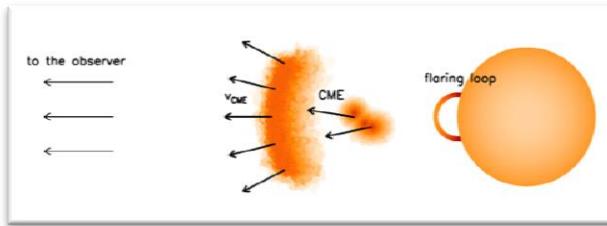


First X-ray detection of plasma motions in a stellar flare and in the associated CME



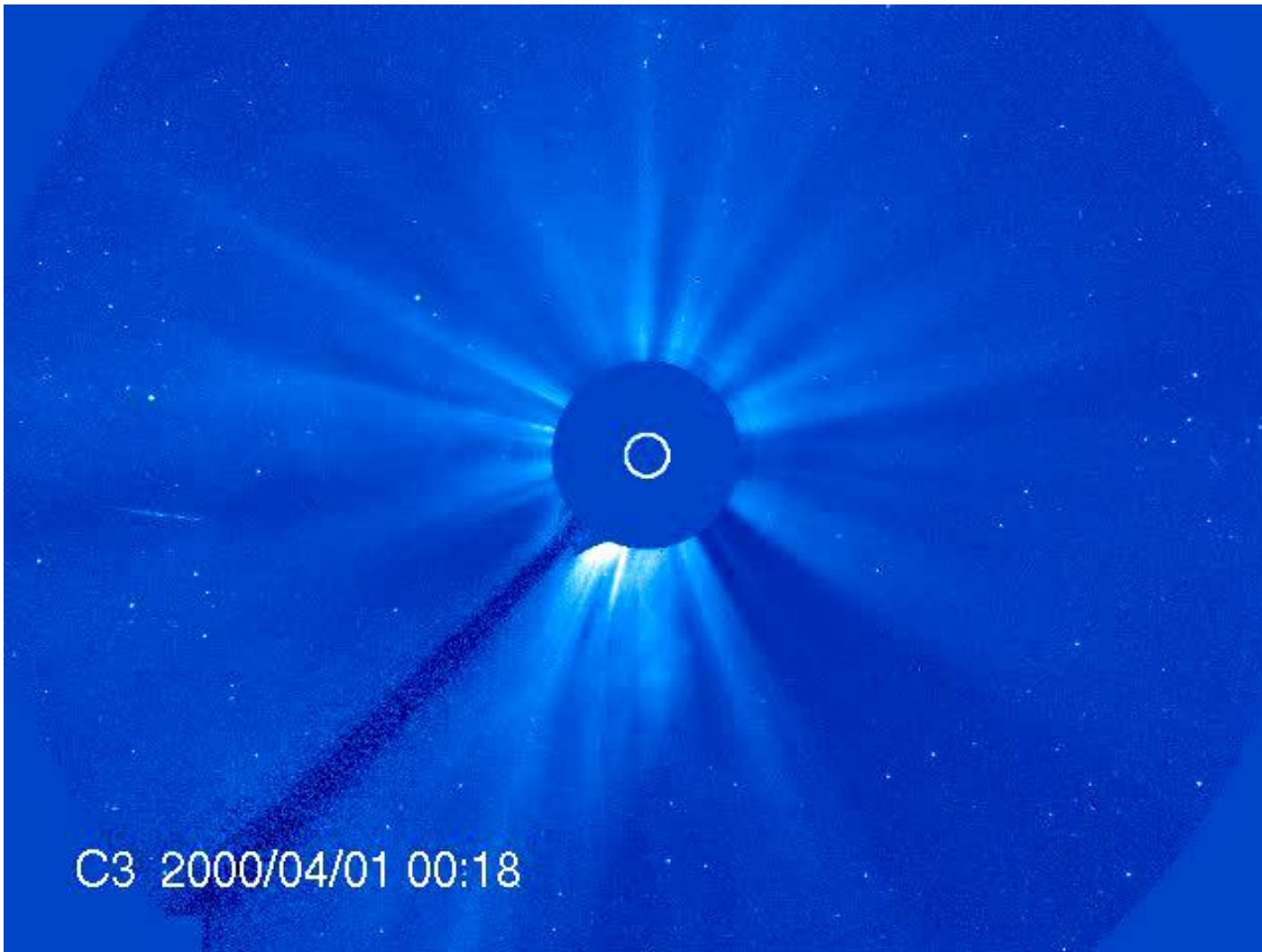
C. Argiroffi^{1,2}, F. Reale^{1,2}, J. J. Drake³, A. Ciaravella², P. Testa³,
R. Bonito², M. Miceli^{1,2}, S. Orlando², and G. Peres^{1,2}

¹ Dip. di Fisica e Chimica, Universita' di Palermo, Italy

² INAF - Osservatorio Astronomico di Palermo, Italy

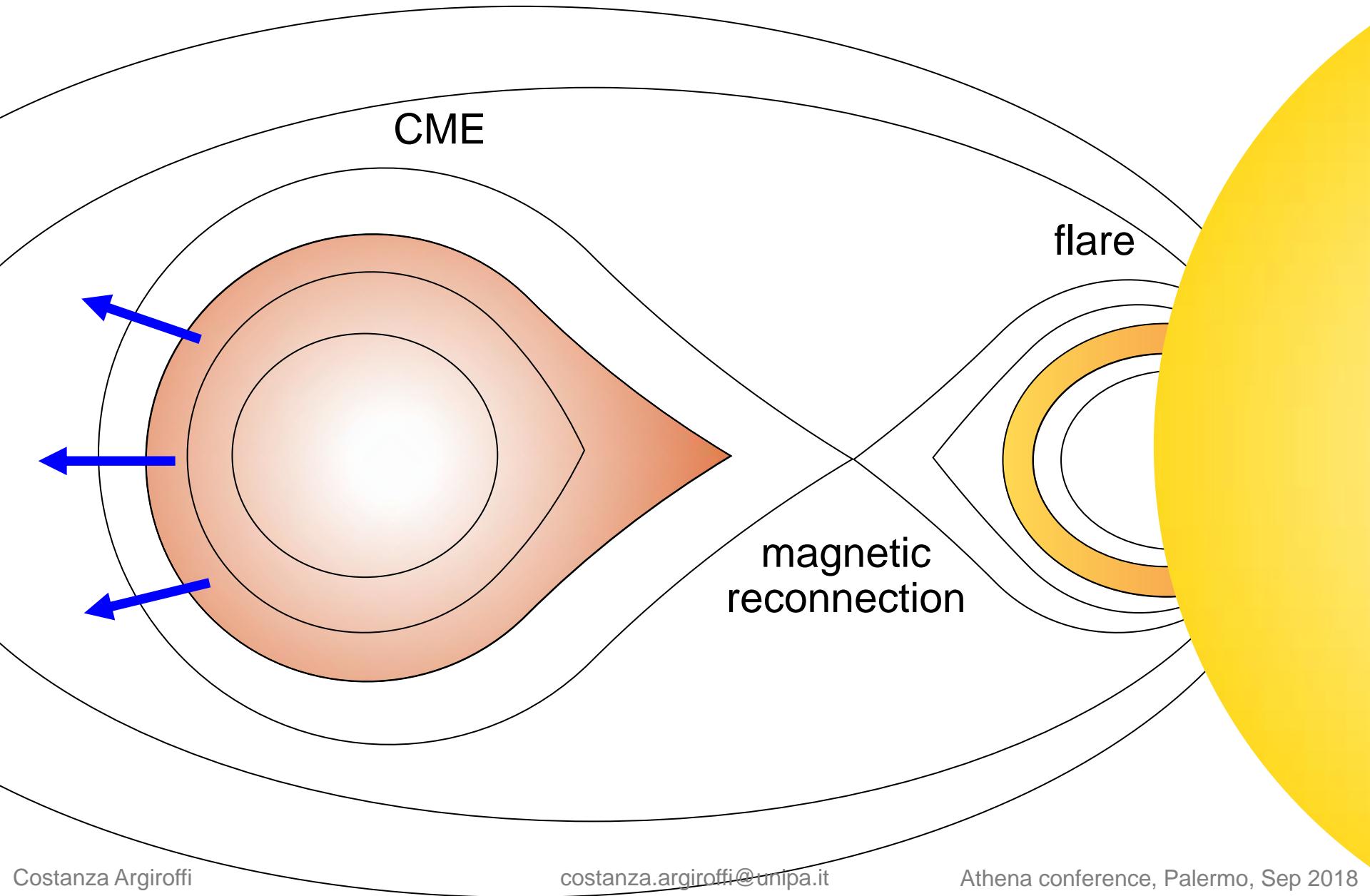
³ Smithsonian Astrophysical Observatory, Cambridge, US

CORONAL MASS EJECTIONS (CMEs) ON THE SUN



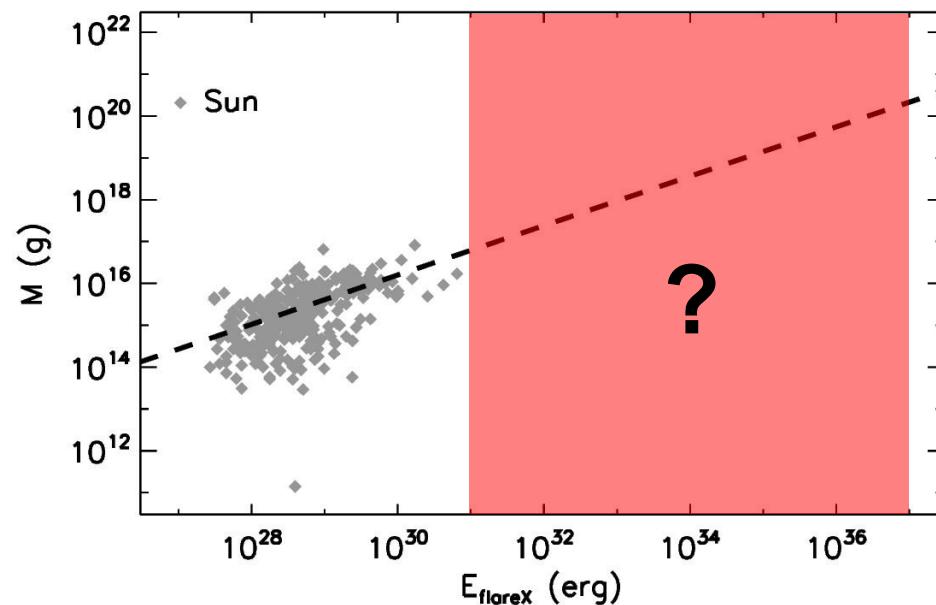
- $v \sim 20 - 3000 \text{ km s}^{-1}$
- $T \sim 10^4 - 10^6 \text{ K}$
- $M \sim 10^{13} - 10^{17} \text{ g}$
- $E_{\text{kin}} \sim 10^{28} - 10^{33} \text{ erg}$

FLARE-CME EVENTS



EXTRAPOLATING SOLAR CMEs

Yashiro & Gopalswamy 2009, Drake et al. 2013



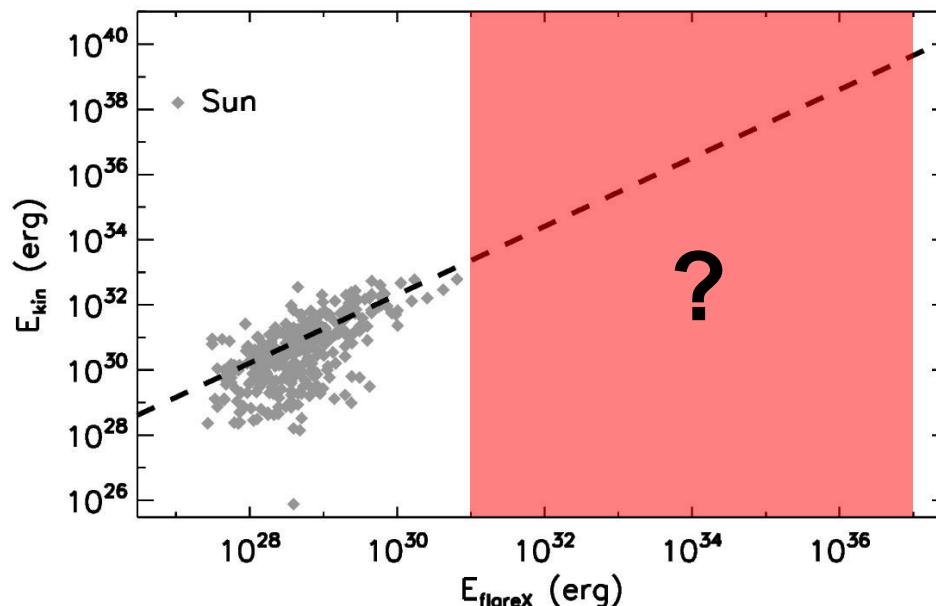
Khodachenko et al. 2007; Lammer et al. 2007; Aarnio et al. 2012; Drake et al. 2013; Osten & Wolk 2015; Cranmer 2017; Odert et al. 2017; Cherenkov et al. 2017.

Stellar CMEs can cause:

- **Mass loss**
up to $10^{-9} M_{\odot} \text{ yr}^{-1}$



Stellar evolution
Rotation evolution

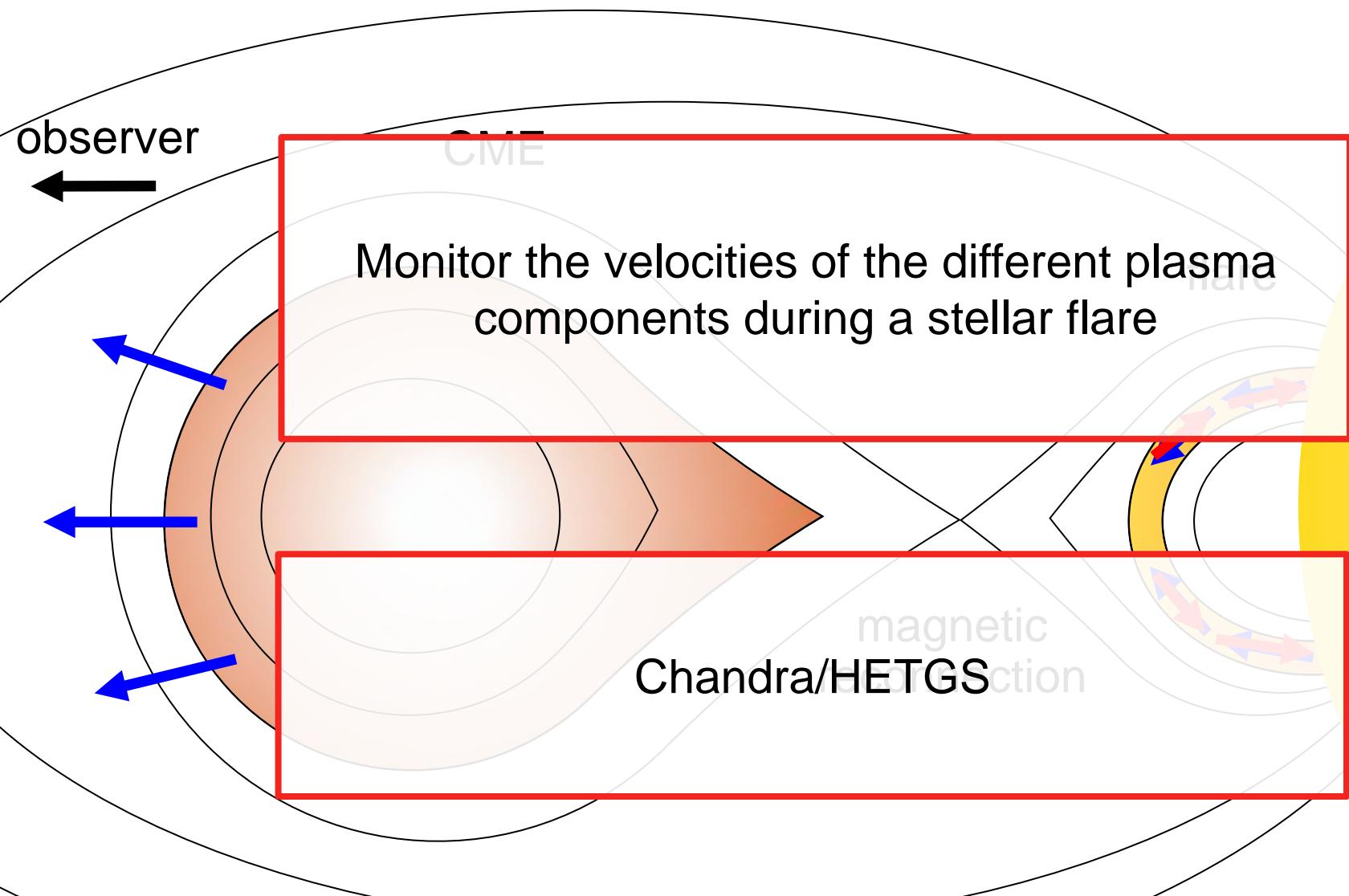


- **Energy loss**
up to $0.1 L_{\odot}$



Stellar evolution

SEARCHING FOR A STELLAR FLARE-CME EVENT



HR 9024

- single G1 III giant

- $M_* \approx 2.85 M_\odot$

- $R_* \approx 9.45 R_\odot$

- $P_{\text{rot}} \approx 24.2 \text{ d}$

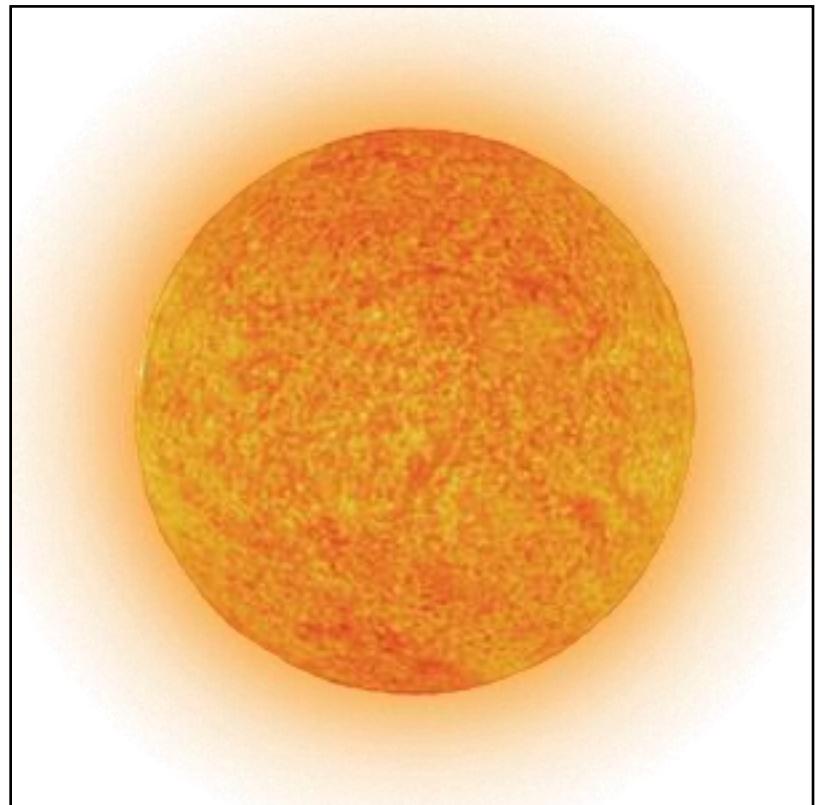
- $v \sin i \approx 21.5 \text{ km s}^{-1}$

- $d \approx 140 \text{ pc}$

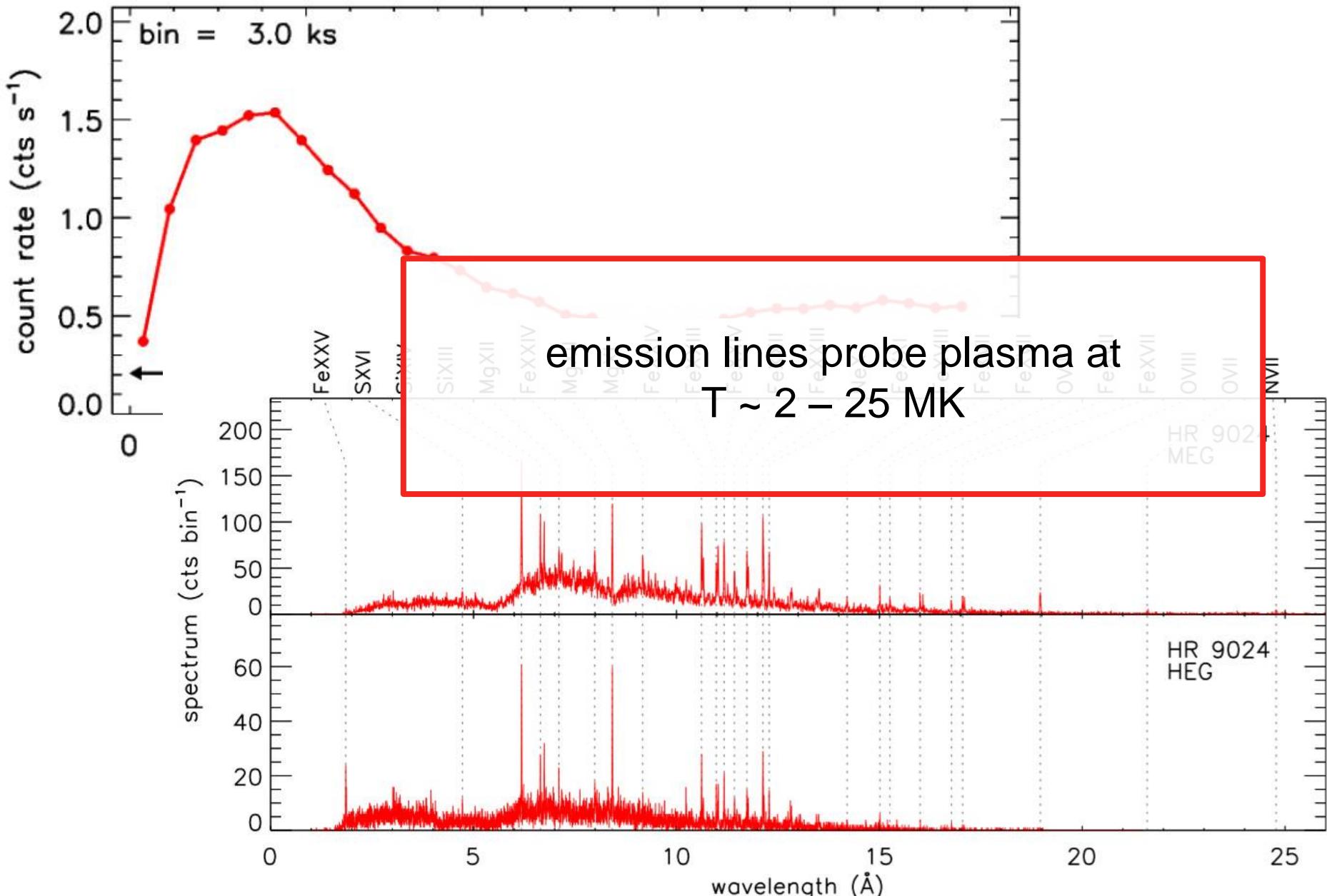
- $L_x \approx 3 \times 10^{31} \text{ erg s}^{-1}$

- Strong flare observed with Chandra/HETGS

- $E_{\text{flareX}} \approx 3 \times 10^{36} \text{ erg}$

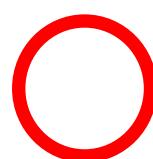
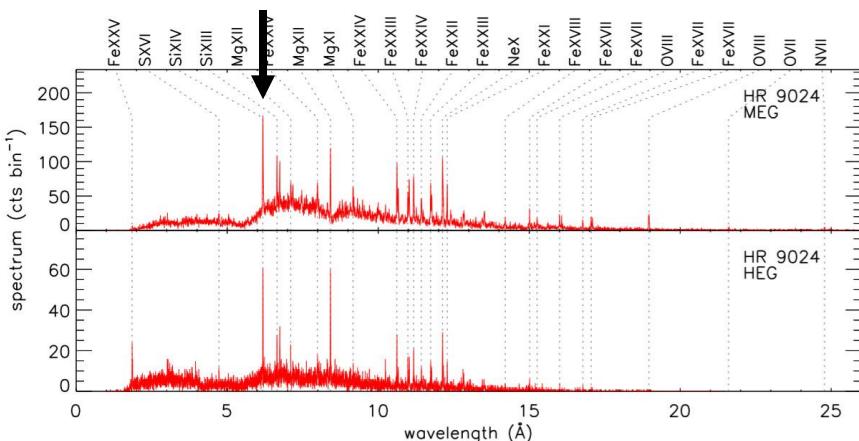


X-RAY FLARE ON HR 9024



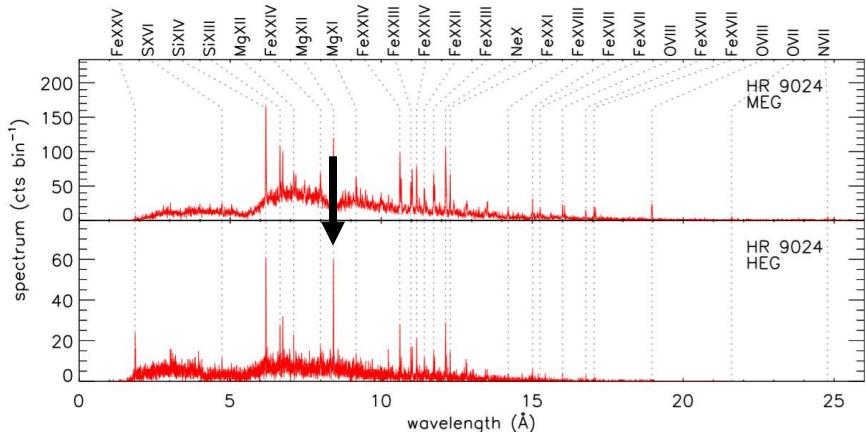
DOPPLER SHIFT - Si XIV

Index	λ (Å)	Elem.	T_{\max} (MK)	F_{heg} (cts)	F_{meg} (cts)
2a	6.1804	Si XIV	15.8	231±21	505±31
2b	6.1858	Si XIV	15.8



DOPPLER SHIFT - Mg XII

Index	λ (Å)	Elem.	T_{\max} (MK)	F_{heg} (cts)	F_{meg} (cts)
6a	8.4192	Mg XII	10.0	228±20	345±26
6b	8.4246	Mg XII	10.0



PLASMA MOTIONS DURING THE FLARE

We detected:

- **blueshifts during the rising phase of the flare from plasma at ~ 20 MK**

S XVI: -400 ± 180 km s $^{-1}$

Si XIV: -270 ± 120 km s $^{-1}$

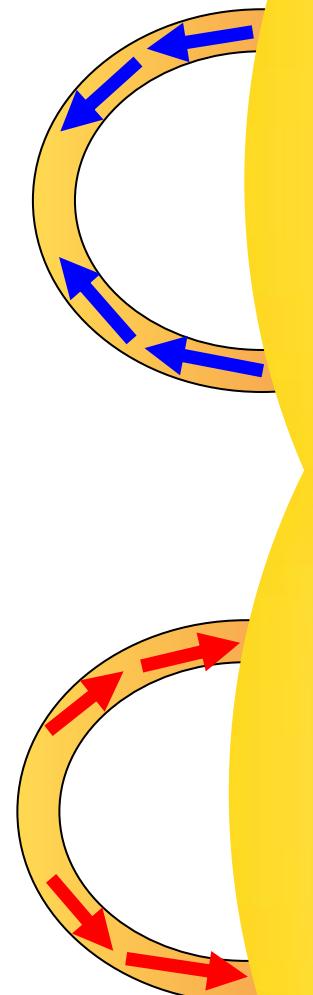
(99.99% combined significance)

- **redshifts during the flare decay from plasma at ~ 10 MK**

Si XIV: 140 ± 80 km s $^{-1}$

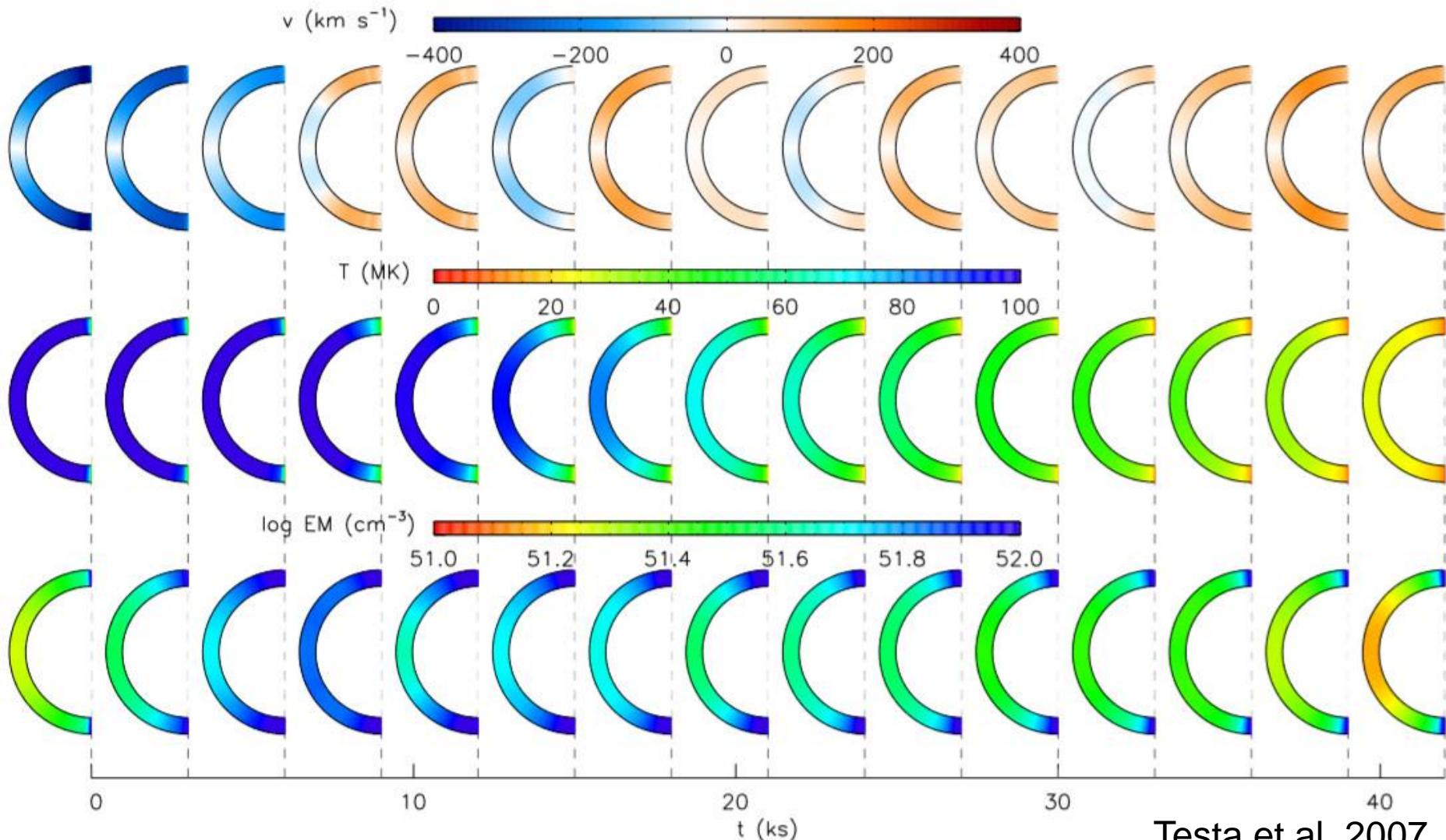
Mg XII: 70 ± 50 and 90 ± 40 km s $^{-1}$

(99.997% combined significance)



FLARING LOOP MODEL

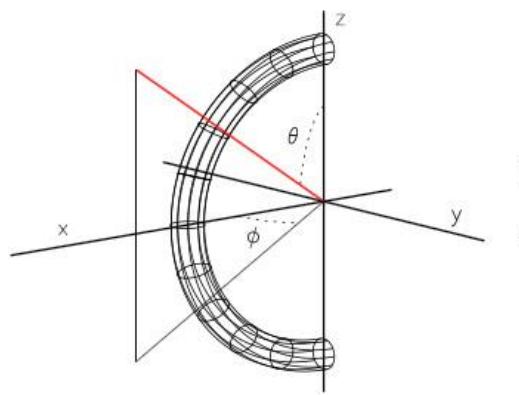
$L = 5 \times 10^{11}$ cm; heat pulse duration = 15 ks; total injected energy = 2×10^{37} erg



Testa et al. 2007

DOPPLER SHIFTS: OBSERVED vs PREDICTED

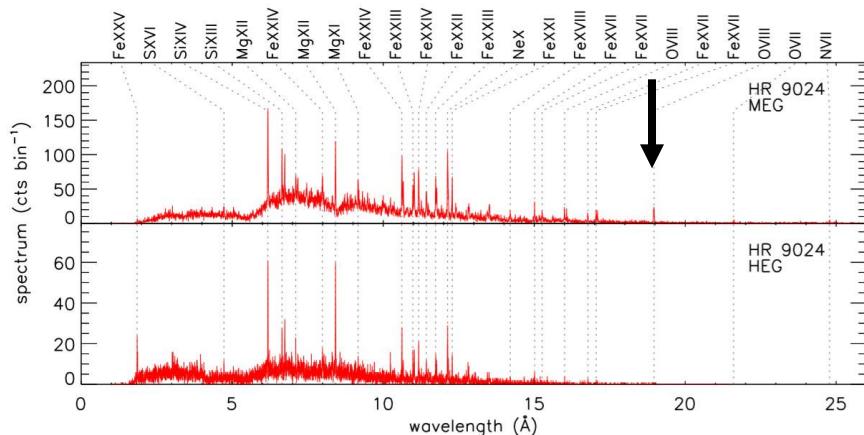
a



- these motions occur in the flaring loop
- the loop is observed from above

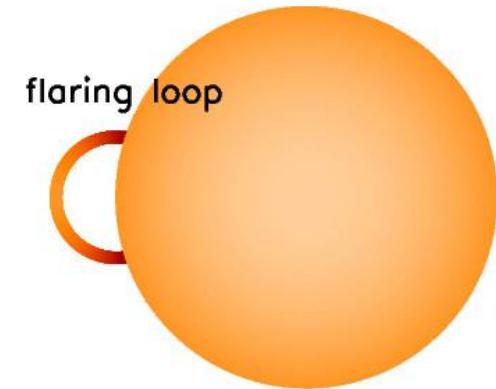
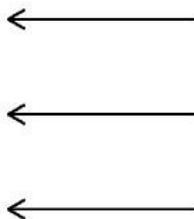
DOPPLER SHIFT - O VIII

Index	λ (Å)	Elem.	T_{\max} (MK)	F_{heg} (cts)	F_{meg} (cts)
13a	18.9671	O VIII	3.2	4±6	112±14
13b	18.9725	O VIII	3.2



PLASMA MOTIONS AFTER THE FLARE

to the observer



CME PROPERTIES

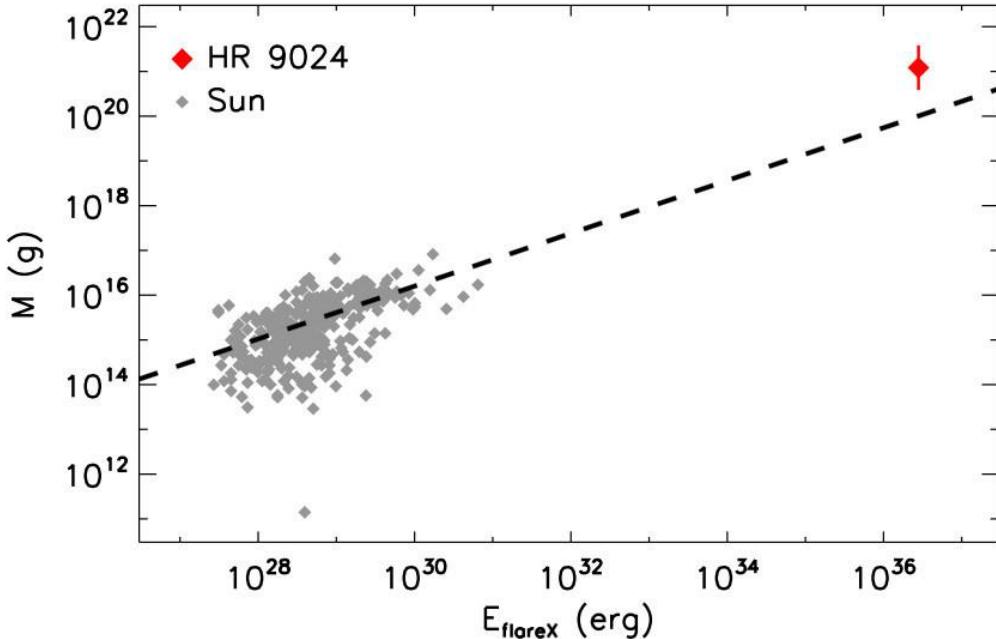
We measure:

- the *EM* responsible for the OVIII emission
- the duration of the OVIII emission
- the CME velocity

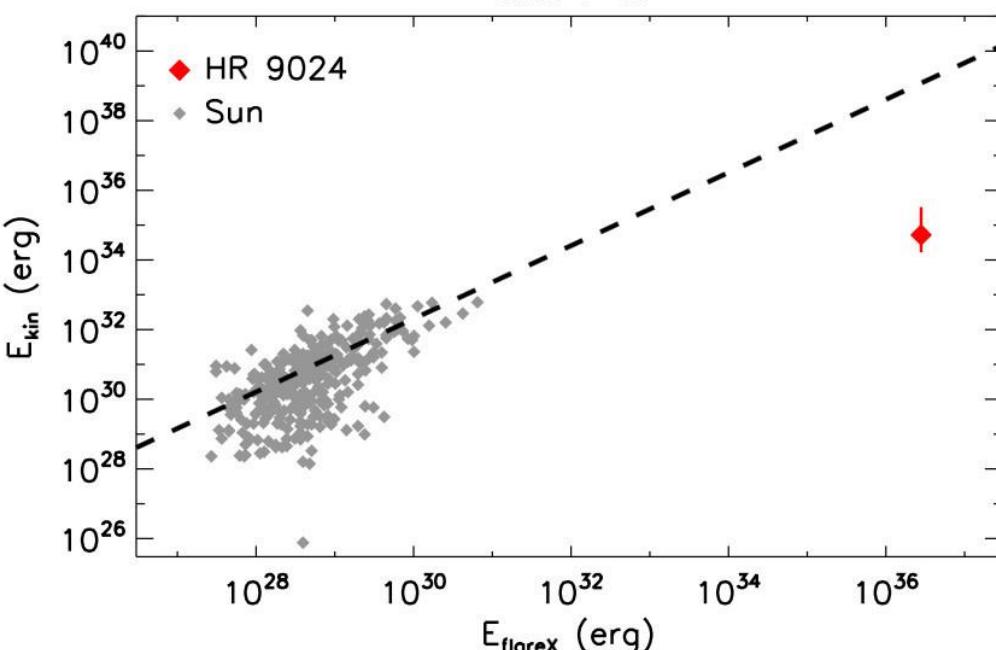
We derive:

- $n_e = (5.5_{-3.7}^{+11.8}) \times 10^8 \text{ cm}^{-3}$
- $V = (1.1_{-1.0}^{+10.3}) \times 10^{36} \text{ cm}^3$
- $M = (1.2_{-0.8}^{+2.6}) \times 10^{21} \text{ g}$
- $E_{\text{kin}} = (5.2_{-3.6}^{+27.7}) \times 10^{34} \text{ erg}$

COMPARISON WITH SOLAR CMEs



M is compatible with solar extrapolations

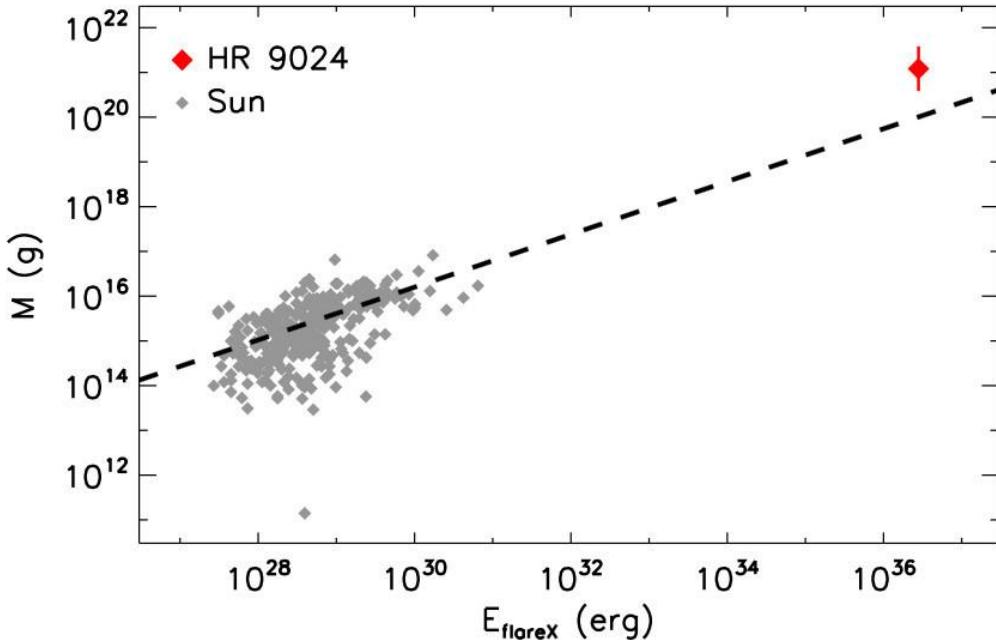


E_{kin} is 10^4 less than expected

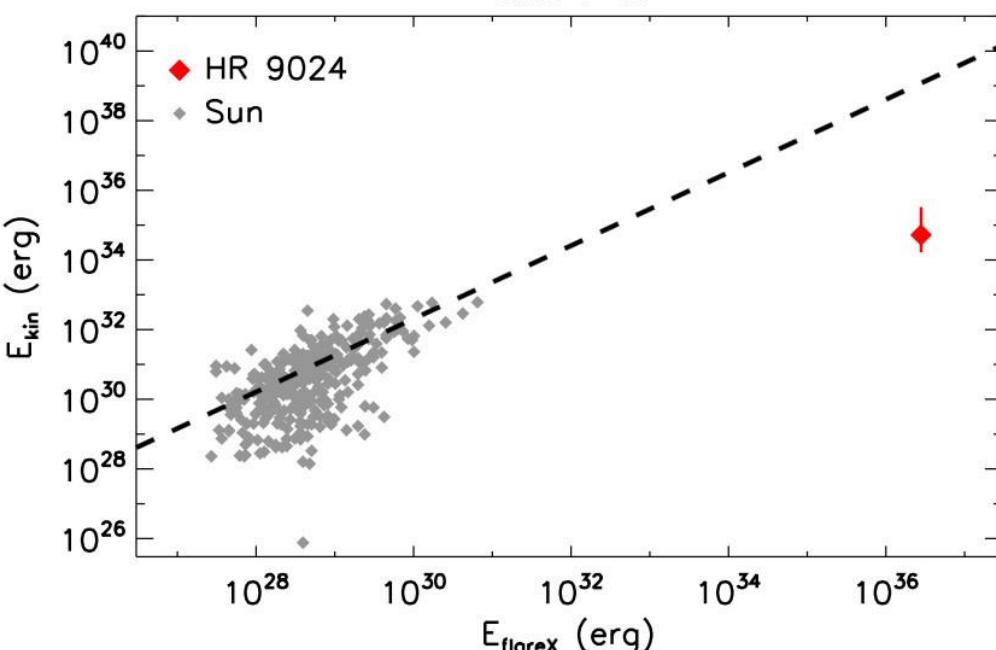
- similar CME formation
- different CME acceleration

(MHD modeling of stellar CMEs by Alvarado-Gómez et al. 2018)

COMPARISON WITH SOLAR CMEs



- CMEs appear to be the prime cause of mass and angular momentum loss



- CMEs appear to not carry out the huge magnetic energy budget inferred from solar extrapolation

CONCLUSIONS

- First X-ray detection of plasma motions in a stellar flare
- First detection of a stellar CME
 - stellar evolution
 - stellar rotation evolution
 - circumstellar disk evolution
 - exoplanetary atmosphere evolution
- This was a *lucky* Chandra/HETGS observation

FUTURE PERSPECTIVE

- X-IFU will routinely probe plasma motions during stellar flares
 - down to flare energy of $\sim 10^{32}$ erg
 - down to time scales of $\sim 10\text{-}10^2$ s
- X-IFU will open a window on unexplored phenomena occurring in stellar atmospheres