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Gefördert durch:
Bundesministerium
für Wirtschaft
und Klimaschutz
aufgrund eines Beschlusses
des Deutschen Bundestages

Investigating the Solar-Stellar Analogy: The flare star AD Leo compared to our Sun

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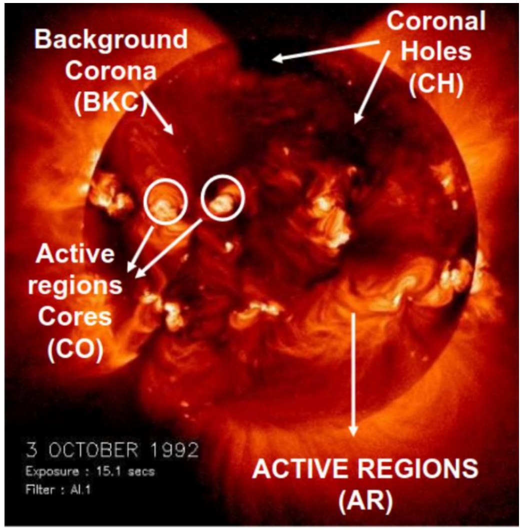
Coronal information

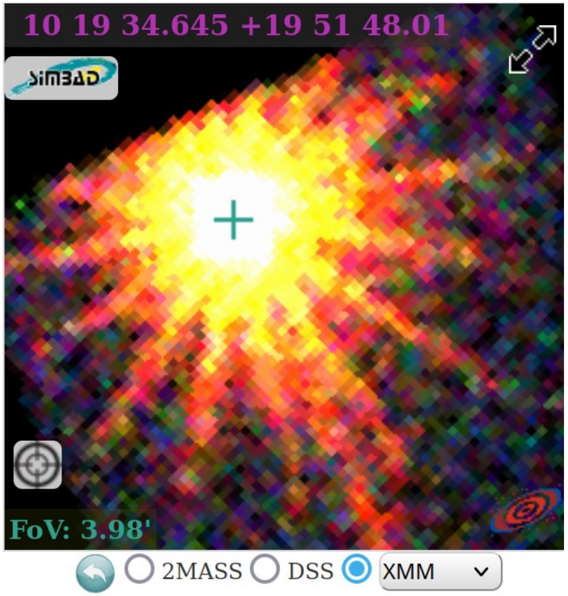


Solar Corona:
→ individual coronal features resolved with Solar missions (e.g. Yohkoh):

1. Background corona (BKC)
2. Active regions (AR)
3. Cores of Active Regions (CO)
4. Flares (FL)

Corona of other stars:
→ surface not resolved
→ Individual coronal features not visible
→ Spectra and light curves only
From, e.g., eROSITA and XMM-Newton

Are stellar coronae covered by Solar-like magnetic structures?

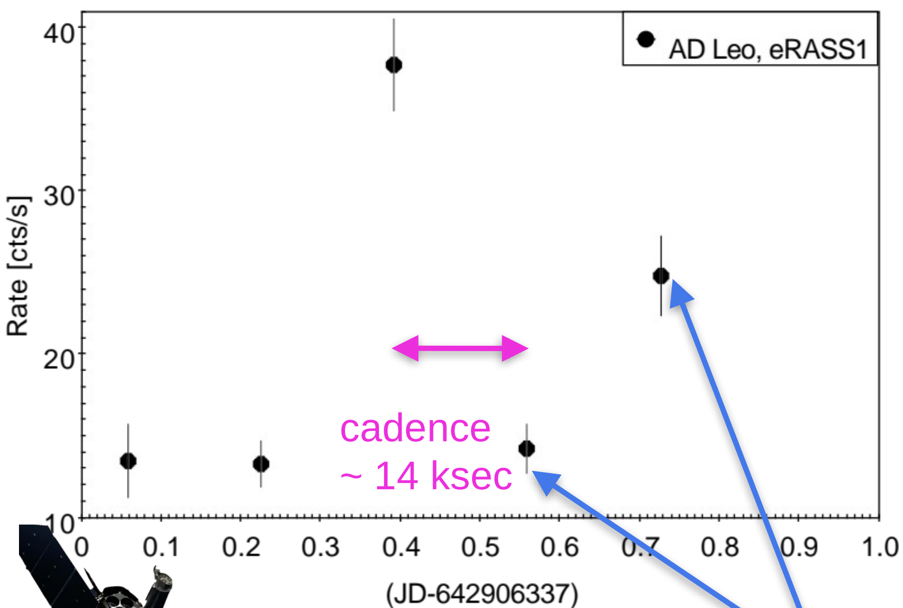


The prototype flare star AD Leo:

-> highly active M dwarf
-> Nearby (5 pc)
-> High signal X-ray observations

benchmark for Stellar activity in low-mass regime

1-day long eROSITA survey 4 coverage



Individual scans of eROSITA over the star

1-day long XMM-Newton coverage

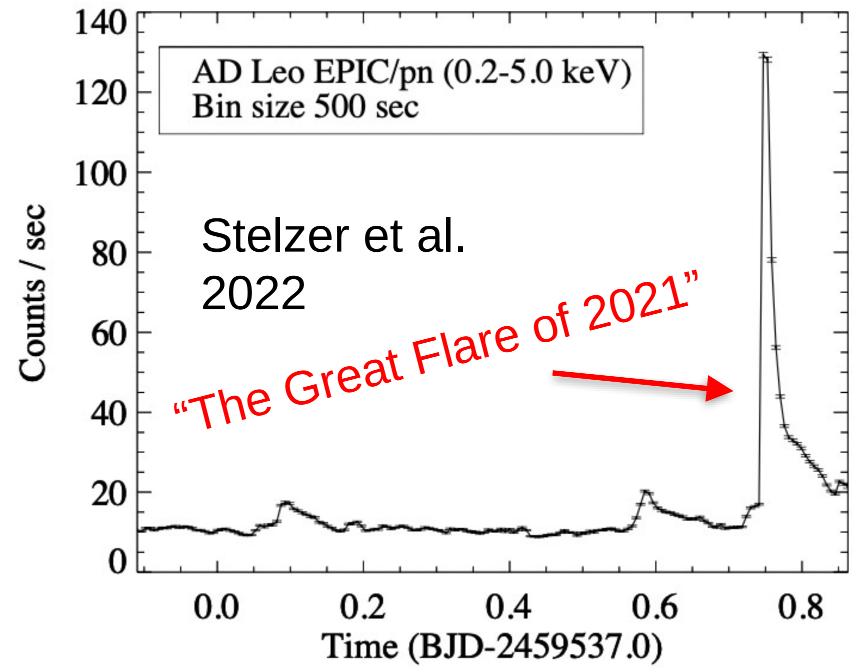
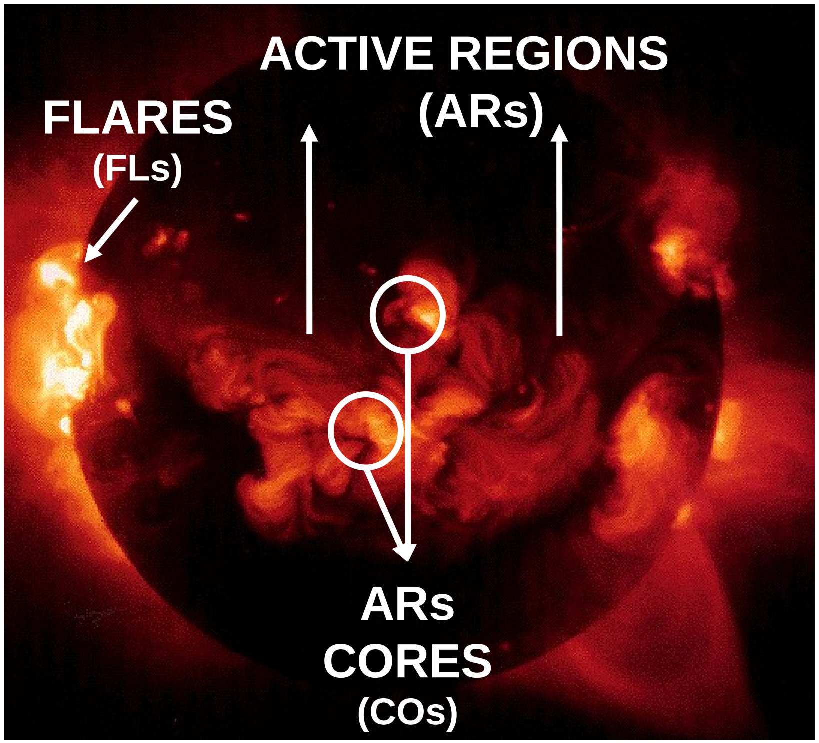


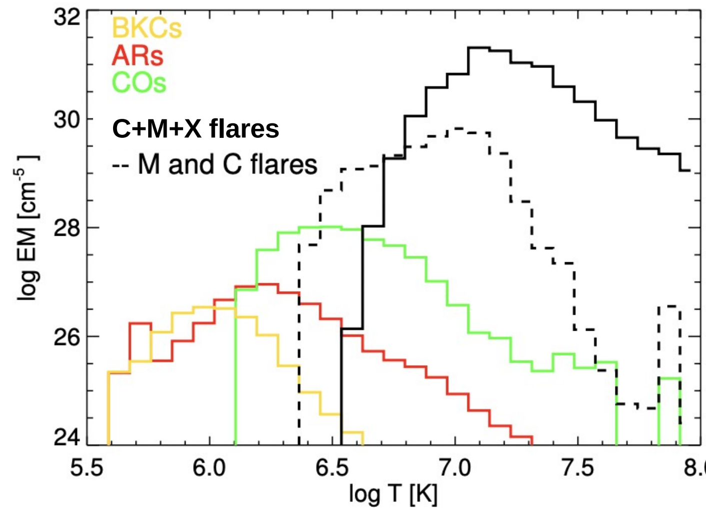
Fig. M.Caramazza

Synthetic X-ray spectra grid from solar magnetic structures.

Sun-as-an-X-ray-Star (SaXS): EM and T from Yohkoh images
(Orlando et al. (2001); Reale et al. (2001))



Yohkoh satellite X-ray image of the Sun and its magnetic structures



* Synthesize total emission measure:

$$EM_{tot} = f_{AR}\, EM_{AR} + f_{CO}\, EM_{CO} + f_{FL}\, EM_{FL}$$

f…filling factors

*GRID of synthetic EM_{tot} (for a range of filling factor values) is generated.

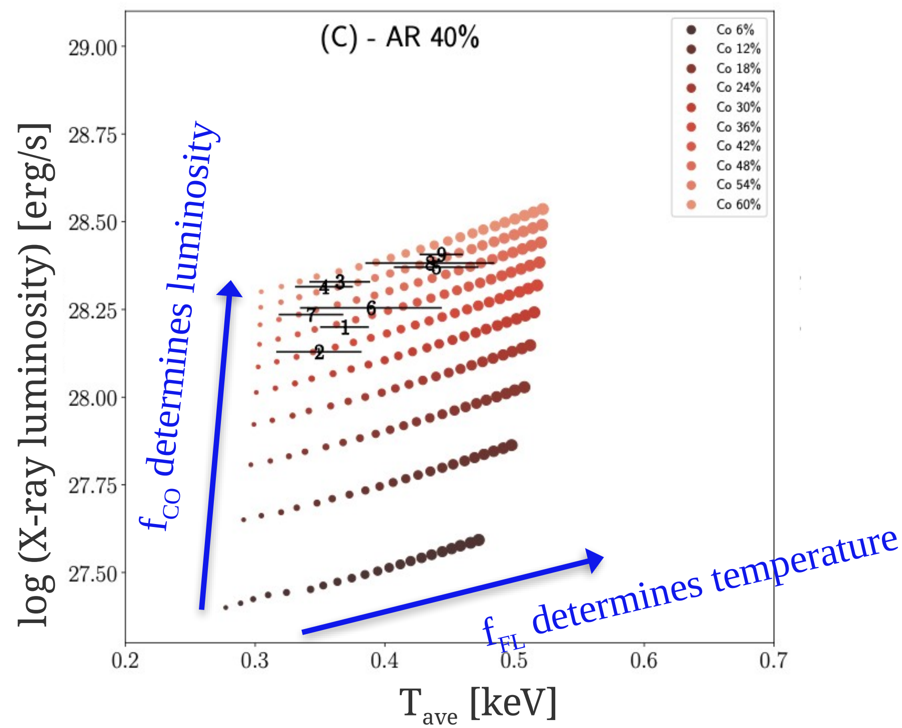
*grid of $EM_{tot} \rightarrow$ grid of synthetic spectra

Grid of stellar properties corresponding to various filling factors:

First applications to stars:
Favata et al. (2004); Favata et al. (2008); Orlando et al. (2017)

Fig.: *Comparison of fit results for grid of synthetic spectra based on solar EMD with observed values for eps Eri*

Coffaro+2020



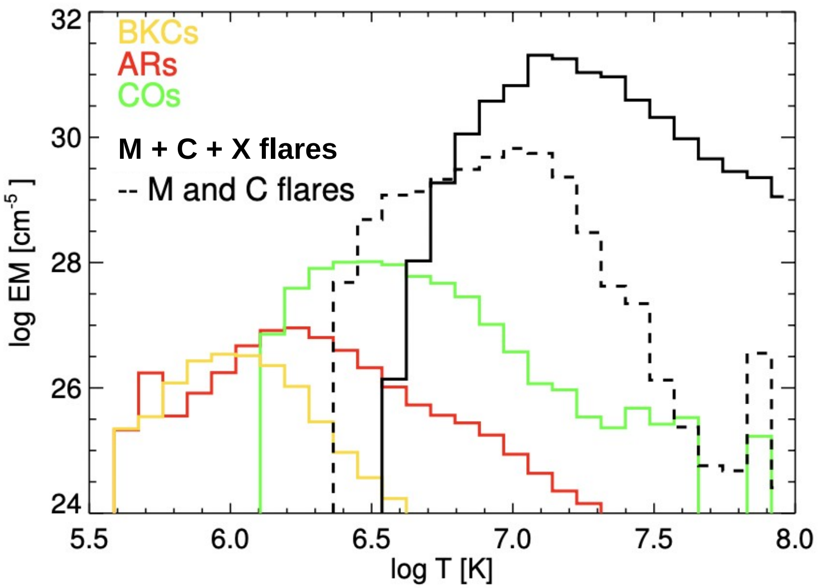
→ Select from grid the best-fitting combination of filling factors

Results:

a) <u>K2 star eps Eridani:</u>
coronal filling factor >90%

Coffaro+2020

Sun-as-an-Xray-star (SaXS)



New approach:

Define for each type of Solar Magnetic Structure (BKC, CO, AR, FL) a multi-temperature APEC model

Each bin in EM(T) for a given region represented by 1 APEC component; $APEC_i$.

→ Spectral model for a given type of region, M_{reg}:

$$\mathbf{M_{reg} = \Sigma\, APEC_{i,Reg}}$$

Total spectral model M_{tot} with, e.g., CO + AR + FL

$M_{tot} = (N_{CO} * M_{CO}) + (N_{AR} * M_{AR}) + (N_{FL} * M_{FL})$
(N_{reg} = Normalization or scaling of M_{reg})

$F_{AR} = N_{AR} / (N_{CO} + N_{AR} + N_{FL})$

Free parameters are:
Abundance + normalizations

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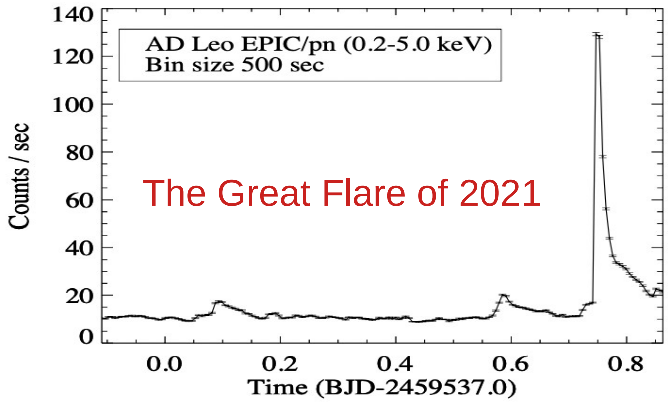
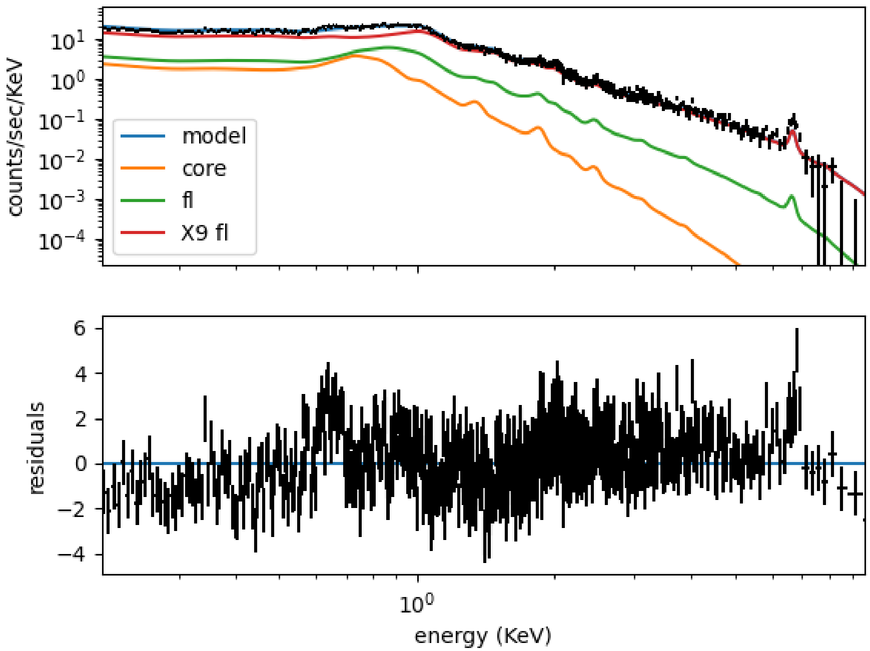
SaXS on AD Leo spectra from XMM-Newton





Example from XMM-Newton:
The Great Flare of 2021 on AD Leo

XMM-Newton EPIC-pn spectrum of The Great Flare of 2021 on AD Leo fit with cores, flares (mixture) and X9 flare models.

elemental abundances:
0.3*solar abundance using XSPEC “aspl” library

Filling factors:
f_X9FL: 0.66%
f_FL: 4.48%
f_CO: 94.86%

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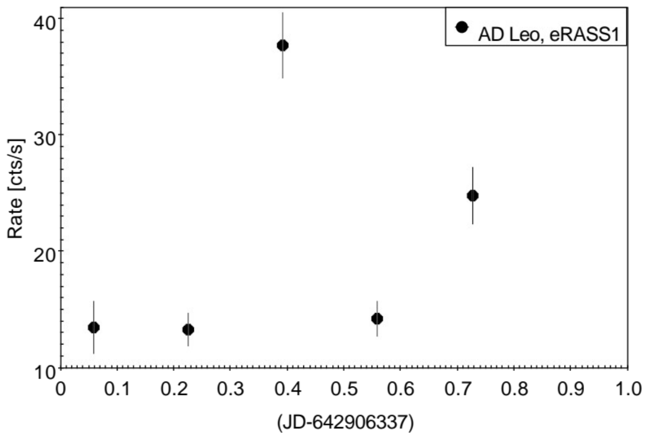
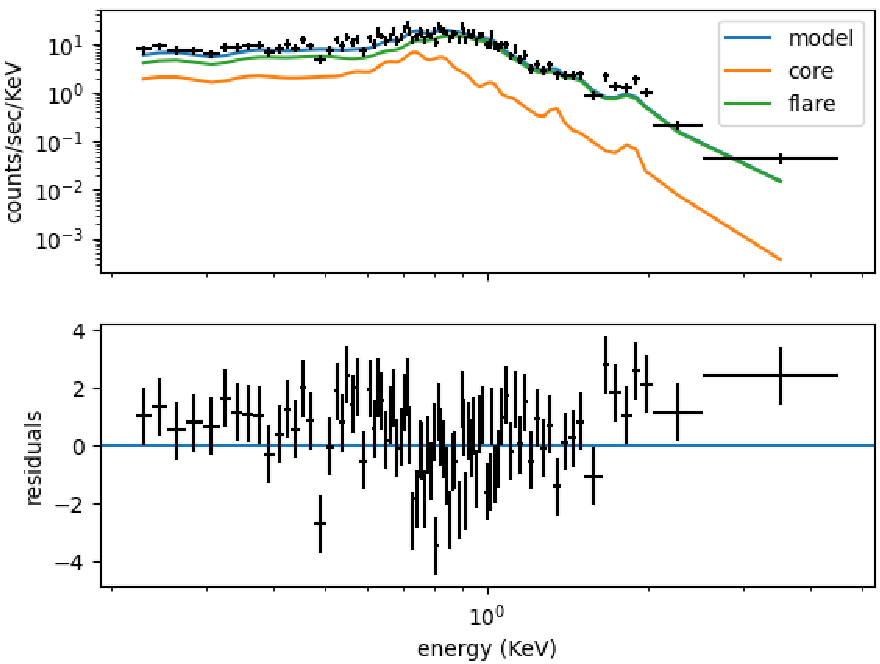
SaXS on AD Leo spectra from eROSITA





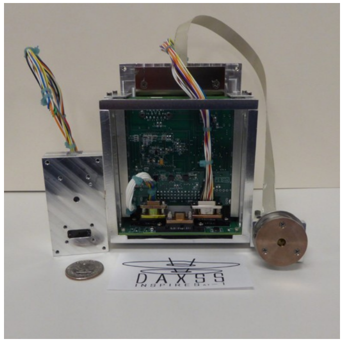
Example for eROSITA:
Time-averaged eRASS1

eRASS1 spectrum on AD Leo fit with
core and flare models.

elemental abundances:
0.3*solar abundance using XSPEC “aspl” library

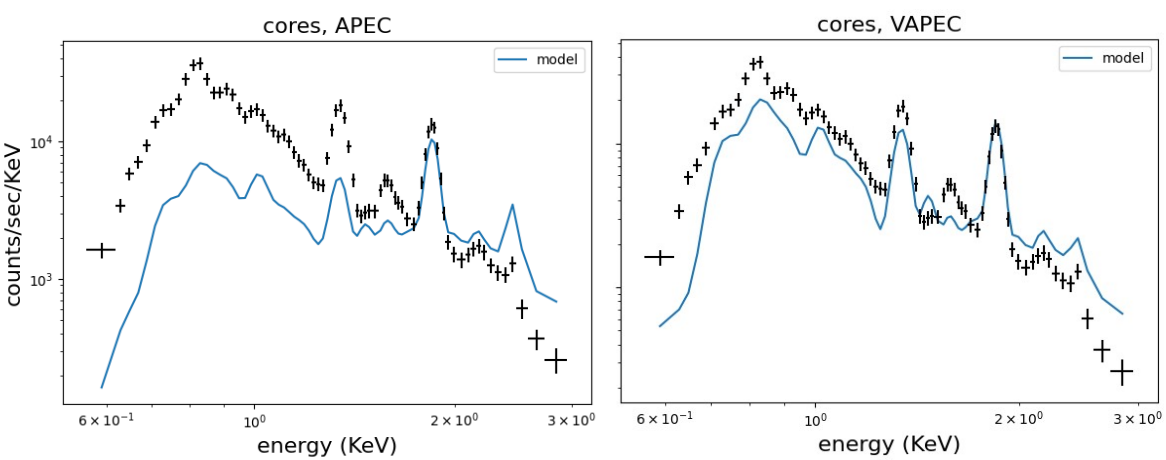
Filling factors:
f_FL: 5.37%
f_CO: 94.62%

Calibrating SaXS on Solar spectra



Dual Aperture X-Ray Solar Spectrometer (**DAXSS**):

* NASA-funded mission INSPIRESat-1
  observing solar flares at **0.3-10 keV**
* launched in Feb. 2022
* fills gap in solar soft-X-ray spectral observations
  (See Woods et al. (2023))



Spectral fit is sensitive to line emission and abundances need to be considered carefully:

Use VAPEC instead of APEC

$$\mathbf{M_{reg} = \Sigma VAPEC_{i,Reg}}$$

SaXS in development

SaXS method now applied using spectral models of coronal regions fitting two (XMM-Newton + eROSITA) AD Leo spectra, we find:

1. AD Leo is highly active → spectra fit with models of the brightest regions
2. Baseline emission in both spectra similar (~94 % co, ~6% fl)
3. flares have low filling factors, but contribute significantly to the flux
4. For the spectrum of Great Flare of 2021, an additional spectral model of a large solar flare was needed

Next steps:

→ systematic analysis of spectra from different states of AD Leo
→ improve fit by refining models on Solar spectra
→ verify models by combining simultaneous information from other solar observatories like GOES light curves and SDO images

THANK YOU