Diagnosing Magnetic Reconnection and Energy Release from High-resolution Observations of Flare Ribbons

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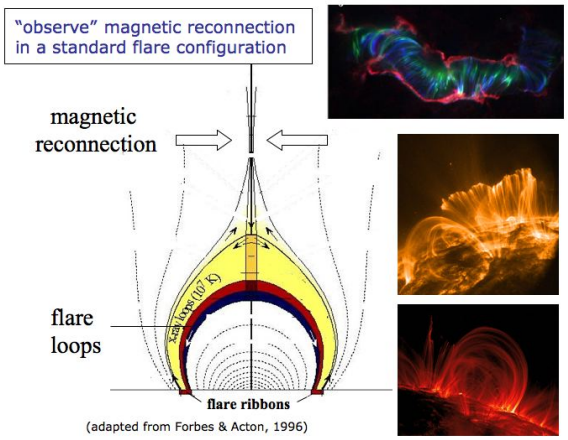
Solar Flare Energy Release Collaboration



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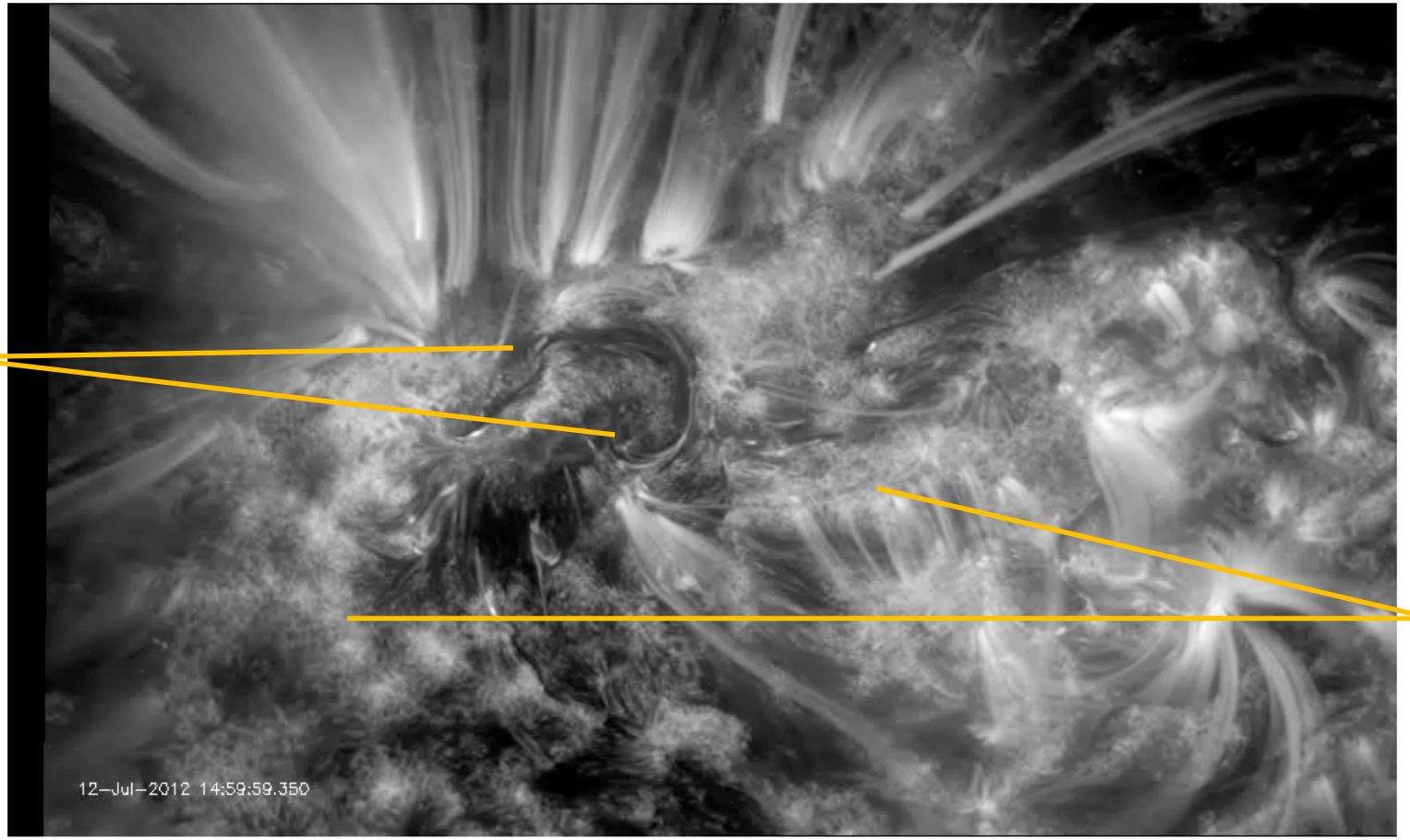
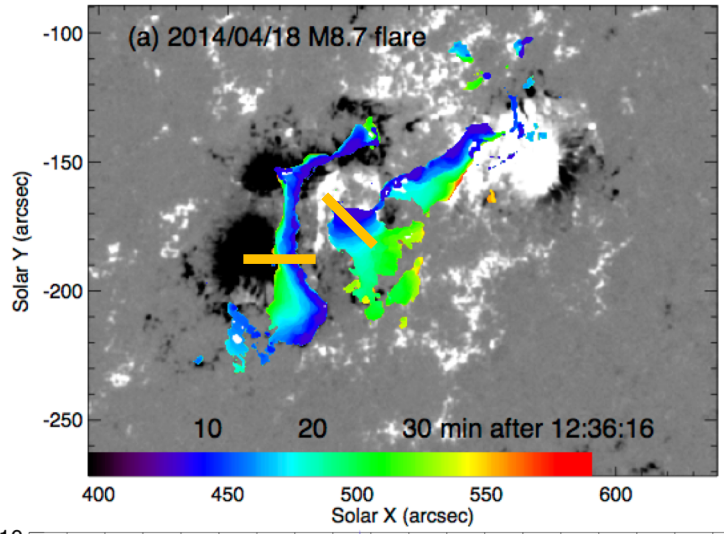
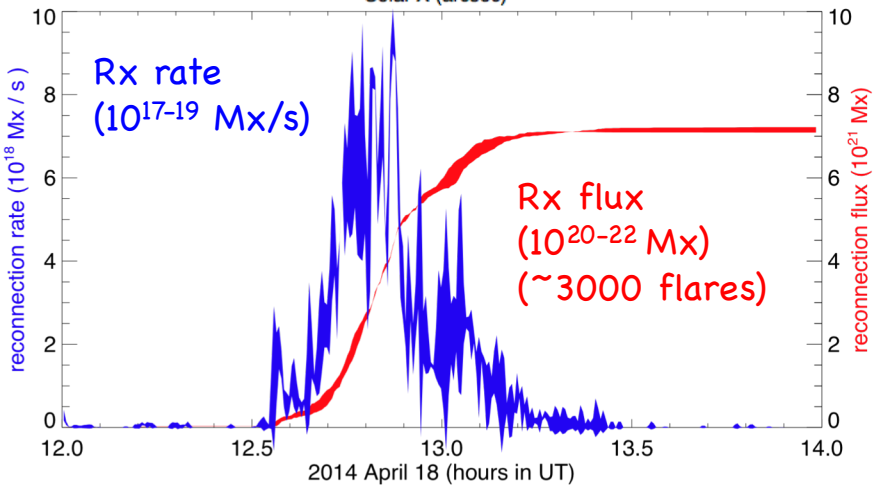
Outline

- Energy release by flare reconnection is instantaneously mapped and "resolved" in the chromosphere.
- Observations by SDO+IRIS reveal the evolution and structure of reconnection energy release across different scales.
- Flare ribbon observations provide diagnostics of flare energetics, or the characteristics of flare heating.
- Advanced missions + models are expected to tackle challenges coupling the chromosphere and corona, magnetically and energetically, solving outstanding problems.

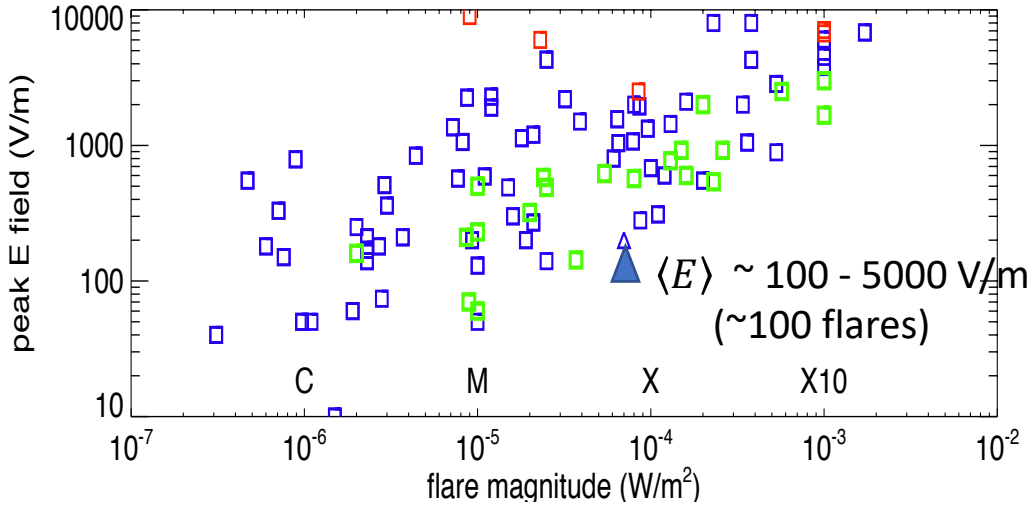


Chromosphere ribbons outline the feet of magnetic field lines being closed, or opened, by magnetic reconnection in the corona.





$$\frac{d\Phi_B}{dt} = \frac{d}{dt}\int B_r dA_r = \frac{d}{dt}\int B_{in} dA_{in} = -\int \vec{E}\cdot\overrightarrow{dl}$$

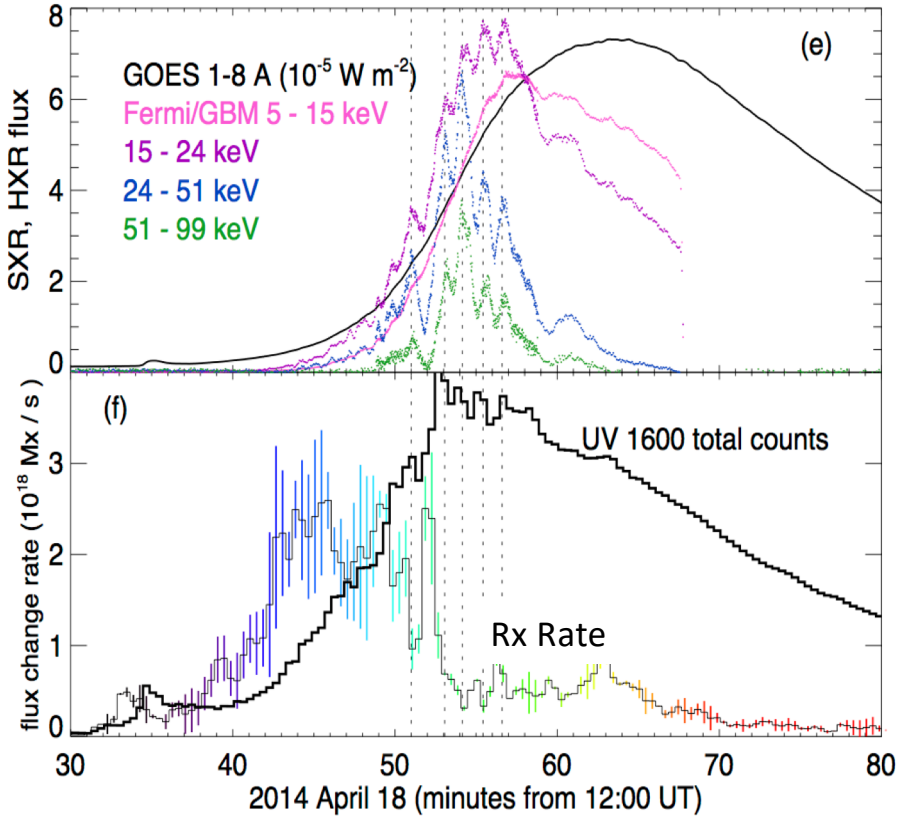


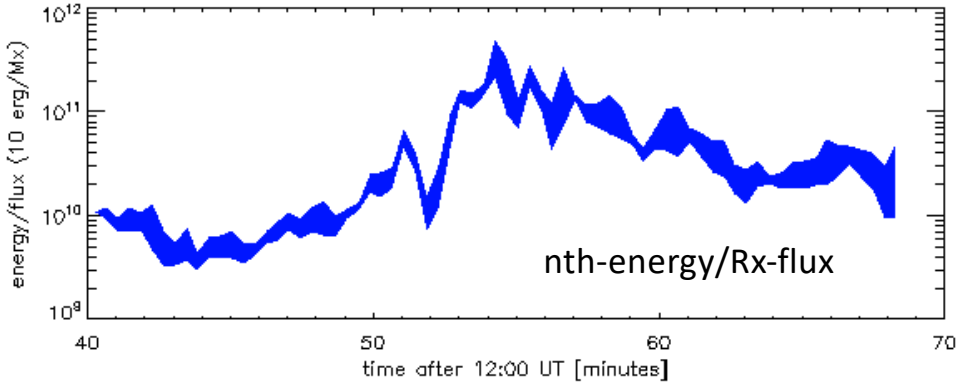
$$\langle E\rangle \approx B_{in}v_{in} \approx v_R B_R \approx \frac{1}{L}\frac{d\Phi_B}{dt} \approx 500\ V/m$$

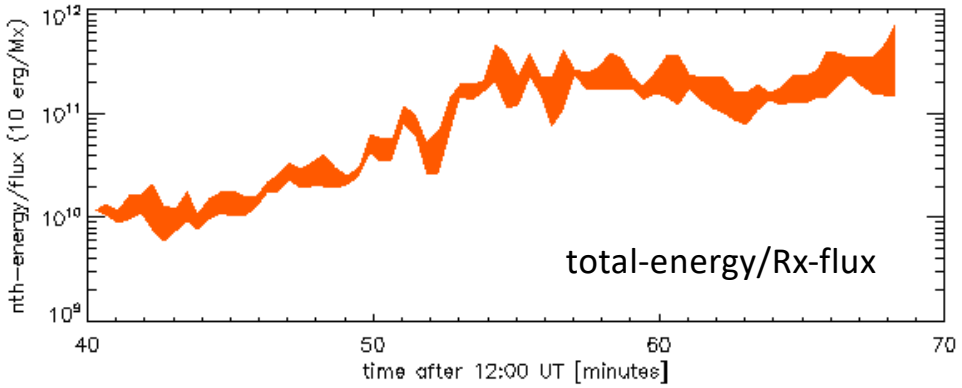
$$M_A = \frac{v_{in}}{v_A} = 0.1\ \frac{E(100\ V/m)/B_{in}\,(10\ G)}{v_A\,(1000\ km/s)}$$

Rx progress inferred from ribbons.

(Poletto+86, Fletcher+01, Isobe+02, Asai+02, Qiu+02, Saba+06, Jing+05, Temmer+07, … Kazachenko+17, Hintereiter+18 ..)

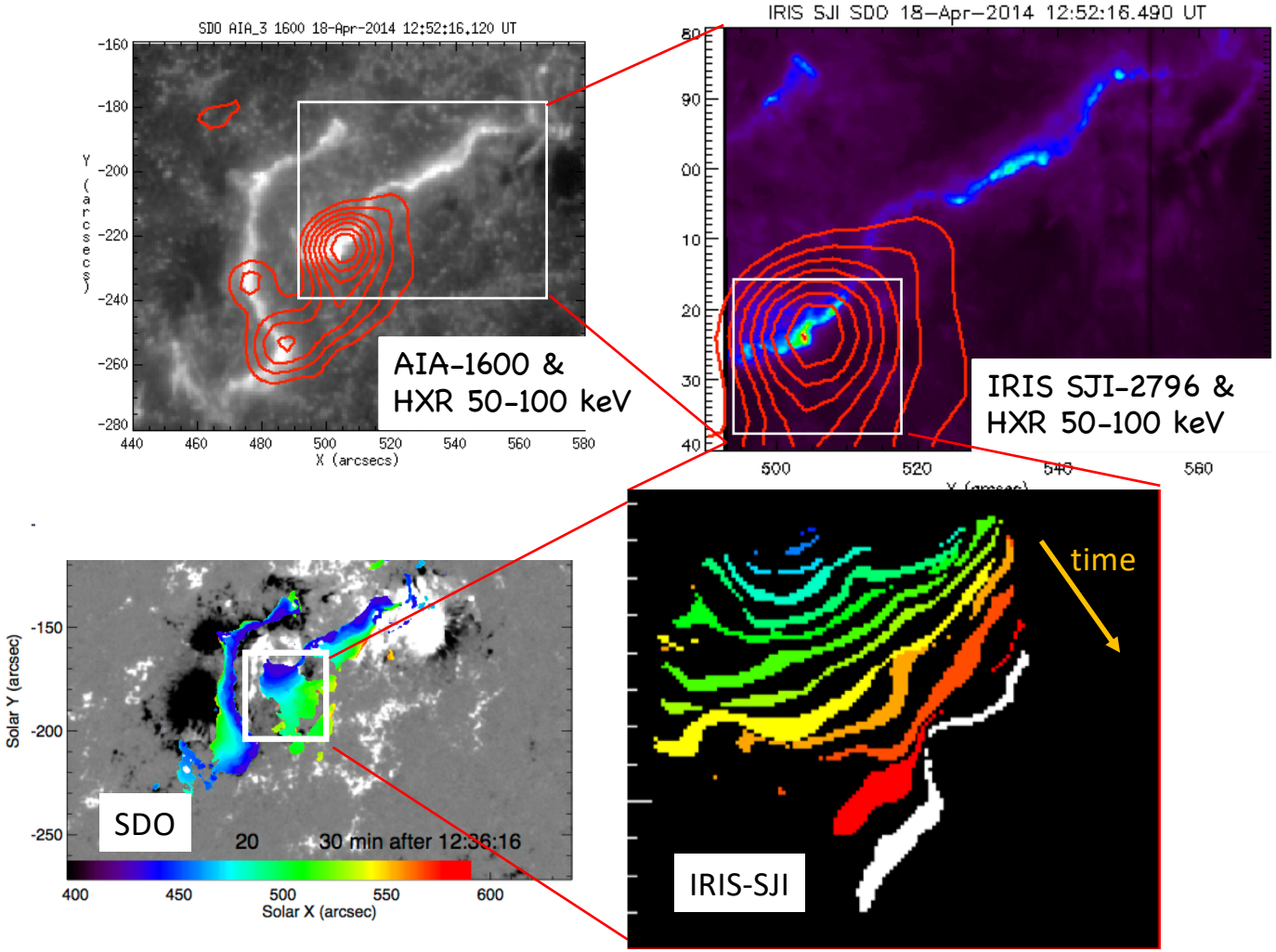




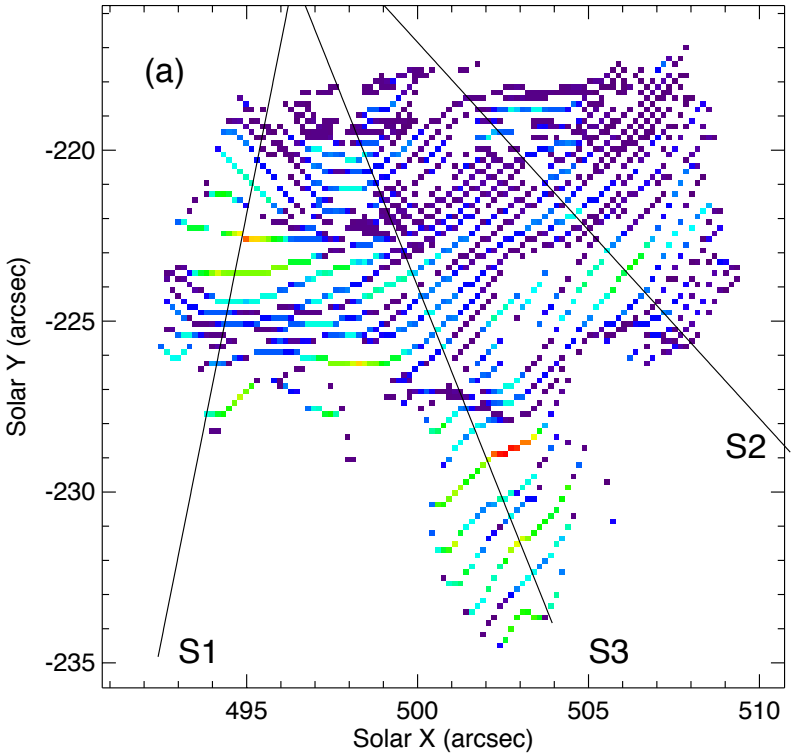


The amount of flare energy, and non-thermal energy, per unit reconnected flux is not uniform during flare evolution, or timescale of energy "dissipation" is delayed or longer than that of reconnection that releases this energy.

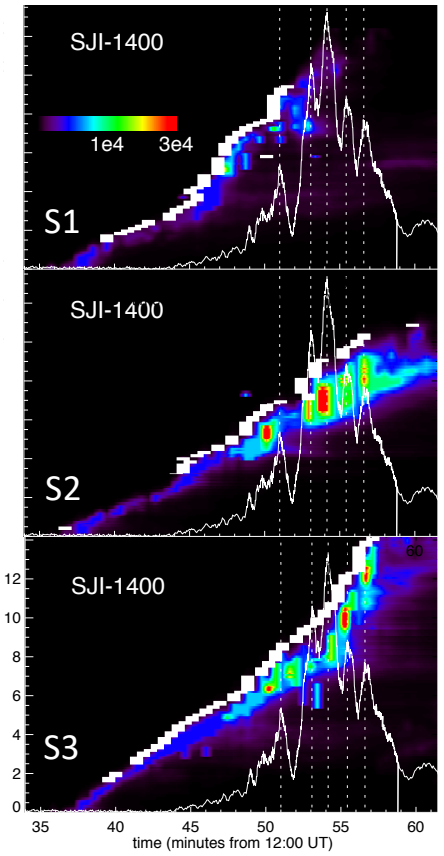
ribbons, ribbon fronts, and HXR "kernels"



Spatio-temporal mapping of the width of the newly brightened ribbon fronts indicative of **non-uniform** reconnection along a **quasi-laminar** structure, with local enhancement of reconnection rate nearly coincident with bursty HXRs (Naus+22).



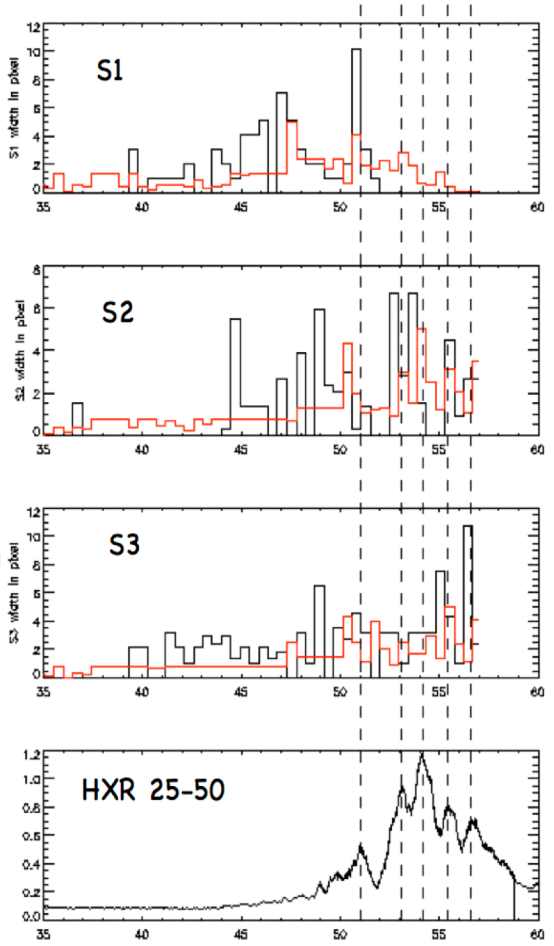
- ribbon front width of **2 – 10 IRIS-SJI pixels**, or 250-1200 km within 28~s;
- QPPs (Brannon+15, Brosius+16, more)
- enhancement of ribbon front width **0.5-2 min prior to** peak UV and HXR emission.



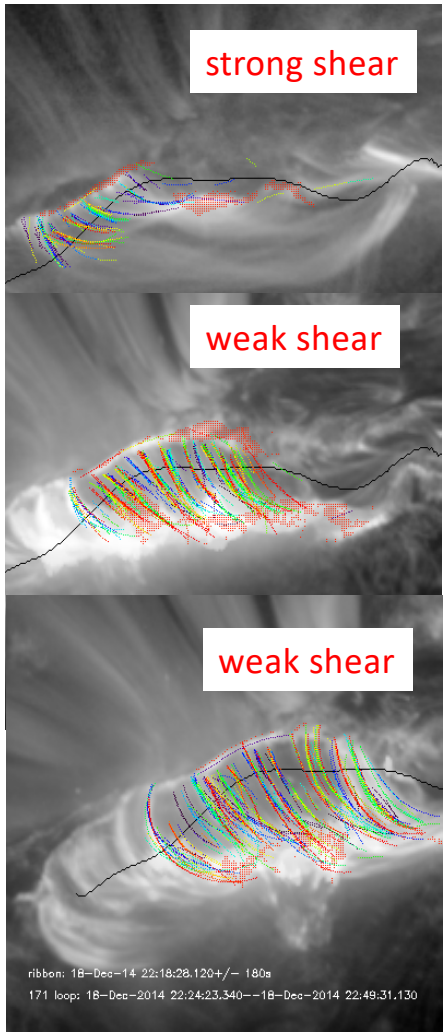
background: time-distanc intensity-gram
white: ribbon front width;
Curve: 25 – 50 keV HXR

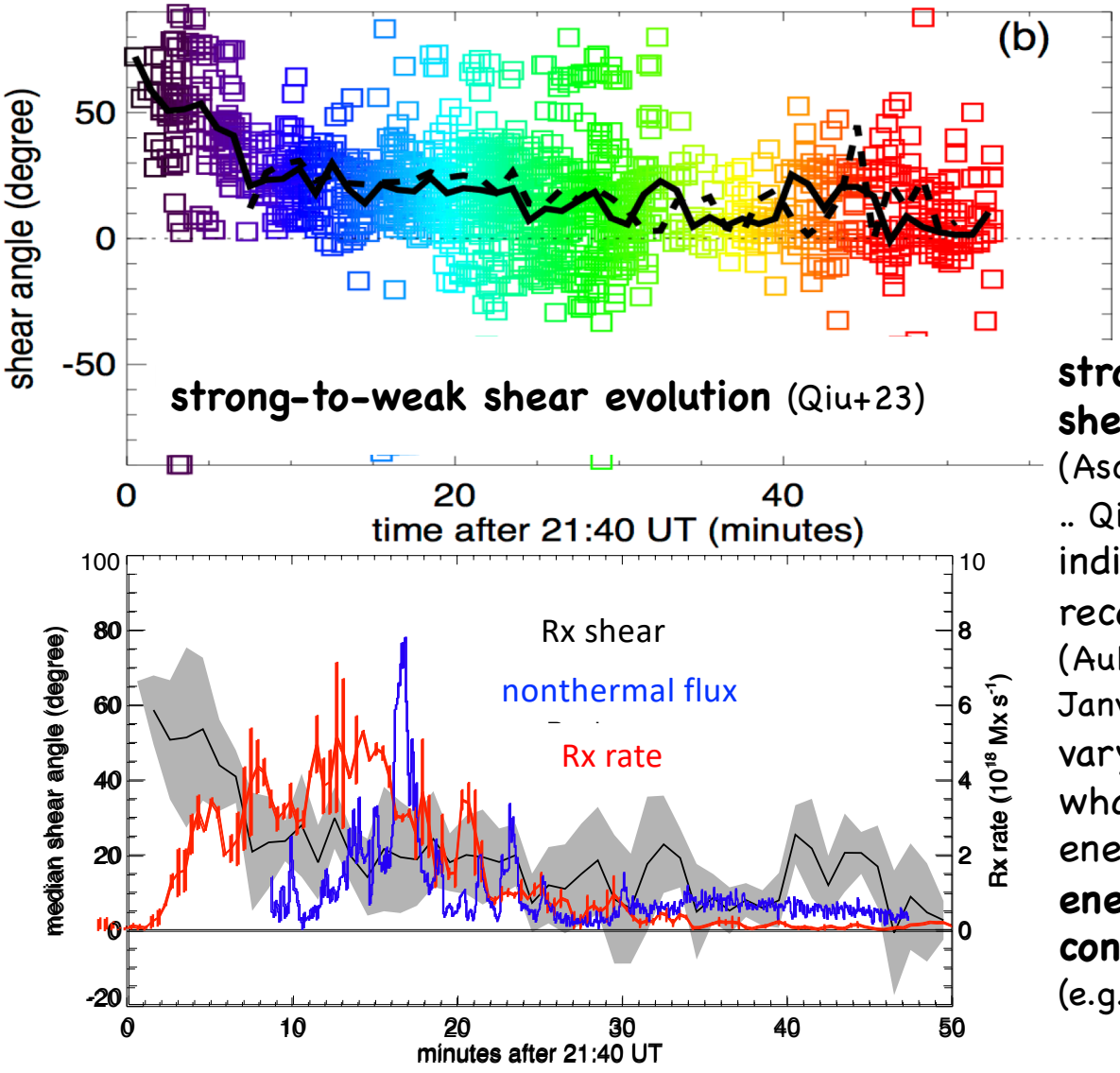
ribbon front width 1400 along slit

peak emission along slit

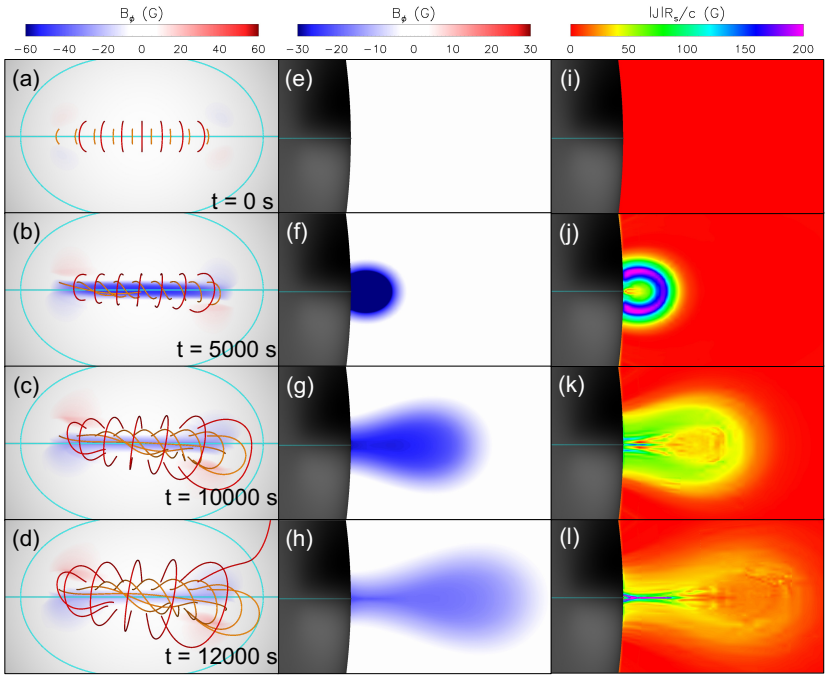


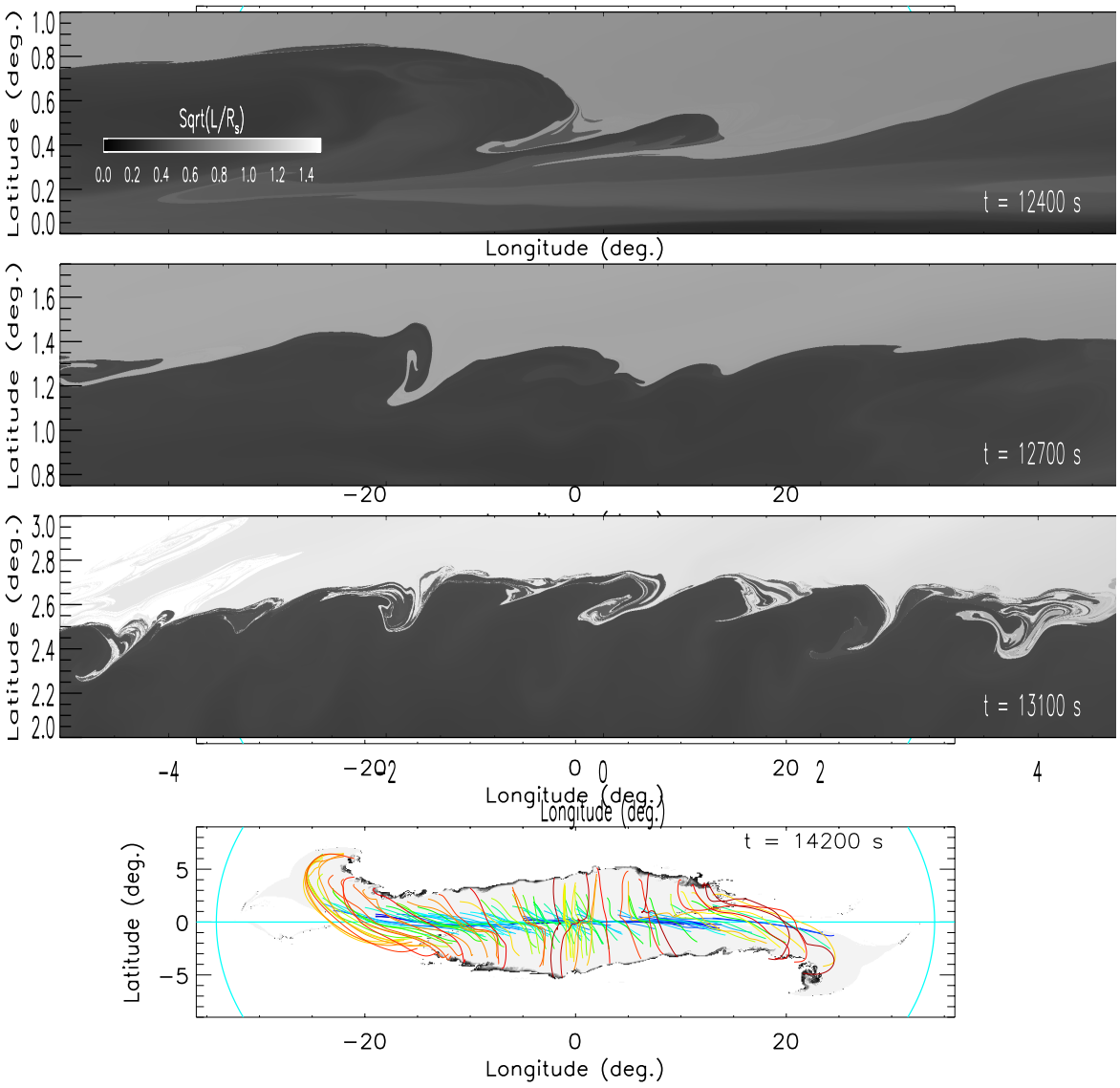
(Falchi+97, Miklenic+07, Xu+2016, Jefferey+18, Pano+18, Kerr+21, **Vievering+23**, Polito+23)



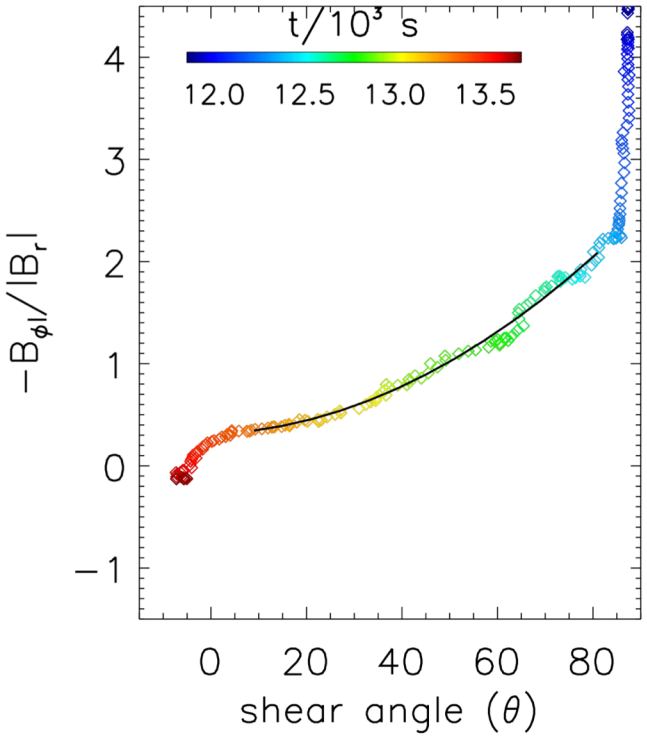


strong-to-weak shear evolution (Aschwanden+02, Su+06 .. Qiu+22, 23) may indicate 3D reconnection (Aulanier+2019, Janvier+2013) with a varying **guide field**– what is the impact on energy release and **energy partition & converstion?** (e.g. Arnold+21)

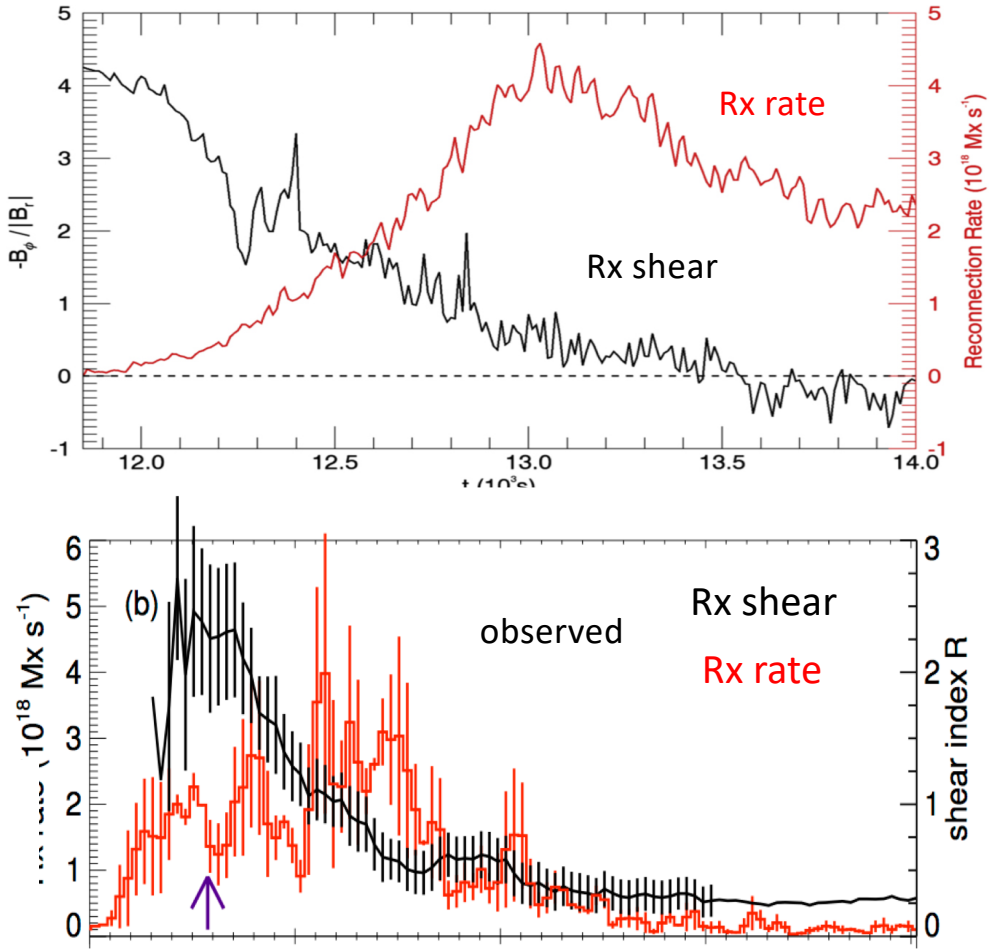


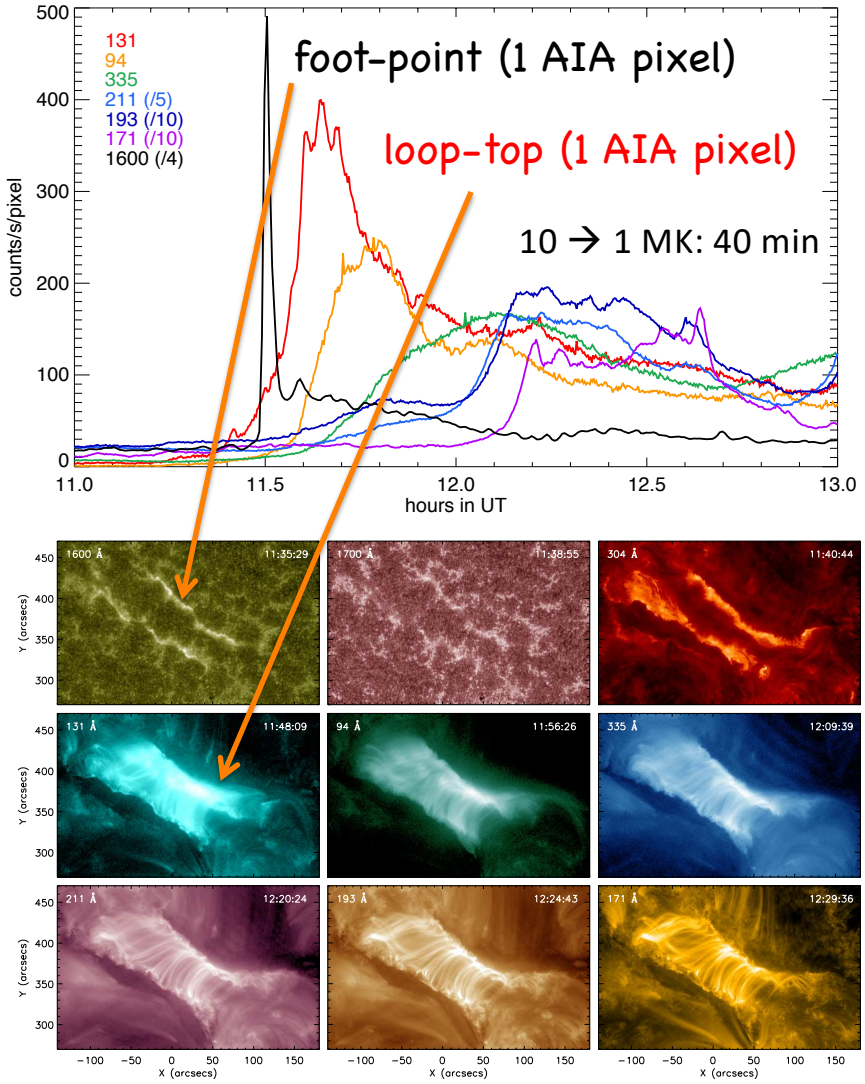


Observed fine-scale structure of flare ribbons may reflect photosphere magnetic field distribution (Fletcher+04), but may also be due to genuine structure developed in the coronal reconnection current sheet and mapped to the lower atmosphere (Wyper+21, Dahlin+22).

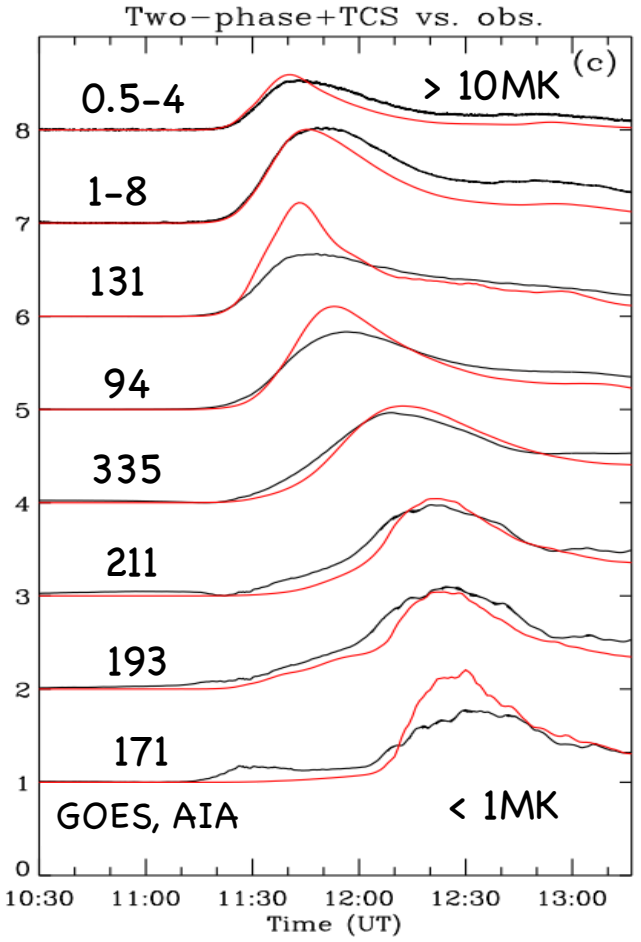


strong-to-weak shear evolution reproduced by high-resolution MHD simulations, reflecting varying guide field (Dahlin+22, Qiu+23).





Spatially resolved spectroscopy and photometry observations at the ribbons can be used to determine characteristics of heating: where, when, for how long, by how much, and in what form (RubioDaCosta+15, Kowalski+17, Kerr+16, Reep+16, Graham+20, Ashfield+21).



Experiments applying the UV Neupert effect to infer global energetics of flare heating (Qiu+12, Liu+13, Qiu+16, Zhu+18, Qiu22) suggest **prolonged (DC) heating over impulsive (AC) heating**.

What has been discovered and what remains unsolved ..

1. Reconnection energy release is globally organized and highly structured.

- what determines the fine-structure of flare ribbons? Magnetic properties in the corona or the lower atmosphere?
- what is the nature of the pre-cursor photometry & dynamics at the leading edges of flare ribbons - local onset problem?
- what is the next order of the elementary scale? And what do we expect to observe differently at that scale?

2. Observations of the flaring chromosphere provide diagnostics of energetics.

- Are electrons ubiquitous or not?
- What governs productions of nth electrons?
- Can optical/UV spectroscopy determine heating mechanism?
- What is the nature of slow "cooling"?