Current progress on multi-instrument DEMs using EVE and RHESSI

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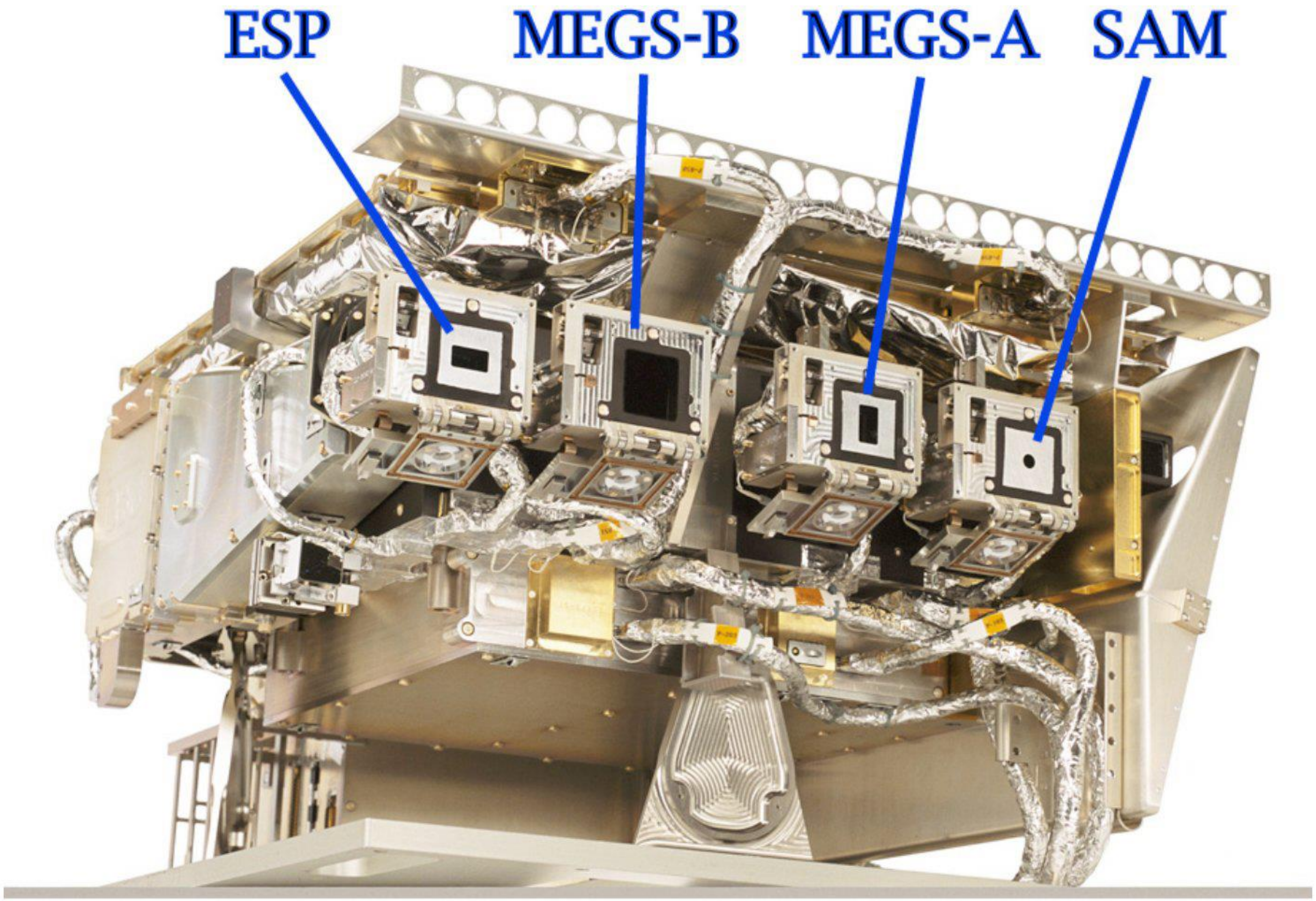
Motivation

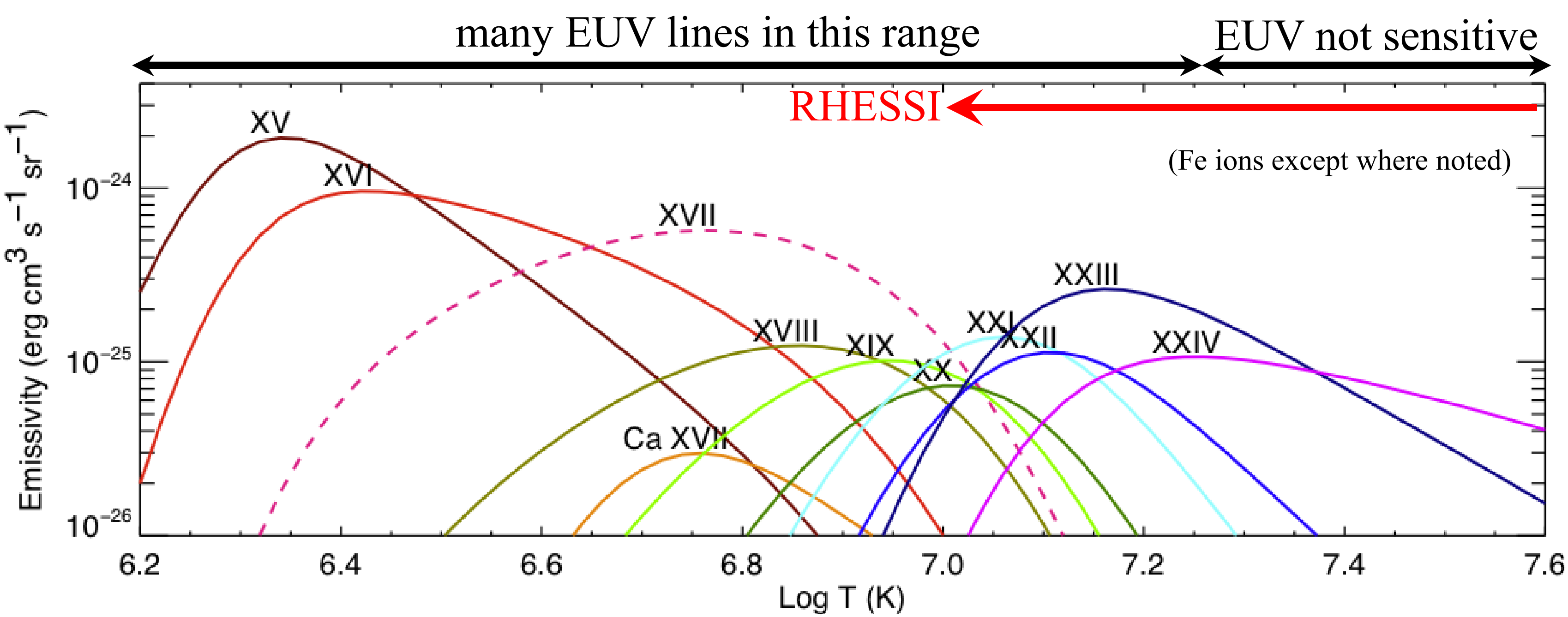
- Quantitative understanding of flare thermal properties enables:
  - Accurate energetics calculations, including energy budgets
  - Investigations of energy *transfer* from one component to another (temporal evolution)
  - Better quantification of *non-thermal* flare properties, by reducing ambiguities in spectral fitting (particularly the low-energy cutoff)
  - Via above, better understanding of the physics driving plasma heating, energy transport, and particle acceleration

EVE



- EUV spectrometer on SDO, objective grating (MEGS A/B) for high-resolution coverage (~0.1 nm FWHM) from ~5 to ~35 nm (MEGS A), up to ~105 nm (MEGS B)

EVE



- EVE (particularly the MEGS-A channel, which we use here) observes many spectral lines with peak formation temperatures covering the ~2-20 MK range
- Added to RHESSI, provides coverage of full temperature range in flares, 2-50 MK

DEMs – EVE+RHESSI

- DEM can be derived from these spectral lines using CHIANTI: the irradiance at a given wavelength represented by

$$I(\lambda) = \frac{1}{4\pi d^2} \int \varepsilon(\lambda, n_e, T_e)\, \xi(T_e)\, dT$$

is modeled using the CHIANTI total line emissivity $\varepsilon(\lambda, n_e, T_e)$ for a given density (n_e) and temperature (T_e), and the volume DEM

$$\xi(T_e) \equiv n_e^2\, dV/dT_e = \sum_{k=1}^{N} \mathrm{EM}_k \exp\left[-\frac{(\log T_e - \log T_k)^2}{2\sigma_k^2} \right]$$

is represented as the sum of Gaussians in log$T$ space, with fixed positions (σ_k) and widths (T_k) but variable intensities (EM_k).

➔ DEM determined by finding the set of EM_k that yields the best match between the modeled I and observed spectrum over the *entire* observed wavelength range, including EVE and RHESSI

Methodology

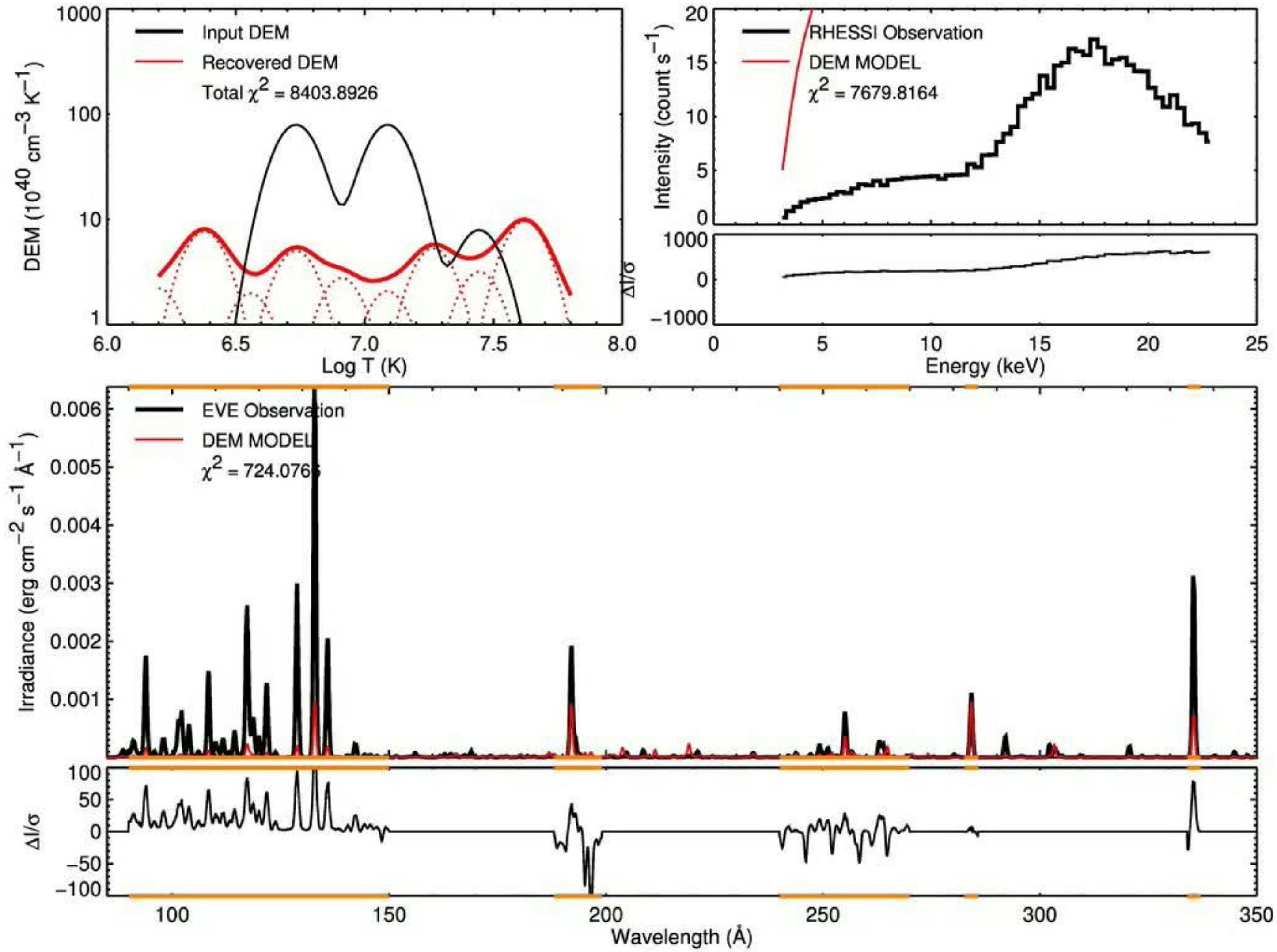
- Prep EVE and RHESSI data
  - EVE data is (currently) just the lines – pre-flare and continuum are subtracted
  - RHESSI data has nighttime background subtracted (based on orbital position)

- Use DEM model (11 Gaussians) to predict observables for EVE and RHESSI by folding through CHIANTI and instrument responses
  - Currently, assumes photospheric abundances (per Warren 2014, ApJ, 786, 2)

- Forward-fit (minimize χ^2) using both data sets *simultaneously*
  - EVE uses selected wavelength ranges (where coronal lines dominate)
  - RHESSI uses "all" data (6 keV up to max. significant energy)

➔ The hybrid method is identical to the original EVE calculation (Warren *et al.* 2013, ApJ 770, 116), with RHESSI data included in the internal object (full details in Caspi *et al.* 2014, ApJ, 788, 31)

DEMs – EVE+RHESSI



(Caspi *et al.* 2014)

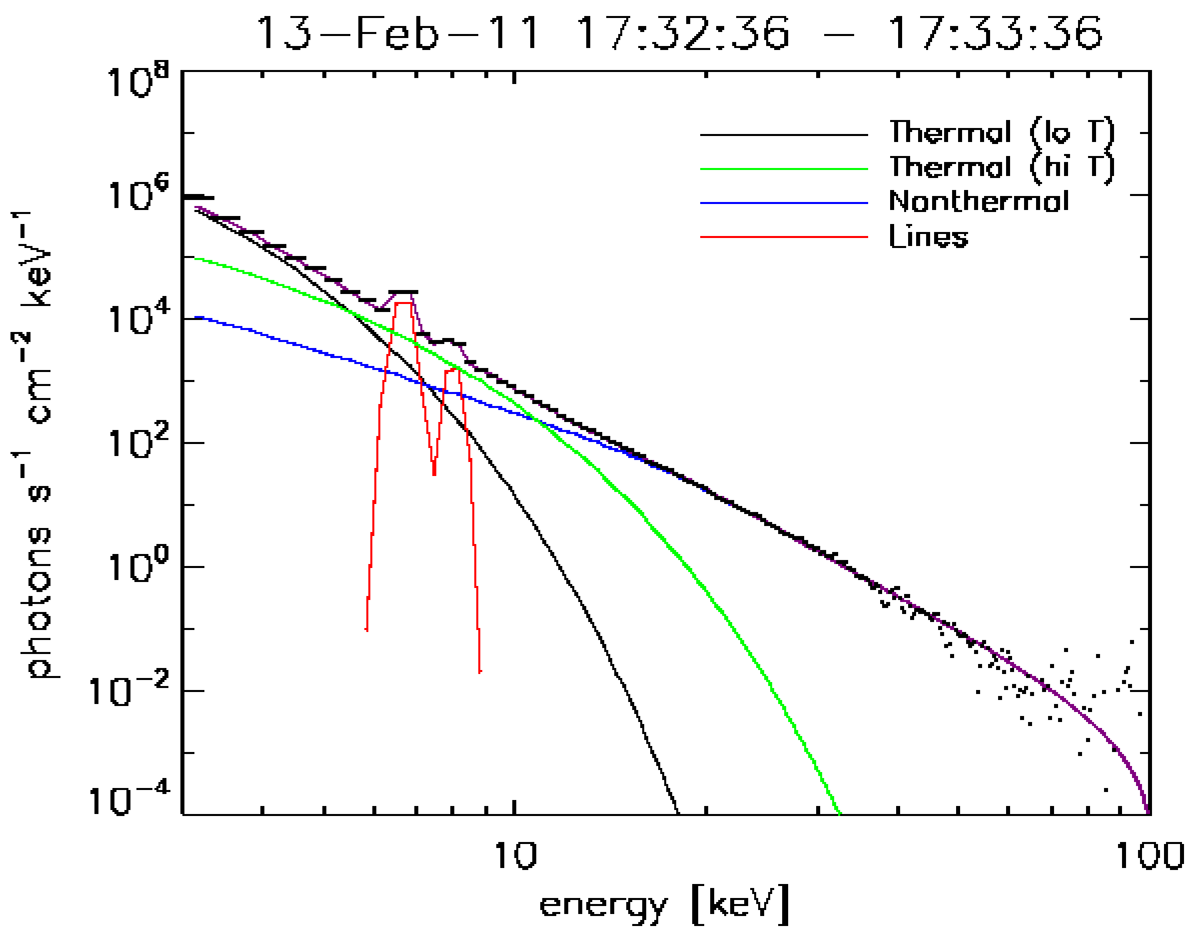
- DEM with EVE & RHESSI, using one instrument to constrain the other

Current Study

- Investigating the "residual" non-thermal emission (after accounting for thermal emission via DEM), to constrain the low-energy cutoff
- Ideally, we would calculate the DEM, subtract it, and the rest would be non-thermal… but:
  - EVE DEM not constrained at high T (>20 MK)
  - Can't easily separate RHESSI thermal/non-thermal (that's the point of this!)
- So, fit everything simultaneously

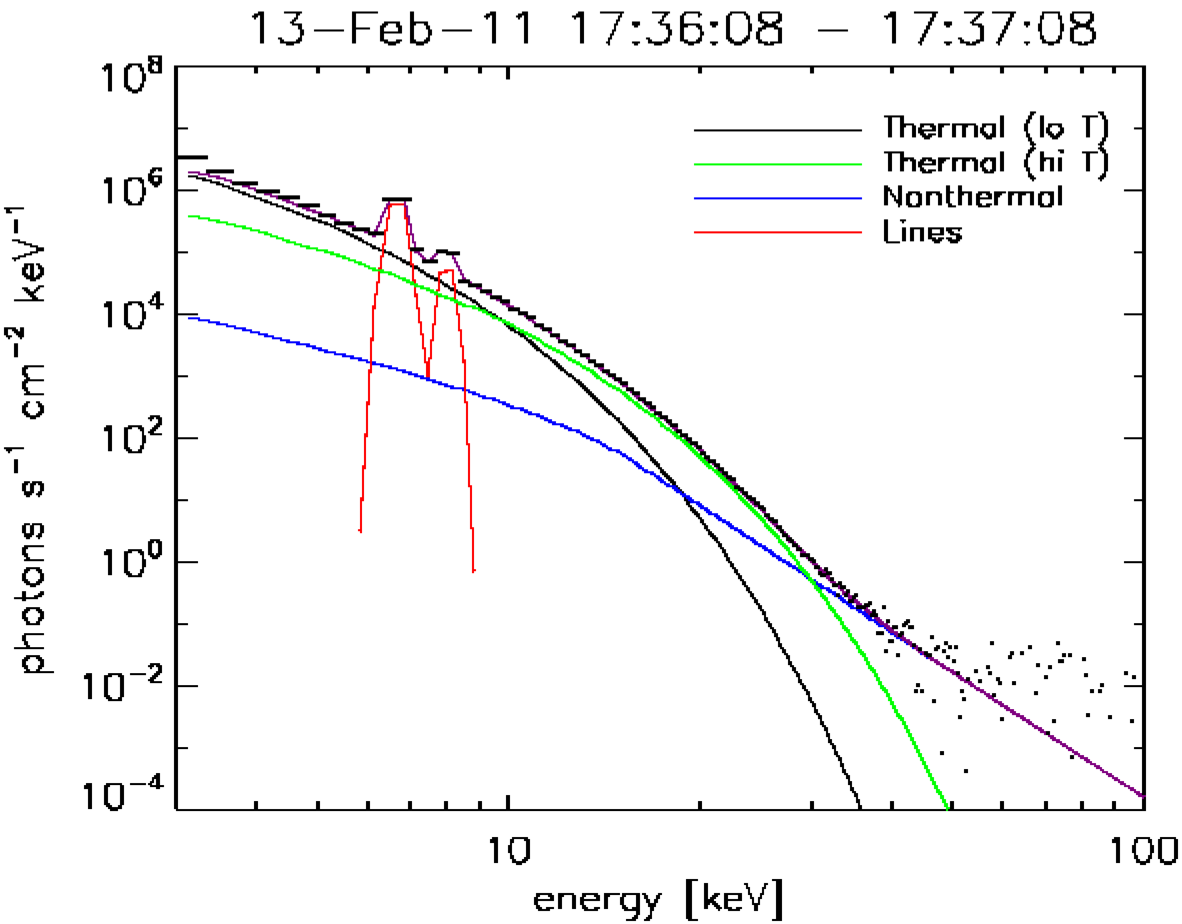
- RHESSI non-thermal fit using "thin2"
  - Instantaneous non-thermal spectrum, very few assumptions
  - Low-E cutoff not well defined – looking instead for a break, since an injected spectrum with cutoff will evolve to a continuous spectrum with break (flatter below the break than above)

Non-thermal constraints



- Early in a flare, where thermal is less dominant -- this makes the time interval a good candidate for possibly isolating a cutoff.

Non-thermal constraints



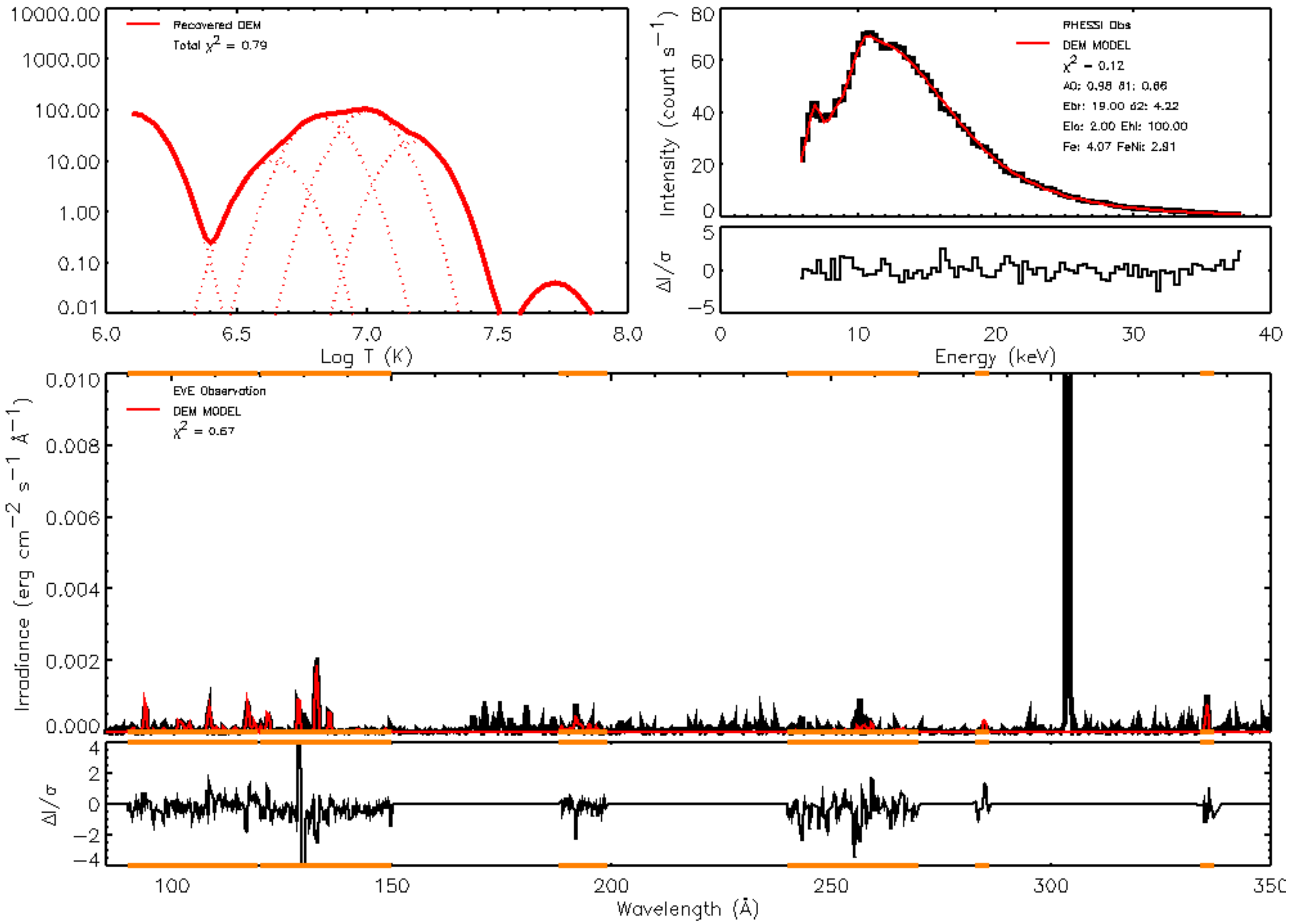
- Later in the flare, thermal component dominates to high energies -- much harder to obtain lower limit on cutoff

Current Study – Methodology

- 40 flares observed by EVE and RHESSI during Feb-Sep 2011.
  - All M-class or larger, with >50 keV emission in RHESSI
- Isolated one-minute time intervals with good conditions:
  - Relatively early in the flare, with a discernible nonthermal component with a good signal to noise ratio in the 40 to 50 keV range, and a photon spectral index in the range from 3 to 7.
- DEM with EVE+RHESSI method; non-thermal fit using "thin2"
  - FREE params: normalization, spectral indices above/below break (index below constrained to be < index above)
  - FIXED: low-E cutoff in thin2 set to 2 keV (minimum)
  - Break energy stepped manually from 3 to 27 keV to map χ^2 space

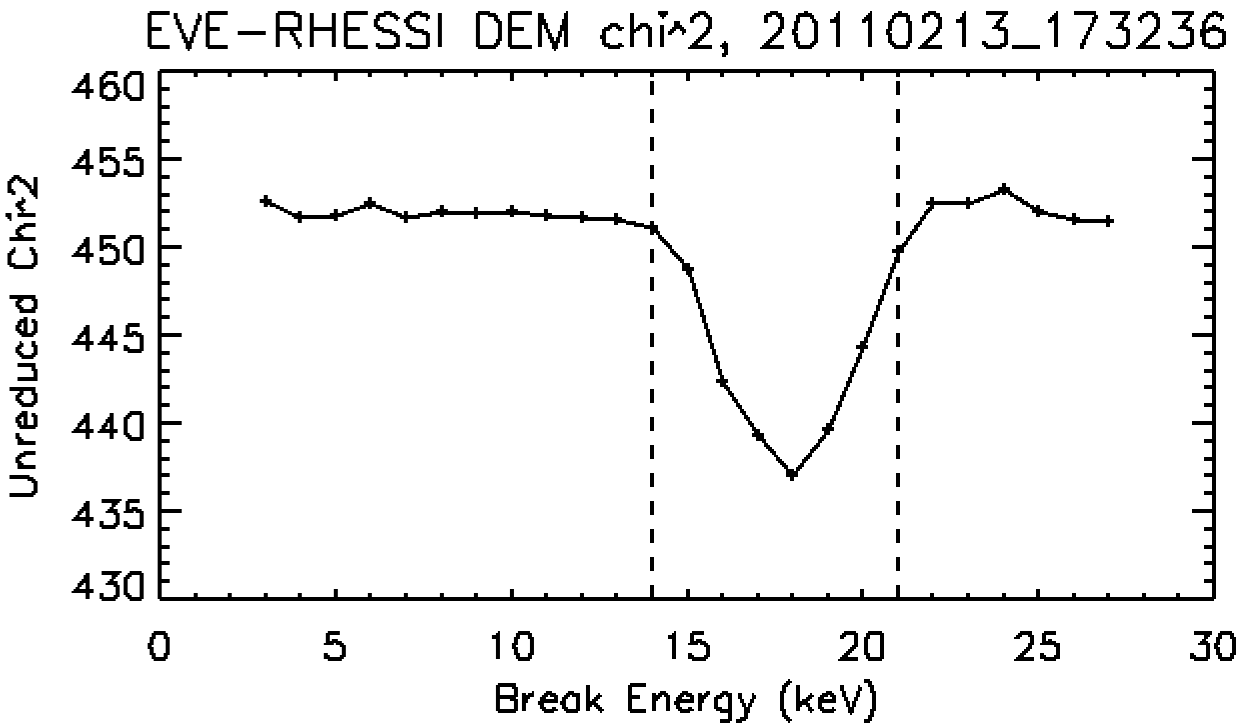
- Note that EVE and RHESSI data are weighted differently
  - Required so the fit process does not ignore the RHESSI data, as there are many fewer independent RHESSI data points than in EVE.

Non-thermal constraints



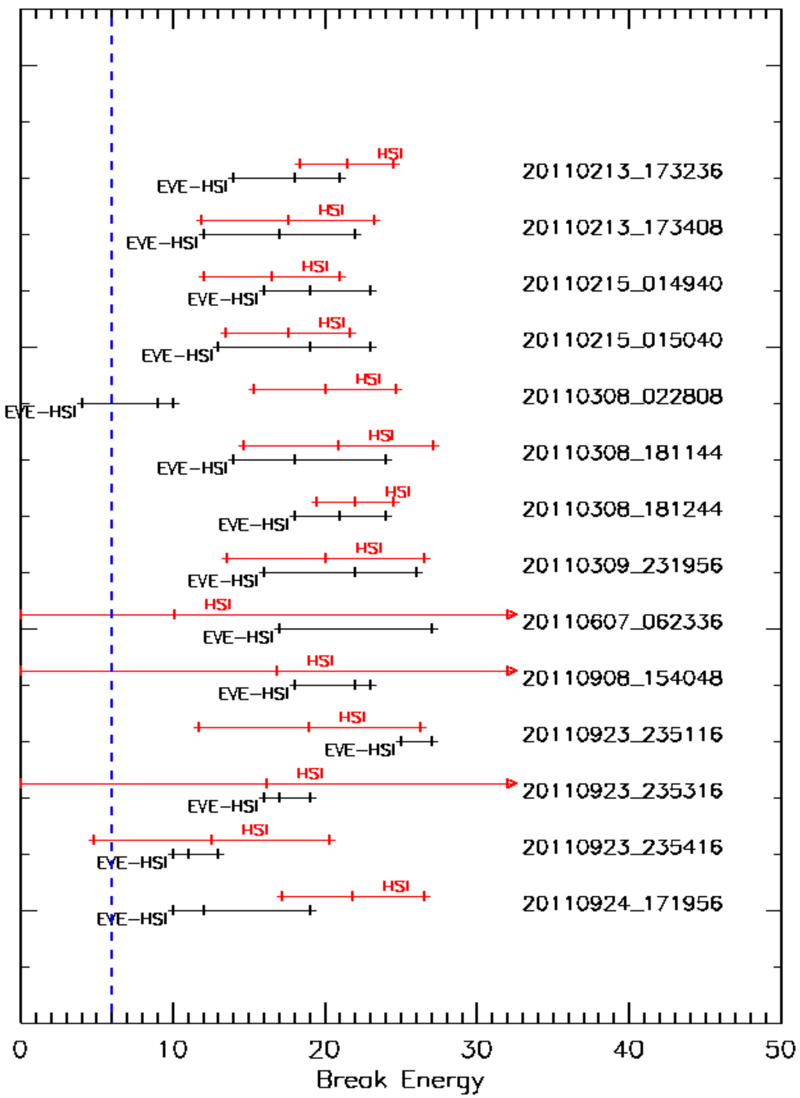
- Example fit for 13 Feb 2011 – good agreement, self-consistent spectrum
- Evidence for high-T emission…

Non-thermal constraints



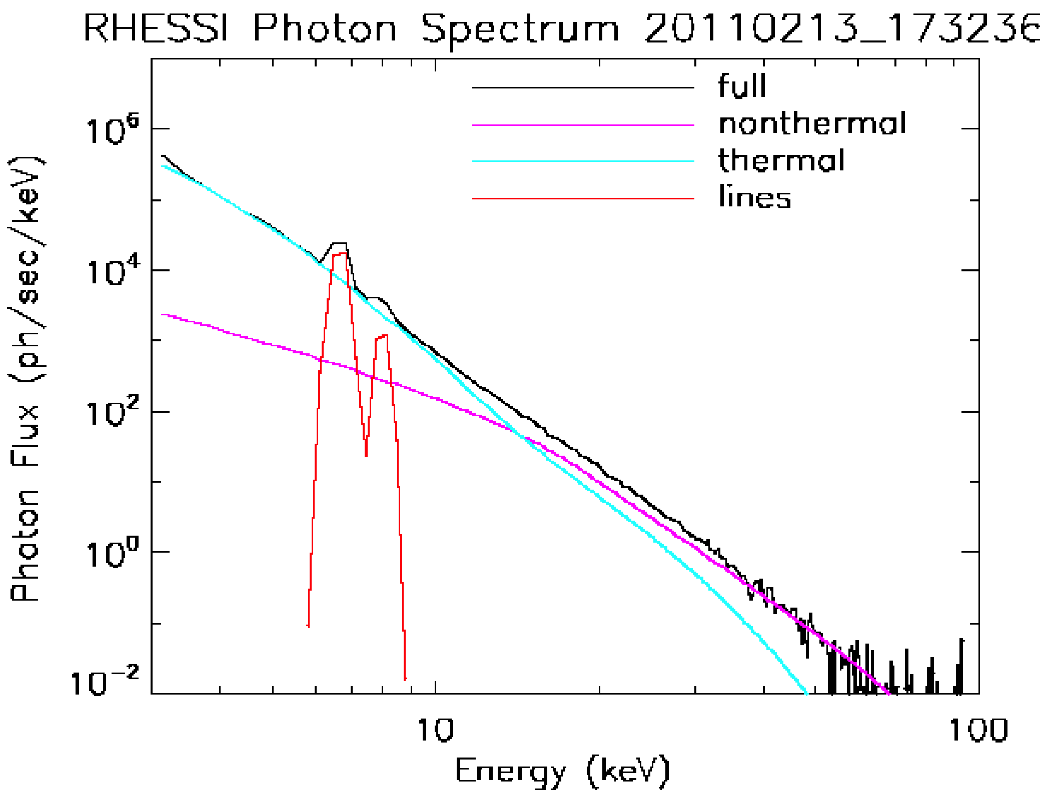
- Unreduced χ^2 vs. break energy, clear minimum is almost always visible
  - Approximately 500 data points, so reduced $\chi^2 \sim 1$
- Uncertainties estimated by 3σ width of χ^2 dip (not always symmetric)

Non-thermal constraints



- Break energy ranges for 14 flares
  - PRELIMINARY
- RHESSI-only values typically agree (not always), usually tighter range w/ DEM method
- DEM method yields range even when RHESSI-only fails to give uncertainties
- Spectral indices from DEM method usually harder than RHESSI-only…

Caveats



- DEM method may overestimate high-T (unconstrained by EVE)
- Fe & Fe/Ni lines not currently utilized – should help provide constraint
  - BUT, will be sensitive to abundances (and CHIANTI accuracy)

Summary

- 40 flare test-bed, 14 flares with “good” early conditions for analysis
  - 100+ flares available over 4-year EVE MEGS-A period (May 2010 to May 2014)

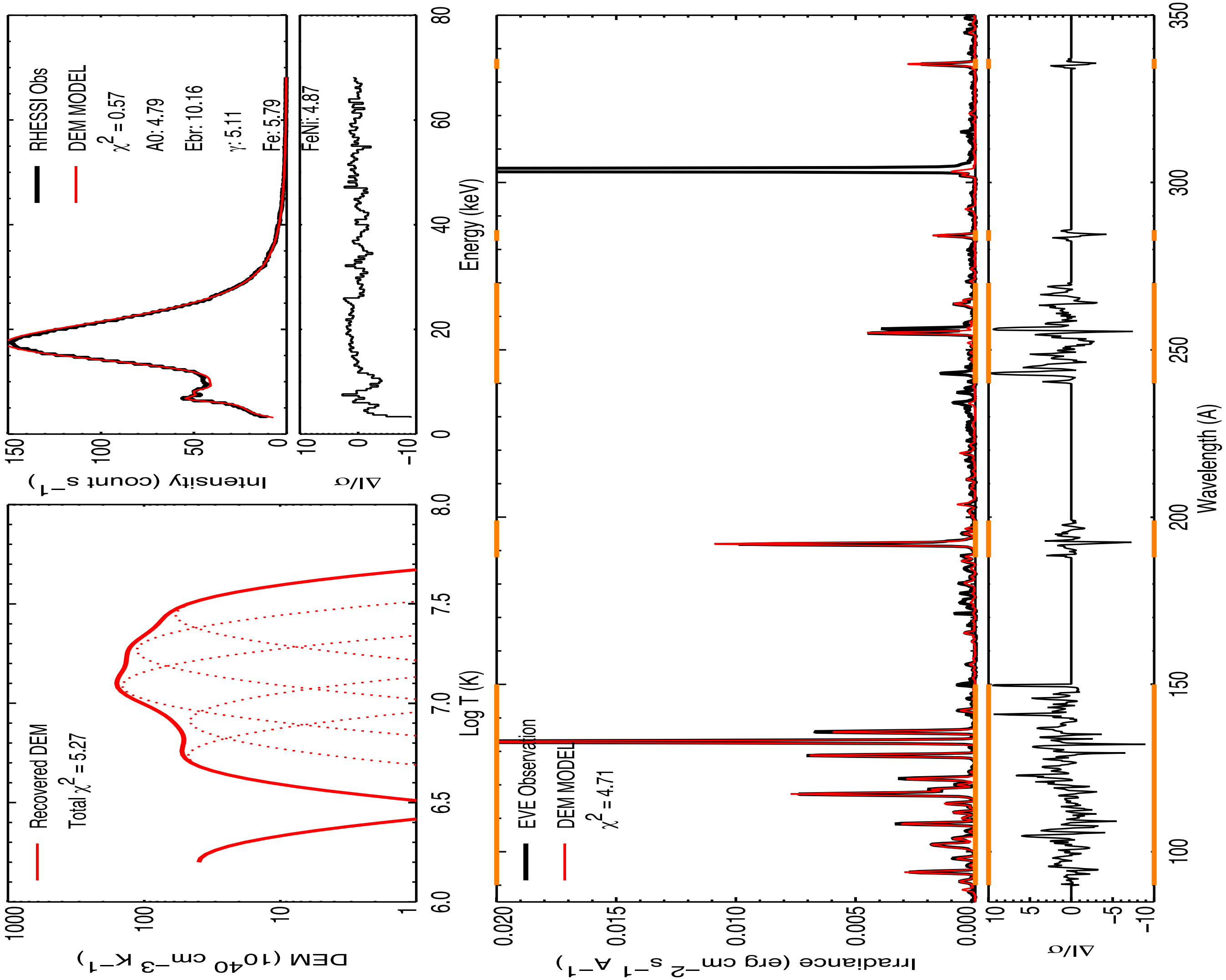
- DEM method converges well, low residuals

- thin2 break energy well-constrained with DEM method
  - BUT… competition between high-T DEM and non-thermal component
  - High-T needs additional constraints

- FUTURE WORK:
  - Model and fitting procedures still being evaluated and modified
  - Incorporating Fe/Fe-Ni lines
  - Investigating weighting options for different model components
  - Adding abundance fitting (low-FIP scalar, and/or individual elements)

EXTRA SLIDES

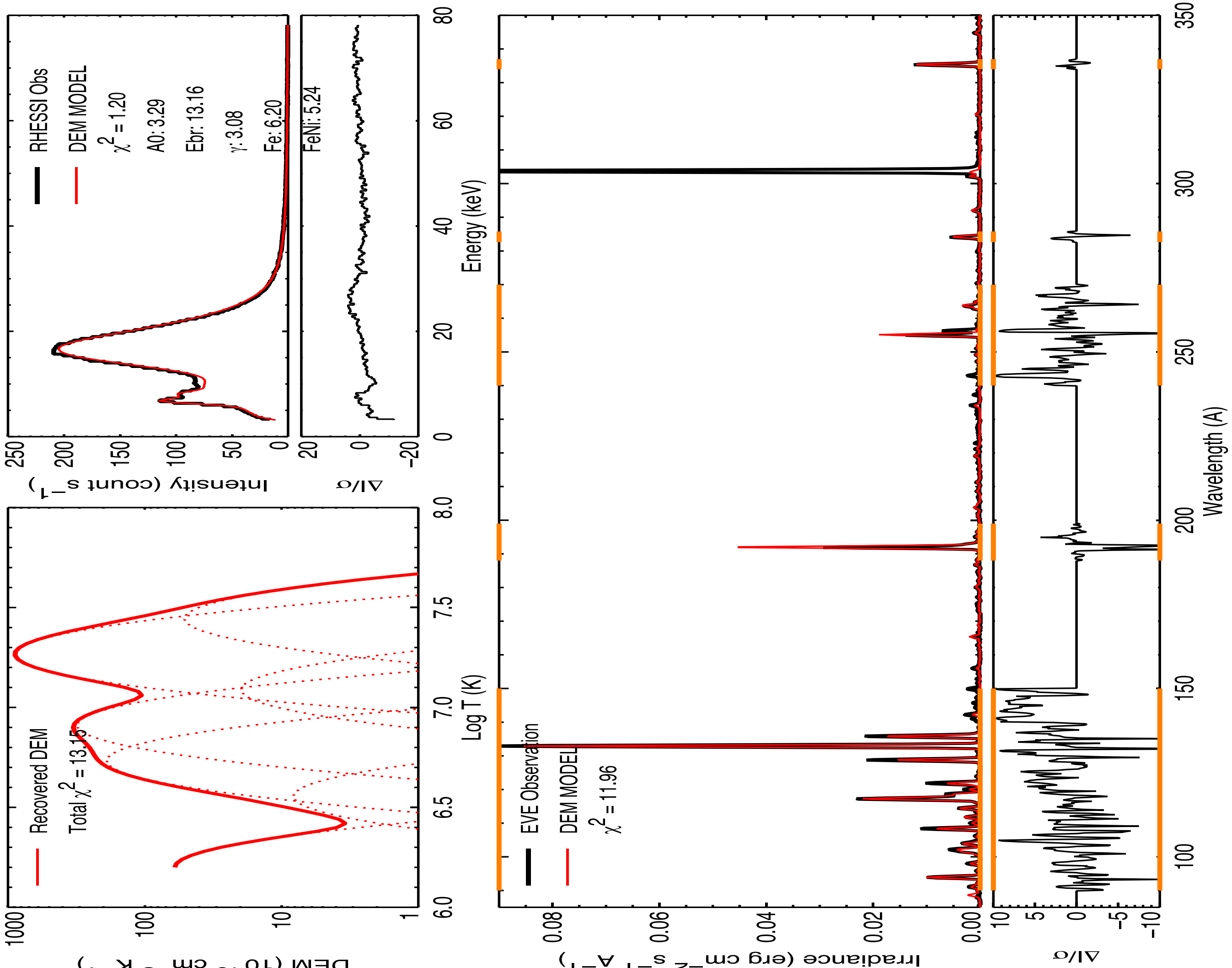
DEMs



(Caspi *et al.* 2014b)

- Real flare data fits well, DEM recovered with good fidelity

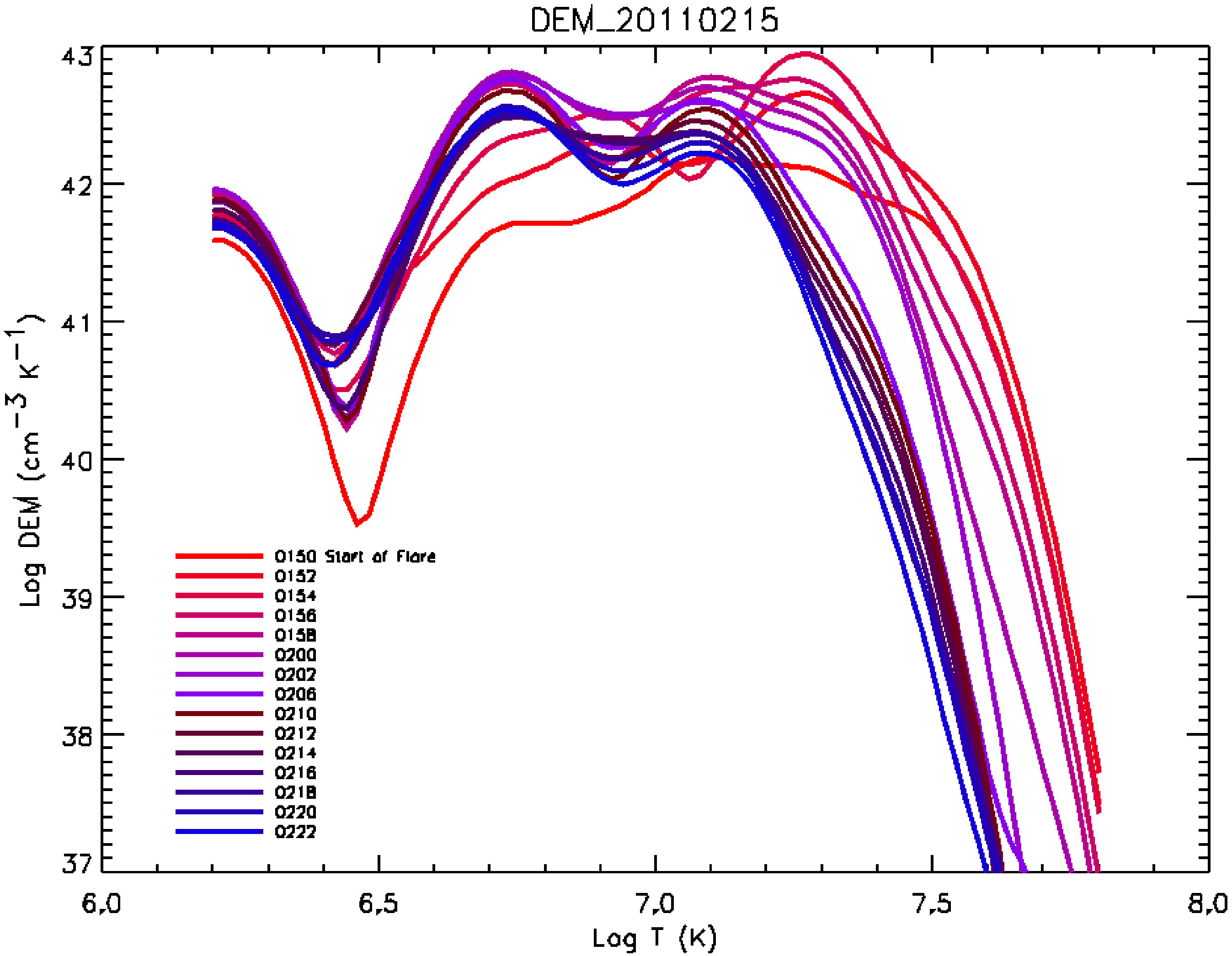
DEMs



(Caspi *et al.* 2014b)

- Bimodal DEM observed often, but no distinct super-hot component

DEMs – EVE+RHESSI



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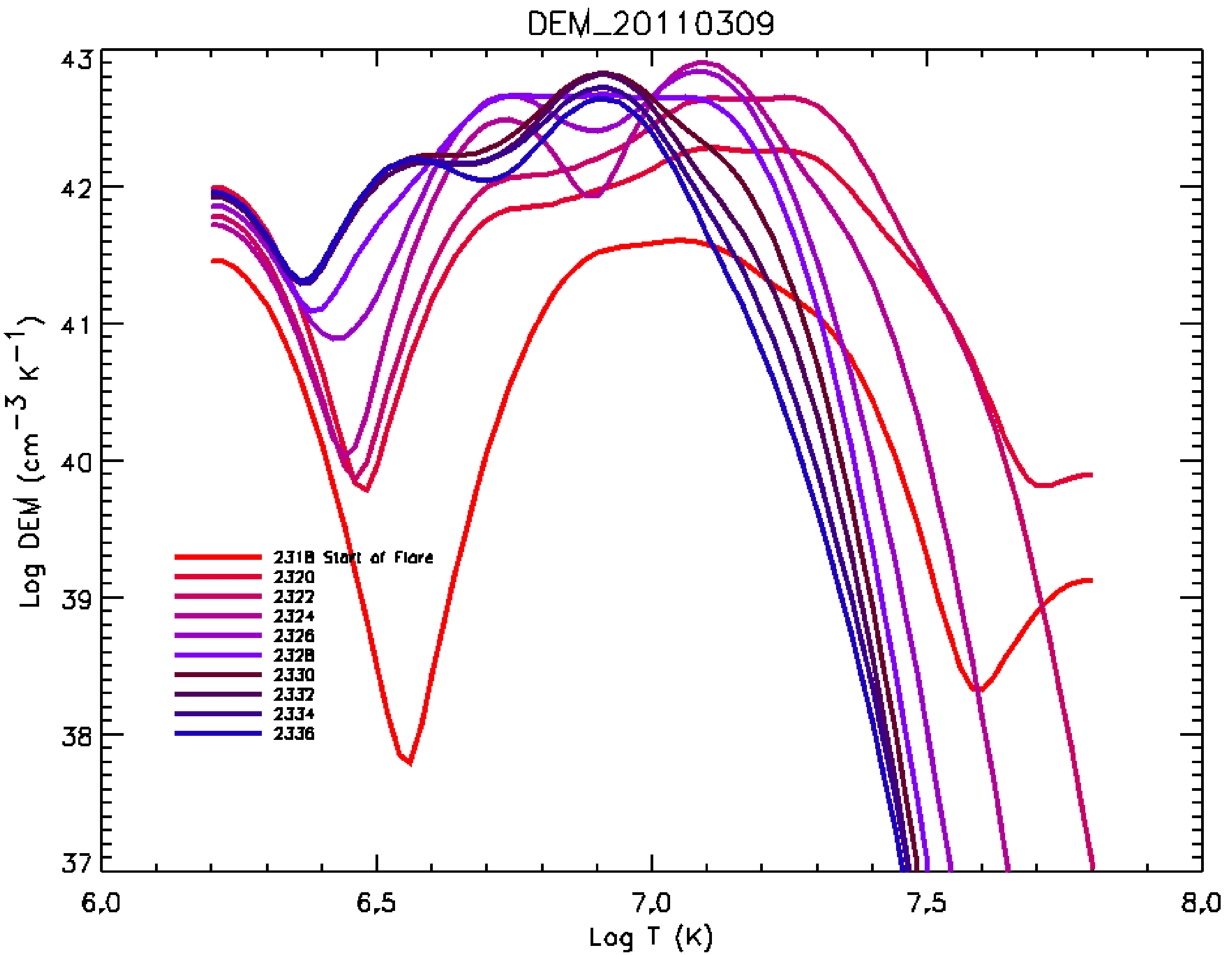

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