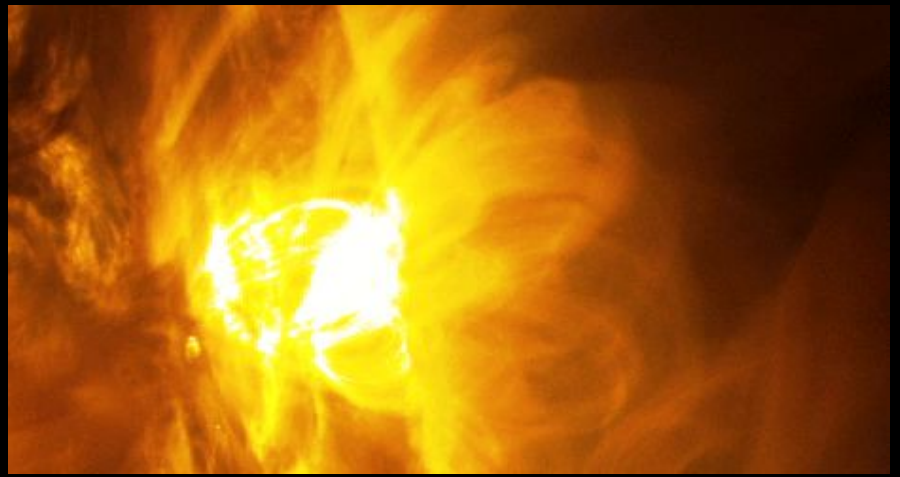
The Role of Flares in Star-Planet Interactions

Ekaterina Ilin, Netherlands Institute for Radio Astronomy (ASTRON)

July 09, 2024



The Role of Flares in Star-Planet Interactions

Flares

Where does the flare energy come from?

linear force-free field =

potential field
$\mathbf{j} \times \mathbf{B} = 0$ and $\nabla \mathbf{B} = 0$

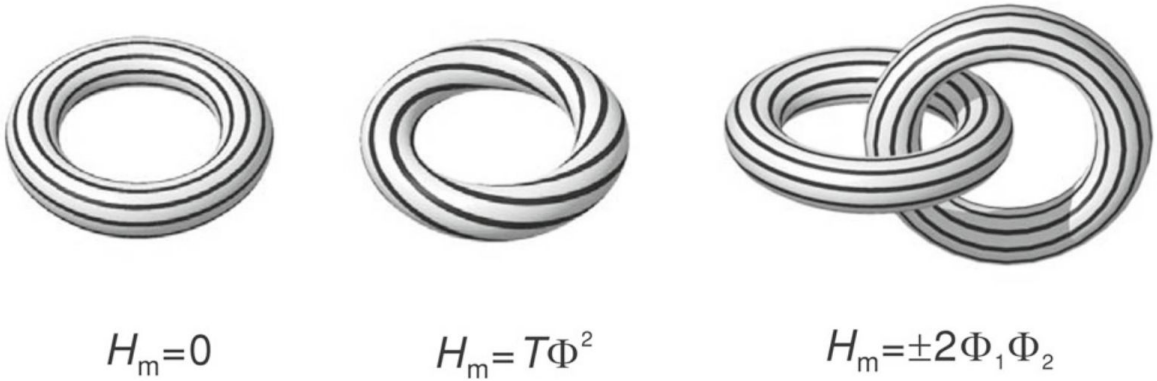
+

magnetic helicity H_m

...from below.

➔ emerging magnetic loops
➔ convective motion of the footpoints of those loops

Both move the coronal magnetic field away from the lowest energy configuration (linear force free field).

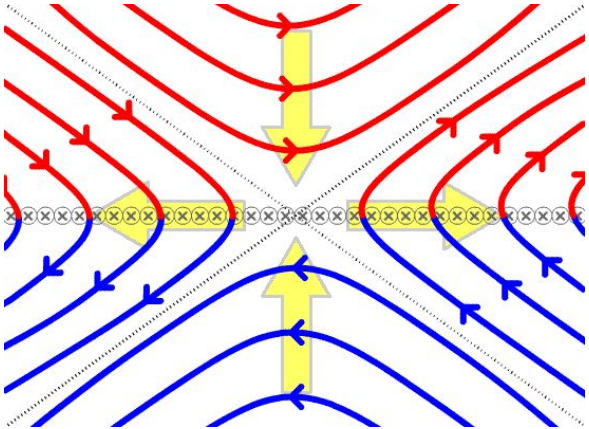


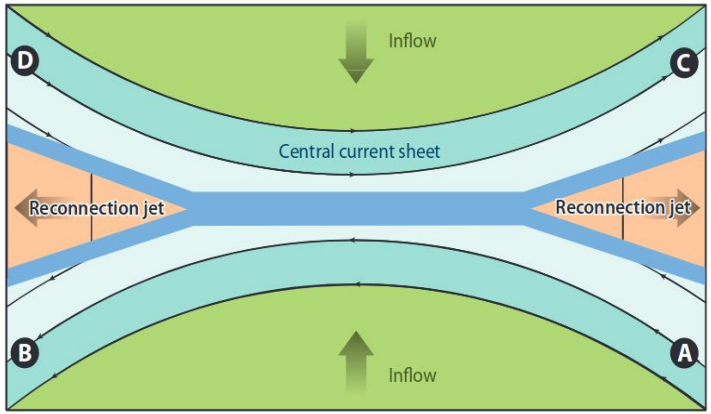
Wiegelmann and Sakurai 2021

What triggers the flare?

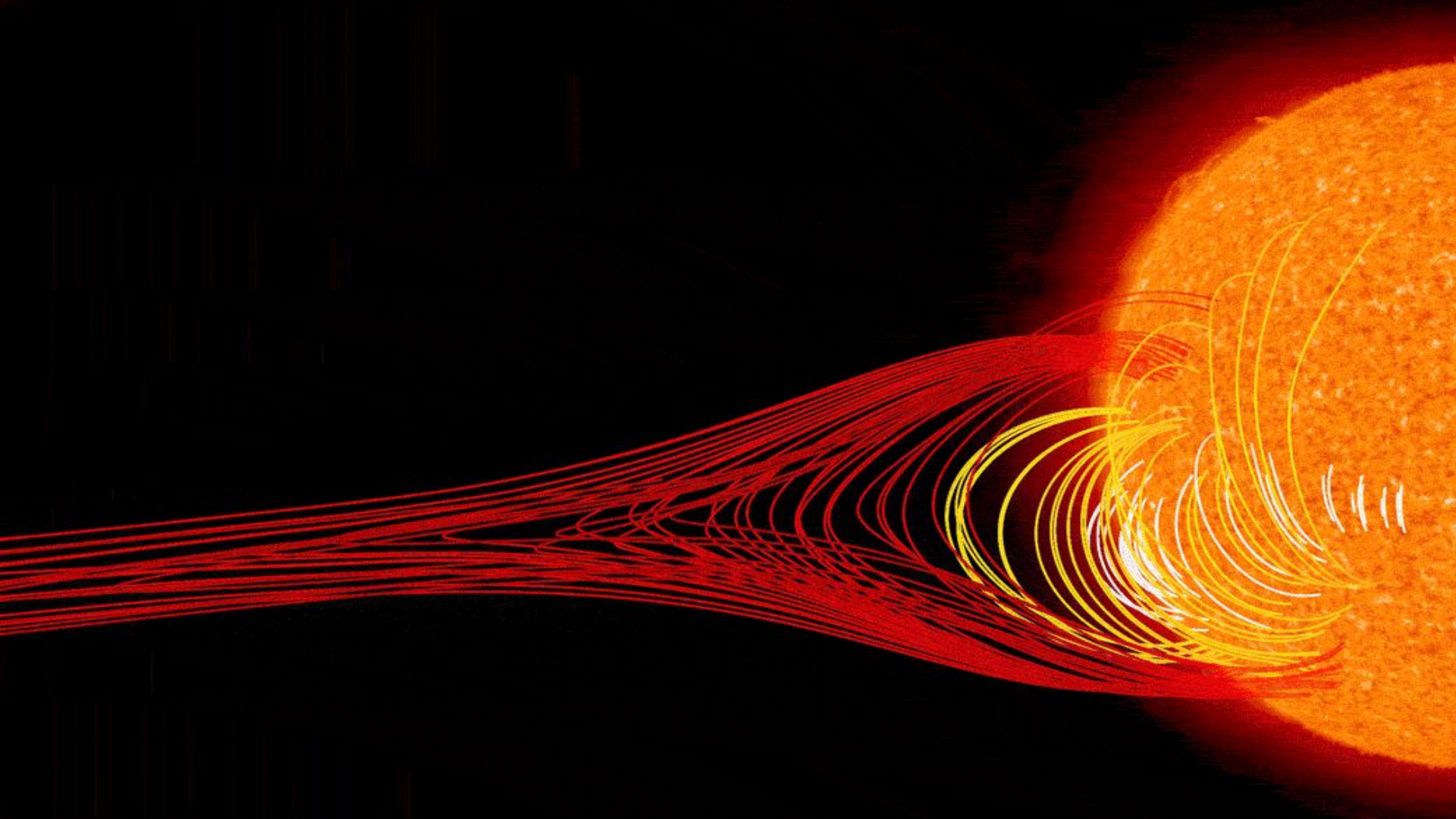
Coronal plasma is fully ionized = no neutral particles to create resistance that would dissipate the excess energy through Ohmic heating.

Re-connection of field lines transfers the magnetic field configuration into a lower energy state by rapidly accelerating plasma into reconnection jets:

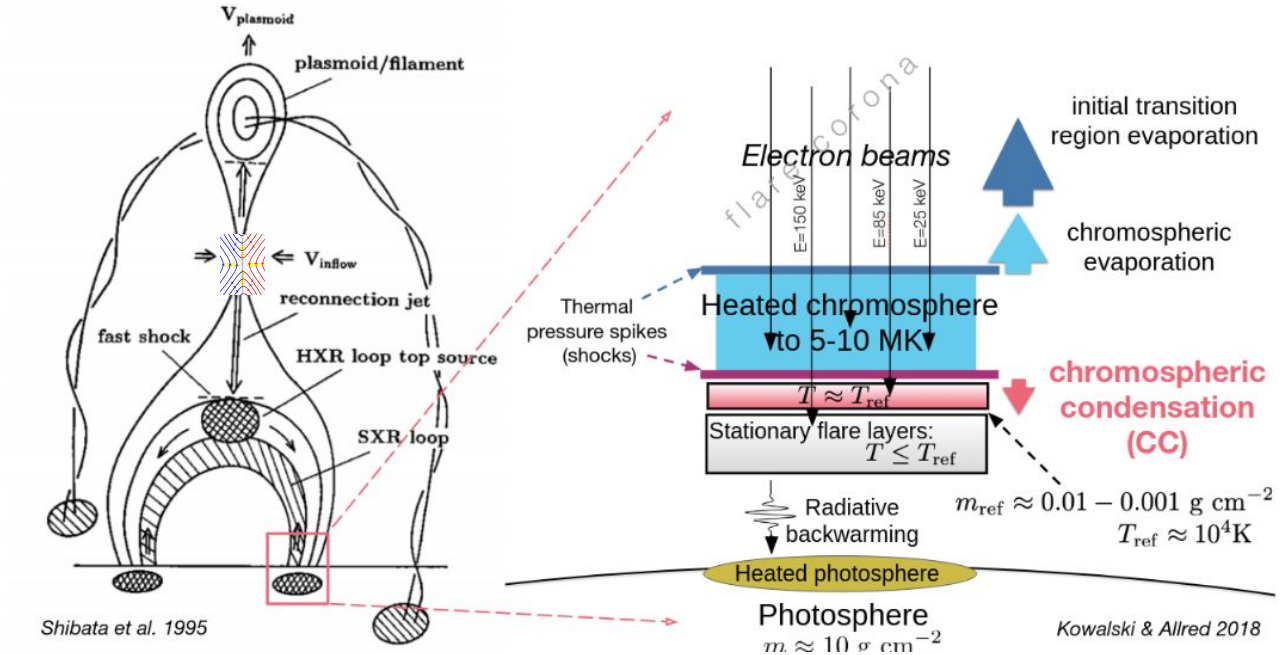


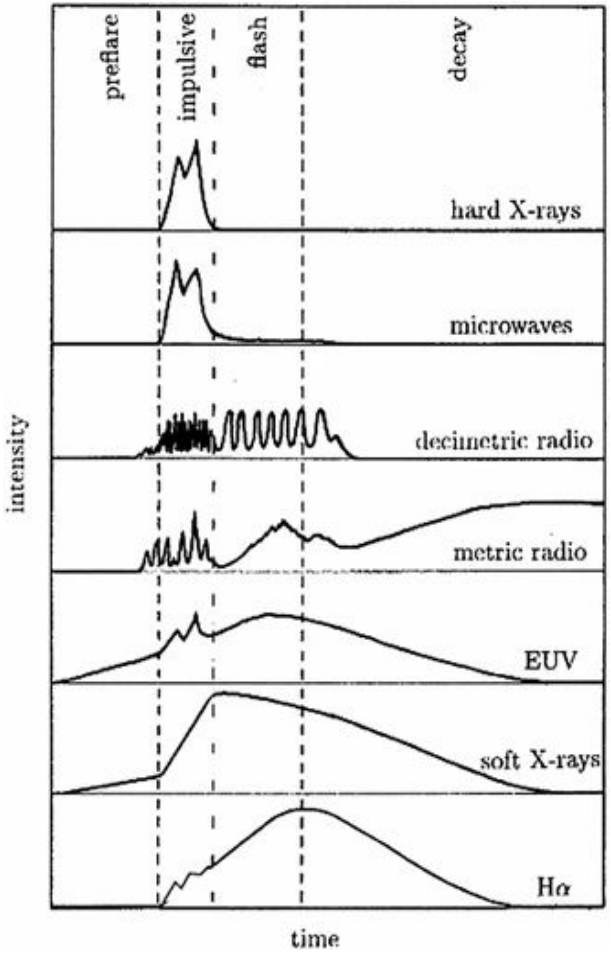


Benz and Güdel 2010

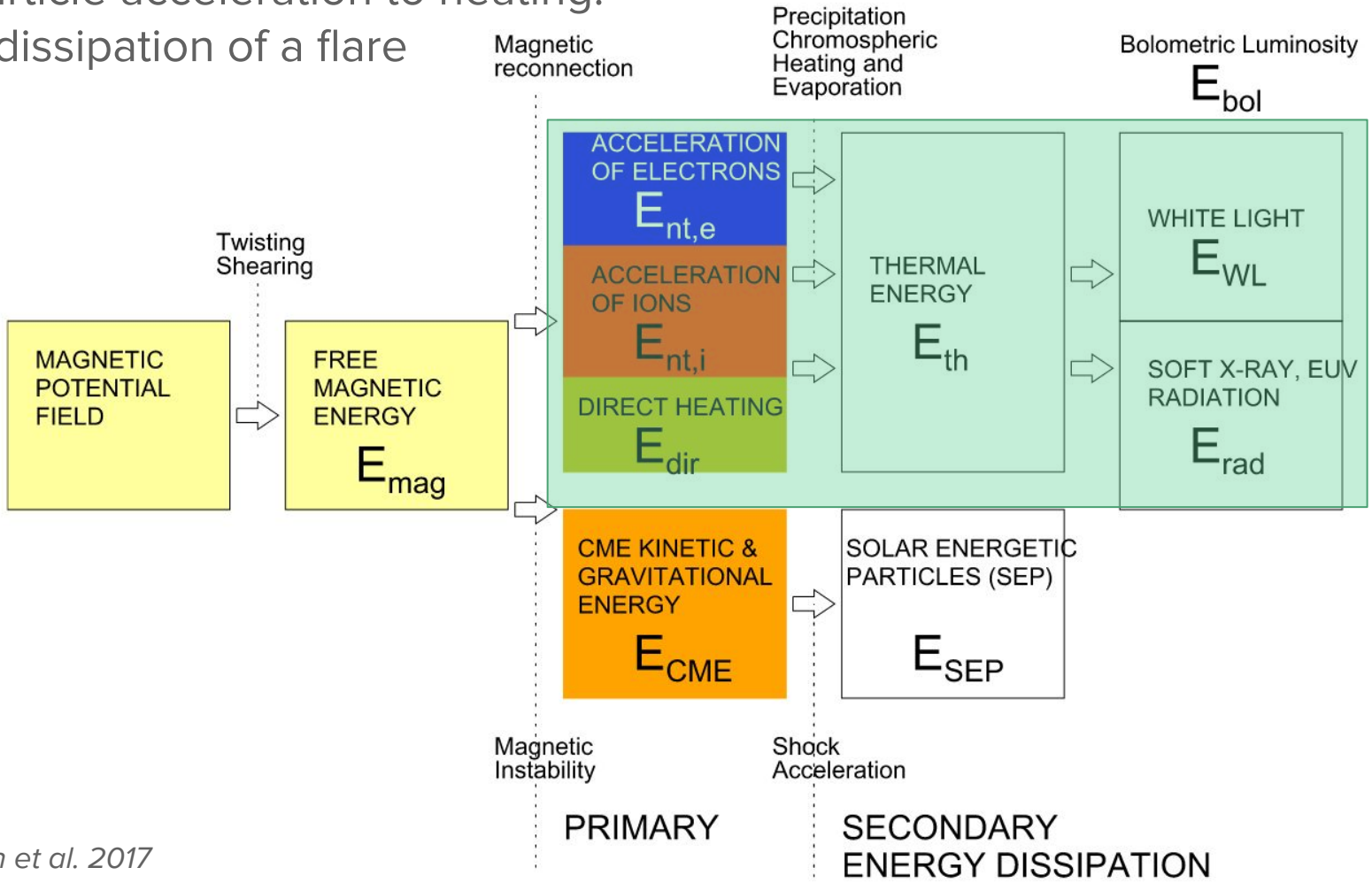


From particle acceleration to heating: energy dissipation of a flare





From particle acceleration to heating: energy dissipation of a flare

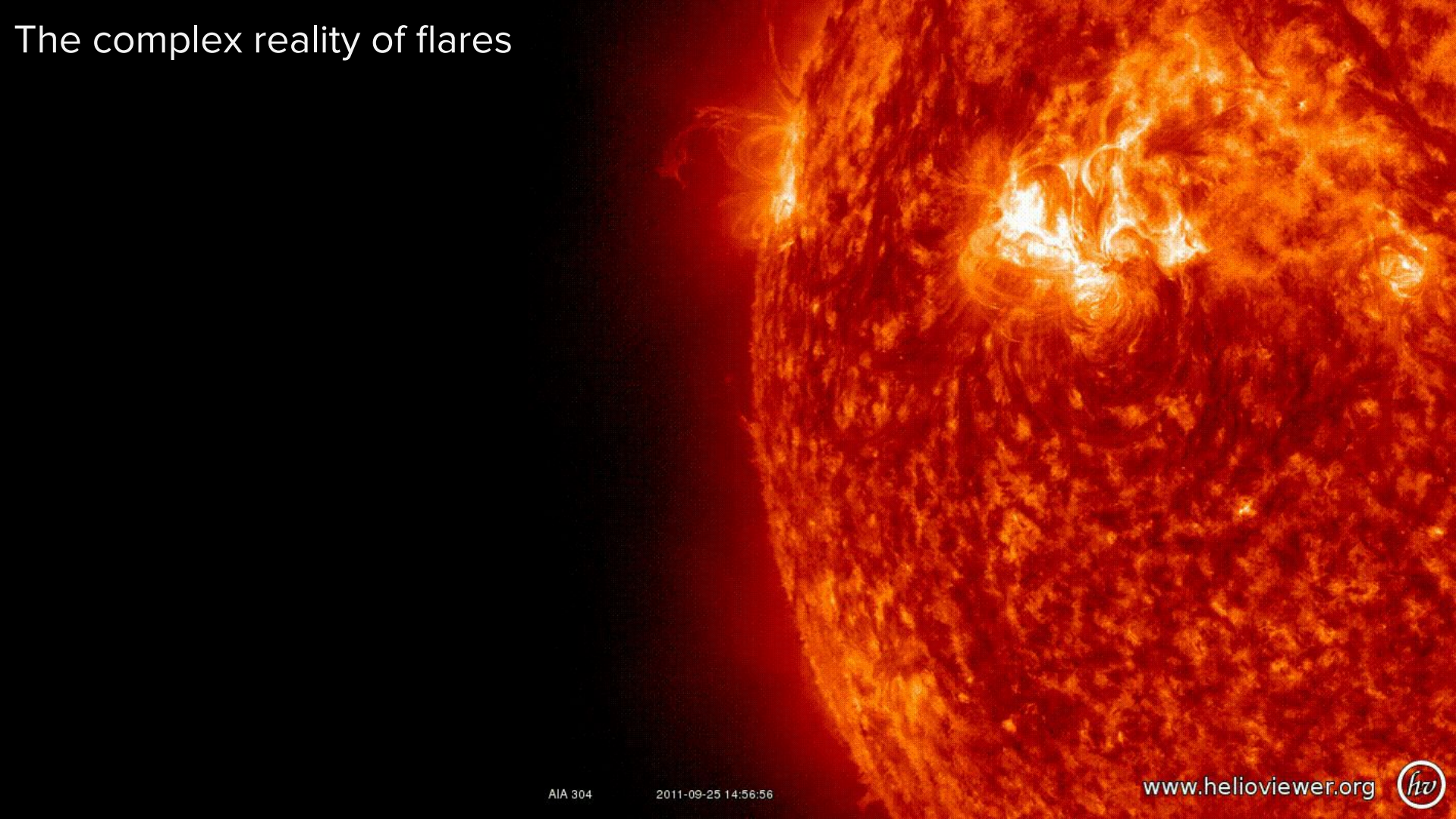


Aschwanden et al. 2017

Flares vs. **c**oronal **m**ass **e**jections vs. **s**olar **e**nergetic **p**article events

	Flares	**CMEs**	**SEPs**
triggered by	reconnection	magnetic instability	shock acceleration in flare or CMEs
main energy dissipation pathway	radiative	kinetic	kinetic
often occurs with	CMEs, impulsive SEPs	large flares, gradual SEPs	flares, CMEs

The complex reality of flares

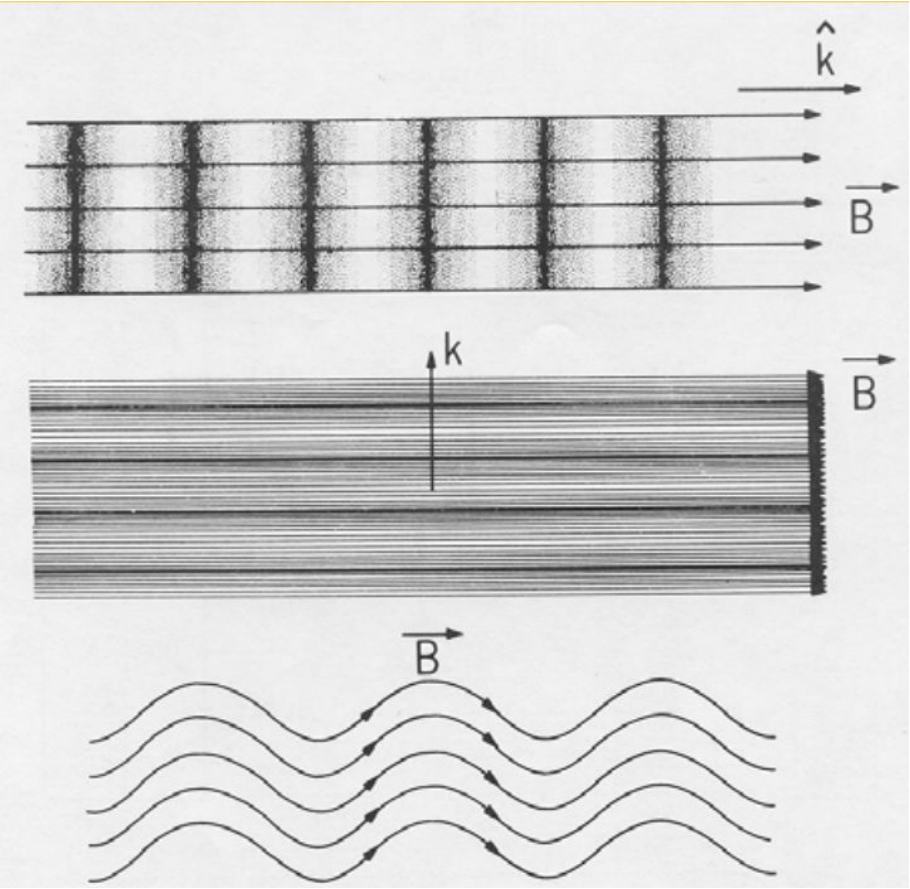


The Role of Flares in Star-Planet Interactions

Star-Planet Interactions


star
planet

Magnetohydrodynamic waves



magnetosonic waves
compressible

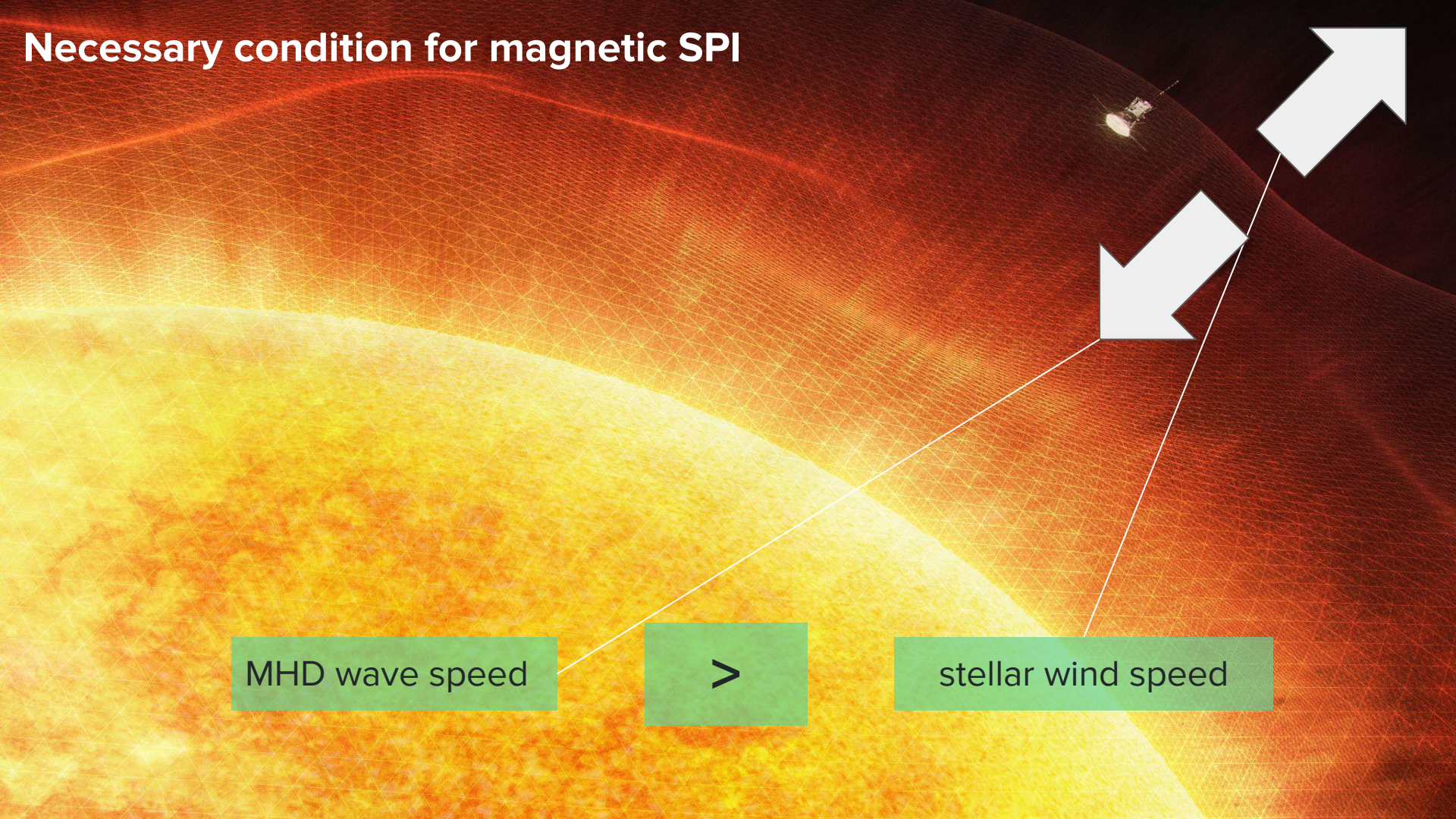
$$c_s = \sqrt{\gamma \cdot \frac{p}{\rho}}$$

$$c_{ms} = \sqrt{v_A^2 + c_s^2}$$

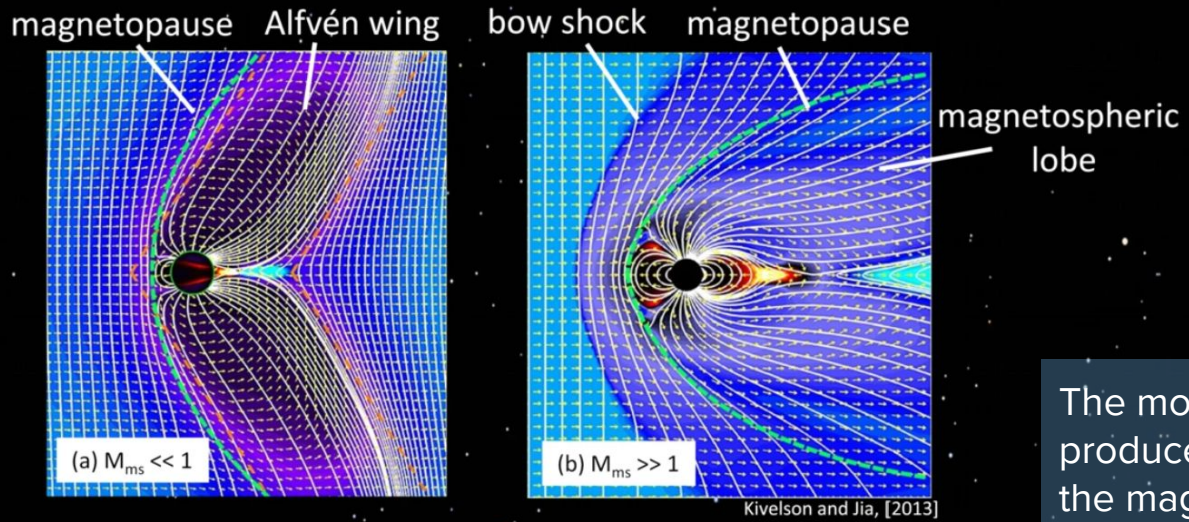
Alfvén waves
***in**compressible*

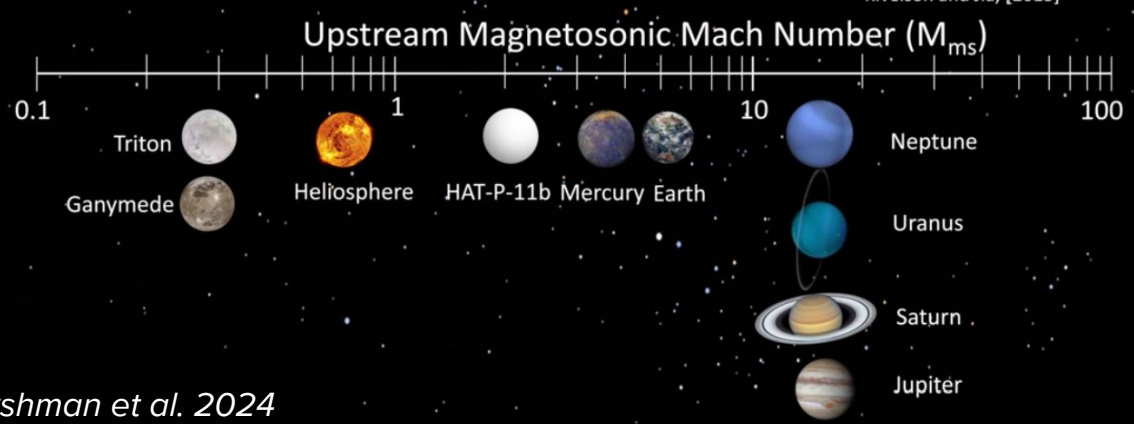
$$v_A \equiv \frac{B}{\sqrt{\mu_0 \rho}}$$

Necessary condition for magnetic SPI



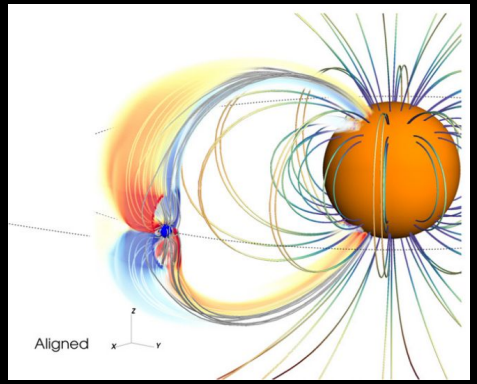
Alfvén Wing model of magnetic star-planet interaction





Gershman et al. 2024

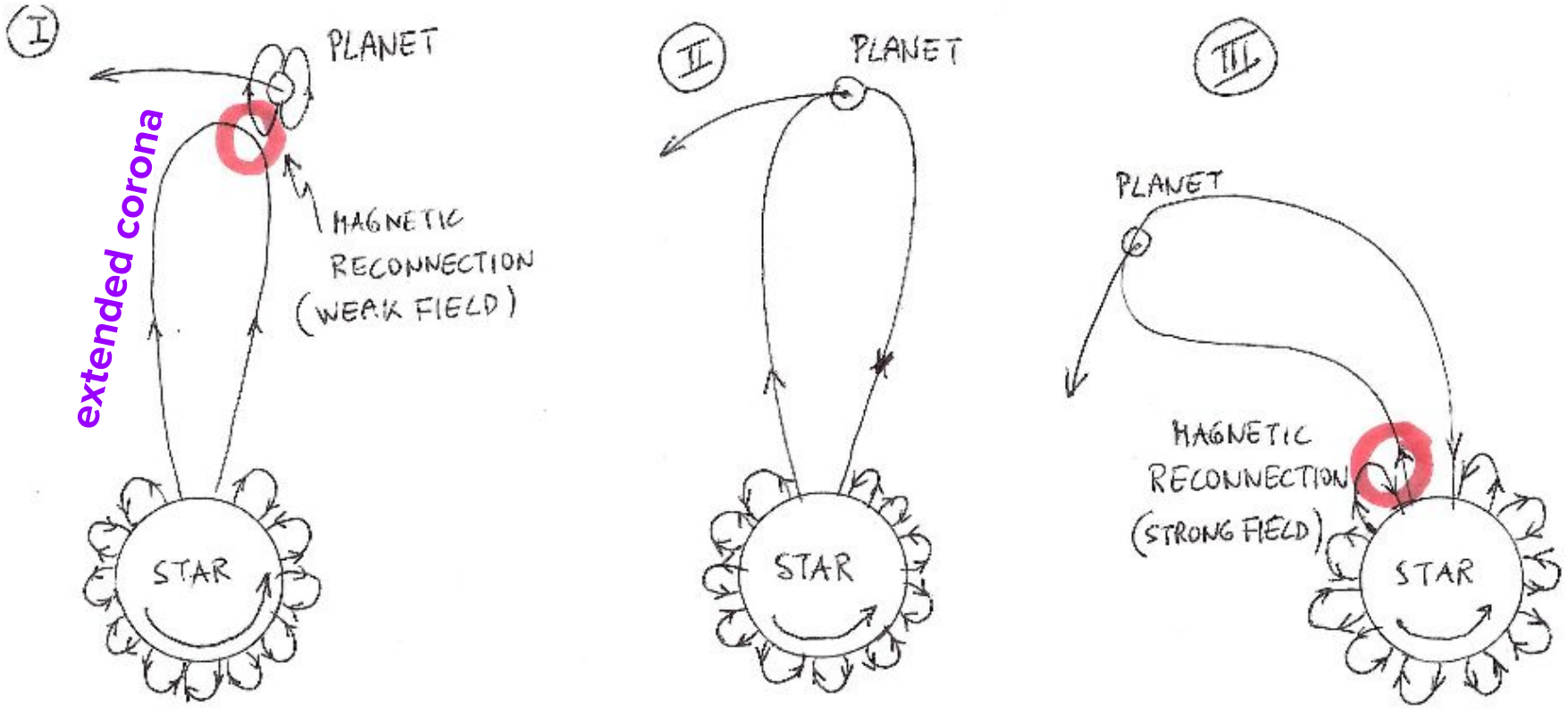
Strugarek et al. 2015



The movement of the planet produces a **steady** perturbation of the magnetic field that travels as MHD waves along the field lines towards the star.

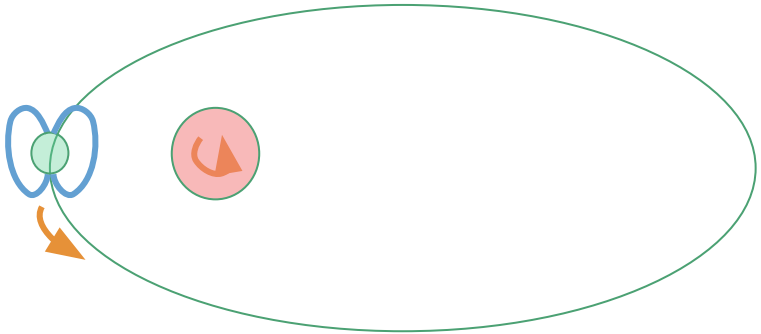
Flares are **not** steady! We need an additional mechanism to store and release energy.

Stretch-and-break model of magnetic star-planet interaction

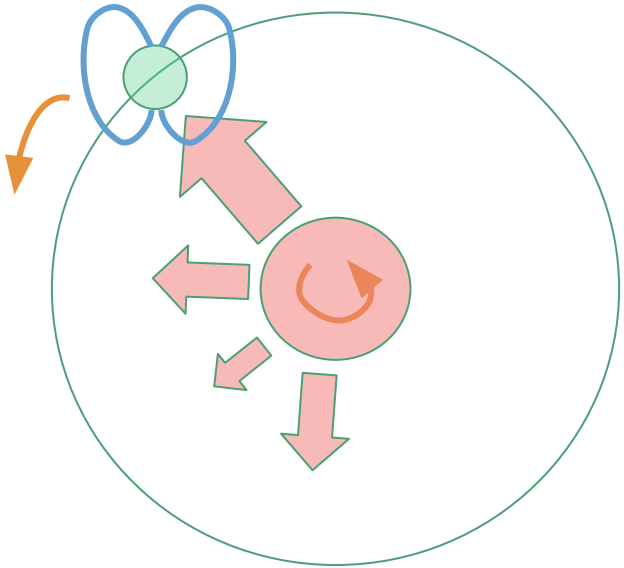


Lanza 2011

Other ways of moving through spatially variable magnetic fields



eccentric orbit

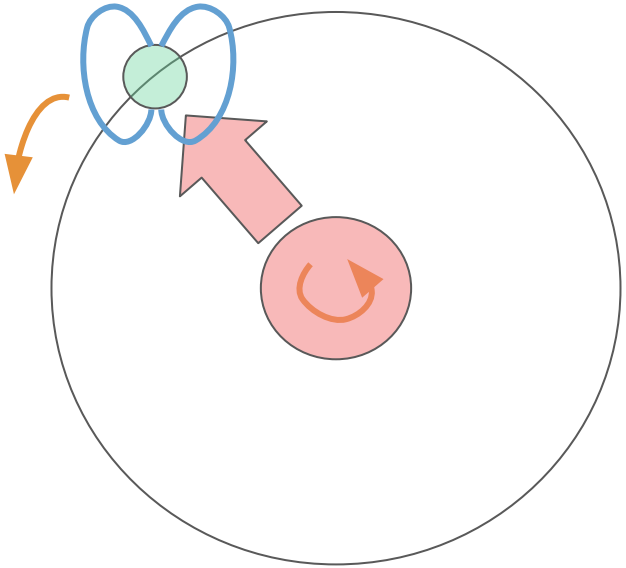


variable stellar winds

Magnetic SPI mechanism:
a planet **perturbs** the magnetic field

$$P_{SPI} \sim R_p^{\,2}\, B_p^{\,2/3}\, B_w^{\,1/3}\, \rho_w^{\,1/2}\, v_{rel}^{\,2}$$

Alfven wings, *Zarka (2007), Saur et al. (2013), Kavanagh et al. (2022)*



Magnetic SPI mechanism:
a planet **perturbs** the magnetic field

$$P_{SPI} \sim R_p^{-2} B_p^{1/3} B_* F_X^{1/6} d^{-2} v_{rel}$$

simple reconnection, *Cuntz et al. (2000)*

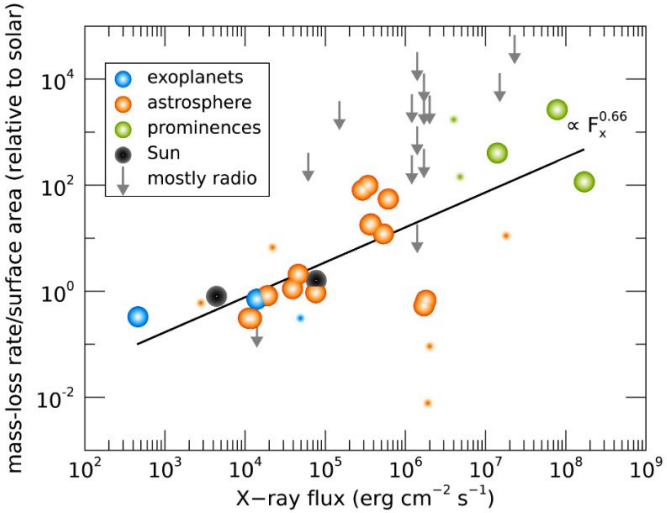
$$P_{SPI} \sim R_p^{2} B_p^{2/3} B_w^{4/3} v_{rel}$$

stretch and break, *Lanza (2012, 2013)*

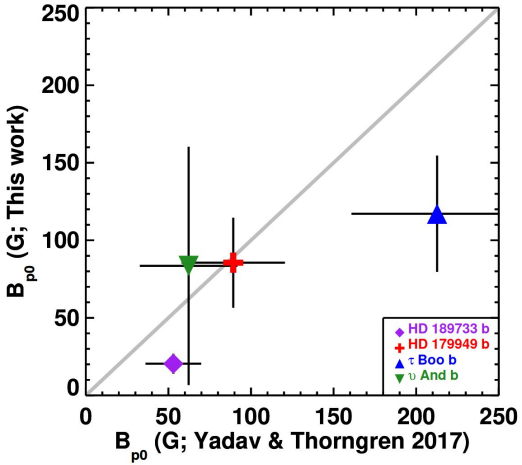
$$P_{SPI} \sim R_p^{2} B_p^{2/3} B_w^{1/3} \rho_W^{1/2} v_{rel}^{2}$$

Alfven wings, *Zarka (2007), Saur et al. (2013), Kavanagh et al. (2022)*

The promise of magnetic SPI



– use planet as a natural probe of the rarified stellar wind



– measure planetary magnetic fields

Vidotto 2021

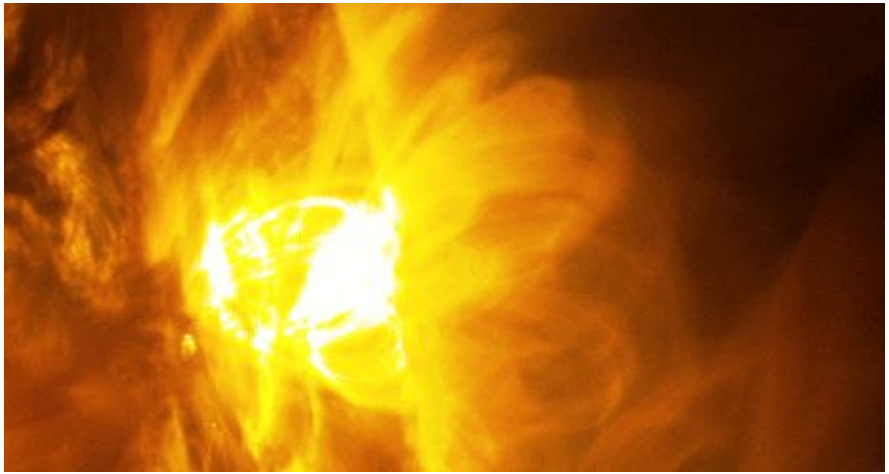
Cauley et al. 2019

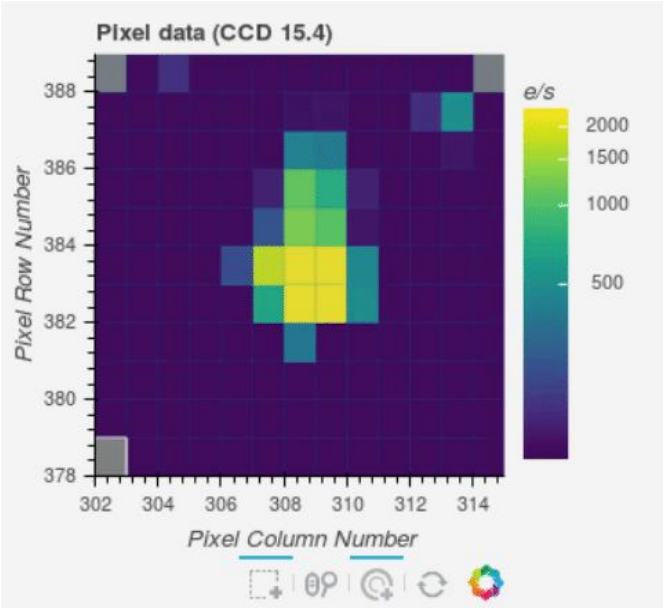
The Role of Flares in Star-Planet Interactions

Flare observations

Solar flares – **high** spatial, **high** temporal, and **high** spectral resolution

Stellar flares – **no** spatial, **medium** temporal, and **little** spectral resolution





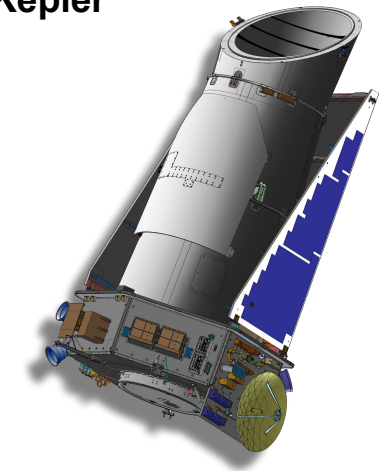
created using `lightkurve`

Solar flares – **high** spatial, **high** temporal, and **high** spectral resolution

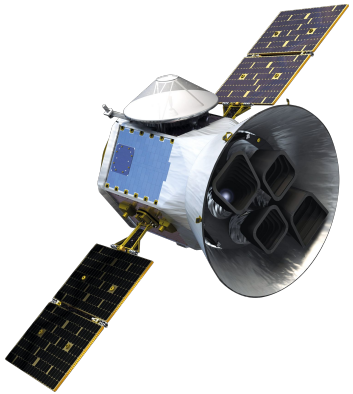
Stellar flares – **no** spatial, **medium** temporal, and **little** spectral resolution

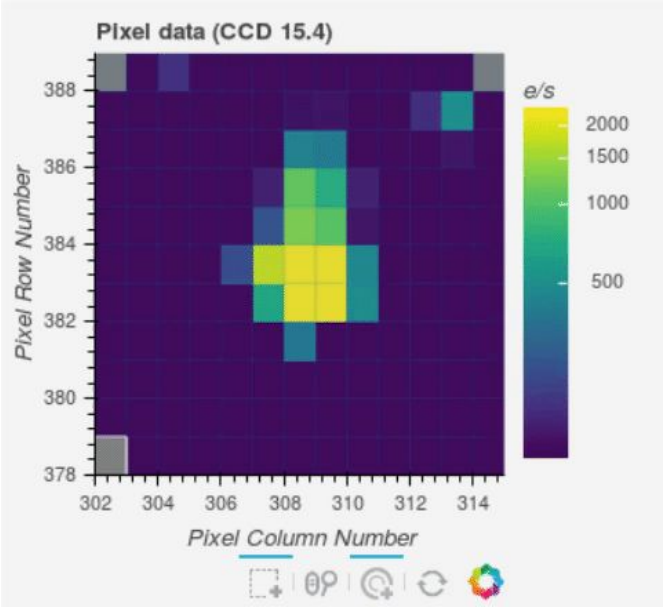
Most efficient flare detection technique:
piggybacking on optical transit searches

Kepler



TESS

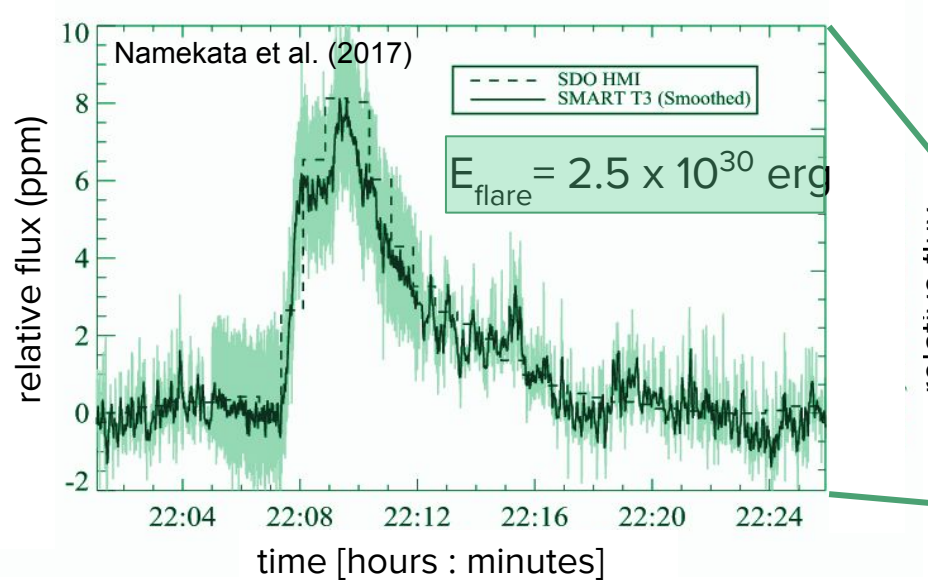


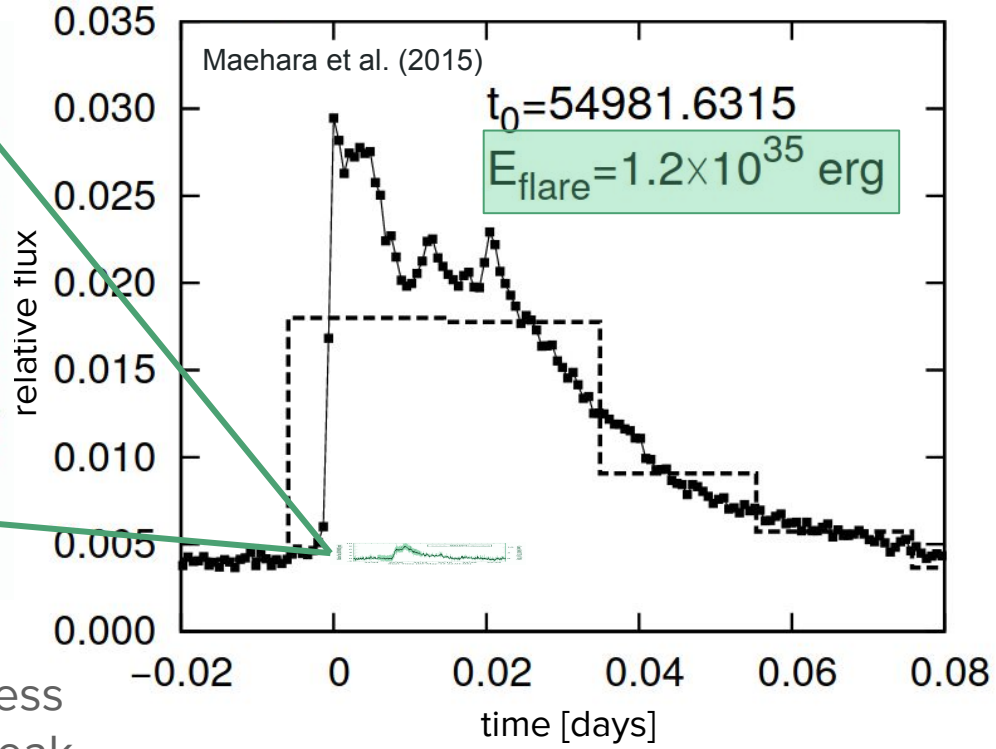


created using `lightkurve`

Stellar flares – **no** spatial, **medium** temporal, and **little** spectral resolution

… but the **high energies** and contrast of individual flares come to save us!



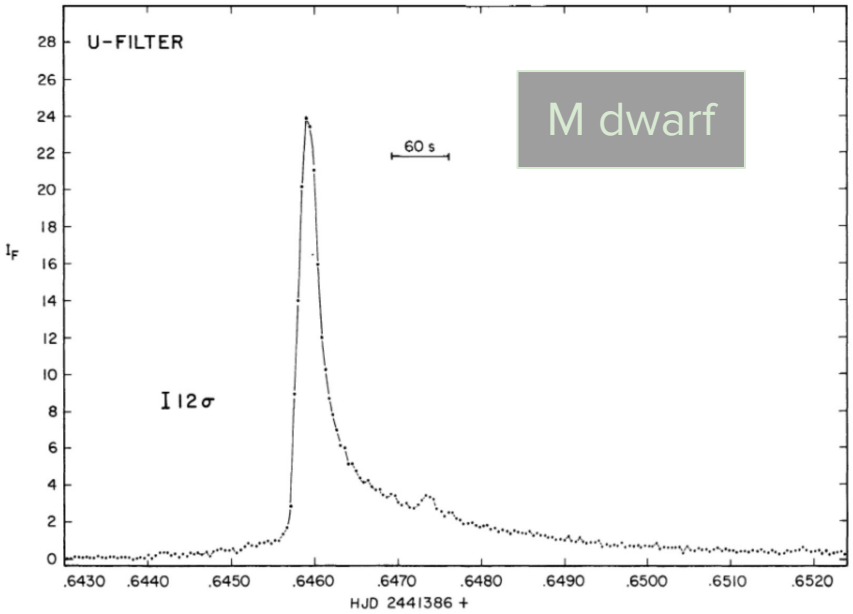


$E_{Carrington\ event}$ = 5×10^{32} erg

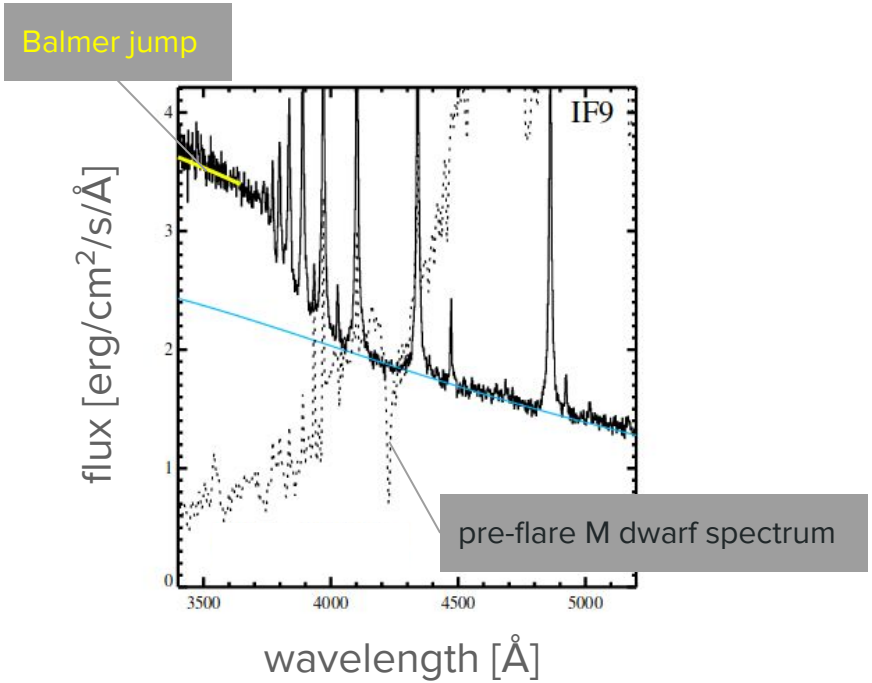
≃ 10^{-4} brightness increase at peak

Stellar flares – **no** spatial, **medium** temporal, and **little** spectral resolution

… but the high energies and **contrast** of individual flares come to save us!

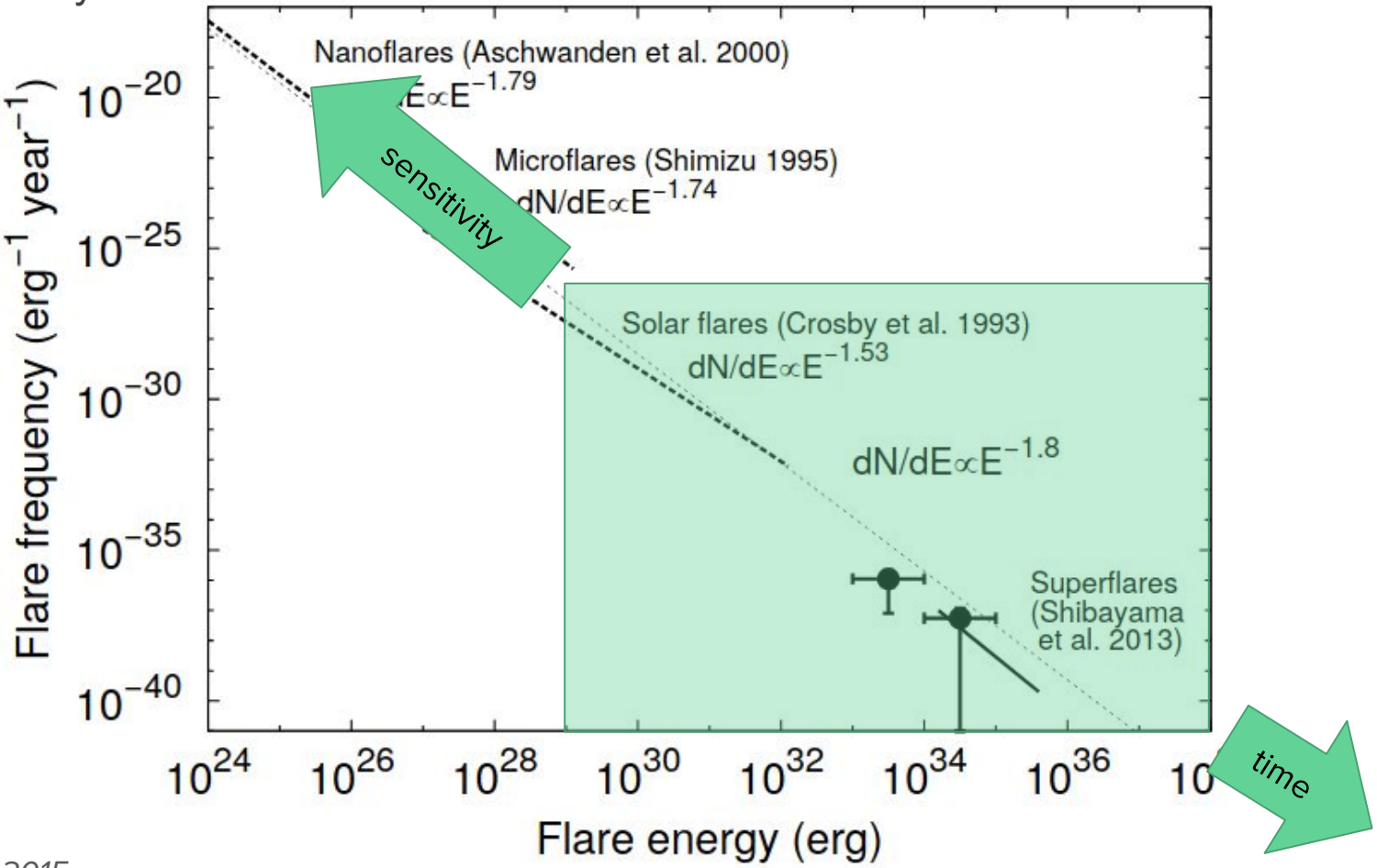


Moffett 1974



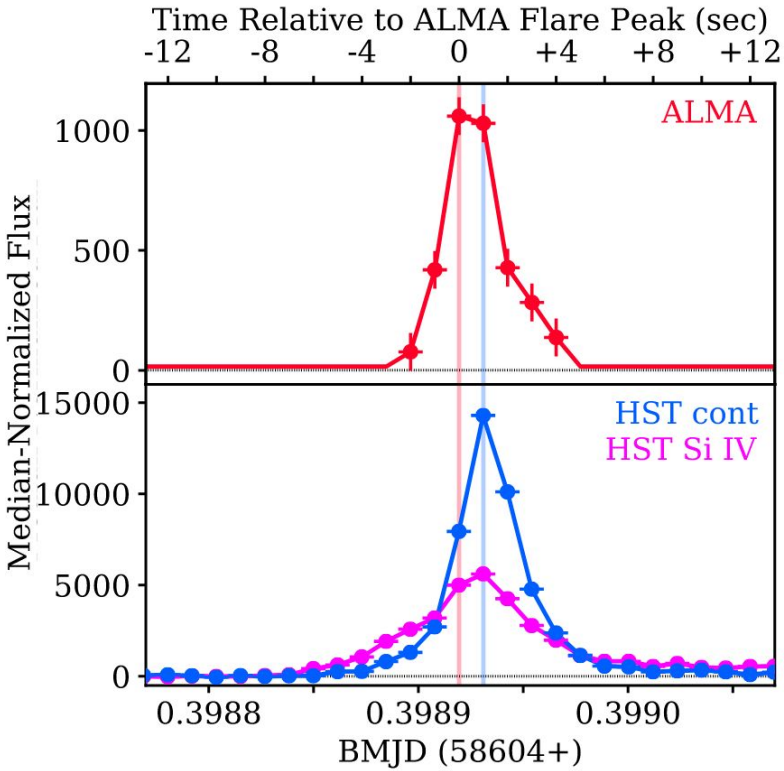
Kowalski et al. 2013

Flare frequency distributions



Maehara et al. 2015

Non-optical stellar flare observations – non-thermal emission



mm flare

=(gyro)synchrotron radiation

FUV flare

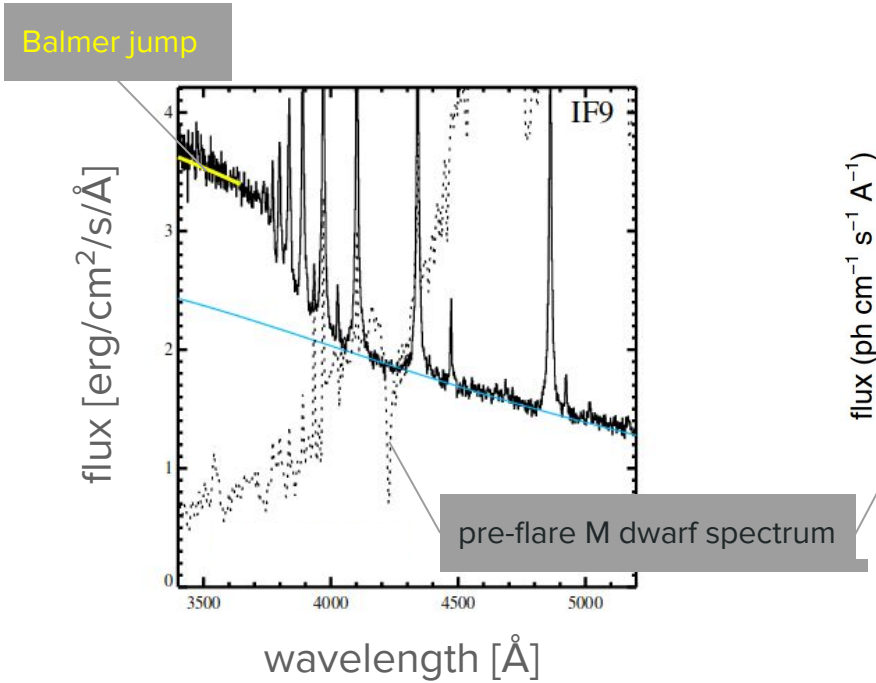
beam collision in stellar transition region
(can have thermal parts, too)

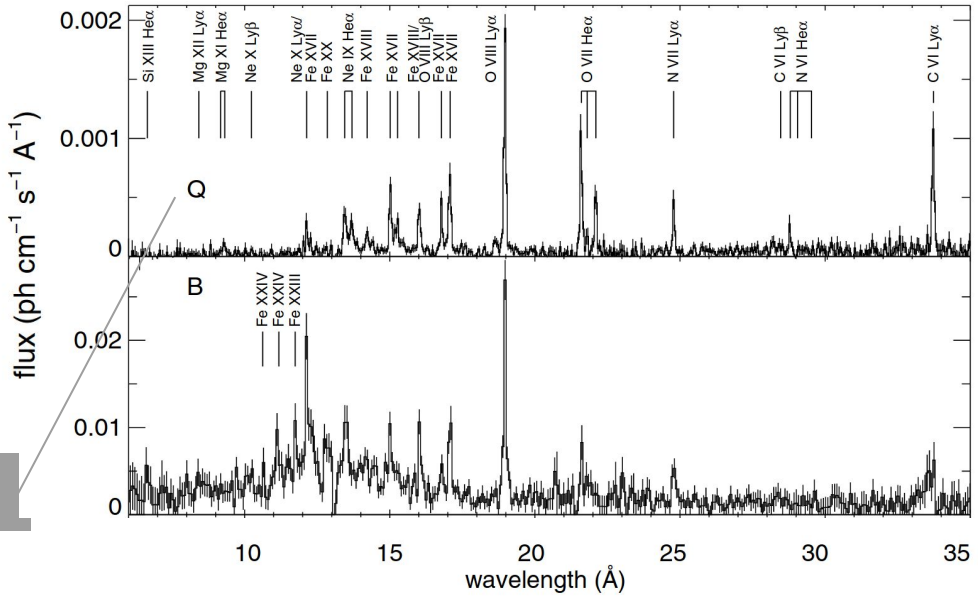
MacGregor et al. 2021

Non-optical stellar flare observations – thermal emission

optical black body emission at about 9000-14000 K

soft X-ray thermal spectrum

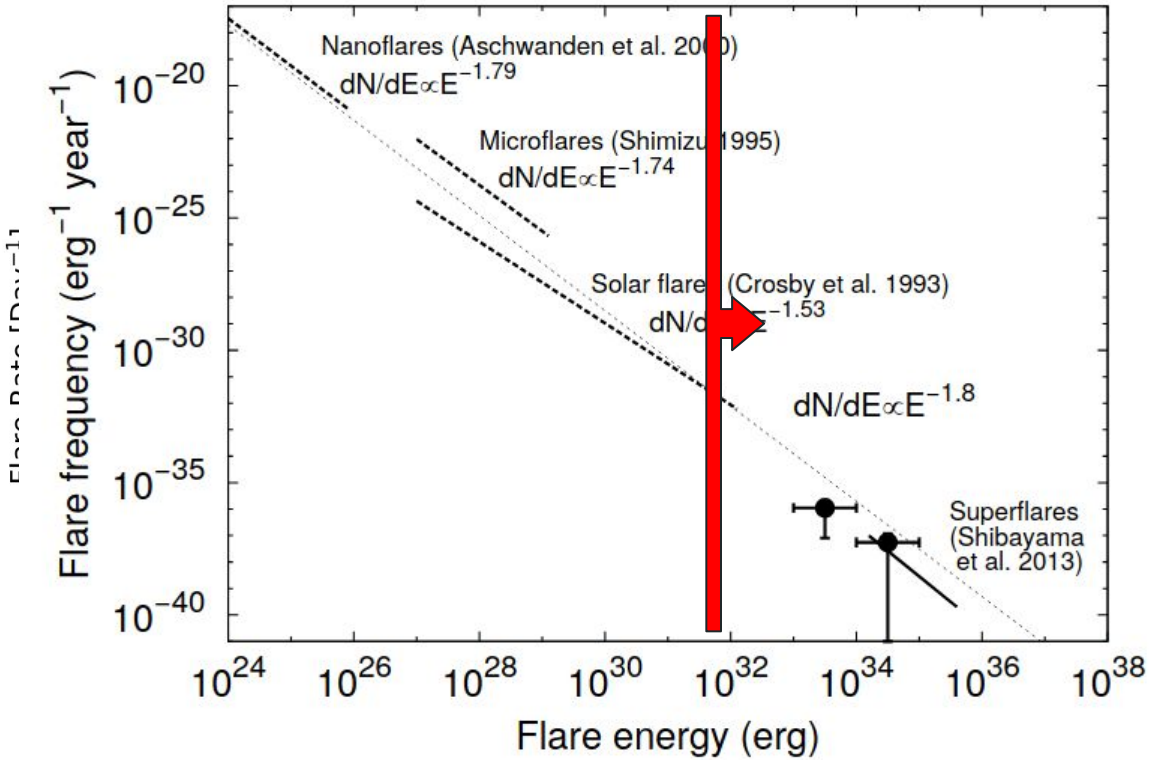


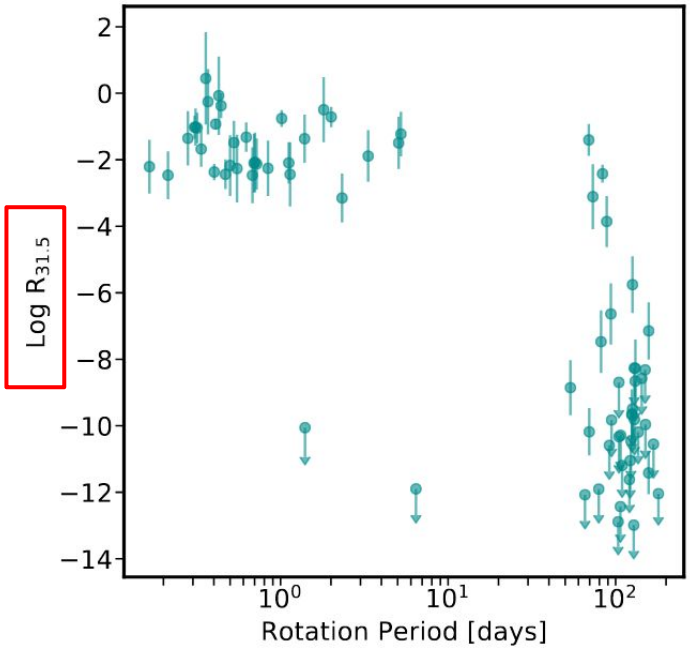


Kowalski et al. 2013

Gudel et al. 2004

Flaring activity depends on stellar **mass** (or *spectral type*) and **age** (or *rotation*)

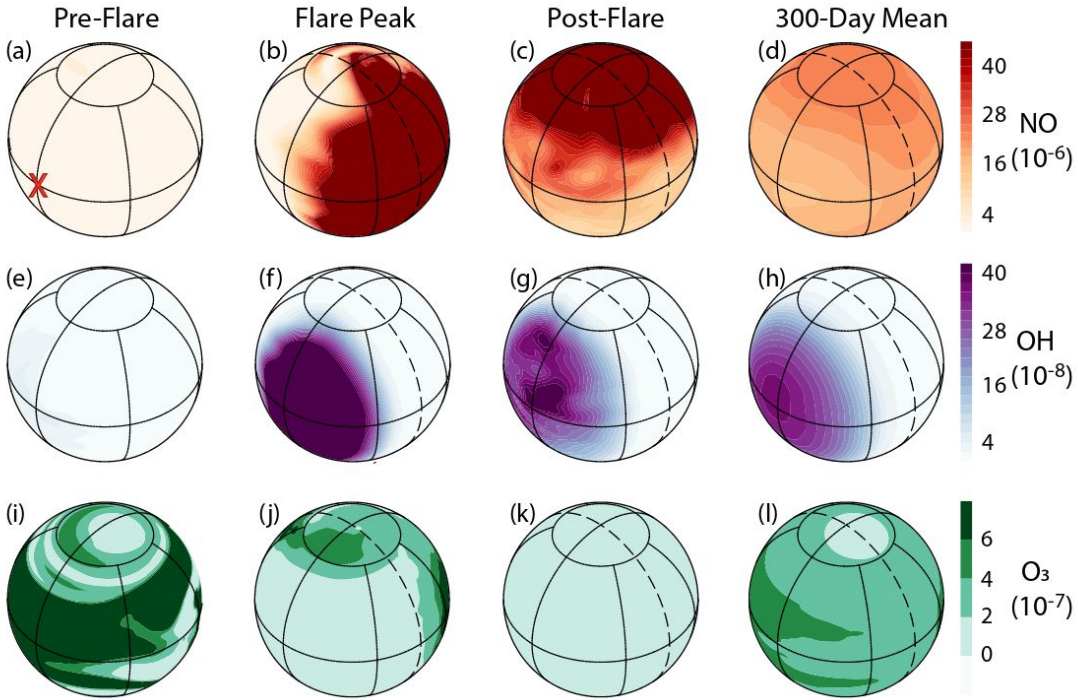




Feinstein et al. 2020

Medina et al. 2020

Effects of flares on exoplanets – short term, individual objects

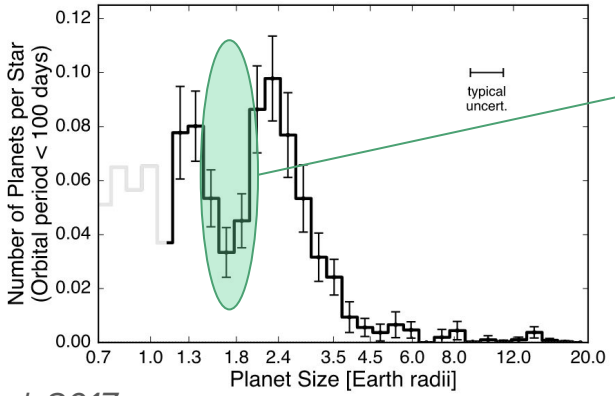


➡ impact on atmospheric chemistry

caused by the flares' ***UV radiation***

Chen et al. 2021

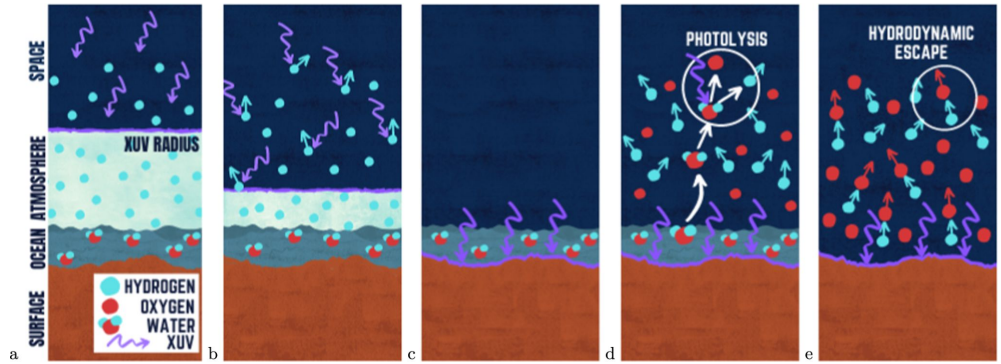
Effects of flares on exoplanets – long term, populations of systems



Fulton et al. 2017

Can't hold on to atmosphere very well here, i.e. not enough gravity.

➡ evaporate atmospheres, potentially even oceans



do Amaral et al. 2022

caused by the flares' ***XUV radiation***

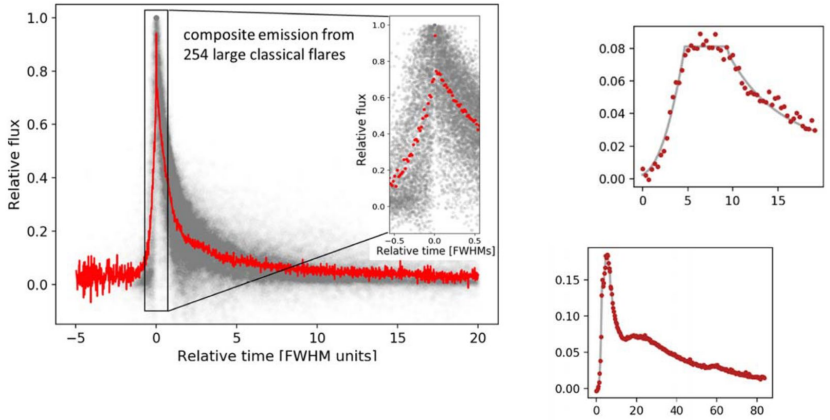
The Role of Flares in Star-Planet Interactions

Observations of Star-Planet Interactions

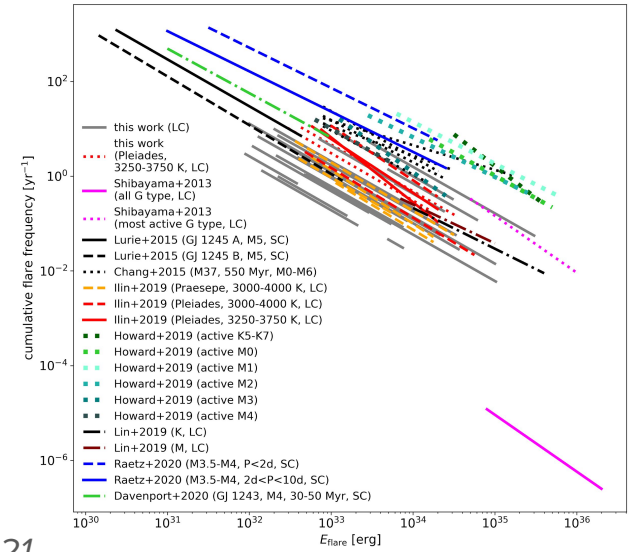
Is the flare planet-induced or not?

(Potential) Flaring SPI signatures

- **individual flare properties**
  deviate significantly from intrinsic flares
  - but flares do all sorts of complex behavior we have not always have an explanation for
- **change in flare frequency distribution**, esp. slope
  - effect must be large given the intrinsic variability
  - alternatively, large samples, i.e. >10^3 flares per system
- **periodicity of flare occurrence** with planetary orbit
  - possibility of confusion with (differential) rotation
  - **probably our best guess because planetary orbital periods are unique**



Howard and MacGregor 2022



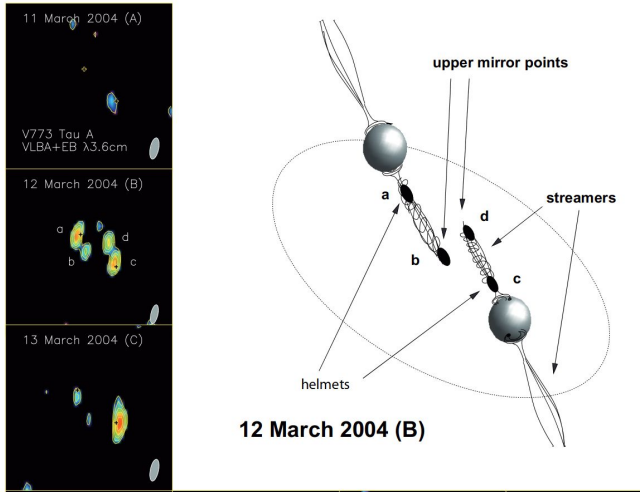
Ilin et al. 2021

What are the best targets for flaring SPI?

Observing strategies: looking for the highest power of SPI

If star-planet interactions are a thing, shouldn't star-brown dwarf and star-star interactions be even more prominent?

most likely a different mechanism

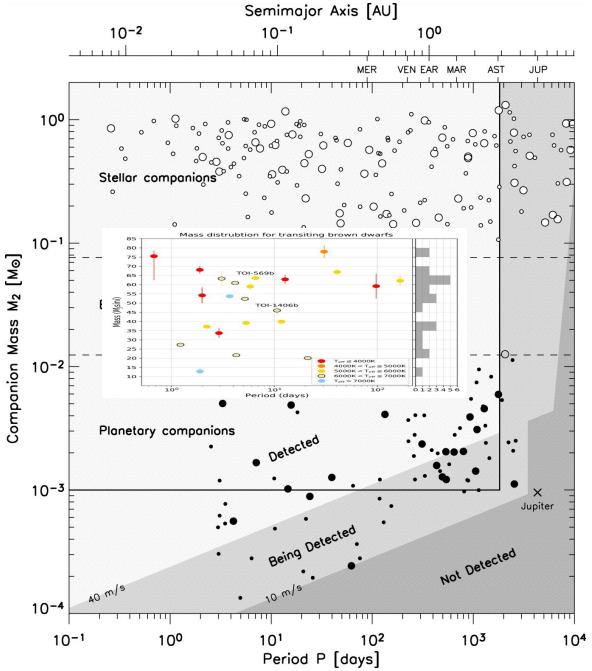


binary interactions

➡ large magnetospheres collide

Massi et al. 2008

not enough targets

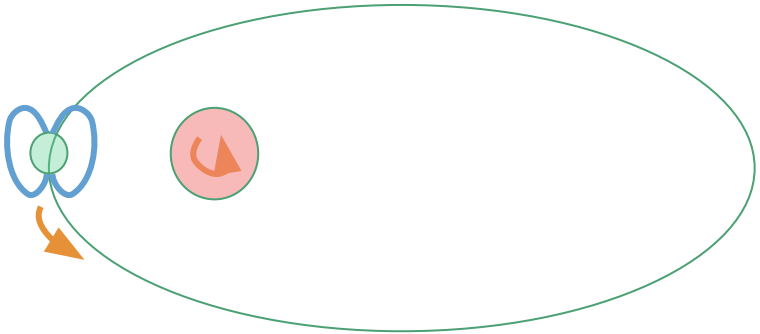


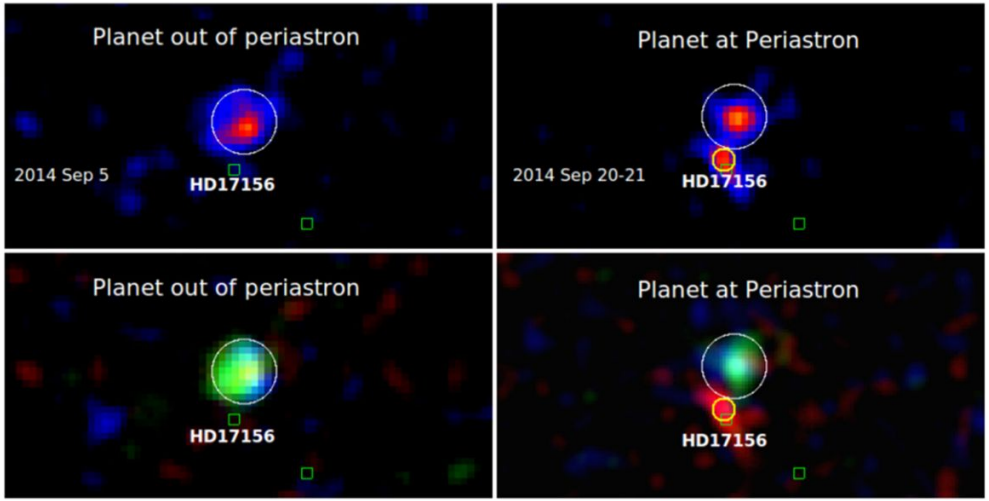
star-brown dwarf interactions

➡ brown dwarf desert

Grether and Lineweaver 2006, Carmichael et al. 2022

Observing strategies: systems with a preferred phase of interaction



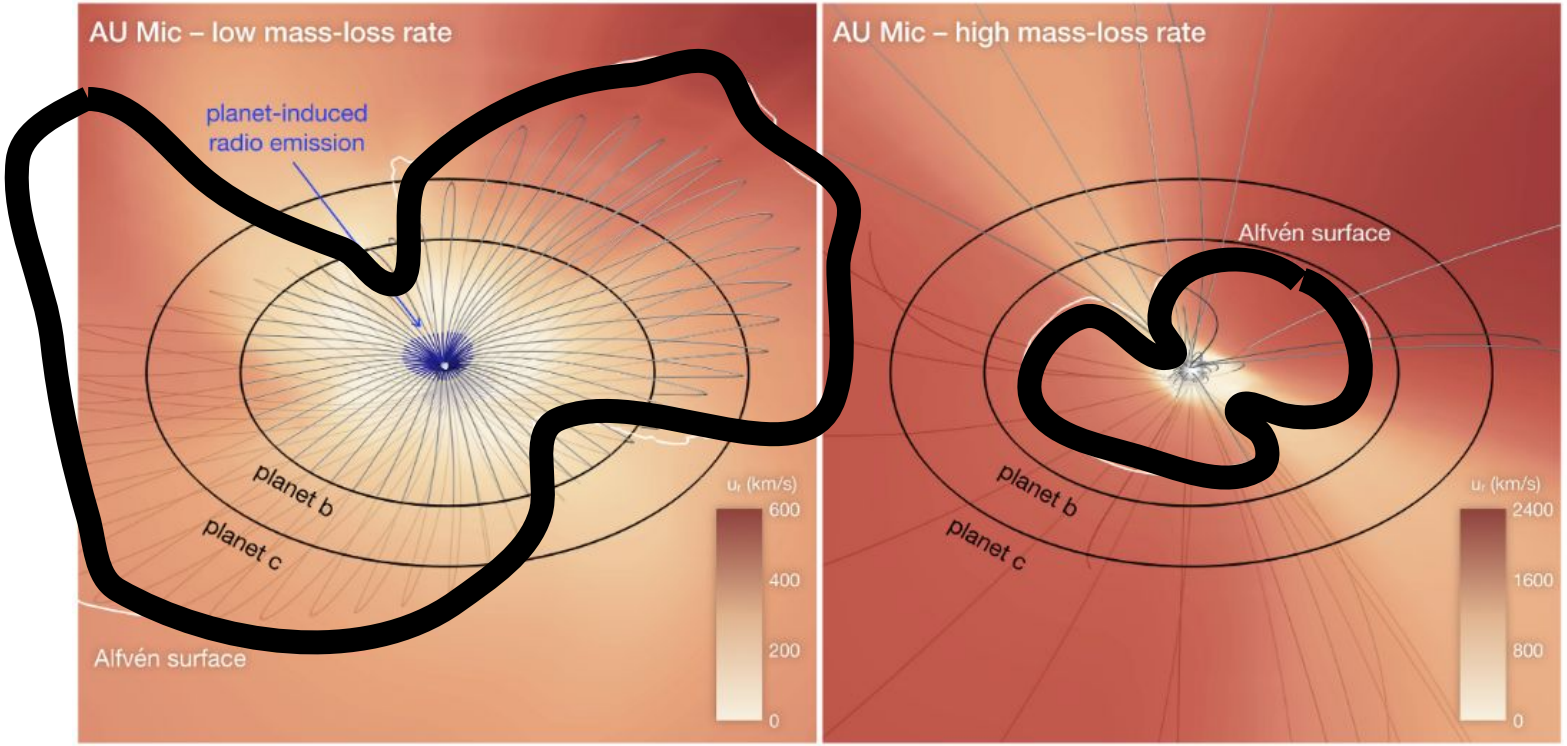


The brightening at periastron also visible in chromospheric emission!
... **BUT** did not repeat in subsequent periastron passages.

problem of (potential) intermittency

Maggio et al. 2015

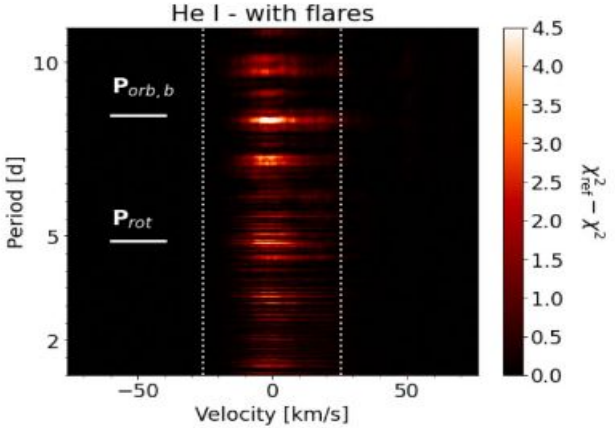
AU Mic, a young M dwarf

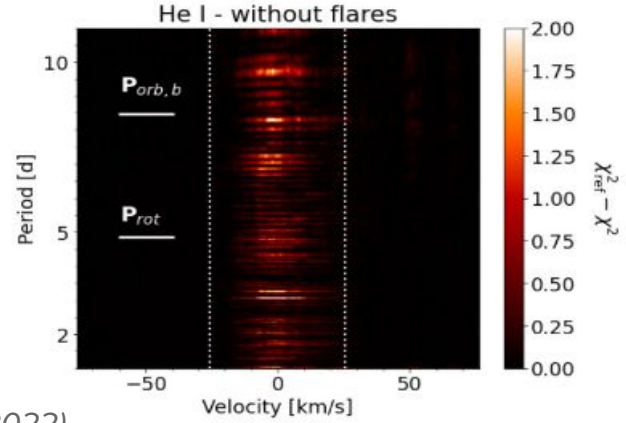


Kavanagh et al. (2021)

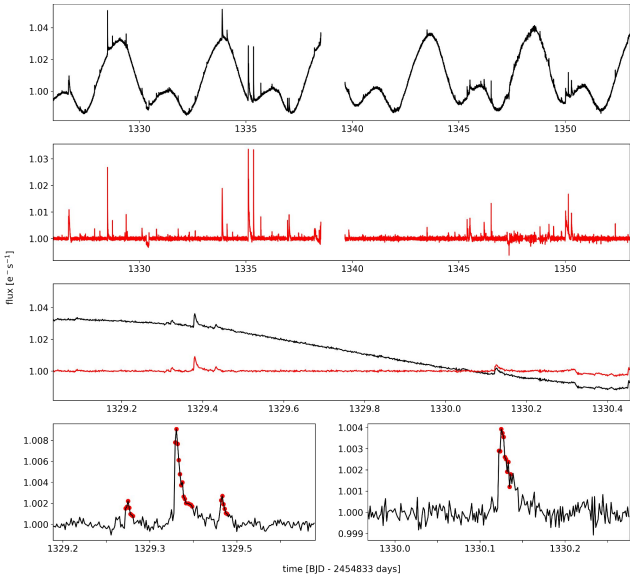
Observing strategies: old systems vs. young systems

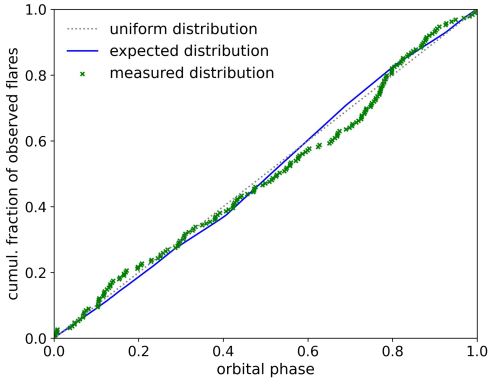
AU Mic, a young M dwarf





Klein et al. (2022)

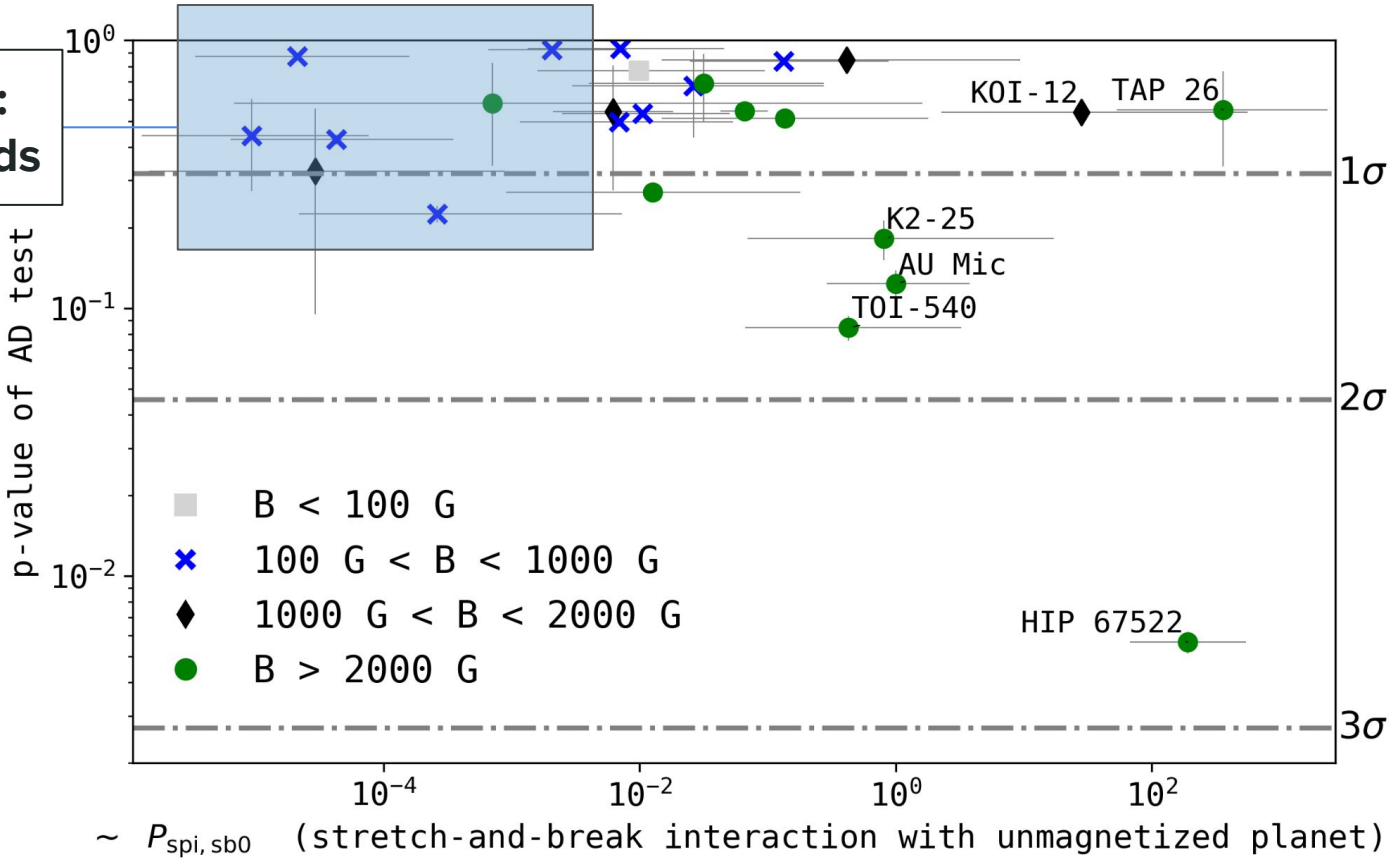




Ilin and Poppenhäger (2022)

Observing strategies: old systems vs. young systems

mostly old systems:
weak magnetic fields



Ilin et al. (2024)

Status quo

- no conclusive detections of flaring SPI
- some preliminary detections, but do not predict interaction in follow up observations
- lack of objects to calibrate models on, so no good sense of what powers of SPI to expect

… and where to go from here

- increase statistics by at least a factor of 10, then try again
  ➡ > 1000 flares per system
- increase sensitivity by at least a factor of 10, then try again
  ➡ flares with energies below 10^{30} erg
- look into other properties of flares, i.e. spectra at various wavelengths

… all of which might take another decade or two to become feasible.