Leibniz-Institut für
Astrophysik Potsdam

Flare energetics deduced from X-ray observations: considering some caveats

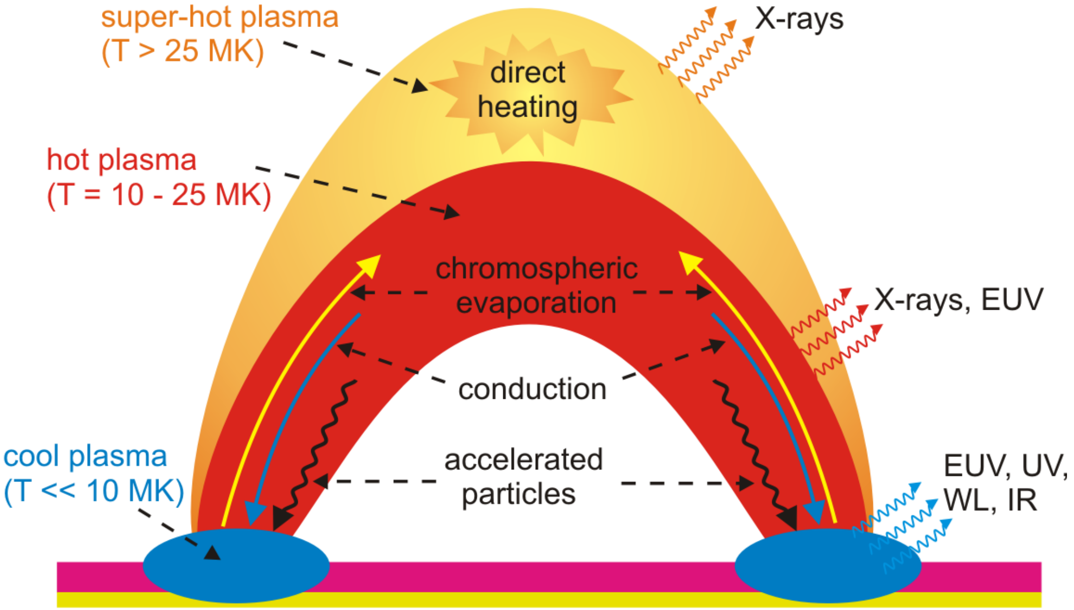
Alexander Warmuth & Gottfried Mann

Leibniz-Institut für Astrophysik Potsdam (AIP)

Study of Warmuth & Mann (2016a/b)

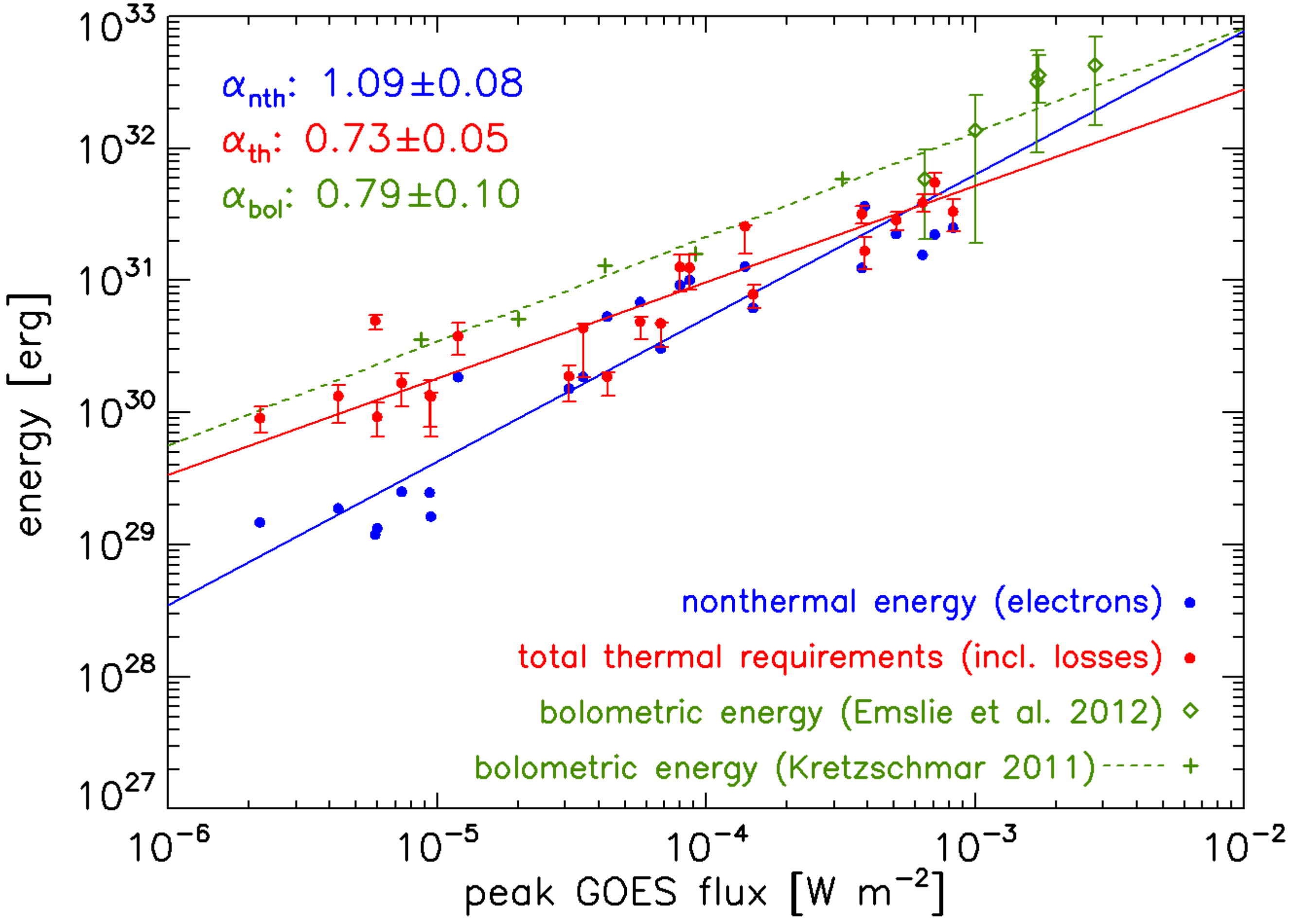
- 24 flares from C3 to X17
- time series of GOES fluxes and RHESSI spectra (isotherm. + CTTM)
- time series of HXR images: source sizes *(Warmuth & Mann 2013a,b)*
- nonthermal electron input: $$P_{nth}(t) = \int_{E_{LC}}^{E_{HC}} dE\, F_0(E,t) \cdot E$$
- thermal energy: $$E_{th}(t) = 3 k_b T \sqrt{EM \cdot V}$$
- radiative loss rate: $P_{rad}(t)$ (from CHIANTI)
- conductive loss rate: $P_{cond}(t) \sim A_{FP} \cdot T^{7/2} \cdot l^{-1}$ (Spitzer, with saturation)
- total heating requirement: $$E_{th,tot} = \int_{t_B}^{t_E} dt \left(\frac{dE_{th}(t)}{dt} + P_{rad}(t) + P_{cond}(t) \right)$$

Results of Warmuth & Mann (2016a/b)



- two thermal components: 10-25 MK (evaporated), > 25 MK (directly heated)
- total energy requirements of hot plasma ~ bolometric energy
- conductive losses are a major contribution
- nonthermal energy input ~ bolometric energy only in large flares
- conduction is required as additional heating mechanism of dense lower atmosphere

Results of Warmuth & Mann (2016a/b)



Consider some caveats…

nonthermal component:

- low-energy cutoff
- energy input by protons

thermal component:

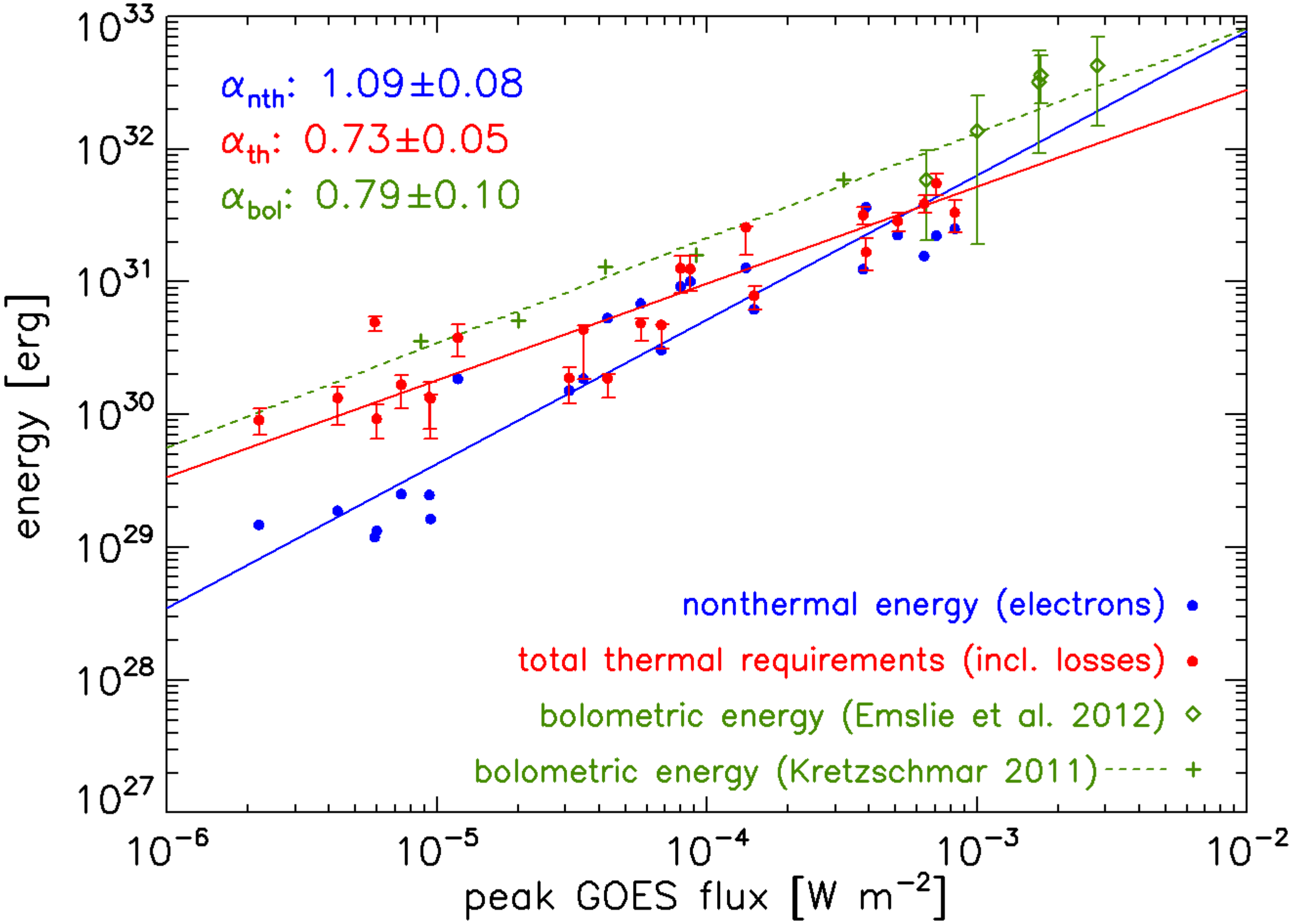
- potential energy and kinetic flow energy plasma
- filling factor
- temperature gradient for conductive losses
- conductive losses as gains (reprocessing)
- multithermality

Nonthermal energy input

- Electrons:
  - low-energy cutoff usually masked by thermal emission
  - highest low-E cutoff consistent with spectra
    $\rightarrow$ lower estimate for injected electron flux and power

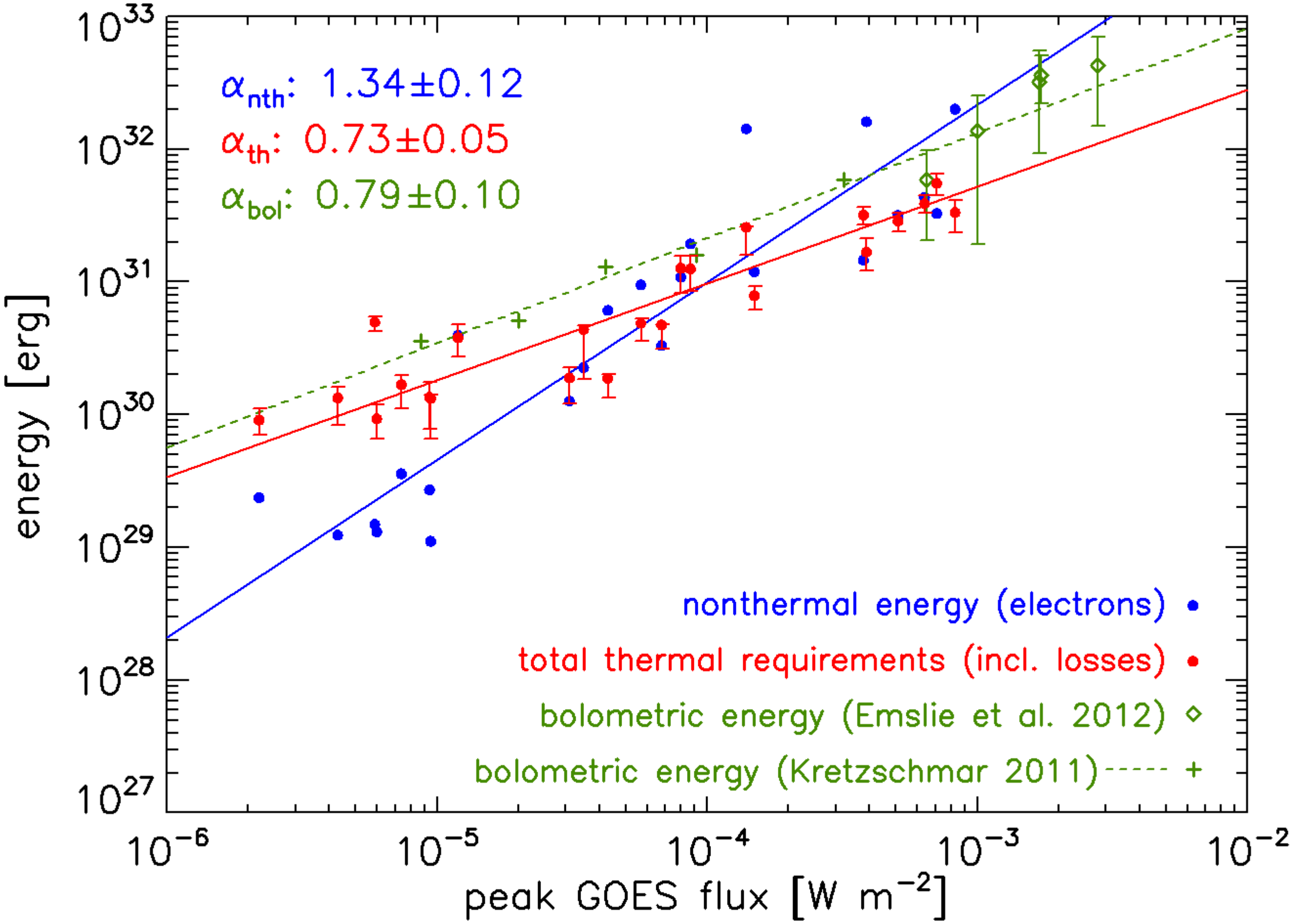
- Ions:
  - energy in >1 MeV ions broadly comparable to energy in electrons (but large uncertainties)
  - no constraints on energy in low-energy ions

Baseline

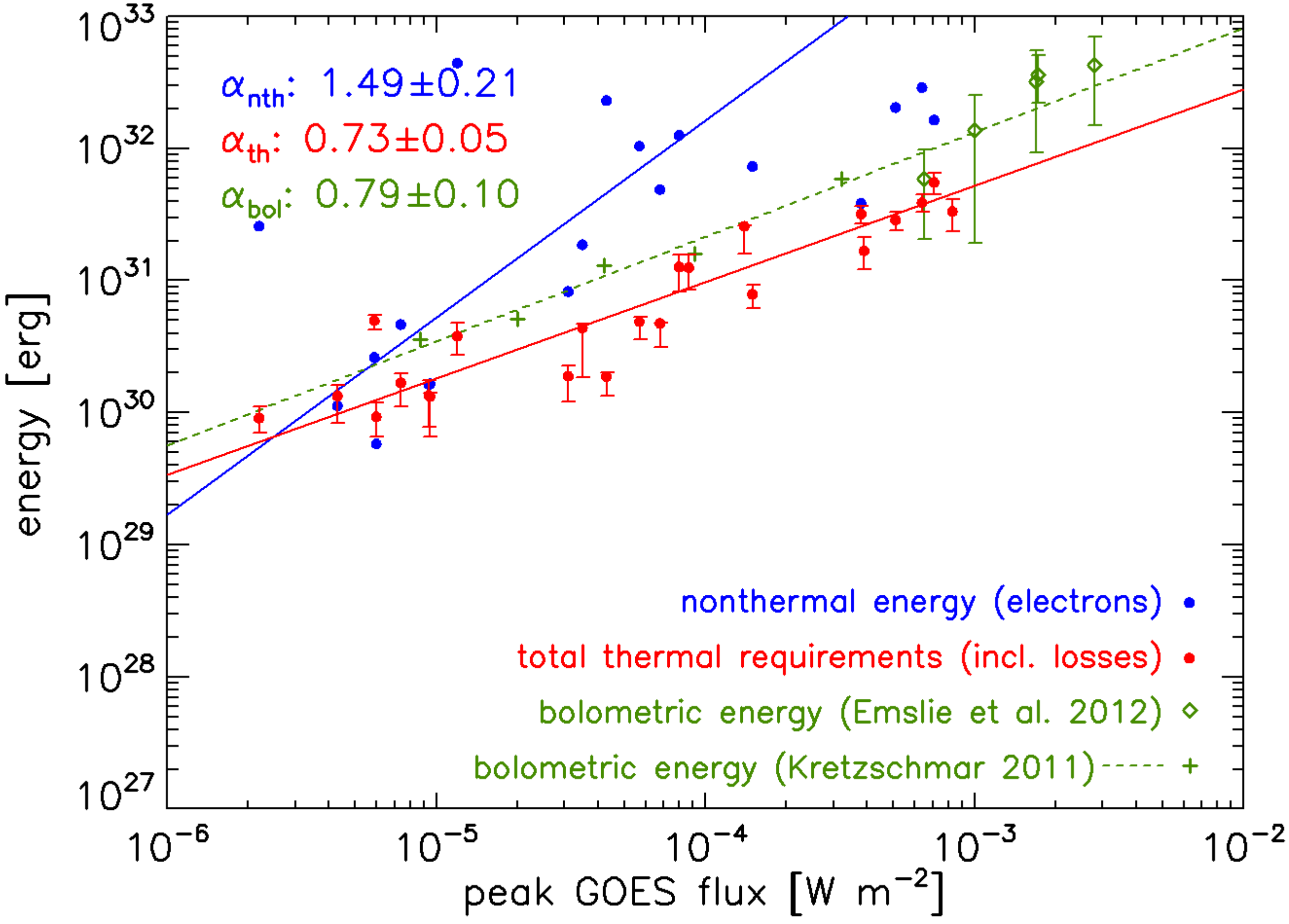


α_{nth}: 1.09±0.08
α_{th}: 0.73±0.05
α_{bol}: 0.79±0.10
nonthermal energy (electrons)
total thermal requirements (incl. losses)
bolometric energy (Emslie et al. 2012)
bolometric energy (Kretzschmar 2011)
energy [erg]
peak GOES flux [W m^{-2}]
10^{27}
10^{28}
10^{29}
10^{30}
10^{31}
10^{32}
10^{33}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

Low energy cutoff: 20 keV



Low energy cutoff: 10 keV



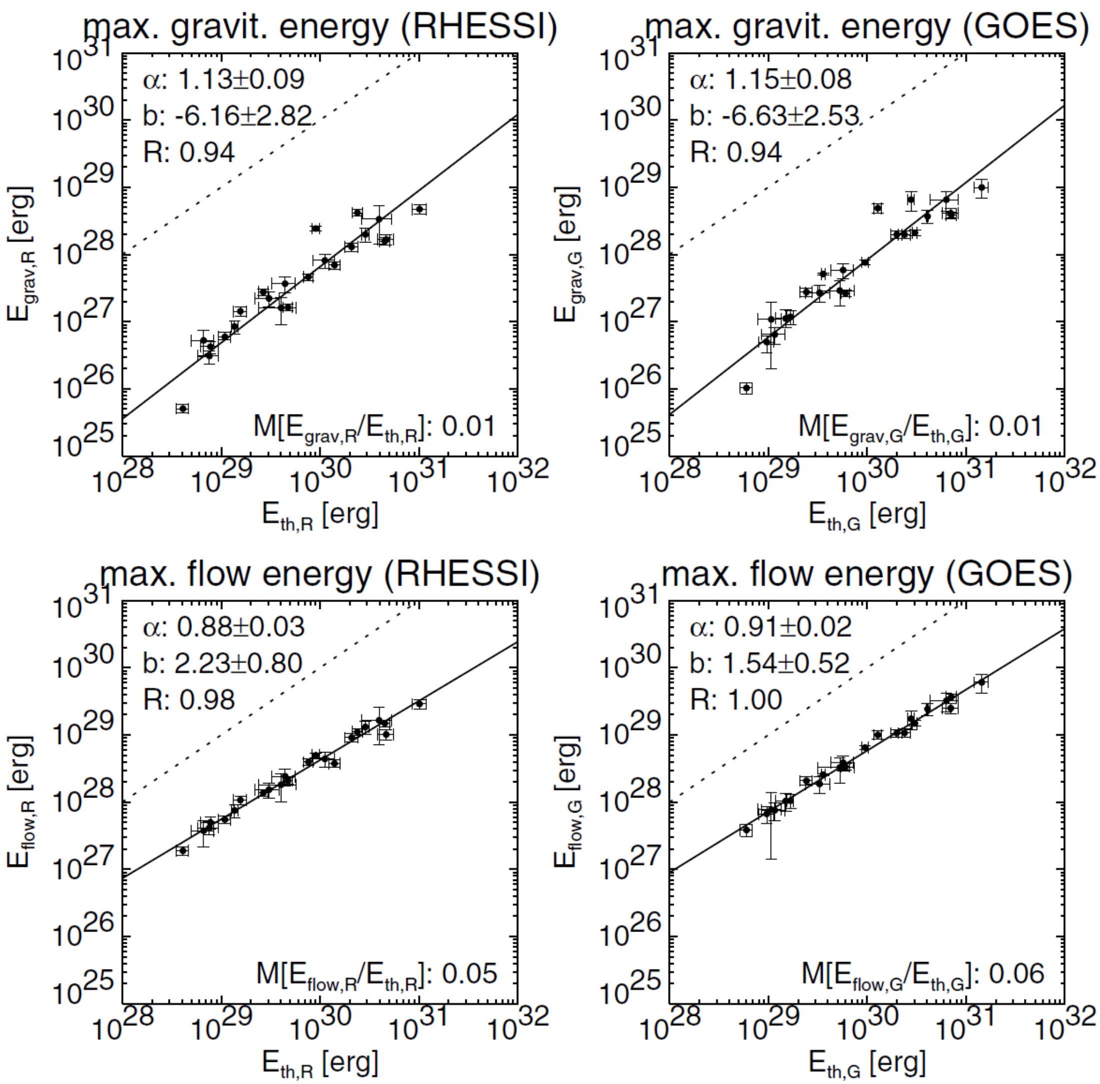
Summary on nonthermal input

- Electrons:
  - low-energy cutoff ~10 keV required to account for thermal component in small flares
  - this steepens power-law
    $\rightarrow$ inconsistent with bolometric energy in strong flares

- Ions:
  - weak flares would require 10x more energy in ions than in electrons
    $\rightarrow$ inconsistent with observations

- Conclusion:
  additional non-beam heating mechanism required

Potential and flow energy



- potential energy negligible (1% of thermal energy)
- flow energy <10% of thermal energy for 200 km/s (equipartition for 700 km/s)

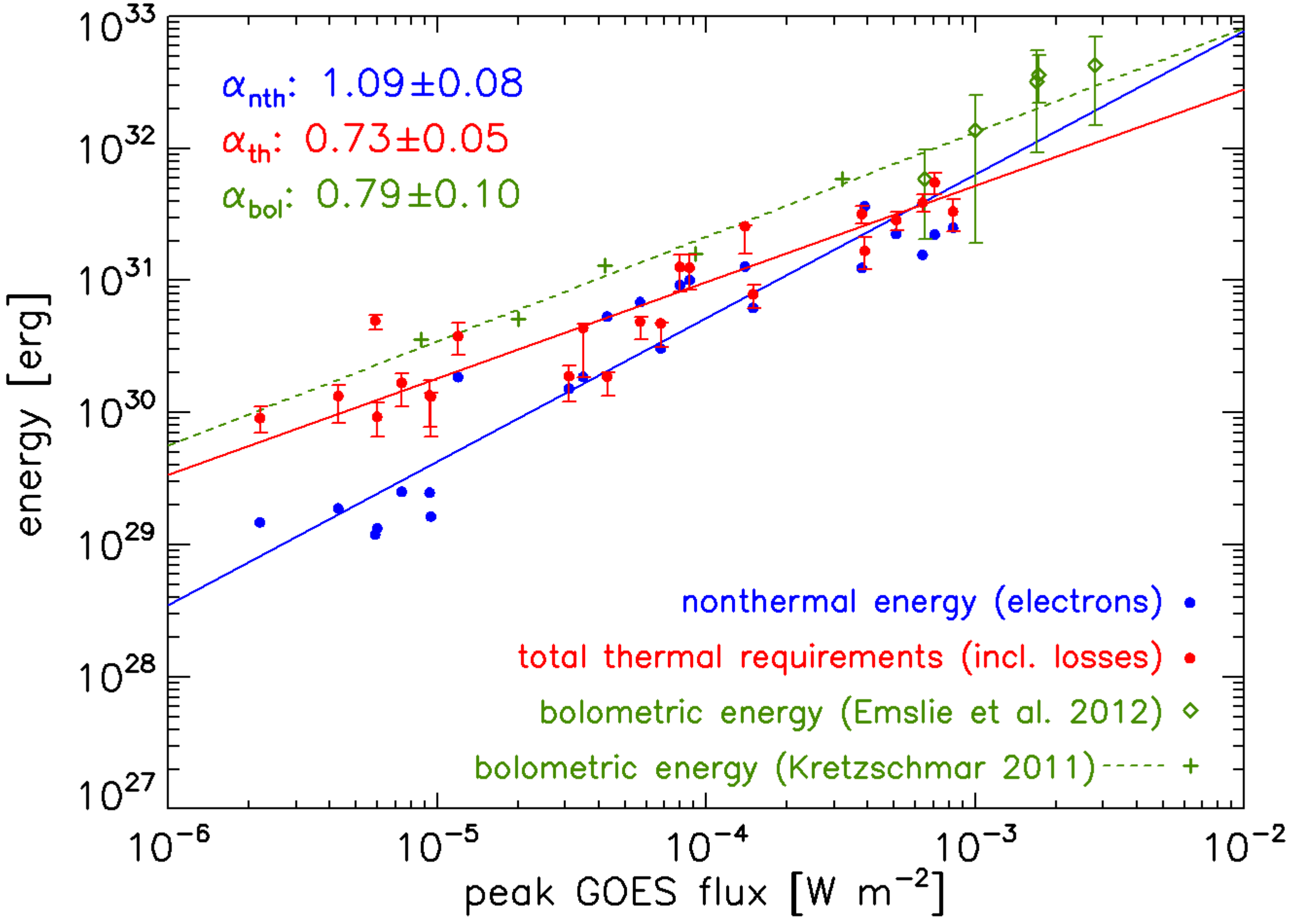
Filling factor of thermal and nonthermal sources

- volume filling factor of coronal source influences thermal energy
  - EUV observations suggest small filling factors ($f_V < 0.1$)
  - X-ray observations suggest larger values ($f_V = 0.1\text{-}1$)
  - constraints by density-sensitive lines and plasma beta

- area filling factor of HXR FPs influence conductive loss
  - HXR FP area taken as thermal loop FP area
  - is this a valid assumption?
  - RHESSI imaging reaches limits for compact FPs
  - observation of compact WL kernels

  $\rightarrow$ real FP areas smaller ($f_A < 1$)

Baseline



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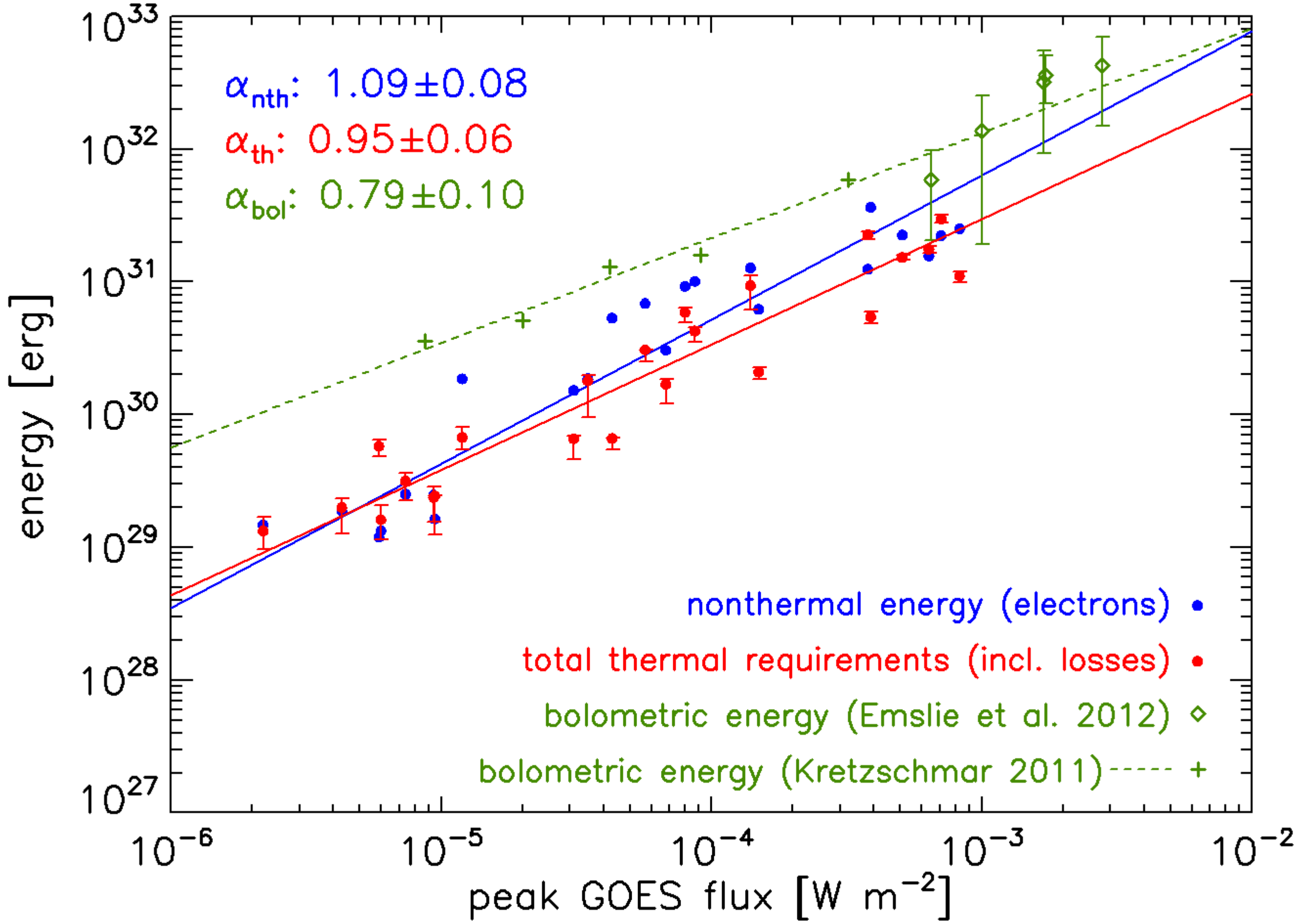
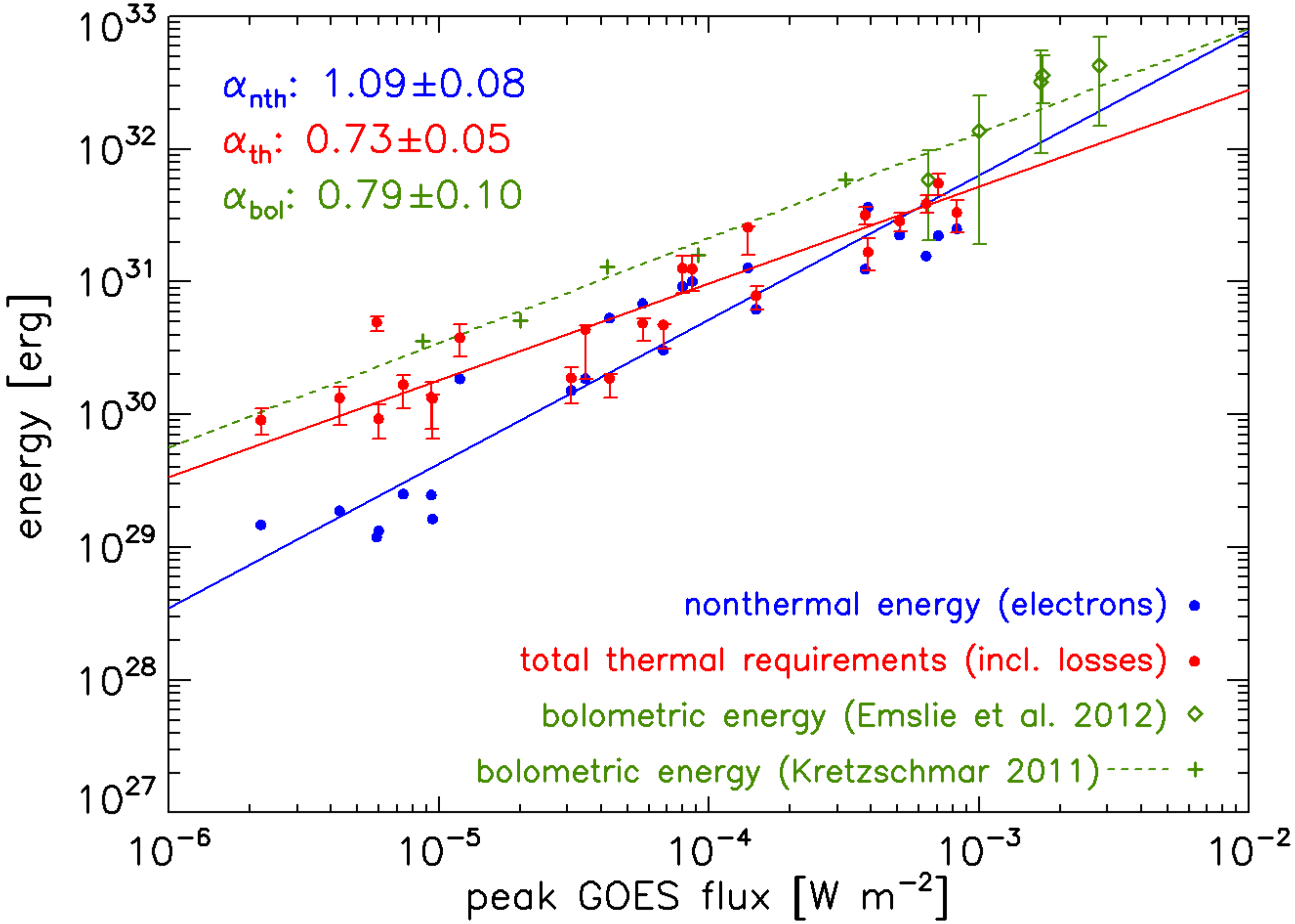
Filling factor: $f_V = 0.1$, $f_A = 0.1$



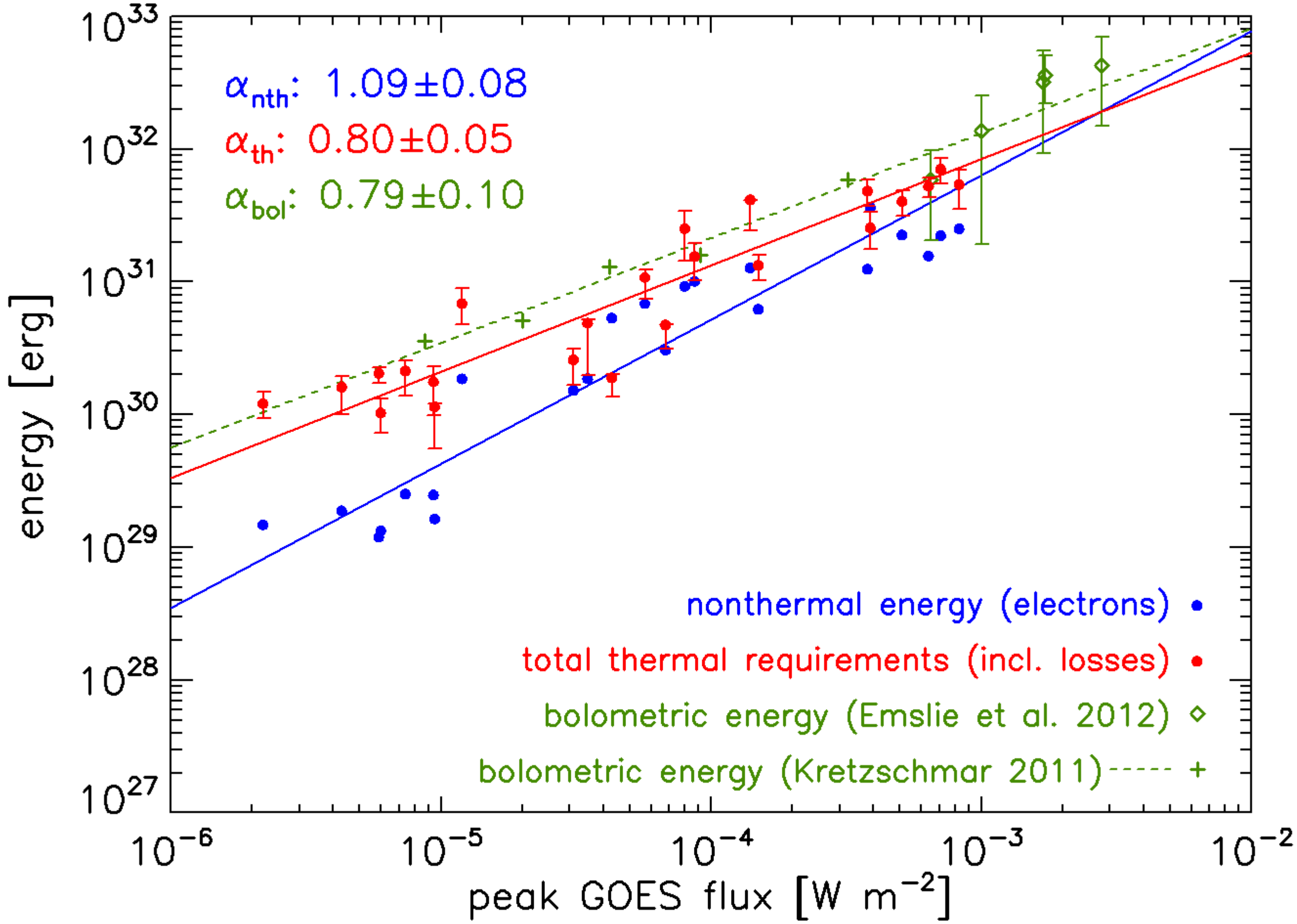
Influences on conductive losses

- loop FP areas
- conductive losses ~ thermal gradient ~ thermal scale length
- partial ‘recycling’ of conductive losses
  - losses can drive chromsopheric evaporation, increasing amount of hot plasma
  - reduces nonthermal energy input requirements
- suppression of conduction by turbulence (cf. talk by Emslie)

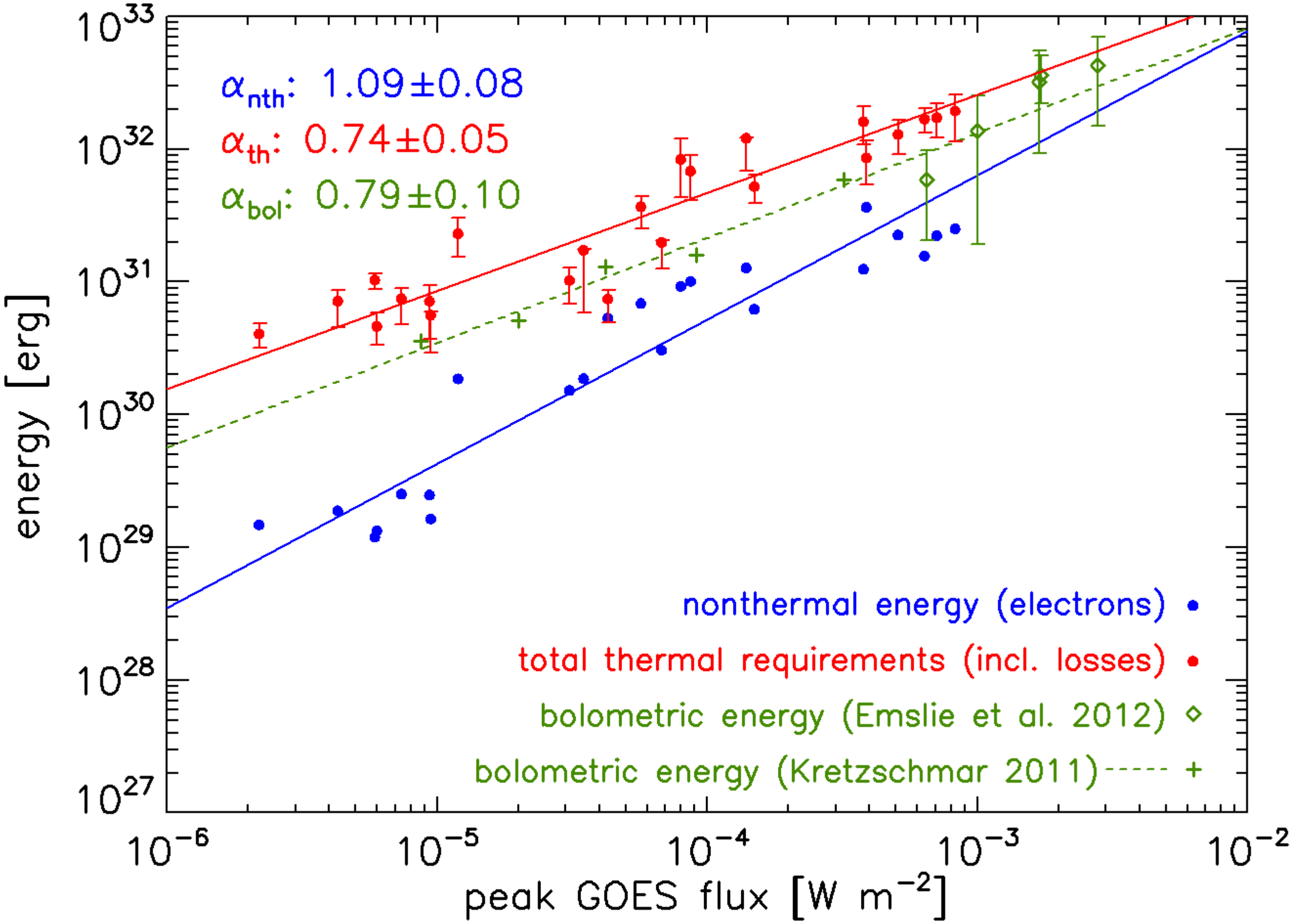
Baseline: temperature scale length = loop half-length



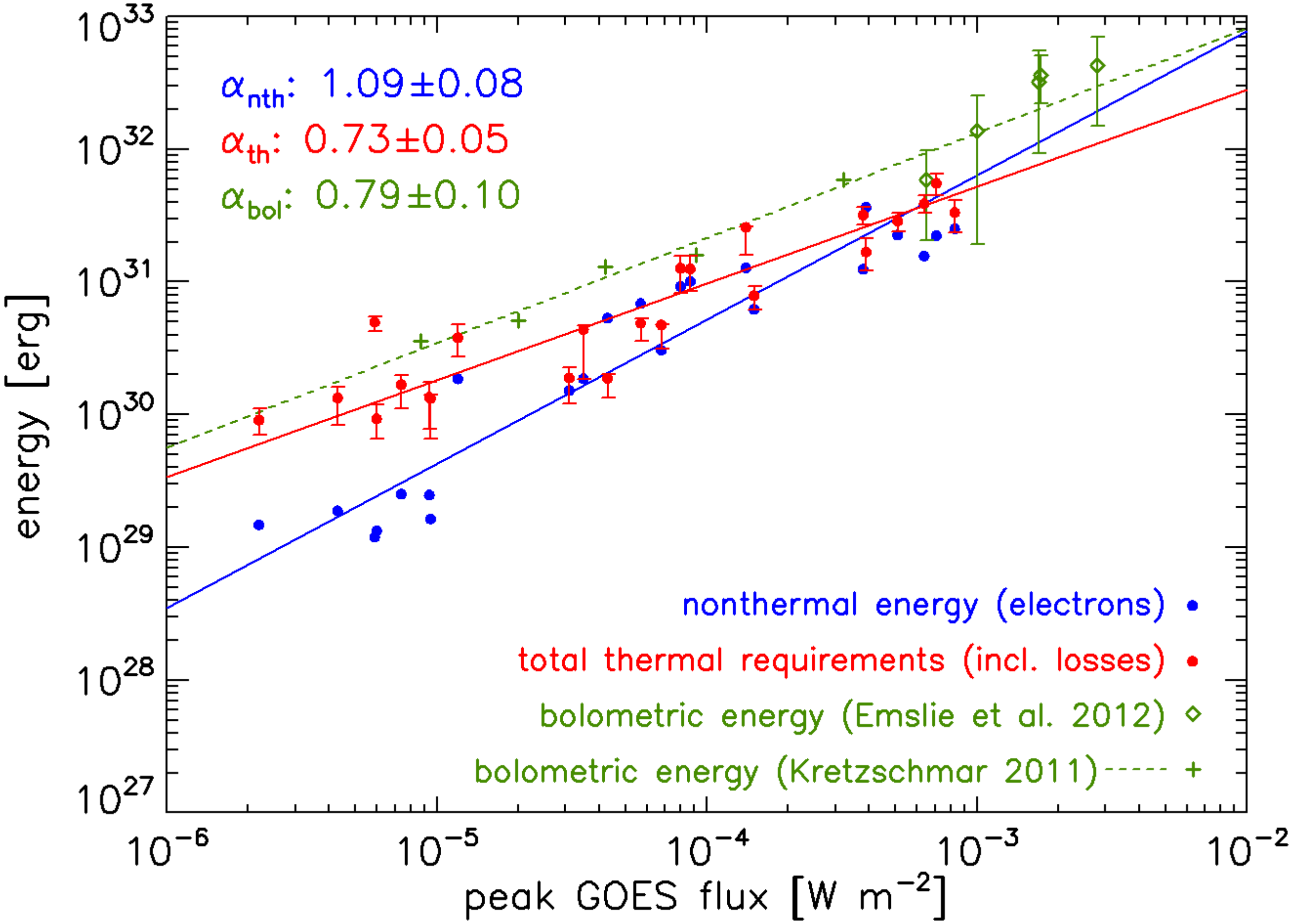
Temperature scale length: 10 Mm



Temperature scale length: 1 Mm



Baseline



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10^{-2}
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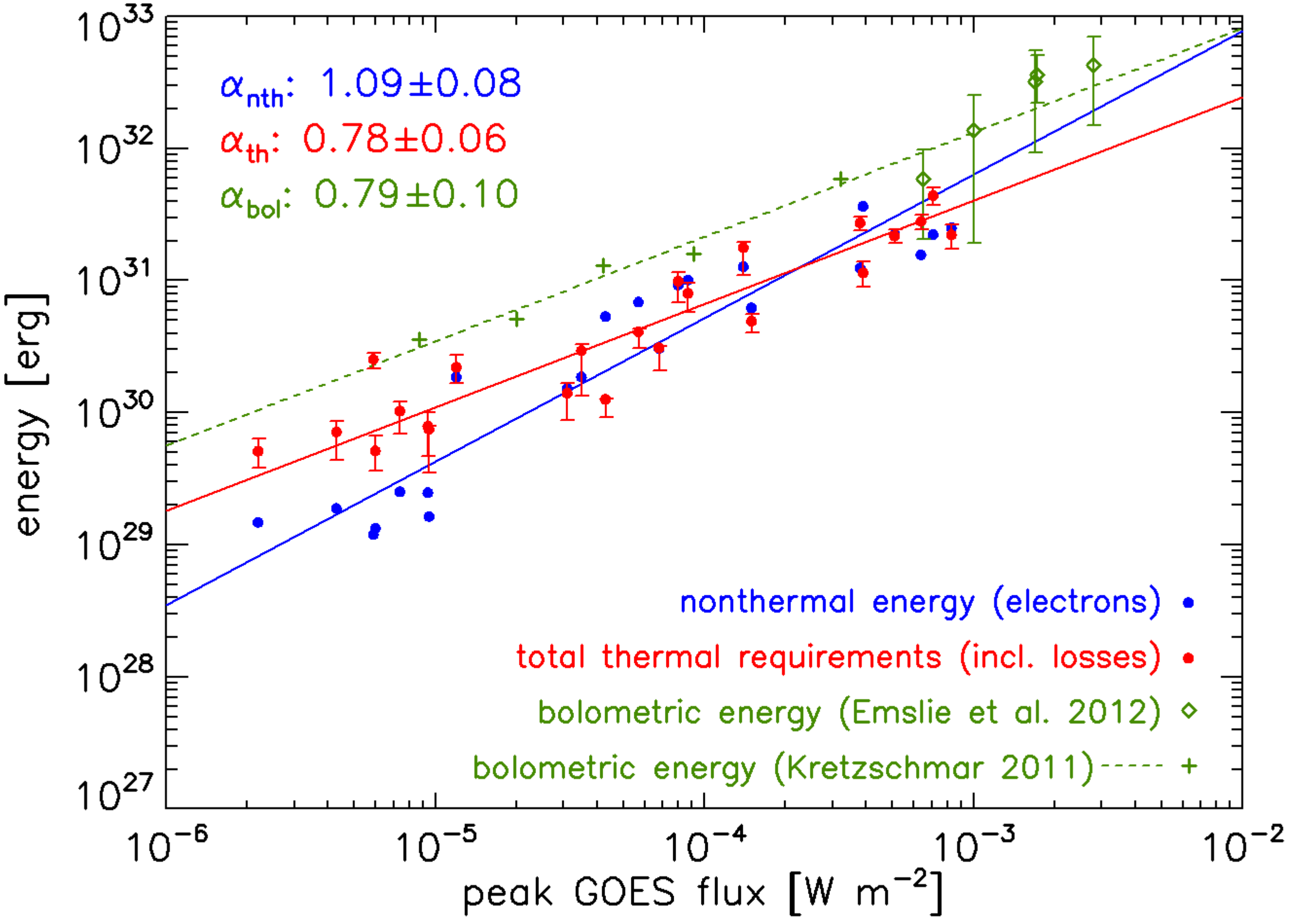
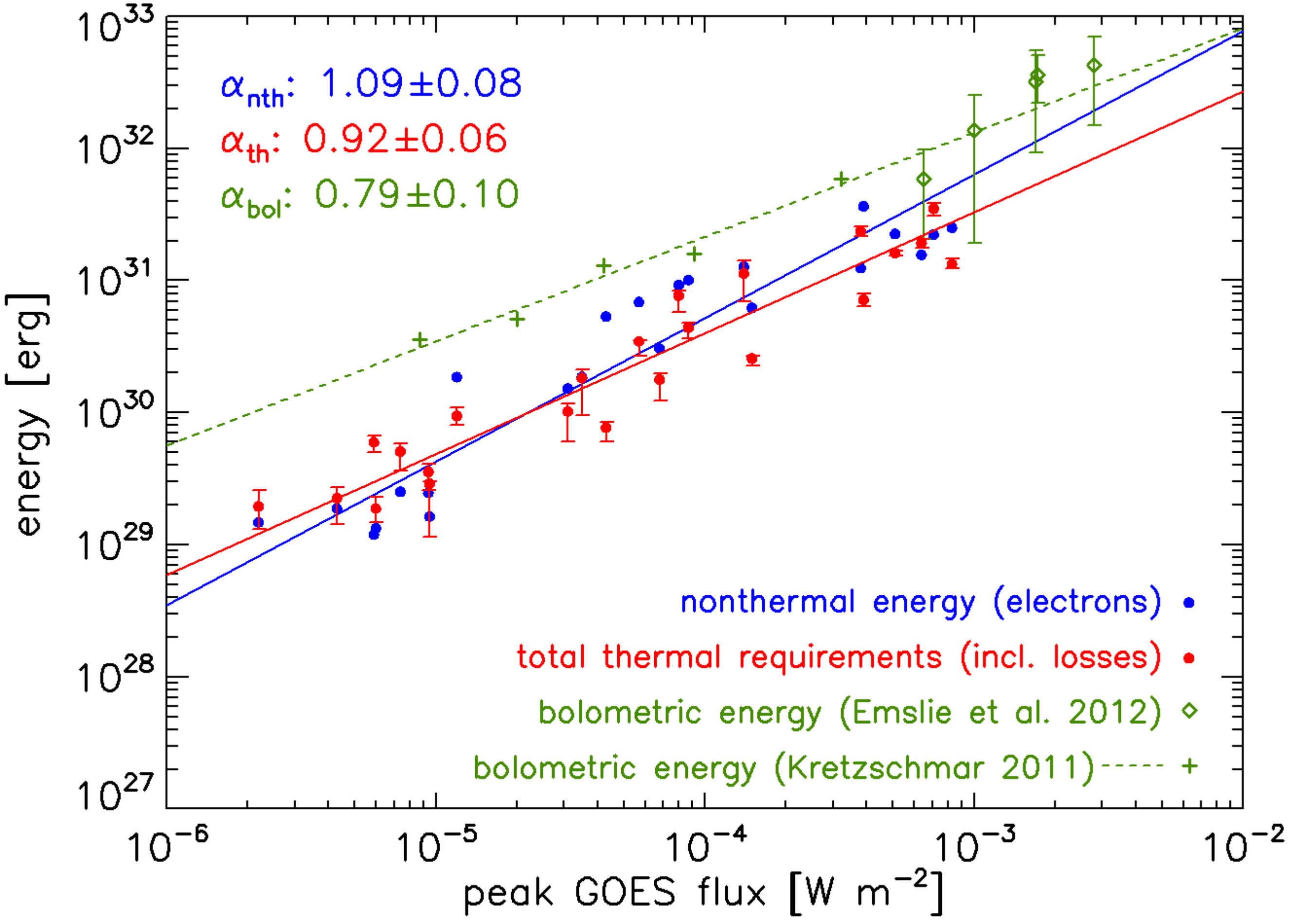
Fraction of conductive loss that is recycled: 0.5



Fraction of conductive loss that is recycled: 0.9



Summary on conductive losses

- Lower conductive losses
  - by reducing FP area, recycling

  $\rightarrow$ would require additional energy release or transport process to heat lower atmosphere

- Higher conductive losses:
  - by decreasing thermal scale length

  $\rightarrow$ inconsistent with bolometric energy loss

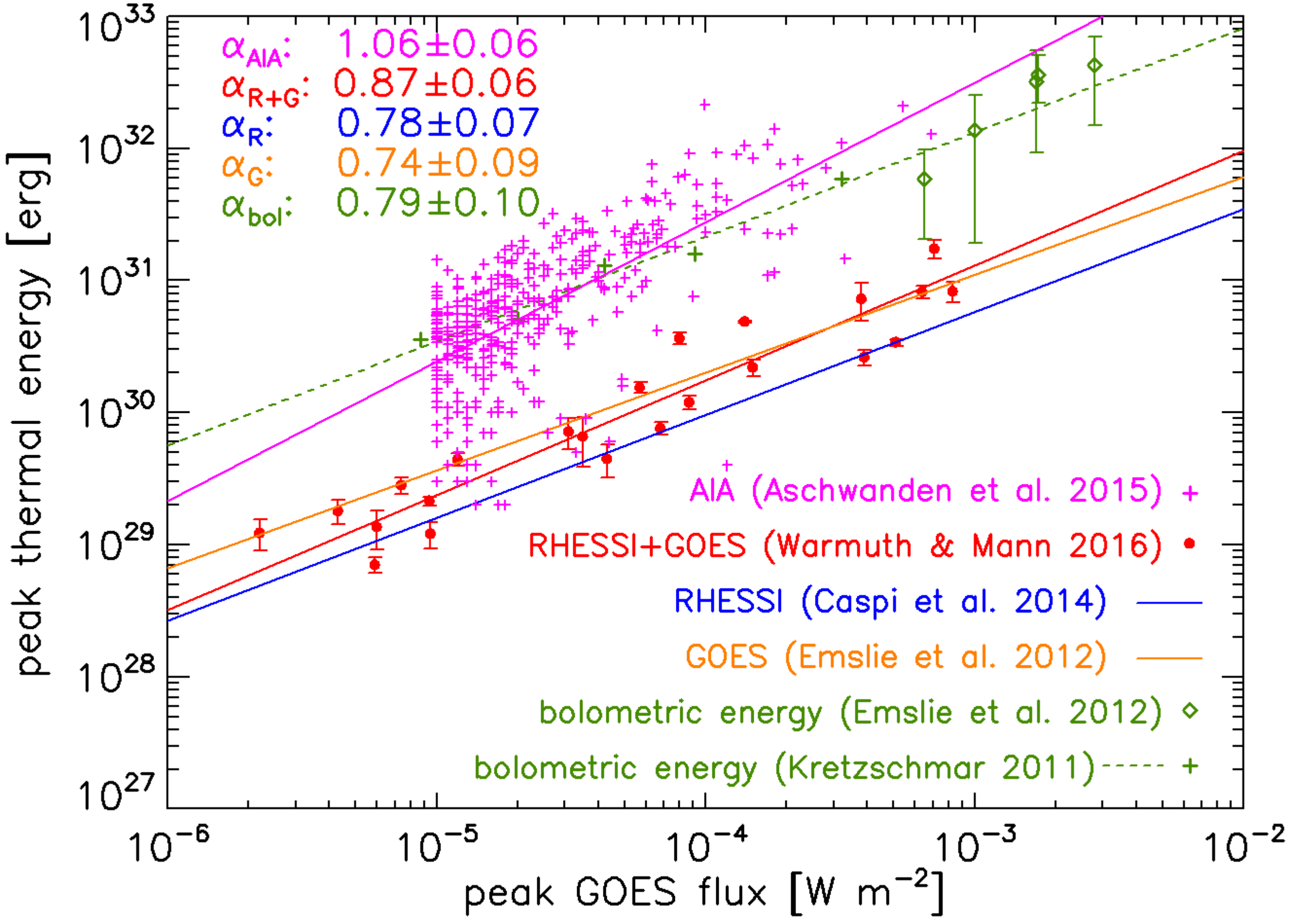
Multithermality

- have considered RHESSI and GOES
  $\rightarrow$ bithermal model for hot plasma component

- difference to bolometric energy shows the strong contribution of cooler plasma

- comparison with true multithermal results (EUV-based DEM reconstructions)

Thermal energies: multithermal (EUV) vs. isothermal/bithermal (X-rays)



Conclusions

- energy requirements of hot plasma can be brought down to be consistent with nonthermal energy input

  $\rightarrow$ inconsistent with bolometric energy (too little energy input into low atmosphere)

- nonthermal energy input can be increased to match heating requirements only by making ad-hoc assumptions

- additional non-beam heating mechanism required

- strong conductive losses of hot plasma required