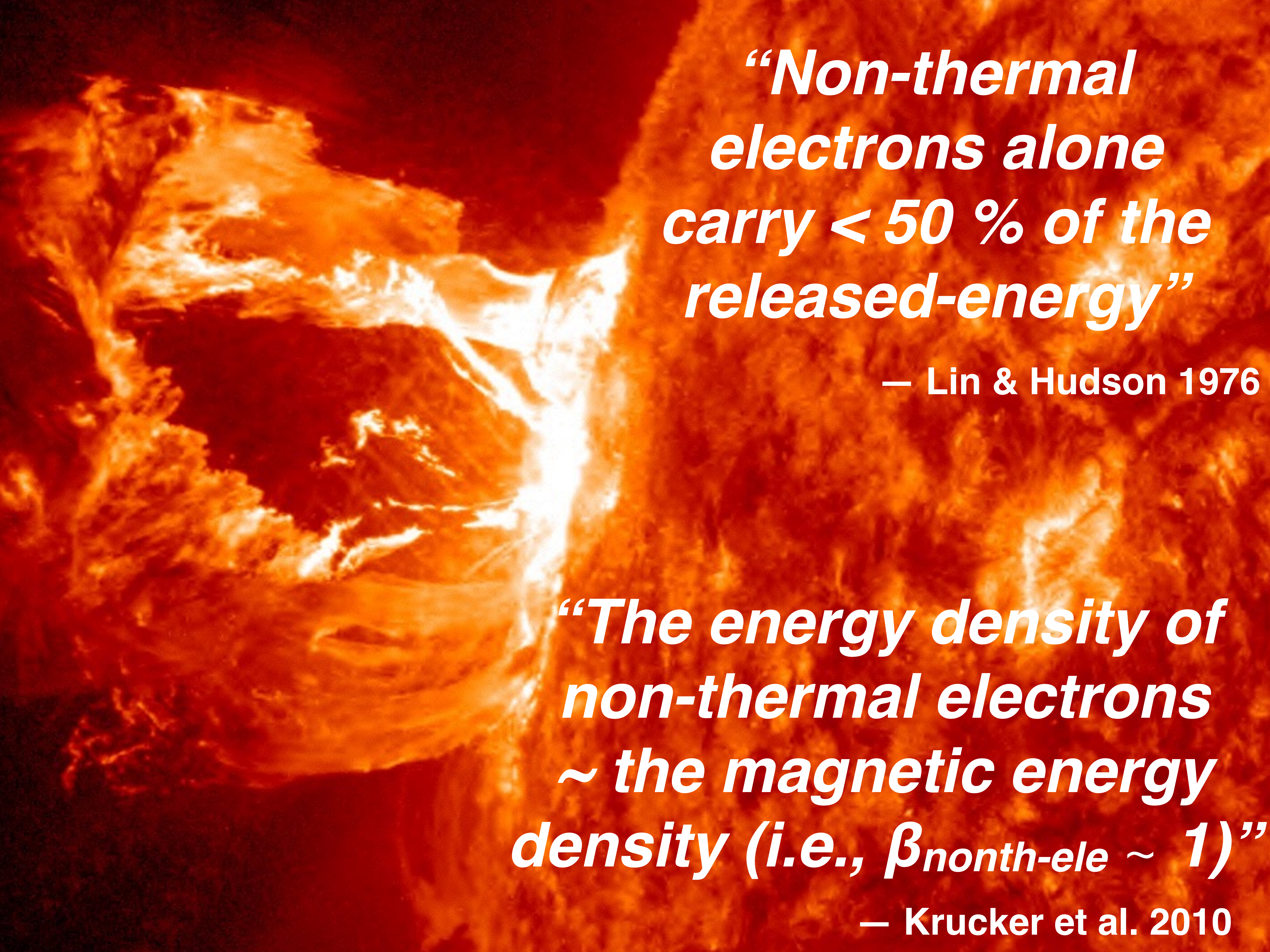

“Non-thermal electrons alone carry < 50 % of the released-energy”
— Lin & Hudson 1976
“The energy density of non-thermal electrons ~ the magnetic energy density (i.e., $\beta_{nonth\text{-}ele} \sim 1$)”
— Krucker et al. 2010

Particle Acceleration
in
Solar Flares & Terrestrial Substorms

Power-law index in various cases
—> δ~4 may be a key number

Outline

- Introduction — Definition of δ
- Solar Flares (δ ≥ 4)
- Terrestrial Substorms (δ ≥ 4)
- Heliosphere (δ **≤** 4)
- Conclusion

Power-law index

Phase space density	$f(p) \propto p^{-s}$	
Phase space density	$f(E) \propto E^{-\Gamma}$	$(E = p^2/2m)$
Differential density	$N(E) \propto E^{-\delta'}$	$(dN = 4\pi p^2 f(p) dp)$
Differential flux (flux density)	$J(E) \propto E^{-\delta}$	$(dJ = v\, dN)$
X-ray photon flux	$I(\varepsilon) \propto \varepsilon^{-\gamma}$	$\gamma_{thin} = \delta + 1$ $\gamma_{thick} = \delta - 1$

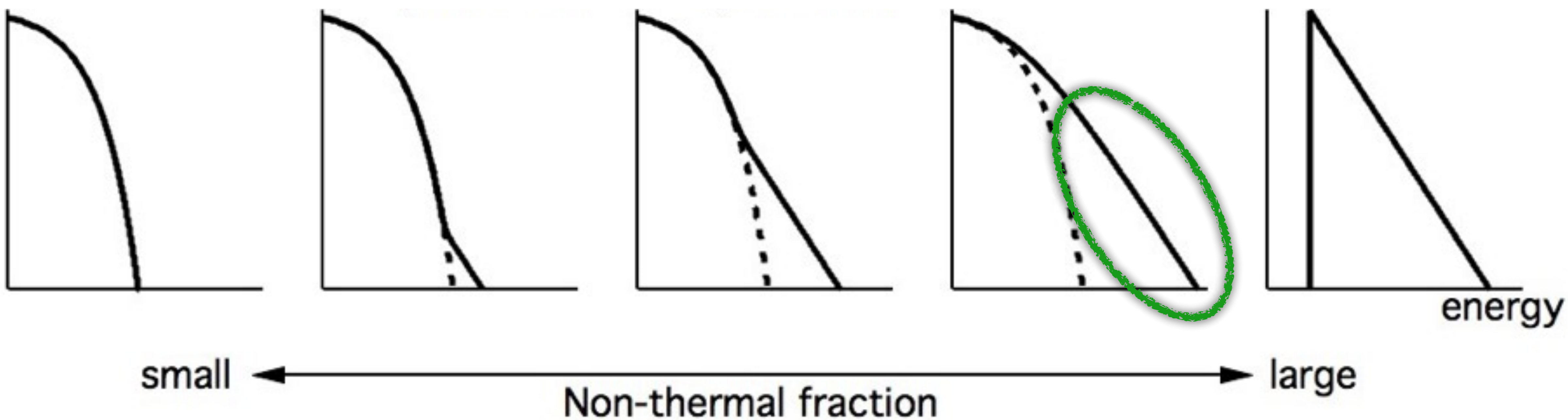
δ is used throughout this talk.

NOTE: Non-relativistic regime
(because we use data below 100 keV)

Kappa distribution

$$\kappa = \delta$$

$$f_\kappa(v) \propto \left(1 + \frac{v^2}{\kappa\theta^2}\right)^{-(\kappa+1)}$$



Oka et al. 2015

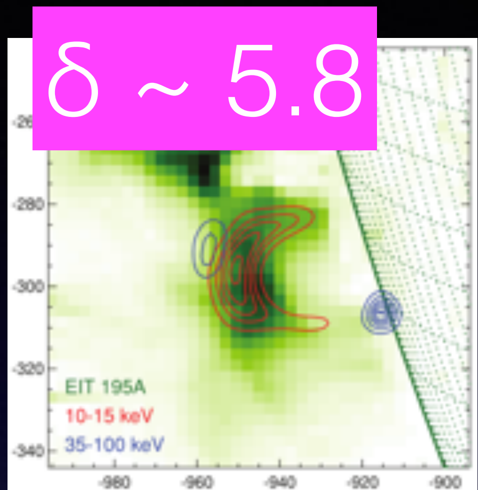
Although I have been using the kappa distribution in data analysis, this talk has nothing to do with this model.

This talk is focused on the slope itself.

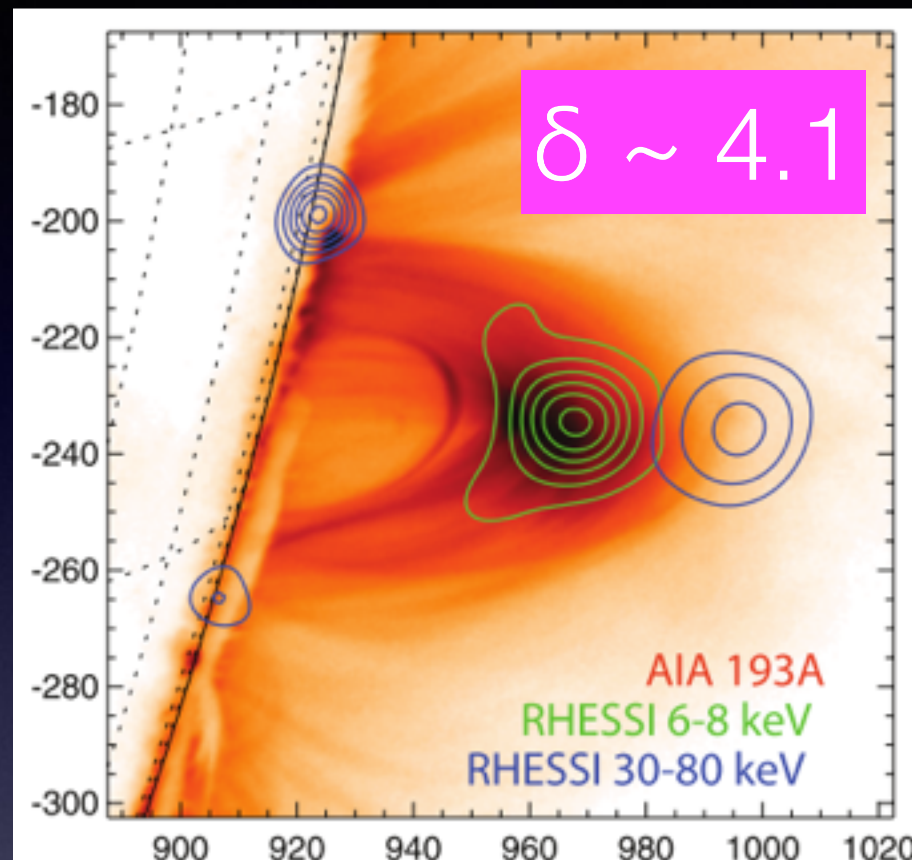
Outline

- Introduction — Definition of δ
- Solar Flares (δ ≥ 4)
- Terrestrial Substorms (δ ≥ 4)
- Heliosphere (δ **≤** 4)
- Conclusion

Coronal Sources

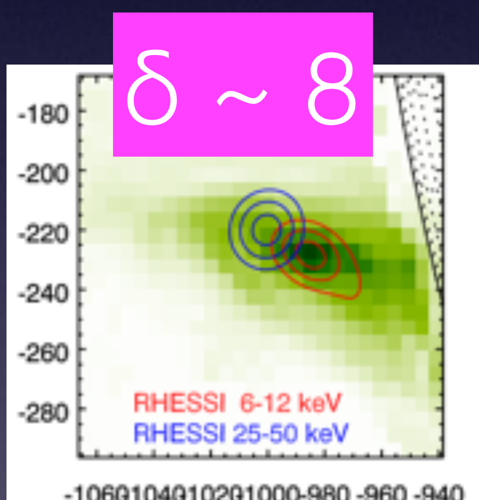


Ishikawa+2011

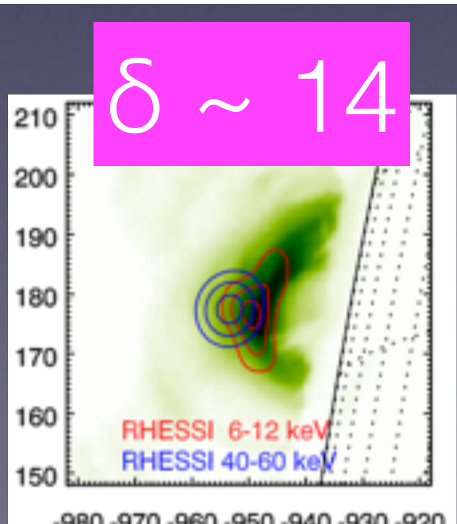


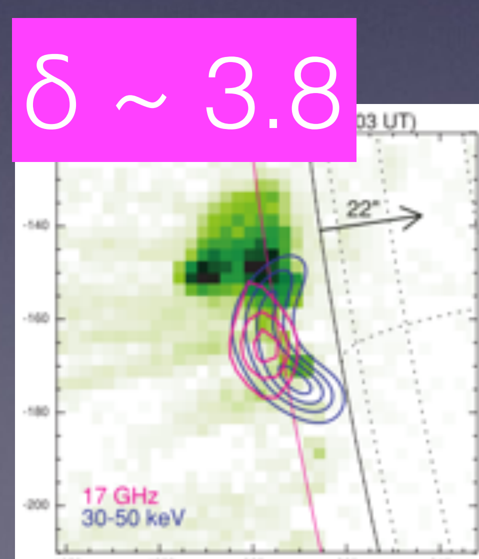
Krucker & Battaglia 2014

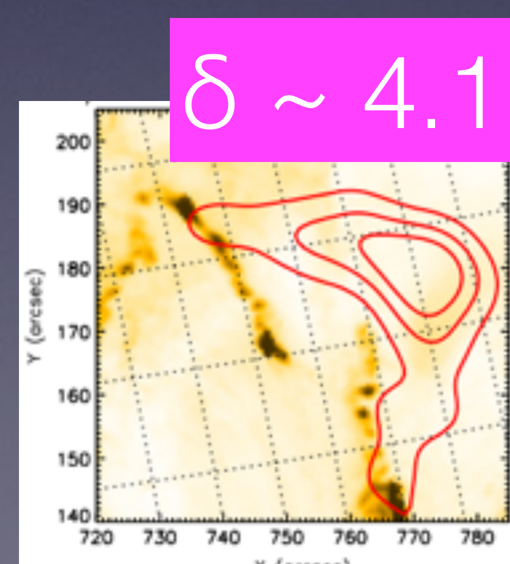
Masuda-Type events analyzed carefully with imaging-spectroscopy **(Likely thin-target)**



The values are obtained based on the kappa distribution (from Oka+ 2013, 2015) but any other power-law model would give similar values.



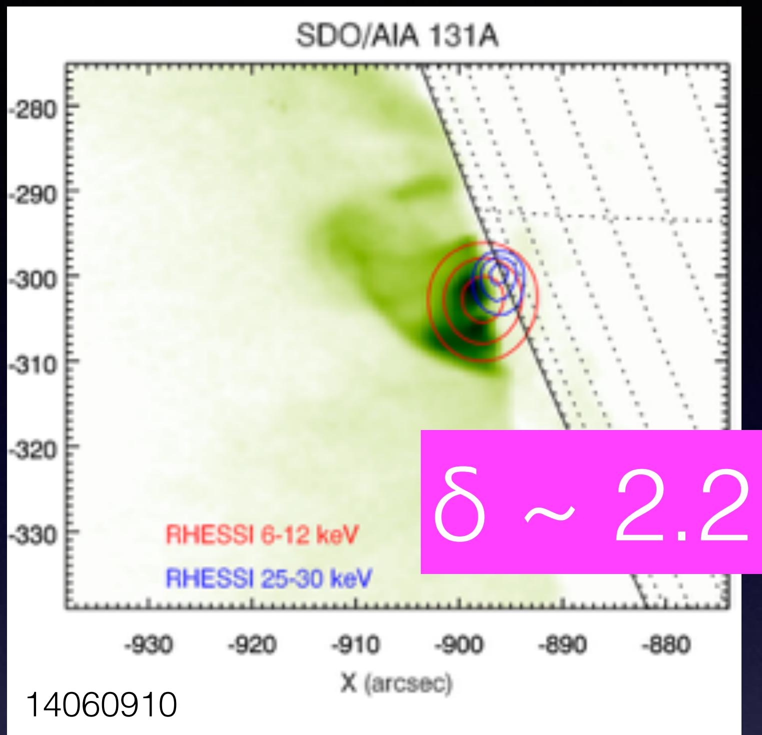




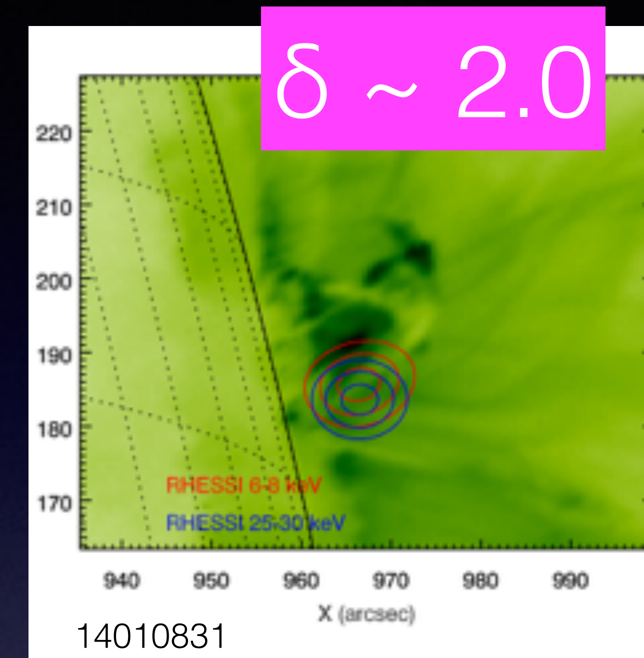
Krucker+2010 Battaglia+ 2015

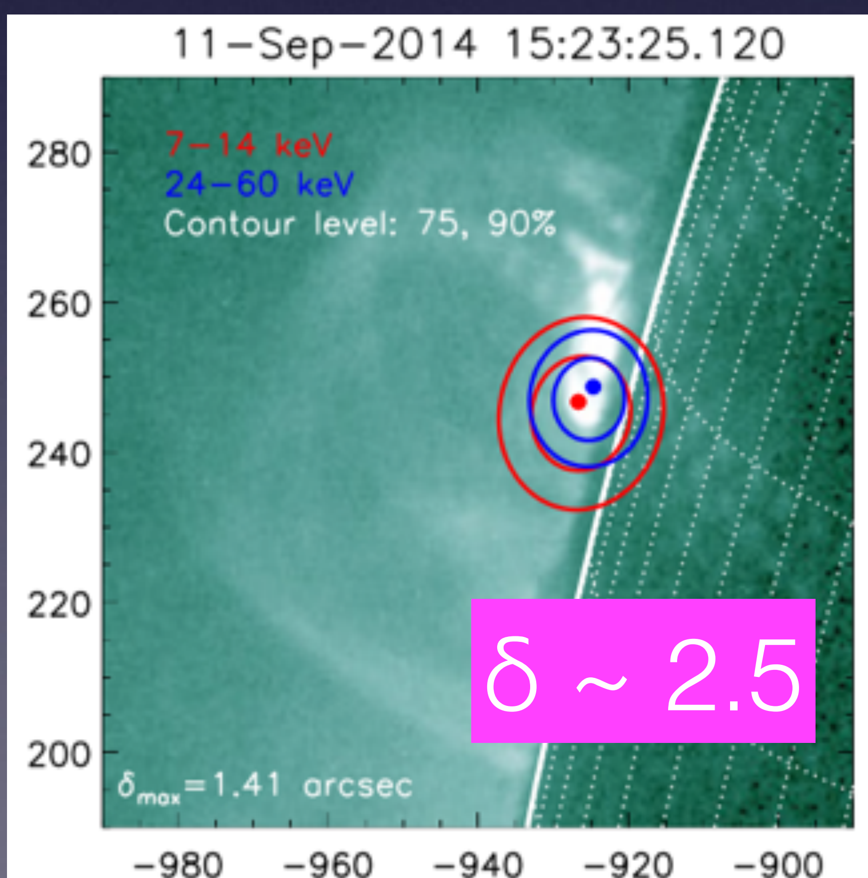
lower limit at $\delta\ (=\kappa) \sim 4$?

κ (= δ) > 2 ?



Ongoing study by Effenberger et et al.



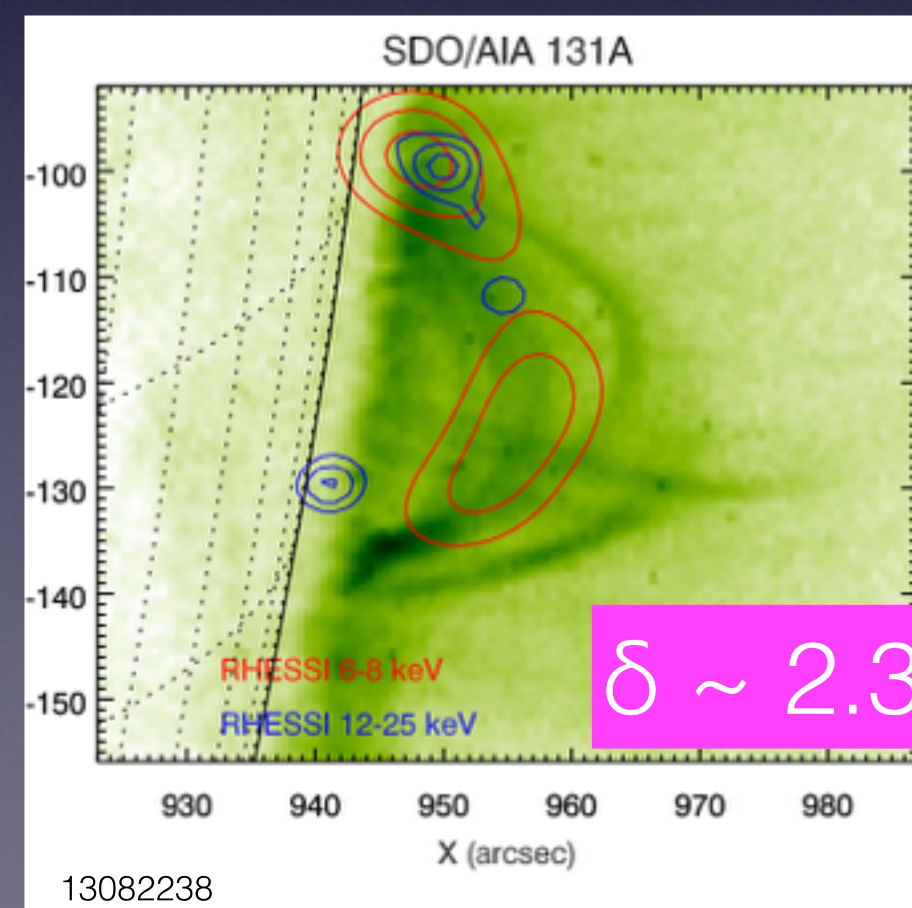


$\kappa_{thin} = 2$

$\gamma = 3$

$\kappa_{thick} = 4$

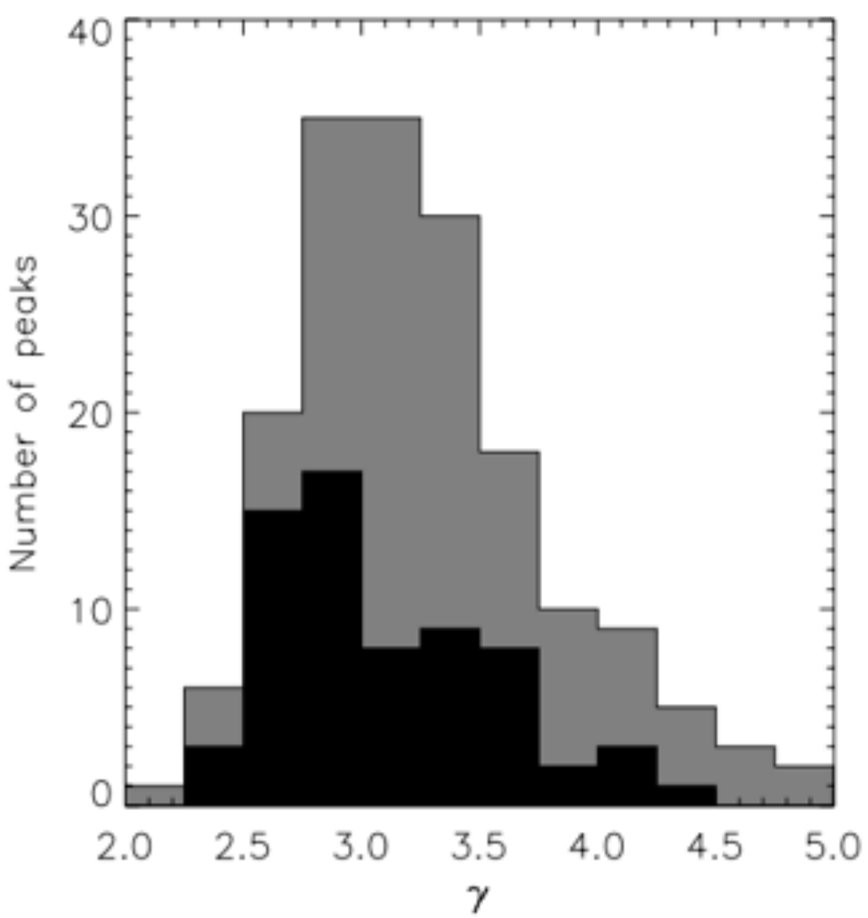
If we assume thick-target, **δ > 4**



Footpoint Sources

- Let's assume thick-target emission

$$\gamma_{thick} = \delta - 1$$



X-ray photon flux $I(\varepsilon) \propto \varepsilon^{-\gamma}$

γ_{thick} = 2.5 - 4.0

Diff. flux (flux density) $J(E) \propto E^{-\delta}$

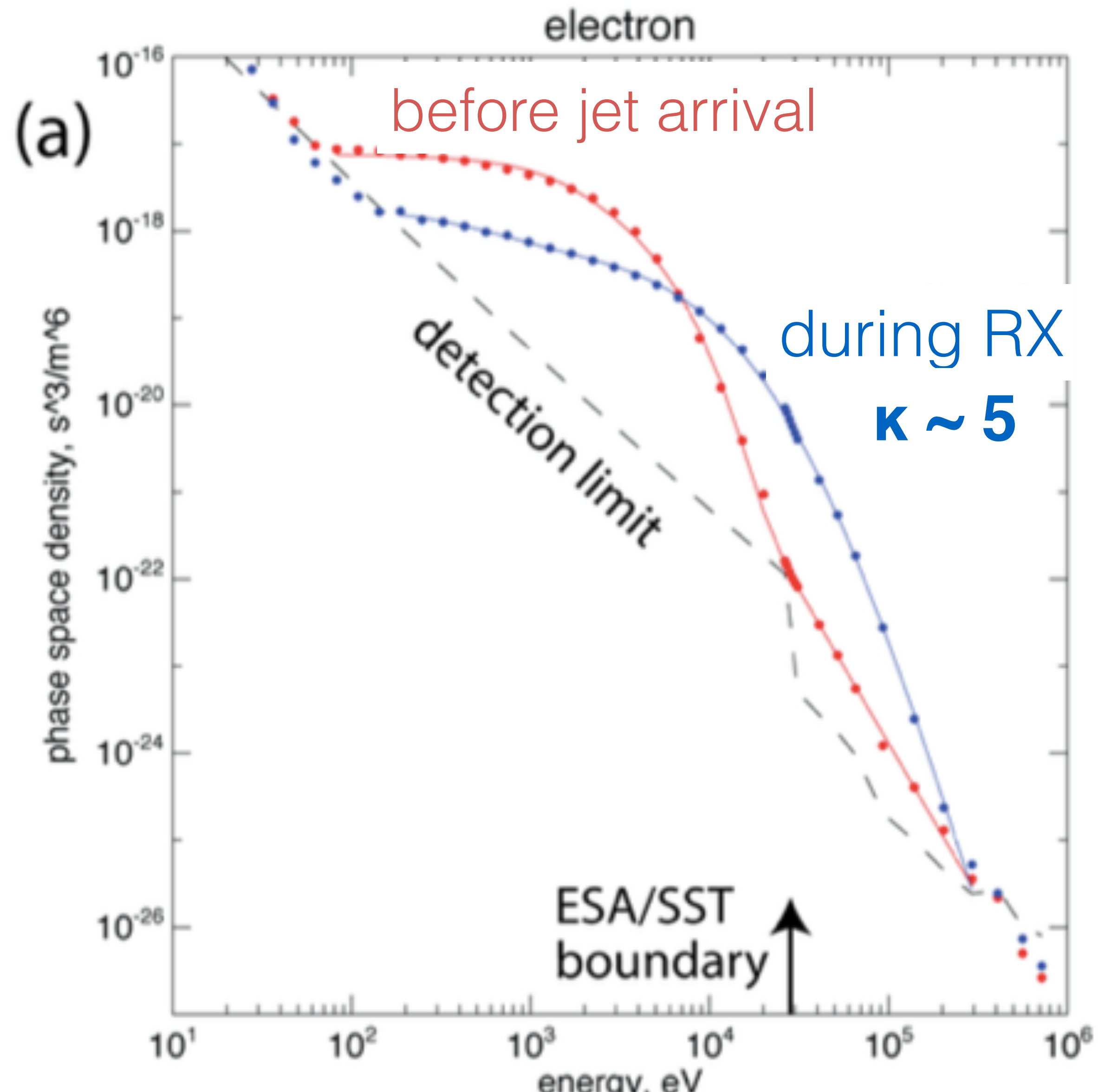
δ = 3.5 - 5.0

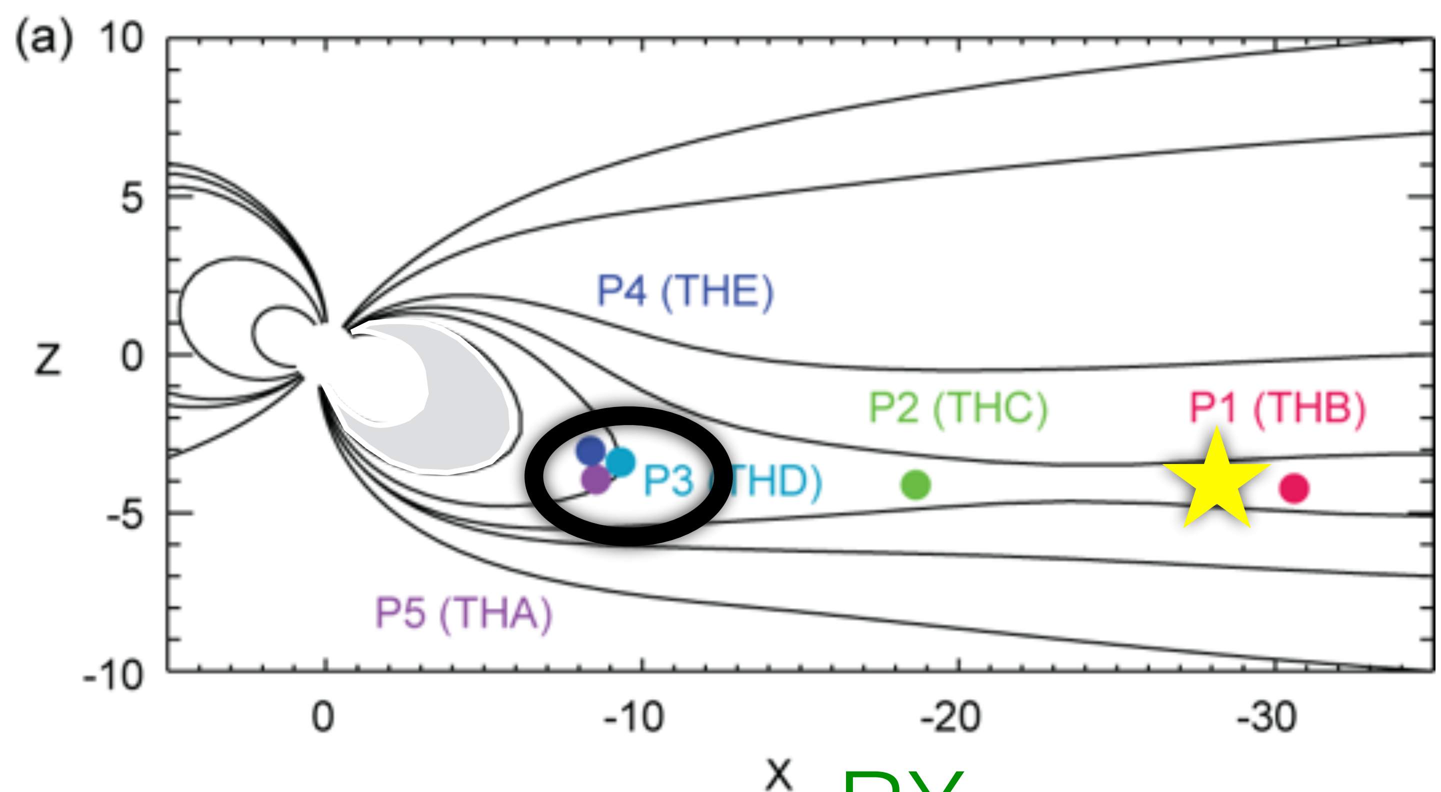
Saint-Hilaire et al. 2007

Outline

- Introduction — Definition of δ
- Solar Flares ($\delta \geq 4$)
- Terrestrial Substorms ($\delta \geq 4$)
- Heliosphere ($\delta \leq 4$)
- Conclusion

Magnetotail





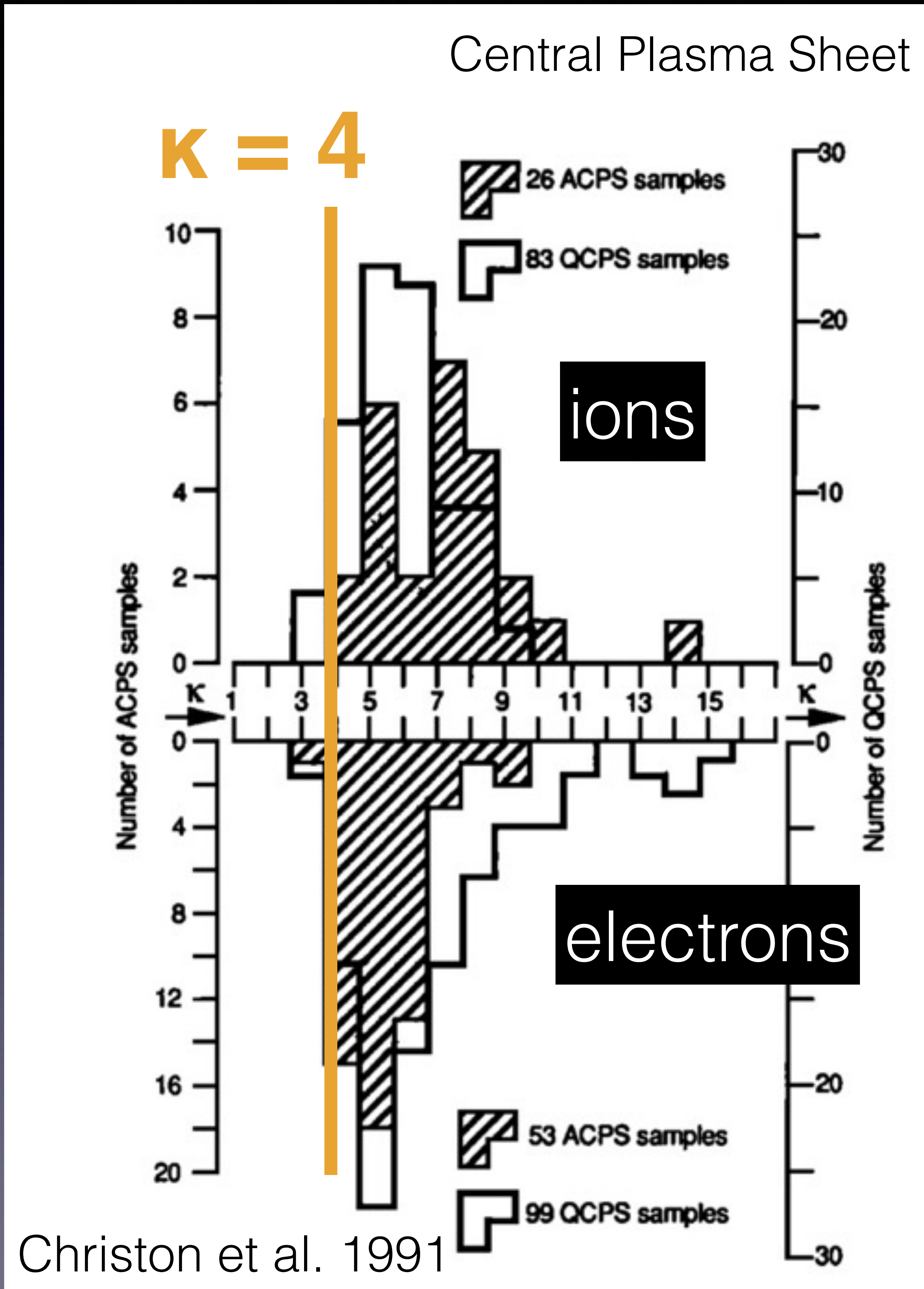
jet braking

RX jet prop.

RX diffusion region

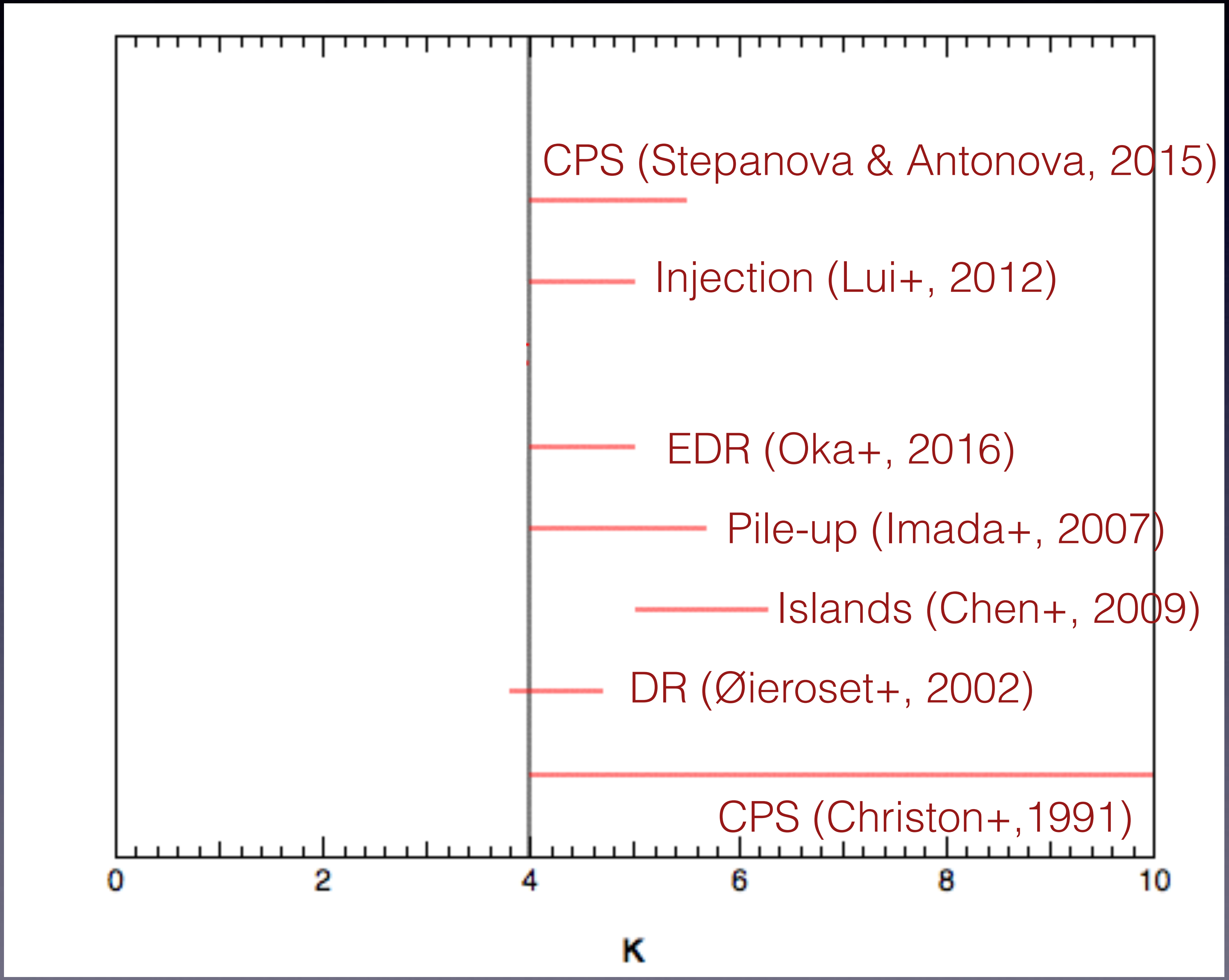
The THEMIS mission, launched in 2007

inner "loop" filled with radiation-belt electrons



Statistical Studies
by
Christon et al.
1988, 1990, 1991
using ISEE
spacecraft
(1970s technology!)

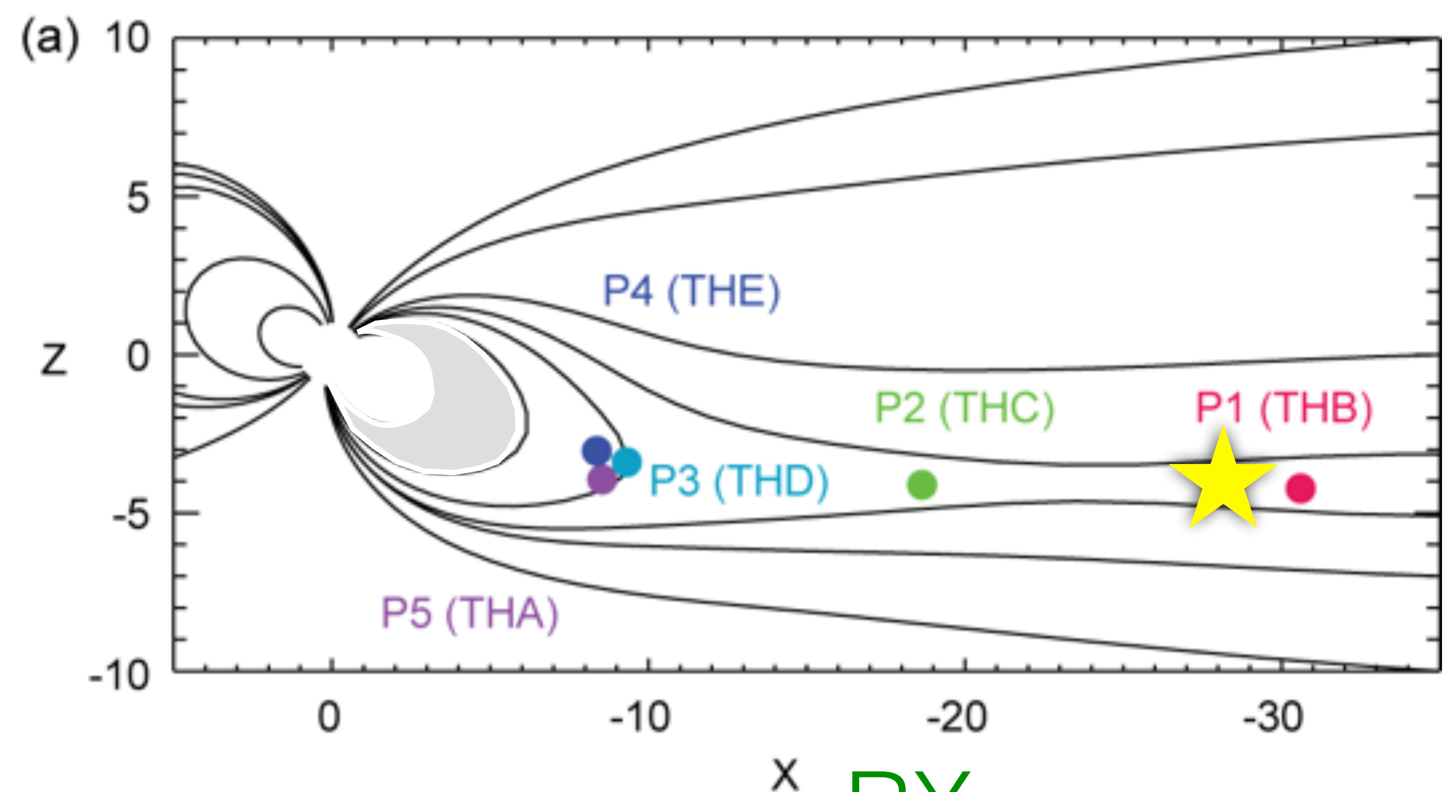
Case studies on fine structures in the magnetotail (by more recent missions)



EDR detection by THEMIS

Where in the magnetotail do we start to see a power-law?

Ultimate source: Electron diffusion region (EDR)?



jet braking

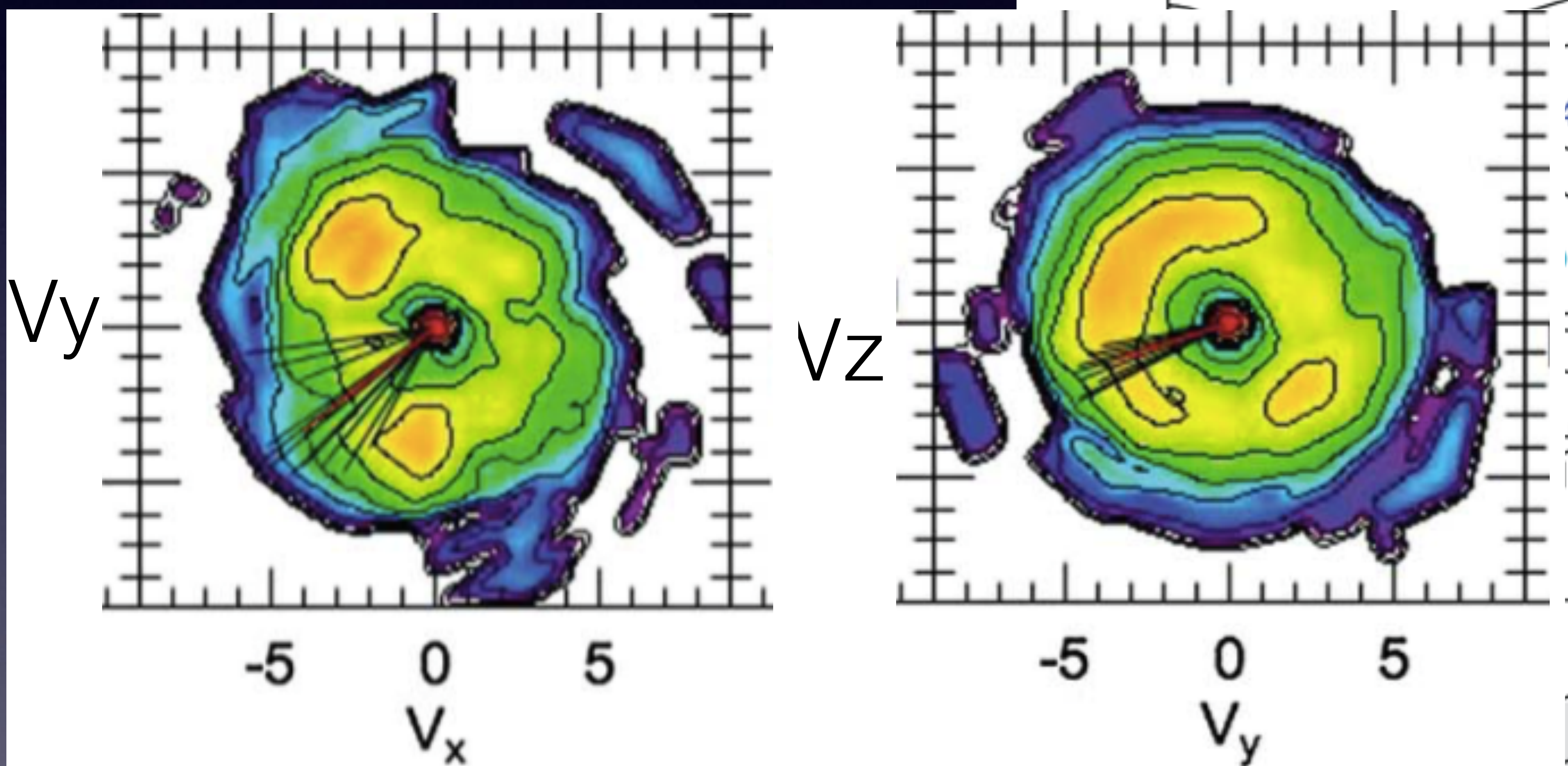
RX jet prop.

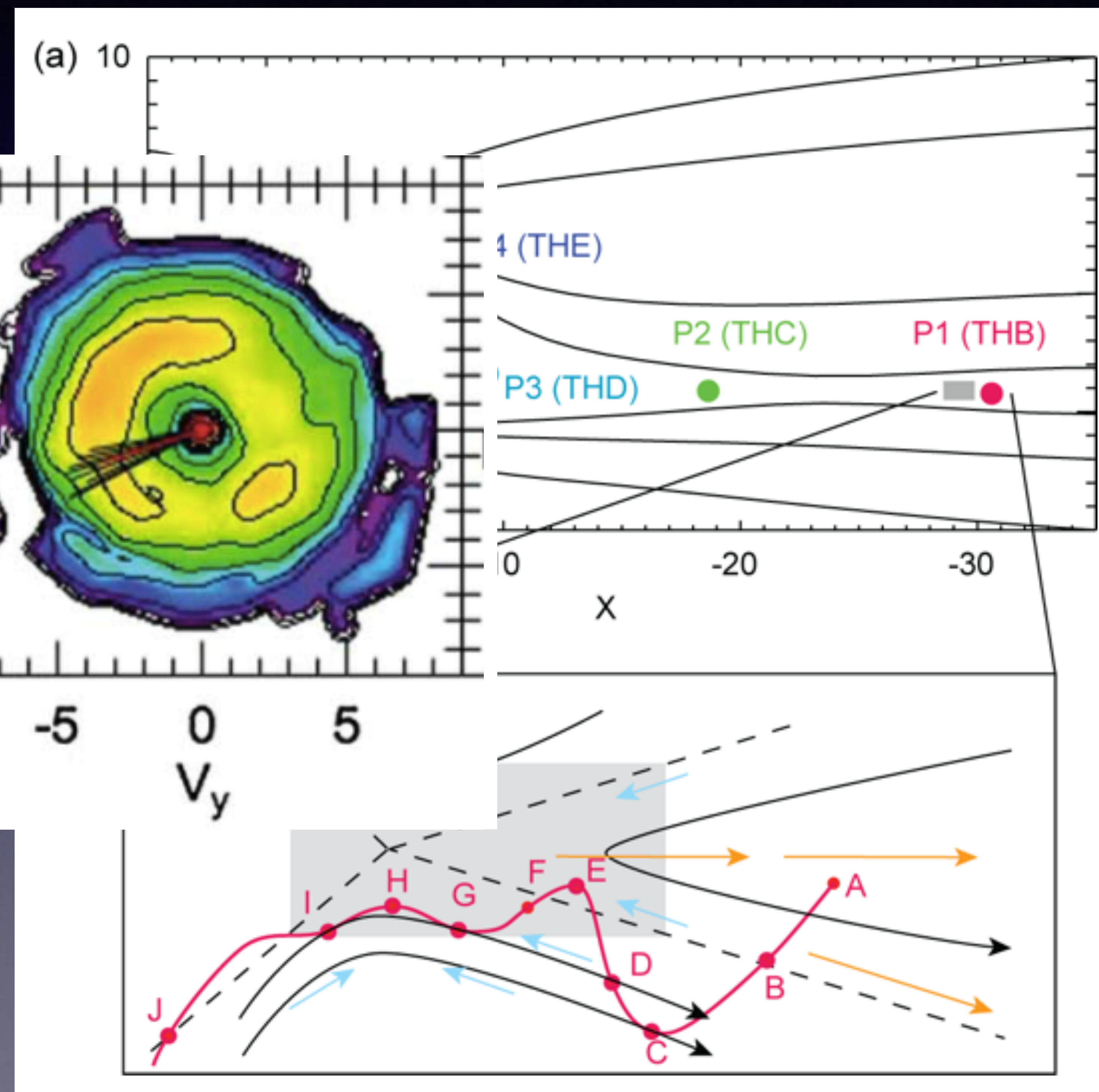
RX diffusion region

inner “loop” filled with radiation-belt electrons

EDR detection by THEMIS

Oka et al. 2016

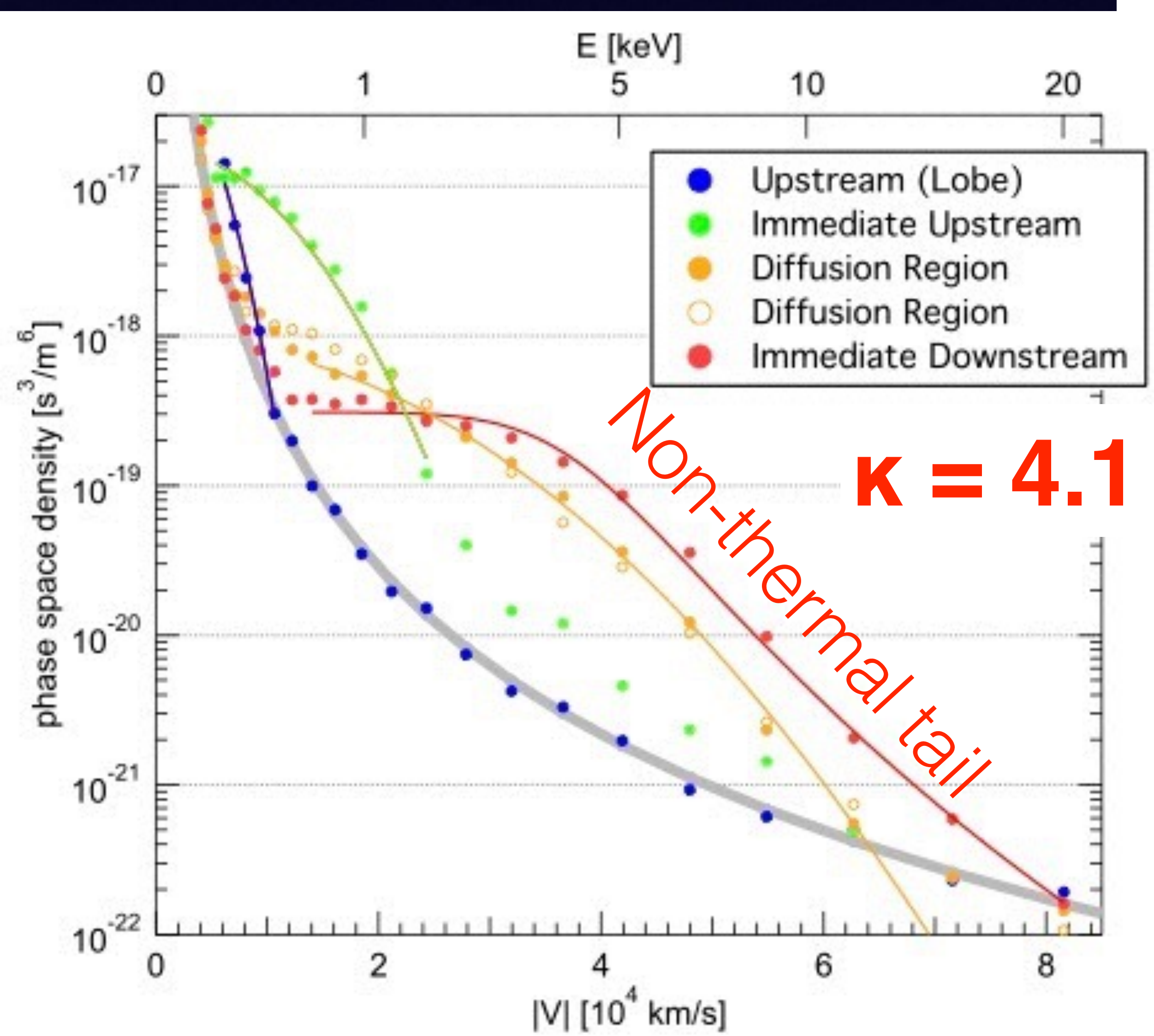


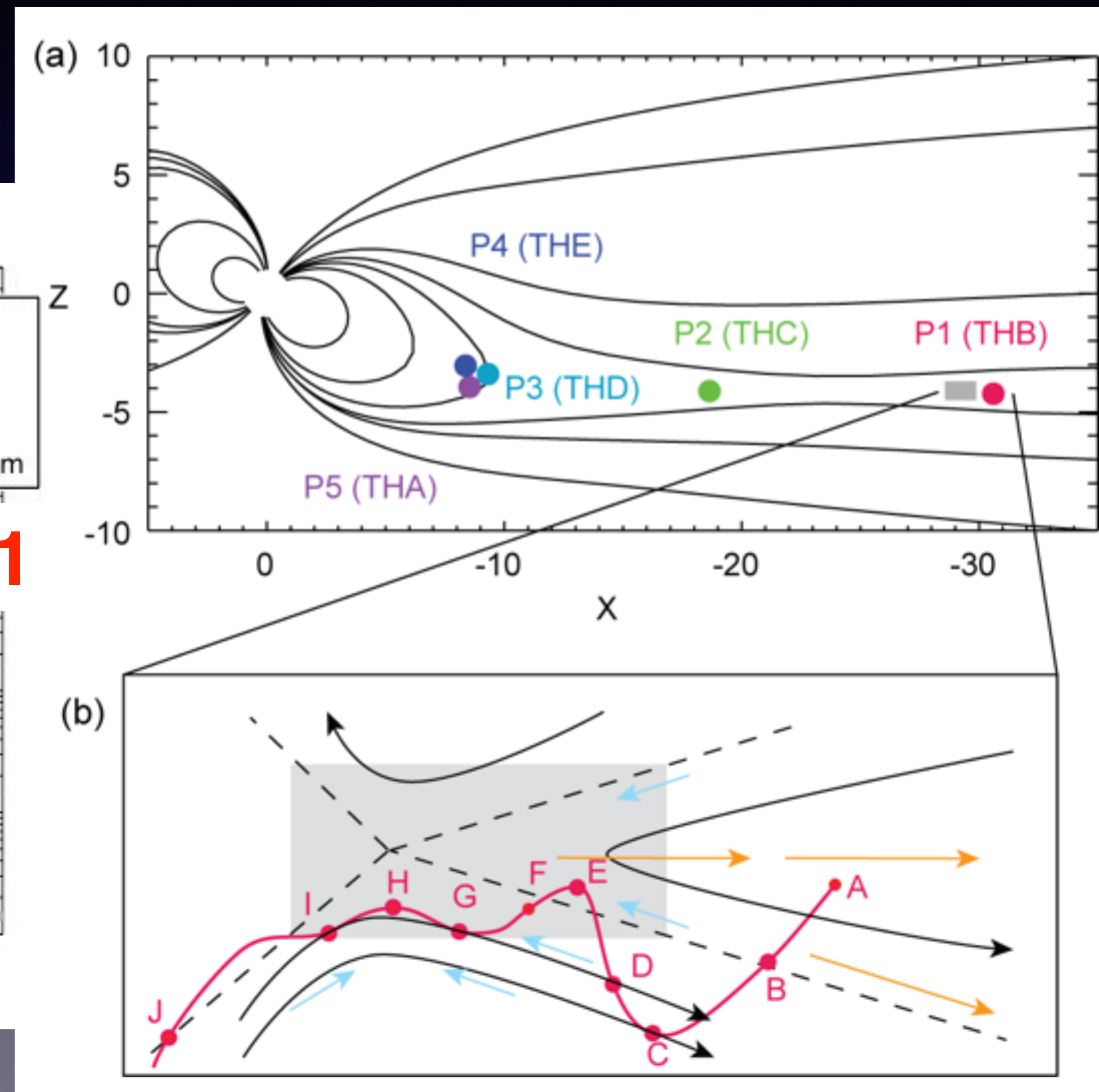


THEMIS
3s sampling time
$B_g \sim 0.06 B_0$

EDR detection by THEMIS

Oka et al. 2016





Outline

- Introduction — Definition of δ
- Solar Flares ($\delta \geq 4$)
- Terrestrial Substorms ($\delta \geq 4$)
- Heliosphere ($\delta \leq 4$)
- Conclusion

Shock (ions)

- e.g. interplanetary (CME) shock and SEPs
- Standard theory: **Diffusive shock acceleration**

of which the solution is

$$f_+(p) = qp^{-q} \int_0^p \mathrm{d}p' \, f_-(p') \, p'^{(q-1)}$$

where

$$q = 3r/(r-1) \, .$$

where r is compression ratio

Phase space density $f(p) \propto p^{-s}$

s >= 4

Diff. flux (flux density) $J(E) \propto E^{-\delta}$

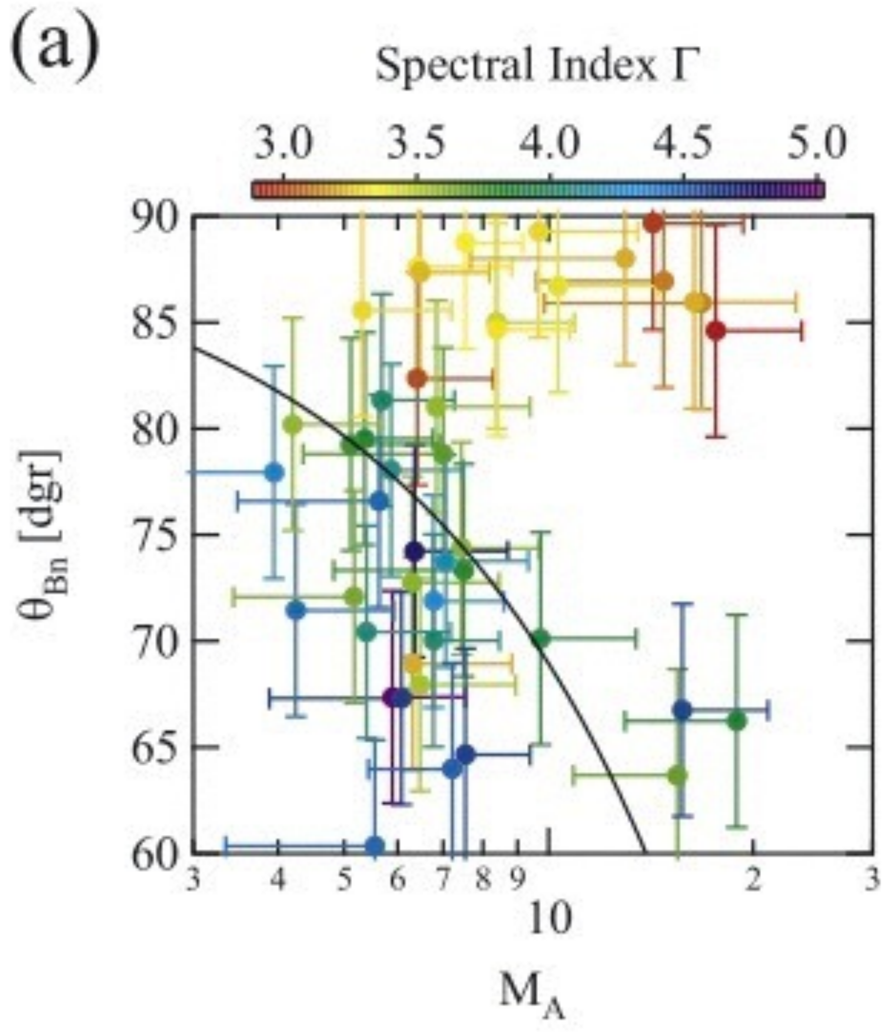
δ >= 1 (theory)

δ = 2-4 (observations)

e.g. a review by Blandford and Eichler, 1987

Shock (electrons)

- Earth's bow shock (M_A can be as high as 10-20)
- Acceleration mechanism remains unclear (but we frequently observe a power-law at the shock front).



Phase space density $f(E) \propto E^{-\Gamma}$

$\Gamma = 3 - 5$

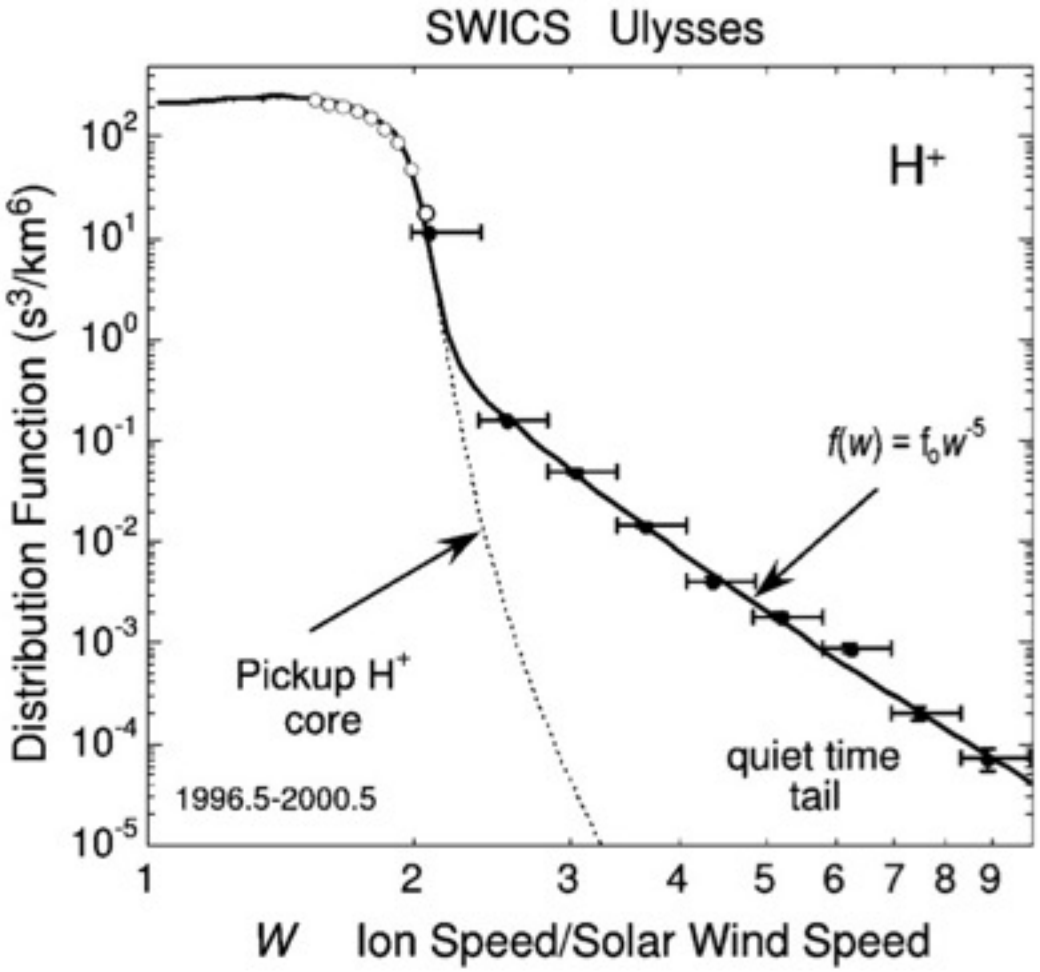
Diff. flux (flux density) $J(E) \propto E^{-\delta}$

$\delta = 2 - 4$

Oka et al. 2006

Quiet time solar wind (ions)

- Interstellar-origin pickup ions
- Ubiquitous power-law (No association with shocks and flares)



Phase space density $f(p) \propto p^{-s}$

s = 5

Diff. flux (flux density) $J(E) \propto E^{-\delta}$

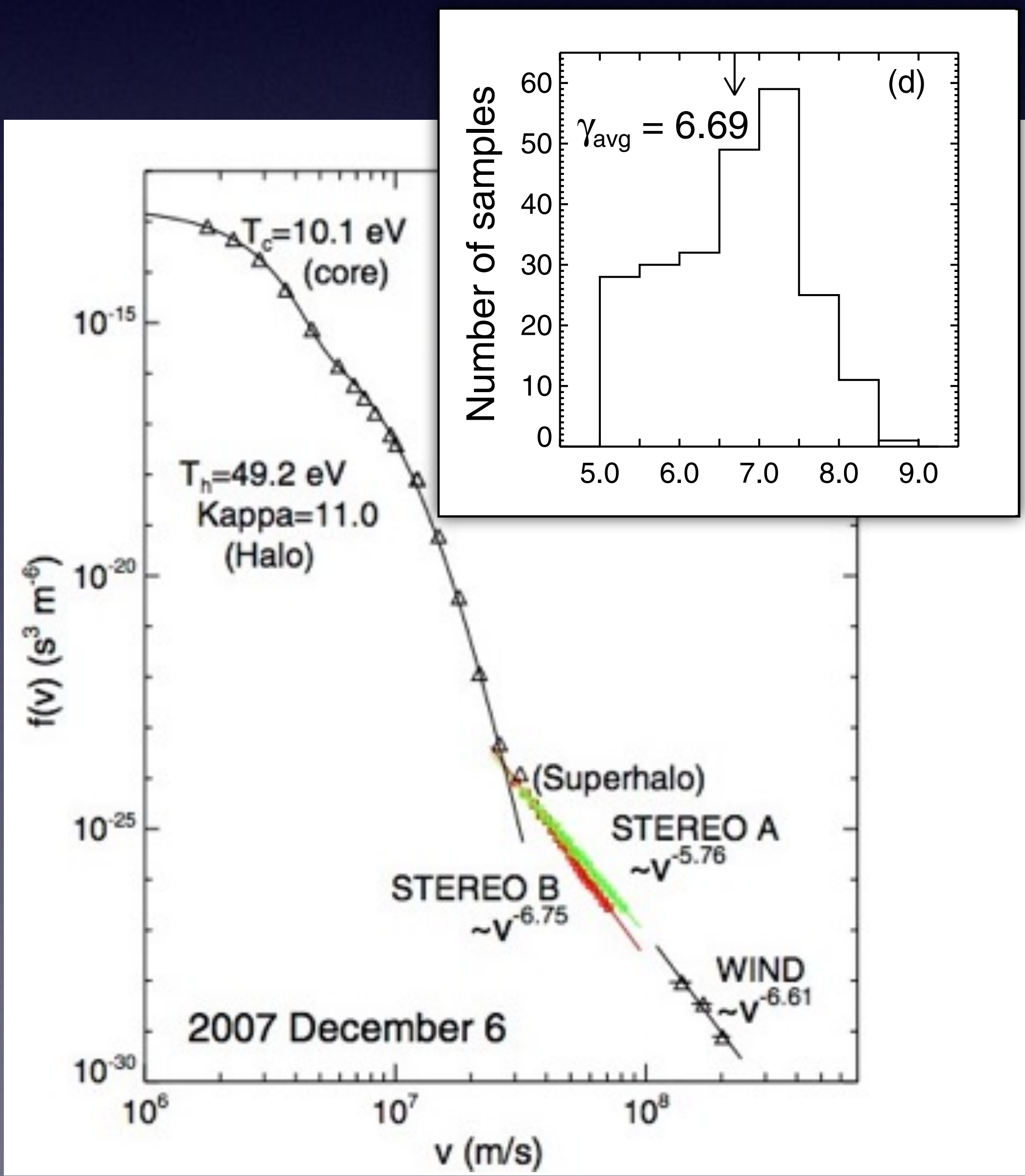
$\delta = 1.5$

Gloeckler+, 2000,2003

See also Fisk+ for the "pump" mechanism

Quiet time solar wind (electrons)

- Super-halo
- Not associated with flares — origin unknown



Phase space density $f(p) \propto p^{-s}$

s = 5 - 9

Diff. flux (flux density) $J(E) \propto E^{-\delta}$

δ = 1.5 - 3.5

Wang+, 2012

Conclusion 1

Explosive energy-release (flares, substorms)

$\delta > 4$

- **common lower limit at $\delta \sim 4$**, suggesting a common (but not-yet-identified) physics in these entirely different environment

Shocks and turbulence (solar wind)

$\delta < 4$

- Much harder (more flat) spectra, suggesting efficient production of non-thermal particles (?)

Discouraging for the flare community?

- We still have outstanding problems "number problems", "energetics problems"

Conclusion 2

We need to expand our investigation

$\delta > 4$ (?)

- **Flares**: Only 6 cases of convincing ALT
- **Substorms**: Only 6 case studies w/ modern datasets
- Interdisciplinary approach w/ a larger number of events.

International Team at ISSI in Bern

Mitsuo Oka	(Leader/Coordinator) UC Berkeley, USA
Marina Battaglia	(Sub-leader) Univ. Applied Sciences Northwestern Switzerland
Joachim Birn	Space Science Institute, USA
Christopher Chaston	UC Berkeley, USA / Univ. Sydney, Australia
Elin Eriksson	Swedish Institute of Space Physics, Sweden
Lyndsay Fletcher	Univ. Glasgow, UK
Shinsuke Imada	(Sub-leader) Nagoya Univ., Japan
Yuri Khotyaintsev	Swedish Institute of Space Physics, Sweden
Matej Kuhar	Univ. Applied Sciences Northwestern Switzerland
George Livadiotis	Southwest Research Institute, USA
Yoshizumi Miyoshi	Nagoya Univ., Japan
Alessandro Retinò	CNRS École Polytechnique, France

- Theoretical interpretation?

$$\frac{dN}{dp} \propto p^{-\left(1+\frac{t_{acc}}{t_{esc}}\right)}$$

cf: Drake et al. 2006,2013
Guo et al. 2014