Stellar CMEs

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Workshop on Space Weather of the Early Sun: Inferences from New Solar and Stellar Observations

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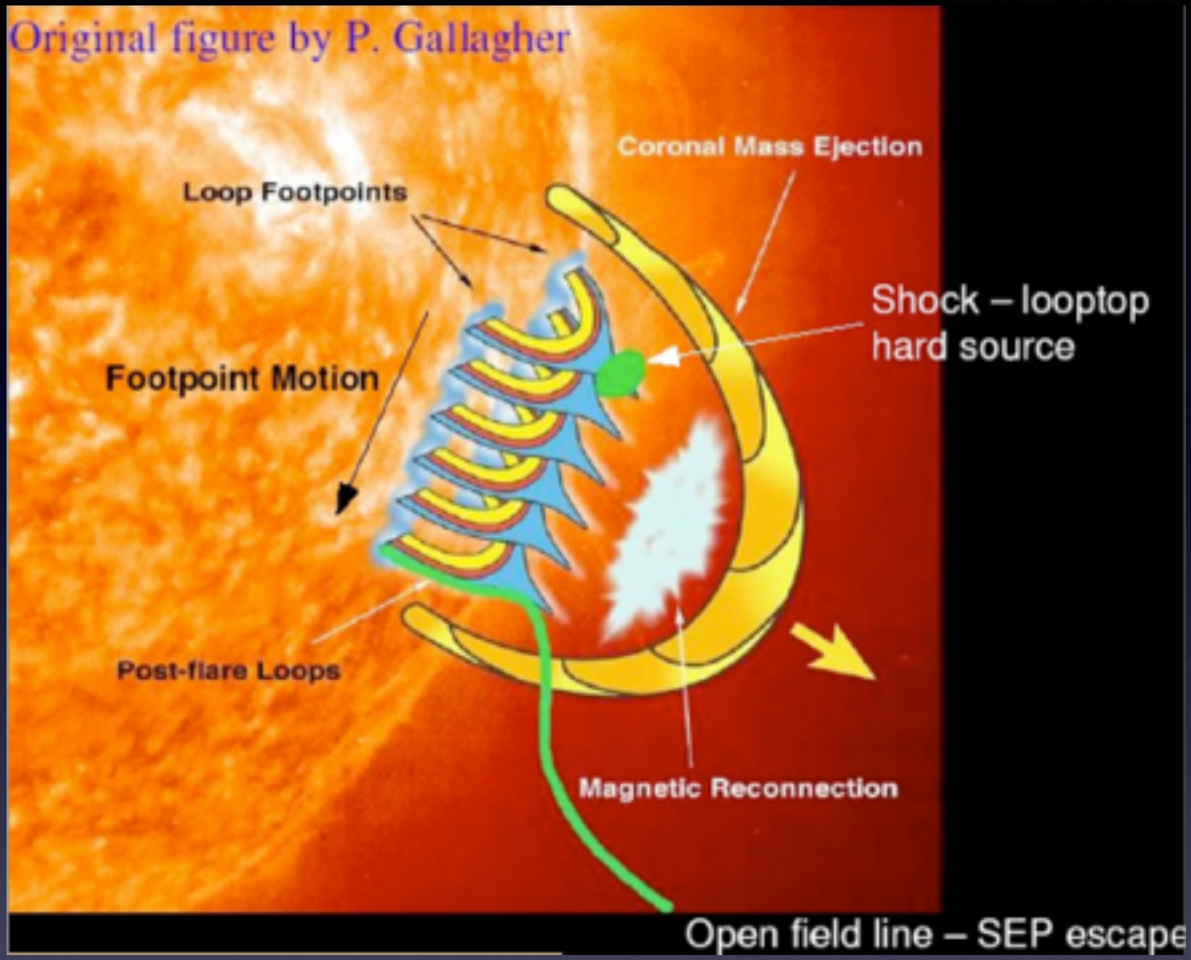
Outline

- Observing CMEs
  - the solar physicist's toolbox
  - the stellar astronomer's toolbox
- Connecting flares and CMEs
- Open questions from an astronomer's perspective on CMEs

Eruptive Events



- CMEs are "geoeffective" (space weather, habitability)
- Carry a large amount of energy with them, comparable to the total radiated energy
- Cumulative effect of CME speeds, masses

CMEs are an integral components of an eruptive event, along with radiative signatures and accelerated particles

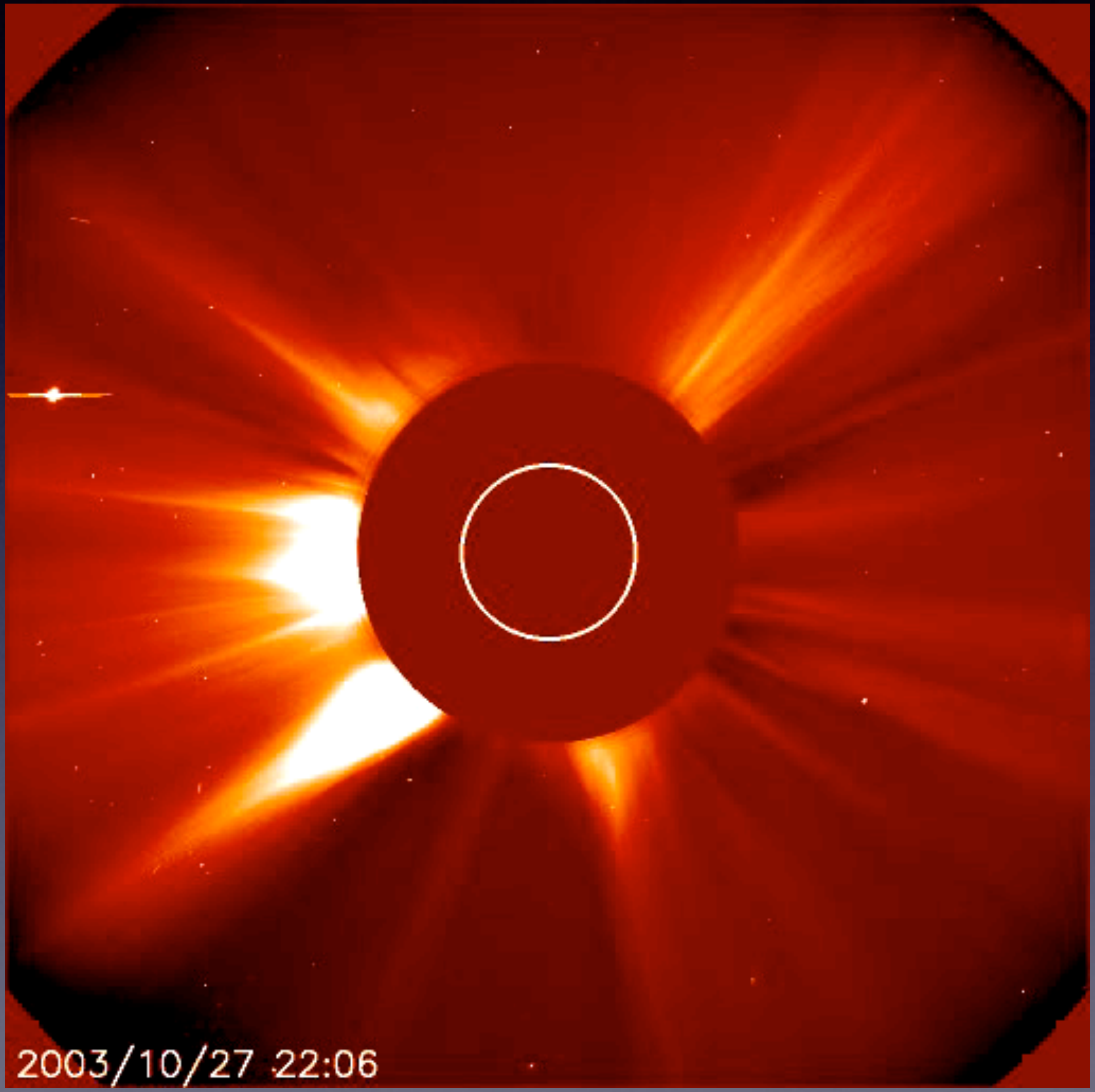
Observational Signature	Sun	Stars*
nonthermal hard X-ray emission	✔	✔?
radio gyrosynchrotron/synchrotron, dm-cm-mm wavelengths	✔	✔
coherent radio emission, m-dm-cm wavelengths	✔	✔
FUV emission lines (transition region)	✔	✔
optical/UV continuum (photosphere)	✔	✔
associated coronal mass ejection	✔	?
energetic particles	✔	?
EUV/soft X-ray emission (corona)	✔	✔
optical emission lines (chromosphere)	✔	✔

cyan=impulsive phase, orange=gradual phase

* across different kinds of stars

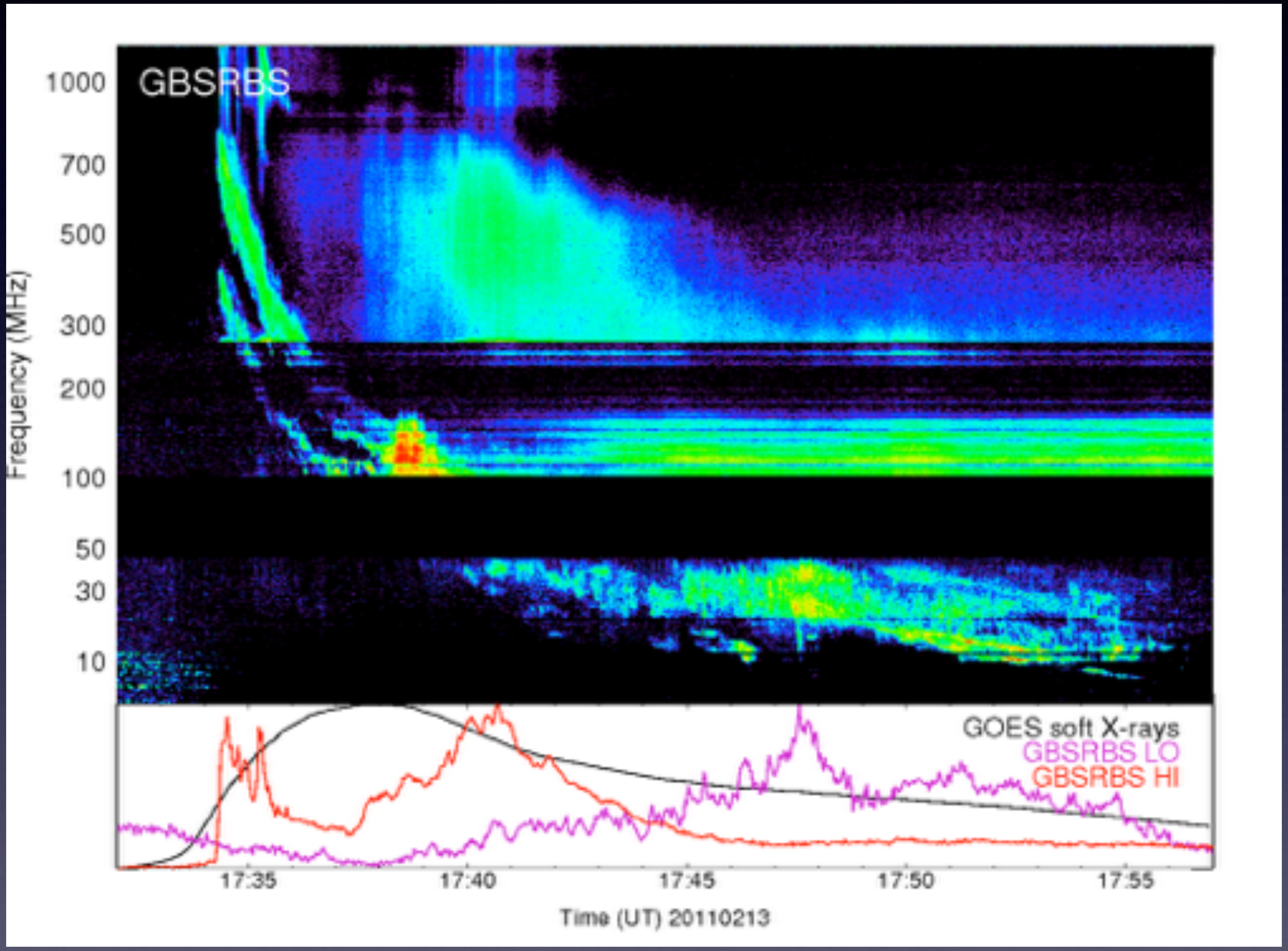
White Light Emission from CMEs

- first clearly identified in 1971
- now coronagraphs routinely detect CMEs through Thomson scattering of photons from the photosphere off coronal electrons
- also associated with energetic electrons (up to GeV level)



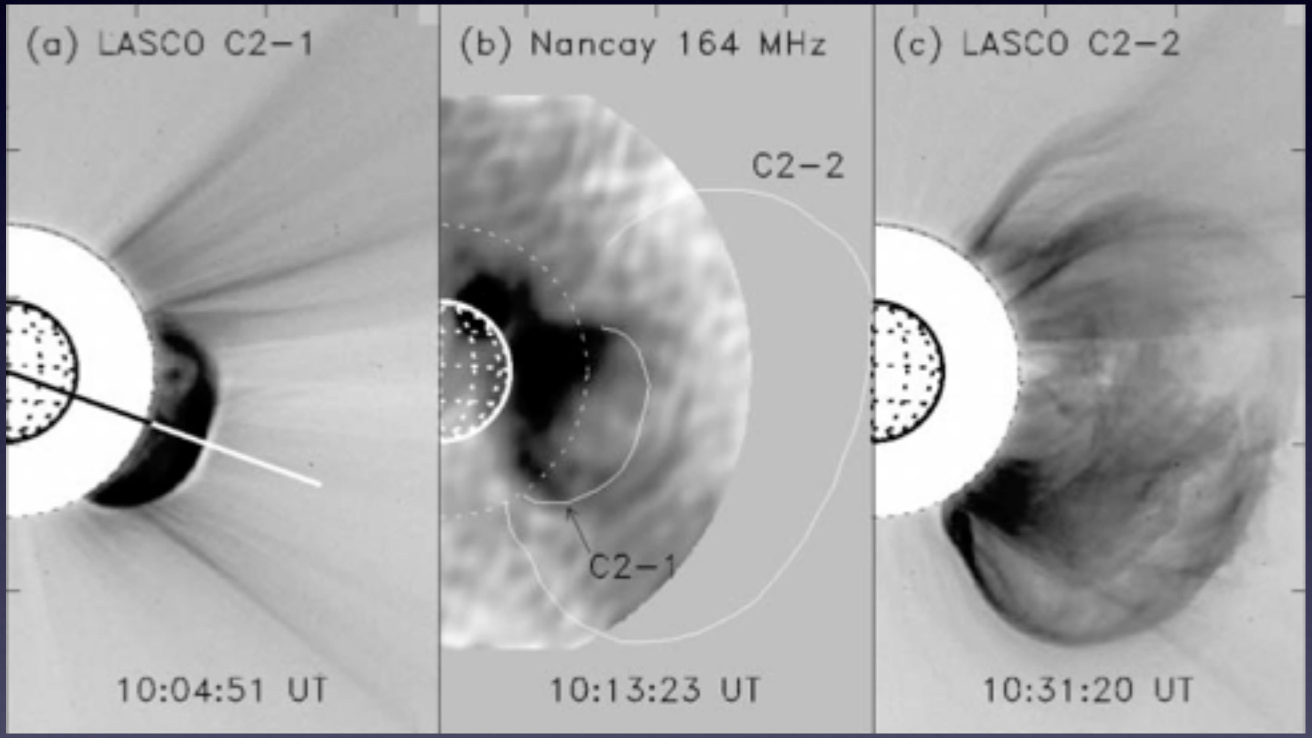
Low Frequency Emission from CMEs

- solar type II radio bursts: drifting radio bursts with slow frequency drift, produced by MHD shock propagating through the solar corona, radiation at ν_p and $2\nu_p$
- strong association between solar CMEs and type II radio bursts.



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

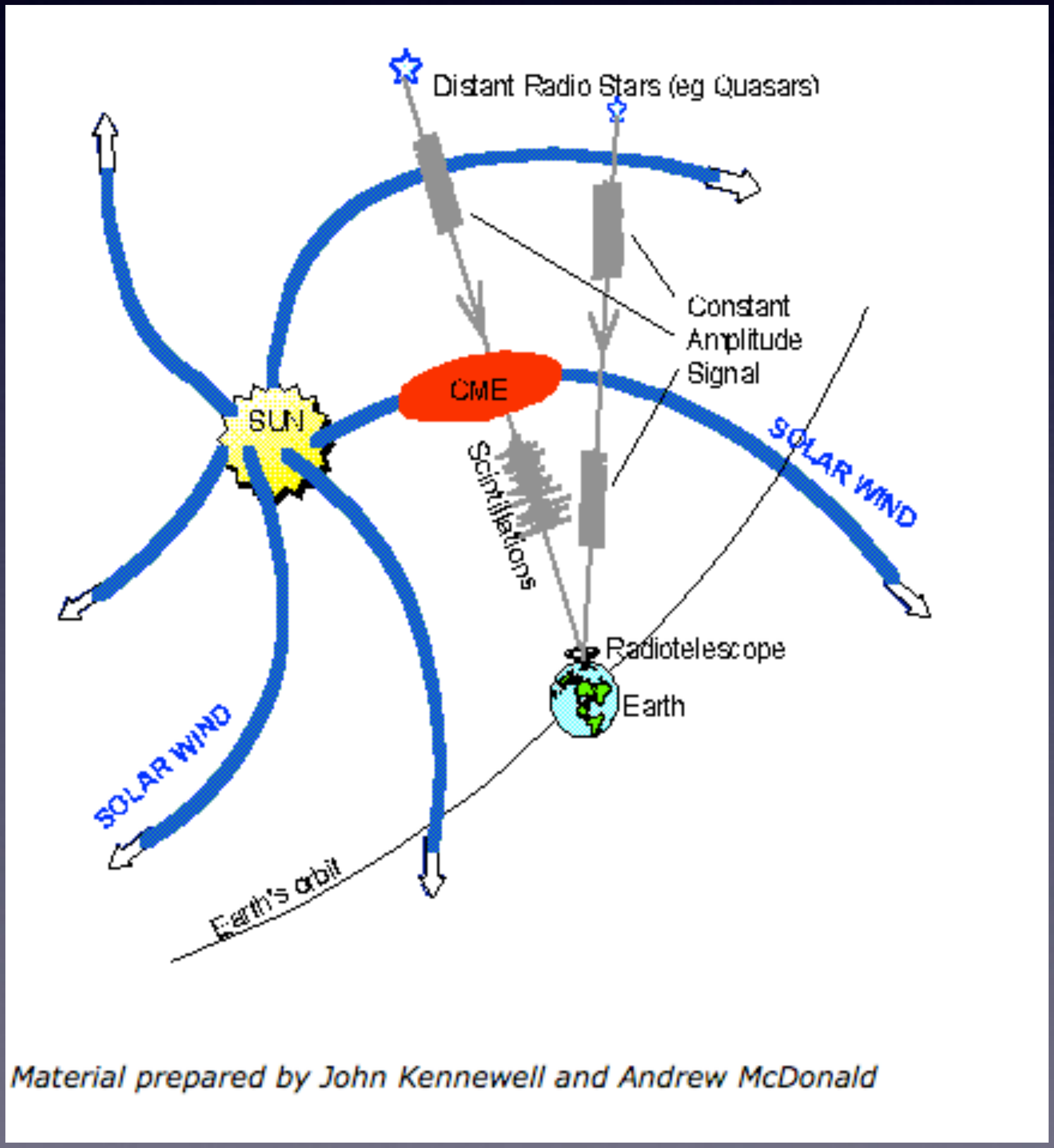
Imaging of nonthermal emission from CMEs



Bastian et al. (2001) directly imaged synchrotron emission (MeV energies) from a CME, consistent with morphology from white-light emissions

Scintillation of point radio sources

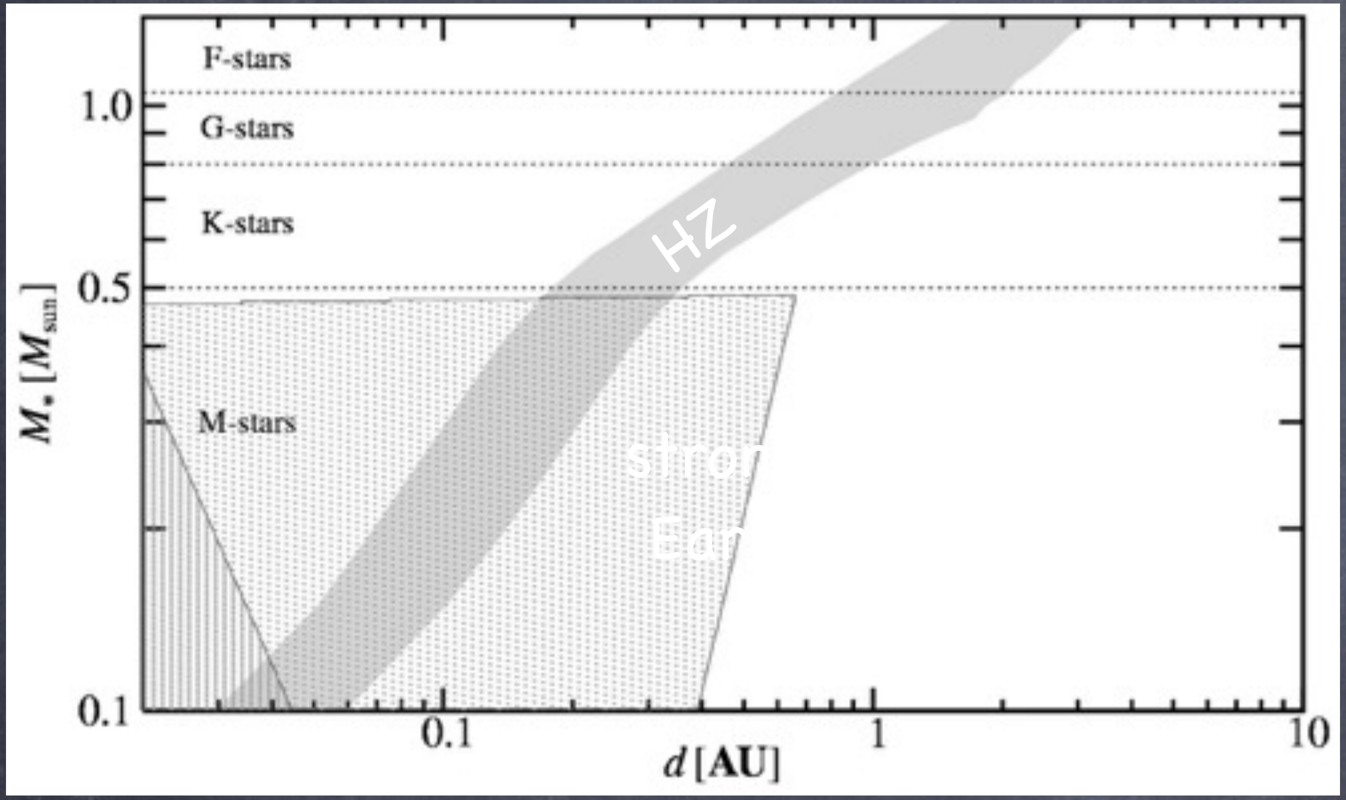
amplitude & phase of signal from background radio sources changes due to CME propagation across the line of sight



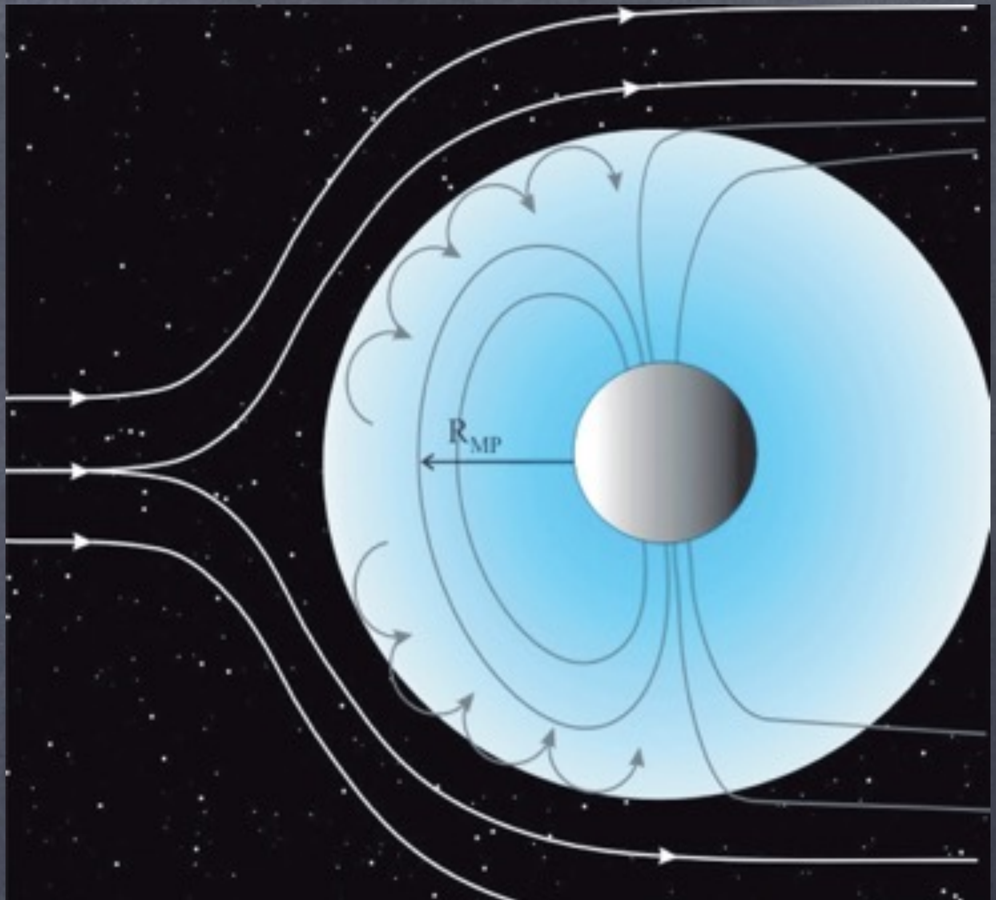
Observing CMEs on Stars

- high velocity outflows seen in emission lines
- pre-flare “dips”
- increase in X-ray absorption
- Effect of CMEs on stellar environment
- type II-like bursts associated with stellar flares
- utilize association with stellar flares

Stellar magnetic events can impact exoplanet habitability



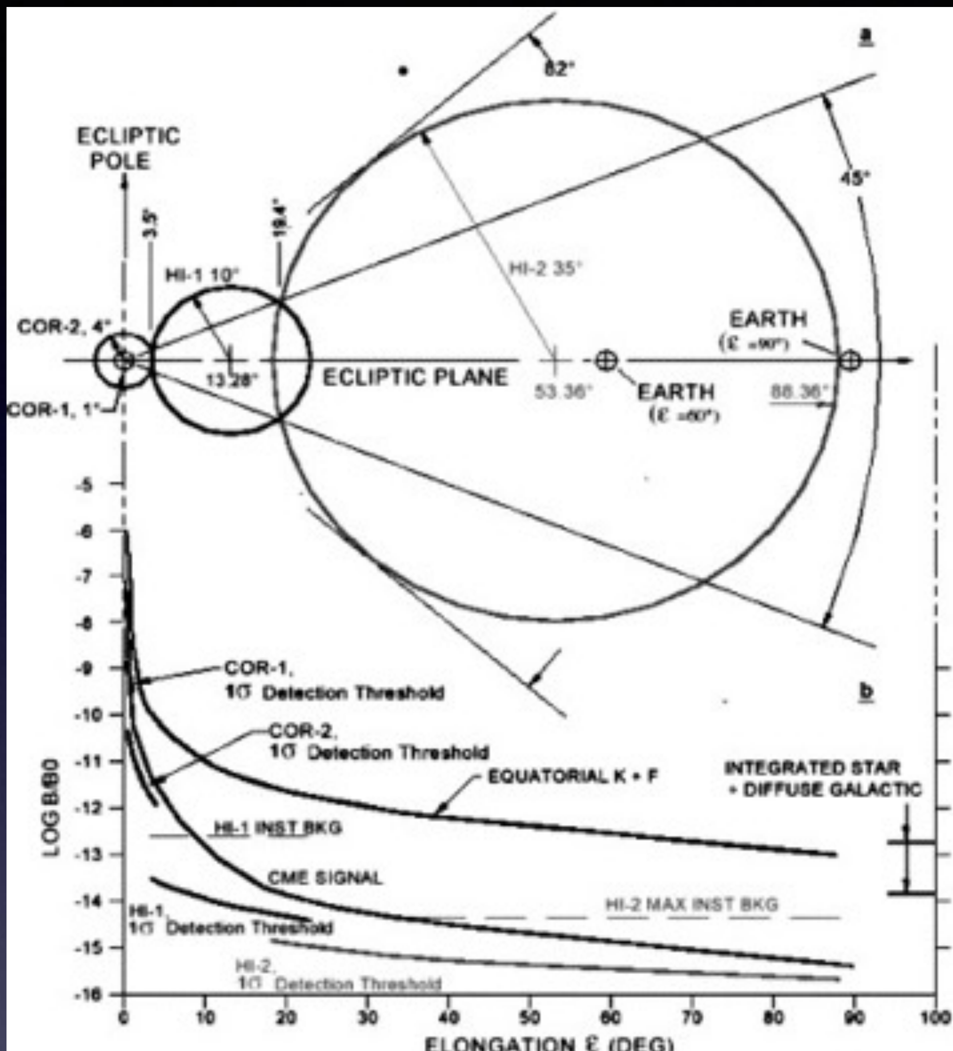
Khodachenko et al. (2007)



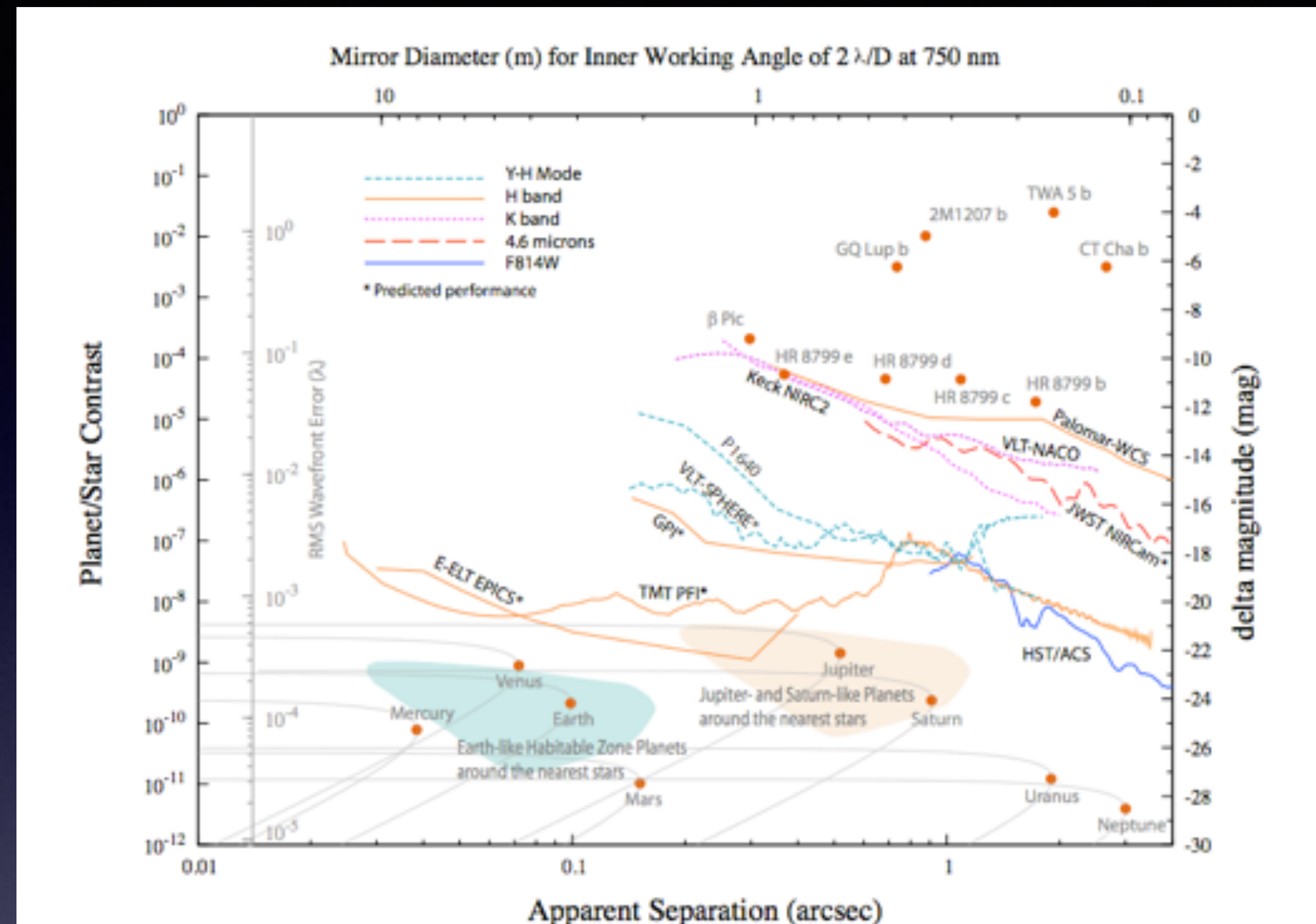
Lammer et al. (2007)

- 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

Solar vs. Astronomical Coronagraphs



Harrison et al. (2005) specs for STEREO coronagraphs

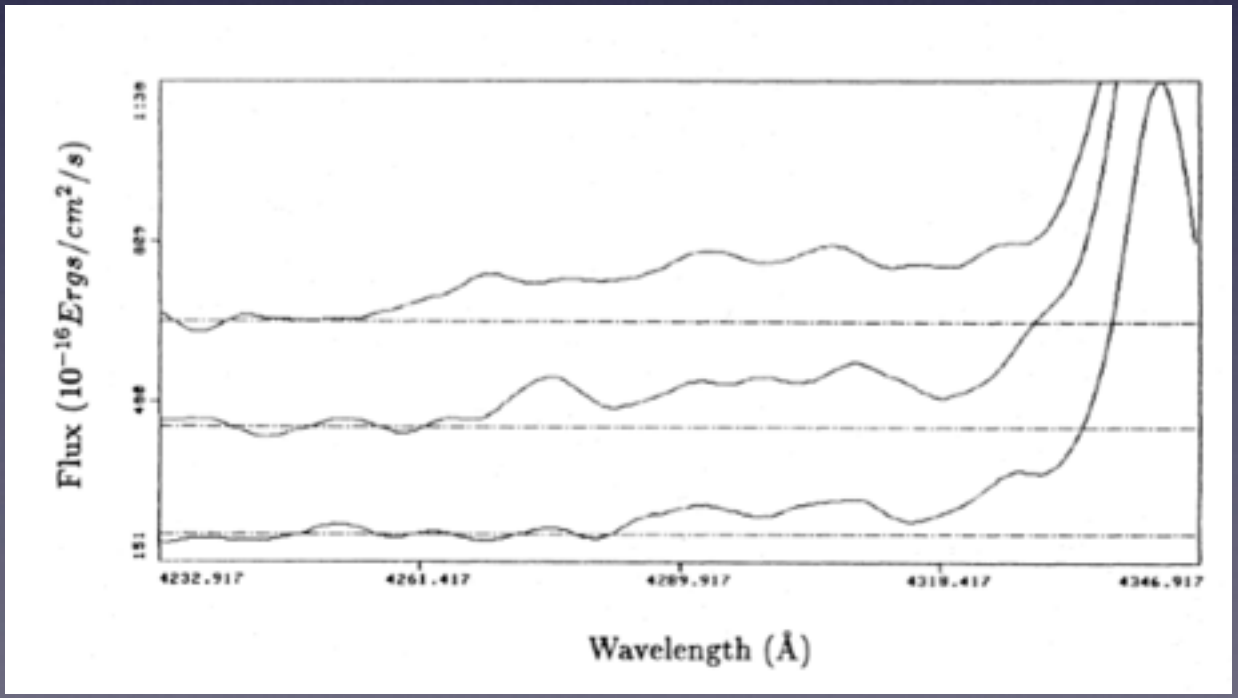


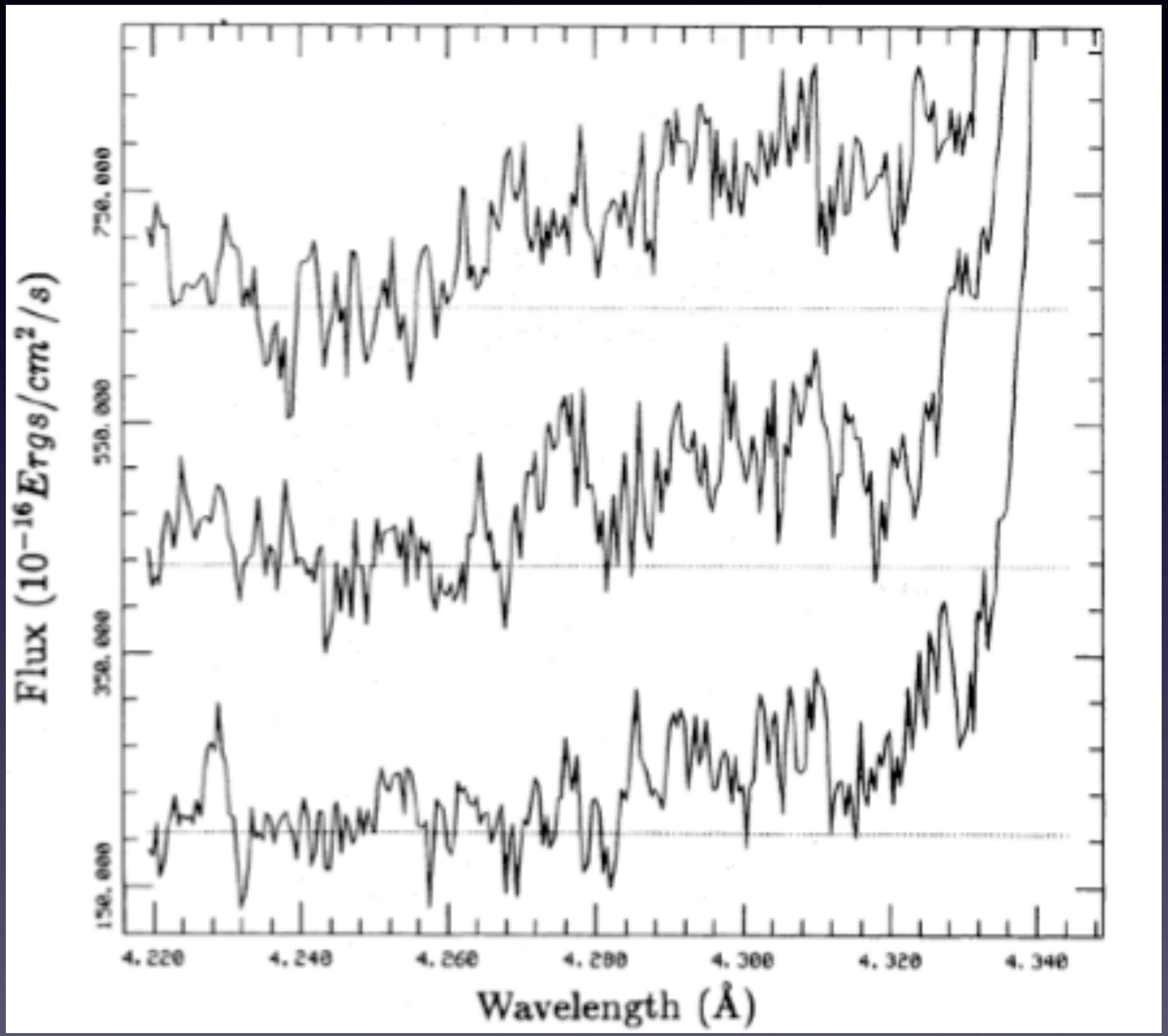
Mawet et al. (2012)

- angular separation of a stellar CME early on: 2 Rstar at 5 pc = 0.5 mas
- contrasts achievable >10^{-7} (point source)
- no prospects for observing stellar CMEs using coronagraphic observations

High velocity outflows

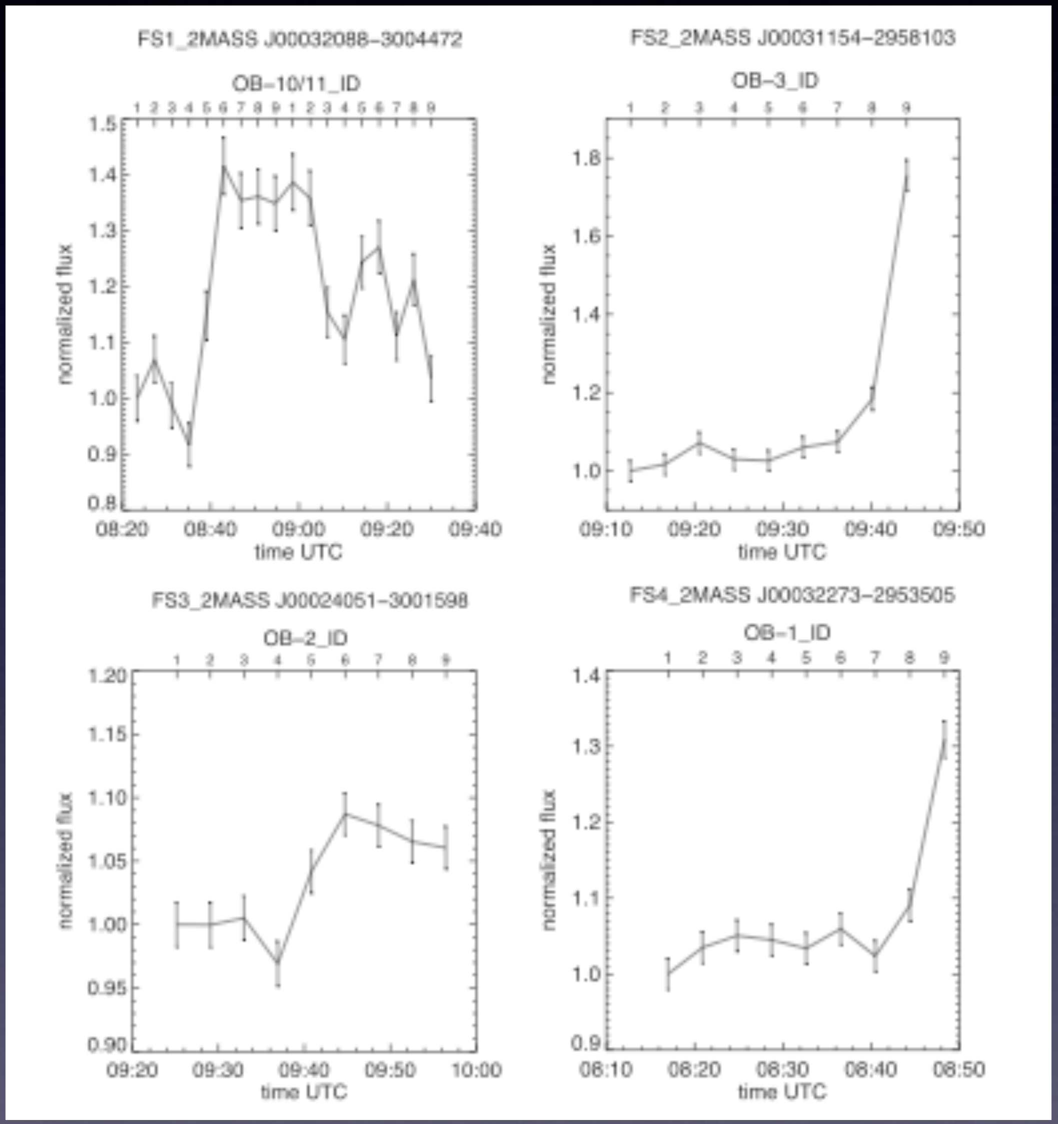
Houdebine et al. (1990) evidence for a ~5800 km/s blueshifted outflow during a moderate flare on the M dwarf AD Leo





Pre-flare "dips"

- dips or diminutions in flux prior to a flare have been claimed to be signatures of CMEs (Leitzinger et al. 2014)
- not regularly occurring
- need a reliable signature which can be ascribed to CMEs, not flare processes

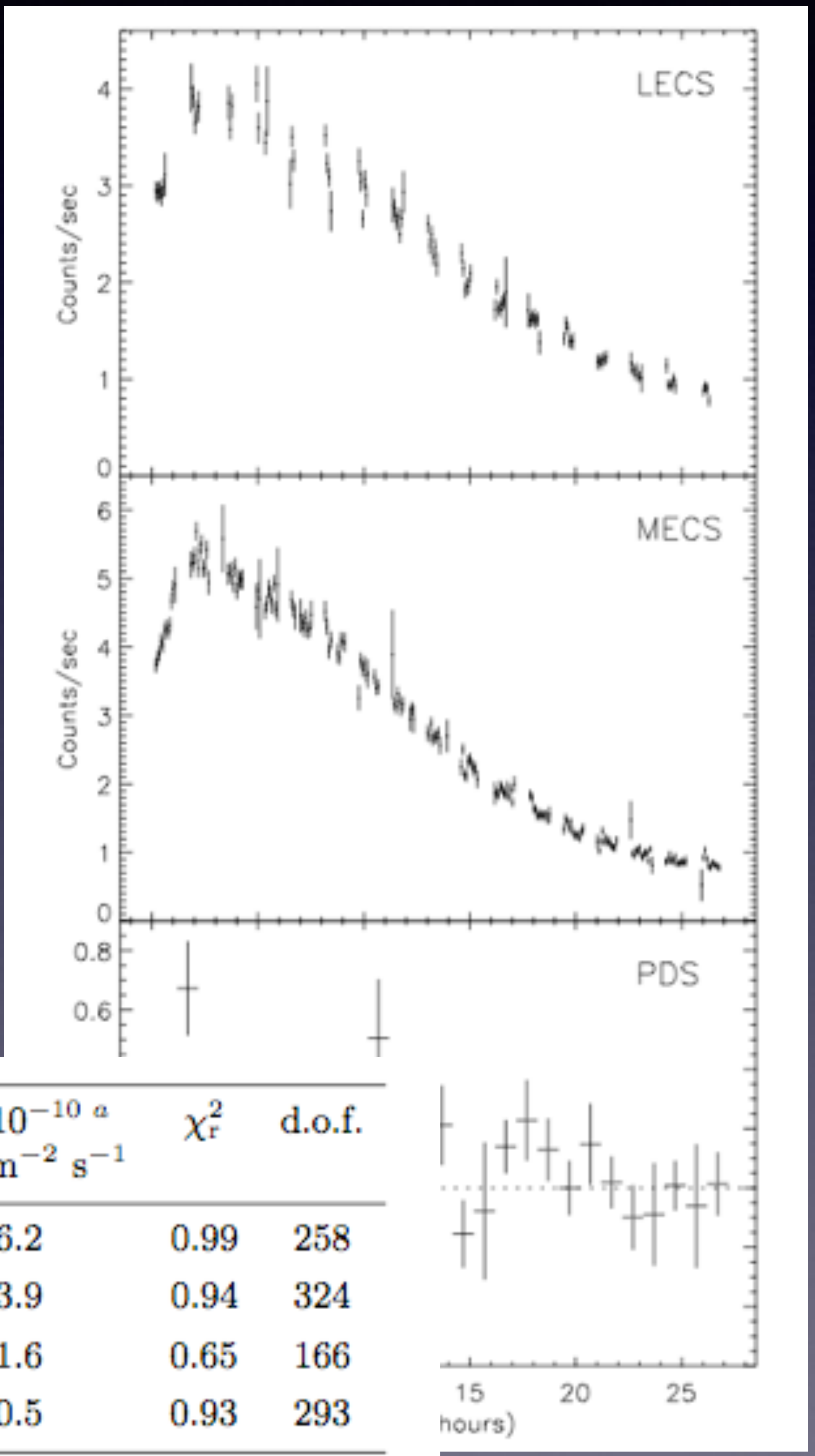


Leitzinger et al. (2014) two flares with 1-2% dips lasting for ~3 minutes

stars in the Blanco-1 young (30-145 MY) cluster

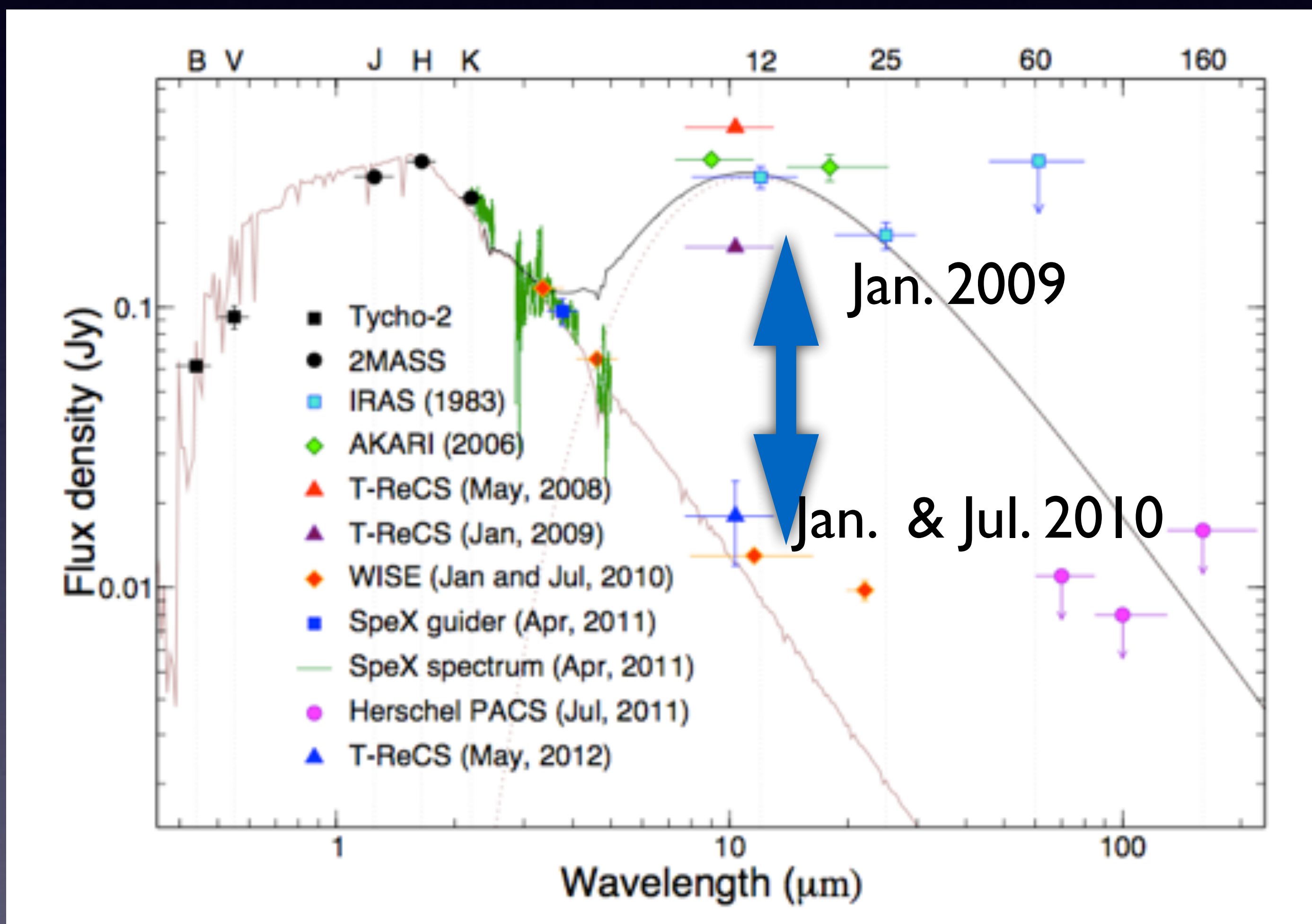
Excess absorption at X-ray wavelengths

- Franciosini et al. (2001) BeppoSAX observations of a large long duration flare on the active binary UX Ari
- N_H during the flare is higher by a factor of ~5, "perhaps due to the ejection of material"



	Interval	$N_H/10^{19}$ cm^{-2}	$Z/Z_\odot$	T_1 keV	T_2 keV	$EM_1/10^{53}$ cm^{-3}	$EM_2/10^{53}$ cm^{-3}	$F_x/10^{-10}$ [a] erg cm^{-2} s^{-1}	χ^2_r	d.o.f.
Aug. 97	peak	$10.7^{+4.3}_{-3.7}$	$0.33^{+0.08}_{-0.09}$	$2.89^{+1.70}_{-0.28}$	$9.54^{+2.58}_{-0.85}$	57.4	52.7	6.2	0.99	258
	decay	$9.2^{+2.7}_{-1.9}$	$0.18^{+0.10}_{-0.04}$	$1.31^{+0.14}_{-0.30}$	$4.00^{+0.27}_{-0.12}$	14.7	65.2	3.9	0.94	324
	end	$10.4^{+5.1}_{-4.1}$	$0.19^{+0.13}_{-0.09}$	$0.90^{+0.32}_{-0.24}$	$2.63^{+0.54}_{-0.23}$	8.4	28.4	1.6	0.65	166
Aug. 98	quiescent	$2.6^{+2.6}_{-2.2}$	$0.25^{+0.09}_{-0.08}$	$0.86^{+0.17}_{-0.11}$	$2.17^{+0.37}_{-0.14}$	3.9	9.0	0.5	0.93	293

CME effect on debris disk



Melis et al. (2012) showing the rapid disappearance of a debris disk on timescales of ~1 year

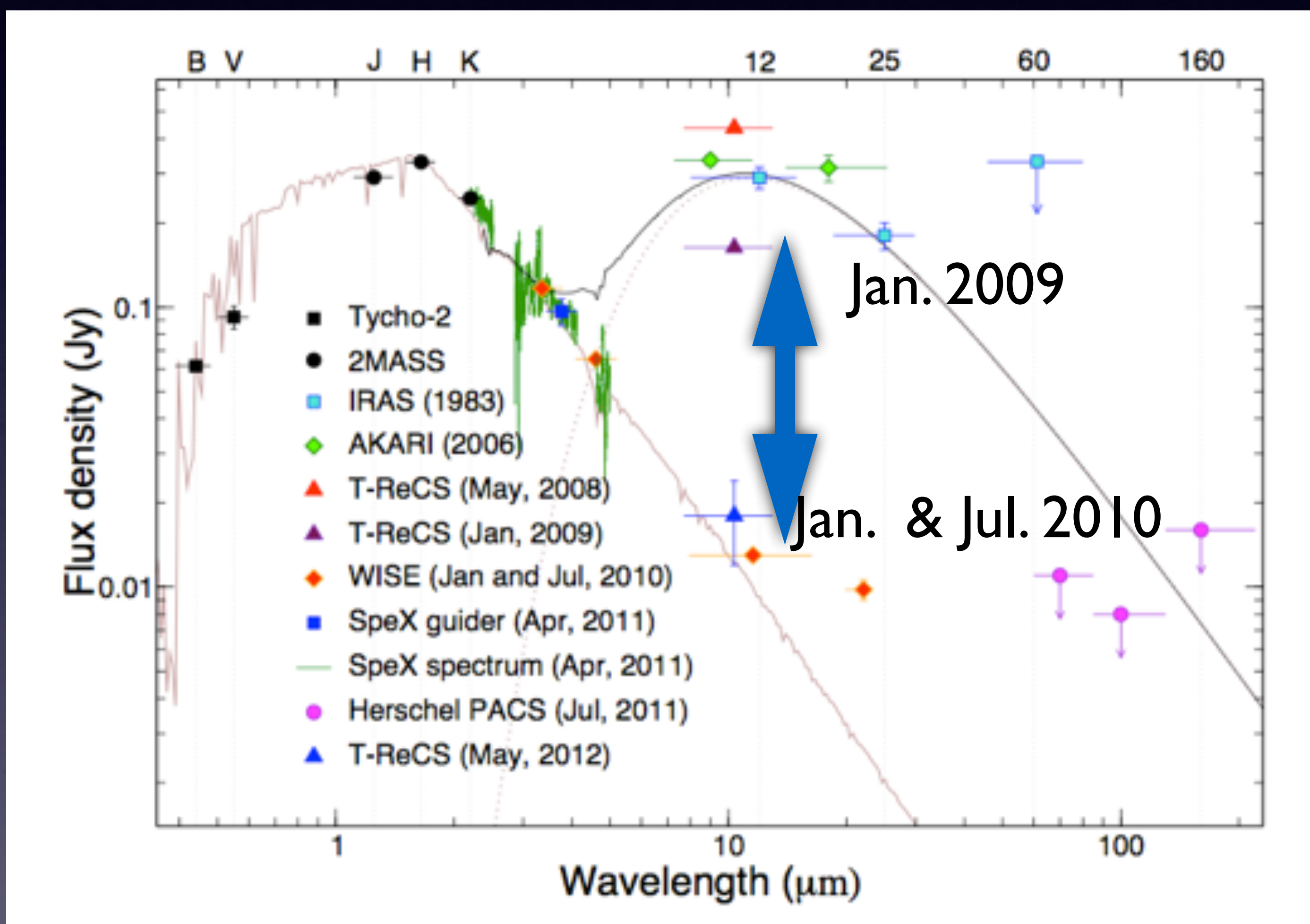
The star, TYC 8241 2652 1, is a K2 dwarf with an age about 10 MY

grains present in 2009 and before modelled as size ~0.3 μm, temperature 450 K, 0.4 AU separation from the star, total mass 5×10^{21} g

grains smaller than 0.2 μm would be radiatively ejected from the system

Melis et al. (2012) considered the effect of X-rays: they are ineffective at heating grains of this size, and would require L_x 10^2-10^3 L_*, E~10^{39} erg

CME effect on debris disk



In addition to the Melis et al. (2012) report, Meng et al. (2010) note mid-IR variability at a level of 10-30% in two late-type stars with debris disks

what about using a CME to remove the grains?
A flare could charge the dust grains in the debris disk, and with sufficiently small gyroradii they would be swept up by the magnetic plasma in the CME and removed

$$m_{\mathrm{CME}} = m_{\mathrm{dust}} \frac{V_e^{\mathrm{dust}}}{V_{\mathrm{CME}}} \simeq 0.07 m_{\mathrm{dust}},$$

For the Melis case, removing ~10^{21}g in grains requires a CME with mass ~10^{20}g. Timescale for removal is on the order of a few days

Stellar radio emission from CMEs

- expectations for drifting radio bursts:

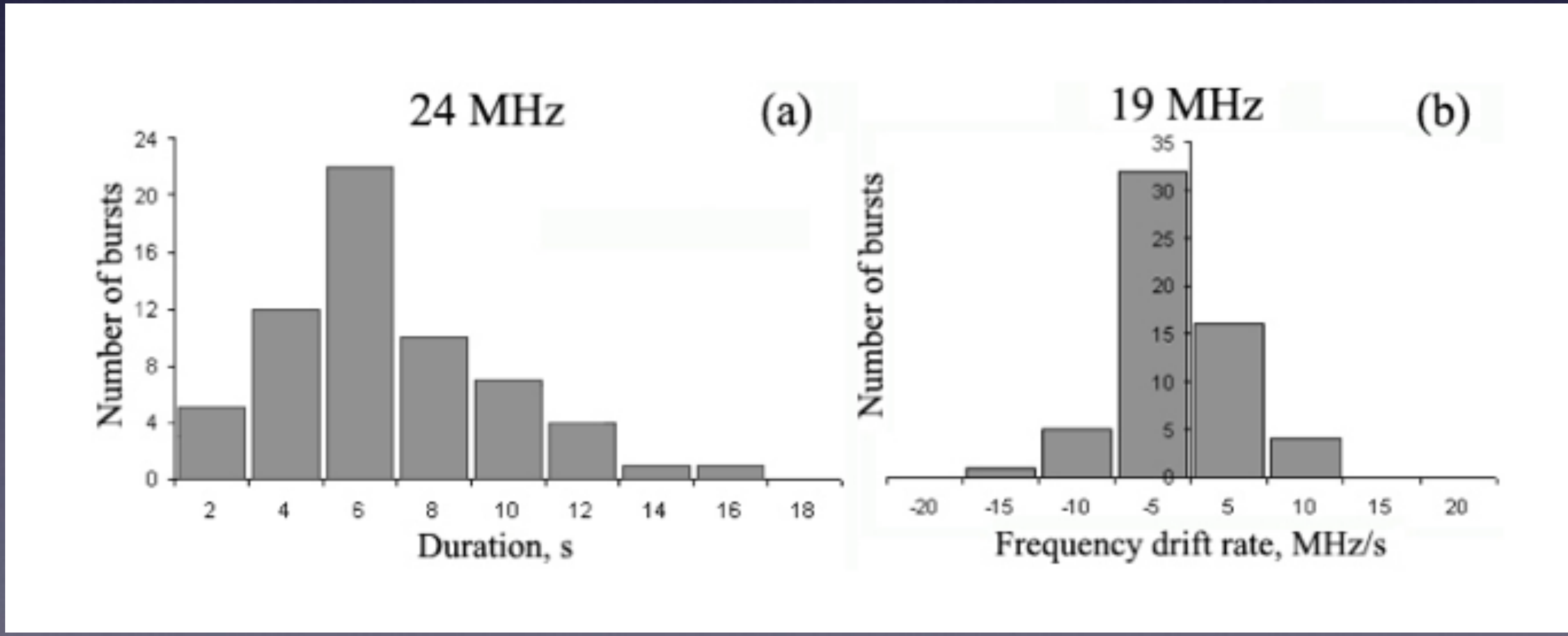
$$\frac{d\nu}{dt} = \frac{\partial \nu}{\partial n_e}\frac{\partial n_e}{\partial h}\frac{\partial h}{\partial s}\frac{\partial s}{\partial t}$$

$$\dot{\nu} = \nu \cos\theta v_B/(2H_n)$$

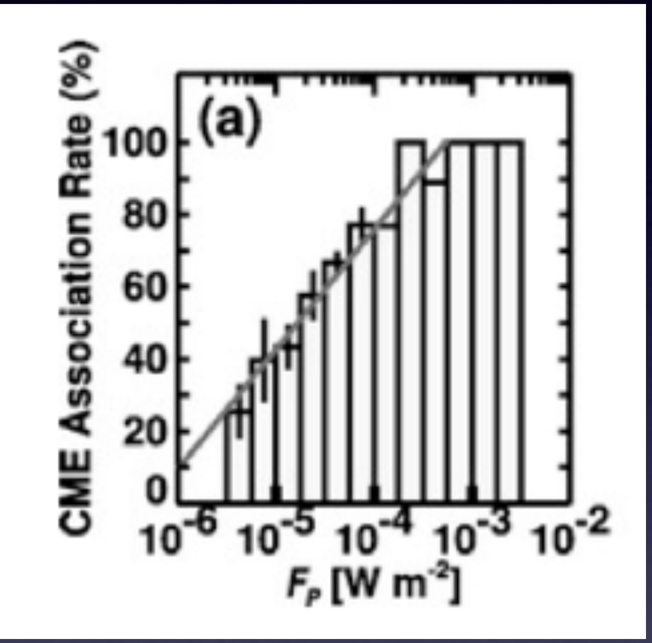
- expected drift rate for coronal parameters of an active star, H_n=2x10^{10} cm for T~10^7 K, weakly super Alvenic shock gives (dependent on B, n) drift rates of a few MHz s^{-1}

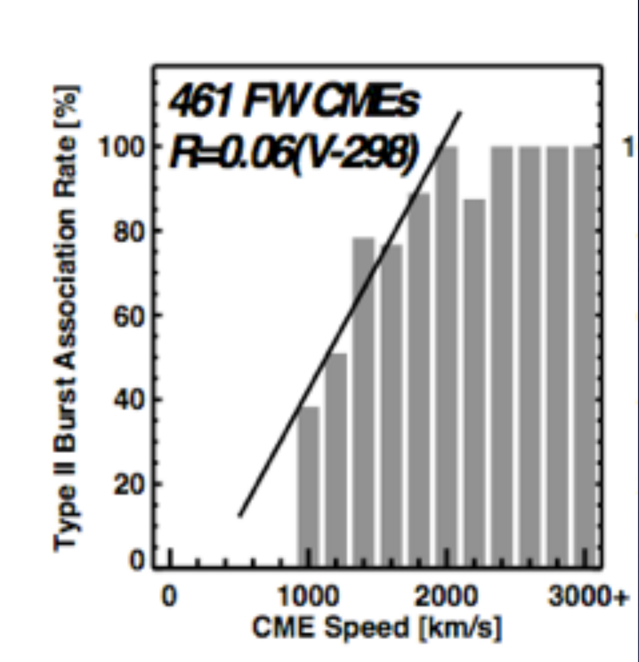
Stellar radio emission from CMEs

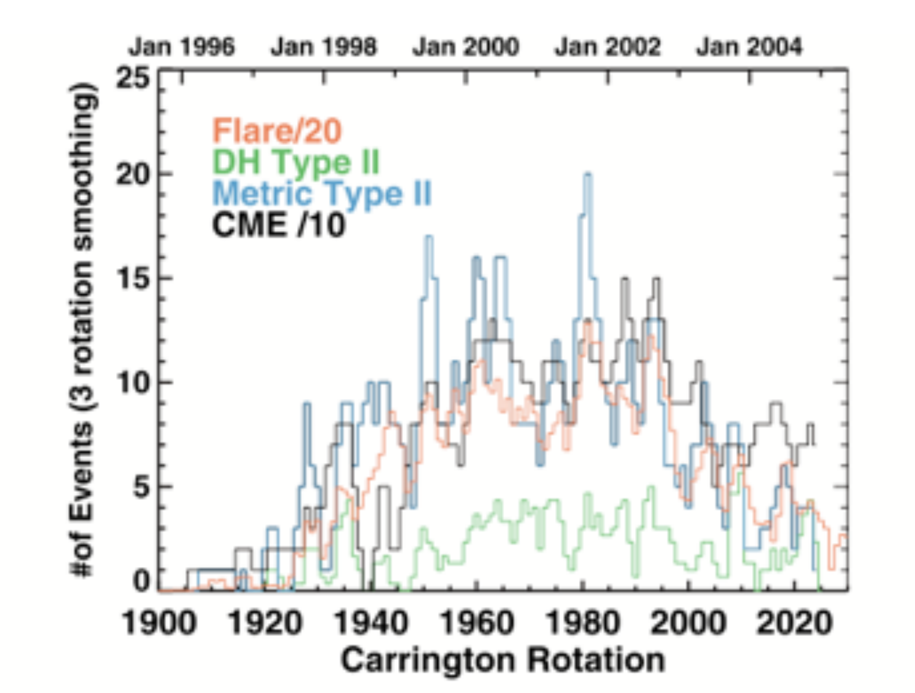
Konovalenko et al. (2012) drifting radio bursts seen at 16.5-33.0 MHz on AD Leo



Observing stellar CMEs through coherent radio emission



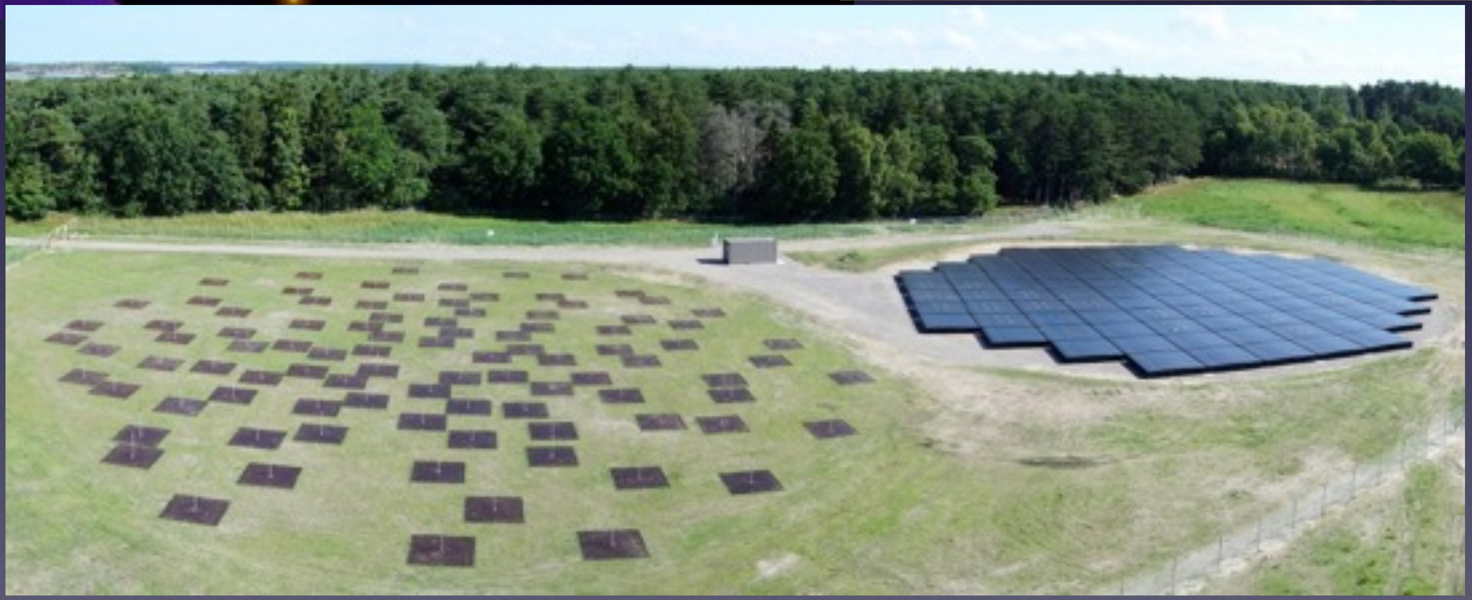




- 100% association between large solar flares and large CMEs (Yashiro et al. 2006)
- type II burst association with CME increases with increasing CME speed (Gopalswamy 2008)
- only ~10% of solar CMEs show decimetric type II bursts (Gopalswamy 2006)

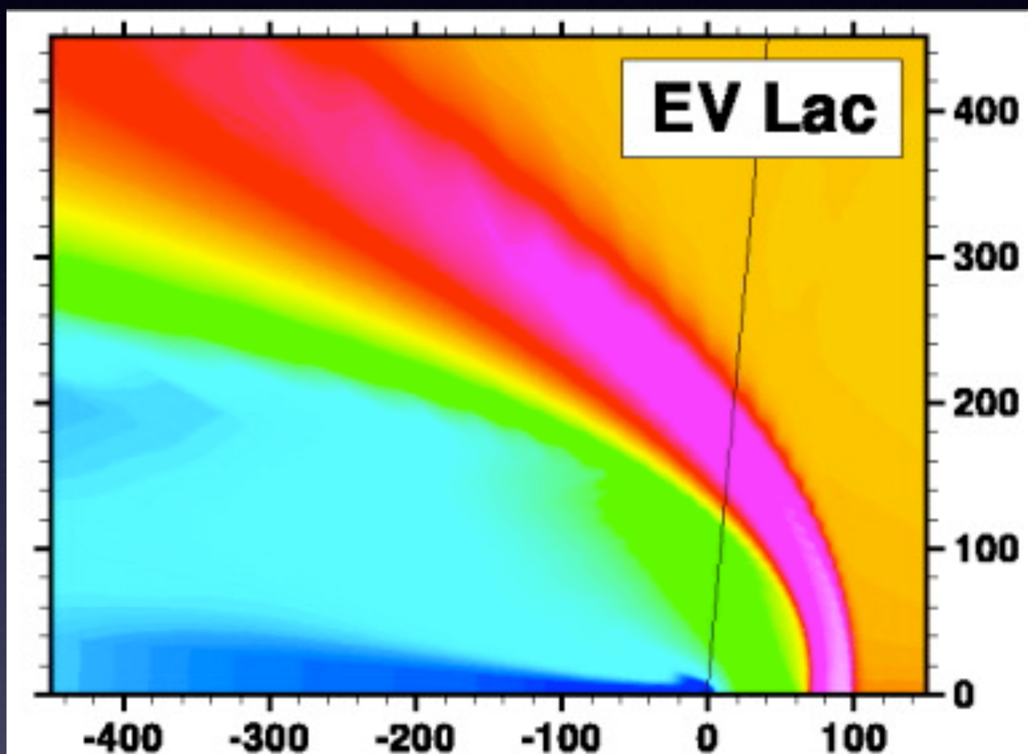
Observing stellar CMEs through coherent radio emission





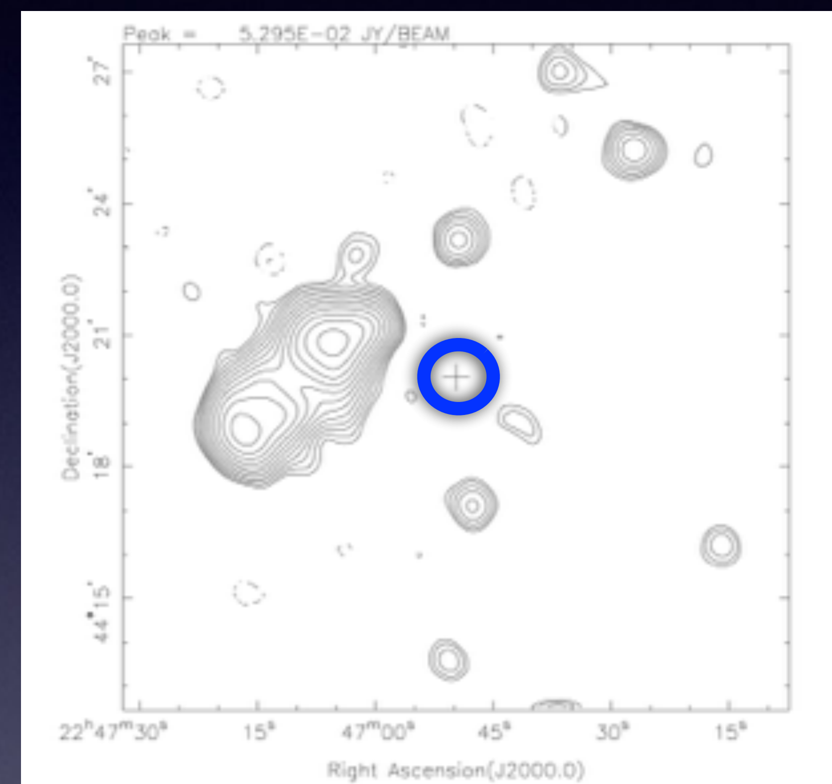
- LOFAR [LBA (10-90 MHz) HBA (110-250 MHz)]
- JVLA (240-480 MHz)
- need the optical observations to confirm that a flare has occurred, measure its gross properties (energy, peak flux, duration)

Observing stellar CMEs through scintillation of background radio sources



Wood et al. (2005) suggested size of EV Lac's astrosphere
300 AU ~ 1 arcminute

would need to find (1) background sources expected to be close enough to the stellar position, and (2) others far enough away to serve as test points



15 arcminute

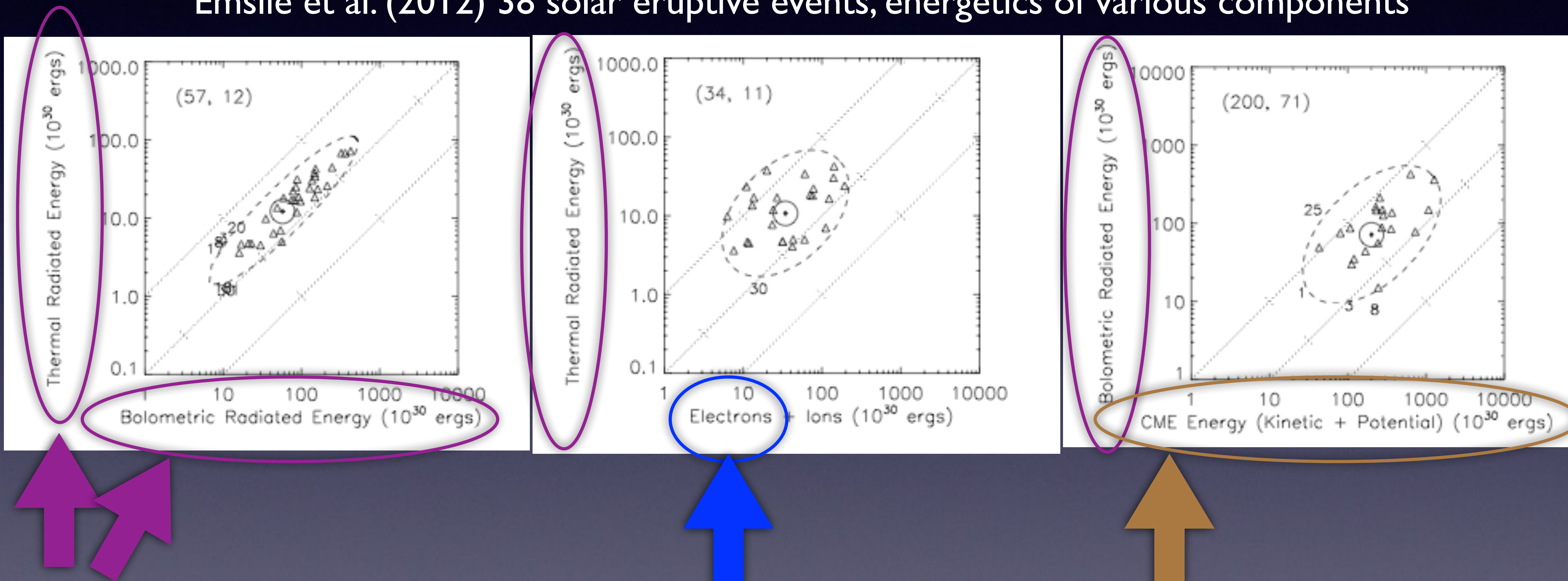
radio sources around the flaring M dwarf EV Lac from NVSS

Connecting Flares and CMEs

- numerous observations of solar and stellar flares show commonalities, which suggests a similar origin
- solar eruptive events show scalings between solar flares and CMEs, which if applied to stellar flares & CMEs could be a powerful (& relatively easy) way to probe stellar eruptive events

Seeing the Forest for the Trees
(e.g. “Global Energetics” and Trends)

Emslie et al. (2012) 38 solar eruptive events, energetics of various components

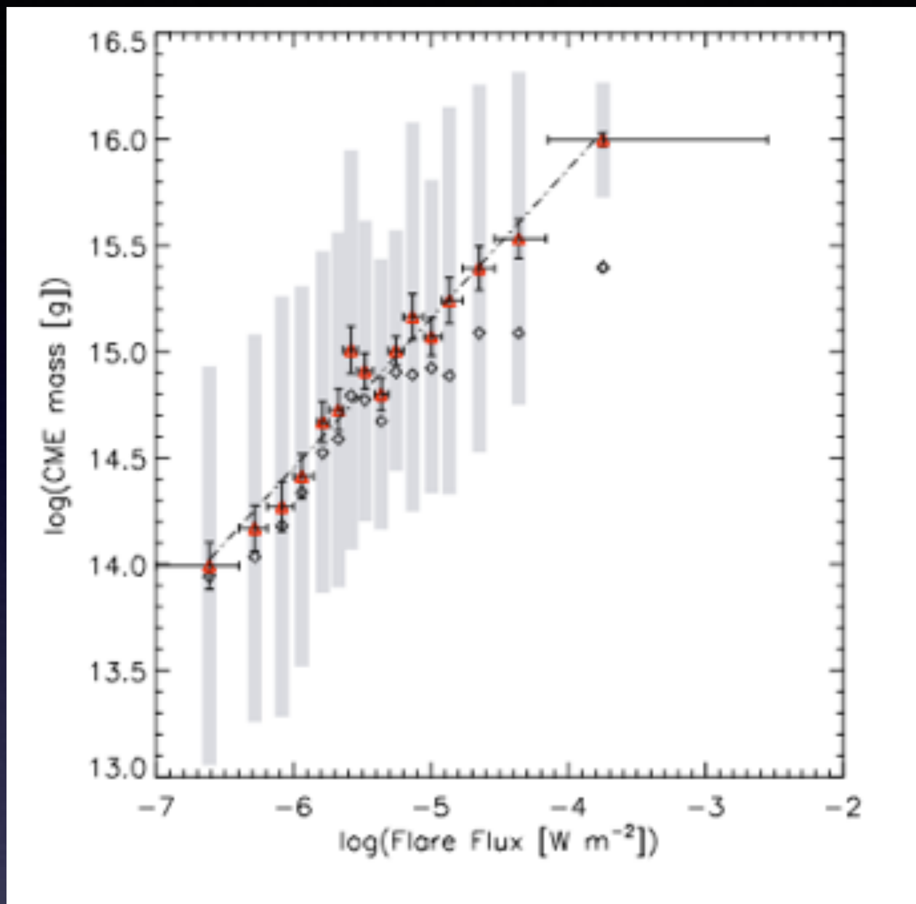


have a hope of measuring in stellar flares

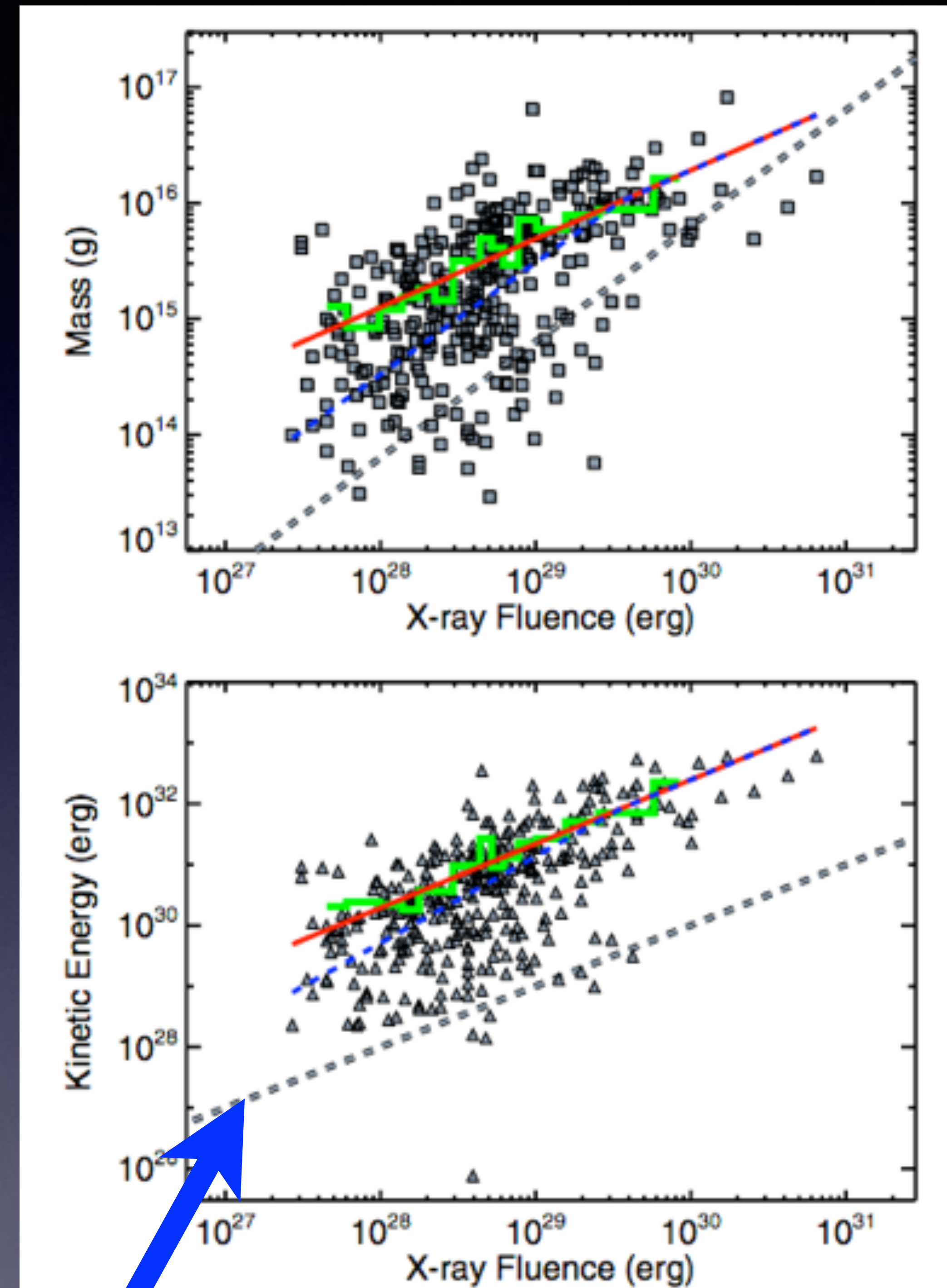
might possibly constrain in stellar flares

might never constrain in stellar flares (but important to try)

Empirical solar CME mass - flare energy scalings



Aarnio et al. (2011, 2012)



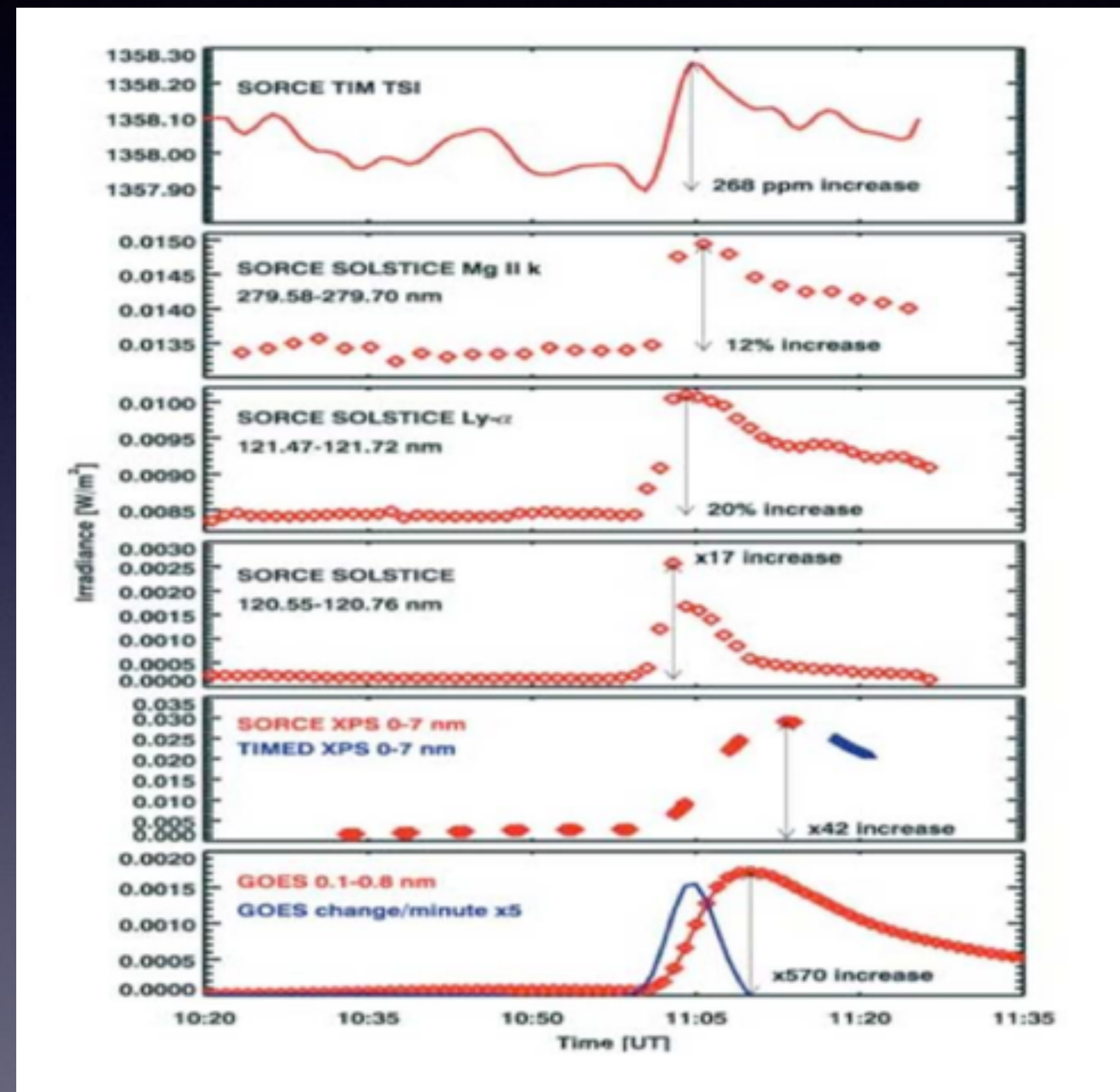
Drake et al. (2013)

both papers find a relation $M_{CME} \propto E_{GOES}^{\beta}$ with $\beta \sim 0.6$

line of equality between X-ray flare energy and CME KE

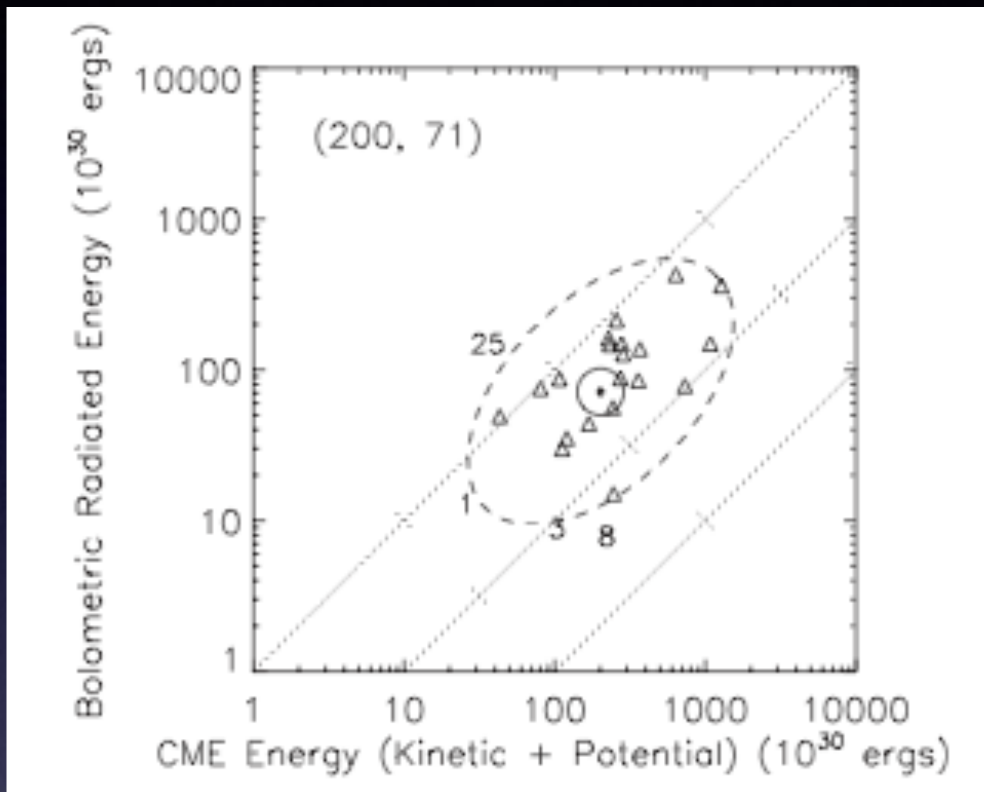
Optical Flares Dominate Energetics

- While flare contrast in total solar irradiance is tiny, energetic importance dominates in solar flares -- 100x the energy seen in X-rays (first seen in 2003!)
- solar flares are seen in white light, but rarely in the stellar equivalent (Total Solar Irradiance)
- Also evidence for a hot blackbody component to blue-optical solar flare spectra, similar in temperature (~9000 K) to what is routinely seen in M dwarf stellar flares (Hawley et al. 1995)



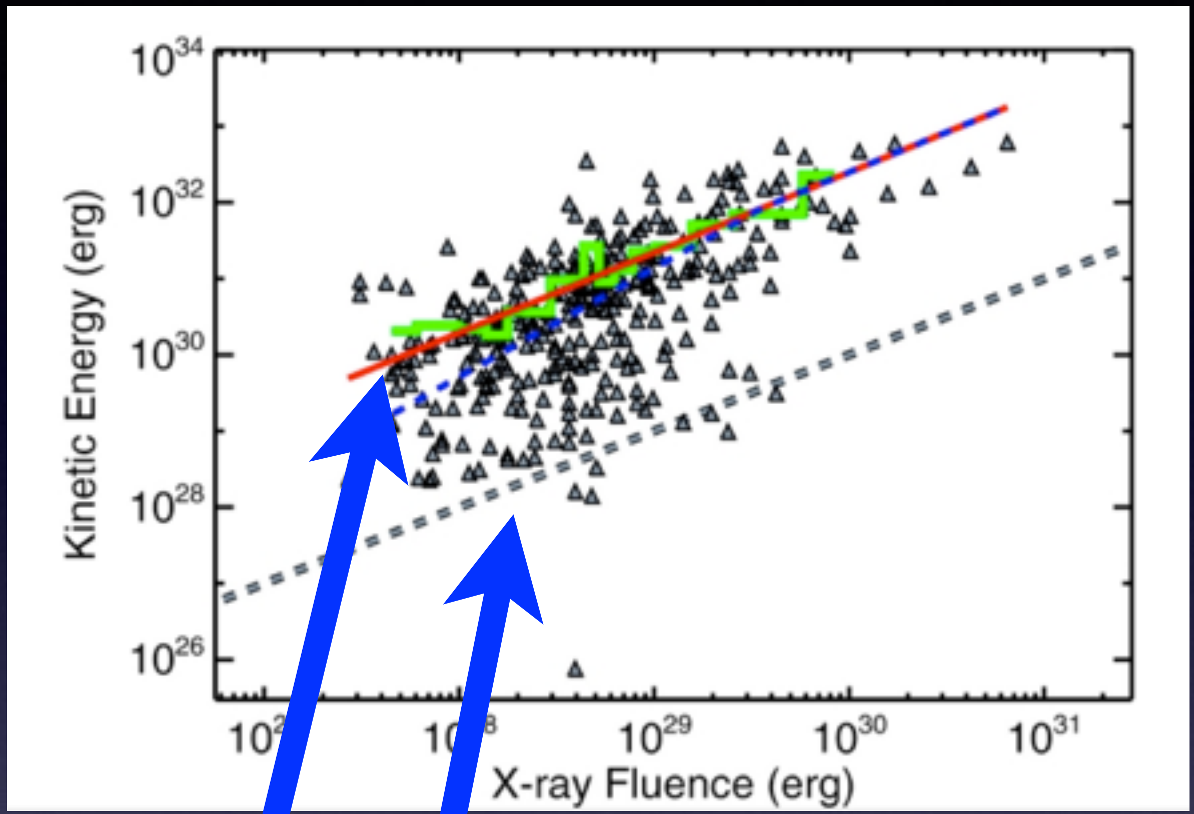
Woods et al. 2004 Kretzschmar et al. 2011

Solar CME energy - flare energy scalings reveal rough equipartition



Emslie et al. (2012)

$E_{CME} \sim 3\ E_{bol}$



Drake et al. (2013)

line of equality between X-ray flare energy and CME KE

with $E_{GOES}/E_{bol} \sim 0.01$, KE $\sim 2\ E_{bol}$

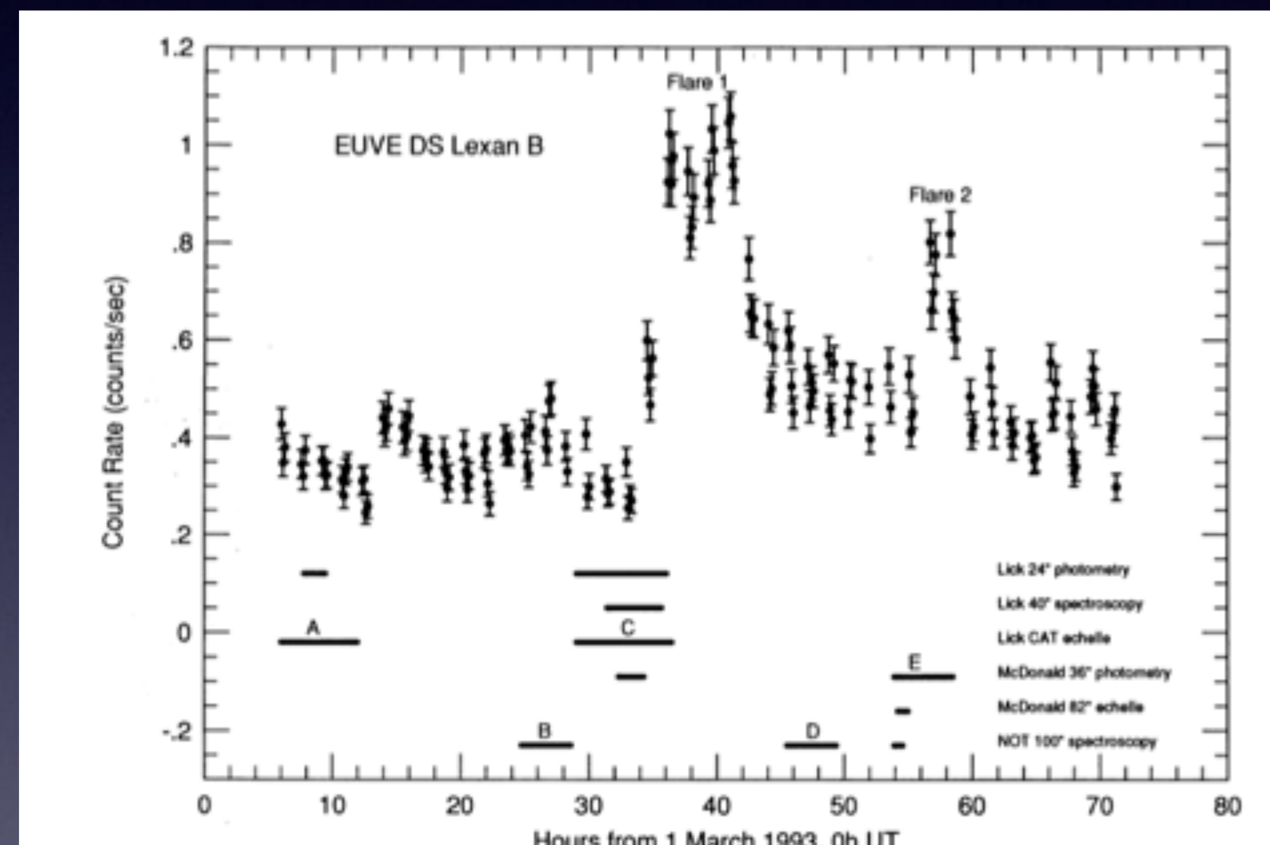
Optical-Coronal stellar flare scaling

many flares studied on nearby stars, few with panchromatic observations

Derived Quantities

Quantity	EF1	EF2	AU Mic
Optical			
T_{fl} (K)	9000	9500	…
A_{opt} (cm^2)	1.1×10^{18}	5.6×10^{17}	…
$A_{opt}/4\pi R_*^2$	1.0×10^{-4}	5.3×10^{-5}	…
E_{opt} (ergs)	$>4.6 \times 10^{33}$	2.8×10^{33}	…
Coronal			
L (cm)	3.8×10^{10}	$<1.5 \times 10^{10}$	2.6×10^{10}
N_{max} (cm^{-2})	1.3×10^{21}	$<1.0 \times 10^{21}$	1.5×10^{21}
P_{max} (dyne cm^{-2})	180	<280	350
A_{cor} (cm^2)[a]	9.1×10^{19}	1.9×10^{19}	1.7×10^{21}
$A_{cor}/4\pi R_*^2$[a]	0.0085	0.0018	0.045
V (cm^3)[a]	7.1×10^{30}	5.6×10^{29}	8.8×10^{31}
EM (cm^{-3})[a]	8.2×10^{51}	2.5×10^{51}	2.9×10^{53}
E_{th} (ergs)[a]	1.9×10^{33}	2.3×10^{32}	4.6×10^{34}

[a] The coronal area coverage, volume, emission measure, and thermal energy listed here assume no correction for possible "dead spot" effects in the AD Leo observation. If a correction factor f_{ds} is applied, each quantity should be multiplied by f_{ds}.



Hawley et al. 1995 flares on AD Leo, M3e

$f_{opt}+f_{cor}=1$ for total radiative energy release, then $f_{cont}=0.6$, $f_{cor}=0.3$

Flare Energy Partition

	λ range	$f=E_{rad}/E_{bol}$ (Sun)	$f=E_{rad}/E_{bol}$ (active stars)
GOES	1-8 Å	0.01	0.06
coronal	0.01-10 keV	0.2	0.3
hot blackbody	1400-10000 Å	0.7	0.6
U band	3000-4300 Å		0.11
Kepler	4000-9000 Å		0.16

Osten & Wolk (2014)

- With an equipartition between flare bolometric radiated energy and CME KE (ε=1), the implications of flare-related transient mass loss can be explored
- Need flare energy partition *f* to relate observed flare energies in a particular waveband to bolometric values

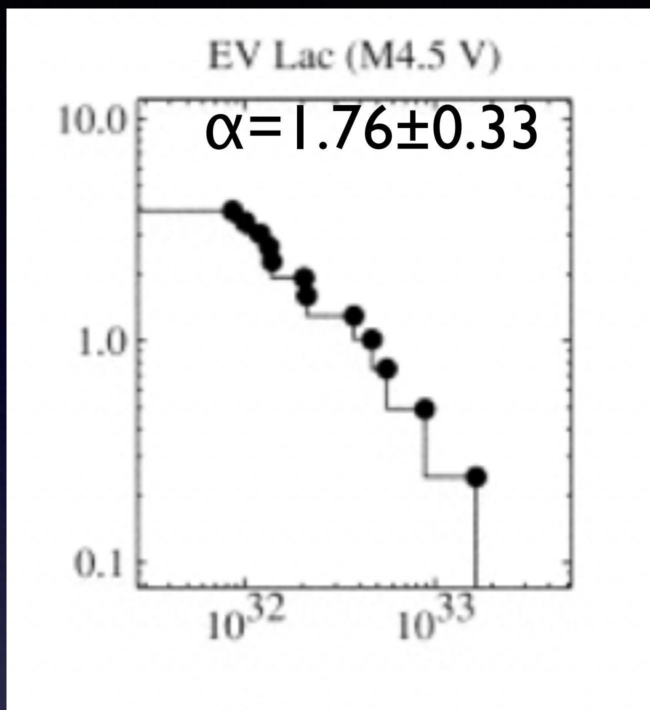
$$\dot{M}_{\rm CME} = \int_{M_{\rm CME,min}}^{M_{\rm CME,max}} M_{\rm CME} \left(\frac{dN}{dM}\right) dM$$

$$\dot{M}_{\rm CME} = \frac{2}{v^2} \frac{N_{\rm tot}}{\epsilon f} \frac{(1-\alpha)}{(2-\alpha)} \frac{(E_{\rm rad,max}^{2-\alpha} - E_{\rm rad,min}^{2-\alpha})}{(E_{\rm rad,max}^{1-\alpha} - E_{\rm rad,min}^{1-\alpha})}$$

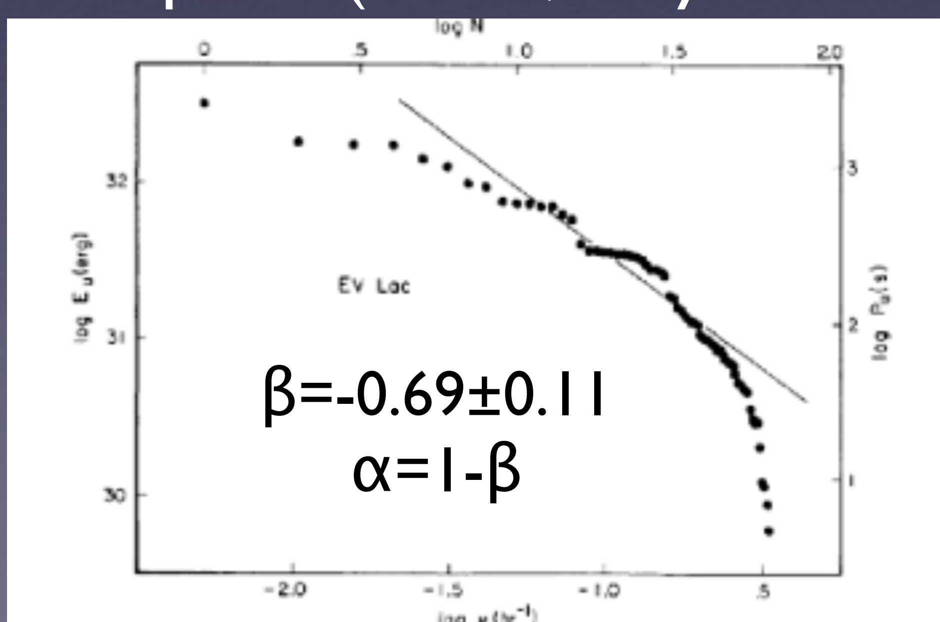
- constant CME speed ~v_{esc}, , N_{tot}, α are from the flare frequency distribution

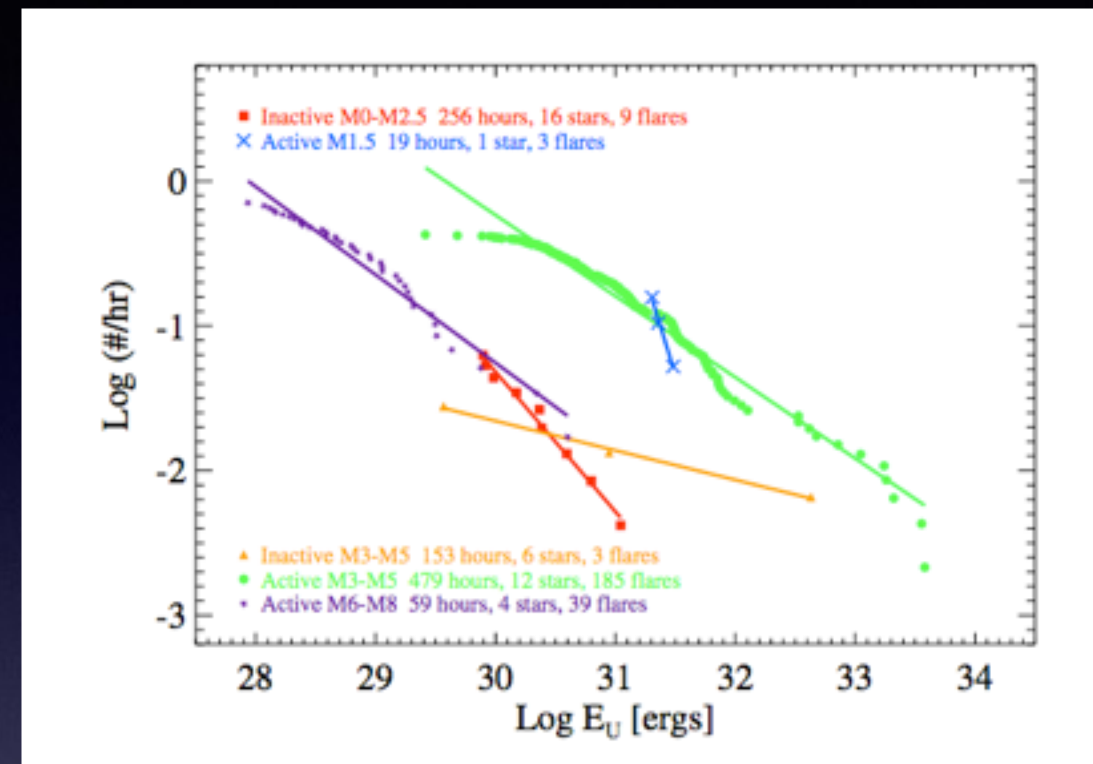
$$\frac{dN}{dE_{\rm rad}} = K_E \ E_{\rm rad}^{-\alpha}$$

Connecting Flares and CMEs



EV Lac flare frequency distribution in coronal (above, Audard et al. 2000), and optical (below, Lacy et al. 1976)





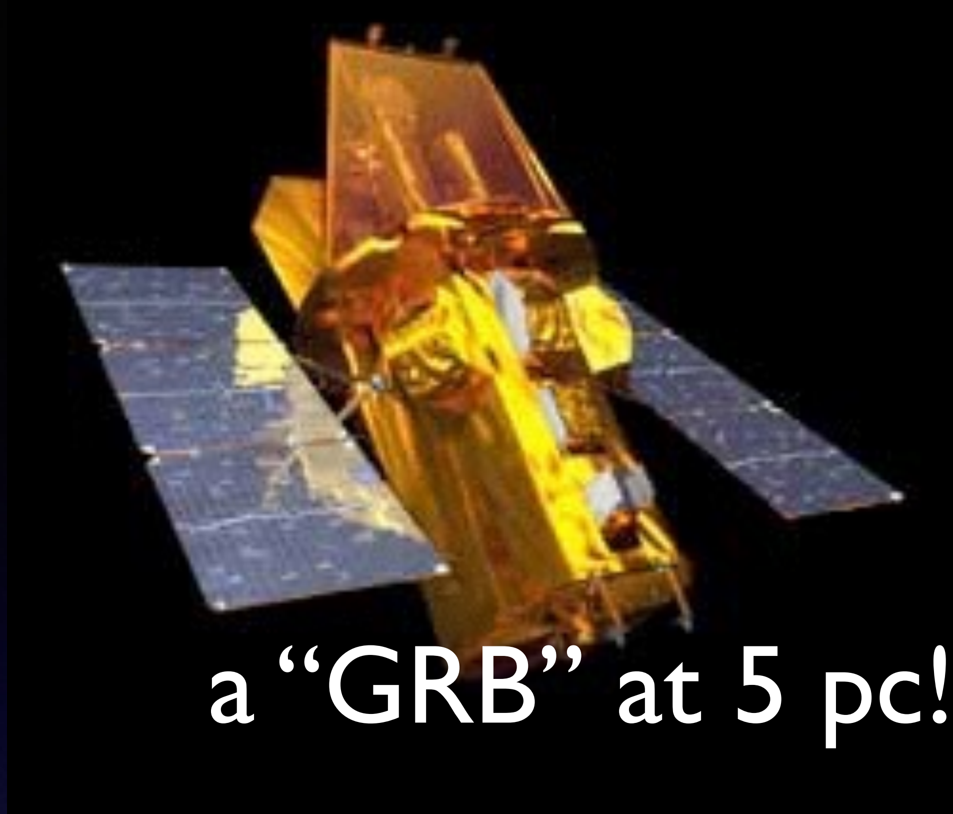
Hilton (2011) PhD dissertation optical flare frequency distributions of different types of M dwarfs

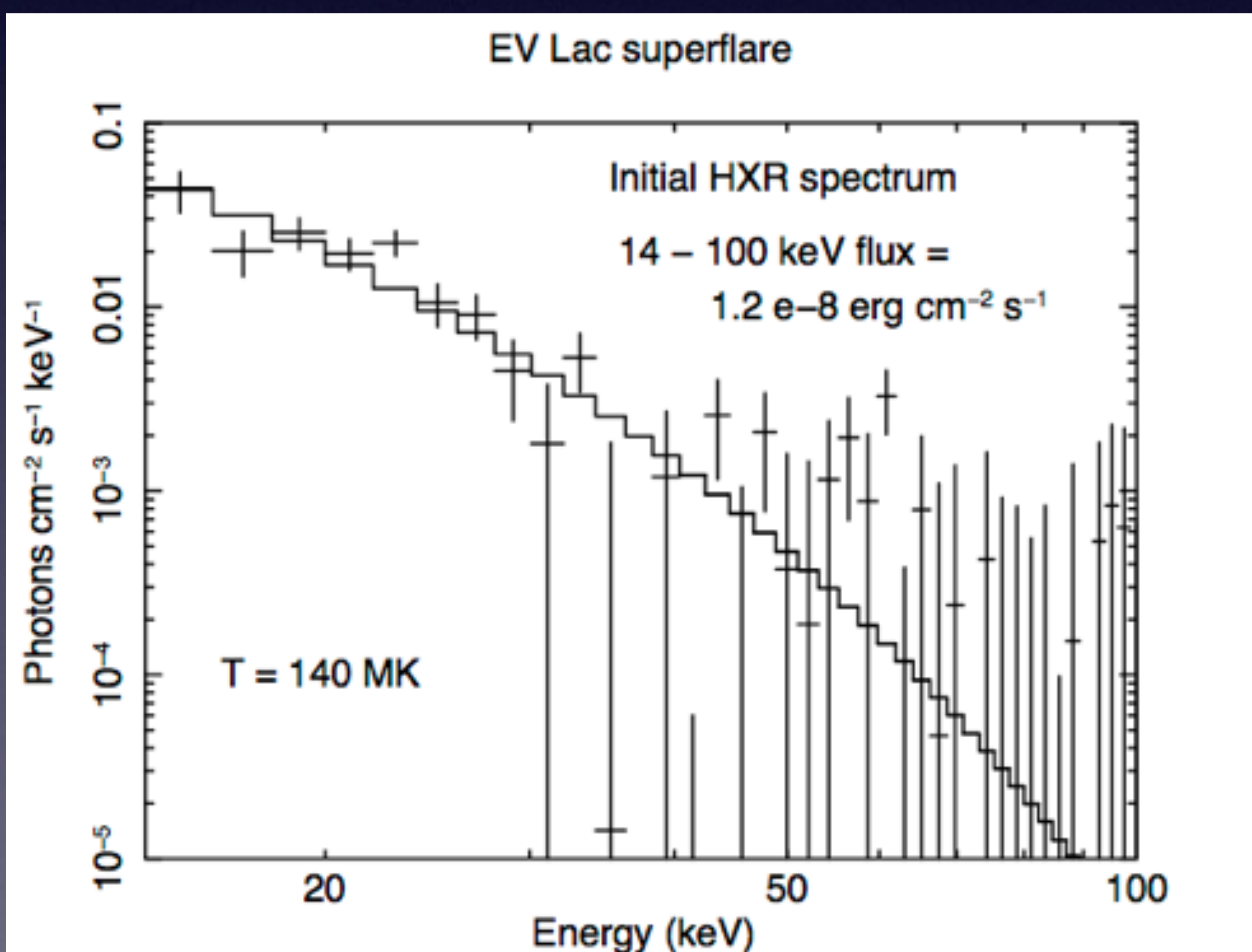
Star	band	Emin	Emax	α	M (equipartition)	M (empirical)
AD Leo	SXR	$6x10^{31}$	$2x10^{33}$	2.02±0.28	$5x10^{-13}$	$3x10^{-13}$
AD Leo	U	$2x10^{30}$	$3x10^{31}$	1.82±0.27	$6x10^{-14}$	$8x10^{-14}$
EV Lac	SXR	$8x10^{31}$	$2x10^{33}$	1.76±0.33	$4x10^{-13}$	$2x10^{-13}$
EV Lac	U	$1x10^{31}$	$5x10^{31}$	1.69±0.11	$9x10^{-14}$	$9x10^{-14}$
Kepler superflares	Kepler	$5x10^{34}$	$2x10^{36}$	2.3±0.3	$8x10^{-13}$	$3x10^{-14}$
inactive early M dwarfs	U	$8x10^{29}$	1031	1.97±0.3	10^{-16}	$3x10^{-16}$
inactive mid-M dwarfs	U	$4x10^{29}$	$4x10^{32}$	1.2±0.1	$4x10^{-15}$	$2x10^{-15}$

Osten & Wolk (2014)

Discussion

- Sun as a star observations of CMEs
- Bulk properties of CMEs, correlations with flares
- CME KE ~ $E_{flare,\ bol}$
- Conditions necessary for formation of type II burst against CME conditions inferred
- CME speed in relation to shock velocity deduced from type II dynamic spectrum
- Confined vs eruptive events, lessons learned for stellar astronomers



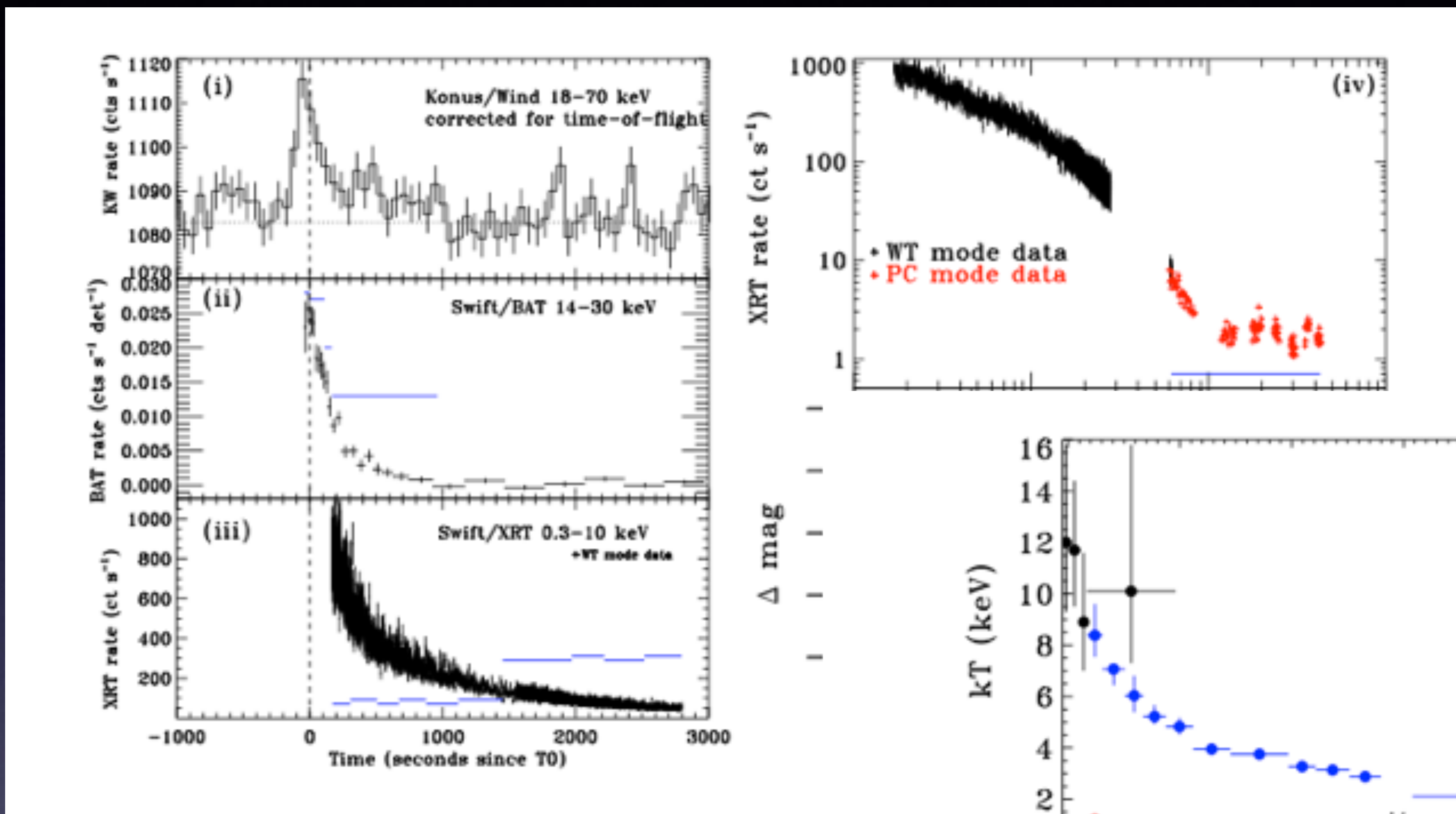


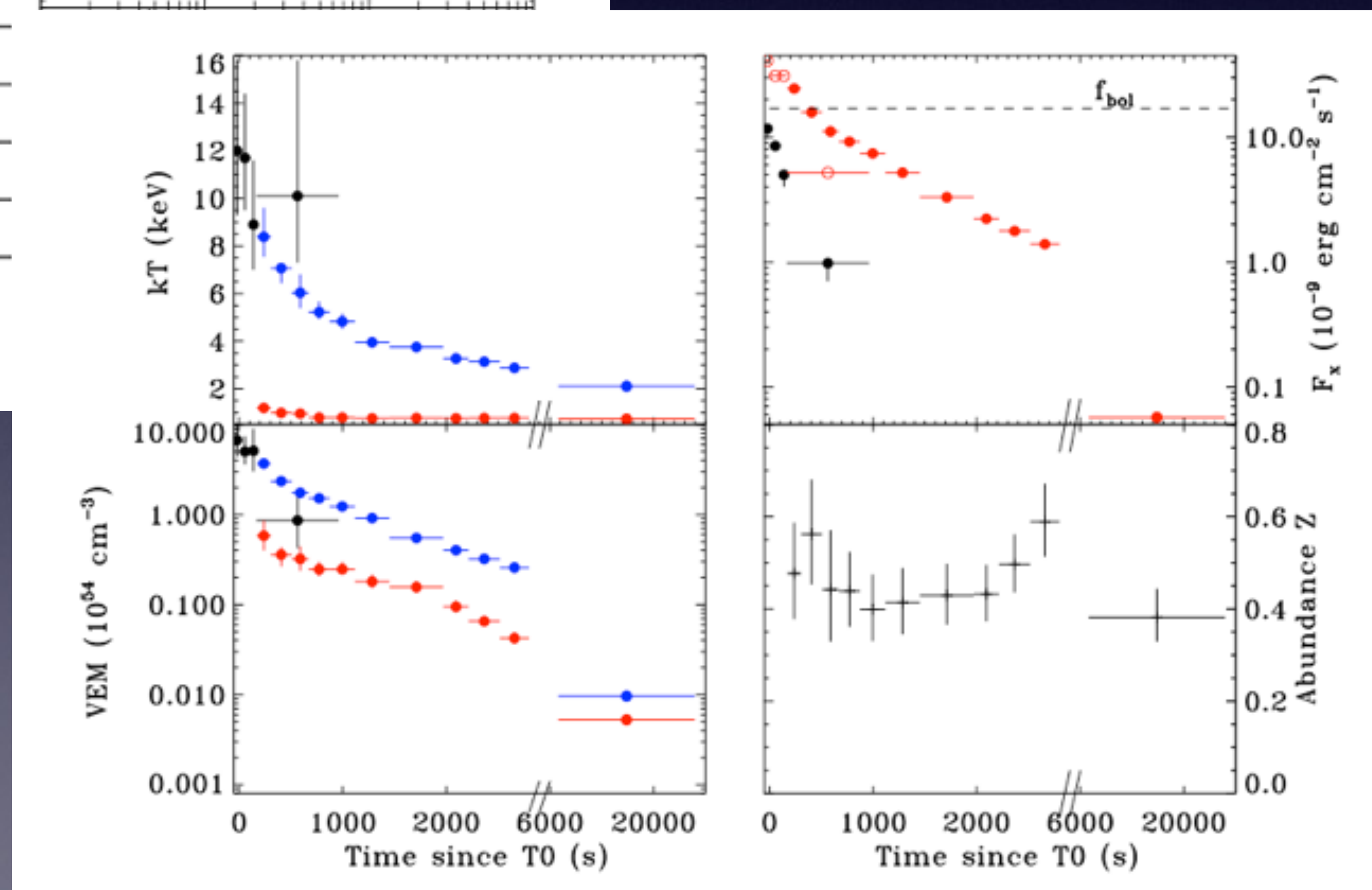
Osten et al. 2010

EV Lac (dM4, d=5 pc) Swift trigger April 25, 2008

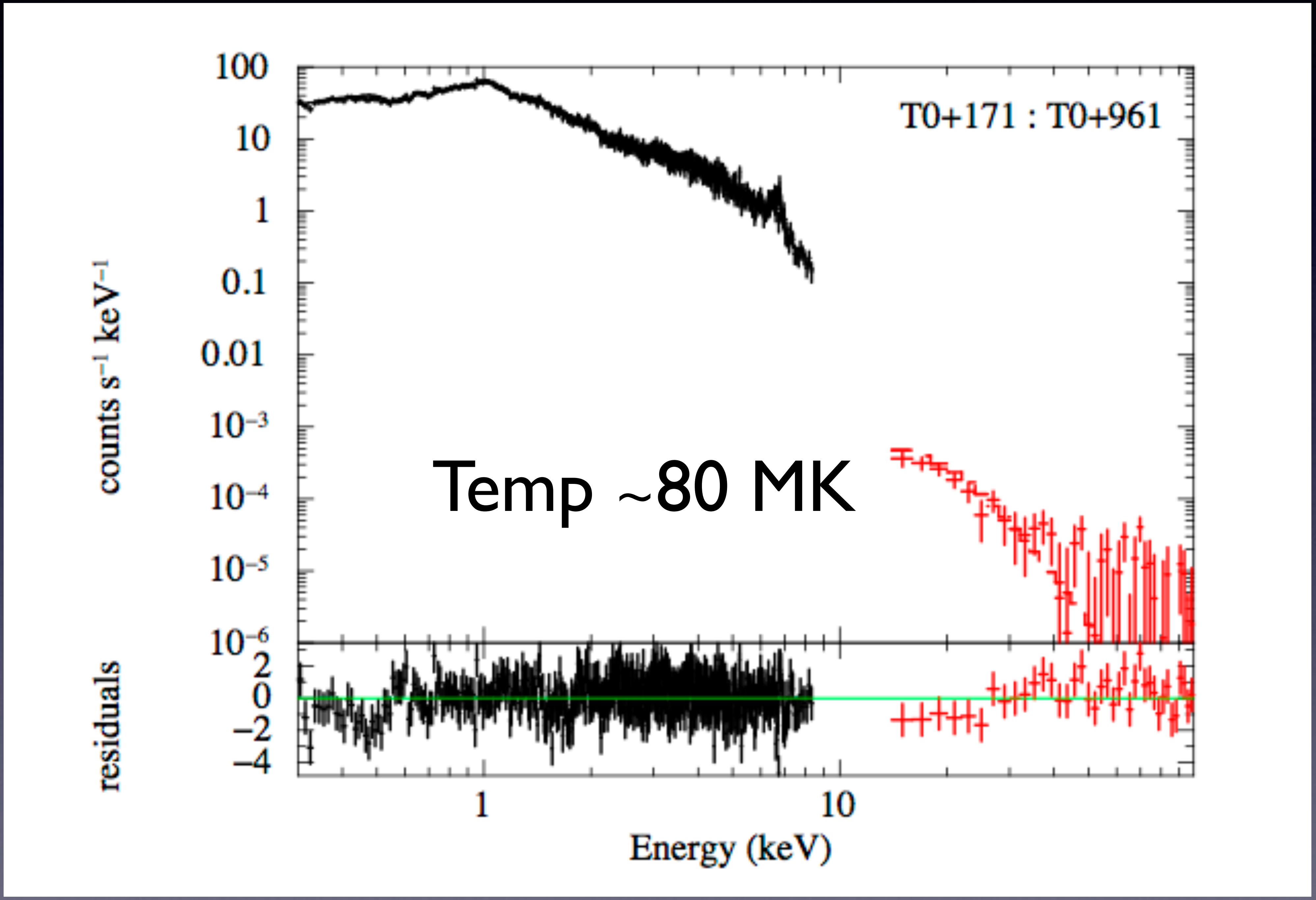
➜F(0.3-100 keV) = 5.3×10^{-8} ergs/cm^2/s
➜factor of 7000 increase over quiescent value
➜peak estimated $L_{X,flare}/L_{bol}$ ~3.1, $L_{v,flare}/L_{bol}$ ~ unity
➜ E_{rad} (0.3-10 keV) ~ 10^{35} ergs
➜typical evolution of flare parameters, except for magnitude
➜ equivalent to X36000000 solar flare

Extremes of stellar flares show energy scaling unheard of in the solar context



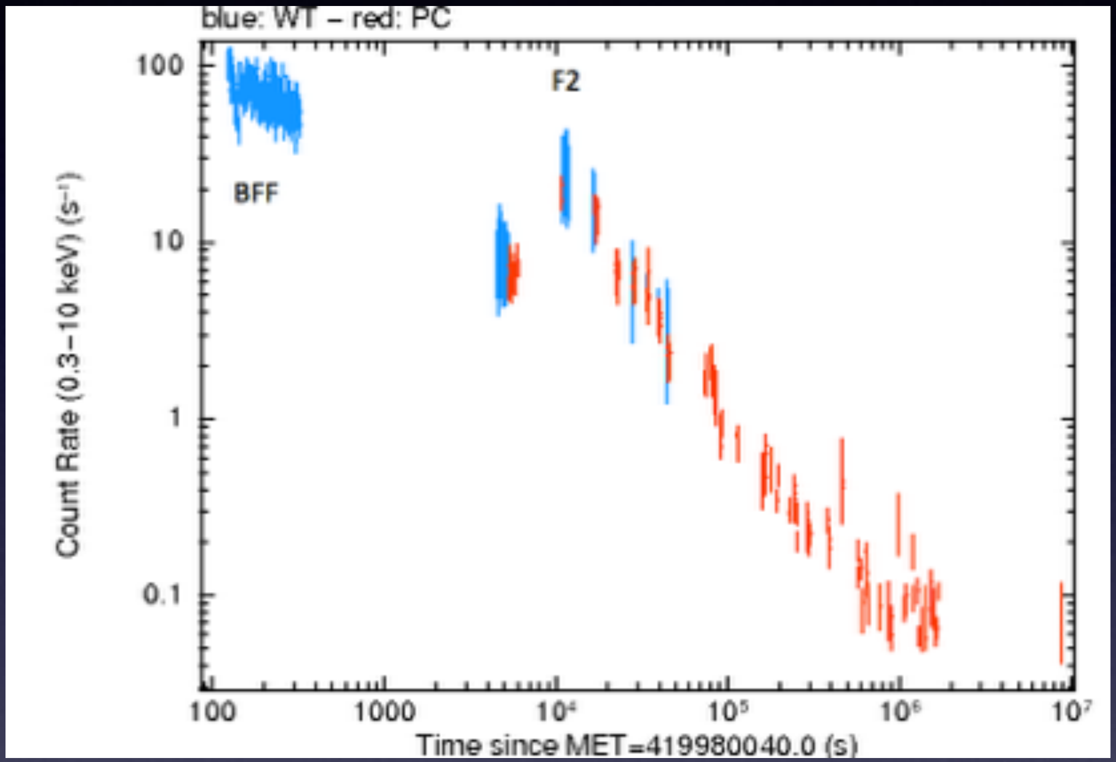


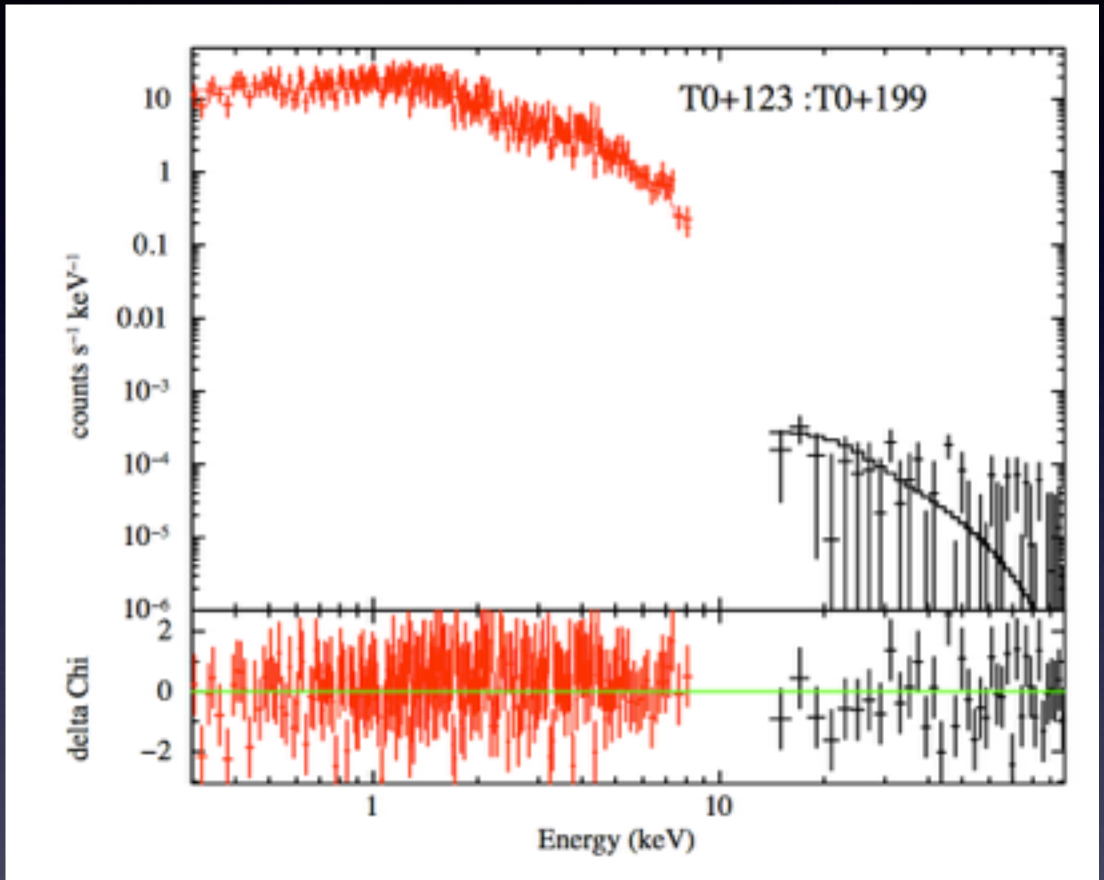
notable for high VEM and T (10^{55} cm^{-3}, 140 MK), high L_x/L_{bol} (> 1!), no abundance variations and no strong evidence for superthermal (>140 MK) or suprathermal component to HXR emission in the EV Lac superflare



Osten et al. (2010)

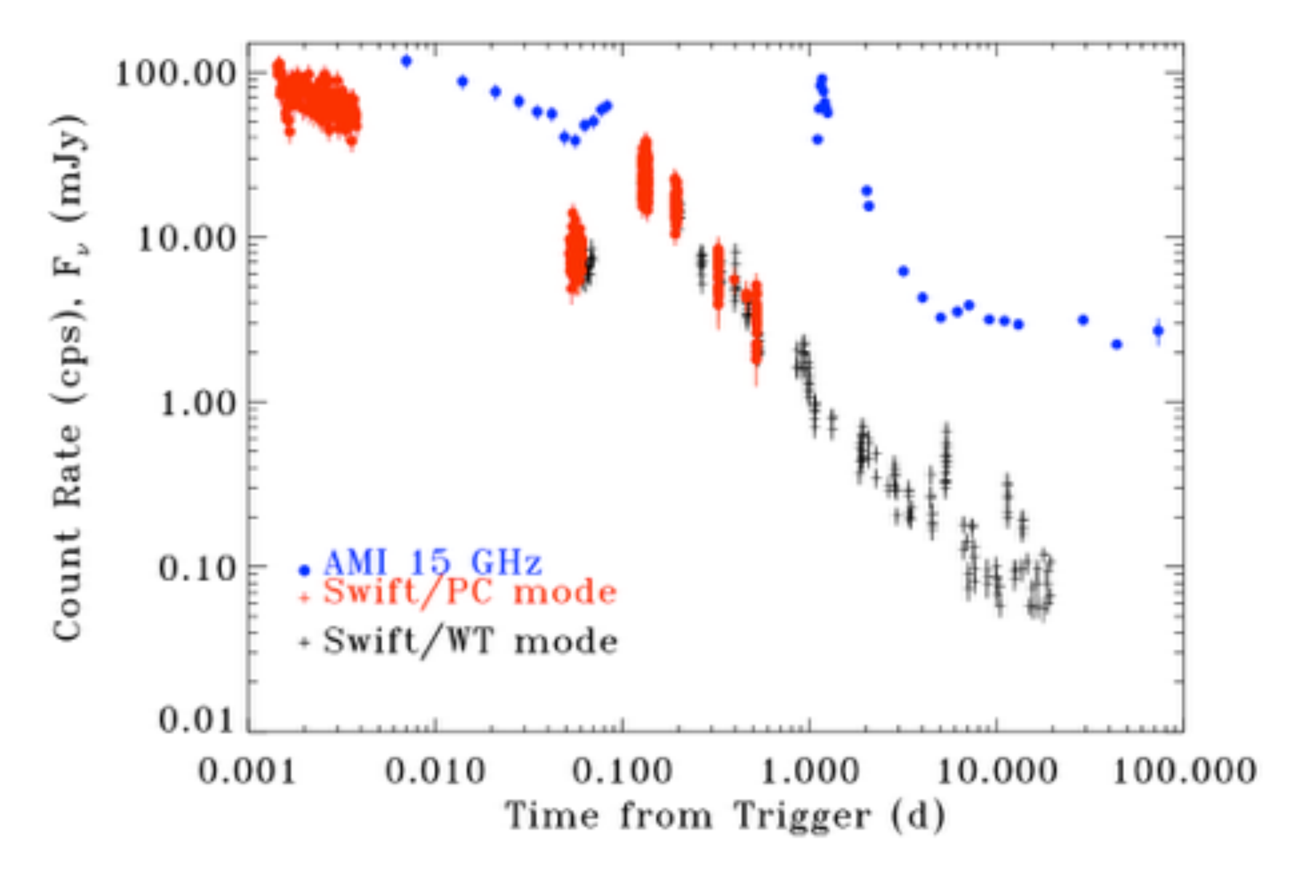
Superflares: DG CVn

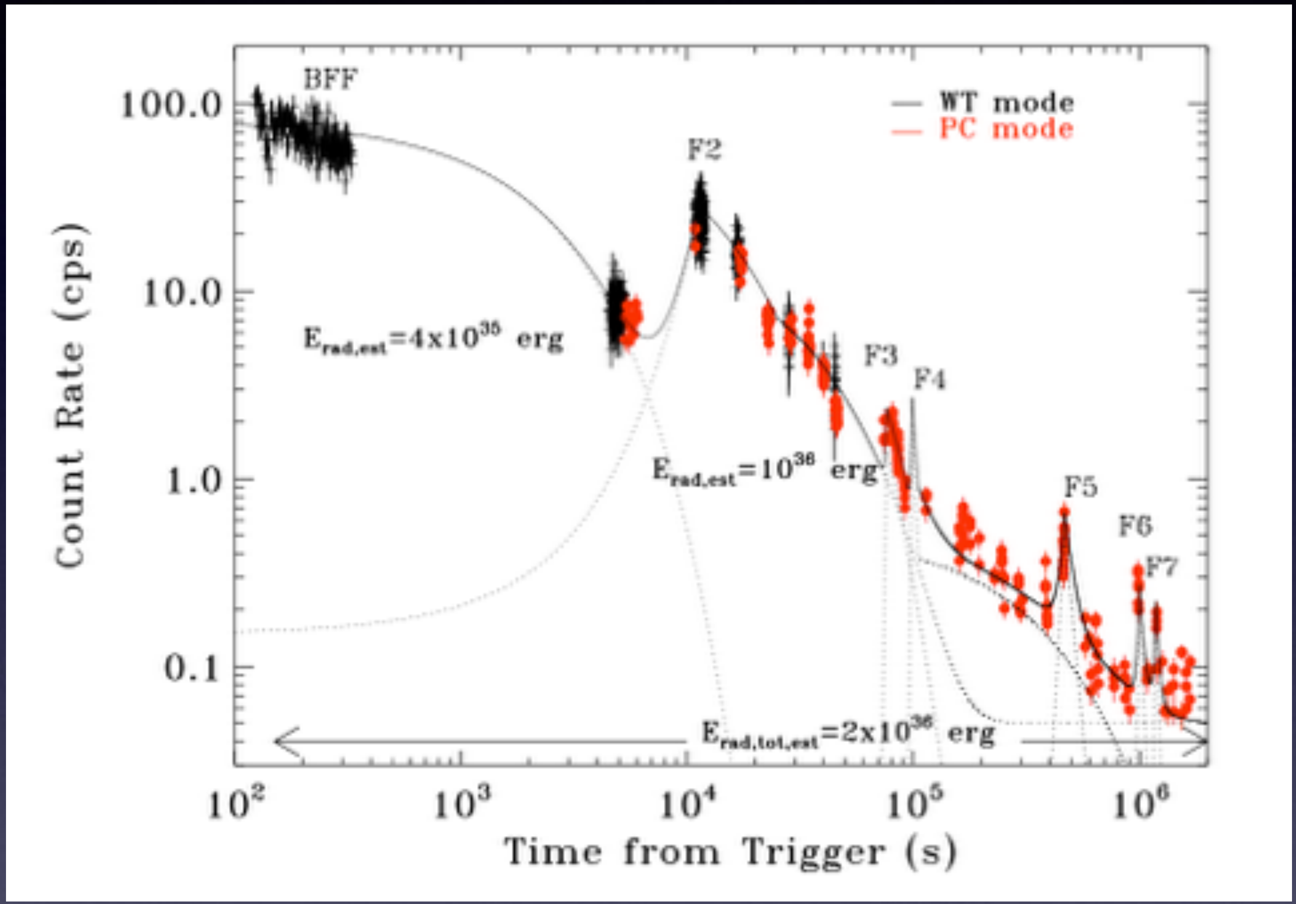




- peak $L_x > L_{bol}$
- peak T_x ~200 MK
- flare was the beginning of a flare complex that lasted ~20 days
- system is a pair of M4 dwarfs, age ~30 MY, distance 18 pc

Superflares: DG CVn





Fender et al. (2014)

- radio coverage shows impulsive response to second event, additional later event missed by Swift
- total integrated X-ray energy: 10^{36} erg