The Orion Radio All-Stars: extreme YSO radio and X-ray variability

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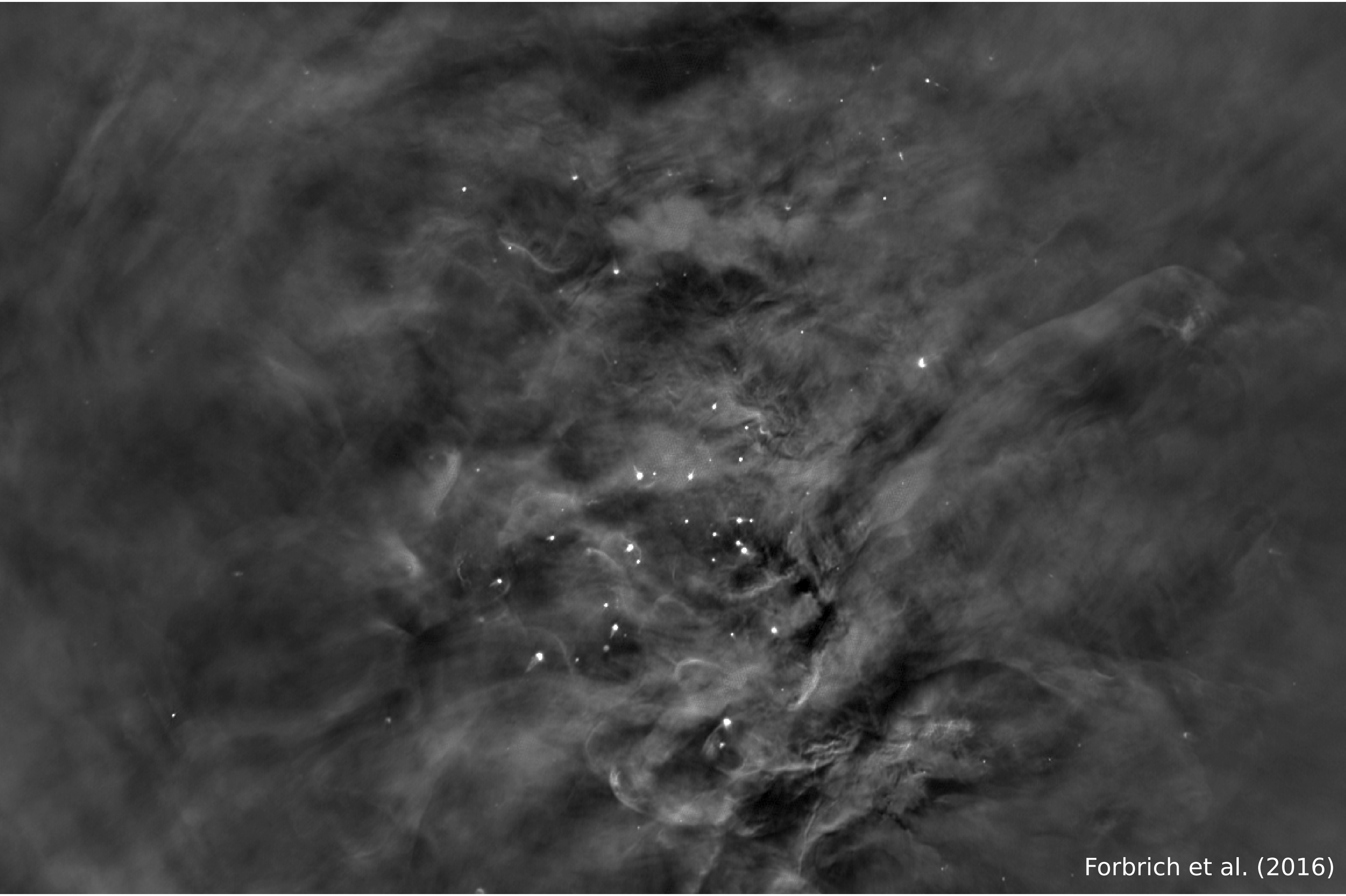
GO HERTS


Forbrich et al. (2016)

COMPACT CONTINUUM RADIO SOURCES IN THE ORION NEBULA[1]

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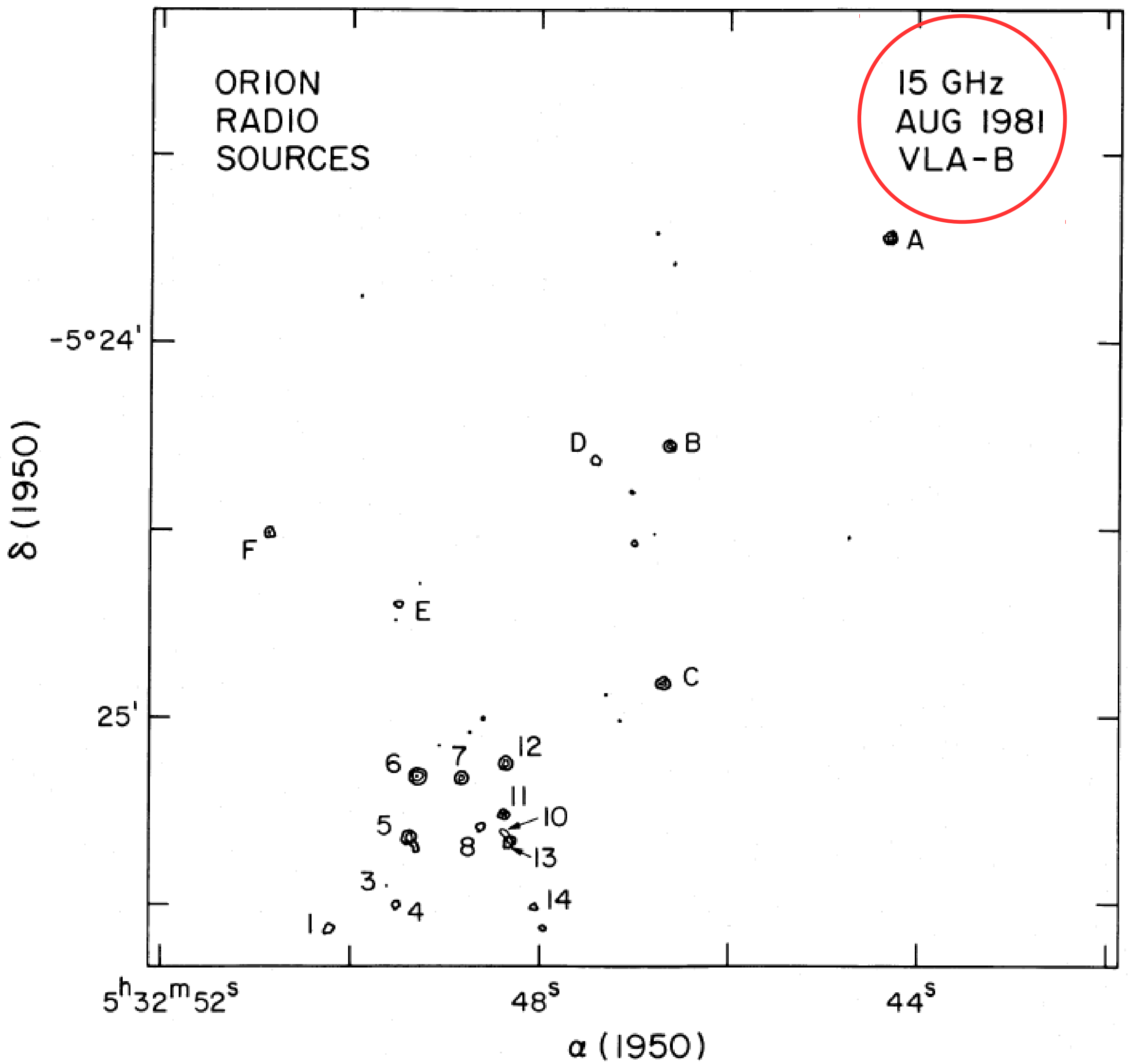
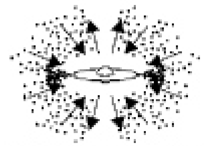
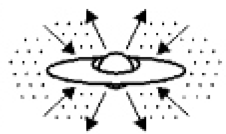
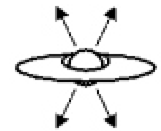
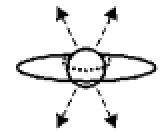
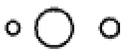
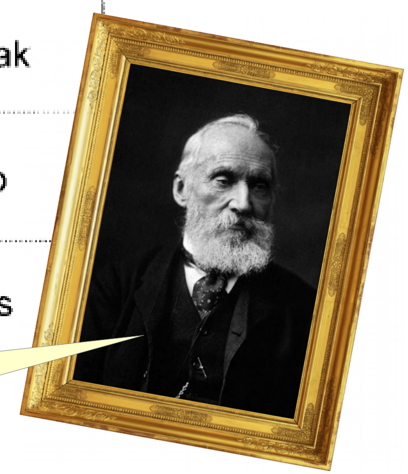


Multi-wavelength properties of Young Stellar Objects

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

Feigelson & Montmerle (1999)



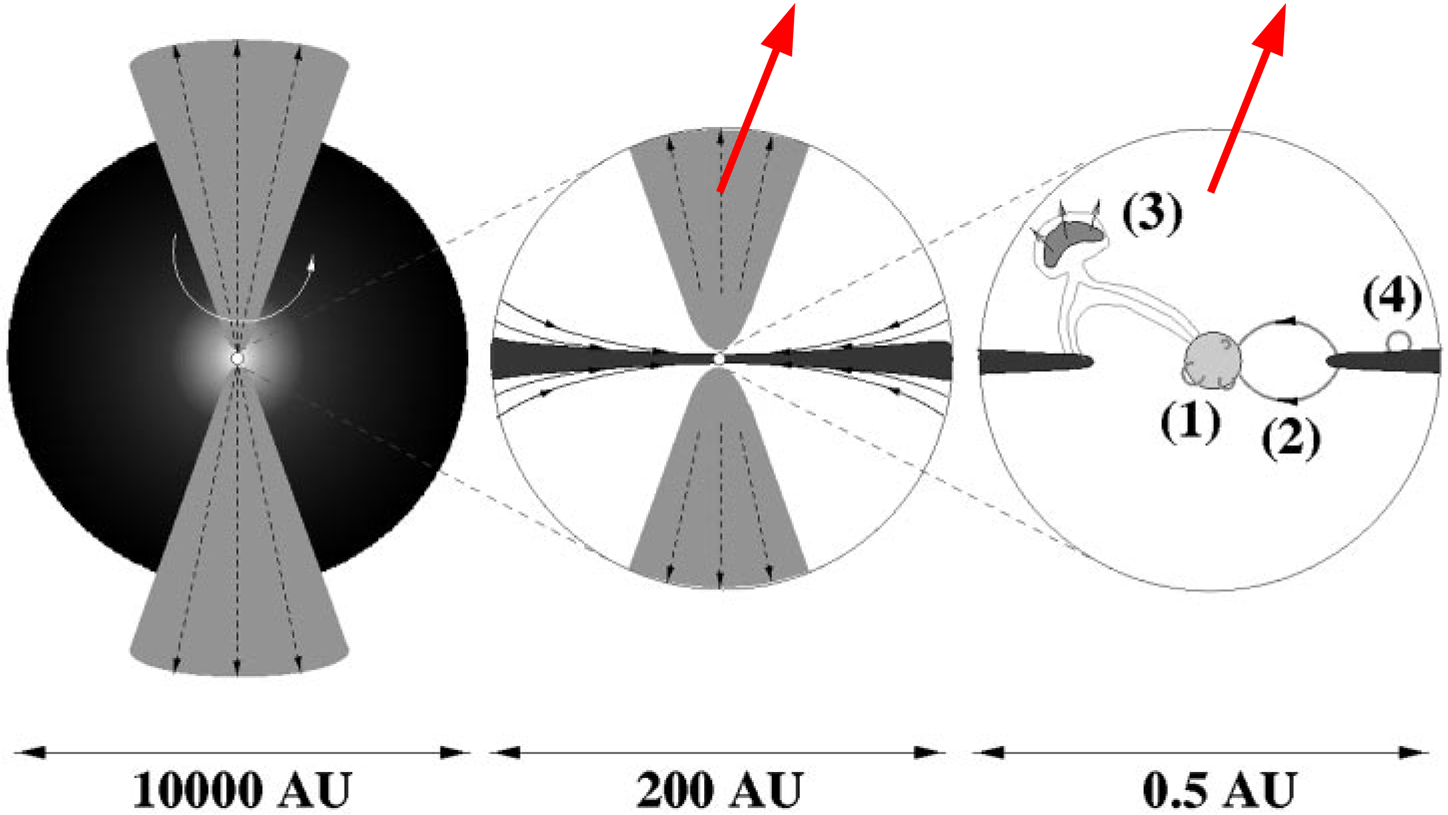
“Radio has no future. […]
X-rays will prove to be a hoax.”
Lord Kelvin

Image: Smithsonian Libraries, via Wikimedia Commons.

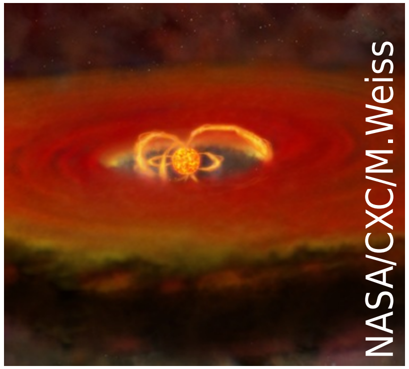
High-energy processes in Young Stellar Objects

Thermal radio emission, could fluctuate with accretion

Thermal X-ray emission, cm&mm nonthermal emission, *flares*



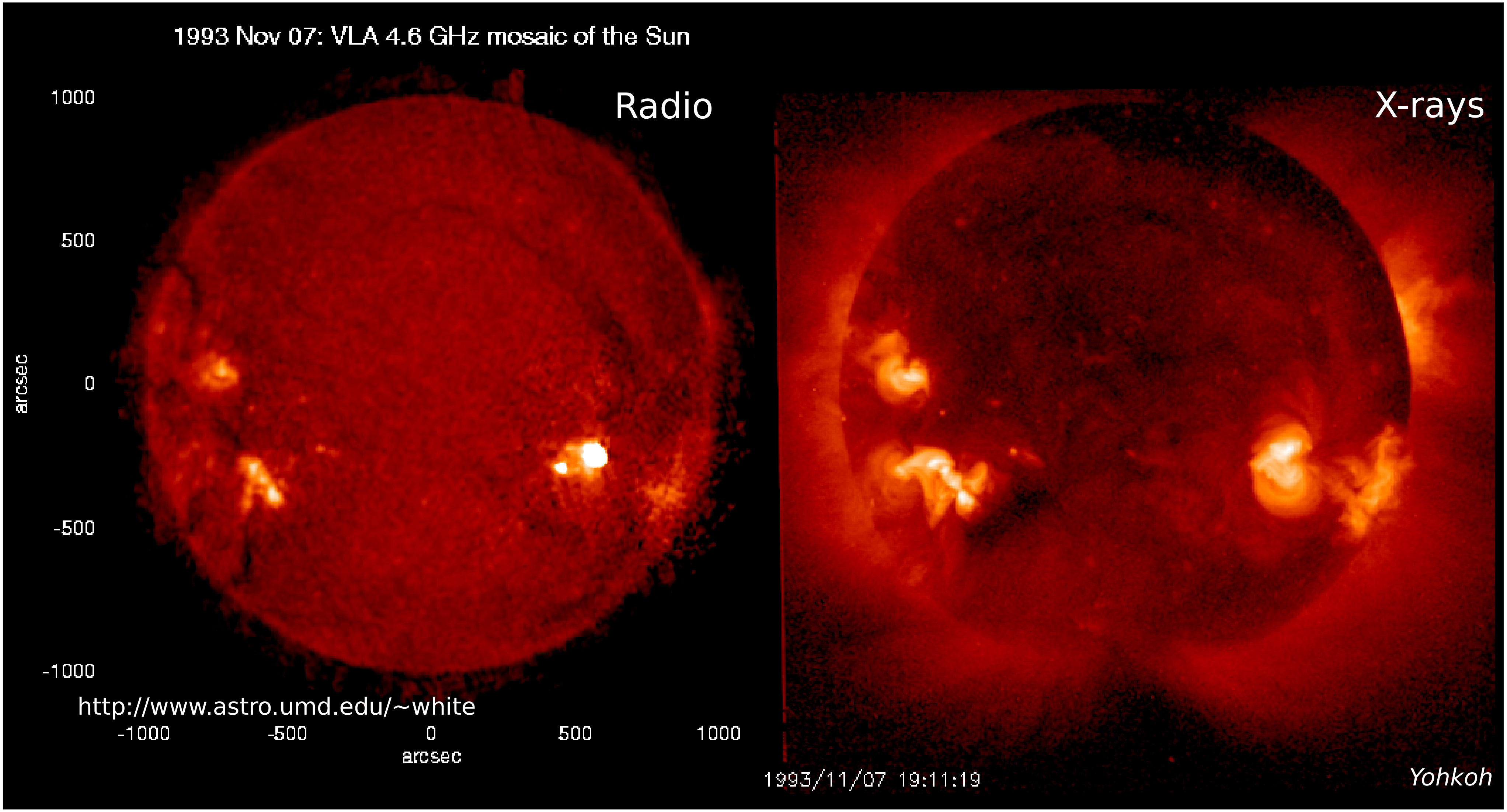
Feigelson & Montmerle (1999)



NASA/CXC/M.Weiss

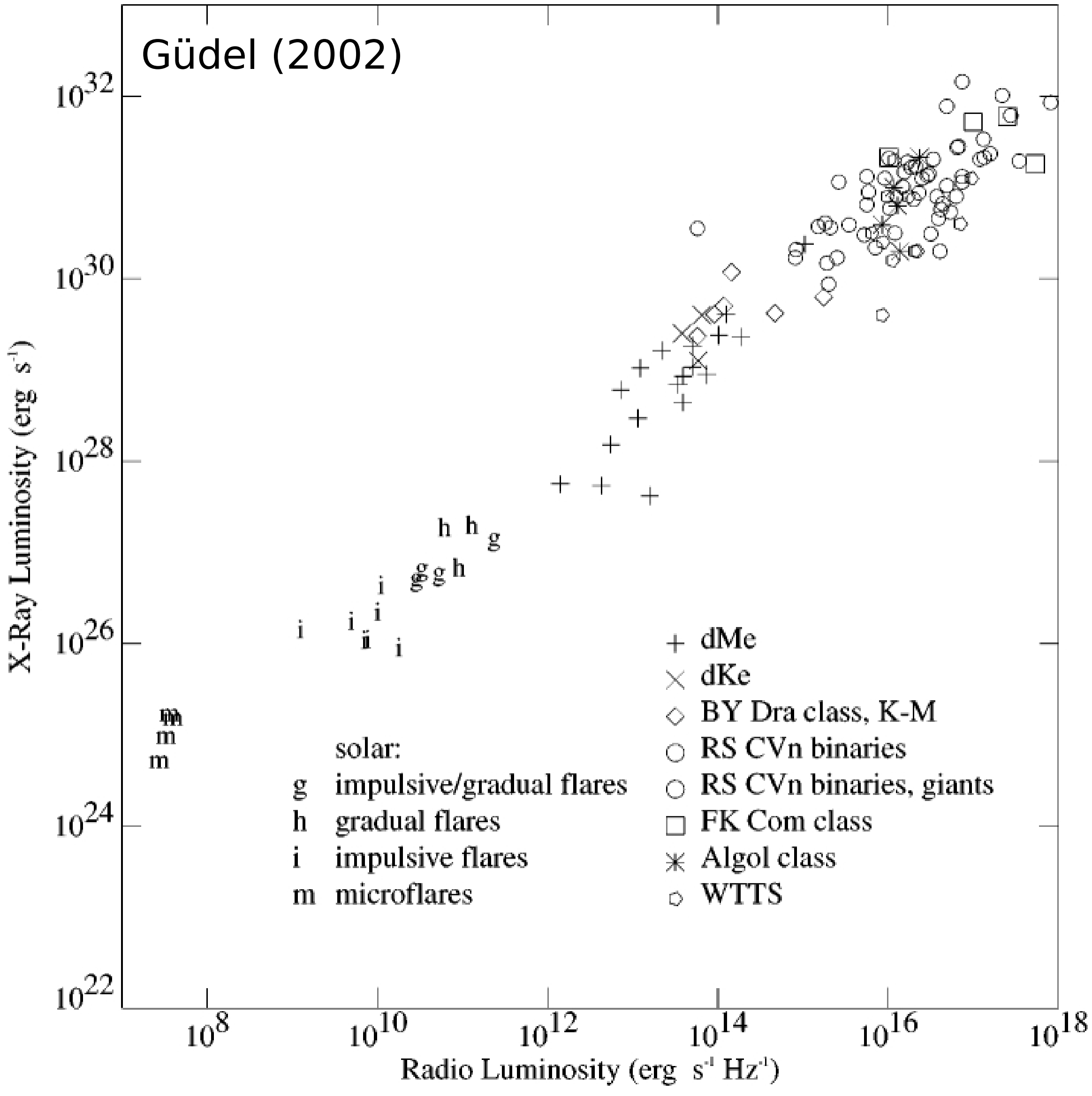
Both X-ray *and* nonthermal radio emission probe the ***innermost vicinities*** of protostars!

The **solar paradigm**

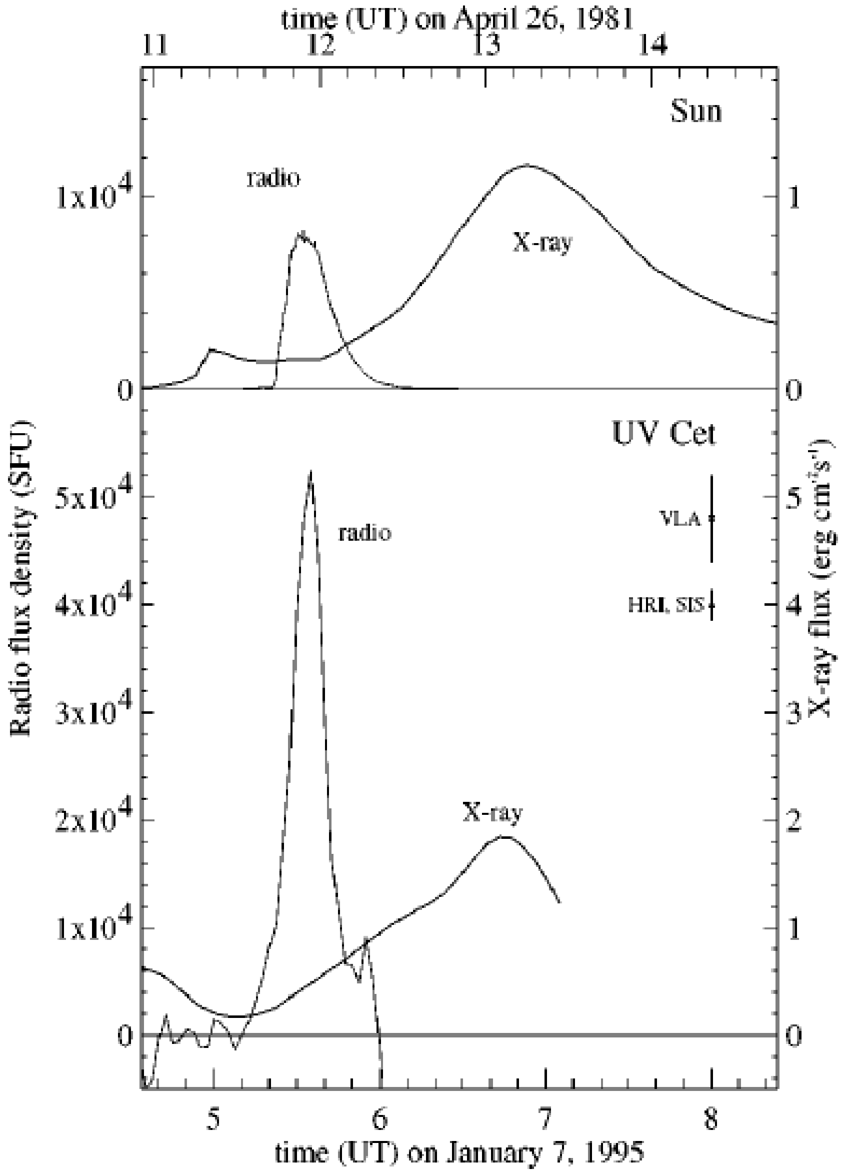


Radio and X-ray emission constrain the **full sequence** of magnetic energy release, particle acceleration, energy transformation, and heating.

The **radio-X-ray connection**



The **radio-X-ray connection**



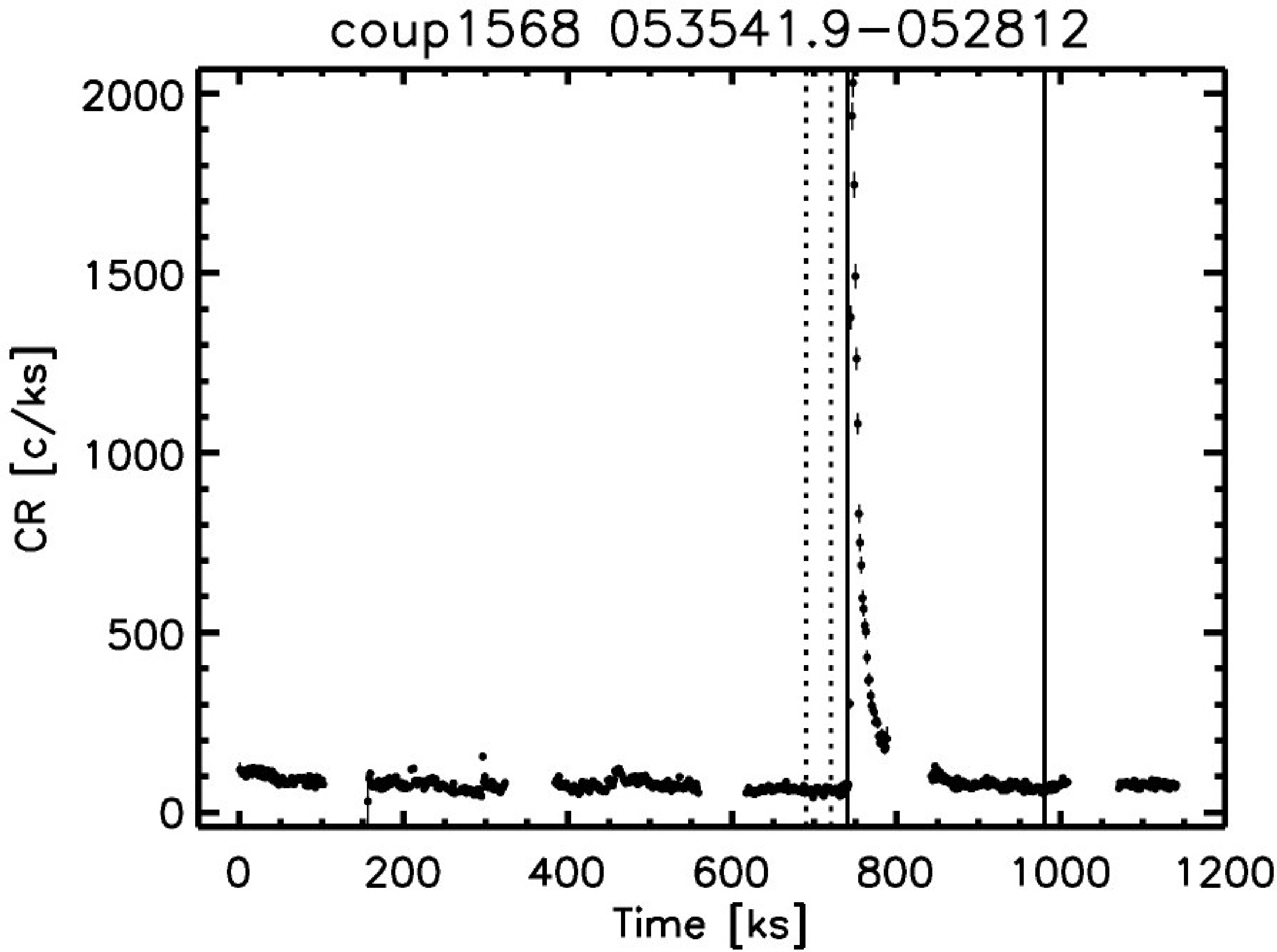
$$L_R(t) \propto \frac{d}{dt} L_X(t)$$

(Neupert 1968)

The radio luminosity traces the fast electrons and thus the energy injected in a flare. The X-rays trace the accumulated energy.

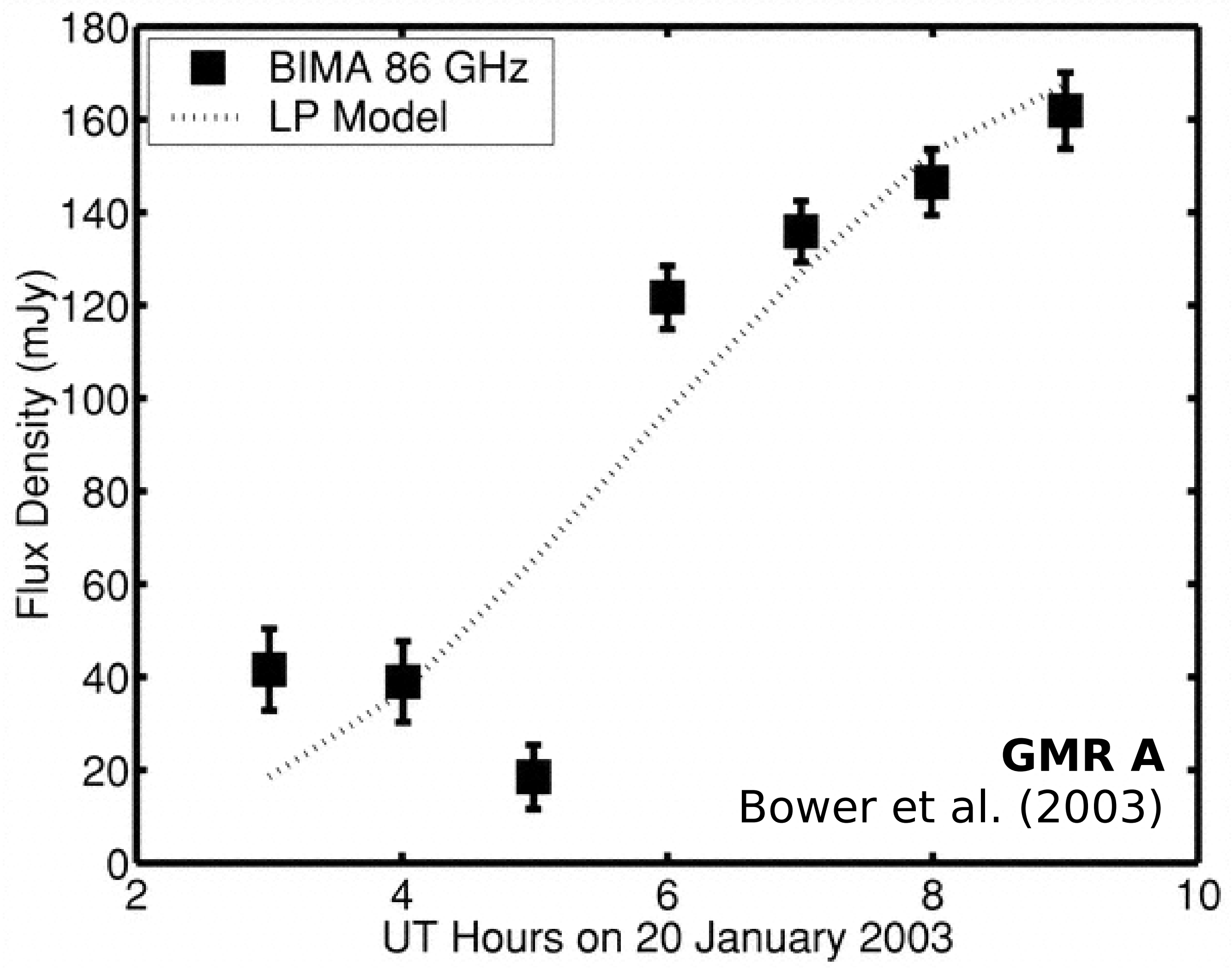
Figure: Neupert effect seen in an M dwarf star, compared with a solar example in the upper panel (Güdel et al. 1996).

YSO **X-ray flares**

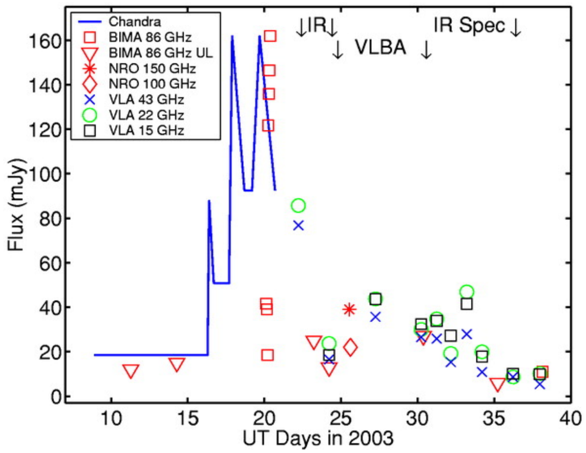


Getman et al. (2009)

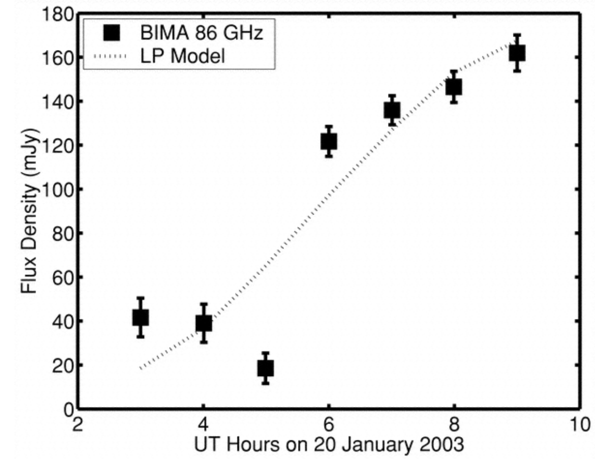
YSO **radio flares**

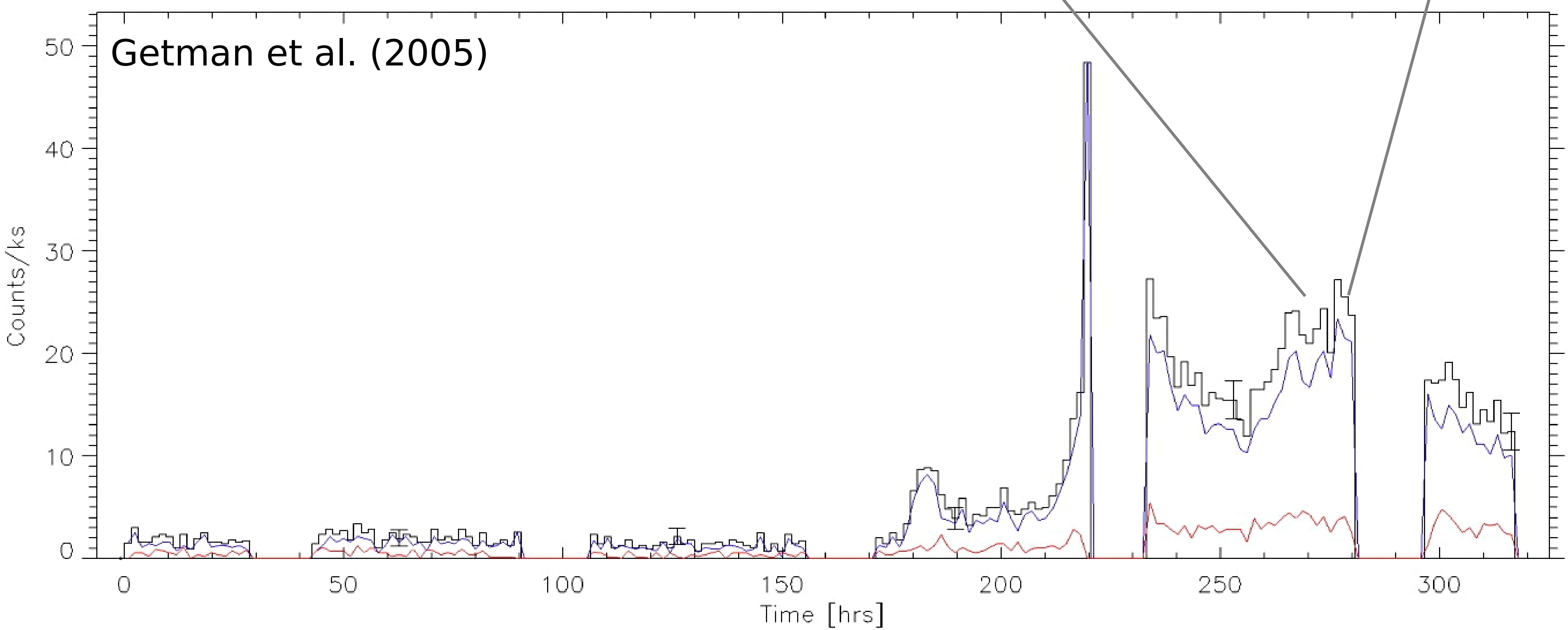


The **radio-X-ray connection**



GMR A
Bower et al. (2003)





Single-event events (SEEs)

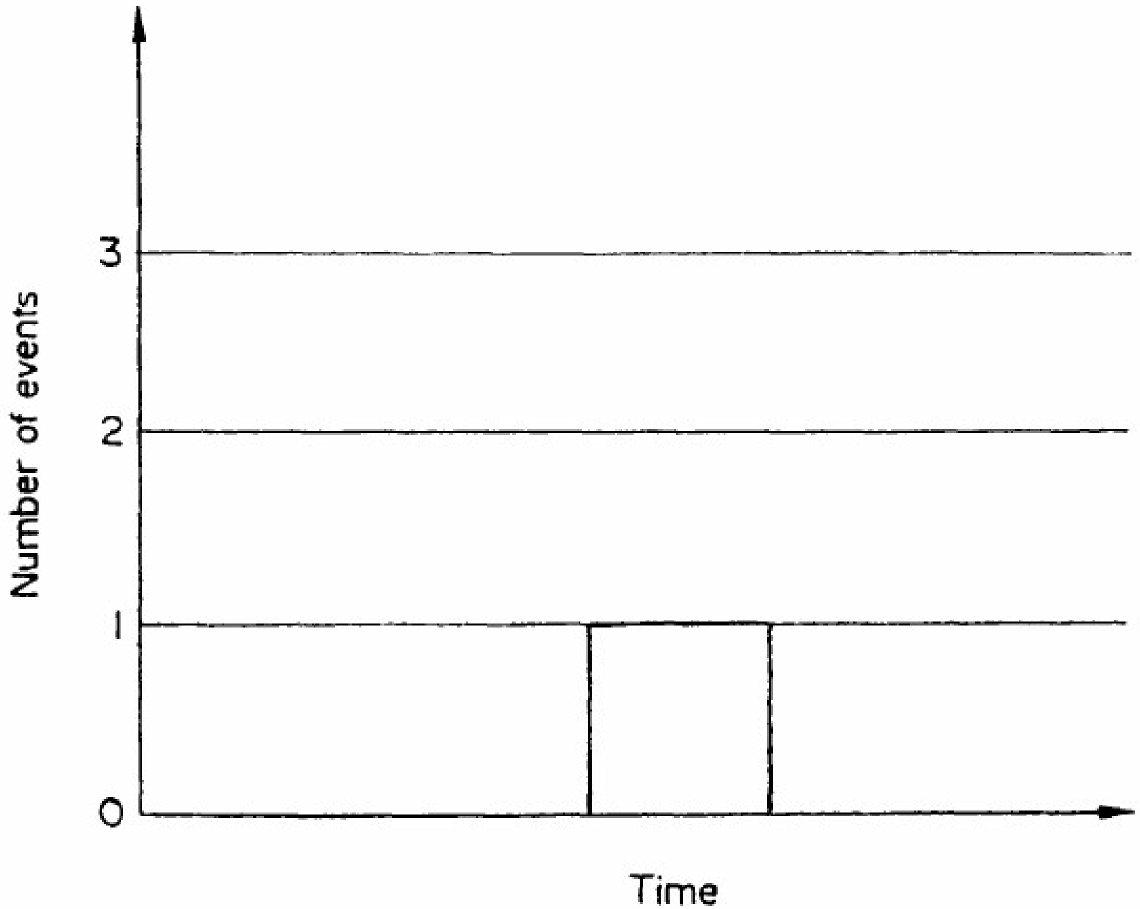


FIG. 1.

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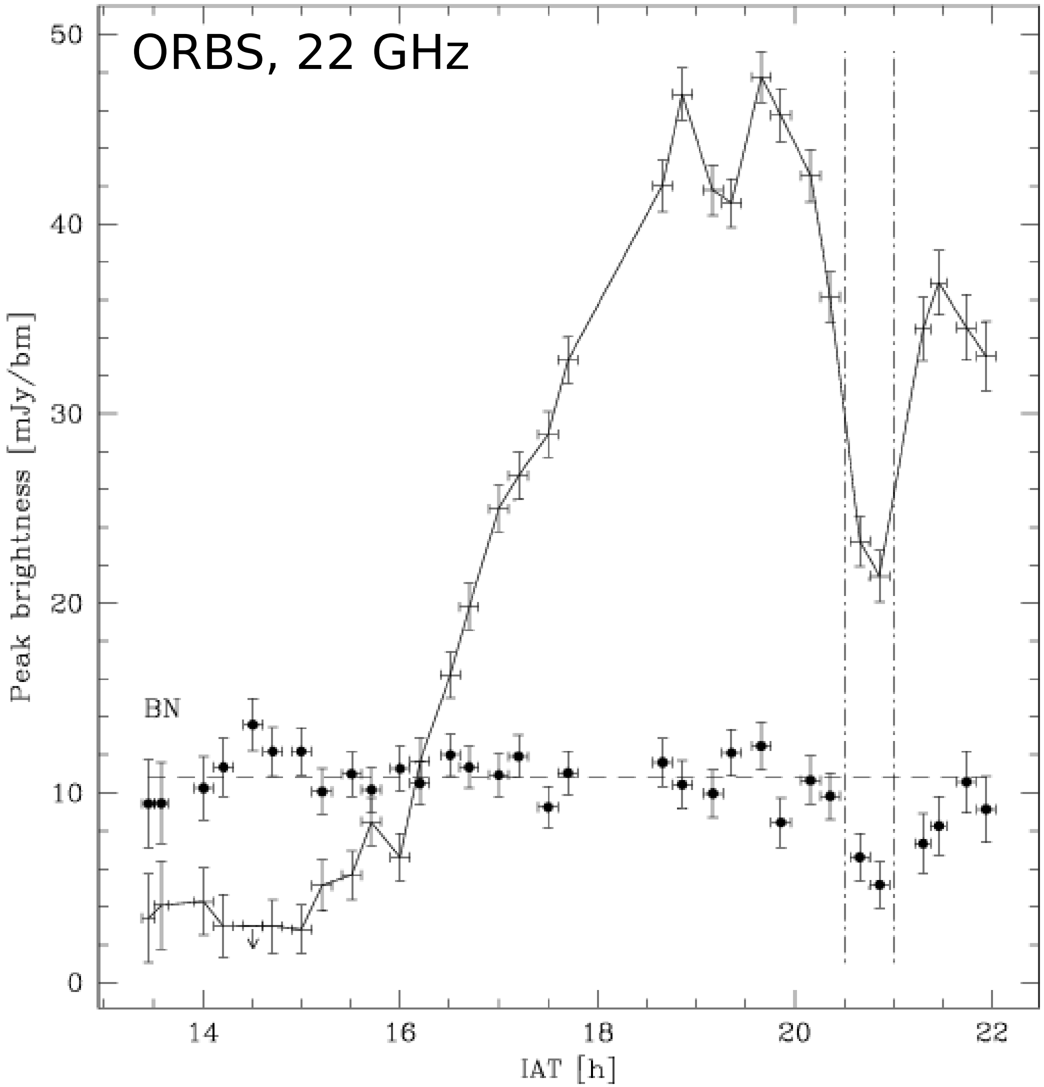
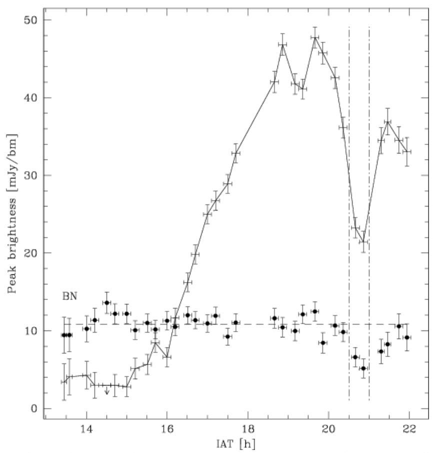
Liebovitch (1974)

YSO **radio flares**

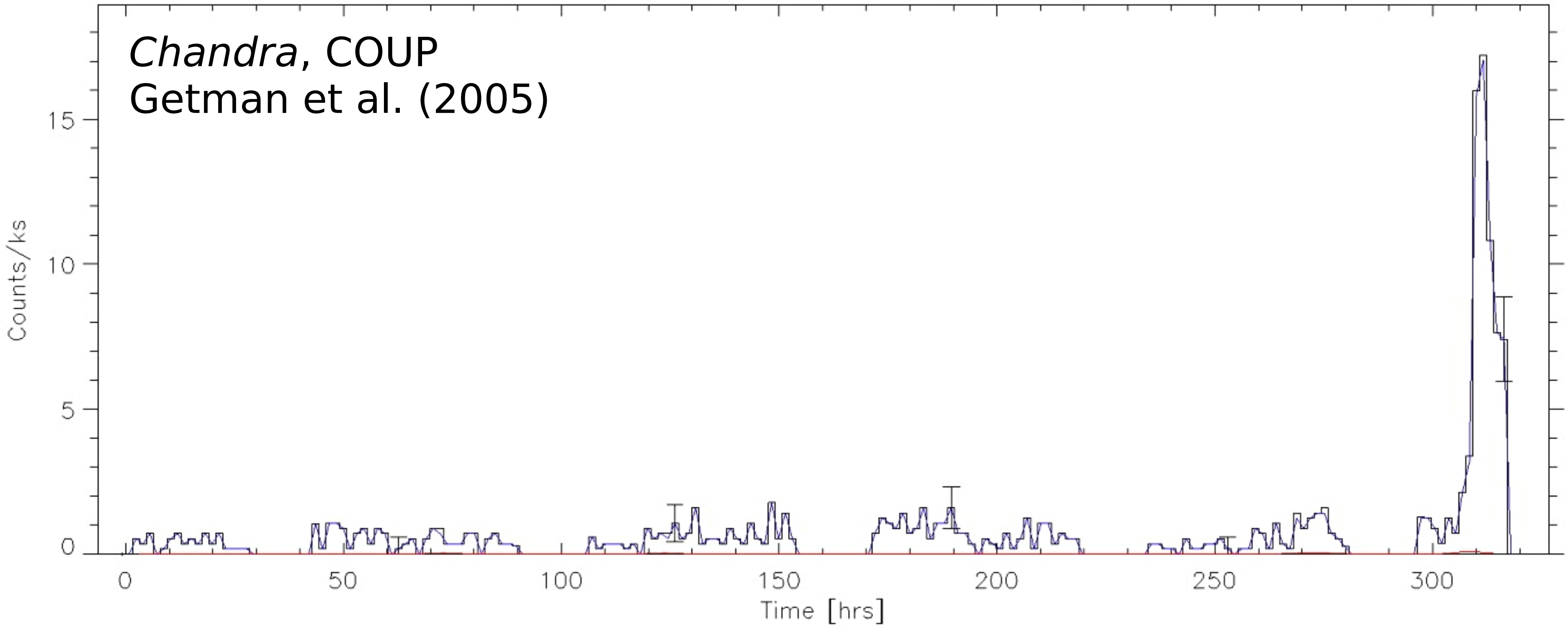


Forbrich, Menten, & Reid (2008)

YSO **radio flares**



ORBS
Forbrich, Menten, & Reid (2008)

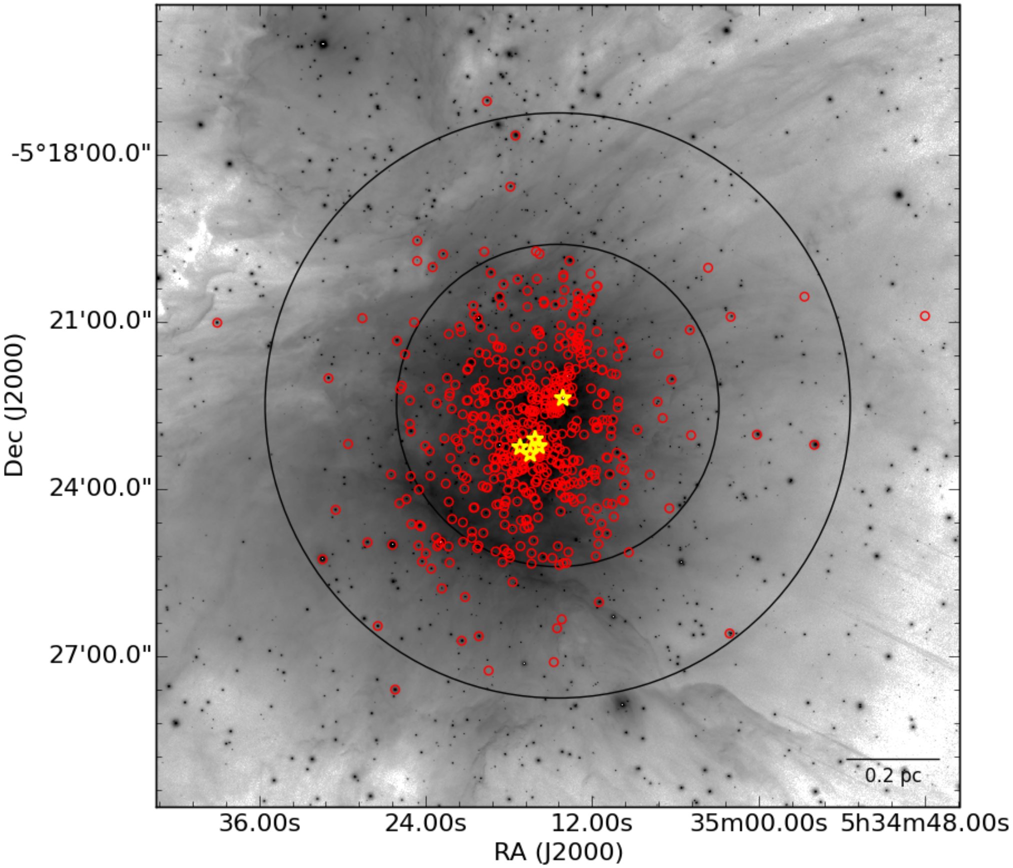


$A_V \sim 160$ mag, no infrared counterpart
(from X-rays, spectrum shows fluorescent iron line emission)

The Orion Radio All-Stars

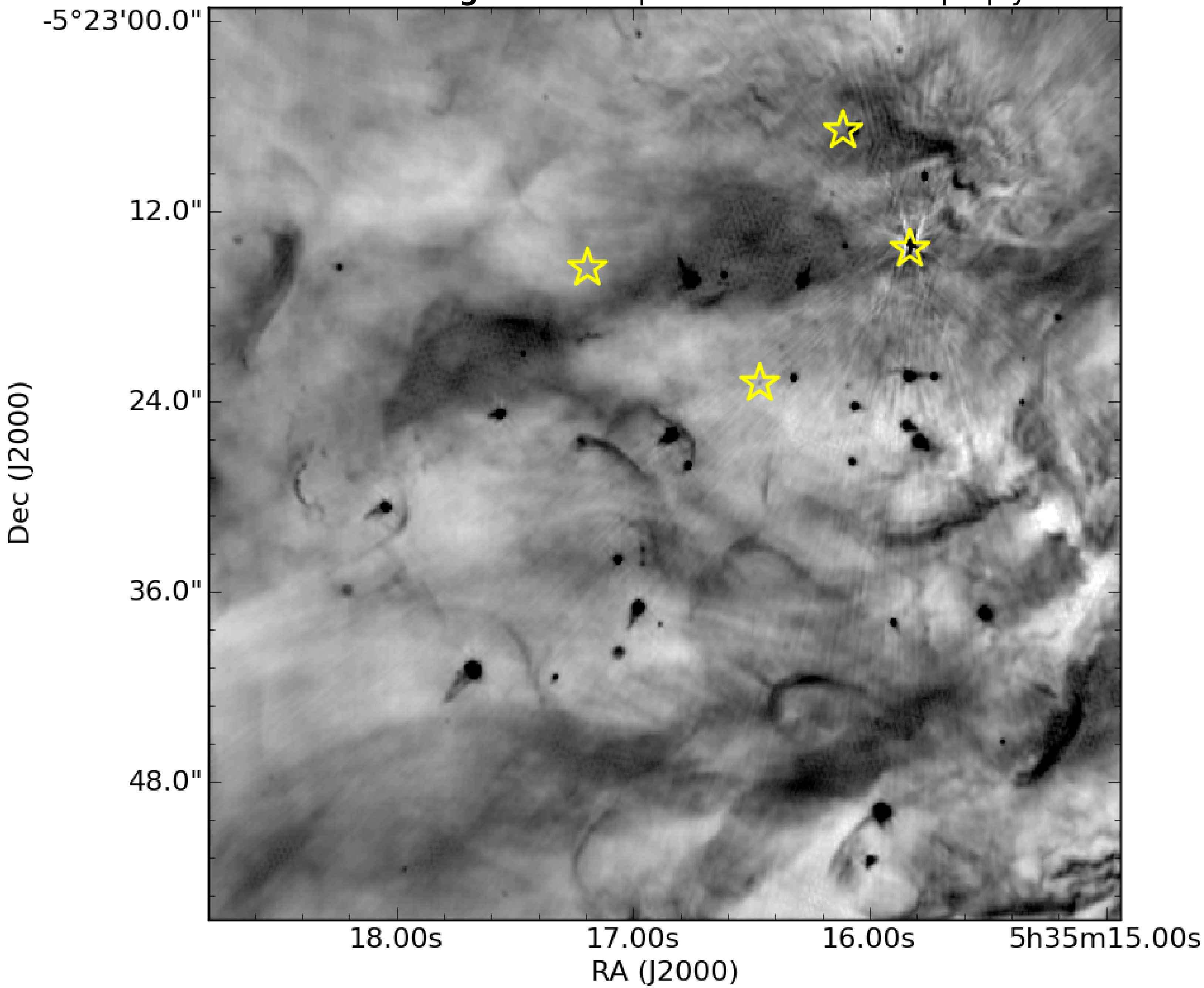
In a deep simultaneous radio and X-ray study of the **Orion Nebula Cluster** (30h), we detected **556 sources**, 7x more than previously known, while obtaining the by far largest set of **simultaneous radio and X-ray lightcurves** of YSOs.

Some of these radio sources are flaring **YSOs not detected in any other wave band**.



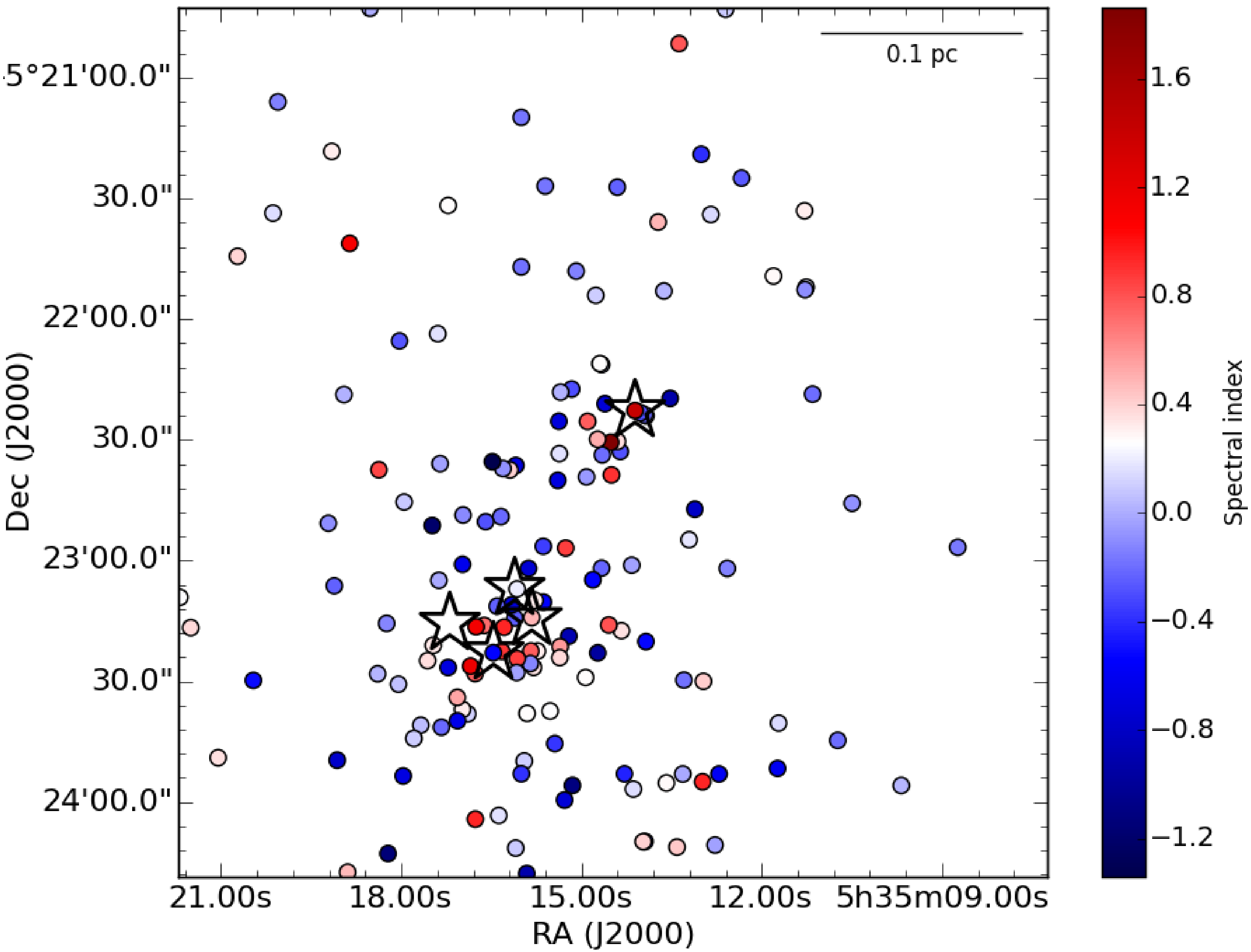
Forbrich et al. (2016)

This is a **VLA image** of the Trapezium and the main proplyds!



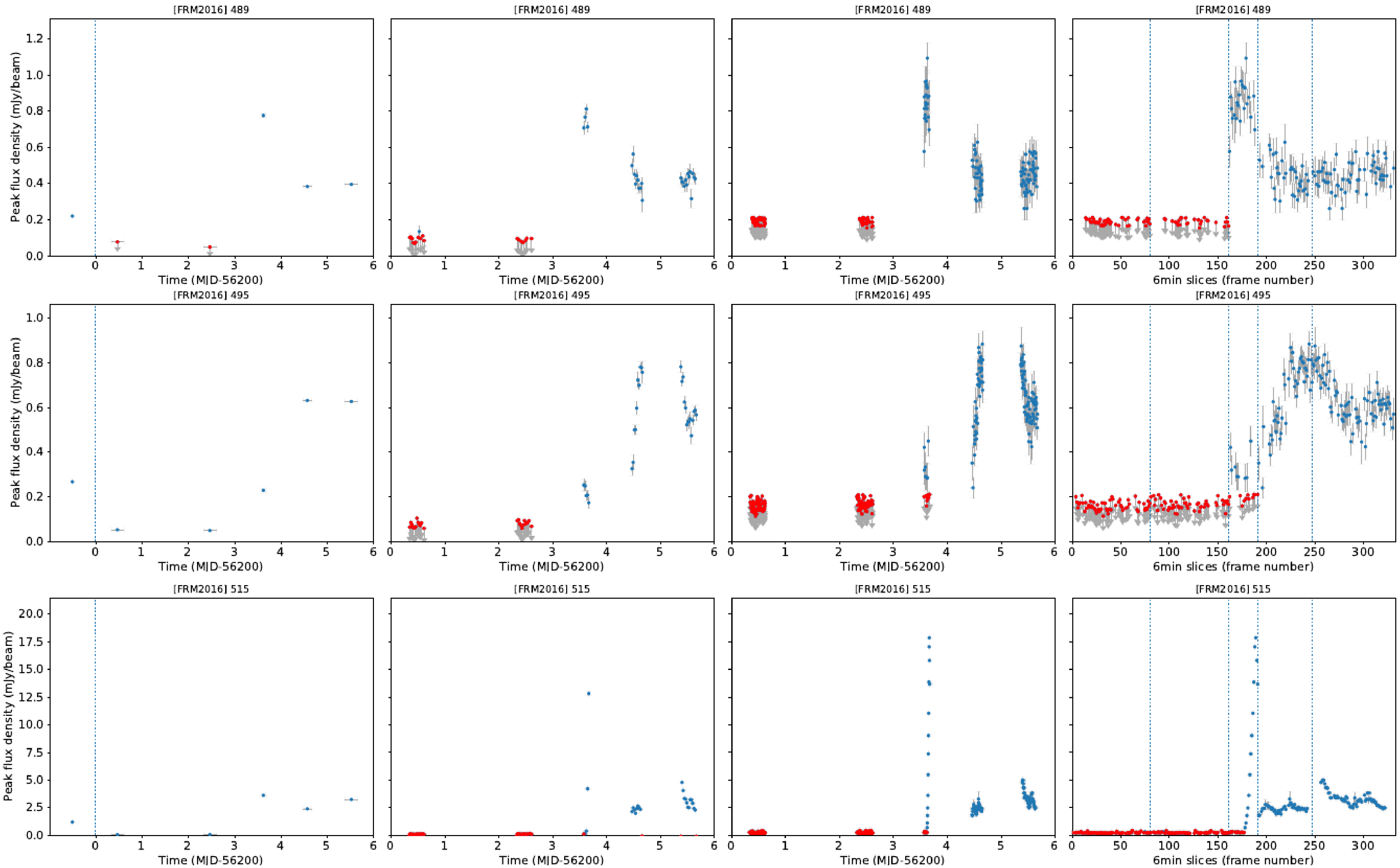
Forbrich et al. (2016); Forbrich, O'Dell, et al., *in prep.*

Radio **spectral indices**



Forbrich et al. (2016)

Exploring YSOs in the radio **time domain**



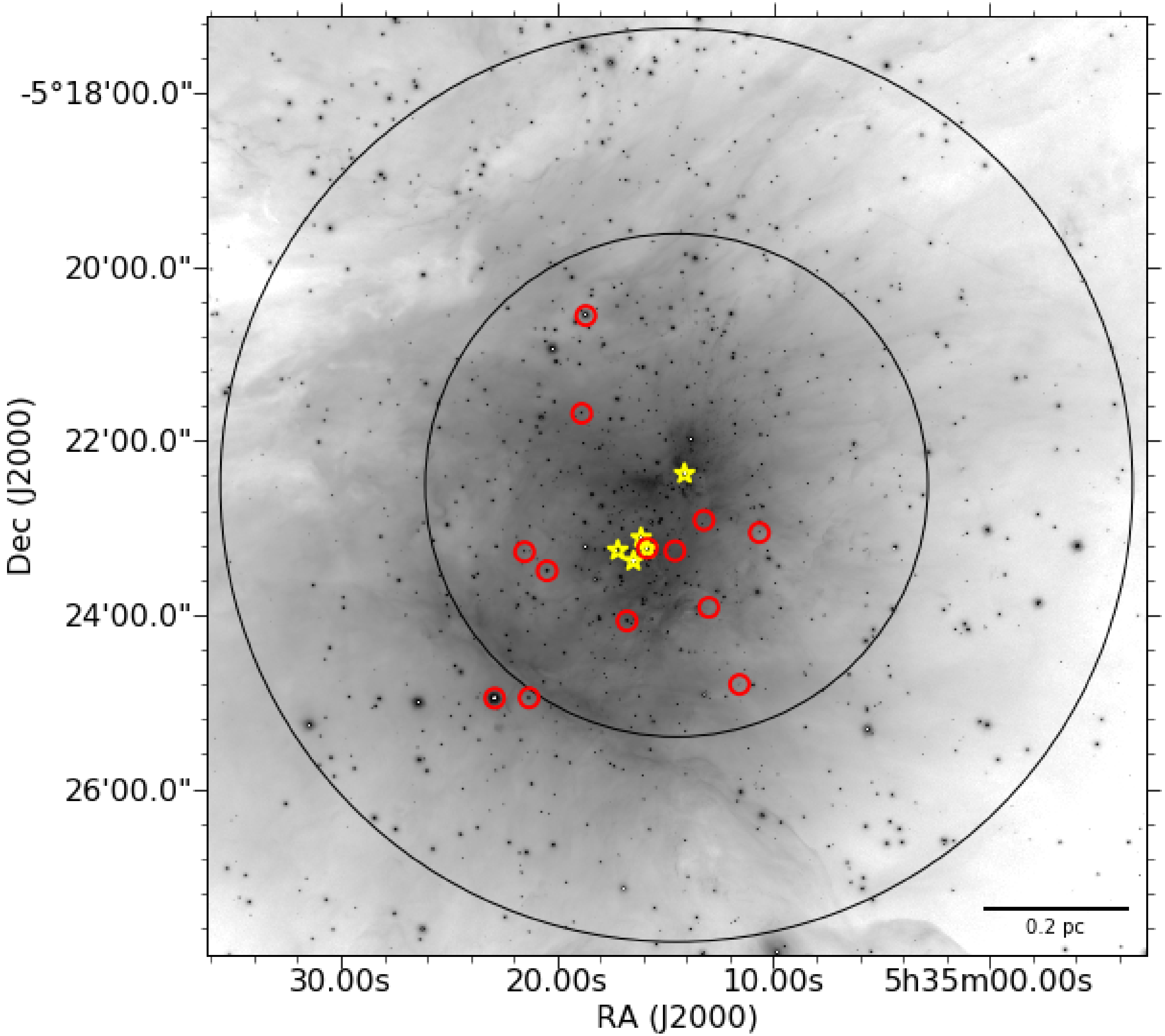
Forbrich et al., *in prep.*

Exploring YSOs in the radio **time domain**

Table 2. Extreme radio variability in the ONC and X-ray properties

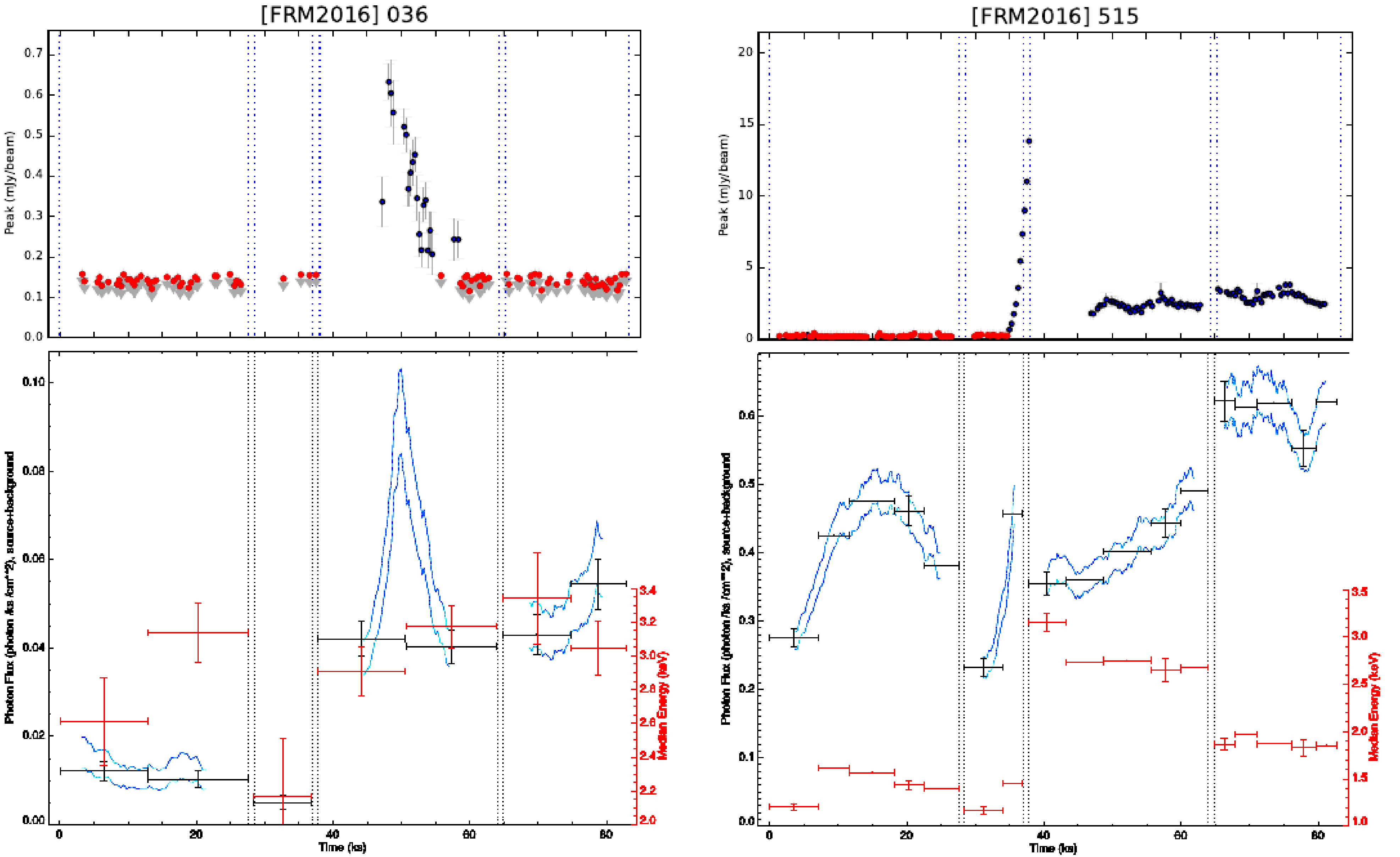
Src[a]	COUP (radio)	prev. ID[b] ($'$)	d (ep.)	$\Delta S_{\max}$ (0–2d) (30 min)	(6 min)	(ep.)	$\Delta t_{\min}$ for x10 var. (30 min)	(6 min)	mJy bm^{-1}	S_C[c] 0.5-8.0 keV	CXO[d] (max)	varindex[e]
36	391	–	1.10	> 11	> 10	> 5	1d	27.0h	–	0.056±0.003	484.2	9
53	427	–	2.40	13	> 12	> 7	1d	17.7h	–	0.165±0.004	514.4	9
98	510	Zap 7, S	1.45	8	> 17	> 17	–	1.1h	0.7h	0.754±0.003	36.8	2
110	530	GMR Q, S	0.51	6	11	> 6	–	24.9h	–	0.303±0.003	35.3	5
189	640	S	0.76	10	34	> 25	1d	20.4h	19.3h	0.690±0.003	155.7	1
254	745	GMR 12, KS	0.80	5	14	19	–	21.2h	20.5h	23.208±0.003	8048.8*	0
319	828	S	1.66	15	> 17	> 34	2d	41.1h	40.7h	2.358±0.003	5095.5*	0
414	985	K	2.21	8	9	> 13	–	–	22.9h	1.324±0.003	2391.7*	0
422	997	–	1.37	> 54	> 30	> 15	2d	41.1h	40.7h	0.676±0.003	2265.9*	6
469	1101	S	1.79	2	12	> 14	–	1.1h	0.6h	0.235±0.003	3740.3*	10
489	1143	K	2.98	> 16	> 11	> 7	1d	27.6h	–	0.219±0.004	1430.8*	0
495	1155	–	1.91	5	> 10	> 7	–	47.4h	–	0.267±0.003	166.9	0
515	1232	K	3.22	52	> 138	> 101	1d	0.5h	0.4h	1.188±0.004	7916.2*	10

Forbrich et al., *in prep.*



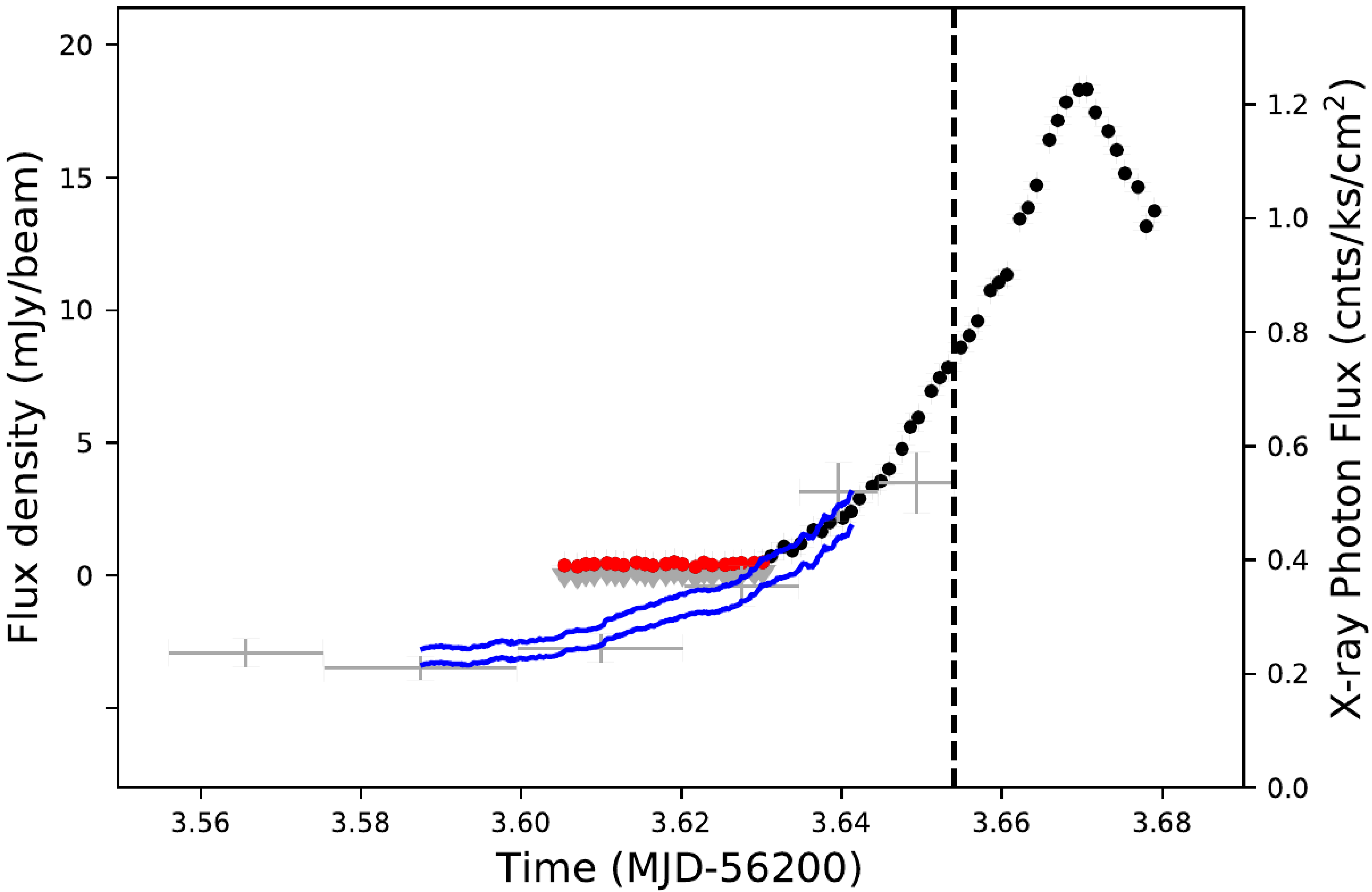
Forbrich et al., *in prep.*

Exploring YSOs in the radio–X-ray **time domain**



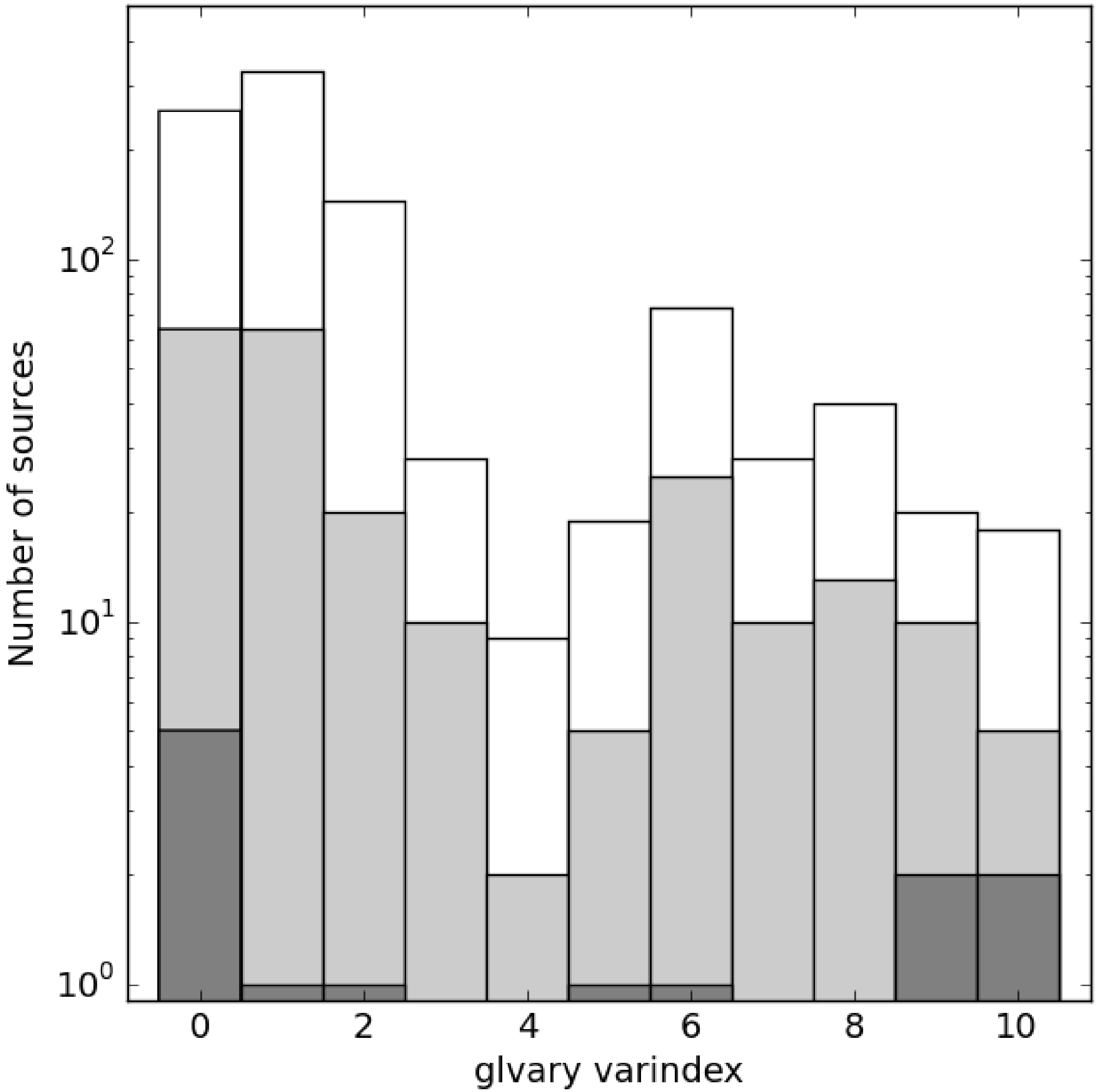
Forbrich et al., *in prep.*

Exploring YSOs in the radio–X-ray **time domain**



Forbrich et al., *in prep.*

Extreme YSO radio and X-ray **variability**



Forbrich et al., *in prep.*

NRAO/AUI/NSF

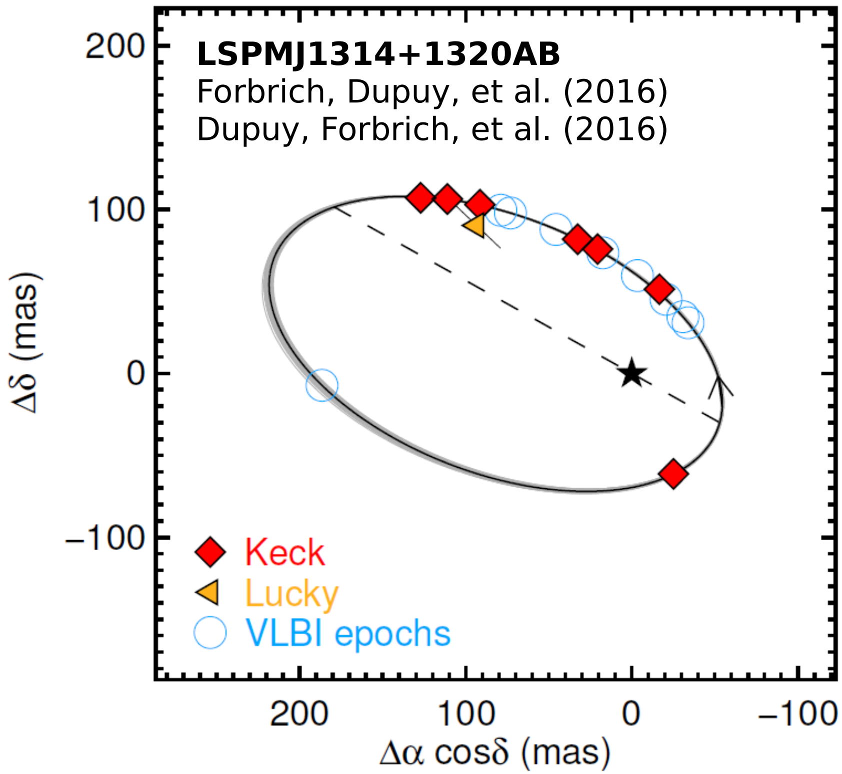
Applications in **precision astrometry**

Nonthermal nearby stars and YSOs can be followed up with the (also upgraded!) **Very Long Baseline Array (VLBA)**, yielding precision absolute astrometry – e.g., for parallax or reflex motion studies:

d(ONC) = 414 ± 7 pc
(Menten, Reid, Forbrich, & Brunthaler 2007, cf. Kounkel et al. 2017)

We have now followed up all 556 VLA detections with the VLBA, a **data record** for the VLBA (Forbrich et al., *in prep.*).

Such YSO astrometry is **complementary to *Gaia* and LSST** astrometry programs.



Summary

1 YSO radio flares now are increasingly accessible, they provide us with a complementary view of high-energy processes.

2 Among 222 Orion radio sources with X-ray counterparts, observed for 30h, we find 13 ORBS-like flux-density changes by 10x on timescales of 20 min to 2 days.

3 The shortest-timescale variability, with such changes on timescales of <1h appear well correlated in radio and X-ray emission, if less extreme in X-rays. Otherwise, the data show complex (non-)correlation of X-ray and radio emission.

4 Selecting the most extreme X-ray variability does not select the most extreme radio variability, nor necessarily emission.

5 Follow-up with VLBA will yield an astrometric census of nonthermal emission and embedded cluster kinematics down to velocities of 0.1 km/s. Extrasolar planets?