# The Space Weather Environment that Stars Create

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Cool Stars 20
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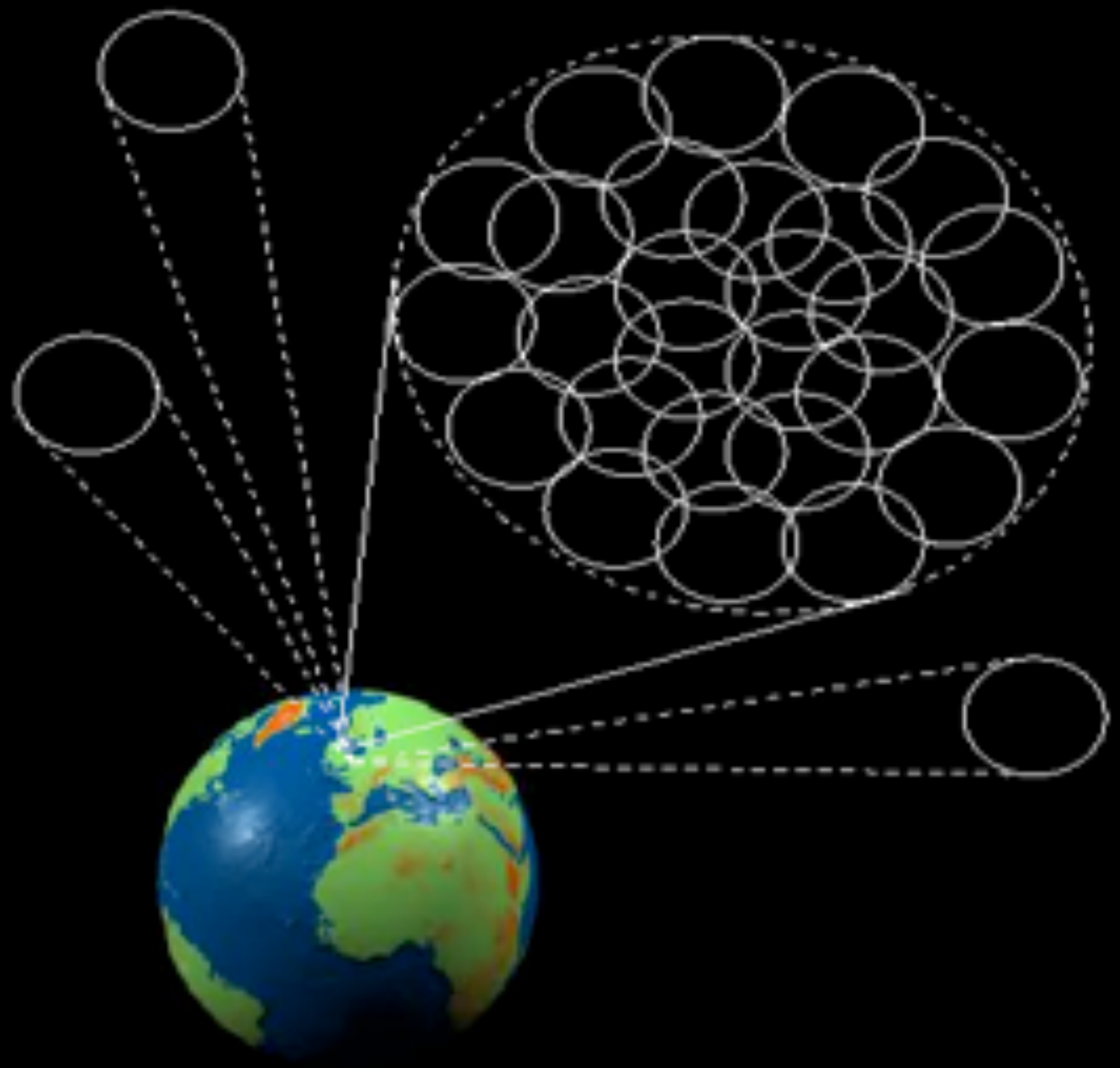
@rachelosten

# With collaborators:

Michael Crosley*
now with PhD!

Scott Wolk



LOFAR Transients Key Project

Colin Norman

# At the beginning. . .

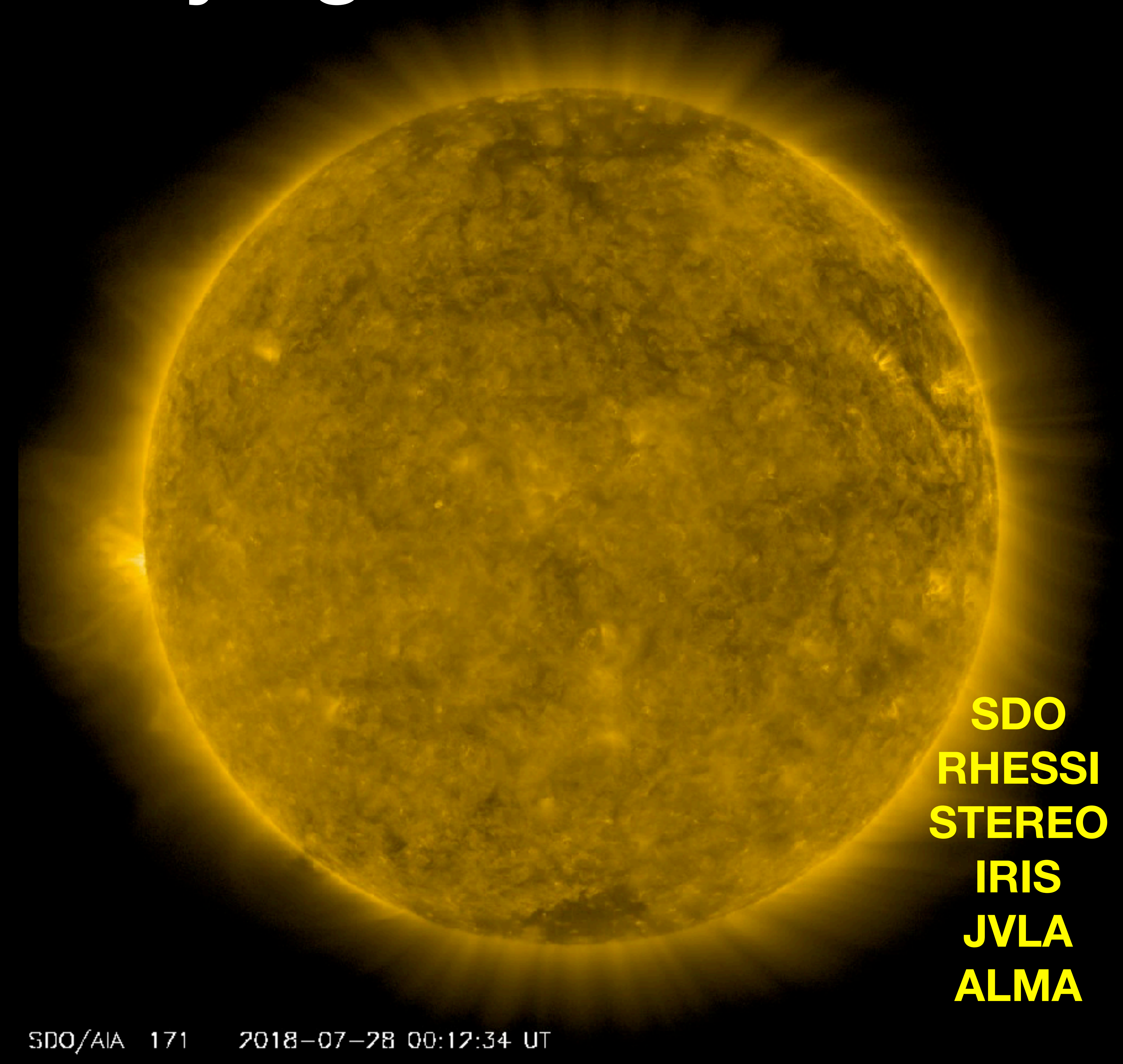
INTRODUCTION

This book represents the proceedings of a NATO Advanced Study Institute which was held at Bonas from August 25 till September 5, 1980 and was devoted to the study of "Solar Phenomena in Stars and Stellar Systems". It is intended for a broad audience. Students and post-doctoral scientists for example can discover new aspects of astrophysics. The general spirit of the ASI was aimed at presenting a unified aspect of astrophysical phenomena which can be studied intensively on the Sun although they are of a much more general nature. On the other hand, specialists in solar or stellar physics will find here the latest theoretical developments and/or the most recent observations made in their own field of research. An extensive bibliography will be found throughout the various sections, to which the reader may refer, for more detailed developments in various specific areas.

In the past, stellar and solar astrophysics have more or less followed their own independent tracks. However, with the rapid development of modern techniques, in particular artificial satellites like the International Ultraviolet Explorer and the Einstein Observatory, which provide a new wealth of data, it appears that chromospheres, coronae, magnetic fields, mass loss and stellar winds, etc.. . ., are found not only in the Sun but occur also in other stars. Frequently these other stars represent quite different conditions of gravity, luminosity, and other parameters from those occurring in the Sun.

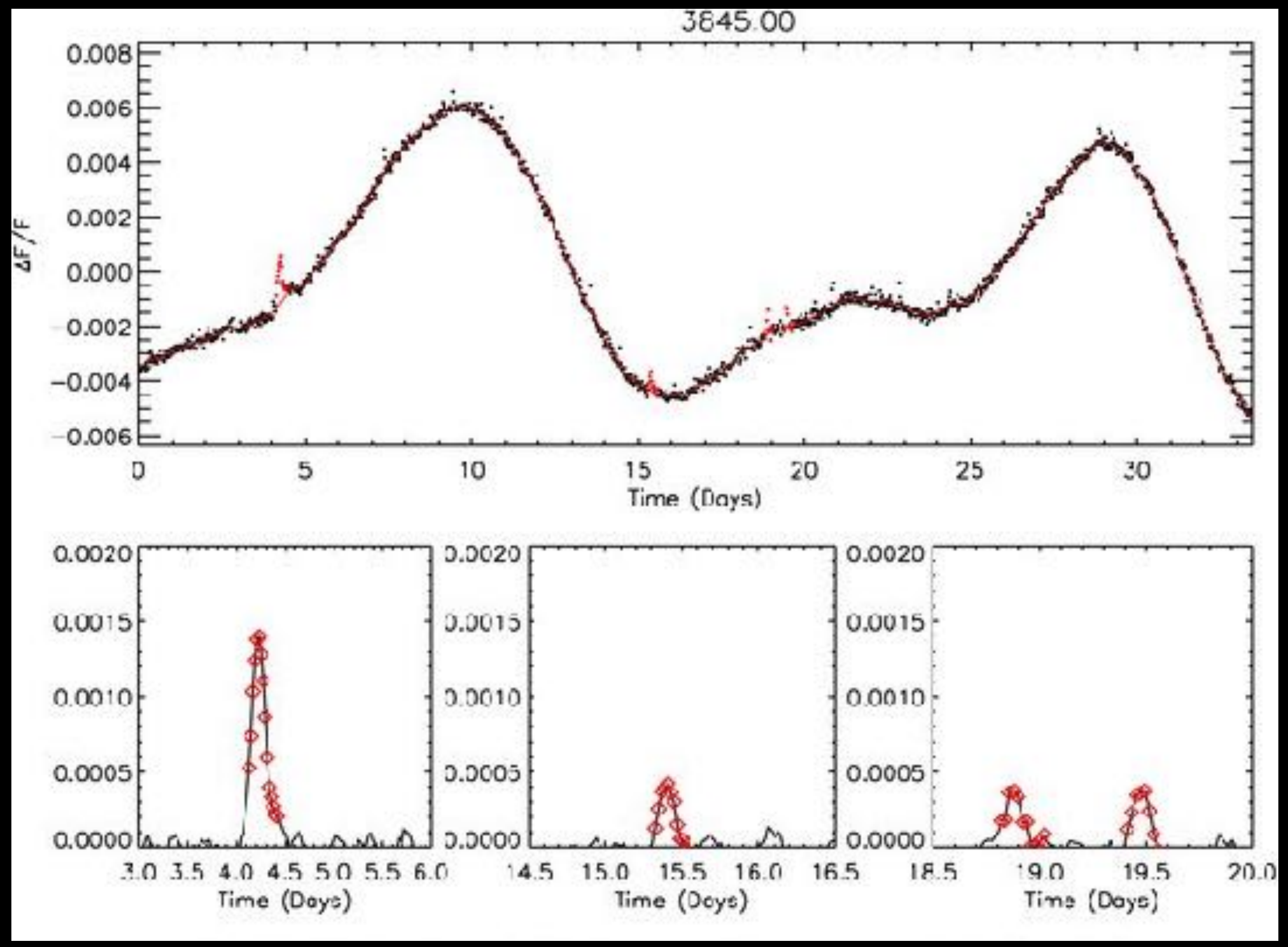
The Sun is no longer an isolated astrophysical object but serves the role of representing the basic element of comparison to a large class of objects. The book reviews these phenomena as exhaustively as possible and a generalization is constantly attempted. When necessary, as for instance in the case of solar flares, the problems are also studied from the basic physics point of view.

# Then as now: differences in studying the Sun and stars

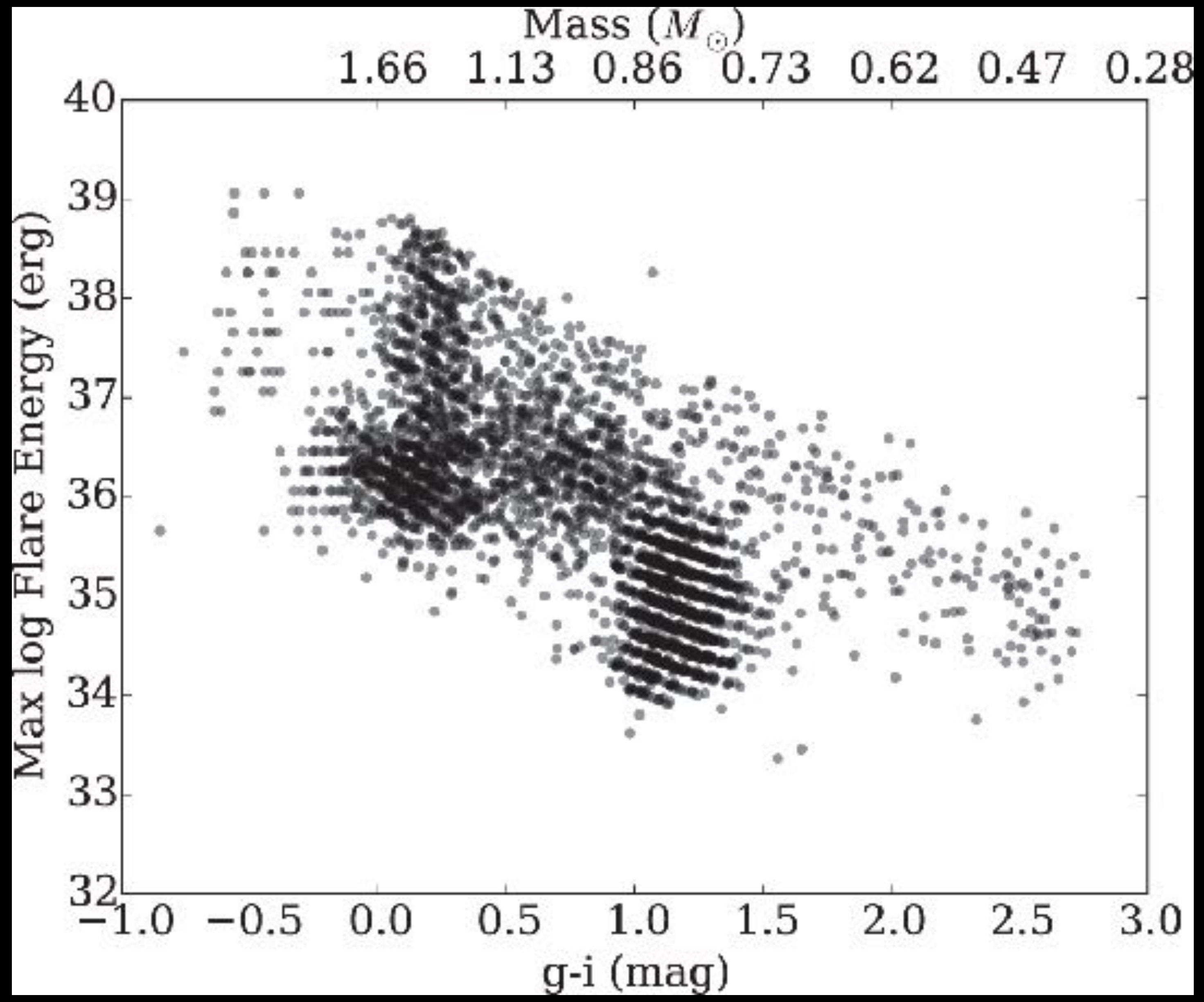



SDO
RHESSI
STEREO
IRIS
JVLA
ALMA

Walkowicz et al. (2011)



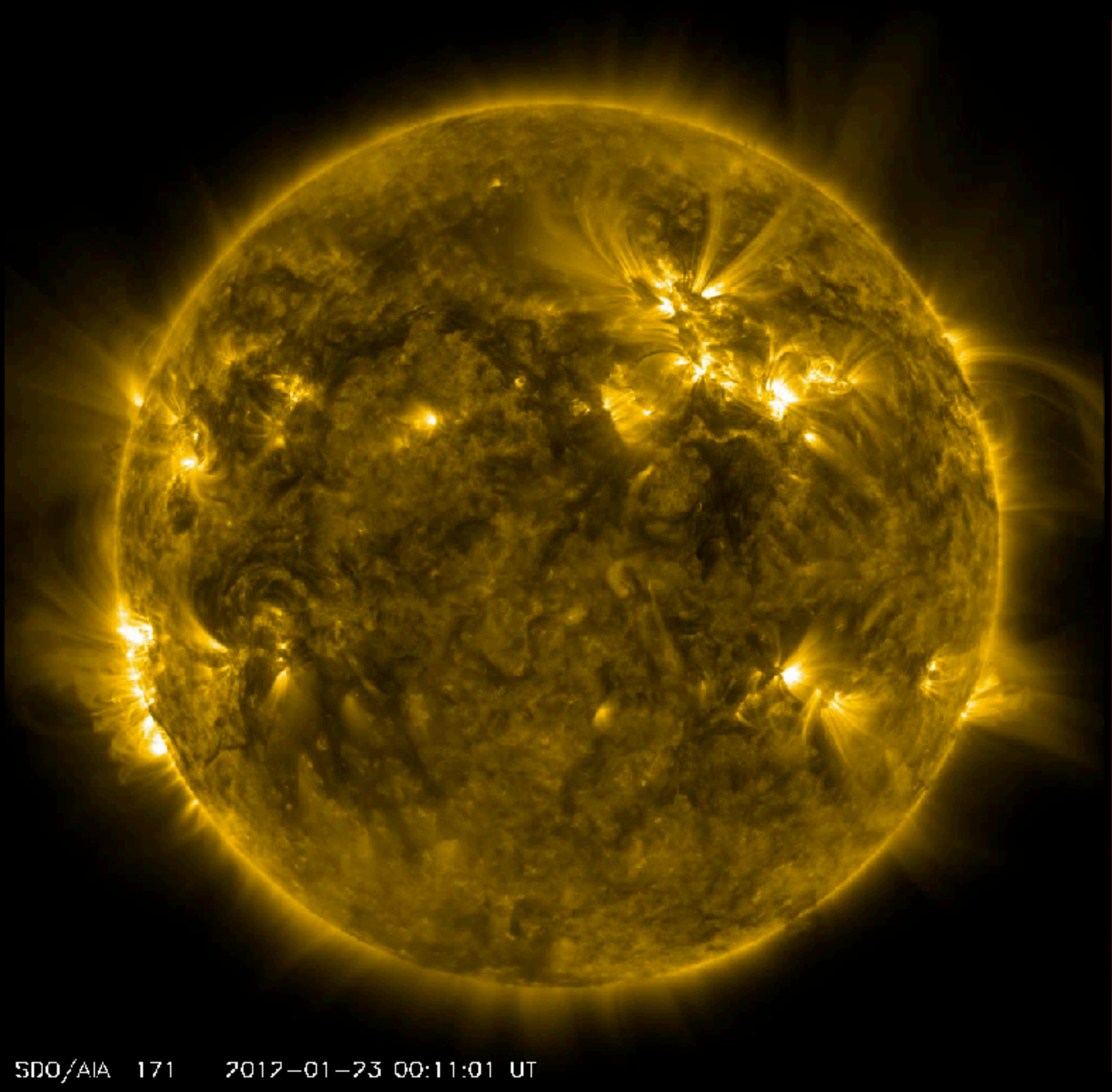

Davenport (2016)

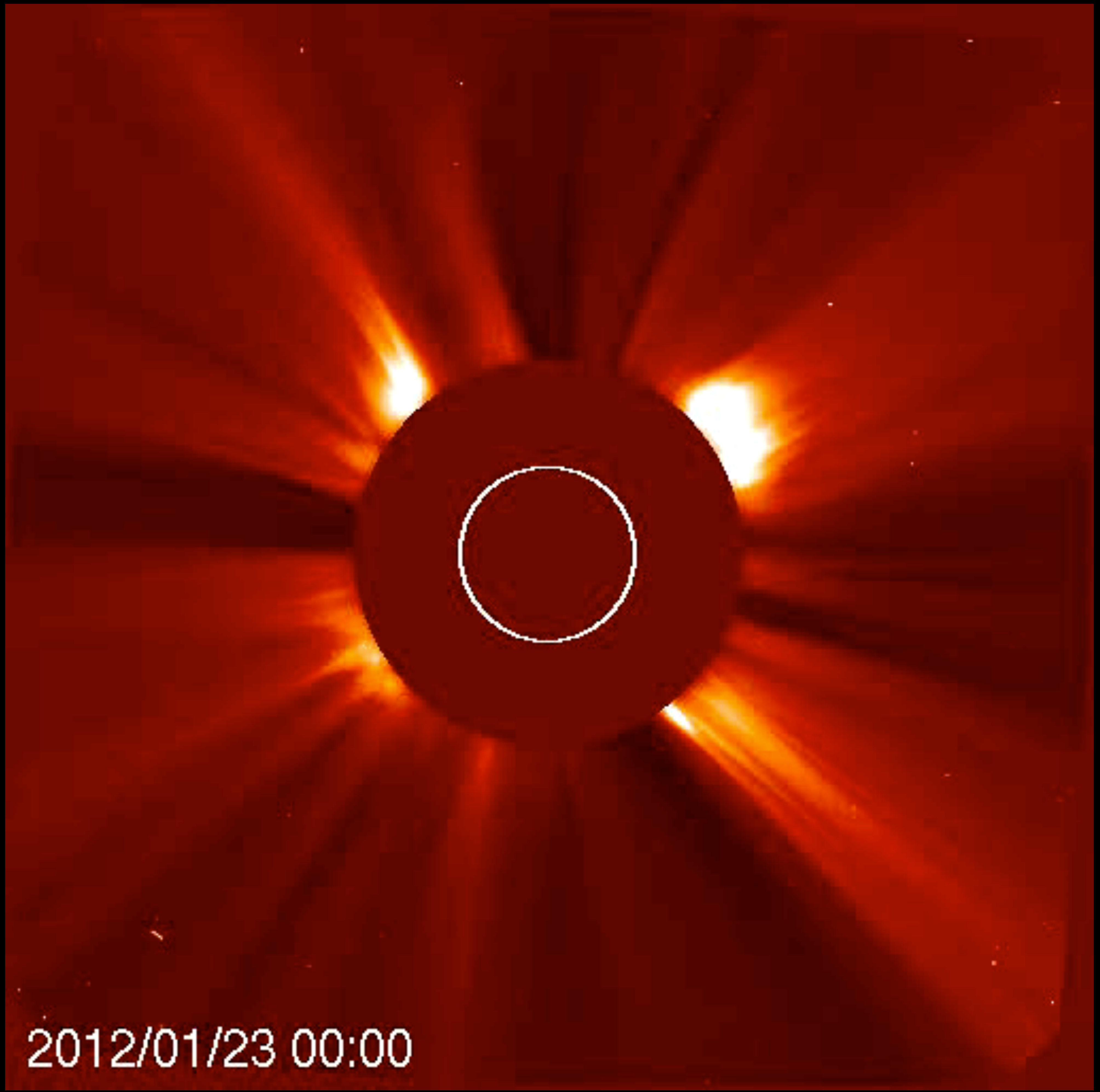



Kepler/K2
Chandra, XMM
HST:STIS and COS
Spitzer
JVLA
ALMA

850,000 flare events on 4000+ stars!

# Solar eruptive events come in three parts



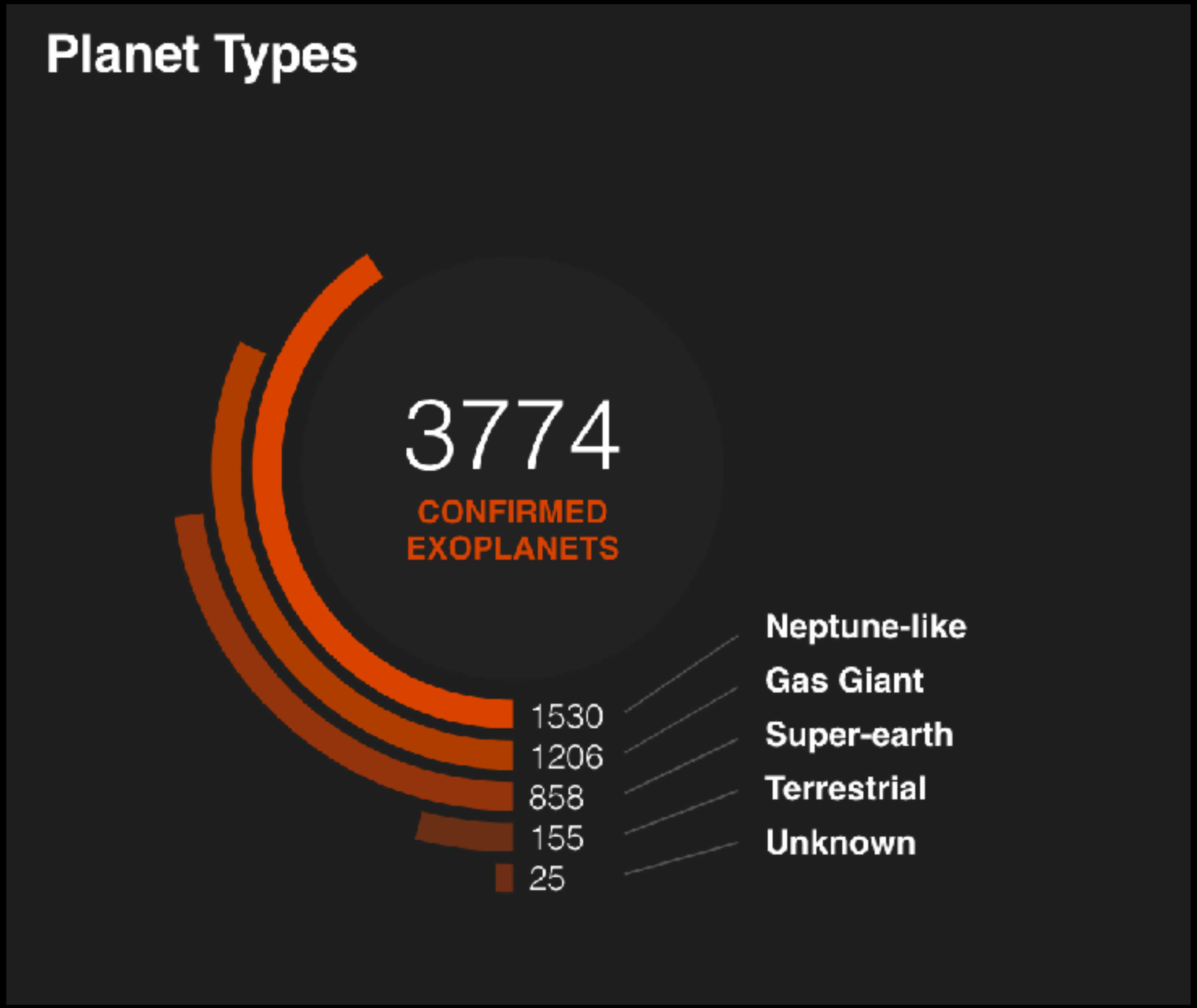




**solar flare**

**solar coronal mass ejection**

**solar energetic particles**

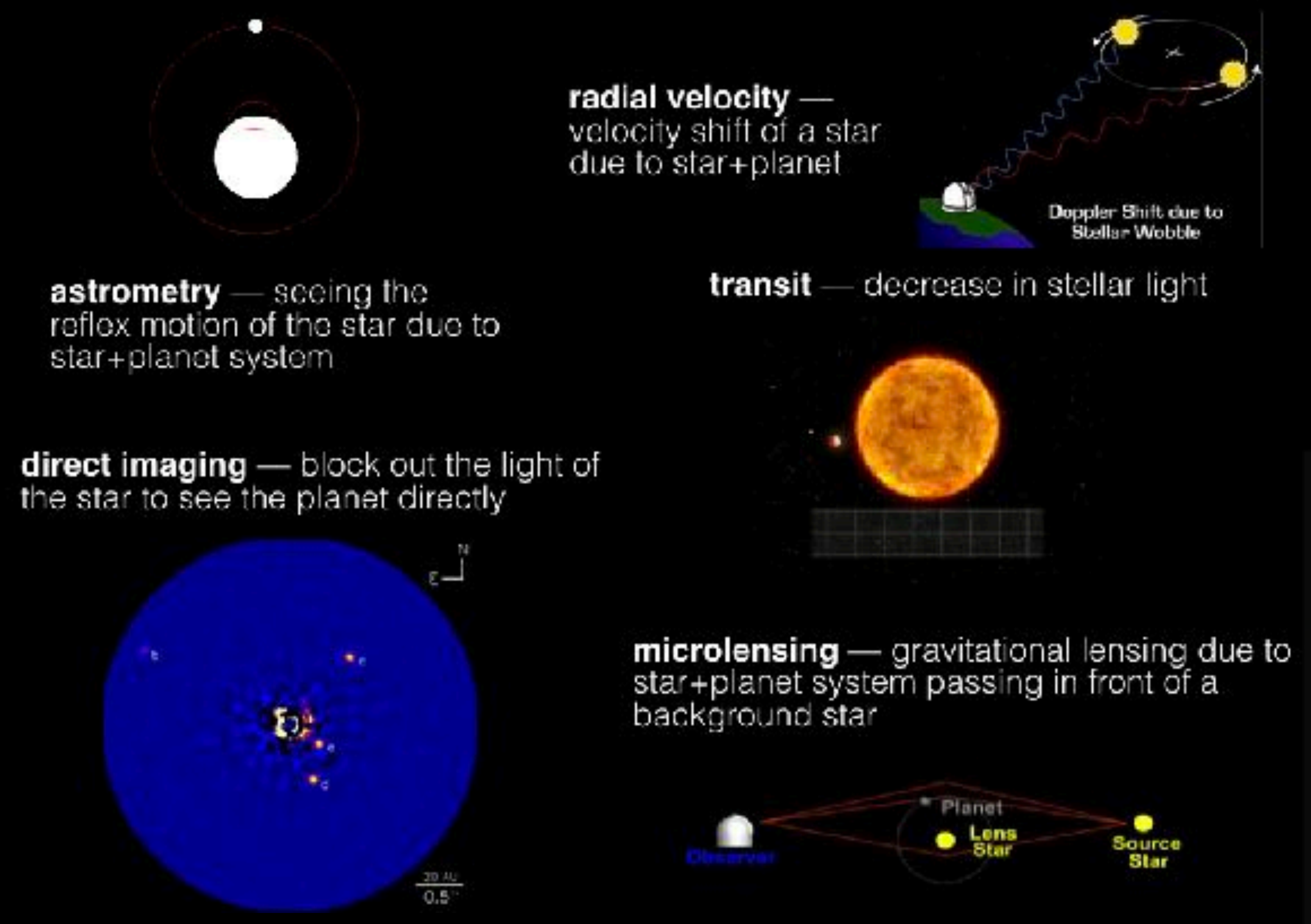
# The age of exoplanets




from exoplanets.nasa.gov

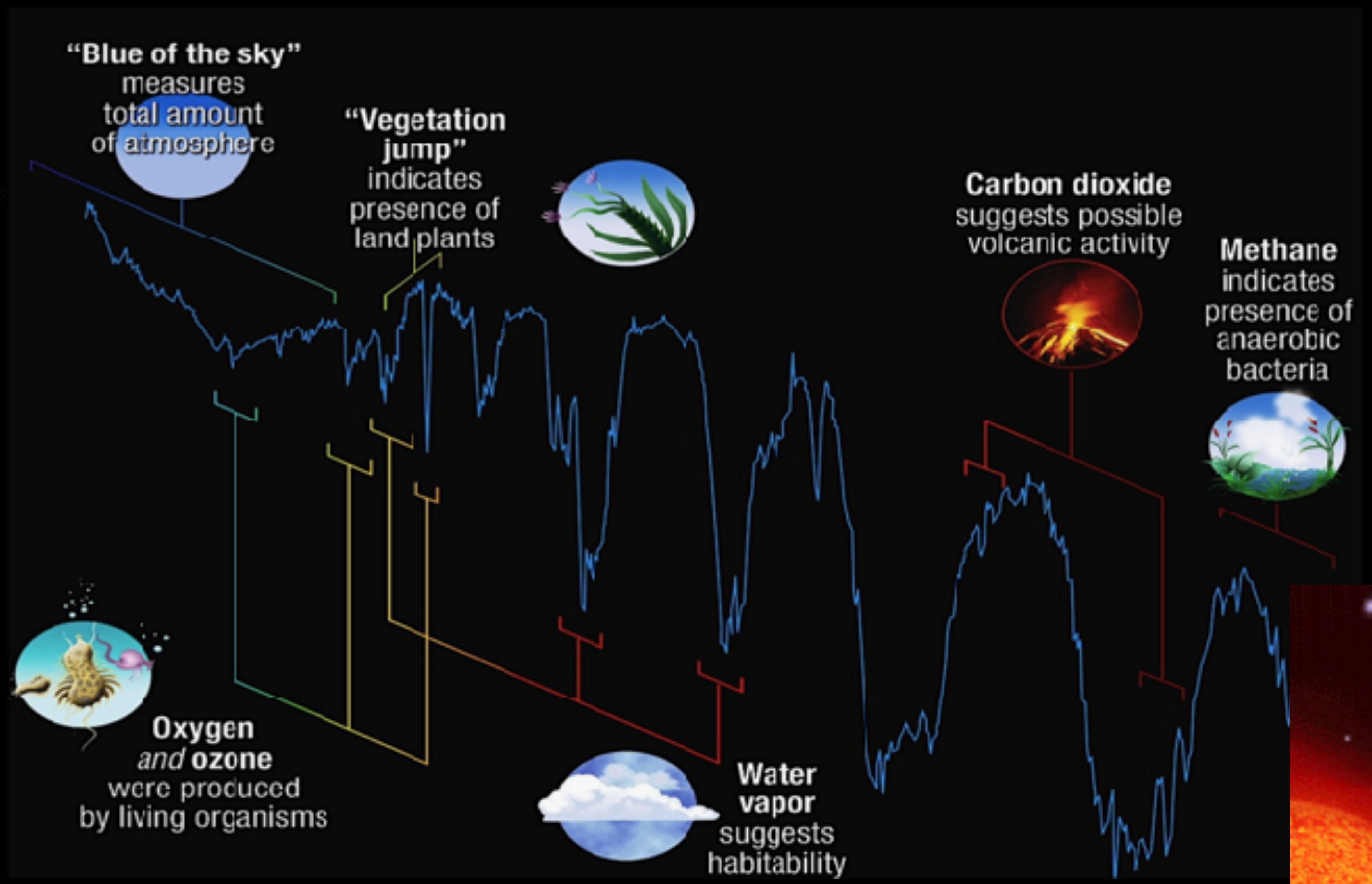
illustration credit: NASA Goddard Space Flight Center

# Intersection of stellar astronomy and exoplanet science

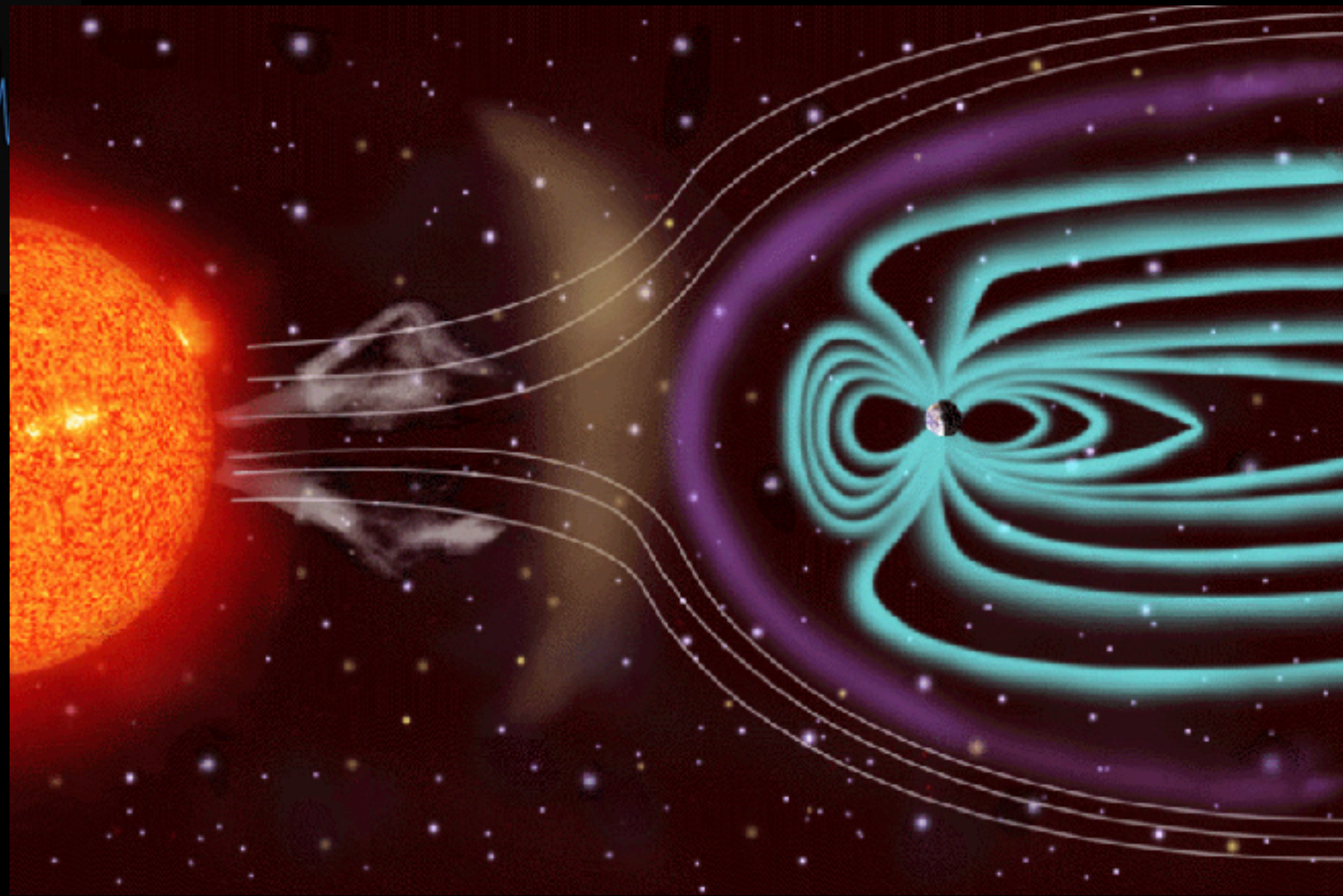



**Find the exoplanets**

**Characterize them**




**Understand their environment**



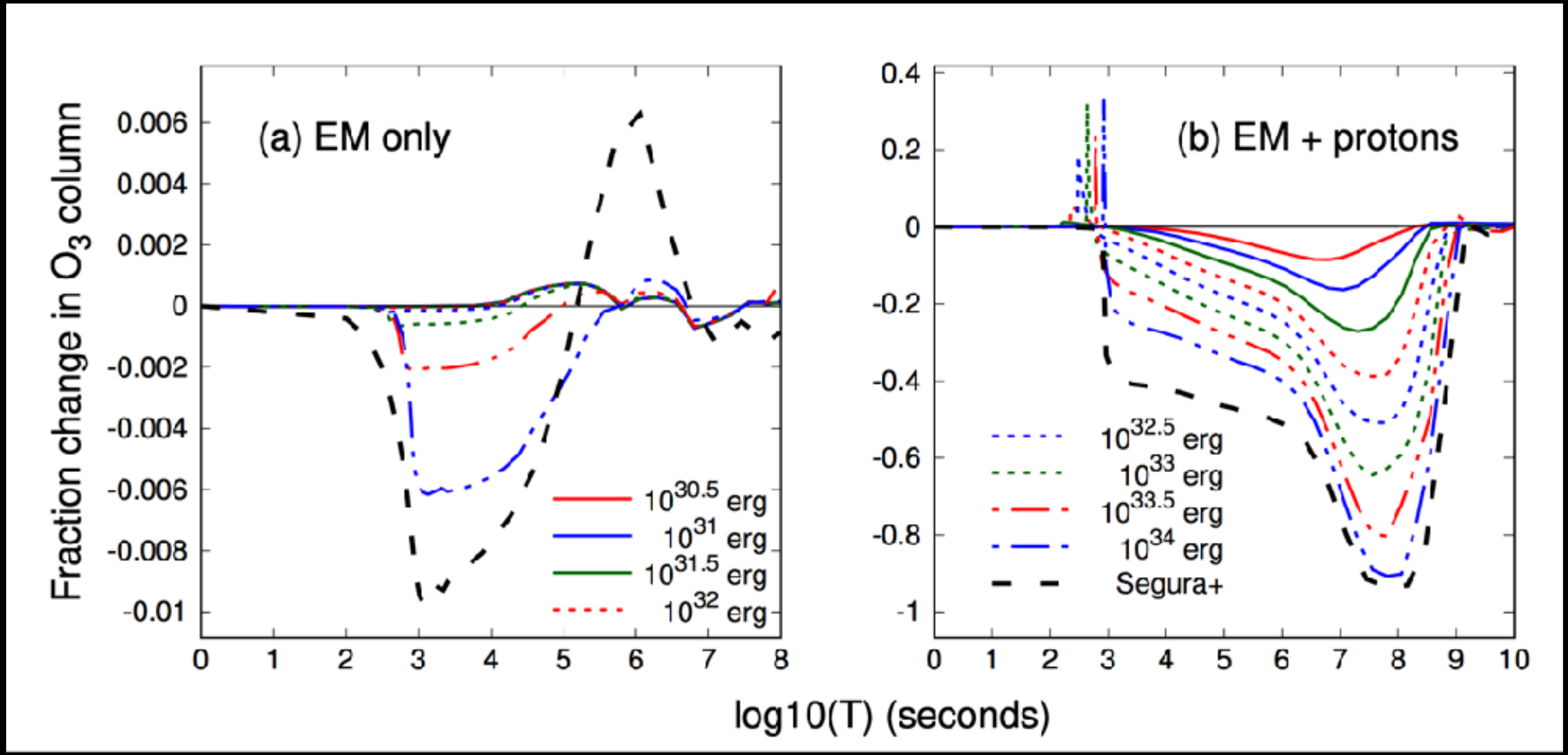
**Understanding stars is an essential component of making progress in answering the question "Are we alone?"**

# Exo-space weather & exoplanet habitability depend on stellar magnetic fields and eruptive events

**Jakosky et al. (2015)**
**impact of an interplanetary coronal mass ejection on Mars**

- ★ The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (e.g. Lingam & Loeb 2018)
- ★ Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017)
- ★ Coronal mass ejections and proton events have the biggest impact in determining the effect of reconnection events on planetary atmospheres, but require scaling from the Sun

# Exo-space weather & exoplanet habitability depend on stellar magnetic fields and eruptive events




Tilley et al. (2017)

★ The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (e.g. Lingam & Loeb 2018)

★ Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017)

★ Coronal mass ejections and proton events have the biggest impact in determining the effect of reconnection events on planetary atmospheres, but require scaling from the Sun

# Observing flares on stars is easy

| Observational Signature | Sun | Stars |
|---|---|---|
| Coherent radio emission, m-dm-cm wavelengths | ✔ | ✔ |
| Radio gyrosynchrotron/synchrotron, dm-cm-mm wavelengths | ✔ | ✔ |
| Optical/UV continuum (chromosphere) | ✔ | ✔ |
| Optical emission lines (chromosphere) | ✔ | ✔ |
| FUV emission lines (transition region) | ✔ | ✔ |
| EUV/soft X-ray emission (corona) | ✔ | ✔ |
| Non thermal hard X-ray emission | ✔ | ? |



**Osten 2016**

# Observing CMEs on stars is hard

| Observational Signature | Sun | Stars |
|---|---|---|
| Thompson scattering via coronagraph | ✔ | ✘ |
| Type II burst | ✔ | ? |
| Non thermal emission from CMEs | ✔ | ? |
| Scintillation of point radio sources | ✔ | |
| Mass-loss coronal dimming during a flare ← James Paul Mason's talk | ✔ | |
| High velocity outflows in emission lines during a flare ← Constanza Argiroffi's talk | ✔ | ? |
| Pre-flare "dips" | ✔ | ? |
| Absorption dimming: increase in $N_H$ during flare ← Sophia Moschou's poster | | ? |
| Effect of CMEs on stellar environment | ✔ | ? |
| Association with stellar flares | ✔ | ? |



Osten & Wolk (2017)

# Extending the solar-stellar connection to flares and CMEs

max energy ~$10^{32}$ erg

Solar flares ⟷ Solar CMEs

masses $10^{16}$-$10^{17}$ g
max energy~$10^{33}$ erg

first detected 1859

routine detections 1971

?

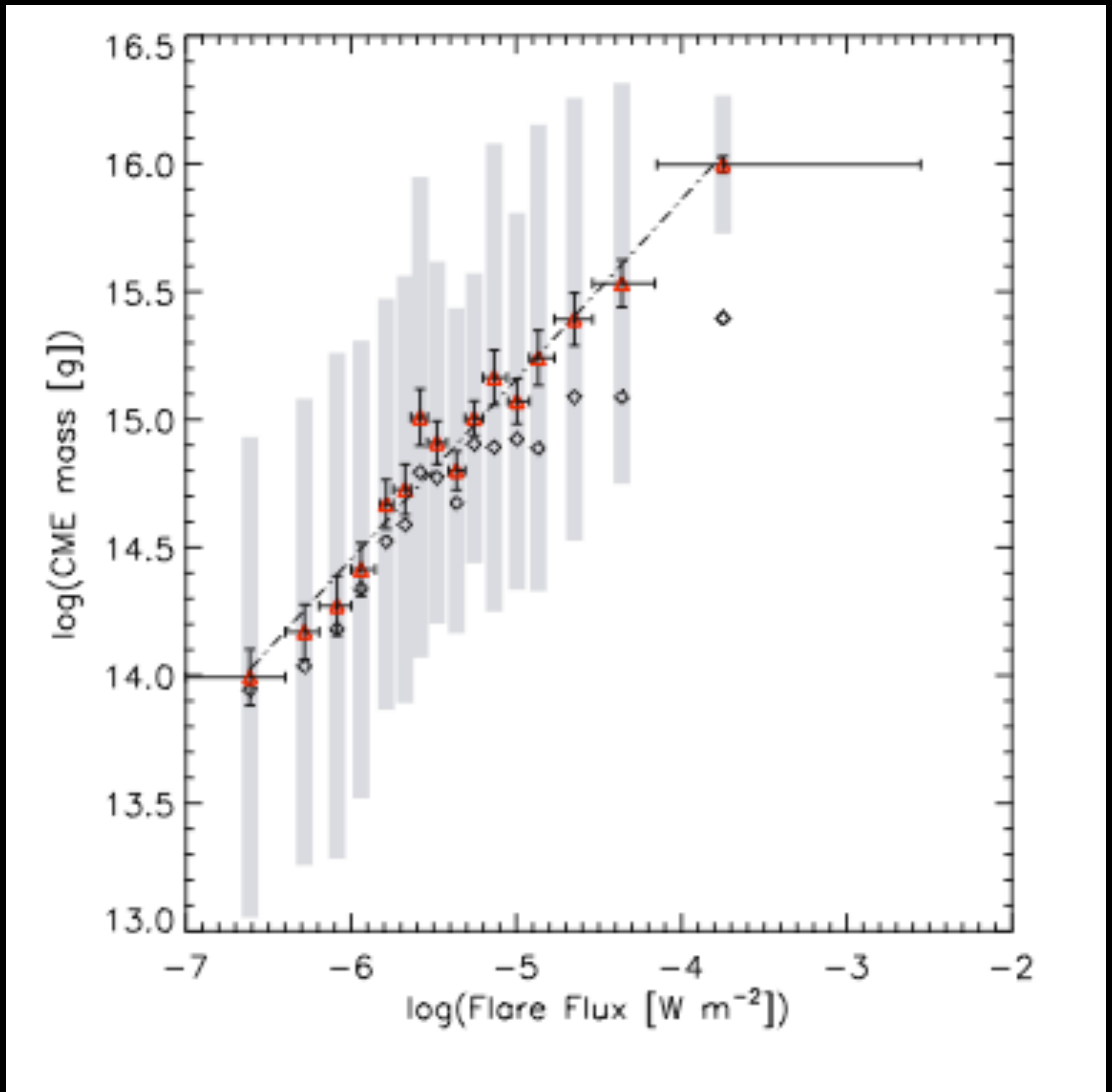
max energy >$10^{36}$ erg

Stellar flares ? Stellar CMEs

first detected 1924

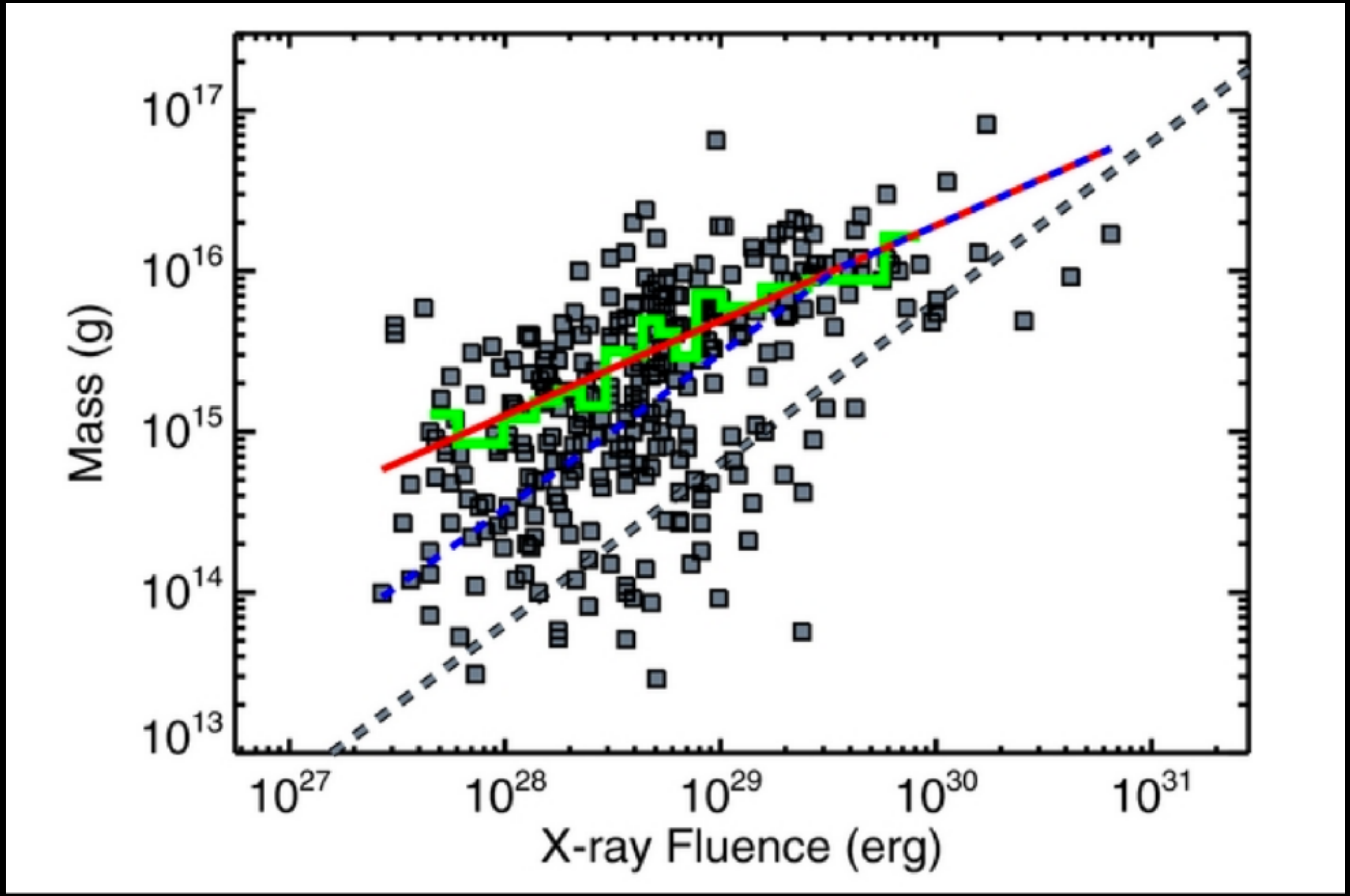
routine detections ?

# Empirical solar CME mass-flare energy scalings




Aarnio et al. (2011, 2012)

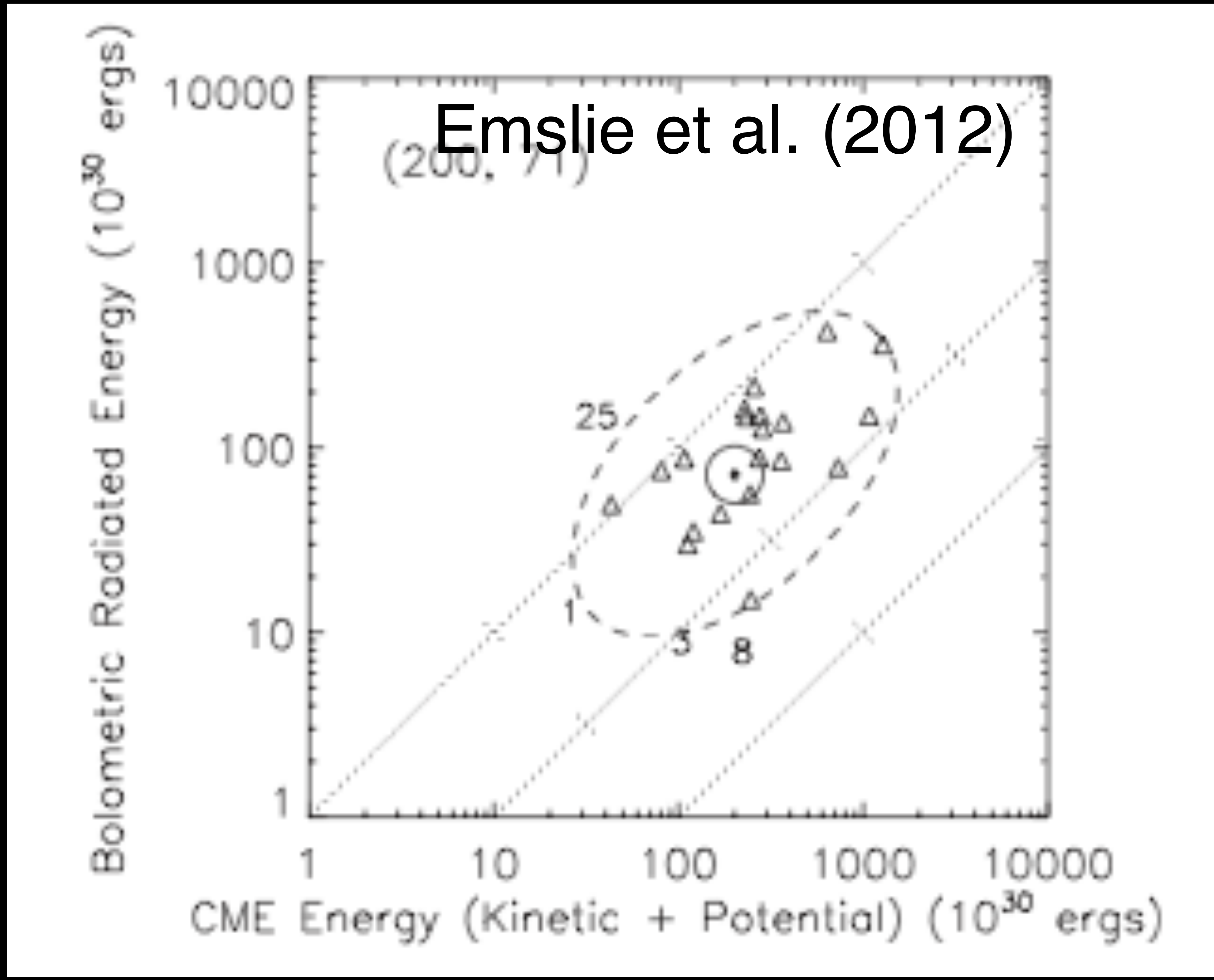
See her poster for more data!

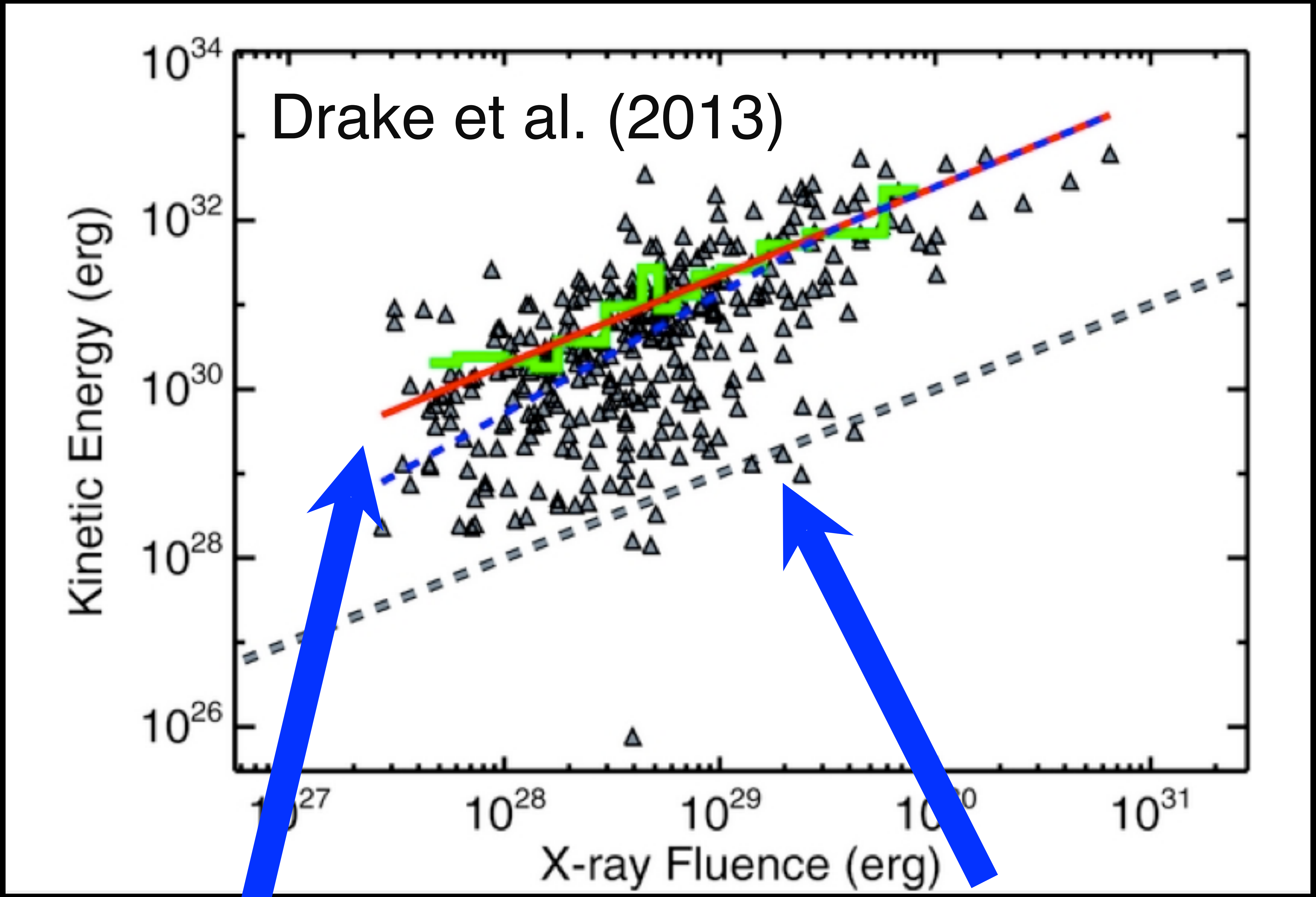



Drake et al. (2013)

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

# Solar CME energy - flare energy scalings reveal rough equipartition




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

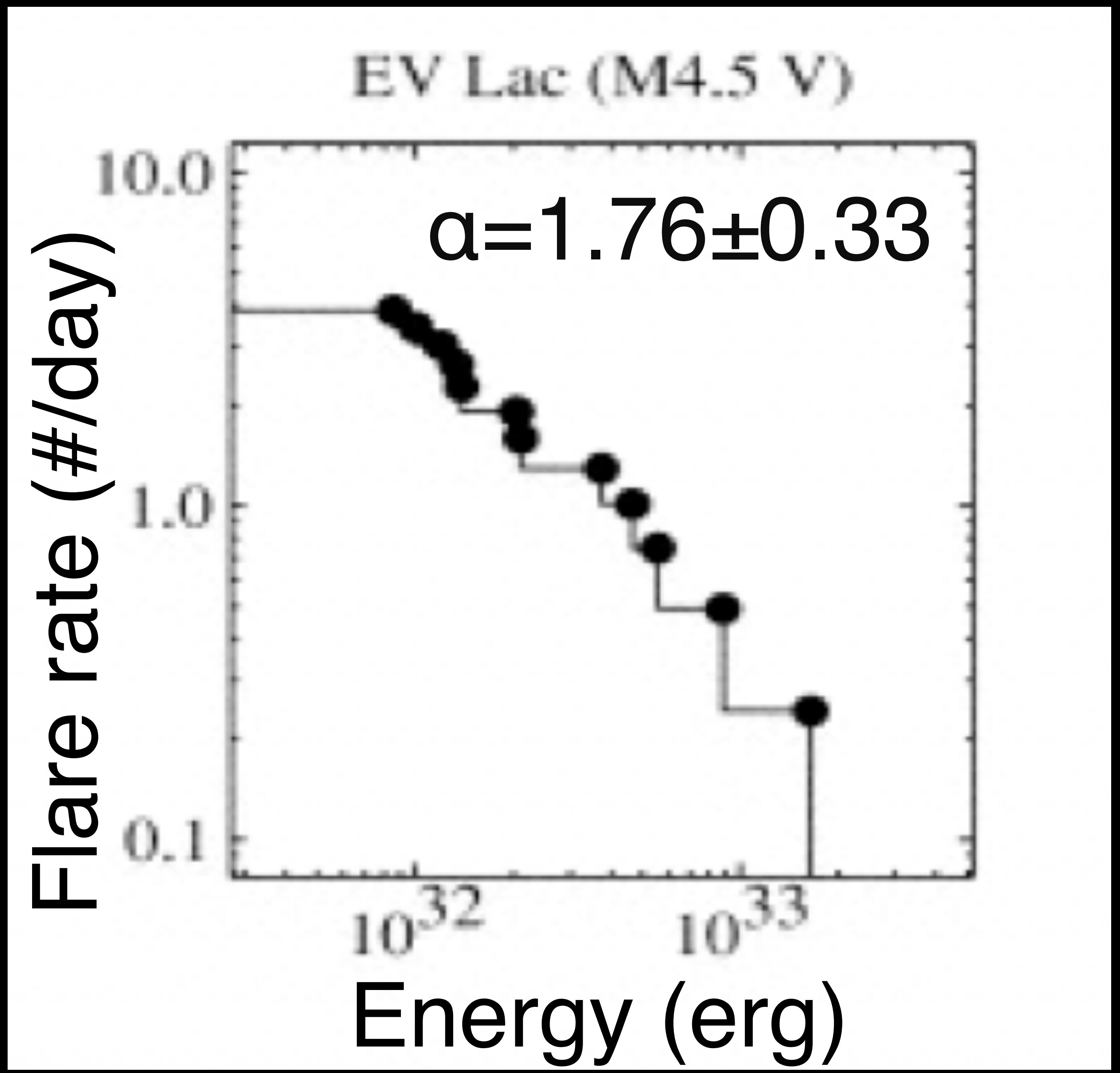
line of equality between X-ray flare energy and CME KE

With $E_{GOES}/E_{bol}$~0.01, CME KE ~2 $E_{bol}$

# Solar-Stellar Flare-CME Connection

Osten & Wolk (2015)

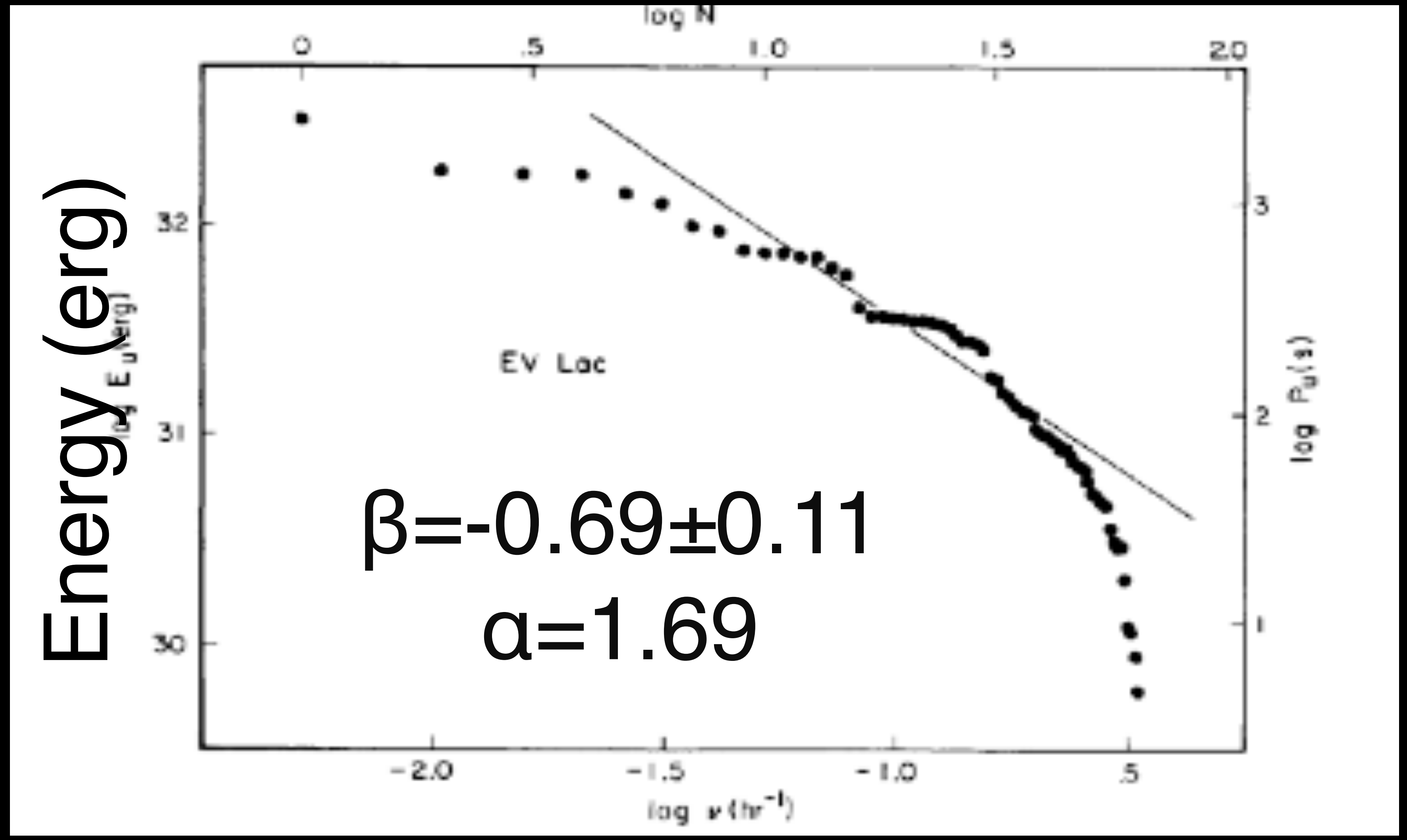
- Assume equipartition between CME kinetic energy, flare energy
- Relate the observed flare frequency distributions to an inferred rate of mass loss associated with the flares
- Apply to any wavelength range where the fraction of total bolometric flare energy in that bandpass can be estimated




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

Implies $\dot{M}$ of ~$10^{-11}$ $M_{\odot}$ $yr^{-1}$

Inconsistent with weak wind ($<2 \times 10^{-14}$ $M_{\odot}$ $yr^{-1}$) from Wood et al. (2014)




Flare rate (#/hr)

# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

10-190 MHz


240-480 MHz

- A new generation of low frequency radio telescopes (LOFAR, JVLA, MWA) combines increased sensitivity and frequency coverage
- Type II bursts originate from CMEs, not flares, and so hold promise for being a tool to explore systematic behavior of stellar CMEs.
- Flare-associated transient mass loss implies large $\dot{M}$ (Aarnio et al. 2012, Drake et al. 2013, Osten & Wolk 2015): what will we find?

# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

What We Expect

Flare

↓

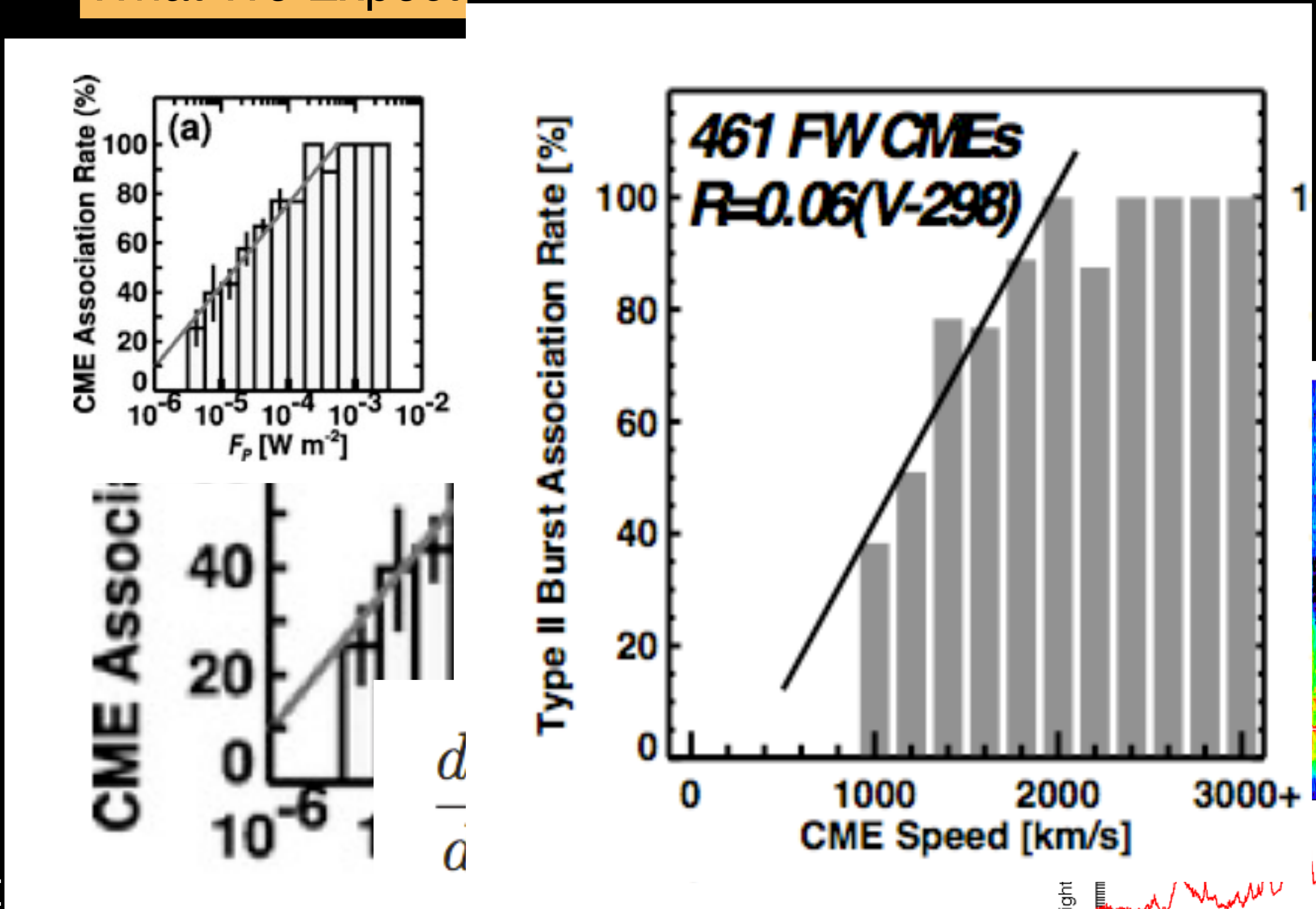
CME

↓

$v > v_A$

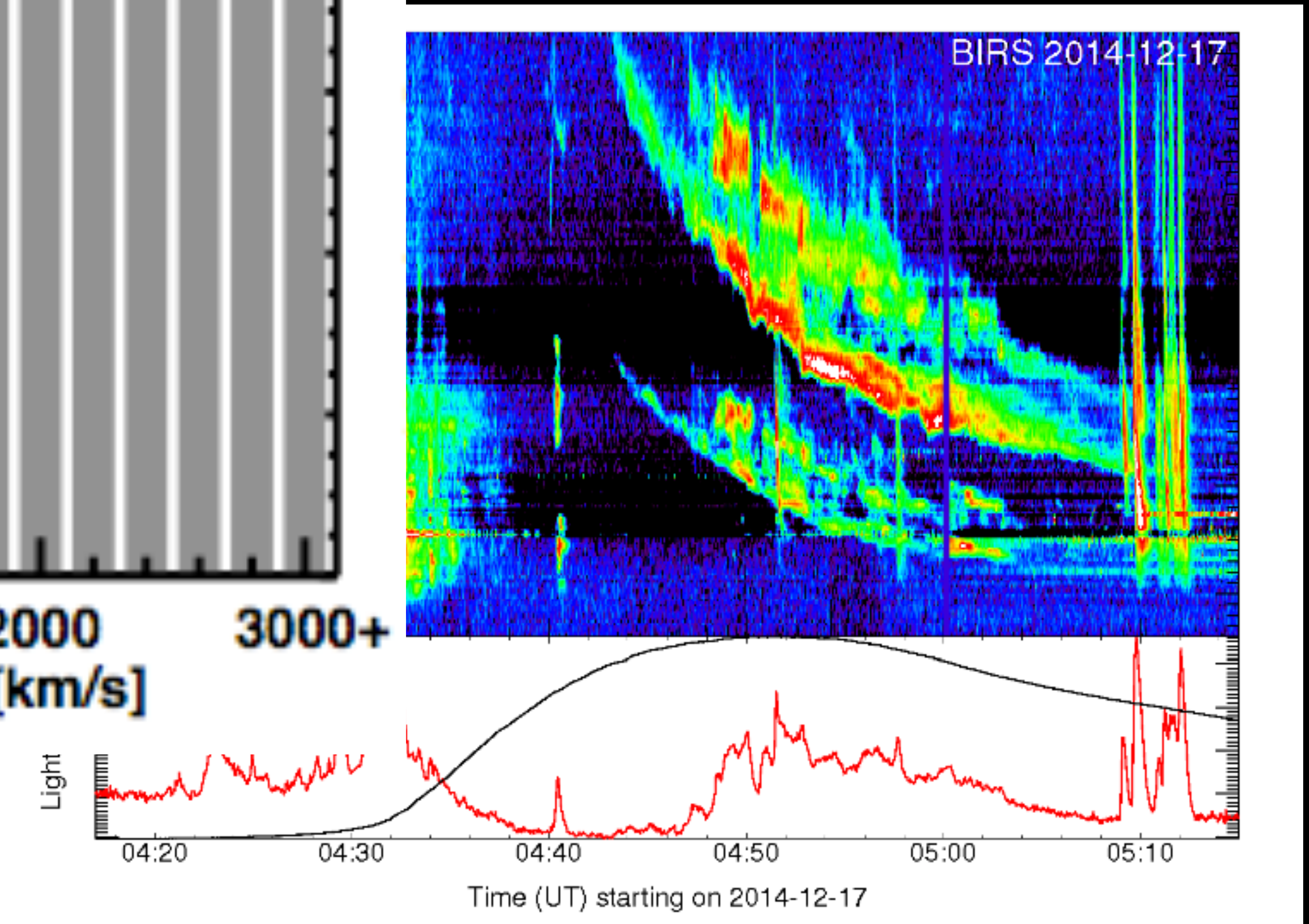
↓

Type II burst




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

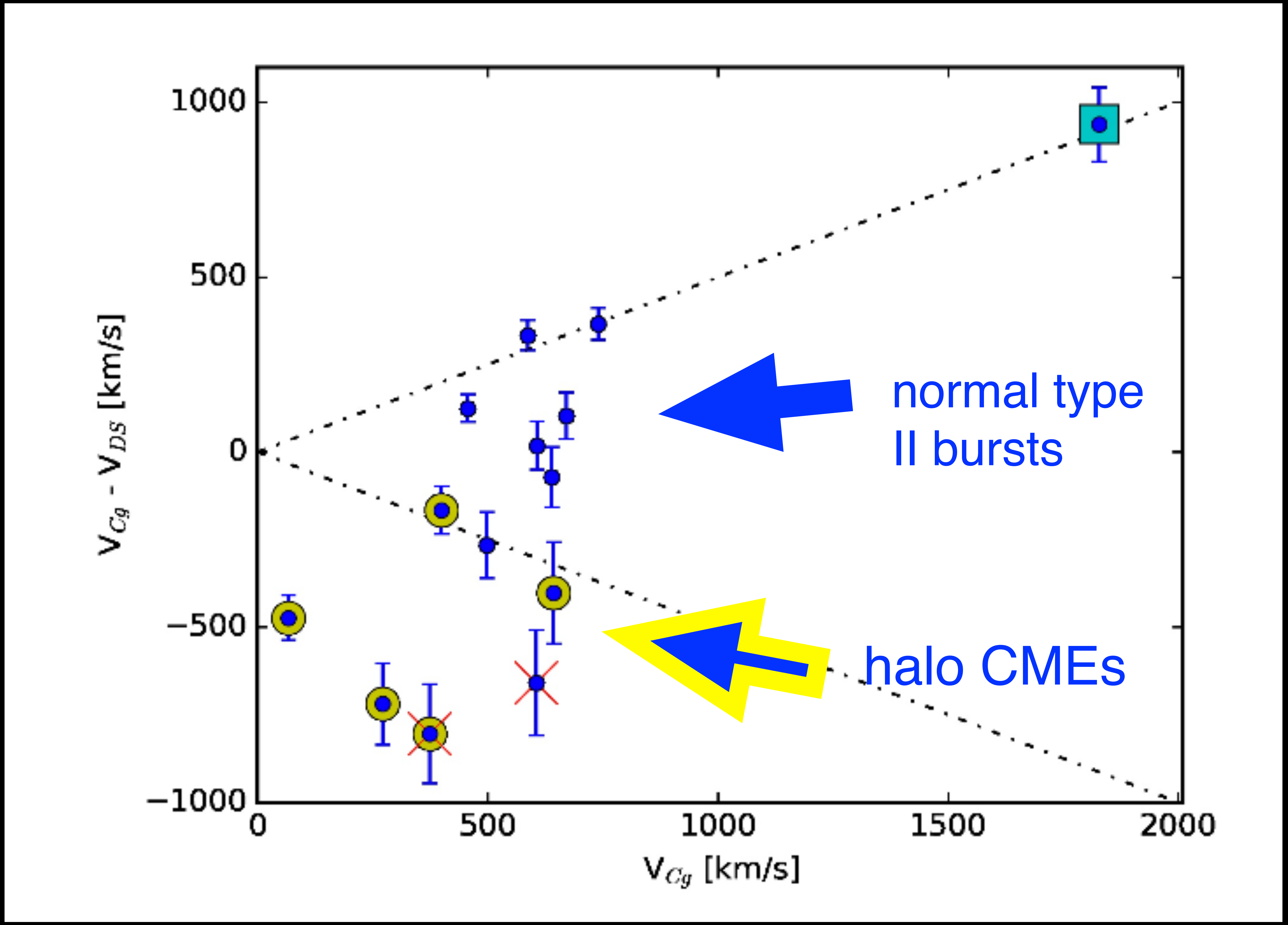
Gopalswamy et al. (2008)



# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

| Requirements | YZ CMi | EQ Peg |
|---|---|---|
| Star w/high flaring rate for close association with CMEs | 0.4 flares/hour | ~1.2 flares/hour |
| Nearby, for sensitivity | 5.9 pc | 6.2 pc |
| Constraints on coronal T, $n_e$ | ✔ | ✔ |
| Photospheric magnetic field measurements | ✔ | ✔ |
| Previous evidence of radio bursts | ✔ | ✔ |
| Searches for type II bursts | Crosley et al. (2016) | Crosley & Osten (2018ab) |

# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?




Crosley et al. (2017)

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

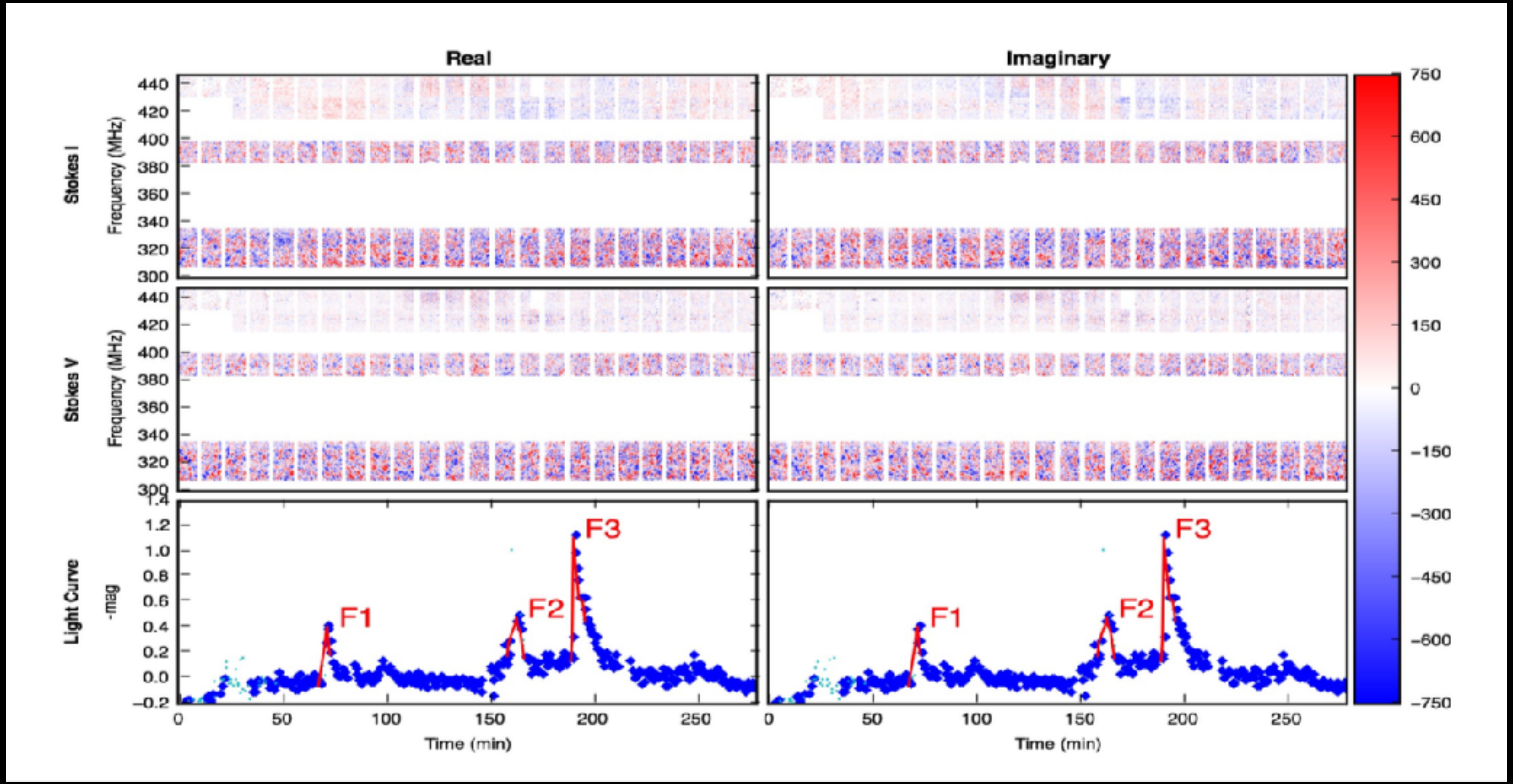
$$\frac{1}{2} M_{CME} v^2 = \frac{E_{rad}}{\epsilon f_{rad}}$$

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

Compare with coronagraphic measurements

CME velocities good to about 50%, masses to an order of magnitude, kinetic energies only ~3 orders of magnitude

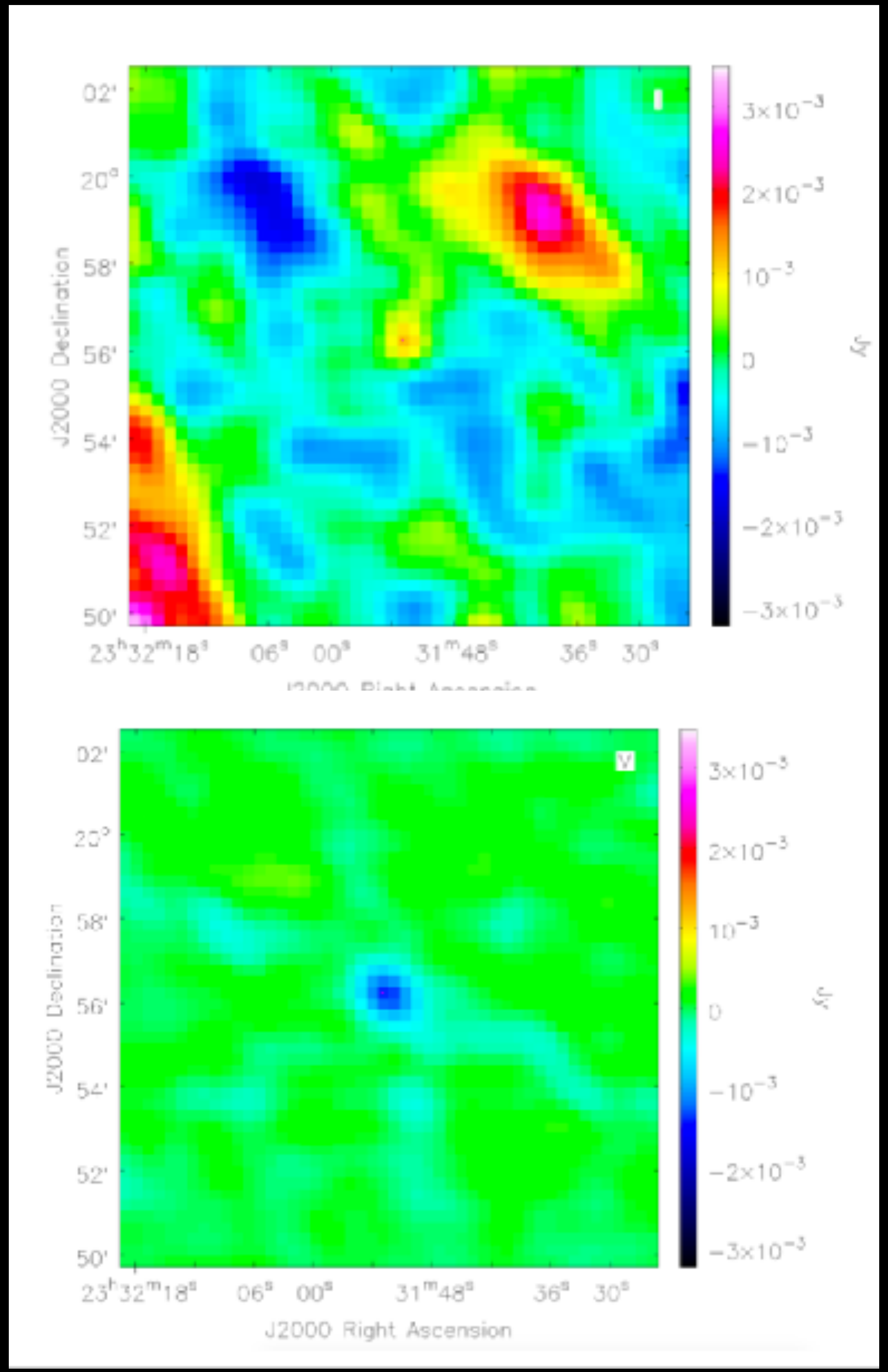
# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

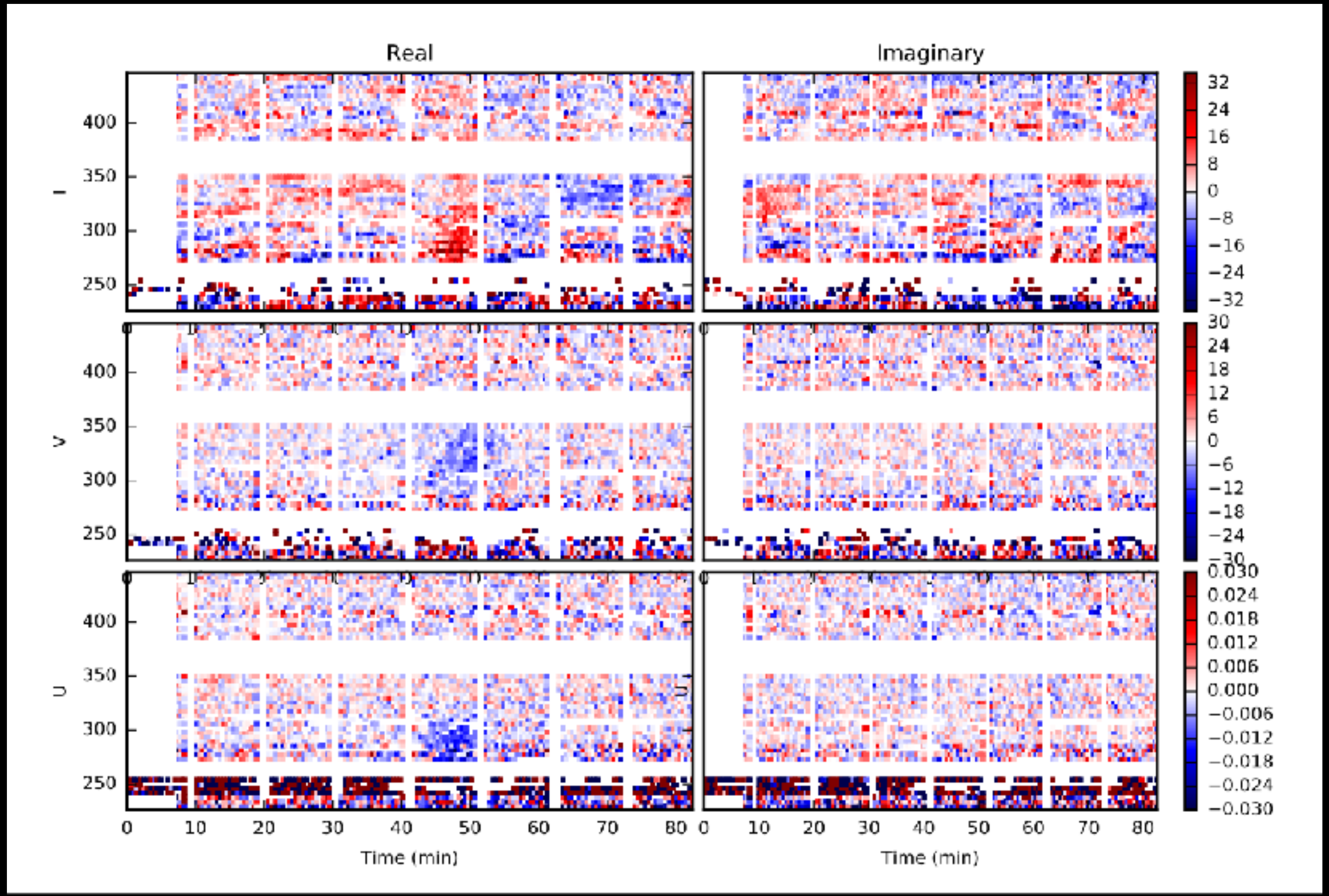



Crosley & Osten (2018a)

- JVLA, APO simultaneous measurements of EQ Peg
- 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 in the dynamic spectrum, period)

# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?




Crosley & Osten (2018b)

- 44 additional hours of JVLA only measurements
- Two low frequency radio bursts from EQ Peg!
- Features of the burst (bandwidth, drift rate, duration) not consistent with expectations for a type II burst

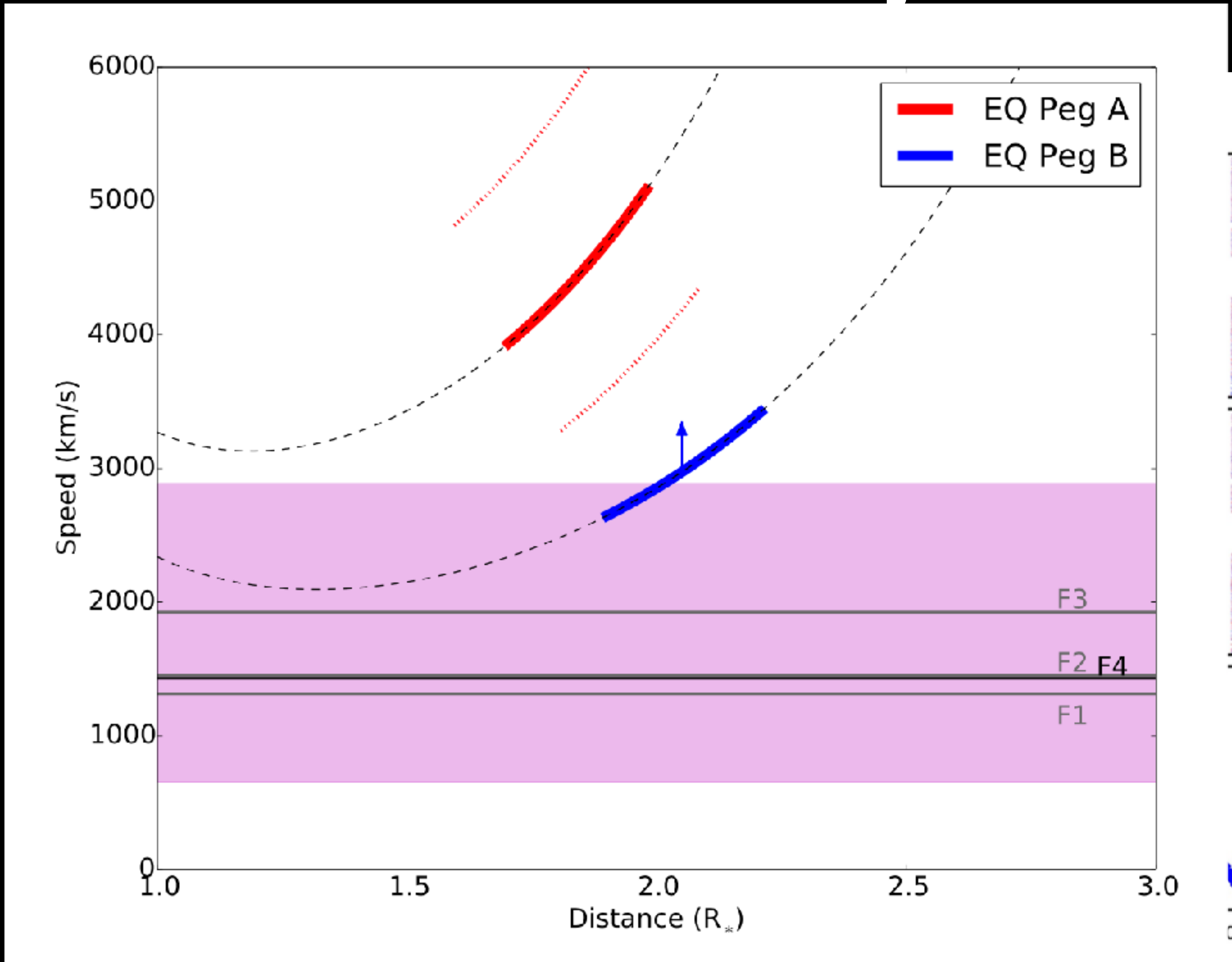
# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

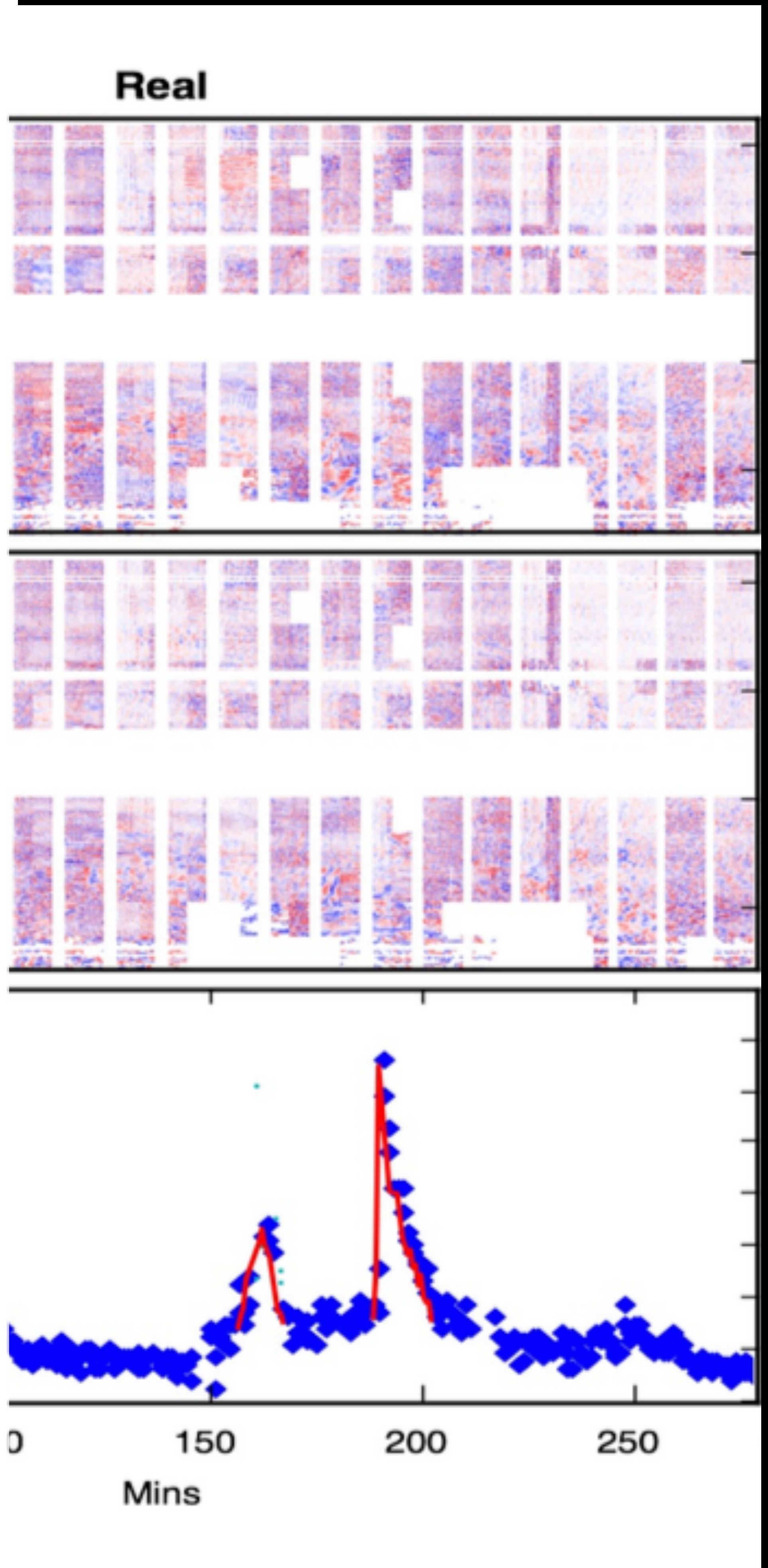
Flares but no CMEs?

is v>$v_A$?

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

no type II burst




What We See

Crosley & Osten (2018ab)

# Does a High Flaring Rate Give Rise to a High Rate of Coronal Mass Ejections?

Longest timescale search of one target for stellar type II bursts at low frequencies (Crosley & Osten 2018ab)

No type II bursts observed in 64 hours of monitoring of EQ Peg

-Expected 1.2 flares/hr above flare energy where all solar flares have an associated CME

-Using large-scale model corona, expect 1 flare every 27 hours to drive an observable shock

Additional 15 hours of LOFAR observations at lower frequencies with no detections (Crosley et al. 2016)

High-risk, high-reward science and the importance of null results

This work is #NSFfunded

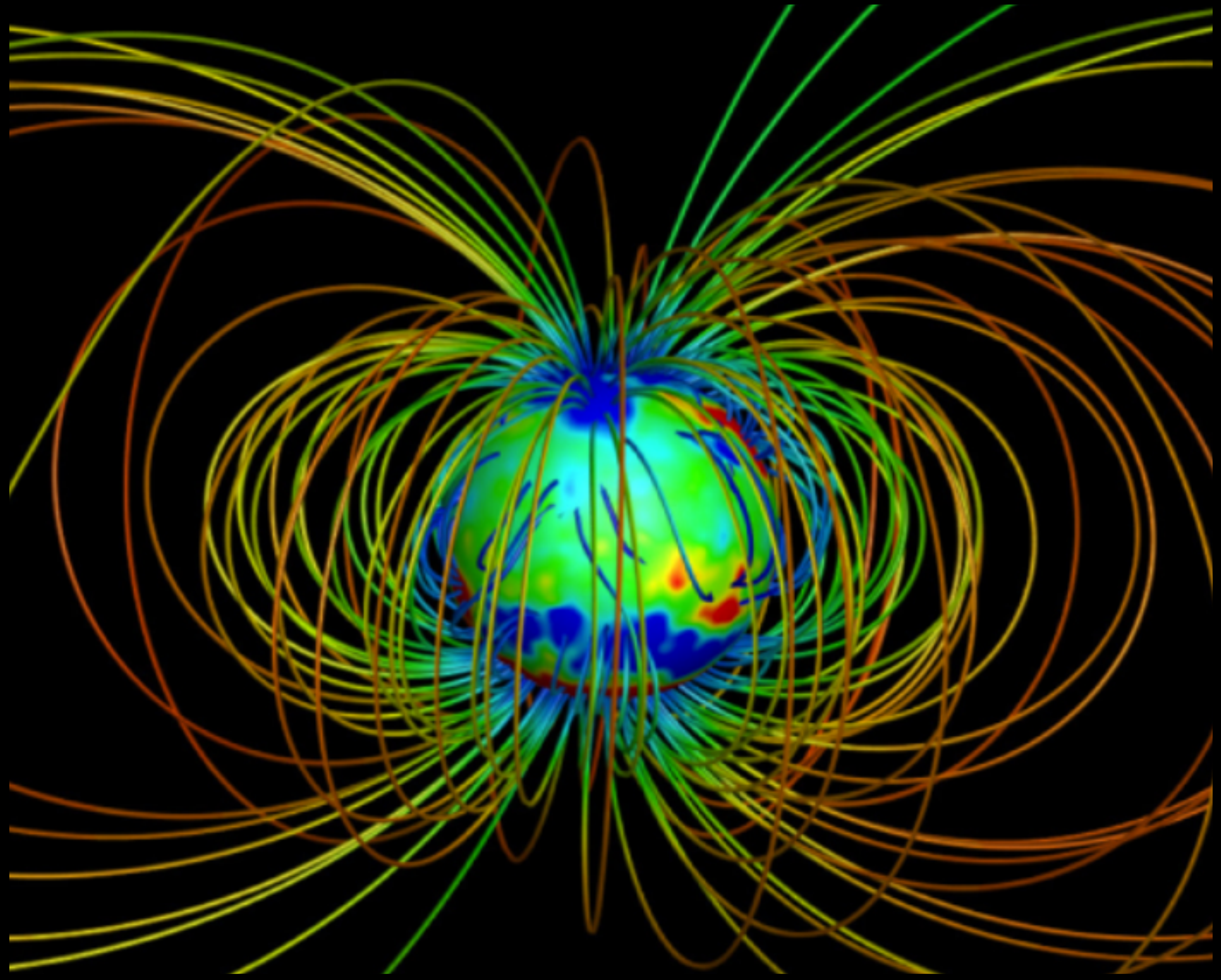
# Do stars produce eruptive events ?
# Can we observe the CMEs?

Active stars have large magnetic field strengths on their surfaces

Large overlying fields (above an active region) may prevent breakout or eruption; solar active region 12192 (fall 2014) produced many X-class flares but few CMEs (Sun et al. 2015)

Do the large scale fields seen on M dwarfs prevent breakout?

Supporting evidence for weak stellar winds, in only a handful of active stars (Wood et al. 2004)



Cohen et al. (2017)

→ Talks by Carolina Villarreal D'Angelo on prominence formation & eruption, J. D. Alvarado-Gómez on suppression of CMEs in active stars

# Future work on observational constraints

- Constraints on the nature of accelerated particles in stellar flares (see Adam Kowalski's poster), differences with solar events
- Look to other potential CME signatures: big data on 1000s of stellar flare observations? scintillation of background radio sources?
- Appeal to modelers to understand when/how breakout may occur

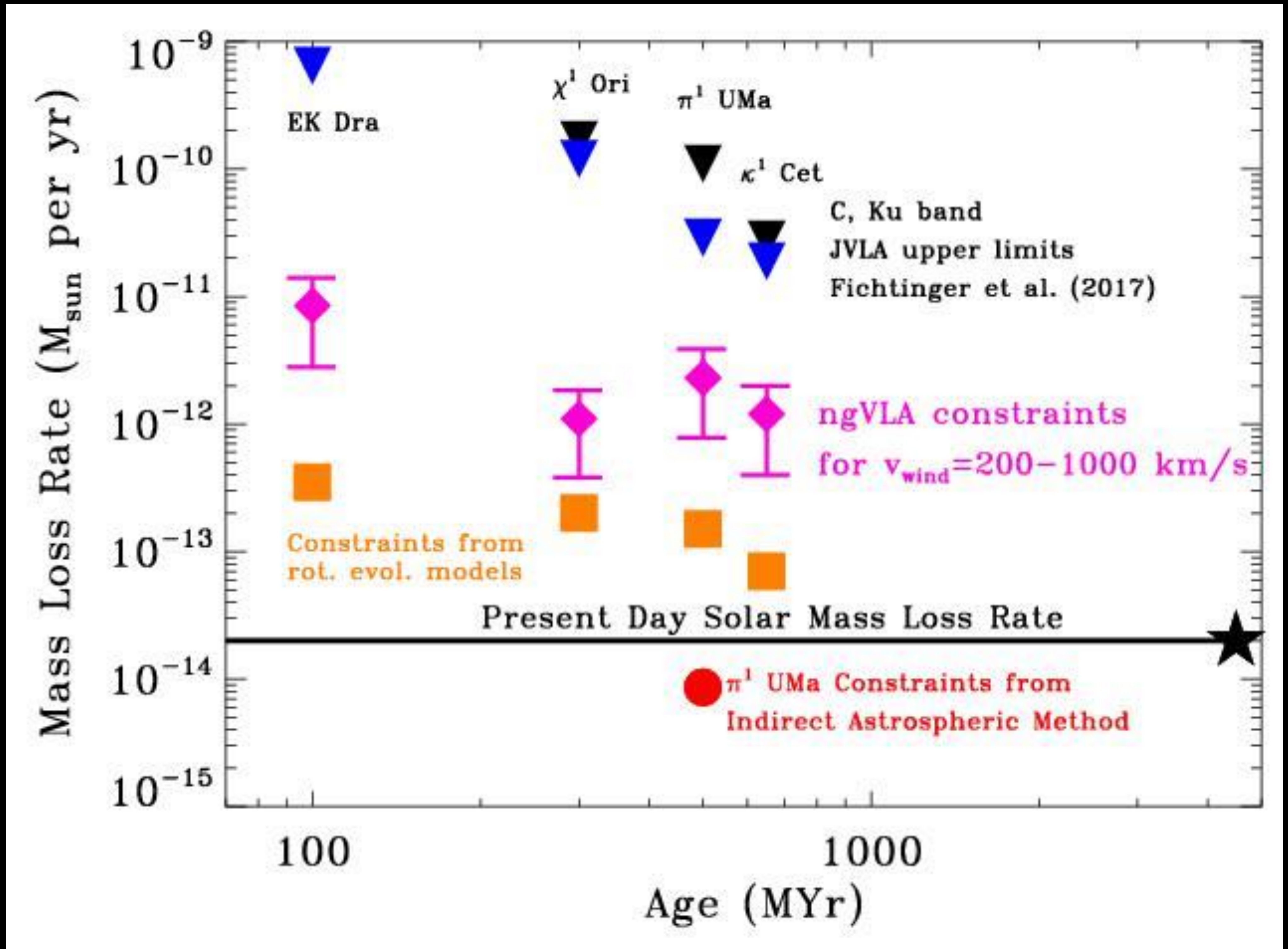
# Future science

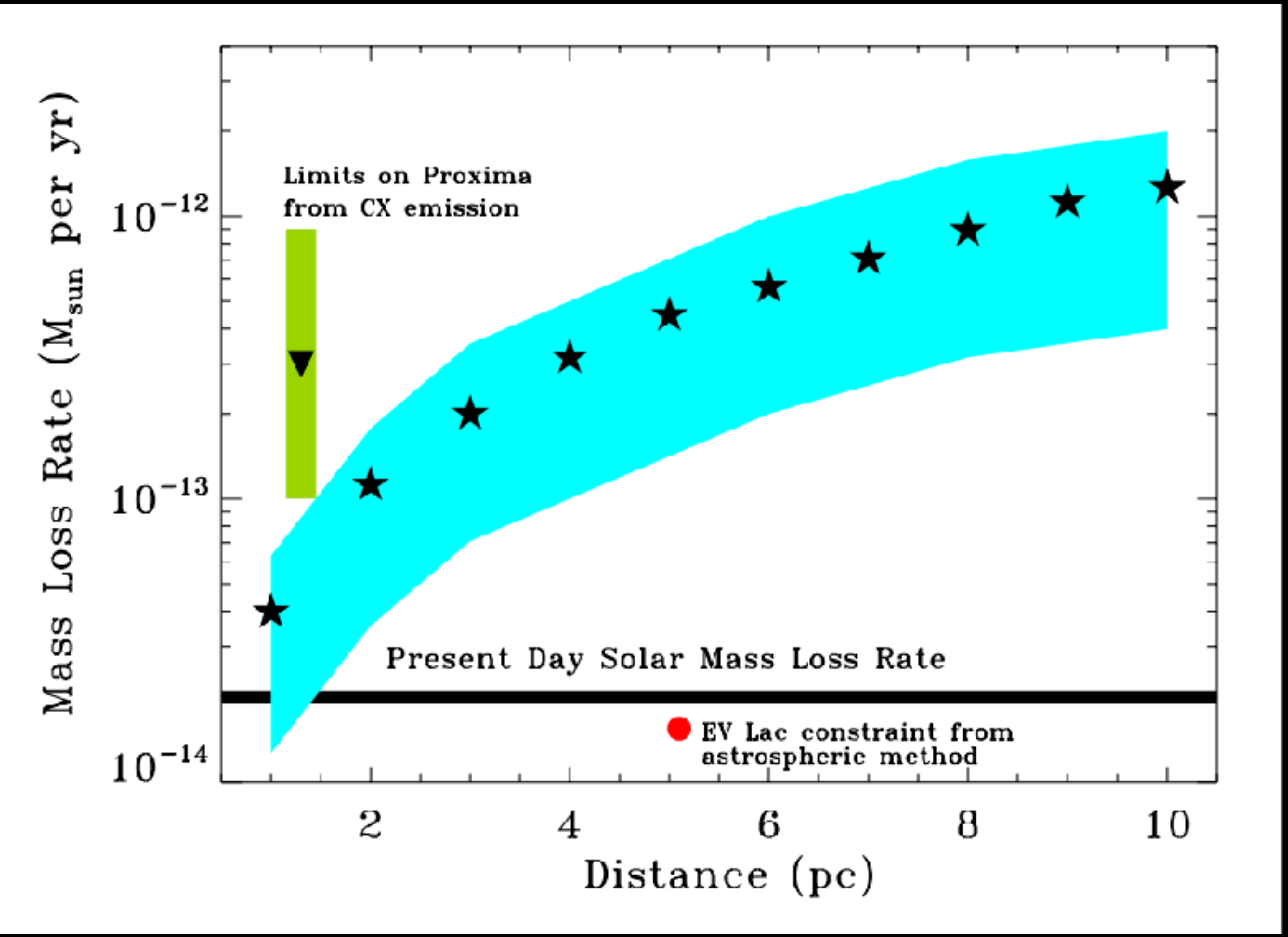
A Southwest Array, the next generation Very Large Array

- Scientific Frontier: Thermal imaging at milli-arcsecond scale resolution
- Core Design Requirements
  - ➢ *10x effective collecting area of JVLA and ALMA*
  - ➢ *10x resolution of JVLA and ALMA*
  - ➢ *Frequency range: 1.2 –116 GHz*
- Located in Southwest U.S. (NM+TX) & Mexico, building from JVLA site
- Baseline design remains under continuous development
- Low technical risk (reasonable step beyond current state of the art)

# Future science

A Southwest Array, the next generation Very Large Array




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



ngVLA Memo #31 the ngVLA and Exo-Space Weather

# Future science

The Lynx large X-ray mission concept under study by NASA for the next astrophysics decadal

*Lynx will provide unprecedented X-ray vision into the "Invisible" Universe with leaps in capability over Chandra and ATHENA:*

- 50–100× gain in sensitivity via high throughput with high angular resolution
- 16× field of view for arcsecond or better imaging
- 10–20× higher spectral resolution for point-like and extended sources

# The Space Weather Environment that Stars Create

- Depends on coronal mass ejections & energetic particles
- These are the least observationally constrained from a stellar perspective
- Scaling up from solar relations provides flare-associated mass loss rates inconsistent with indirect stellar wind results
- The first systematic probe for CME signatures has not revealed anything convincing
- Maybe this problem for M dwarf habitability is not so bad?

High-risk, high-reward science and the importance of null results

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