

LA-UR-15-25574

Approved for public release; distribution is unlimited.

Title: Electron energy partition in the 'above-the-looptop' solar hard X-ray sources

Author(s): Oka, Mitsuo
Guo, Fan

Intended for: Plasma Energization: Exchanges between Fluid and Kinetic Scales, 2015-05-04/2015-05-06 (Los Alamos, New Mexico, United States)
Web

Issued: 2015-07-21

Disclaimer:

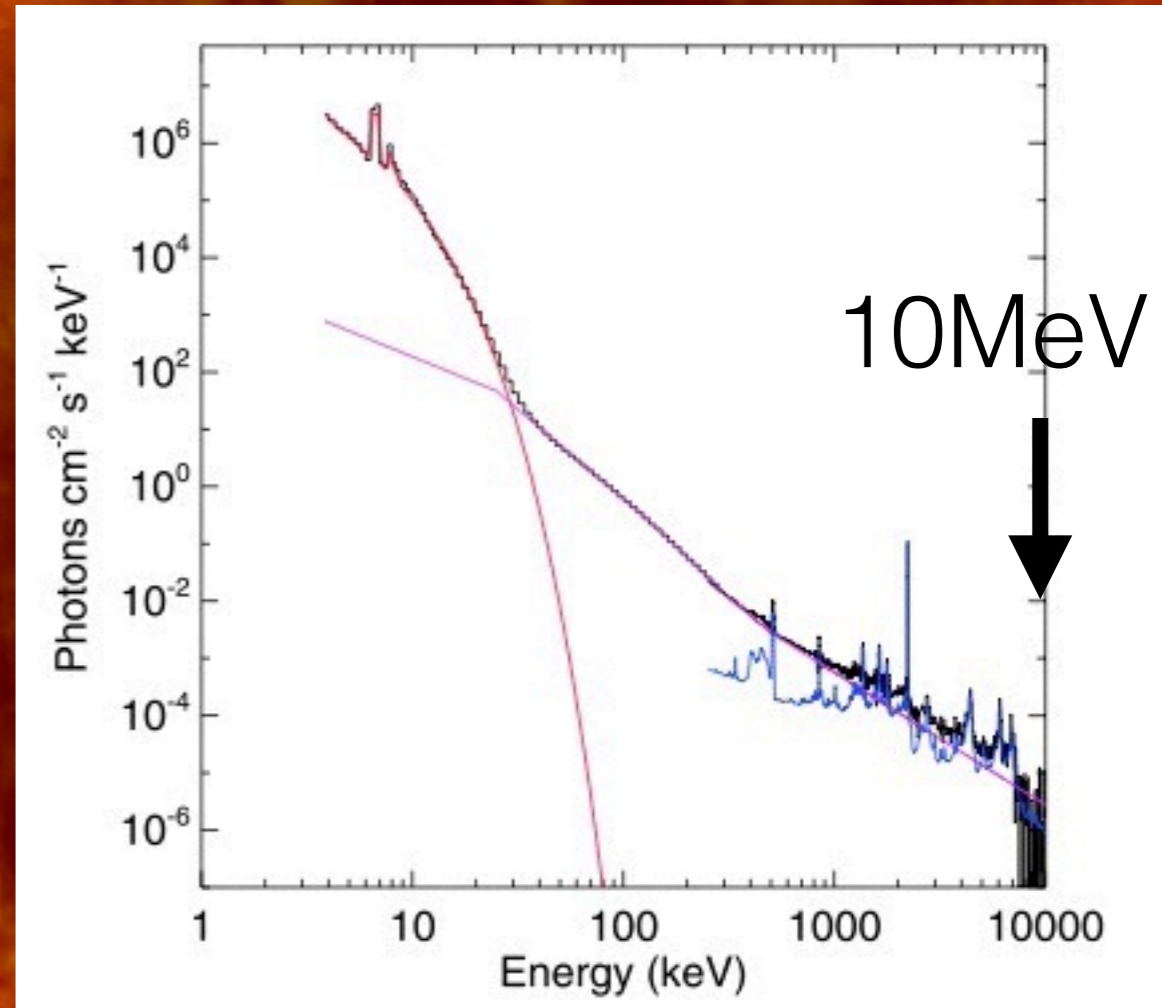
Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Electron energy partition in the 'above-the-looptop' solar hard X-ray sources

M. Oka,
S. Krucker, H. Hudson and P. Saint-Hilaire

Plasma Energization : Exchanges between Fluid and Kinetic Scales
at LANL (2015-05-05)

X-ray spectrum from the entire solar disk



Lin RP et al. 2011

***Non-thermal electrons alone
carry < 50% of released energy***

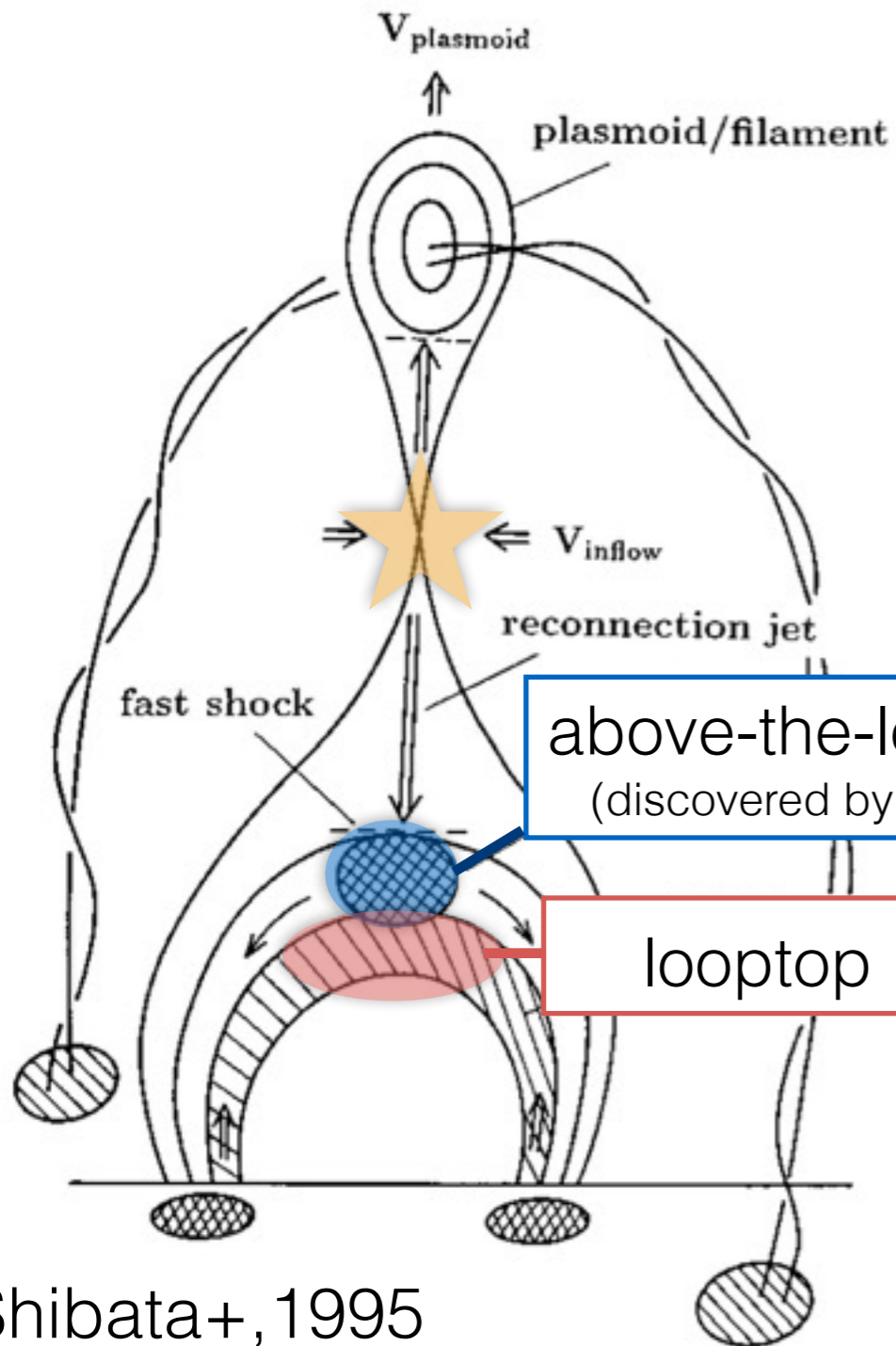
(Lin and Hudson, 1971)

***All electrons are accelerated into a power-law
(i.e., no thermal core) (Krucker et al., 2010,2014)***

Outline

- **Introduction**
 - Basic Idea of Analysis
 - Kappa distribution
- Analysis
- Discussion
- Conclusion

How much non-thermal electrons exist in ALT?



above-the-looptop (ALT)
(discovered by Masuda+, 1994)

looptop

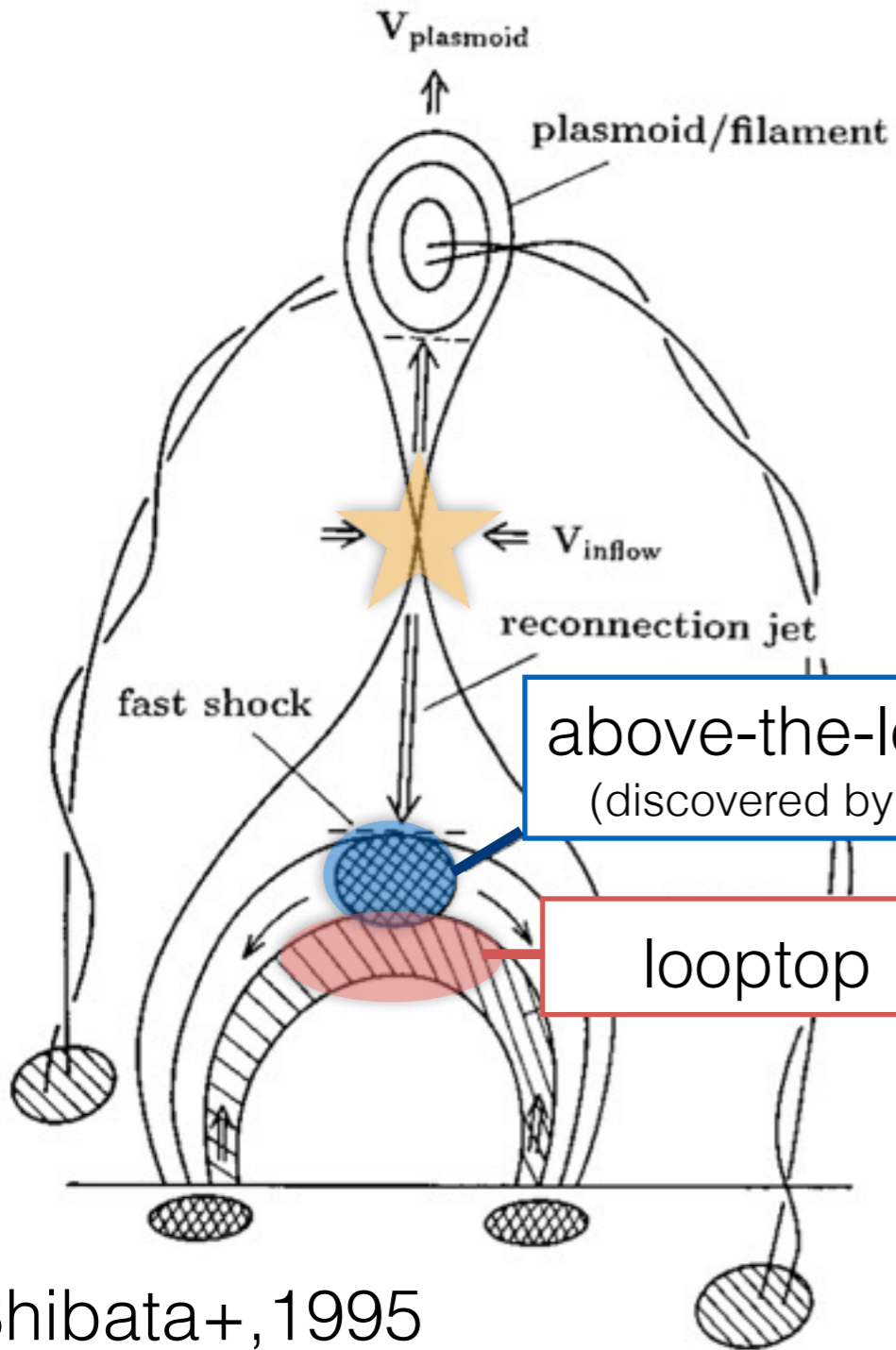
Shibata+, 1995

non-thermal fraction of electron **energies**

$$R_{\varepsilon} = \frac{\varepsilon_{\text{nt}}}{\varepsilon_{\text{total}}}$$

non-thermal fraction of electron **energies**

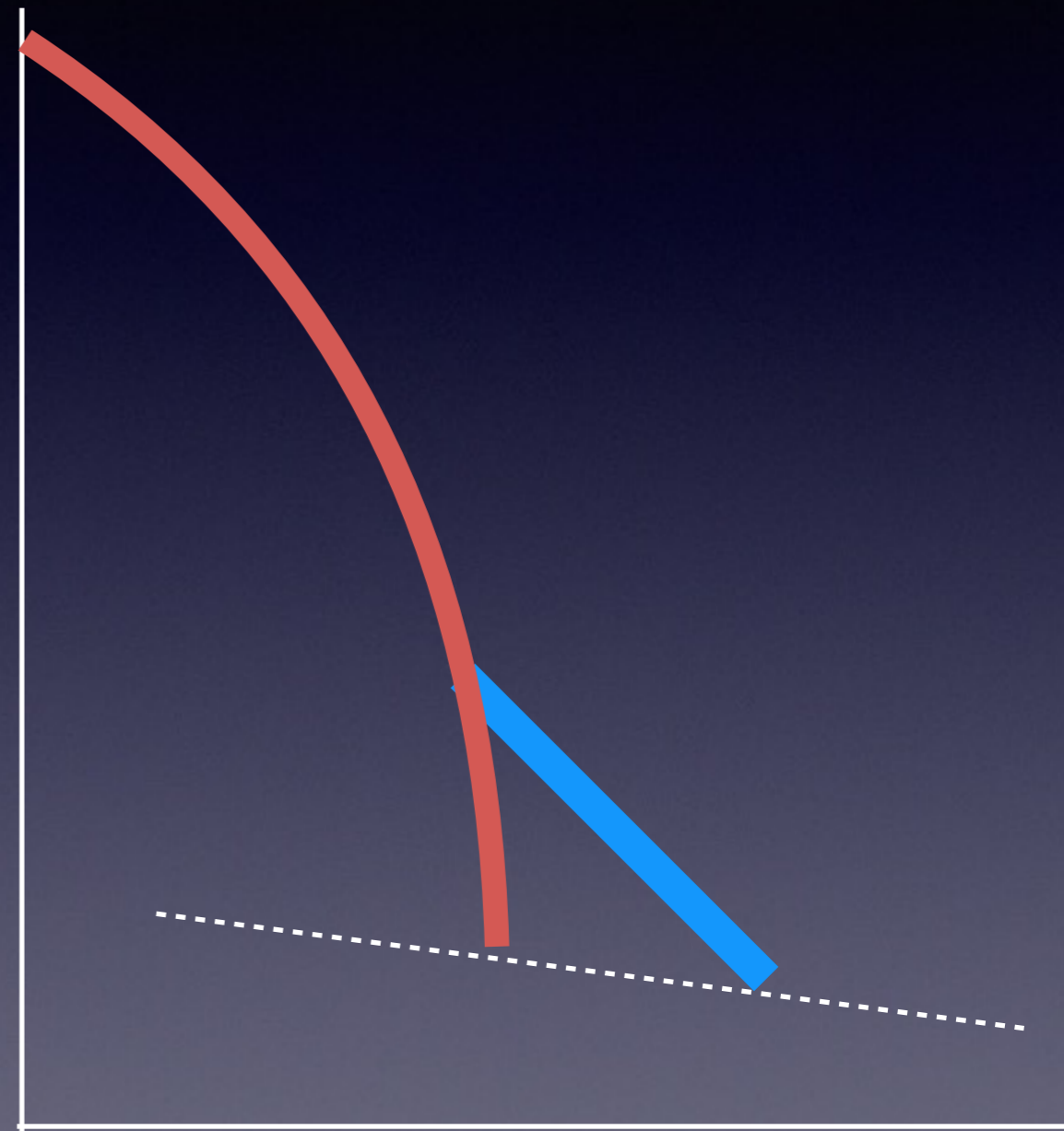
$$R_{\varepsilon} = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$



above-the-looptop (ALT)
(discovered by Masuda+, 1994)

looptop

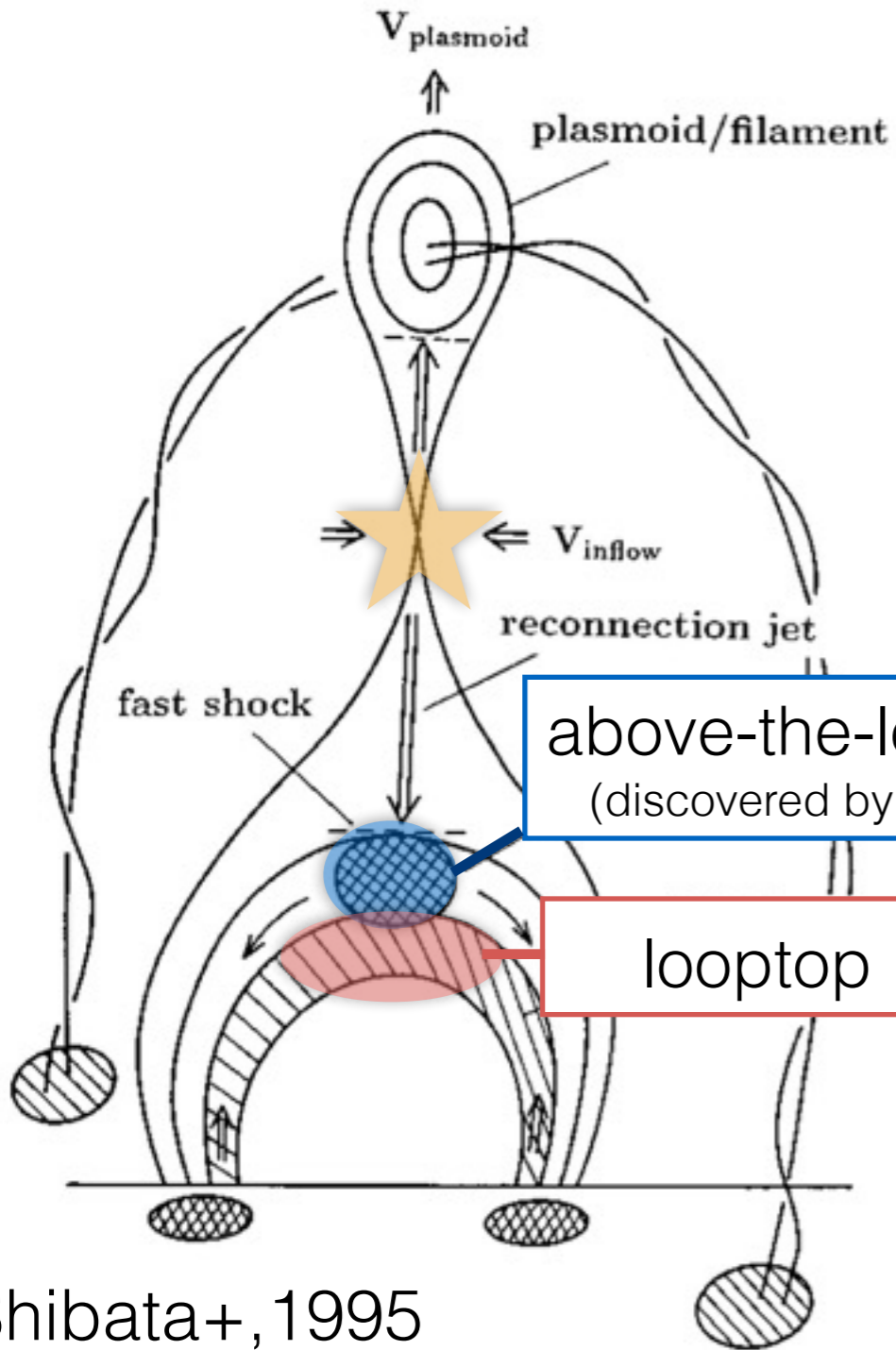
Shibata+, 1995



15 - 80 keV

non-thermal fraction of electron **energies**

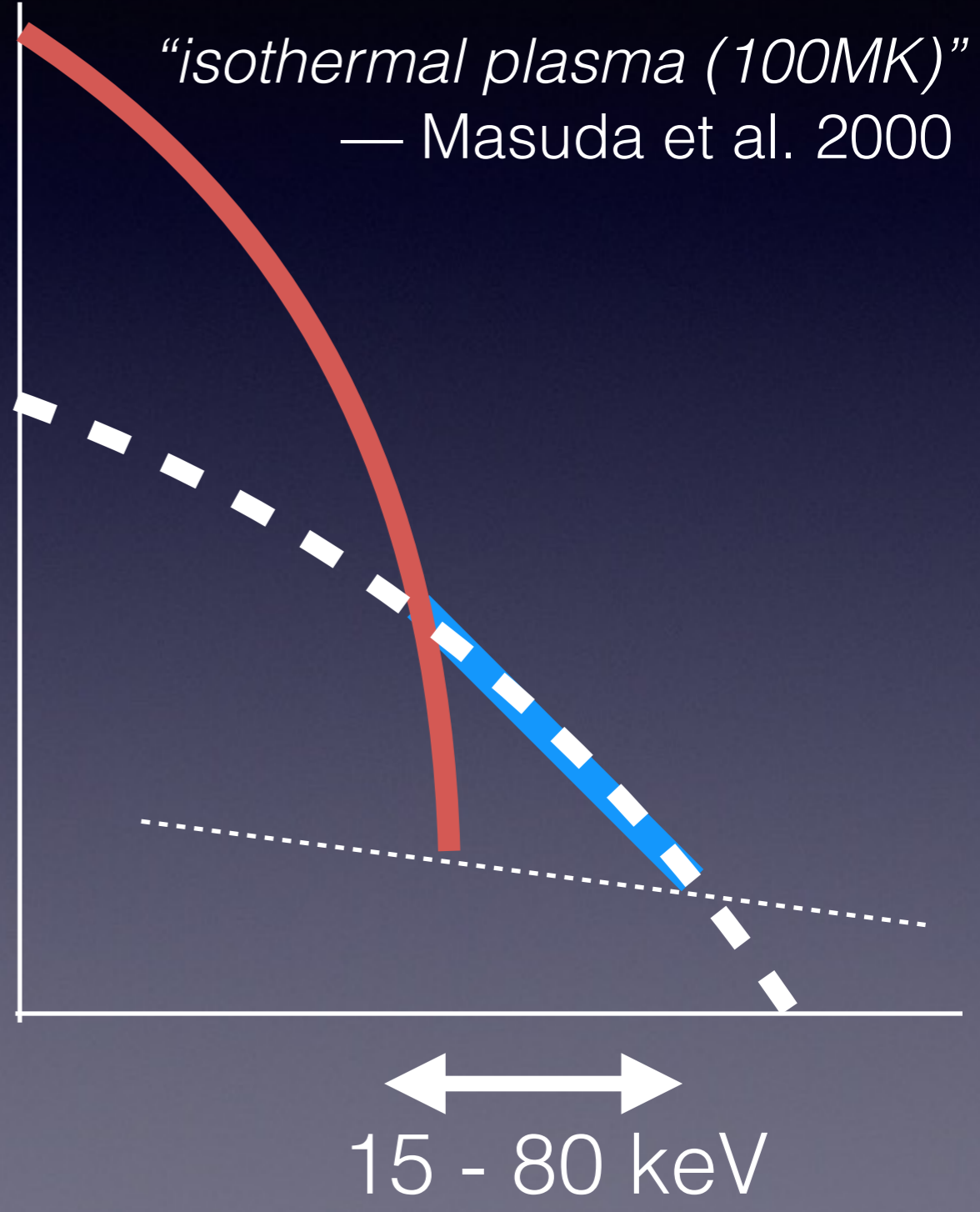
$$R_\varepsilon = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$



above-the-looptop (ALT)
(discovered by Masuda+, 1994)

looptop

Shibata+, 1995

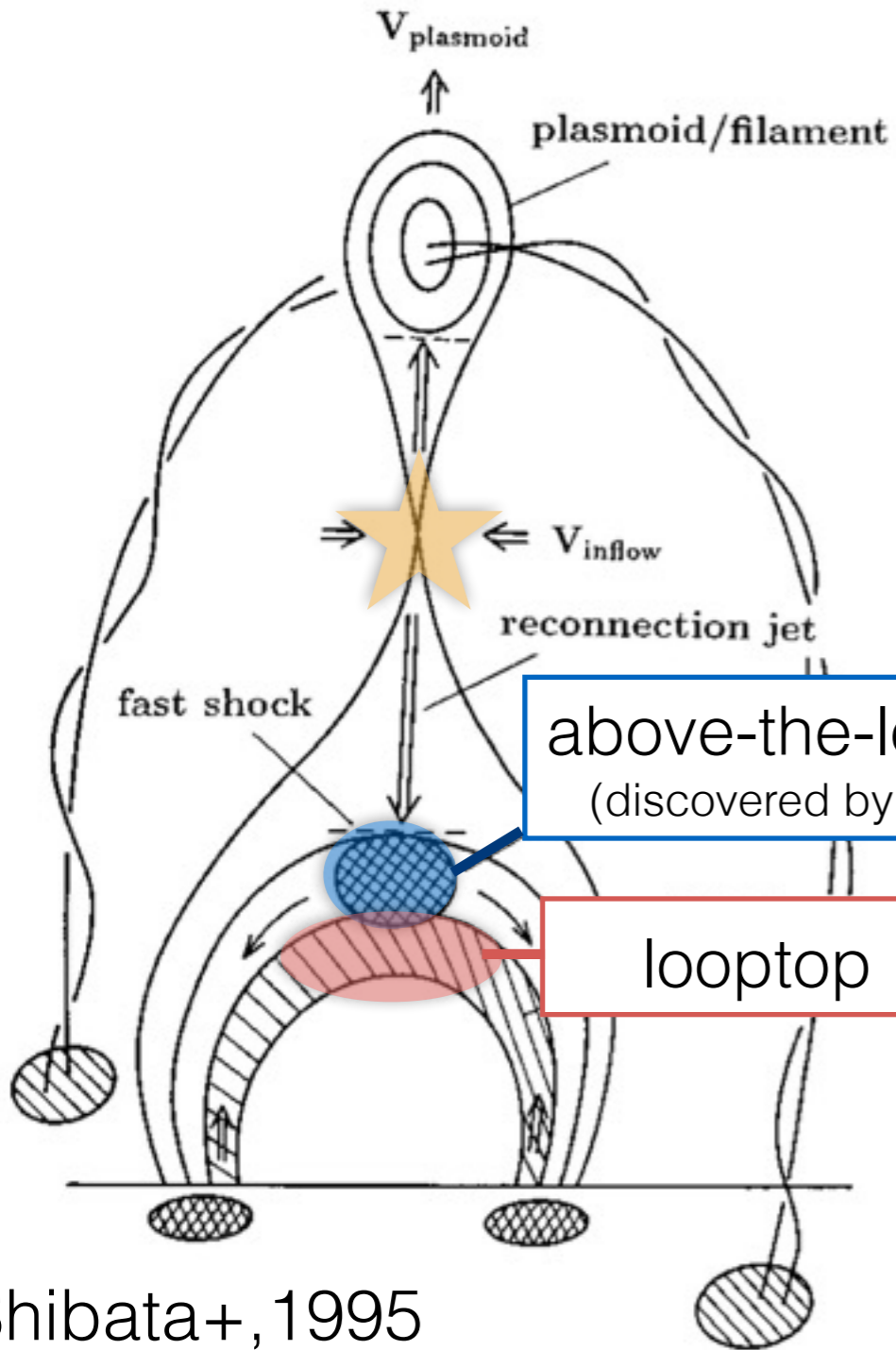


"isothermal plasma (100MK)"
— Masuda et al. 2000

15 - 80 keV

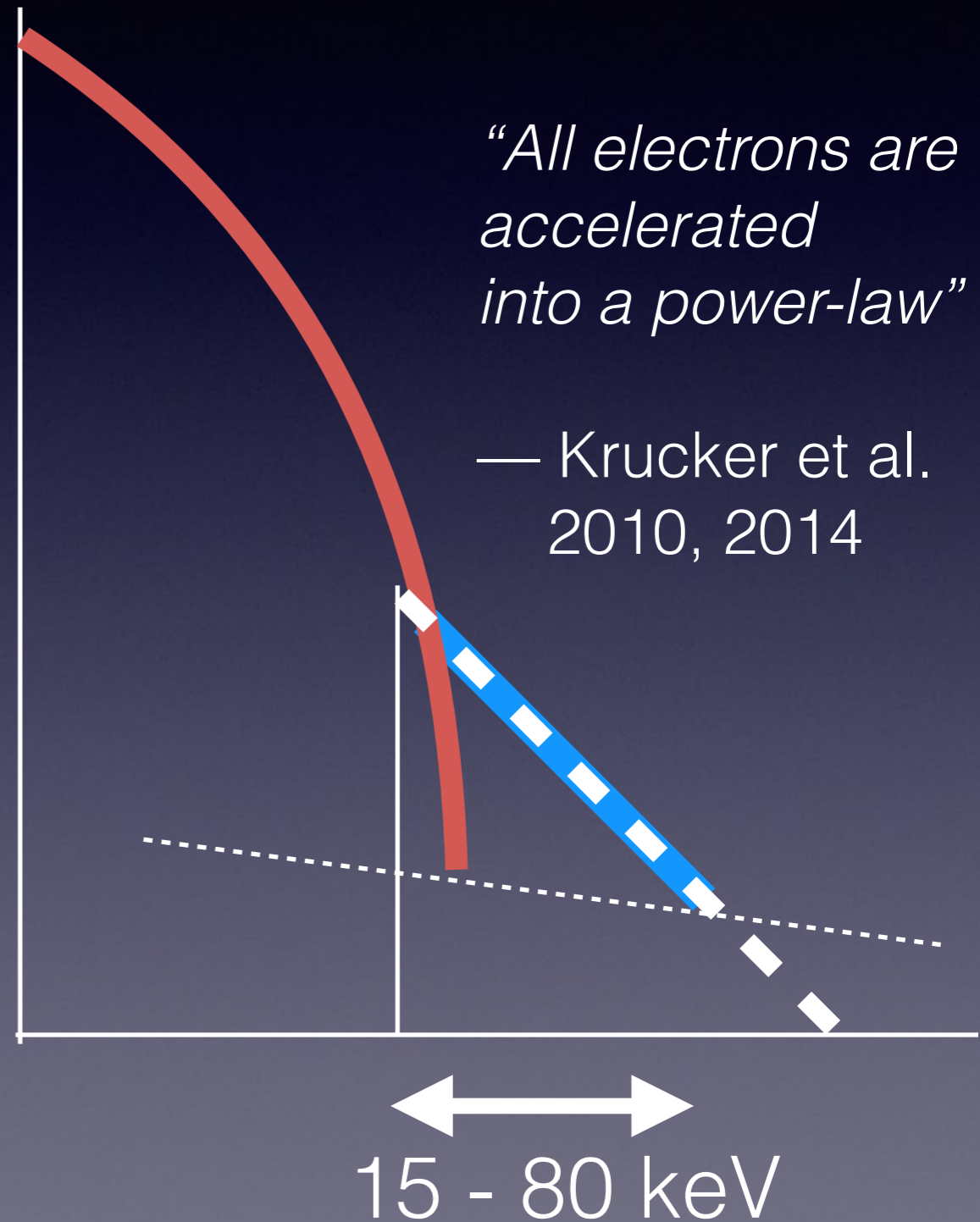
non-thermal fraction of electron **energies**

$$R_{\varepsilon} = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$



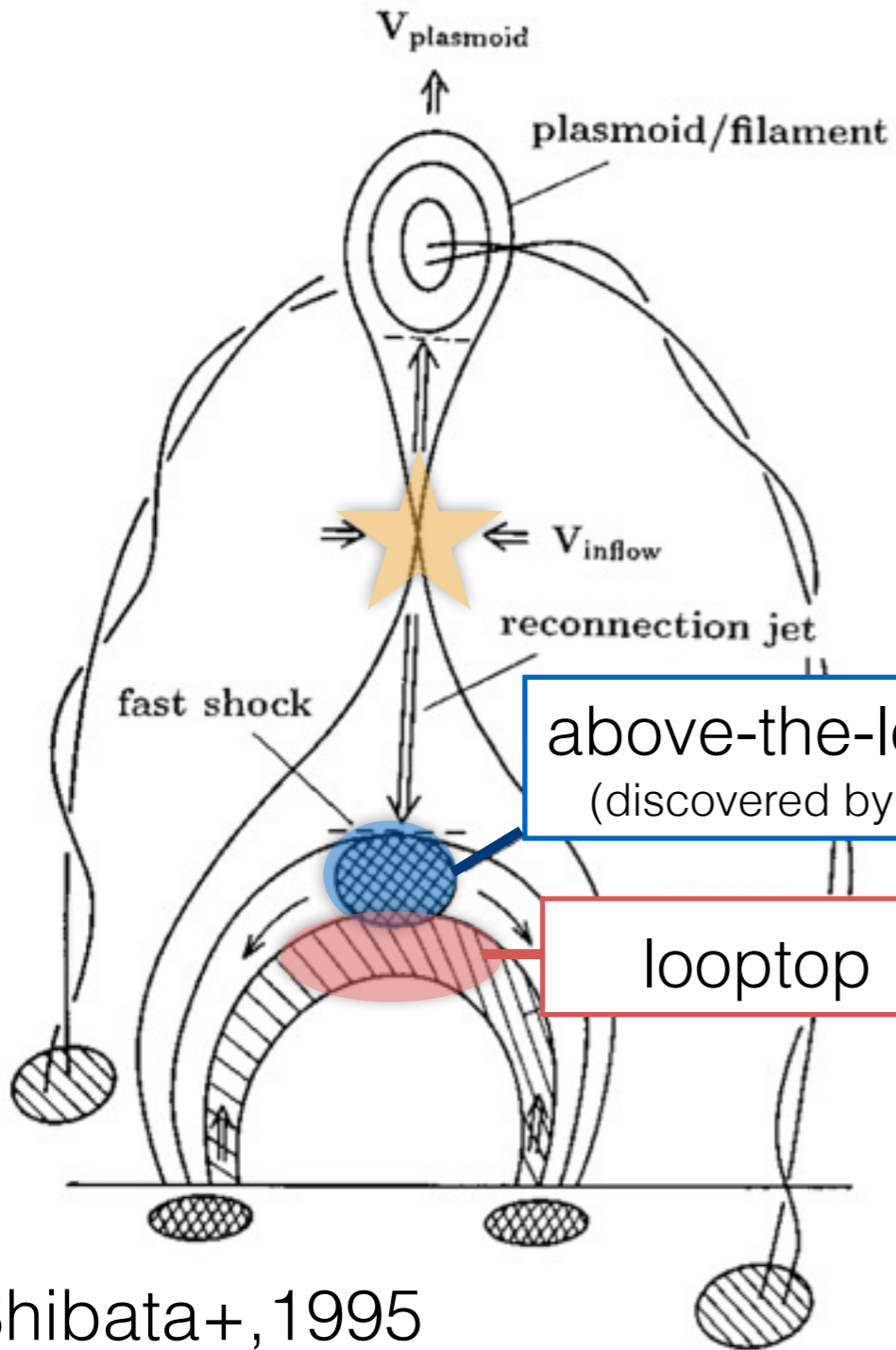
“All electrons are accelerated into a power-law”

— Krucker et al.
2010, 2014



non-thermal fraction of electron **energies**

$$R_\varepsilon = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$



Shibata+, 1995

Iso-thermal model

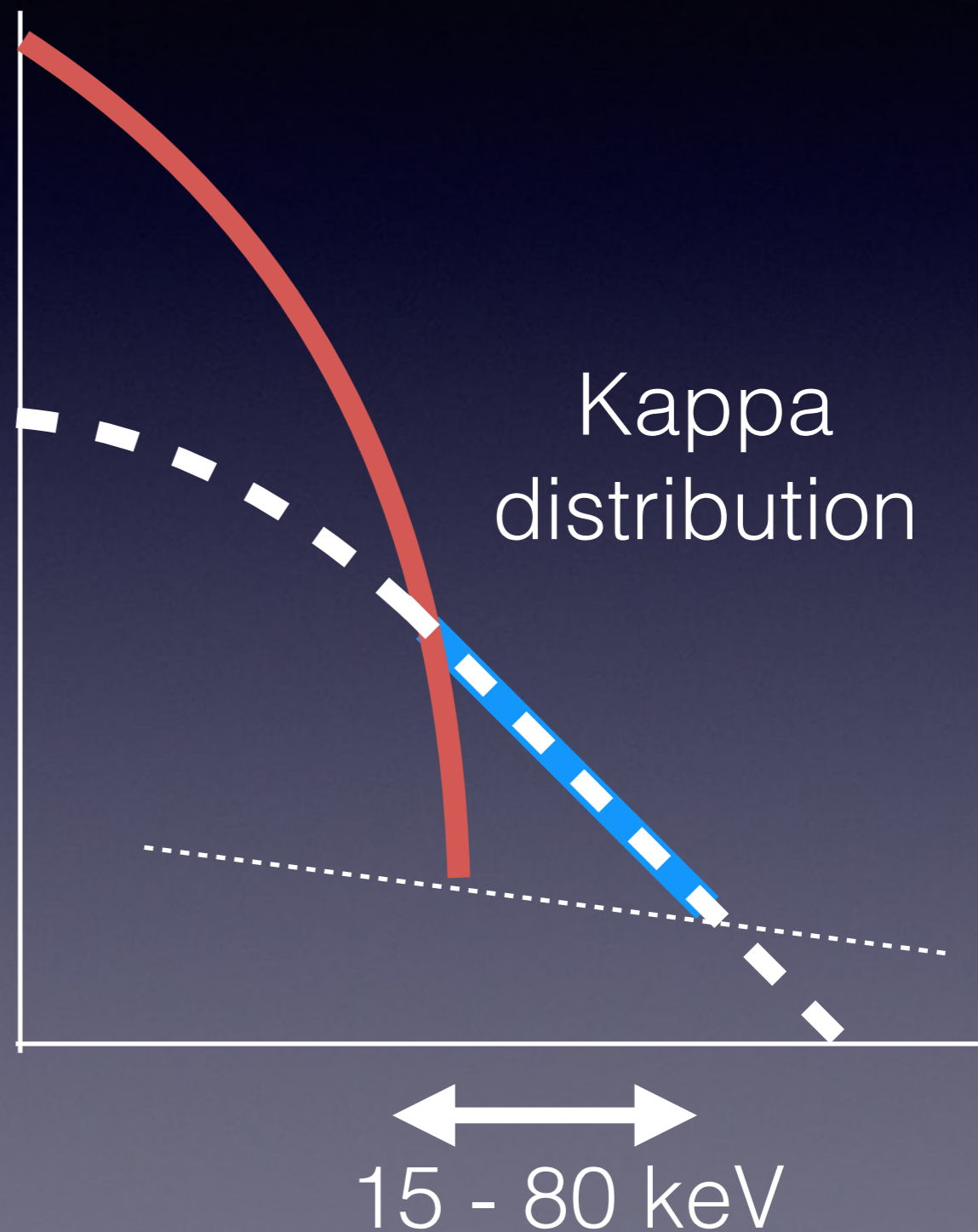
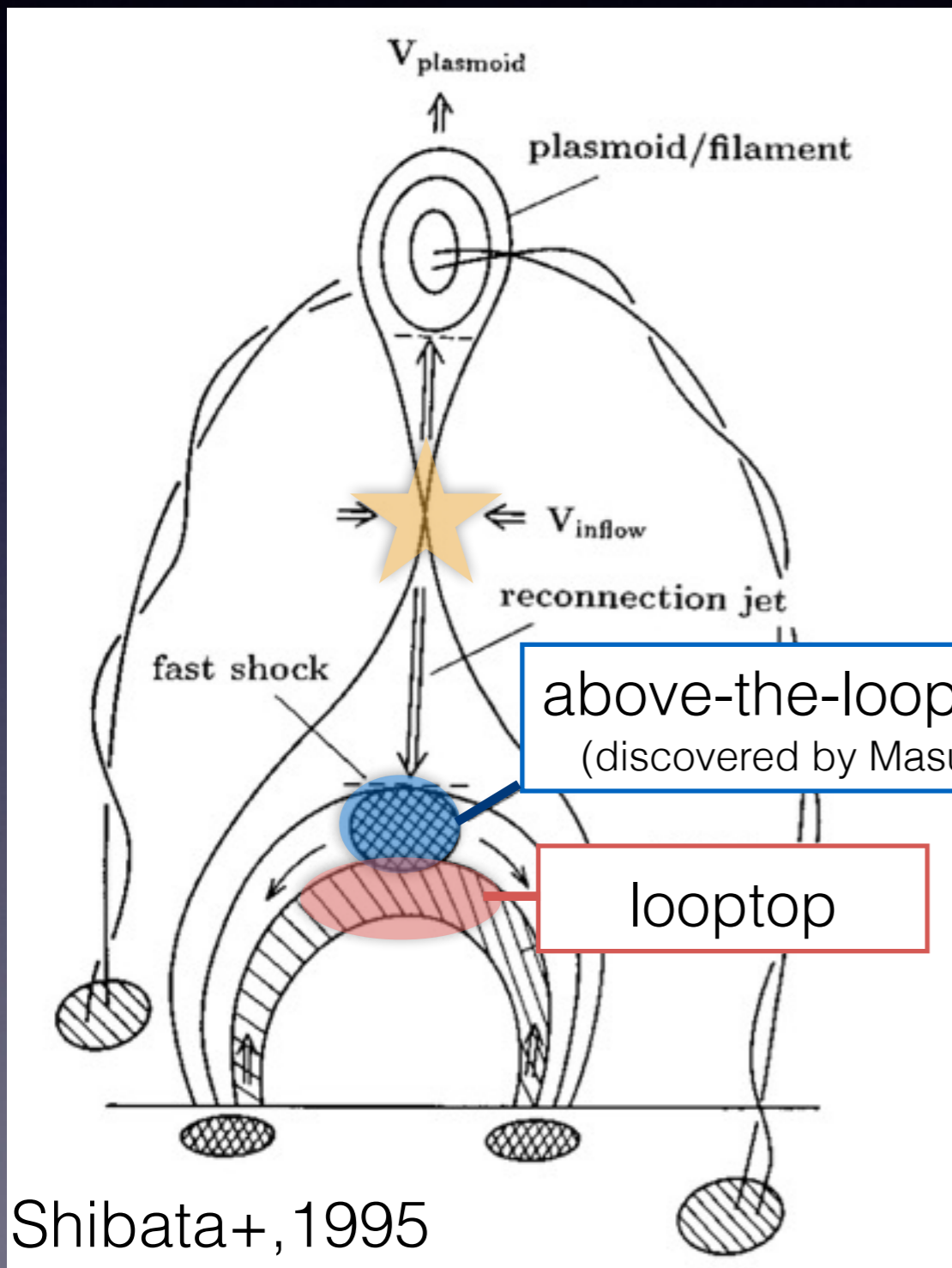
In some cases, there is clearly a non-thermal tail.

power-law

(no particles $< E_c$)

Coulomb collisions and wave particle interaction should fill the 'gap' below E_c .

This talk: $R_\varepsilon \sim 50\%$



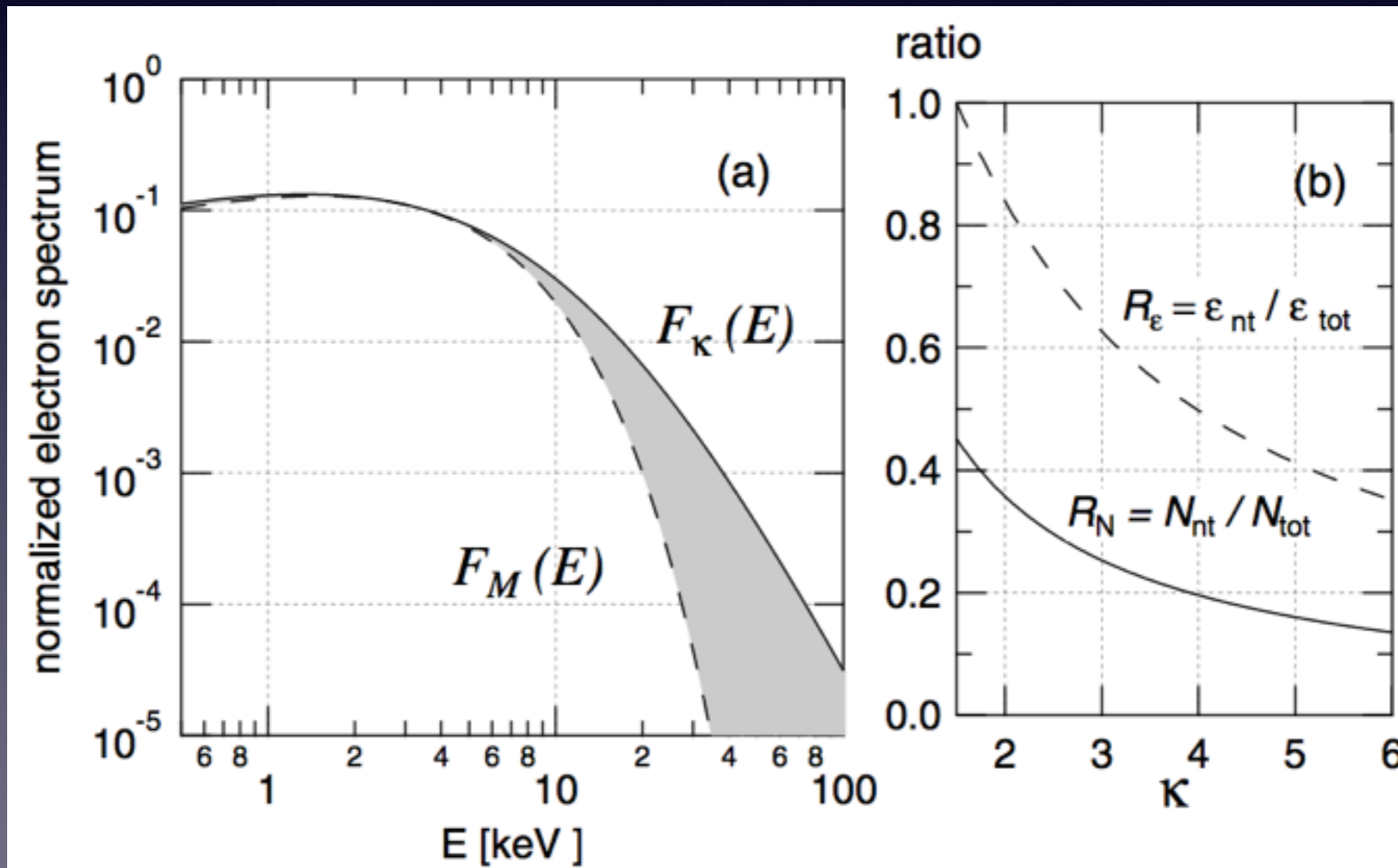
Outline

- **Introduction**
 - Basic Idea of Analysis
 - Kappa distribution
- Analysis
- Discussion
- Conclusion

Kappa distribution

$$f_{\kappa}(v) = \frac{N_{\kappa}}{(\pi\kappa\theta^2)^{3/2}} \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \left(1 + \frac{v^2}{\kappa\theta^2}\right)^{-(\kappa+1)}$$

Olbert 1968



Oka et al. 2013, 2015

Derivation of Kappa distribution

Empirical derivation

- Electrons in the magnetosphere
- Olbert, 1968; Vasyliunas, 1968

Assumed diffusion coefficient

- e.g. Ma and Summers, 1998; Bian et al. 2014

Wave particle interaction

- Yoon et al. 2006

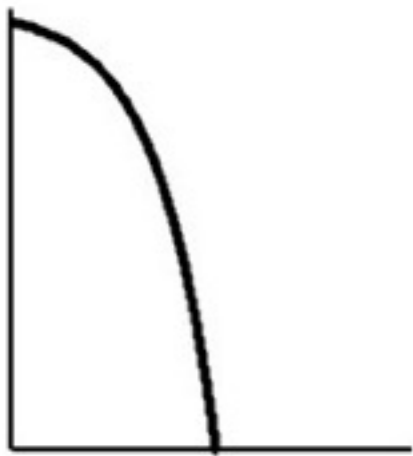
Tsallis statistics

- e.g. Leubner 2004; Livadiotis & McComas 2009

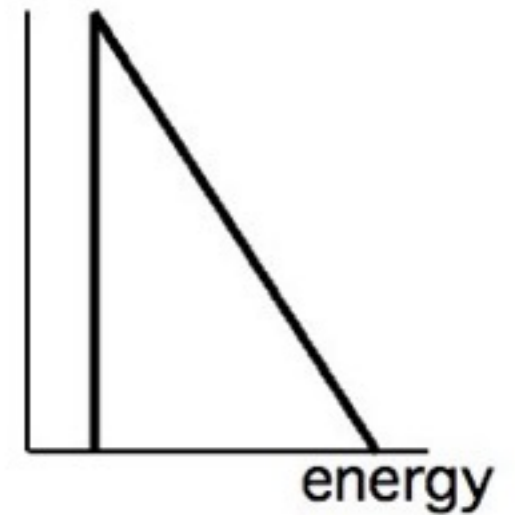
Any intuitive explanation??

Spectral Models

(a) thermal



(e) power-law

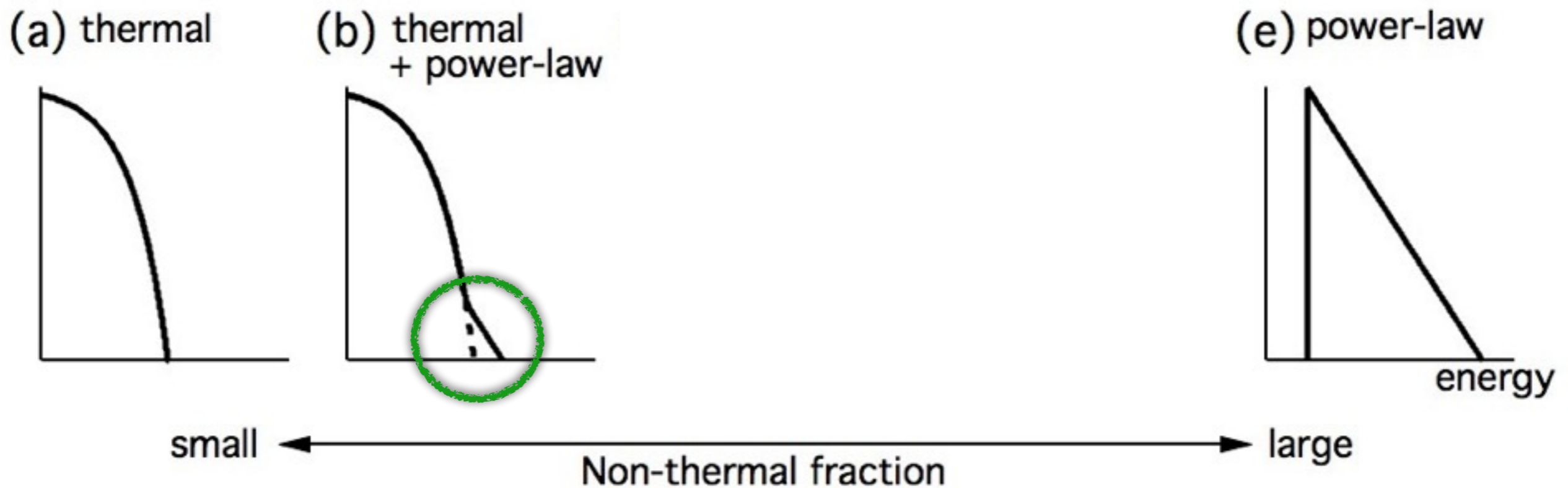


small

Non-thermal fraction

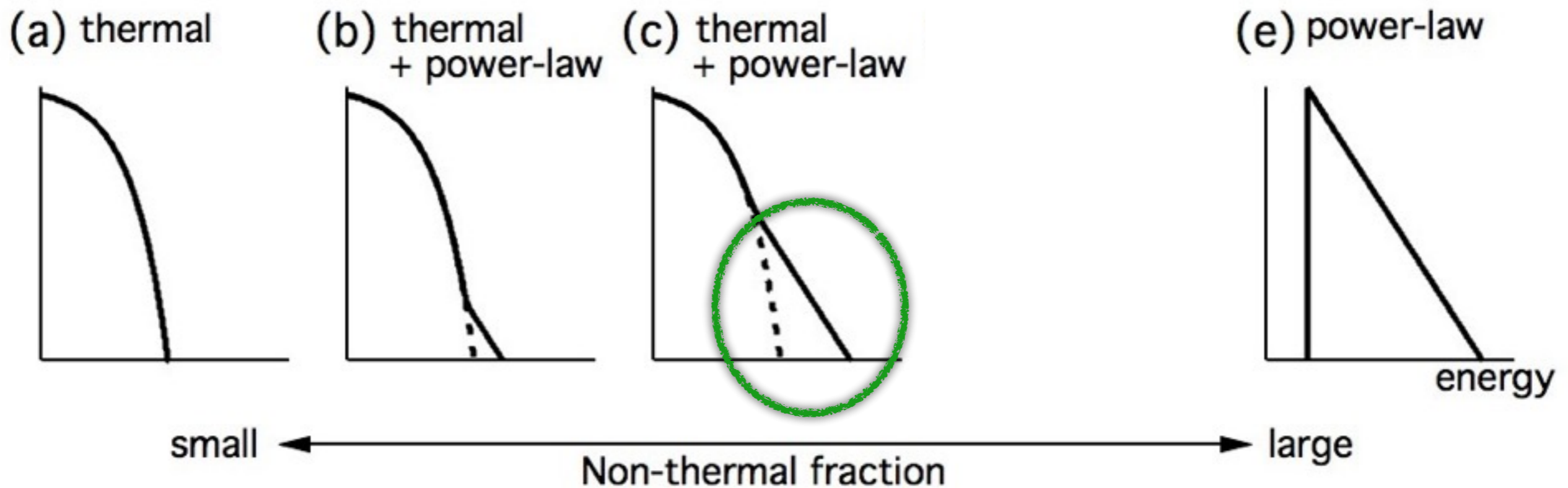
large

Spectral Models



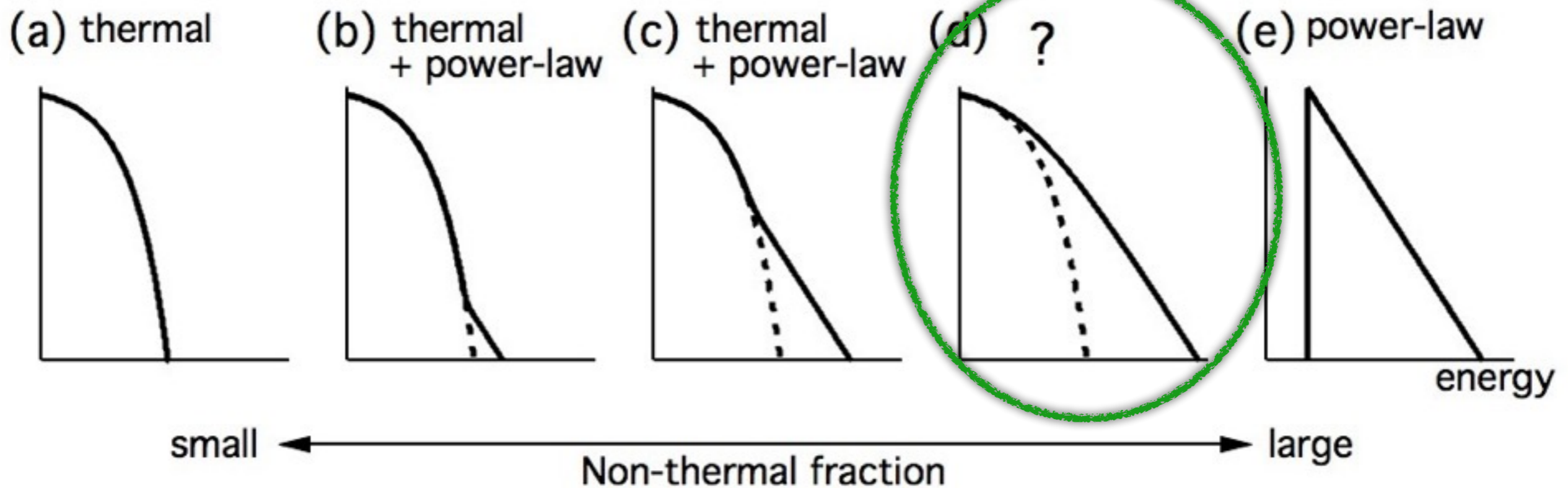
Let's consider a fixed spectral slope
(determined by the acceleration mechanism)

Spectral Models



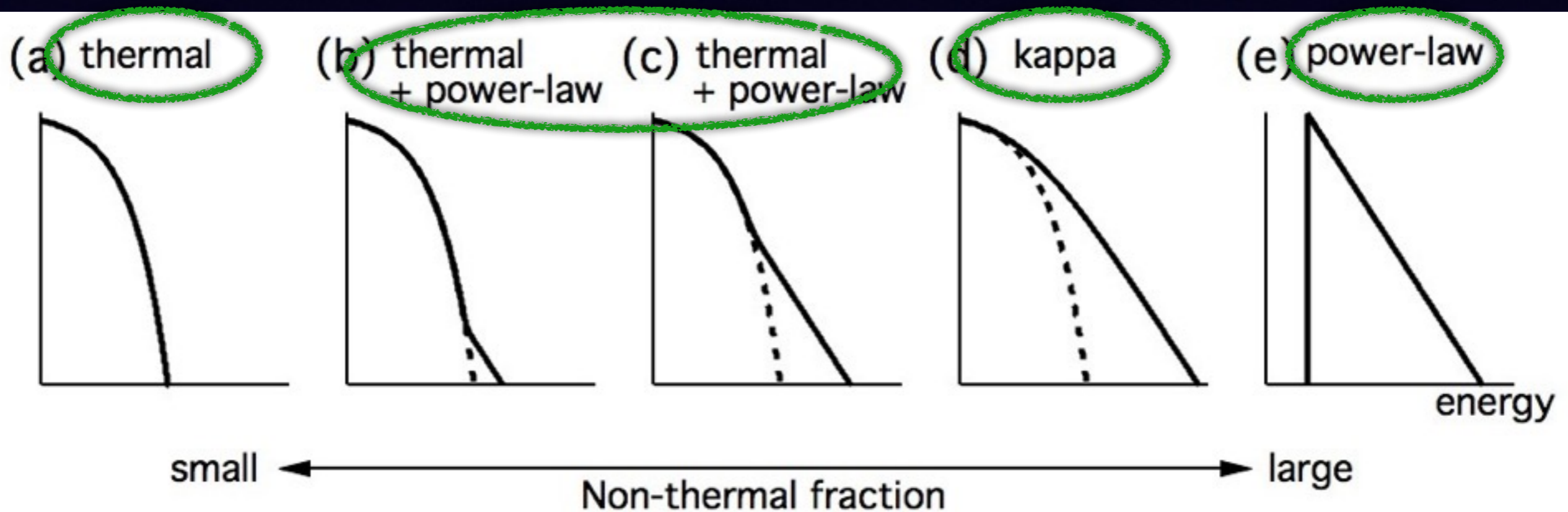
Let's consider a fixed spectral slope
(determined by the acceleration mechanism)

Spectral Models



**A super-hot thermal core plus
'saturated' non-thermal tail !?**

Spectral Models



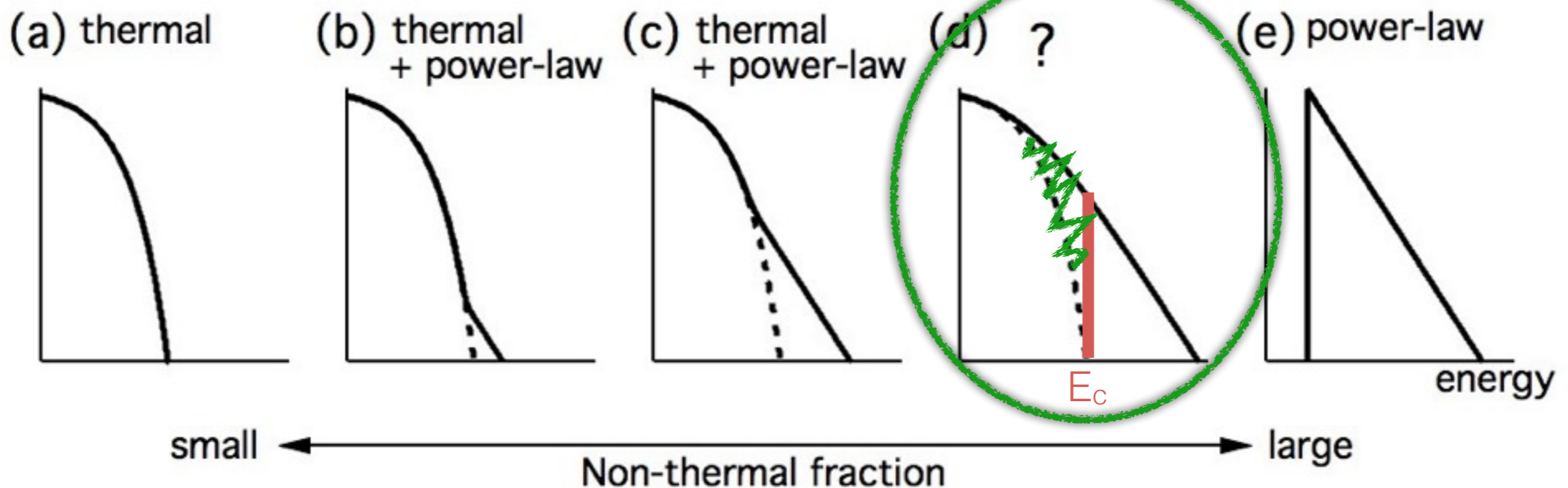
Kappa distribution

Olbert 1968

Kašparová & Karlický, 2009

Spectral Models

Artifact of the lower-energy cutoff E_c !!



‘thermal+power-law’ requires an unusually high temperature to fill the gap between the thermal and power-law components.

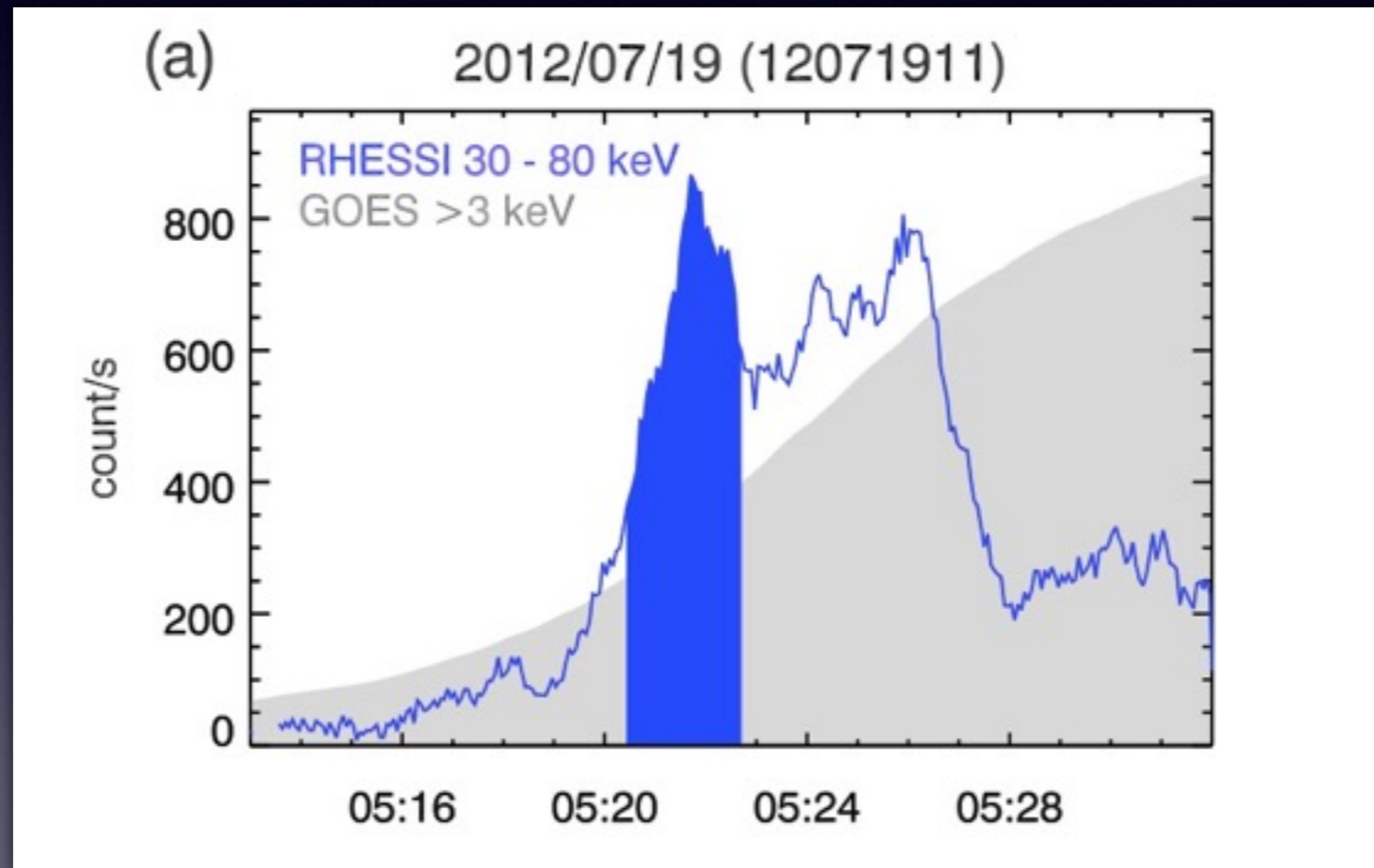
Outline

- Introduction
- **Analysis**
 - RHESSI: imaging spectroscopy
 - SDO/AIA: ~~DEM analysis~~ (important for lower E)
- Discussion
- Conclusion

Note again, conventional models can fit the data well. We're just proposing that 'kappa distribution' can be another interpretation.

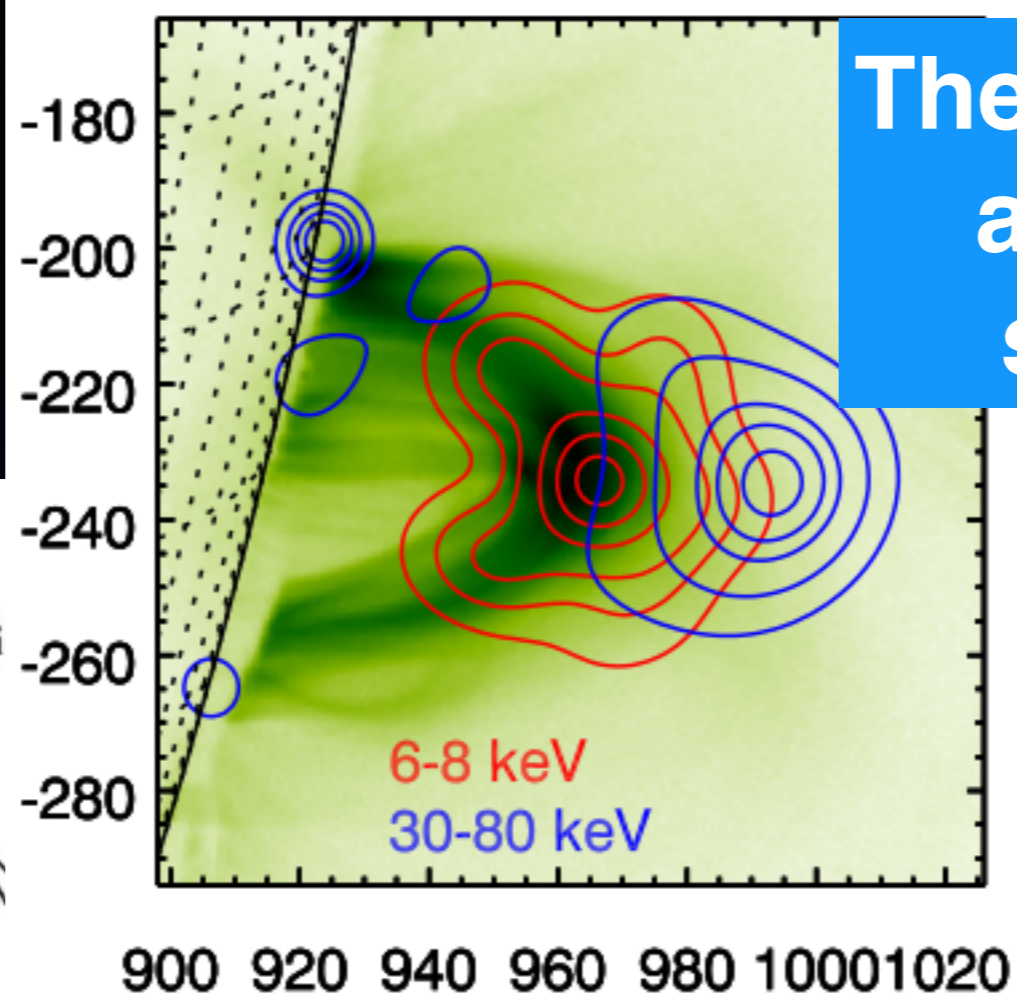
RHESSI

Reuven Ramaty High Energy Solar Spectroscopic Imager



Already analyzed by Krucker+, 2014;
Use the same time period, same data

Background image by SDO AIA 193Å

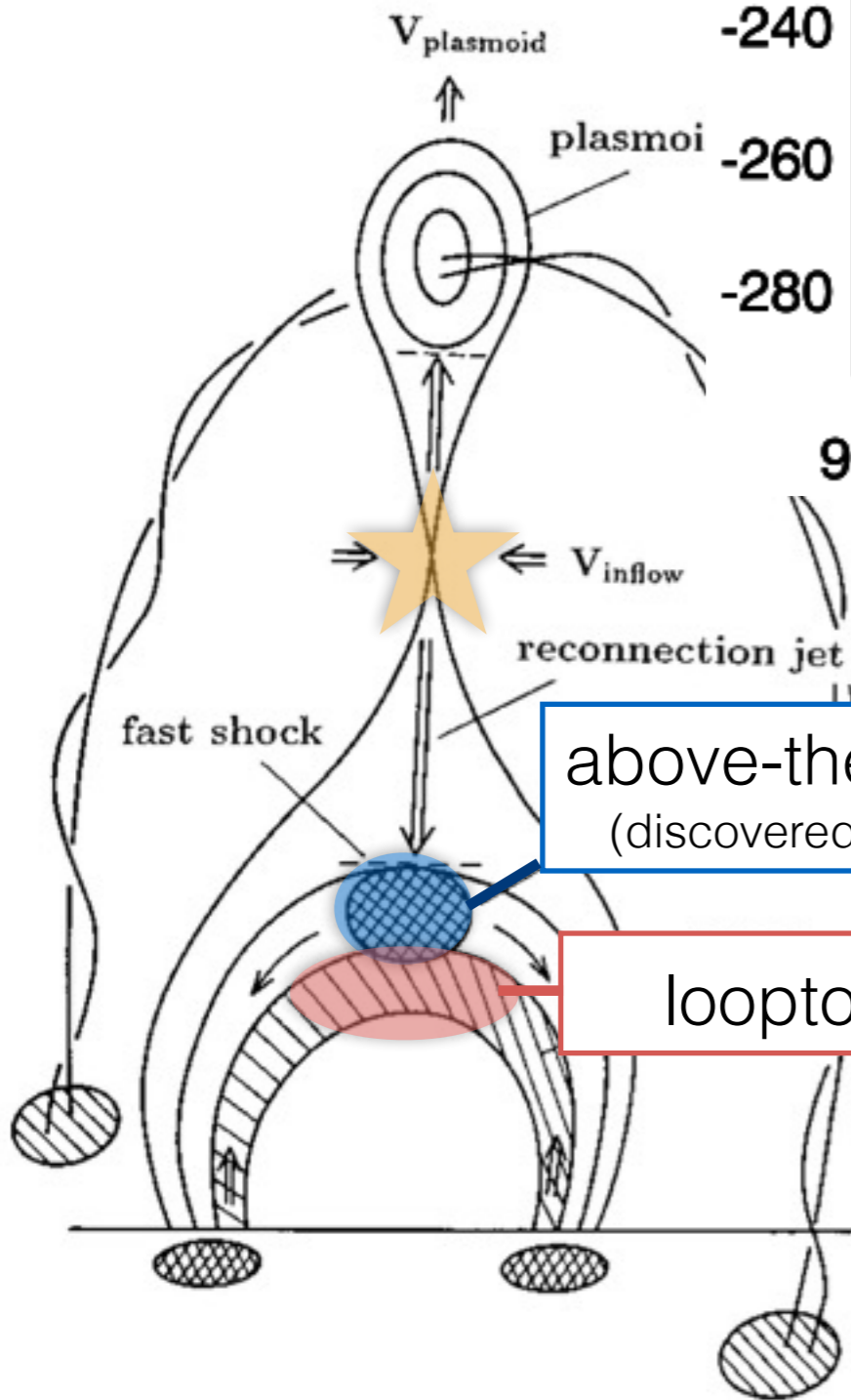


The two sources are not well separated.

Contour levels: 10,20,30,50,70,90%

Coronal sources
size 10-20"
resolution (G3) ~7"

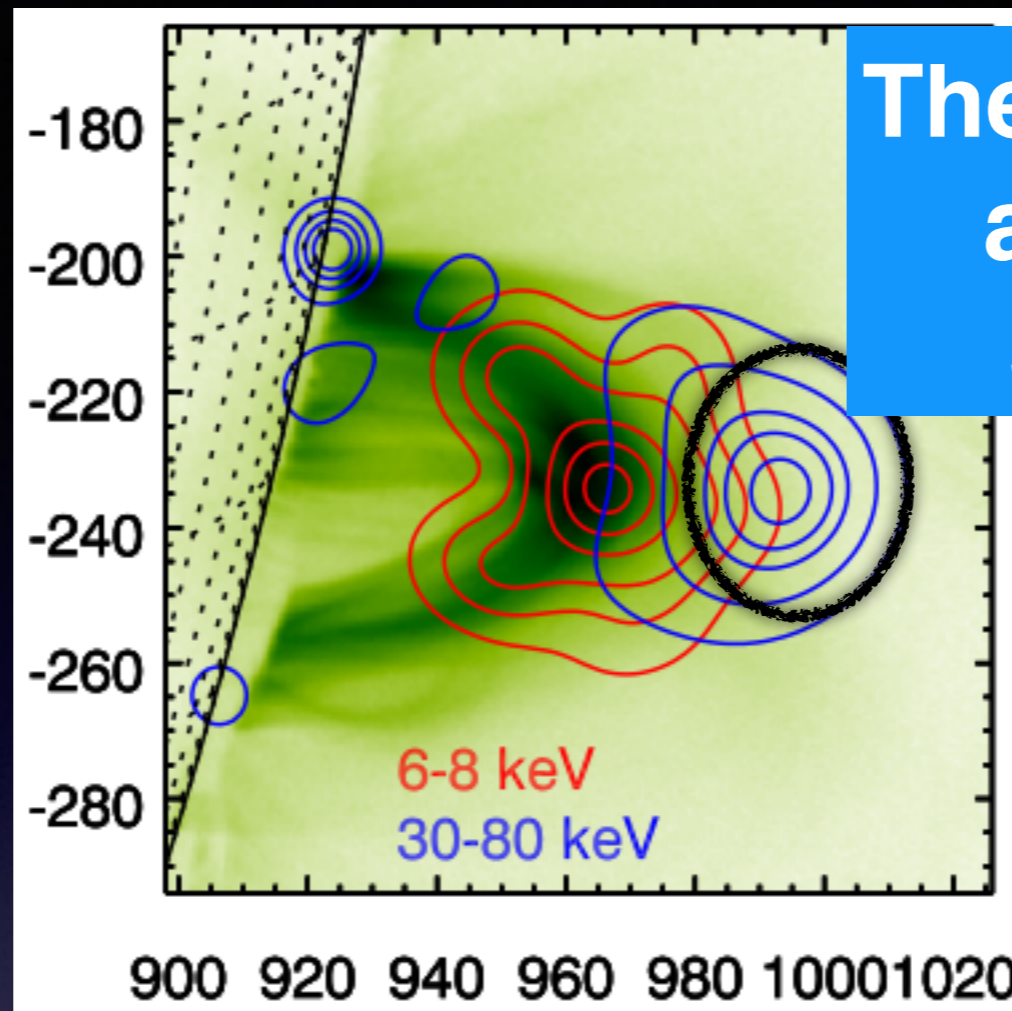
Footpoint sources
size 5-10"
resolution (G1) ~ 2"



above-the-looptop (ALT)
(discovered by Masuda+, 1994)

looptop

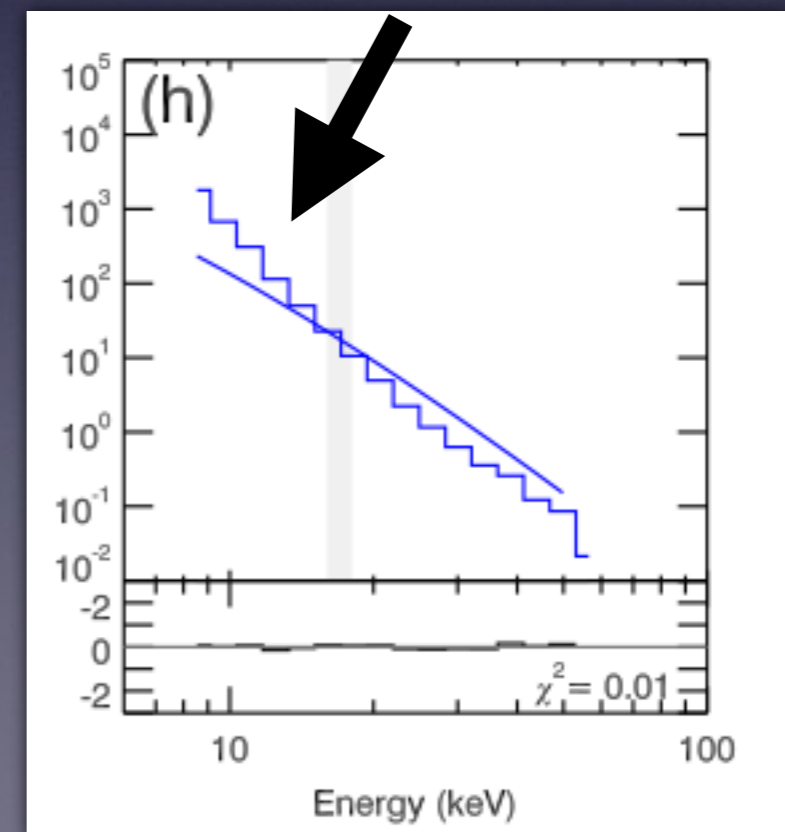
Background
image by
SDO
AIA 193Å



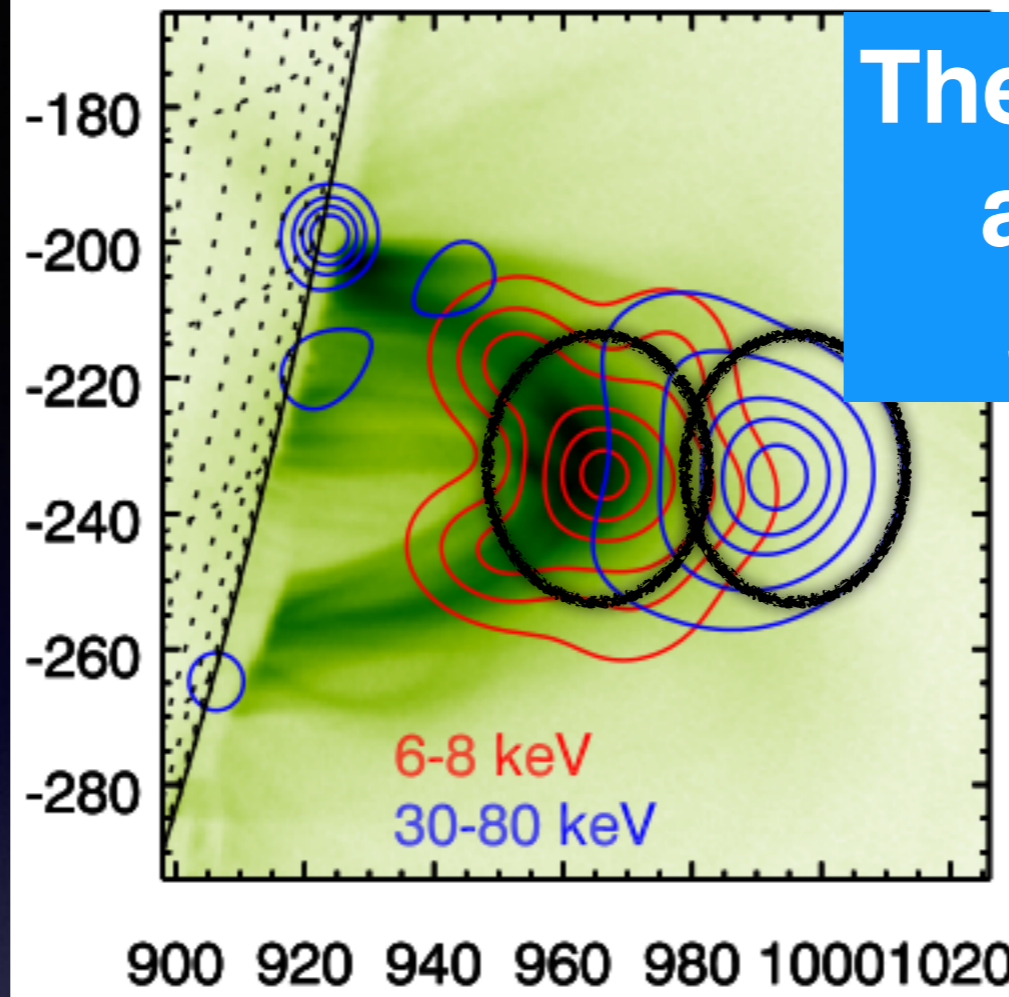
**The two sources
are not well
separated.**

Contour levels:
10,30,50,70,90%

Contamination
from the adjacent source



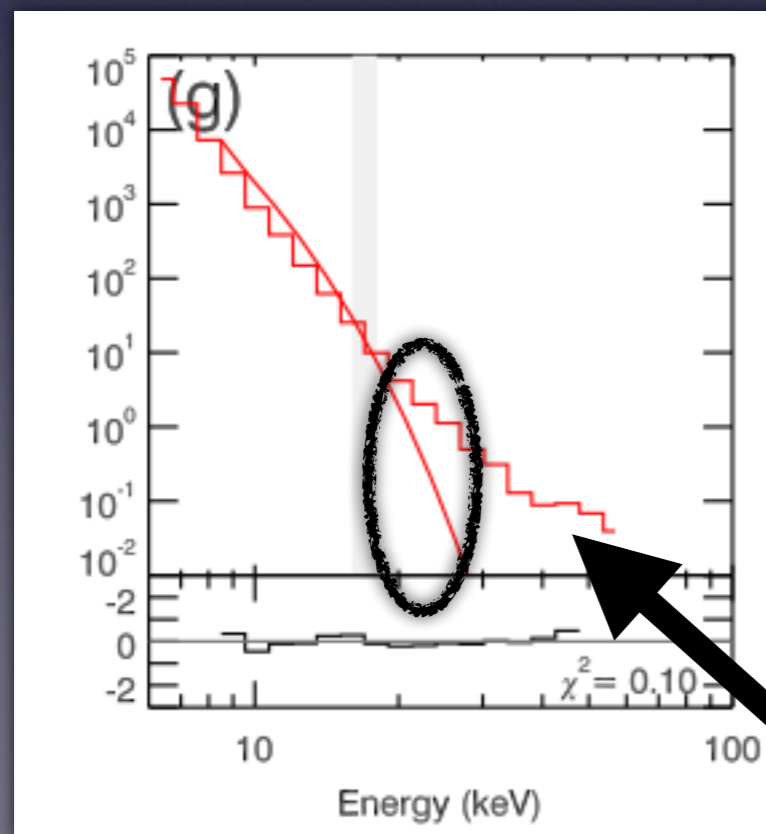
The two sources are not well separated.



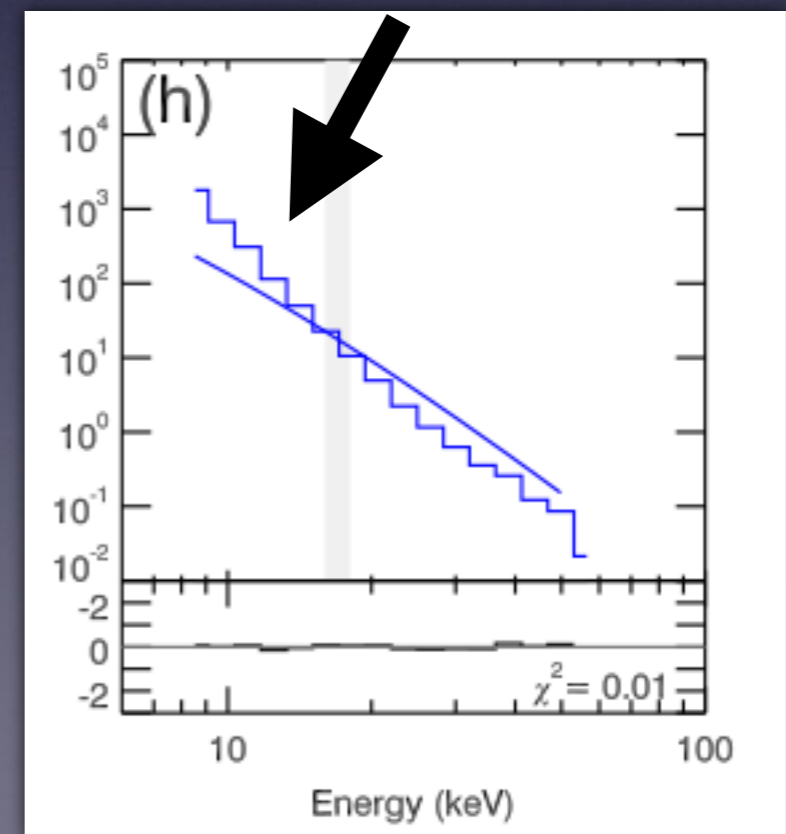
Contour levels:
10,30,50,70,90%

Looptop may also contain non-thermal tail but a κ -distribution fit leads to large κ values.

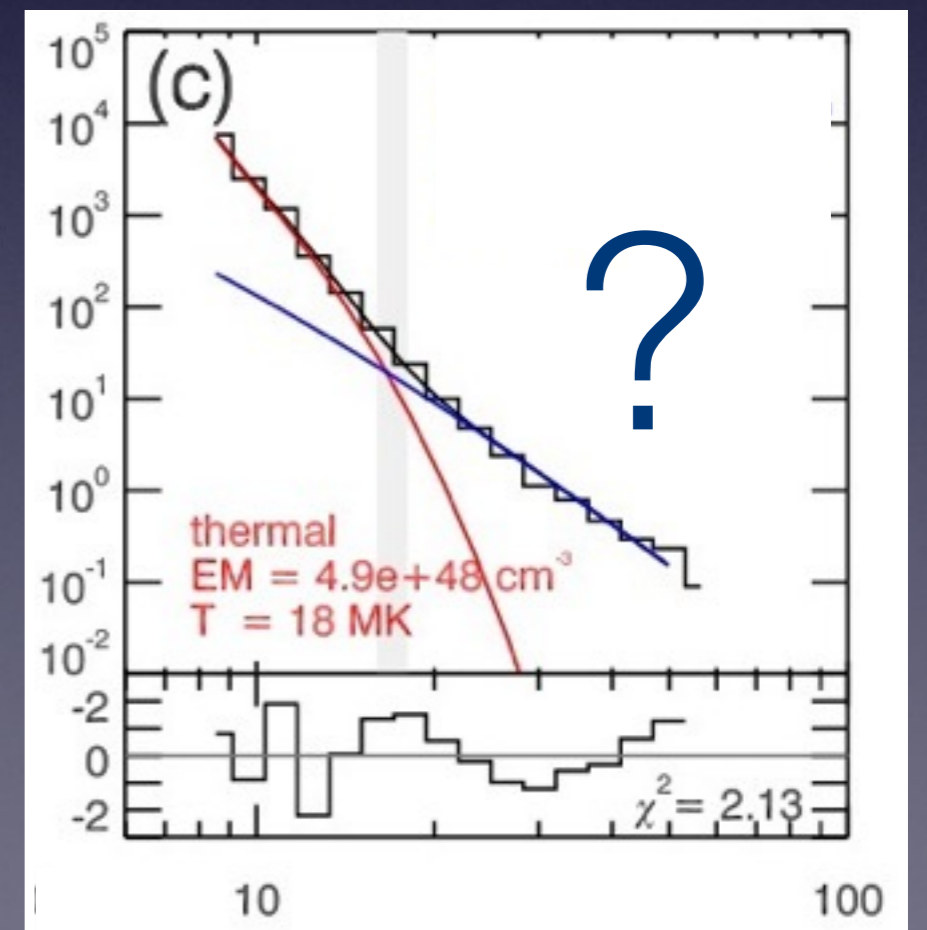
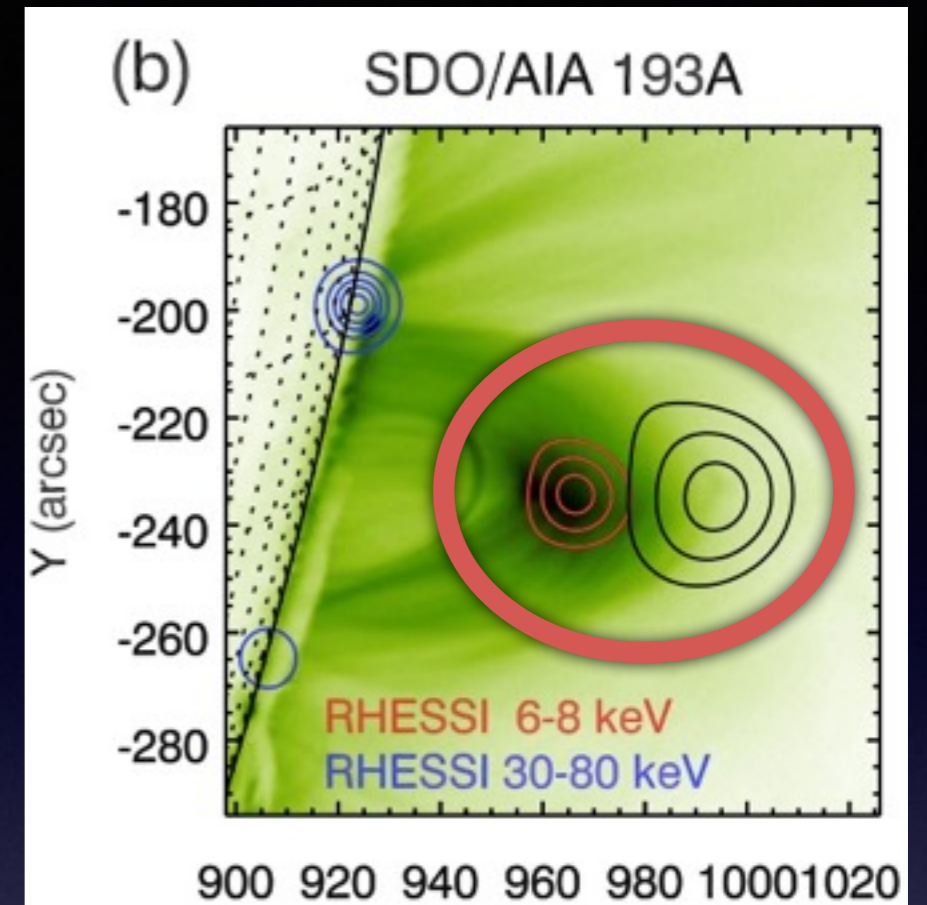
Contamination from the adjacent source



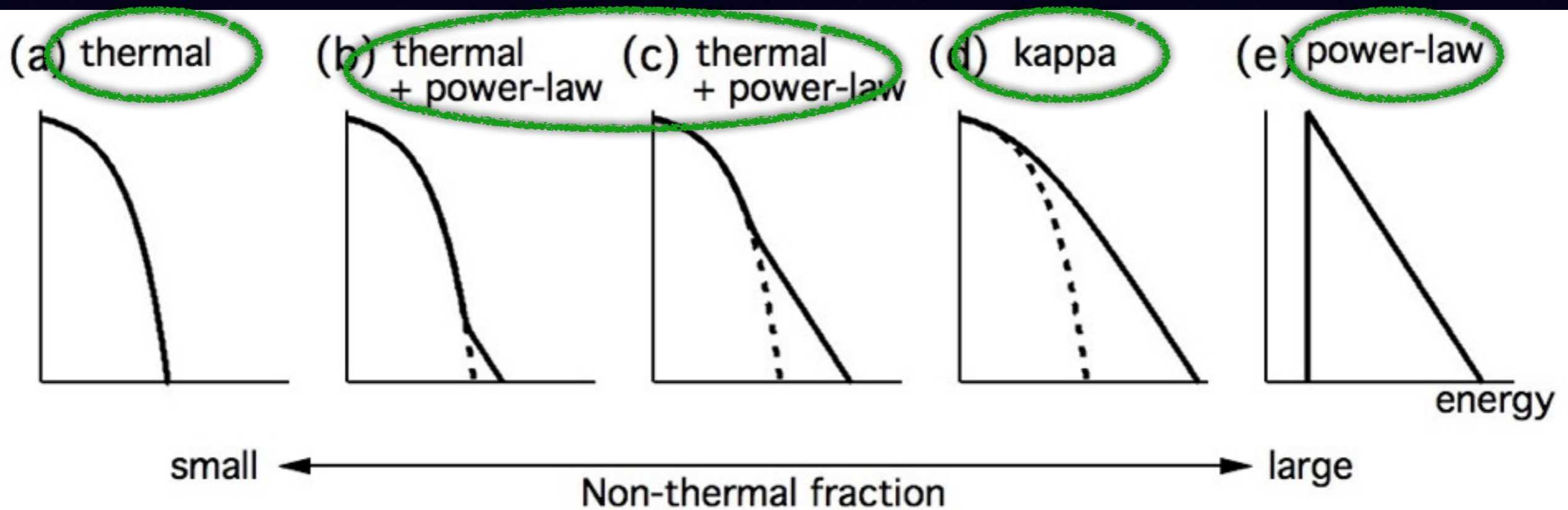
Contamination from ALT



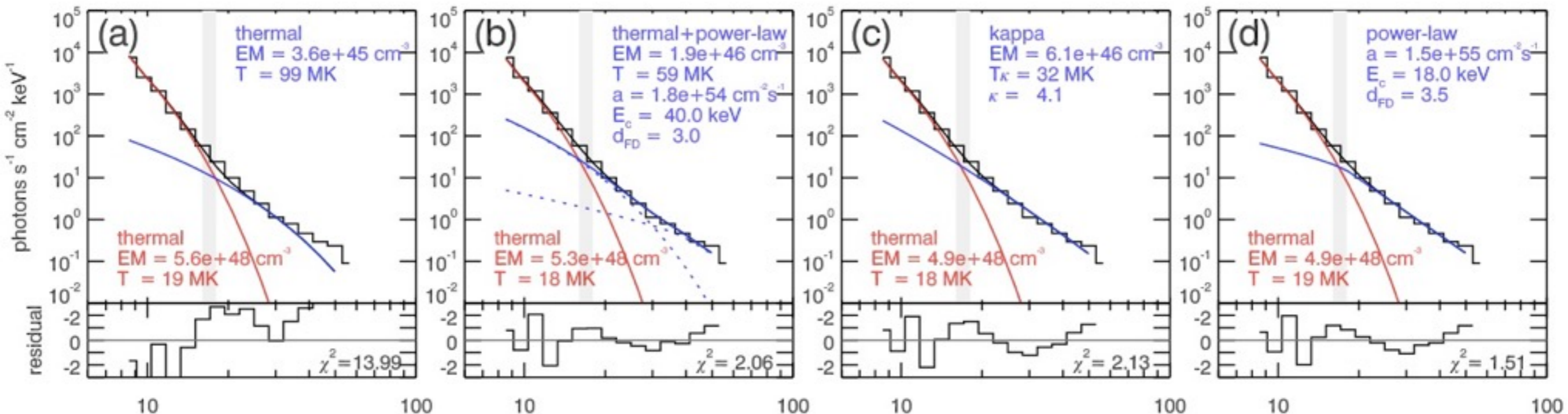
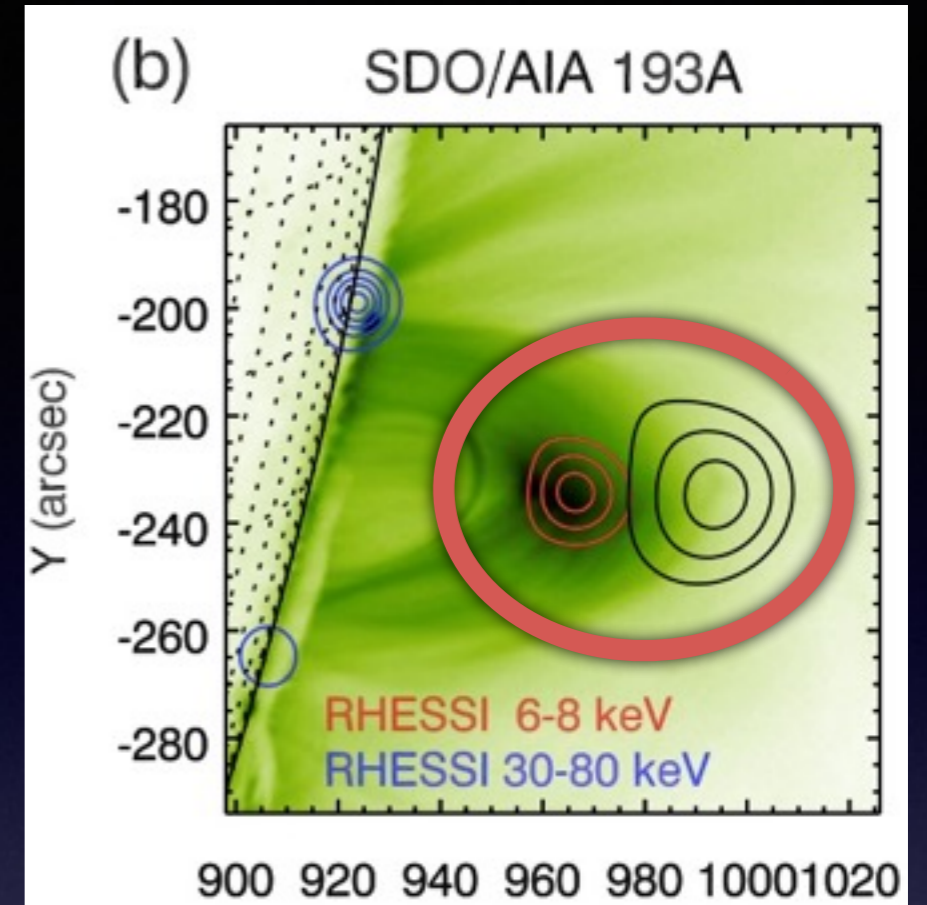
- Combine photons from both sources to generate a spectrum
- Combine two separate spectral models to fit the data
 - Use Maxwellian for looptop
 - Use different models for ALT
 - Ignoring fine structures in each source
- One model for each pixel?
 - too many free parameters



Spectral Models



- Combine photons from both sources to generate a spectrum
- Combine two separate spectral models to fit the data
 - Use Maxwellian for looptop
 - Use different models for ALT
 - Ignoring fine structures in each source



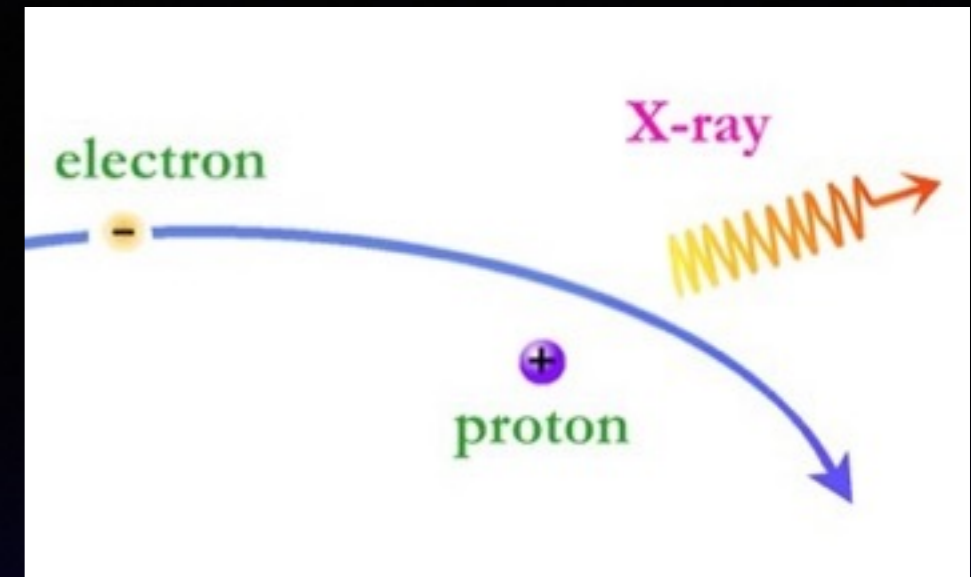
$R_\varepsilon \sim 0\%$

$R_\varepsilon \sim 1\%$

$R_\varepsilon \sim 50\%$

$R_\varepsilon \sim 100\%$

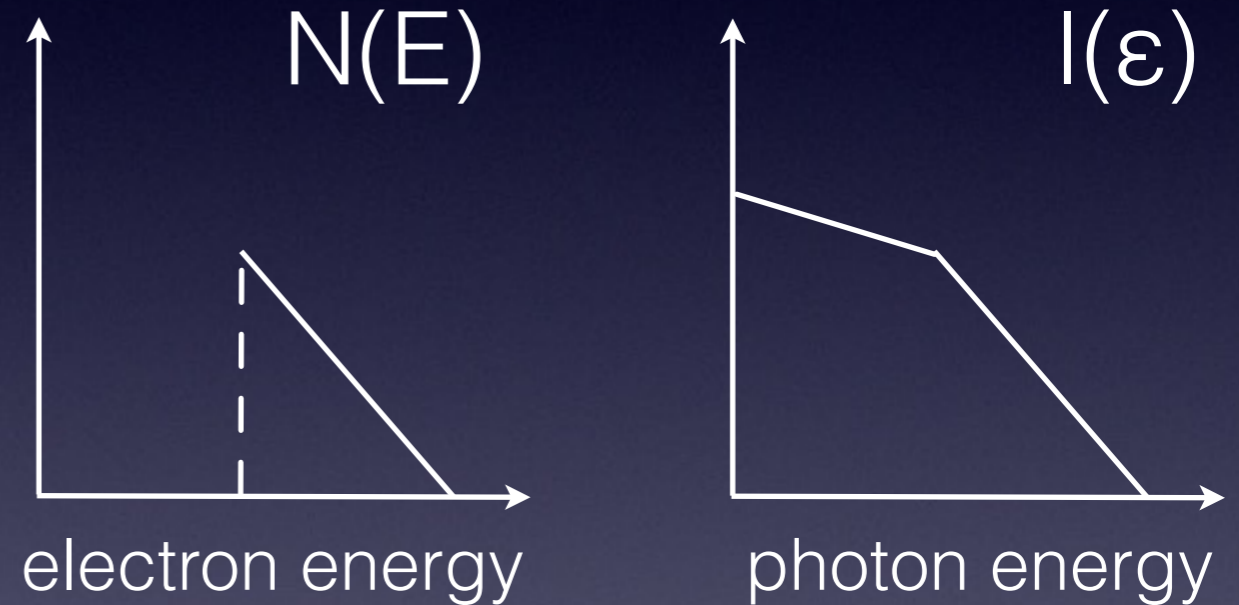
Bremsstrahlung



<http://www.astro.wisc.edu/~bank/>

The high energy electron gradually loses its energy.

Accordingly, the energy of emitted photon decreases.



Bethe-Heitler cross section

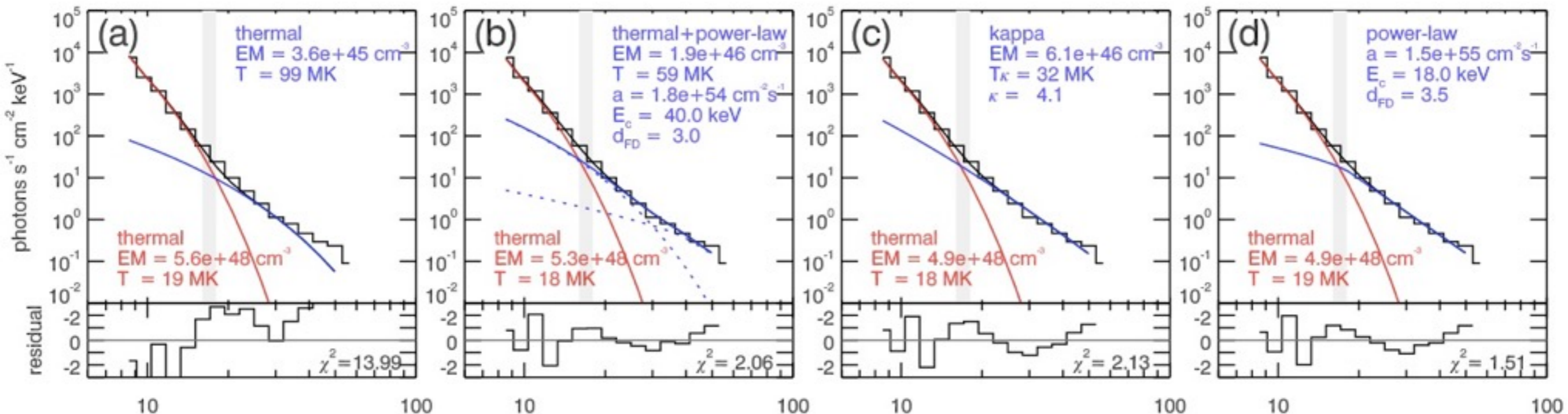
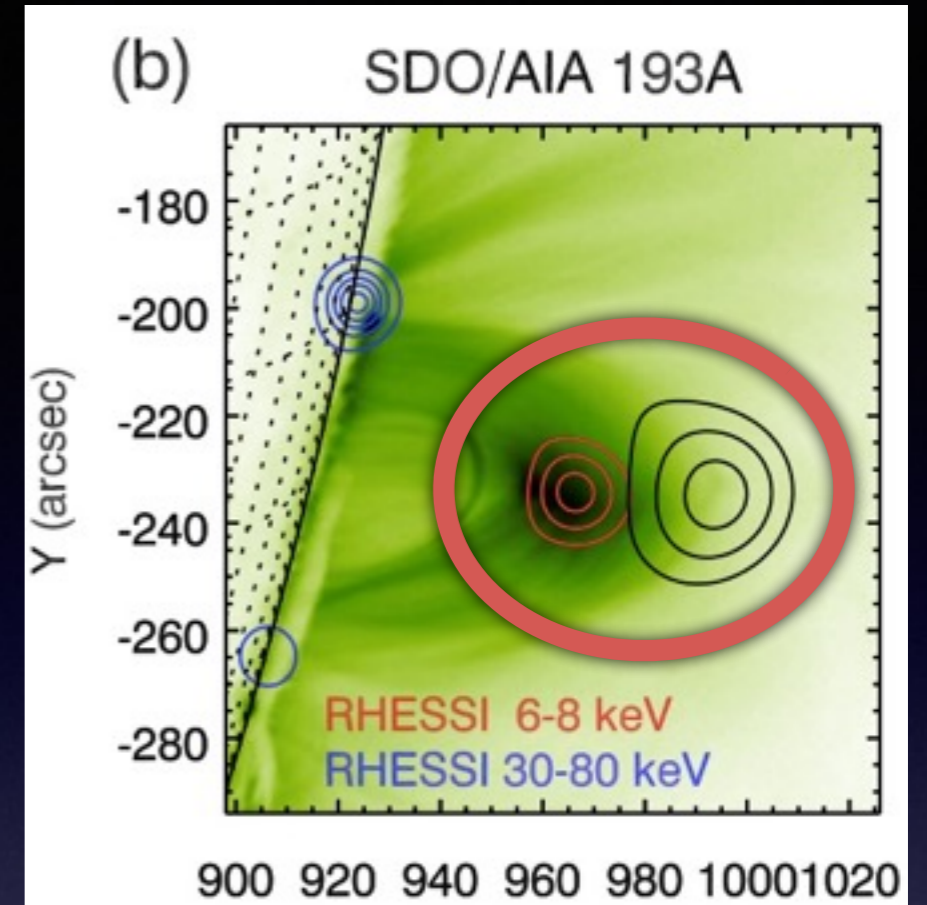
Required for an electron (E)
to emit a photon (ϵ)

$$Q_{\epsilon}(E) = \frac{8}{3} \frac{r_0^2}{137} \frac{mc^2}{\epsilon E} \log \frac{1 + \sqrt{1 - \epsilon/E}}{1 - \sqrt{1 - \epsilon/E}}$$

The total X-ray emission $I(\epsilon)$

$$\int_{\epsilon}^{\infty} Q_{\epsilon}(E) v(E) \left(\int_V n_p n(E) dV \right) dE \quad (\text{photons/sec per unit } \epsilon)$$

- Combine photons from both sources to generate a spectrum
- Combine two separate spectral models to fit the data
 - Use Maxwellian for looptop
 - Use different models for ALT
 - Ignoring fine structures in each source



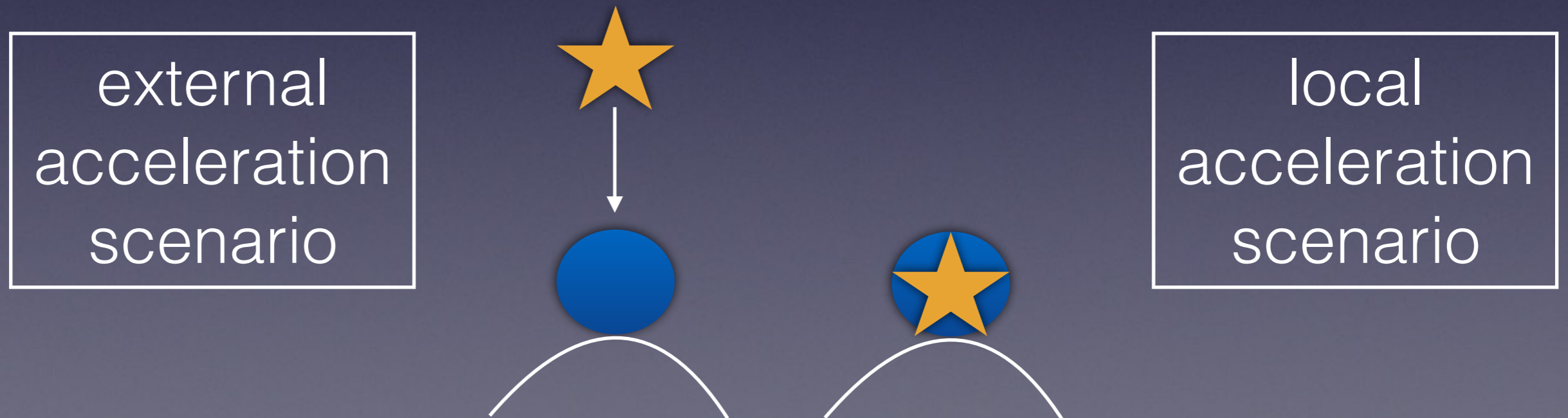
$R_\varepsilon \sim 0\%$

$R_\varepsilon \sim 1\%$

$R_\varepsilon \sim 50\%$

$R_\varepsilon \sim 100\%$

- Technically, all 3 non-thermal models can fit the data.
- Physically, we think the kappa model is better.
 - **thermal+power-law** the artificial effect of E_c remains — systematically larger T_e , smaller N_e
 - **power-law (with no core)**.... pre-existing plasmas? Thermalization (by Coulomb collisions and waves $\tau_{\text{RHESI}} \sim 4\text{s} \sim 10^6\omega_{pe}^{-1}, 10^6\Omega_{ce}^{-1}$)?



Outline

- Introduction
- Analysis
- **Discussion of flare scenario**
 - Energy Partition
 - Energization Mechanism
 - Collisionality
- Conclusion

Assuming that the kappa distribution is a better model.

5 ALT events

$$R_{\varepsilon} = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$

- 2007 Dec 31 — $\kappa \sim 3.8$, $R_{\varepsilon} \sim 51\%$
 - 2012 Jul 19 — $\kappa \sim 4.1$, $R_{\varepsilon} \sim 49\%$
 - 2003 Oct 22 — $\kappa \sim 5.8$, $R_{\varepsilon} \sim 36\%$
 - 2003 Nov 18 — $\kappa \sim 8$, $R_{\varepsilon} \sim 27\%$
 - 2013 May 13 — $\kappa \sim 14$, $R_{\varepsilon} \sim 16\%$
- Upper-limit at $R_{\varepsilon} \sim 50\%$, meaning **equipartition** of energies (!?)
 - We need a larger number of events to establish this idea of upper-limit.

5 ALT events

$$R_{\varepsilon} = \frac{\varepsilon_{nt}}{\varepsilon_{total}}$$

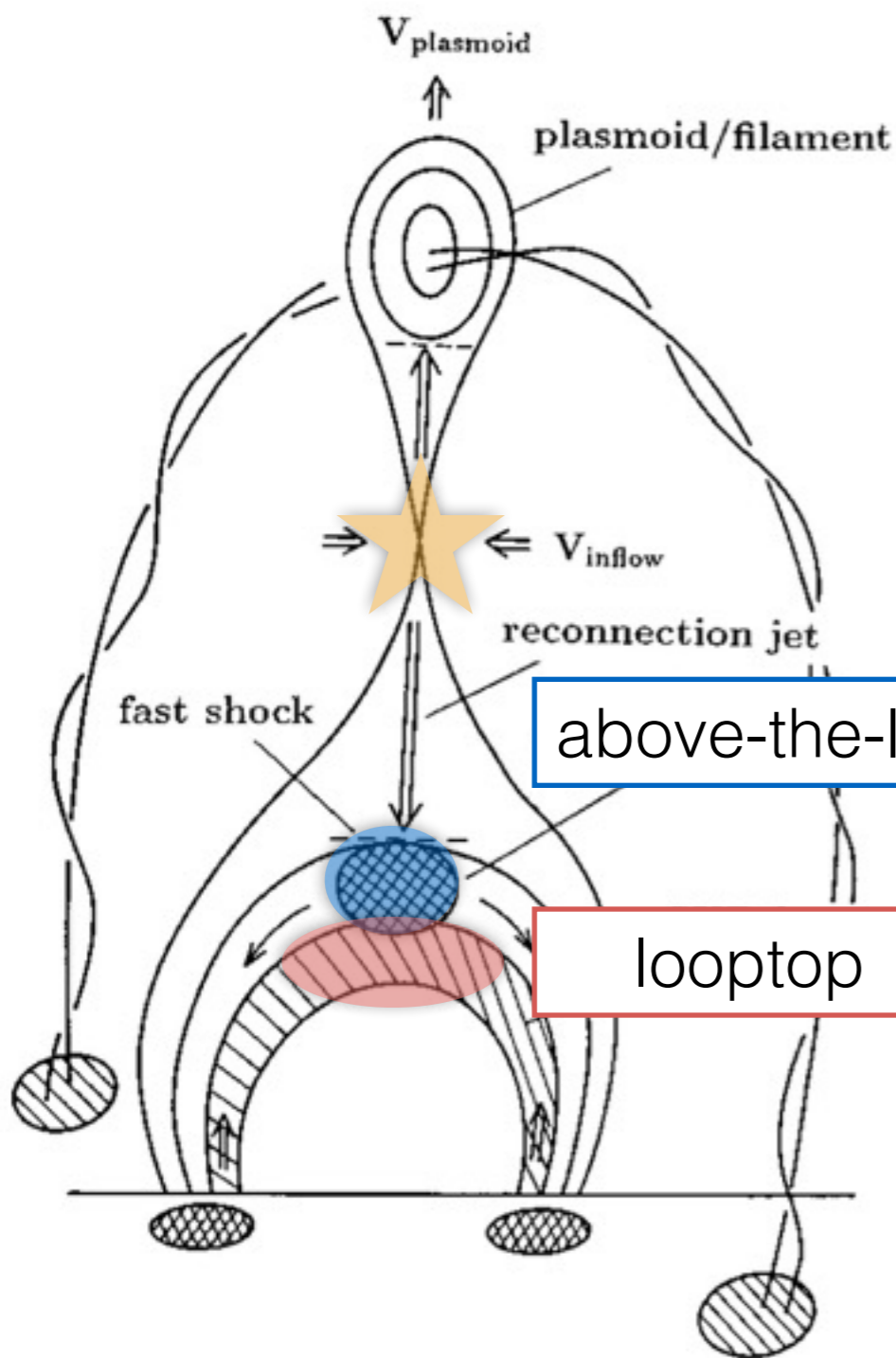
- 2007 Dec 31 — $\kappa \sim 3.8$, $R_{\varepsilon} \sim 51\%$
- 2012 Jul 19 — $\kappa \sim 4.1$, $R_{\varepsilon} \sim 49\%$
- 2003 Oct 22 — $\kappa \sim 5.8$, $R_{\varepsilon} \sim 36\%$ flat

- 2003 Nov 18 — $\kappa \sim 8$, $R_{\varepsilon} \sim 27\%$ steep
- 2013 May 13 — $\kappa \sim 14$, $R_{\varepsilon} \sim 16\%$

Why flat and steep cases?

Let us first consider flat cases...
(energization mechanism)

Energization Mechanism?



above-the-looptop (ALT)

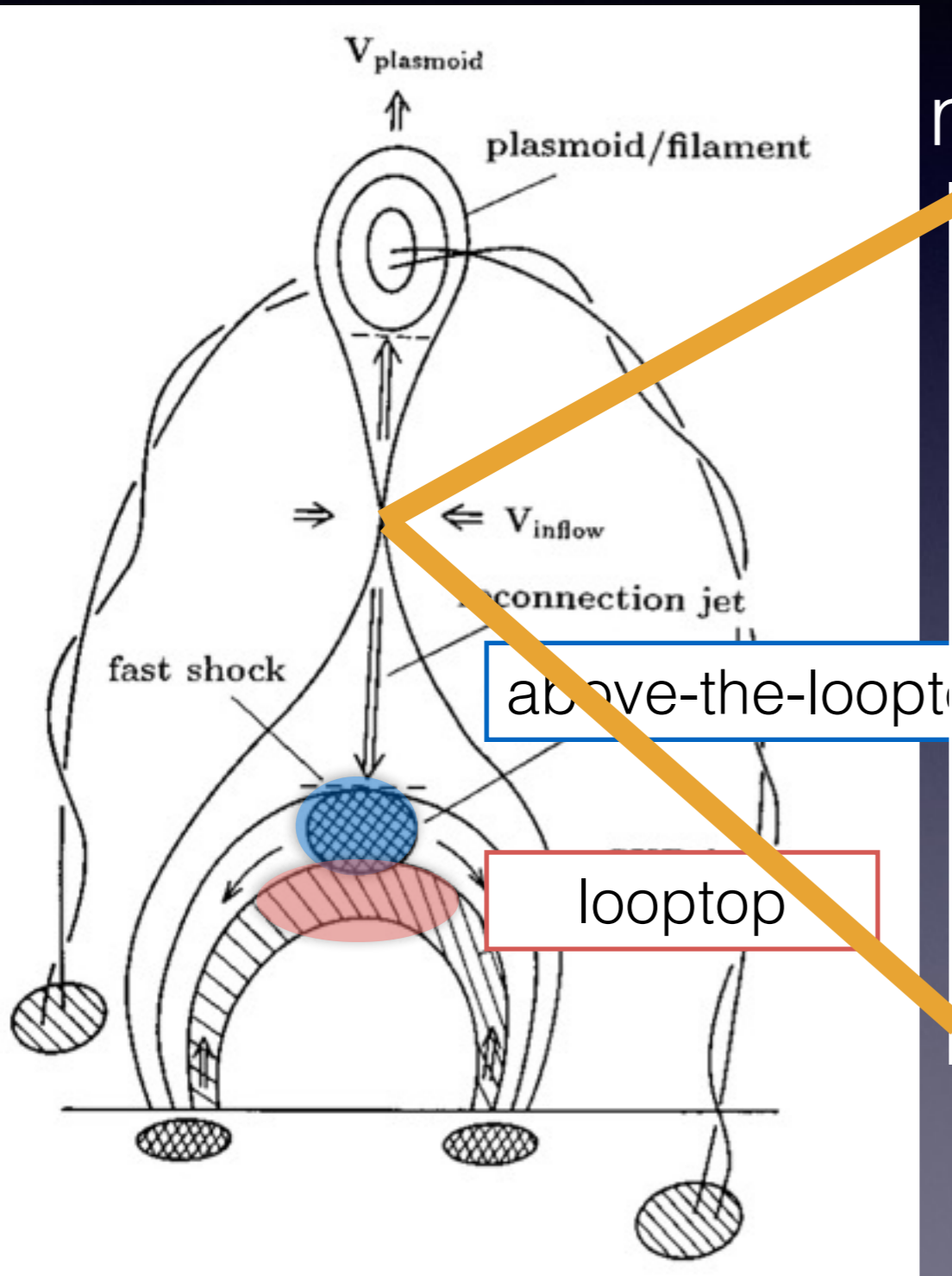
looptop

betatron collapsing-trap
contracting-island drift DSA Fermi fractal
islands parallel-electric-field potential
shock stochastic Super-Dreicer-field
turbulence

Let's start from a simple 2D reconnection scenario.

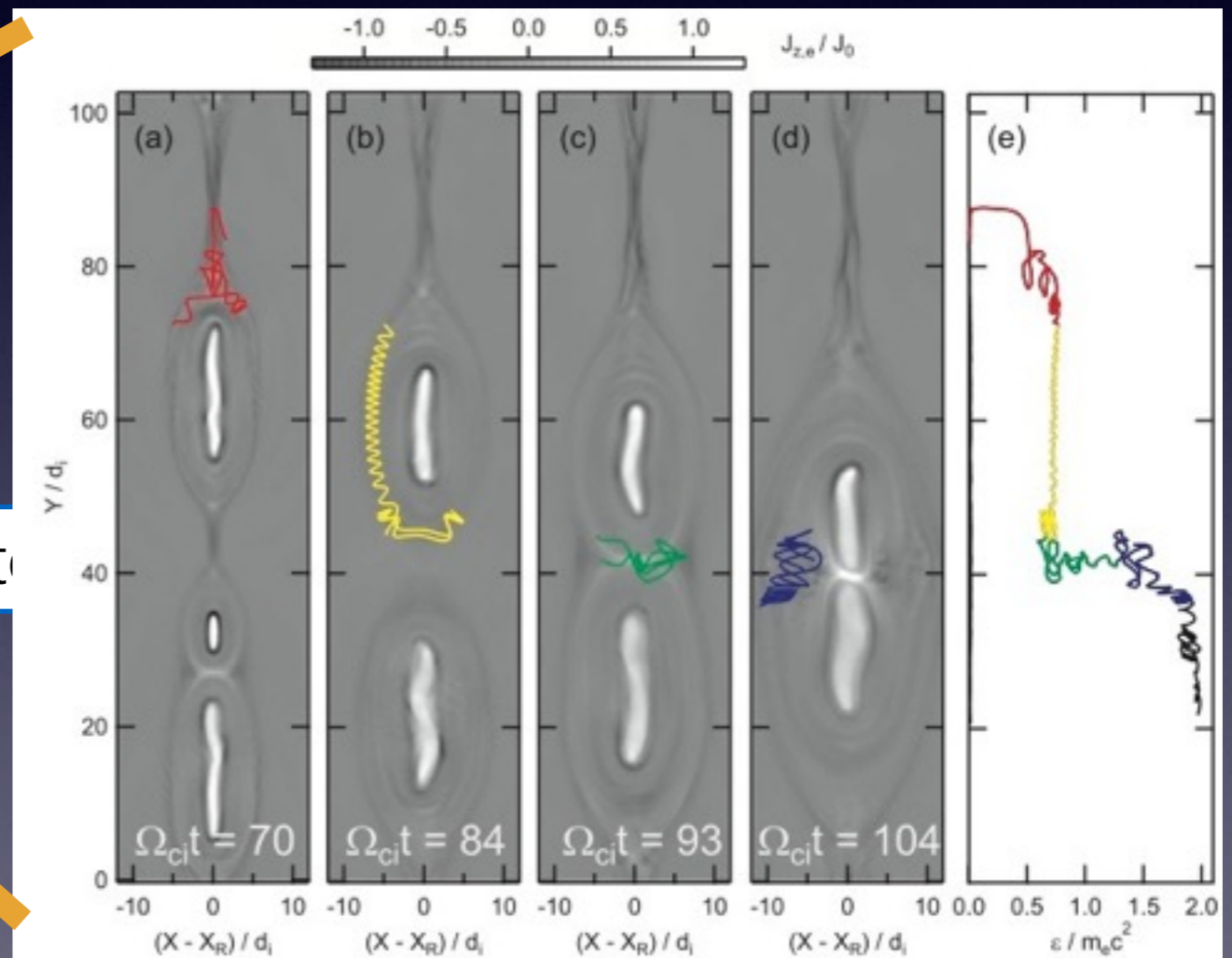
PIC Simulation

Just a start. More sophisticated model should be considered later.



above-the-looptop

looptop



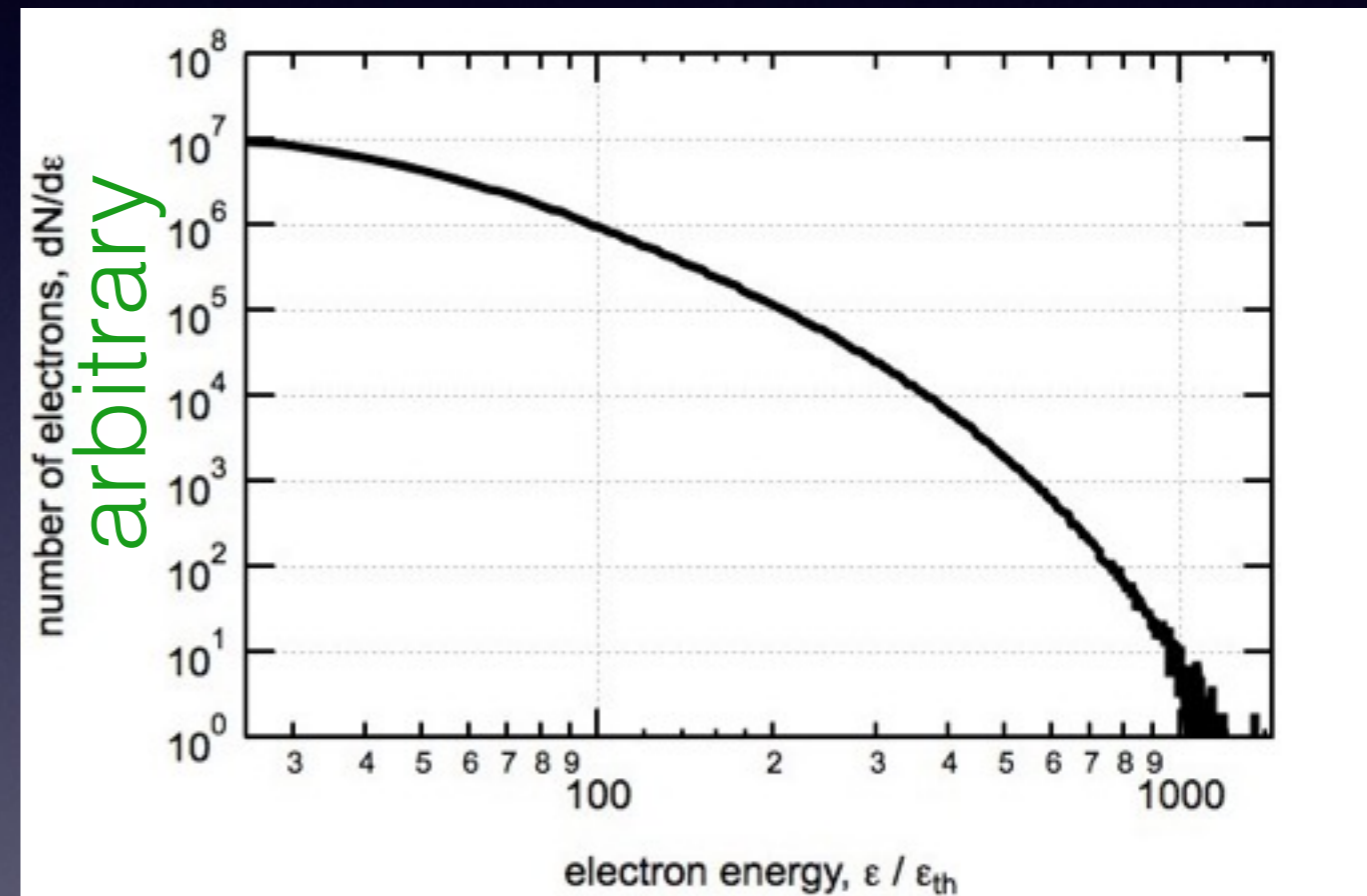
Oka et al. 2010

The real reason of using this simulation:
The simulation data was already in my computer!

PIC Simulation

Energy spectrum from the entire simulation box but the inflow ('lobe') particles have been subtracted.

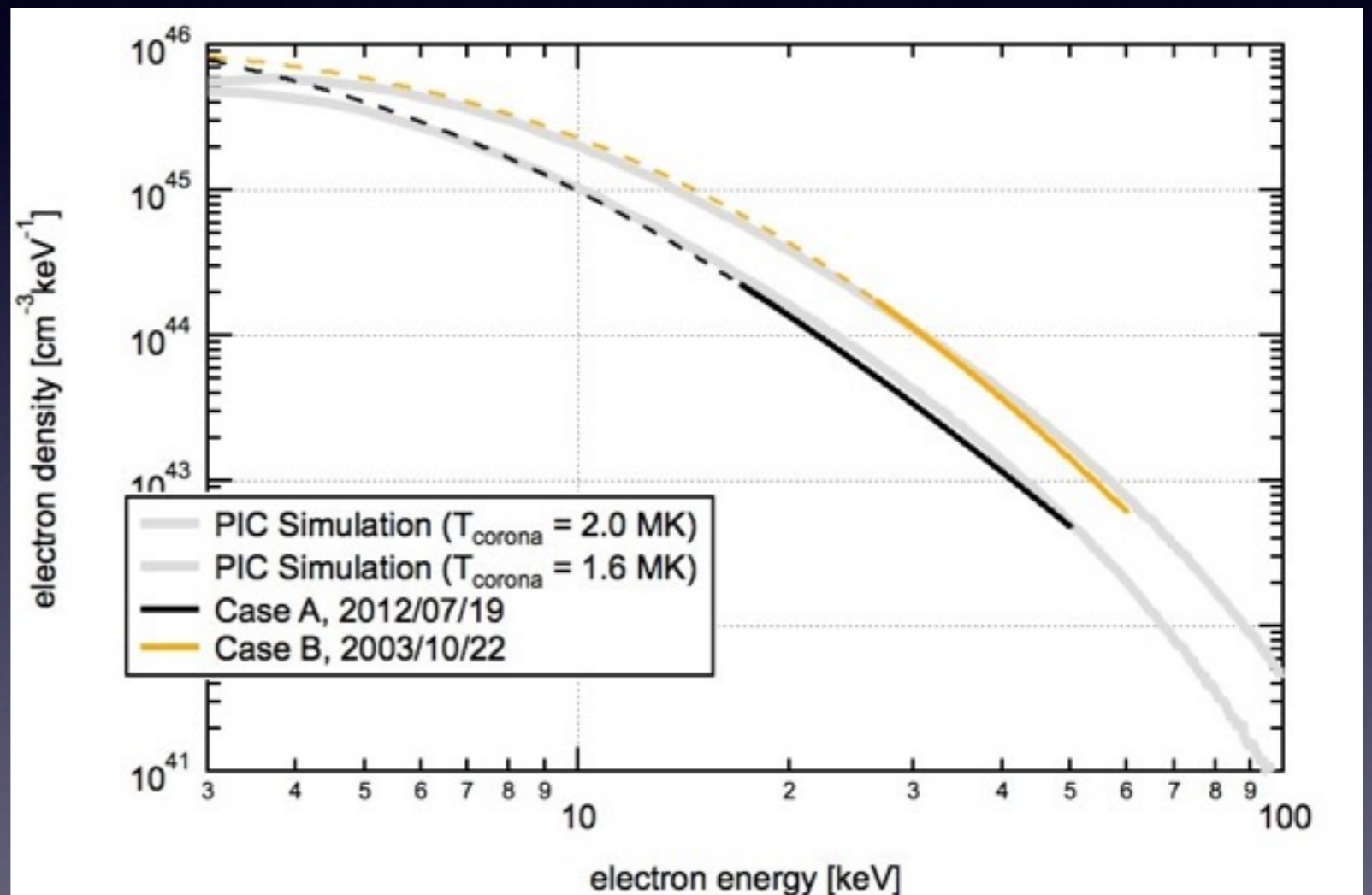
Particle energies normalized by the initial thermal energy of the current sheet.



- Kappa-like spectrum (slightly differs at different locations within the simulation box)
- **We need T_{corona} for comparison with observation.**

Comparison

A simple reconnection model alone can already achieve ~ 100 keV !!



Simplifications/Assumptions

- 2D
- no guide field
- $\beta = 0.2$
- small simulation box ($200 d_i \times 100 d_i$)
- $m_i/m_e = 25$
- and many more !!!!

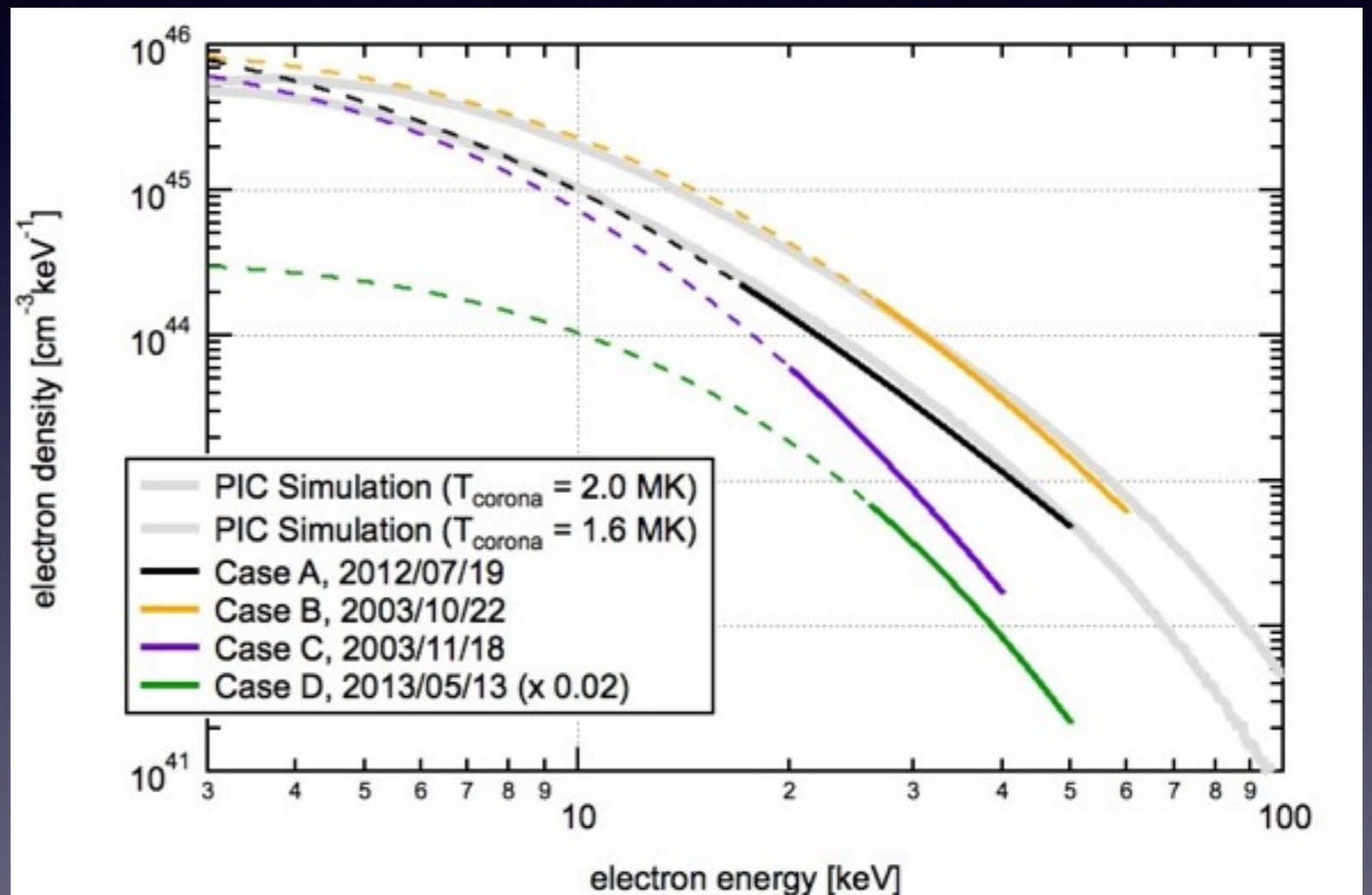
- In future studies, we need to take into account other theoretical ideas
 - Transport from RX region to ALT region (e.g. Somov et al. 1997)
 - Multi-island model (e.g. Tajima & Shibata, 2002; Drake+, 2006)
 - turbulence (e.g. Miller+, 1997)
 - fast-mode termination shock (if existed) (e.g. Masuda+ 1994)
 - and many more !!!!

- Nevertheless, **a simple reconnection model already agrees (roughly) with the observations**
- **Magnetic reconnection is a promising mechanism for understanding electron acceleration in solar flares.**

Why steep events?

‘Steep’ events are actually equally energetic (i.e. high temperature)

magnetic reconnection may still be important for energization.



Collisionality

For 30 keV electrons to be collisional.....

For the source to be collisional,

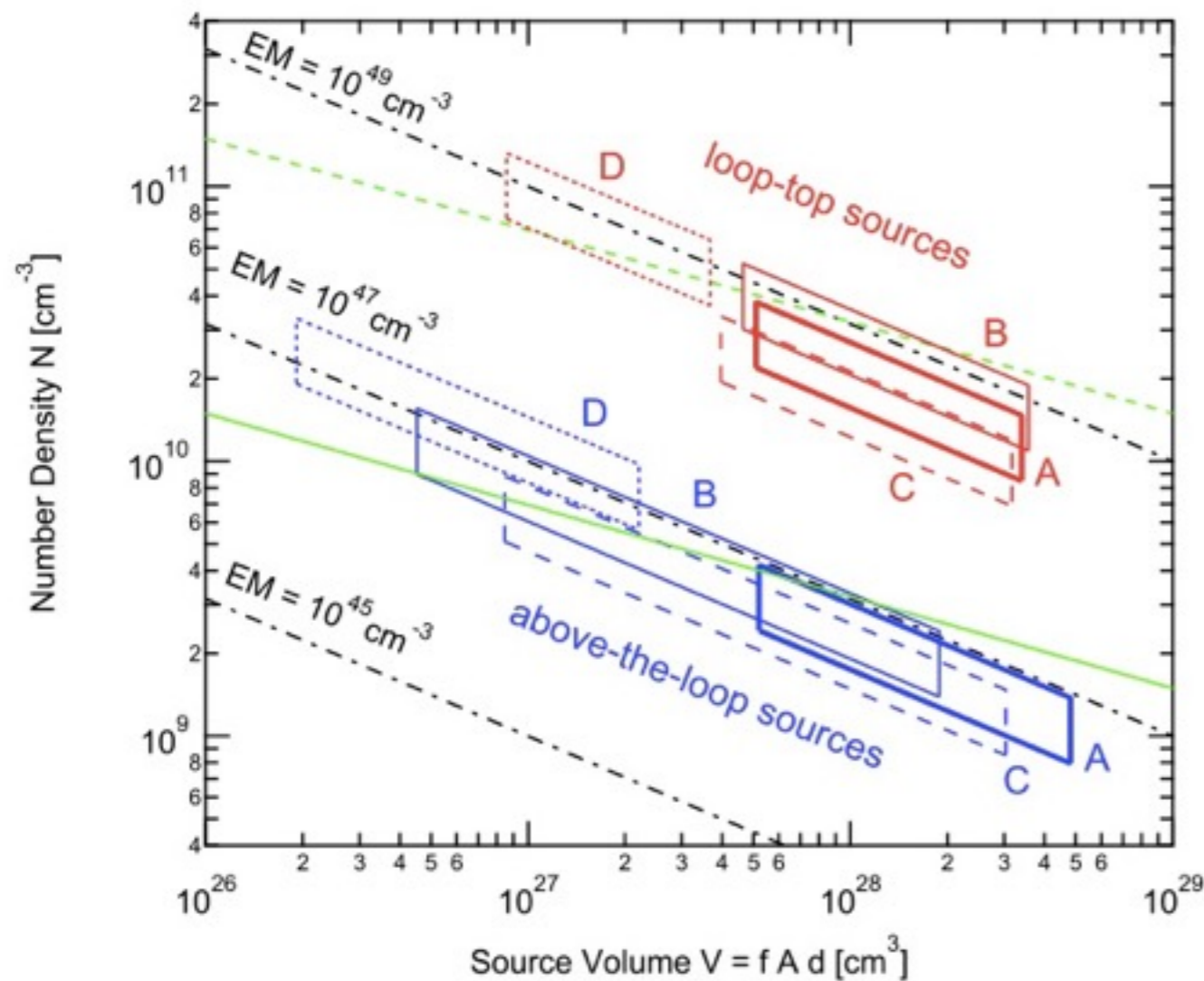
$$\lambda_{\text{mfp}} < d = 2 \left(\frac{3V}{4\pi} \right)^{\frac{1}{3}}$$

Taking electron-electron collision time from a textbook (A. O. Benz),

$$\lambda_{\text{mfp}} = v_e \tau_{\text{coll}} = 3.1 \times 10^{-20} \frac{v_e^4}{N_e}$$

Then, the critical density becomes

$$N_{\text{crit}} \sim 6.9 \times 10^{10} \left(\frac{E}{30 \text{ keV}} \right)^2 \left(\frac{V}{10^{27} \text{ cm}^3} \right)^{-\frac{1}{3}} \text{ cm}^{-3}$$



30 keV electrons with **turbulent scattering** become collisional above the solid line

$$\lambda_{\text{mfp}} \sim 0.1 \lambda_{\text{mfp, coll}}$$

Conclusion

- **Kappa distribution works — $R_\varepsilon \sim 50\%$ (or less)**
 - Need a larger number of events to establish the idea of upper-limit at 50%.
- **Magnetic reconnection scenario works**
 - Need simulations with more realistic parameters and configurations to establish this scenario
- **Coulomb collisions may reduce the non-thermal fraction of electron energies**
 - This scenario requires a turbulent scattering that is strong enough to reduce the mean free path by an order of magnitude in case of, for example, 30 keV electrons.