Solar Energetic Electron Events with Associated Hard X-ray Flares

(Wang et al., 2021 ApJ, 913, 89)

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Outline

1. Introduction – Solar Energetic Electrons (SEEs)

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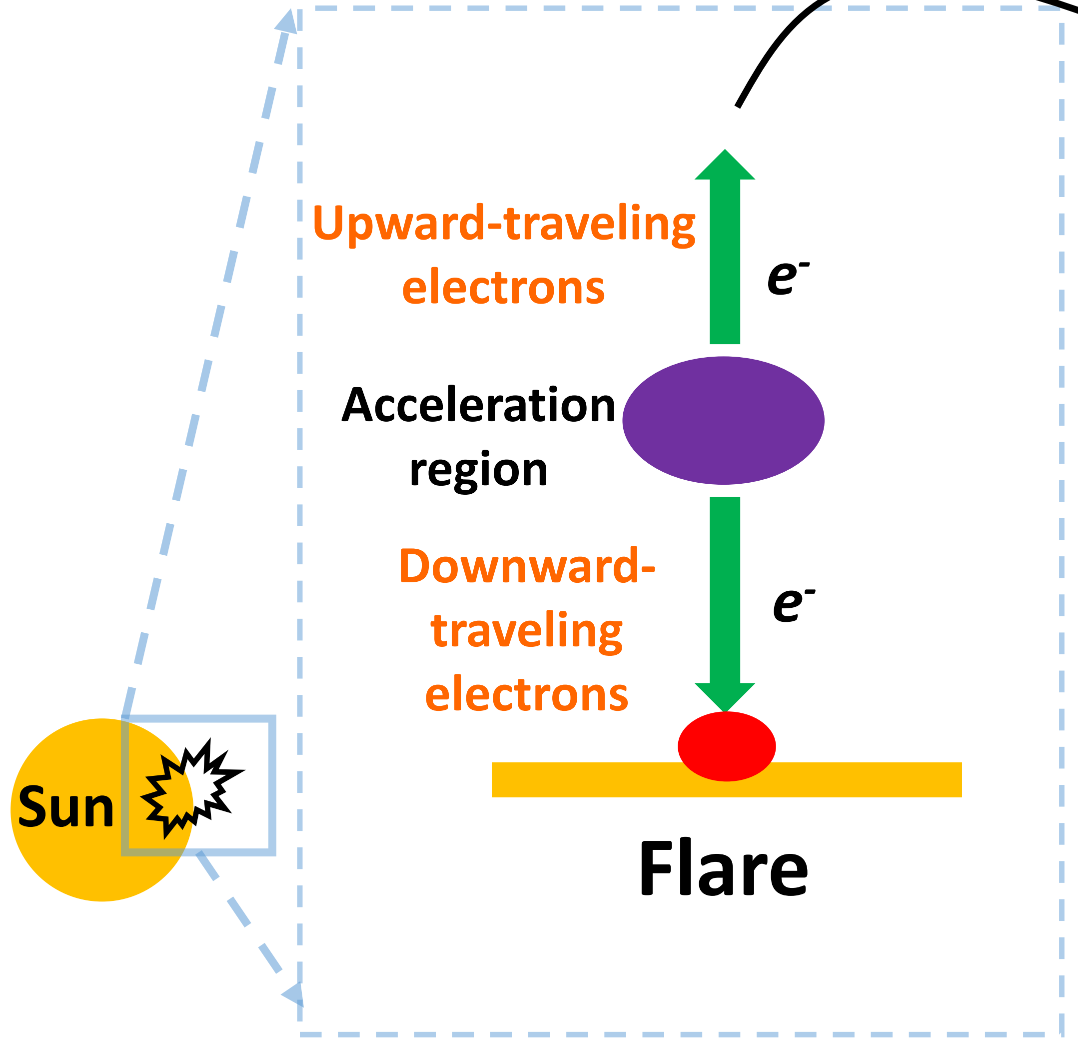
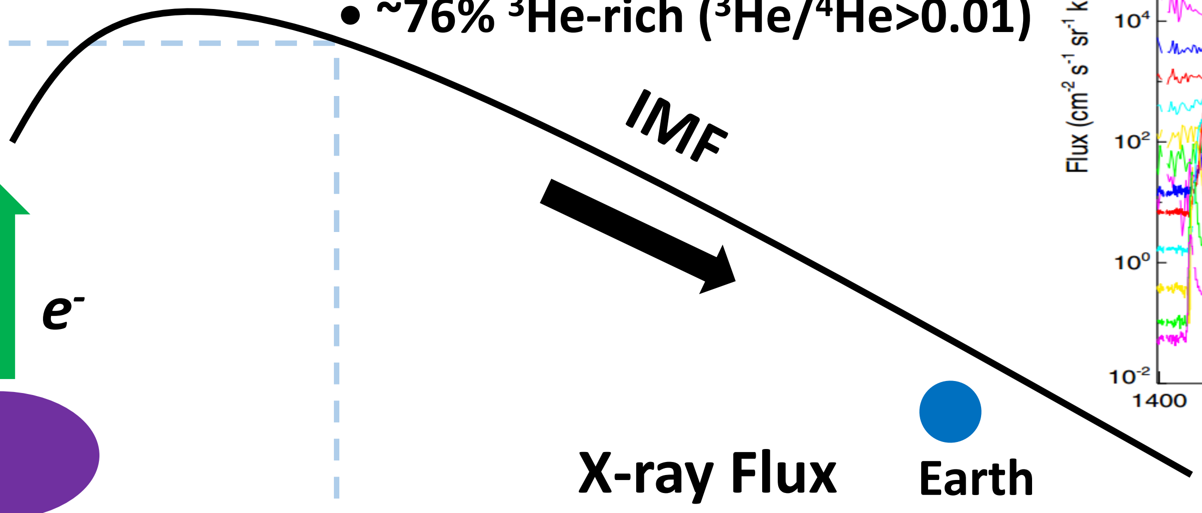
1. Introduction

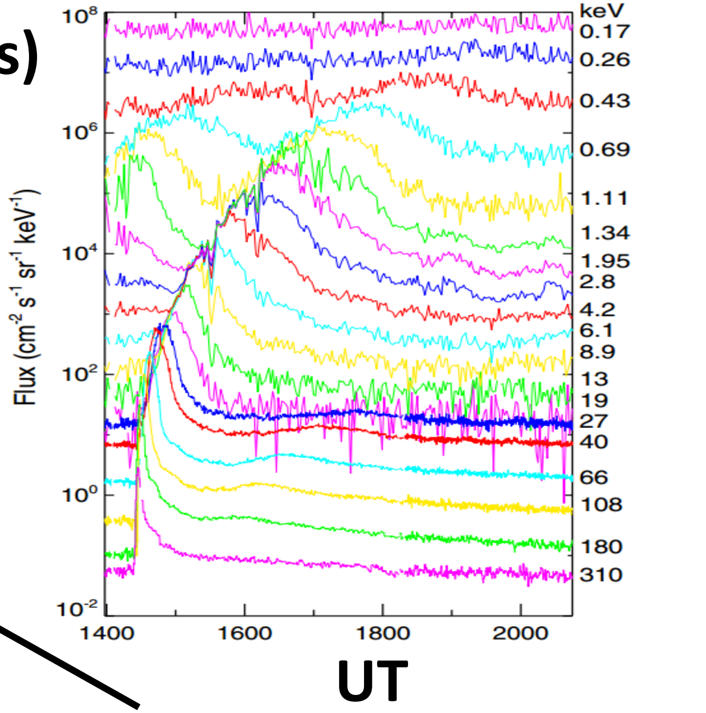
1.1 Classic Scenario



Solar Energetic Electrons (SEEs)

- ~ keV to hundreds of keV
- ~10^4/year (solar maximum)
- ~76% ^{3}He-rich ($^3He/^4He>0.01$)

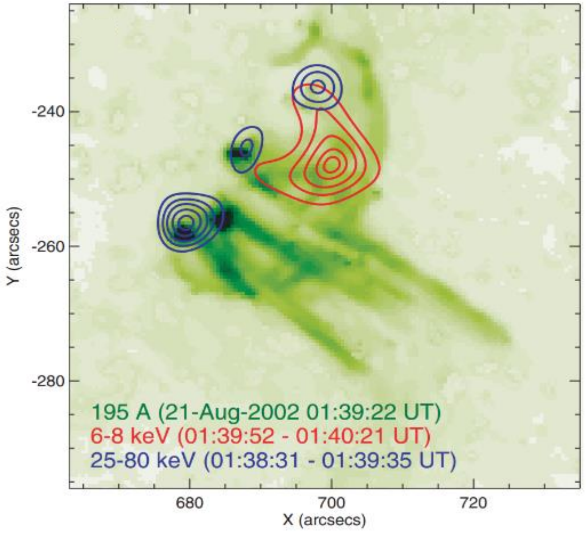


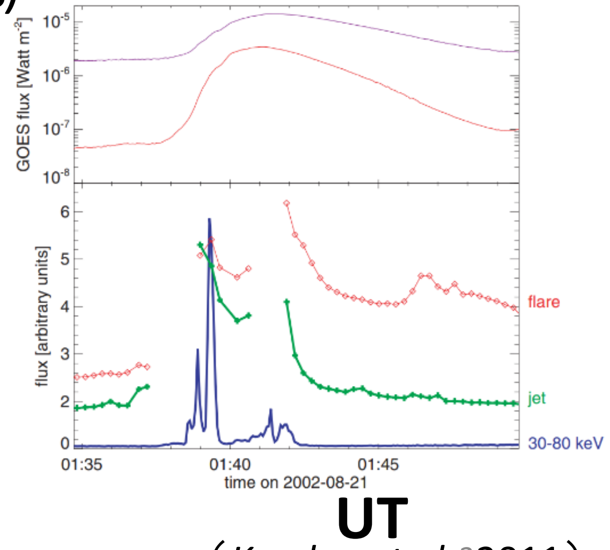


(*Wang et al.*, 2012)

X-ray Flux

- ~45% Hard X-rays (HXR) ***(Lin, 1985)***





(*Krucker et al.*, 2011)

1.2 Previous Studies

- (>50keV) $\beta = \gamma + 0.1$
- escaping electrons N_{SEE} ~0.1% of HXR-Producing Electrons N_{HPE}

(*e.g.*, Lin, 1974; Krucker et al., 2007)

- HXR-Producing Electrons (HPEs) : In flares ($<1.02R_s$)

(Effenberger et al., 2017)

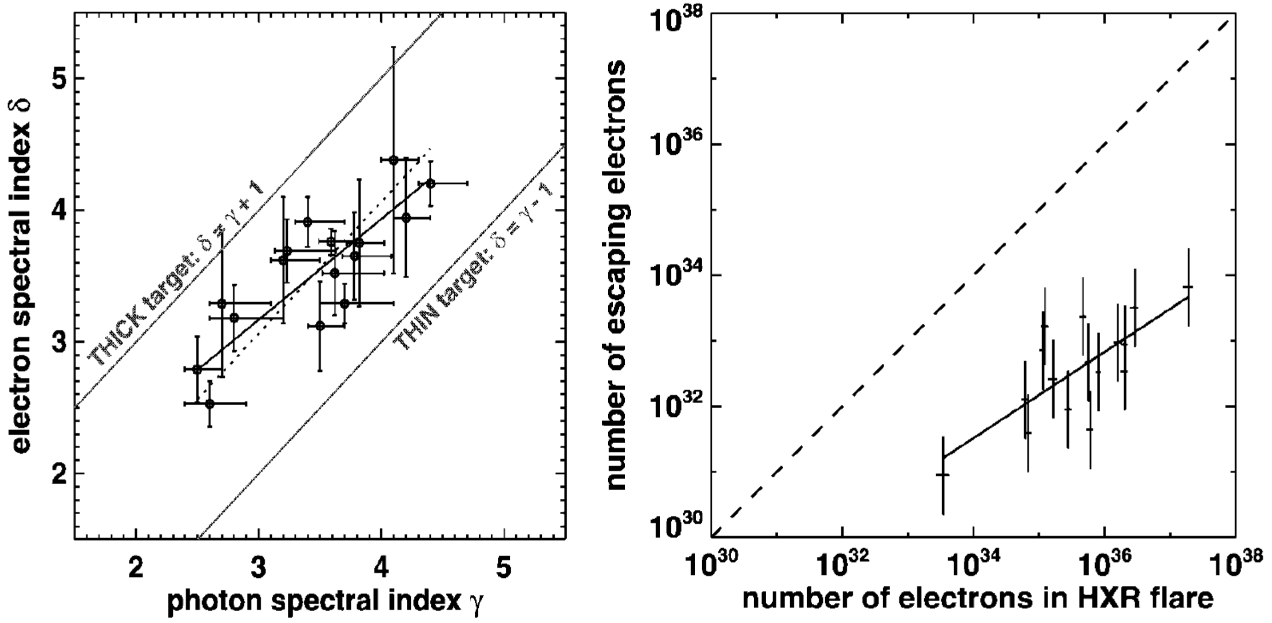
- Source of SEEs : high in the corona

(*e.g.*, Lin, 1985; Wang et al., 2006)

Motivation:

Figure out the association & acceleration of HPEs & SEEs

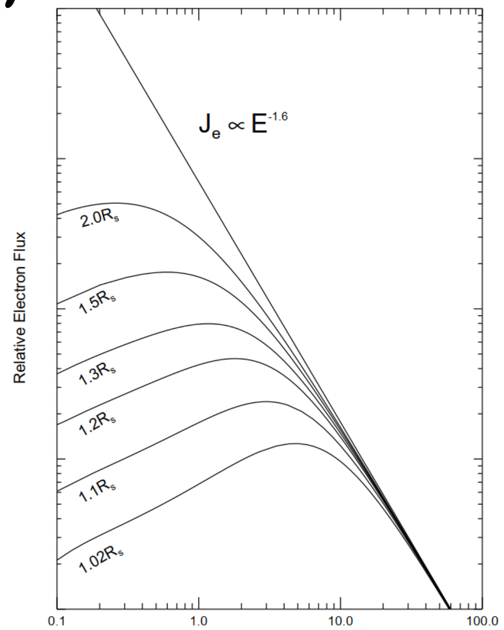
β



γ

(*Krucker et al., 2007*)

Electron Flux



Energy

SEE from source to 1AU

Coulomb Collision

2. Observations

2.1 Event Selection

Time range: 2002.2 – 2016.12

Data: WIND/3DP & RHESSI

Selection rules:

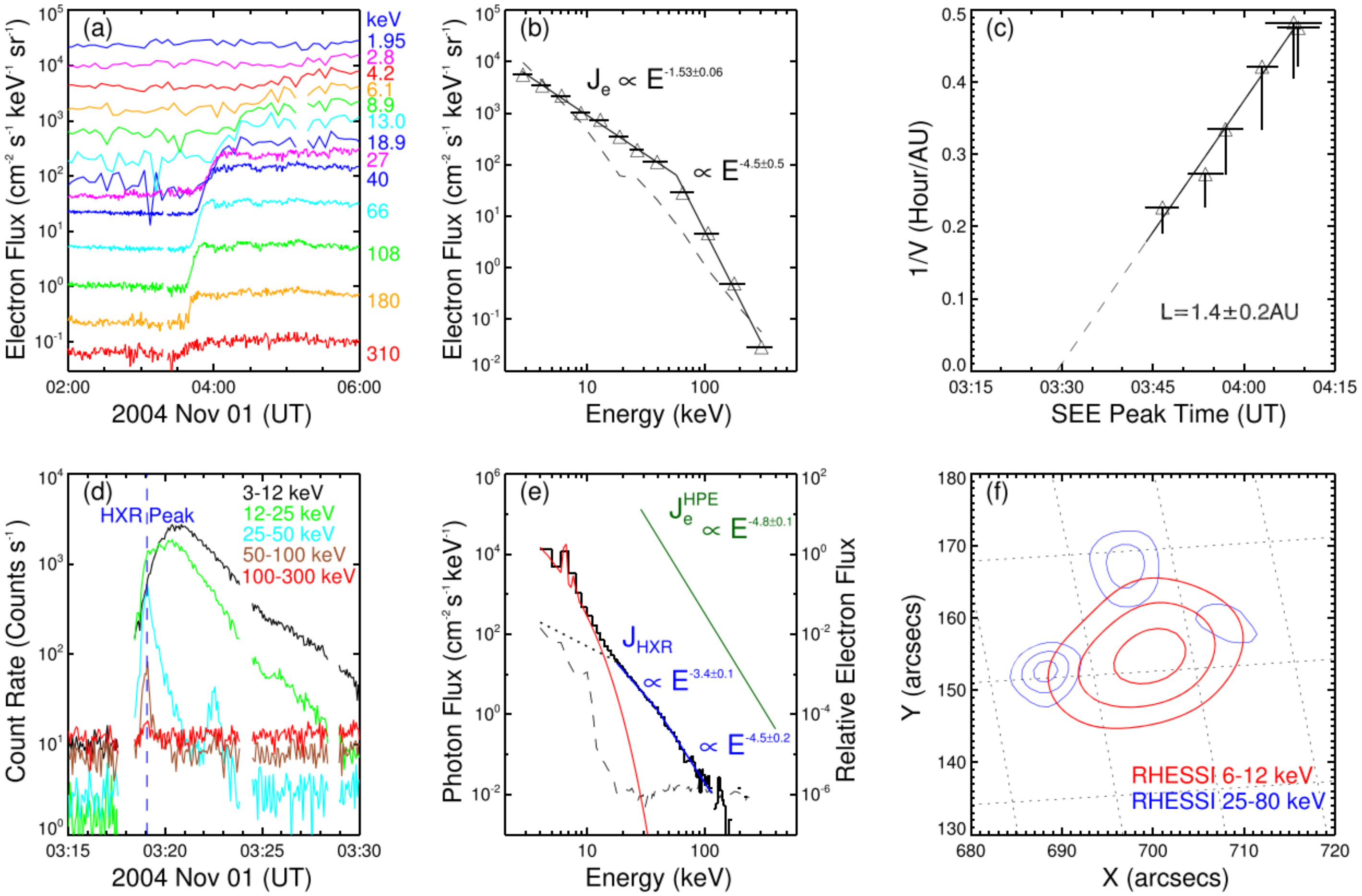
For SEEs:

1. Clear peak velocity dispersion
2. double-power-law spectrum covering **≦5keV** to 200keV

For HXRs:

3. Good spectrum reaching ≧40keV
4. Good magnetic connectivity (W30°-W90°)

16 cases selected.



2.2 Spectrum fitting

a. SEE **Double-Power-Law (DPL) fitting**

Self-consistent fitting

Considering errors of E channel & flux

(Liu et al, 2020)

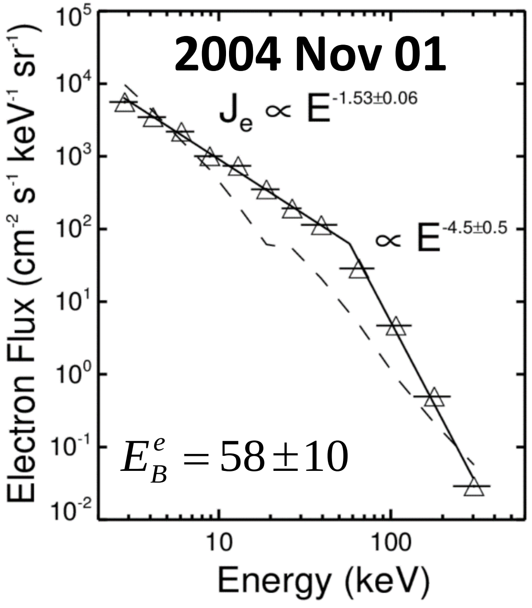
$$J_e \propto \begin{cases} E^{-\beta_1}, E < E_B^e \\ E^{-\beta_2}, E > E_B^e \end{cases}$$

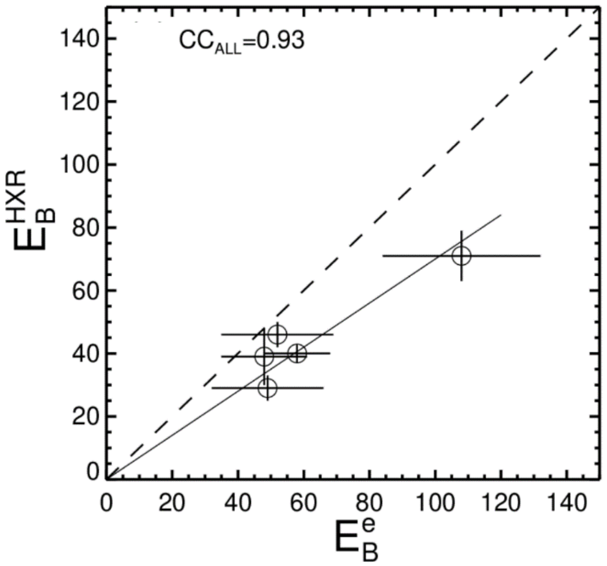
b. HXR

DPL/SPL (Single-Power-Law) fitting

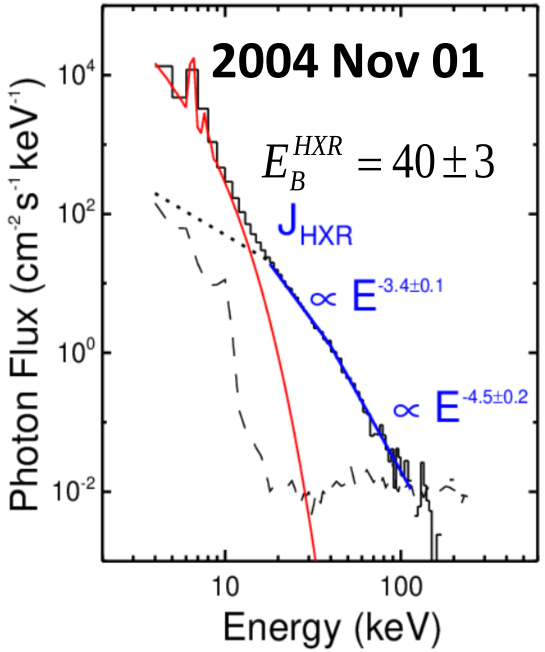
$$J_{HXR} \propto \begin{cases} E^{-\gamma_1}, E < E_B^{HXR} \\ E^{-\gamma_2}, E > E_B^{HXR} \end{cases} \qquad J_{HXR} \propto E^{-\gamma}$$

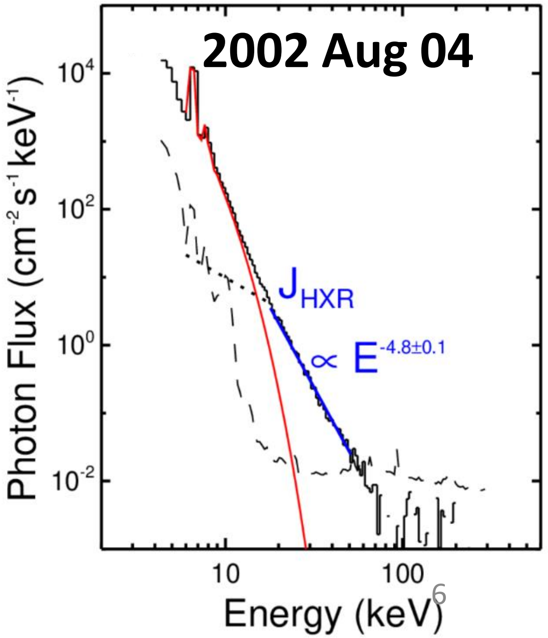
5 cases HXR DPL, 11 cases HXR SPL





$$E_B^{HXR} = (0.7 \pm 0.1) E_B^e$$





2.3 Deriving HXR Producing Electrons (HPEs)

We assumed a single power-law form of HPEs for all events

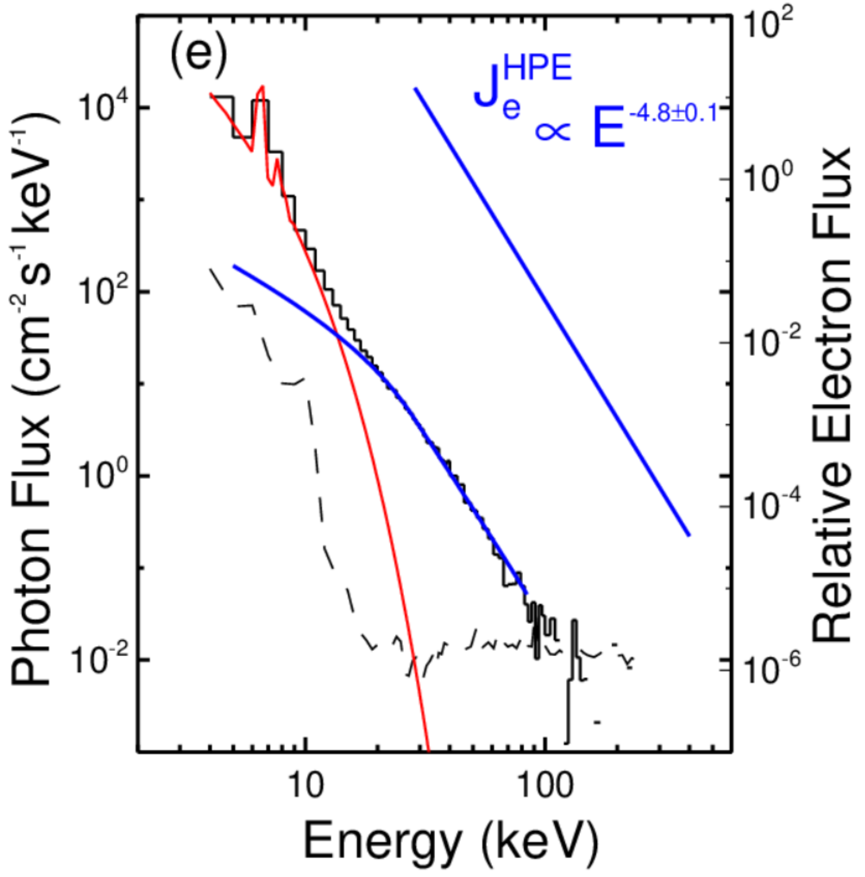
$$J_e^{HPE} \propto E^{-\beta^{HPE}}$$

Relativistic Thick-target bremsstrahlung model

Pileup & albedo effects

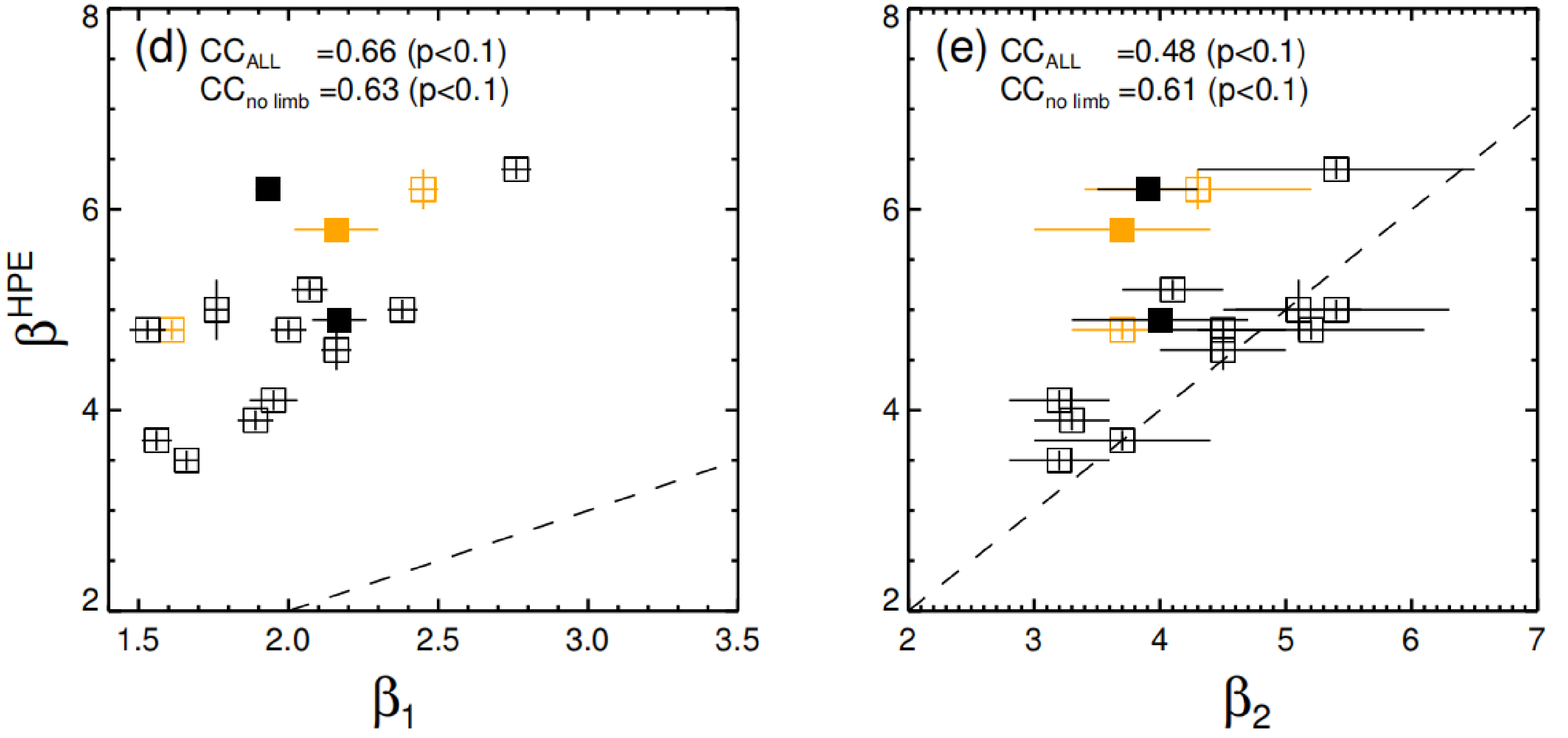
(Smith et al., 2002; Kontar et al., 2006)

2004 Nov 01



2.4 HPEs & SEEs

a. Indexes



SEE electrons below the break **SEE electrons above the break**

- $\beta_1 \propto \beta^{HPE}$
  $\beta_1 < \beta^{HPE}$

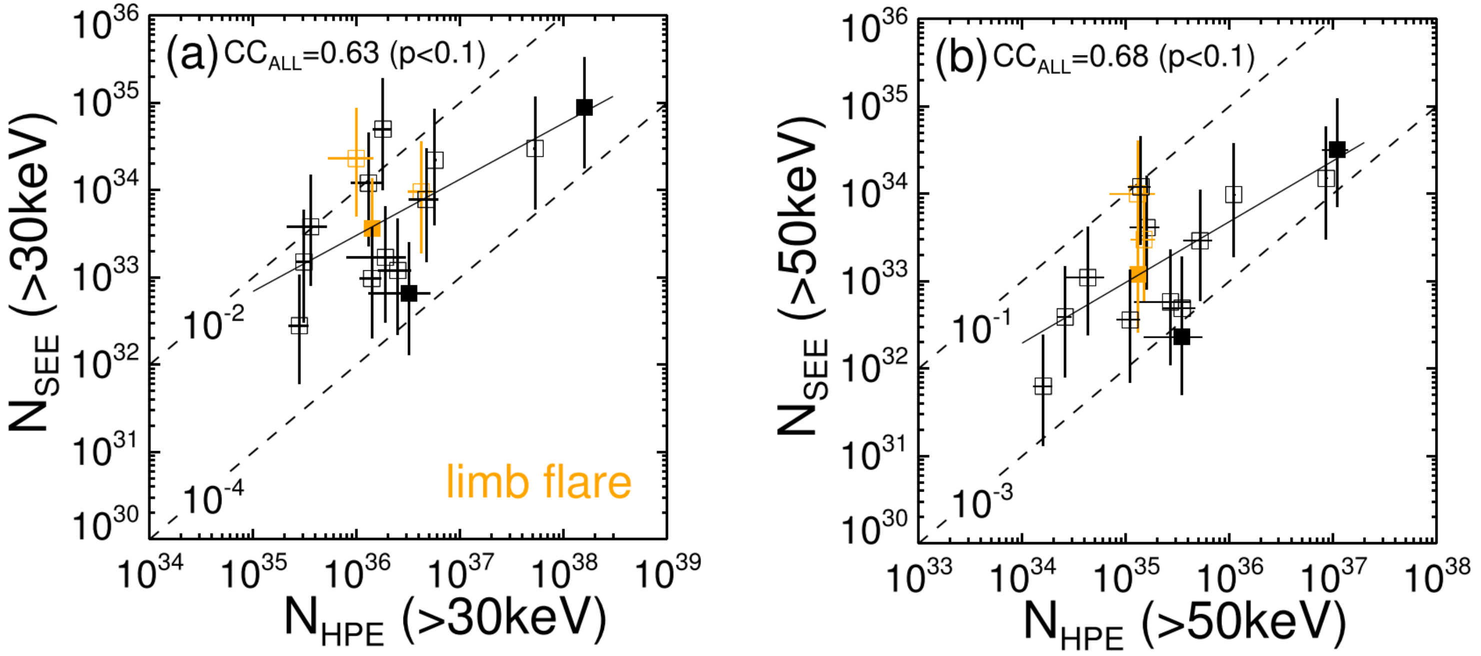
- $\beta_2 \propto \beta^{HPE}$
  50% $\beta_2 \approx \beta^{HPE}$
  50% $\beta_2 < \beta^{HPE}$

HPEs are closely related with high-energy SEEs

But HPEs and SEEs are unlikely from same accelerated population

2.4 HPEs & SEEs

b. Total number of HPEs & SEEs



$$N_{HPE} \propto N_{SEE}^{0.6\pm0.3}$$

$$N_{HPE} \propto N_{SEE}^{0.7\pm0.3}$$

>30keV N_{SEE}/N_{HPE} ~ 0.6%

>50keV N_{SEE}/N_{HPE} ~ 2%

N_{SEE}/N_{HPE} ranges from
10^{-4}-10^{-2} (>30keV)
10^{-3}-10^{-1} (>50keV)

2.5 Source region of SEEs

DPL spectrum from source to 1AU

Coulomb Collision & Ambipolar potential

$$\frac{dE}{dr} = \left(\frac{dE}{dr}\right)_{Coll} + \left(\frac{dE}{dr}\right)_{AEP}$$

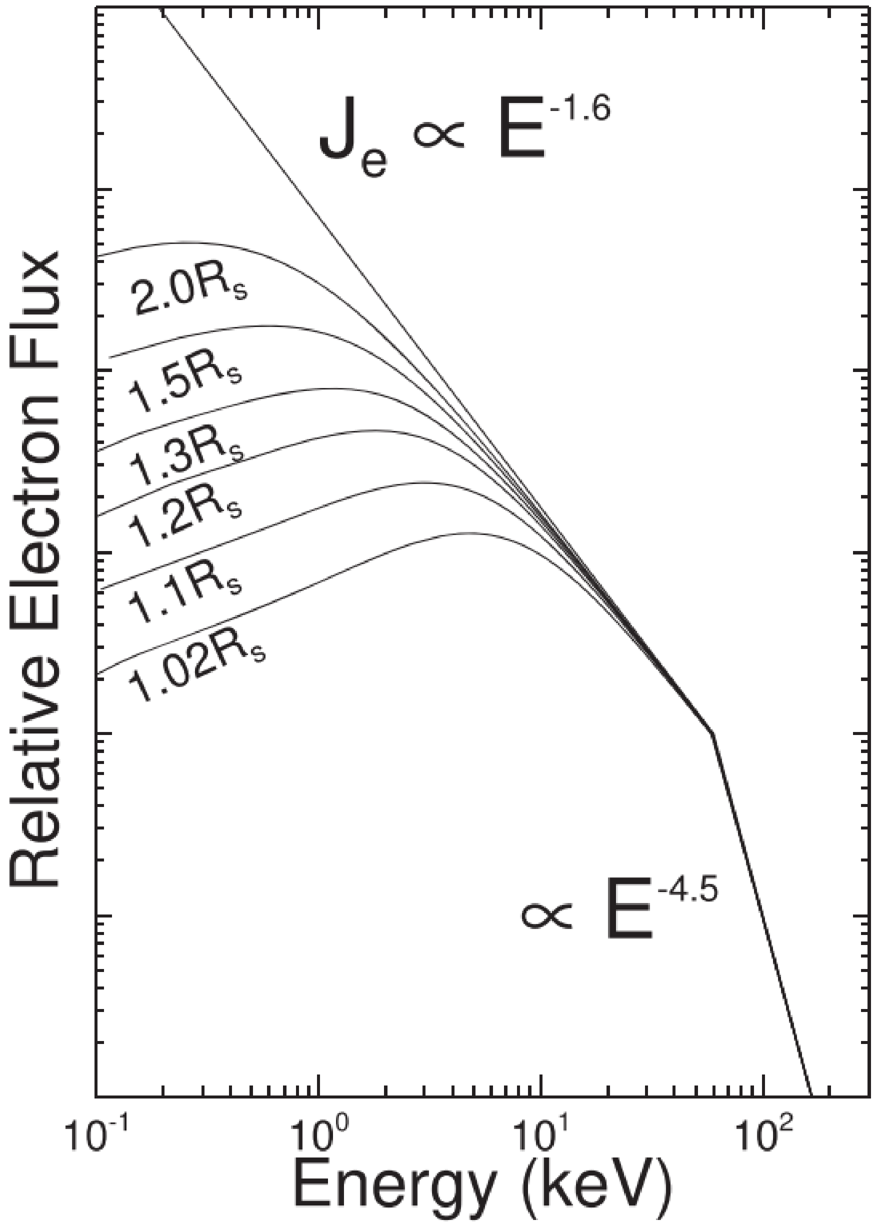
$$= -1.82\times10^{-7}\frac{n(r)}{E} - \frac{0.994}{r^2}$$

(Wang et al., 2006)

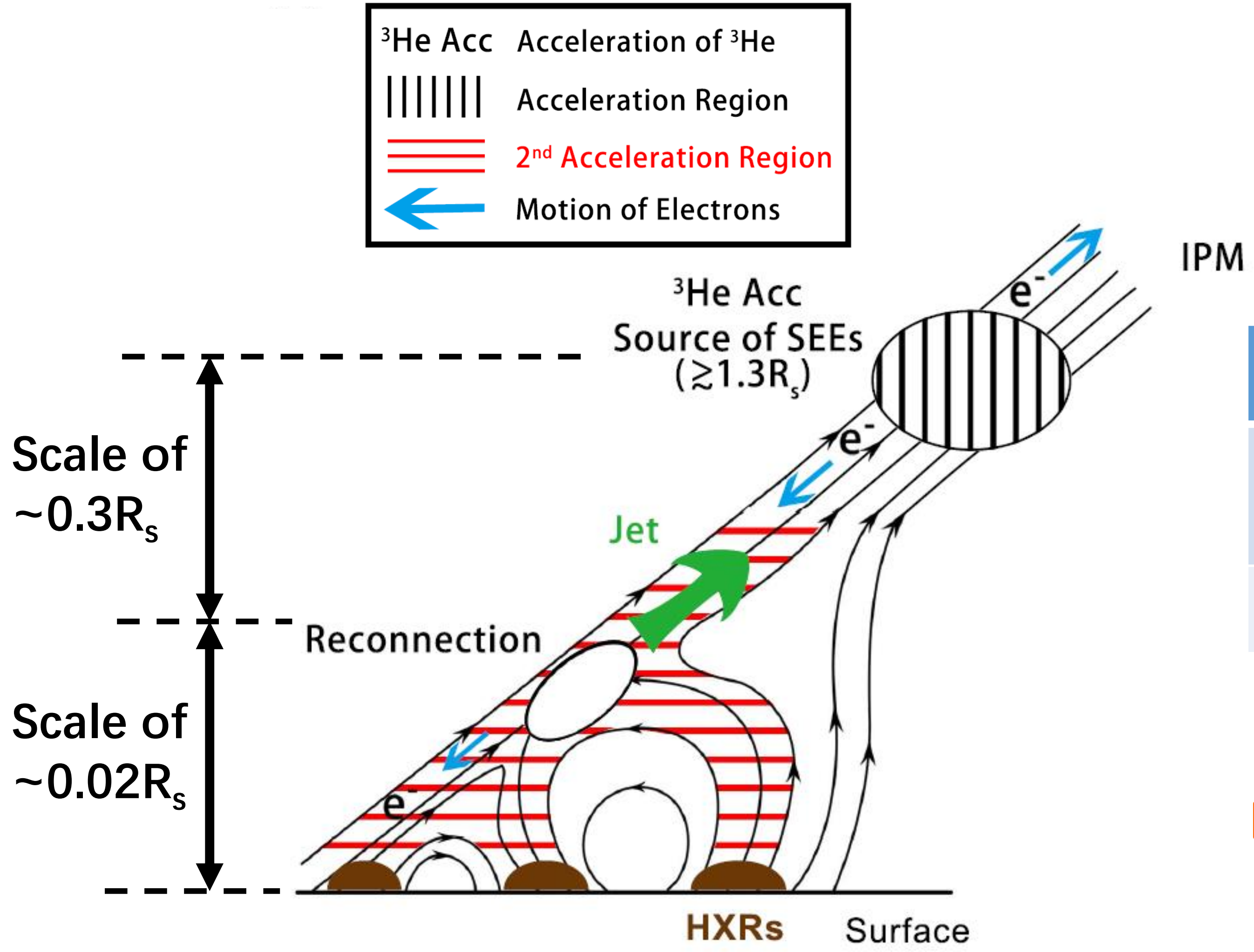
Conservation of electron number

$$J_{e1}\cdot S_1\cdot \Delta E_1 = J_{e2}\cdot S_2\cdot \Delta E_2$$

To maintain a power-law down to 5keV, source of SEEs must be ≧1.3R_s



2.6 Updated Scenario (Secondary Acceleration)



	Observation	Scenario
N	N_{SEE}/N_{HPE} ≈0.1-1%	$N_{SEE}/N_{HPE}<1$
Index	$\beta_2 \leq \beta^{HPE}$	Possible

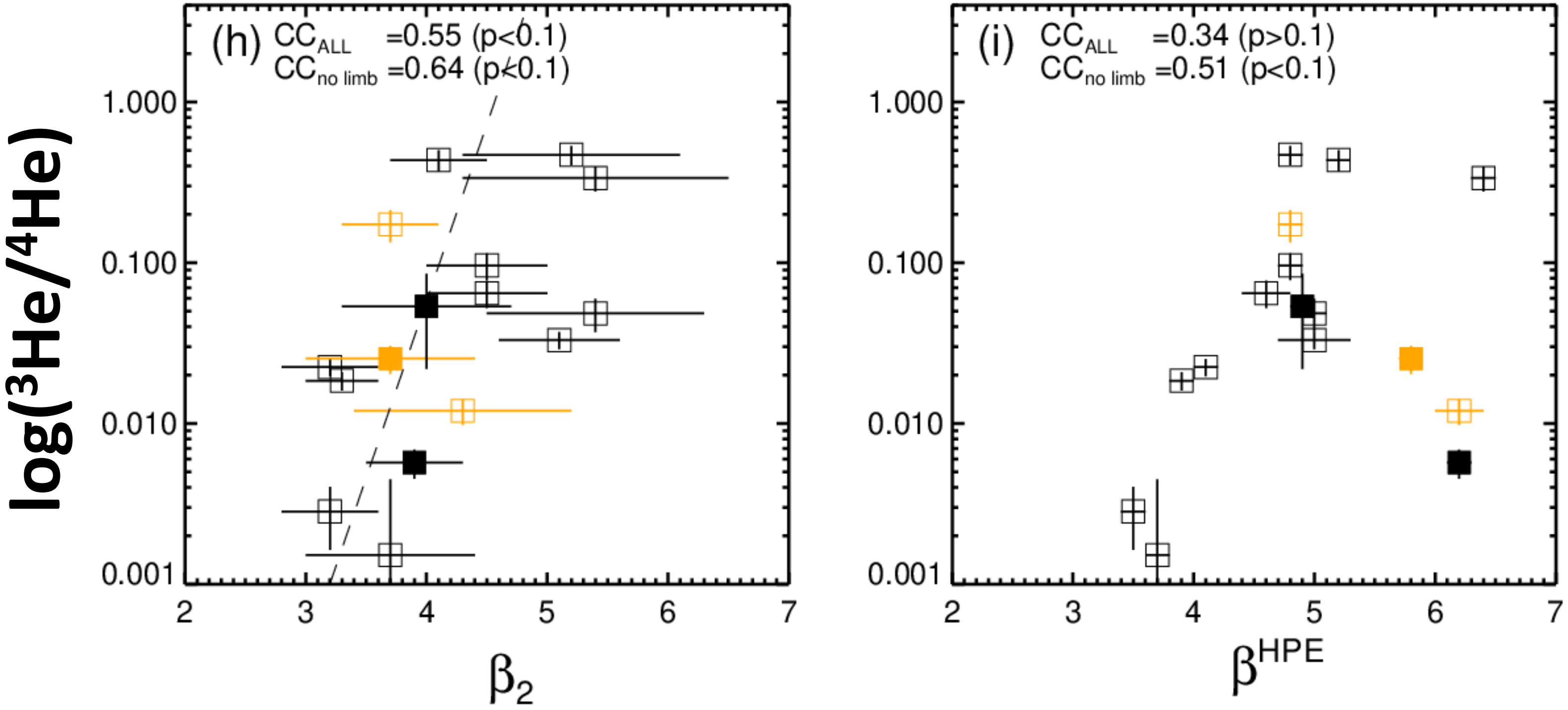
Better agreement with observations

2.7 Association of HPEs & SEEs with $^3He/^4He$

$\beta_2 \propto \log(^3He/^4He)$

Acceleration of ^3He could be related with high-energy SEEs

Possibly occur high in corona



3. Summary

Observations:

1. $E_B^{HXR}=0.7E^e_B$
2. $\beta^{HPE} \geqq \beta_2$
3. $N_{SEE}/N_{HPE} \approx 1\%$
4. $\beta_2 \propto \log(^3He/^4He)$

Explanations:

1. Source of SEEs high in the corona ($\geqq 1.3R_s$)
2. Introducing secondary acceleration more efficient to lower energy electrons
3. The Acc of ^3He may be related to the high energy SEEs and occurs in high corona

(Wang et al., 2021 ApJ, 913, 89)