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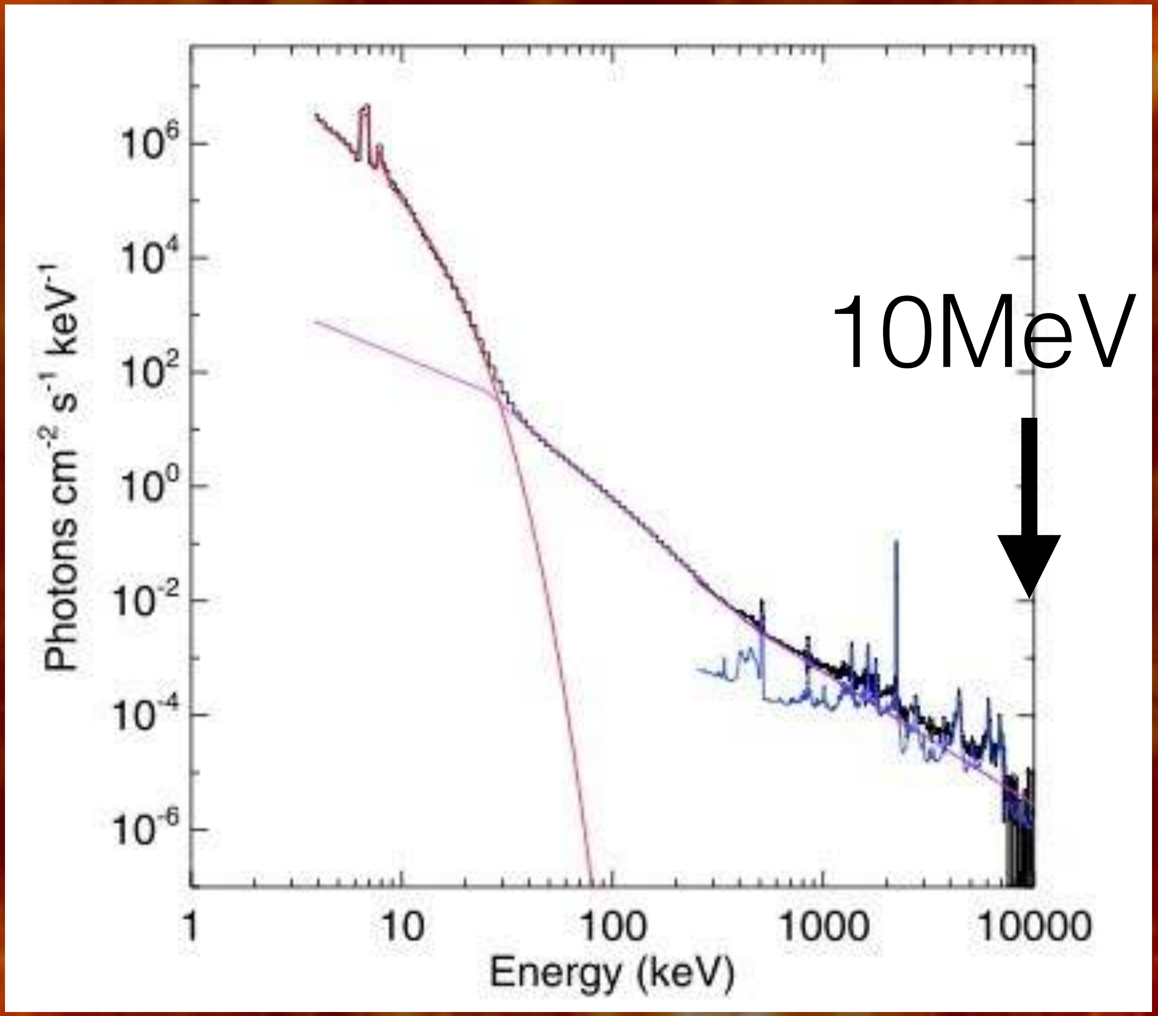
Electron energy partition in the 'above-the-looptop' solar hard X-ray sources

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)

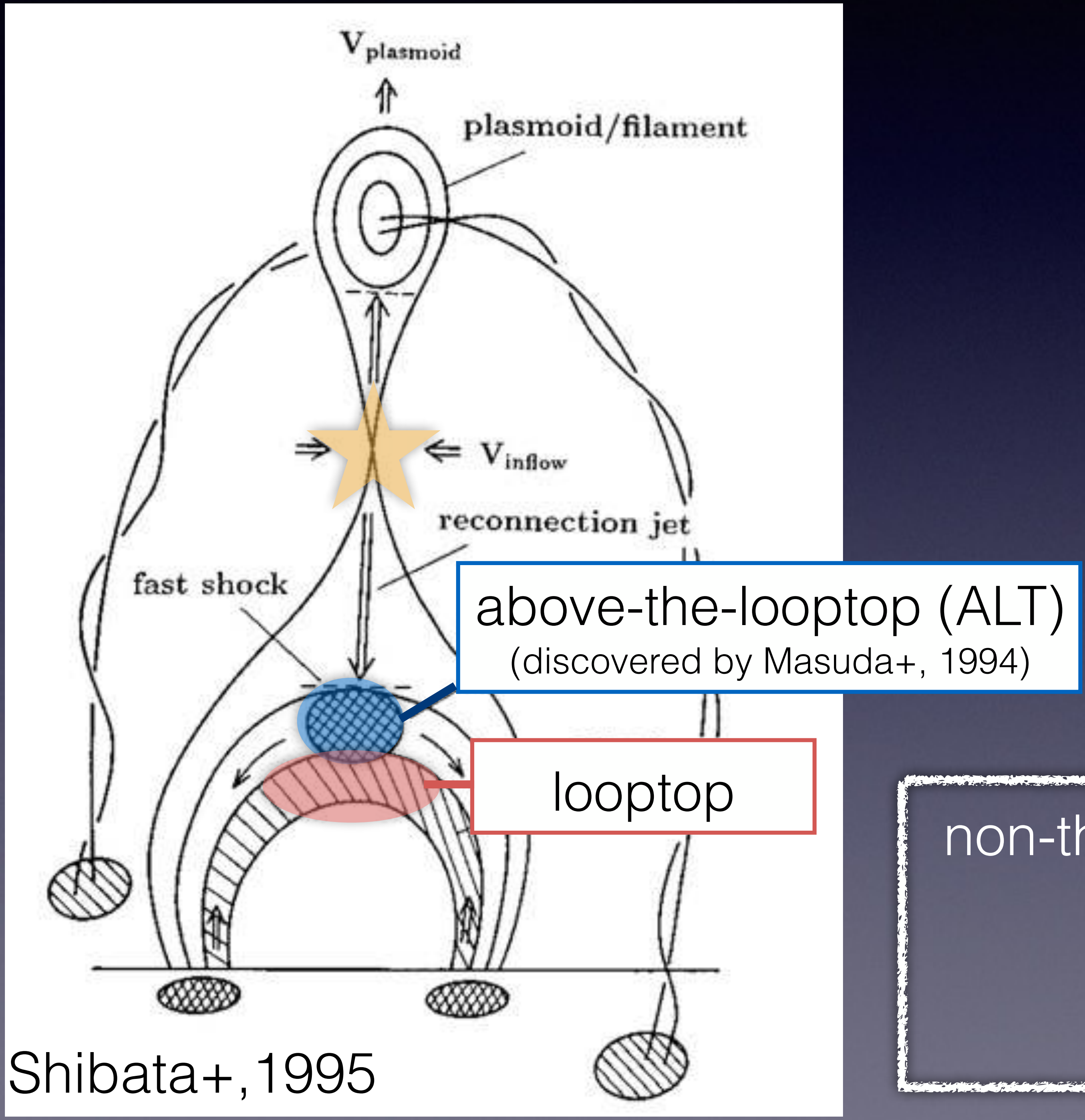
All electrons are accelerated into a power-law

(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

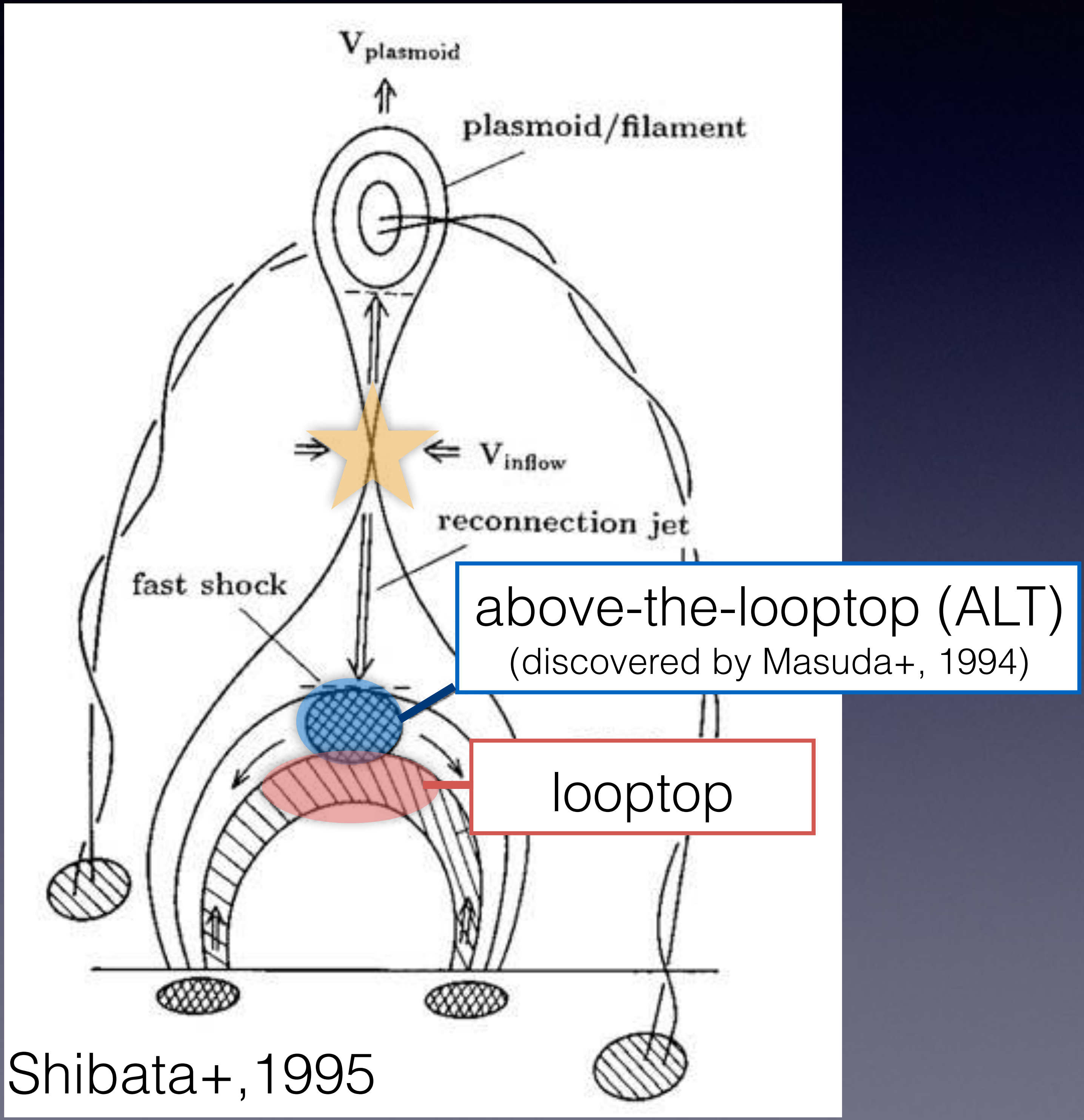
Shibata+,1995

non-thermal fraction of electron **energies**

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

non-thermal fraction of electron **energies**

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



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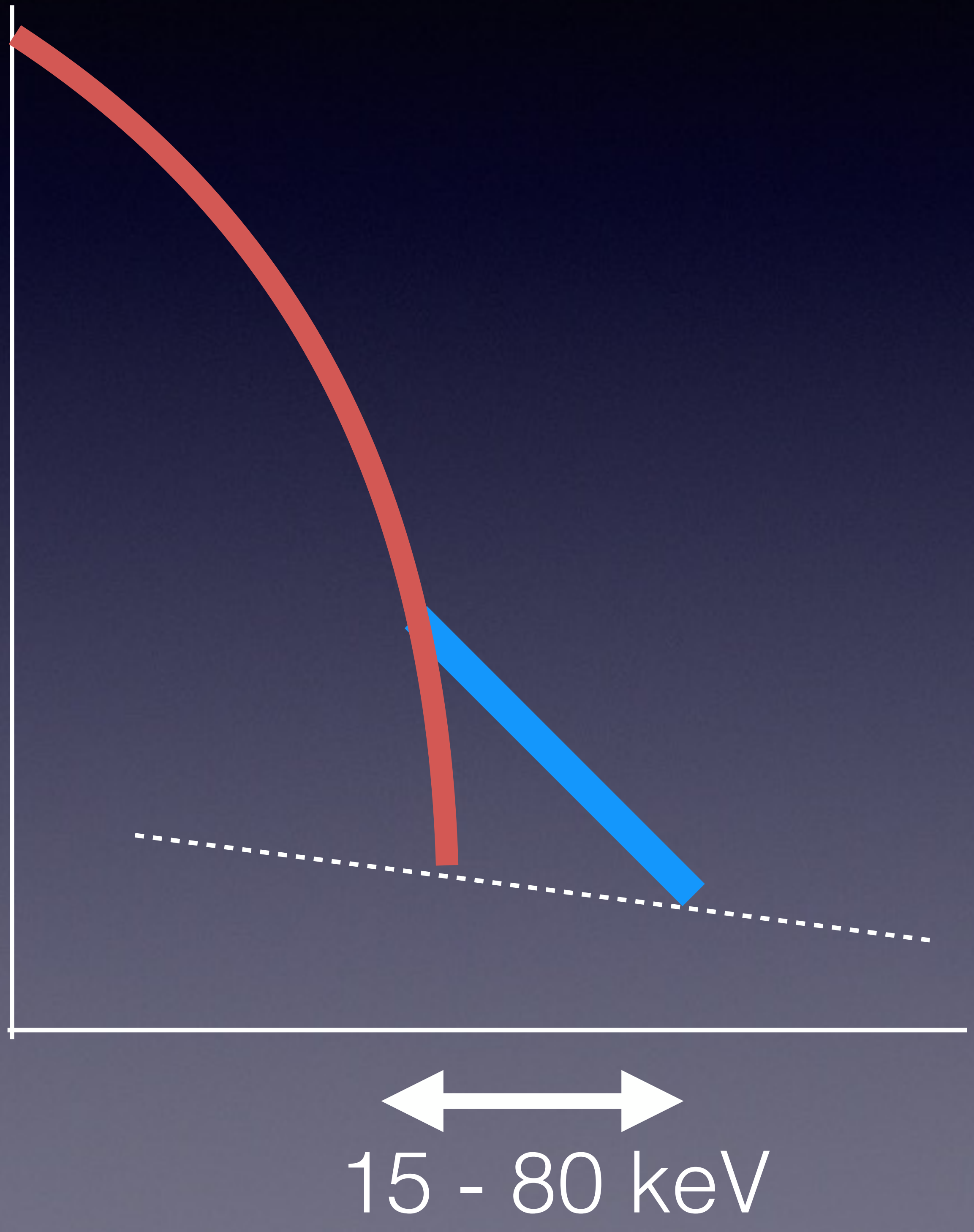

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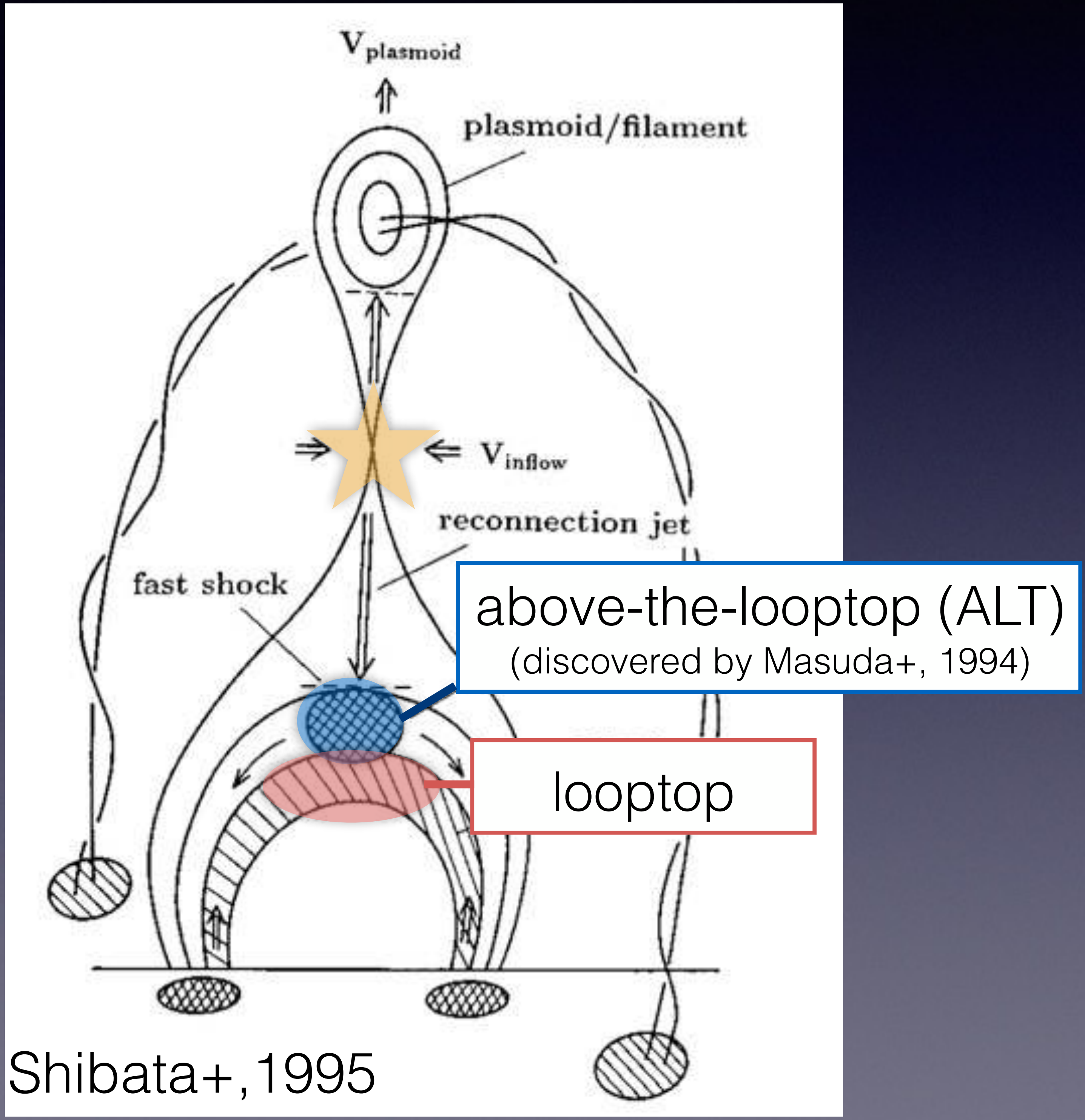

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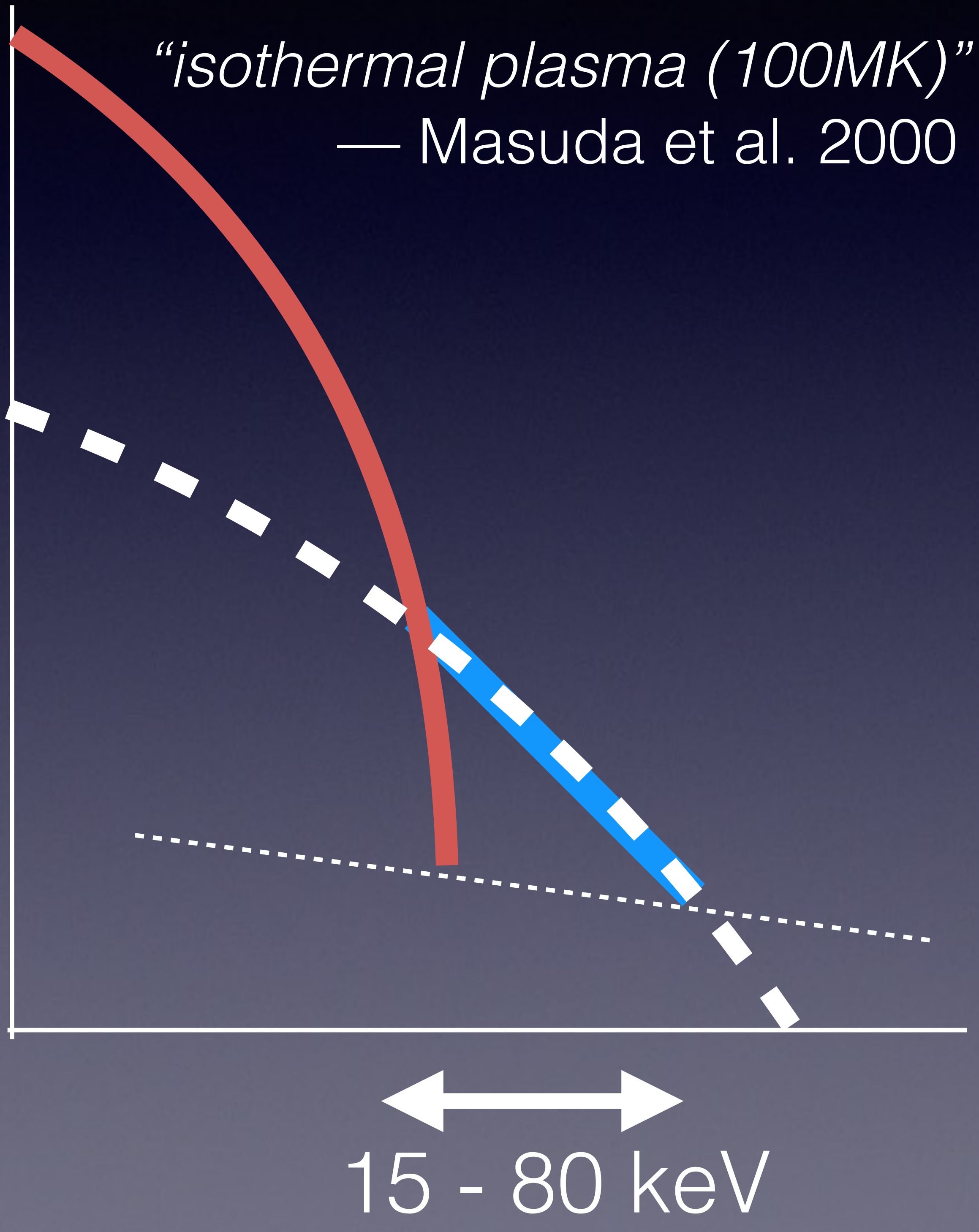
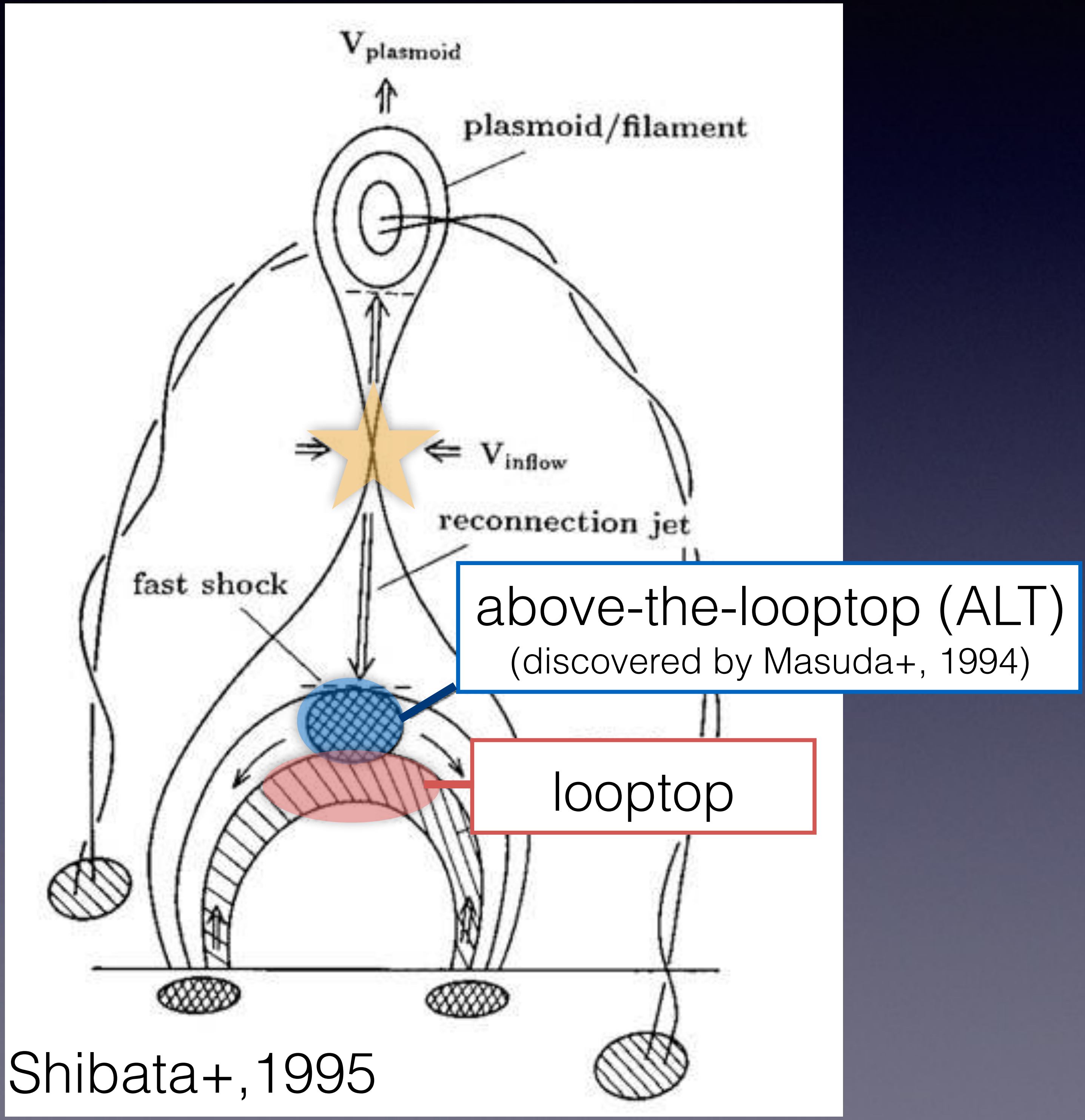

"isothermal plasma (100MK)"
— Masuda et al. 2000

15 - 80 keV

non-thermal fraction of electron **energies**

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



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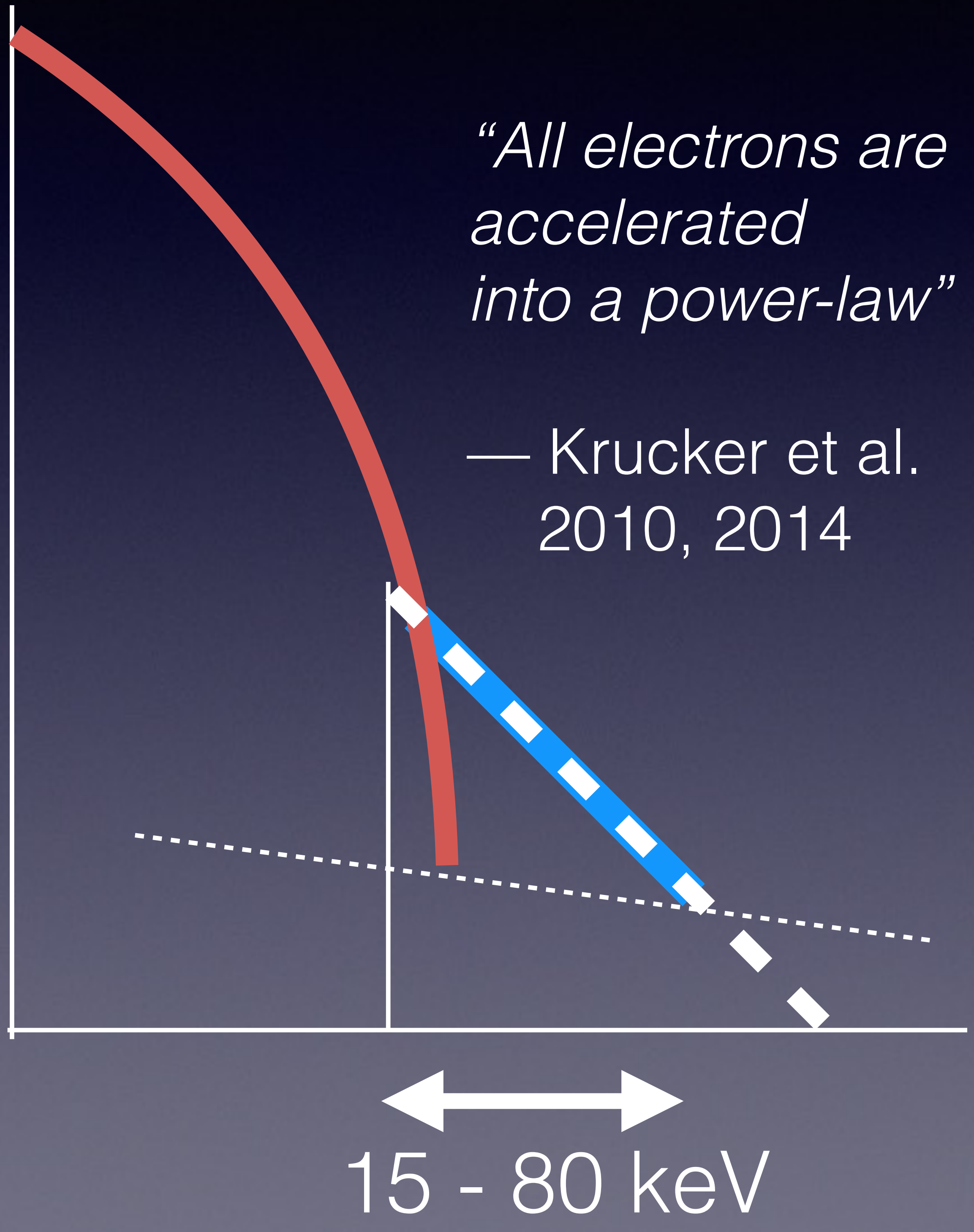
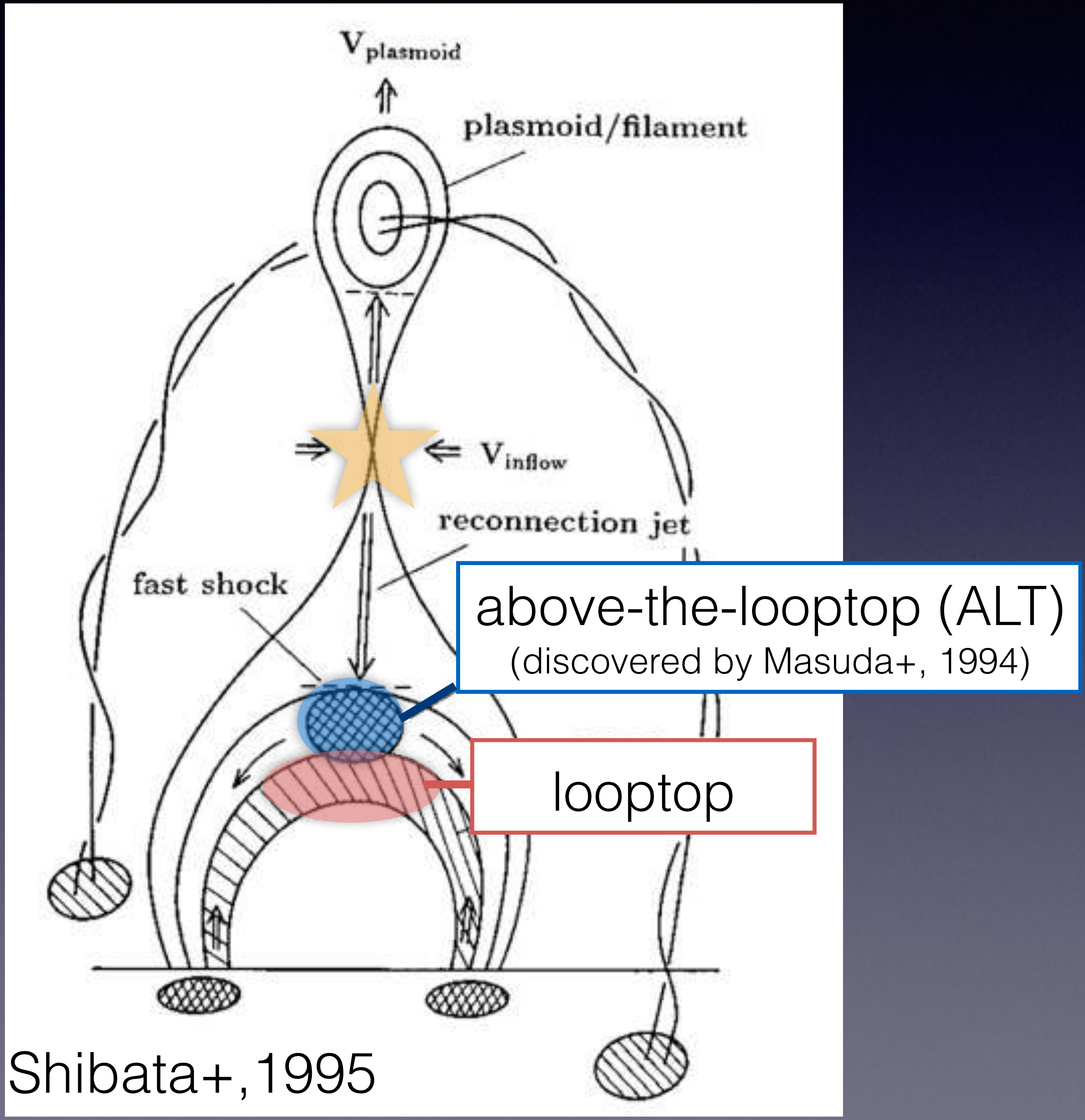


"All electrons are accelerated into a power-law"

— Krucker et al. 2010, 2014

non-thermal fraction of electron **energies**

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

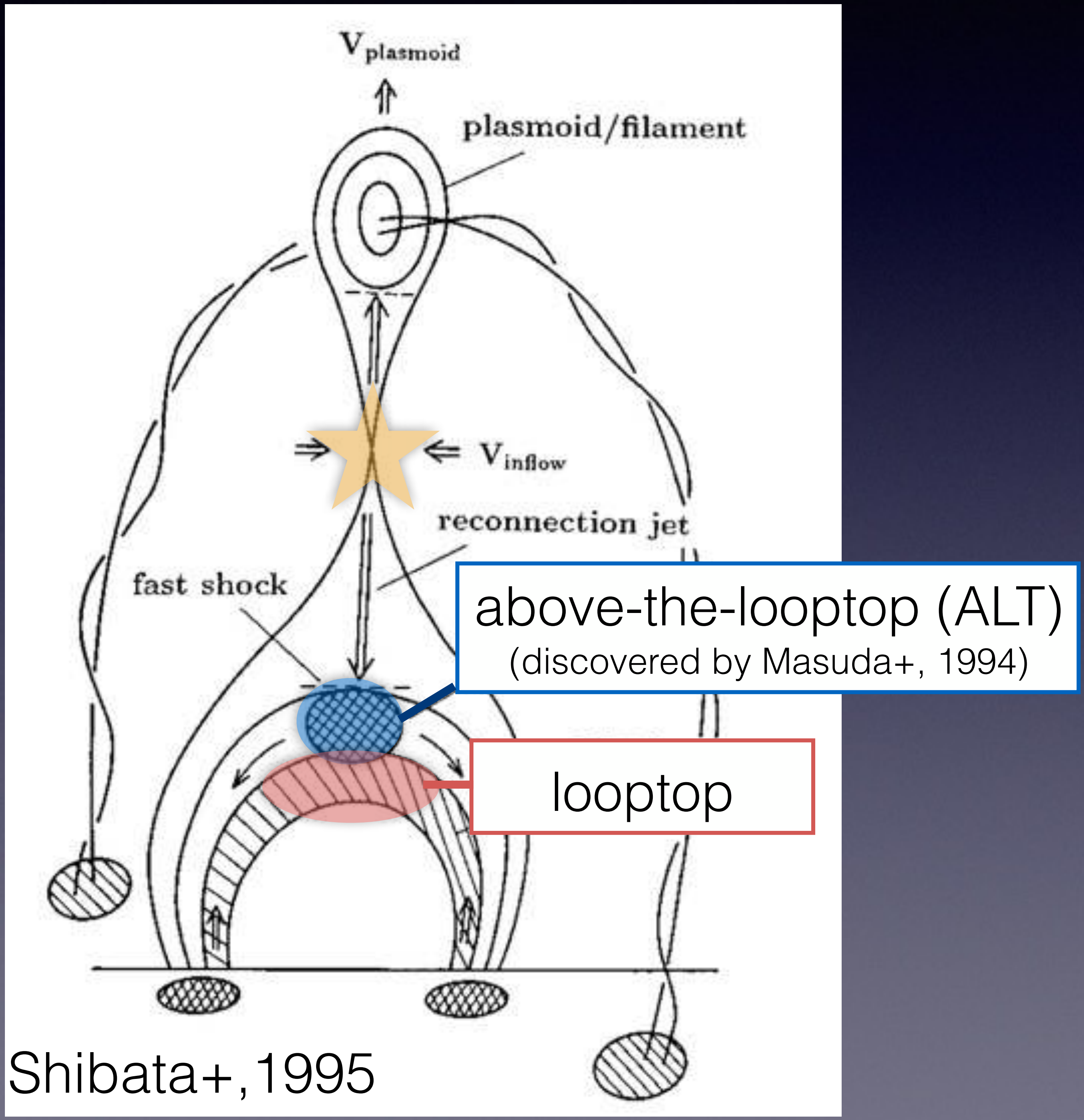


Shibata+,1995

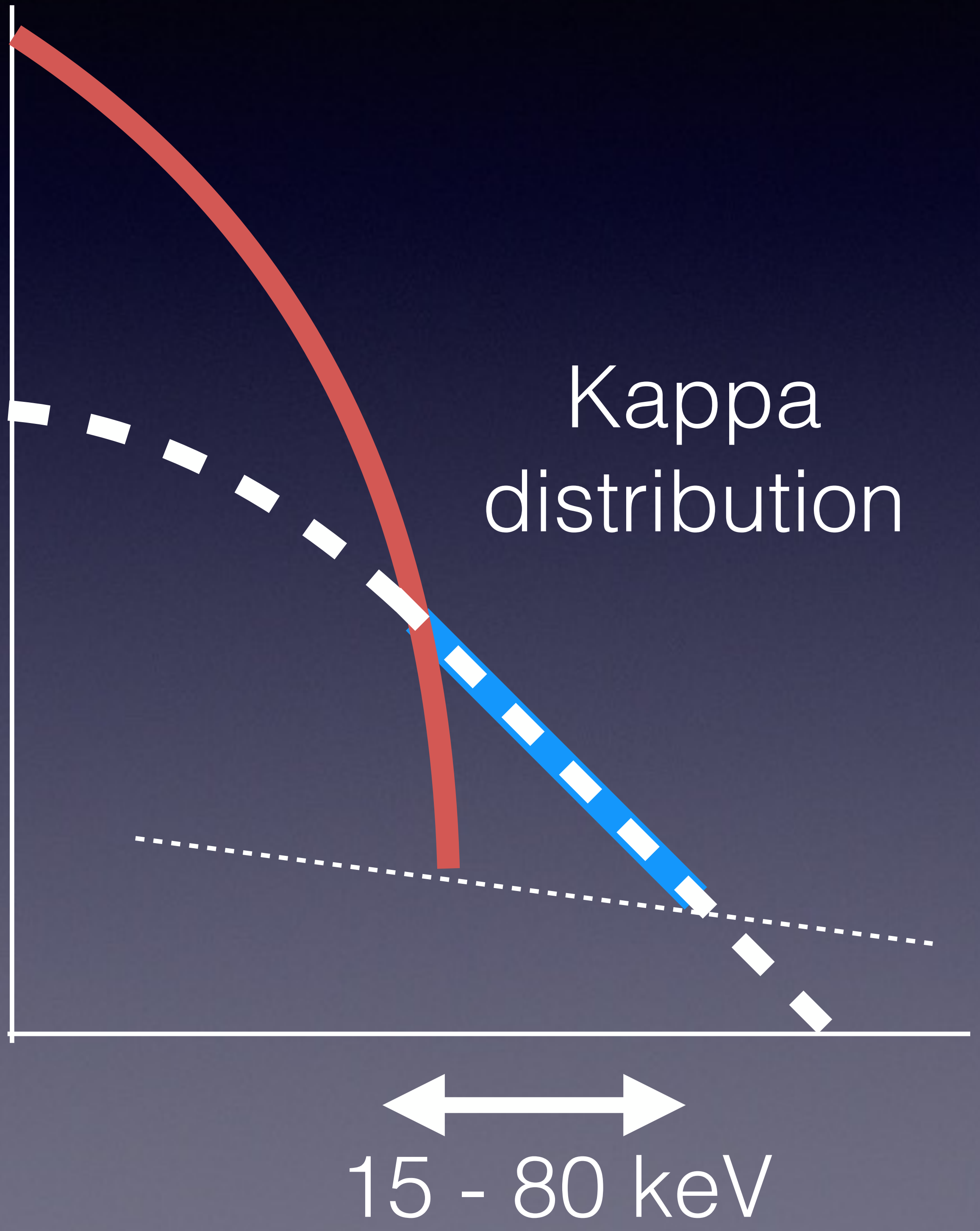
Iso-thermal model
In some cases,
there is clearly
a non-thermal tail.

power-law
(no particles < E_c)
Coulomb collisions and
wave particle interaction
should fill the 'gap'
below E_c.

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



Shibata+,1995



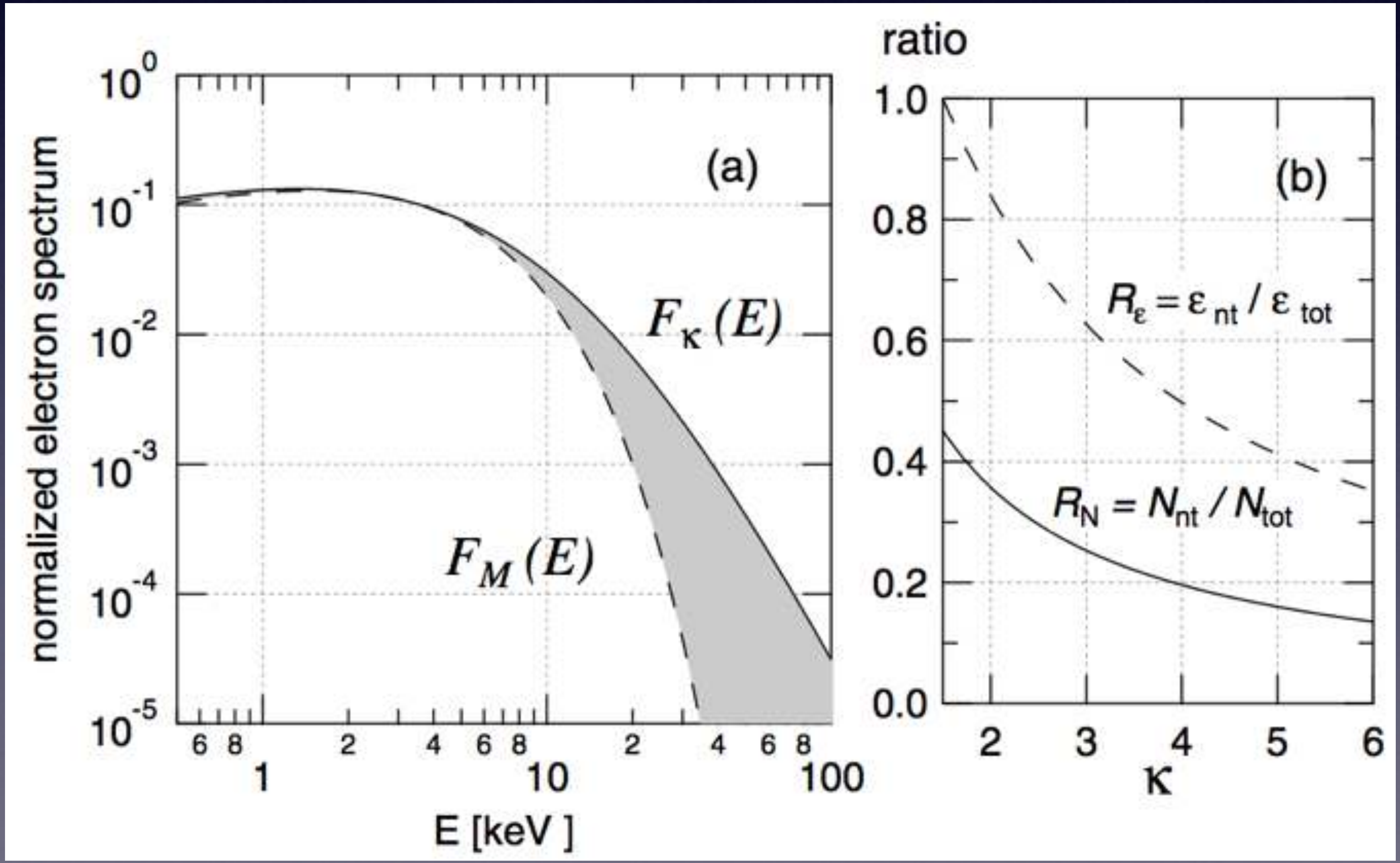
Outline

- **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

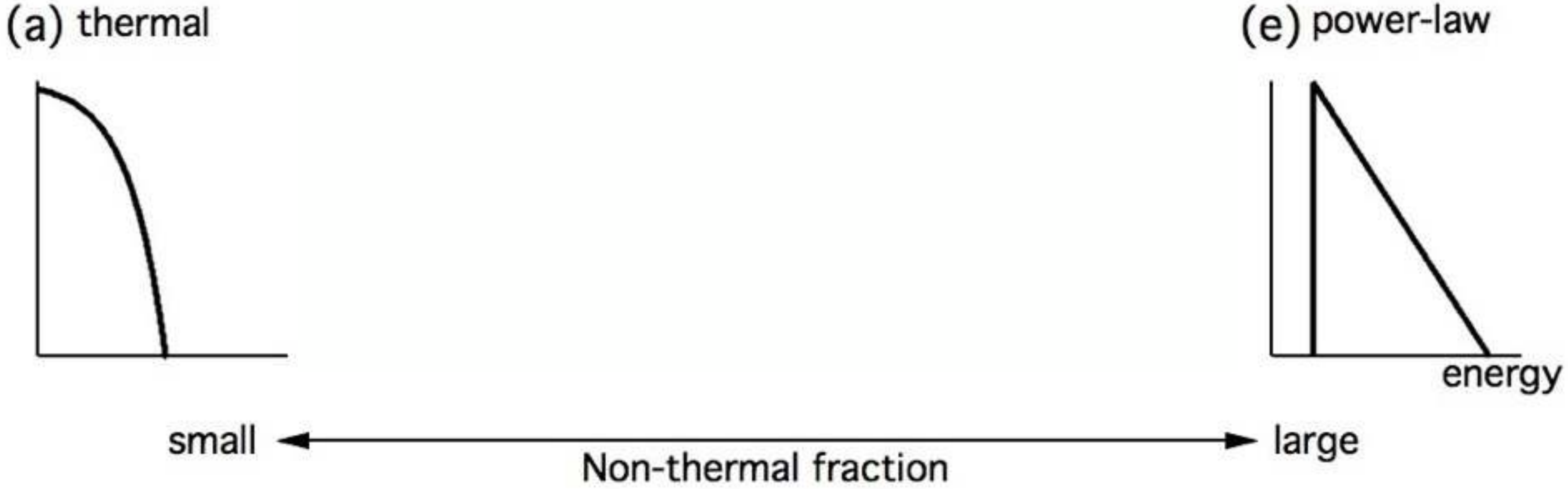
- Yoon et al. 2006

Tsallis statistics

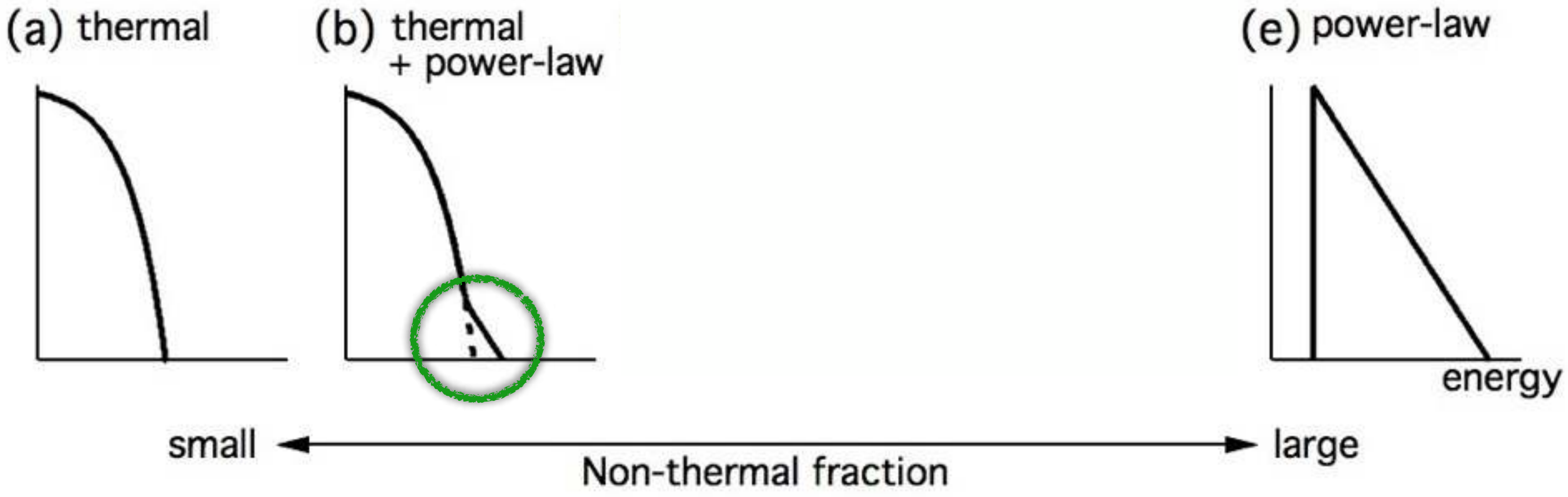
- e.g. Leubner 2004; Livadiotis & McComas 2009

Any intuitive explanation??

Spectral Models

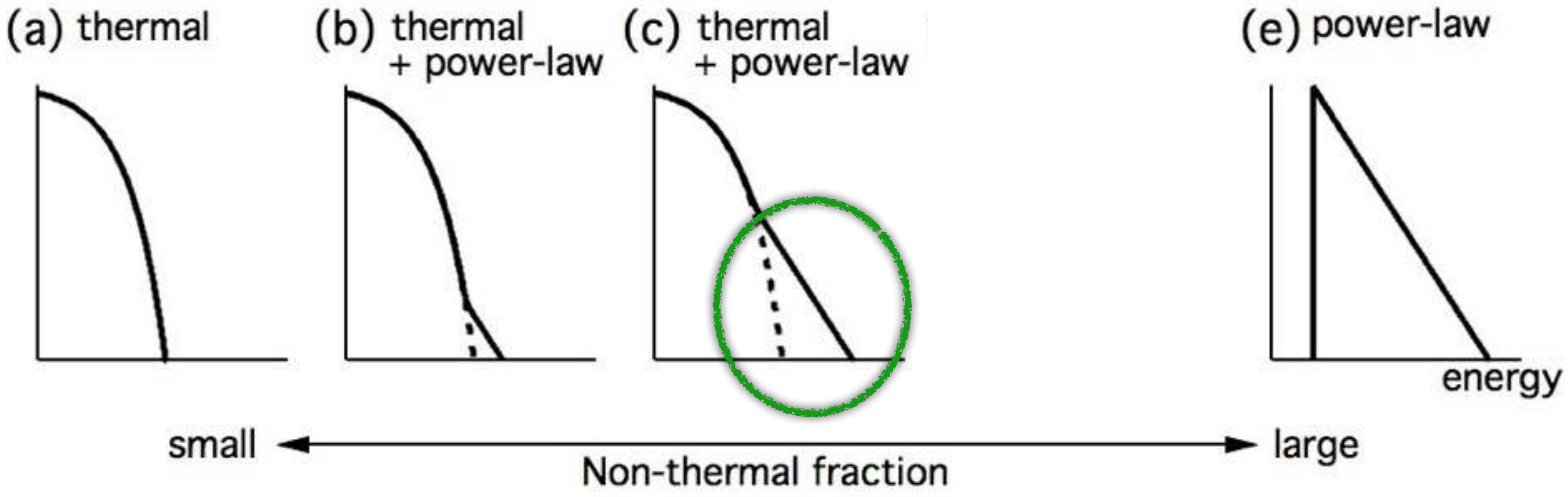


Spectral Models



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

Spectral Models



Let’s consider a fixed spectral slope
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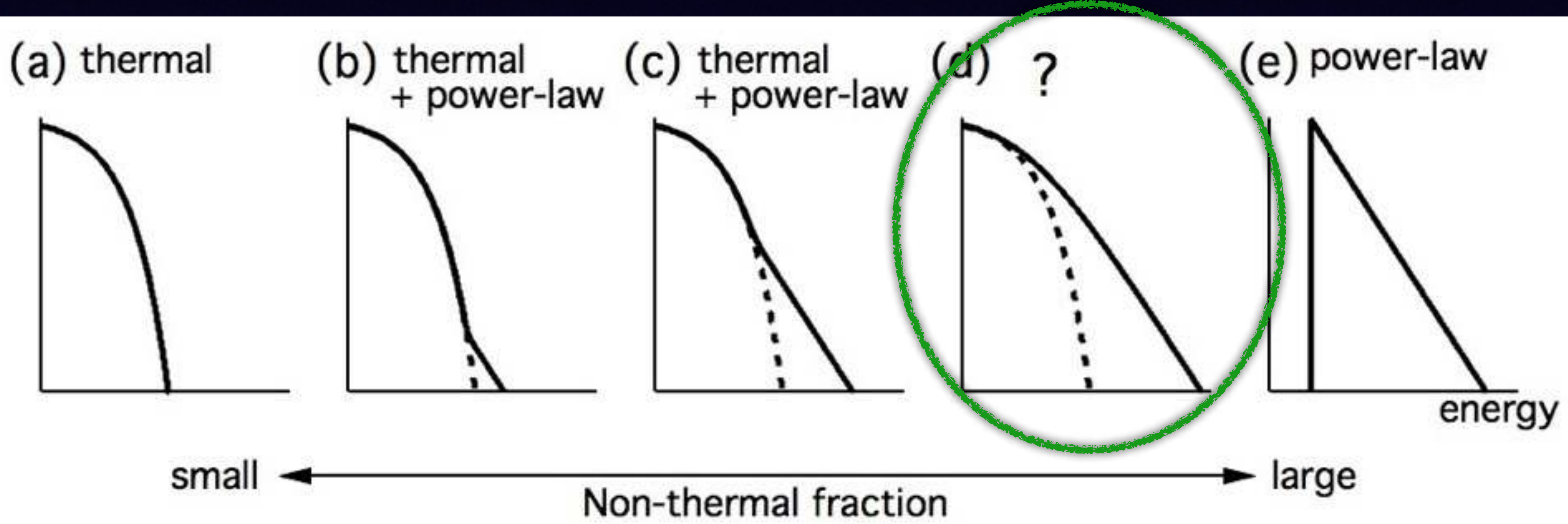
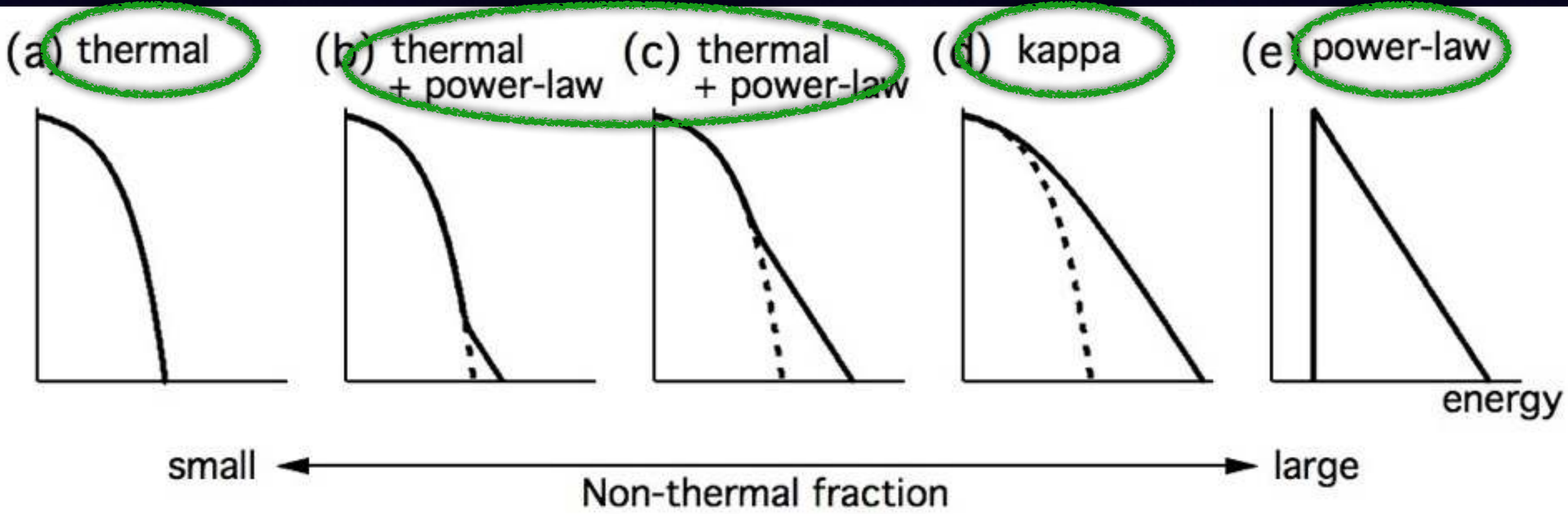
Spectral Models



A super-hot thermal core plus ‘saturated’ non-thermal tail !?

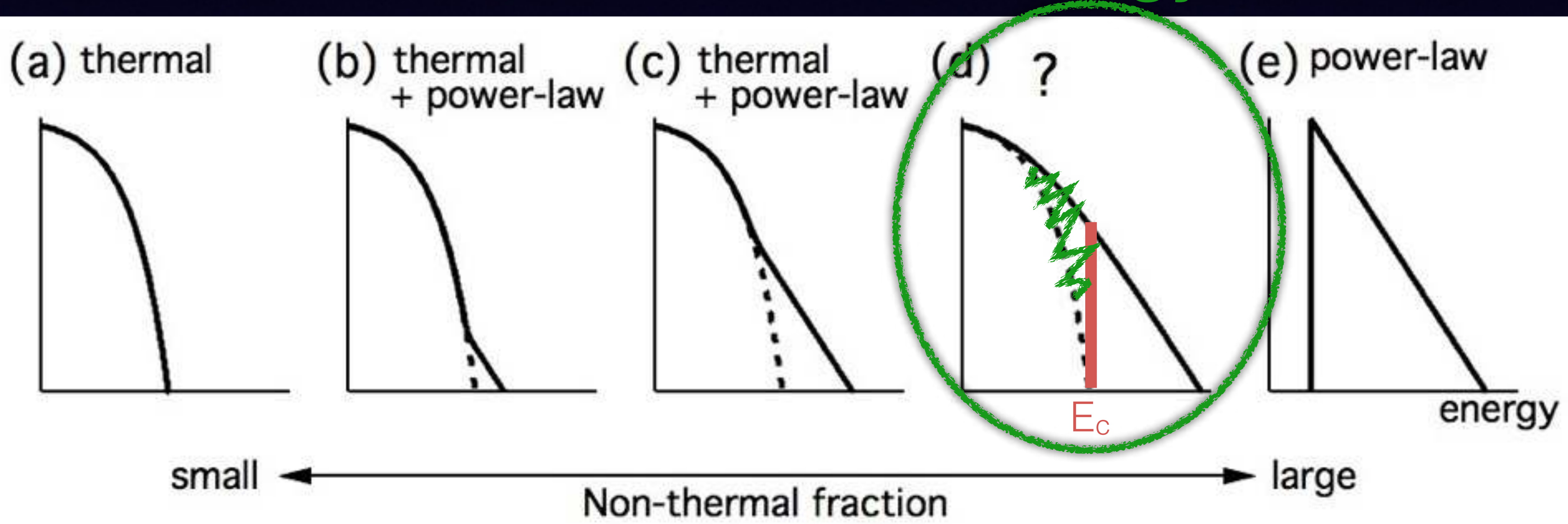
Spectral Models



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.

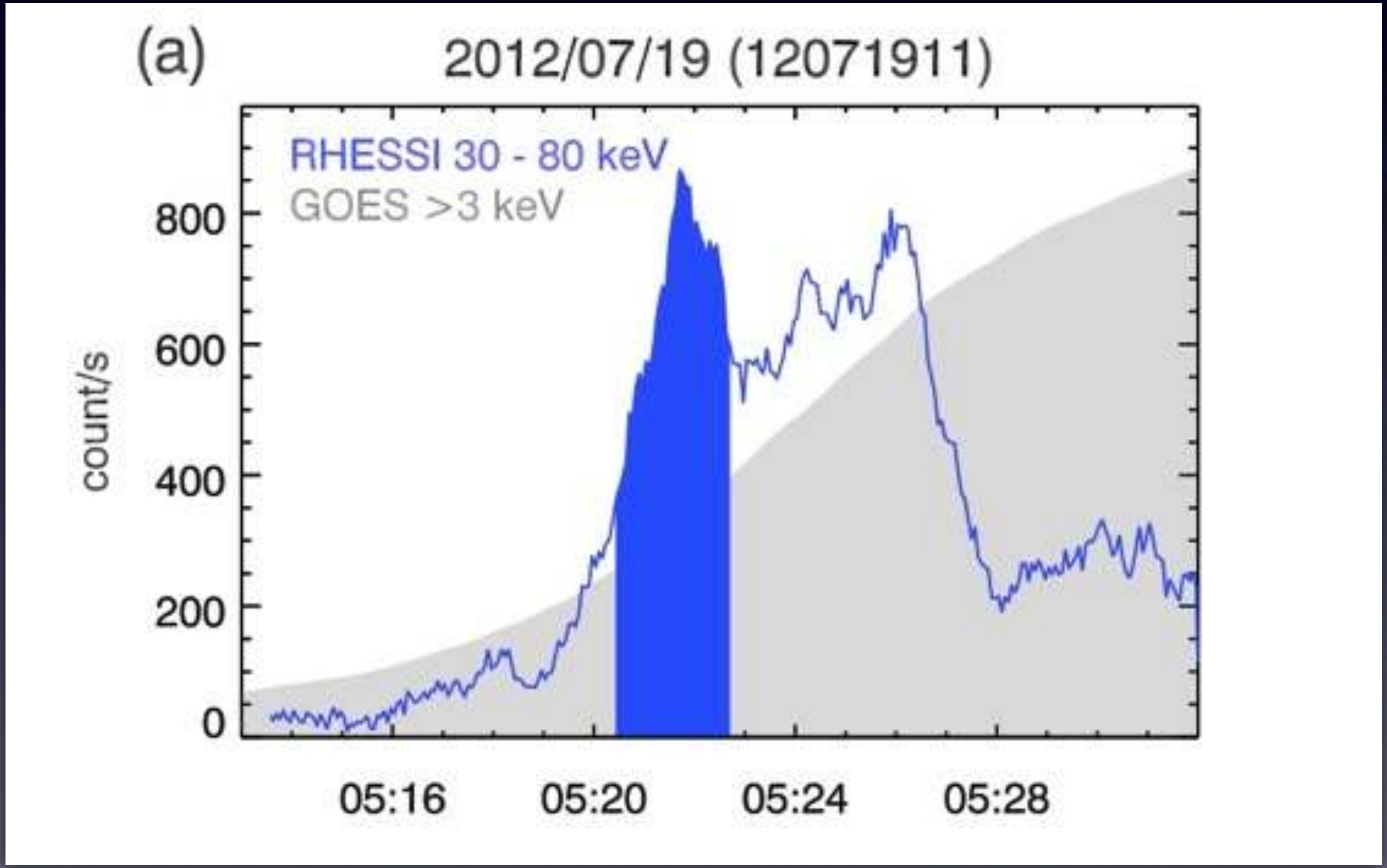
Outline

- 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.

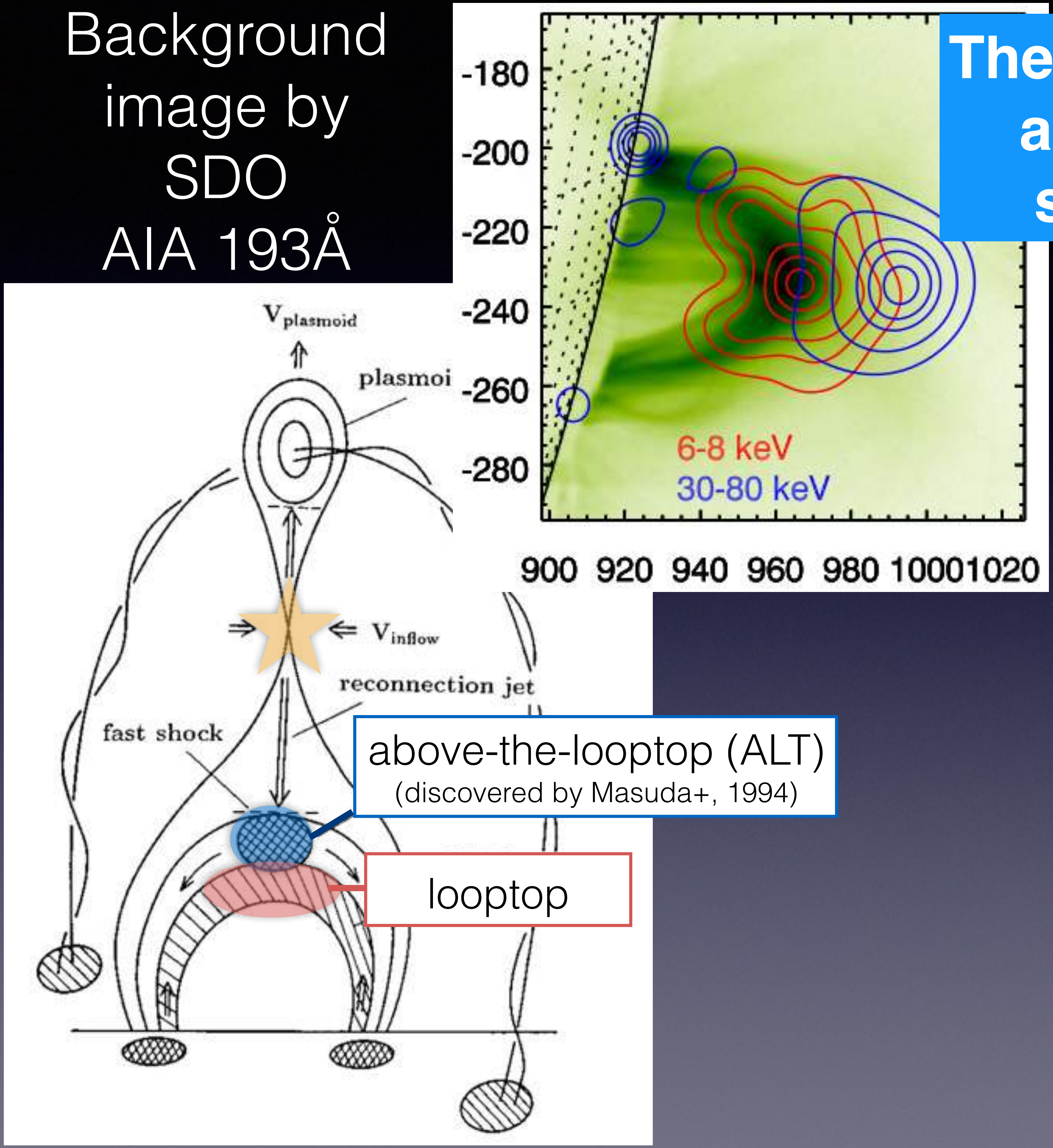
RHESSI

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



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

looptop

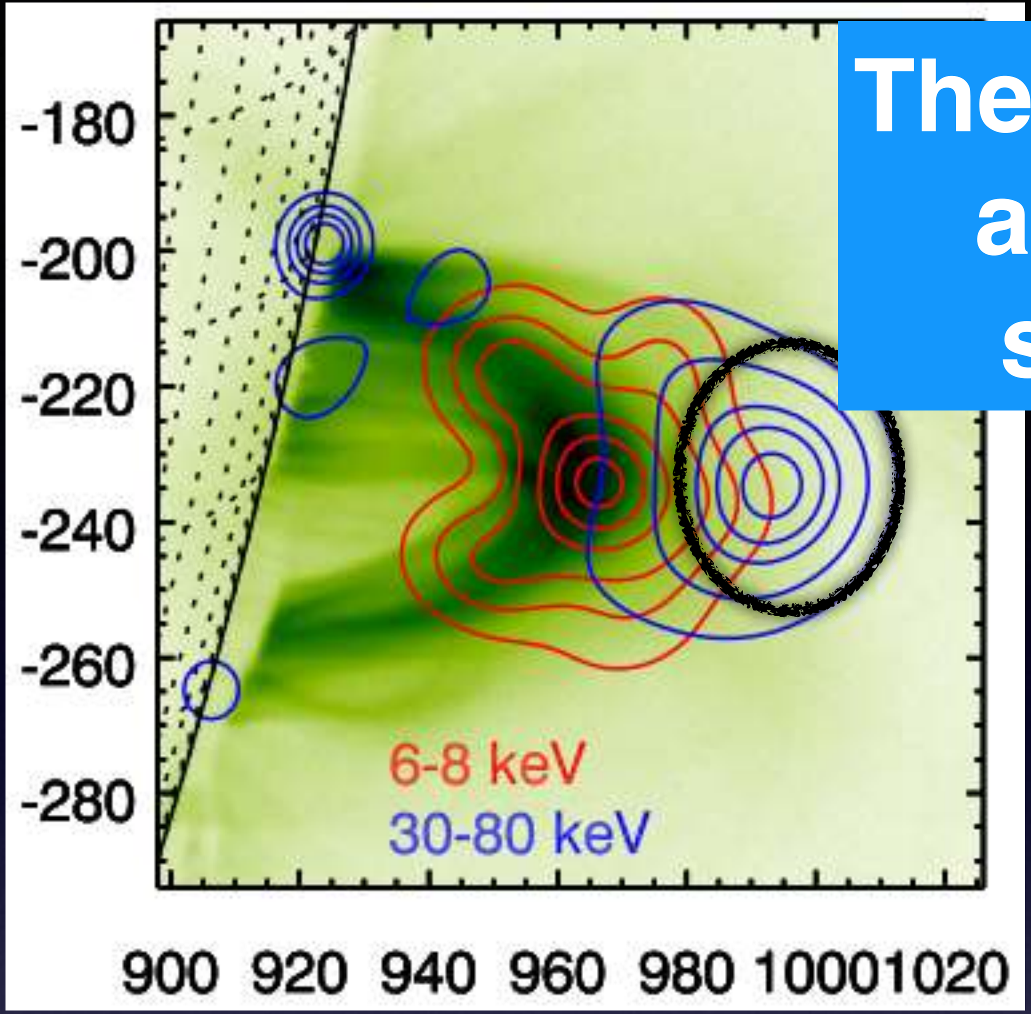
The two sources are not well separated.

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

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

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

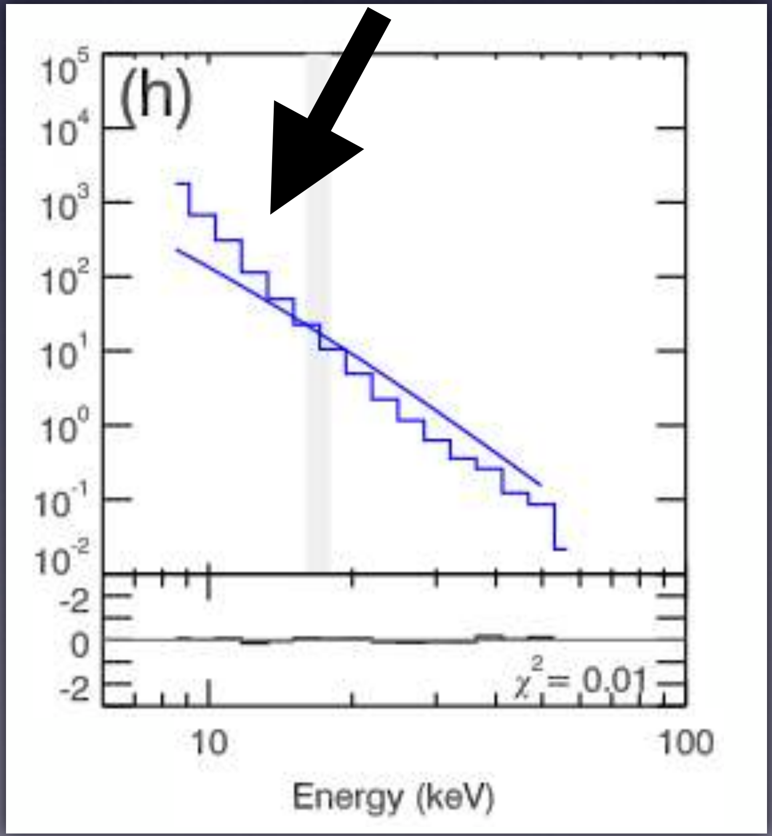
Background image by SDO AIA 193Å



The two sources are not well separated.

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

Contamination from the adjacent source



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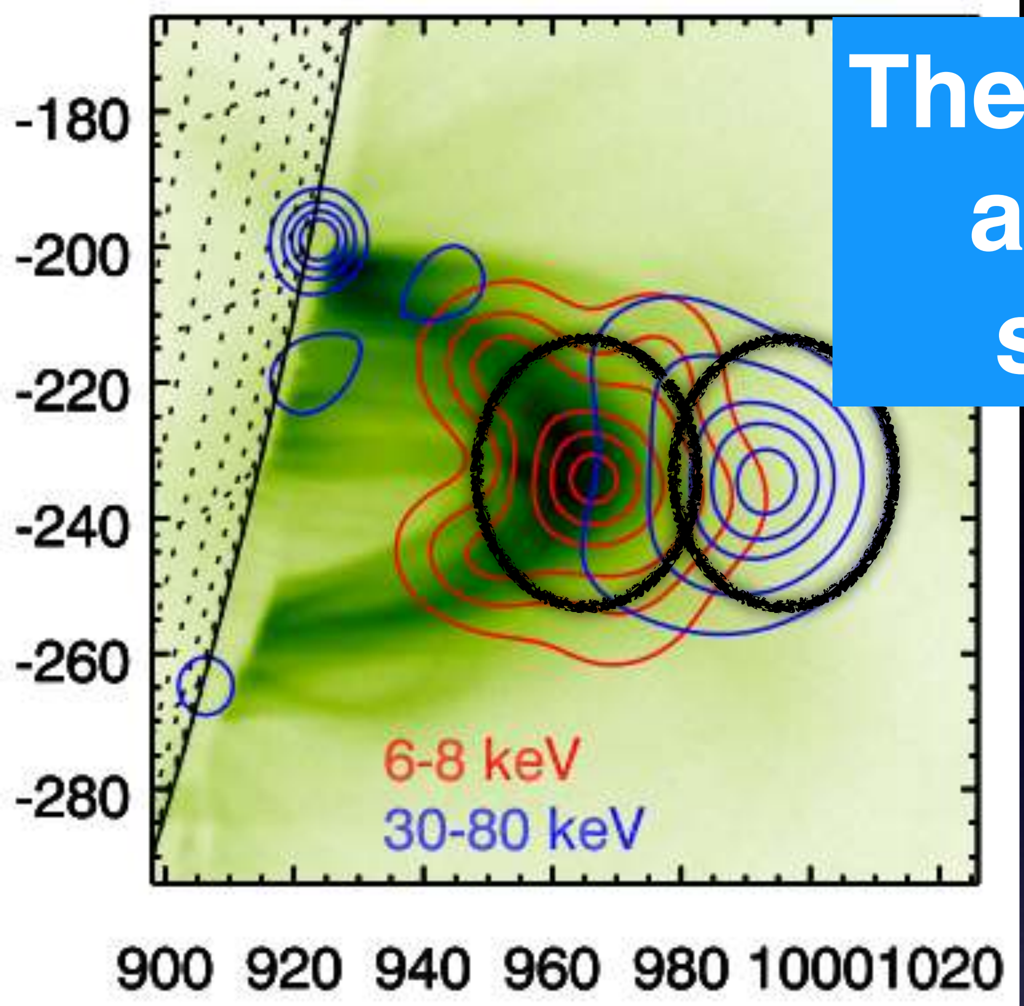
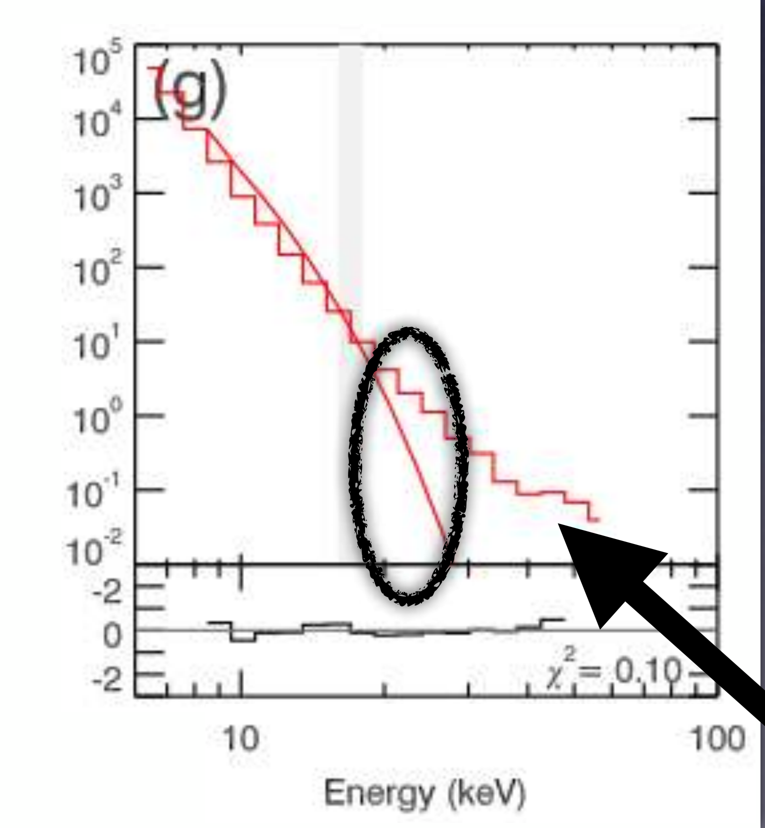
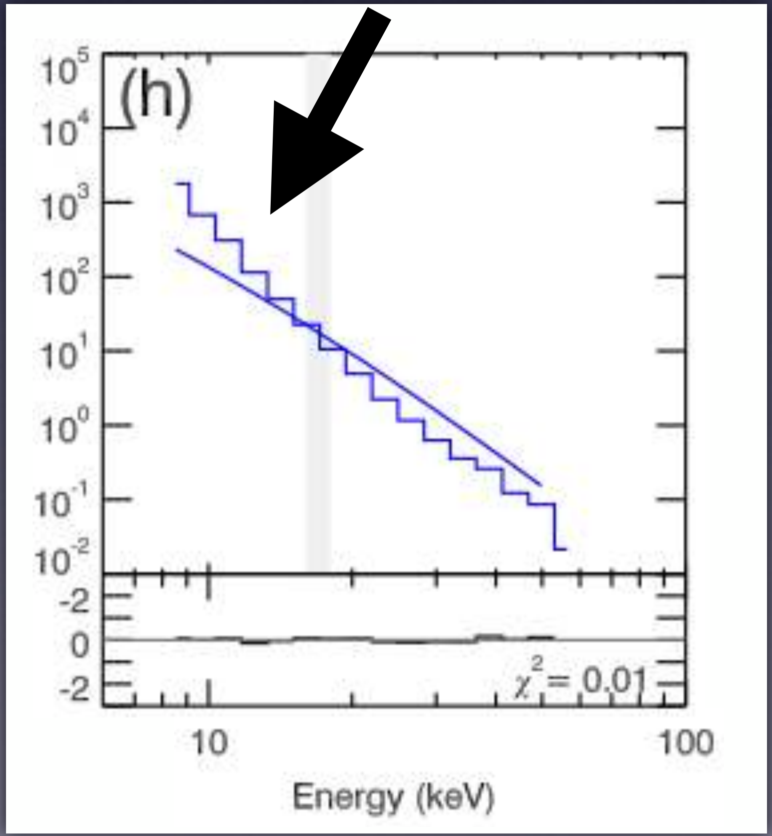


Contour levels:
10,30,50,70,90%

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

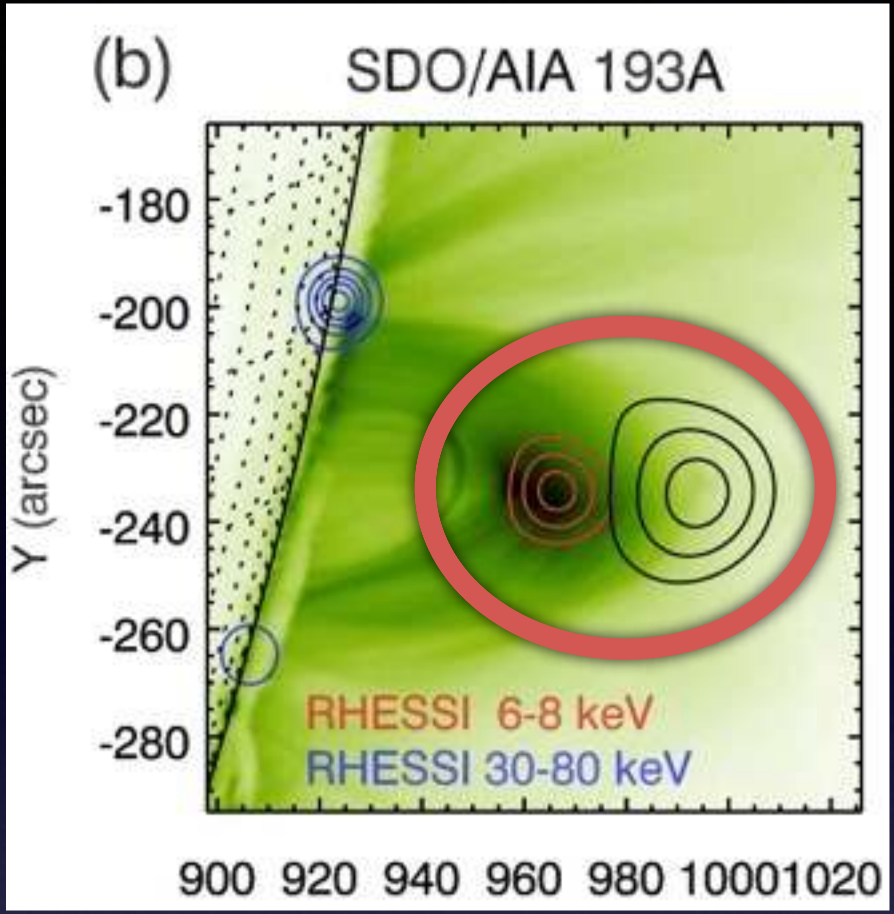
Contamination
from the adjacent source

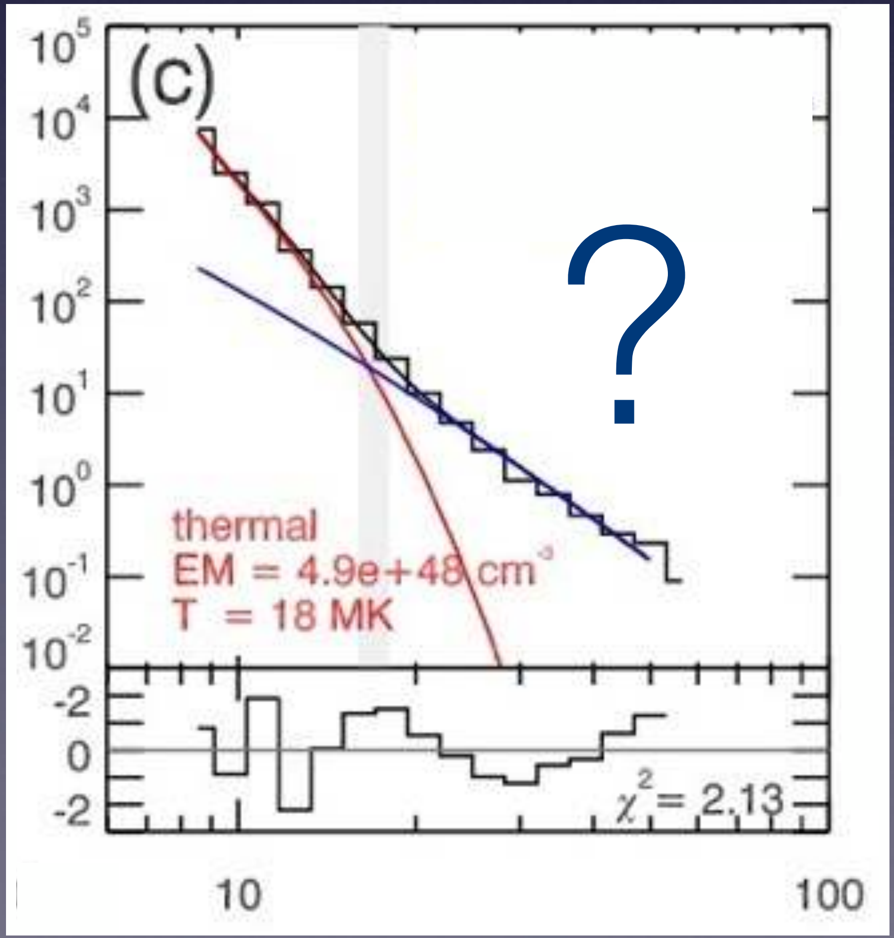




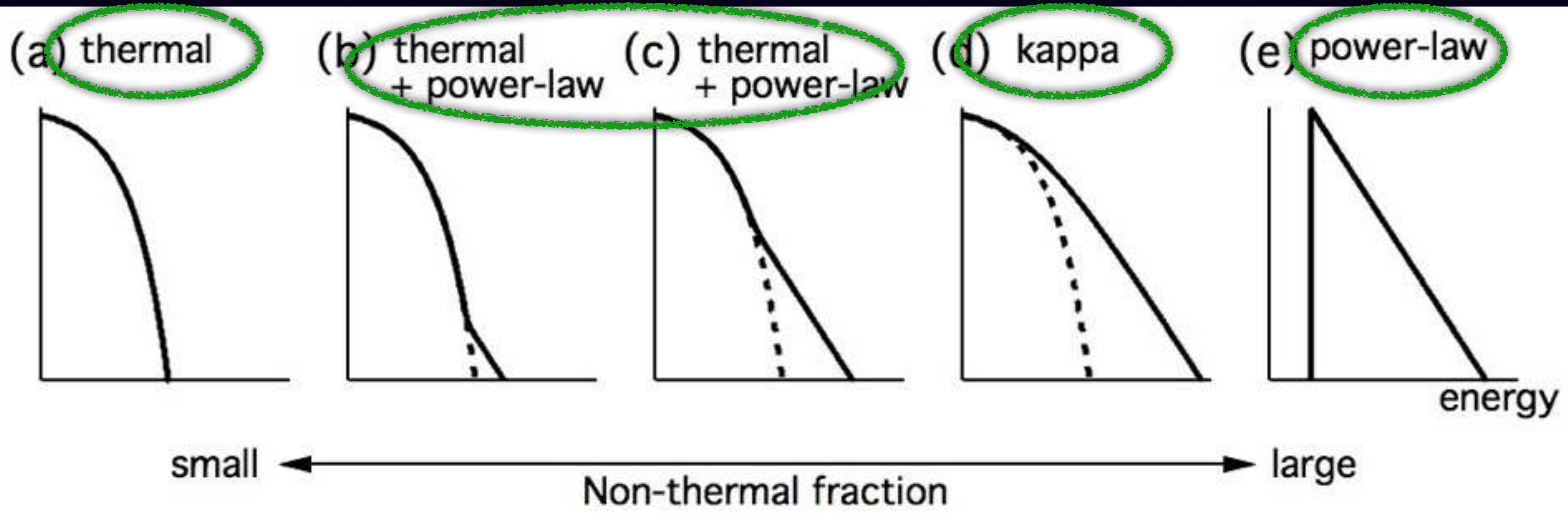
Contamination
from ALT

- 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



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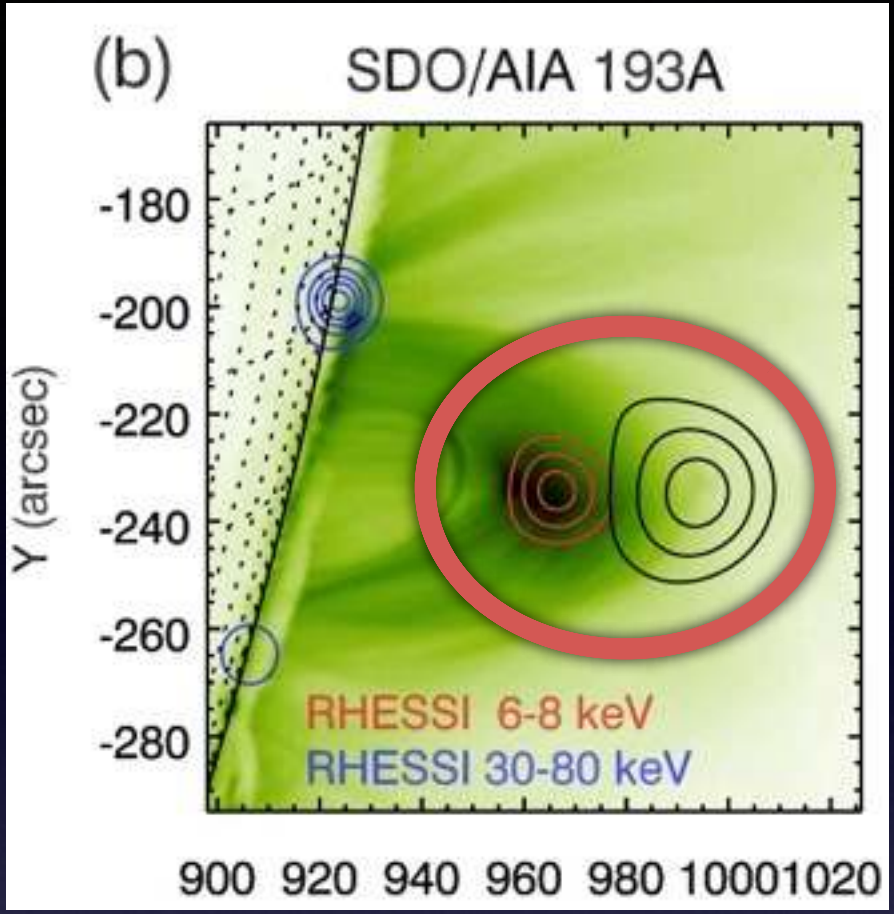
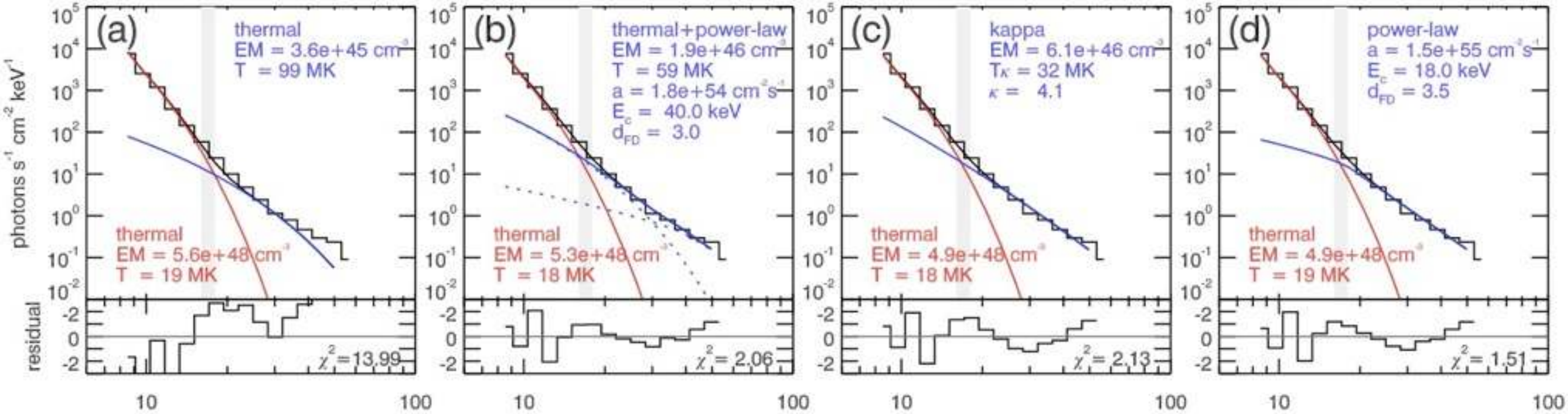
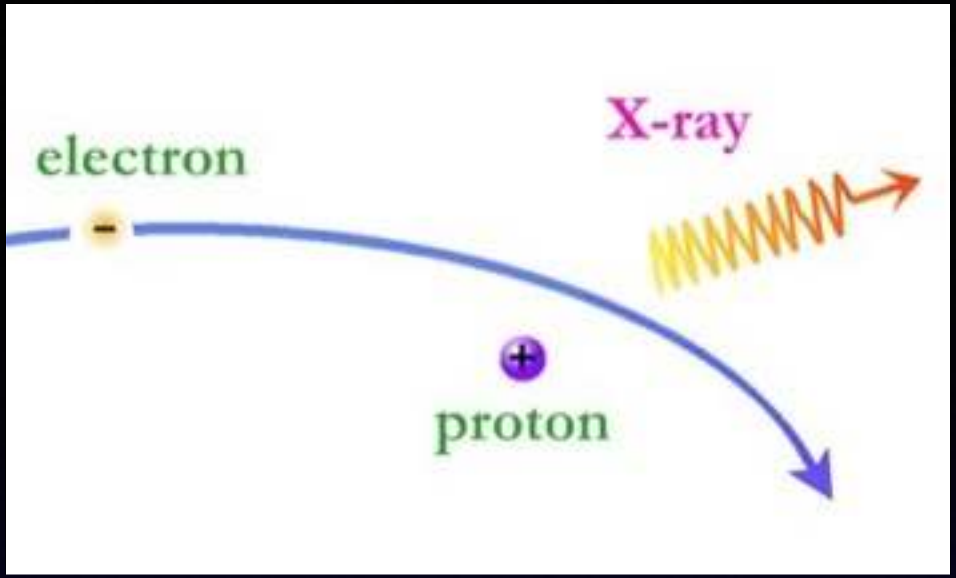




$R_\varepsilon \sim 0\%$ $R_\varepsilon \sim 1\%$ $R_\varepsilon \sim 50\%$ $R_\varepsilon \sim 100\%$

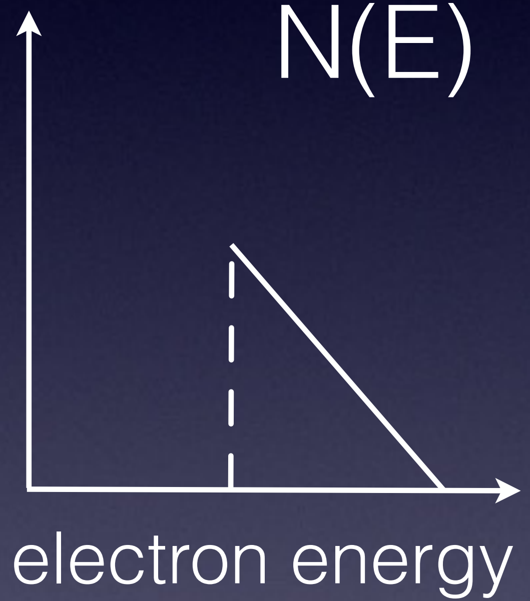
Bremsstrahlung

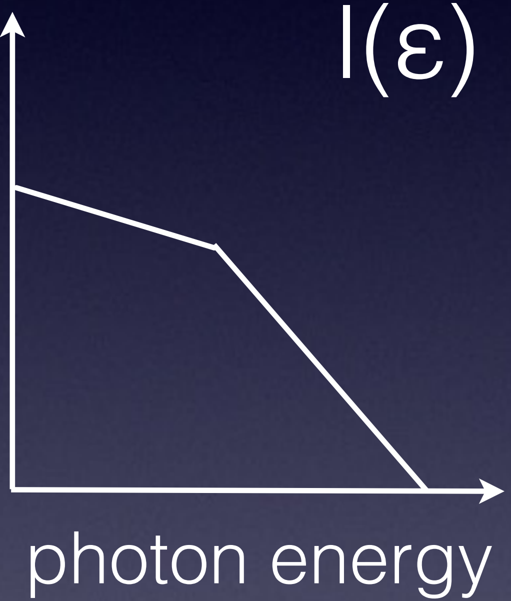


http://www.astro.wisc.edu/~bank/

The high energy electron gradually looses its energy.

Accordingly, the energy of emitted photon decreases.





Bethe-Heitler cross section

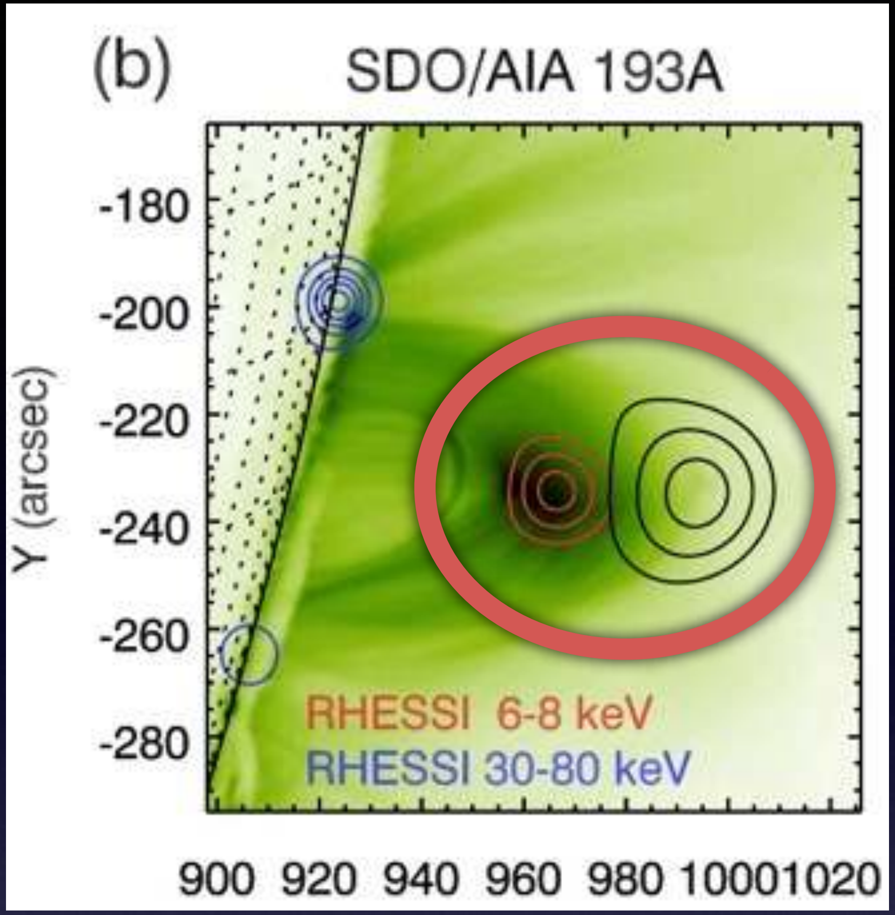
Required for an electron (E) to emit a photon (ε)

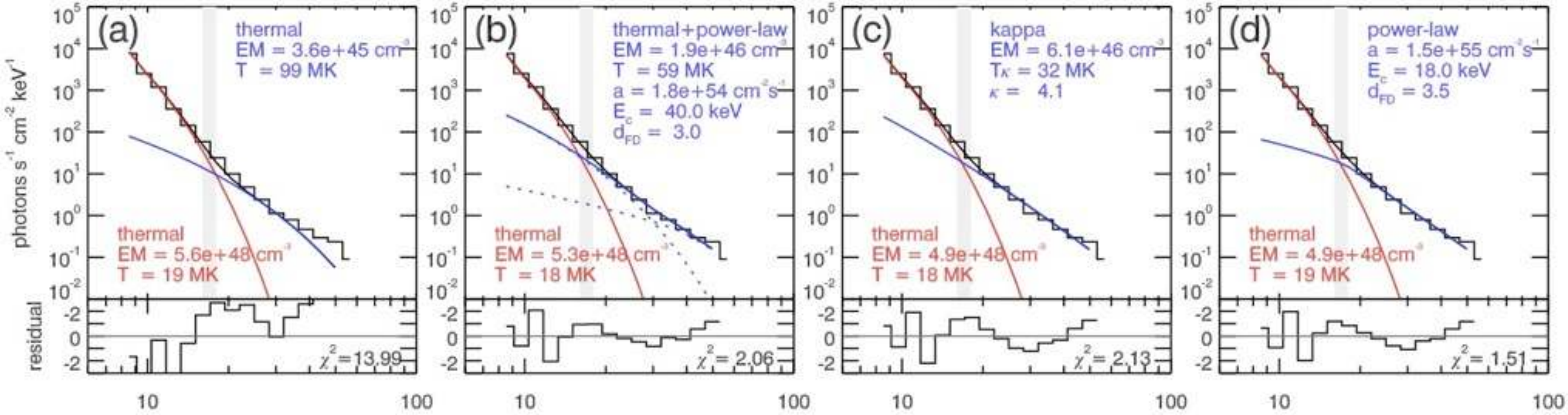
$$Q_\varepsilon(E) = \frac{8}{3}\frac{r_0^2}{137}\frac{mc^2}{\varepsilon E}\log\frac{1+\sqrt{1-\varepsilon/E}}{1-\sqrt{1-\varepsilon/E}}$$

The total X-ray emission I(ε)

$$\int_\varepsilon^\infty Q_\varepsilon(E)\, v(E)\left(\int_V n_p n(E)\, \mathrm{d}V\right) \mathrm{d}E \quad \text{(photons/sec per unit } \varepsilon)$$

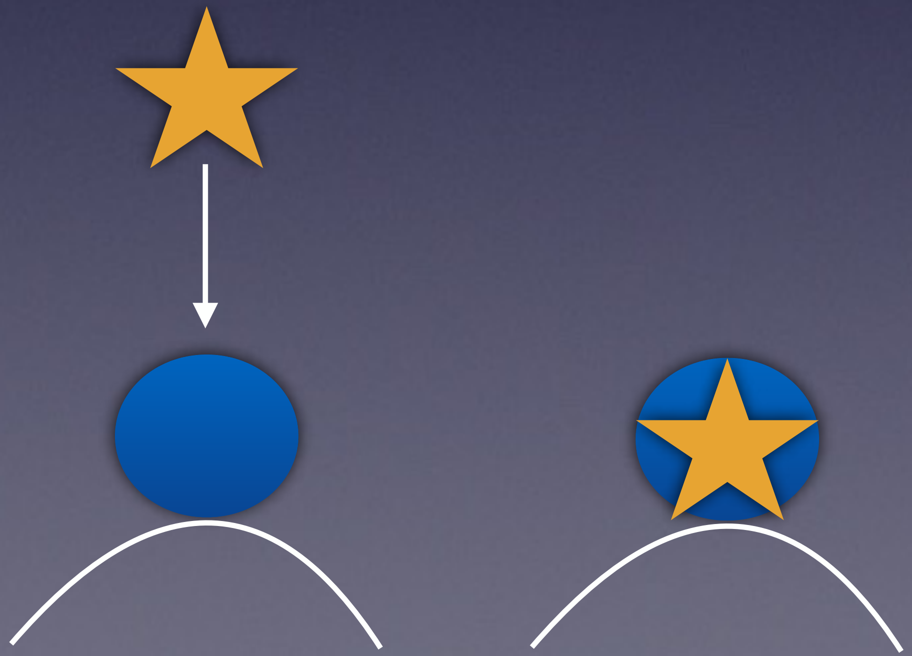
- Combine photons from both sources to generate a spectrum
- Combine two separate spectral models to fit the data
  - Use Maxwellian for looptop
  - Use different models for ALT
  - Ignoring fine structures in each source





R_ε ~ 0% R_ε ~ 1% R_ε ~ 50% R_ε ~ 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 $\tau_{RHESSI} \sim 4s \sim 10^6 \omega_{pe}^{-1}, 10^6 \Omega_{ce}^{-1}$)?



external acceleration scenario

local acceleration scenario

Outline

- Introduction
- Analysis
- **Discussion of flare scenario**
  - Energy Partition
  - Energergization 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— **κ ~ 3.8**, R_ε ~ 51%
- 2012 Jul 19 — **κ ~ 4.1**, R_ε ~ 49%
- 2003 Oct 22 — **κ ~ 5.8**, R_ε ~ 36%

- 2003 Nov 18 — **κ ~ 8**, R_ε ~ 27%
- 2013 May 13 — **κ ~ 14**, R_ε ~ 16%

  - Upper-limit at R_ε ~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— **κ ~ 3.8**, R_{ε} ~ 51%
- 2012 Jul 19 — **κ ~ 4.1**, R_{ε} ~ 49%
- 2003 Oct 22 — **κ ~ 5.8**, R_{ε} ~ 36%

flat

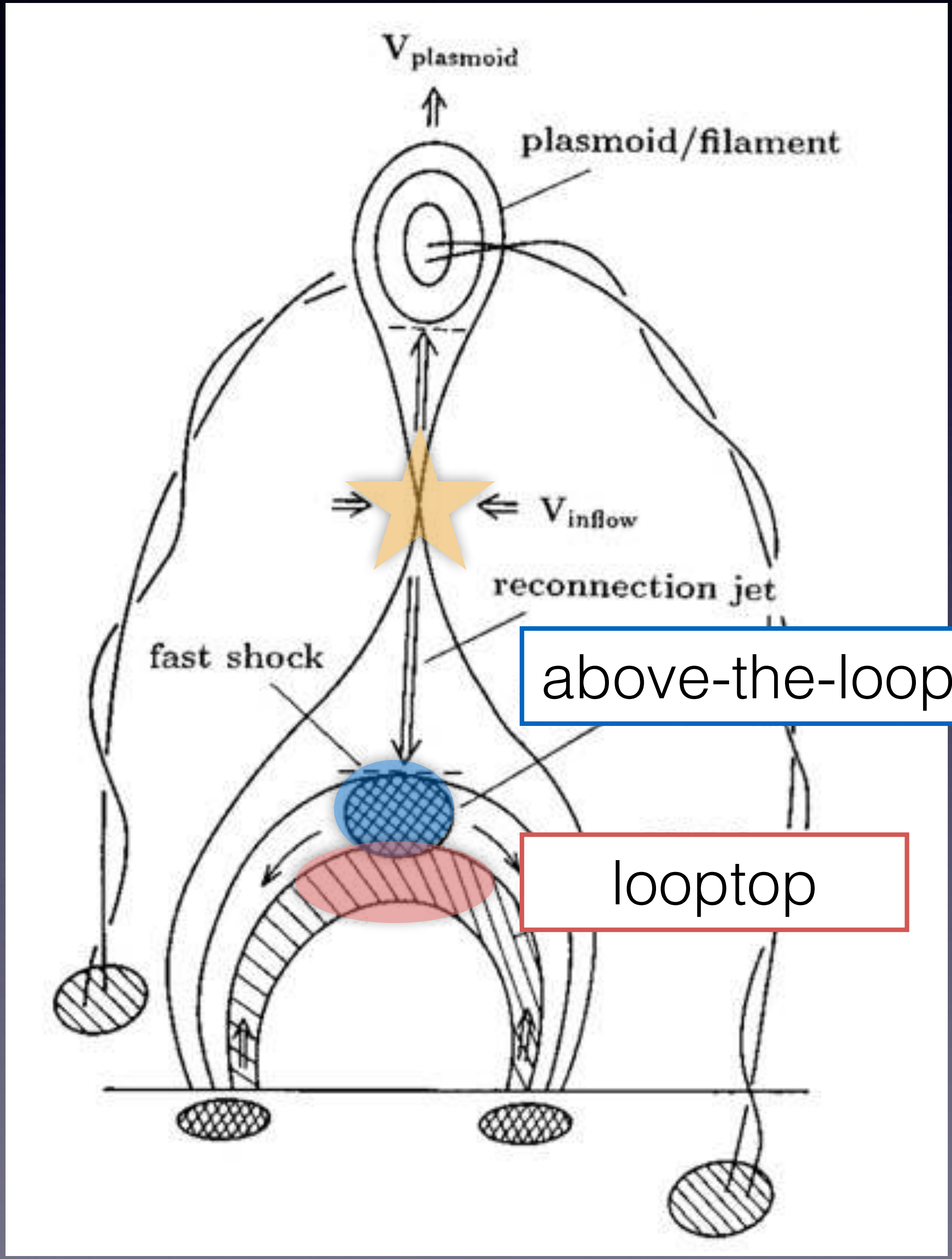
steep

- 2003 Nov 18 — **κ ~ 8**, R_{ε} ~ 27%
- 2013 May 13 — **κ ~ 14**, R_{ε} ~ 16%

Why flat and steep cases?

Let us first consider flat cases…
(energization mechanism)

Energization Mechanism?



above-the-looptop (ALT)

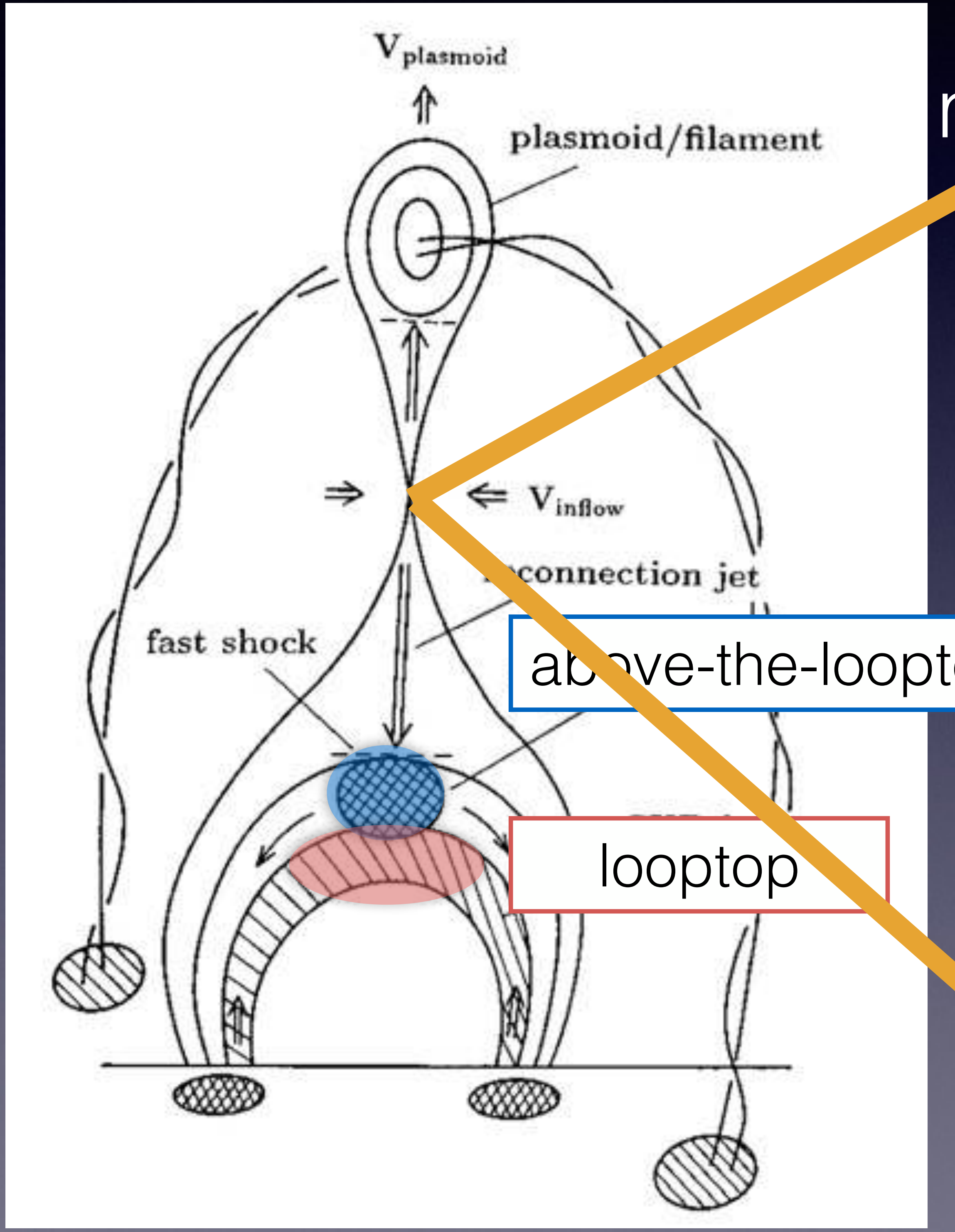
looptop

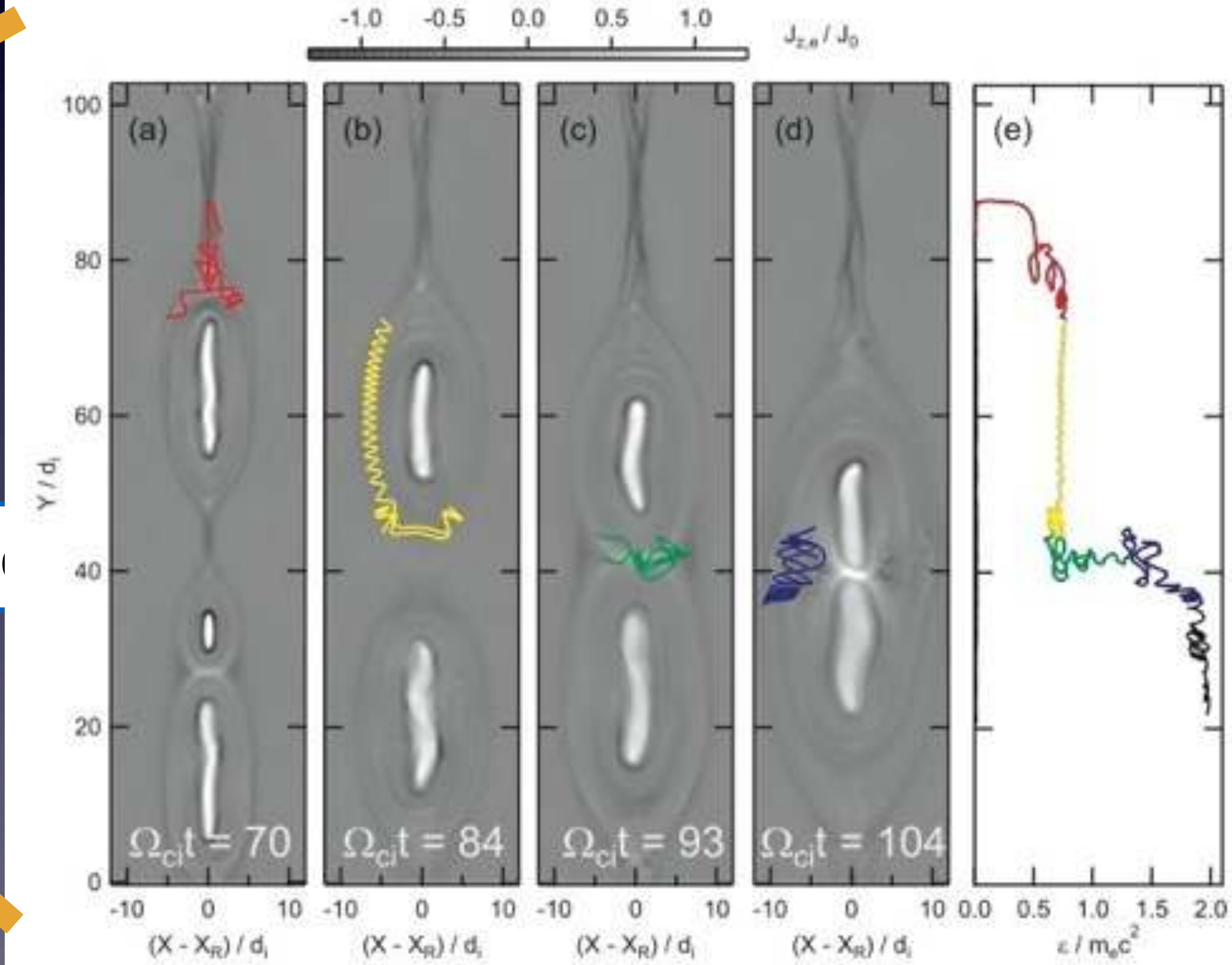

betatron collapsing–trap
contracting–island drift DSA Fermi fractal
islands parallel–electric–field potential
shock stochastic Super–Dreicer–field
turbulence

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

PIC Simulation

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





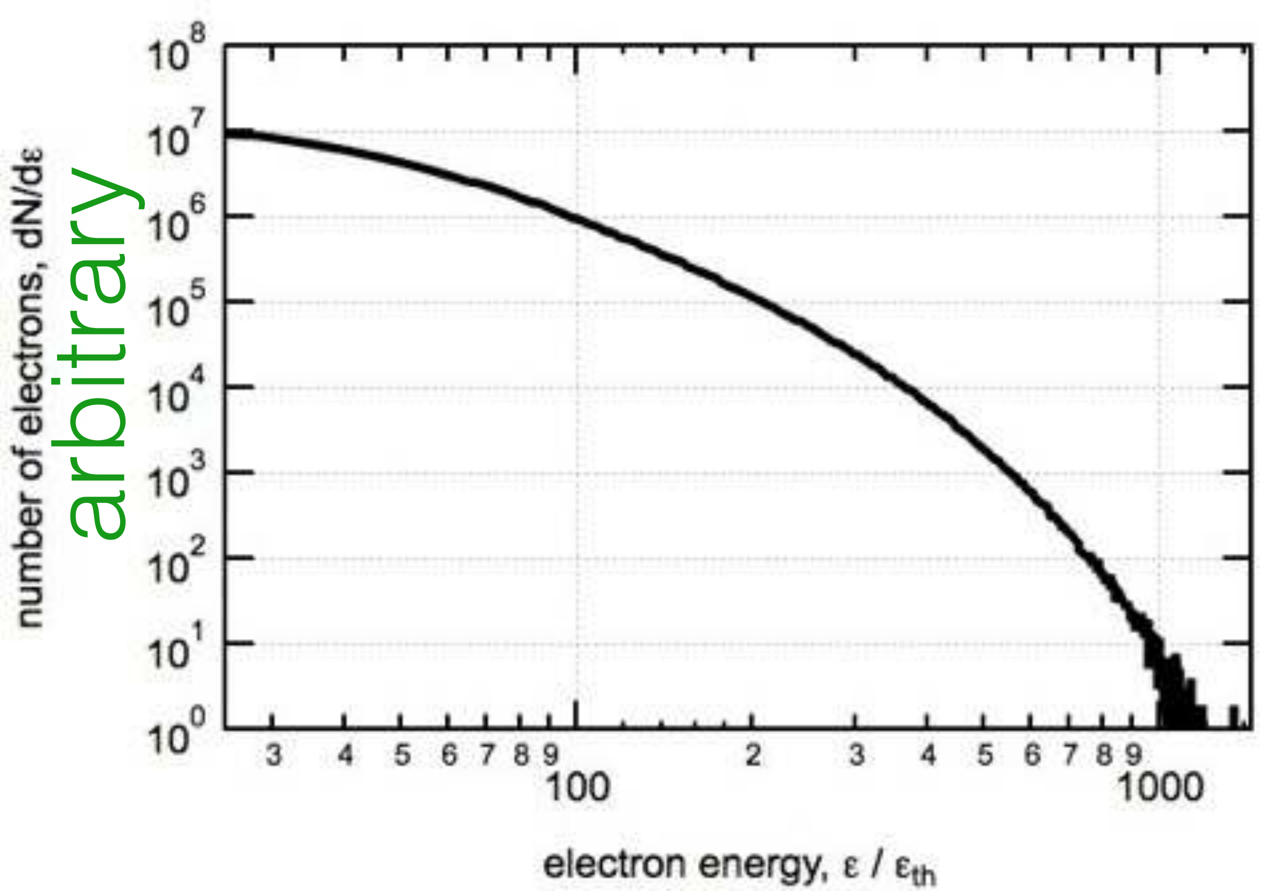
Oka et al. 2010

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.

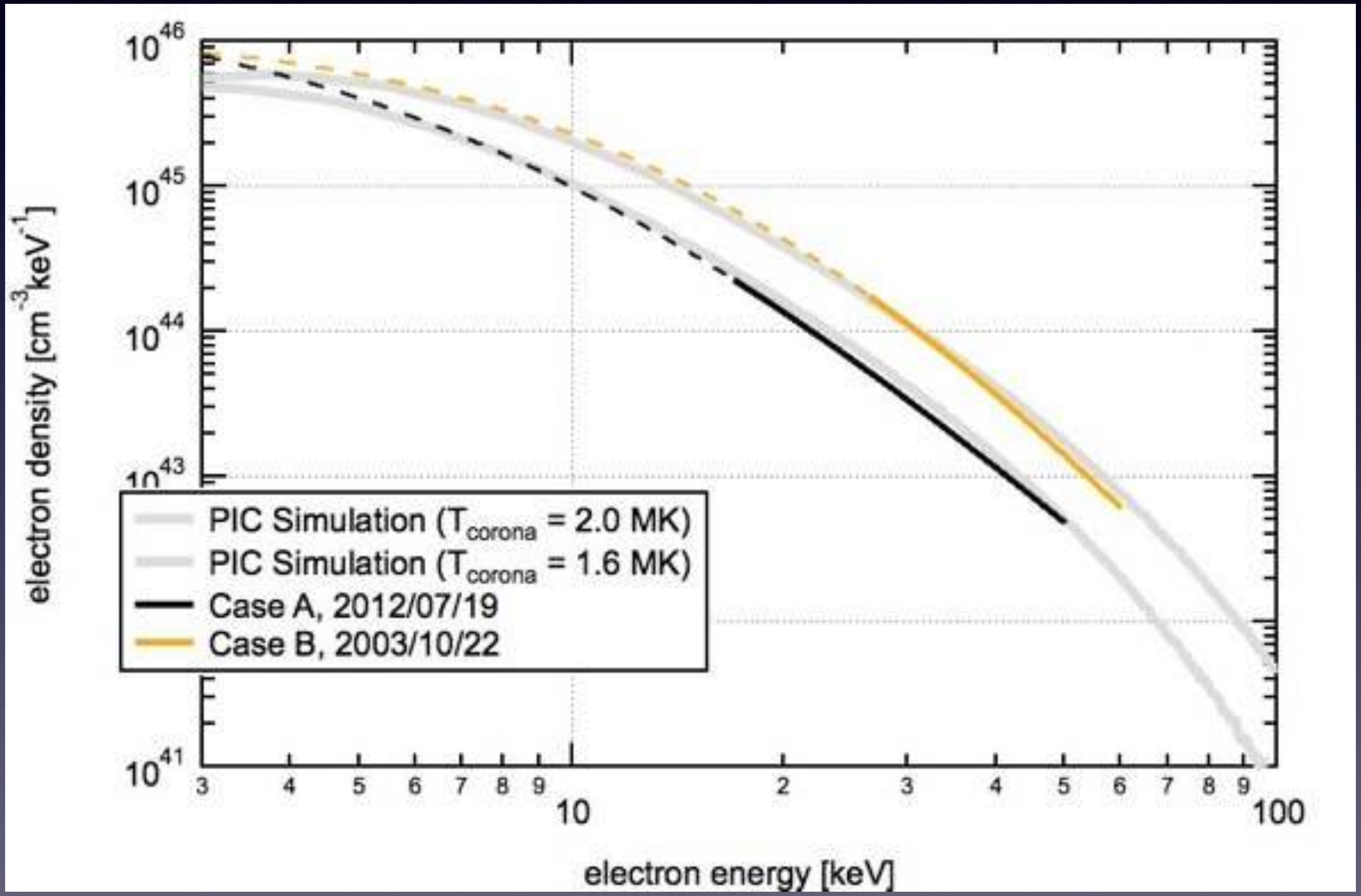
Particle energies normalized by the initial thermal energy of the current sheet.



- 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 x 100 d_i)
- $m_i/m_e = 25$
- and many more !!!!

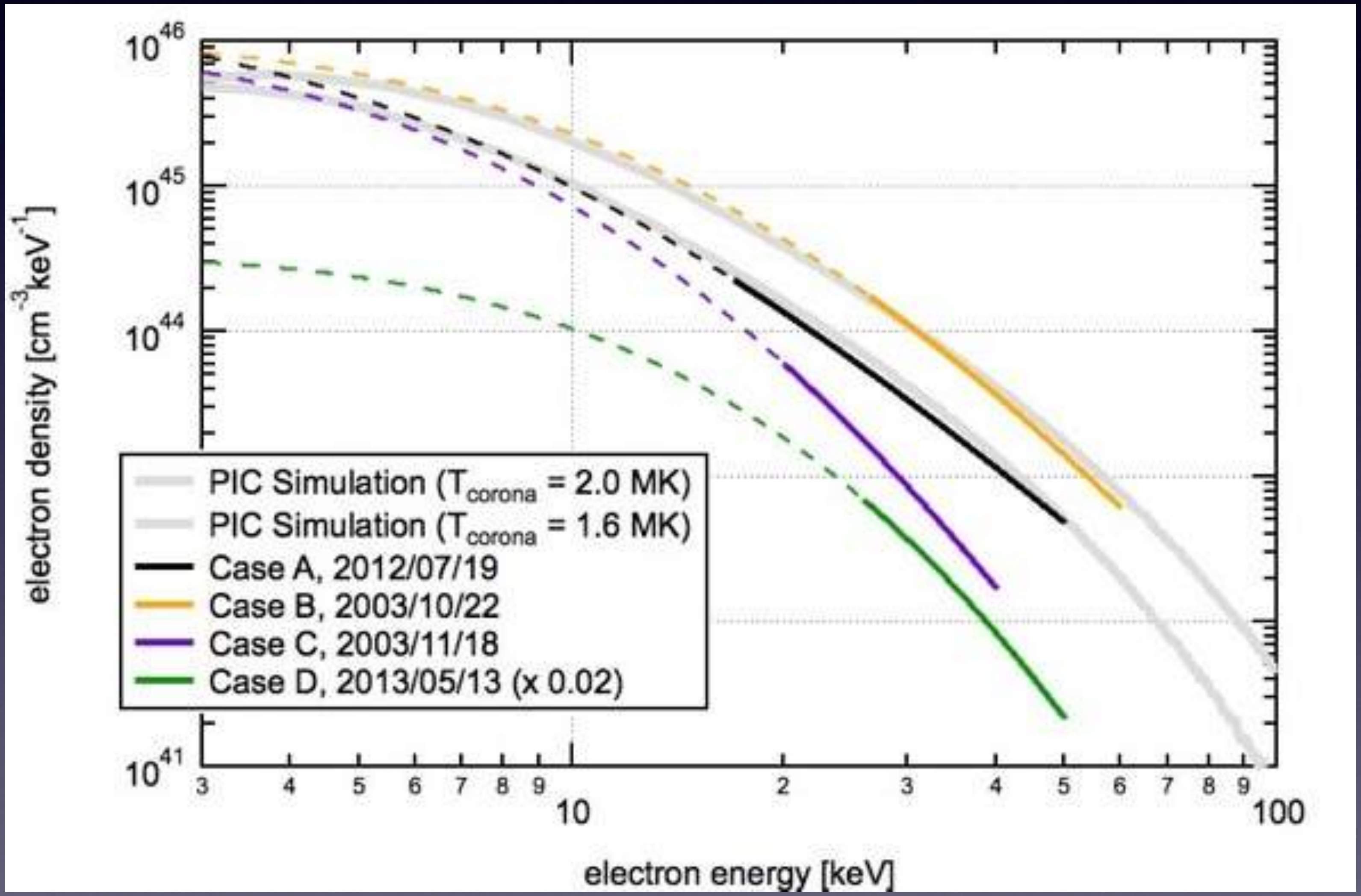
- In future studies, we need to take into account other theoretical ideas
  - Transport from RX region to ALT region (e.g. Somov et al. 1997)
  - Multi-island model (e.g. Tajima & Shibata, 2002; Drake+, 2006)
  - turbulence (e.g. Miller+, 1997)
  - fast-mode termination shock (if existed) (e.g. Masuda+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

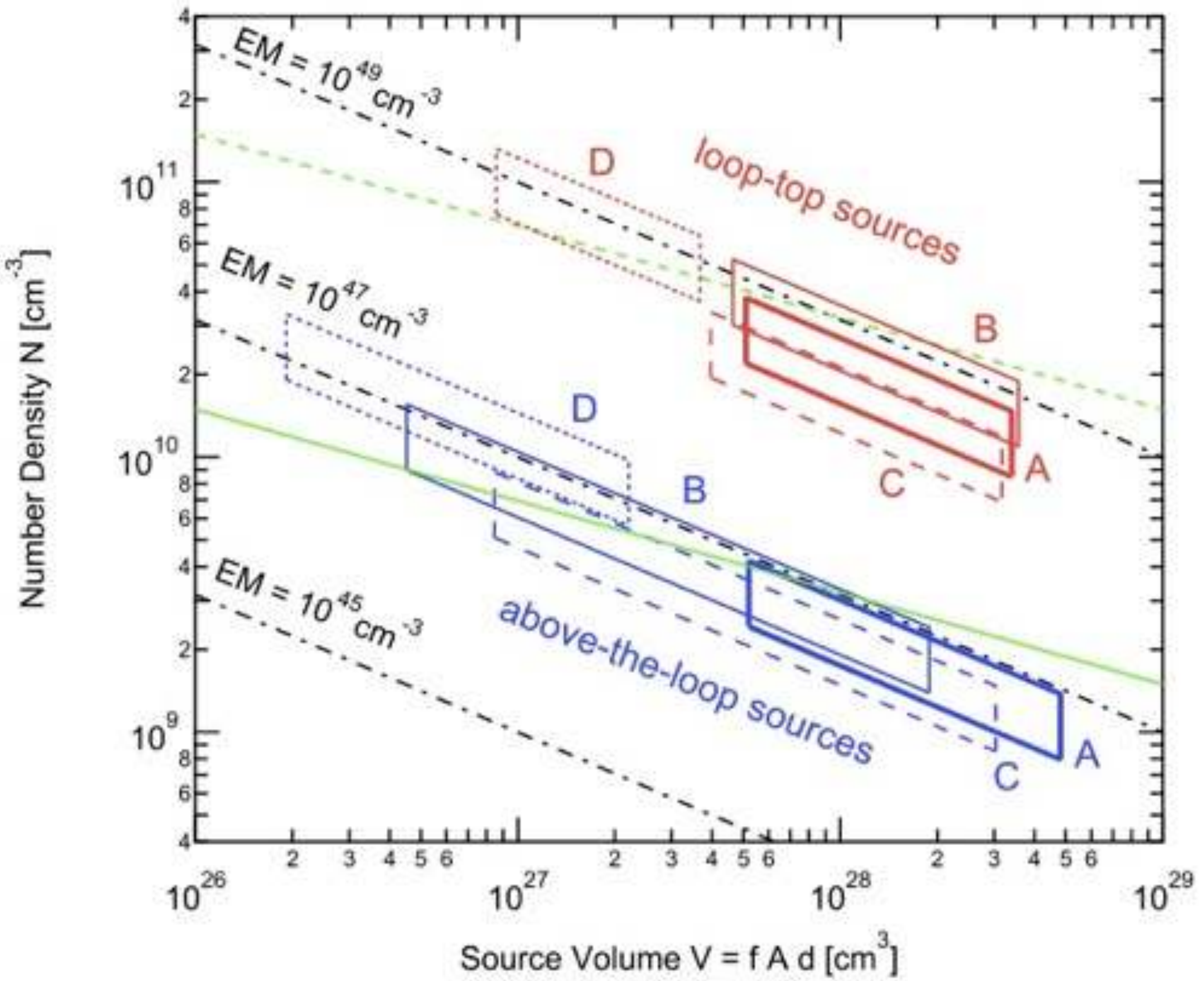
‘Steep’ events are actually equally energetic (i.e. high temperature)

magnetic reconnection may still be important for energization.



Collisionality

For 30 keV electrons to be collisional…..



For the source to be collisional,

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

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

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

Then, the critical density becomes

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

30 keV electrons with **turbulent scattering** become collisional above the solid line $\lambda_{\rm mfp} \sim 0.1\ \lambda_{\rm mfp,coll}$

Conclusion

- **Kappa distribution works — R_ε ~ 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.

Oka et al. ApJ 799:129, 2015