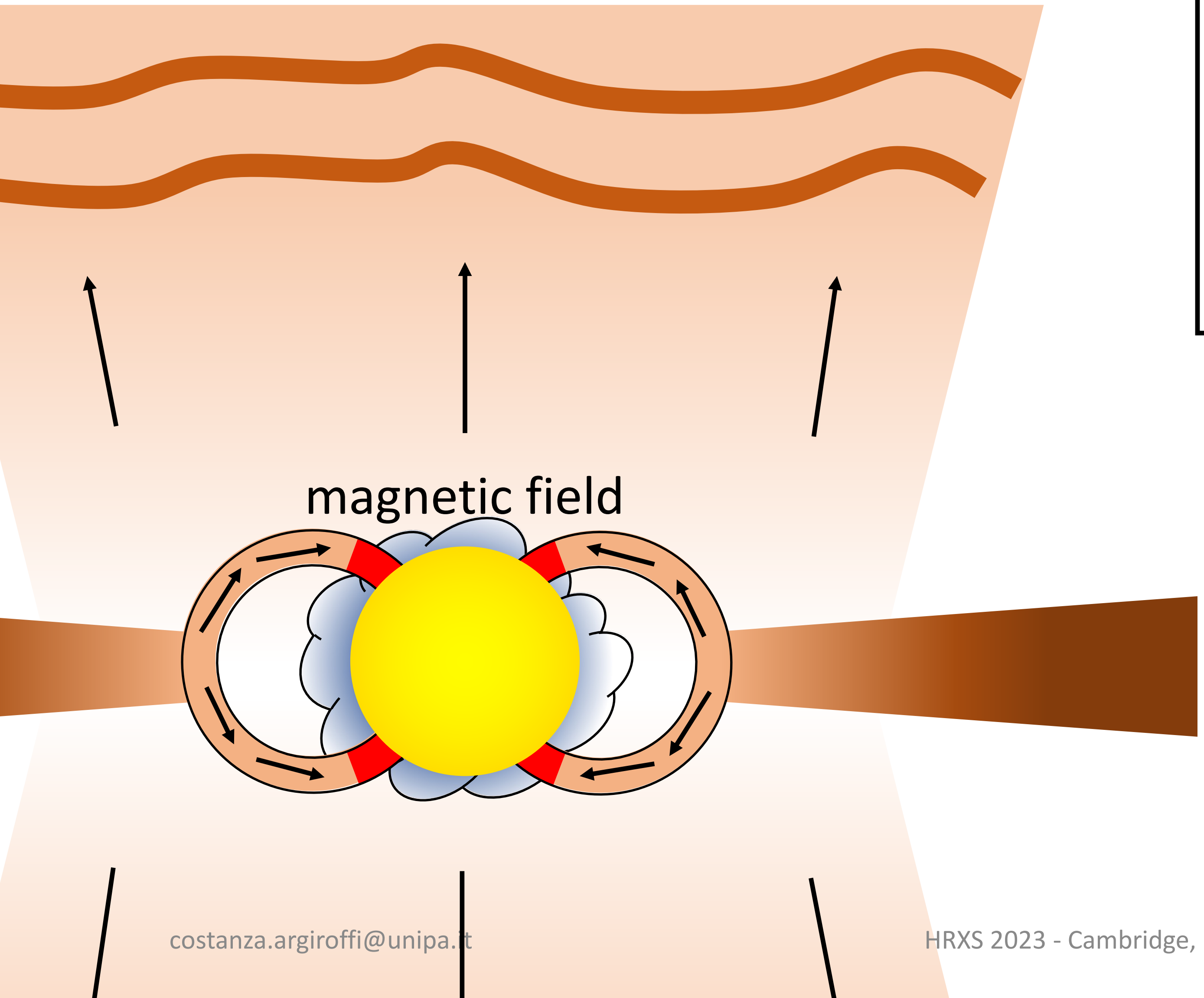
High-resolution X-ray spectroscopy: a fundamental tool to study magnetic phenomena in the atmospheres of cool stars

Costanza Argiroffi

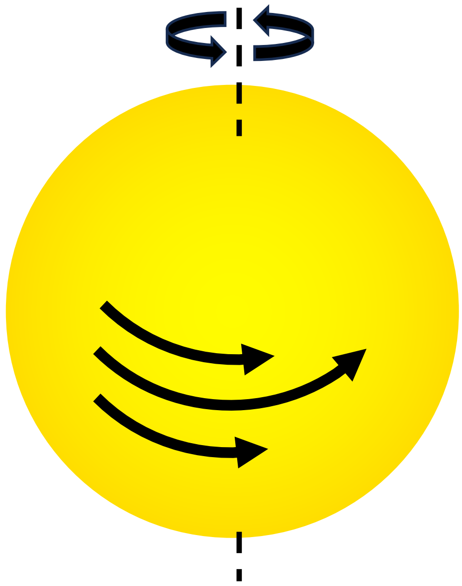
DiFC, University of Palermo, Italy
INAF – Osservatorio Astronomico di Palermo, Italy

X-ray emission from late type stars



- Coronal plasma
- Plasma heated in the accretion shock
- Plasma heated in outflow shocks
- Fluorescence from cold material

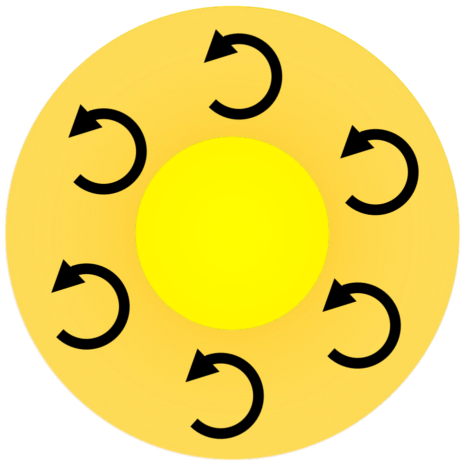
Magnetic field production in late type stars



Differential rotation

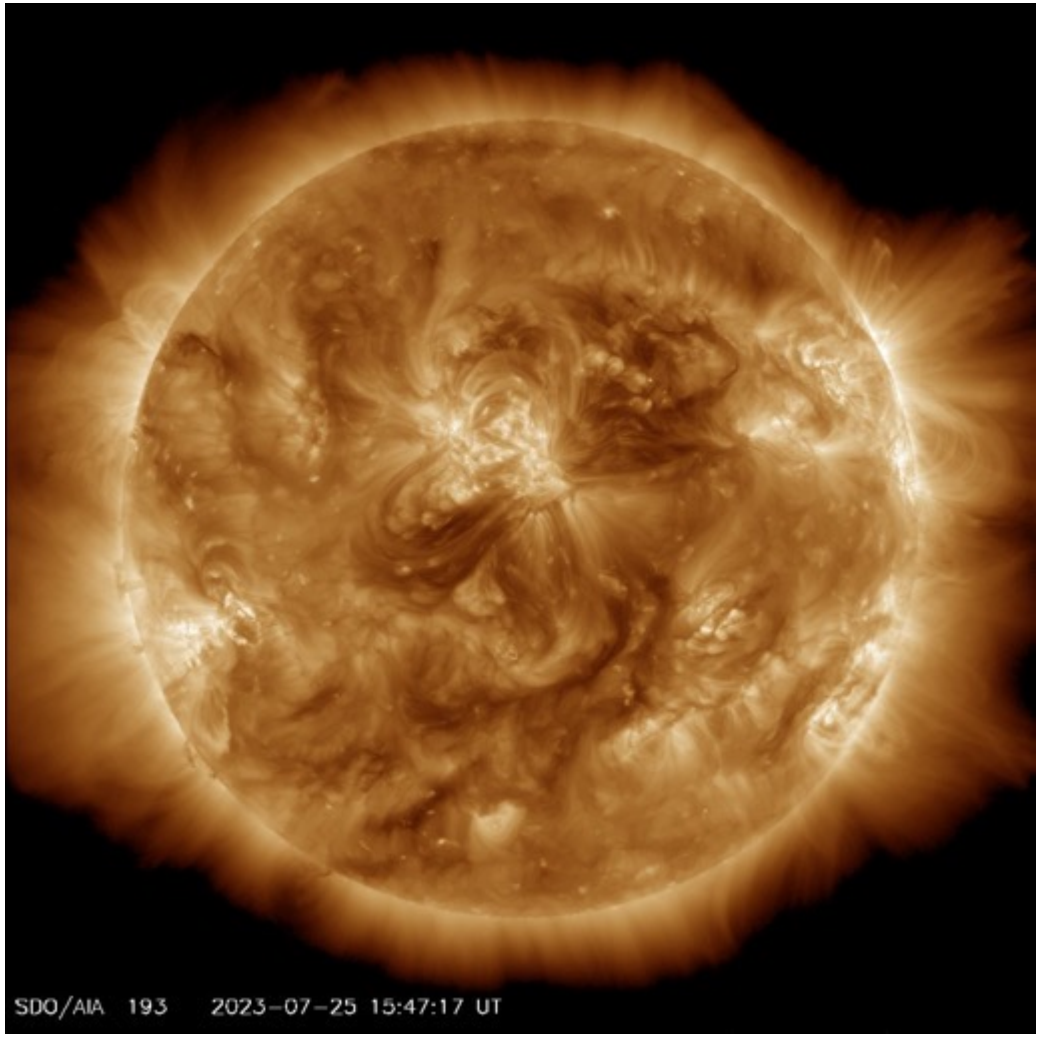
+

Outer convective envelope



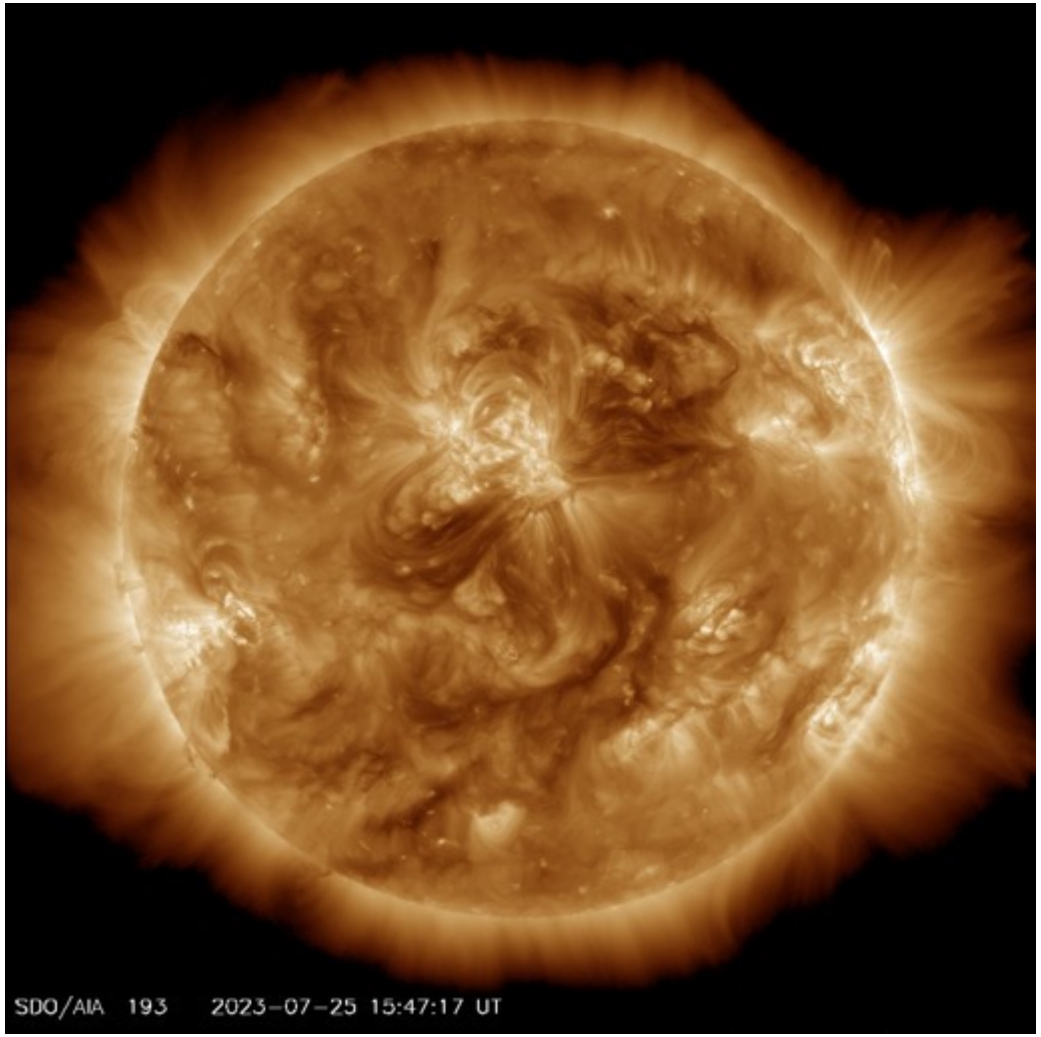
➔ Magnetic field

Stellar coronae



- Hot plasma (10 MK) at low-density located in the outer stellar atmosphere
- X-ray emission is optically thin
- Coronal luminosity L_{X} up to 10^{32} erg s^{-1}
- Stellar activity level $\left(\frac{L_{\mathrm{X}}}{L_{\mathrm{bol}}}\right)$ up to 10^{-3}

Stellar coronae: open issues



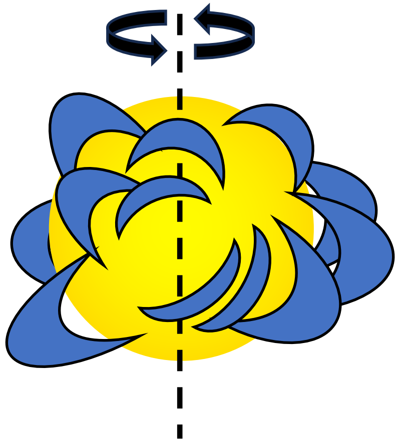
Thanks to spatial resolution, the solar corona can be observed in great detail

However, the Sun is not an active star (P_{rot} ~27 d, $L_X \sim 10^{27}$ erg s^{-1})

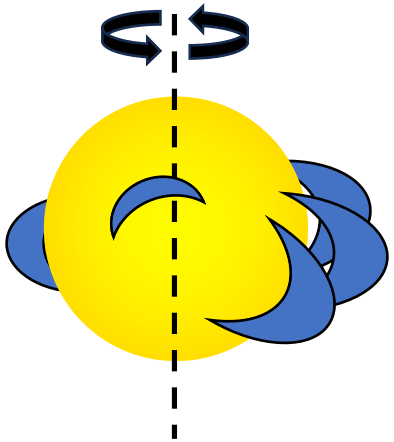
- What are the physical properties of active stellar coronae?
- Whether and how do coronal properties depend on stellar mass, rotation, age?
- Are energetic flares a scaled-up version of solar flares?
- Do coronal mass ejections occur also in active stars?

Spatial distribution of coronal plasma

In rapid rotators, equatorial velocity can reach ~100 km s^{-1}



coronal plasma at low latitude ⟷ line broadenings



coronal plasma at a given longitude ⟷ line shifts

Spatial distribution of coronal plasma

AB Dor

K0 dwarf, *v* sin *i* ~ 100 km s^{-1}, *i* ~ 60 deg

(Chandra/LETGS, Hussain et al. 2005, 2007)

- No line broadening
- Rotationally modulated line shifts

(Chandra/HETGS, Drake et al. 2015)

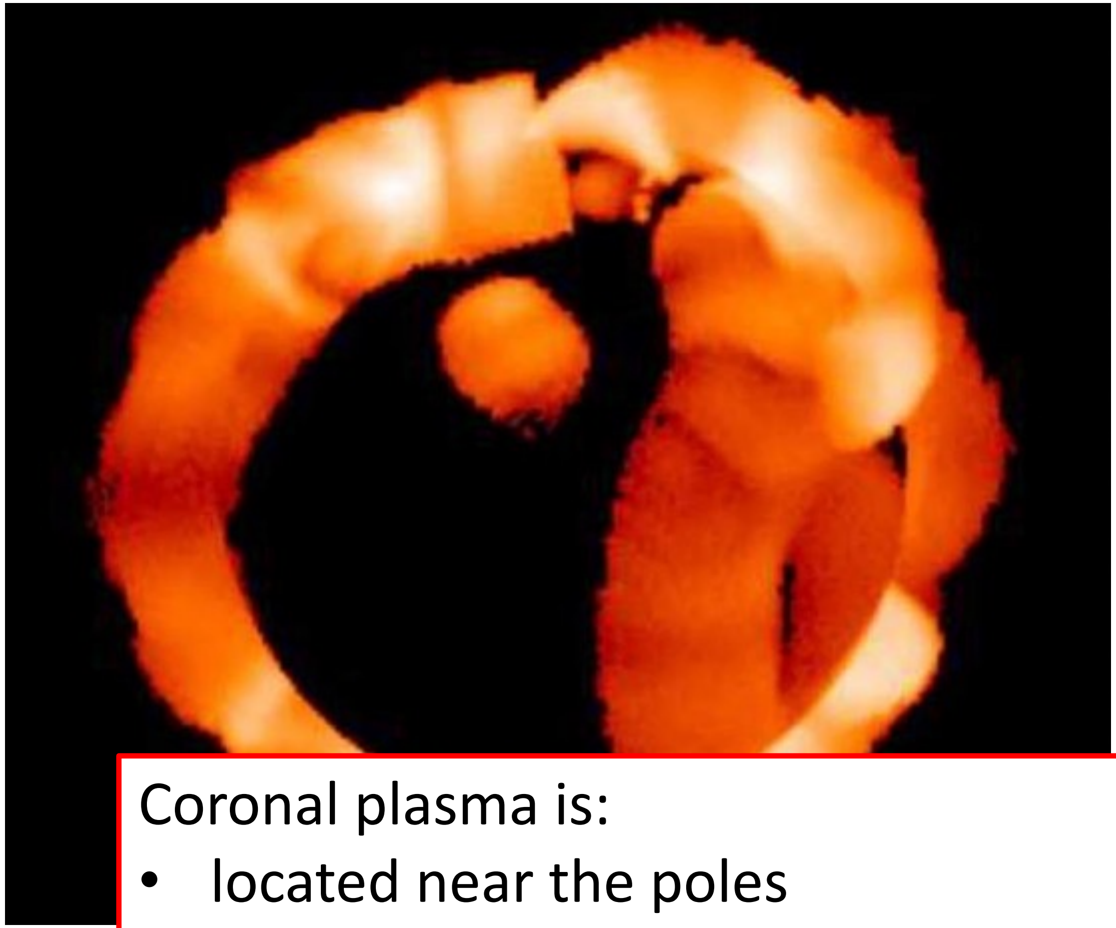
- No line broadening
- No line shift

FK Com

G4 giant, *v* sin *i* ~ 160 km s^{-1}, *i* ~ 60 deg

(Chandra/HETGS, Drake et al. 2008)

- Line shifts



Coronal plasma is:

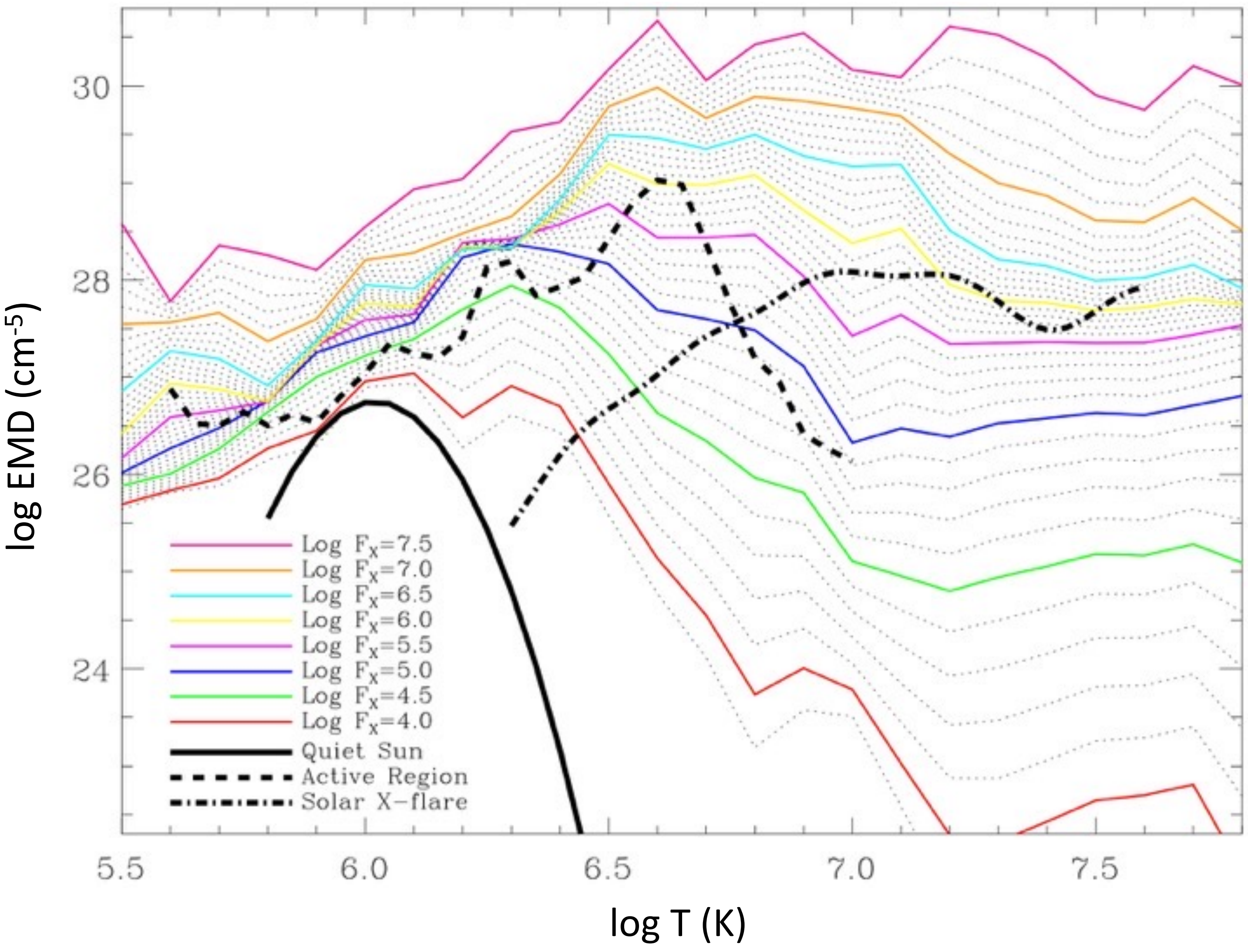
- located near the poles
- unevenly distributed in longitude

EMD of stars at different activity levels

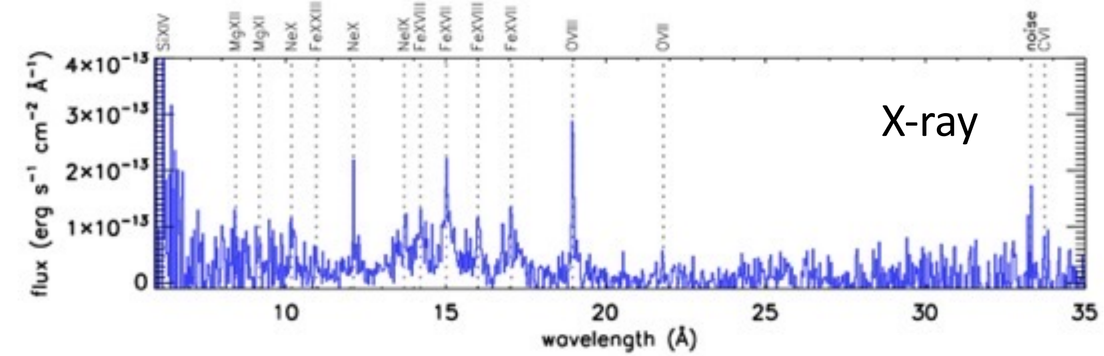
Wood et al. 2018

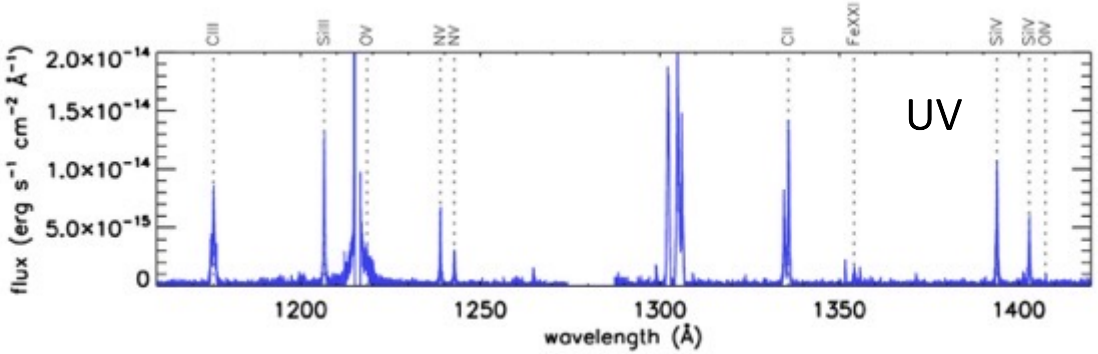
- 19 main sequence stars observed with Chandra/LETGS (Wood et al. 2018)
- Spectral type from F1 to M4.5
- L_X from 10^{27} to 10^{30} erg s^{-1}
- Activity level probed by the surface X-ray flux *F*x

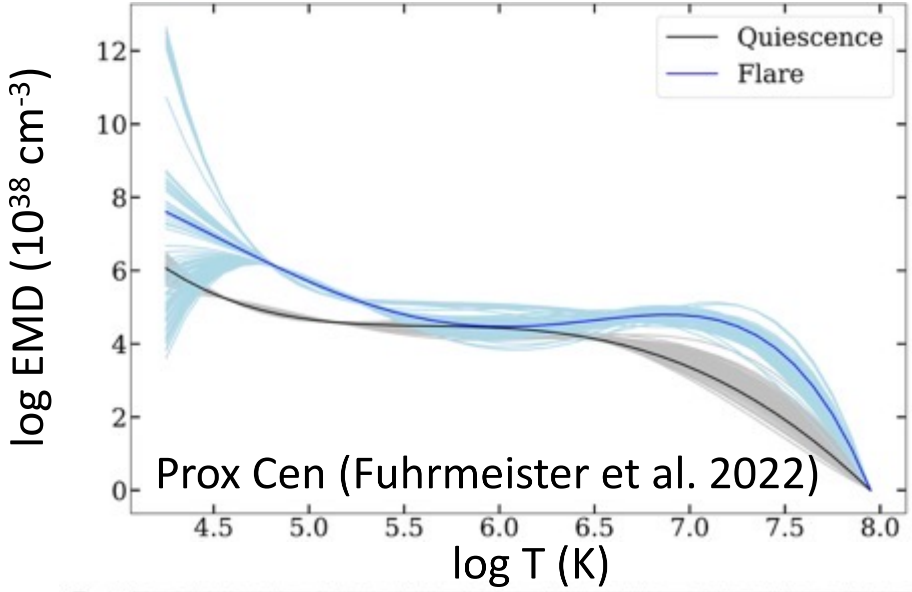
(See also Scelsi et al. 2005, Wood & Linsky 2006, Huenemoerder et al. 2013)

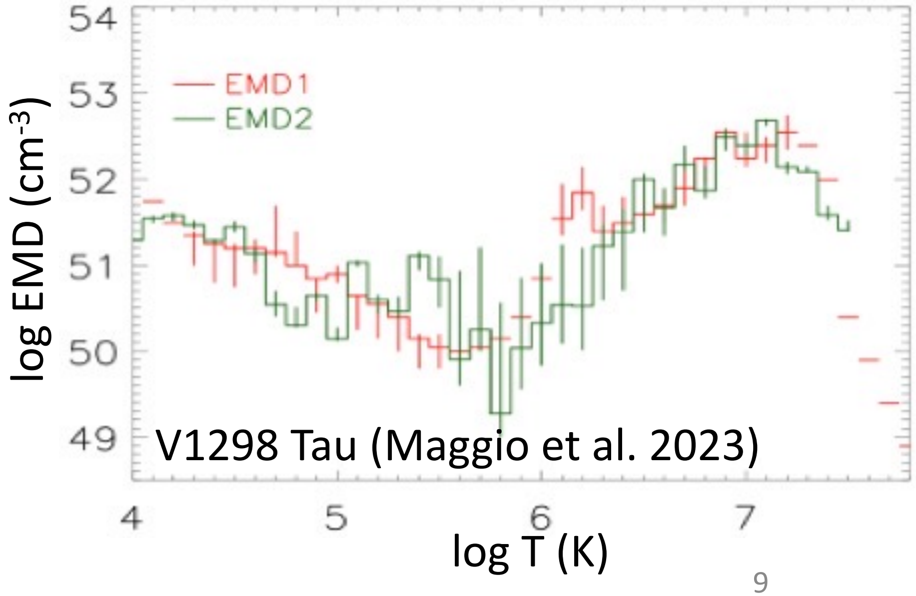


EMD: from the chromosphere to the corona









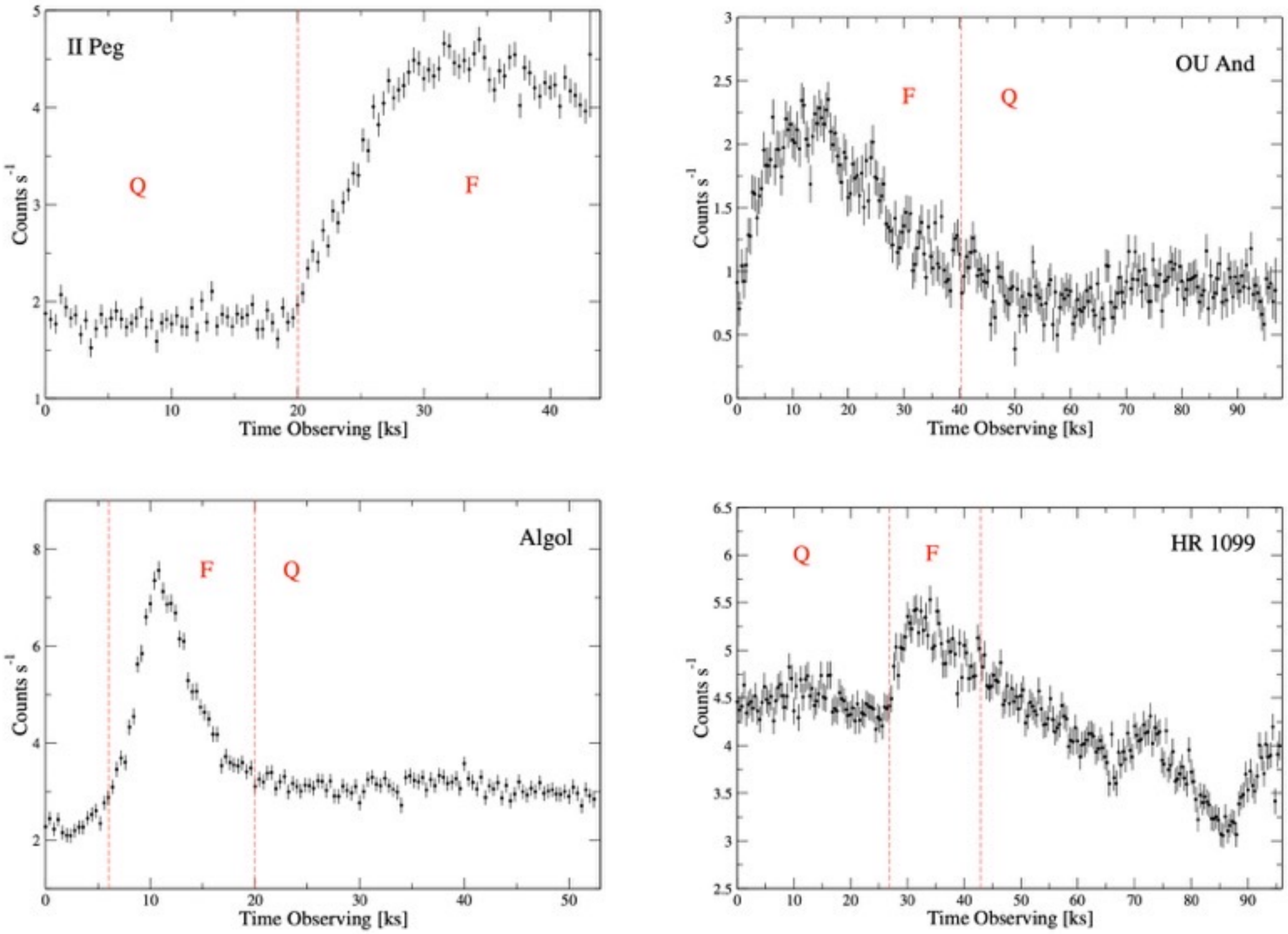
Aims:

- Have a thermal profile of the entire atmosphere from 10^4 to 10^8 K
- Constrain the EUV (~100-1000 Å) radiation from planet-hosting stars to infer effects on planetary atmospheres

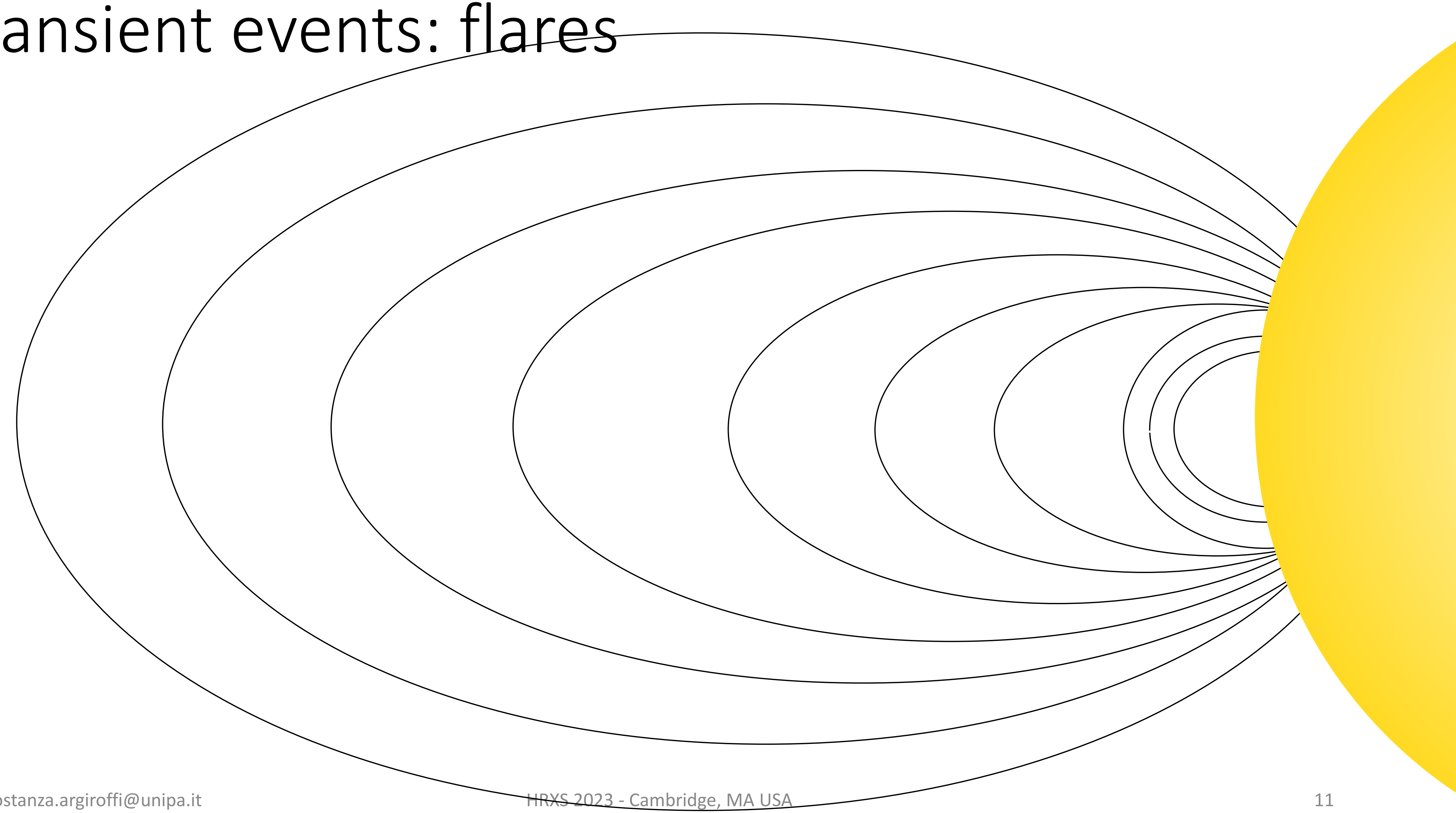
See also Bourrier et al. 2020, Duvvuri et al. 2021

Transient events: flares

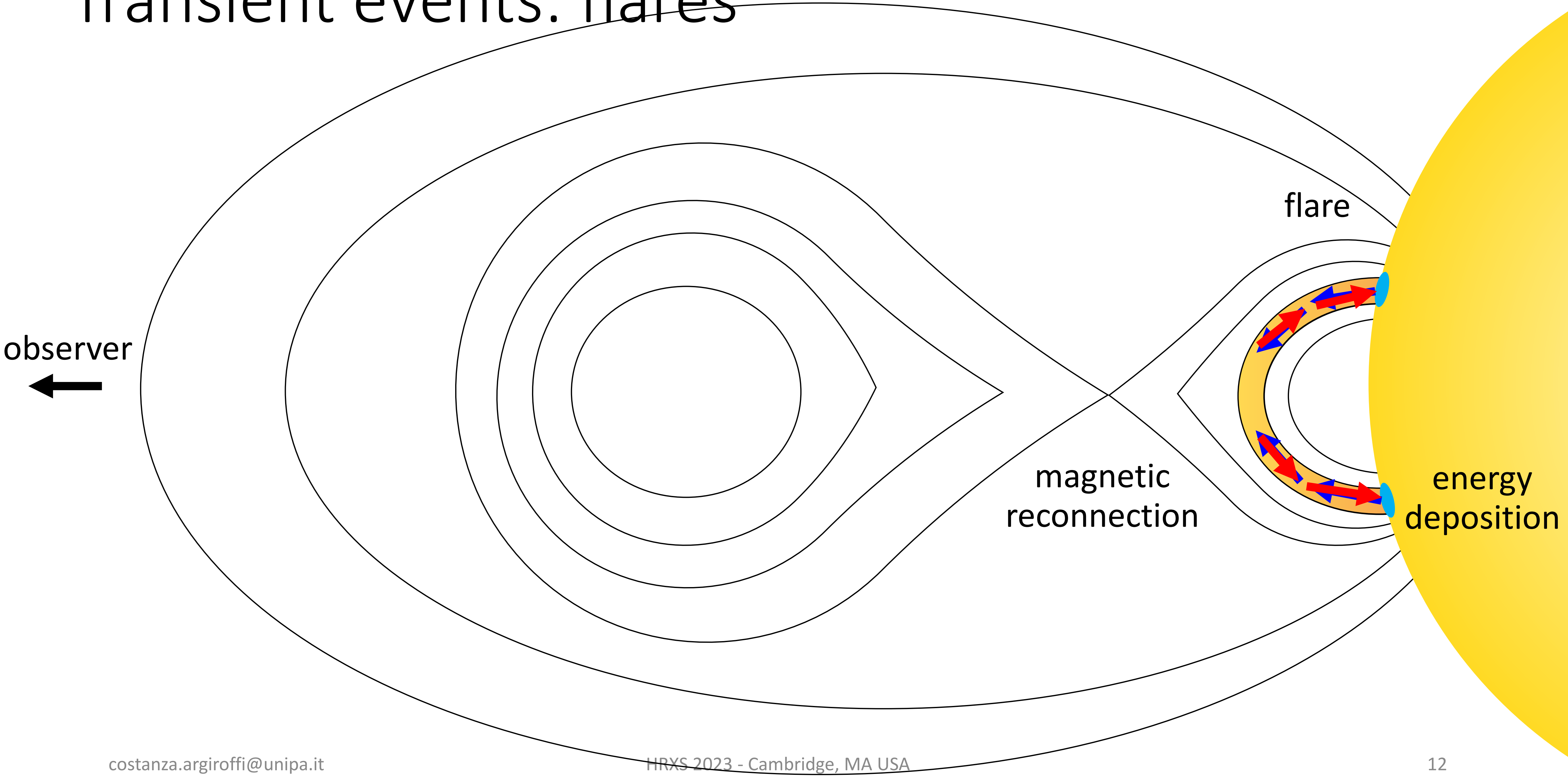
Nordon & Behar 2007



Transient events: flares

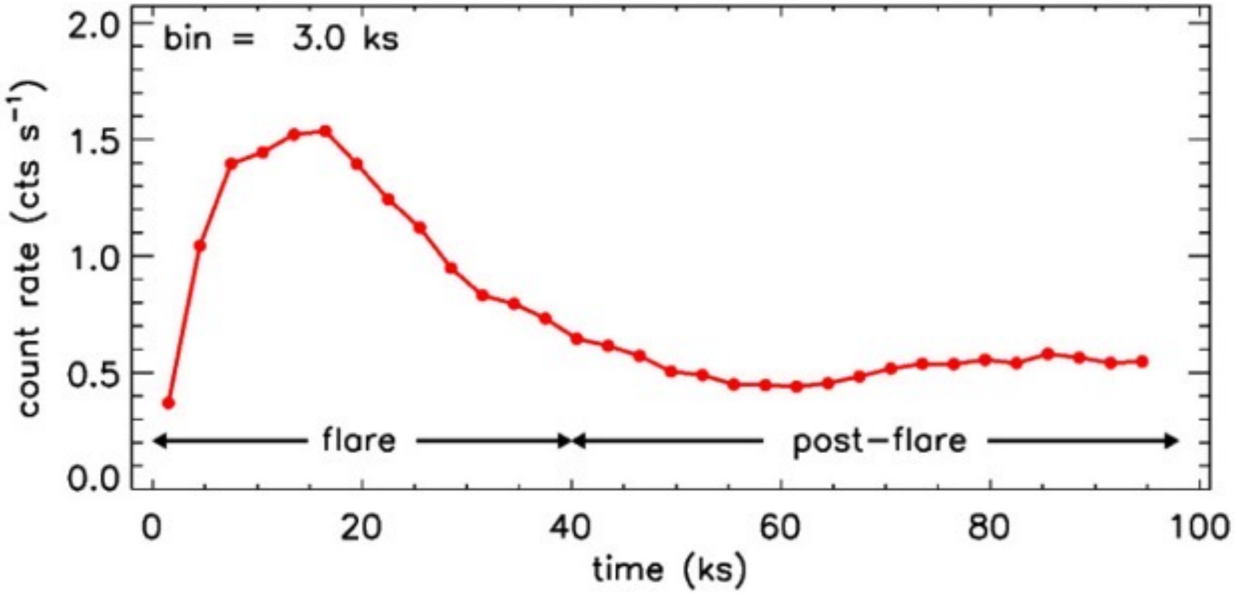


Transient events: flares



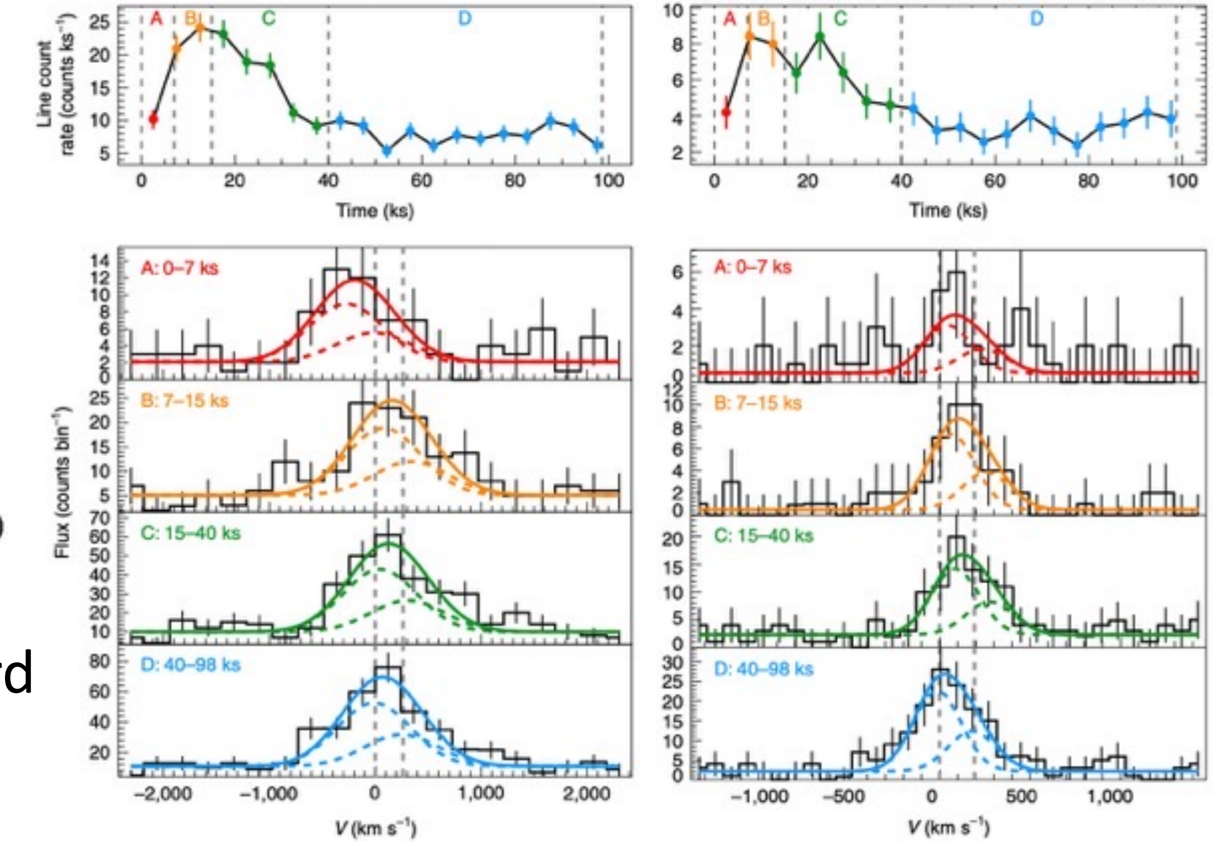
Transient events: plasma motions during flares

HR 9024 observed with Chandra/HETGS (Argiroffi et al. 2019)



Si XIV, 16 MK

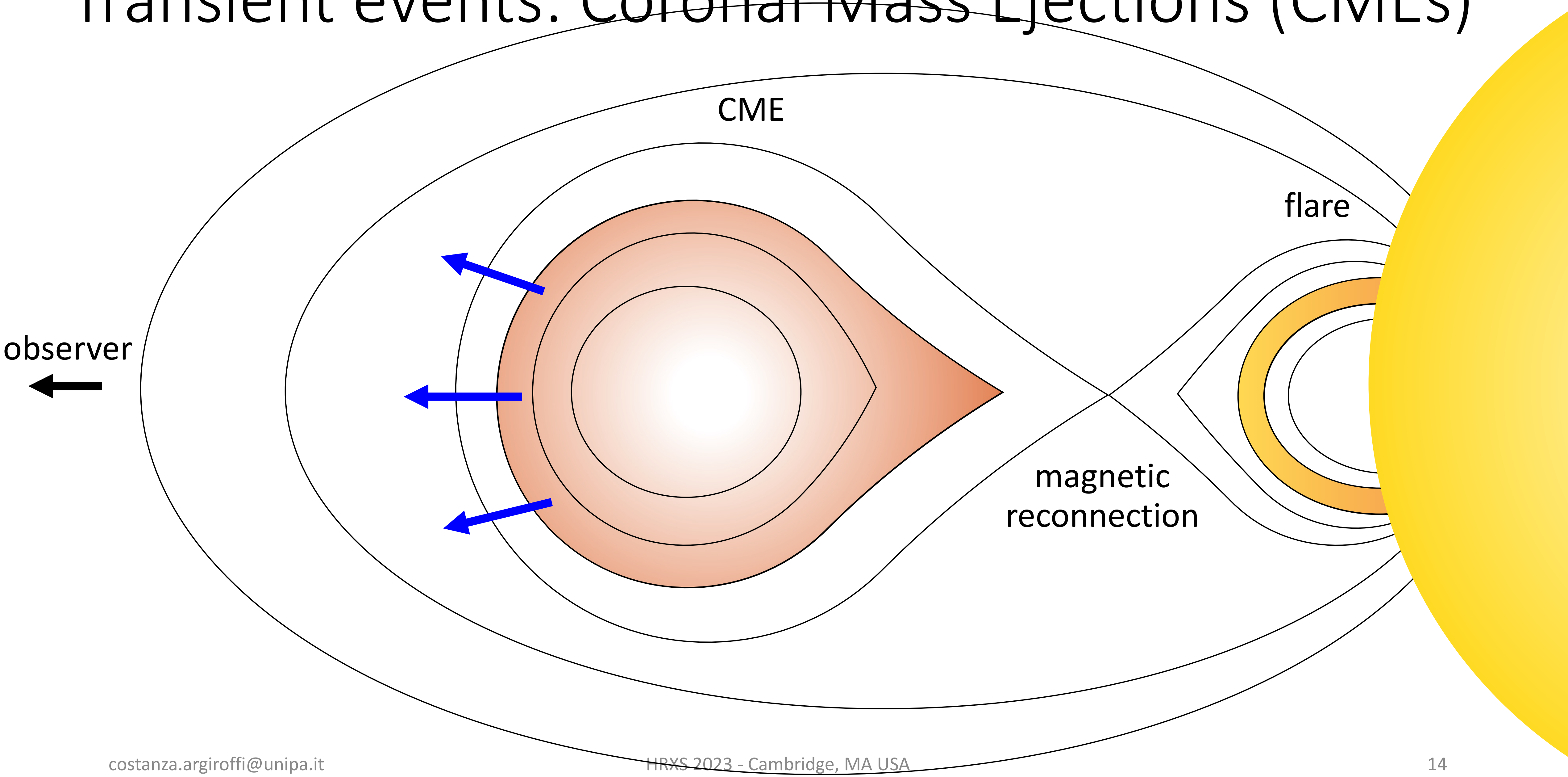
Mg XII, 10 MK



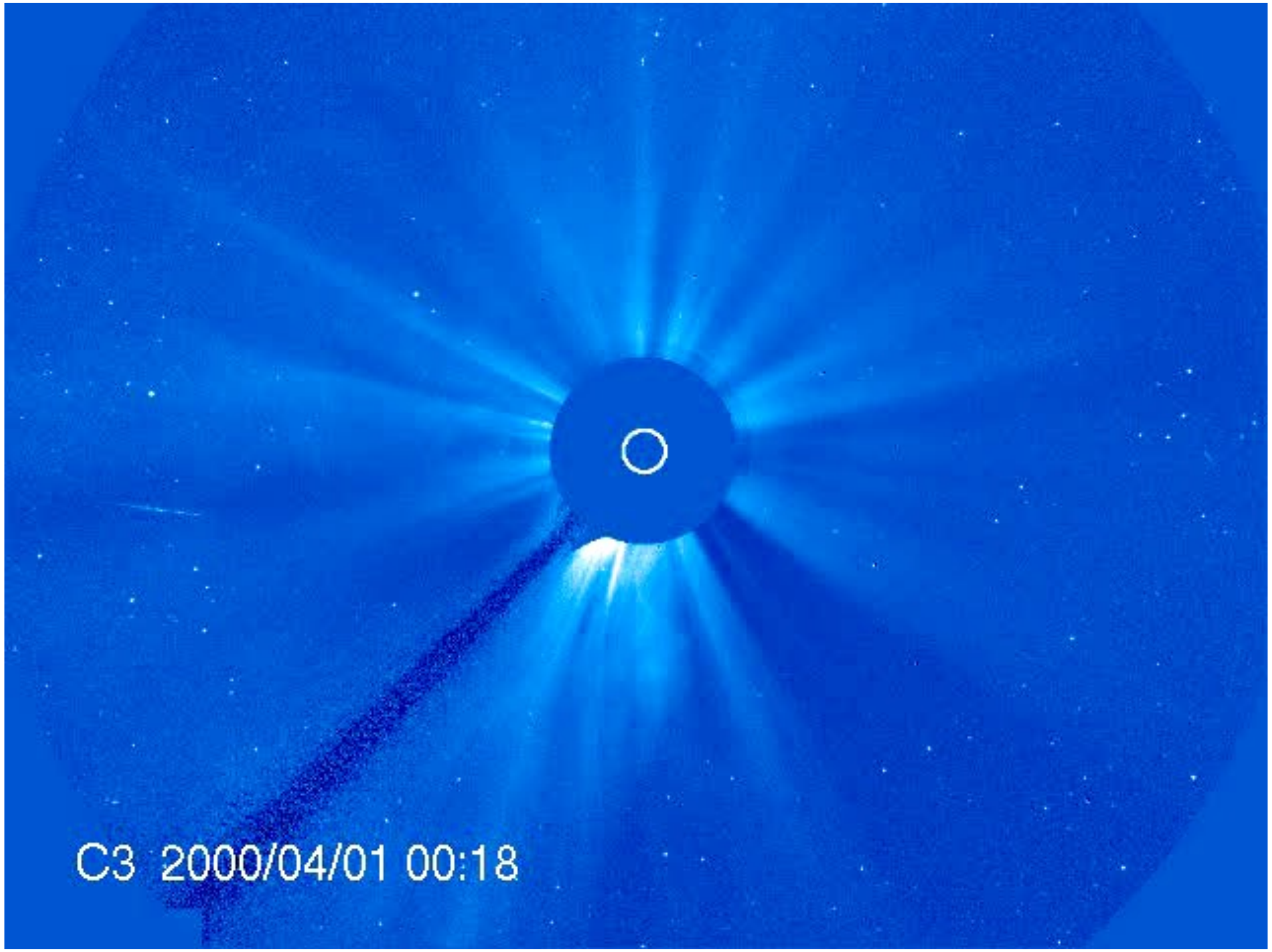
- First X-ray detection of upward and downward plasma motion during a stellar flare
- Validation of the standard flare model

See also Chen et al. 2022

Transient events: Coronal Mass Ejections (CMEs)



Transient events: CMEs

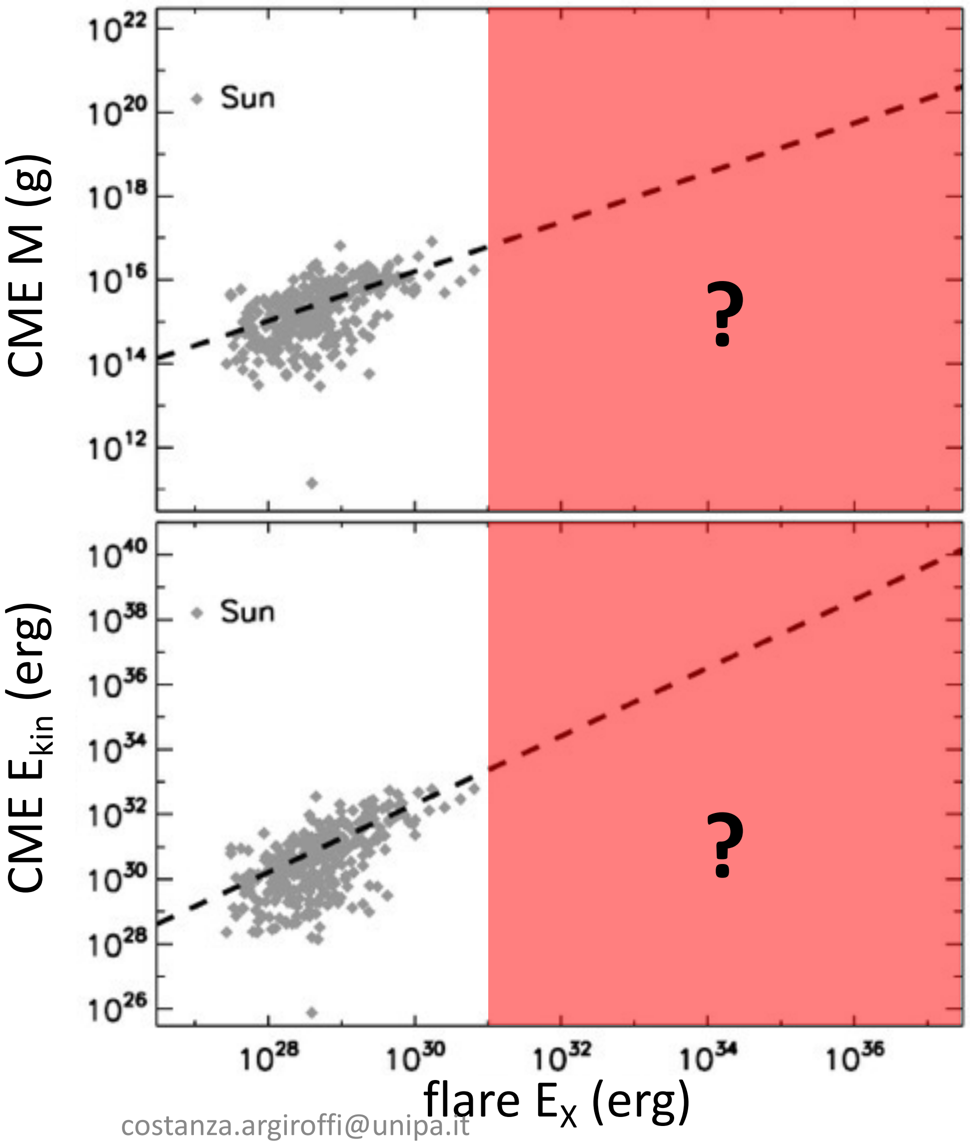


Solar CMEs:

- v ~ 20 – 3000 km s^{-1}
- $T \sim 10^4 - 10^6$ K
- $M \sim 10^{13} - 10^{17}$ g
- $E_{kin} \sim 10^{28} - 10^{33}$ erg

Importance of stellar CMEs

Yashiro & Gopalswamy 2009, Drake et al. 2013



Khodachenko et al. 2007; Lammer et al. 2007; Aarnio et al. 2012; Drake et al. 2013; Osten & Wolk 2015; Cranmer 2017; Odert et al. 2017; Cherenkov et al. 2017.

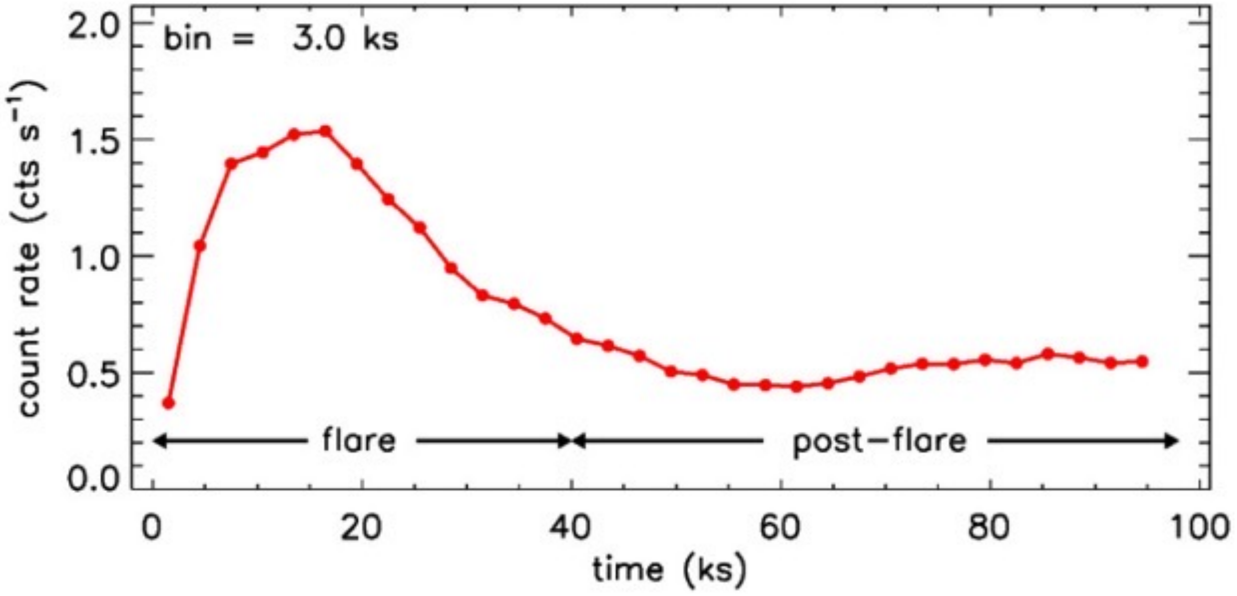
Stellar CMEs can cause:

- **Mass loss**
  up to 10^{-9} $M_{\odot}$ yr^{-1} → Stellar evolution, Rotation evolution
- **Energy loss**
  up to 0.1 L_{bol} → Stellar evolution

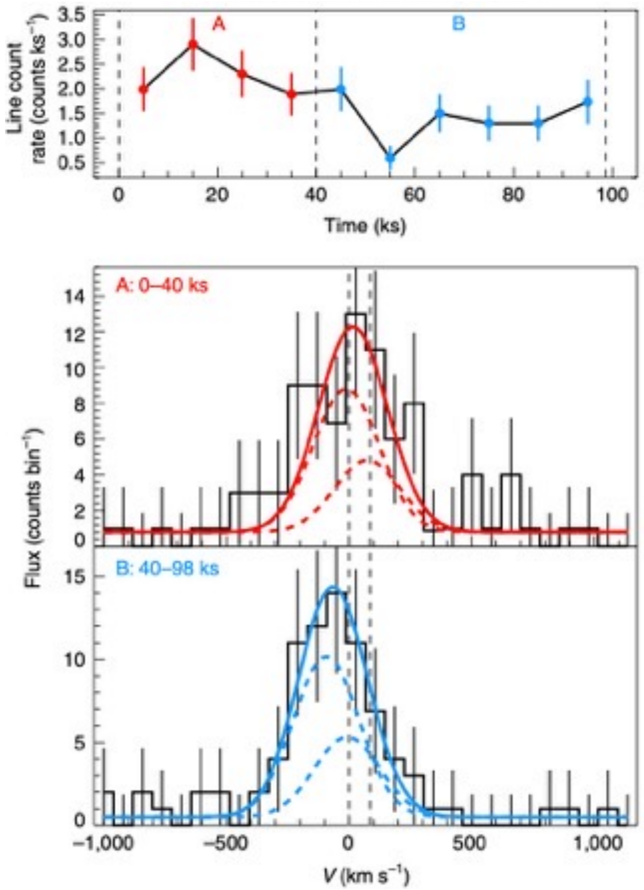
→ Planetary system evolution

Stellar CME detection

HR 9024 observed with Chandra/HETGS (Argiroffi et al. 2019)

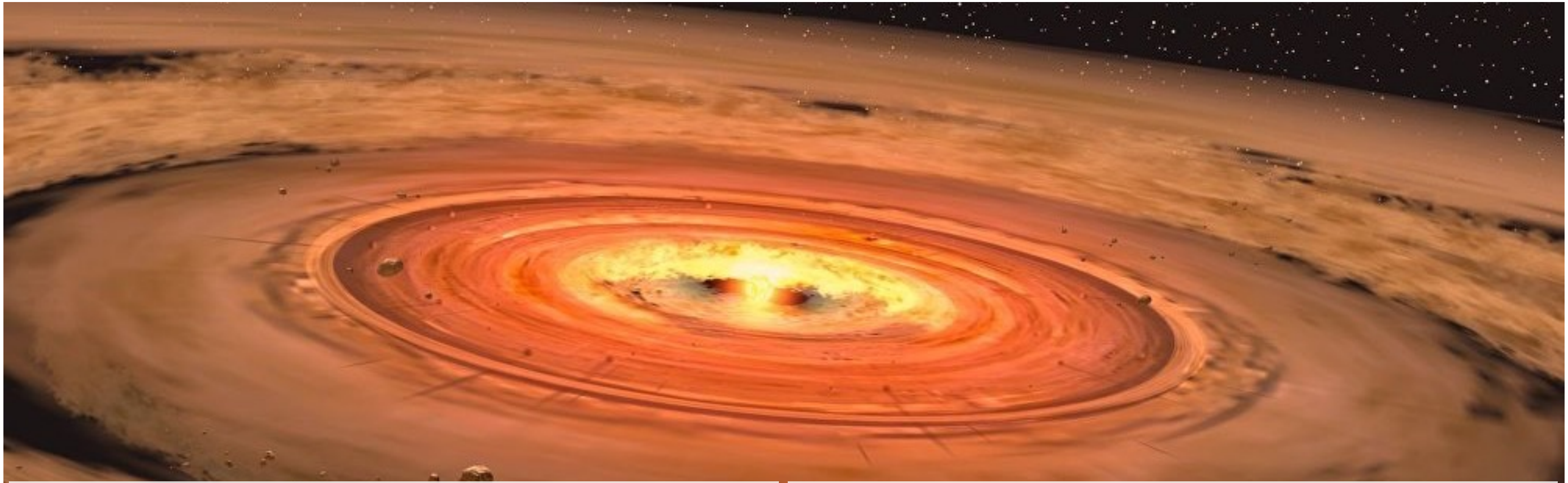


O VIII, 3 MK



- First X-ray detection of a stellar CME
- A new CME detection technique, important in the light of future X-ray missions

Accretion in young stars



Important because:

- exchanges of mass/angular momentum/energy
- stellar evolution
- rotation evolution
- circumstellar disk evolution
- accretion vs magnetic activity interplay

Open issues:

- accretion geometry
- structure of the shock region
- origin of radiation from IR to X-rays
- local absorption

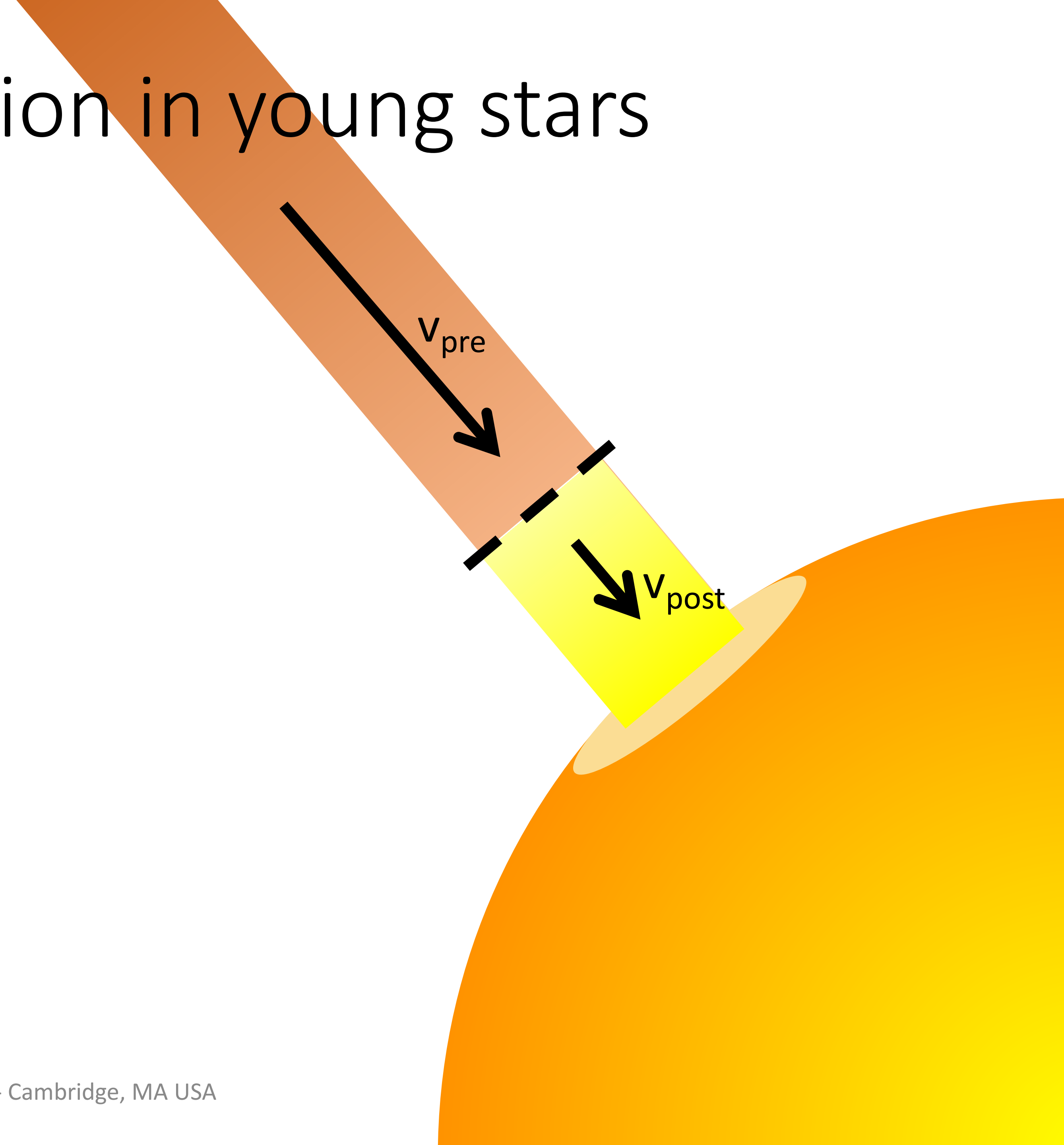
Magnetospheric accretion in young stars

$v_{pre} \approx 300 - 500$ km s^{-1}

$v_{post} = v_{pre}/4 \approx 100$ km s^{-1}

$n_{post} = 4\, n_{pre}$

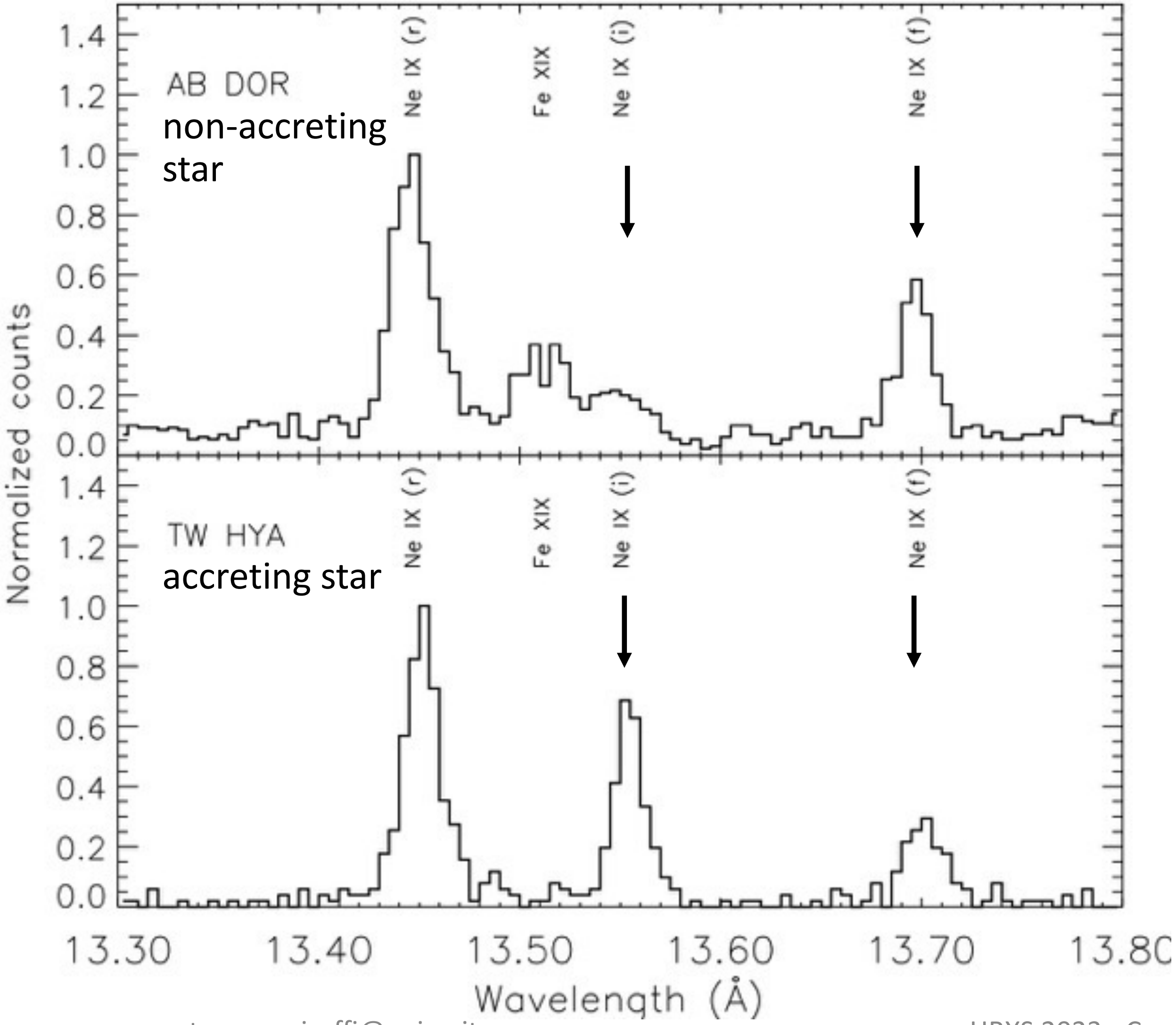
$T_{post} = (3 m v^2_{pre})/(16 k_b) \approx 1 - 3$ MK



costanza.argiroffi@unipa.it

Soft X-rays from the accretion shock

Ne IX triplet



Non accreting stars

➔plasma at a few MK has low density

Accreting stars

➔plasma at a few MK has high density

In young accreting stars, plasma at a few MK is not coronal plasma but plasma heated in the accretion shock

X-rays as a probe of the accretion shock region

$v_{pre} \approx 300 - 500$ km s^{-1}

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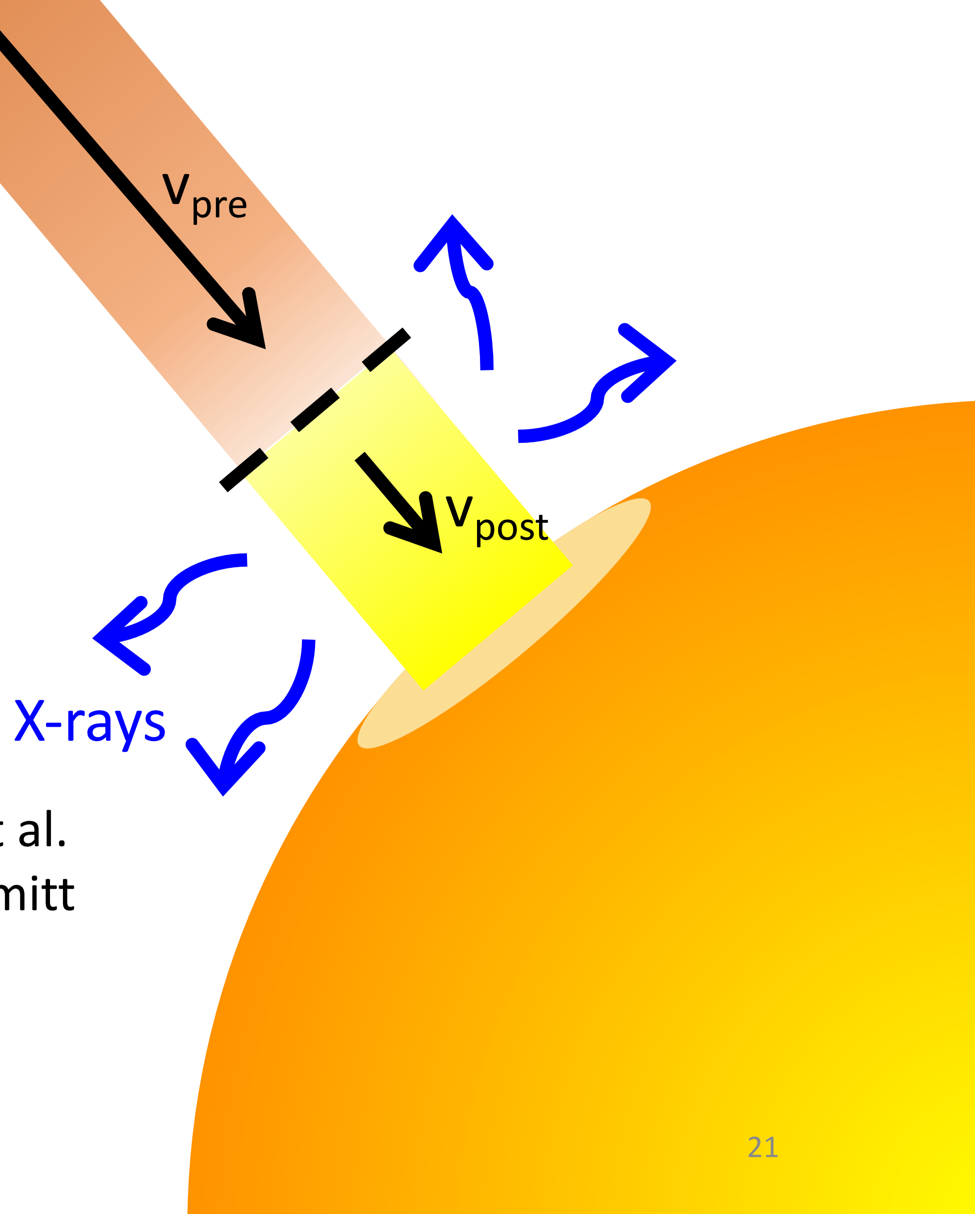

Kastner et al. 2002, Stelzer et al. 2004, Schmitt et al. 2005, Günther et al. 2006, Heunemoerder et al. 2007, Argiroffi et al. 2007, Robrade & Schmitt 2007, Argiroffi et al. 2011, Günther et al. 2013

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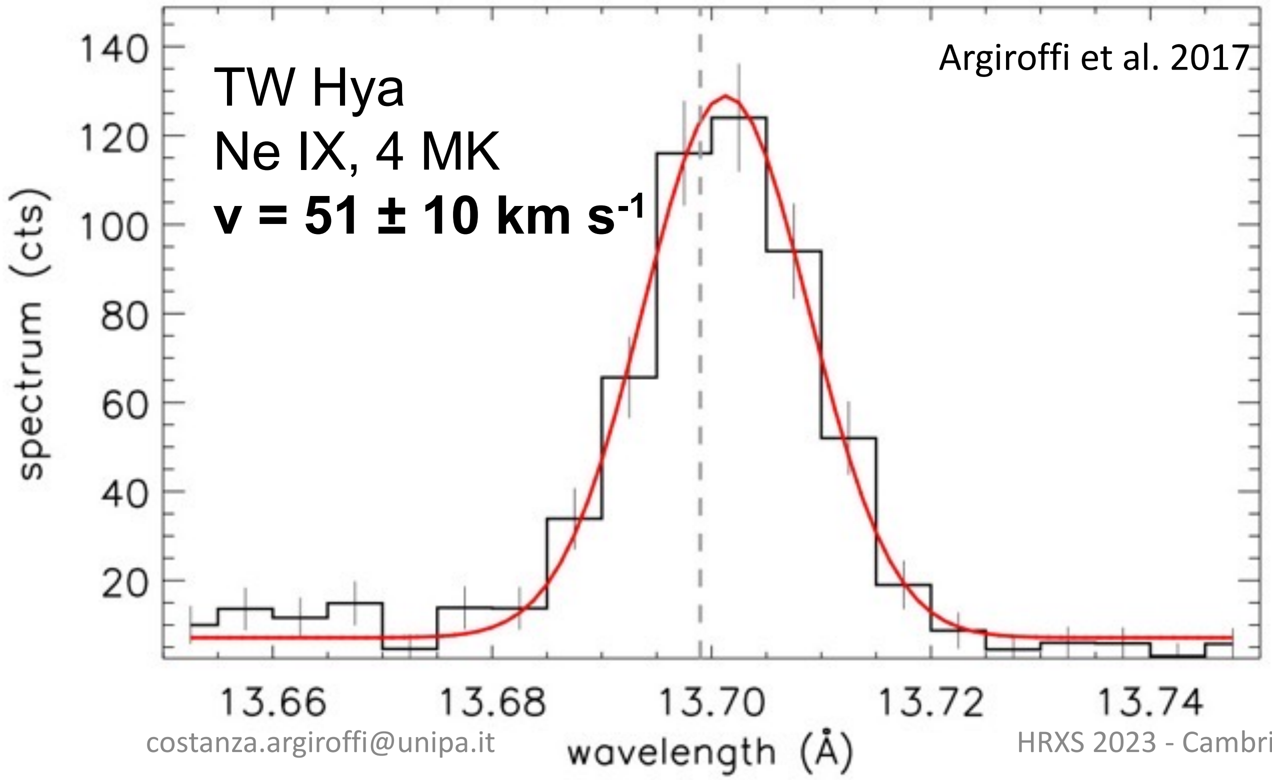

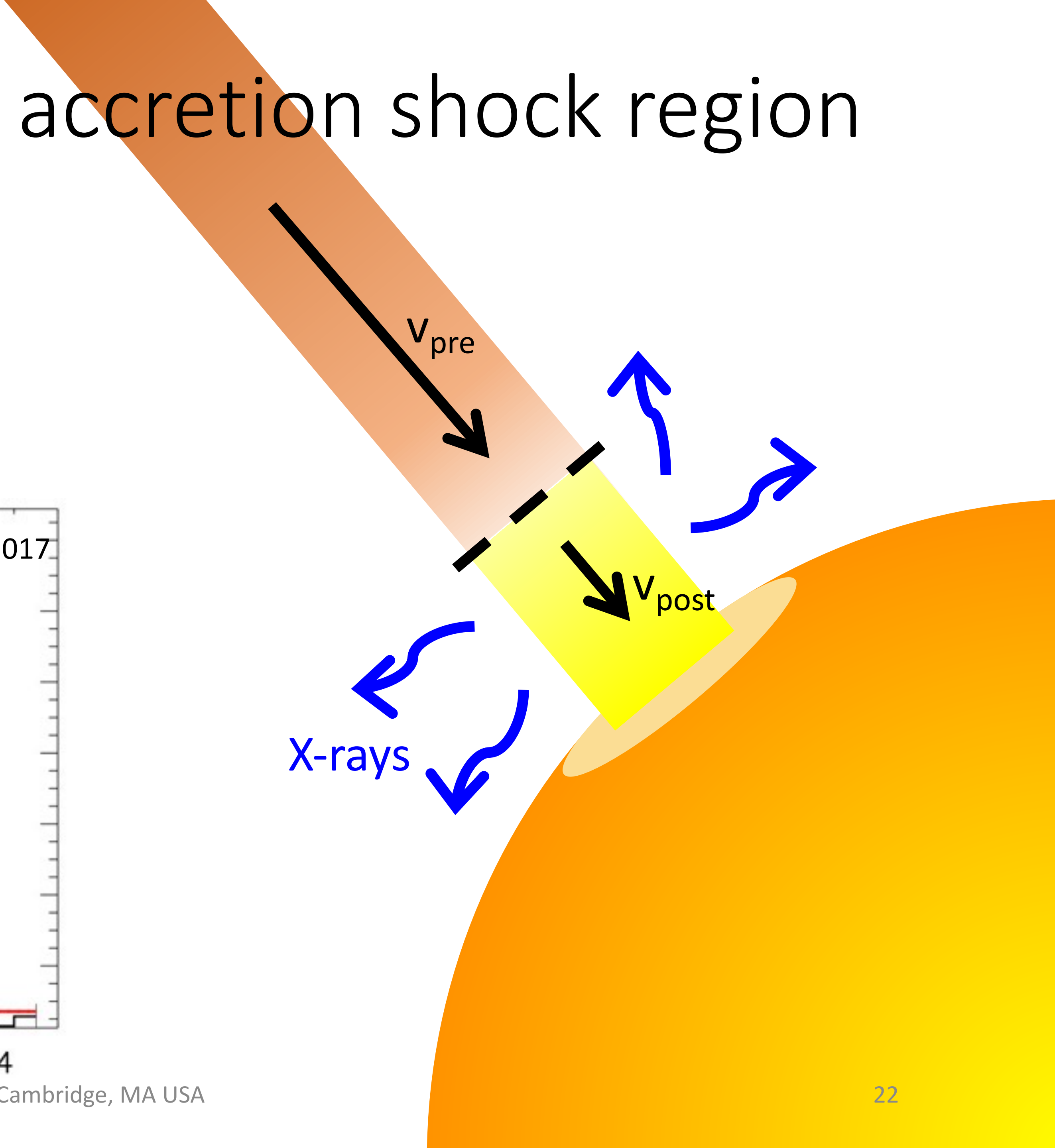

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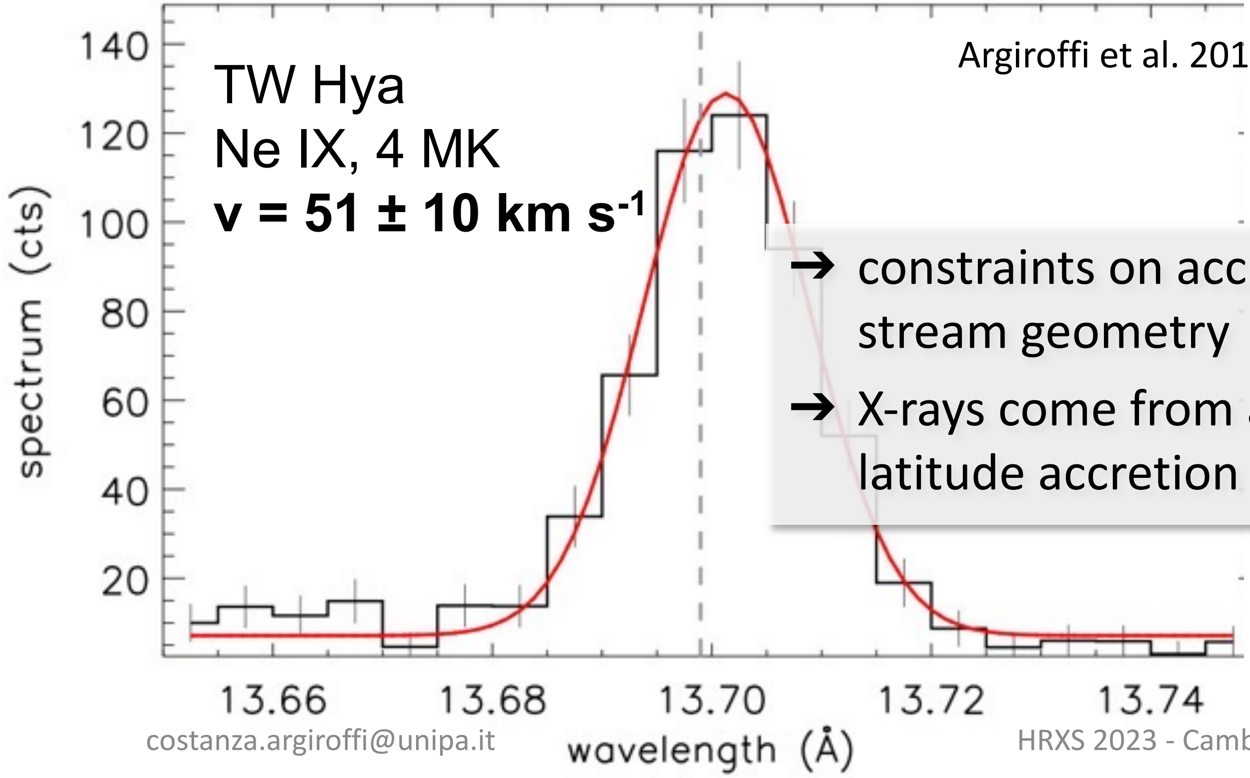
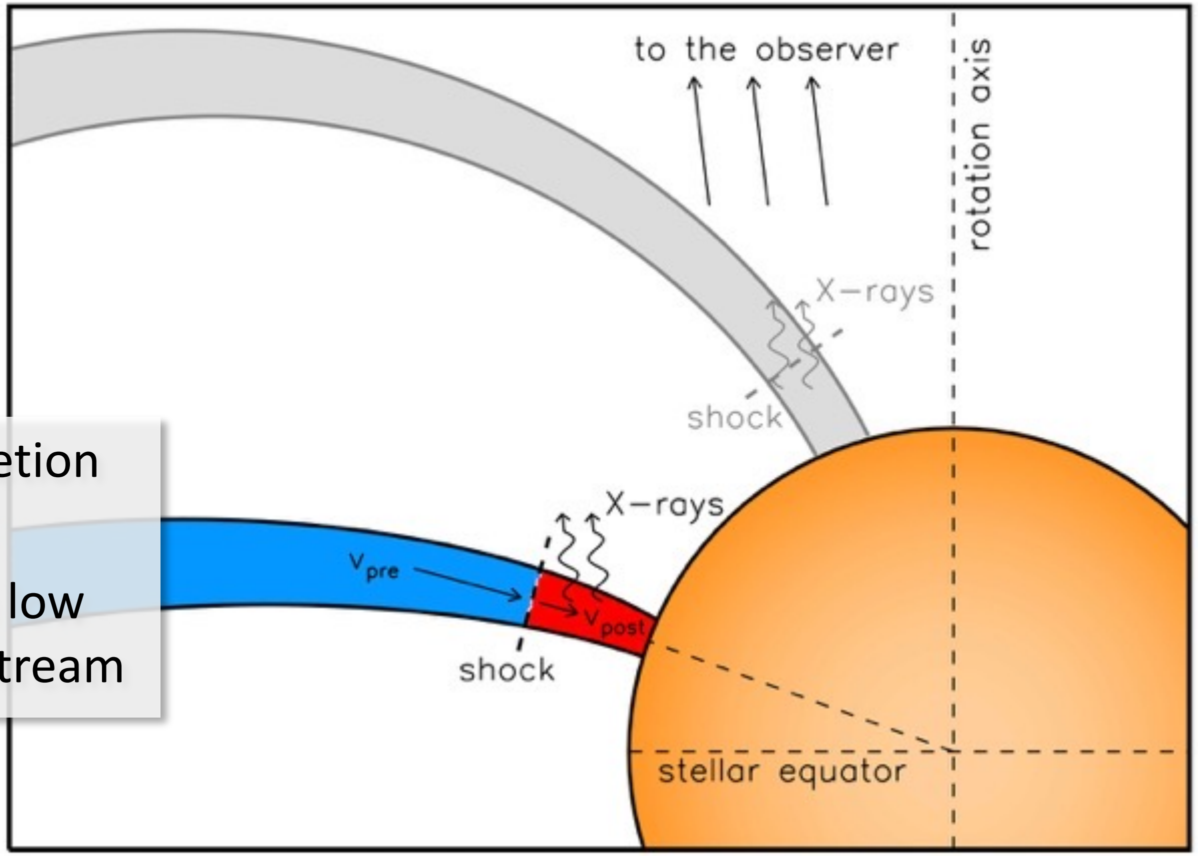


Argiroffi et al. 2017



- ➔ constraints on accretion stream geometry
- ➔ X-rays come from a low latitude accretion stream

X-rays as a probe of the accretion shock region

Other important results obtained with high resolution X-ray spectroscopy

- Measure the chemical composition of the accretion stream
  - ➔ Study the chemical evolution of the acretion disk (Drake et al. 2005)

- Measure rotational modulation effects
  - ➔ Constrain the accretion geometry (Argiroffi et al. 2011, 2012)

- Measure short term variability
  - ➔ probe intrinsic variations of the accretion stream (Brickhouse et al. 2012)

Summary

Stellar coronae

- Spatial structuring
- Plasma EMD distribution
- Flaring-CME plasma motions and properties

Accretion process in young stars

- properties of the accretion stream (density, temperature, abundances, velocity)
- accretion geometry

The future of high resolution X-ray spectroscopy

Large effective area will allow us to:

- Enlarge the samples of inspected sources
- Probe the inspected phenomena on shorter time scales

↓

- Routinely search for stellar CMEs
- Study stellar flares (density, velocities, abundances) in great detail
- Measure accretion velocity to constrain the accretion geometry in several stars
- Explore short time scale variations in the accretion streams