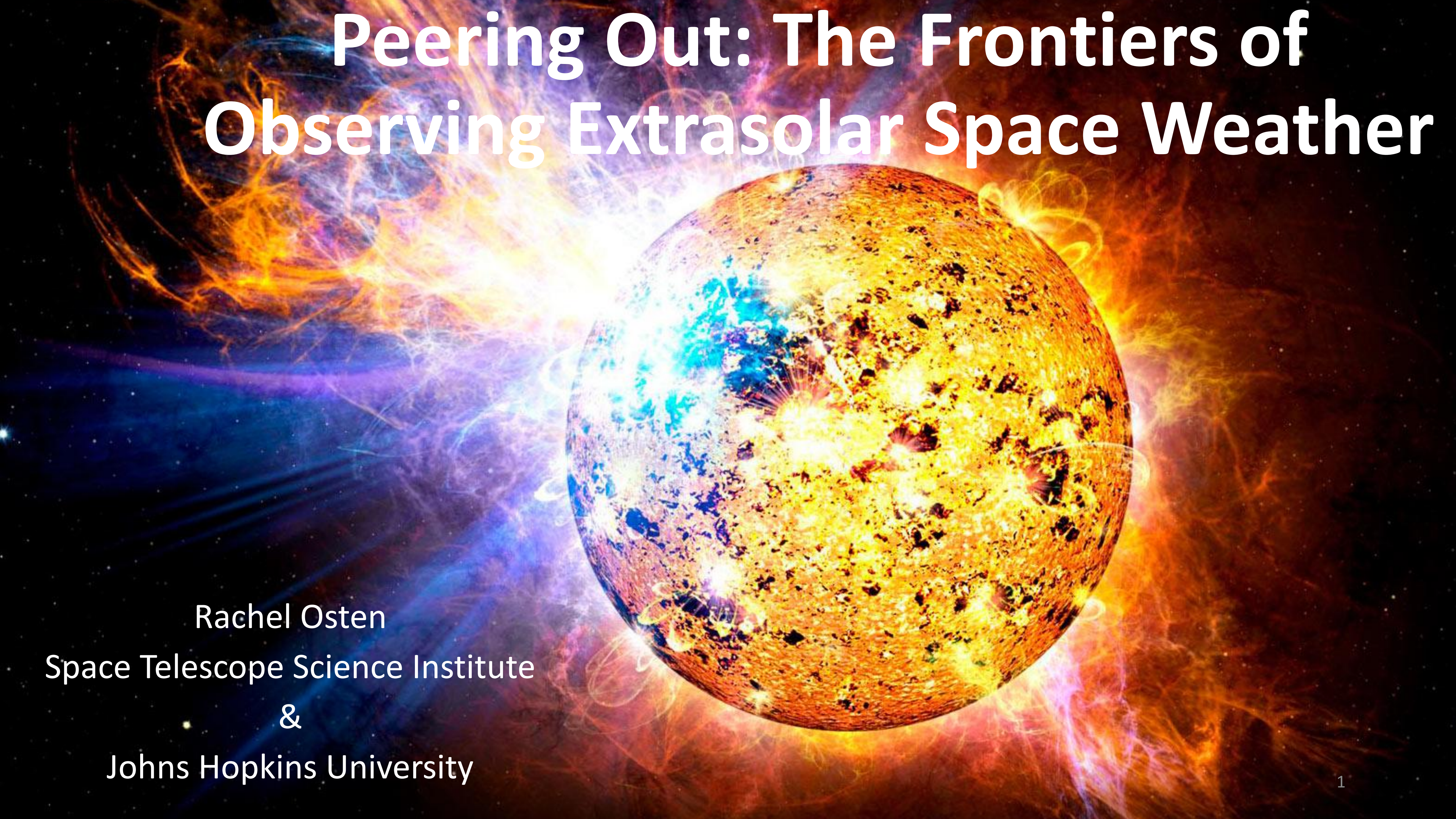
Peering Out: The Frontiers of Observing Extrasolar Space Weather

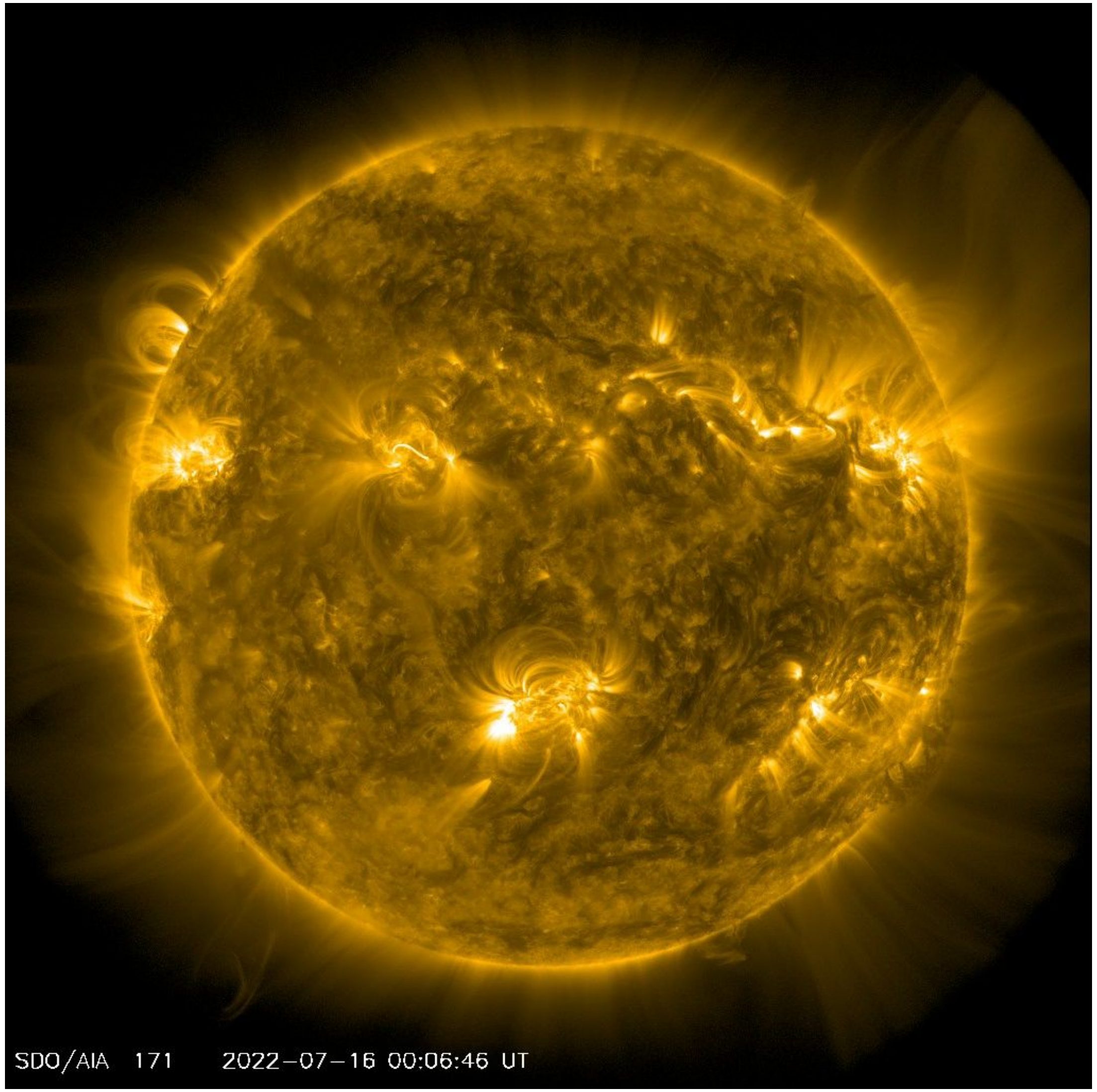


Rachel Osten
Space Telescope Science Institute
&
Johns Hopkins University

Outline

- Sun vs other stars
- Stellar magnetic fields
- Space weather: radiation
- Space weather: magnetized winds, stellar mass loss and its impacts
- Space weather: accelerated particles

Studying the Sun vs. Other Cool Stars



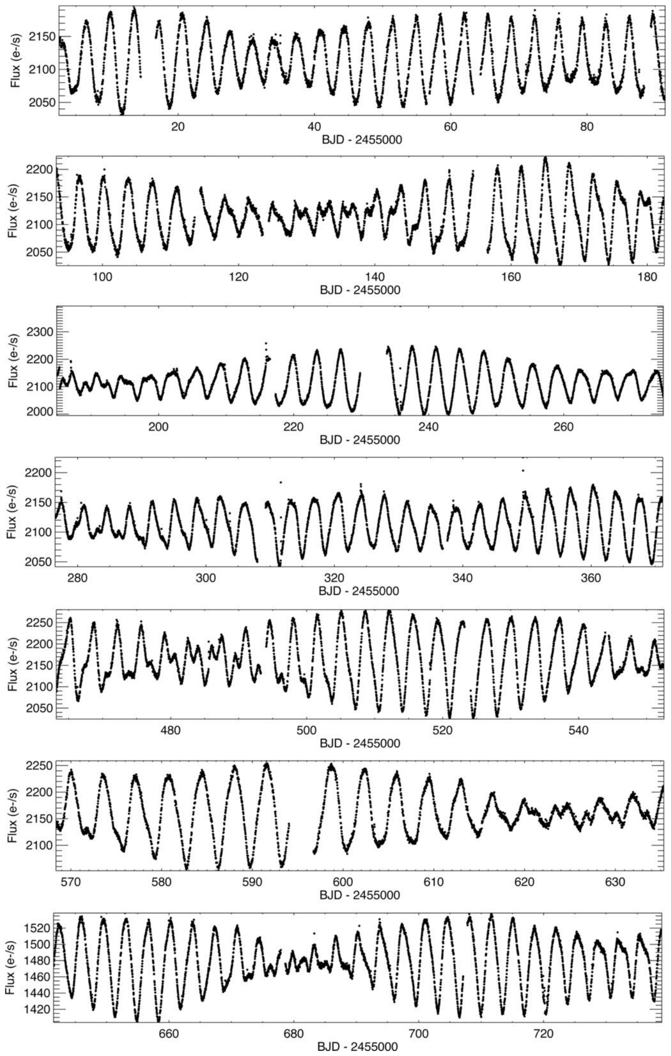
- \+ One star, exquisite spatial, spectral, temporal resolution
- \+ Daily global monitoring from ground and space, multi-wavelength context
- \+ An entire NASA Division devoted to its study!
- \+ Specialized instruments/telescopes for its study

- − One star, at one point in its evolutionary sequence
- − G stars are not representative of most stars in our Galaxy
- − Specialized instruments/telescopes for its study
- − How universal are the processes occurring in this atmosphere?

Studying the Sun vs. Other Cool Stars

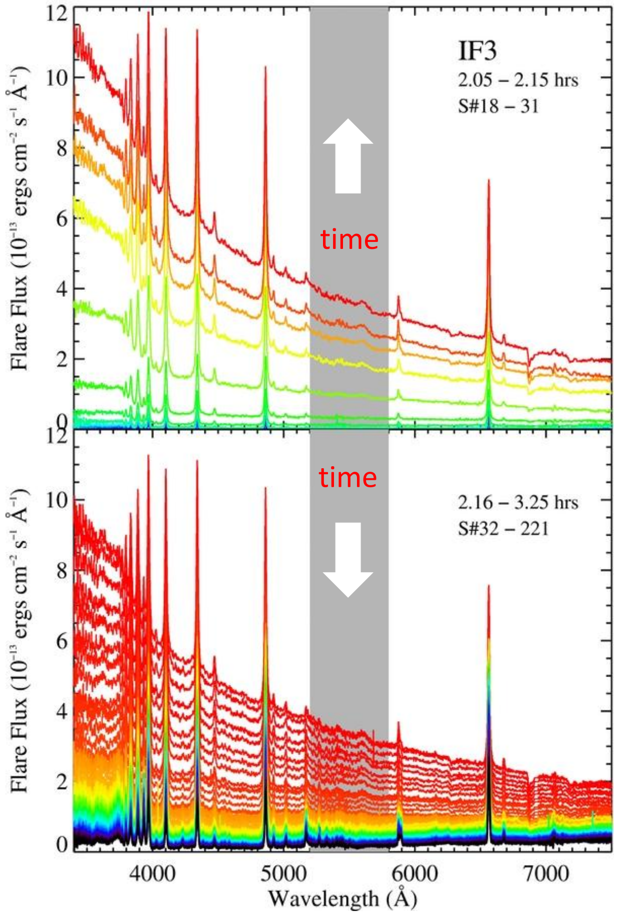
- \+ Millions (billions!) of stars to study
- \+ Low-mass M dwarfs are the most common type of star
- \+ Span a range of ages, rotation rates, evolutionary histories

- − Cannot spatially resolve
- − Typically sparse observations, little multi-wavelength context
- − Different instruments/telescopes used to study compared to solar observations
- − Competes with the rest of the universe for observing time, funding

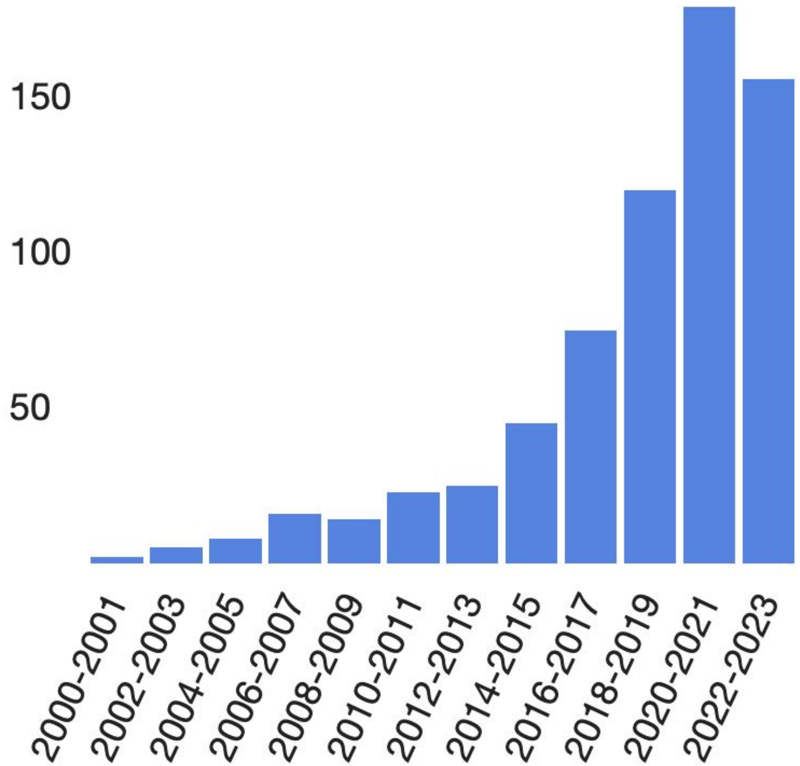


Roettenbacher et al. (2013) Kepler photometry

Kowalski et al. (2013) time-resolved spectroscopy through flare phases



Growth in interest in this field



ADS search of refereed papers with “exoplanet” and ”space weather” by year

One of 3 science areas called out for special emphasis in the coming decade by the US National Academy’s Decadal Survey in Astronomy & Astrophysics

Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds

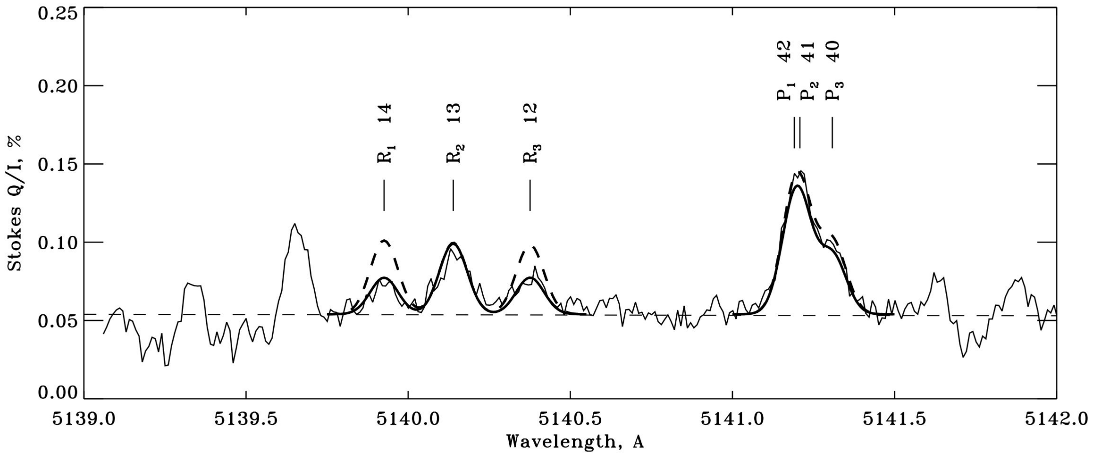
Understanding the connections between stars and the worlds that orbit them, from nascent disks of dust and gas through formation and evolution, is an important scientific goal for the next decade. The effort to identify habitable Earth-like worlds in other planetary systems and search for the biochemical signatures of life will play a critical role in determining whether life exists elsewhere in the universe.

KEY RECOMMENDATIONS:

Measuring stellar magnetic fields

Direct methods:

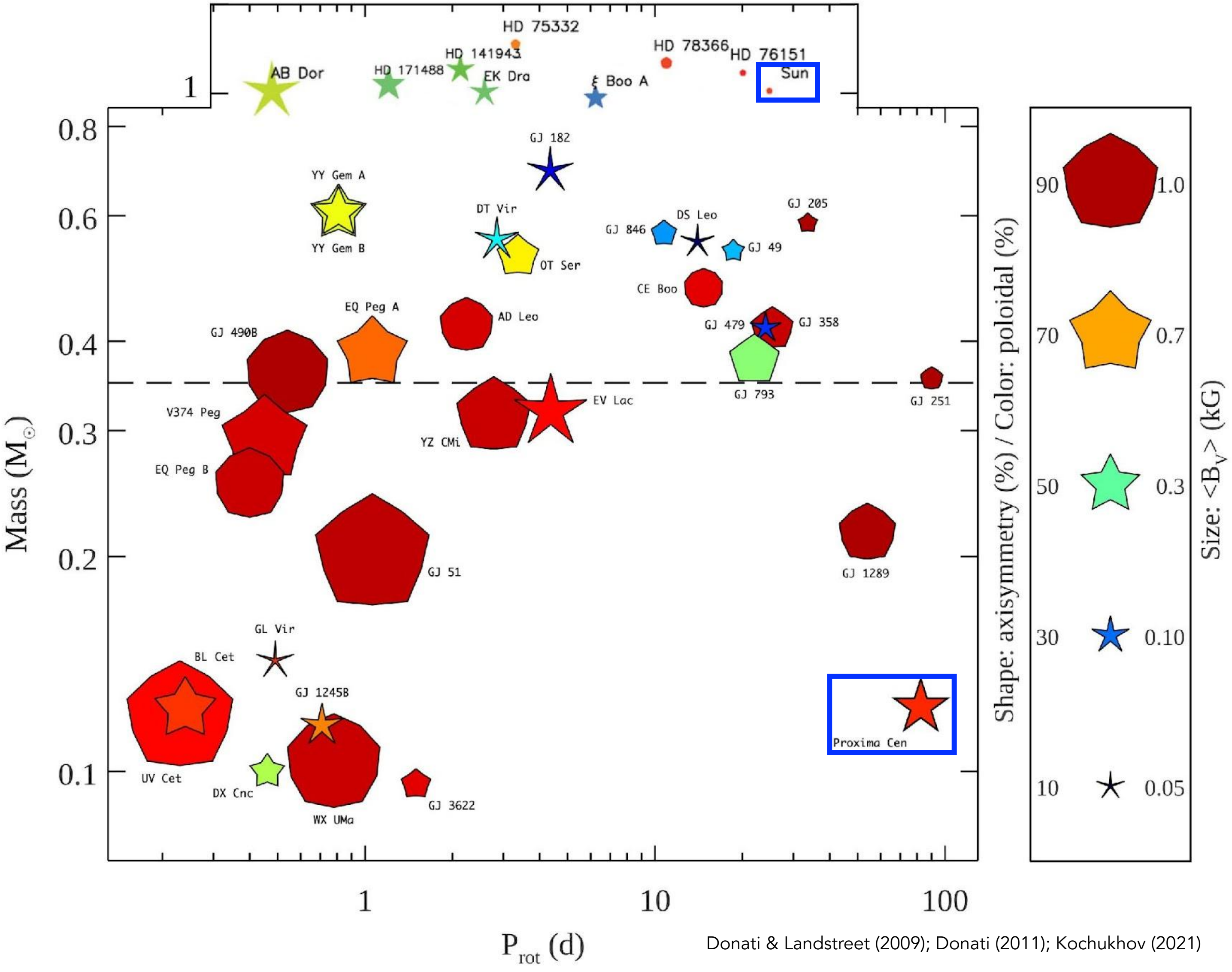
- Zeeman effect (circular polarization)
- Hanle effect (linear polarization)



www.eso.org

Berdyugina & Fluri (2004)

Magnetism in cool main sequence stars: The "Confusogram"
(derived from Zeeman Doppler Imaging reconstructions)



Donati & Landstreet (2009); Donati (2011); Kochukhov (2021)

Sizes: Field Strength
(3 – 1000 G)

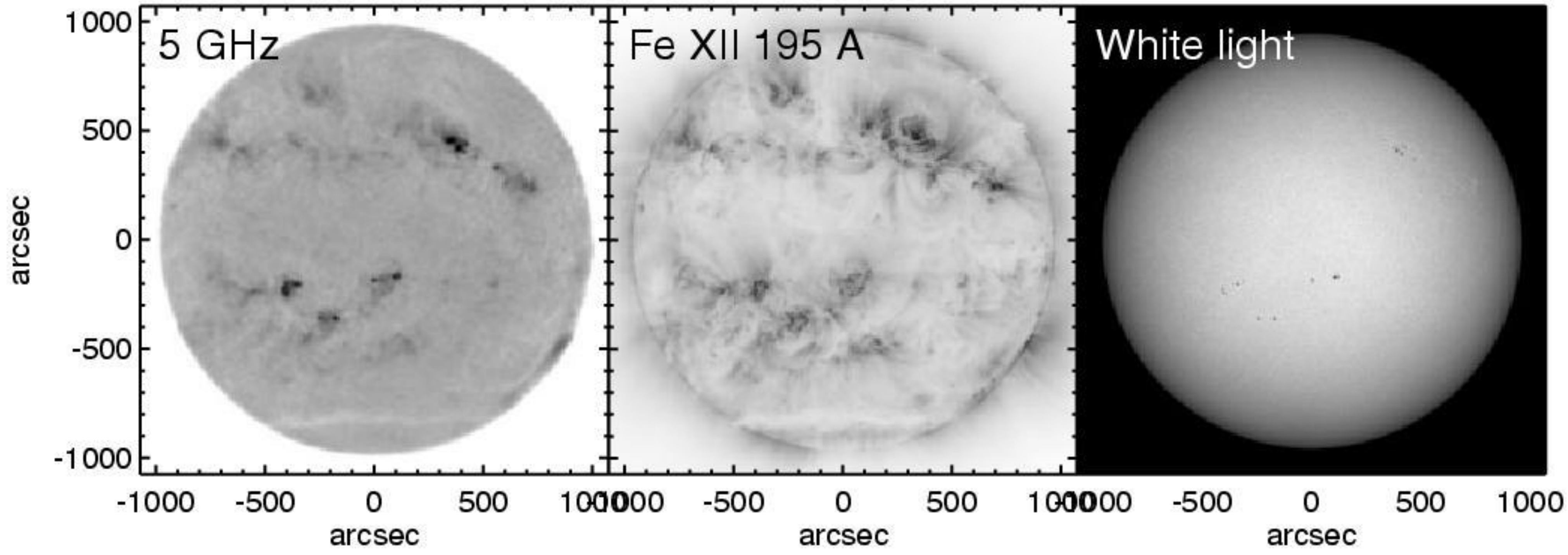
Color: Main Geometry
(Red: Poloidal | Blue: Toroidal)

Shapes: Symmetry
(Decagons: Axisymmetric
Stars: Non-Axisymmetric)

Measuring stellar magnetic fields

Indirect methods

- Stellar magnetic activity twiddles magnetic fields



White et al. (2002)

Measuring stellar magnetic fields

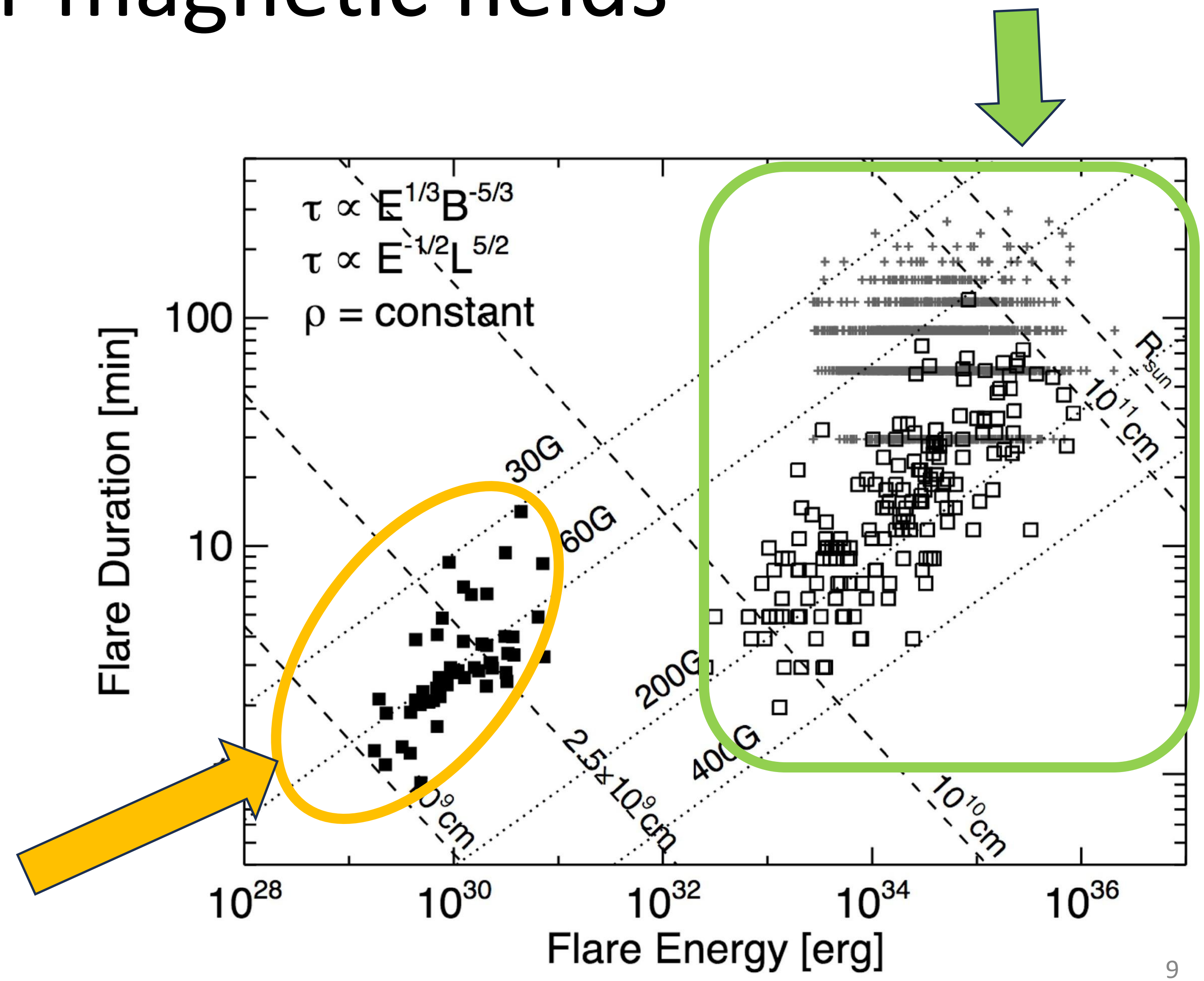
Solar-like stars

Indirect methods

- Flare energy vs energy, dependence on length scale or magnetic field

Namekata et al. (2018) relation between white light flare duration and energy for solar WLFs (filled squares), Kepler WLF on solar-like stars (open squares in short cadence, pluses in long cadence)

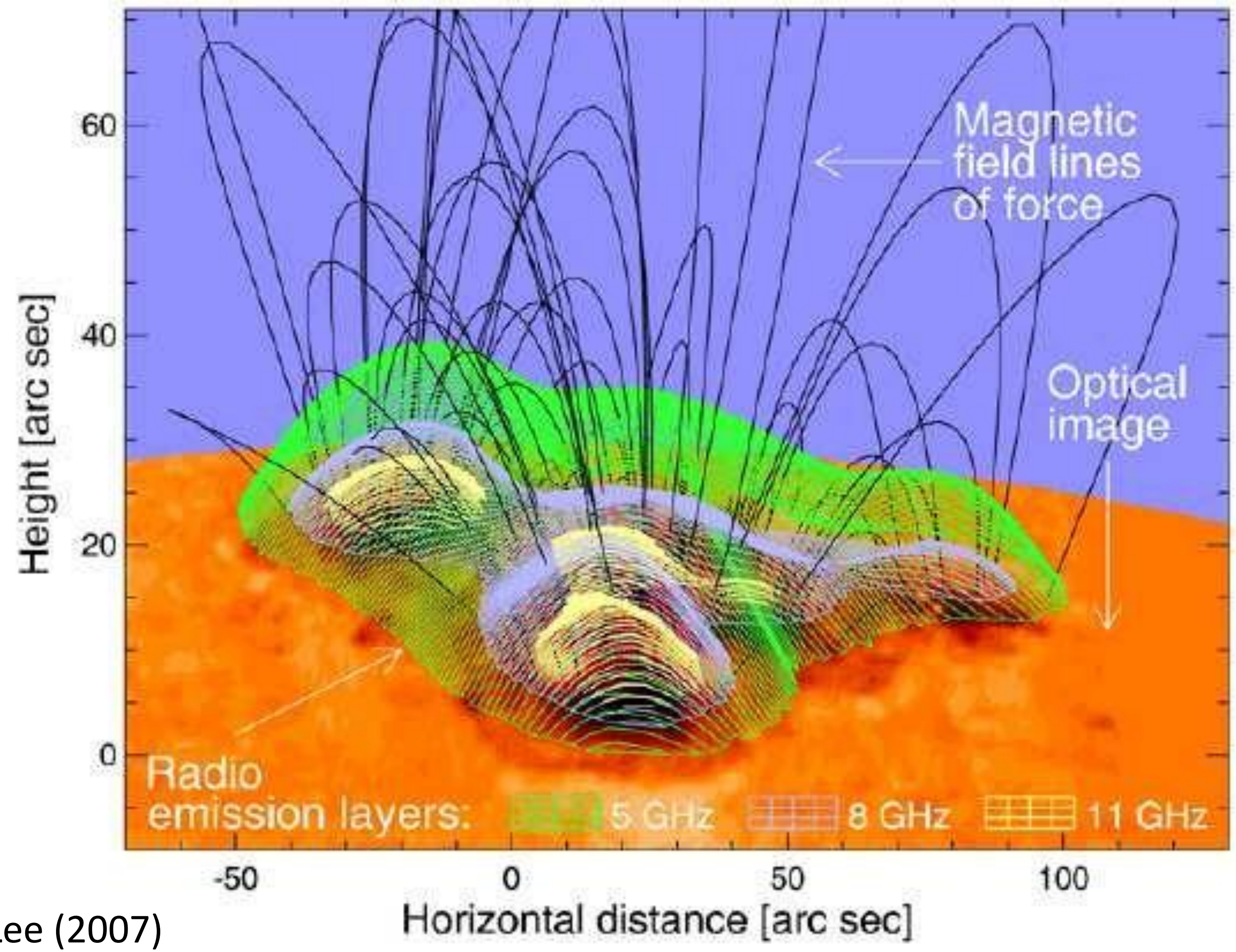
Solar flares



Measuring stellar magnetic fields

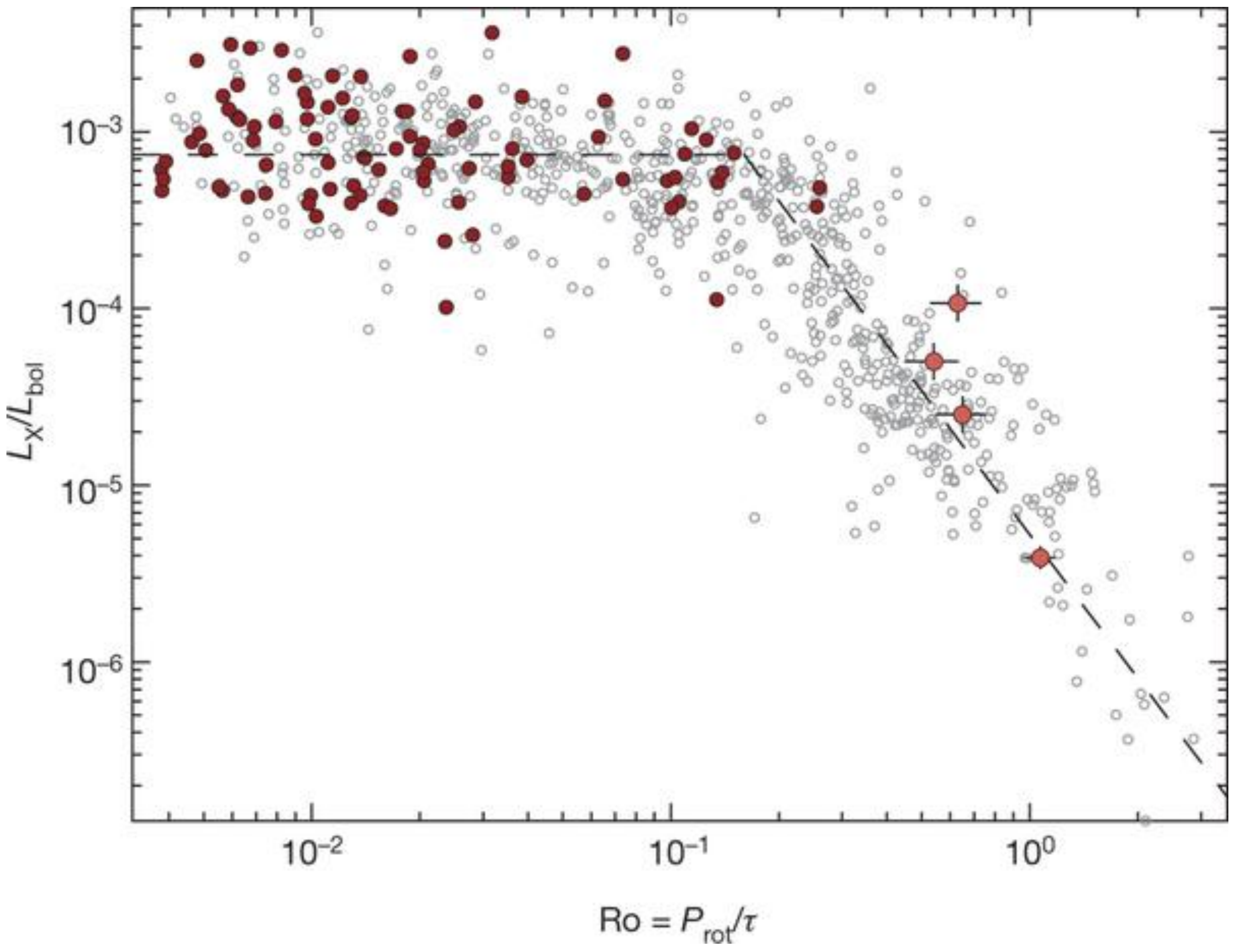
Indirect methods

- Radio observations loosely constrain magnetic fields through incoherent & coherent emission mechanisms



Lee (2007)

The rotation-activity correlation for stars



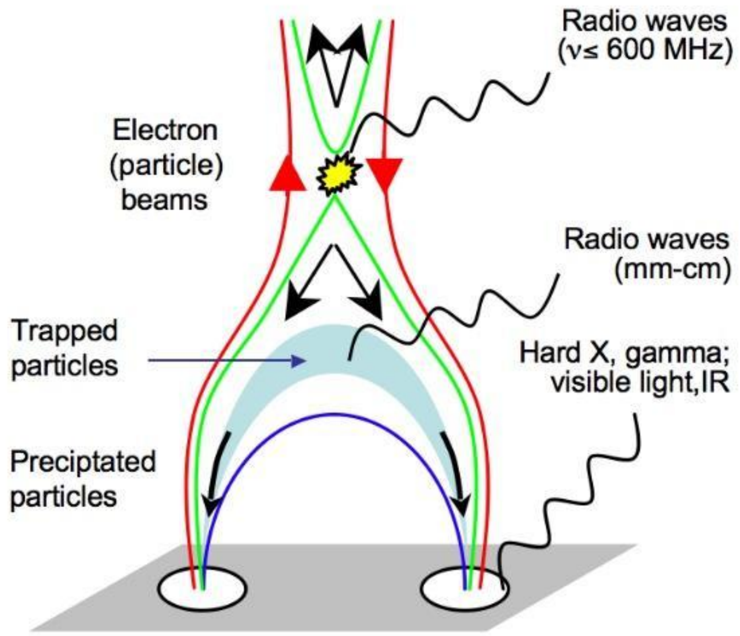
Wright & Drake (2016)

- Activity correlates with rotation – saturated and unsaturated regimes.
- In single main sequence stars, rotation is a function of stellar age, due to angular momentum loss from a magnetized wind

We observe stellar flares across the EM spectrum

Observational Flare Signature	Solar	Stellar*
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)	✔	✔
EUV/soft X-ray emission (corona)	✔	✔
optical emission lines (chromosphere)	✔	✔

*across different cool stars

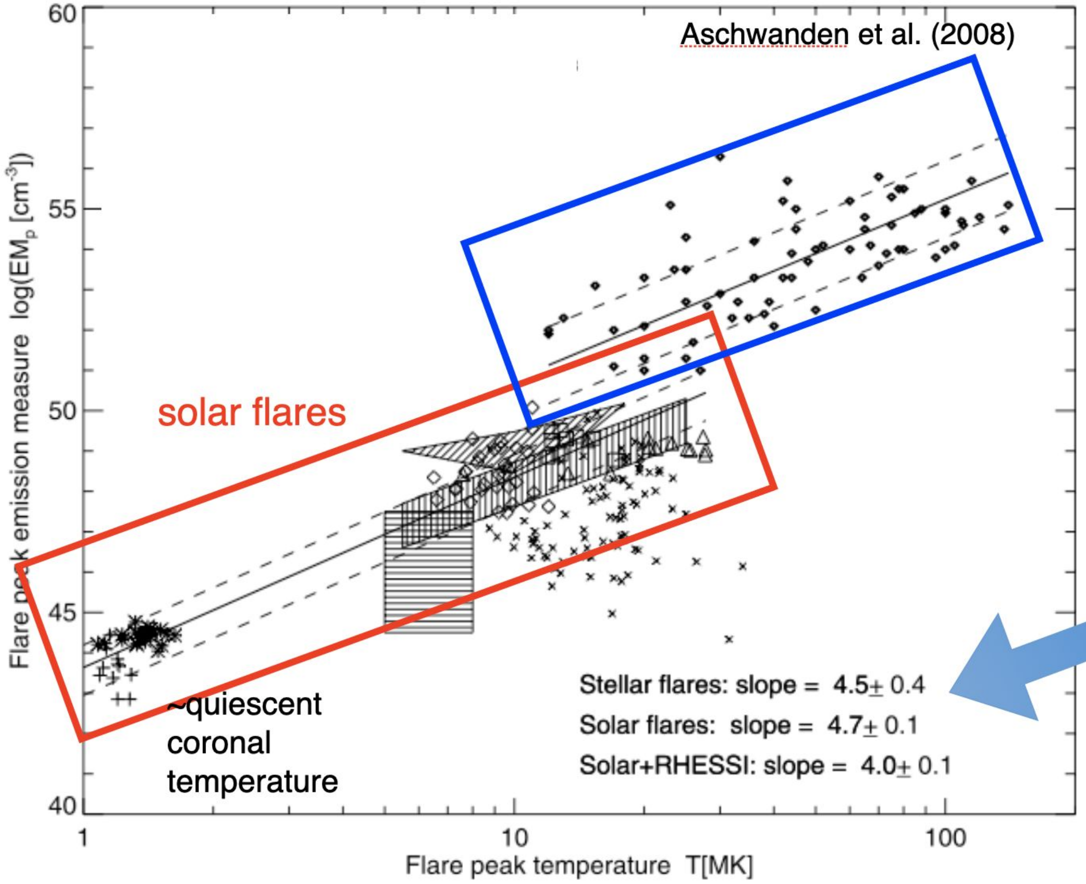


Klein & Dalla (2017)

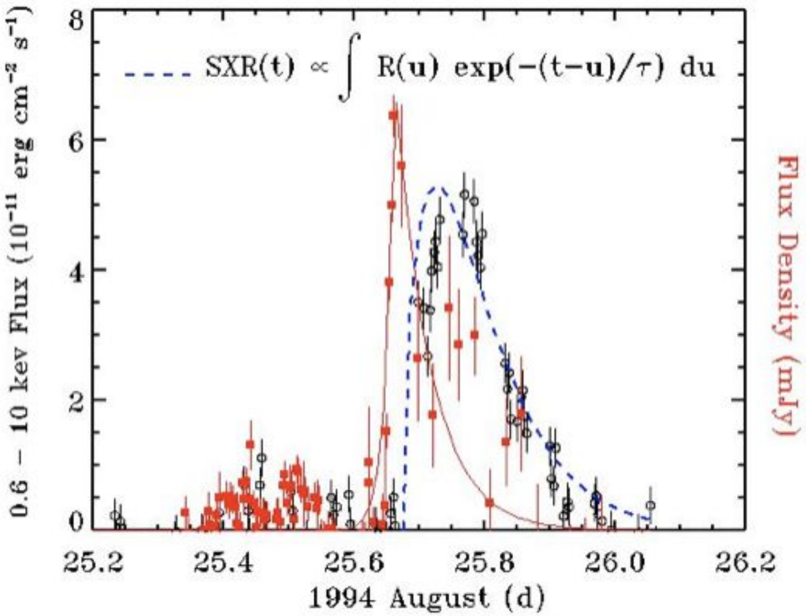
See Osten (2016) in Heliophysics: Active Stars and their Astrospheres for a comprehensive description of stellar flaring as a function of both wavelength and age

And we infer the same physical processes as in solar flares

Osten et al. (2004)



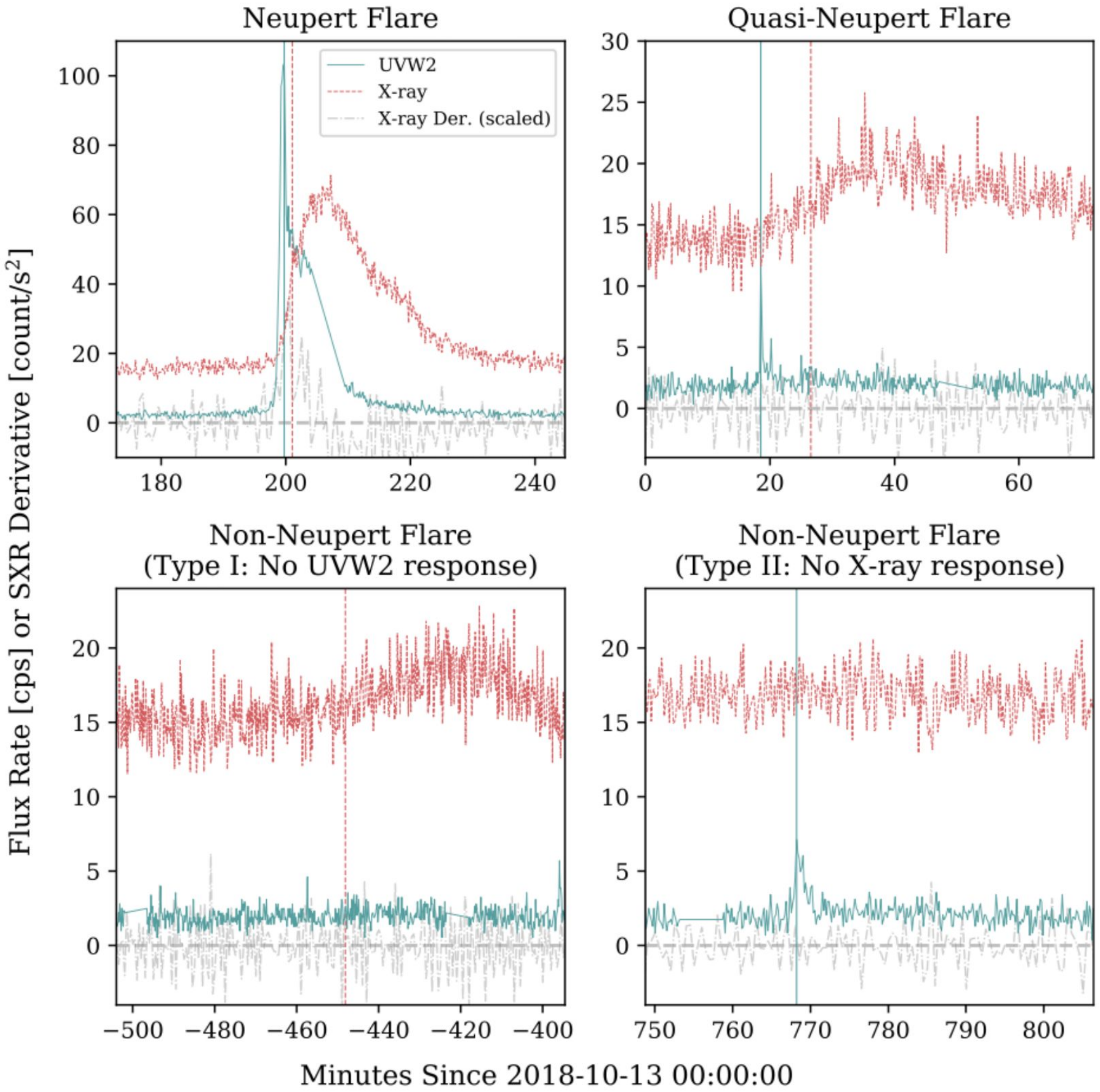
Same power-law slope for solar & stellar flares!



Neupert effect seen in stellar flares

Long heritage: trend also reported in papers by Shibata, Feldman

But there is complexity in what is seen



Flares on the planet-hosting M dwarf AU Mic sometimes show the Neupert effect, but have a variety of responses

Signals complexities in how energy is propagating through the stellar atmosphere, what layers are involved

Tristan et al. (2023)

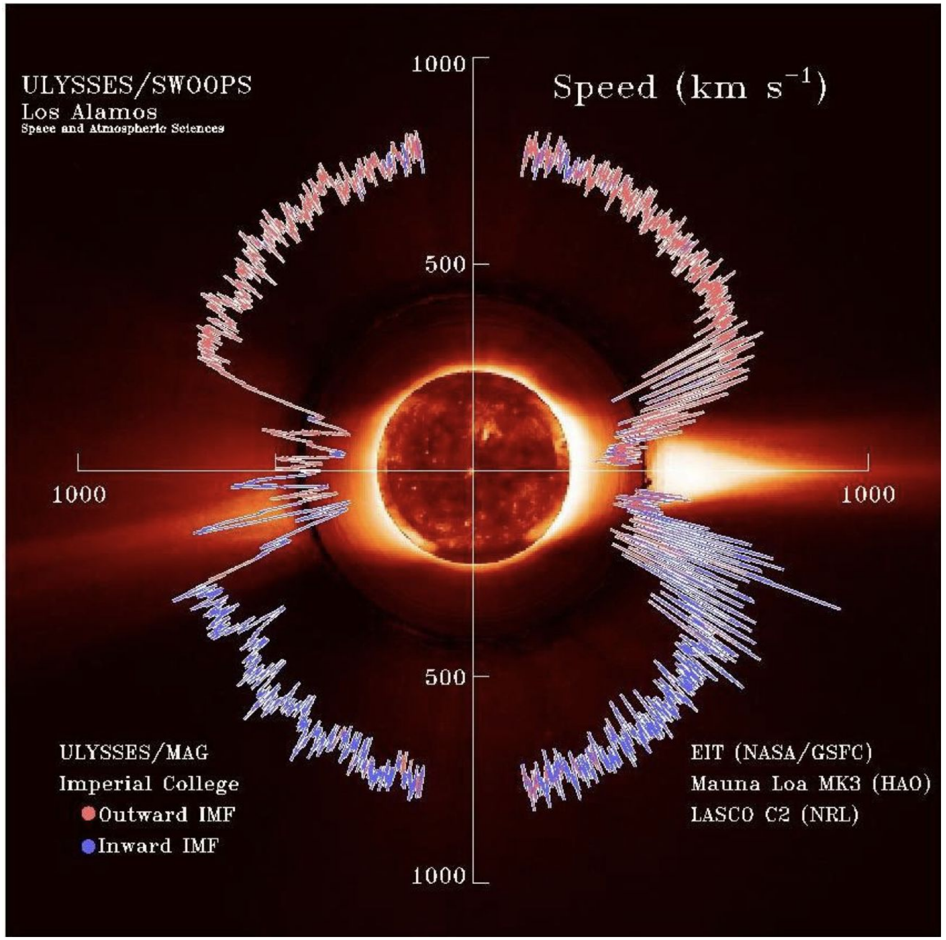
Observational signatures of magnetized winds in cool stars

More like “space climate” than space weather; impact on evolutionary timescales

Stellar astronomers need to be creative!

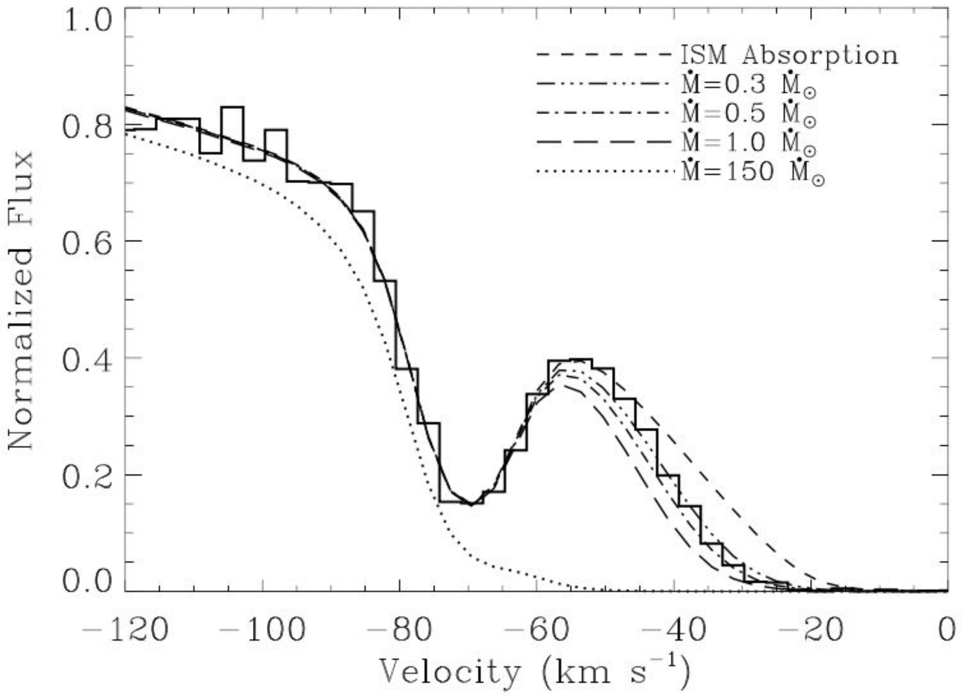
Observational signatures of stellar winds in low-mass stars

- UV Lyman alpha
- Radio bremmstrahlung
- X-ray scattering from charge exchange emission



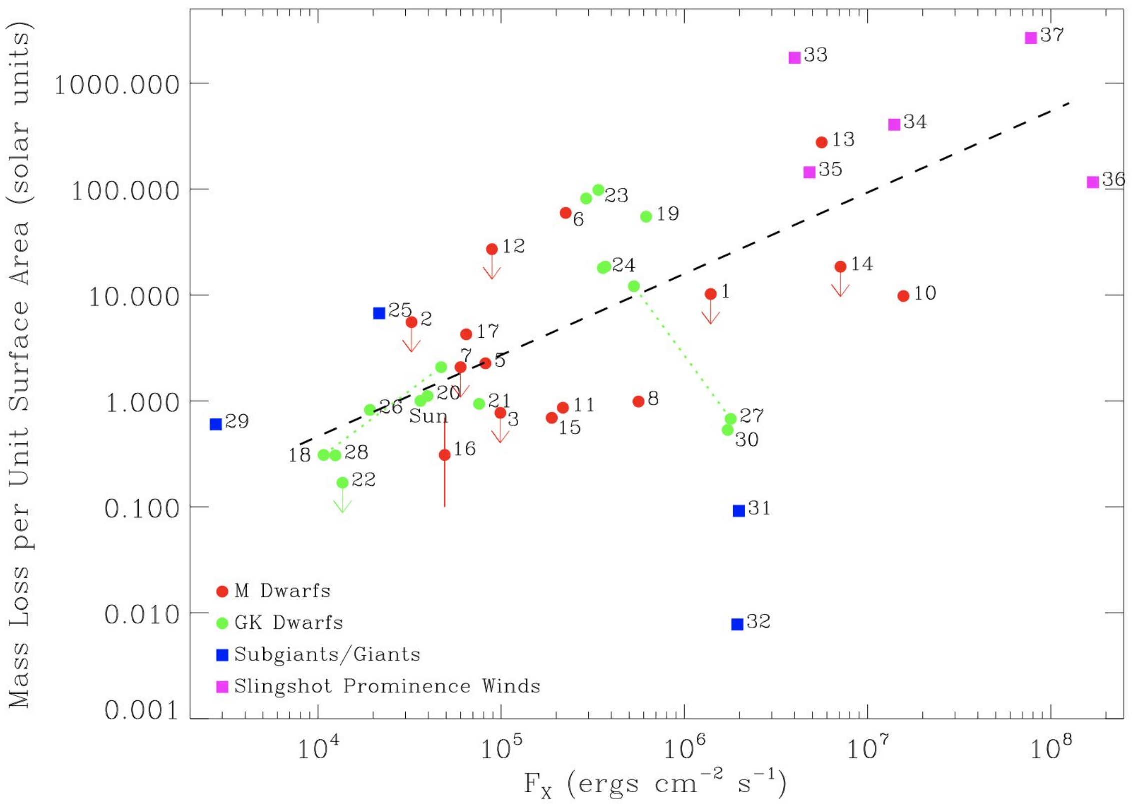
Lyman α astropheric constraints on cool stellar winds

- Lyman alpha astrospheric absorption is currently the main way to produce constraints on steady stellar winds in the cool half of the main sequence
- Can only be done with high-res spectrograph from space (STIS on HST)
- Does not detect the wind, detects the bow shock created when the wind interacts with the local ISM
- Non-detections do not provide upper limits to stellar mass loss



Evidence for a weak wind from the young Sun from astrospheric detection towards π^1 Uma (Wood et al. 2014)

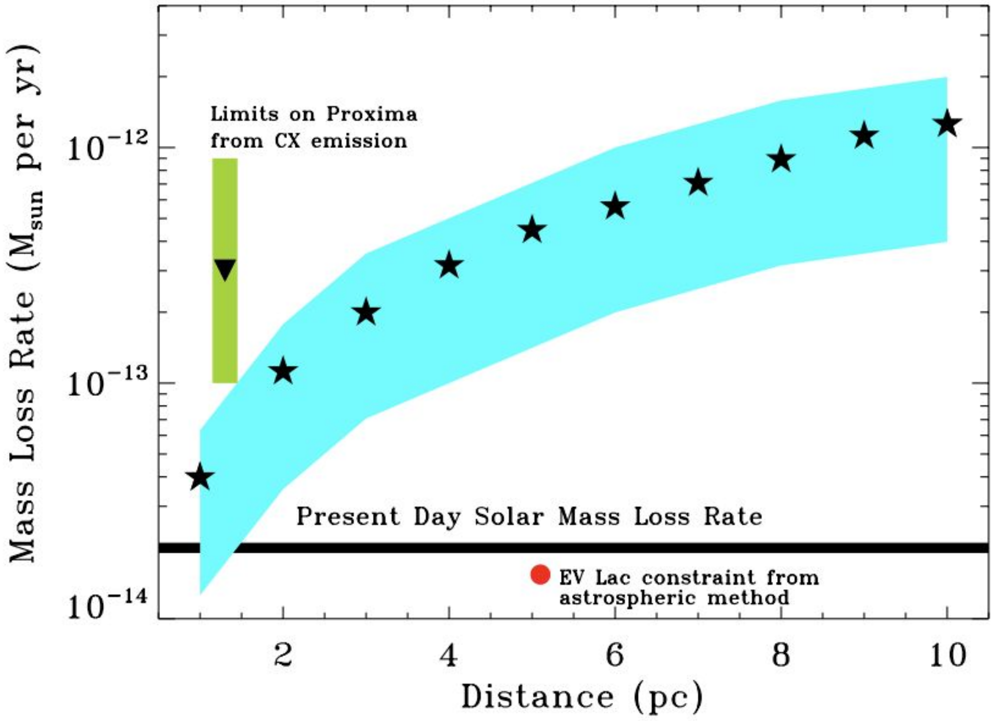
Lyman α astropheric constraints on cool stellar winds

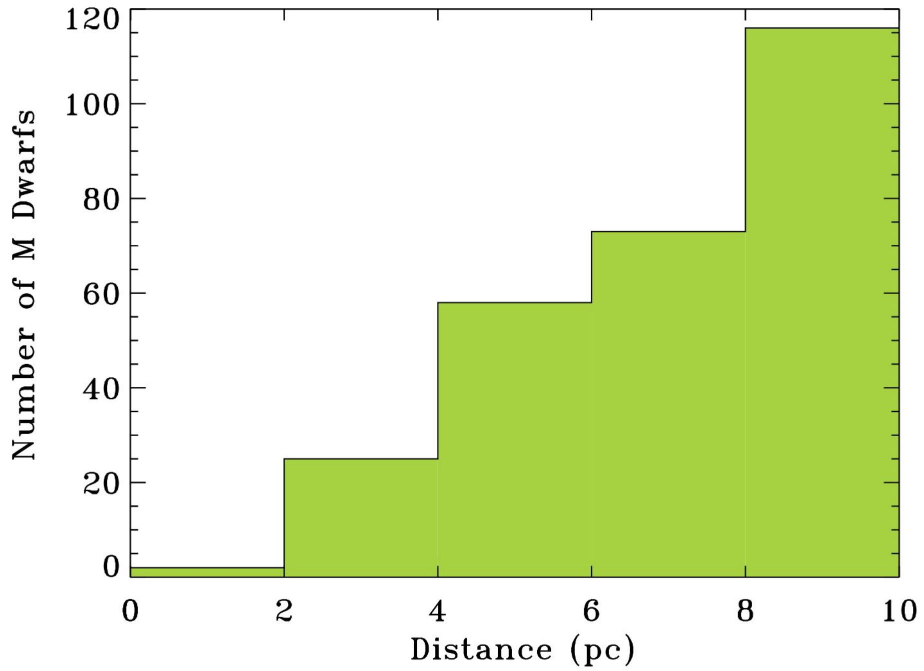


New results from Wood et al. (2021)

- Coronal activity and spectral type alone do not determine wind properties
- 13/15 M stars have $\dot{M}$<1 $\dot{M}_{sun}$, 2 much higher, but still inconsistency between CME-dominated winds from extrapolating solar flare/CME connection

Radio bremsstrahlung signatures of low-mass stellar winds



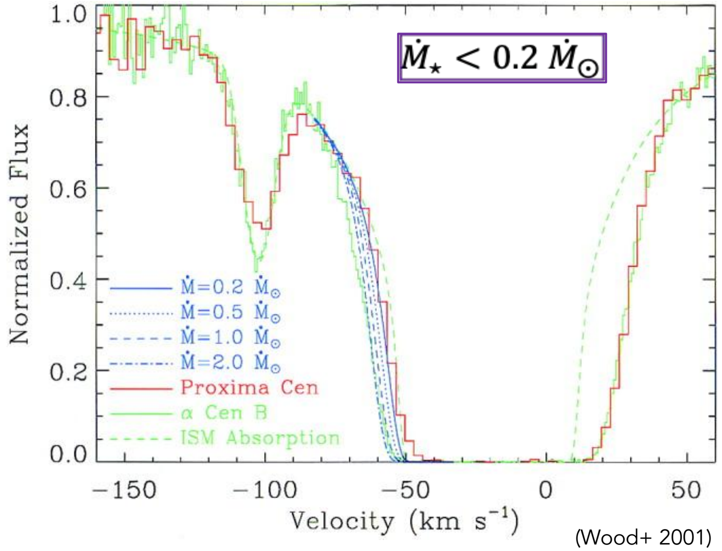


Detect or constrain radio emission from an ionized stellar wind with sensitive surveys of nearby planet-hosting M dwarfs

Osten & Crosley (2017) ngVLA Memo #31 the ngVLA and Exo-Space Weather

The stellar wind of Proxima Centauri

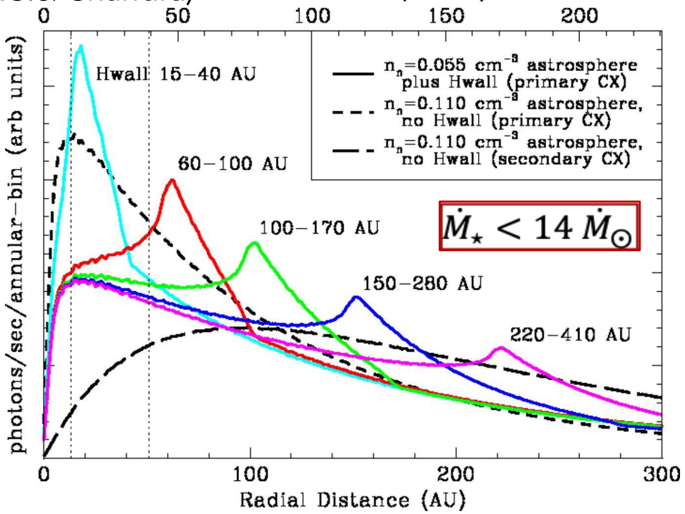
Lyman-α Astrosphere (STIS/HST)



(Wood+ 2001)

X-ray Halo due to Charge-Exchange

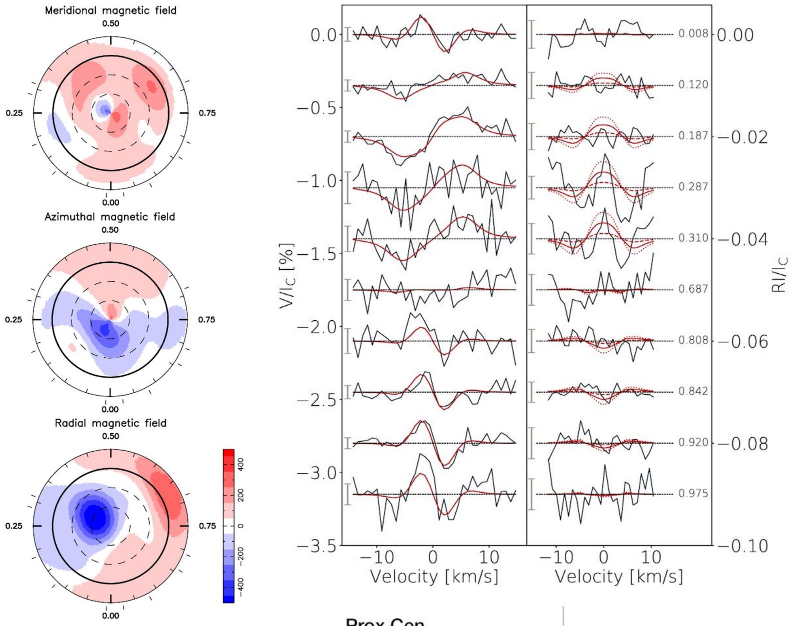
(ACIS/Chandra)

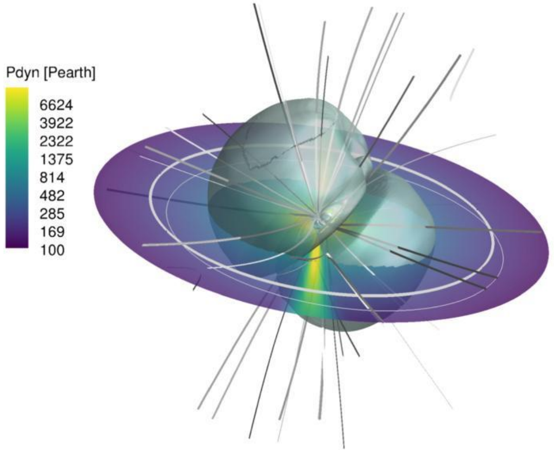


(Wargelin & Drake 2002)

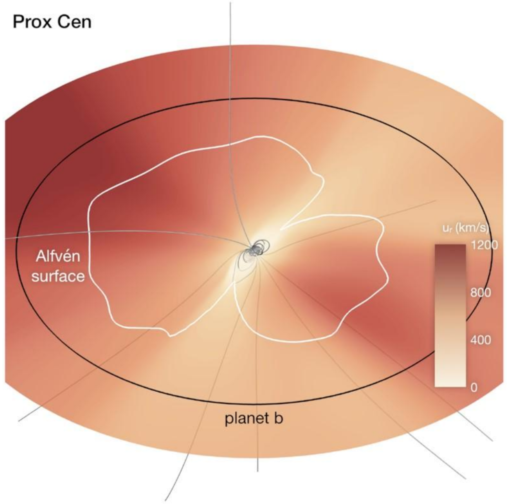
Large-Scale Magnetic Field Reconstruction

(HARPSpol + ZDI | Klein+ 2021)





(Garraffo+ 2016, 2022)



(Kavanagh+ 2021)

Stellar Wind Models

(AWSoM/SWMF | 3D MHD)

Observational techniques for transient stellar mass loss

Observational Signature	Sun	Stars
Thompson scattering via coronagraph	✓	X
Type II burst	✓	✓
Non thermal emission from CMEs	✓	
Scintillation of point radio sources	✓	
Mass-loss coronal dimming during a flare	✓	✓
High velocity outflows in emission lines during a flare	✓	✓
Pre-flare “dips”	✓	
Absorption dimming: increase in N_H during flare		✓
Effect of CMEs on stellar environment	✓	✓
Association with stellar flares	✓	✓

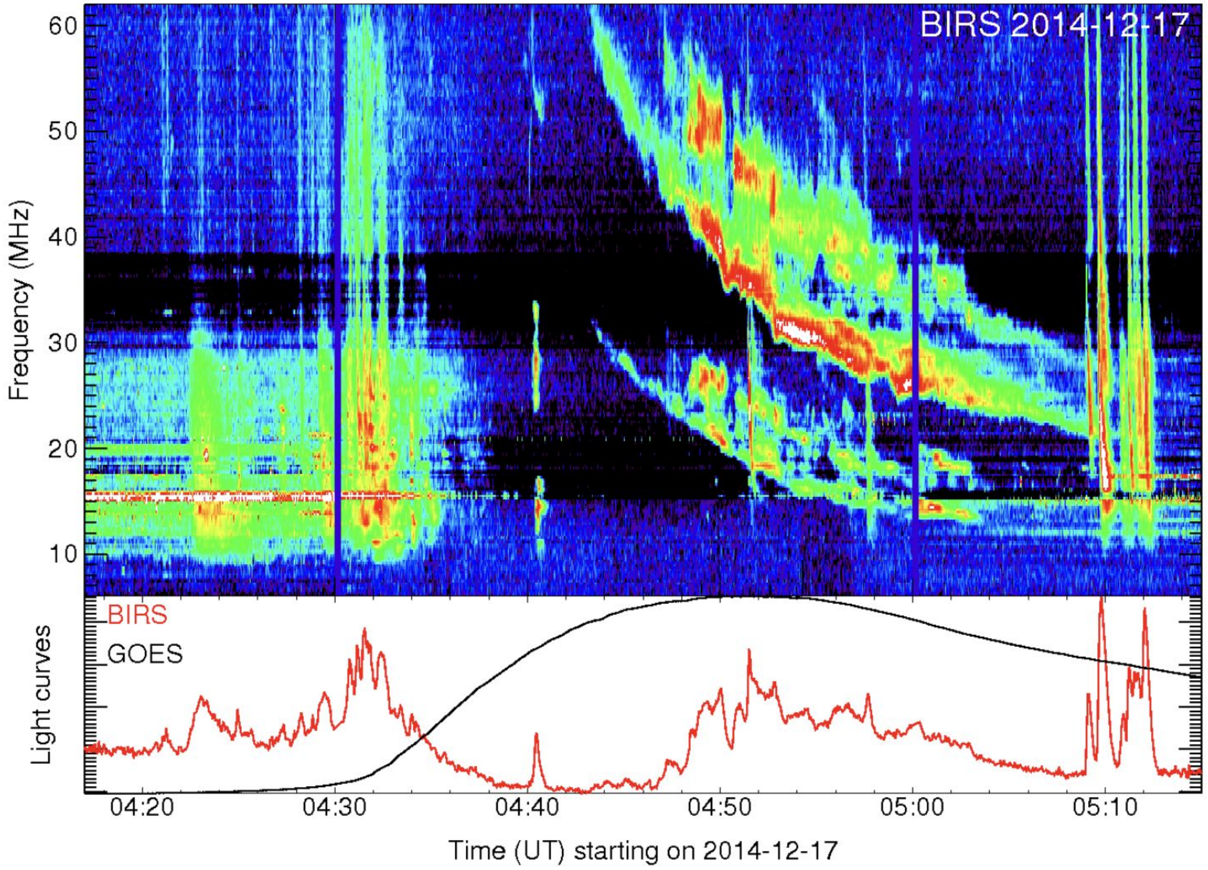
Osten & Wolk (2017)

Type II Radio Bursts: Unfulfilled (as yet) Potential

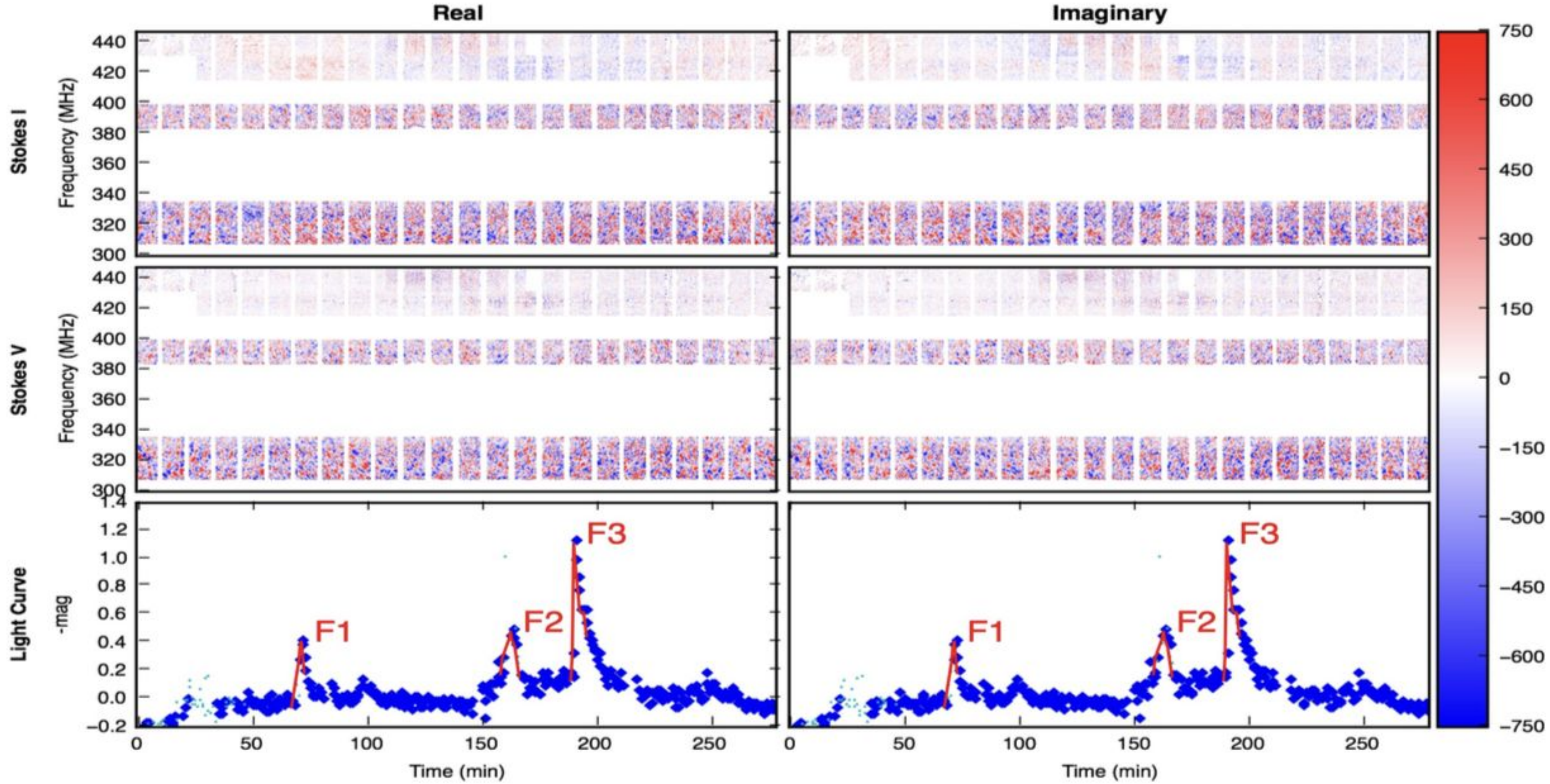
Unique radio signature formed from super-Alfvenic shock as CME propagates through the stellar atmosphere: produces a predictable signal shape in frequency and time, offers diagnostics of propagation speed

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

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

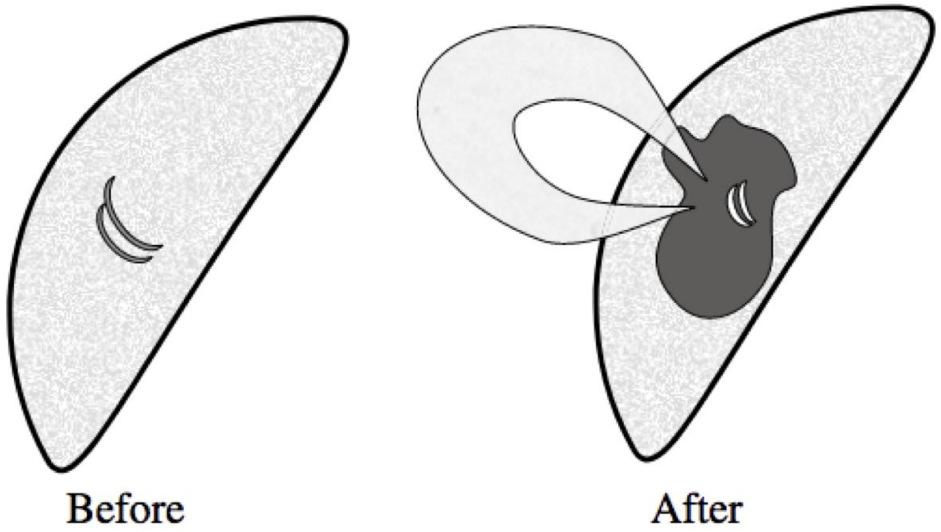


Type II Radio Bursts: Unfulfilled (as yet) Potential

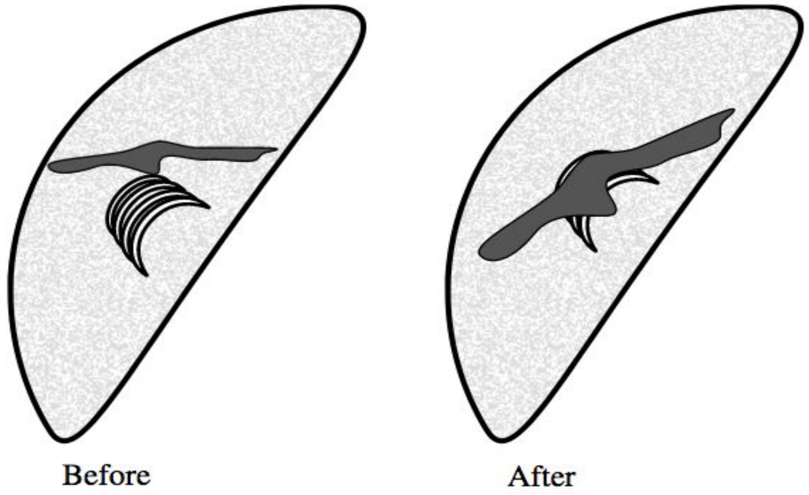


The situation: after 64 hours on the high flaring rate (>1 flare/hr) binary EQ Peg (Crosley & Osten 2018a&b), no detections of bursts that resemble expected properties of type II bursts. Either CMEs with flares are rare, or the conditions to create shocks aren't present at the observing frequencies/distances we are probing

Dimming and Outflow Signatures during Flares as Signatures of Eruptive Events



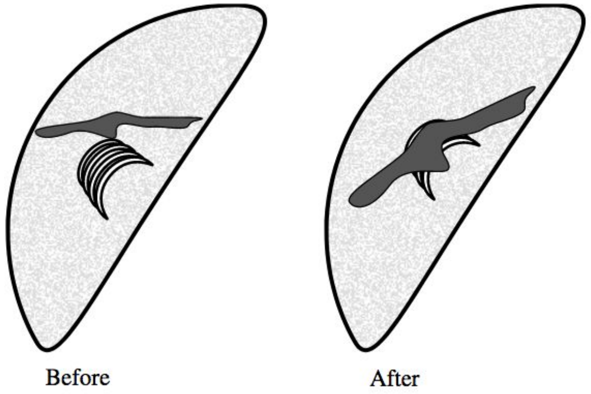
Mass-loss dimming: decrease in emission due to evacuation of material



Mason et al. (2014)

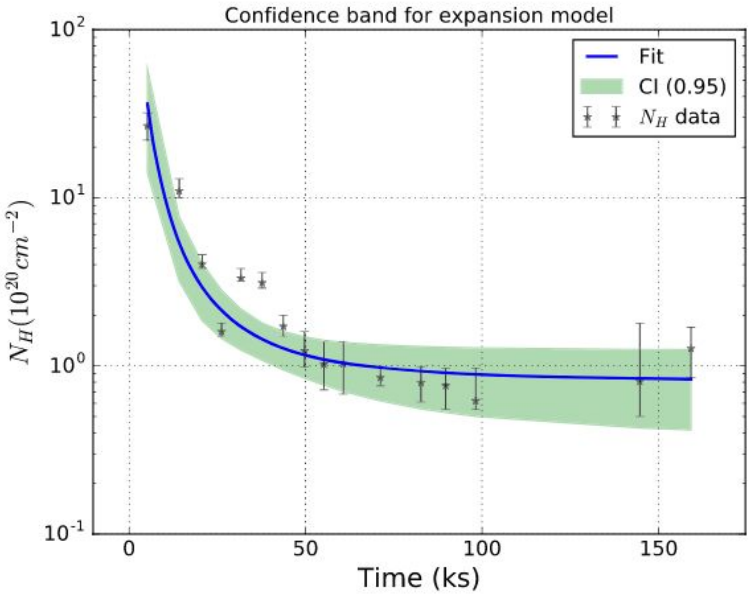
Absorption dimming: temporary increase in absorption as absorbing material moves across the line of sight

Absorption Dimming as a Promising Signature of Stellar CMEs



Mason et al. (2014)

absorption dimming: temporary increase in absorbing column as material covers the flaring region

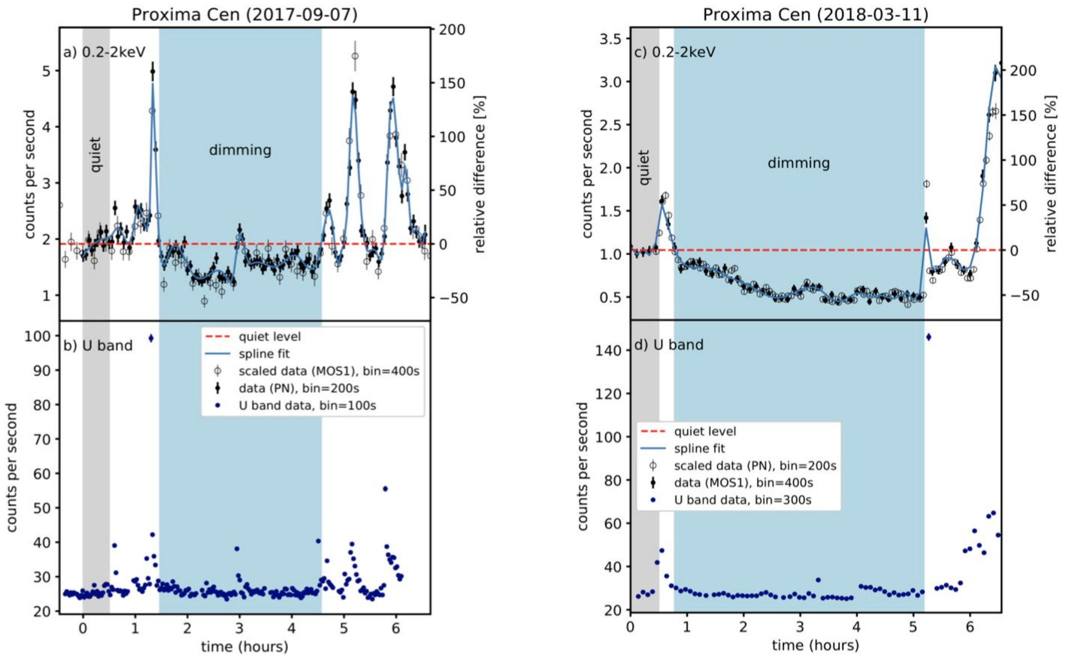


Moschou et al. (2017) interpretation of N_H variations in an earlier seen giant flare on the active binary Algol

Moschou et al. (2017) interpreted the N_H variations as originating from a constant velocity, self-similar expansion of a CME front

$$N_H(t) \propto t^{-2}$$

Mass-loss Dimming as a Promising Signature of Stellar CMEs



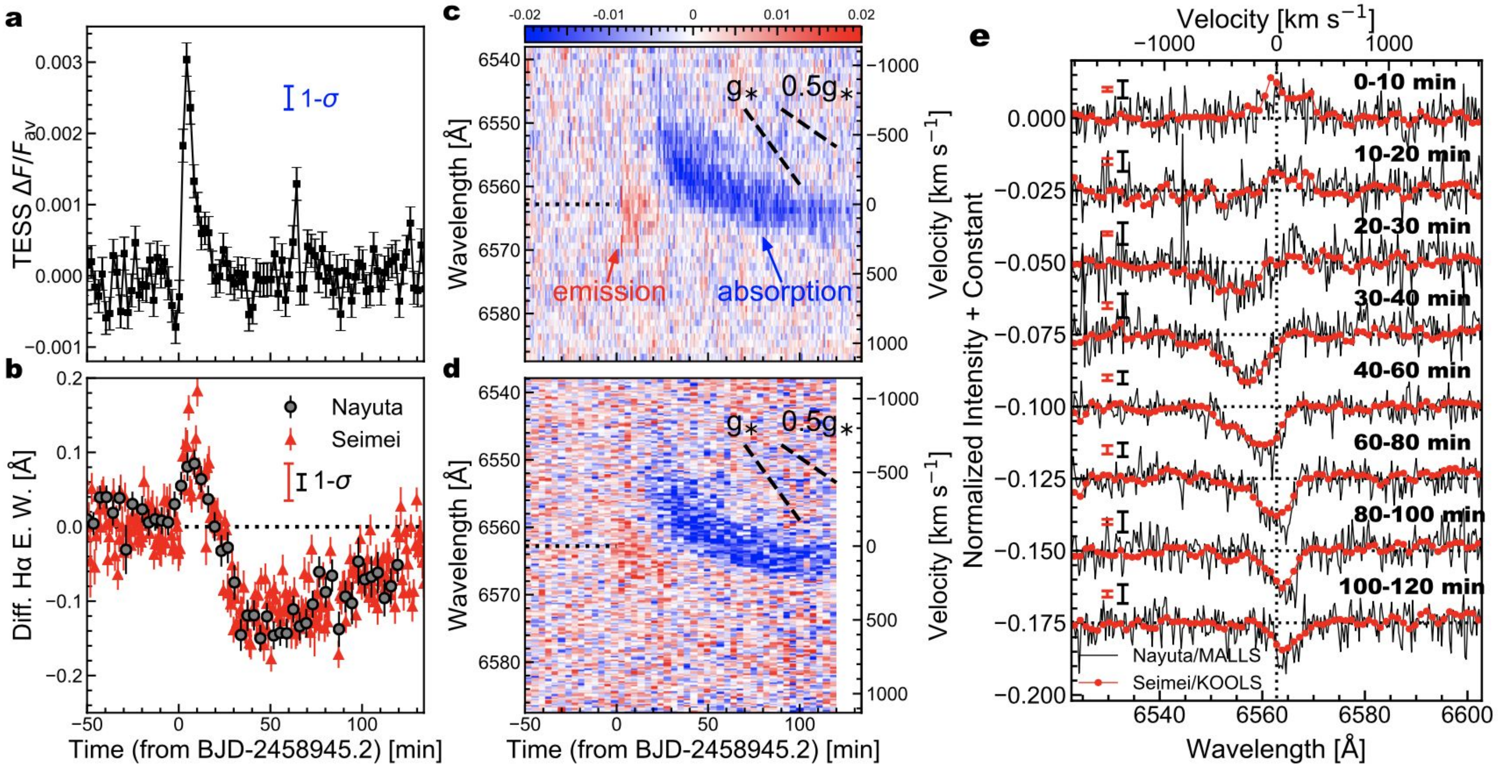
Dimming signatures seen in X-ray and EUV light curves of magnetically active stars (Veronig et al. 2021)

- Dimming detections associated with flares on cool stars
- Indicative of stellar CMEs and benchmarked by Sun-as-a-star EUV measurements
- Quiescent levels of stars show large variations, only strong dimmings can be identified

Dimmings and High Velocity Outflows in Chromospheric Lines during Flares

Namekata et al. (2021)

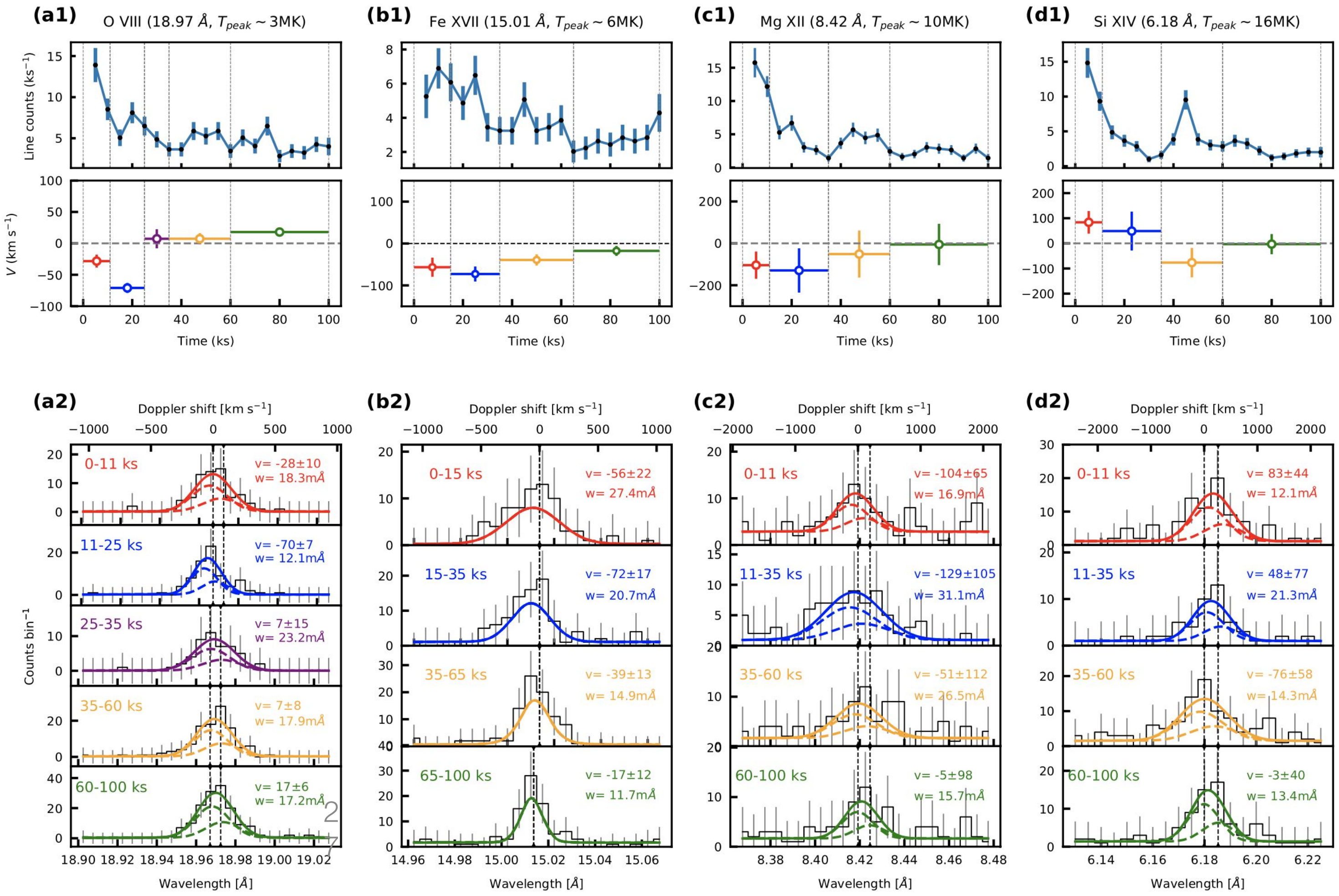
Detection of an eruptive filament during a superflare on the solar-type star EK Dra Hα absorption as well as blueshifts



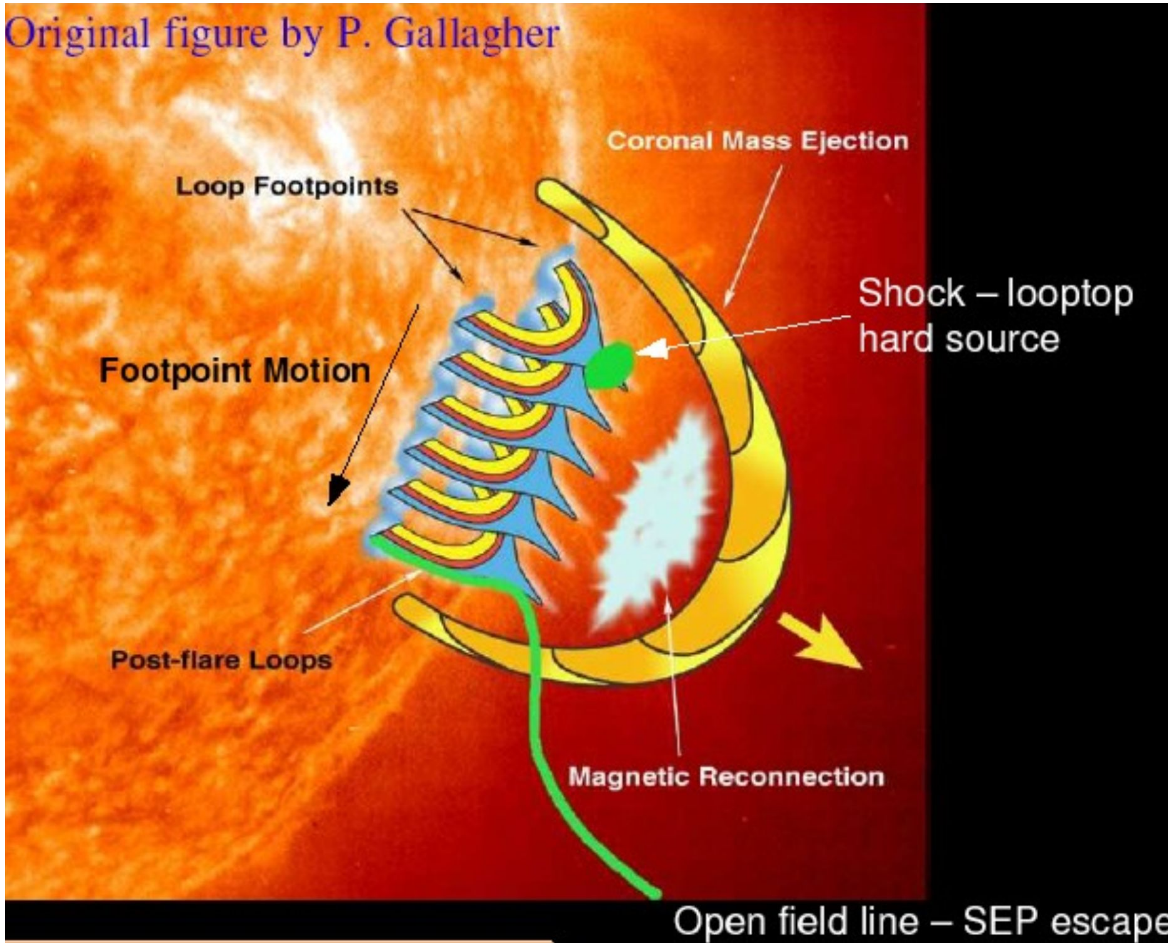
High Velocity Outflows in Coronal Lines during Flares

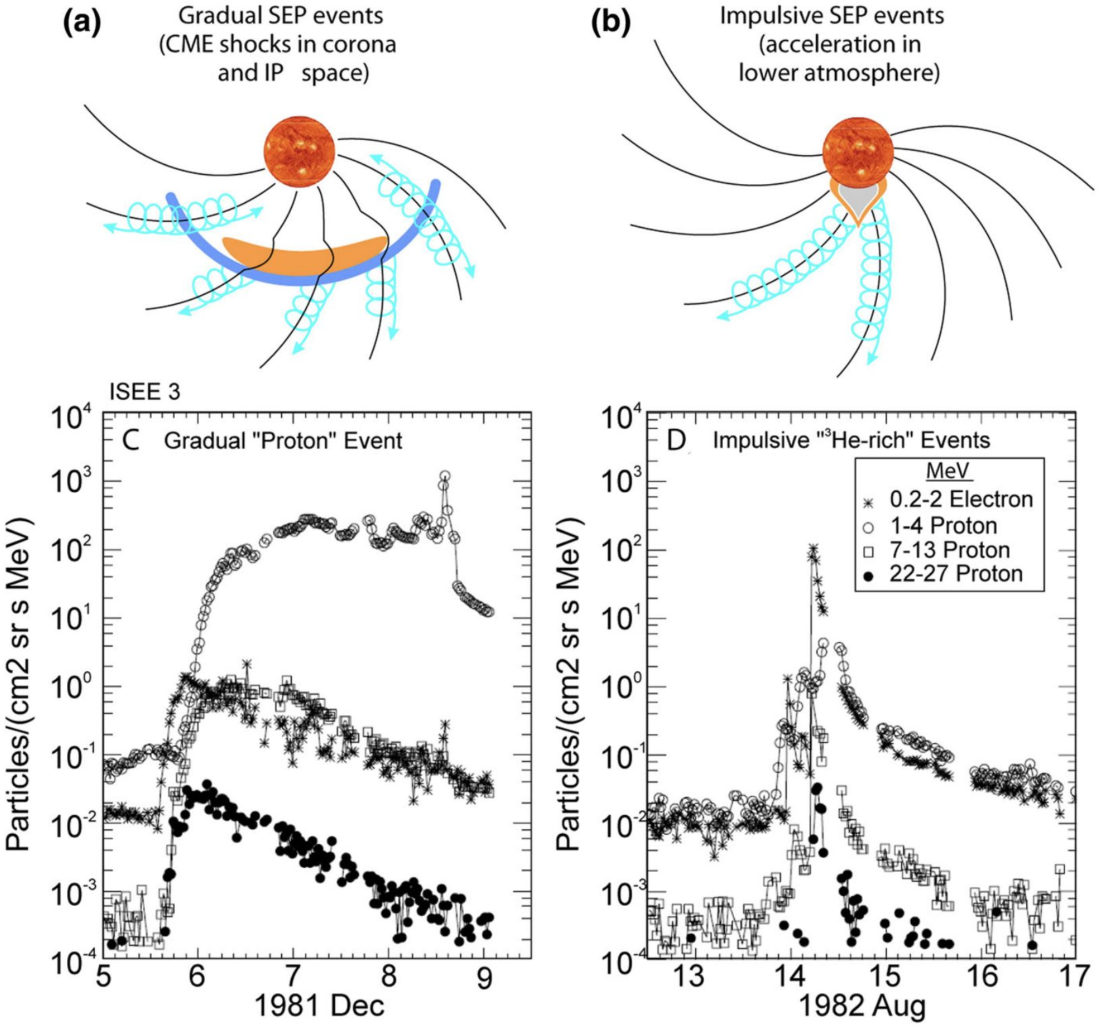
Chen et al. (2022) signatures of flows during several flaring events on the M dwarf EV Lac

Blue-shifted O VII during the decay of a large flare (but not in higher temperature material) is suggestive of an outflow, but travelling at less than escape velocity



Particle acceleration occurs in flares and CMEs

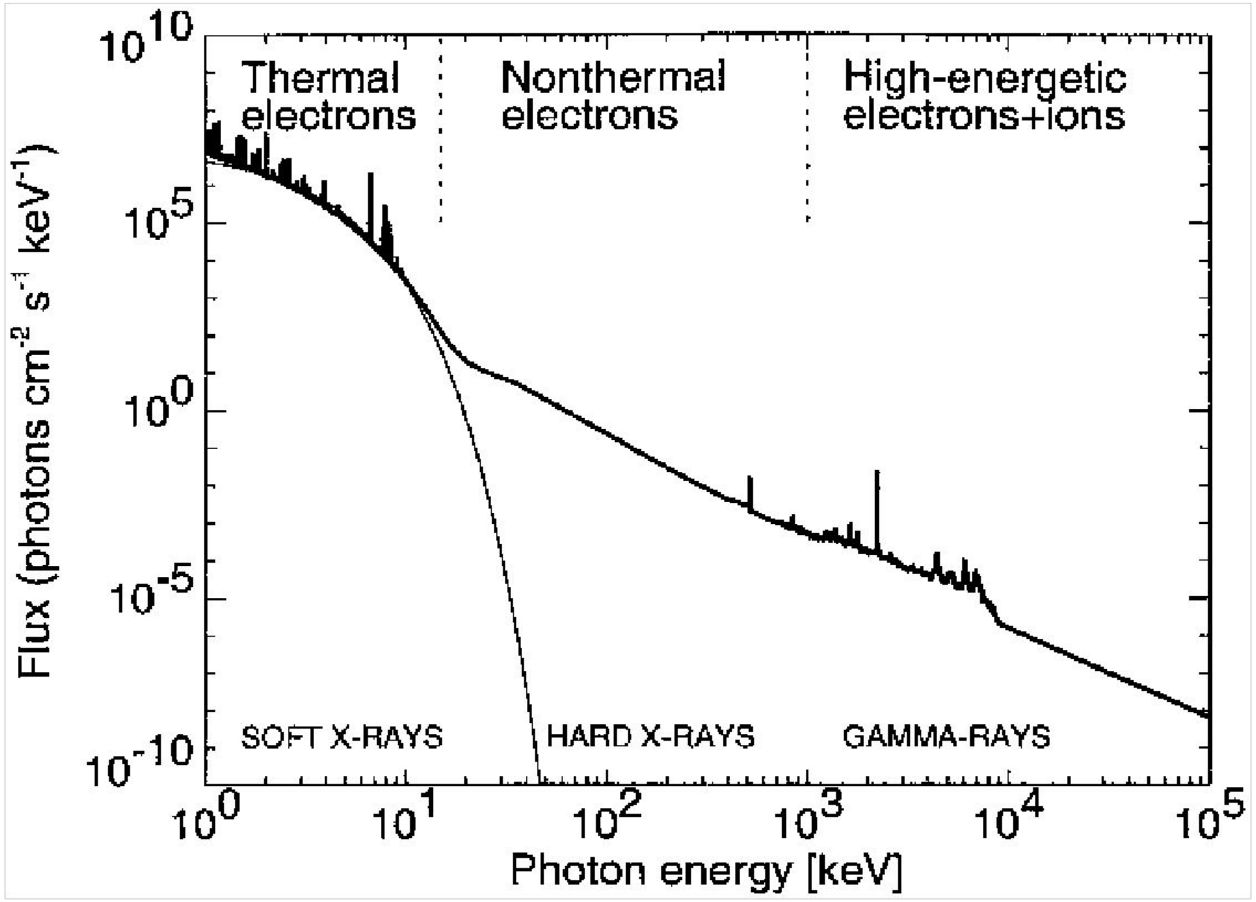




Reames (1999)

Particle acceleration in flares

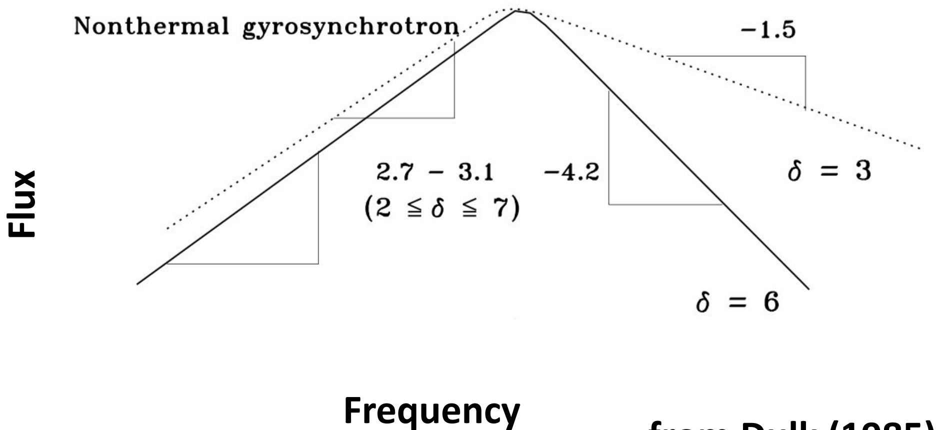
- Collisional energy losses exceed bremsstrahlung losses by 10^5.
- Attempts to detect nonthermal hard X-ray emission in stellar flares have not been productive: need to overcome sensitivity & bandpass effects, coupled with much larger temperatures in large stellar flares
- Radio observations offer the most direct constraint on nonthermal particles in stellar flares, but come with interpretation effects



Aschwanden (2002)

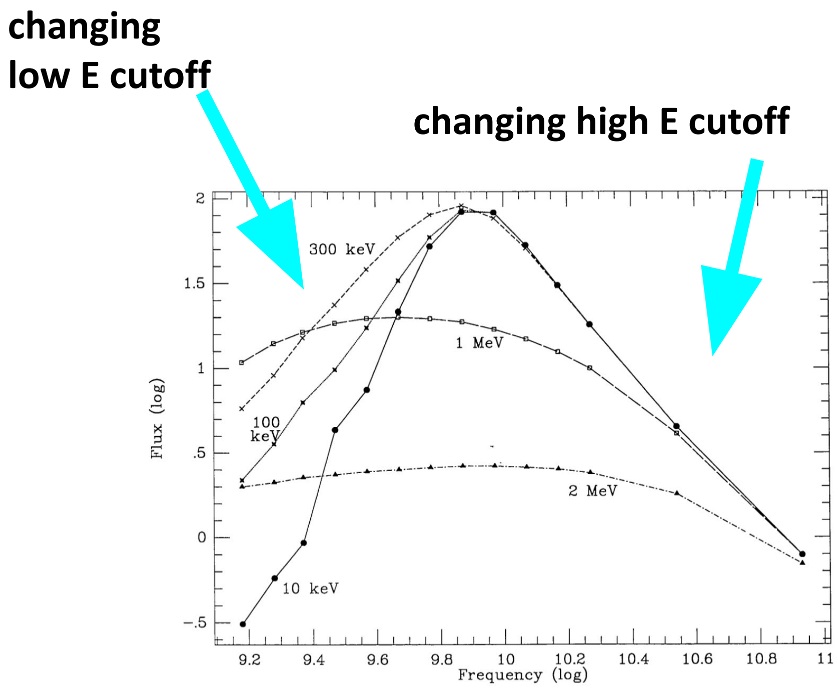
Radio observations of accelerated particles

Gyrosynchrotron emission



from Dulk (1985)

optically thin emission: direct constraint on index of accelerated particles

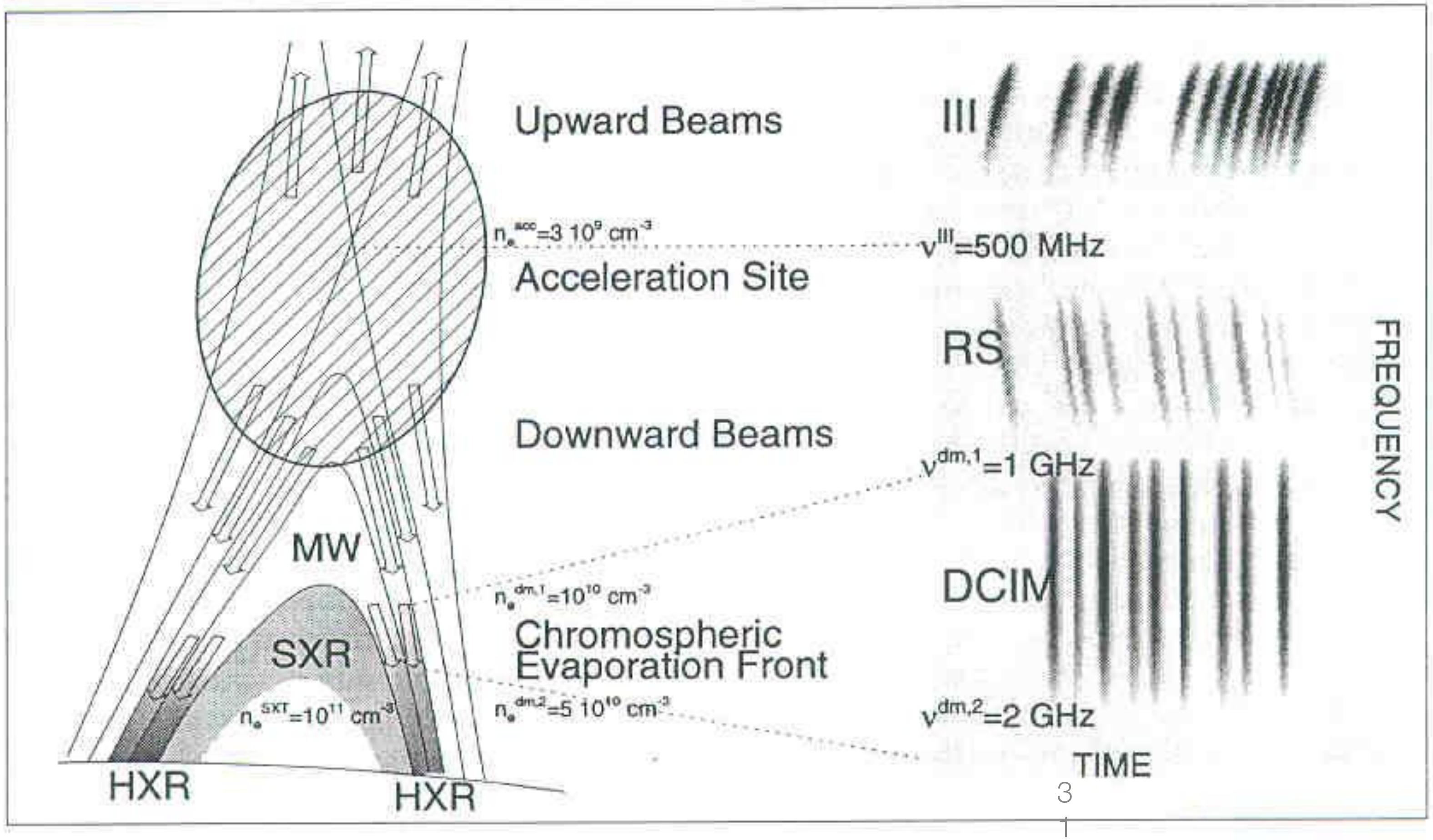


White & Kundu (1992)

spectral shape: high/low energy cutoffs of the accelerated particle distribution

Radio observations of accelerated particles

Coherent emission

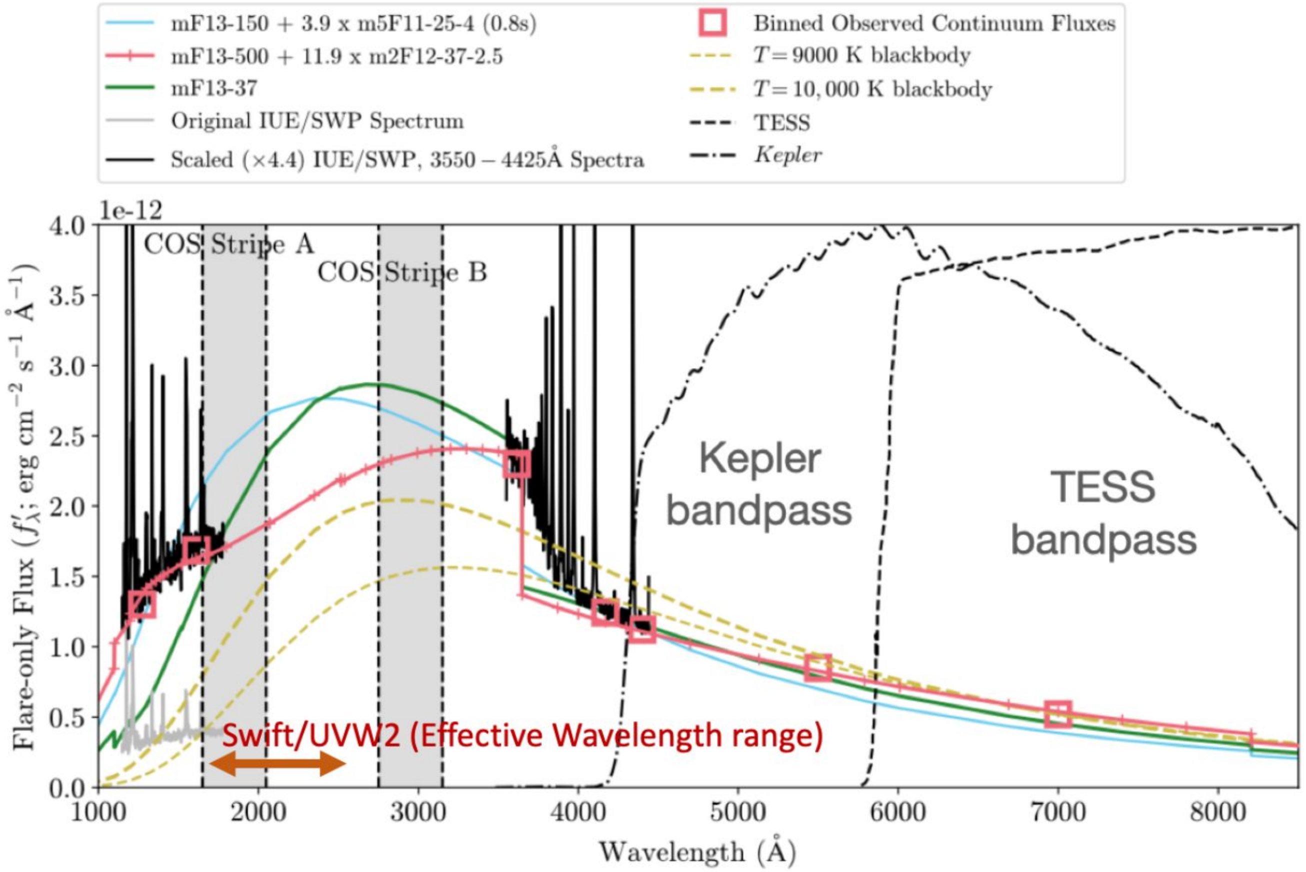


Aschwanden et al. (1997)

In plasma emission, $\nu \sim \nu_p$ ~9000 $\sqrt{n_e}$ Hz

in cyclotron maser emission, $\nu \sim \nu_B = eB/\gamma mc$

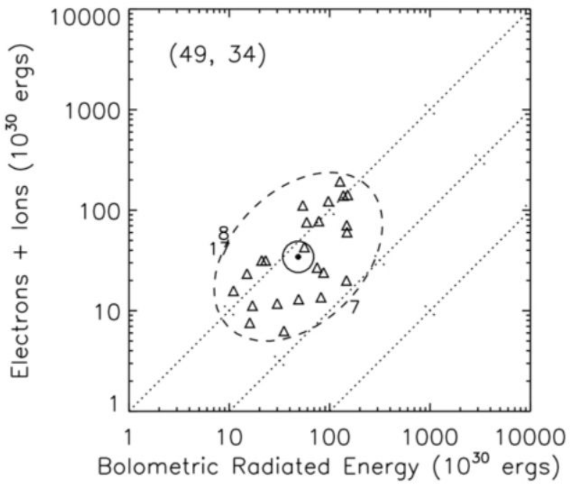
Constraining Particle Acceleration in Stellar Flares



- Blue-optical flare spectral energy distribution has the shape of a black-body with T_{BB}~10^4 K
- Modelling this white light continuum enhancement requires a beam of accelerated electrons
- Allred et al. (2005, 2006) showed difficulty in reproducing M dwarf white light flare with solar-like electron beam
- Kowalski et al. (2016) showed that increasing the beam flux by two orders of magnitude from the largest beam flux seen in a solar flare can reproduce M dwarf flare signatures

Kowalski et al. (2022)
Modelling the Great Flare of AD Leo, commonly used in astrobiology studies, and attempting to reconcile the spectral and photometric information

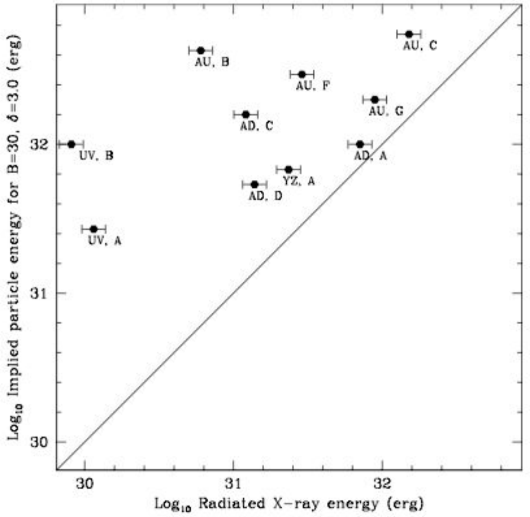
Hints of a disconnect in particle acceleration between solar and stellar flares



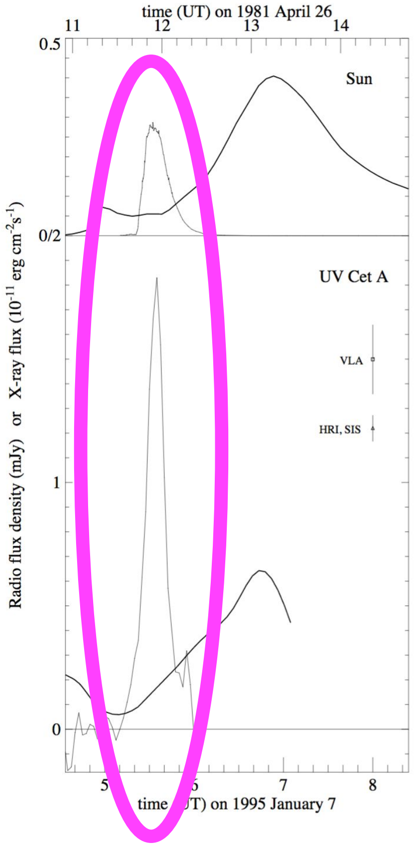
solar eruptive events,
~ equal amounts of energy
Emslie et al. (2012)

Relative to the flare X-ray emission, stellar flares produce larger radio amplitudes than for solar

Explaining white light flare emission requires fluxes of accelerated particles 100x higher than the maximum seen in solar flares



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

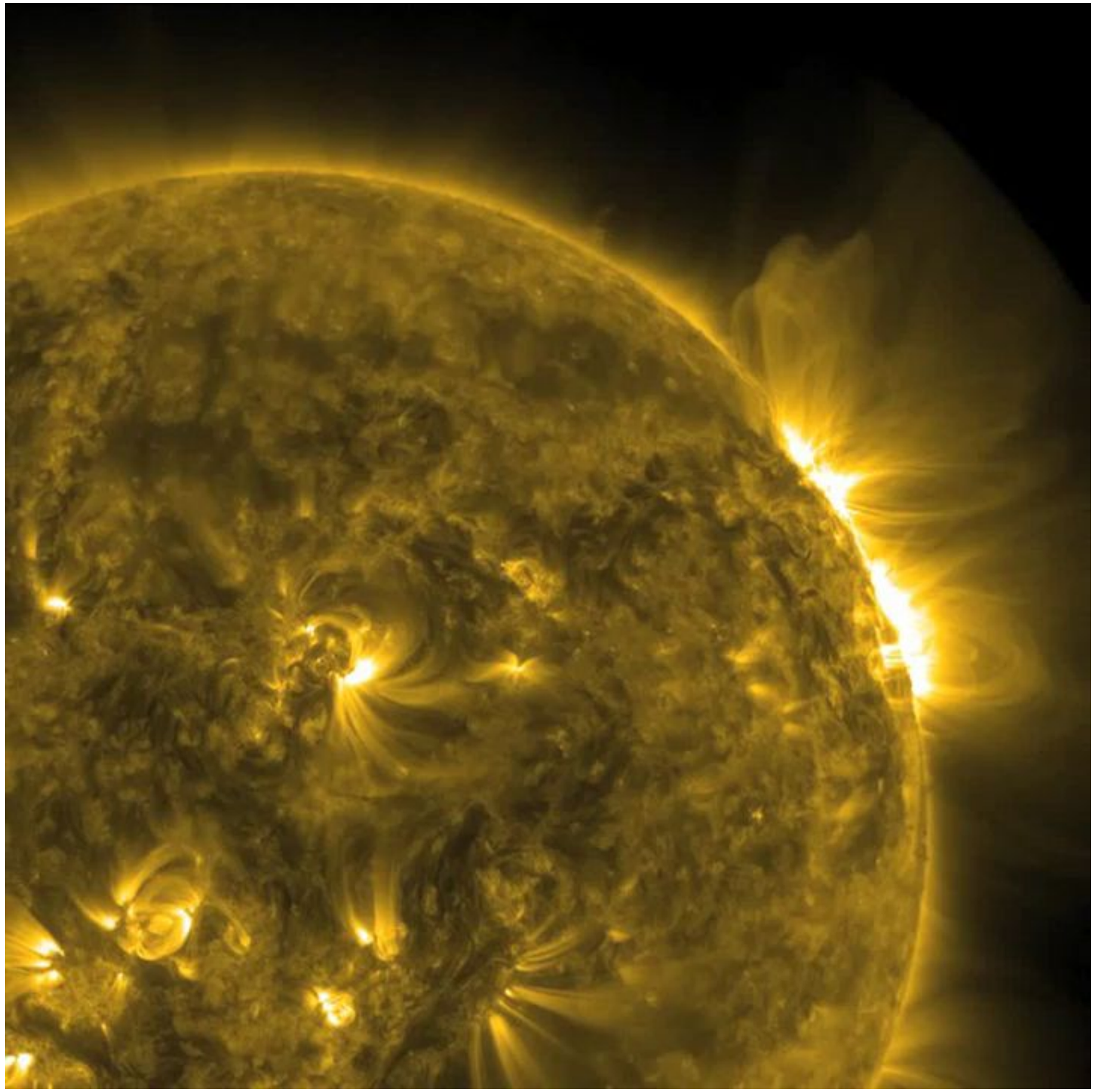


Güdel et al. (1996)
M dwarf X-ray-radio flare compared to solar

Conclusions

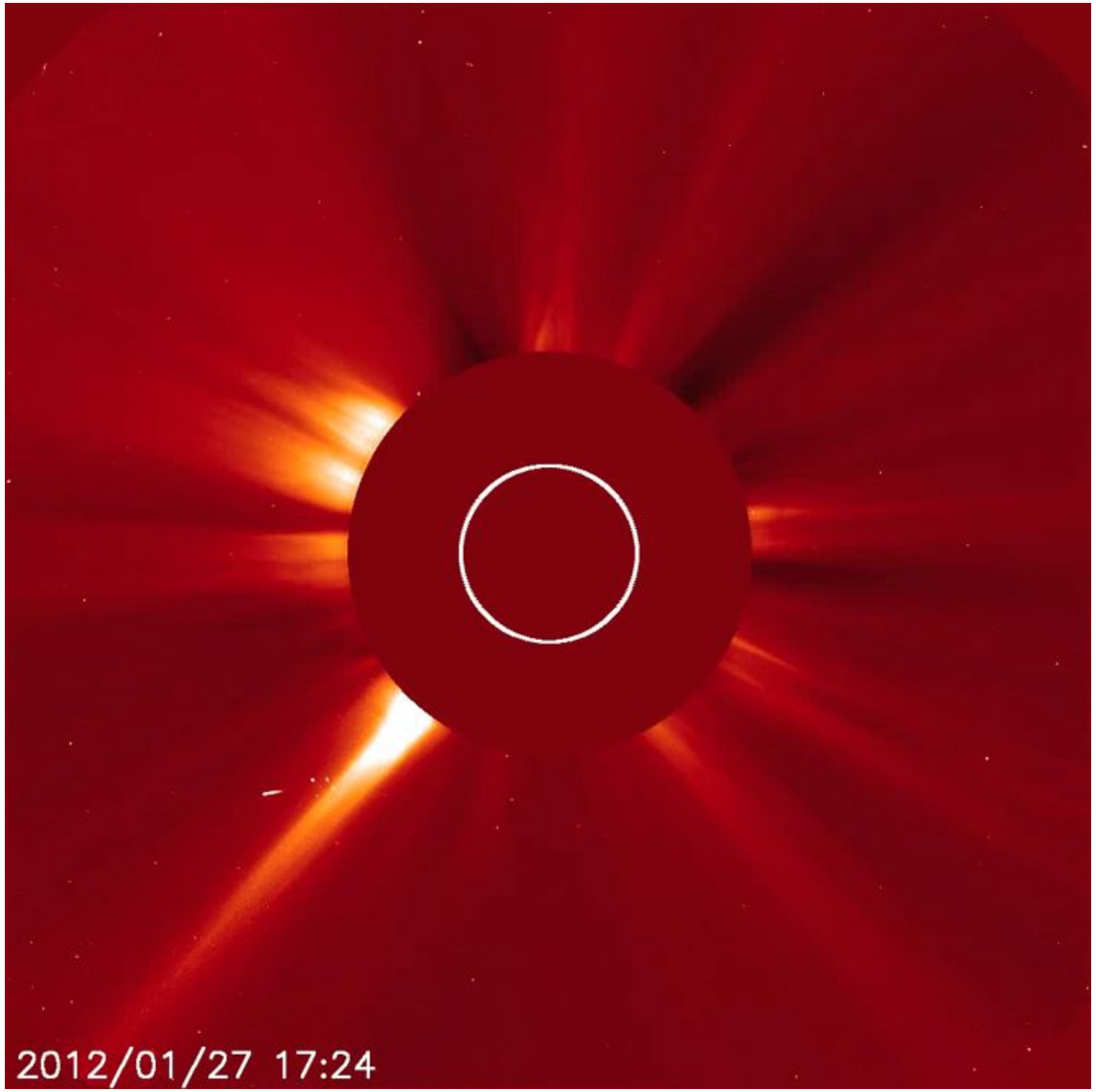
- Definite bias in stellar types observed for space weather signatures: Sun, active stars
- Much more in the way of constraints for flaring radiation than for CMEs and energetic particles
  - Increasing multi-wavelength knowledge is revealing complexitites to our understanding of flares
- Making headway in developing observational tools that can probe stellar CMEs in a systematic way
  - Need to be able to constrain CME parameters
- We can start to constrain the properties of accelerated particles near the stellar surface, but outward-directed particles are still not constrained
  - Need to explore whether active stars have differences in accelerated particle characteristics compared to the Sun

The Trifecta of Space Weather



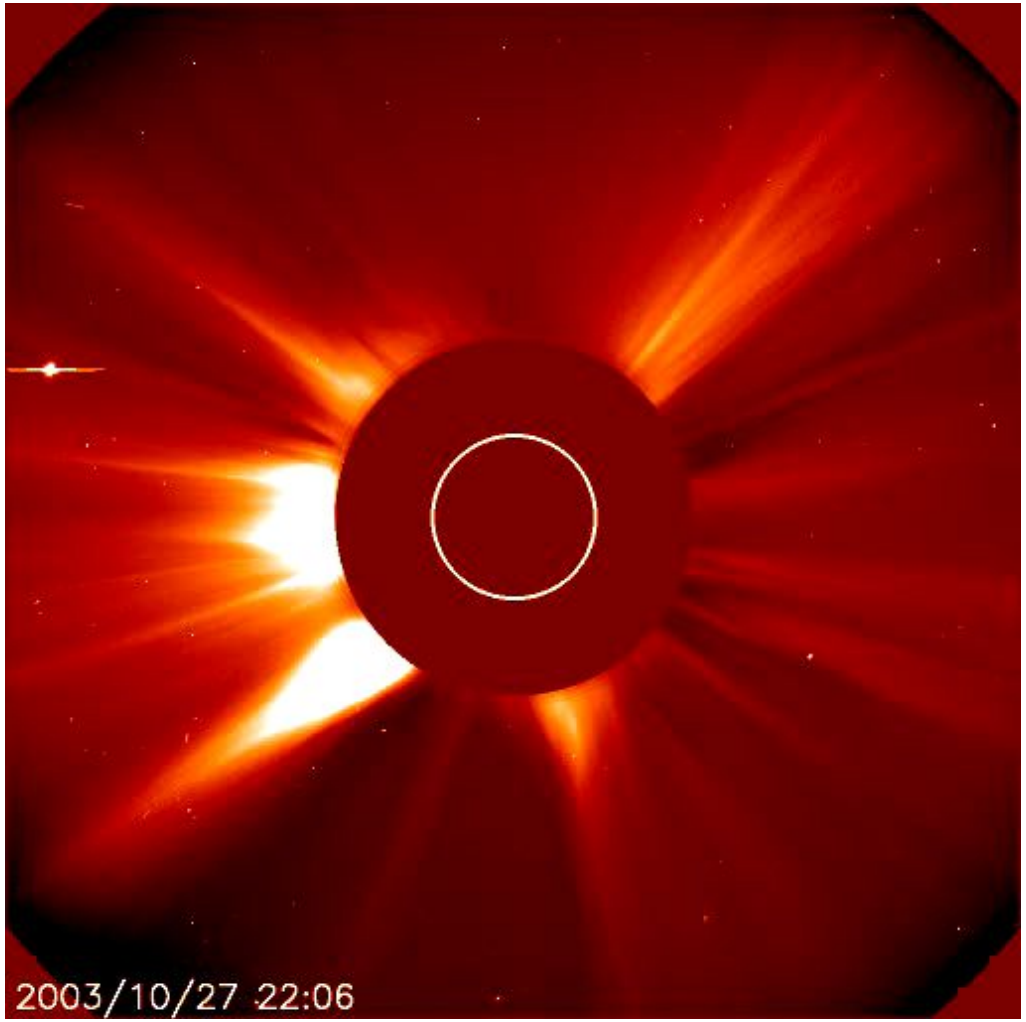
solar flares

The Trifecta of Space Weather



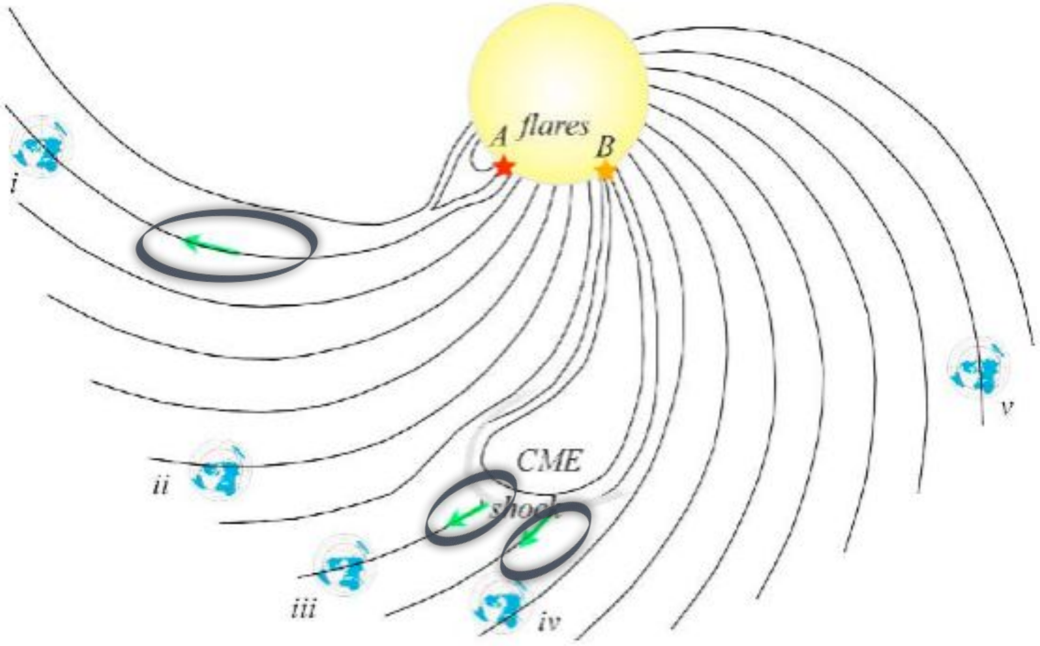
Coronal mass ejections

The Trifecta of Space Weather



Solar 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

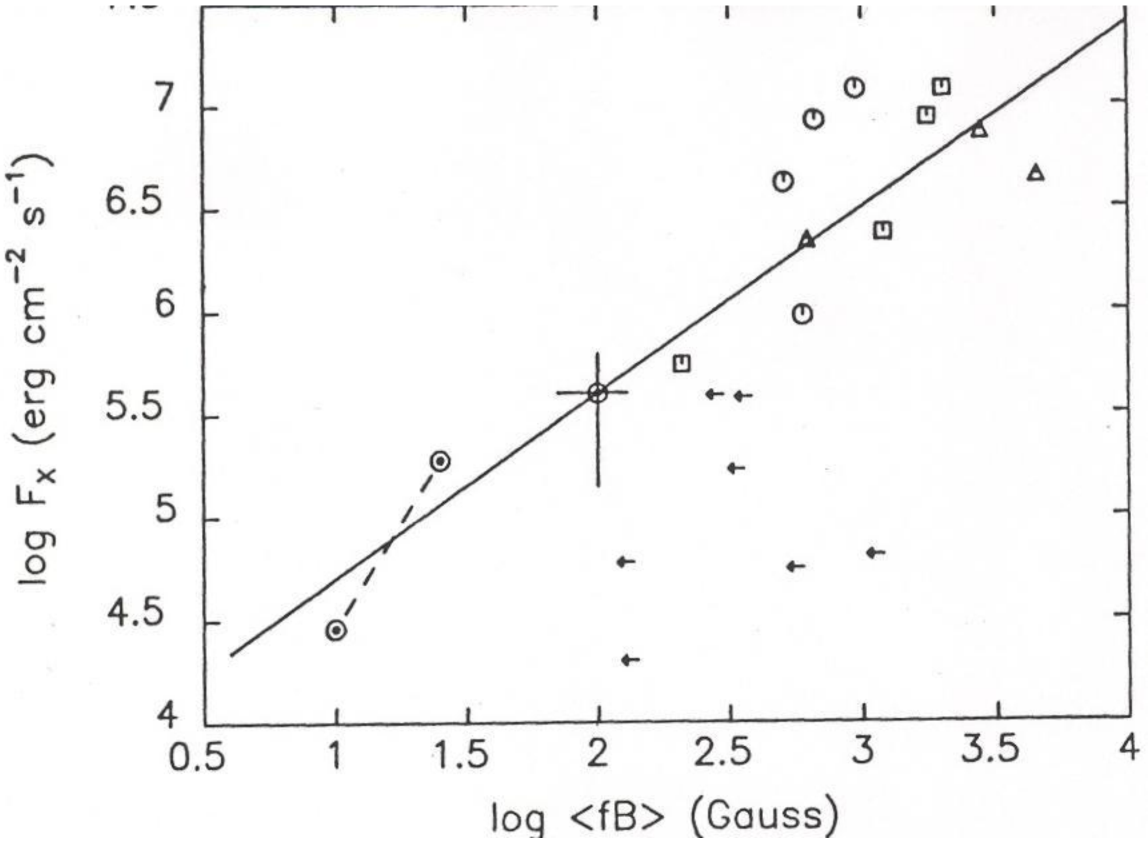


Schrijver et al. (2012)

Measuring stellar magnetic fields

Indirect methods

- Stellar magnetic activity twiddles magnetic fields



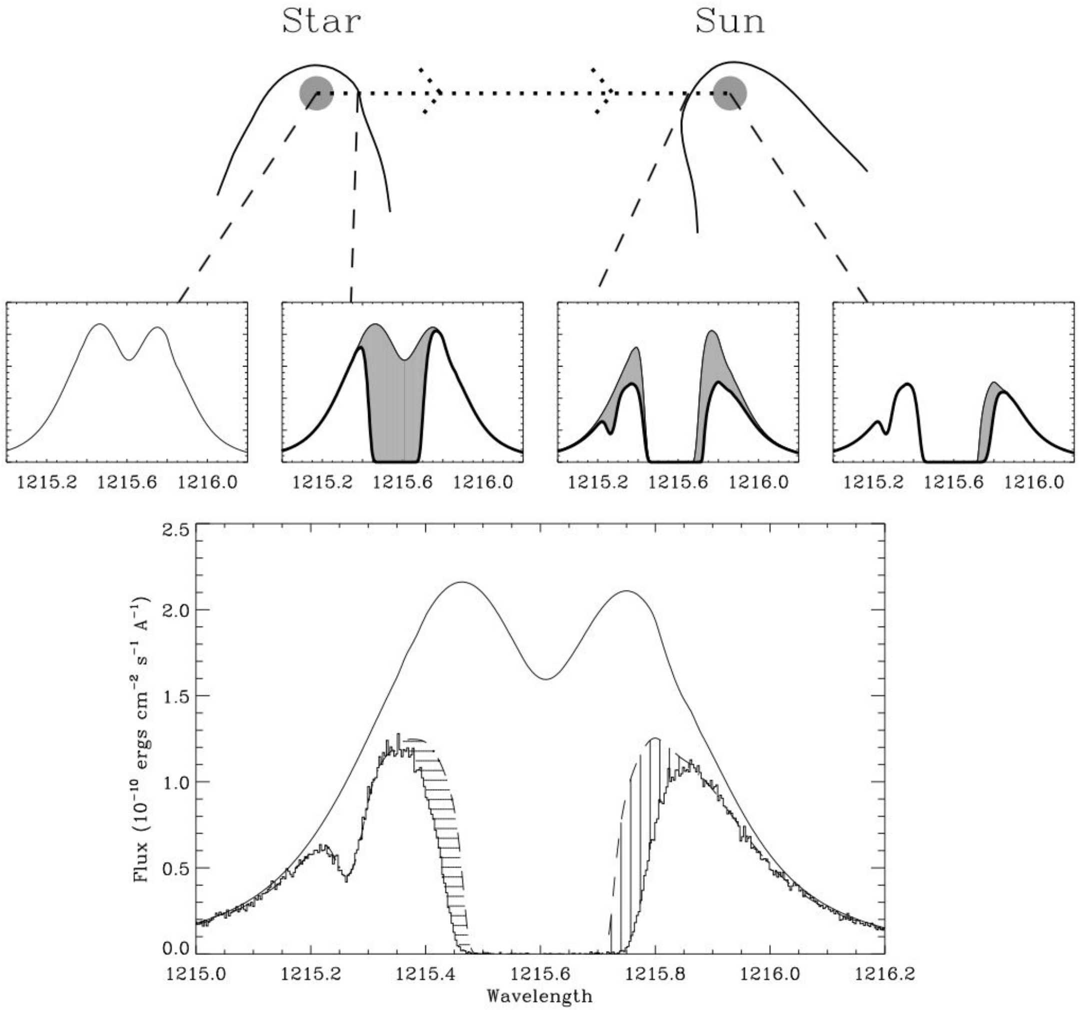
Saar (1988)

Space Weather Comes in Three Forms

- Electromagnetic Radiation (speed = c)
- Accelerated particles travelling ~relativistically (speed = 0.1-0.6 c)
- Mass ejections (max speed 2000 km/s)

Lyman α astropheric constraints on cool stellar winds

- Lyman alpha astrospheric absorption is currently the main way to produce constraints on steady stellar winds in the cool half of the main sequence
- Can only be done with high-res spectrograph from space (STIS on HST)
- Does not detect the wind, detects the bow shock created when the wind interacts with the local ISM



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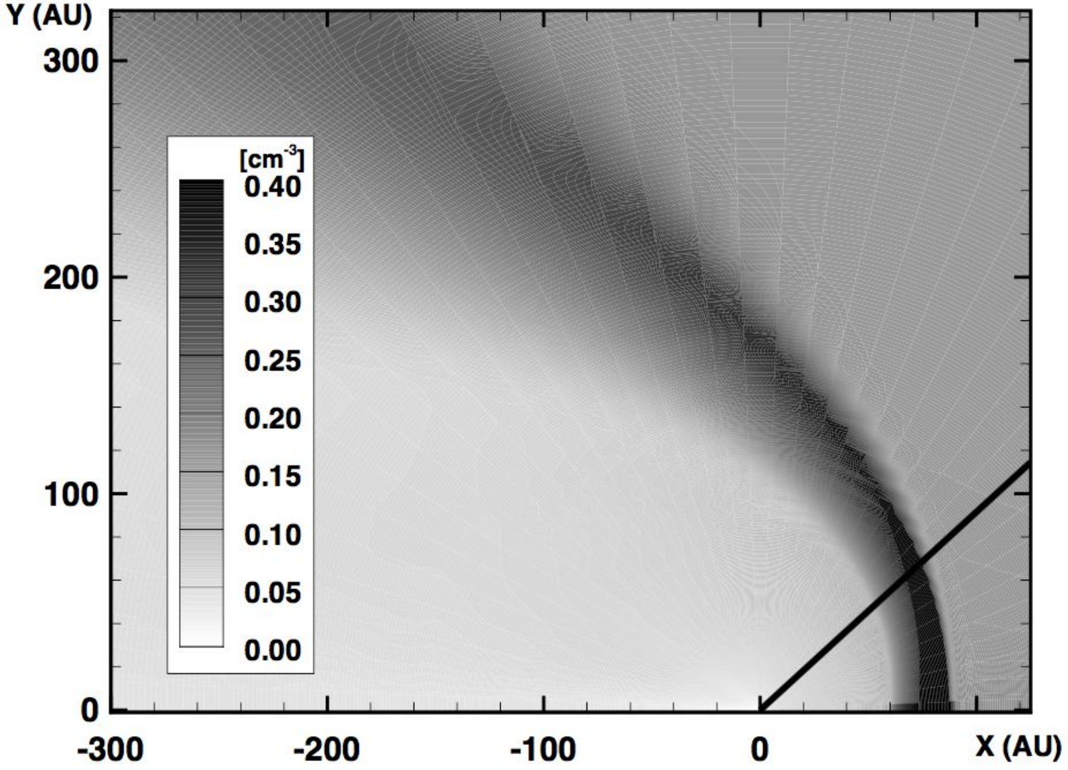
- Non-detections do not provide upper limits to stellar mass loss



Evidence for a weak wind from the young Sun from astrospheric detection towards π[1] Uma (Wood et al. 2014)