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Institute of Physics
Dept. Astrophysics & Geophysics

FWF
Der Wissenschaftsfonds.

Stellar coronal mass ejections

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(in alphabetical order)
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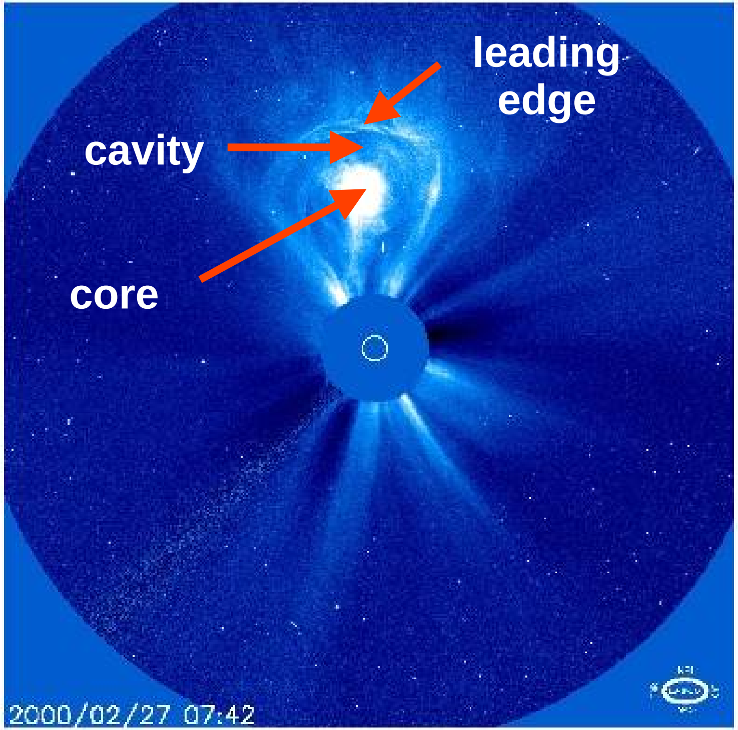
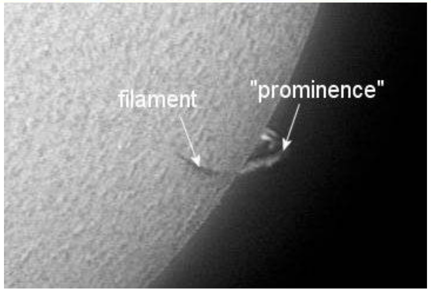
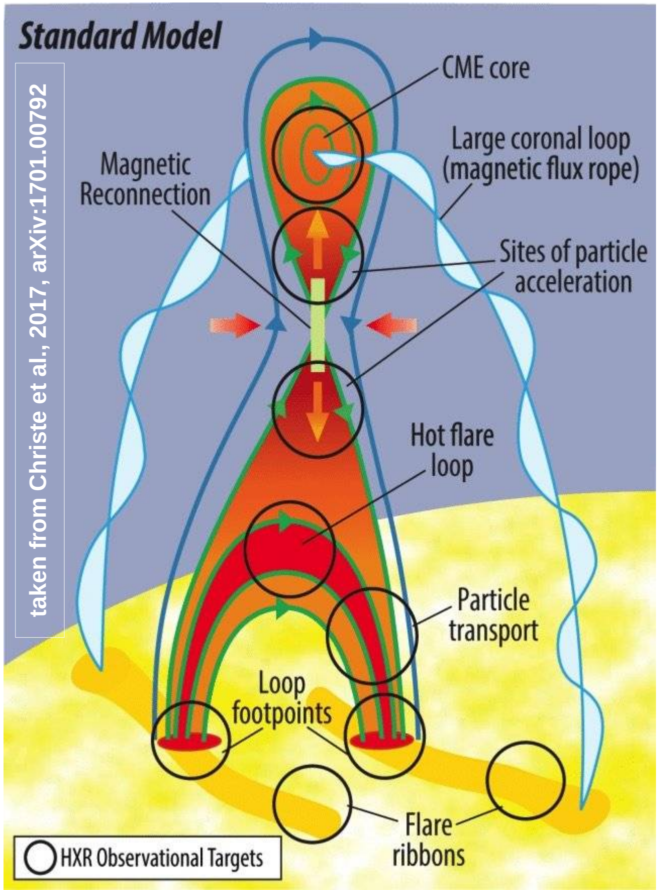
CMEs on the Sun

Solar Coronal Mass Ejections (CMEs)

Large Angle Spectrometric Coronagraph - LASCO

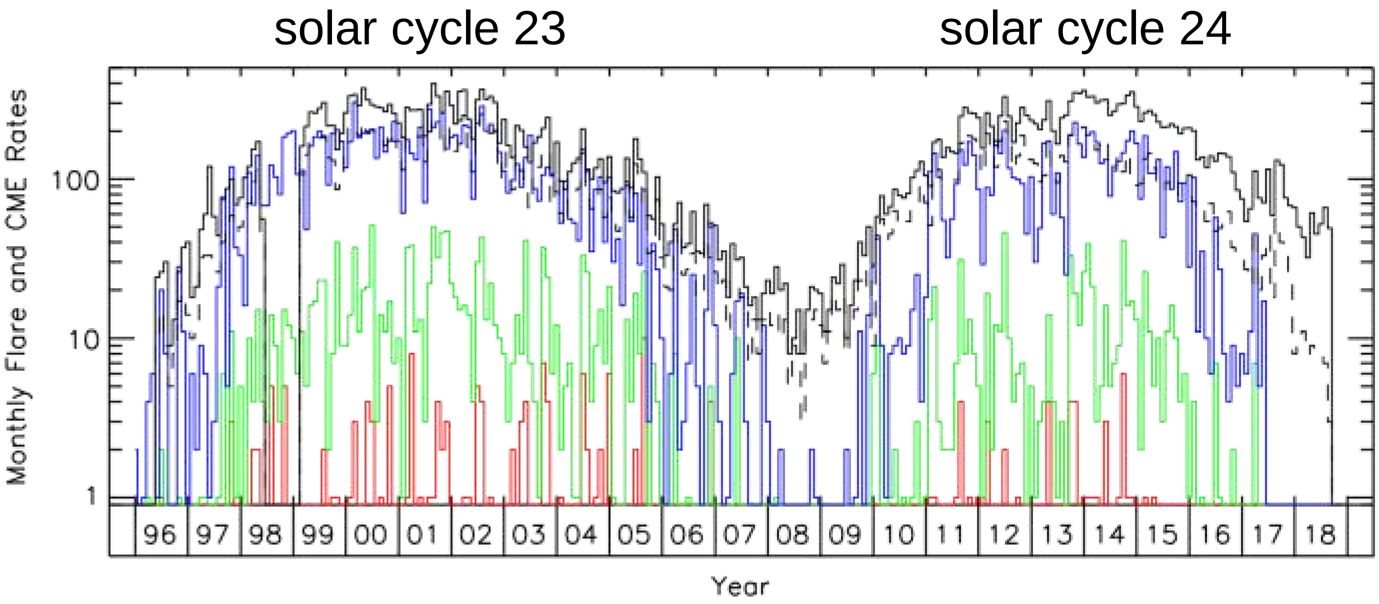






Standard model for solar eruptive events
CSHKP model

Solar CME and flare occurrence frequency



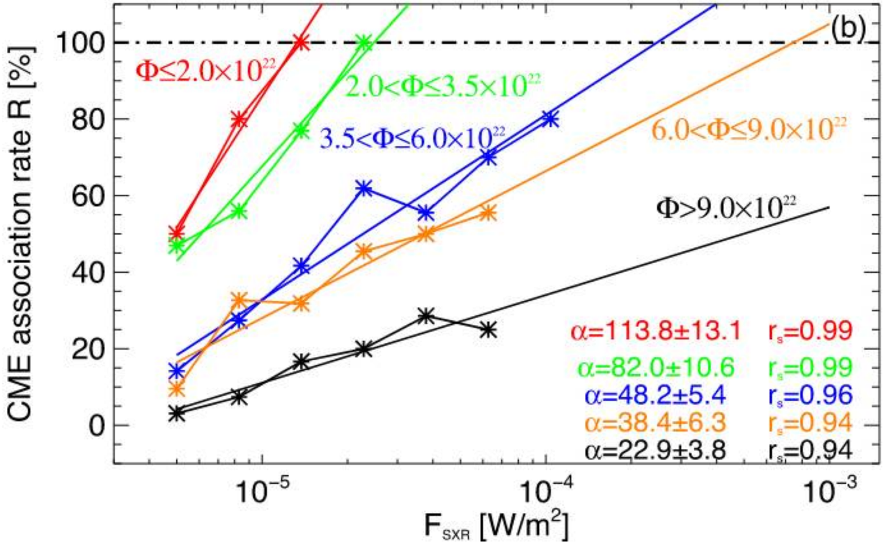
Lamy et al., 2019, Space Sci Rev, 215, 39

Blue: C-class flares Green: M-class flares Red: X-class flares Black: CMEs

One could conclude here that all flares (especially C-class) are correlated to CMEs. Is that so?

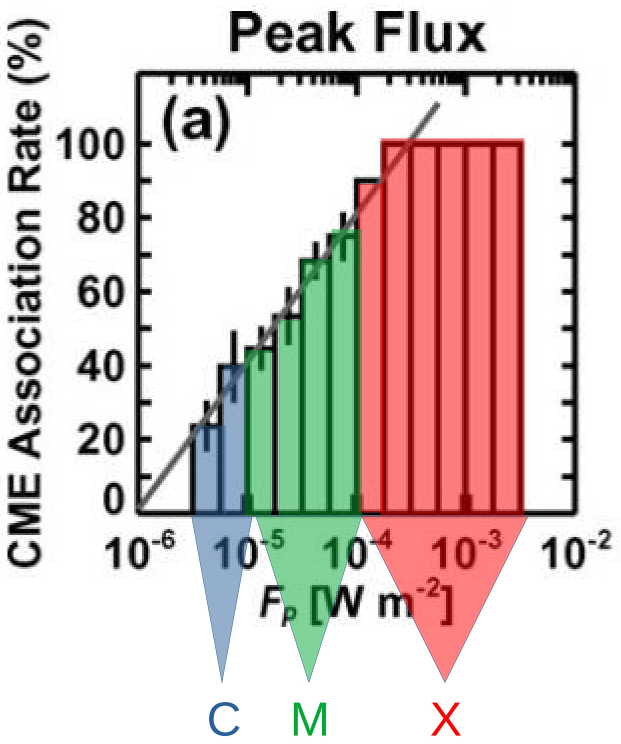
Solar flare-CME relationship

The association rate increases with flare energy, but the stronger the magnetic field of the active region the association rate is lower than for active regions with smaller magnetic fields. Here confinement plays a role.



Li et al., 2021, ApJL, 917, 7

Yashiro & Gopalswamy, 2009, IAU, 257, 233



The more energetic the flares the higher the flare-CME associations rate

Exception to the rule
the Oct. 2014 active region NOAA 2192 produced 6 X-class flares, but none of them had a accompanying CME

Solar CMEs are well studied and statistics are available.
But what about the stellar side and why is it relevant to investigate stellar CMEs?

Relevance of stellar CMEs

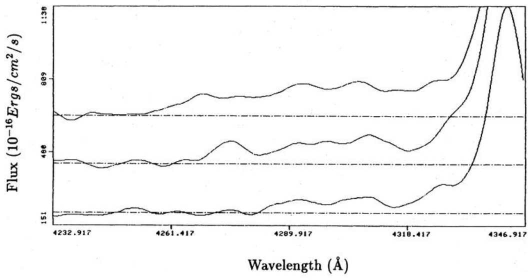
- Characterization
  a) What is the CME occurrence rate of young stars/Suns?
  b) What are their parameters?
  c) How does the flare/CME relationship looks like?
- Influence on exo-planetary atmospheres
  If CMEs are frequent and energetic they can erode, in the worst case, atmospheres of close-in orbiting planets
- What is the CME-related mass and angular momentum loss of young stars/Suns?

How can we detect stellar CMEs?

A wealth of methodologies

Direct signatures

Doppler shifted emission/absorption



Houdebine et al., 1990, A&A, **238**, 249

type II radio bursts

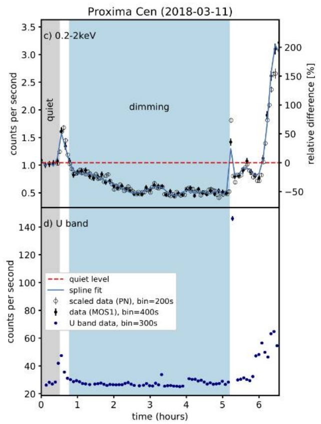
so far not detected, but several attempts

In-direct signatures

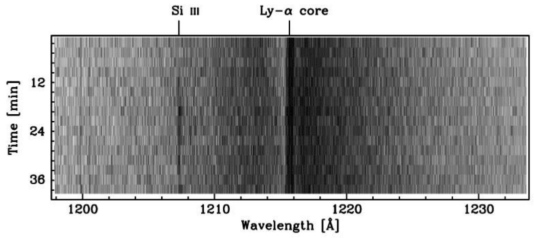
solar signatures

Coronal dimmings

Veronig et al., 2021, NatAst, **5**, 697

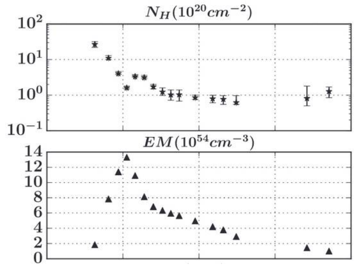


Absorptions in UV spectral lines



Bond et al., 2001, ApJ, **560**, 919

Continuous absorption in X-ray flares

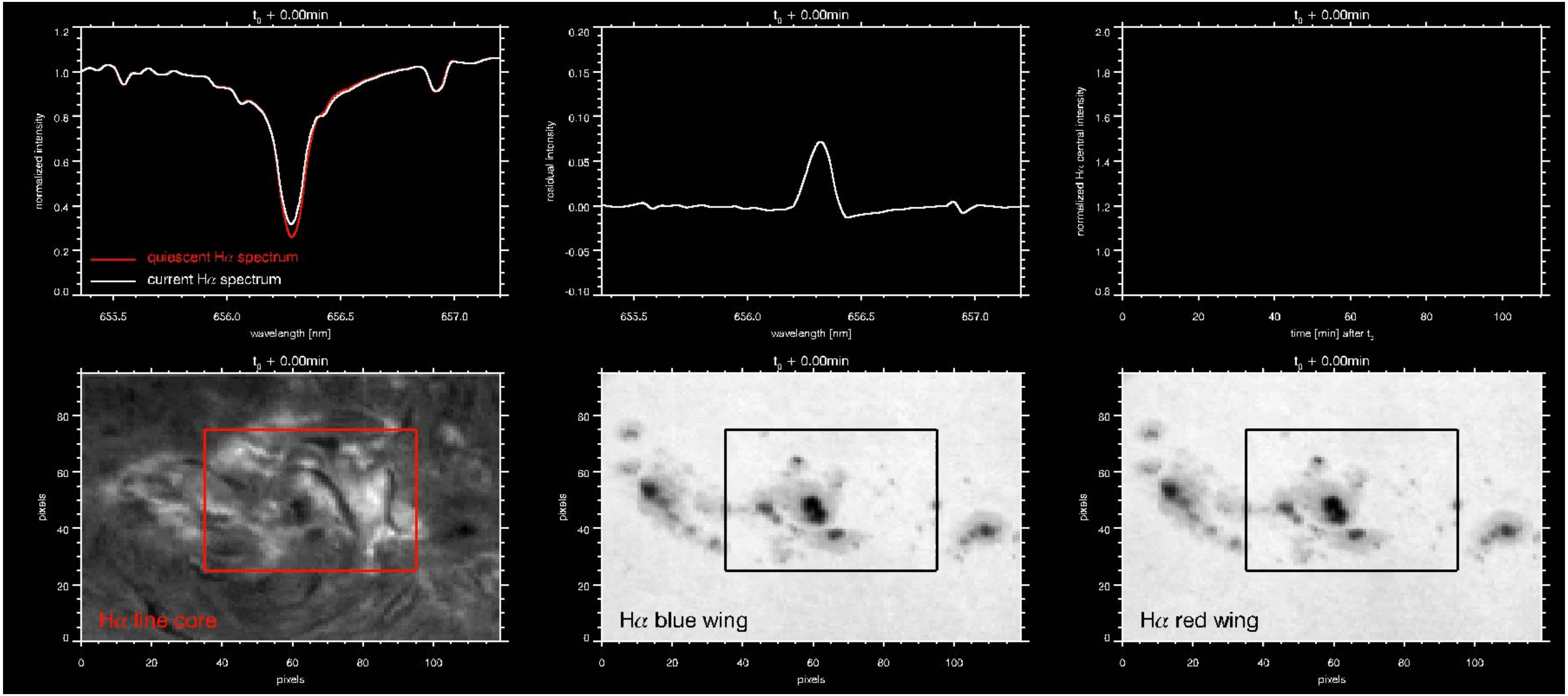


Moschou et al., 2017, ApJ, **850**, 191
based on
Favata&Schmitt, 1999, A&A, **350**, 900

alltogether yielding dozens of possible stellar CMEs but many more candidate events

Direct signatures
The method of Doppler shifted extra emission/absorption
A solar example

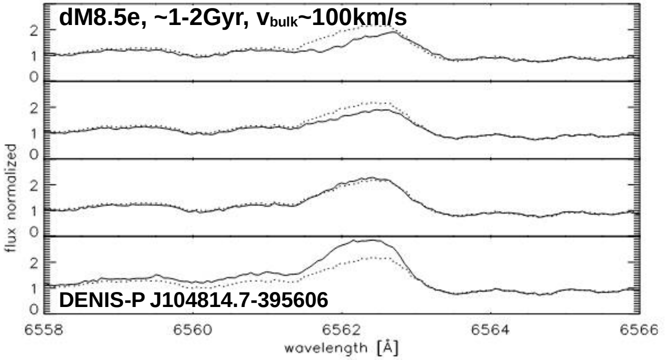
15/07/2002
NOAA 10030
active region observed
by MSO/MCCD*



*https://www.cora.nwra.com/MCCD/

Direct signatures

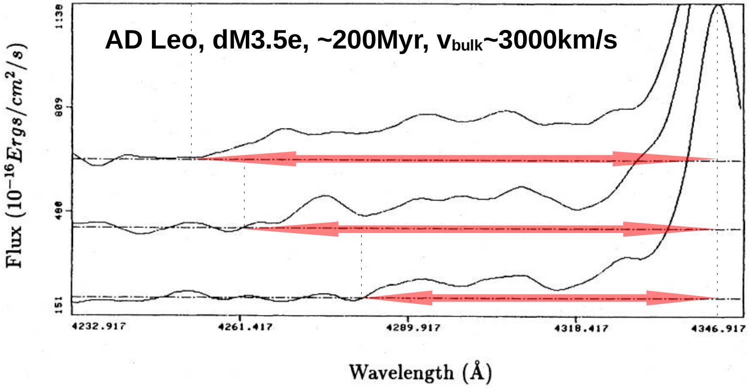
The method of Doppler shifted extra emission/absorption



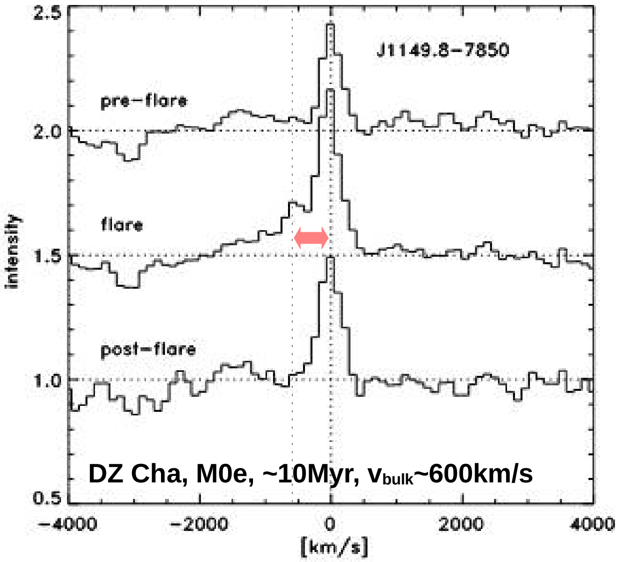
Fuhrmeister & Schmitt, 2004, A&A, 420 1079

- flux produced by erupting prominence/filament is superimposed on the stellar spectrum, according to its projected velocity it is shifted to the blue or red

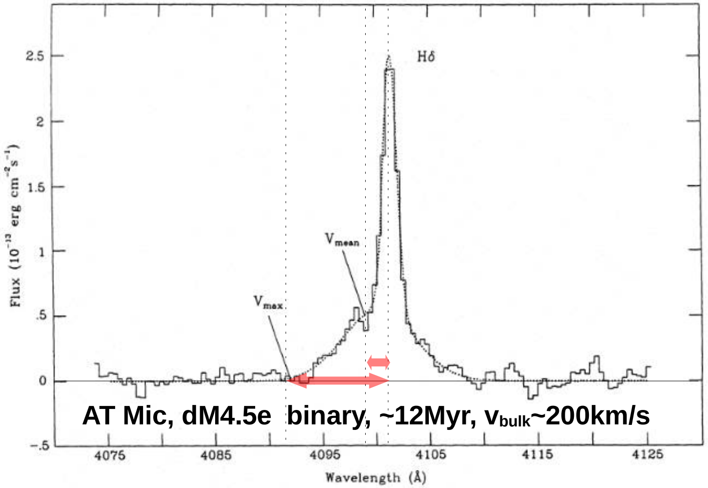
At optical wavelenghts:



Houdebine et al., 1990, A&A, 238, 249



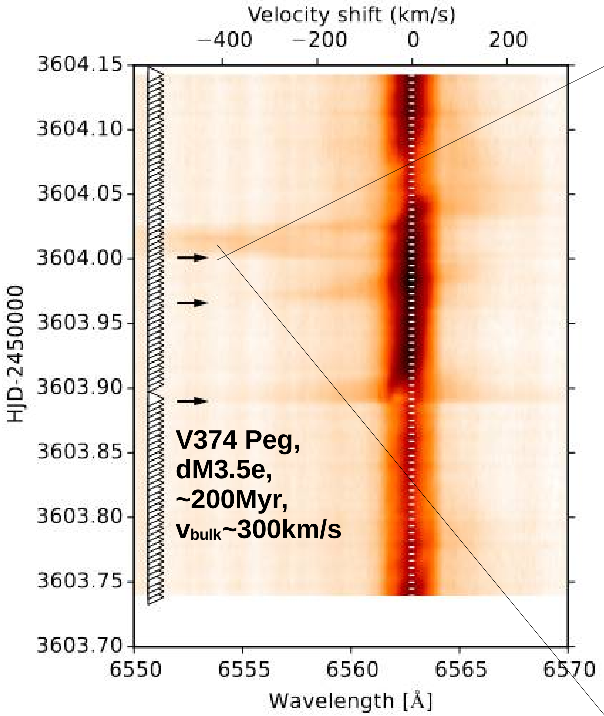
Guenther & Emerson, 1997, A&A, 321, 803



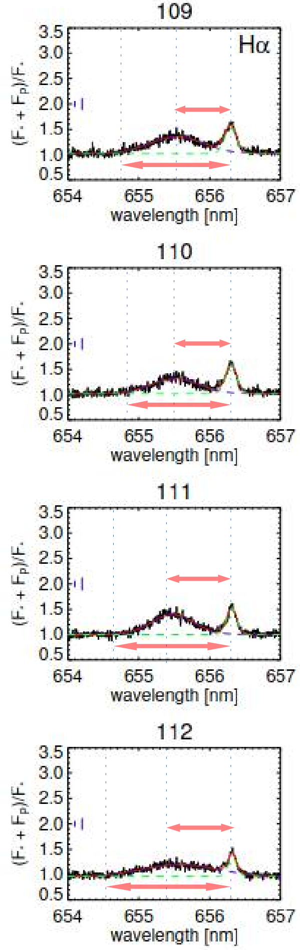
Gunn et al., 1994, A&A, 285, 489

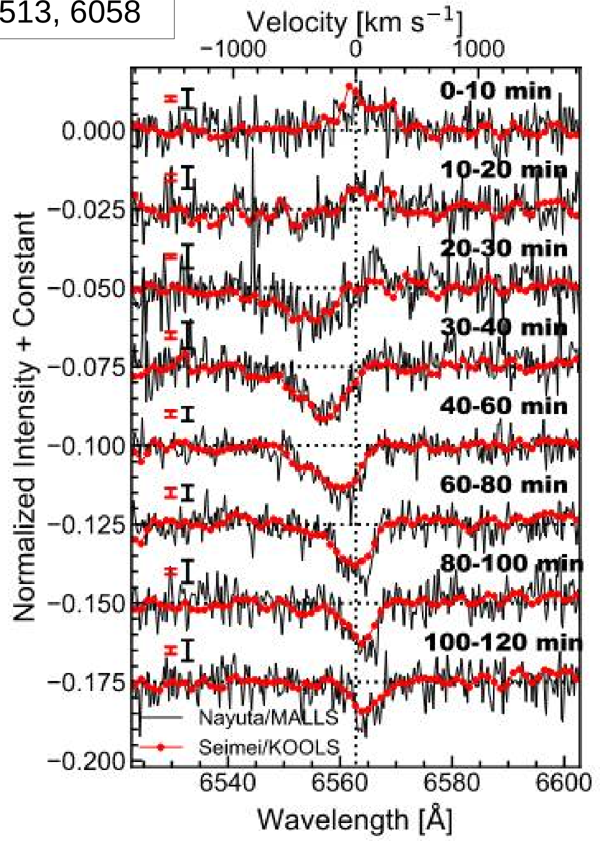
At optical wavelenghts:

Leitzinger et al., 2022, MNRAS, 513, 6058



Vida et al., 2016, A&A, 590, 13

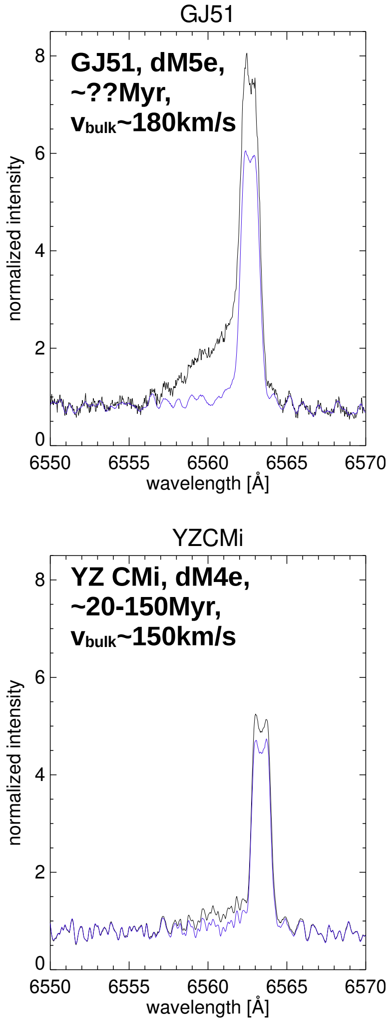




Namekata et al., 2022, NatAst, 6, 241

EK Dra, dG1.5, ~100Myr, v_{bulk}~510km/s

Vida et al., 2019, A&A, 623, 14



At optical wavelengths - searches in survey data:

SDSS DR14

Out of 630 000 F-M main-sequence stars only a handful of possible CME events (6) on dM stars and 281 flares found on dK-, and dM-stars

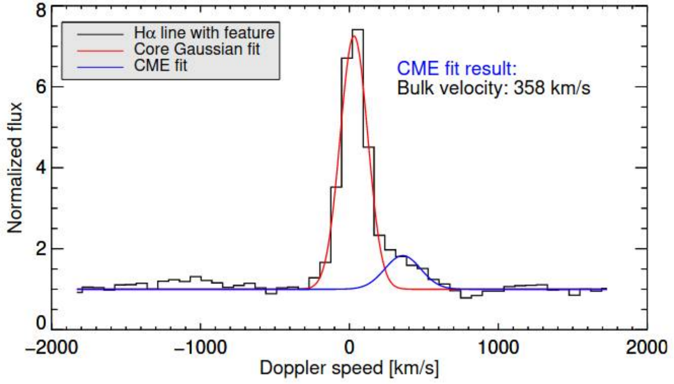
LAMOST MRS

Out of >1.3 million spectra of >200 000 late-type main-sequence stars only a handful of possible CME events (3) on dM stars

Carmenes data

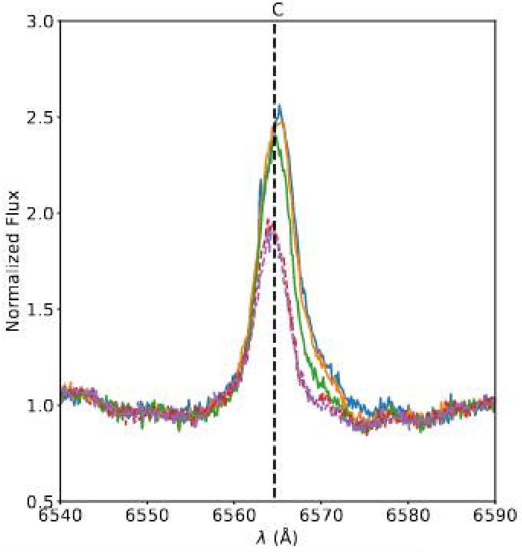
67 blue/red asymmetries on 28 dM stars

SDSS J042139.64+264913.8, dM6e, ~??Myr, v_{bulk}~360km/s



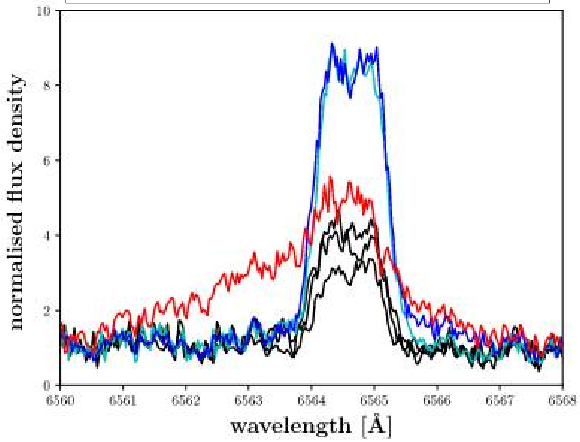
Koller et al., 2021, A&A, 646, 83

LAMOST J041827.35+145813.6, dM2e, ~??Myr, v_{bulk}~340km/s



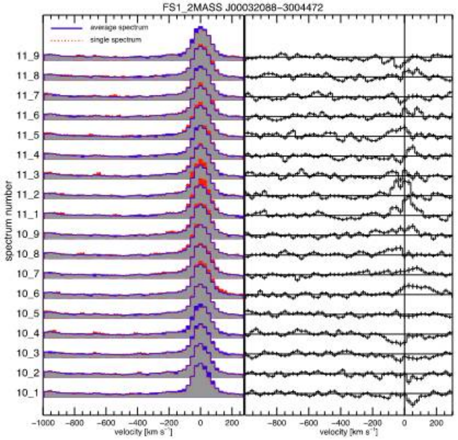
Lu et al., 2022, A&A, accepted, arXiv:2205.09972

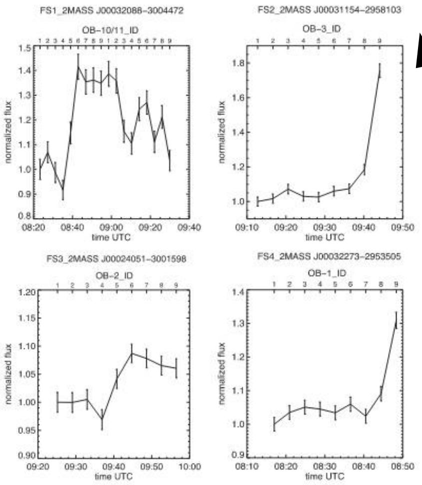
vB 8, dM7e, ~??Myr, v_{bulk}~150km/s



Fuhrmeister et al., 2018, A&A, 615, A14

Further dedicated searches for stellar CMEs (yielding non-detections only):

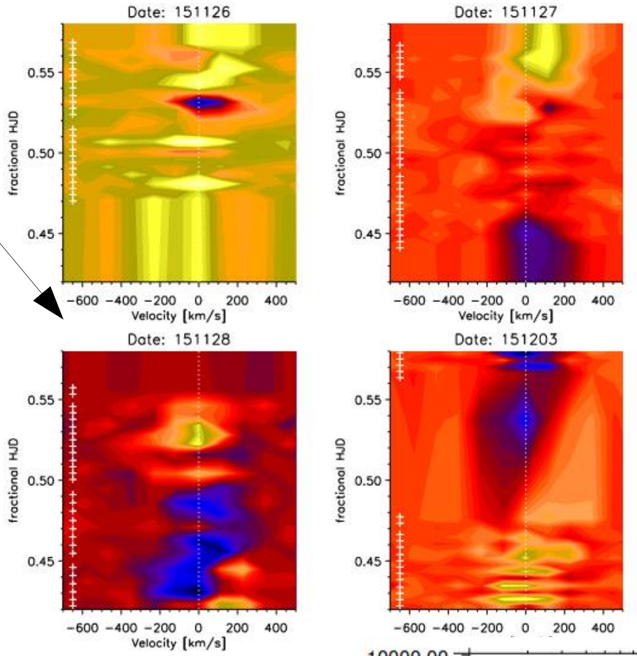




- few dozens of late-type main-sequence stars in open clusters
- 9 nights of multi-object spectroscopy
- no CMEs

- 28 K-, M-stars of the open cluster Blanco-1
- 5h of multi-object spectroscopy
- 4 flares no CMEs

Leitzinger et al., 2014, MNRAS, 443, 898

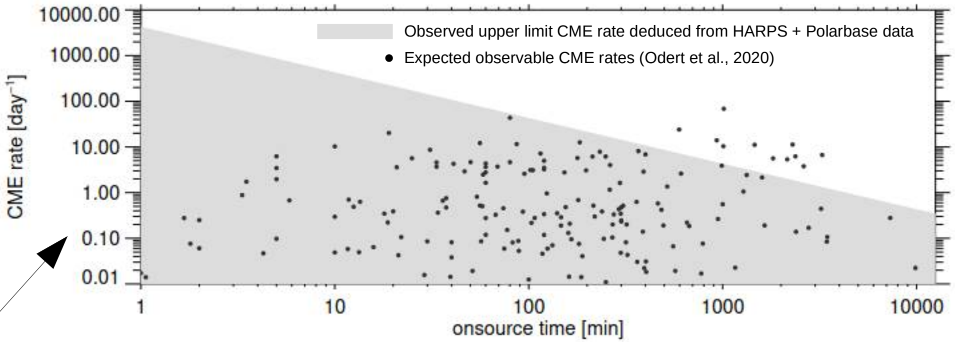


Korhonen et al., 2017, IAUS, 328, 198

- 3 years of spectroscopic monitoring (2018-2021) at Observatory Lustbühel Graz/OLG of bright solar-like stars – in more than 30000 spectra only one signature of a CME
- 3 nights of spectroscopic monitoring at the Anglo-Australian-Telescope (AAT) of pre-main-sequence stars in the Orion Nebula Cluster (ONC) – no signatures of CMEs

not published yet

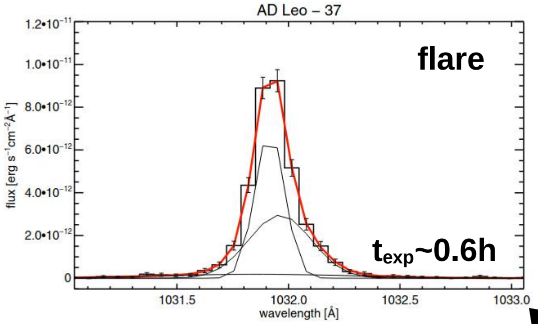
- 425 F-K stars
- 3700h of on-source time
- few flares no CMEs

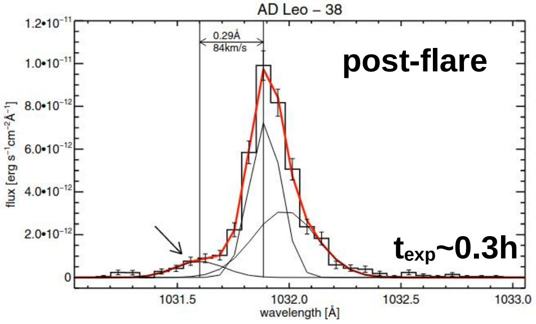


Leitzinger et al., 2020, MNRAS, 493, 4570

At FUV/X-ray wavelenghts:

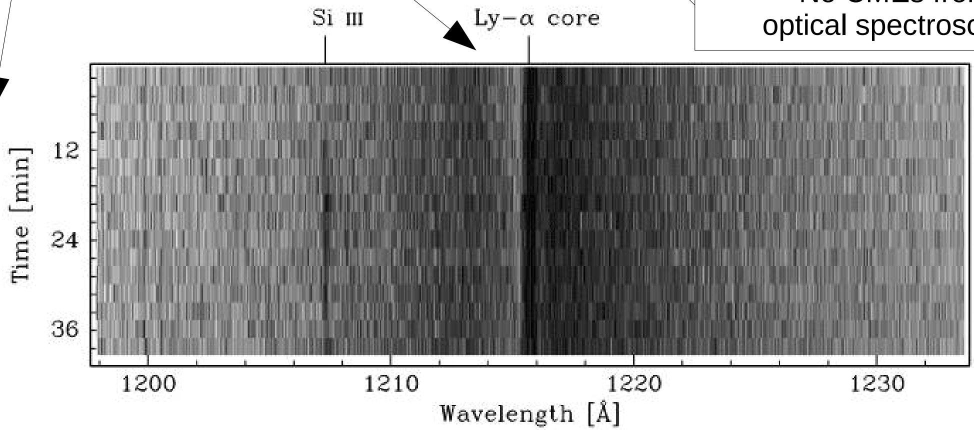
- 24 late-type stars in the FUSE archive of which 3 showed flaring, AD Leo, AB Dor, AU Mic
- AD Leo spectrum no.37 = flare
- AD Leo spectrum no.38 = possibly still belonging to the flare tail because of a higher count rate, blue-wing asymmetry in the OVI line, with **v_{bulk}~84km/s**





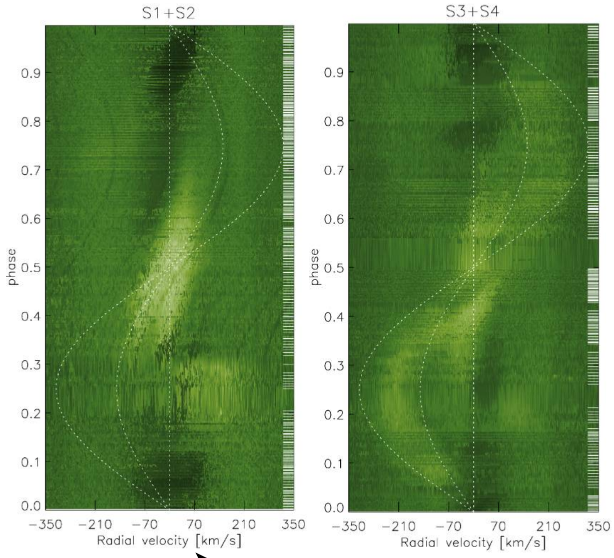
Leitzinger et al., 2011, A&A, 536, 62

- V471 tau is a pre-cataclysmic binary, i.e. hot white dwarf and cool red dwarf
- Suddenly the SiIII line appeared in absorption – CMEs crossing the line of sight? WD shines like a light bulb through which the CMEs are seen in absorption
- Predicted CME rate per day ~ 100-500



Bond et al., 2001, ApJ, 560, 919

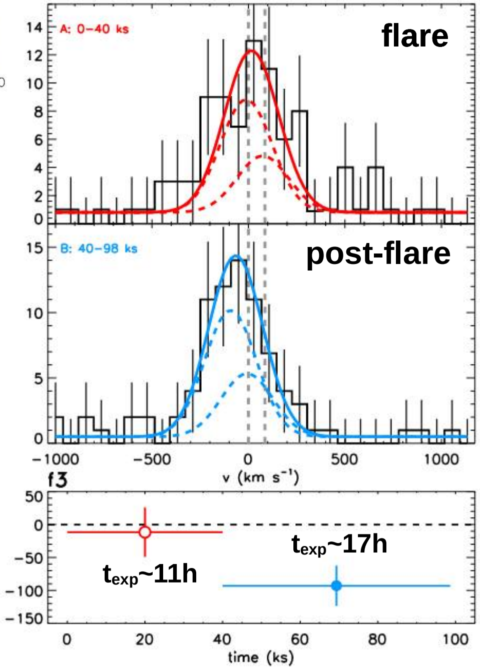
Kövari et al., 2021, A&A, 650, 158



No CMEs from optical spectroscopy

- HR9024/OU And G1IIIe giant
- shift of the OVIII line (in the flare tail) with **v_{bulk}~90km/s**

Argiroffi et al., 2019, NatAst, 3, 742

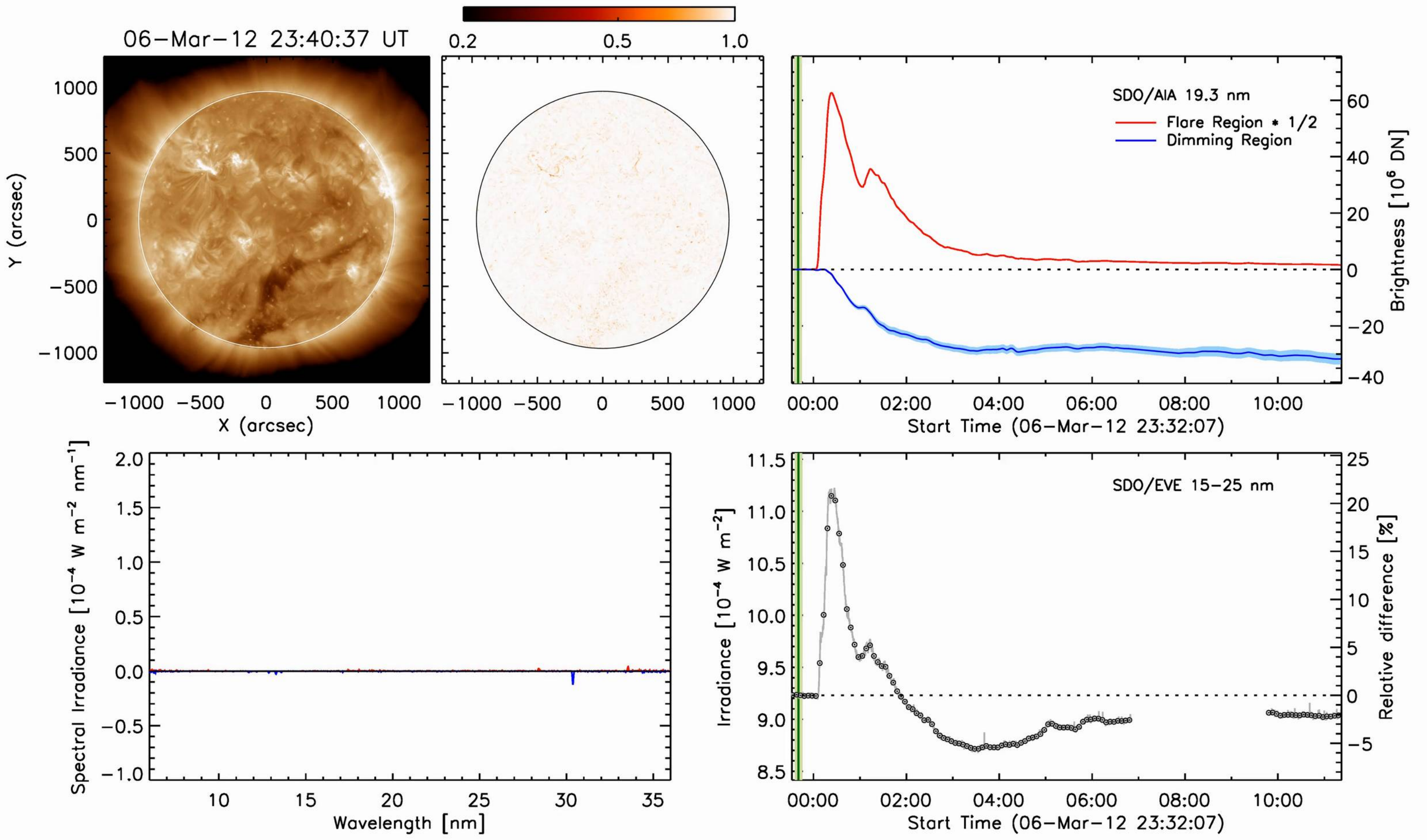


Indirect signatures

Xray/EUV dimming
A solar example

SDO/AIA (19.3nm) dimming (blue) and flaring (red) region

SDO/EVE full-disk spectra and light curve



Indirect signatures

The method of coronal dimmings

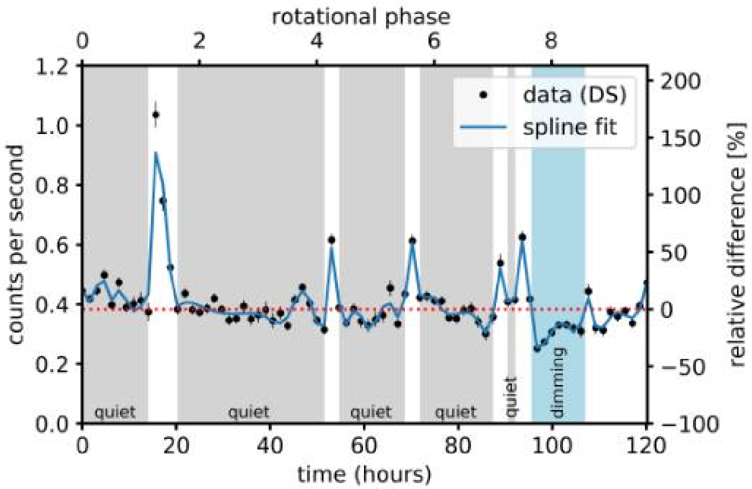
Establishing the full disk signature on the Sun

Looking for that signature on stars

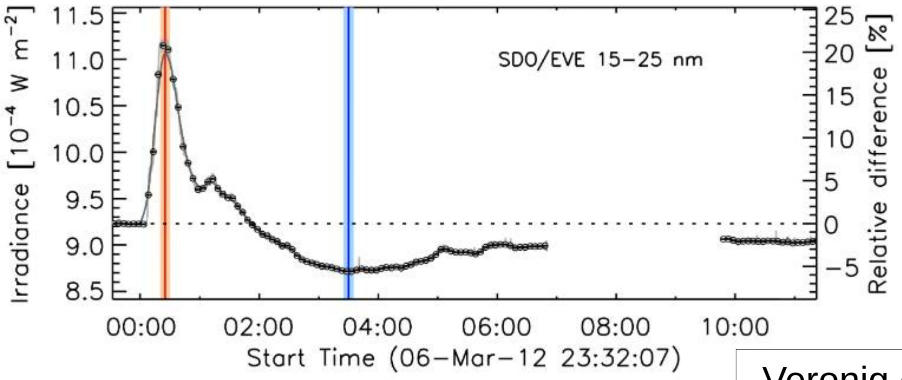
in the EUV

High conditional probability for CME occurrence with observed dimmings

AB Dor, K0, ~50Myr



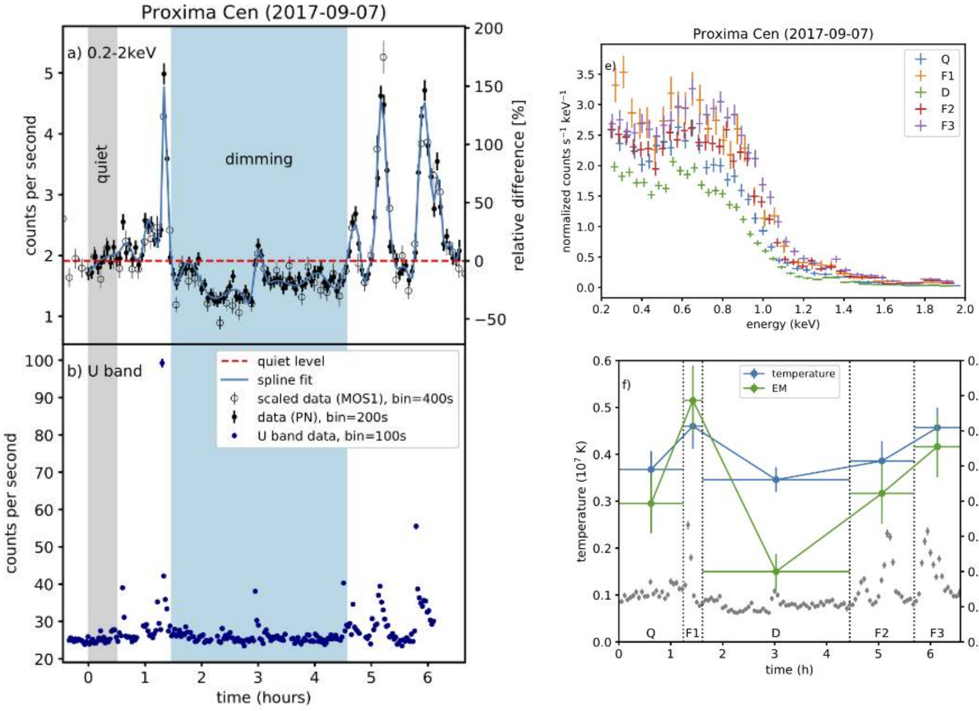
Sun, dG2, ~4.6Gyr



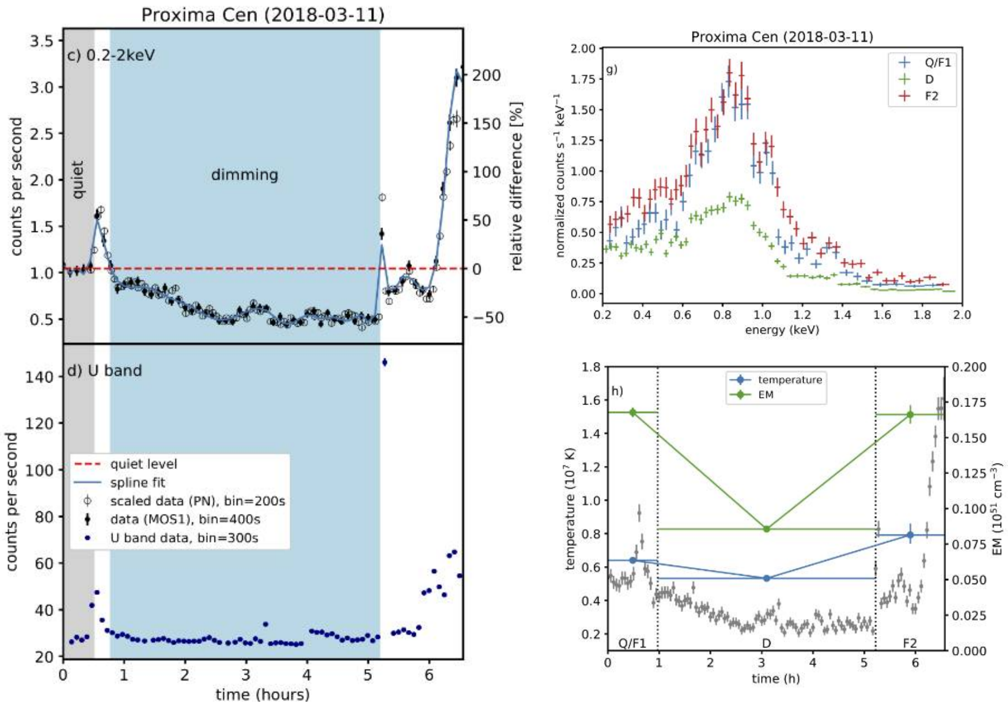
Veronig et al., 2021, NatAst, 5, 697

and in X-rays

Proxima Cen, dM5.5e, ~4.85Gyr



example 1



example 2

Veronig et al., 2021, NatAst, 5, 697

Indirect signatures

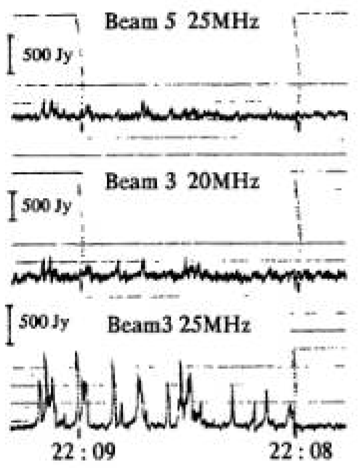
The method of radio bursts

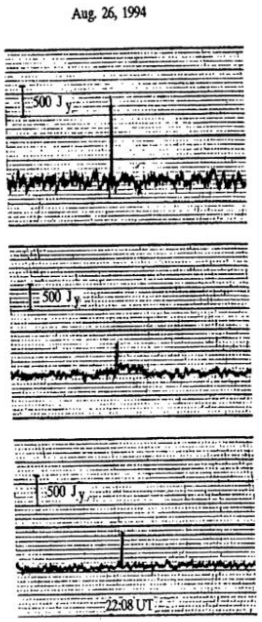
Usage of the solar radio signature of CMEs, i.e. radio type II bursts (signature of a shockwave - e.g. Reiner et al., 2001; Gopalswamy et al., 2001, 2005 Claßen & Aurass, 2002) and also (moving) type IV (signature of trapped electrons in CME loops, e.g. Gopalswamy, 2011 Planetary Radio Emissions VII, held in Graz).

Observing at low frequencies

Monitoring of EV Lac using single channel receivers at the Ukrainian T-shaped radio telescope (UTR-2)

EV Lac, dM4e, ~200-300Myr

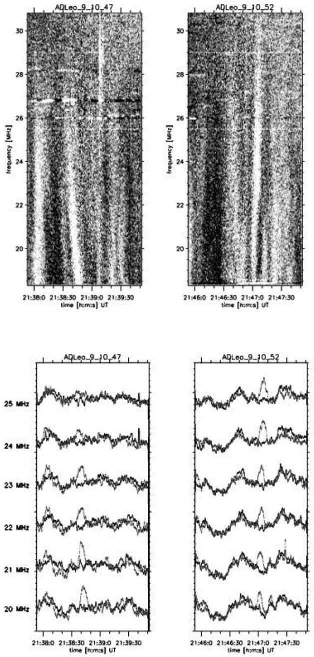




Abdul-Aziz et al., 1995, A&AS, 114, 509

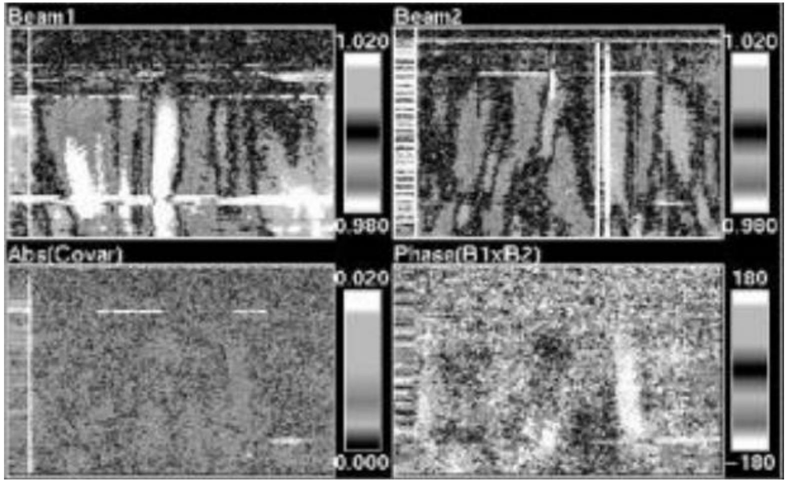
Abranin et al., 1998, A&AT, 17, 221

Monitoring of AD Leo using multi channel receivers at the Ukrainian T-shaped radio telescope – 2nd modification (UTR-2)



AD Leo, dM3.5e, ~200Myr

Radio bursts with similarities to solar type III bursts were detected



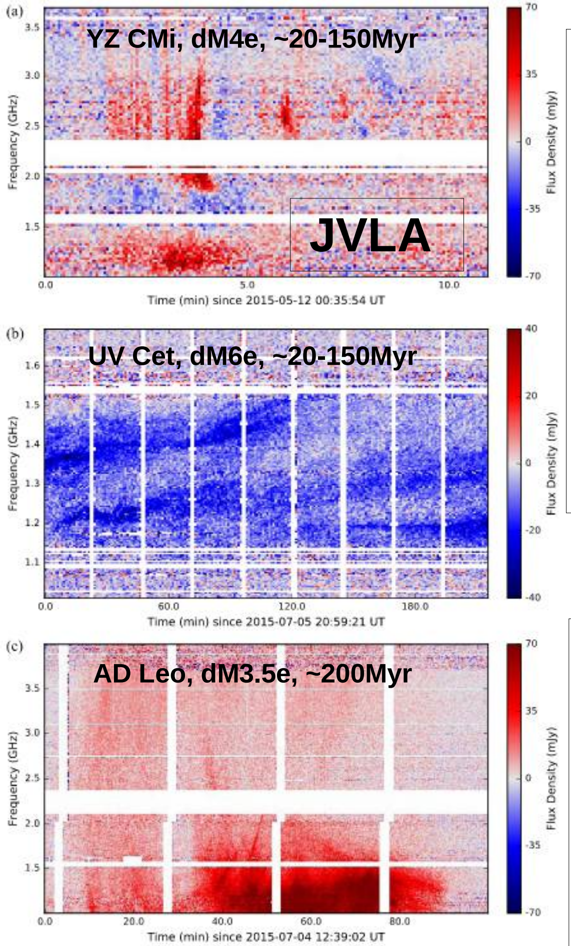
Leitzinger et al., 2009, AIPC, 1094, 680

Konovalenko et al., 2012, EPSC, 7, 902

Boiko et al., 2012, AASP, 2, 121

Observing at higher frequencies

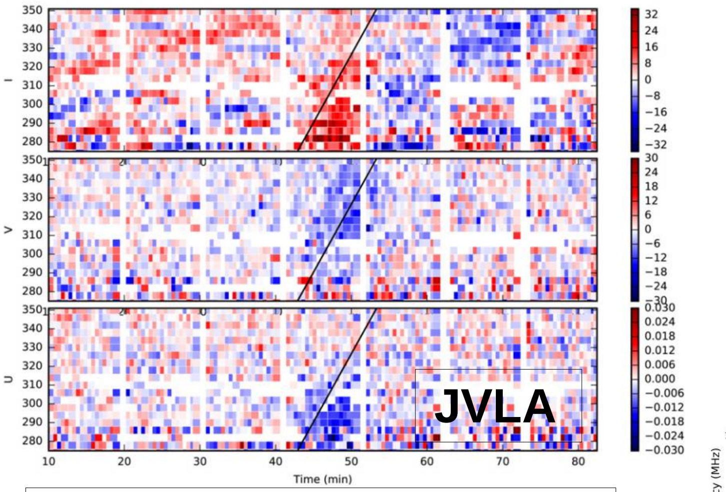
Villadsen & Hallinan, 2019, ApJ, 871, 214



- 22 coherent bursts
- high degree of polarisation
- no type II emission

Crosley & Osten, 2018, ApJ, 862, 113

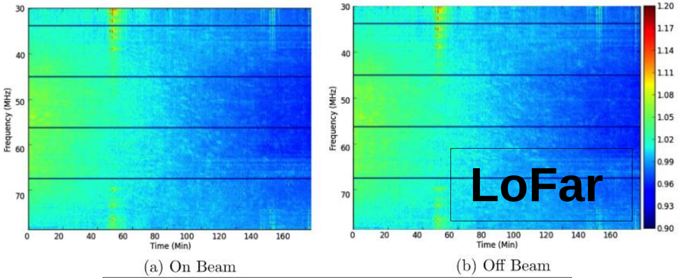
EQ Peg, dM3.5e+dM4.5e, pms … ~1Gyr



- 2 bursts, likely to be not type II-like
- 44hr of observations
- the authors doubt that a high stellar flaring rate means also a high stellar CME rate

Crosley et al, 2016, ApJ, 830, 24

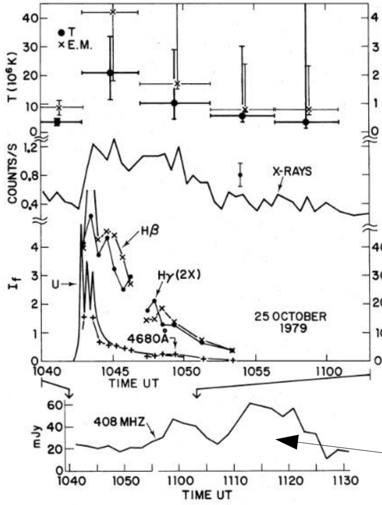
YZ CMi, dM4e, ~20-150Myr



(a) On Beam (b) Off Beam

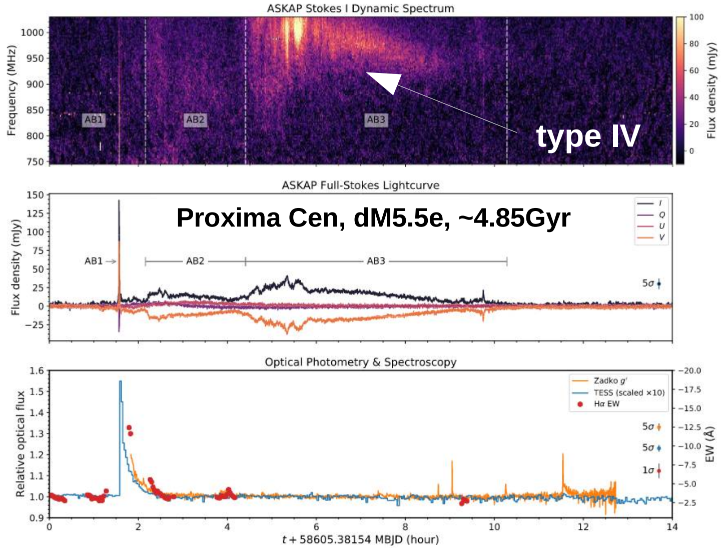
- no radio bursts in 15hr observation

Kahler et al, 1982, ApJ, 252, 239



YZ CMi, dM4e, ~20-150Myr

type IV

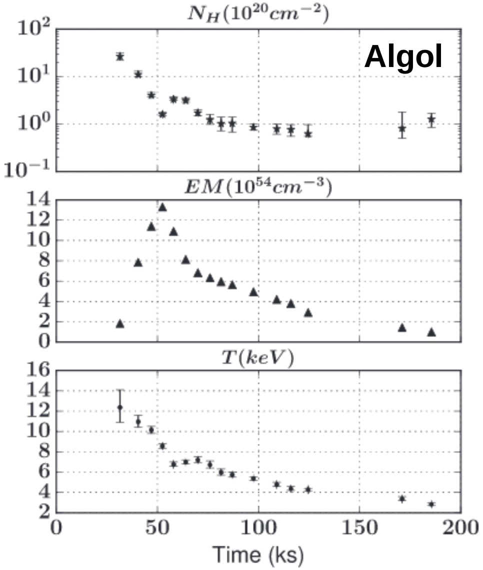


Zic et al, 2020, ApJ, 905, 23

Indirect signatures

The method of continuous X-ray absorptions during stellar flaring

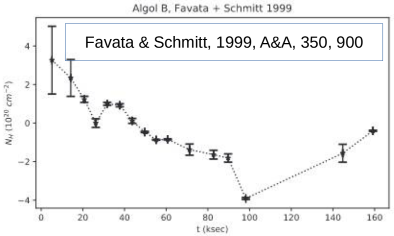
Here the temporal decay of hydrogen column density, obtained from fitting X-ray spectra, during flaring is explained by an expanding and obscuring neutral plasma (reminiscent of a solar filament) of the flaring region



Moschou et al., 2017, ApJ, 850, 191
originally from
Favata & Schmitt, 1999, A&A, 350, 900

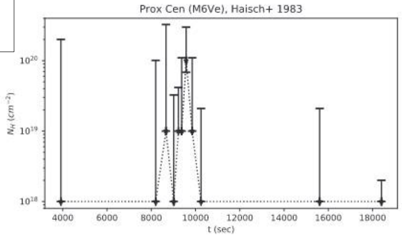
Algol (dB8+K2IV)
ProxCen (dM5.5e) Algol V773 tau (dK3e)
UX Ari (K0IV+dG5) HII 1100 (K3V) σ Gem (K1III+dwarf)

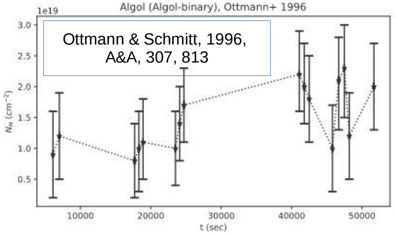
Algol … ecl. Binary
ProxCen … dwarf
V773tau … dwarf
UX Ari … RS Cvn
HII 1100 … dwarf
σ Gem … RS CVn



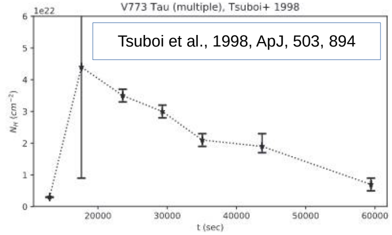
Favata & Schmitt, 1999, A&A, 350, 900

Haisch et al., 1983, ApJ, 267, 280

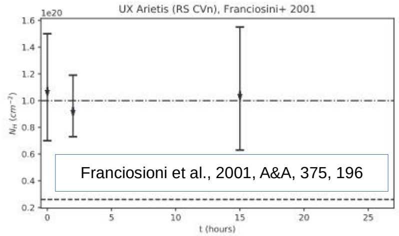




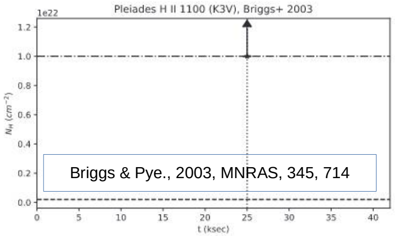
Ottmann & Schmitt, 1996, A&A, 307, 813



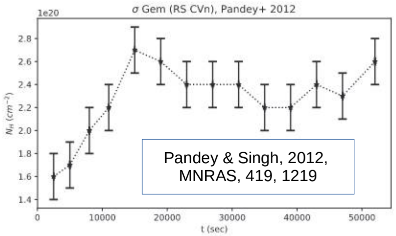
Tsuboi et al., 1998, ApJ, 503, 894



Franciosioni et al., 2001, A&A, 375, 196



Briggs & Pye., 2003, MNRAS, 345, 714



Pandey & Singh, 2012, MNRAS, 419, 1219

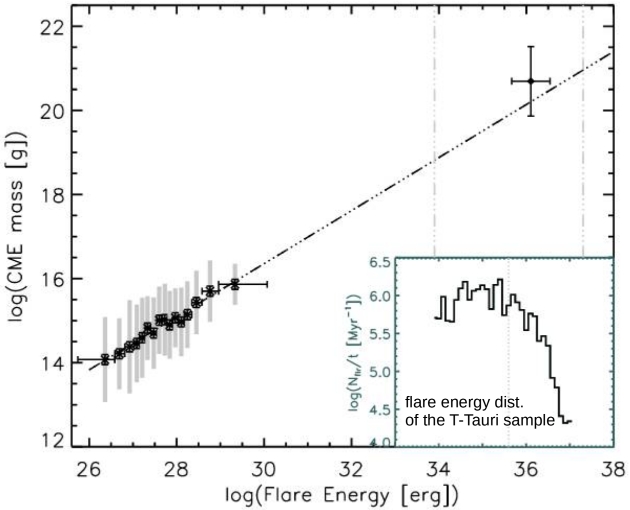
Moschou et al., 2019, ApJ, 877, 105

Theoretical CME rates

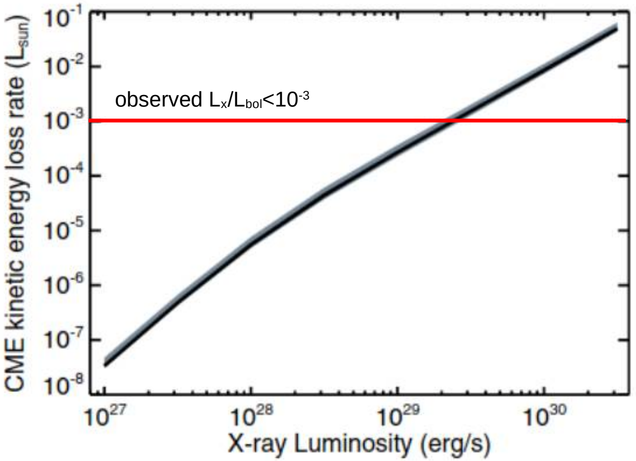
The approach of using the solar flare energy/CME-mass distribution to access stellar CME parameter distributions

- extrapolating the solar flare energy/CME-mass distribution to larger energies

- testing for the case of T-Tauri stars in Orion, assuming every flare has a CME, which is reasonable for pre-main-sequence stars as those have strong flares, on the Sun strong flares show a 100% association rate with CMEs



Aarnio et al., ApJ, 760, 9, 2012

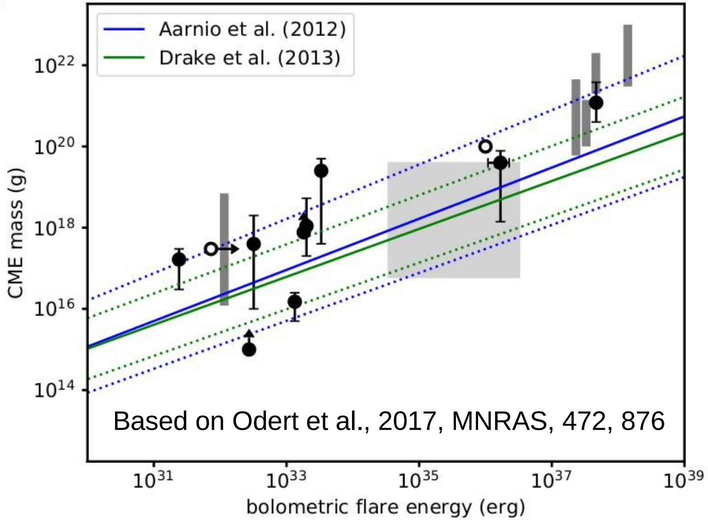


Drake et al., ApJ, 760,9, 2013

- extrapolating solar flare energy/CME mass relatioship to higher energies, leads to unreastically high loss rates, and flare energy budget problems – X-ray saturation limit

- either the flare energy/ CME-mass relation needs to flatten for flare energies larger 10^31erg
  or
  the CME/flare association rate must be significantly below 100% for energetic events

- flare energy/CME mass relations from Aarnio2012 and Drake2013, overplotted with their 1 and 2σ ranges (dotted lines)
- the grey shaded area corresponds to the typical mass range of stellar Prominences
- the grey shaded vertical bars indicate events detected from X-ray absorption
- filled circles are events from literature determined using the Doppler method



Leitzinger & Odert , SerAJ, 205,1L, 2022

Theoretical CME rates

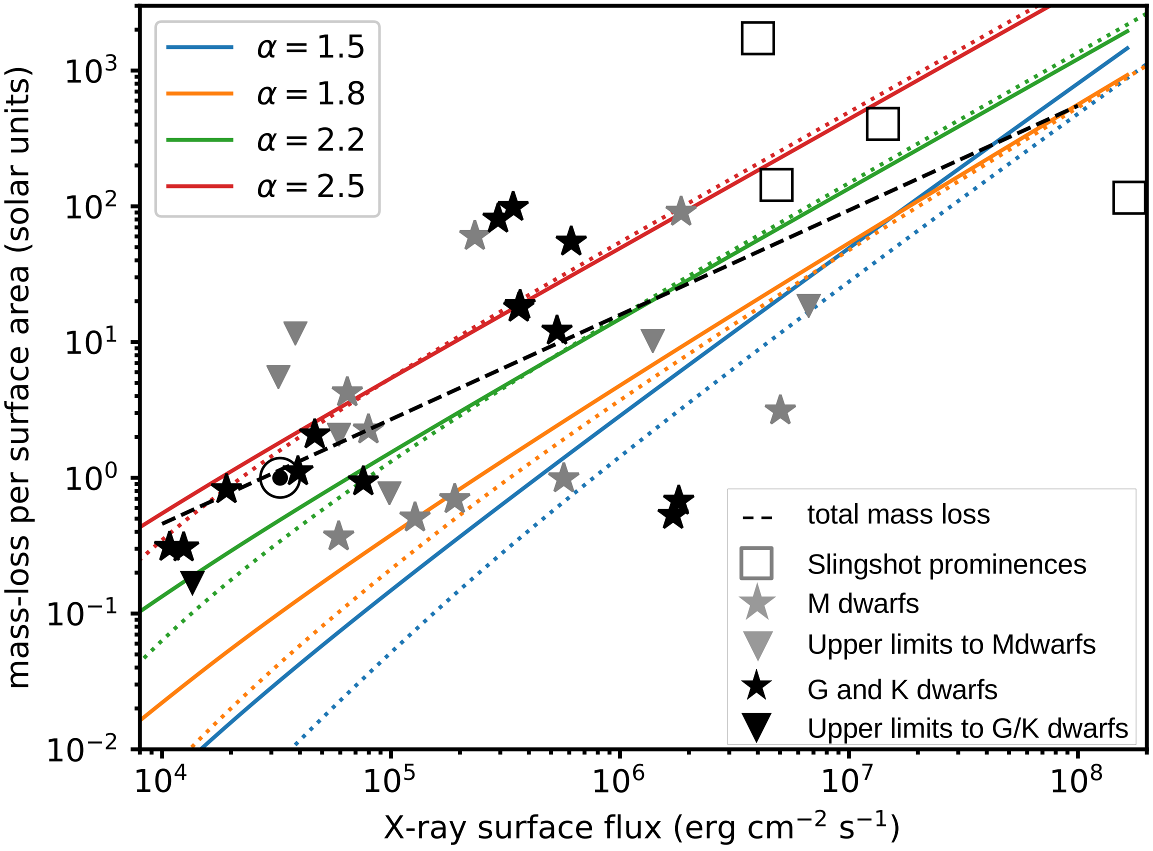
Total mass loss versus CME induced mass loss

- Odert2017 refined and extended the approaches from Aarnio2012 and Drake2013 by incooporating a flare power law, deduced from observations (Audard et al., ApJ, 541, 396, 2000) , as well as considering energy band conversions of solar and stellar instruments

- relation of wind-induced (black dashed line) and CME-induced mass loss (colored/dashed solid lines, solid: normalized to the surface area of a solar-like star; dashed=normalized to the surface area of a dM star)

- extrapolation of CME induced mass loss is consistent with total mass loss measurements for less active stars

- energy budget problem when extrapolating solar scalings to larger energies → alternative explanation from Odert2017: the solar flare/CME association rate shifts to higher energies, so currently highly energetic flares are frequent but super-energetic flares are still rare



based on Odert et al., 2017, MNRAS, 472, 876

Examples of physical CME models

- usage of numerical modelling of erupting flux ropes to evaluate if CMEs may erupt on active stars or not

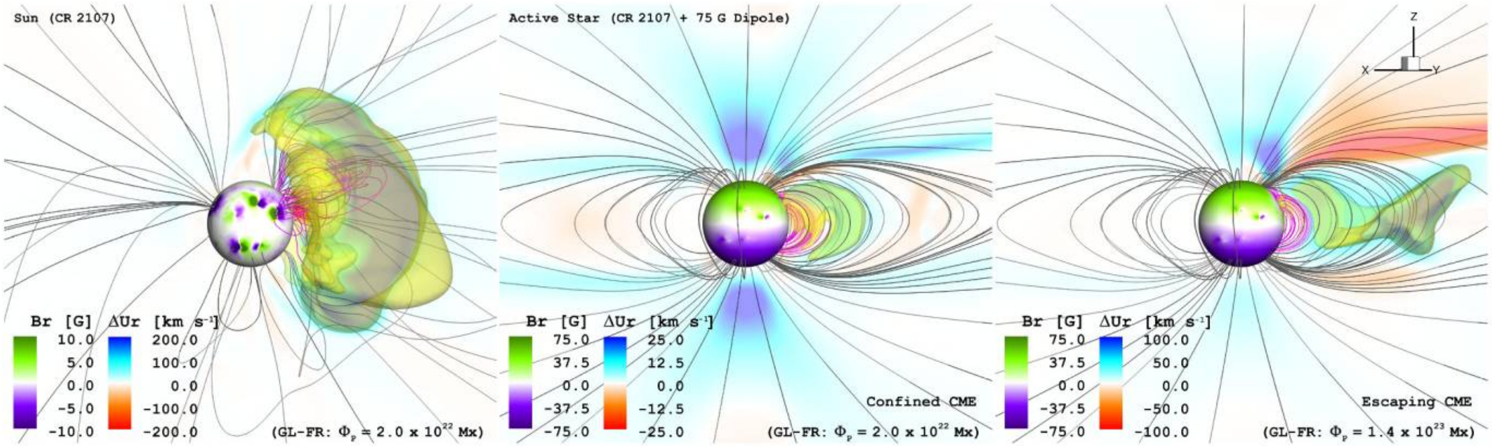
- magnetic suppression is evident, much energy is needed to overcome the suppression

- this is consistent with the suggestion by Odert et al. (2017, 2020), for active stars the solar flare/CME association rate may shift to larger energies

Solar CME with X5 flare

Solar CME with X5 flare but with a 75G dipole field = confined

Solar CME with X150 flare and with a 75G dipole field = erupting



Alvarado-Gomez et al., AN, 343, 10100e, 2022

What are the advantages and disadvantages of the methods used so far for the detection of stellar CMEs and which method to prefer?

	advantages			disadvantages		
Doppler-shifted absorption/emission (2 events with $v>v_{esc}$ and >**200** candidate events with $v<v_{esc}$)	Requires optical observations – relatively easy to acquire	Simultaneous observations of several targets is possible	A large number of candidate events and archival data is existing	Signature of erupting filament not CME	Measured velocity is projected only	No continuous time Series, such as for satellite/radio obs. feasible
Coronal dimmings (**21** events)	Revealed in one study the largest number of CMEs	Simultaneous observations of several targets is possible	?	Requires X-ray obs. – harder to acquire than optical obs.	Definition of the quiet stellar X-ray level	Determination of CME parameters is dependent on solar scalings
Radio bursts (**1** type IV and no type II)	Night and day time observations possible (daytime obs. contaminated by interferences)	?	?	Simultaneous observations of several targets is not possible	At low frequencies, spatial res. and sensitivity, is very limited	Determination of CME parameters is dependent on solar scalings
Continuous X-ray Absorption (**7** events)	Simultaneous observations of several targets is possible	?	?	Requires X-ray obs. – harder to acquire than optical obs.	Signature is model dependent	so far only few events available

Conclusion and outlook

- no statistics so far
- we know that there are CMEs from dG to dM stars
- on dM stars we see blue-wing asymmetries frequently

How to proceed?

- dedicate more observing time
- use the potential of all methodologies
- explore data archives
- aim for coordinated multiwavelength campaigns – high risk!
- use the candidate events known so far and learn from Sun-as-a-star observations of erupting filaments to better interpret stellar candidate events of CMEs