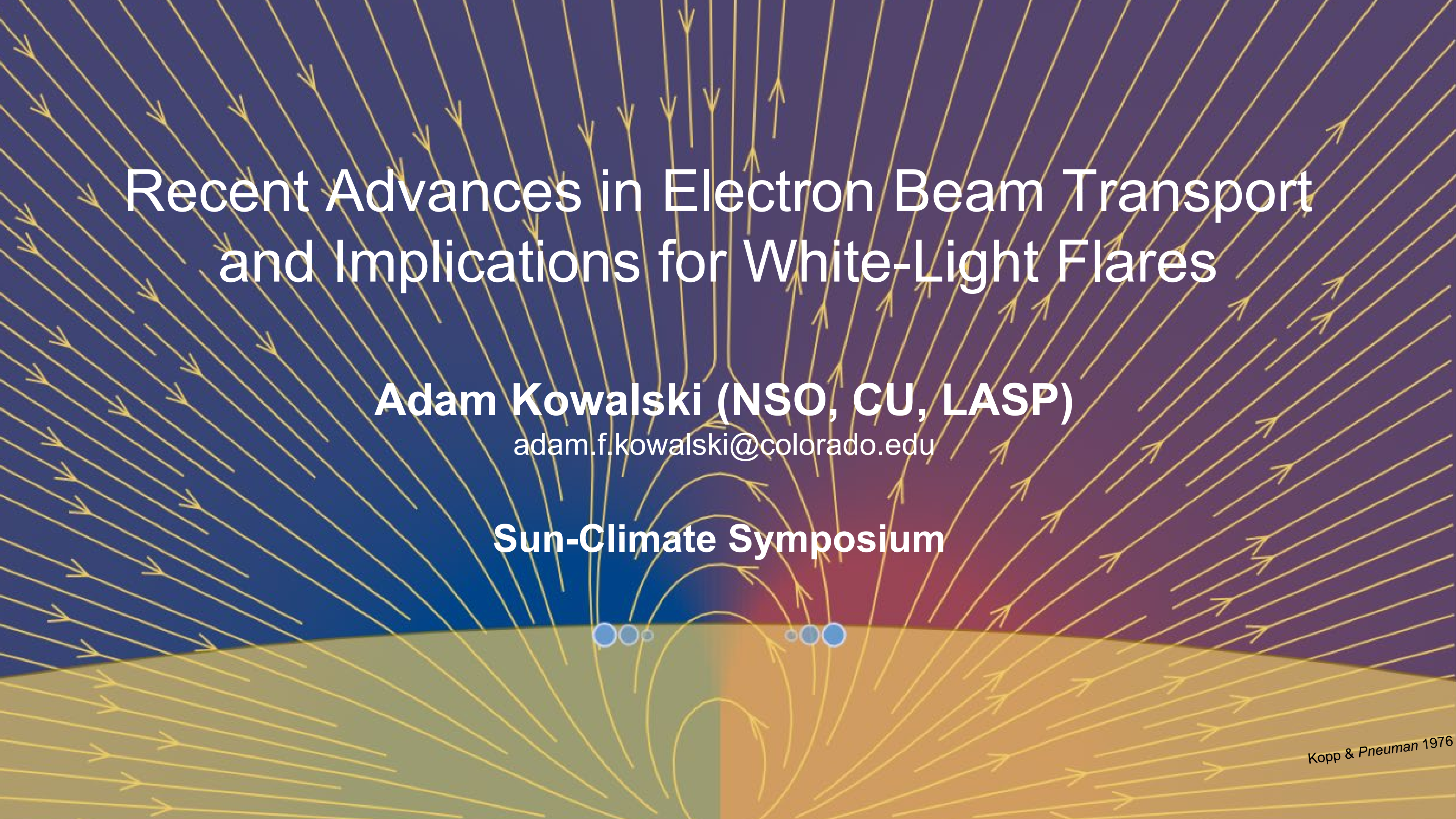
Recent Advances in Electron Beam Transport and Implications for White-Light Flares

Adam Kowalski (NSO, CU, LASP)
adam.f.kowalski@colorado.edu

Sun-Climate Symposium



Kopp & *Pneuman* 1976

Overview of Talk

White-light (optical and NUV continuum) radiation

Electron beams in solar and stellar flares

- **The problem of high energy fluxes**

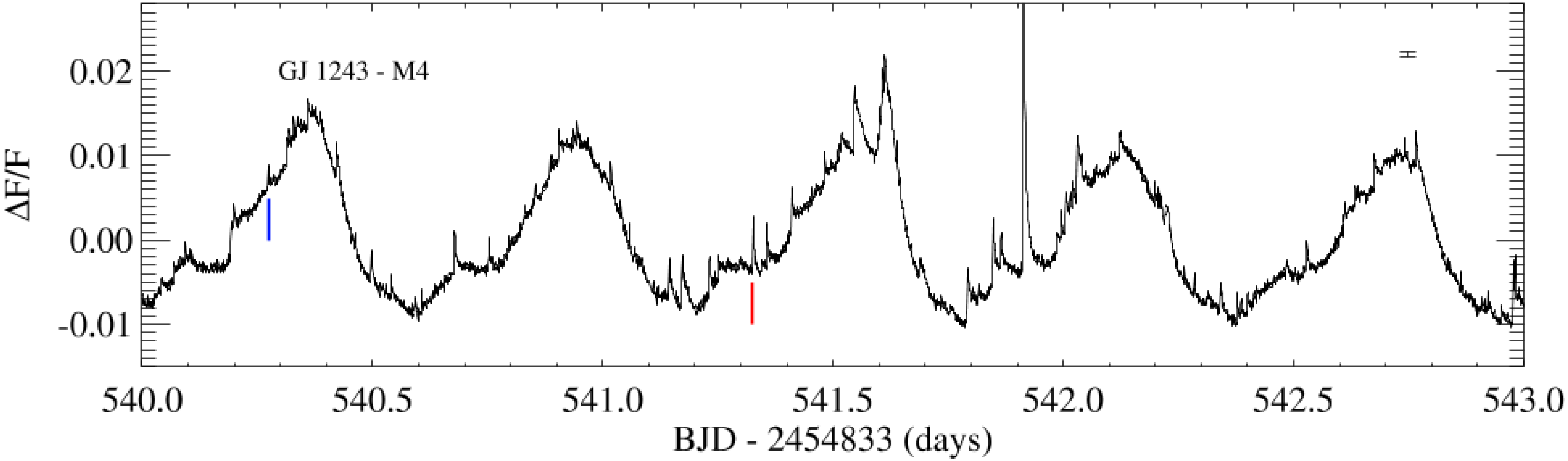
Overview of Kontar et al. 2012 beam-plasma transport theory and results

- **Application to white-light & line emission in stellar flares (Kowalski 2023 *ApJ Letters*)**

New directions: some first results

White-Light Stellar Flares

Broadband optical continuum enhancements observed on cool stars with Kepler, K2, TESS



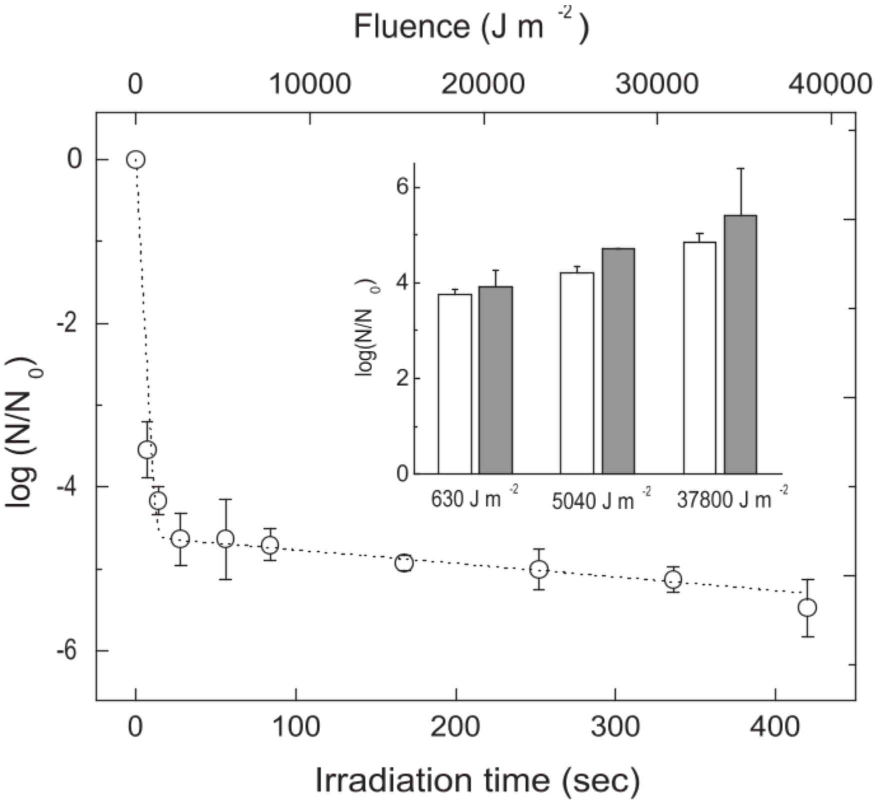
Hawley et al. 2014 (Kepler data of GJ 1243 -- active M4 main-sequence star)

11 mo of 1-minute cadence data

Biological Effects in M-dwarf Habitable Zones

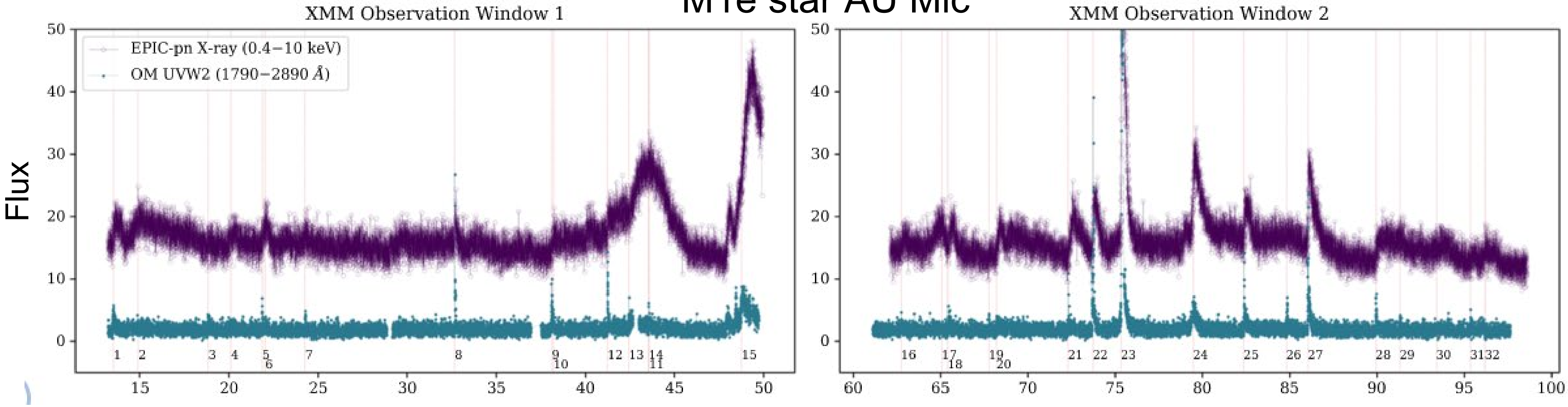
Laboratory experiments of 2000-2800 Å superflare irradiation of an exoplanet (Abrevaya et al. 2020; right)

X-rays from flare can be reprocessed into NUV (Smith et al. 2004)



Flares are faster in NUV, slower in SXR

M1e star AU Mic



Tristan et al. 2023

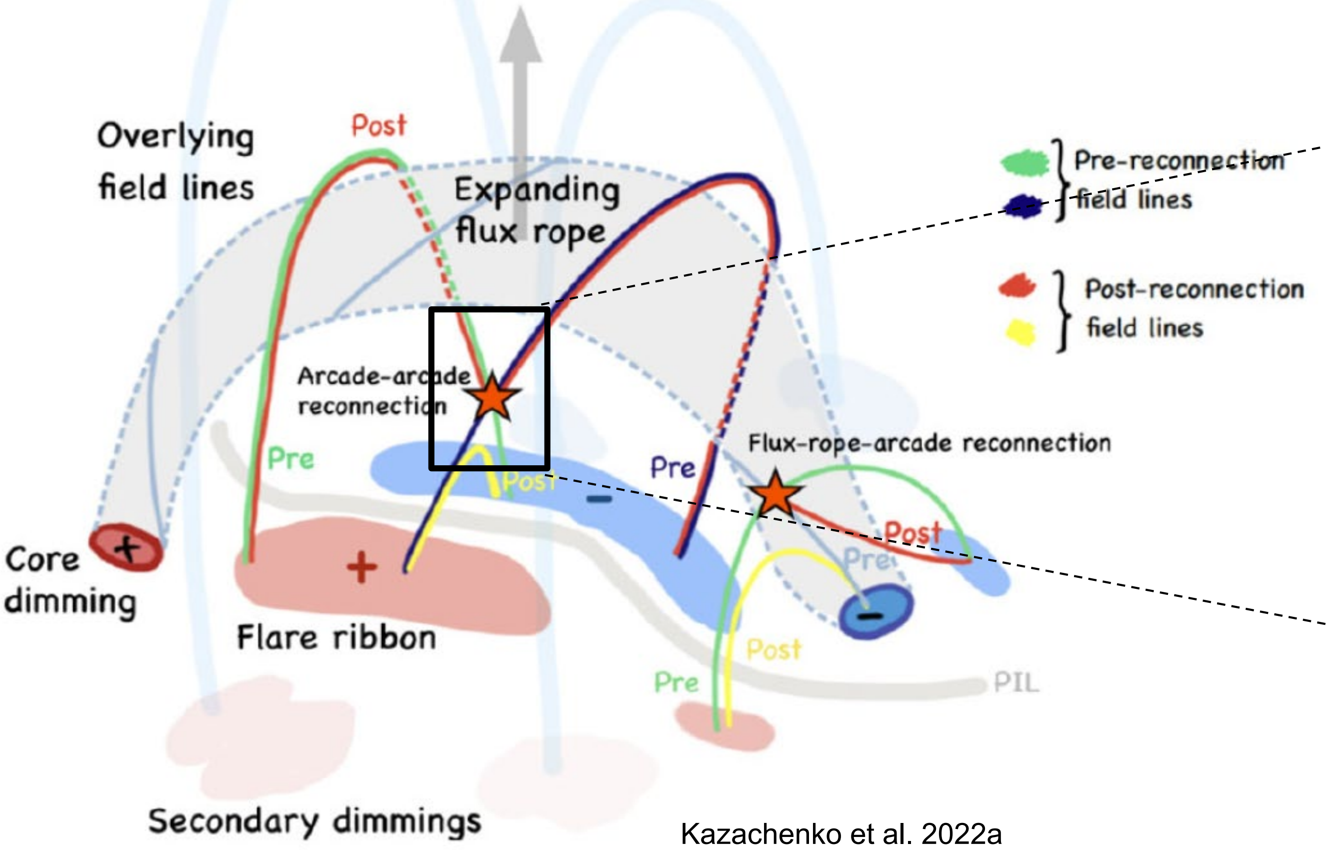
Hours from Oct 10 2018 00:00

$$2/3\ E_{SXR} \sim E_{U\text{-band}} \sim 1/10\ E_{Bol}$$

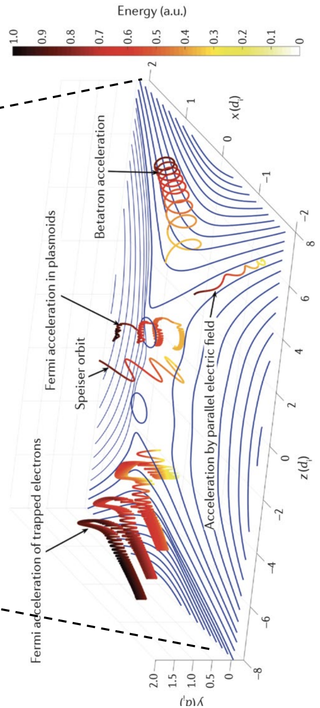
See also Osten & Wolk 2015

Reconnection **under** erupting filament and **with** erupting filament

Particle acceleration & transport are key in **linking** magnetic field action to heating/radiation



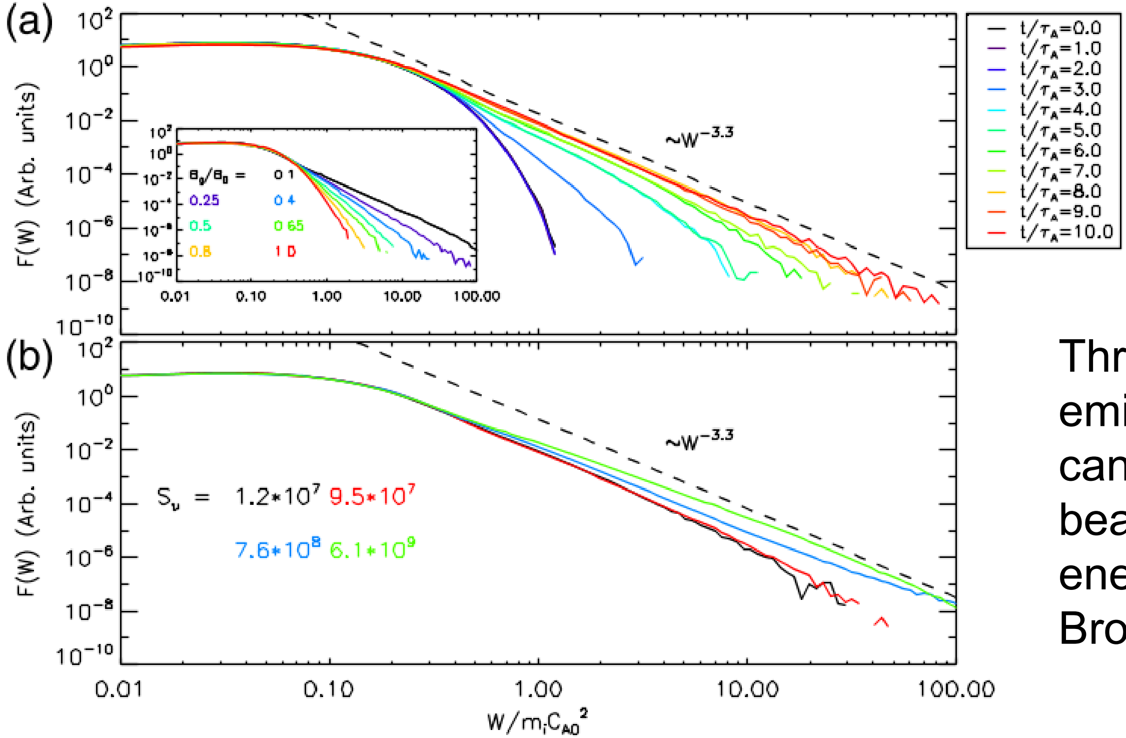
Kazachenko et al. 2022a



Ji et al. 2022
Dahlin 2020

Power-laws of electron beams produced in corona

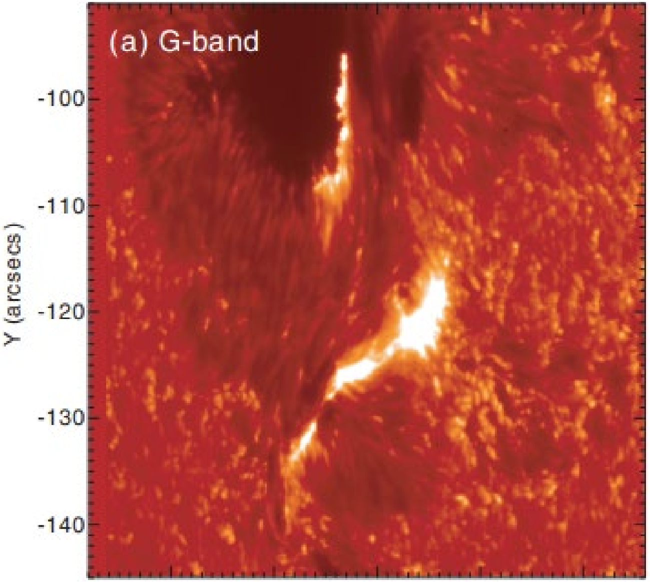
~ 5-20% of background plasma accelerated into power-laws



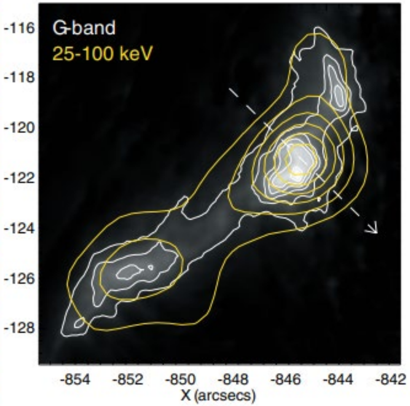
Arnold et al. 2021, Drake et al. 2019

Through hard X-ray bremss emission in chromosphere, we can infer the properties of the beams assuming collisional energy loss only (“CTTM” theory; Brown 1971)

Large Nonthermal Electron Fluxes (erg/s/cm^2) into the Chromosphere



Krucker et al. 2011



Standard collisional thick target modeling (CTTM) infers fluxes of 10^{12} - 10^{13} erg/s/cm^2 above E_{cutoff} = 18-20 keV

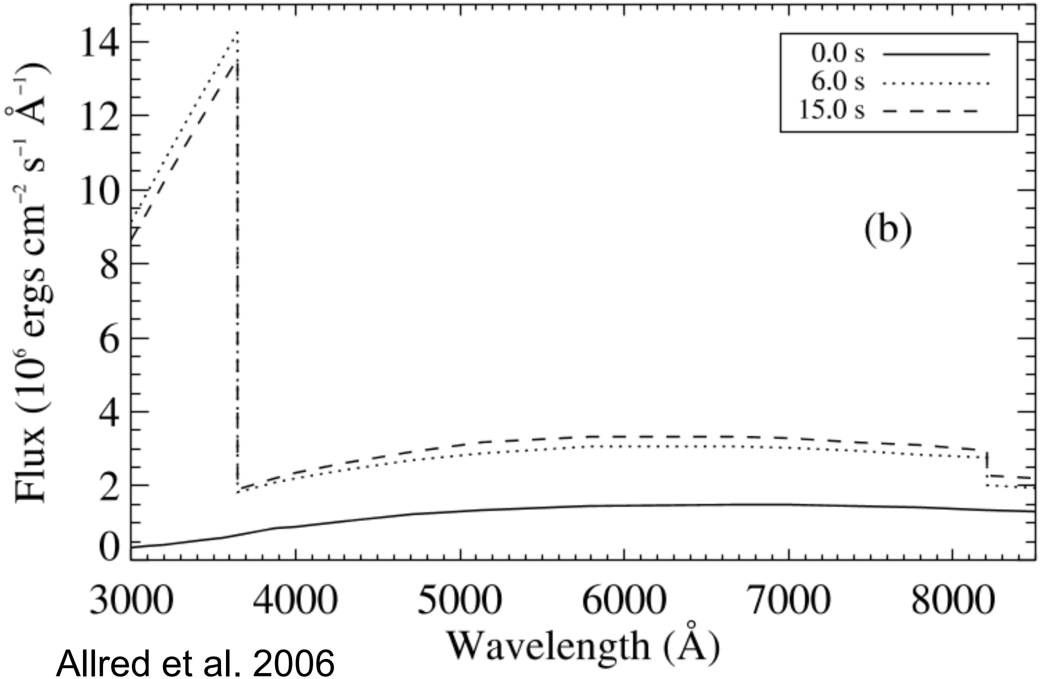
25-100 keV: Non-thermal Bremss hard-X-rays (from RHESSI)

Another flare (Mar 29 2014): 3.5 x 10^{11} ("3.5F11"; Kleint et al. 2016) to ~2x10^{12} erg / s / cm^2 ("2F12"; Kowalski et al. 2017) above ~20 keV inferred.

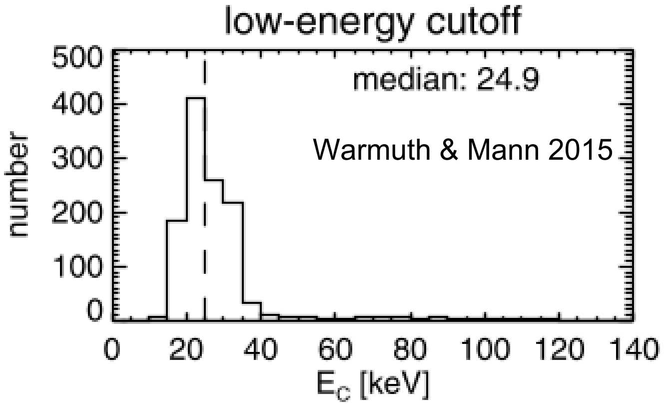
Long story short: beam particles should **thermalize** in corona through return current electric fields and beam-plasma instabilities... Only catastrophic energy loss = **DOOM** of coronal electron beams ?!

Solar-type Electron Beams with small low-energy cutoffs

Models of M-dwarf flare heating using electron beam parameters derived from "CTTM" (collisional thick target model") of hard X-ray footpoints (Brown 1971)



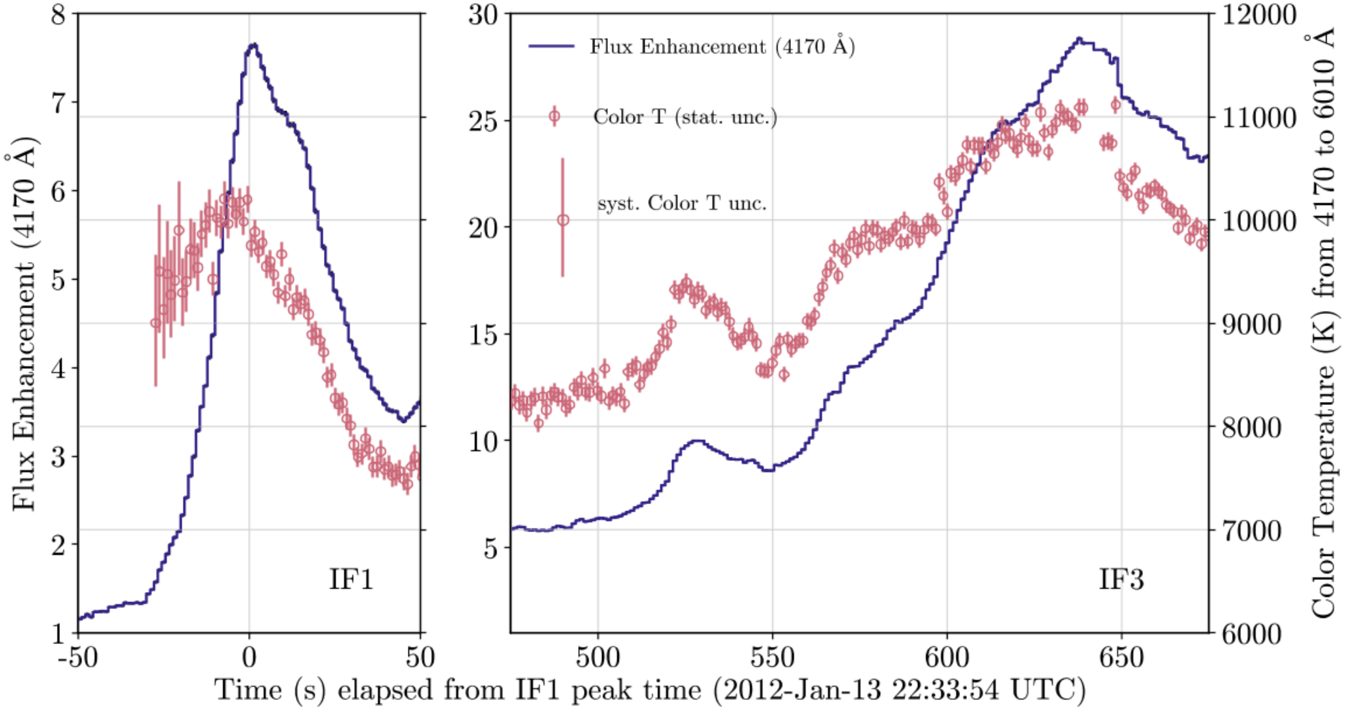
Allred et al. 2006



$$f(E) = f_o\left(\frac{E}{E_{\mathrm{cutoff}}}\right)^{-\delta}$$

Giant Flare from YZ CMi

Observational evidence for deep heating in stellar (M dwarf) flares



Nothing new to see here, folks, except **high-time res of T ~ 9000 - 11,000 K** color temp in rise and peak phases

(Hawley & Fisher 1992, Fuhrmeister+08, Kowalski+2013, ...)

ULTRACAM data from Kowalski+16, filter ratios (**4170/6010Å**) converted to color temps in K2023

What physical processes could (possibly) explain extreme beams -- **and the deep heating** -- in stellar flares?

Thankfully, I didn’t have to ask ChatGPT.

I thank Eduard Kontar for pointing me in a productive direction and for helpful discussions.

Modeling nonthermal particle transport in an atmosphere

A: Particle-in-cell (e.g., Li, Drake, & Swisdak 2012)

- collisionless (Vlasov-Maxwell), very short temporal & spatial scales

B: Beam distribution function in phase space (Allred+2020)

- collisional Fokker-Planck treatment, time-indepen
- able to calculate background plasma heating

$$\cancelto{0}{\frac{\partial f_a}{\partial t}} + \nabla_r \cdot (\boldsymbol{v} f_a) + \nabla_p \cdot (\boldsymbol{F}^e f_a)$$
$$+ \sum_b \nabla_p \cdot \boldsymbol{j}^{a/b} = 0,$$

C: Time-dependence of background plasma wave energy density (Kontar+2012)

- the “quasilinear” / weak turbulence theory
- Coulomb collisions included but other simplifications made

Option C: Time-Dependence and Background Plasma Evolution (Langmuir and Ion-Acoustic Waves):

Kontar et al. 2012 solves time-dependent distribution function (t = 0 to 1s) with background plasma waves and with Coulomb collisions

$$f(v, t=0) = \frac{n}{\sqrt{2\pi} v_{\mathrm{Te}}} \exp\left(-\frac{v^2}{2v_{\mathrm{Te}}^2}\right) + g_0(v),$$

1) $$\frac{\partial f}{\partial t} = \frac{4\pi^2 e^2}{m^2} \frac{\partial}{\partial v}\left(\frac{W_k}{v}\frac{\partial f}{\partial v}\right) + St_{\mathrm{col}}(f),$$

2) $$\frac{\partial W_k}{\partial t} - \frac{\partial \omega_{\mathrm{pe}}(x)}{\partial x}\frac{\partial W_k}{\partial k} = \frac{\pi \omega_{\mathrm{pe}}^3}{nk^2} W_k \frac{\partial f}{\partial v} - \gamma_{\mathrm{col}} W_k + \frac{\omega_{\mathrm{pe}}^3 m_{\mathrm{e}}}{4\pi n_{\mathrm{e}}} v \ln\left(\frac{v}{v_{\mathrm{Te}}}\right) f + St_{\mathrm{decay}}(W_k, W_k^s).$$

Low-energy electrons lost fastest due to Coulomb collisions (bump-on-tail) ⇨ background electron (Langmuir) waves

W_k : Langmuir waves
W_k^s : ion-sound waves (ion-acoustic)

Critically, includes 3-wave langmuir$_{k1}$ ⇆ langmuir$_{k2}$ + ion-sound

Summary of Kontar et al. 2012 results

Solved simultaneous equations of (1) distribution functions for Maxwellian backgd + Powerlaw beam (for n_beam / n_backgd ~ 1e-2) and (2) backgd plasma waves over **Δ**t = 1 s

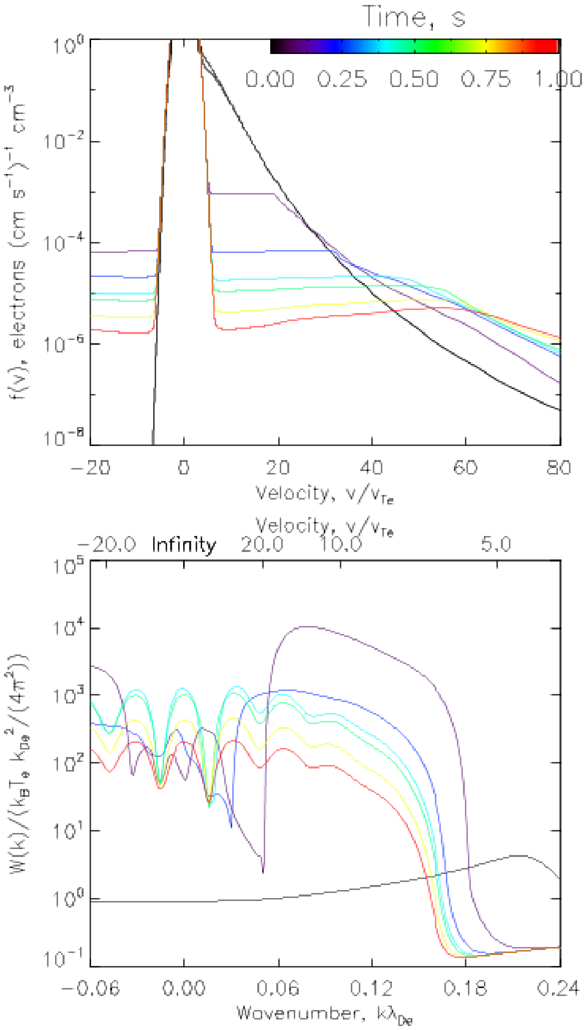
Collisional loss terms (drag and diffusion) on beam electrons (simplified Fokker-Planck)

Regimes not accessible in PIC simulations (but have been investigated with PIC)

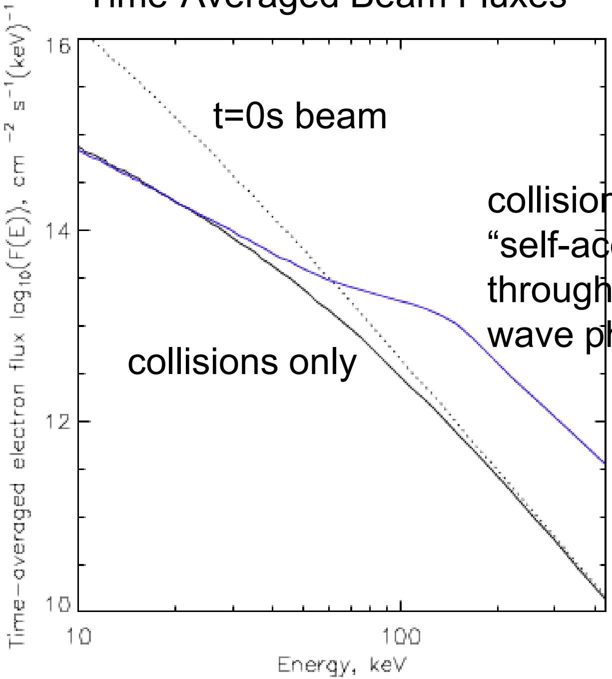
Ion-acoustic and Langmuir plasma waves: diffusion, refraction, and **non-linear wave-wave interactions (decay and scattering)**

Background density fluctuations and density gradient (important too)

Kontar et al. 2012 A&A: Main Results



Time-Averaged Beam Fluxes



t=0s beam

collisions and “self-acceleration” through wave-wave physics

collisions only

Fig. 5. Same as Fig. 2 but with ion-sound wave interactions as well as density fluctuations.

Langmuir Wave Demo (mono-k)

$T = 10^6$ K $n_e = 5 \times 10^{10}$ cm^{-3} $\omega_{pe} \approx 10^{10}$ rad s^{-1}

$$v_{\text{phase}} = \frac{\omega_{pe}}{k(t)} \approx 0.5c$$

k changes smoothly through diffusion & refraction

k decreases abruptly through non-linear 3-wave processes

resonant acceleration of beam electrons (here, 80 keV) with phase velocity of electric fields in wave (~Landau damping)

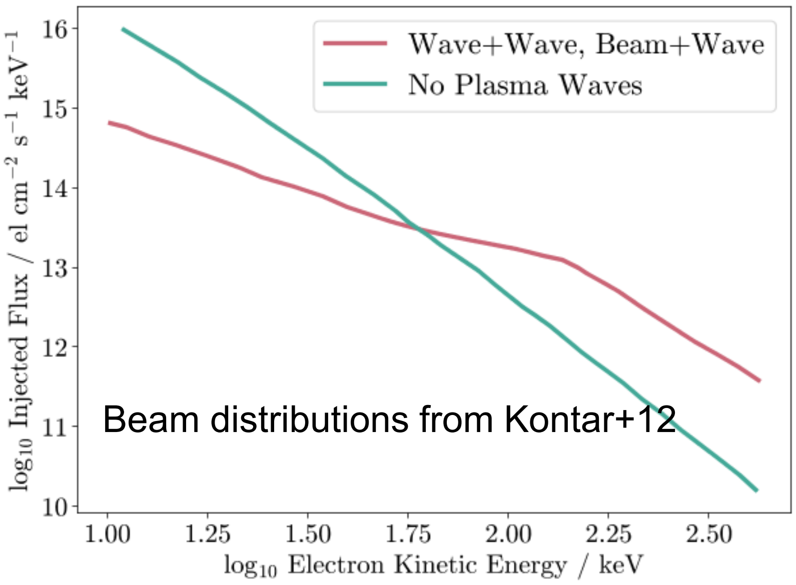
Story so far

Kontar et al. 2012: postulated that increase in E > 100 keV electrons systematically leads to higher production of hard X-rays with far fewer number of total electrons; possibly alleviates problems from large fluxes inferred using CTTM, as in Krucker et al. 2011

For stellar flares (Kowalski 2023): With a 10x larger number of E > 100 keV electrons than typically assumed from CTTM power-laws in solar flares, what are the implications for heating the low chromosphere and producing NUV and optical continuum radiation?

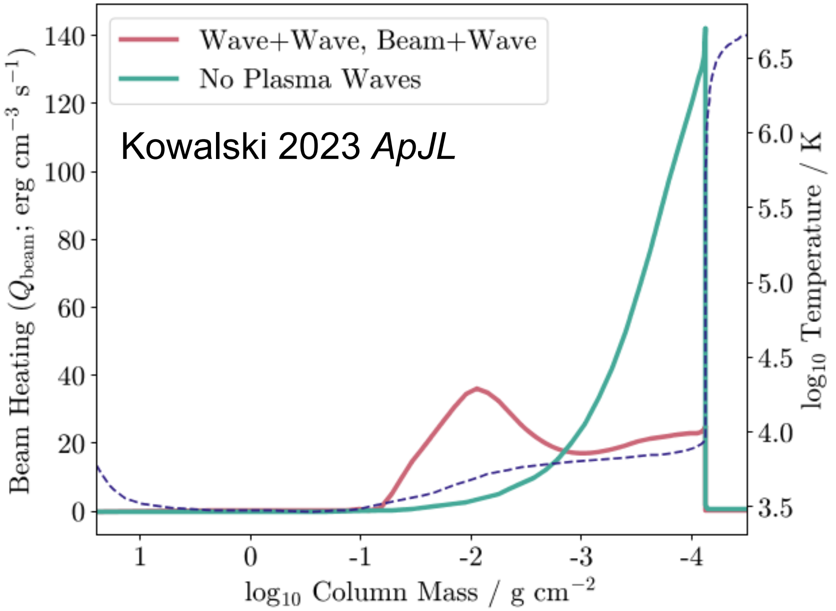
Simulated M-dwarf chromospheric heating to Kontar et al. 2012 beam

Use RADYN and Fokker-Planck solution (Allred et al. 2015)



Beam distributions from Kontar+12

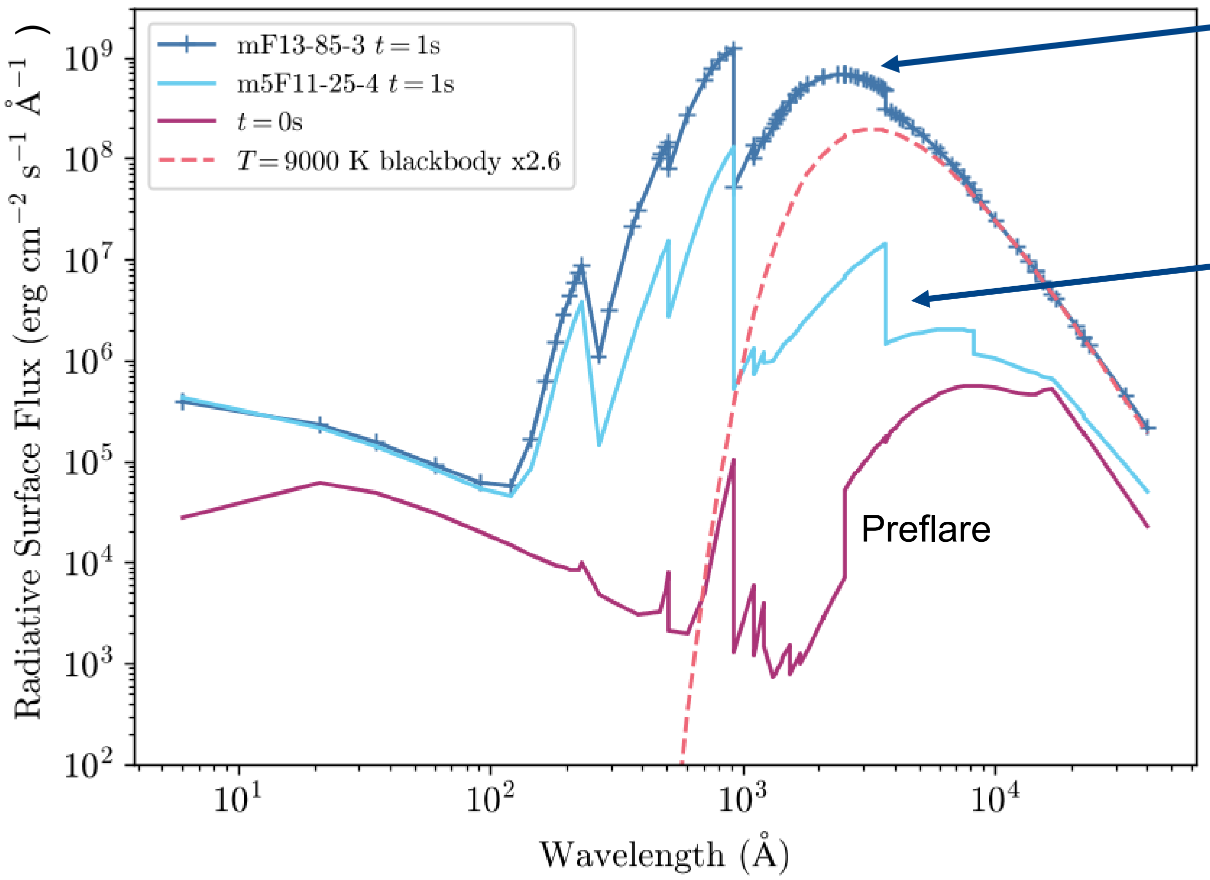
(a)



Kowalski 2023 *ApJL*

(b)

Heating in low vs. high chromosphere

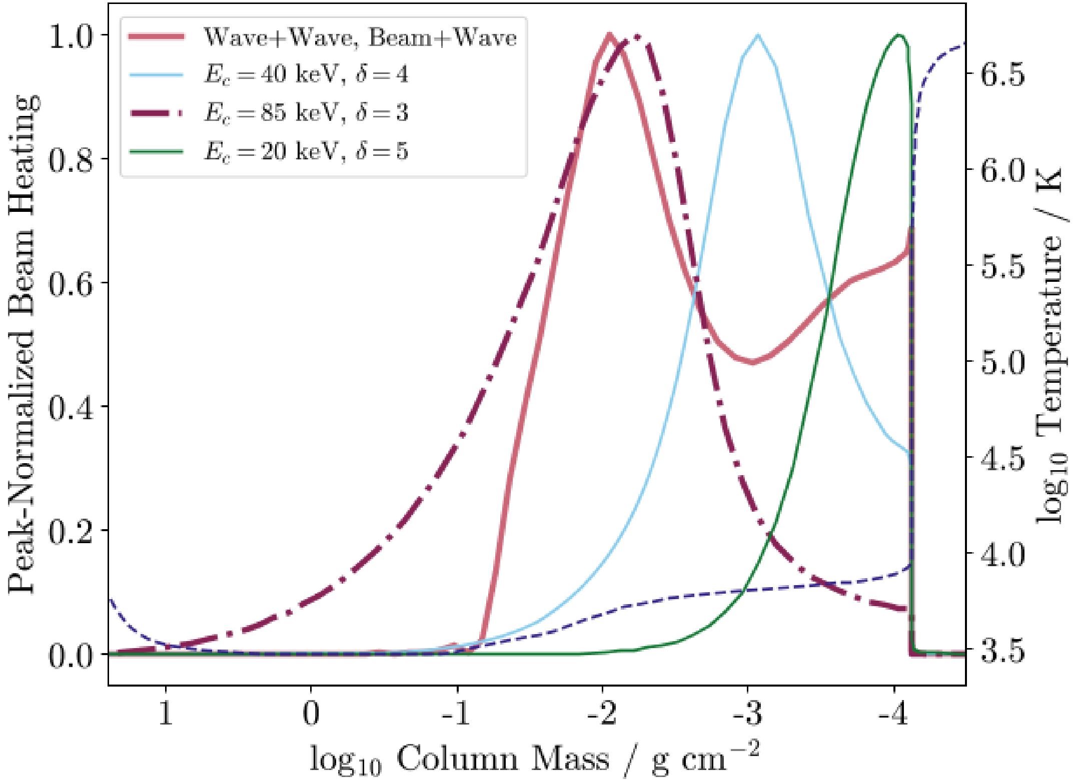


Heating m_{col} ~ 0.01 g/cm^2 to 1e4 K

Heating m_{col} ~ 0.001 g/cm^2 to 1e4 K

Calculations from RADYN
(Carlsson & Stein 1995/97)

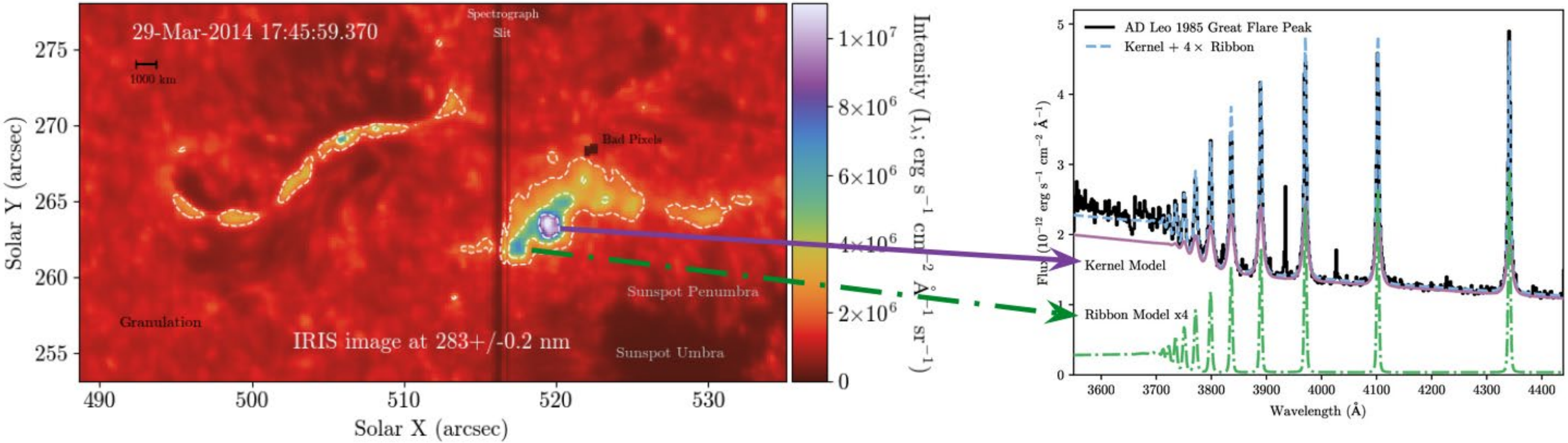
Compared to Heating Rates from Large E_{cutoff}



Heating rate maximum around 0.01 g/cm^2 column mass similar to *semi-empirical forward modeling* approach with large, E_{cutoff} = 85 keV and **δ** = 3 RADYN models (Kowalski+17, 2022) and in upcoming public grid

Kowalski 2023

Kernels: most of wing broadening and optically thick T~ 1e4 K continuum (with Large E_{cutoff} Model)



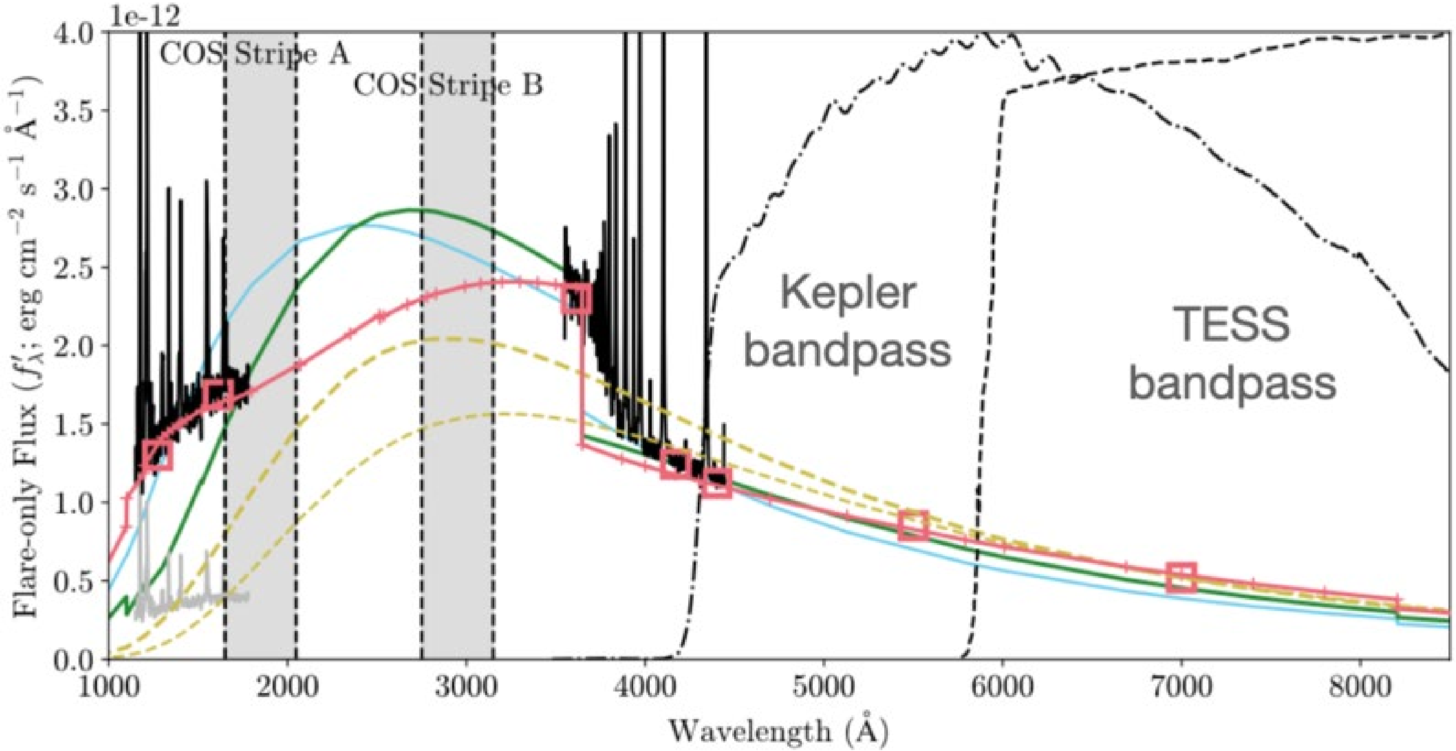
IRIS SJI 2832 image of 2014-Mar-29 solar flare

A superflare ($10^{34\text{-}5}$ erg) event on AD Leo from Hawley & Pettersen 1991

Kowalski 2022 (*Frontiers*)

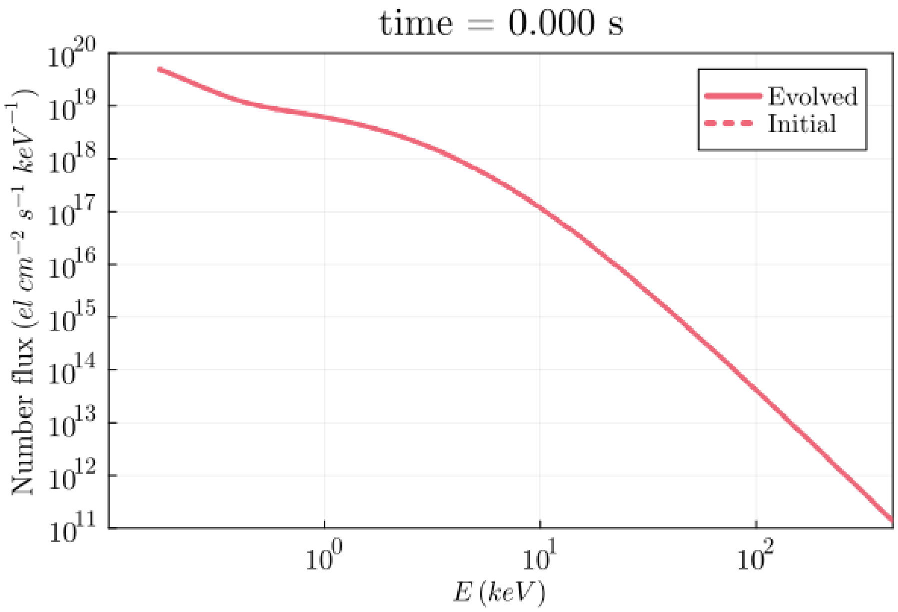
Models: using RADYN and RH codes

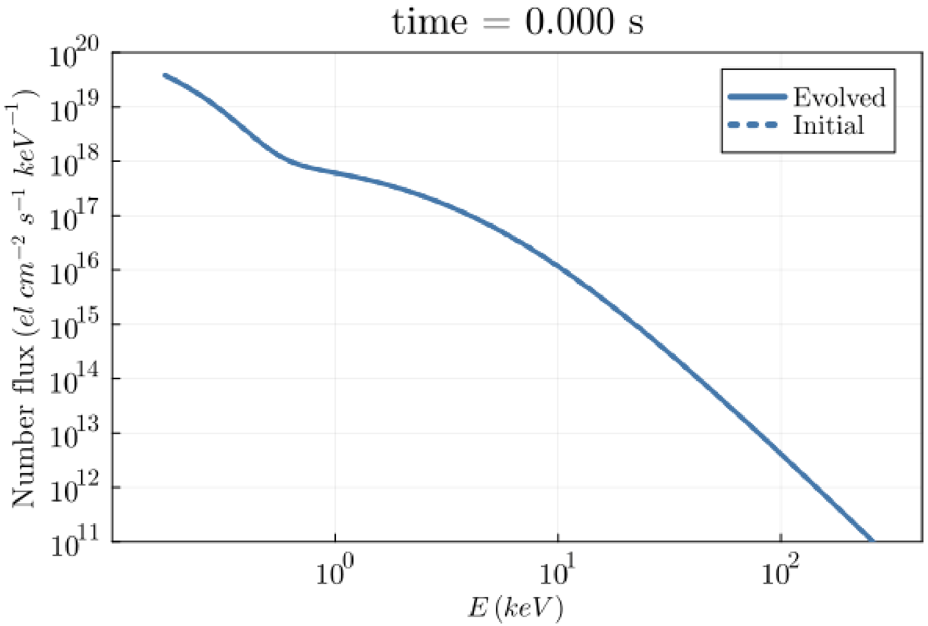
Can use good models to predict missing wavelengths



Kowalski 2022 (*Frontiers*)

Much parameter space to explore with Kontar+12 code!

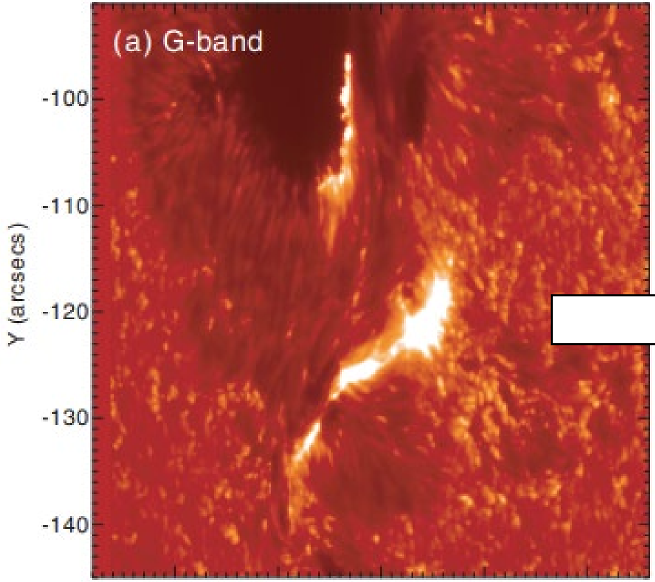




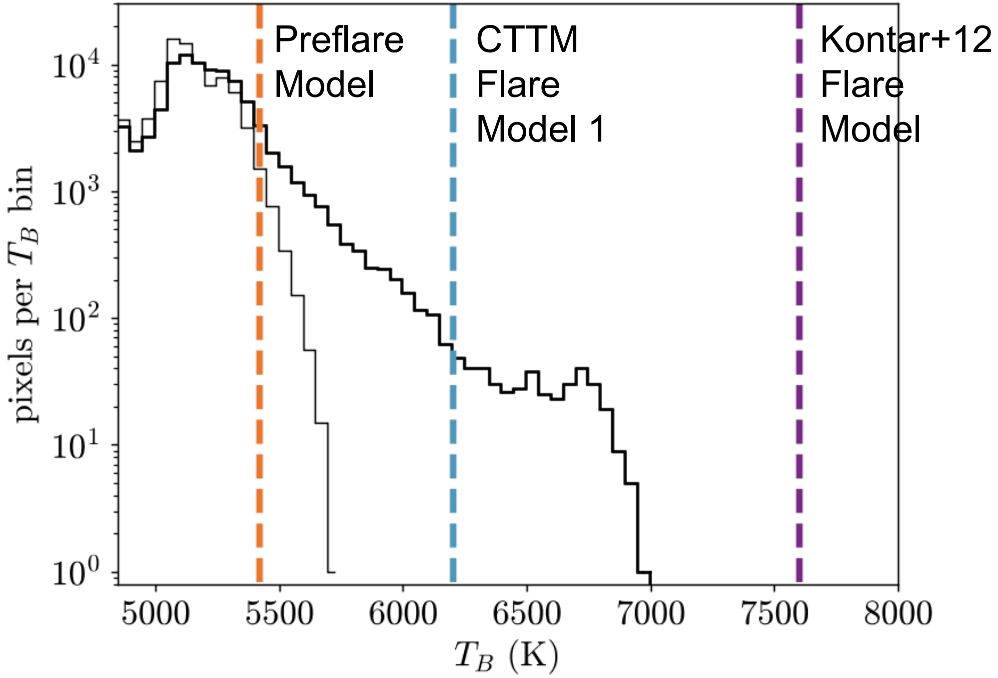
New simulation (left) with larger beam density

Note: still some problems to work out (short-timescale effects, fully relativistic theory d.n.e.)

New interpretations of solar flare optical and hard X-ray data



Krucker+2011 (430 nm)



New radiative-hydro RADYN calculations driven by Kontar+12 beam heating

Conclusions

The **beam transport and plasma wave interaction** theory of Kontar et al. 2012 produces an **enhancement in E > 100 keV electrons** that may plausibly provide a physical explanation for the **deep heating in stellar flares around log col mass ~ -2**

An *alternative hypothesis* to CTTM-inferred power-laws is now possible using RADYN simulations of solar and stellar flares

Many other problems in solar / stellar flares can be investigated (interpretation of HXR data, multi-wavelength energy budgets, anomalies in radio spectra, etc...)