

# The Time Domain in Stellar Radio Astronomy

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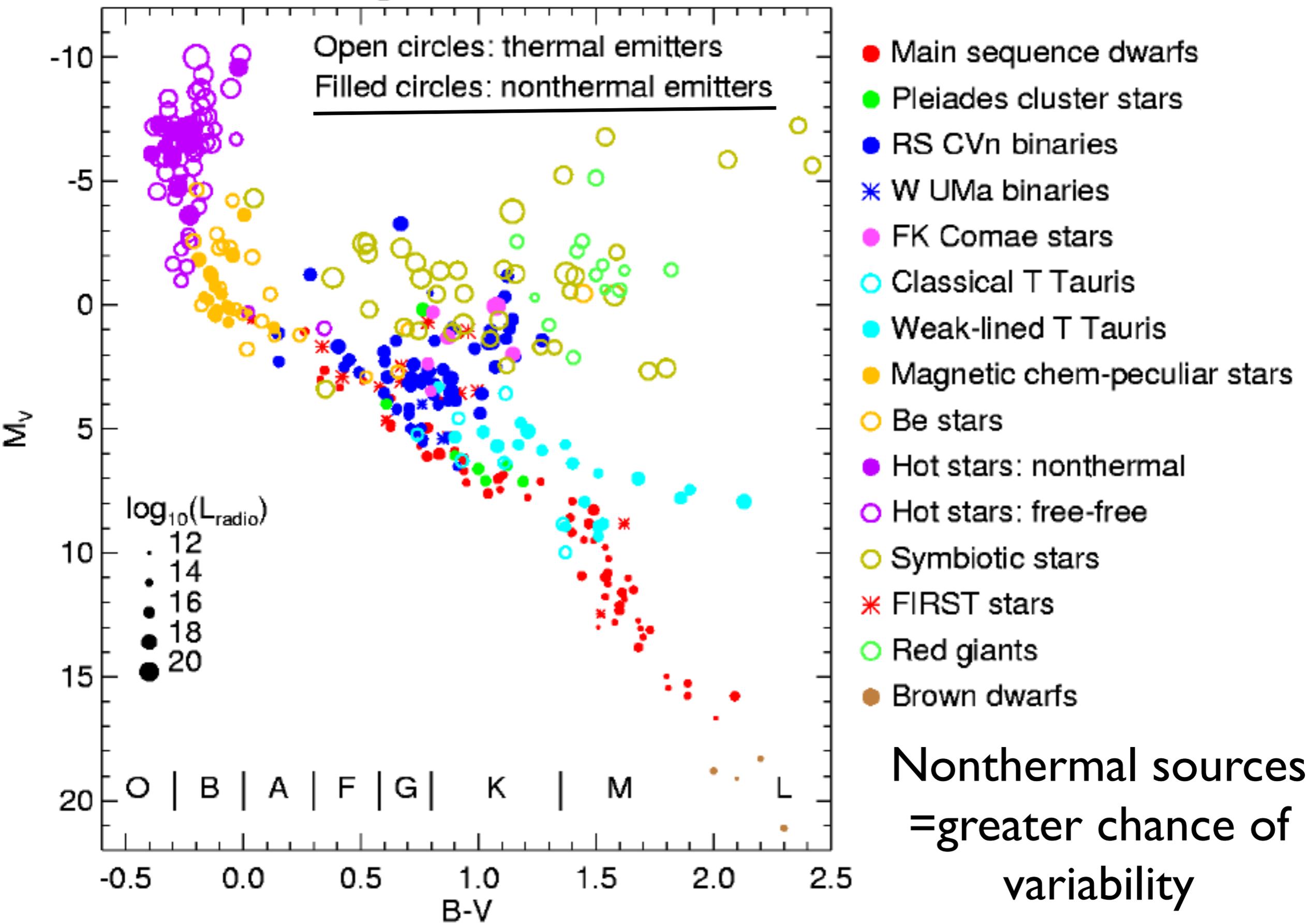
Radio Stars and Their Lives in the Galaxy

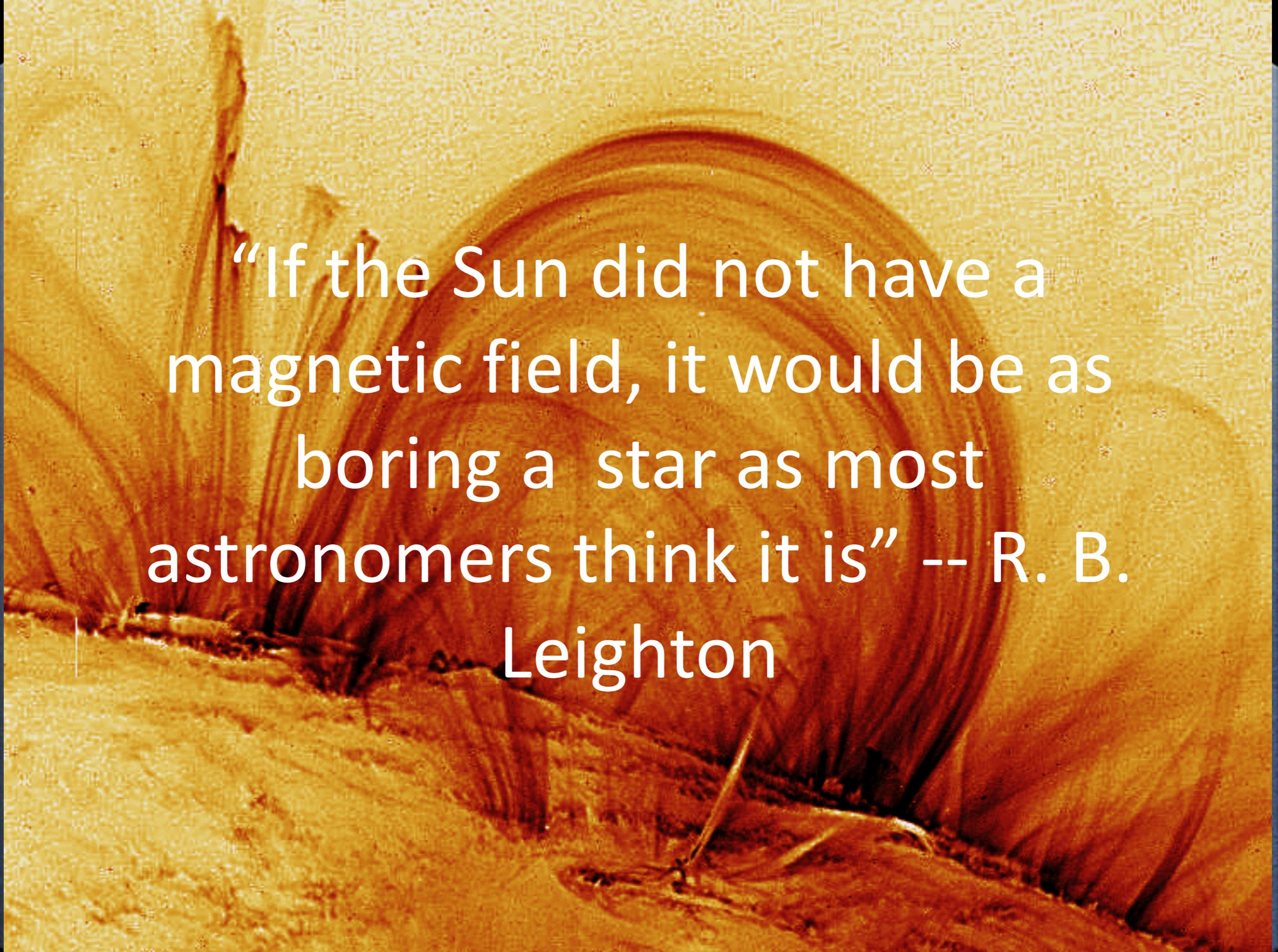
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# What do Studies of the Time Domain Tell Us About Stellar Astrophysics?

- Changes in emission characteristics (flux densities, polarizations, spatial scales) leads to studies of the stars themselves & changes in their environments
- Usefulness as tools in transient studies
- Metric bursts have the potential to constrain transient stellar mass loss

# Radio H-R Diagram: Radio Luminosities



A close-up photograph of a tree trunk, showing concentric growth rings. The wood is a warm, golden-brown color. The rings are clearly visible, with some darker, more irregular rings interspersed among the smoother ones. The texture of the wood is visible, with some small knots and imperfections. The lighting is soft, highlighting the natural grain and color of the wood.

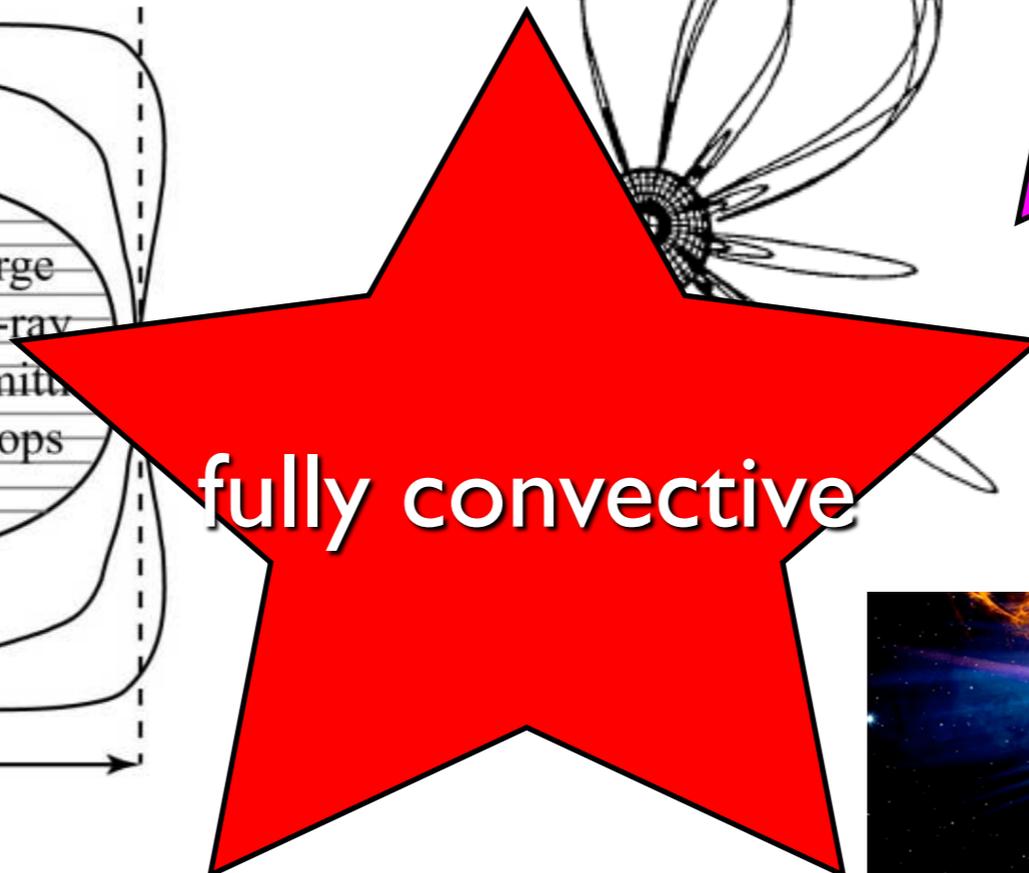
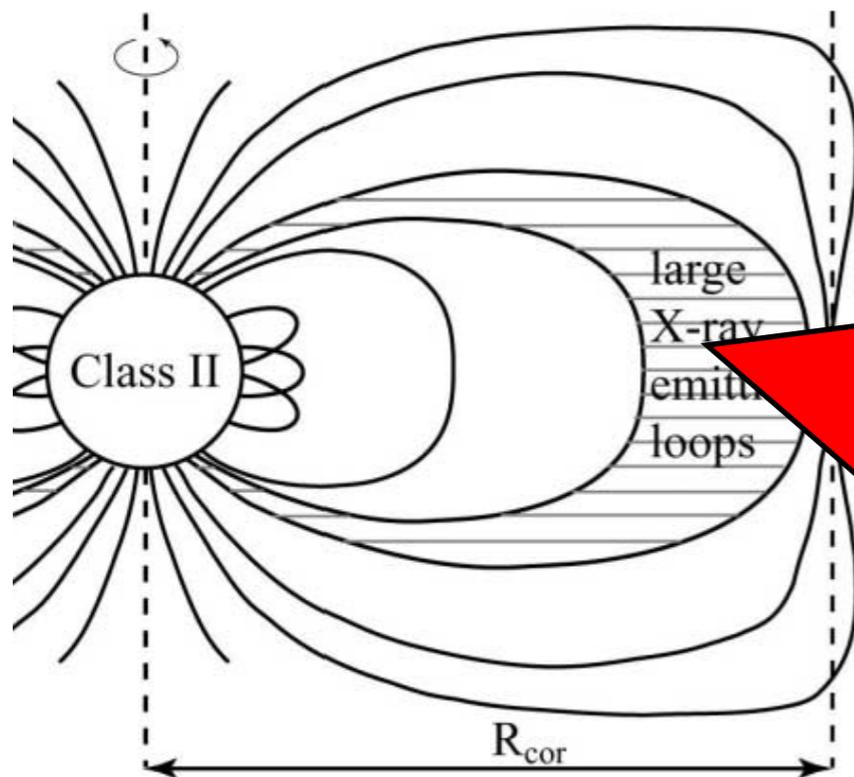
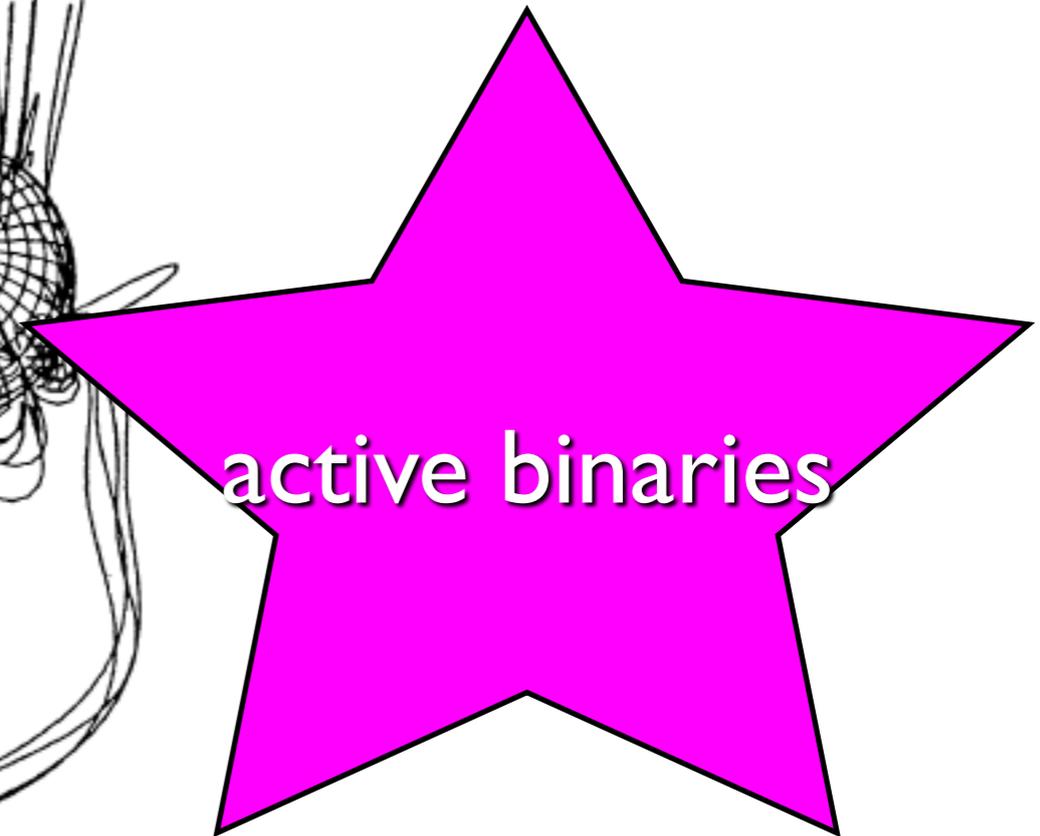
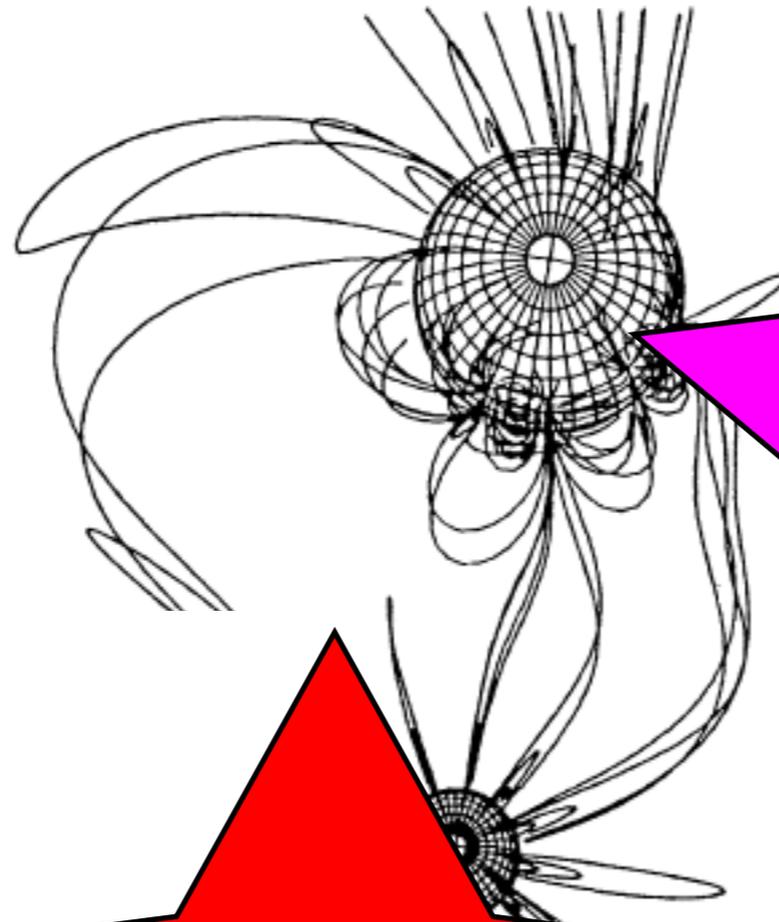
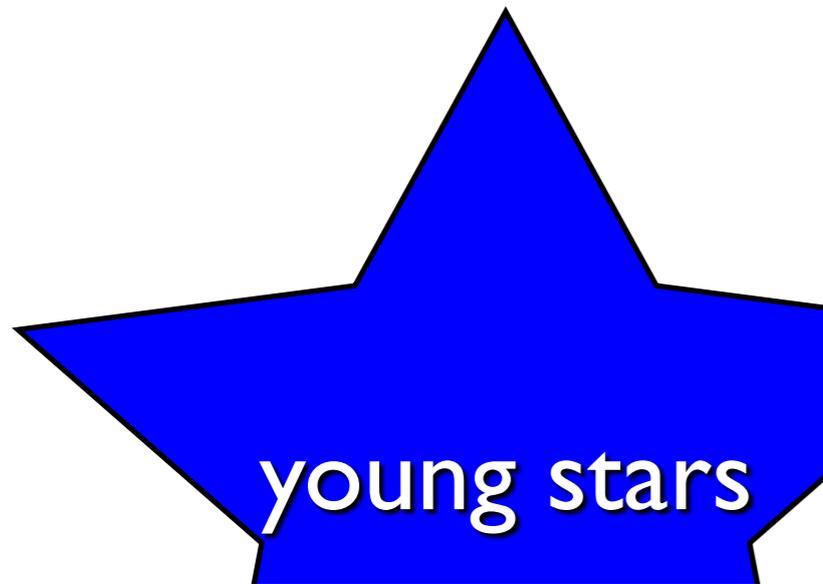
“If the Sun did not have a magnetic field, it would be as boring a star as most astronomers think it is” -- R. B. Leighton

# Observations of particle acceleration in stellar coronae constrain the importance of rotation and magnetic fields

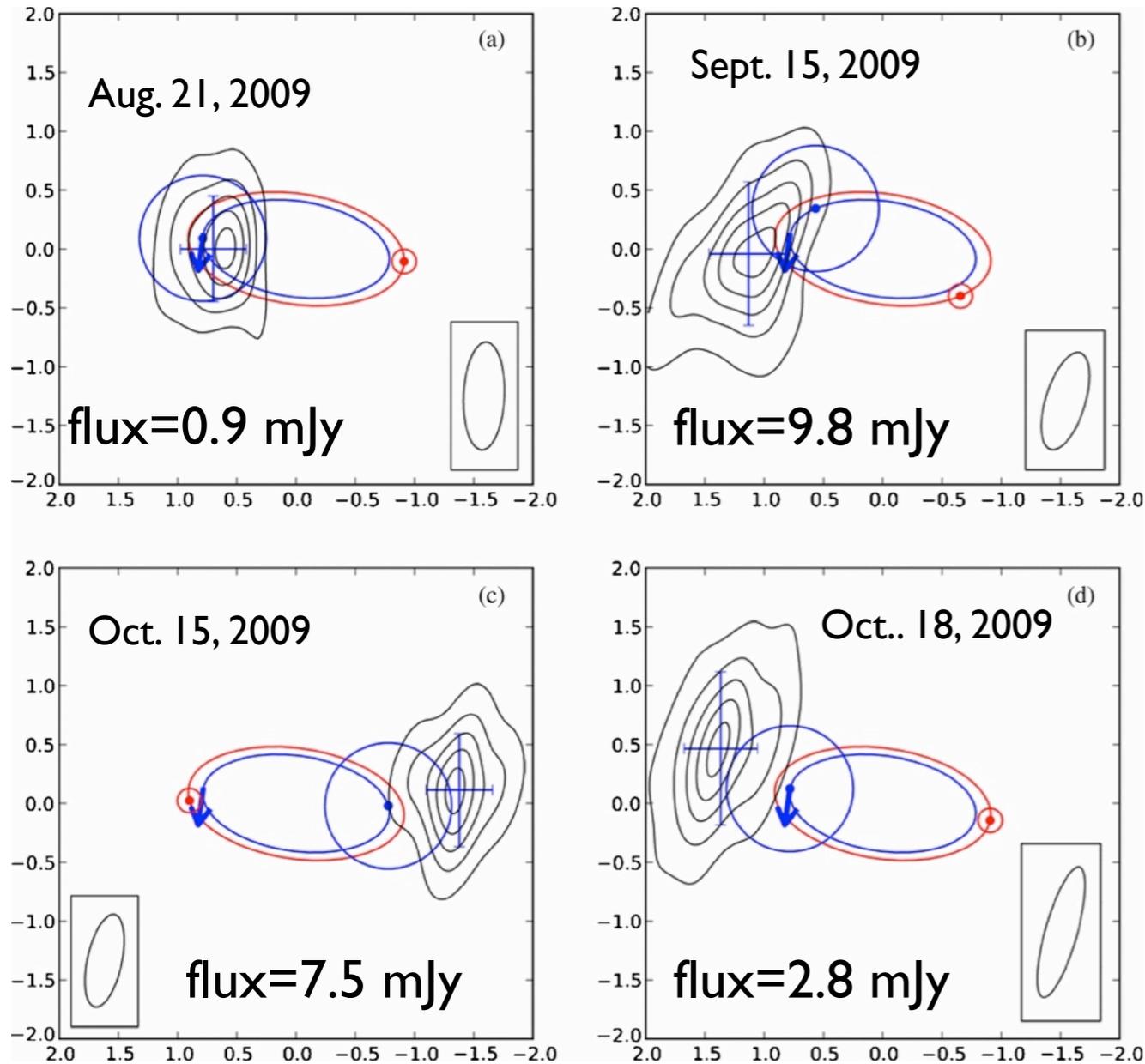
- coherent and incoherent processes at work
  - plasma emission:  $\nu_p \propto \sqrt{n_e}$
  - cyclotron maser emission:  $\nu_B \propto B$
  - gyroresonance,  $s\nu_B$ ,  $s$  a few
  - gyrosynchrotron emission:  $s\nu_B$ ,  $s$  10-100
  - synchrotron emission:  $s$  large

- Variability of nonthermal radio emission from cool stars is an important factor in their radio emission levels of brightness increase
  - most salient features of variability: timescales and levels of brightness increase
  - milliseconds to weeks, months years
  - brightness increase by factors up to  $\sim 1000$
- no real “quiescent” level, as opposed to other wavelengths
- no evidence for saturation in  $L_r/L_{bol}$ ; in  $L_x$ , supposition is that the maximum amount of plasma heating that can take place is occurring. Saturation levels  $L_x/L_{bol} \sim 10^{-3}$
- nonthermal emission originates from corona: see changing  $B, N, T, n_e$  due to particle acceleration, changing optical depth effects, polarization
- limitation: non-unique inversion of observed

# THE KINDS OF STARS TYPICALLY TARGETED FOR RADIO VARIABILITY STUDIES

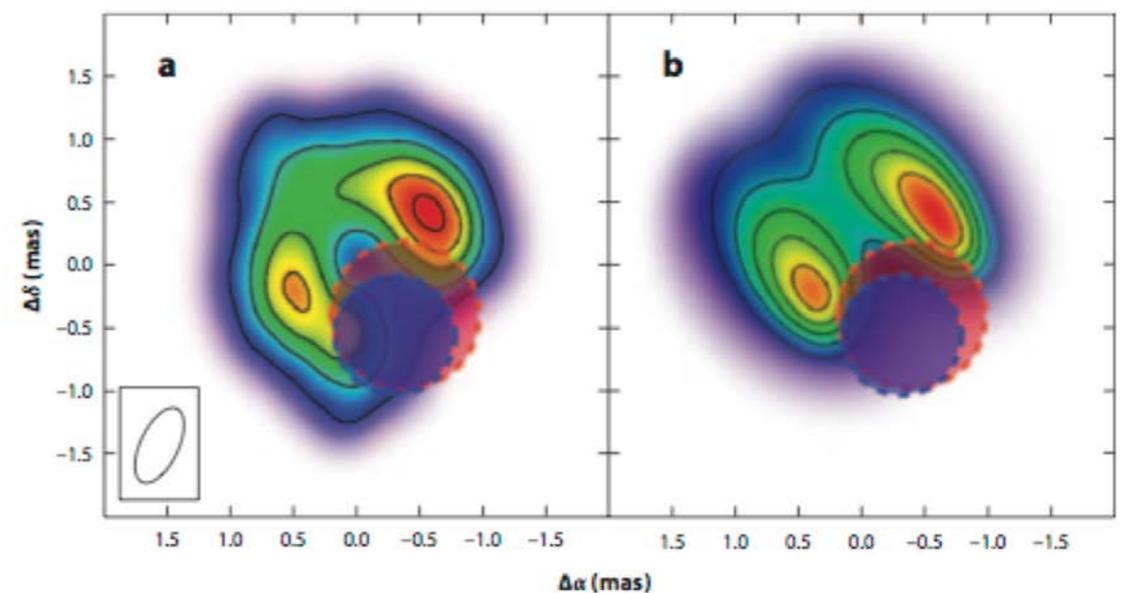


# Orbits and Coronal Structures using VLBI Techniques



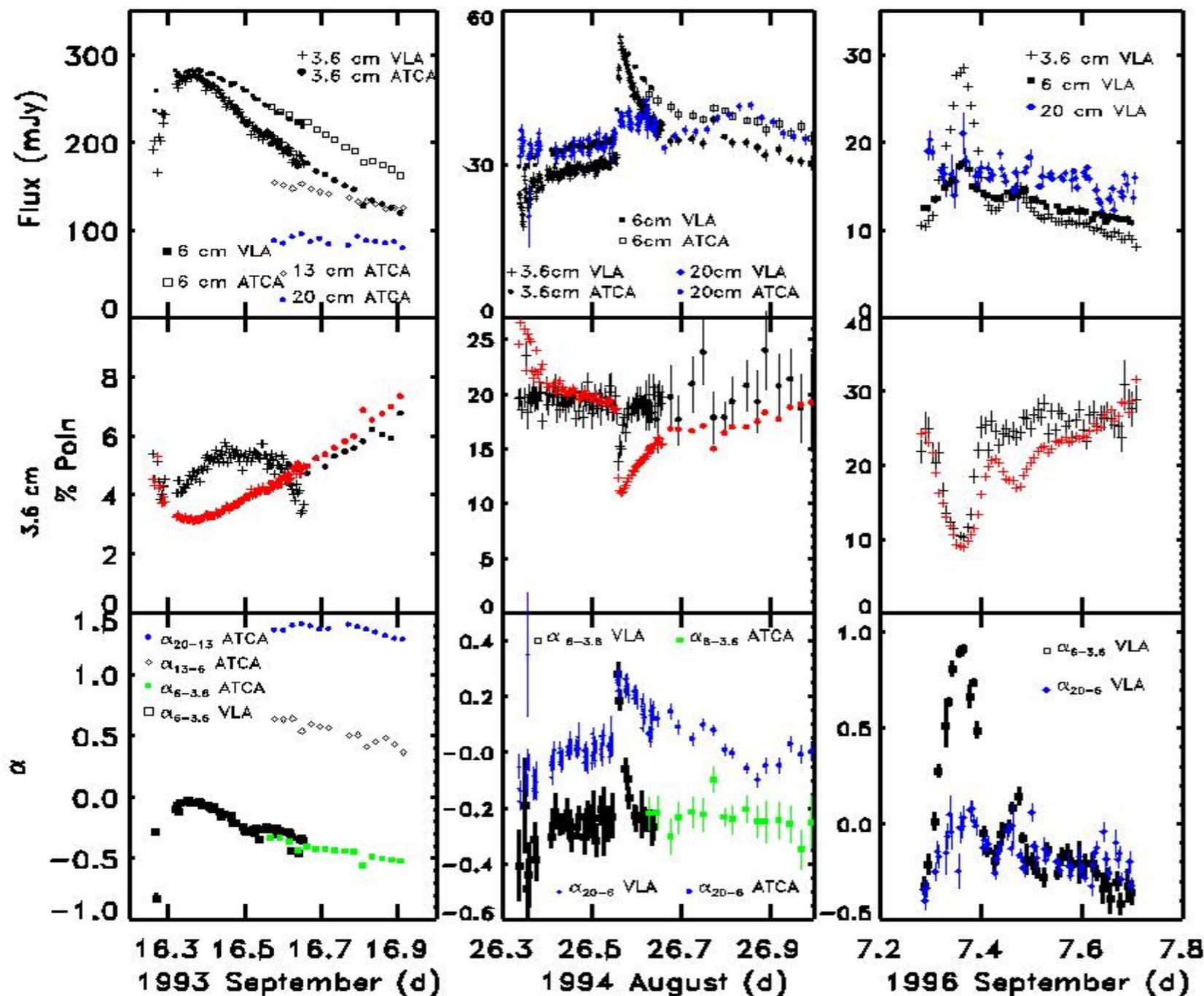
blue=orbit & predicted location of KIV, red=orbit & predicted location of secondary

- Peterson et al. (2011, 2010) VLBA observations of short-period active binaries (UX Ari, Algol) to refine orbits
- radio emission confined to K subgiant binary member; morphology consistent with coronal loop, likely associated with persistent polar spot
- proper motions, orbital elements consistent with tertiary in systems: 0.75  $M_{\text{sun}}$  tertiary on UX Ari pinned down for the first time



# Using Variability to Probe Characteristics of Energetic Particles

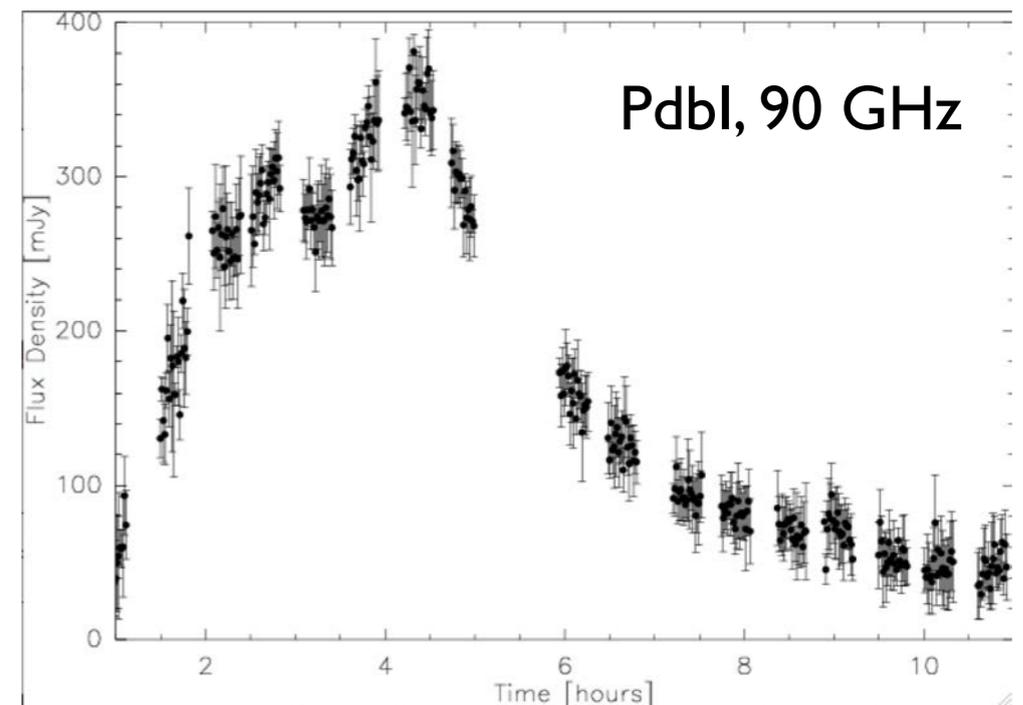
3 well-studied radio flares on HR 1099 (K1 IV+ G5IV d=28 pc,  $P_{\text{orb}}=P_{\text{rot}}=2.8$  d)  
with accompanying multi- $\lambda$  observations



παριατιον οφ φλυξ,  
πολαριζατιον,  
σπεχτραλ ινδεξ δυρινη  
φλαρες ιμπλιεσ:  
(1) φλυξ, πολαριζατιον  
~ινπερσελψ  
χορρελατεδ, 0%  $\pi_c$   
during flares  
(2)  $\nu_{\text{peak}} > 8$  GHz  
at flare peak  
(3)  $\nu_{\text{peak}} < 5$  GHz during  
flare decays

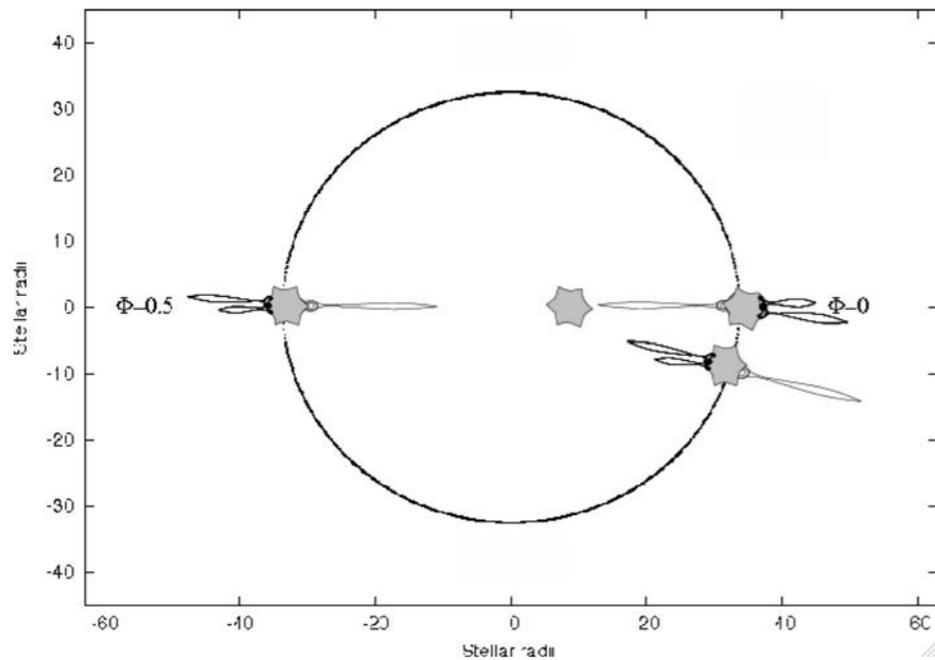
# importance of mm variability

- mm emission generally ascribed to dust emission from disks
- to date, a few YSOs have illustrated spectacular mm flares
- appears to be periodic, interacting magnetospheres
- attributed to synchrotron emission based on spectrum and timescales
- does this only affect binaries? what is the impact on SED modelling, particle environment for forming planets?
- Bower et al. (2003) noted a mm-flare in Orion from a K5 pre-main sequence star, and estimated that even a short ALMA exposure with 10  $\mu$ Jy sensitivity will find 100s-1000s of flares from YSOs

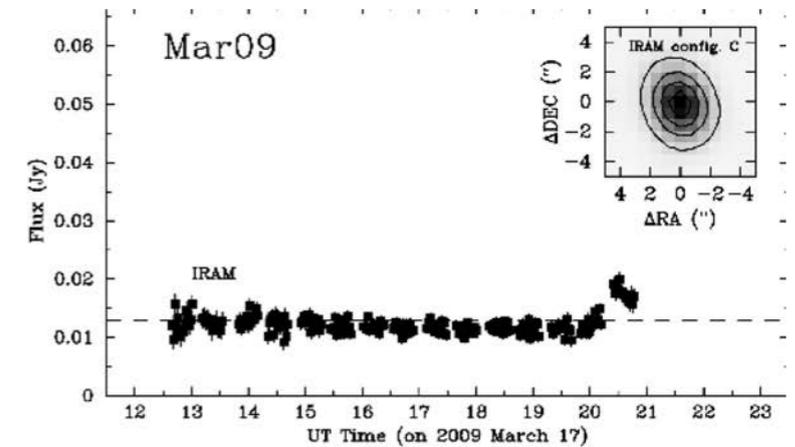
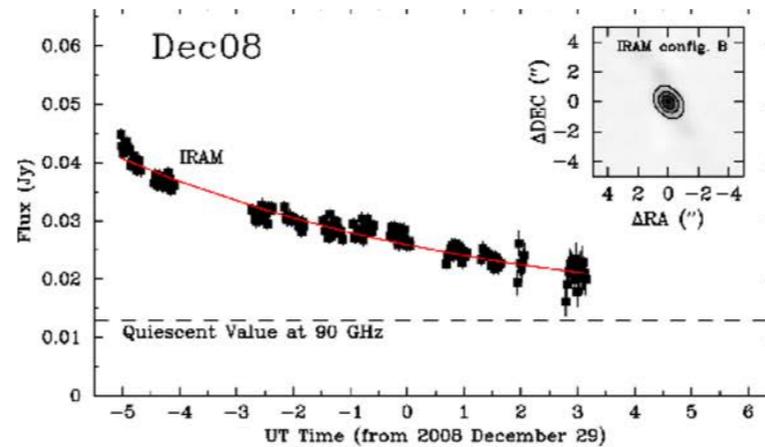


V773 Tau; Massi et al. 2006  
mm flares with a periodicity on the order of the orbital period,  $\sim 52$  days

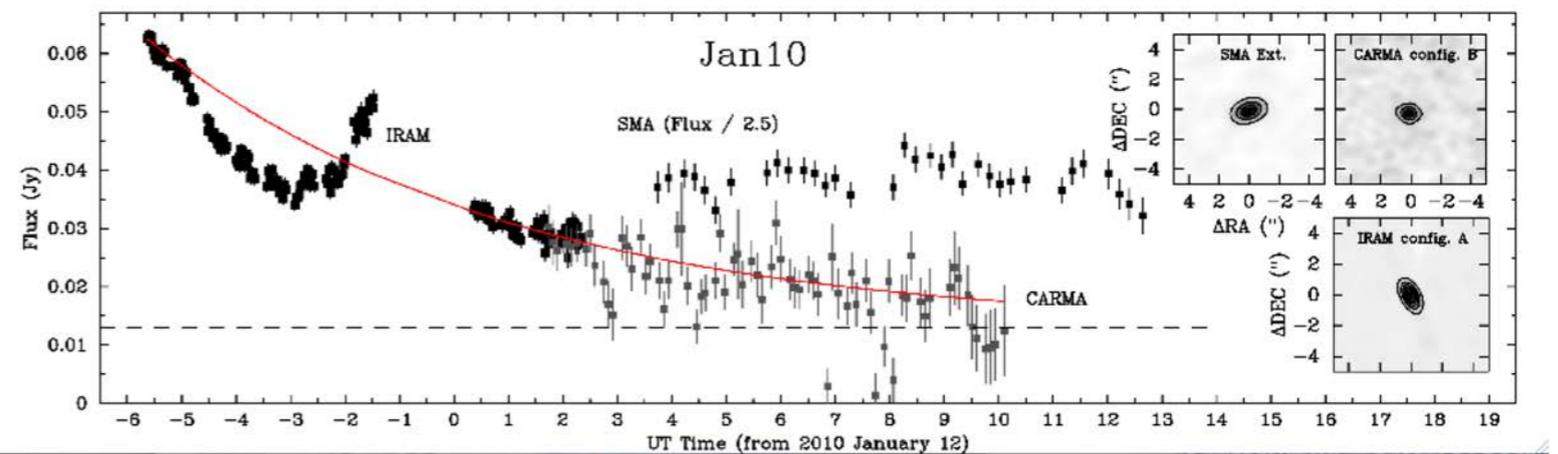
# importance of mm variability



also seen in DQ Tau; Salter et al. 2010



## Interacting magnetosphere scenario



# Using Variability to Probe Dynamo Processes

cyclic radio flaring on  
HR 1099 (=V711 Tau;  
KIV+G5V,  $P_{\text{cyc}} \sim 120$  d,  
 $P_{\text{orb}} = P_{\text{rot}} = 2.8$  d  
(also note elevated  
states can last  $\sim 40$   
days!)

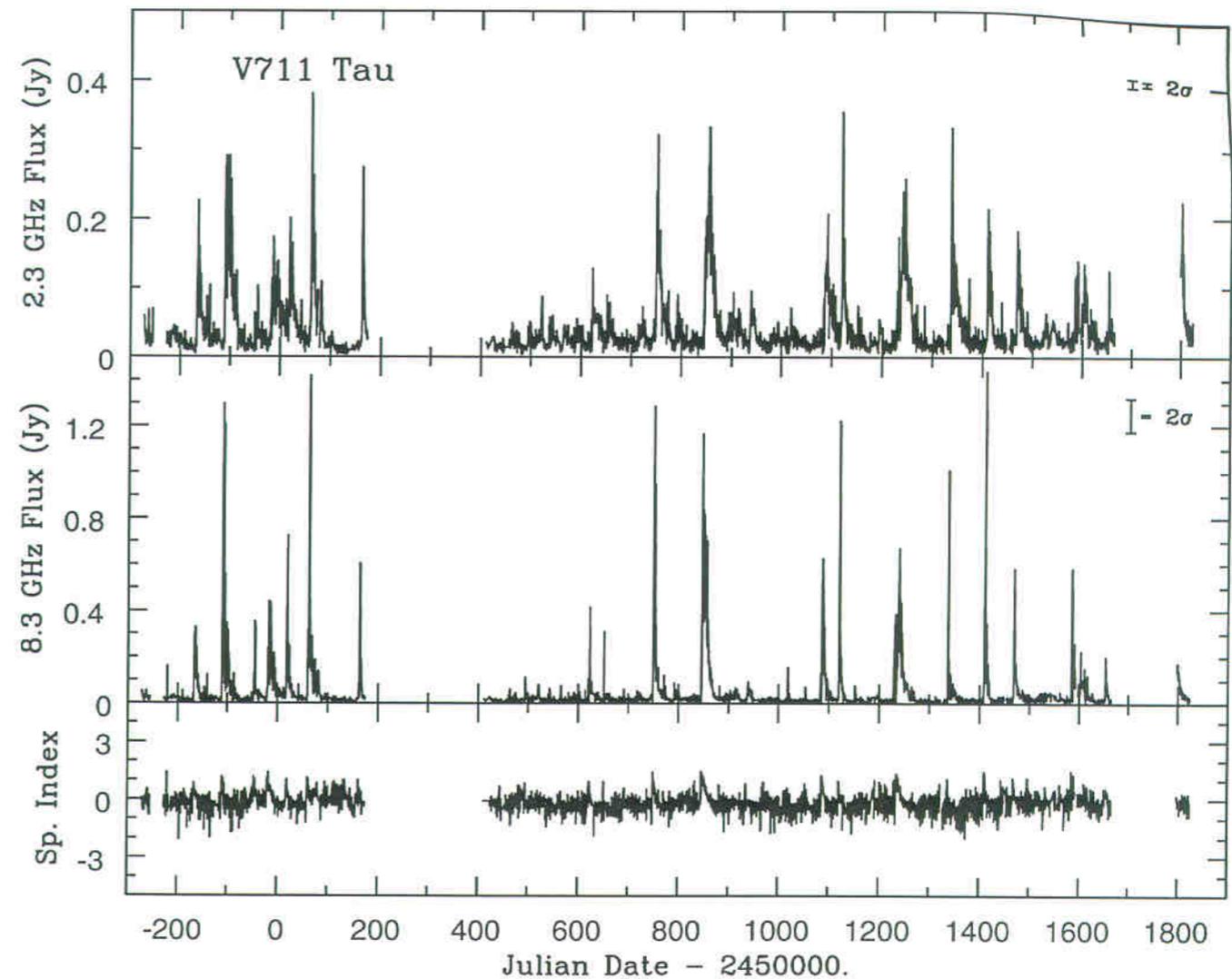
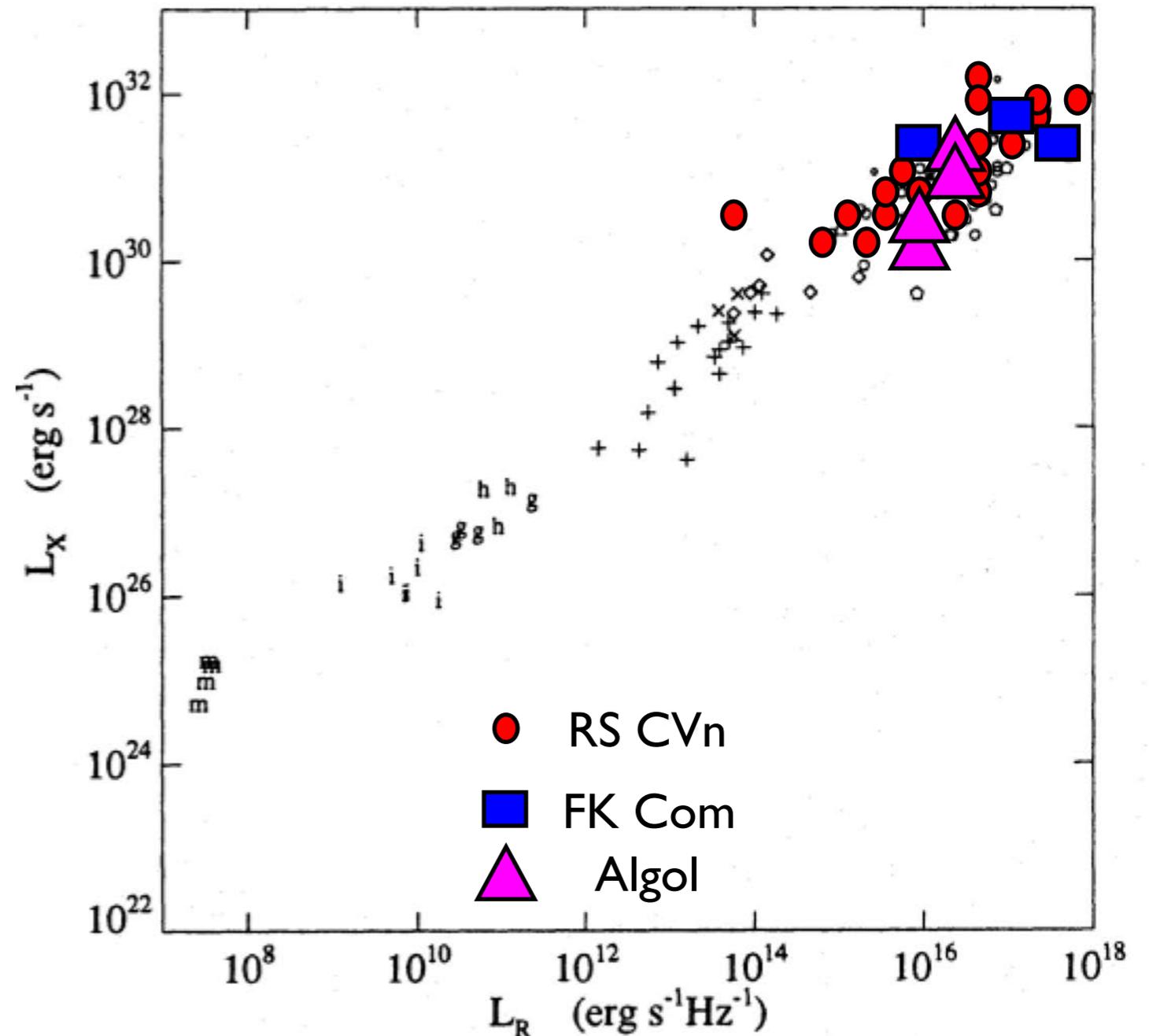


FIG. 9.— Flux density at 2.3 GHz and 8.3 GHz, and spectral index for V711 Tau from 1995 January 10 to 2000 October 5. The larger error bar represents the  $2\sigma$  error during the strongest flares, and the smaller error bar represents the quiescent level.

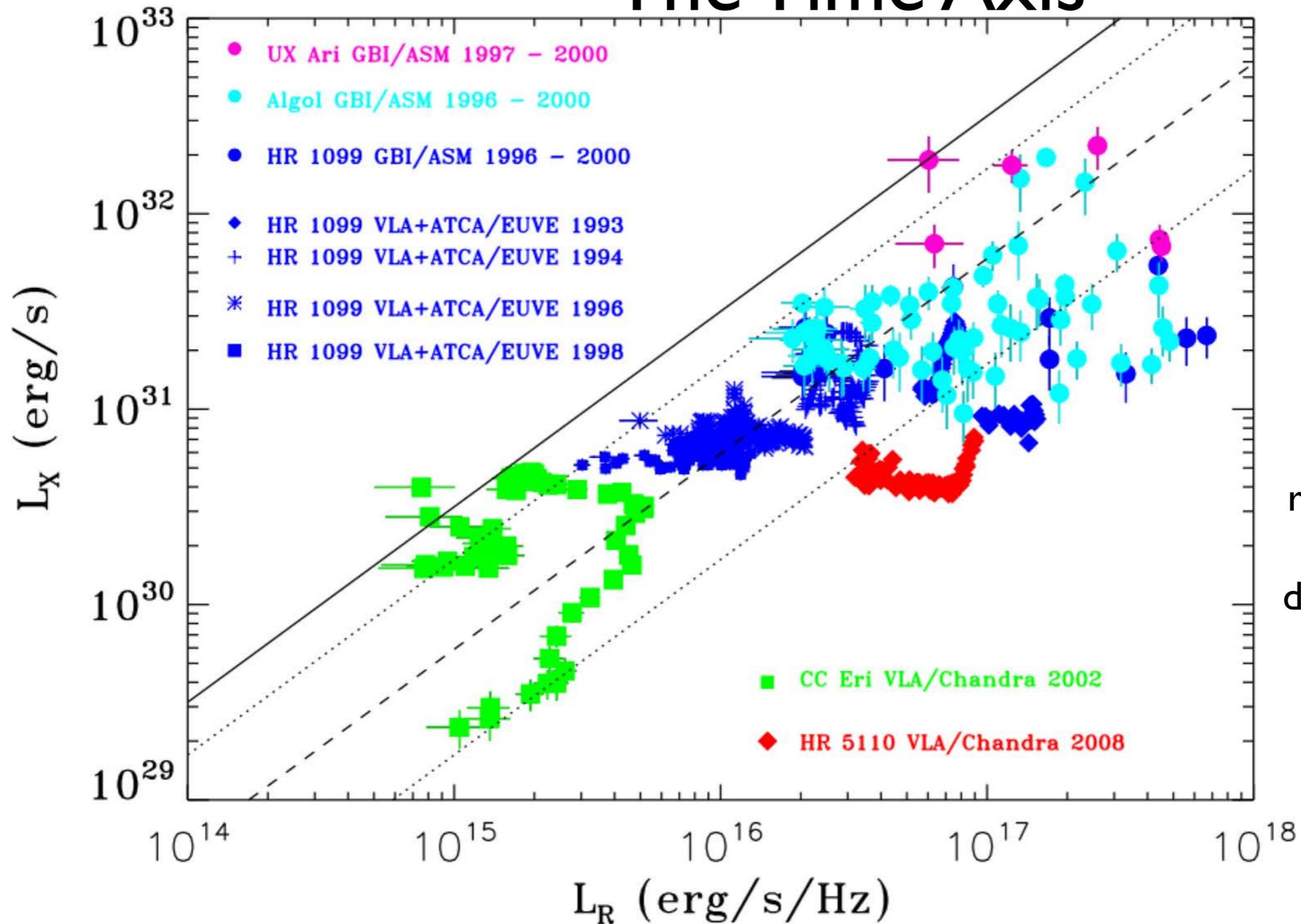
Richards et al. 2003; multi-year monitoring from the  
GBI

# The extremes of magnetic activity

- RS CVn, FK com, Algal systems lie at the upper right end of the Benz & Güdel (1994) diagram
- interpretation for scaling between  $L_r$  and  $L_x$ : common energy reservoir out of which both particle acceleration & plasma heating occur
- also known to be time-variable sources
- examine the time axis



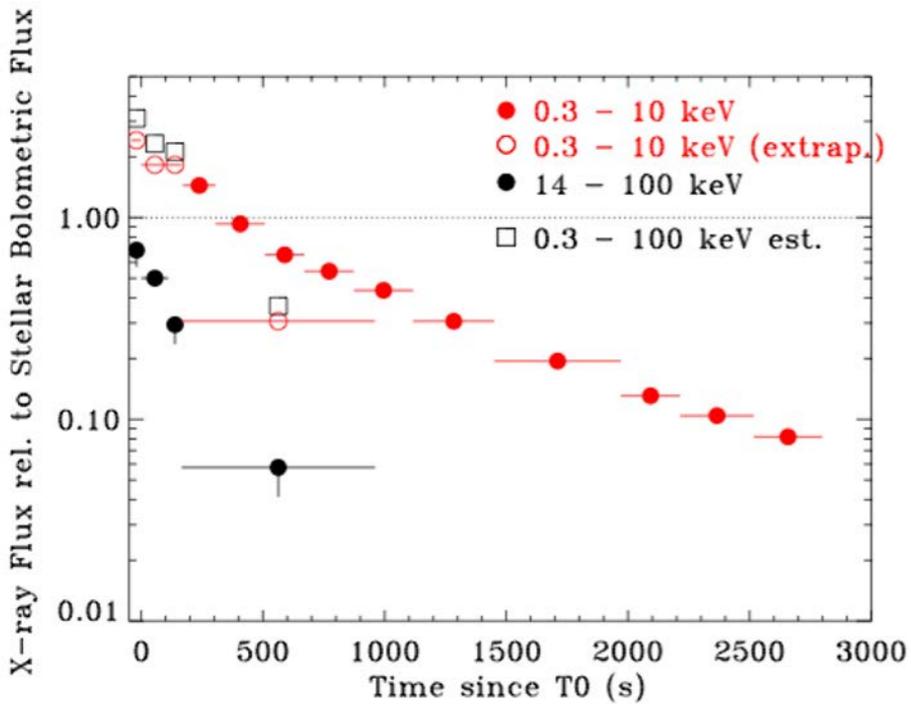
# The Time Axis



dotted lines= GB  
 relation,  $L_x/L_r = \kappa 10^{15.5 \pm 0.5}$ ,  
 $\kappa = 0.17$ , solid line  $\kappa = 1$ ,  
 dotted line=average  $L_x/L_r$   
 from these data

- flaring introduces variability in correlated  $L_x$ - $L_r$  which increases the spread, but generally falls within the order of magnitude range of GB relation
- radio variability appears to be a larger factor than X-ray variability
- there are situations where even these well-understood (!) systems belie our expectations

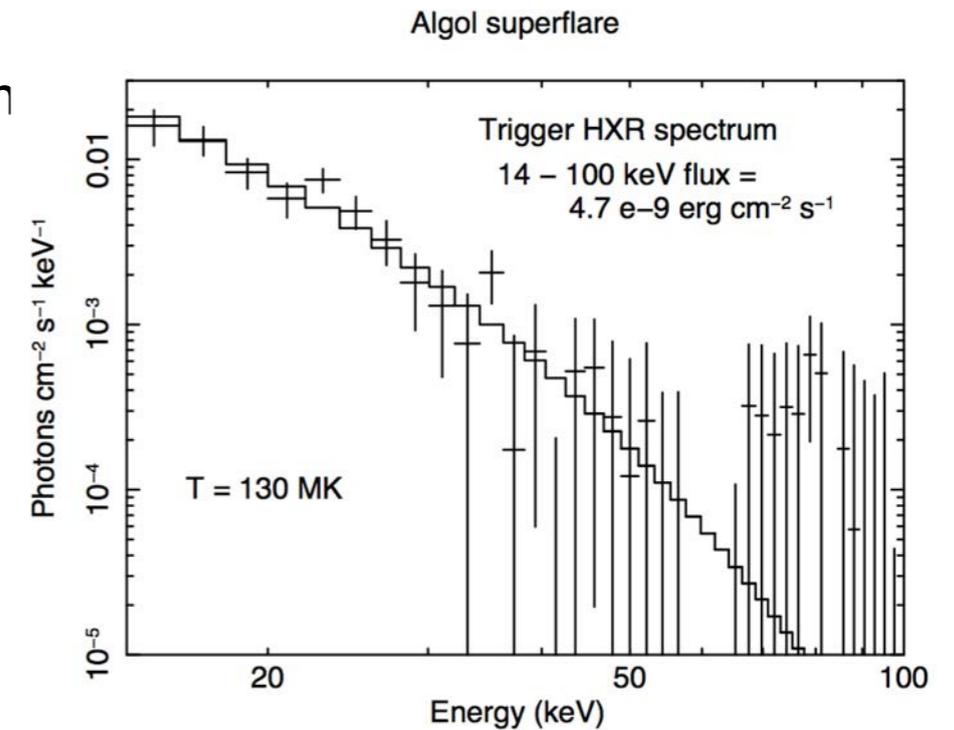
# Stellar Radio Transients



- gyrosynchrotron emission associated with X-ray flares
- Swift triggers on hard X-ray emission from transient sources with quick reaction times
- need commensurate radio transient capability
- impact on habitability

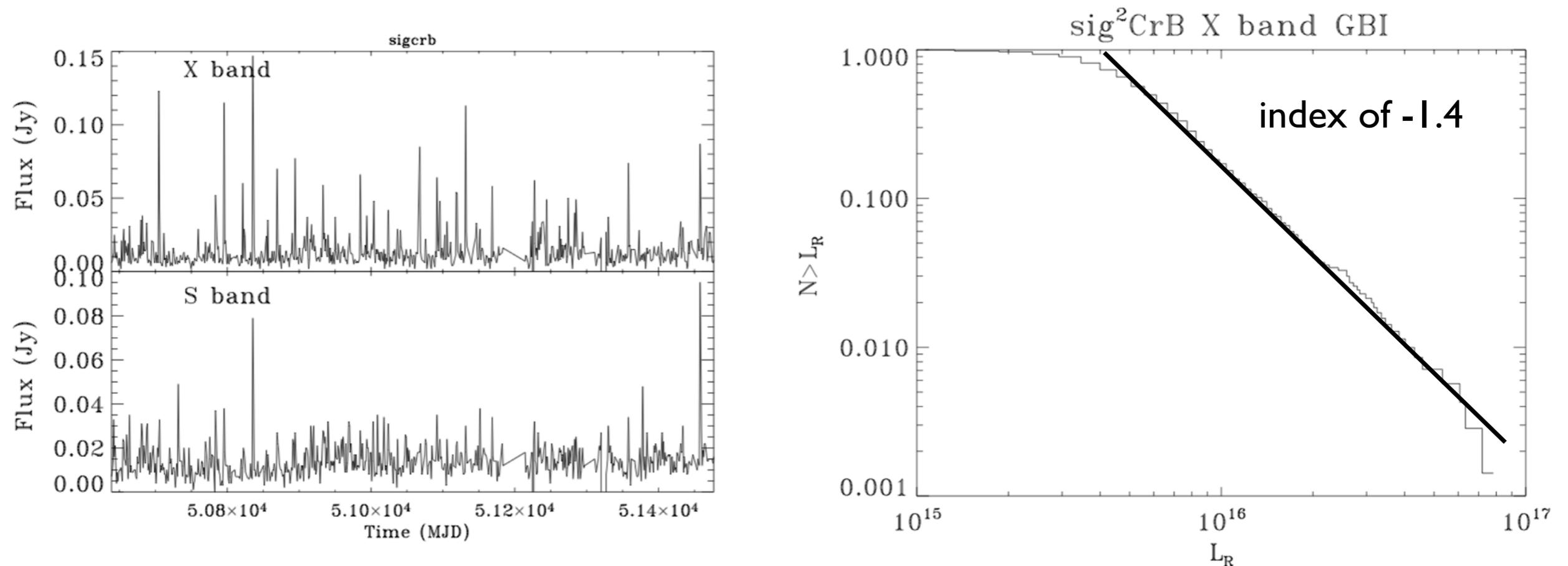
Osten et al. 2010, "GRB" on a flare star at 5 pc

What is the radio equivalent of this?



# “The probability distribution of radio activity in low-mass stars is not well quantified.” (Bower et al. 2007)

- while the radio transients in Bower et al. have been reexamined and the transient rate revised downward significantly (Frail et al. 2012), it is true that the radio probability distribution for radio-active stellar sources has not been investigated. The overlap in parameter space with other types of radio transients necessitates constraints on “mundane” explanations.



long term monitoring; multi-year monitoring of known radio-active sources by the GBI, including several “usual suspects”

# Solar/Stellar “Flare” (Eruptive Events) Commonalities

	Sun	Other Cool Stars*
nonthermal hard X-ray emission		maybe
radio gyrosynchrotron/synchrotron		
coherent radio emission		
FUV lines (transition region)		
optical/UV continuum (photosphere)		
associated Coronal Mass Ejection		?
solar energetic particles		?
EUV/soft X-ray emission (corona)		
optical lines (chromosphere)		

\* across different kinds of stars

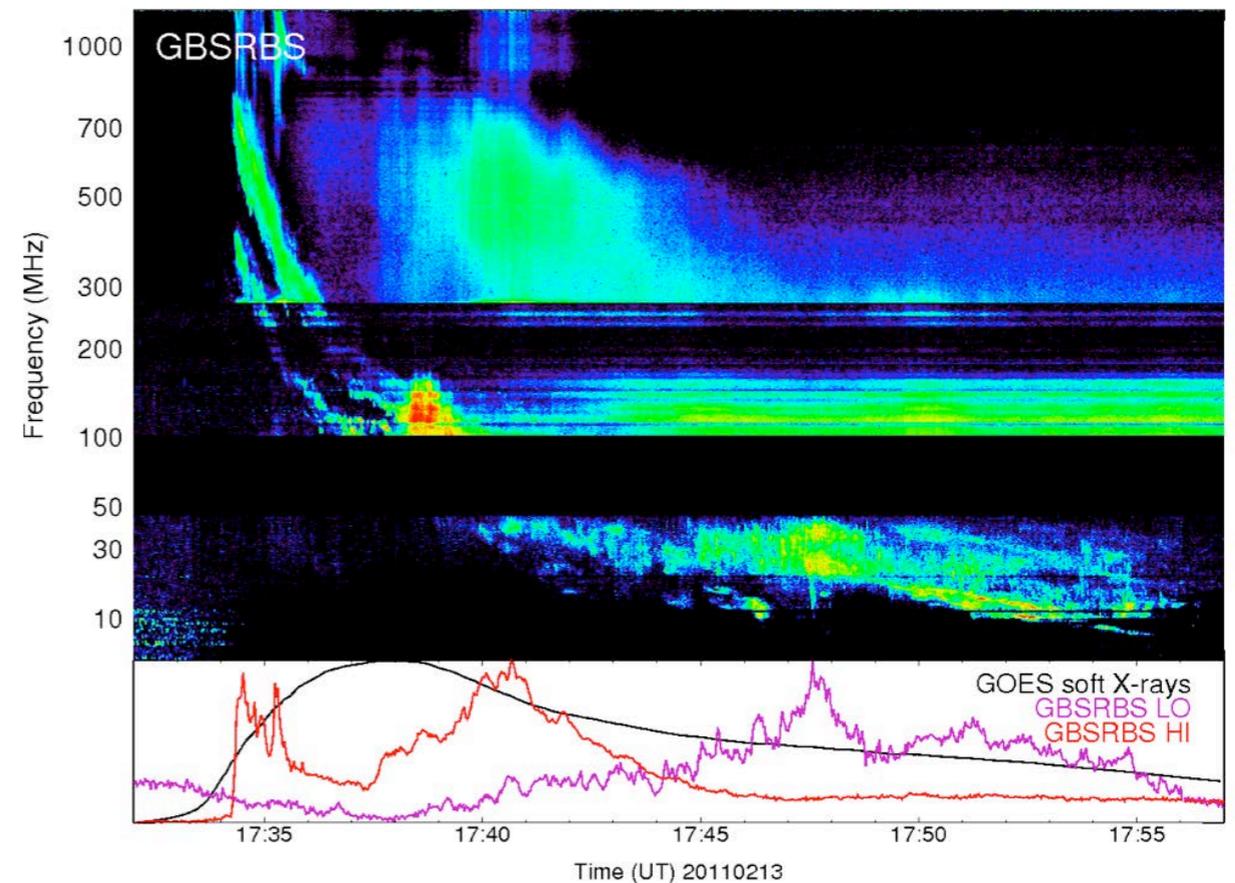
cyan=impulsive phase, orange=gradual phase

# Mass Loss in Cool Stars

- Detecting mass loss in cool stars on the main sequence has proved to be a thorny issue -- MS cool stellar winds are feeble ( $(dM/dt)_{\odot}$  is  $\sim 10^{-14} M_{\odot}/\text{yr}$ )
- expect both steady and variable mass loss, in analogy with Sun.
- scattered measurements of X-ray absorption enhancements during stellar flares have been interpreted as CMEs. few and far between (esp. given number of stellar X-ray flares)
- charge exchange X-ray emission provides upper limits on mass loss within astrospheres
- enhanced astrospheric absorption in stellar Lyman  $\alpha$  profiles
- affects circumstellar environment, can alter the character of planetary atmospheres (viz. Mars)

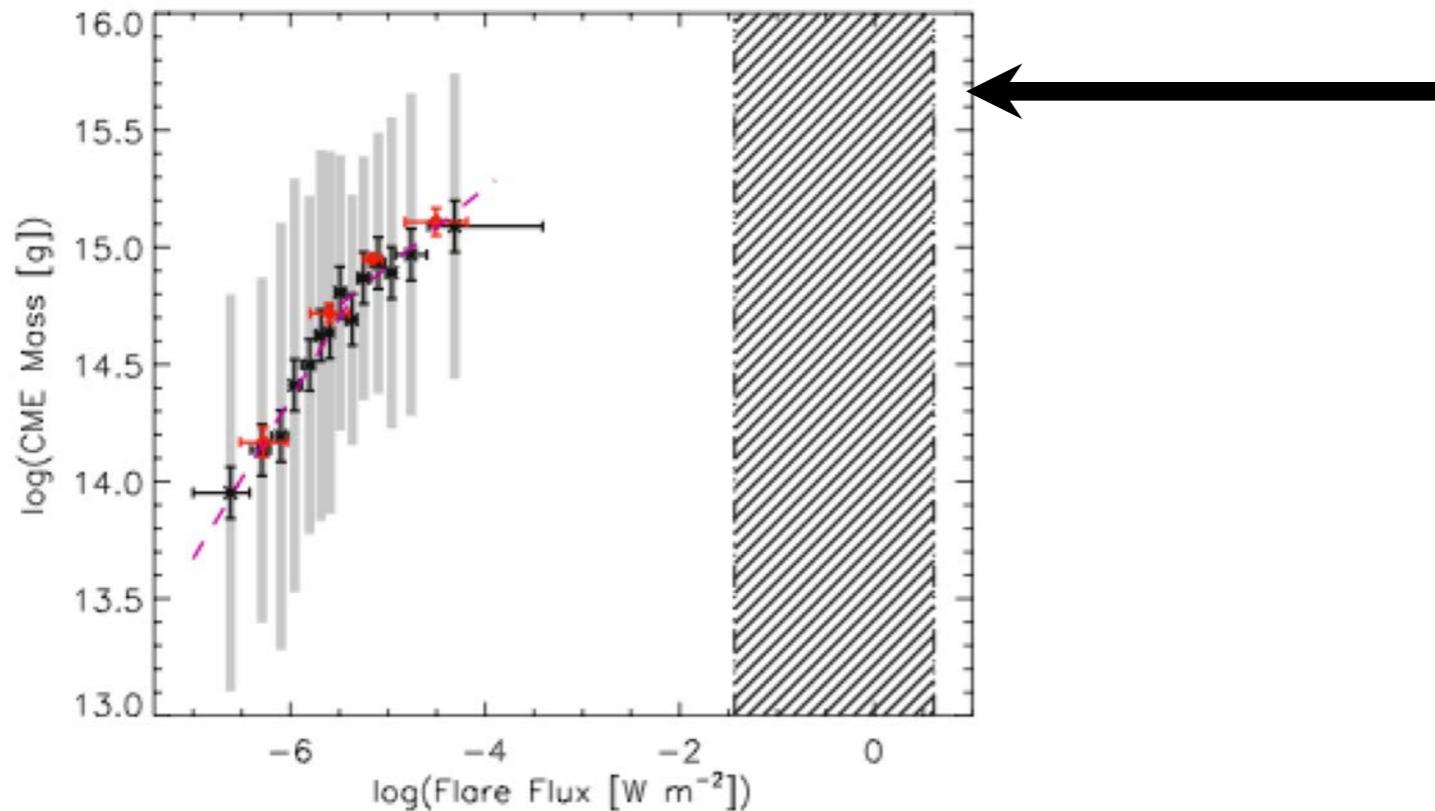
# Low Frequency emission from Stellar Coronal mass ejections

- solar type II radio bursts: slowly drifting radio bursts (0.1 MHz/s) produced by MHD shock (associated with CME) propagating through the solar corona, radiation at  $v_p$  and  $2v_p$
- CME-driven shocks can explain type II bursts at all wavelengths (Gopalswamy et al. 2009)
- Based on the good correspondence with flare signatures seen at other wavelengths in stars (X-ray emission from plasma heating, white-light flare emission, and type III-like stellar radio emission at longer wavelengths), we expect there to be similar analogs to the so-called type II and type III solar radio bursts at long wavelengths in other stars.
- These can be detected with the new generation of low frequency arrays like LOFAR, MWA, LWA

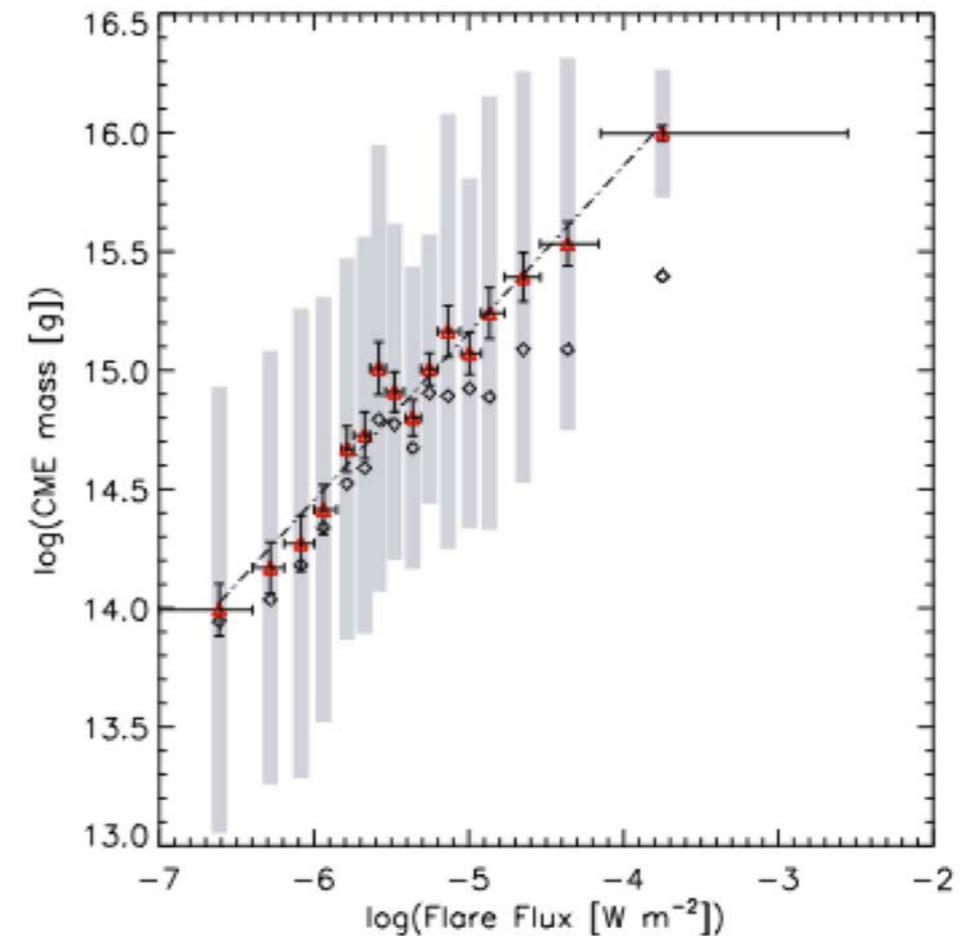


GBSRBS example (Feb. 13, 2011)  
of a type II burst

# Potential Importance of Coronal Mass Ejections in Astrophysical Situations



soft X-ray flares  
from young stars



Aarnio et al. (2011)

solar flares & CMEs: flare flux & CME mass correlation from spatially, temporally correlated events

including halo CMEs:  
 $\log \text{ CME mass} = (18.67 \pm 0.27) + (0.70 \pm 0.05) \log \text{ flare flux}$

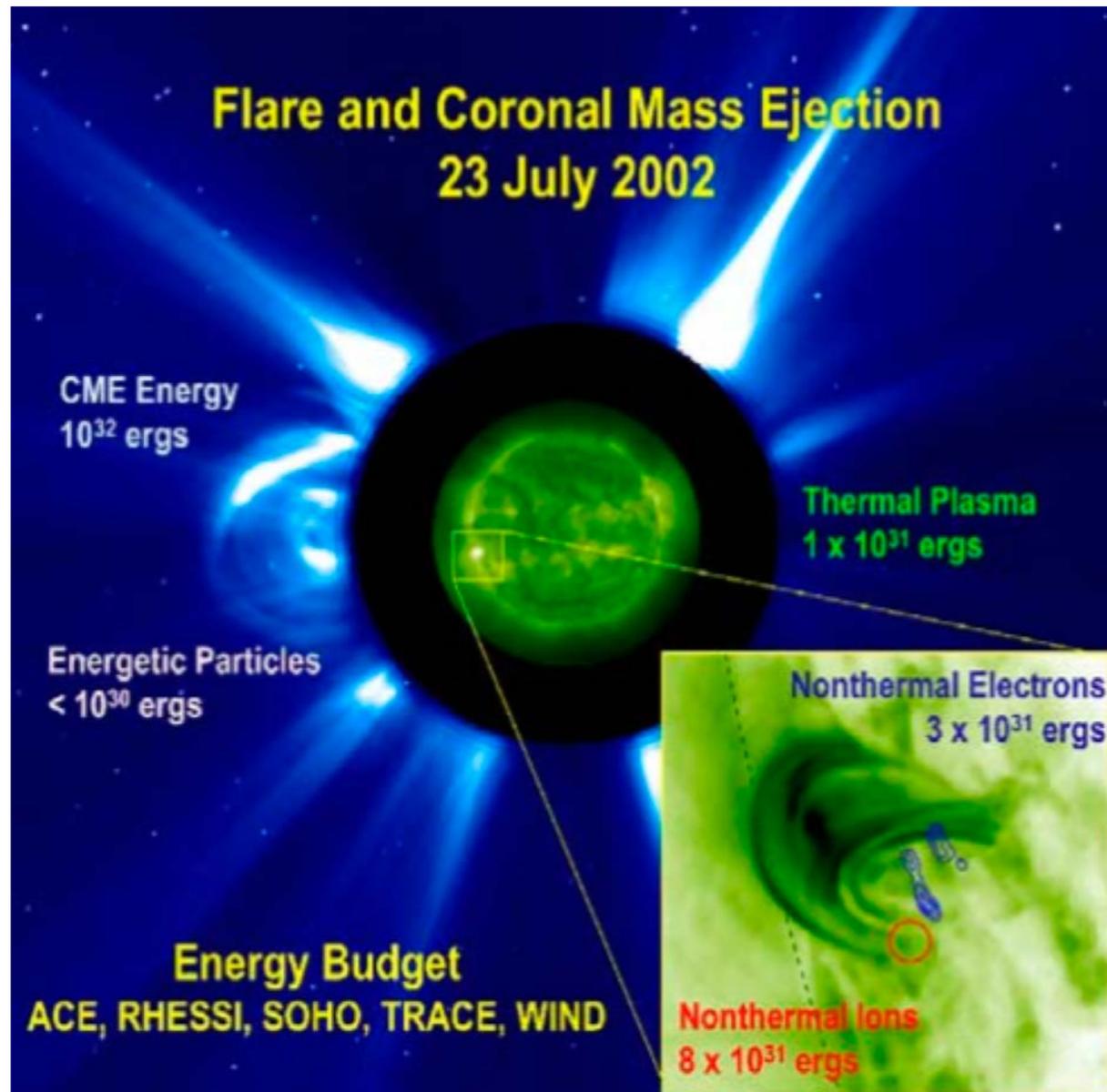
# Why is this useful?

- X-ray flares on the Sun & cool stars are routinely measured, easy coronal diagnostic to pick up flares (dynamic range on Sun is orders of magnitude)
- large solar flares (as measured in X-rays) have a nearly 100% association with CMEs (Yashiro et al. 2006)
- If one supposes that this scaling relation also applies to different kinds of stars, it implies a substantially enhanced mass loss rate
- CME mass loss on Sun is generally taken to be a minor ( $\sim 5\%$ ) component of the overall feeble solar mass loss ( $2 \times 10^{-14} M_{\text{sun}}/\text{year}$ )
- CMEs can remove mass; not clear how connected they are to the solar surface, effectiveness in removing angular momentum (they do remove magnetic helicity)

# The Energy Budget of Solar Eruptive Events

Emslie et al. 2004, 2005

Emslie et al. (2004) examined two flare/CME events and investigated energy partition:

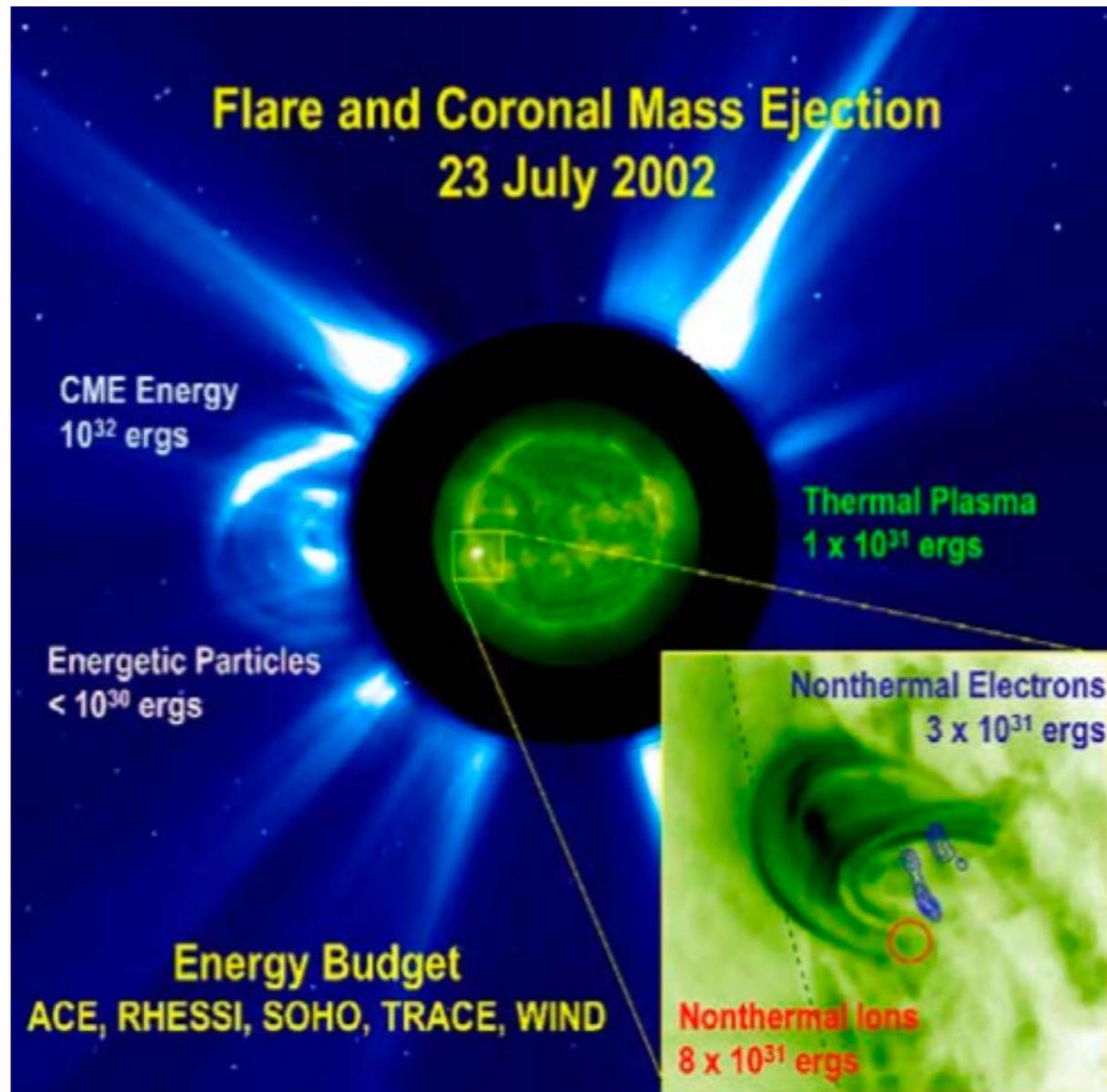


- magnetic
- flare:
  - thermal plasma
  - nonthermal electrons
  - nonthermal ions
- CME:
  - kinetic
  - gravitational potential
- energetic particles at 1 AU

they concluded that the CME contained the dominant mode of released energy, containing a substantial fraction of the available magnetic energy

# The Energy Budget of Solar Eruptive Events

Emslie et al. 2004, 2005



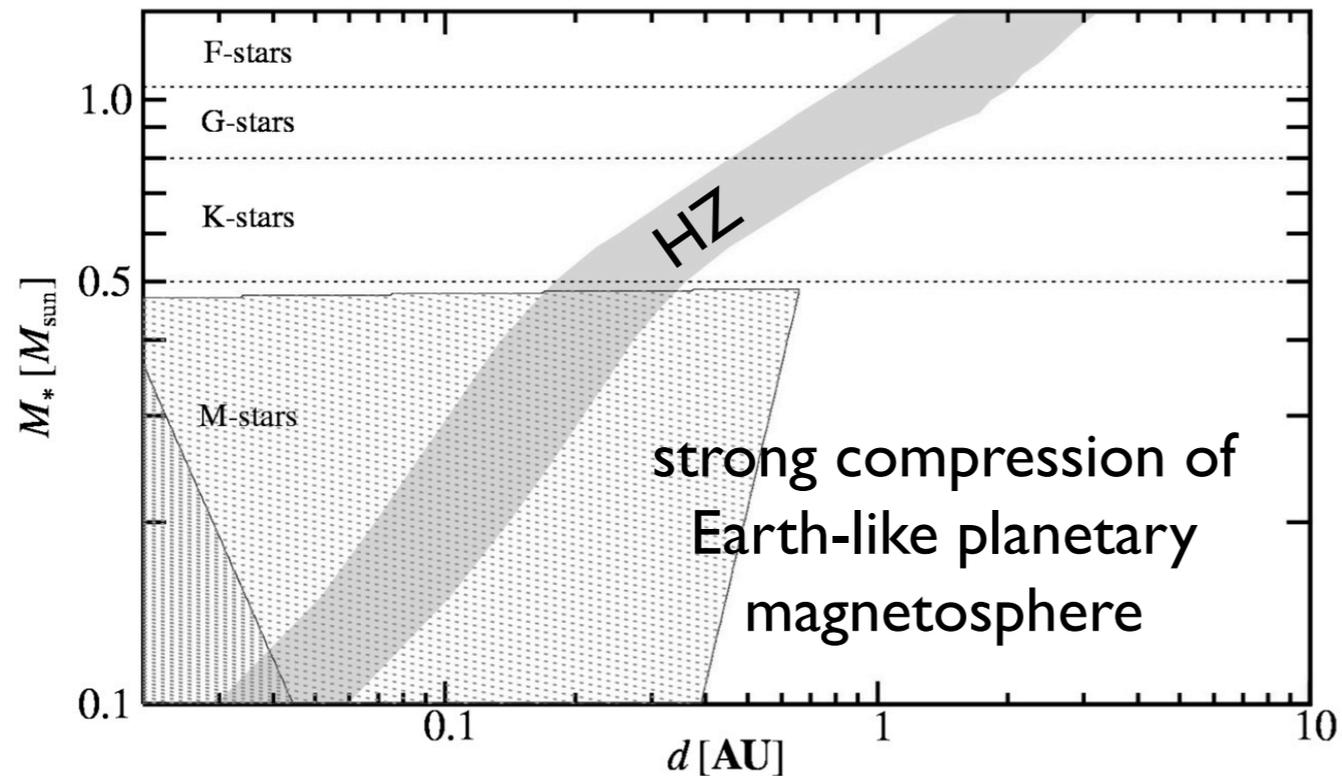
The 2005 paper was based on work by Woods et al. (2004), in which a solar flare was detected in total solar irradiance (TSI) for the first time

Although the increase of the X17 flare on 28 October 2003 was only 260 ppm in TSI, it was energetically dominant over the X-ray counterpart, with  $L_{\text{tot}} \sim 100 L_x$

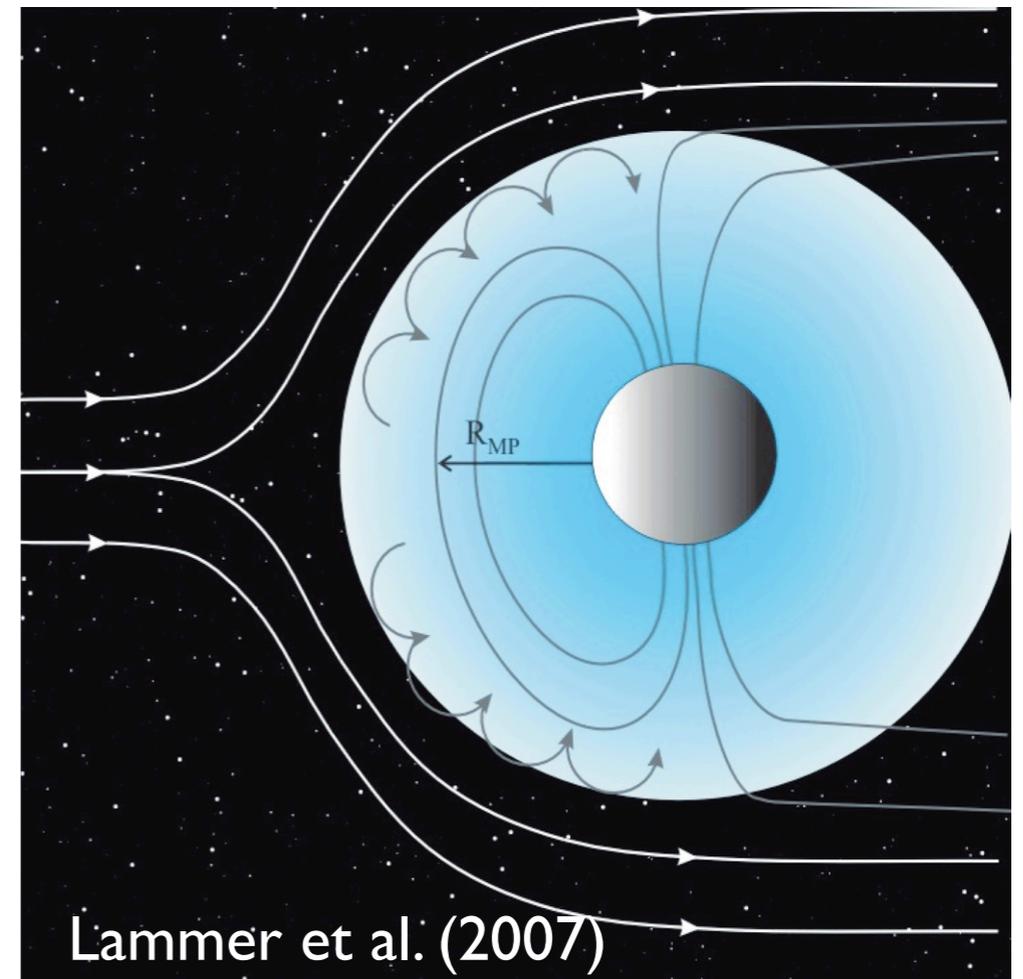
Emslie et al. (2005) note "...the total flare energy could be significantly higher than any of the component energies, and indeed comparable to the energy in the CME"

- make the ansatz that  $\epsilon = E_{\text{tot,rad}}/E_{\text{KE,CME}}$  is  $\sim 1$ , and  $E_{\text{tot,rad}} = E_{\text{X}}/f$ , where  $f \sim 0.01$ . Take a constant linear CME speed  $v$
- then use distributions of flare X-ray energy to estimate the total mass lost by CMEs
- complete energy budget for stellar flares has been probed quantitatively for only a few M dwarfs
- using results from solar flares (Veronig et al. 2002), estimate  $M_{\text{tot,CME}} \sim 4 \times 10^{-16} M_{\text{sun}}/\text{yr}$
- same application to young low mass stars in Orion (Caramazza et al. 2007 X-ray flare energy distribution), higher energy X-ray flares  $\rightarrow$  higher  $M_{\text{tot,CME}} \sim 2 \times 10^{-11} M_{\text{sun}}/\text{yr}$ , and to two nearby dMe

# Stellar magnetic events and their impact on exoplanet habitability



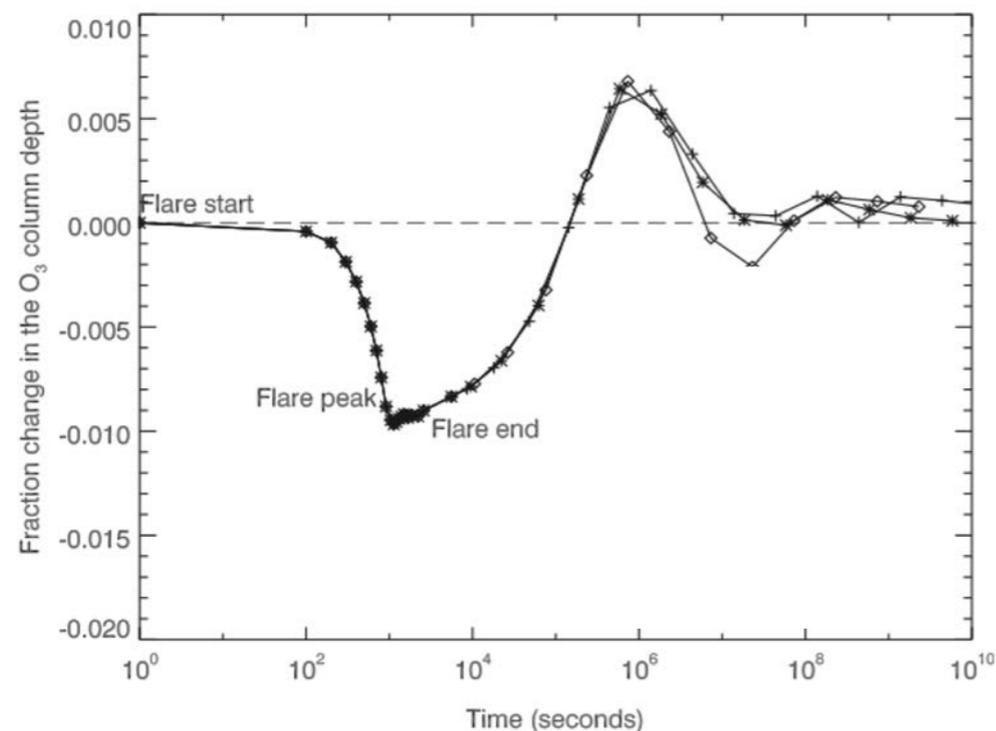
Khodachenko et al. (2007)



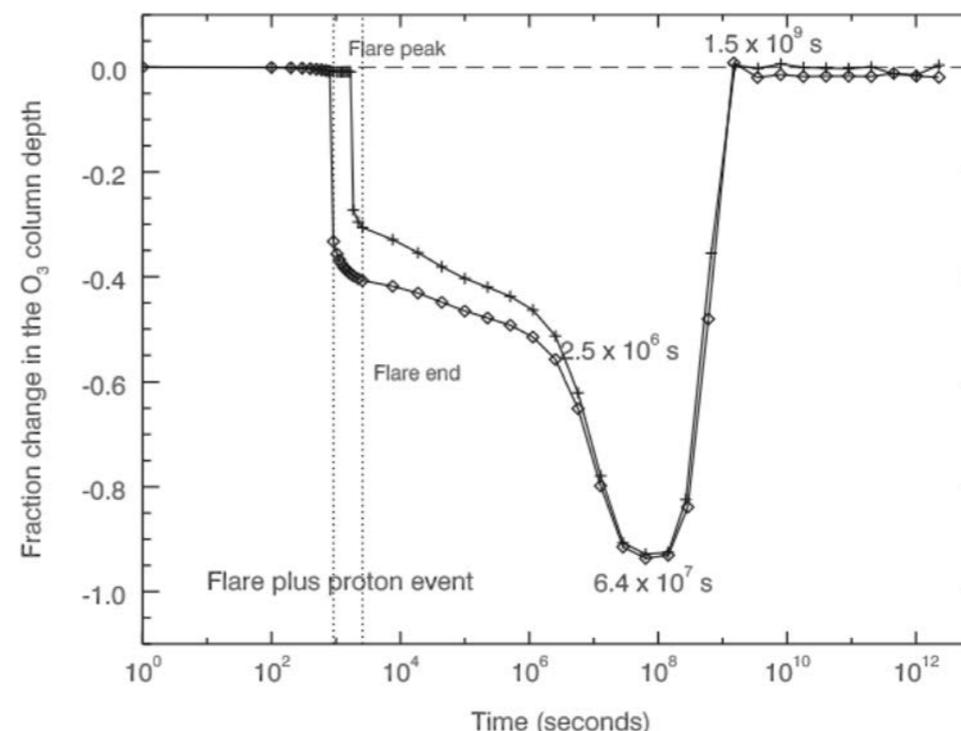
Lammer et al. (2007)

- M dwarfs need close-in planets to be habitable, rendering the planets more susceptible to the effects of the host star
- tidally locked, weak magnetic moment: little or no magnetospheric protection from flares & coronal mass ejections
- M dwarfs expected to have enhanced flare, CME rate: like a dense stellar wind

# Stellar magnetic events and their impact on exoplanet habitability



ozone column depth vs. time,  
for a UV flare only



ozone column depth vs. time, for a UV flare  
+ proton event ( $>10$  MeV)

- Segura et al. (2010) studied the impact of a large flare from the M dwarf AD Leo on a putative Earth-like planet in the habitable zone, using scaling relations to get from stellar UV  $\rightarrow$  stellar X-ray  $\rightarrow$  estimated stellar proton fluence for a planet with no magnetic field

# Conclusions

- variability in different radio wavelength regions provides diagnostics of different types of accelerated particles, locations in the stellar atmosphere
- new instruments like the JVLA, ALMA will hopefully overcome selection biases in targets studied
- interpretation can sometimes be challenging: “you learn a lot by looking”
- amongst magnetically active stars, radio variability appears to be a larger factor than X-ray variability