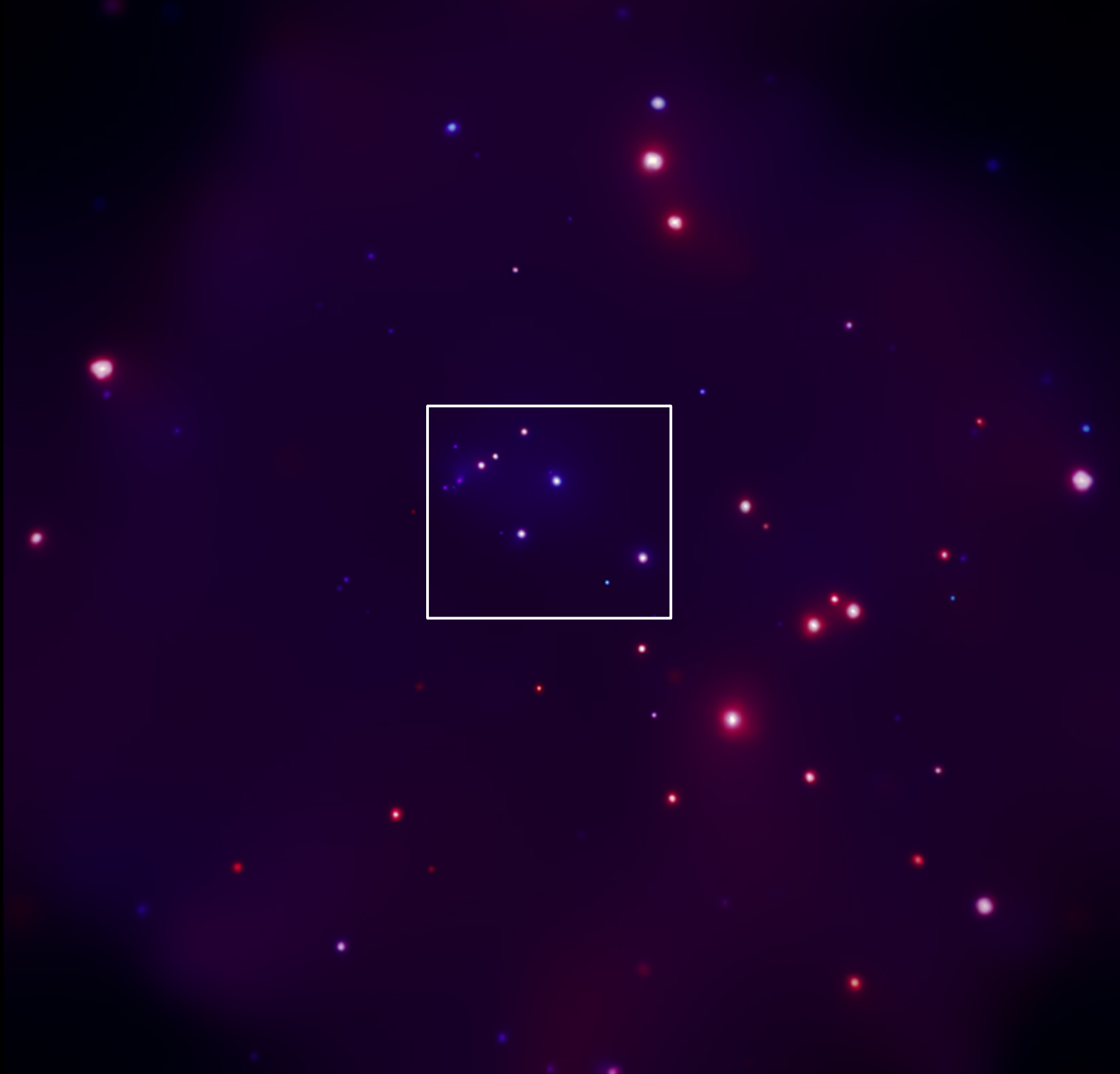


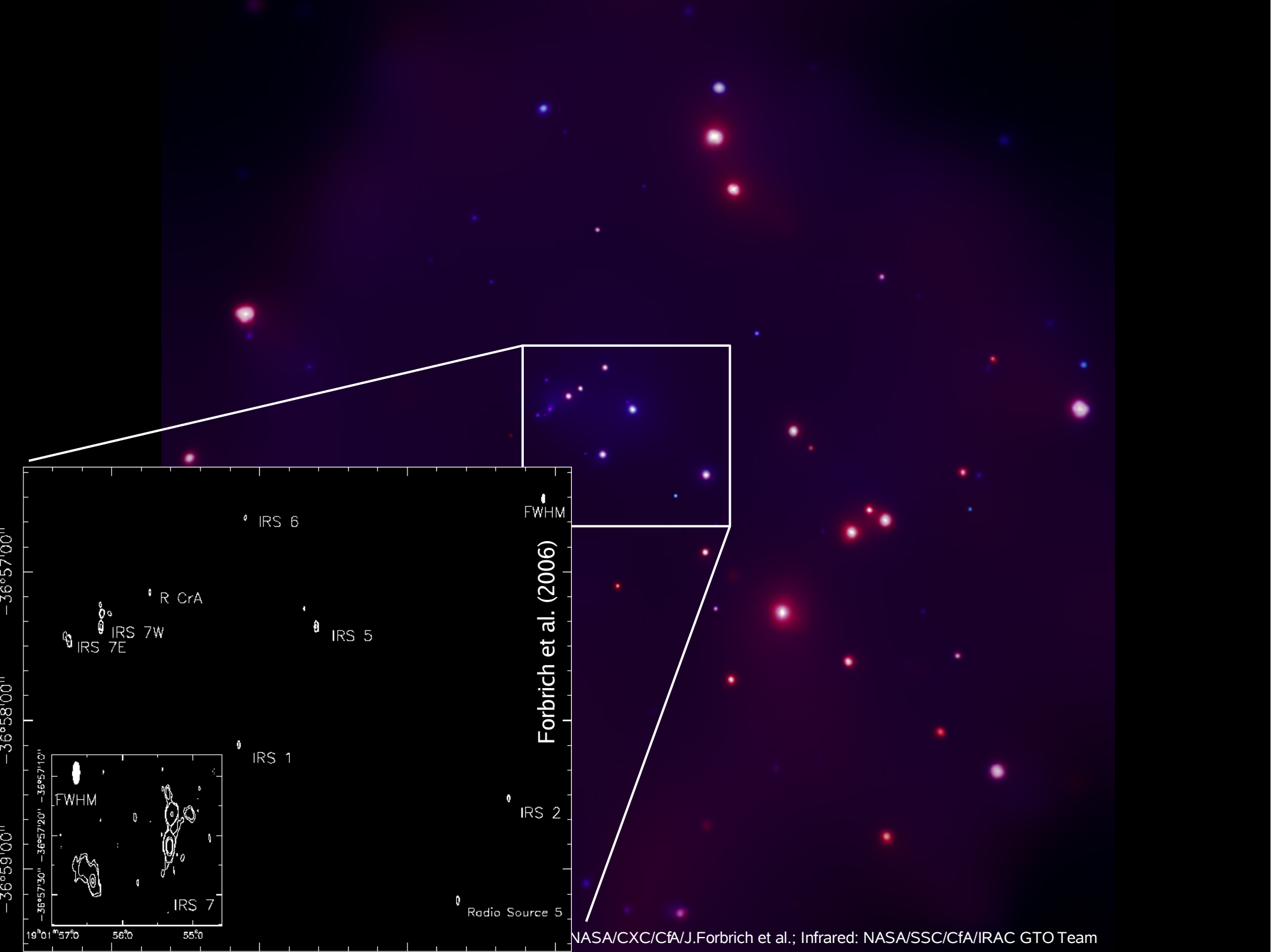
d = 130 pc

Review: Neuhäuser & Forbrich (2008)

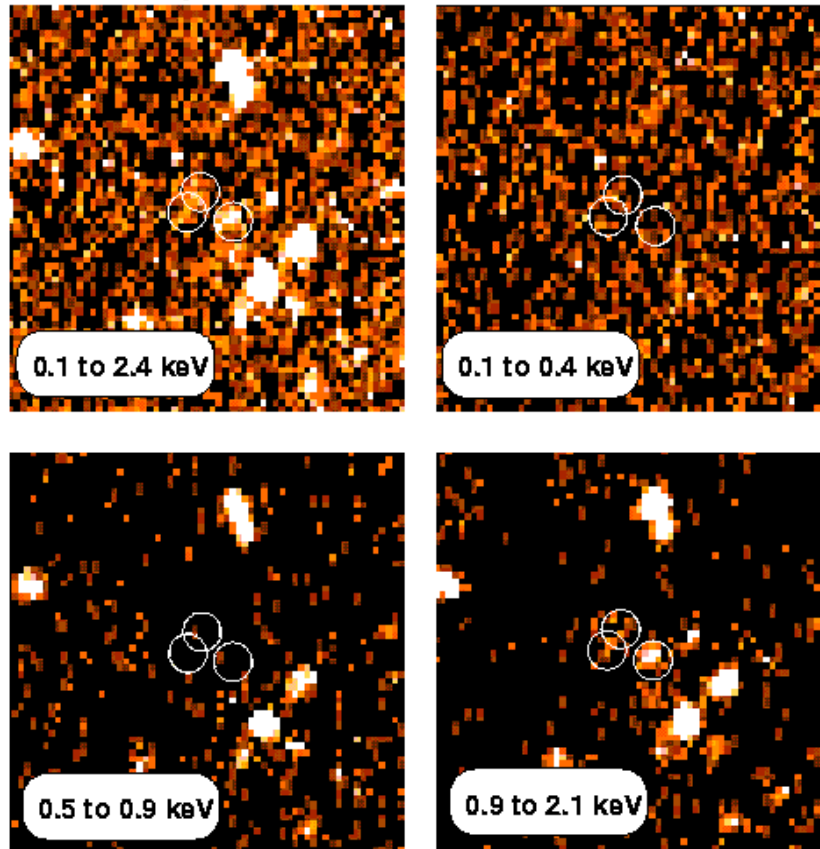


Credit: X-ray: NASA/CXC/CfA/J.Forbrich et al.; Infrared: NASA/SSC/CfA/IRAC GTO Team



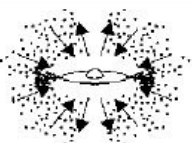
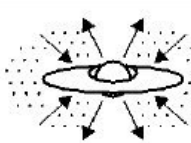
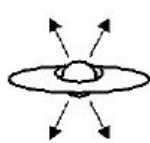
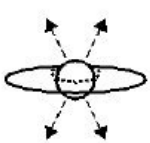



**ROSAT PSPC detection of optically invisible infrared
Class I protostars in the R CrA coronet cluster**



**The protostar infrared positions are indicated by circles.
The protostars are detected only in the very hard band
(Neuhäuser & Preibisch, 1997, A&A 322, L37).**

Radio, X-ray, and infrared emission of protostars

PROPERTIES	<i>Infalling Protostar</i>	<i>Evolved Protostar</i>	<i>Classical T Tauri Star</i>	<i>Weak-lined T Tauri Star</i>	<i>Main Sequence Star</i>
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)
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

subsequently less embedded

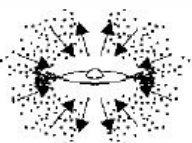
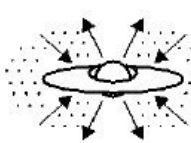
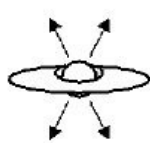
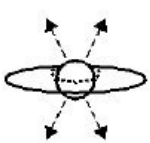
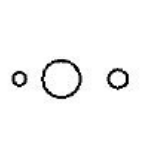
magnetospheric Bremsstrahlung and/or accretion

e.g., from shock-induced ionisation

e.g., gyrosynchrotron radiation

protostars

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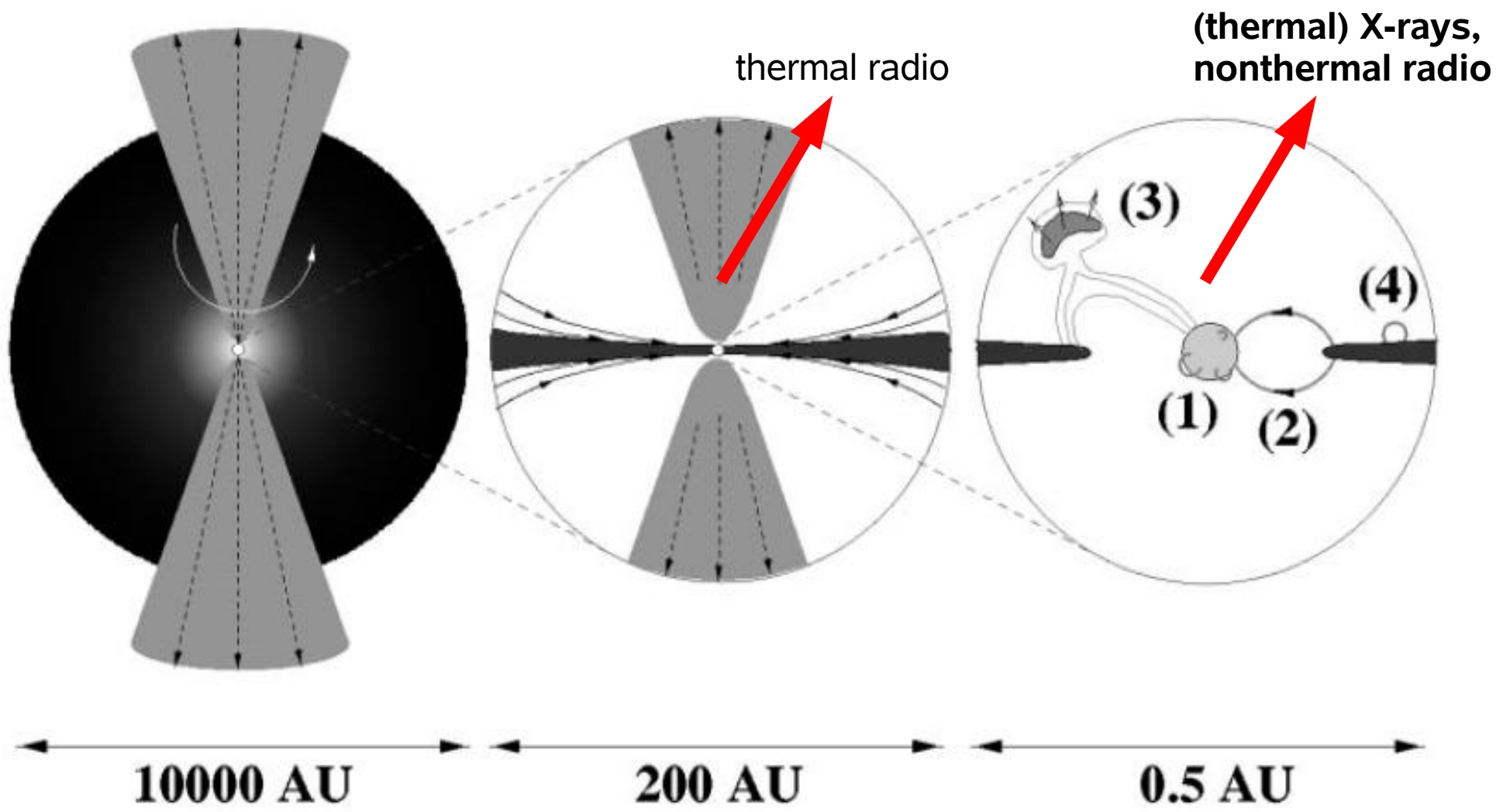
e.g., from shock-induced ionisation

e.g., gyrosynchrotron radiation

protostars

two sources...

High-energy processes in protostars



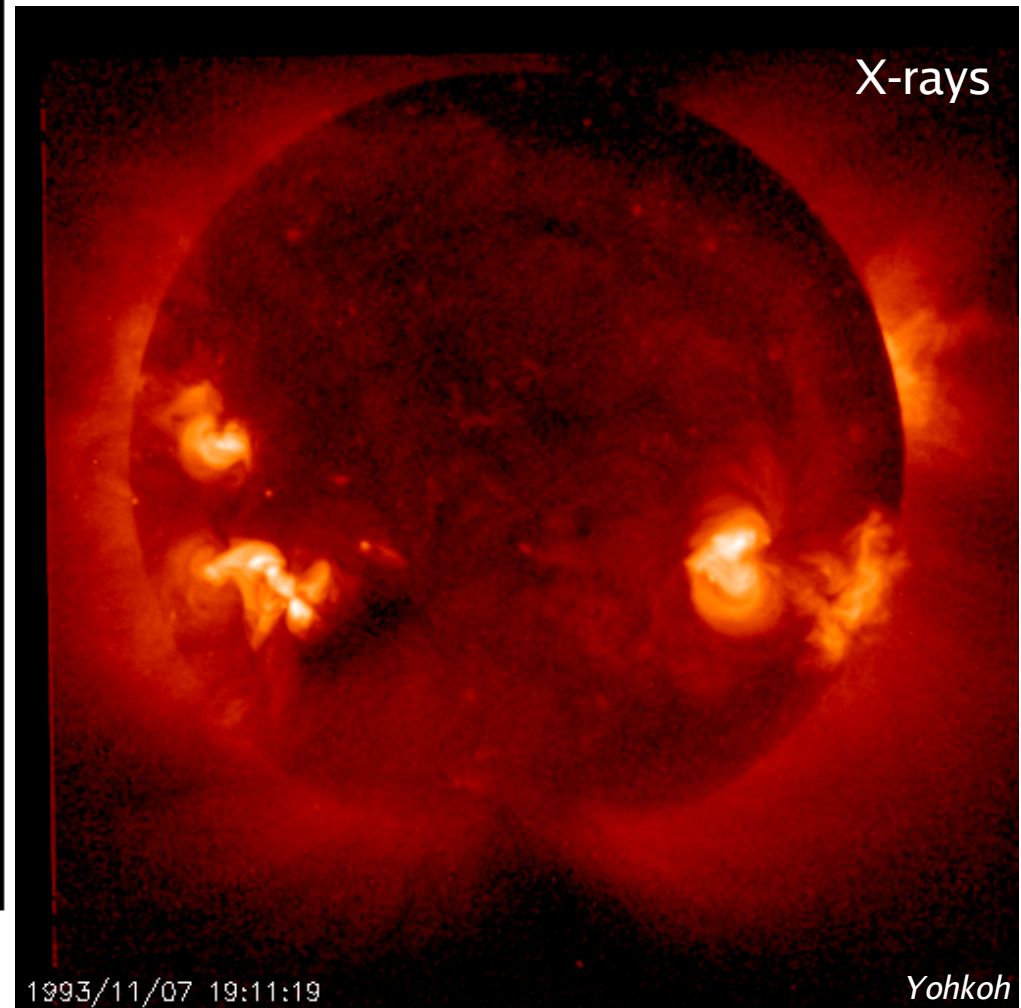
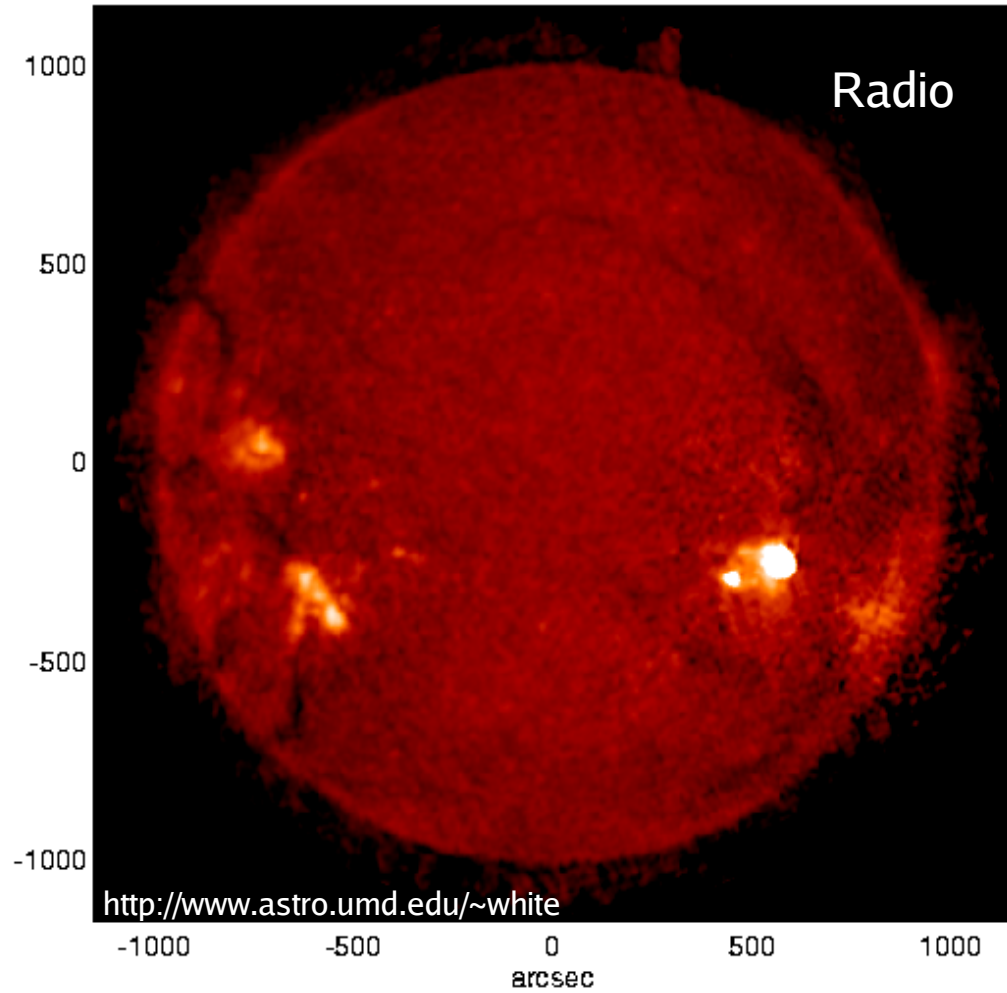
X-ray *and* radio observations probe the **innermost vicinities** of protostars

Non-thermal vs. thermal radio emission

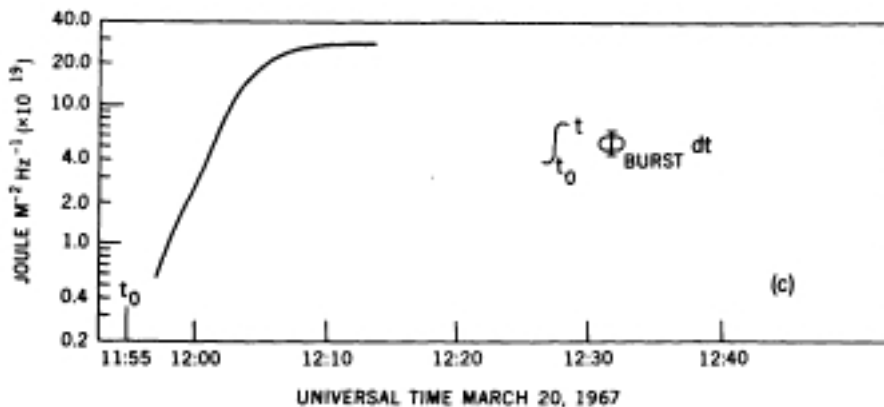
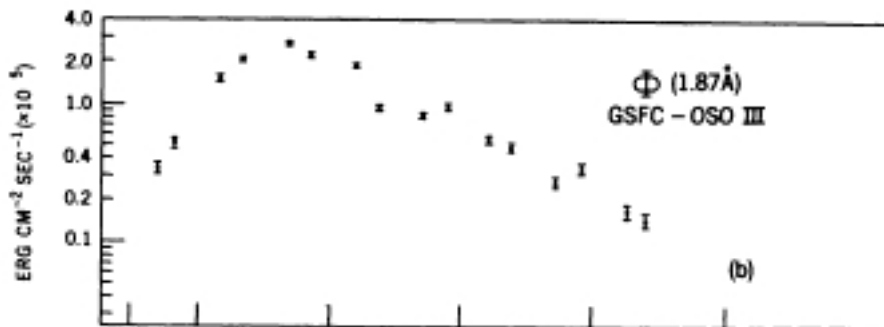
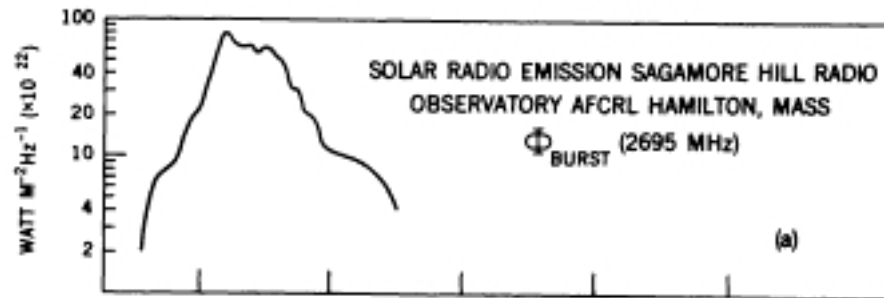
- many processes contribute to radio emission
- thermal emission not directly from protostar ... and easily optically thick (André 1987)
- signs of non-thermal emission: rapid variability, polarization, negative spectral index, high brightness temperatures
- conclusively detecting non-thermal emission usually requires a high SNR, large bandwidth, and/or several simultaneously observed radio bands

The solar paradigm

1993 Nov 07: VLA 4.6 GHz mosaic of the Sun



Radio/X-ray correlations on the Sun

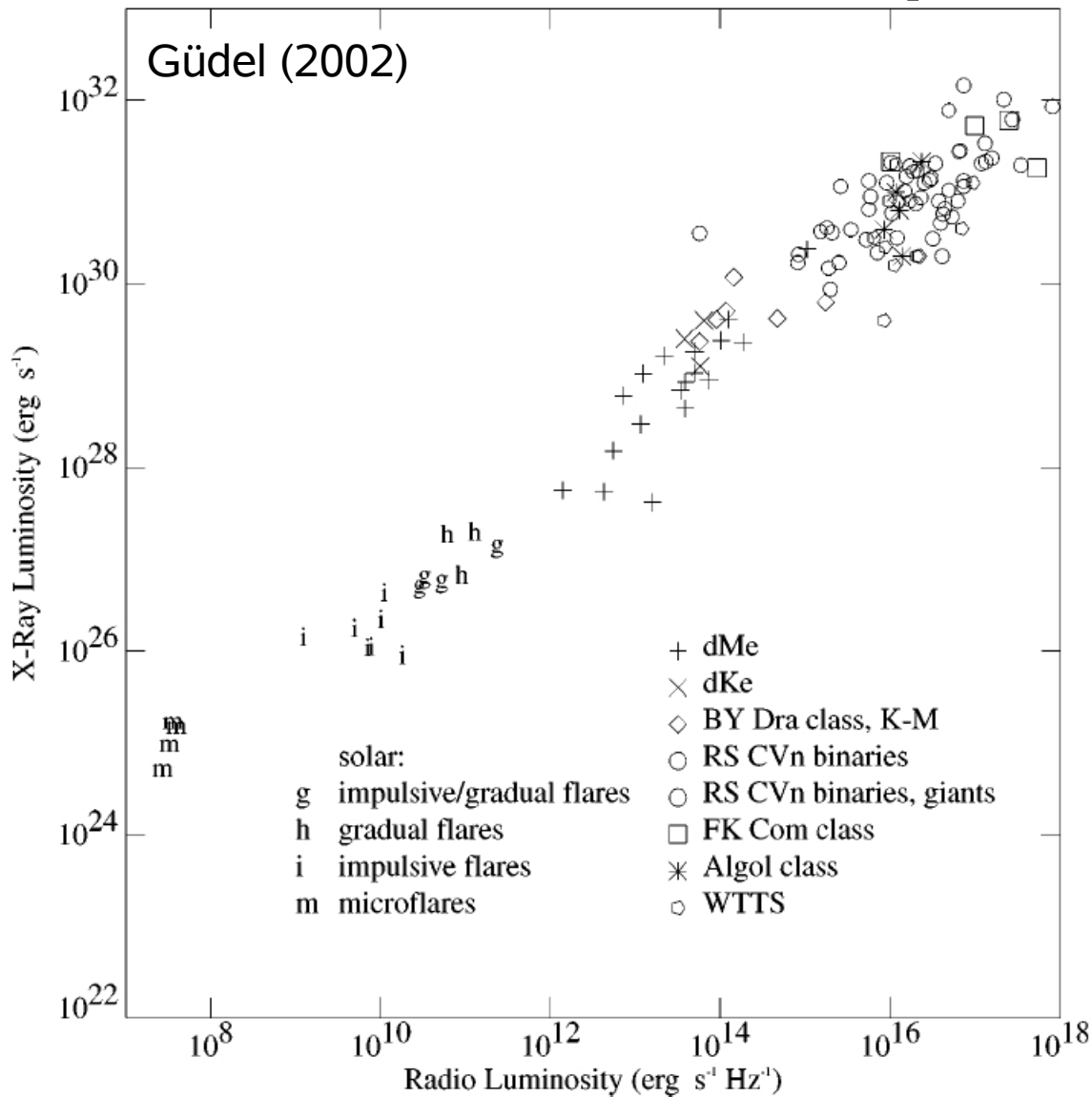


$$L_R(t) \propto \frac{d}{dt} L_X(t)$$

(Neupert 1968)

The Neupert effect does not occur in all flares.

Radio/X-ray correlations



The radio and X-ray luminosities of stars ranging from the Sun to late-type active stars are correlated.

Figure 6 Correlation between quiescent radio and X-ray luminosities of magnetically active stars (*symbols*) and solar flares (*letters*) (after Benz & Güdel 1994).

Simultaneous X-ray/radio observations of YSOs

- V773 Tau, a WTTS multiple (near-simultaneous in Feigelson et al. 1994), see also Guenther et al. (2000) with a short span of simultaneous data
- GMR A (Bower et al. 2003), a WTTS, with a *flare!*
- ρ Oph (Gagné et al. 2004), six TTS
- *Coronet* cluster (Forbrich et al. 2007), six class I, one CTTS, one HAeBe
- LkH α 101 (Osten & Wolk 2009), six(+1?) TTS
- IC 348, NGC 1333 *in prep.* (Osten, Wolk, Forbrich)

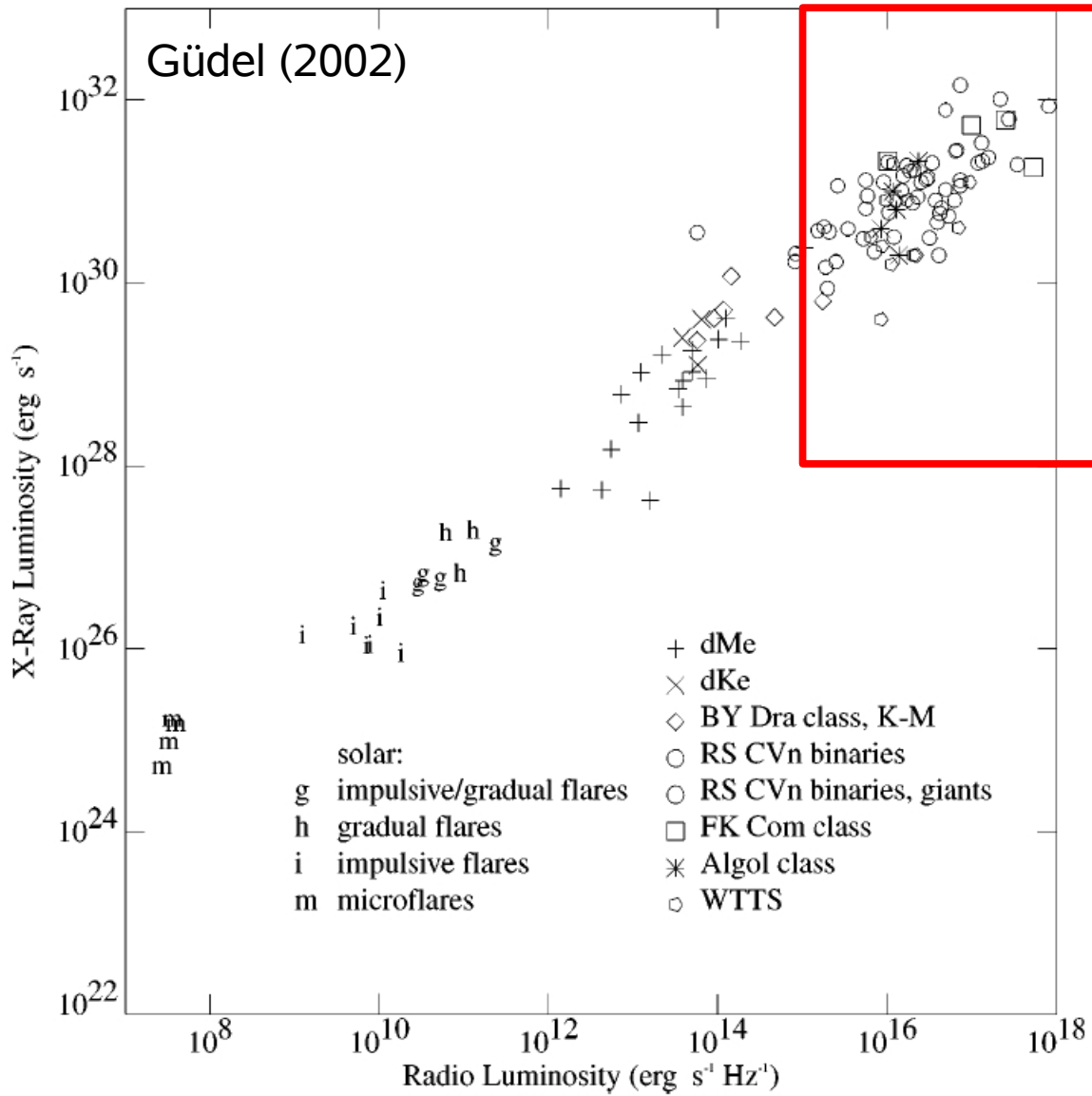
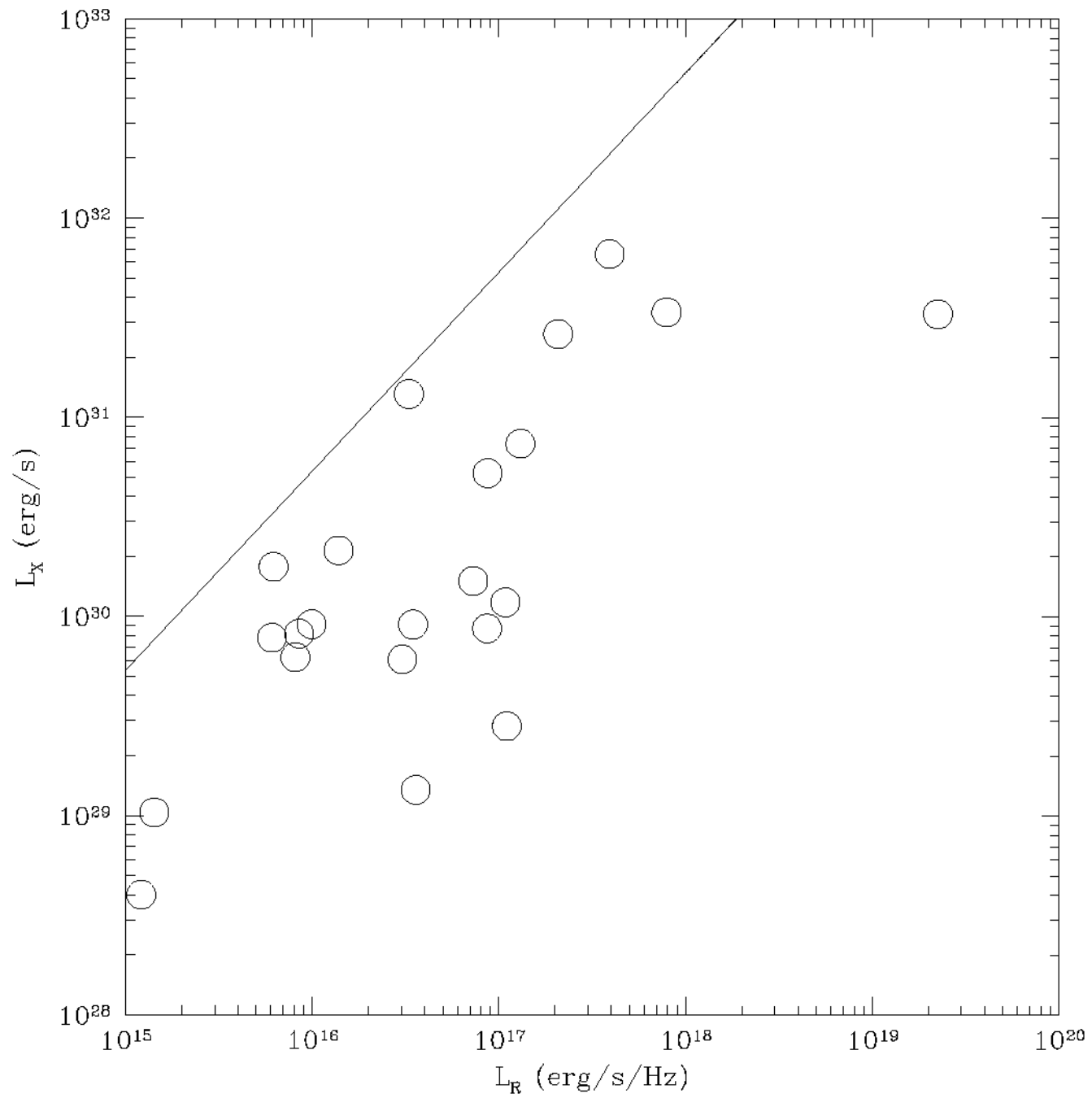
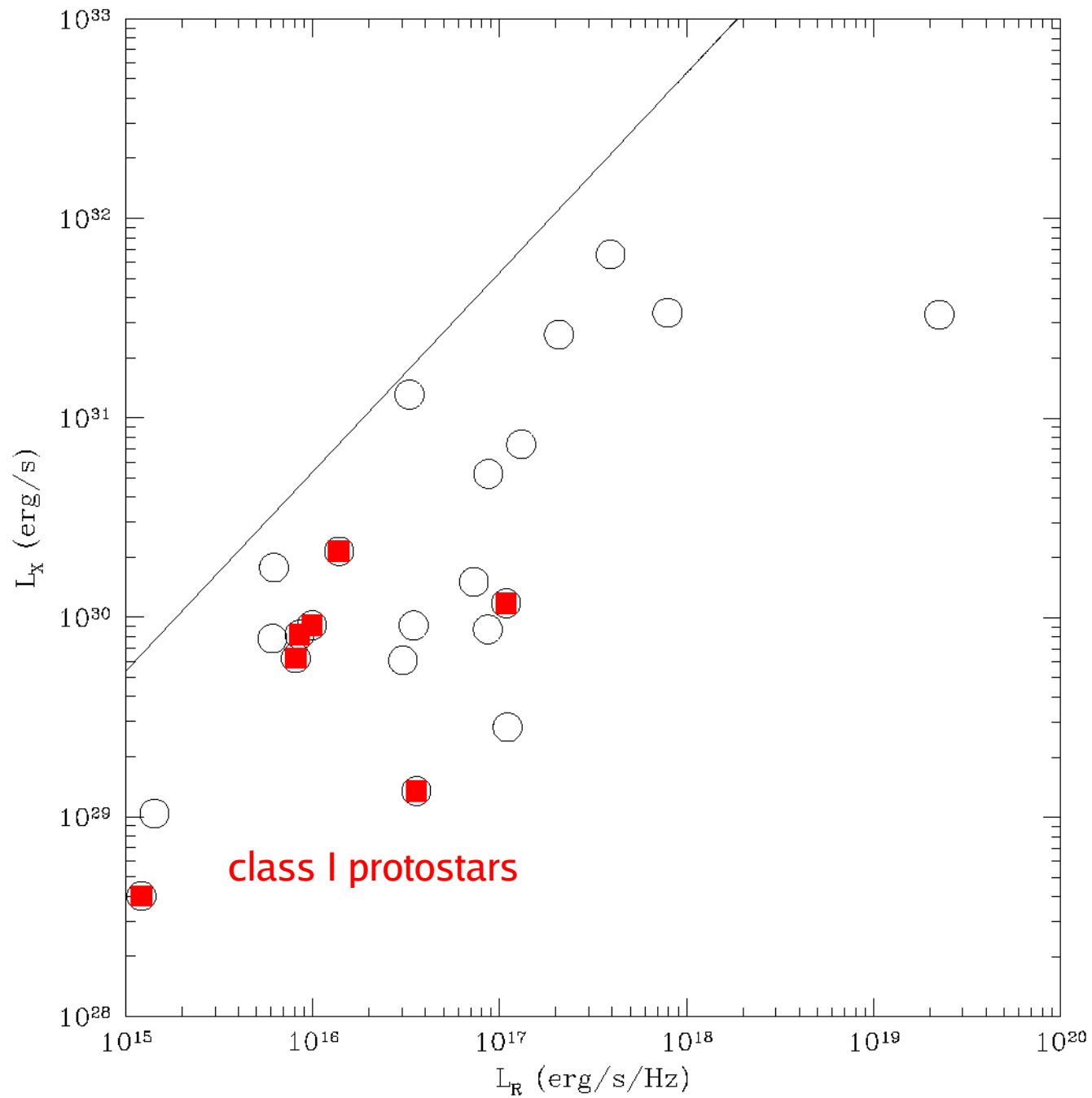


Figure 6 Correlation between quiescent radio and X-ray luminosities of magnetically active stars (*symbols*) and solar flares (*letters*) (after Benz & Güdel 1994).

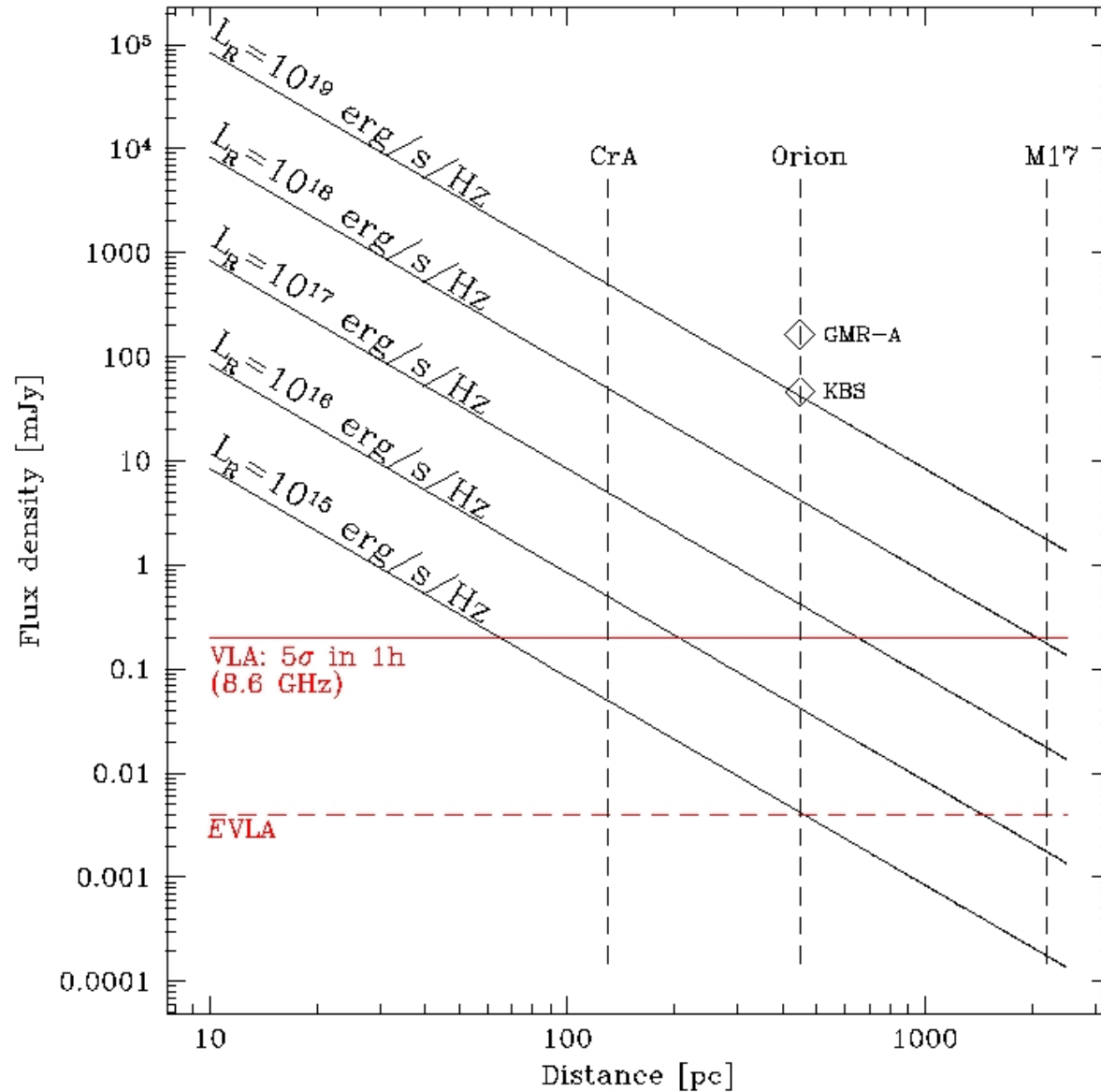




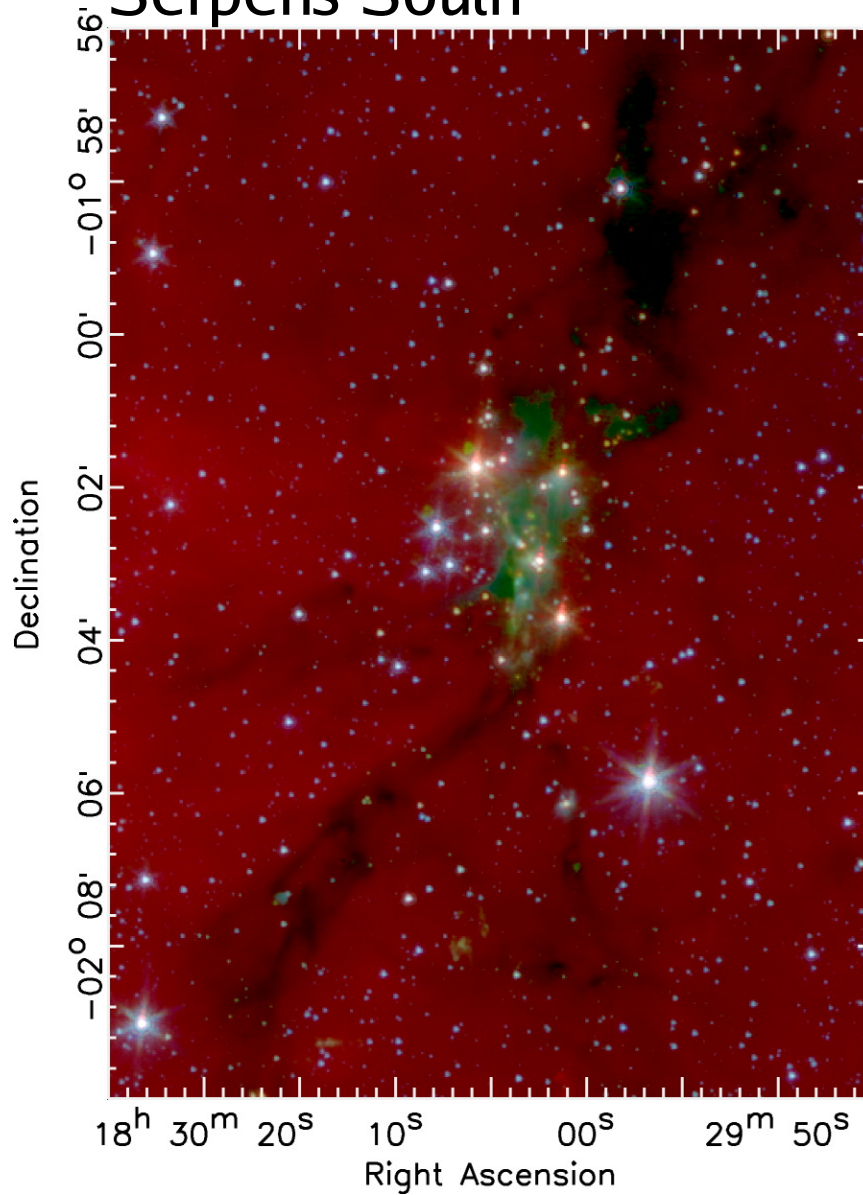
VLA observations of YSOs

- Based on 2MASS, *Spitzer* and *Chandra/XMM-Newton*, we have a well-defined sample of (candidate) *protostars* which can be studied in the radio range.
 - Example: Serpens South (densest *Spitzer* cluster)
- To what degree does distance (sensitivity) currently play a role?
 - Example: Barnard 59 (compared to the *Coronet*)

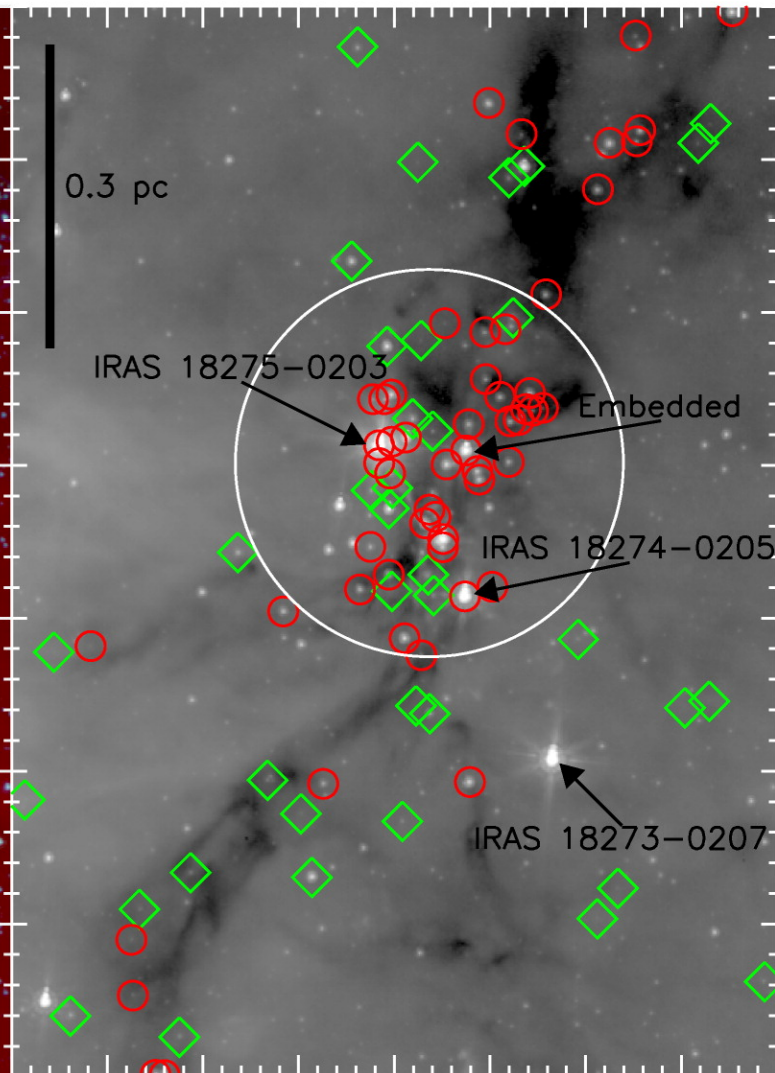
VLA observations of YSOs



Serpens South



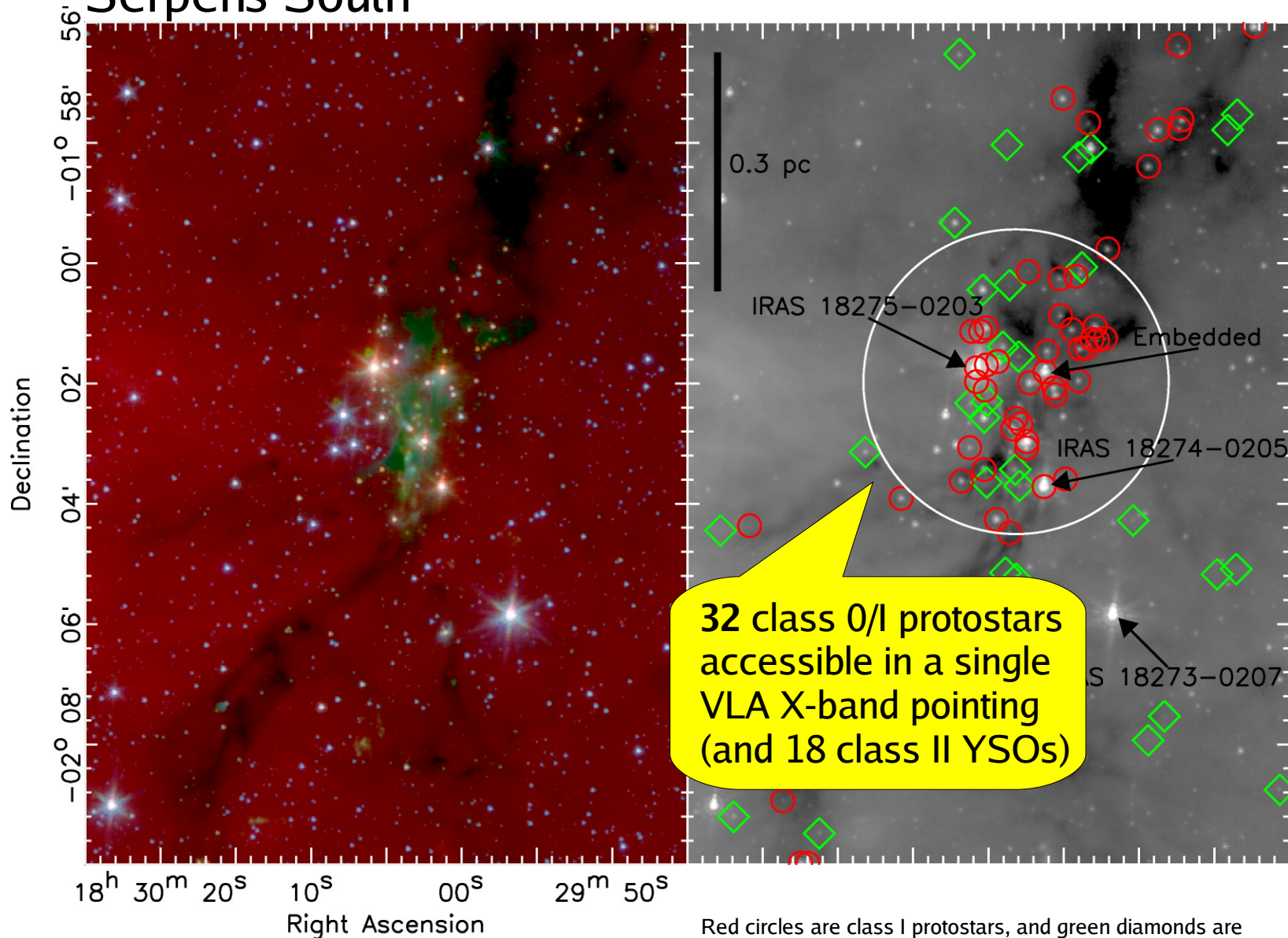
d = 260 pc



Gutermuth et al. (2008)

Red circles are class I protostars, and green diamonds are class II stars with disks.

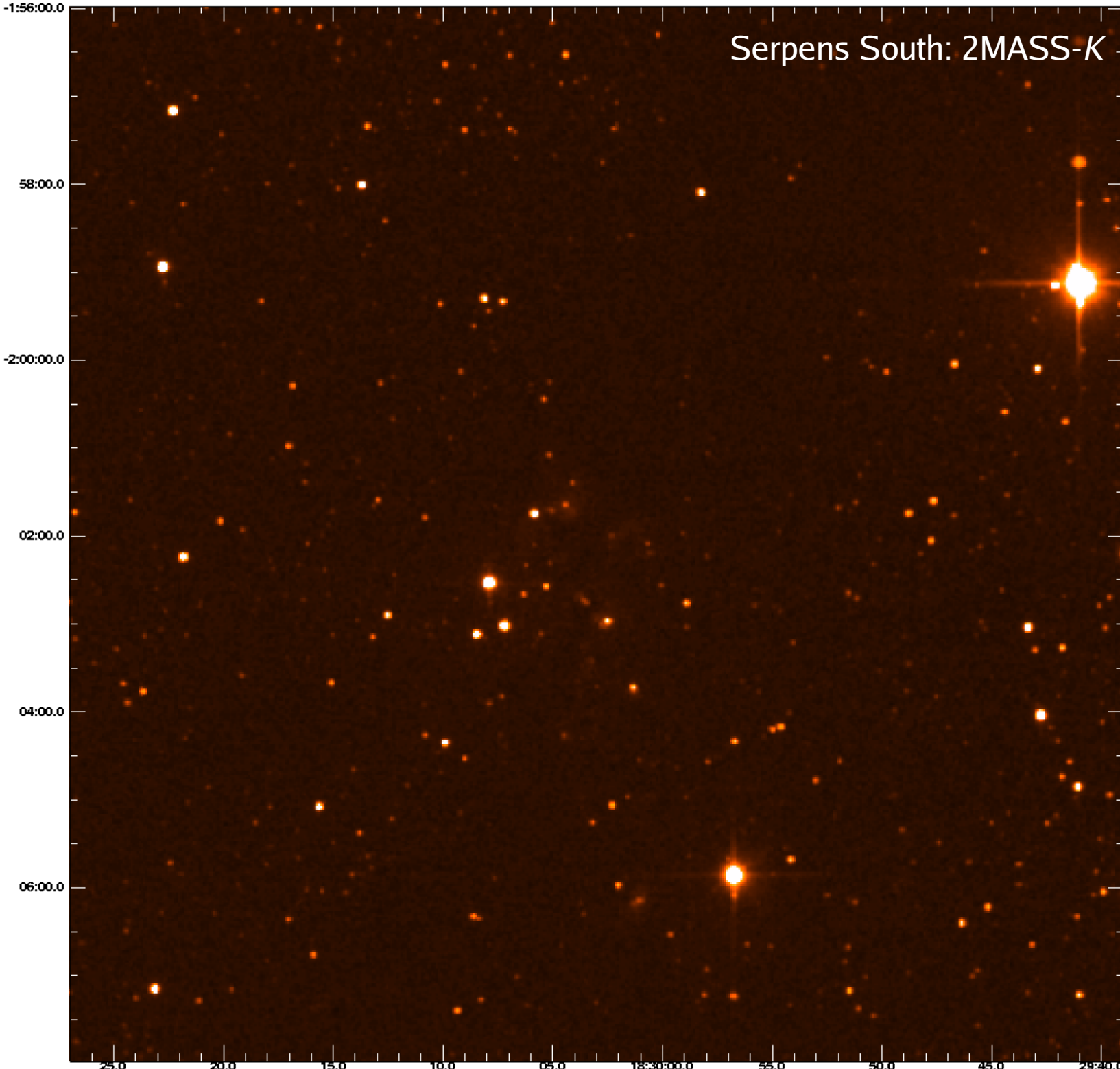
Serpens South

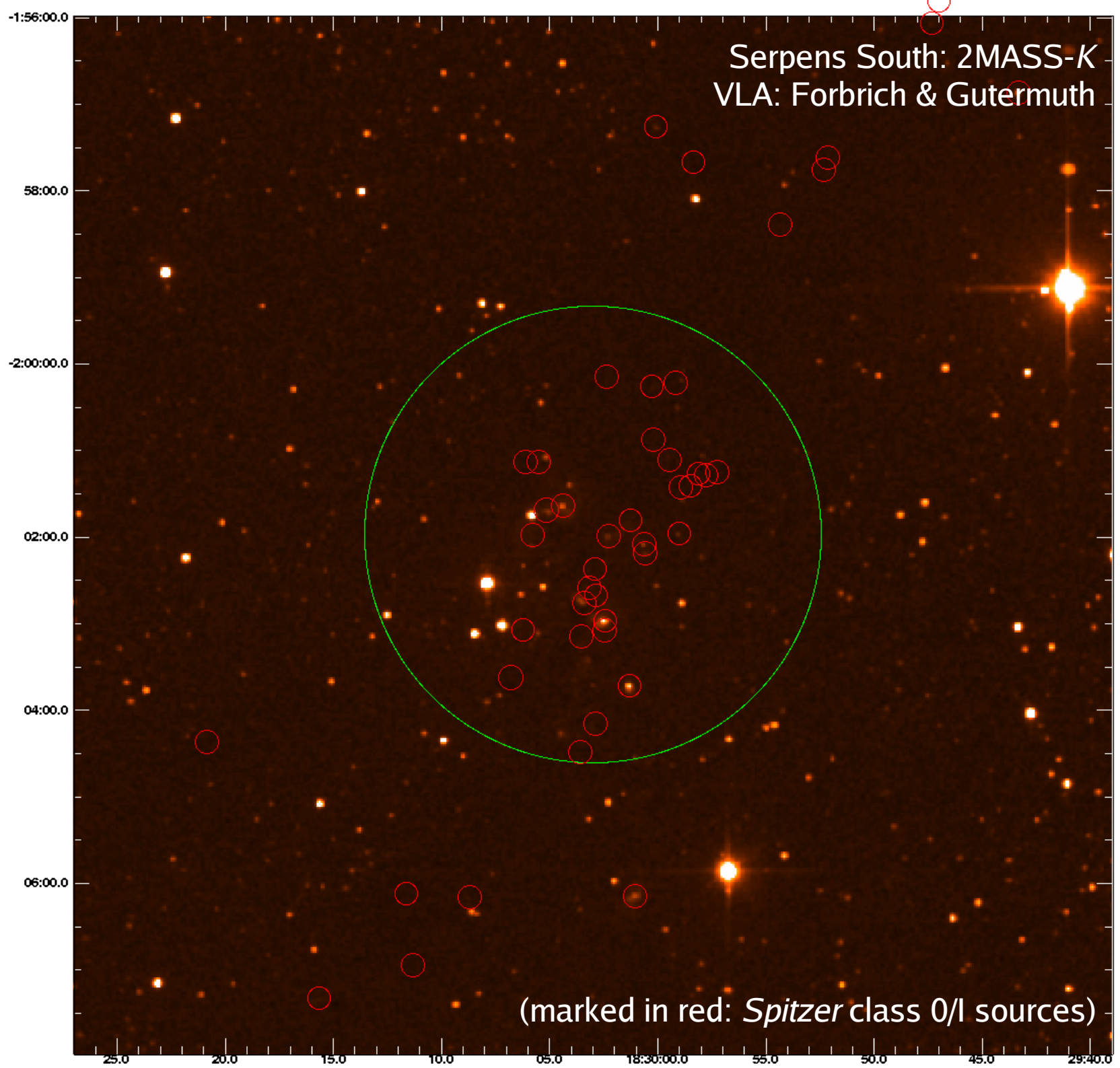


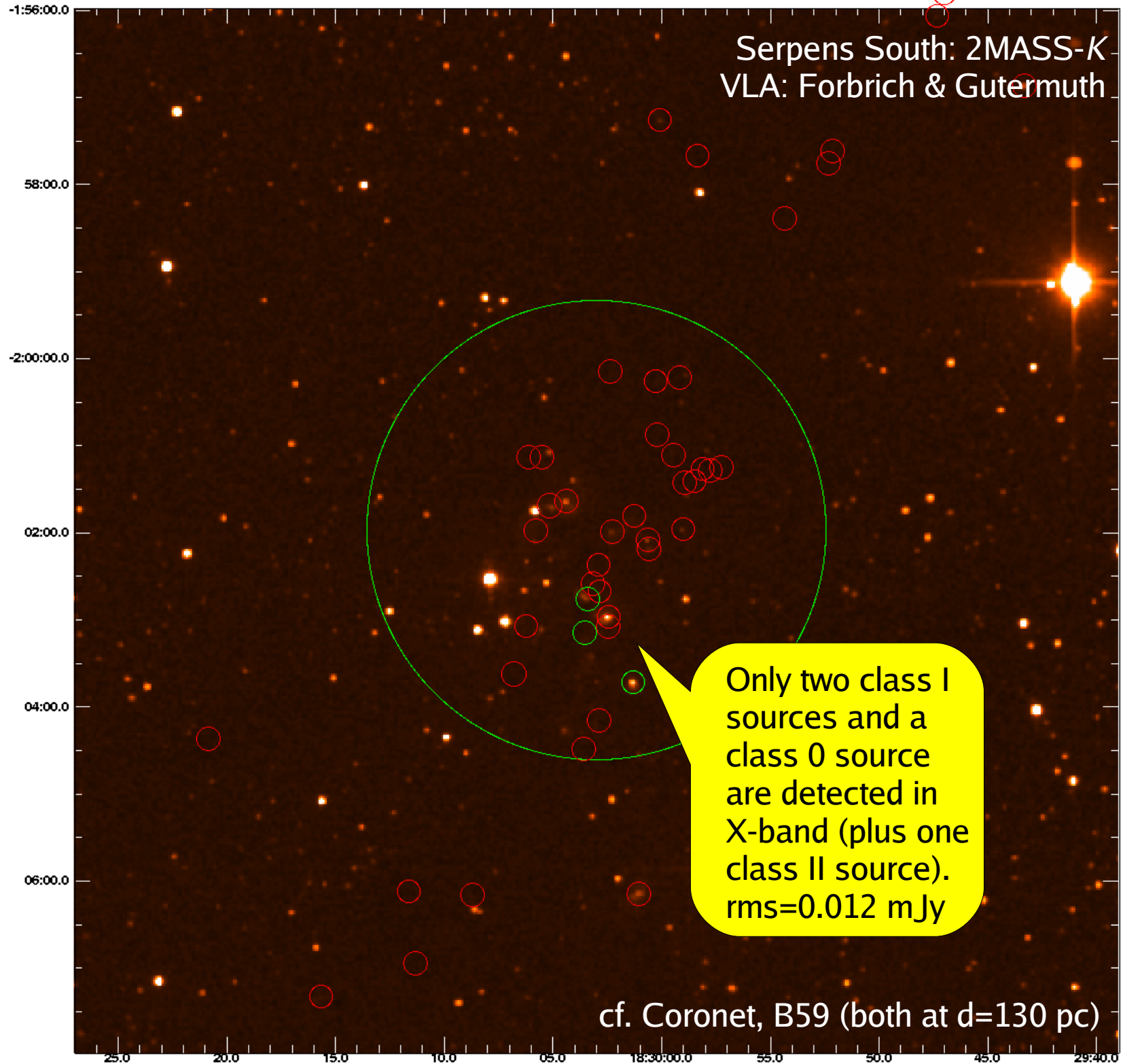
Gutermuth et al. (2008)

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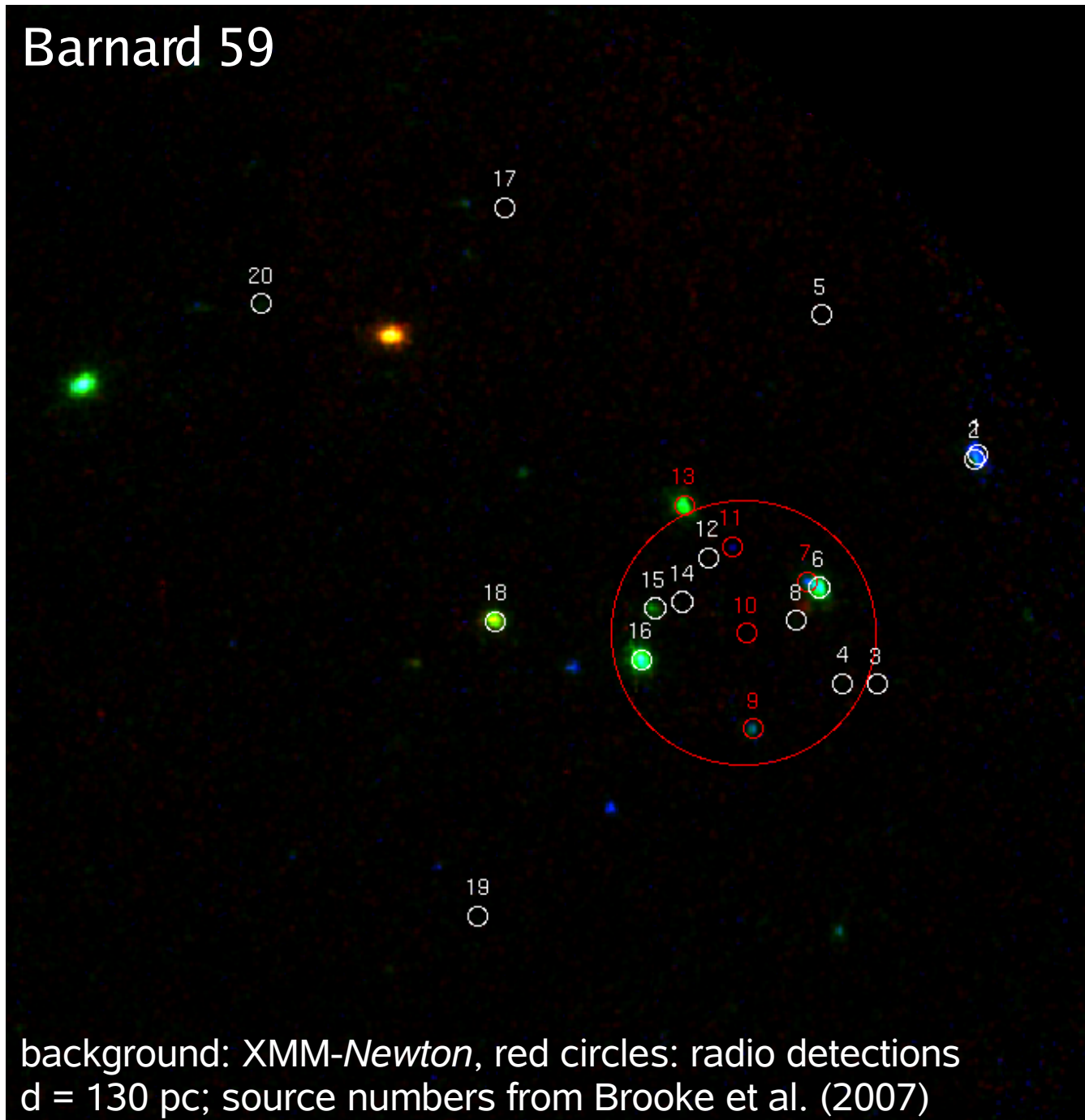
Serpens South: 2MASS-K







Barnard 59



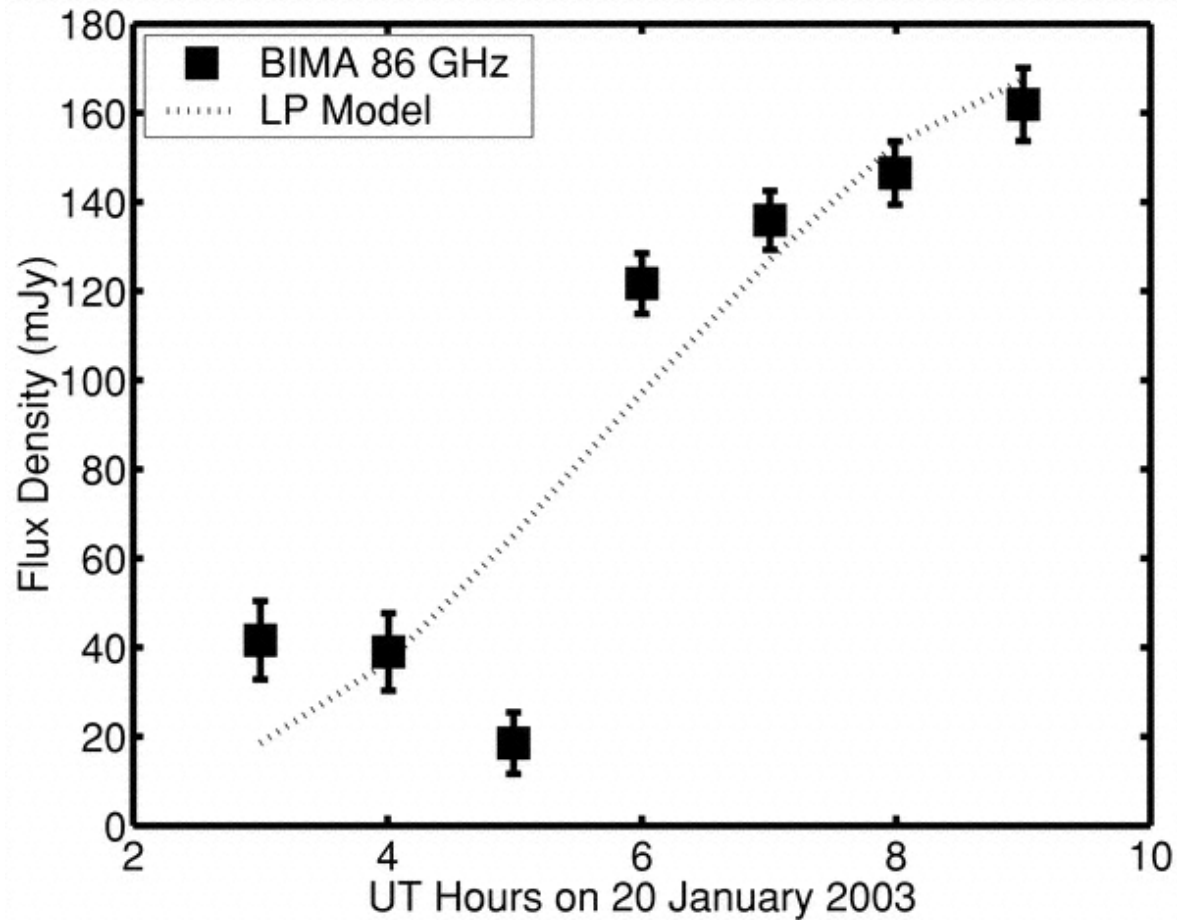
background: *XMM-Newton*, red circles: radio detections
d = 130 pc; source numbers from Brooke et al. (2007)

YSOs as transient radio sources?

- few known (major) cases:
 - GMR A (WTTS), observed in the radio range (86 GHz, BIMA) *and X-rays* (Bower et al. 2003)
 - ORBS (class 0/I?), observed in cm radio (22 GHz, VLA; Forbrich, Menten, & Reid 2008)
 - DQ Tau (class II), observed in mm radio (115 GHz, CARMA; Salter et al. 2009)
- implications for dynamic range of observations of SFR (EVLA, ALMA!)
- correlation with X-ray flares? (currently better statistics)

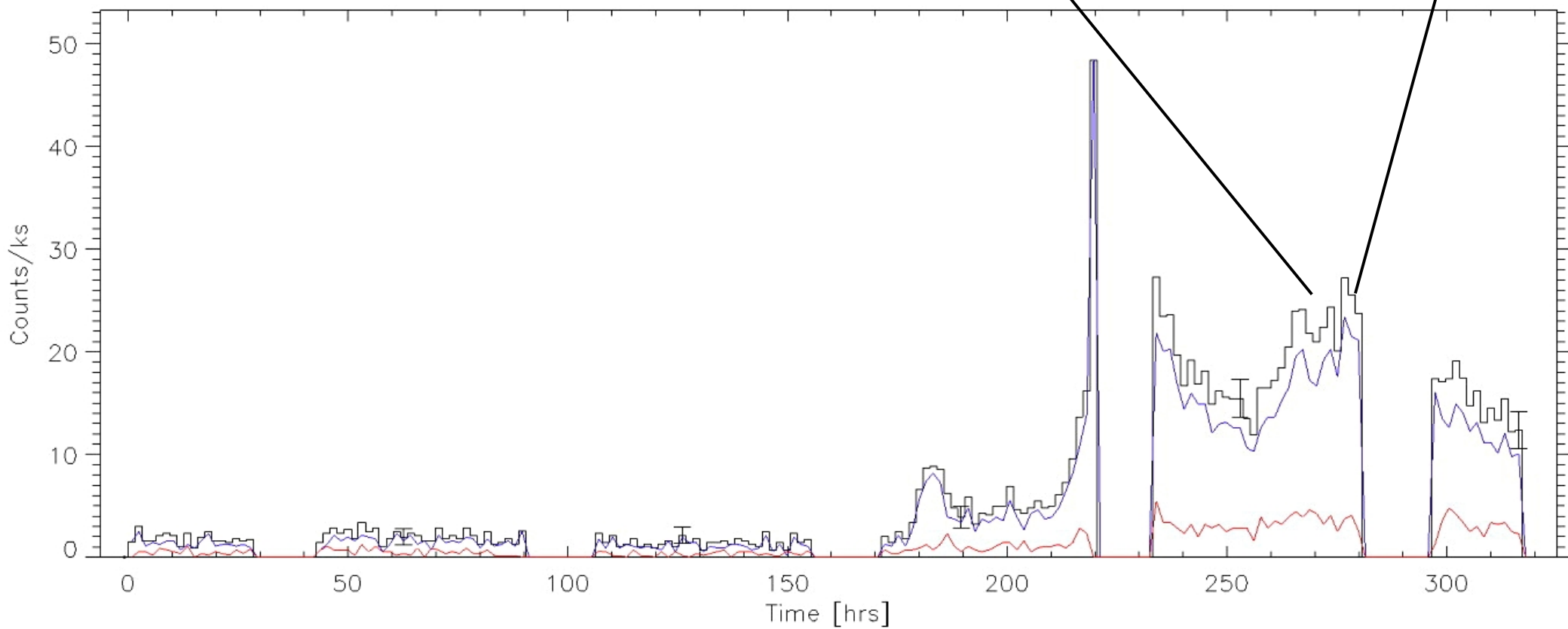
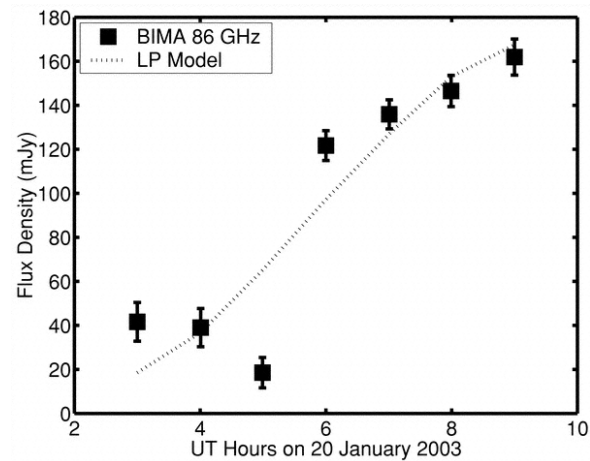
YSOs as transient radio sources?

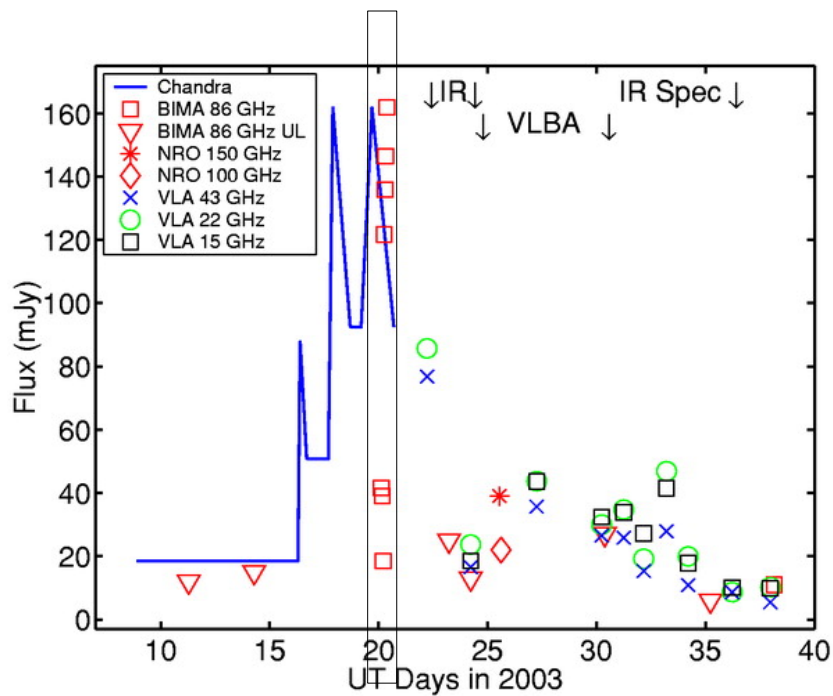
GMR A
Bower et al. (2003)



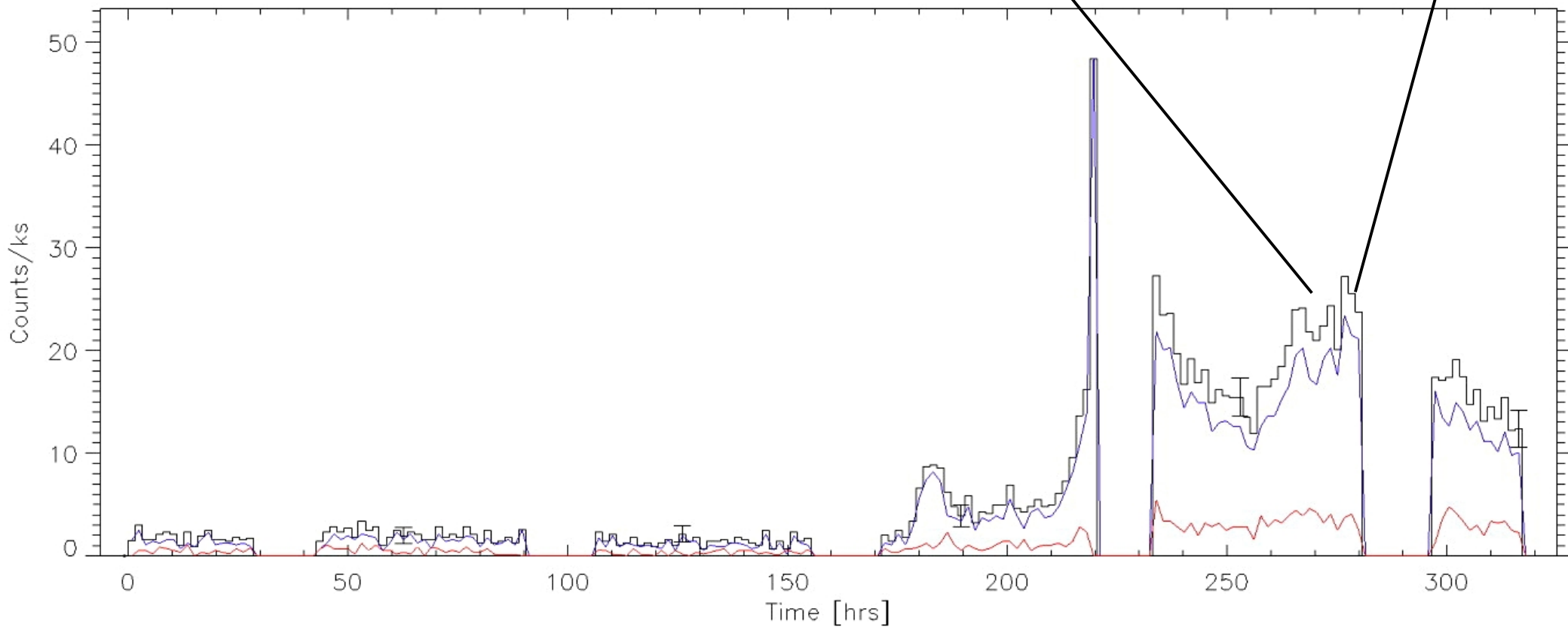
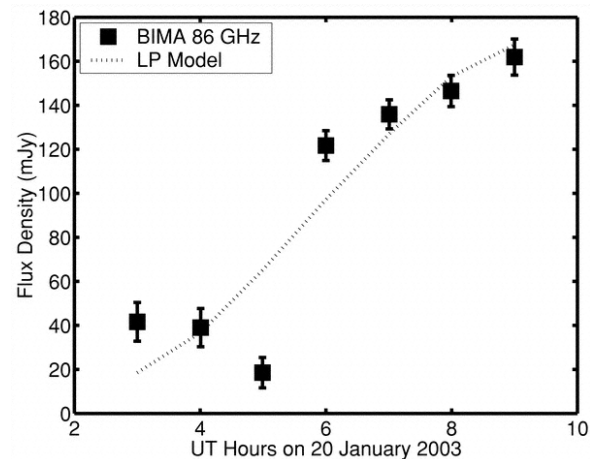
GMR A

Bower et al. (2003)

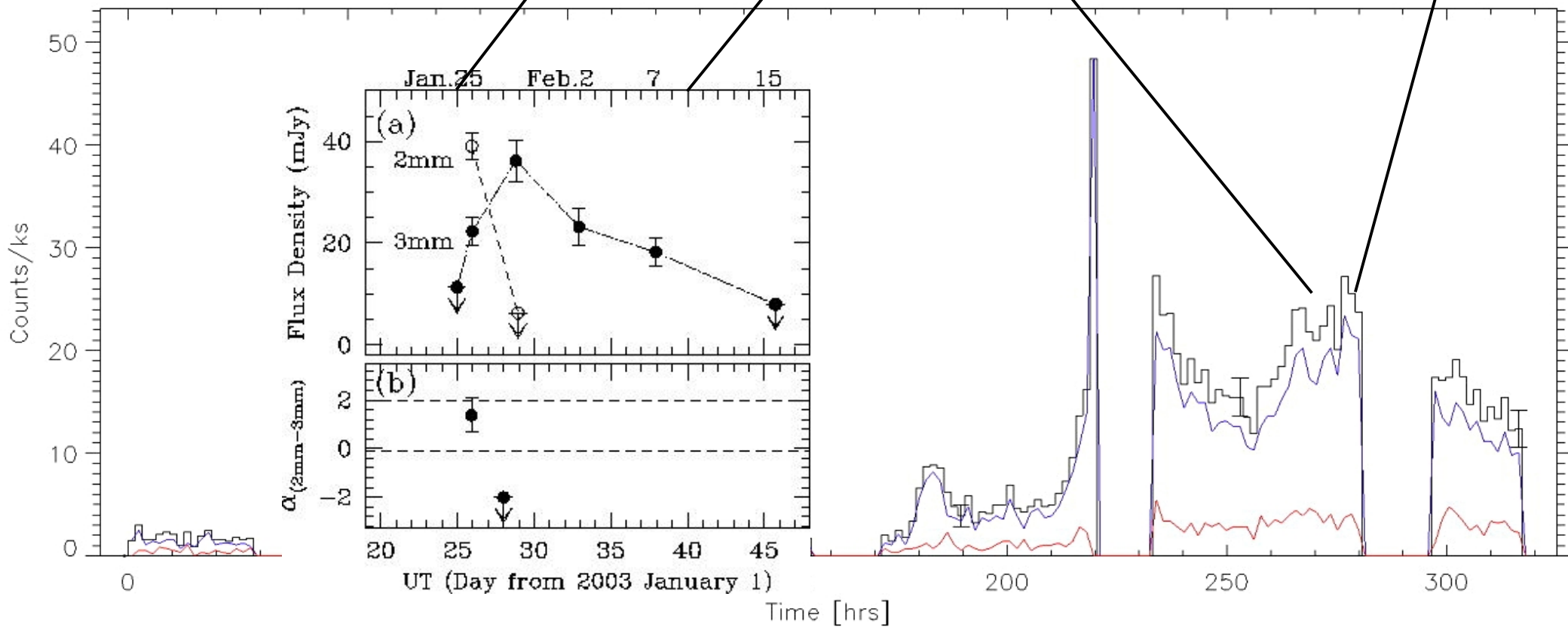
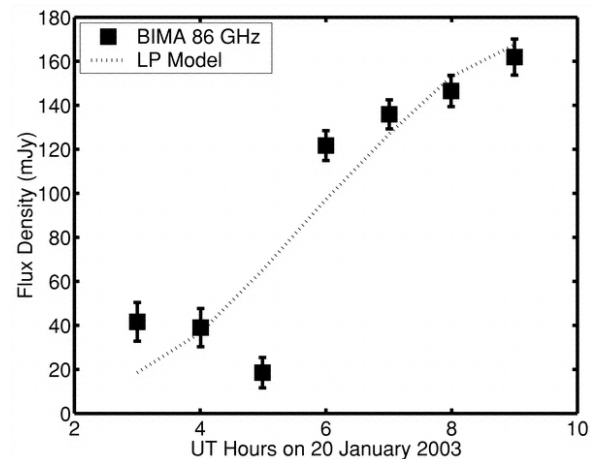
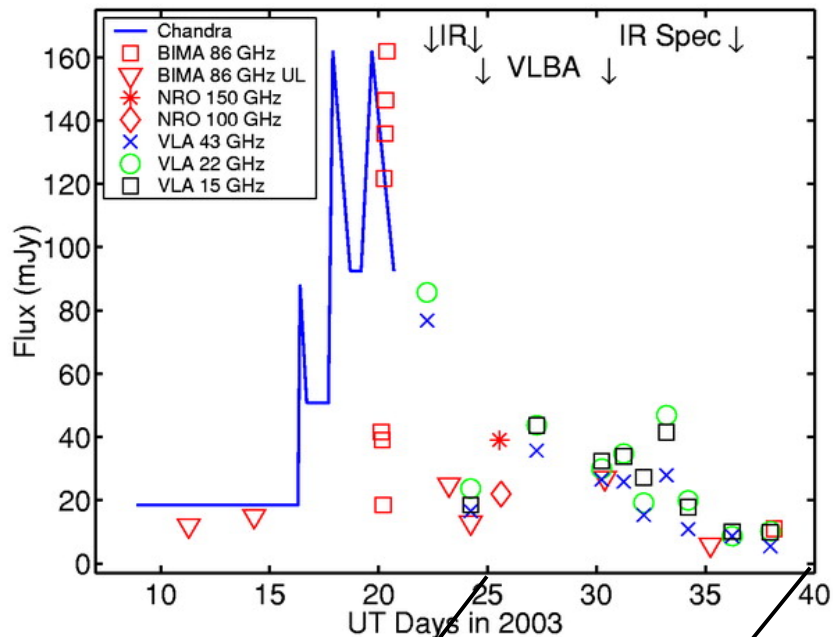


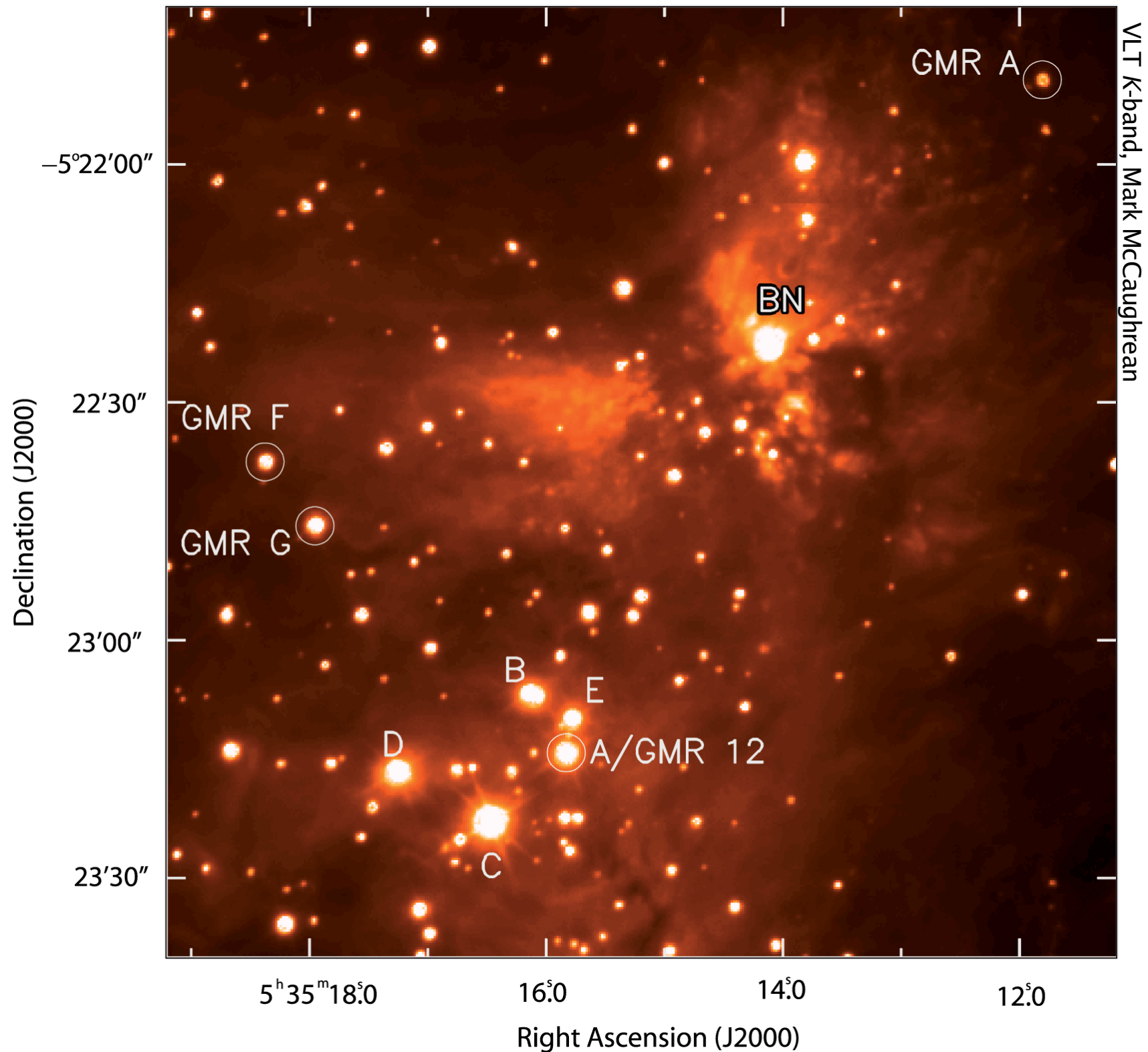


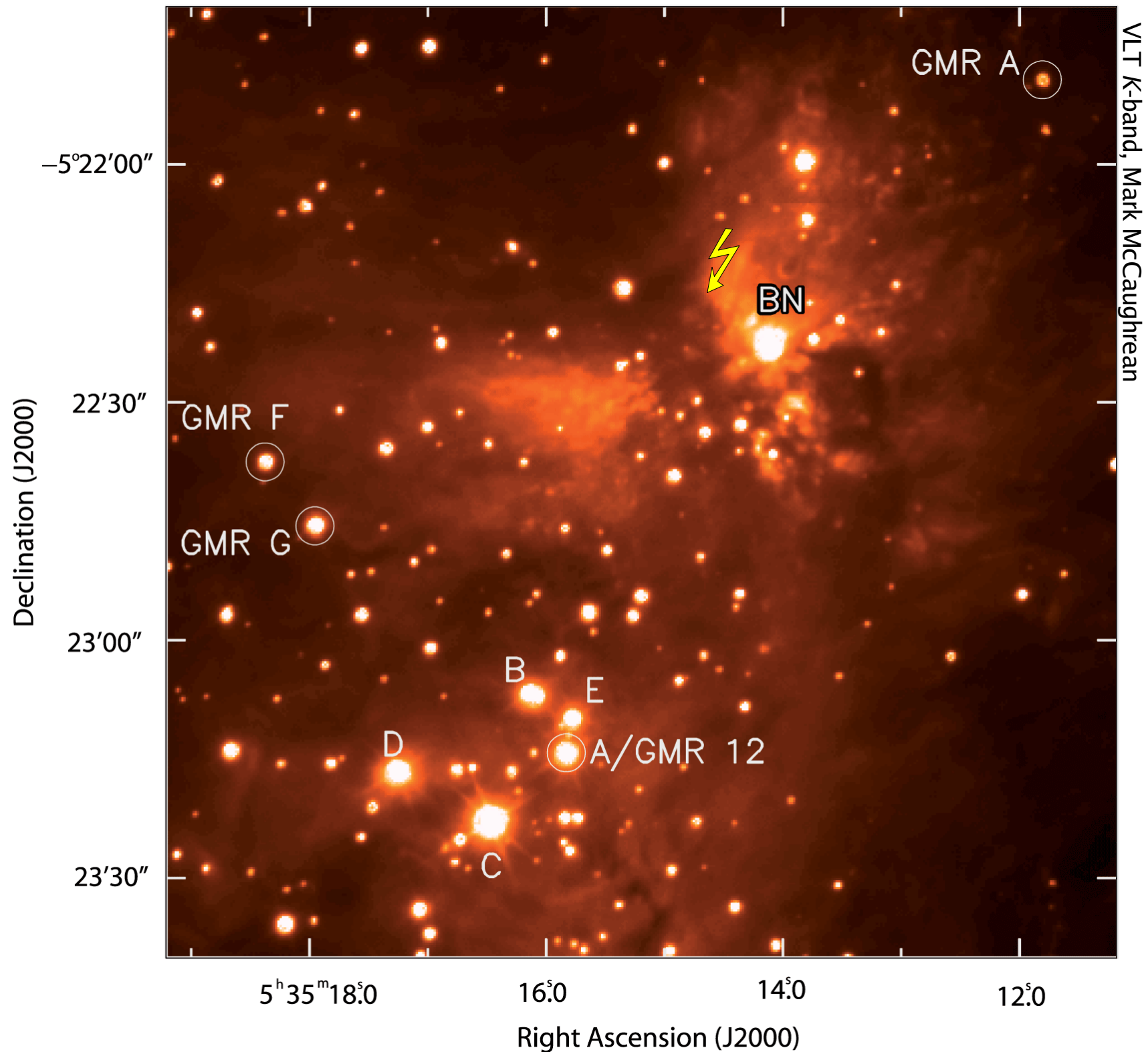
GMR A Bower et al. (2003)

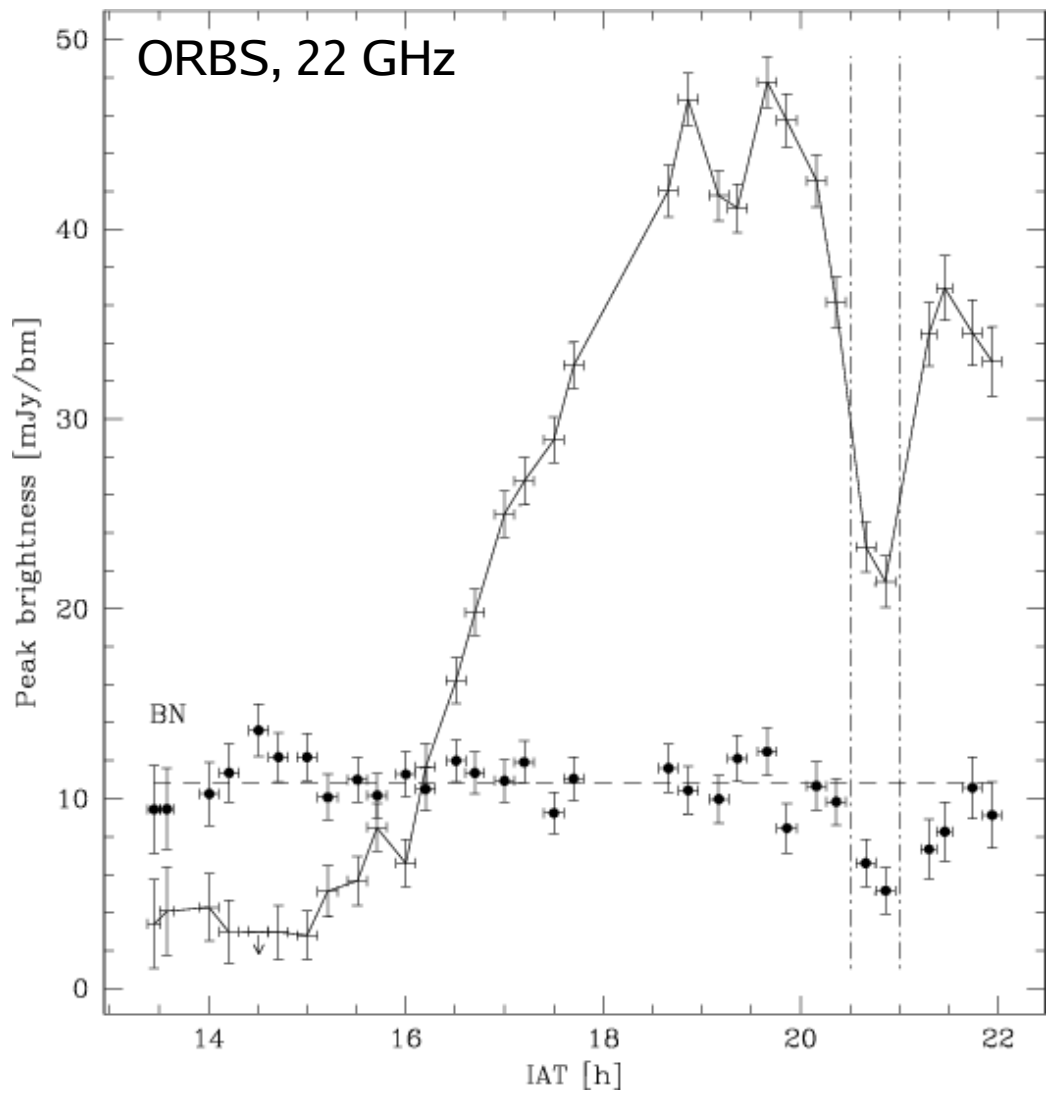


GMR A Bower et al. (2003)

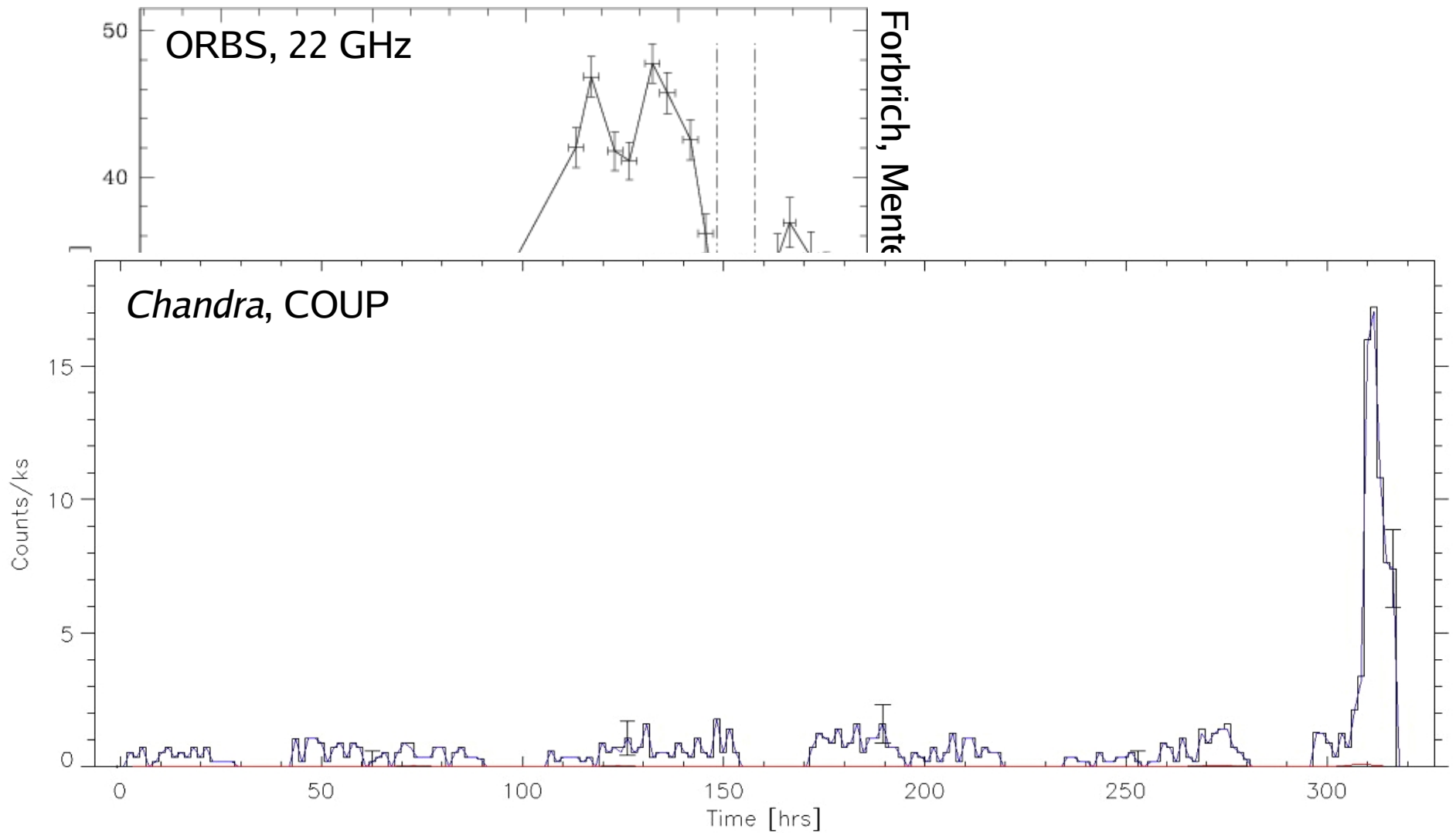




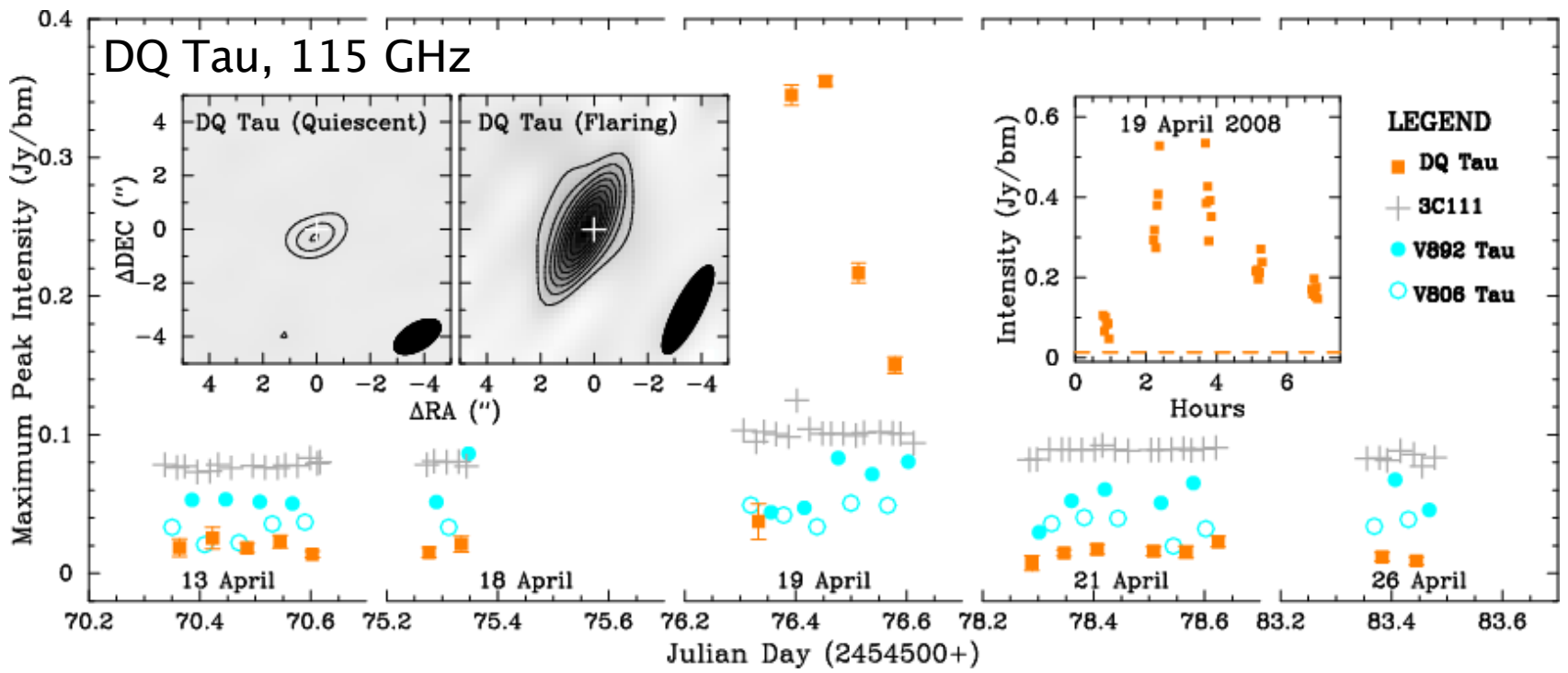




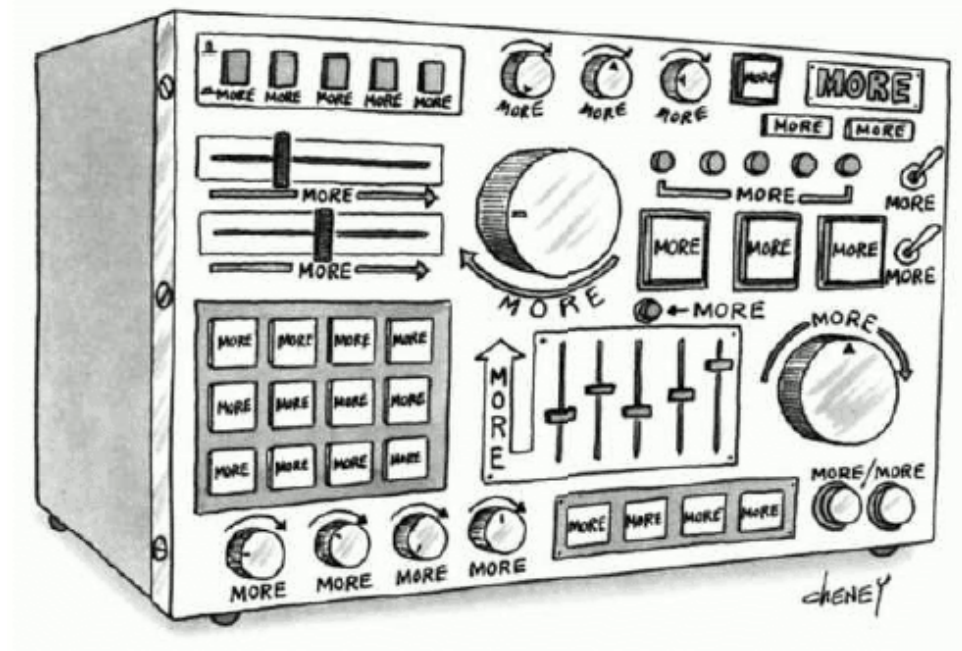
Forbrich, Menten, & Reid (2008)



$A_V \sim 160$ mag, no infrared counterpart
(from X-rays, spectrum shows fluorescent iron line emission)



The prospect of the EVLA



The New Yorker

- leap in sensitivity will allow better detection of nonthermal emission
- also allows wider-area searches with current sensitivity
- better spectral coverage instead of spectral indices based on (often non-simultaneous) single bands (X, C)
- enable variability studies on previously inaccessible time scales
- studies can be guided by vast amounts of mid-infrared and X-ray data

Already some 30% of the time on the VLA is devoted to stellar observations, and one has the feeling that numerous other stellar radio phenomena have yet to be discovered or properly explored. Reasons for this conclusion include the following: (a) The sources have flux densities near or just below the present sensitivity limit of the VLA; (b) they are outside its frequency range; (c) they are not quite resolvable with the present VLA; and (d) they are too weak to be detected with present very long baseline (VLB) networks. But new and improved radio telescopes are now being constructed or planned (for example, VLB arrays, an Australian telescope, and an augmented VLA with increased sensitivity, frequency coverage, and resolution). With these improvements, many of the present problems will be solved, and undoubtedly new phenomena will be revealed.

Dulk (1985), *Radio Emission from the Sun and Stars*, ARA&A