

# Radio Probes of Extrasolar Space Weather

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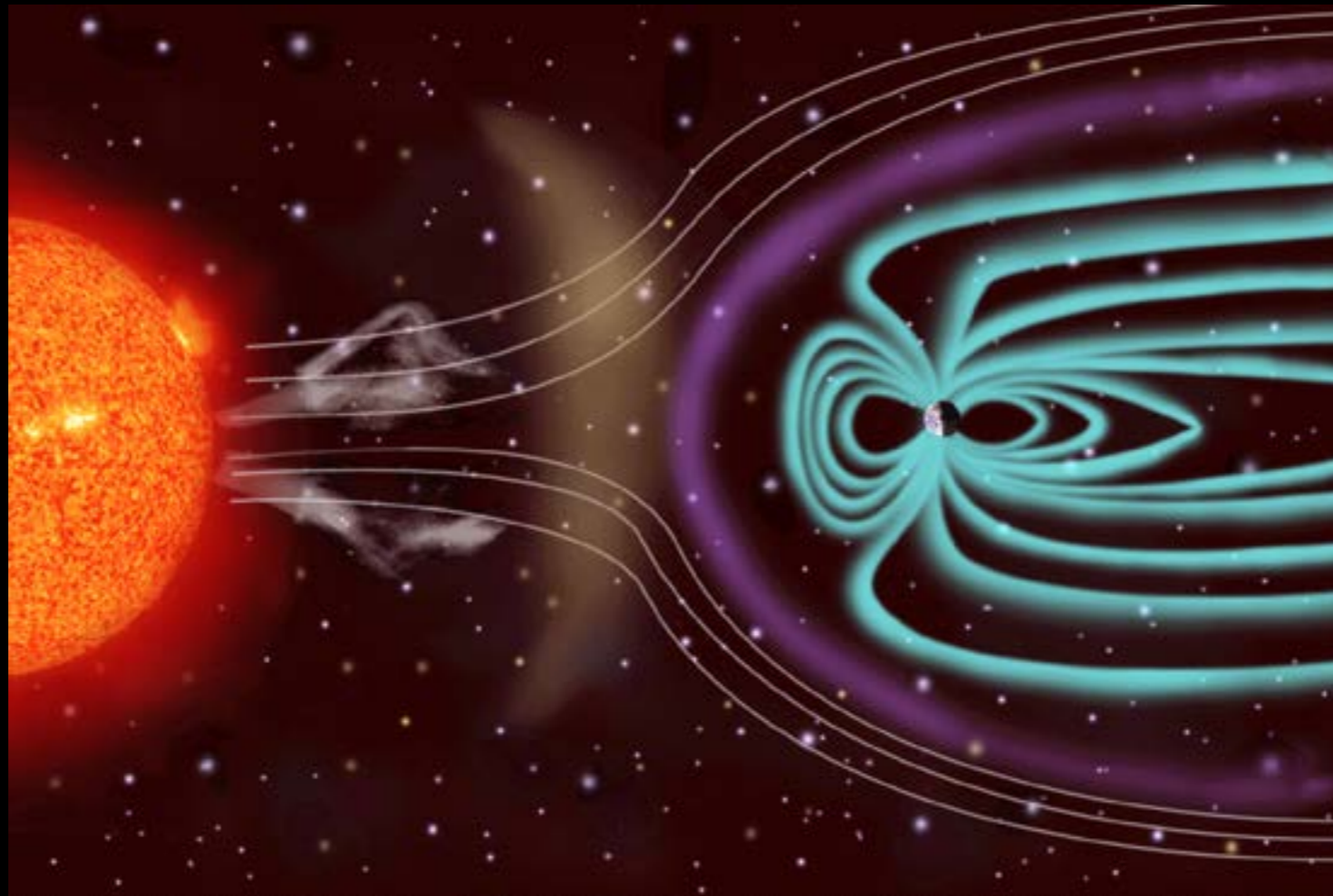
Radio Stars: from kHz to THz

Haystack Observatory

November 2, 2017



# Star's magnetic field helps to set the environment for planets and life



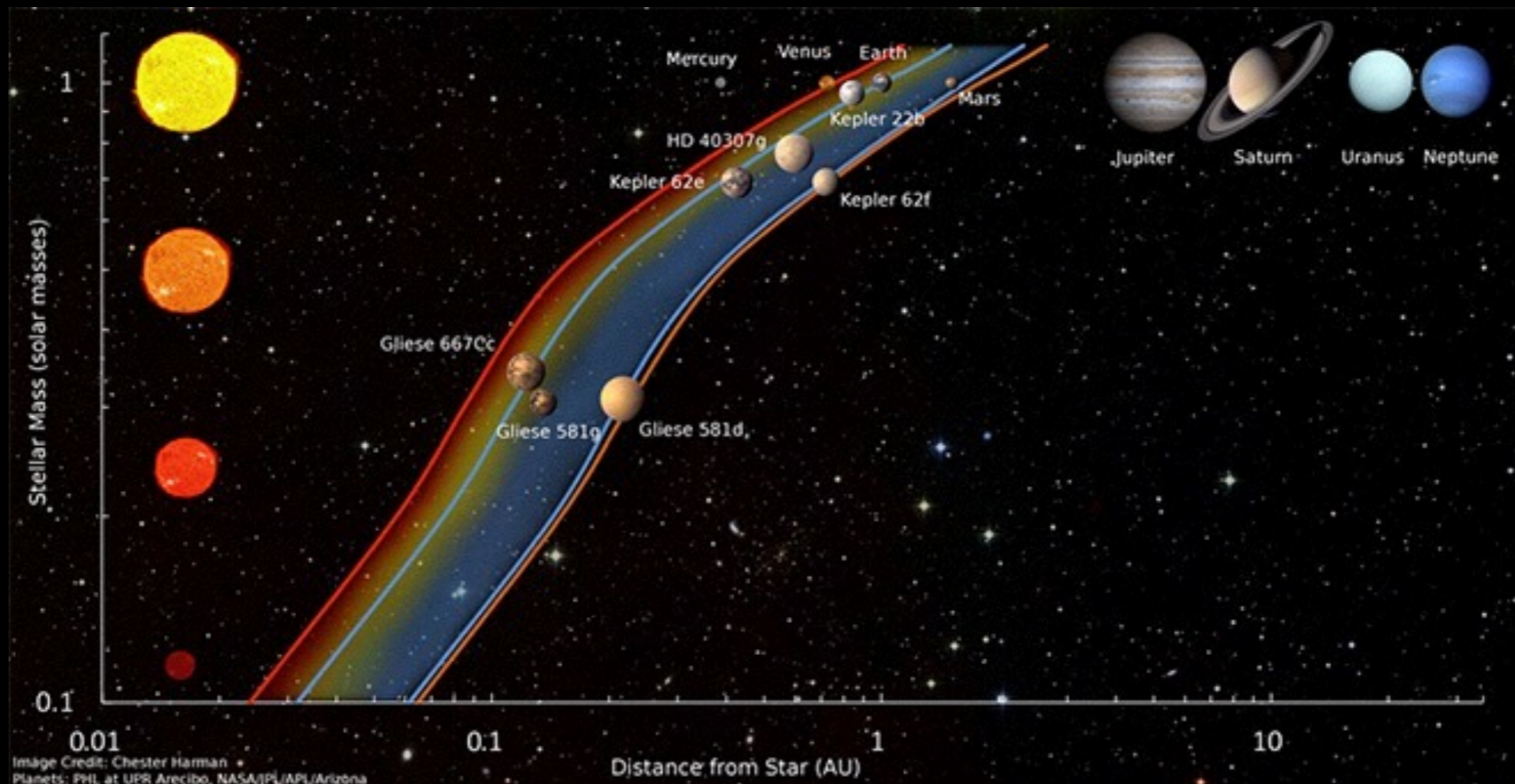
A star's magnetic field:

- **Heats plasma to temperatures up to several tens of millions of degrees (chromosphere, corona)**
- **Expels material (wind, coronal mass ejection)**
- **Accelerates particles to very high energies (energetic particle events)**

# Space Weather With the Knob Turned Up is a Habitability Concern

Solar eruptive event: flare, coronal mass ejection, energetic particles

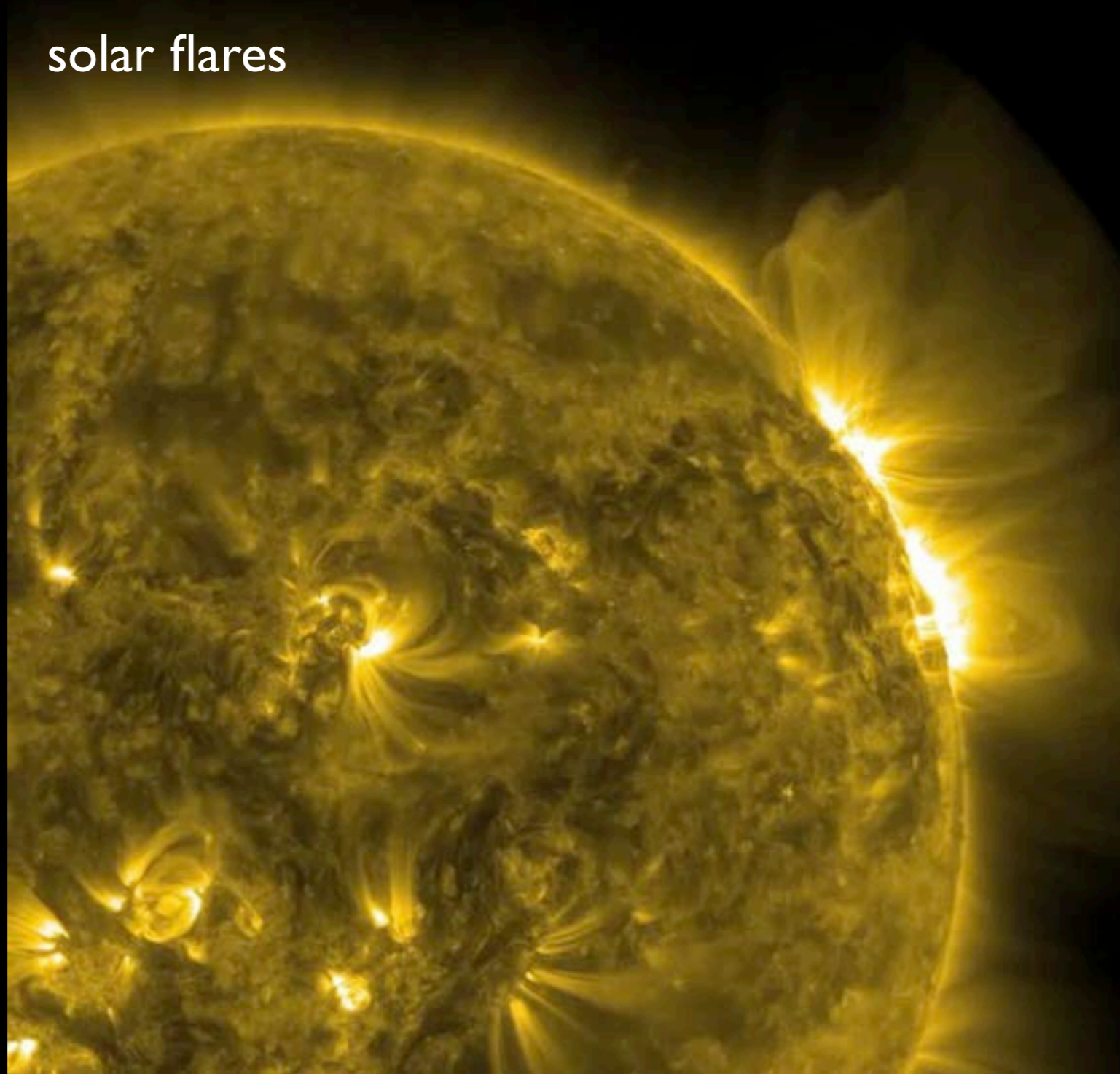
The “geoeffective” part of the eruptive event is the CME and the energetic particles, and their effect depends on where Earth is in its orbit, and where the event originates on the Sun’s surface





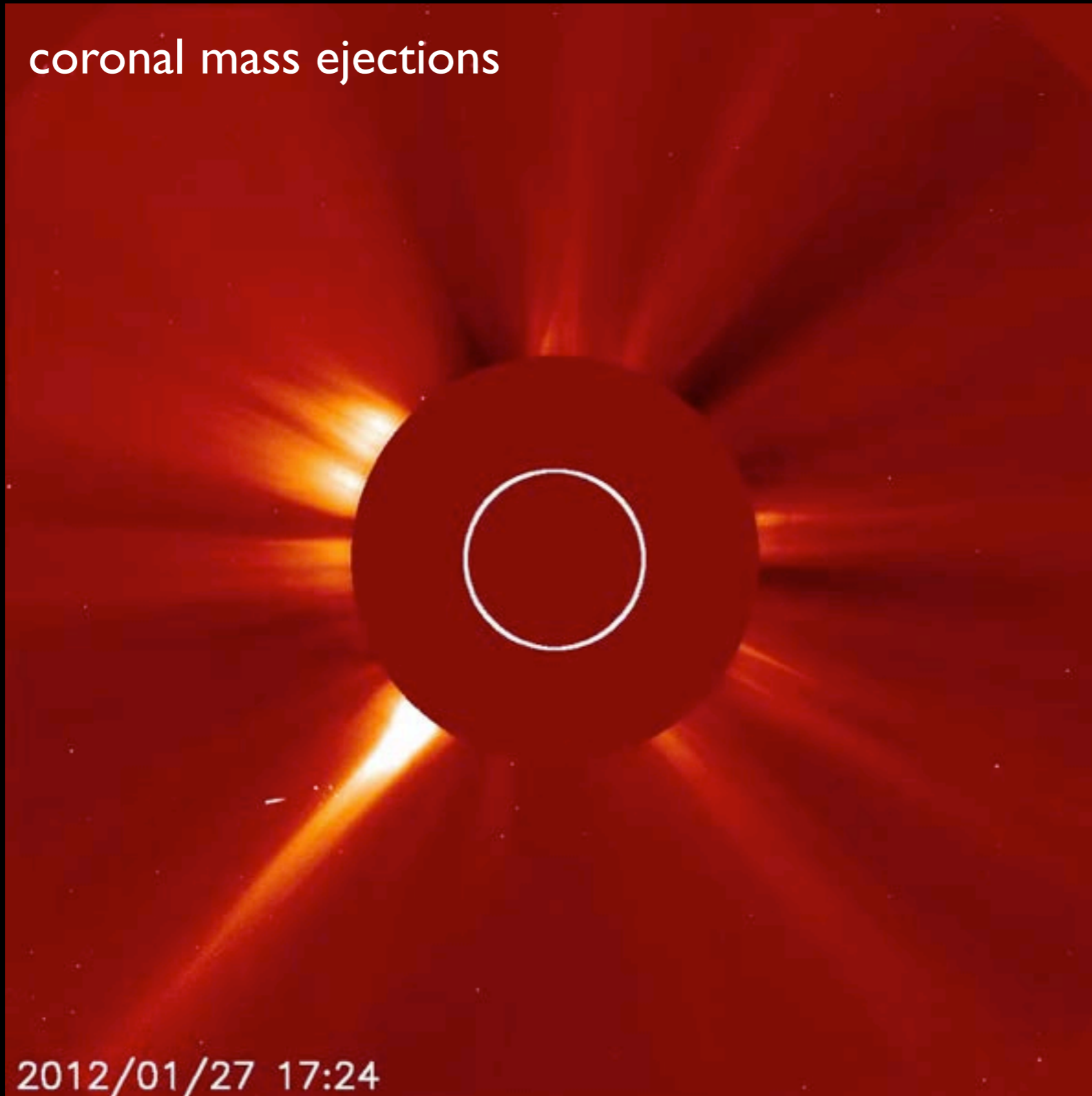
Space weather events are made of

solar flares



Space weather events are made of

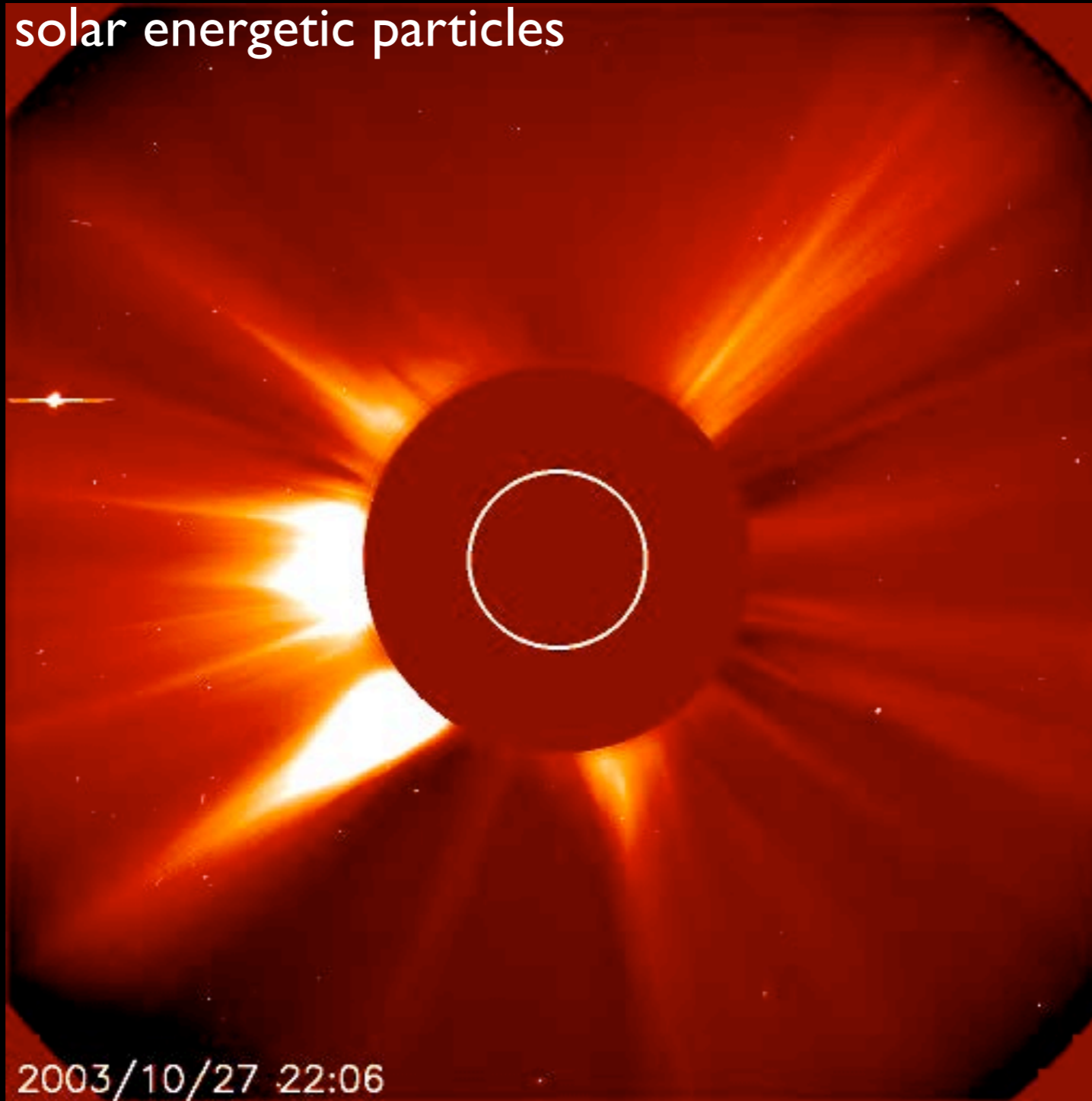
coronal mass ejections



2012/01/27 17:24

Space weather events are made of

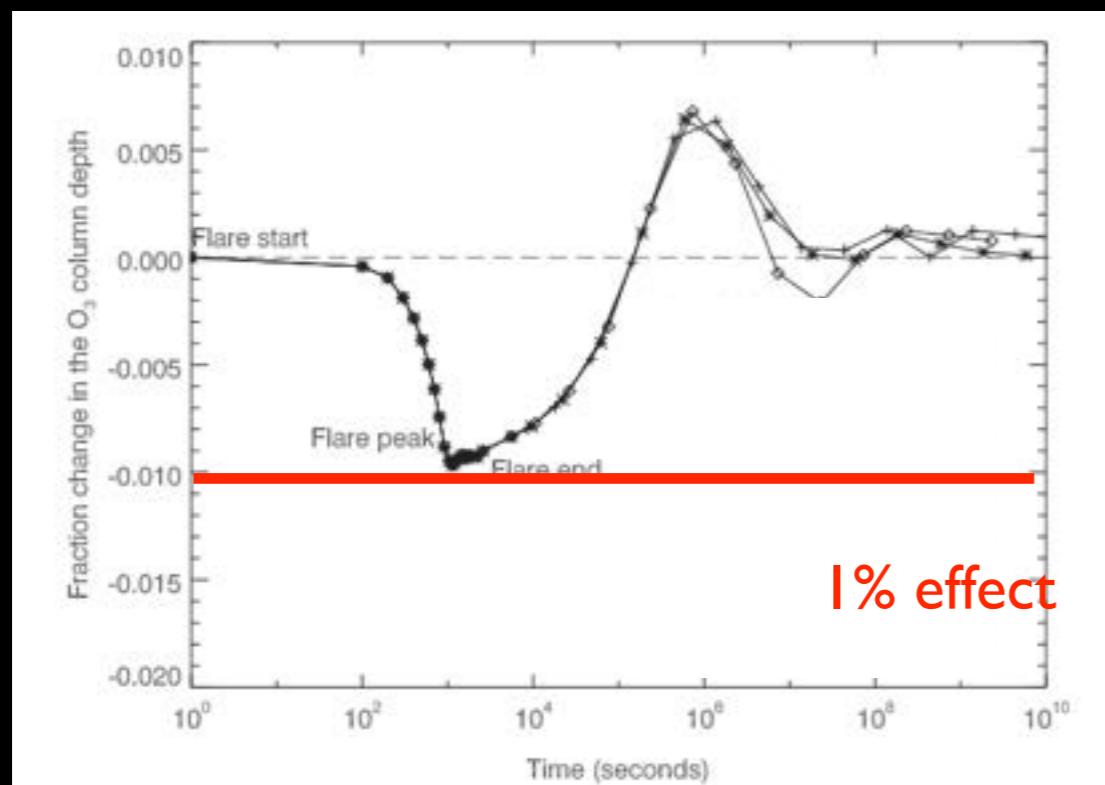
solar energetic particles



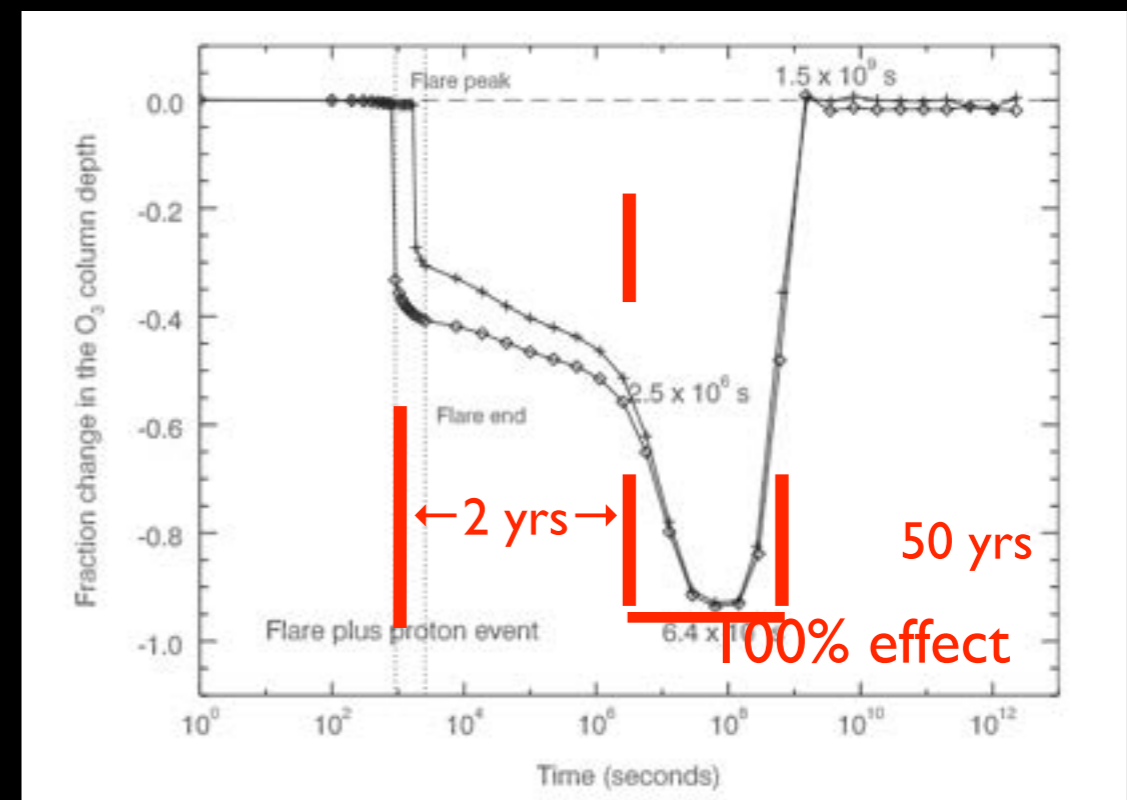
# How do Flares and Associated Events Affect Habitability, Space Weather?

- We can study stellar flares, see (gross) similarities to solar flares in the heated plasma
- We cannot at present detect stellar coronal mass ejections, or energetic particles directed away from the star
- For now, astrobiological investigations of stellar flares extrapolate from solar eruptive events by orders of magnitude (Segura et al. 2010, Airapetian et al. 2016, Atri 2017): unclear if these scalings apply!

# How do Flares and Associated Events Affect Habitability, Space Weather?



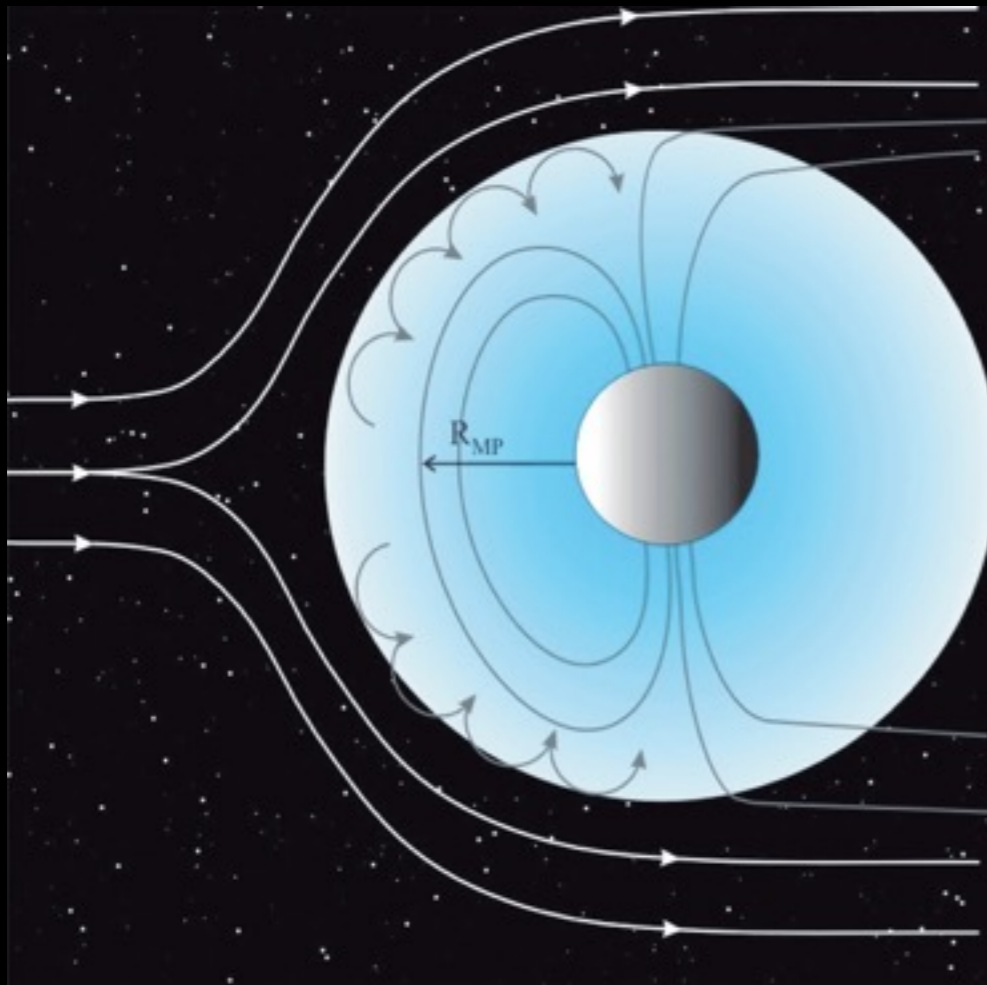
A UV flare only has a 1% effect on the depletion of the ozone layer of an Earth-like planet in the habitable zone of an M dwarf



A UV flare + proton event (>10 MeV) inferred from scaling from solar events, results in complete destruction of the ozone layer in the atmosphere of an Earth-like planet in the habitable zone of an M dwarf



# How do Flares and Associated Events Affect Habitability, Space Weather?



Lammer et al. (2007)

Need to test the assumption that a high flaring rate = a high rate of CMEs

- Potentially habitable M dwarf planets are close to their host star, so more susceptible to the effects of the host star
- These planets will be tidally locked, with weak magnetic moment → little or no magnetospheric protection from flares & coronal mass ejections

# Solar & Stellar Flares Have Similar Radiative Energy Partitions

	$\lambda$ range	$f=E_{\text{rad}}/E_{\text{bol}}$ (Sun)	$f=E_{\text{rad}}/E_{\text{bol}}$ (active stars)*
GOES	1-8 Å	0.01 <sup>A</sup>	0.06
coronal	0.01-10 keV	0.2 <sup>B</sup>	0.3
hot blackbody	1400-10000 Å	0.7 <sup>C</sup>	0.6
U band	3000-4300 Å		0.11
Kepler	4000-9000 Å		0.16

<sup>A</sup> Woods et al. (2004); <sup>B</sup> Emslie et al. (2012); <sup>C</sup> Kretzschmar et al. (2012);  
\*Osten & Wolk (2015)

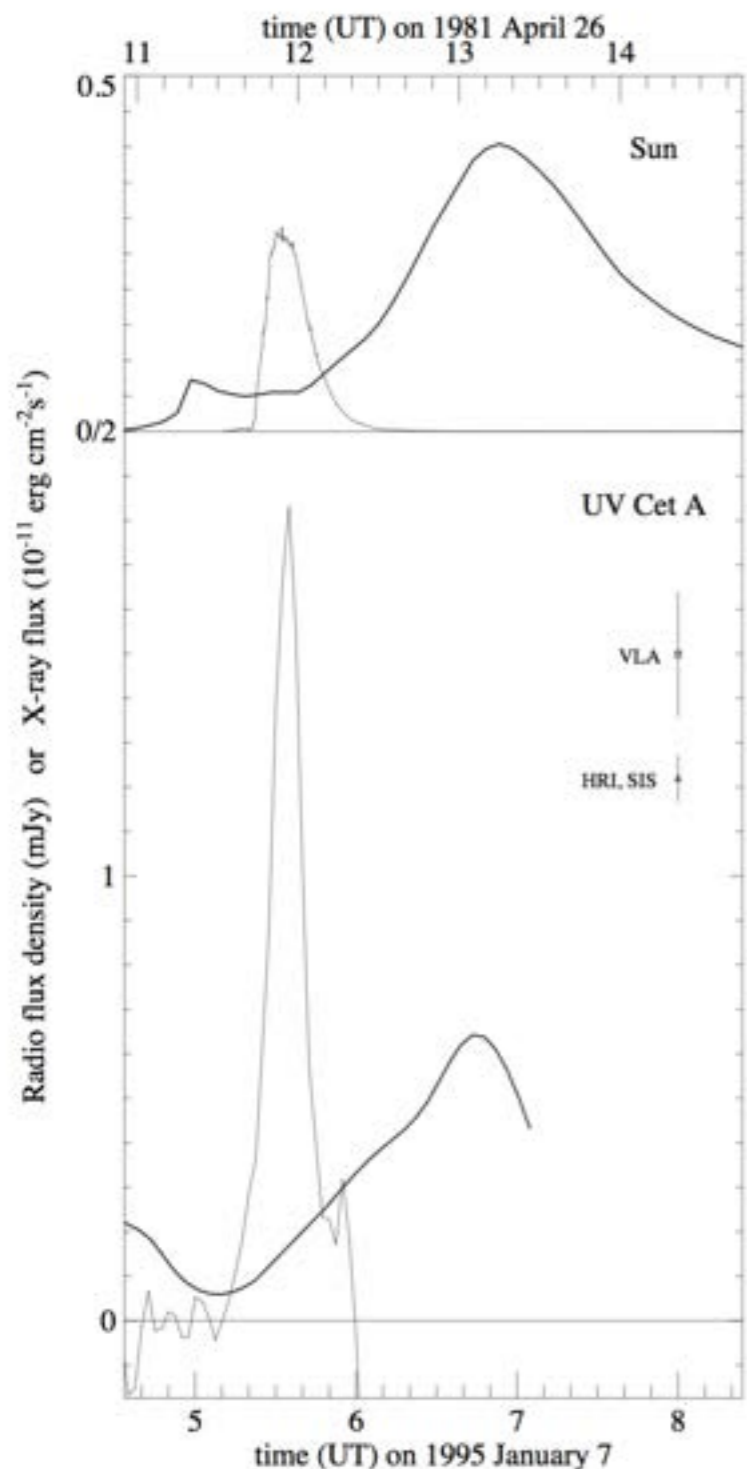


# But Dissimilar Accelerated Particle Characteristics?

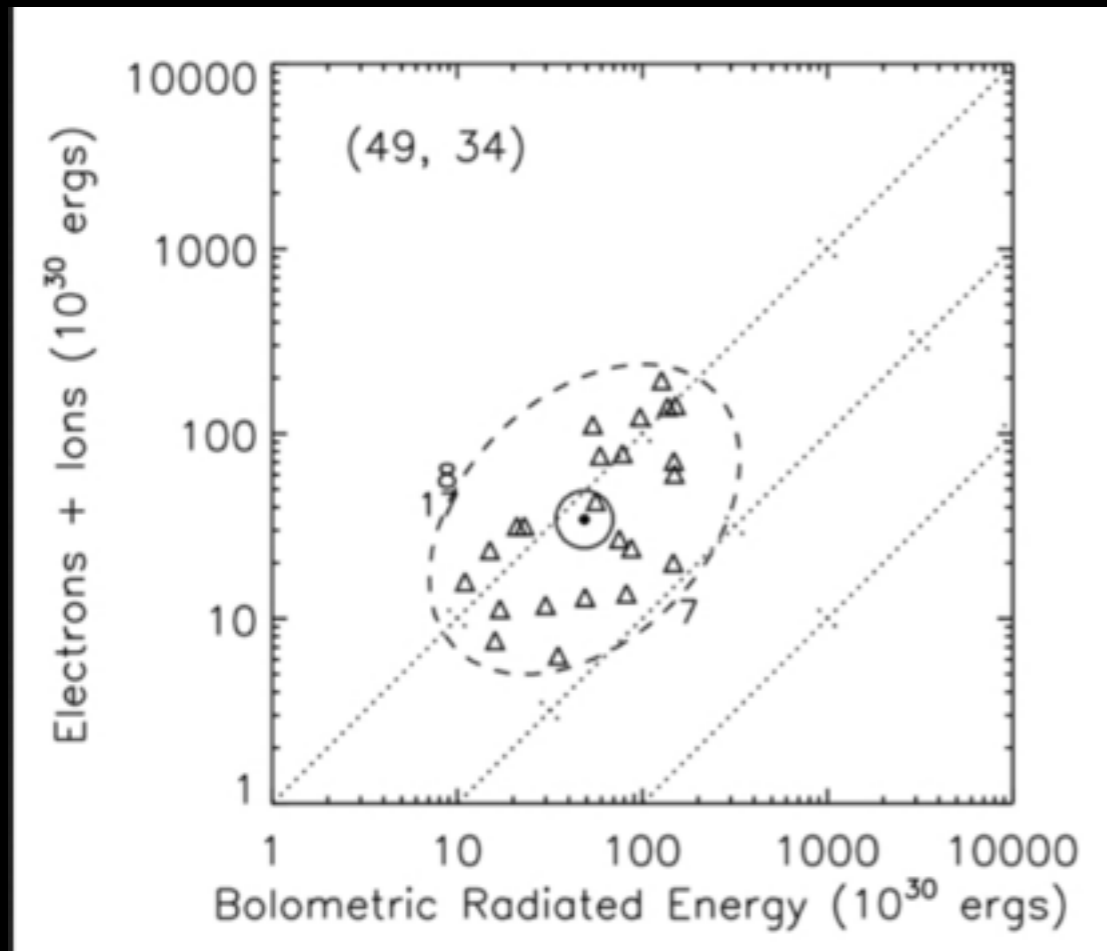
➔ Stellar flare cm-wavelength radio emission comes from gyrosynchrotron emission from accelerated particles

Relative to the flare X-ray emission, stellar flares produce larger radio amplitudes than for solar flares (Güdel et al. 1996)

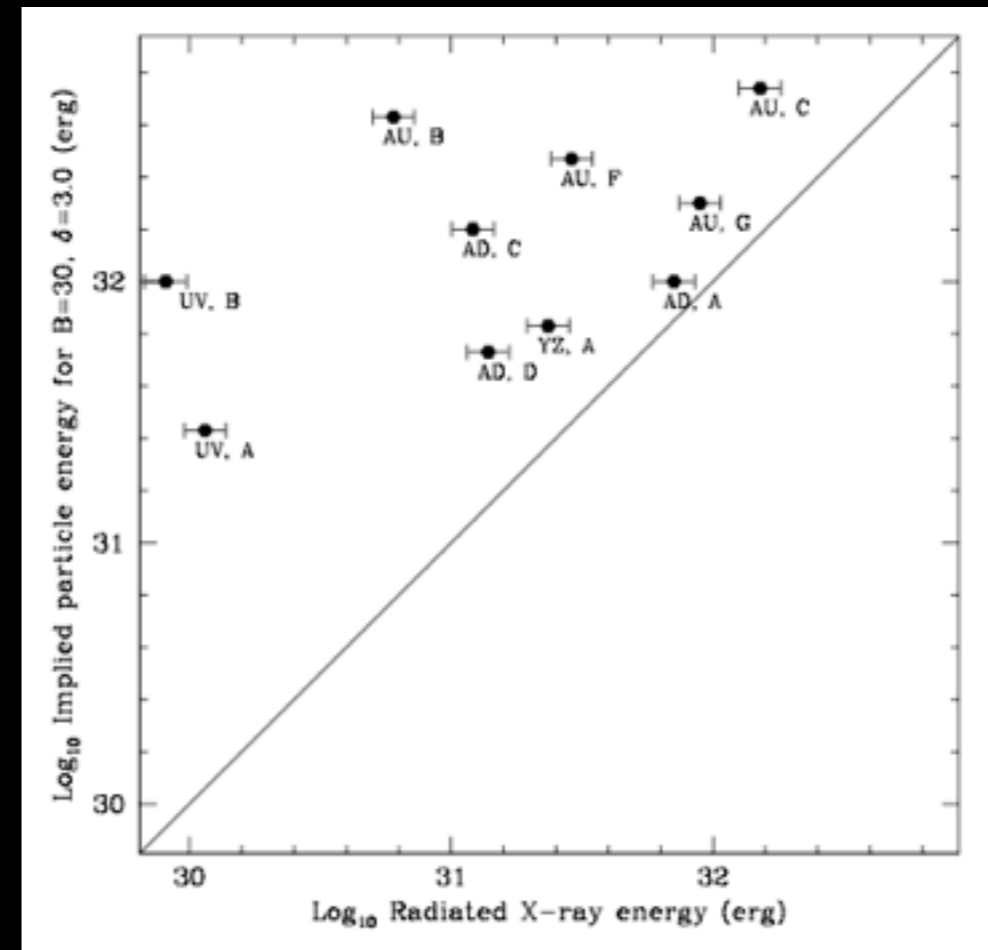
Güdel et al. (1996)  
M dwarf X-ray-radio flare compared to solar



# But Dissimilar Accelerated Particle Characteristics?



Solar eruptive events,  
~ equal amounts of energy in  
accelerated particles and radiated  
flare energy  
Emslie et al. (2012)

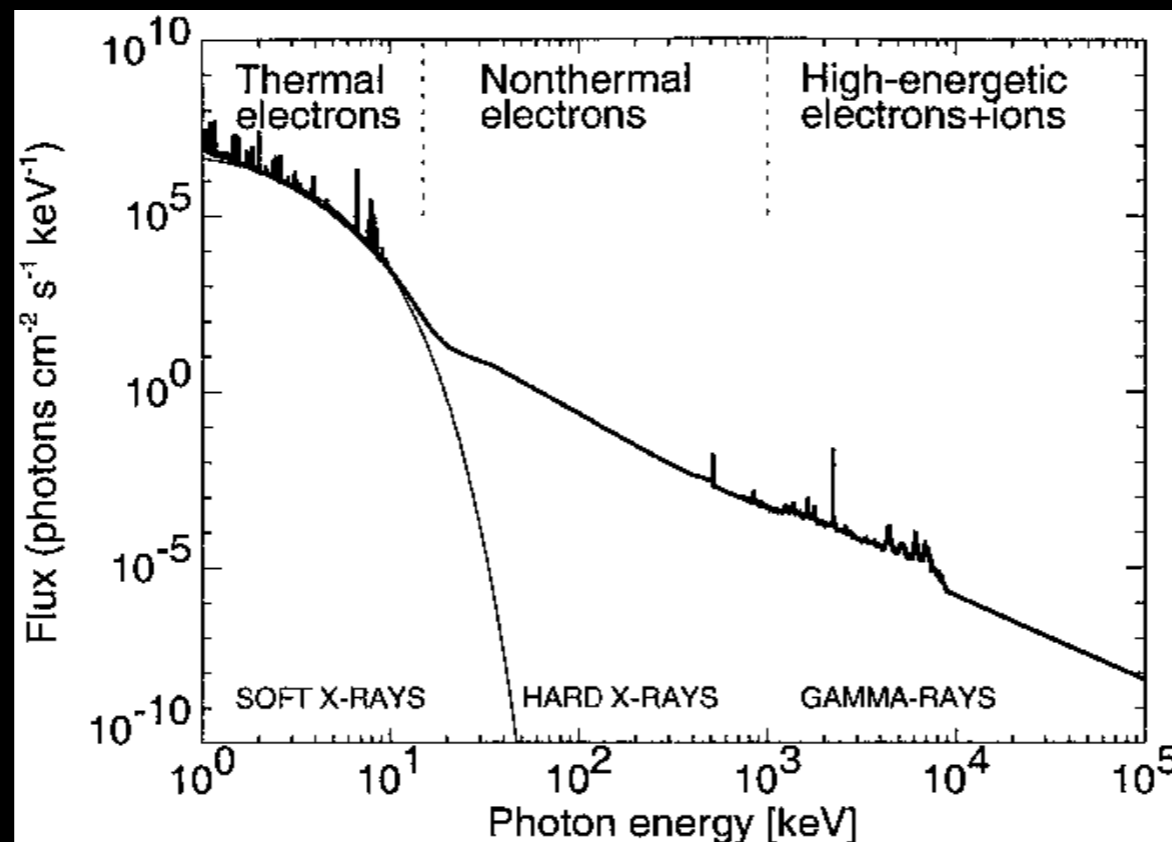


M dwarf flares  
more energy in non thermal  
particles than in coronal plasma  
Smith et al. (2005)



# But Dissimilar Accelerated Particle Characteristics?

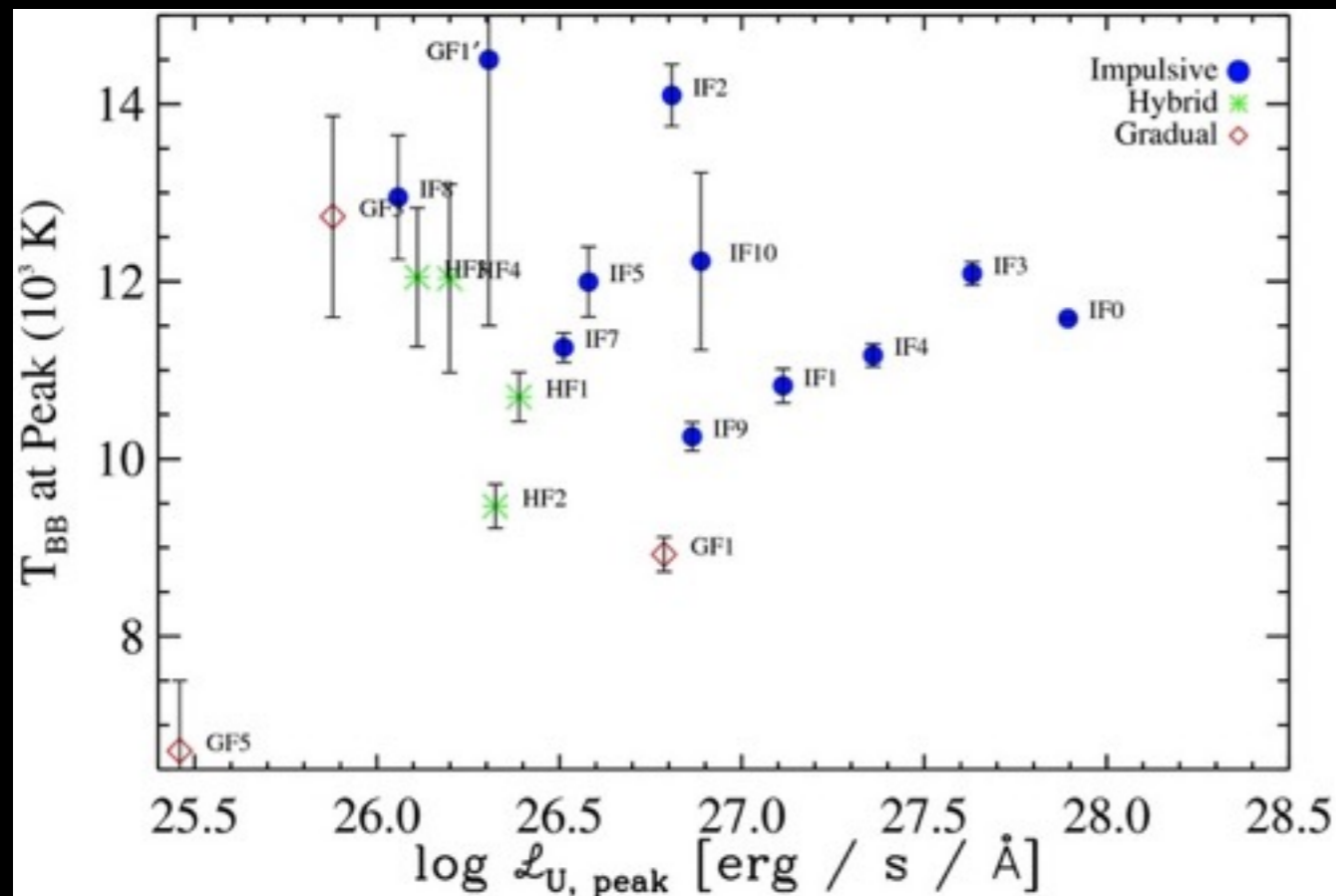
- ➔ Have we seen nonthermal hard X-ray emission (bremsstrahlung emission from a power-law distribution of electrons) in stellar flares? It's complicated, but probably not.



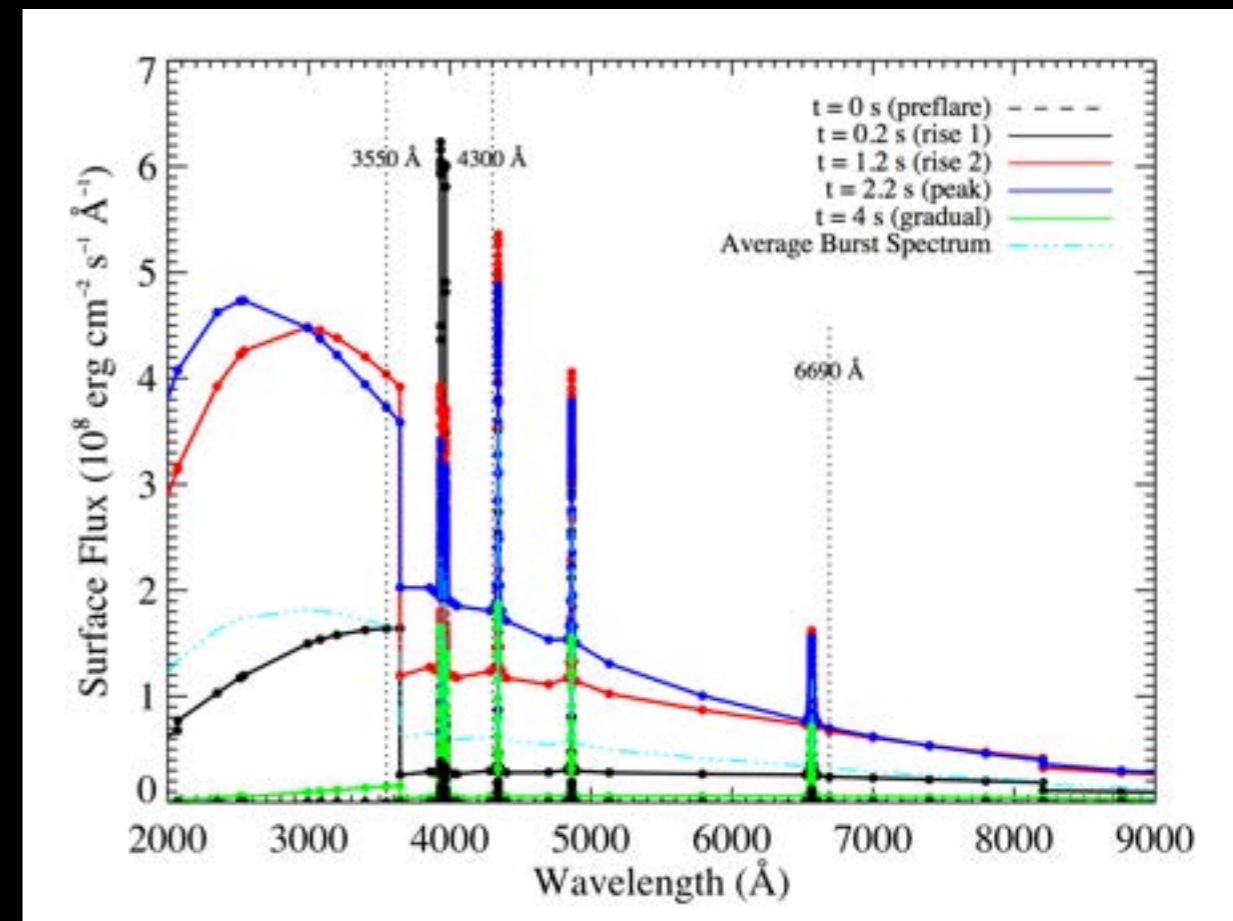
Aschwanden (2002)

- ➔ Hot stellar flare temperatures  $T_x$ , coupled with declining HXR detector sensitivity, make it difficult. There are a few cases of transient HXR stellar flare detections (Osten et al. 2005, 2010, 2016, Karmakar et al. 2017). Multi-wavelength data allow us to rule out nonthermal HXR emission.

# But Dissimilar Accelerated Particle Characteristics?



Kowalski et al. (2013)



Kowalski et al. (2015)

- ➔ Stellar flare white-light emission is produced deep in the photosphere, characterized by a hot black-body  $\gg T_{\text{eff}}$ ; this is ubiquitous
- ➔ Allred et al. (2005, 2006) showed difficulty in reproducing M dwarf white light flare with solar-like electron beam (while it works in the solar case)
- ➔ Kowalski et al. (2015) showed that increasing the beam flux by two orders of magnitude from the largest beam flux seen in a solar flare can do the trick. There are problems, however, with return currents.



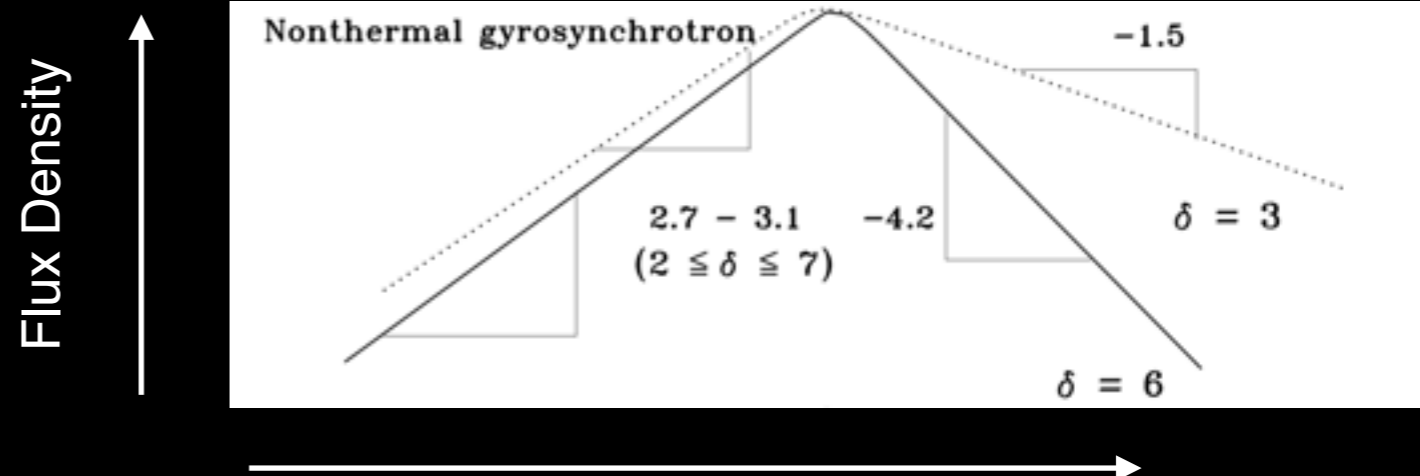
# Constraining the Kinetic Energy in Stellar Radio Flares

using formalism described in Smith et al. (2005), also Osten et al. (2016)

$$n(E, t) = \frac{N(t)(\delta_r - 1)}{E_0} (E/E_0)^{-\delta_r}$$

$$L_r(\nu, t) = 4\pi\eta(\nu, t)V(t)$$

$$N(t)V(t) = \frac{\int L_r(t, \nu) d\nu}{4\pi \int A(\nu) d\nu}$$



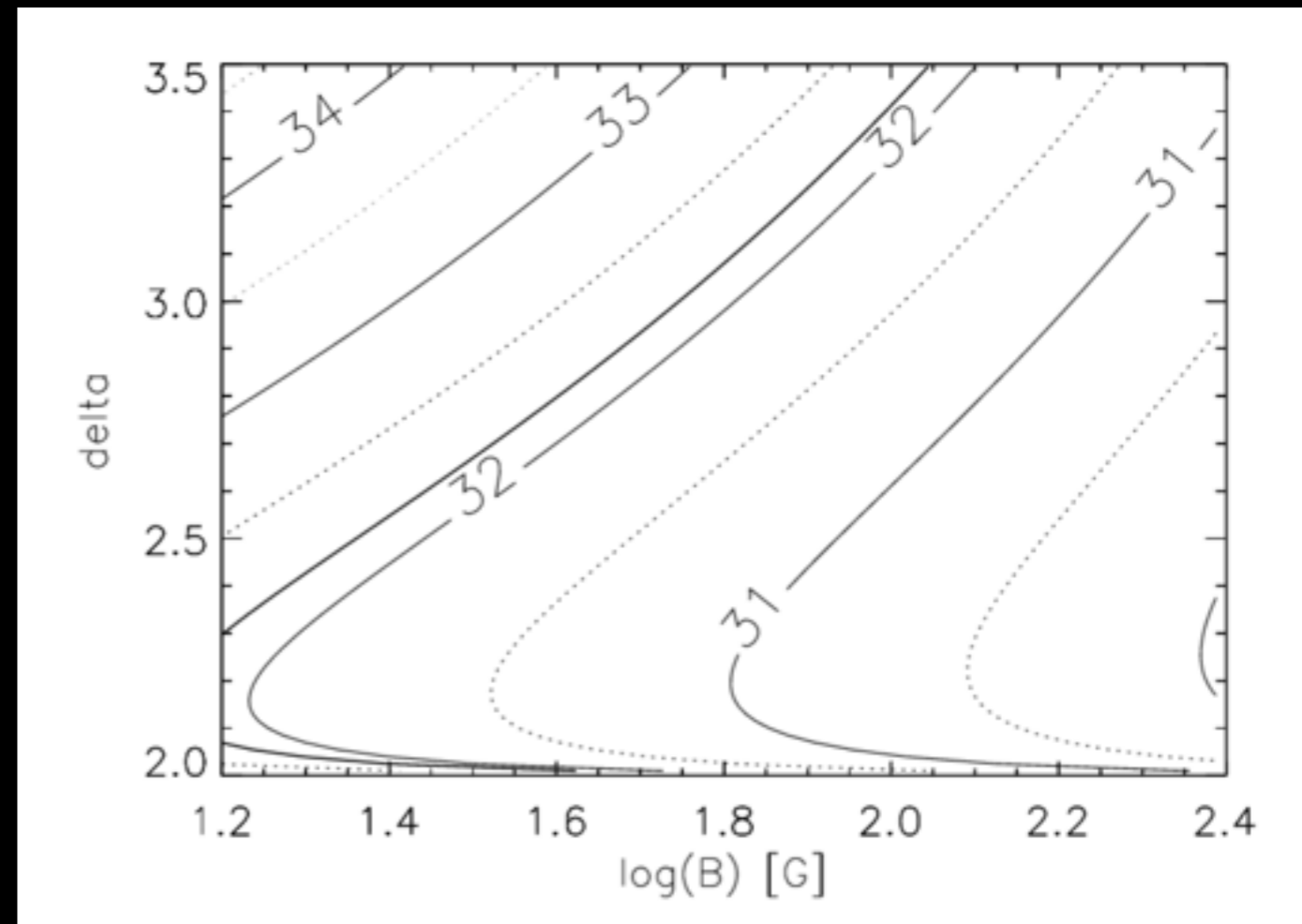
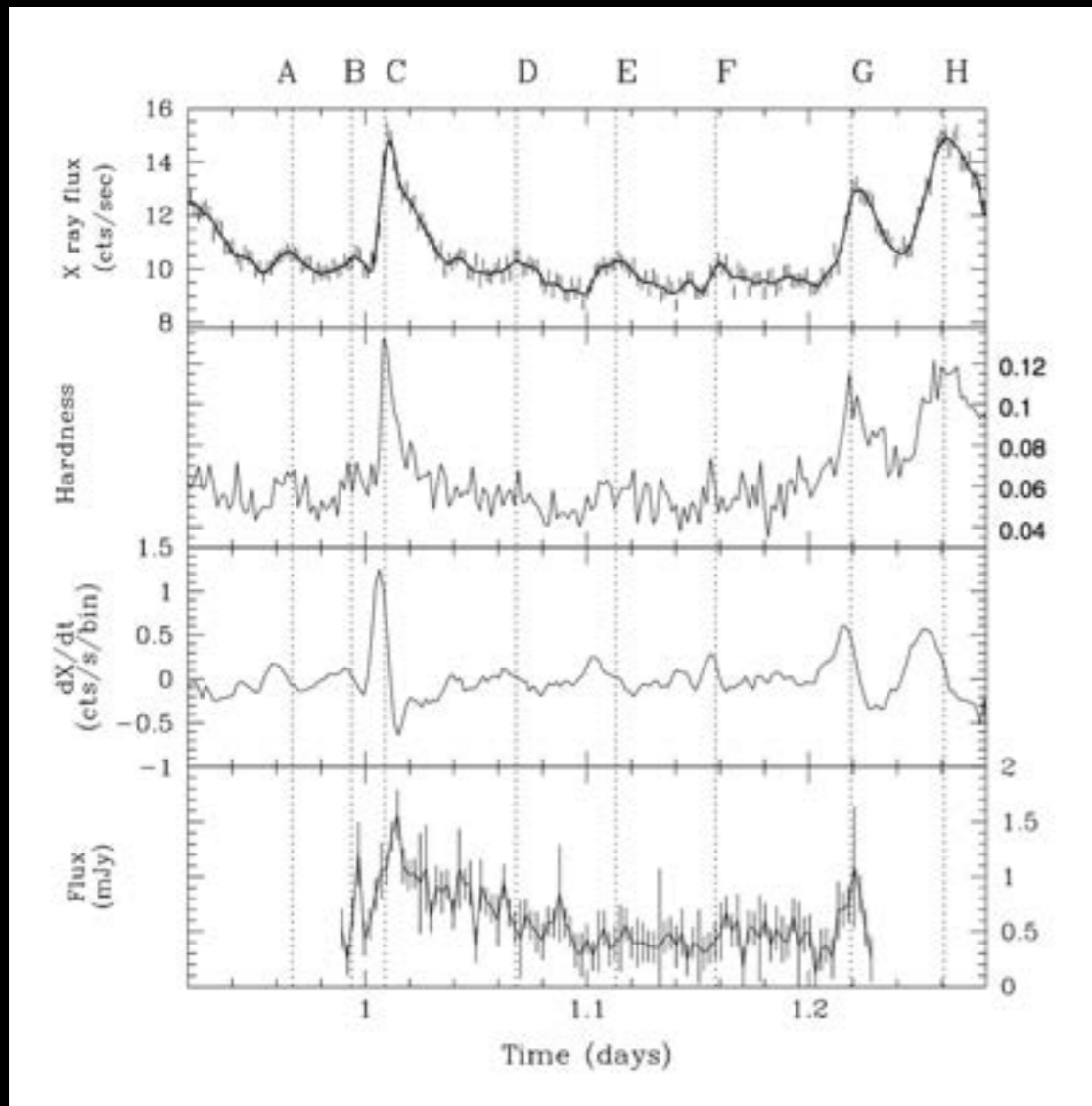
Frequency

$$\alpha_1 = 2.5 + 0.085\delta_r$$

$$\alpha_2 = 1.22 - 0.90\delta_r$$

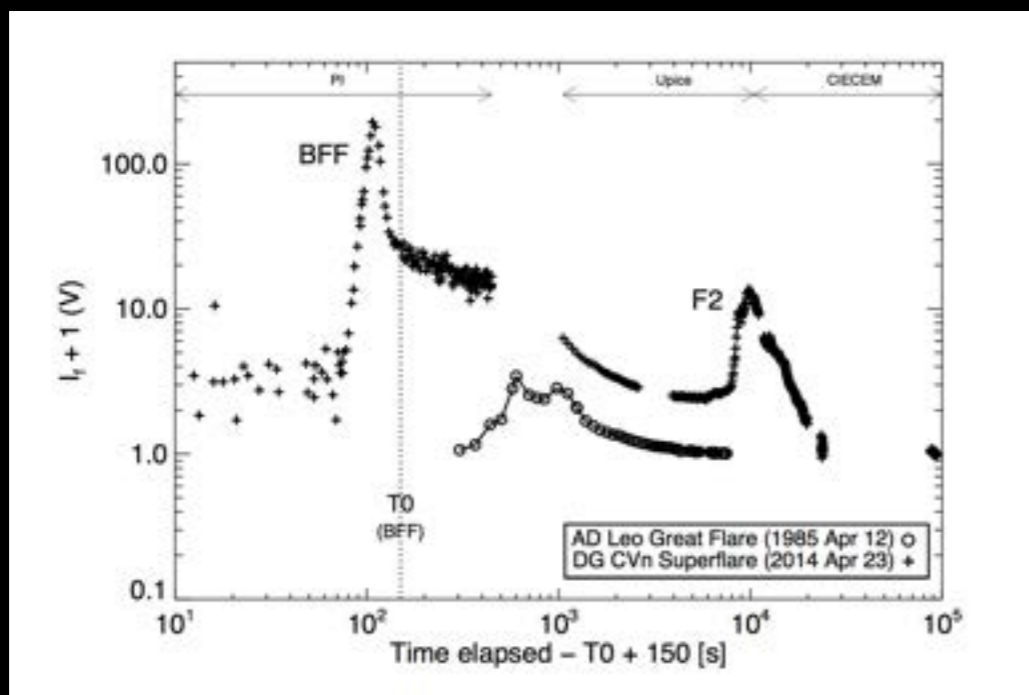
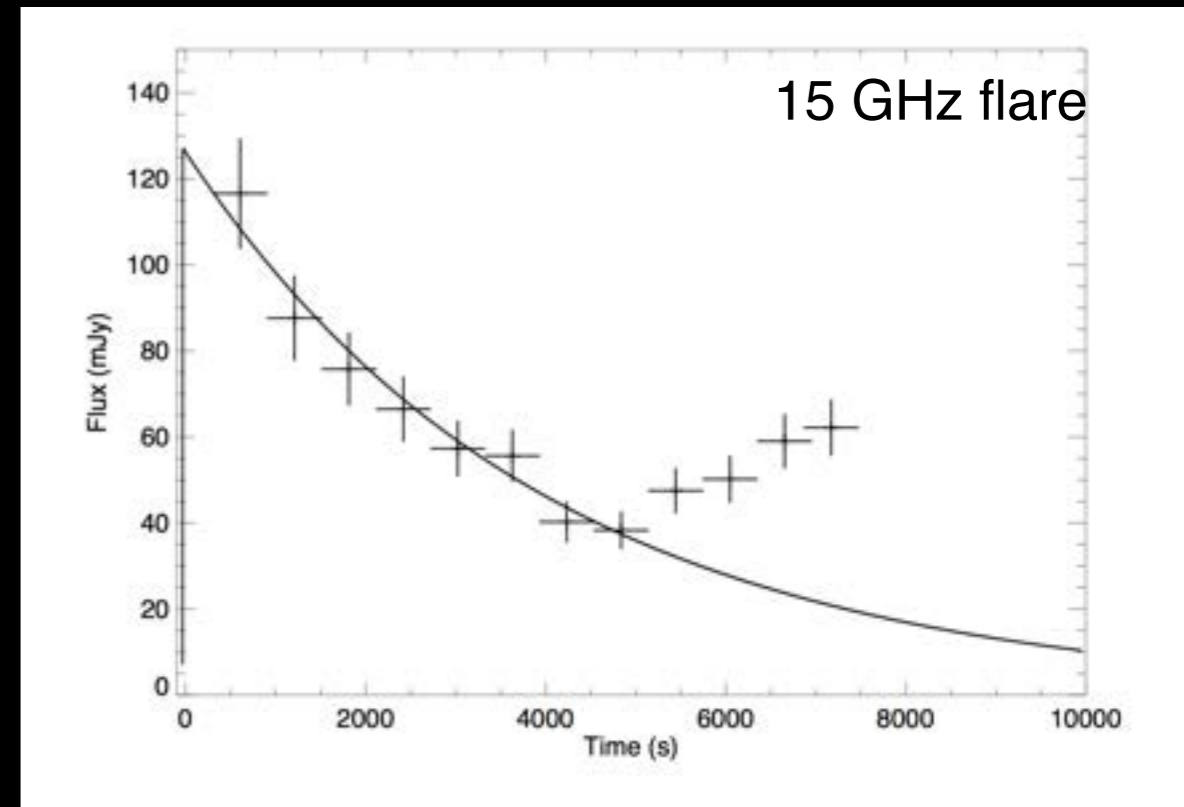
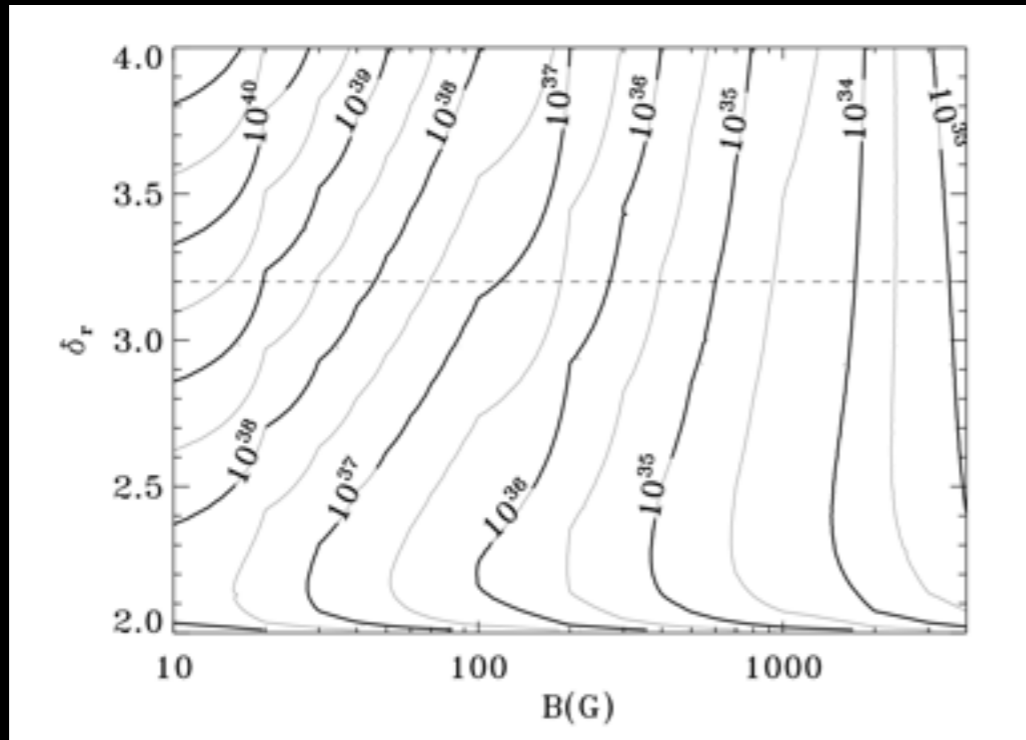
$$E_{\text{kin,tot}} = \int N(t)V(t) \frac{\delta_r - 1}{\delta_r - 2} E_0 dt.$$

# Constraining the Kinetic Energy in Stellar Radio Flares



Smith et al. (2005), flare on AU Mic,  
 $E_{\text{rad}} \sim 2 \times 10^{32}$  erg

# Constraining the Kinetic Energy in Stellar Radio Flares



Osten et al. (2016) flare on DG CVn  
 $E_{\text{rad}} \sim 2 \times 10^{35}$  erg  
 $E_{\text{kin}} \sim E_{\text{rad}}$  suggests several hundred G  
 Radio measurements helped rule out NT  
 HXR emission for large X-ray flare; 300 MK  
 plasma instead



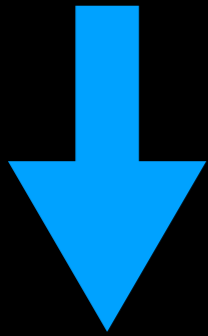
# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?



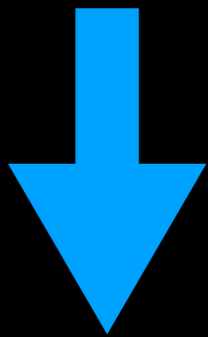
- ➔ Just starting to explore whether we can see stellar CMEs in a systematic way
- ➔ Flare-associated transient mass loss implies large  $\dot{M}$  (Aarnio et al. 2012, Drake et al. 2013, Osten & Wolk 2015)
- ➔ Influence of large-scale stellar magnetic fields may prevent breakout/ejection

# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?

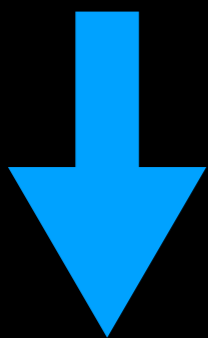
Flare



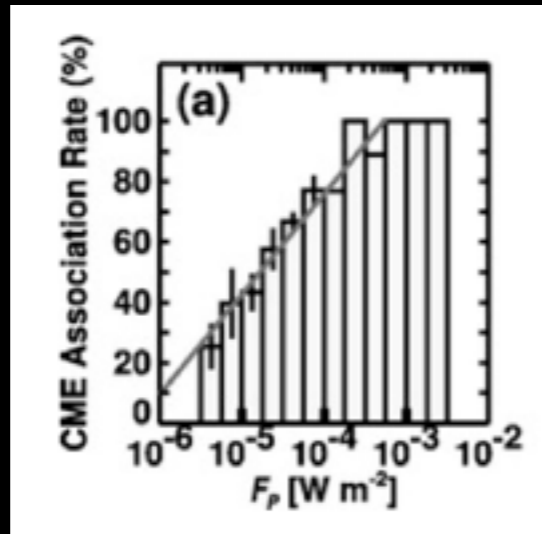
CME



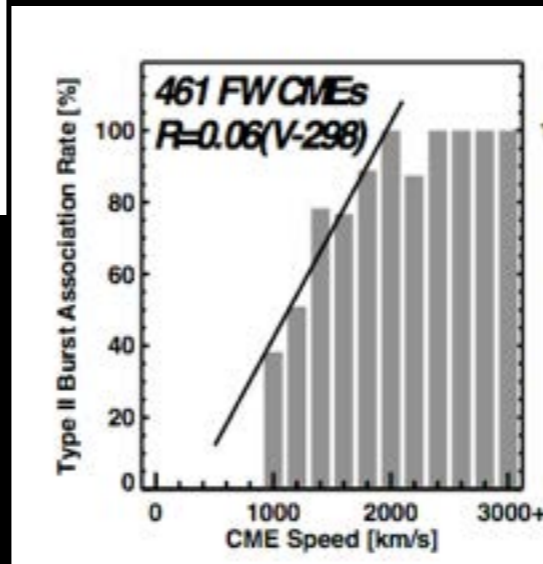
$v > v_A$



Type II burst



Yashiro et al. (2006)

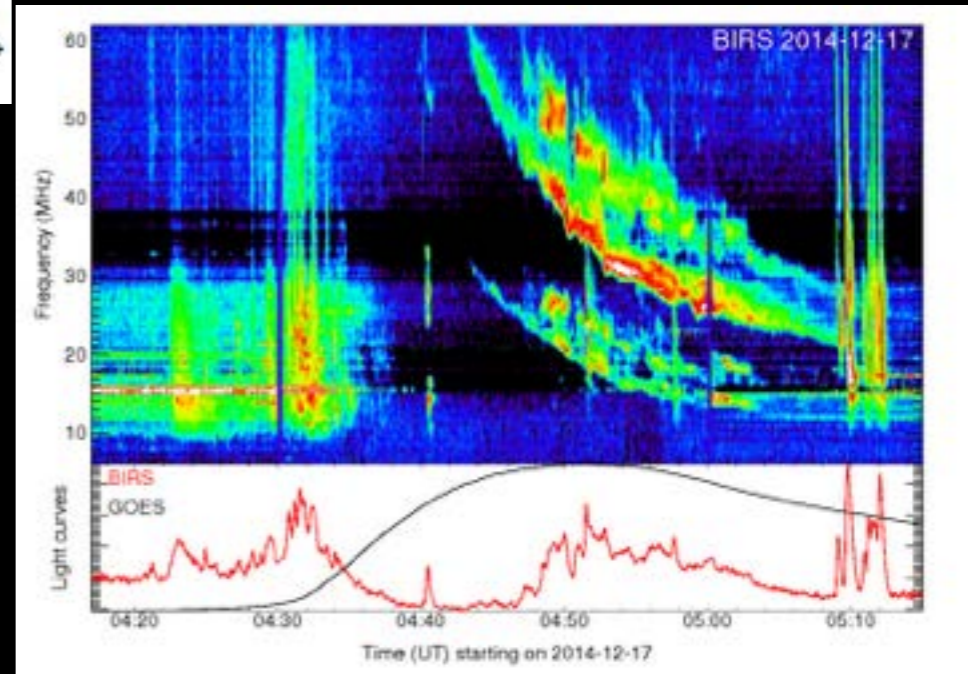


Gopalswamy et al. (2008)

What We Expect

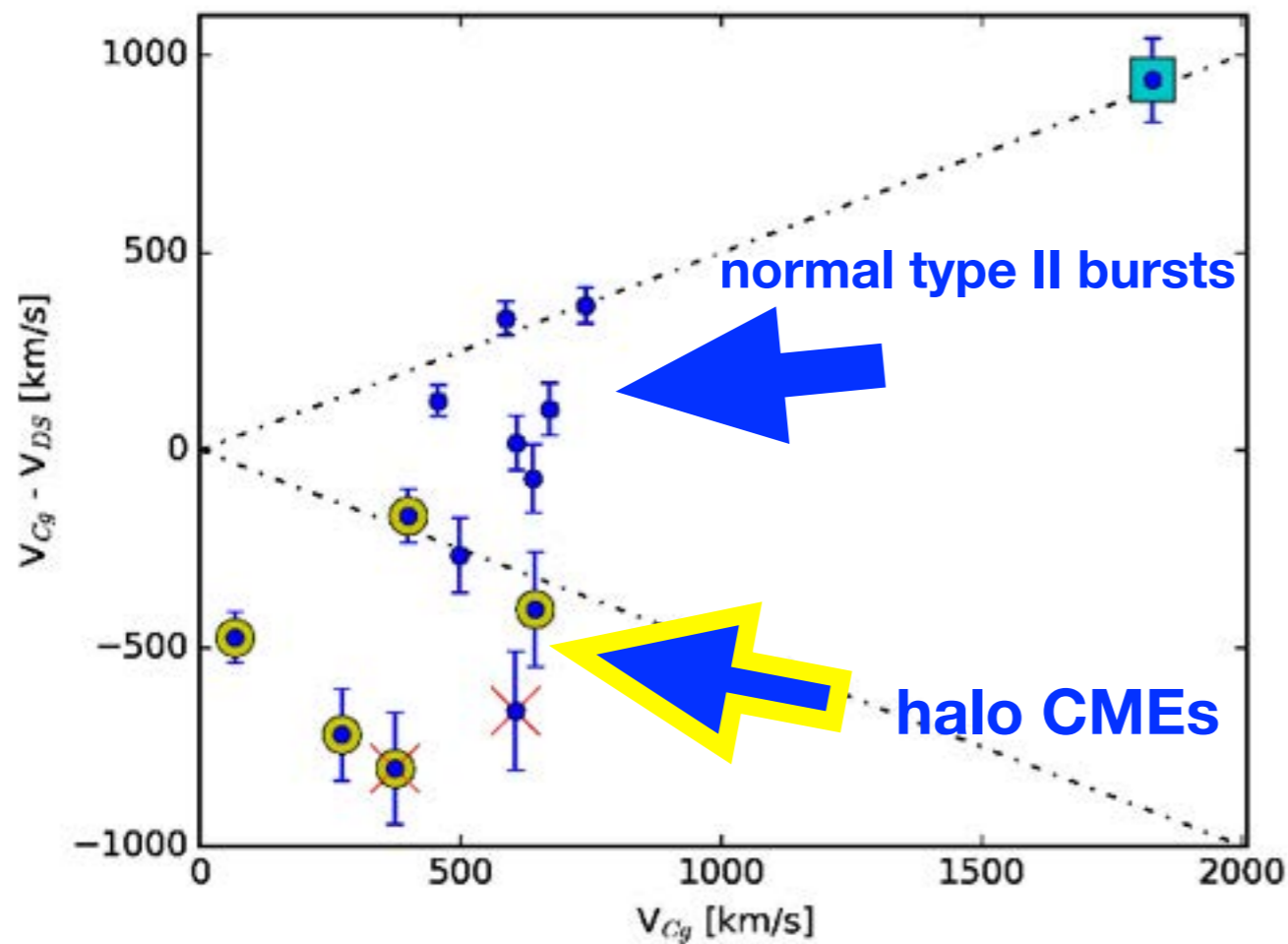
$$\frac{dv}{dt} = \frac{\partial v}{\partial n_e} \frac{\partial n_e}{\partial h} \frac{\partial h}{\partial s} \frac{\partial s}{\partial t}$$

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



Crosley et al. (2017)

# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?



Crosley et al. (2017)

- Pretend the Sun is a star: solar type II dynamic spectra, X-ray flares, scaling relations

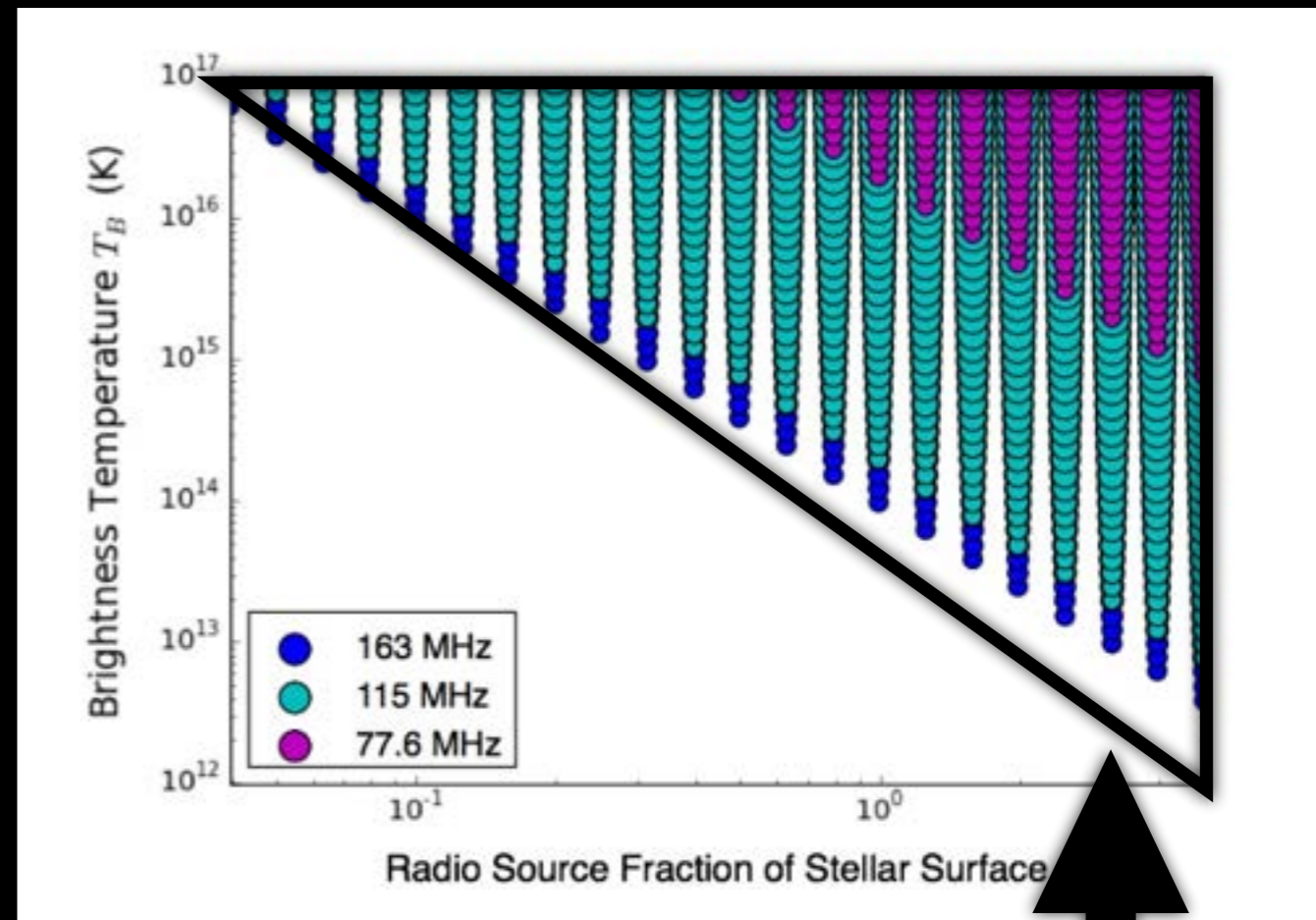
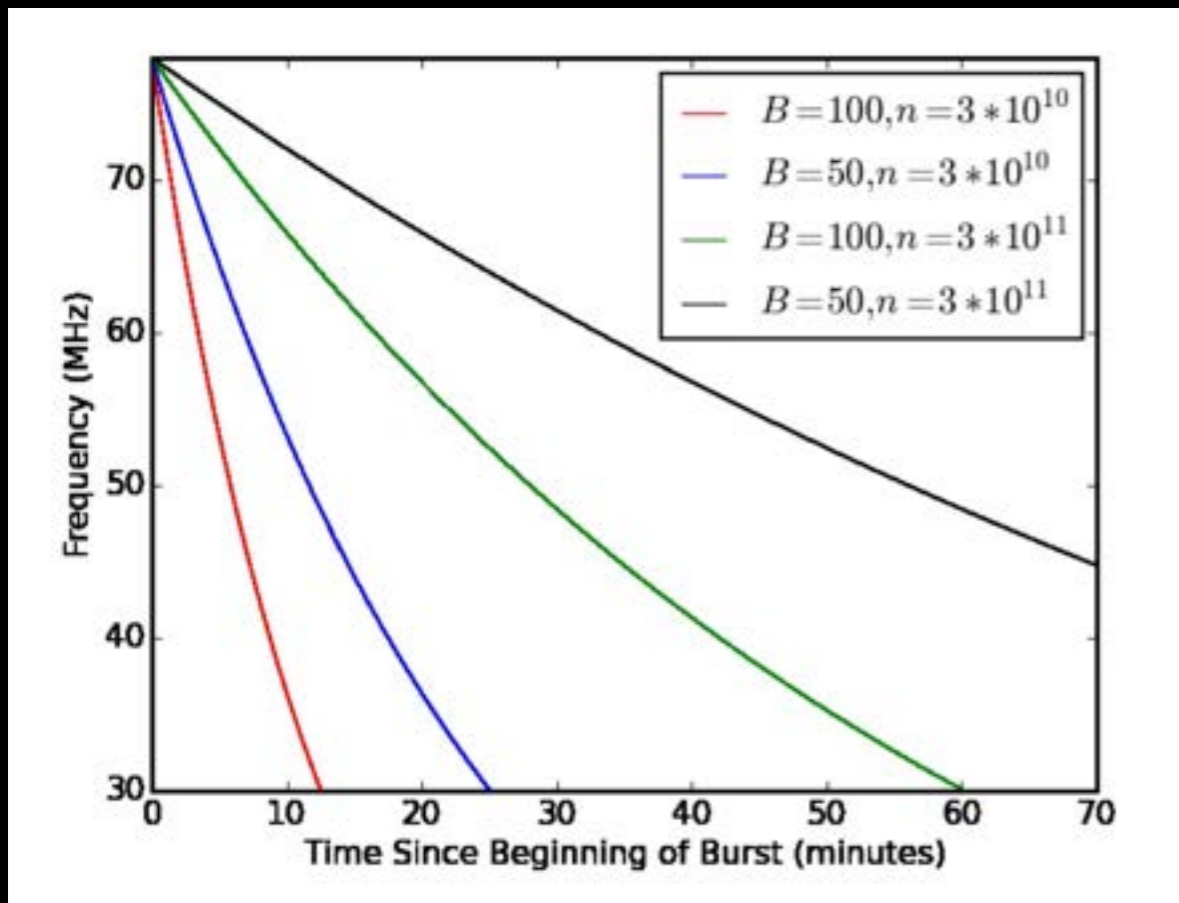
$$\frac{1}{2}M_{CME}v^2 = \frac{E_{rad}}{\epsilon f_{rad}}$$

$$M_{CME} = AE^\gamma \text{ [g]}$$

- Compare with coronagraphic measurements
- CME velocities good to about 50%, masses to an order of magnitude, kinetic energies only ~3 orders of magnitude



# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?



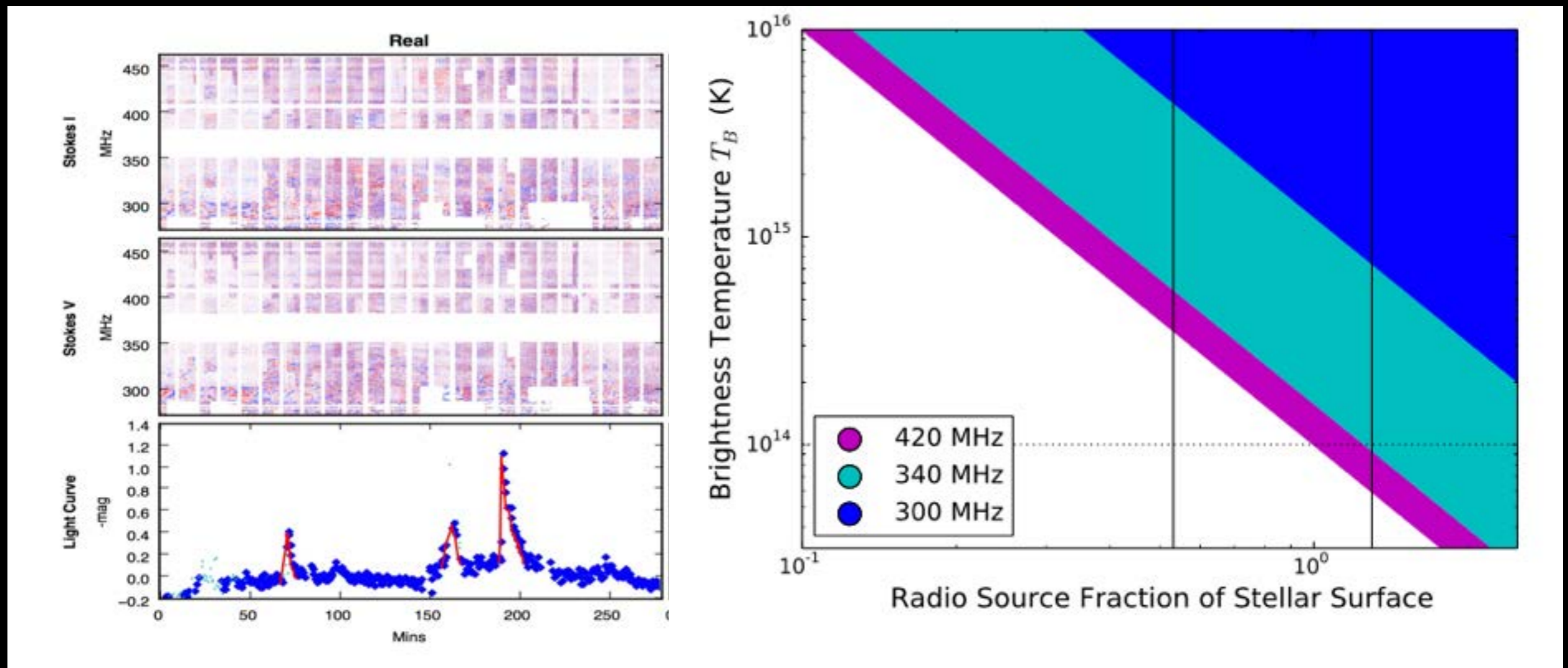
sensitive to this area

expect a burst of this shape

Crosley et al. (2016)

- ➔ Constraints on the rate of stellar CMEs from LOFAR observations of a well-studied nearby M dwarf (YZ CMi)
- ➔ Optical flare rate is 1.2 flares every 3 hours; expect a CME to accompany each powerful flare. For 15 hours of radio observations we expected several flares/CMEs to have occurred

# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?

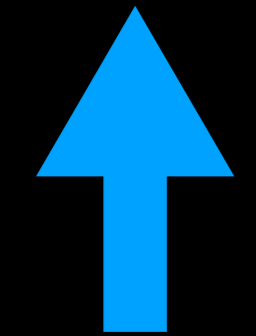


Crosley & Osten in prep.

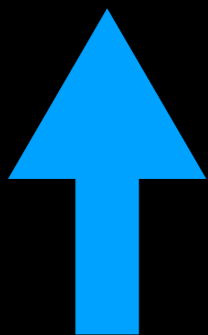
- JVLA, APO simultaneous measurements
- Each pixel in the dynamic spectrum image is 15 s by 500 kHz (total span is 4 hours and ~240 MHz)
- 20 hours of overlapping radio/optical data, several moderate flares
- No features identifiable as type II bursts (no features, period)

# Do Active M Dwarfs Produce Frequent Coronal Mass Ejections?

Flares but no CMEs?



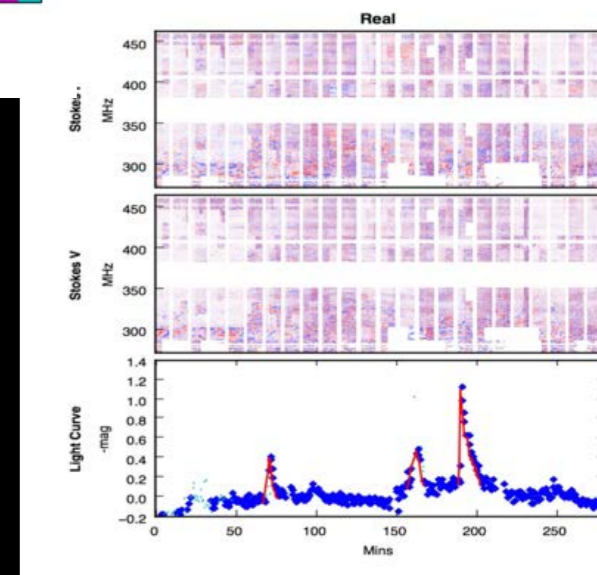
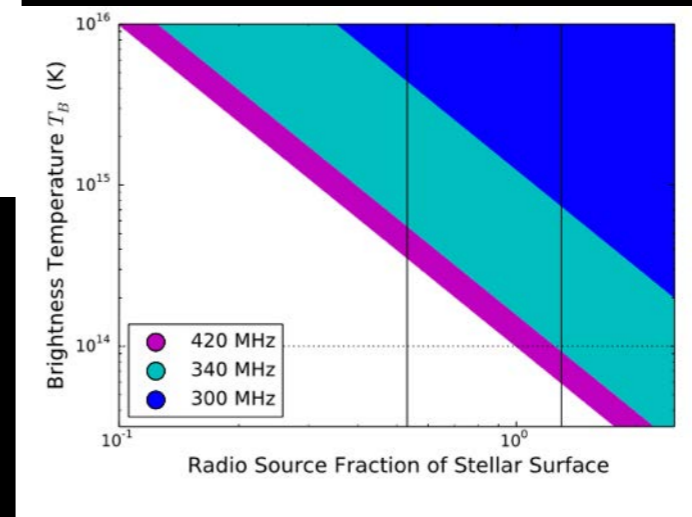
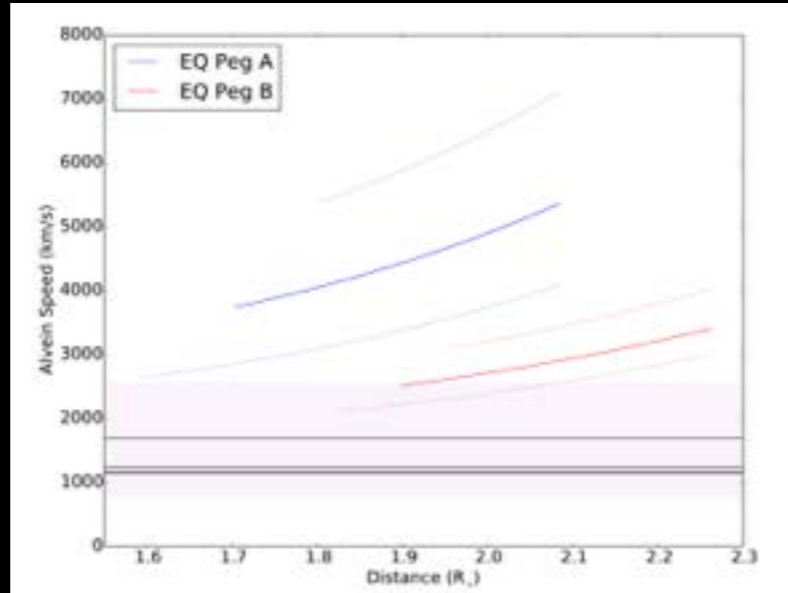
is  $v > v_A$ ?



unlucky? (mismatch between type II params & observing sensitivity)



no type II burst

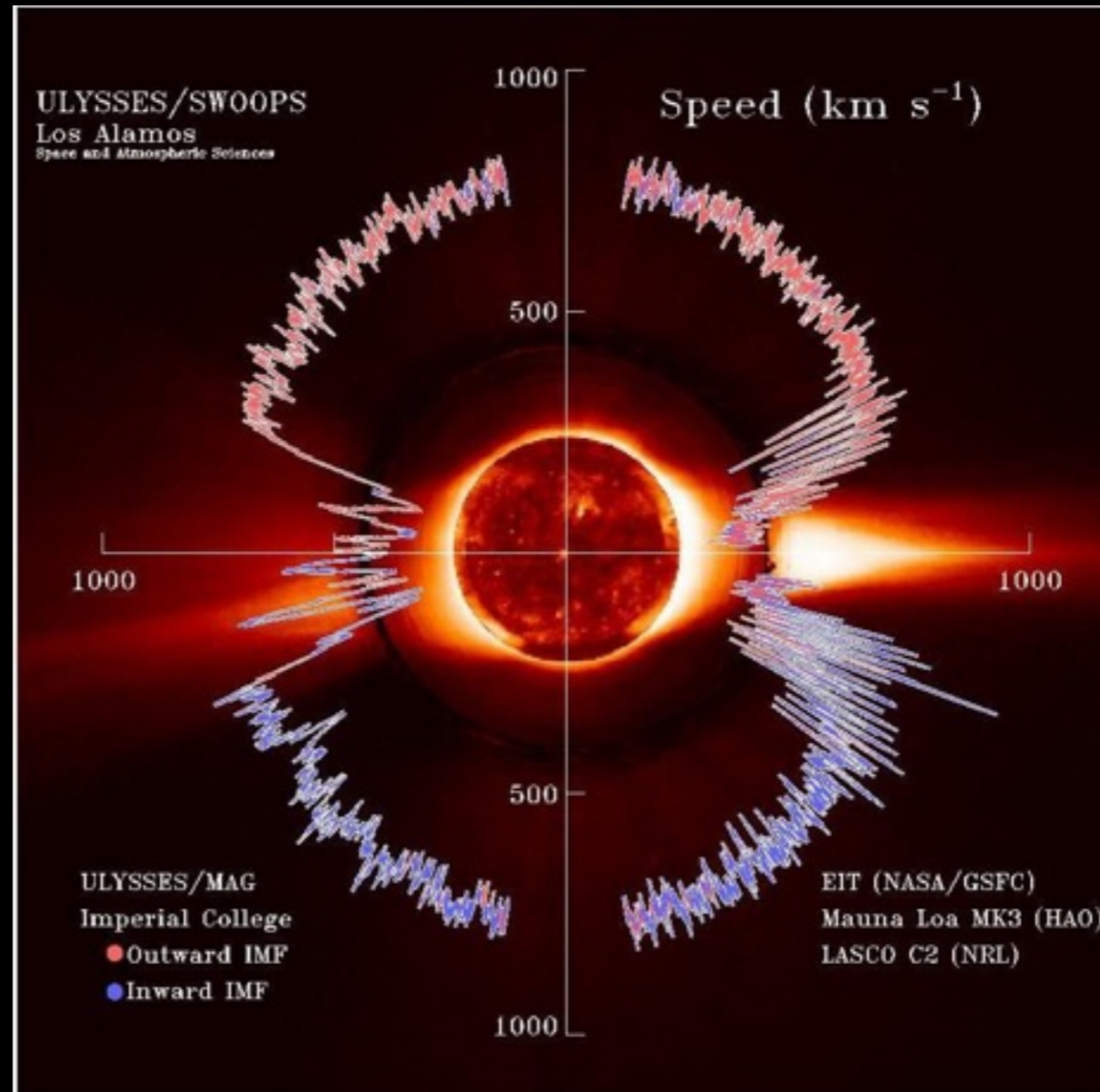


**What We See**

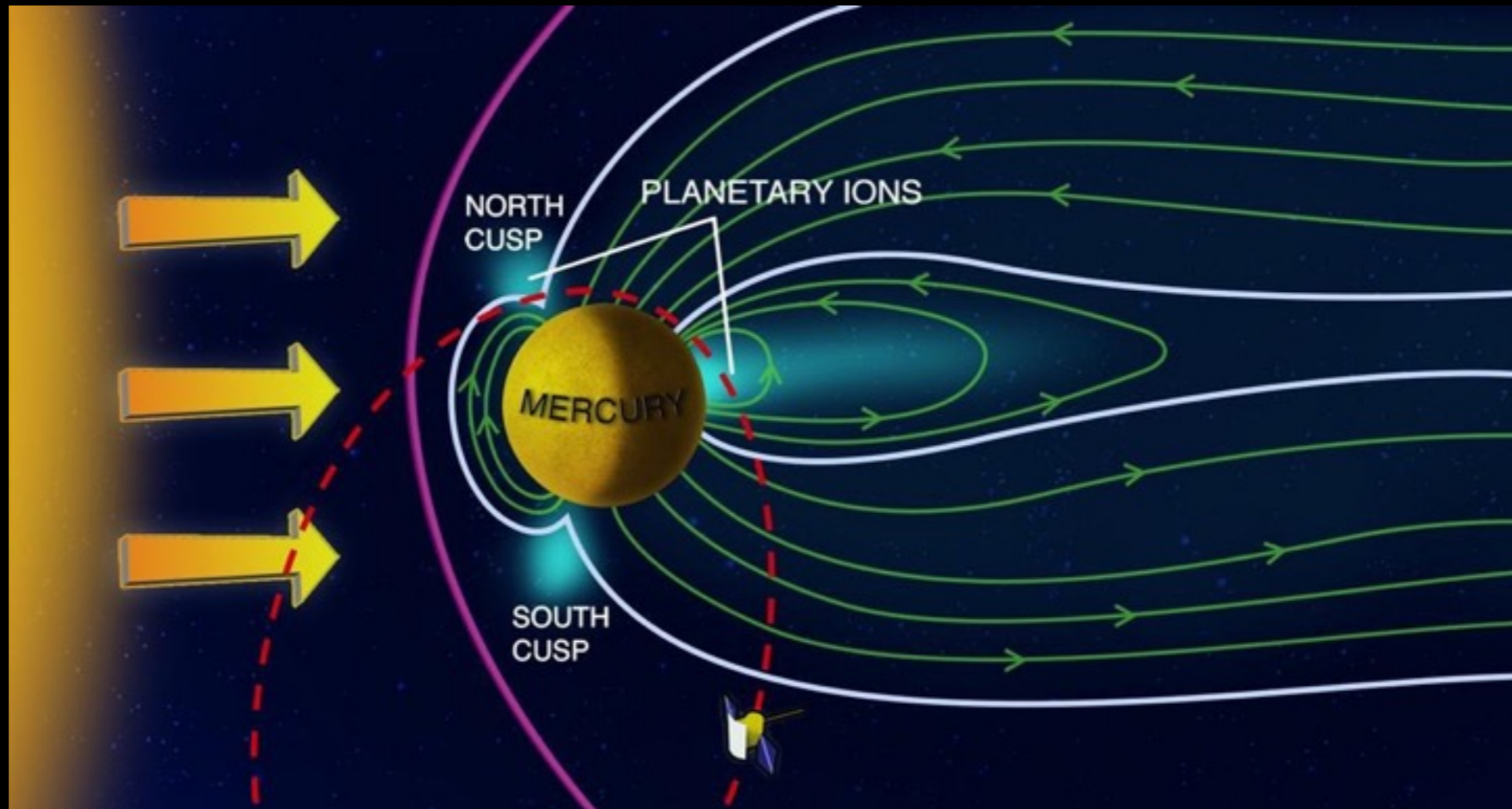


# The impact of a stellar wind

We have direct measurements of the Sun's feeble wind: for all other types of main sequence cool stars, only inferences (or upper limits)

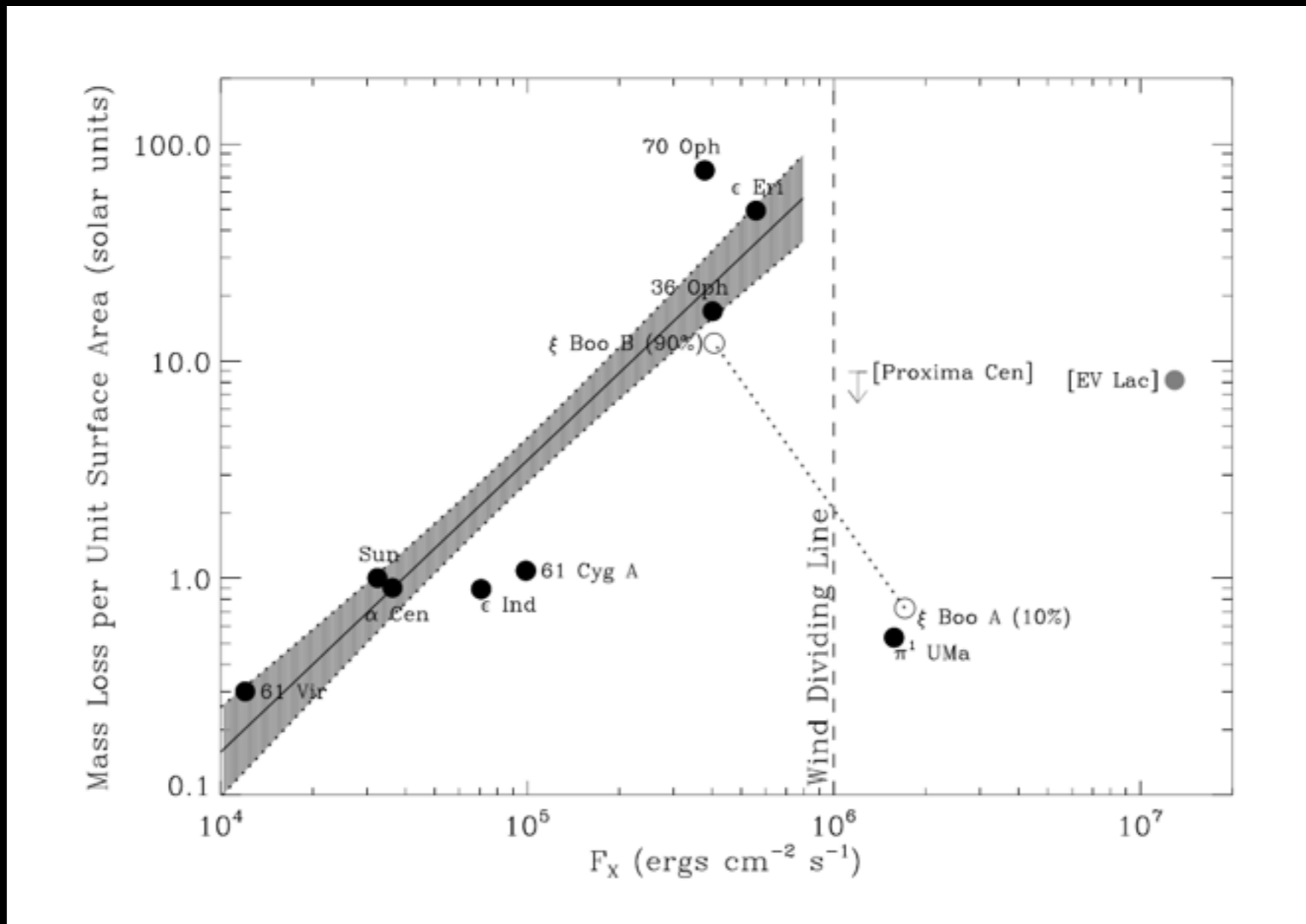


# The impact of a stellar wind



Solar wind may have prevented a strong planetary dynamo in Mercury's interior, leading to a weak planetary magnetic field

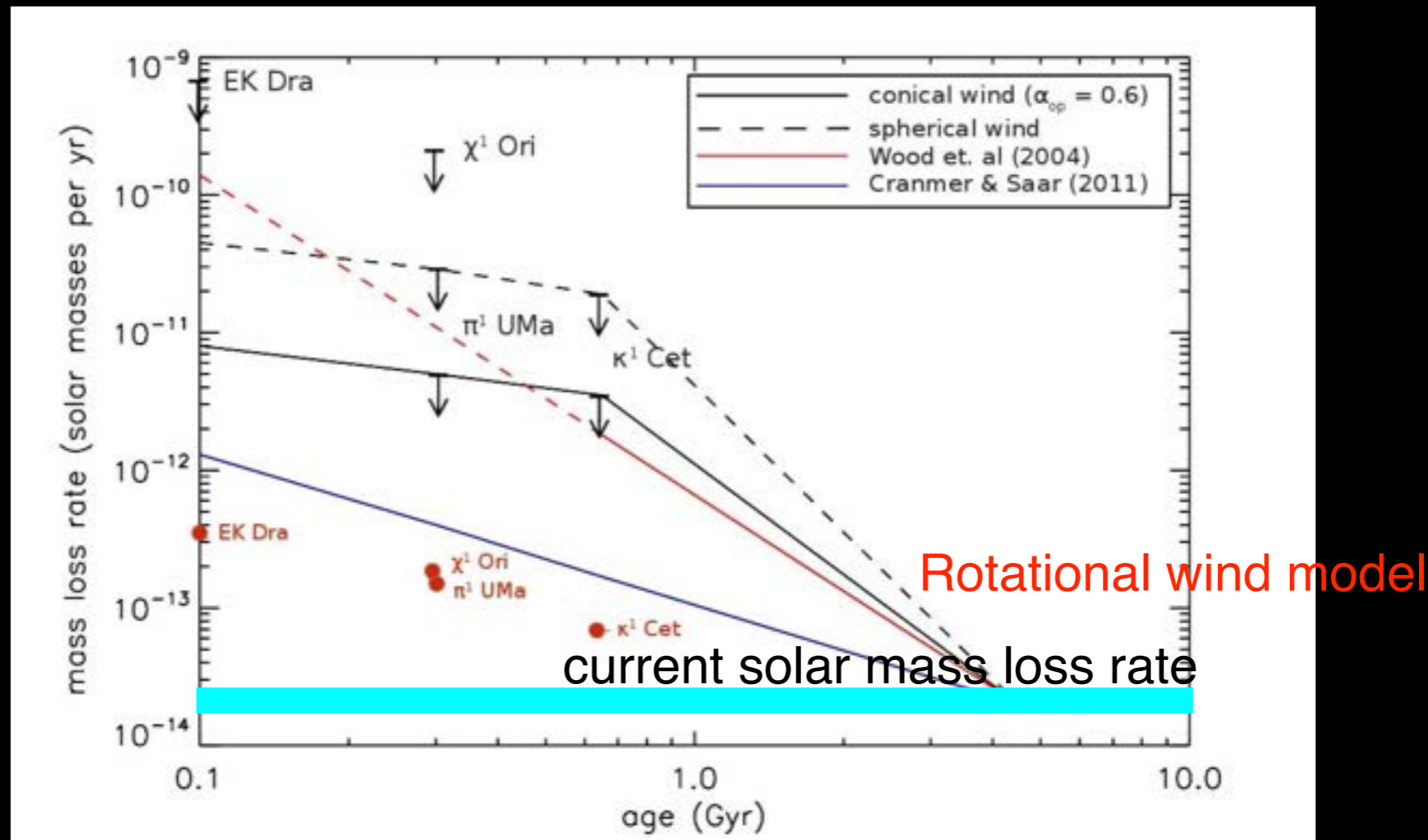
# The impact of a stellar wind



Wood et al. (2014)

The most active stars do not appear to possess strong stellar winds  
Limits investigation of the mass-loss history of the Sun

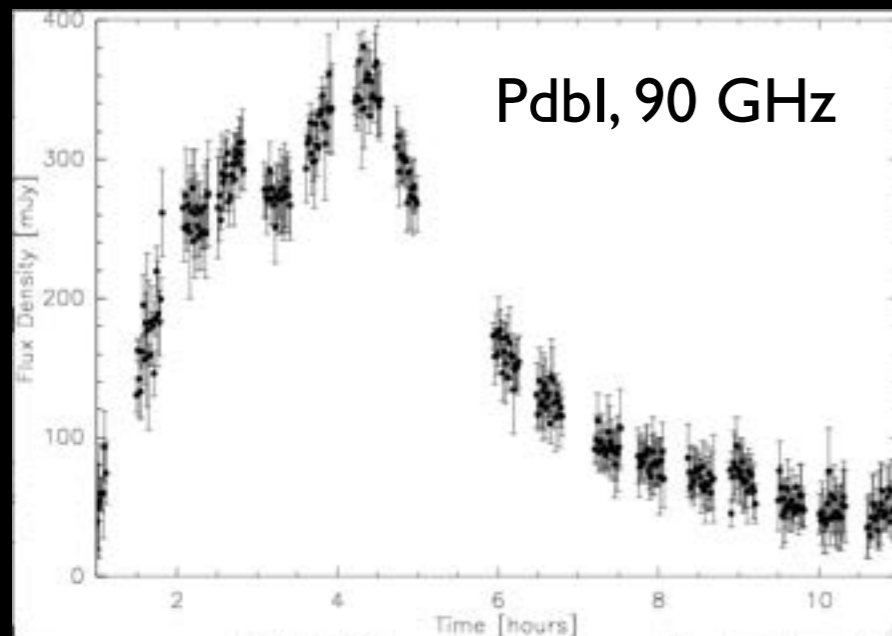
# The impact of a stellar wind



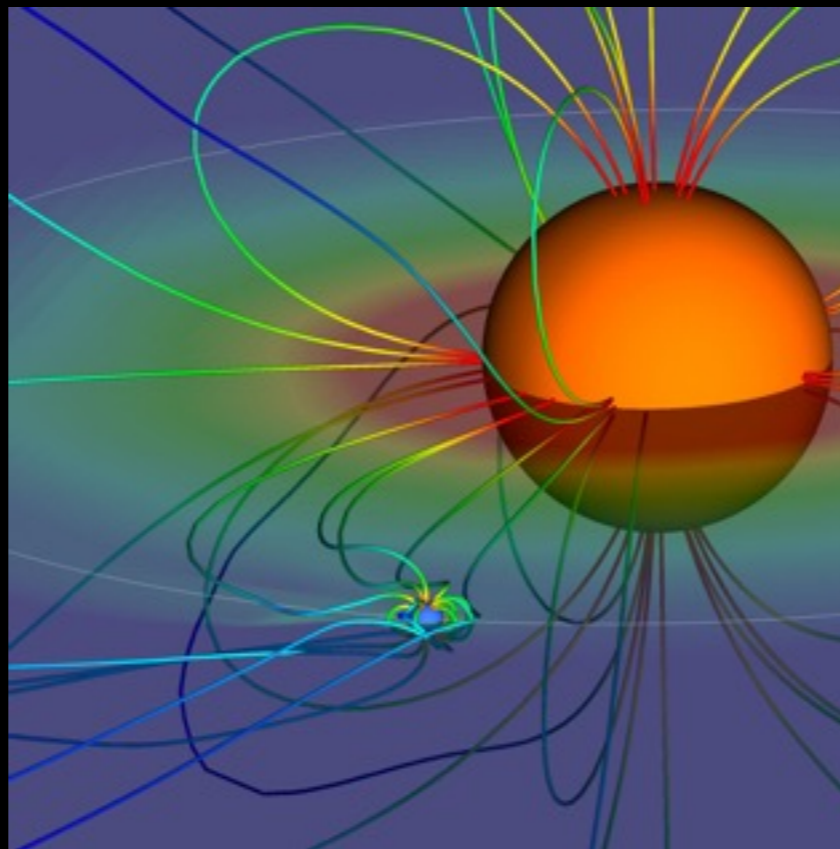
- Fichtinger et al. (2017) constraints from JVLA and ALMA observations of nearby solar analogs
- The rotational wind model of Johnstone et al. (2015) requires higher wind mass loss rates than astrospheric constraints to explain the observed spin-down rates for solar-like stars



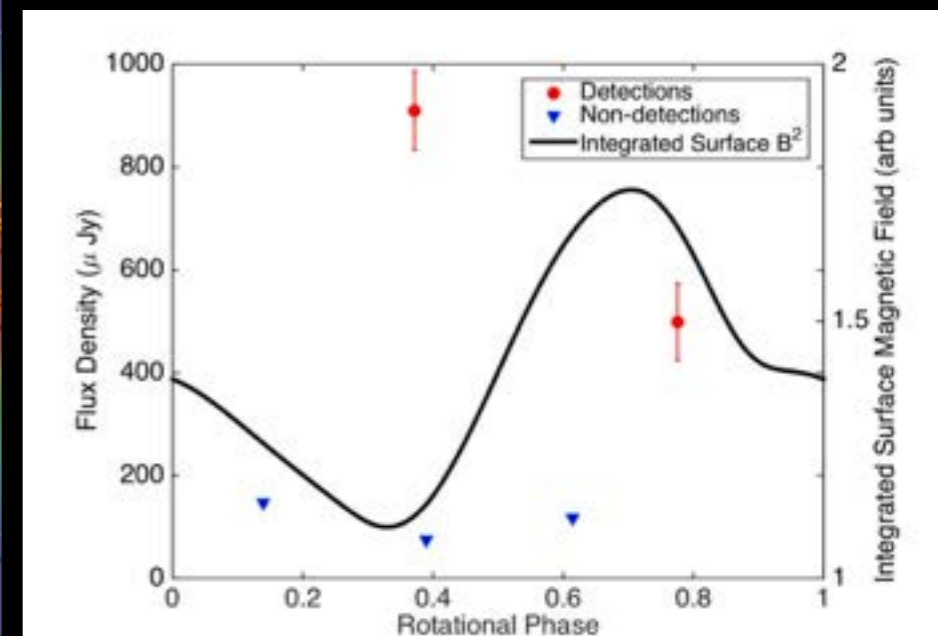
# Might the Planet Impact Radio Emission of its Host Star?



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



credit: A. Strugarek



Sparse radio light curve of V830  
Tau (Bower et al. 2016), a 2 MY  
star hosting a 4.93 d  $P_{\text{orb}}$  hot  
Jupiter

Possibility of seeing signature of interacting star-planet magnetospheres: stellar radio emission modulated on planetary orbital period timescale, triggered flares like in X-rays (Pillitteri et al. 2014)

# How Stellar Magnetic Activity Affects Planetary Habitability

- Material expelled from star (steady wind, transient mass loss) can affect anything in the star's environment; space weather or habitability impact on close-in planets?
  - ◆ Does the solar scaling apply?
  - ◆ Does a high rate of flaring imply a similarly high rate of CMEs?
  - ◆ What is the importance of overlying magnetic structures in the eruption, breakout of material from the stellar surface?
- Radio observations allow for a unique diagnosis of close-in accelerated particles
  - ◆ Is this revealing a difference from particle acceleration in solar situations?
- Need to consider the full feedback loop: planets affecting stars
- Stellar twins are not magnetic twins: how generalizable are the results?

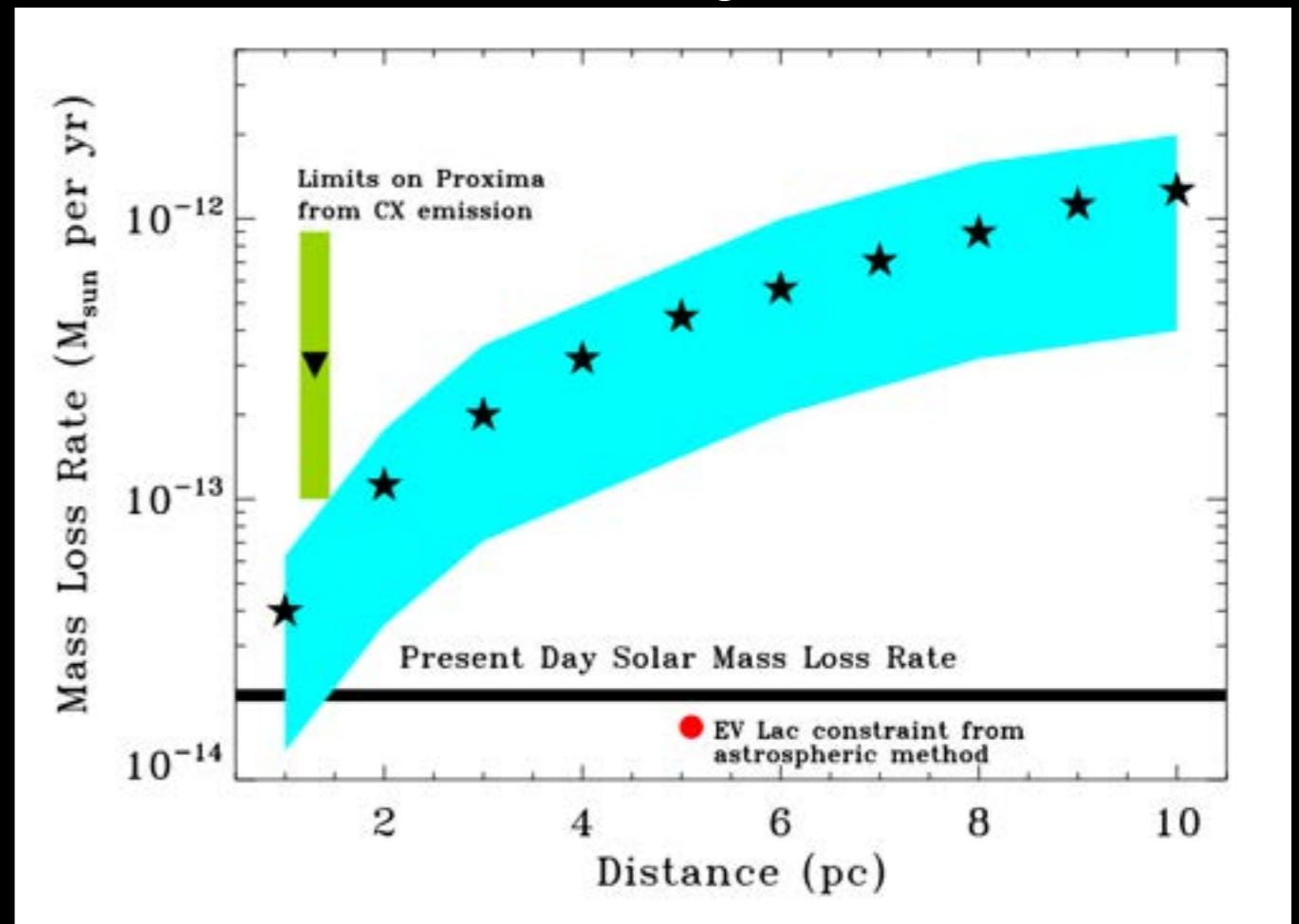
# More Distant Prospects

Ability to constrain wind mass loss rates for M dwarfs in the solar neighborhood

A Southwest Array, the next generation Very Large Array

*Sensitive high spatial resolution radio observations >10 GHz*

- Detect or constrain radio emission from an ionized stellar wind, improving current radio upper limits for solar analogues by ~two orders of magnitude, sensitive surveys of nearby planet-hosting M dwarfs



Osten & Crosley, ngVLA Memo

