Non-thermal Emissions from Cluster Cores

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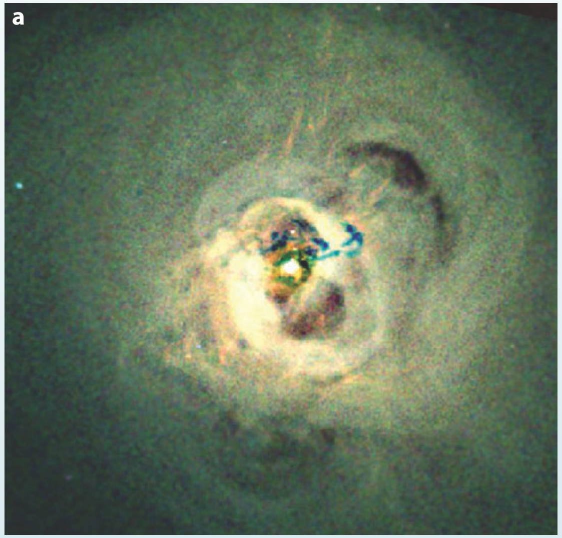
Outline

- Observations of non-thermal emissions from cluster cores
- Origin of non-thermal emissions
- Turbulence and heating of cluster cores

Observations of non-thermal emissions from cluster cores

Cluster cores

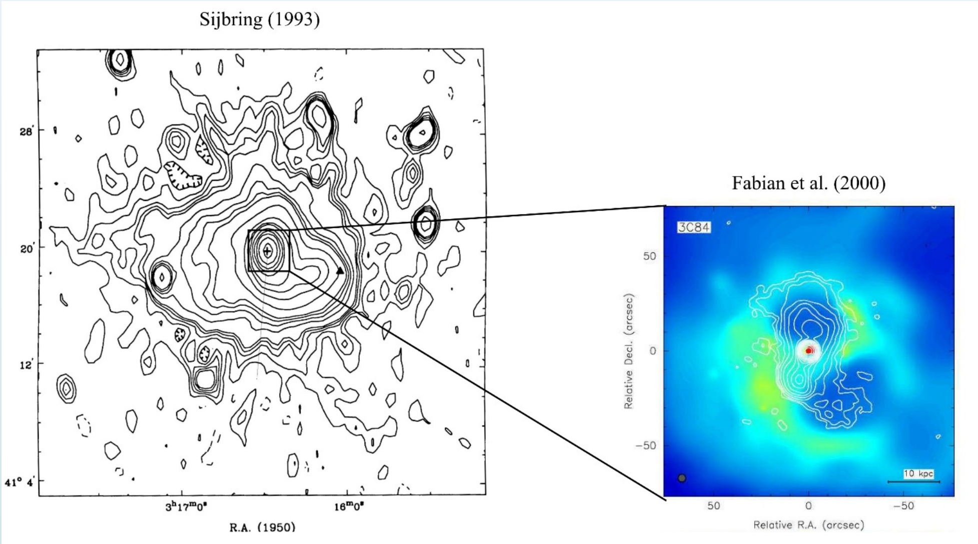
- Region within ~100 kpc from the cluster center
- Bright in X-rays
  - High gas density (~ 0.1 cm^{-3})
- Low temperature
  - ~1/3 – 1/2 of the surroundings
- Cooling time
  - ~ 10^{8-9} yr
  - Much smaller than the cluster age
  - There must be a heating source
- AGN activities are often seen



Core of the Perseus Cluster
(Fabian at al. 2012)

Non-thermal emissions from cores

- Radio observations
  - Mini-halos
    - Diffuse synchrotron emission
    - Comparable to the size of a core (~ 100 kpc)
    - Rare, but the number is increasing (Giacintucci et al. 2013)

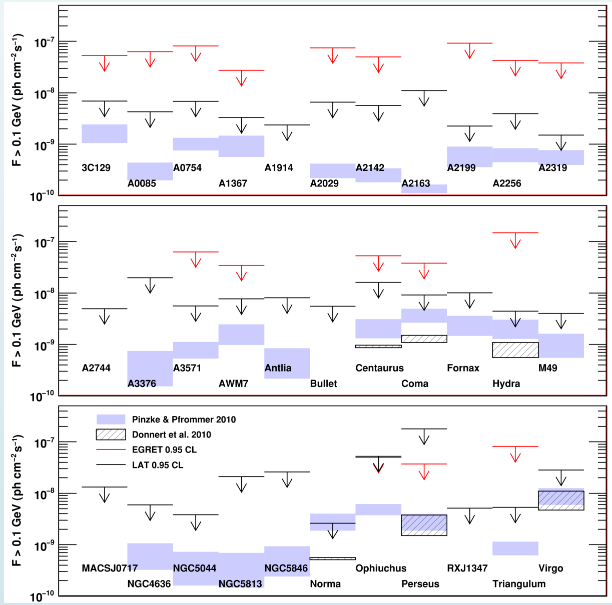


Gitti et al. (2003)

Non-thermal emissions from cores

- X-ray observations
  - Controversial, but probably not detected
    - Chandra (Sanders et al. 2005)
    - XMM-Newton (Molendi, & Gastaldello 2009)

- Gamma-ray observations
  - Not detected



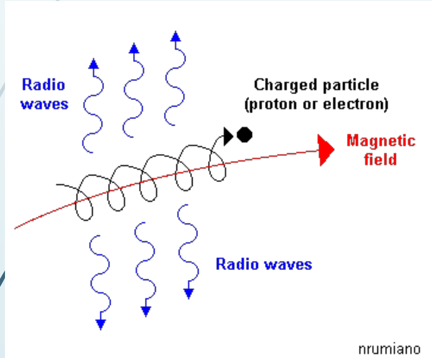
Ackermann et al. (2010)

Origin of non-thermal emissions

Non-thermal emissions from cosmic-rays

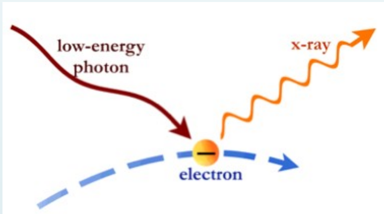
- Cosmic-rays (CRs) produce emission through various mechanisms

Synchrotron emission



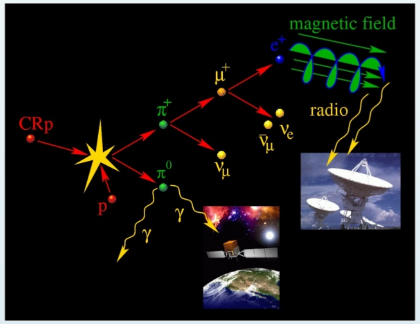
Radio

Inverse Compton (IC) scattering



X-ray

p-*p* interaction (π^0-decay)



CR proton – ICM proton

γ-ray

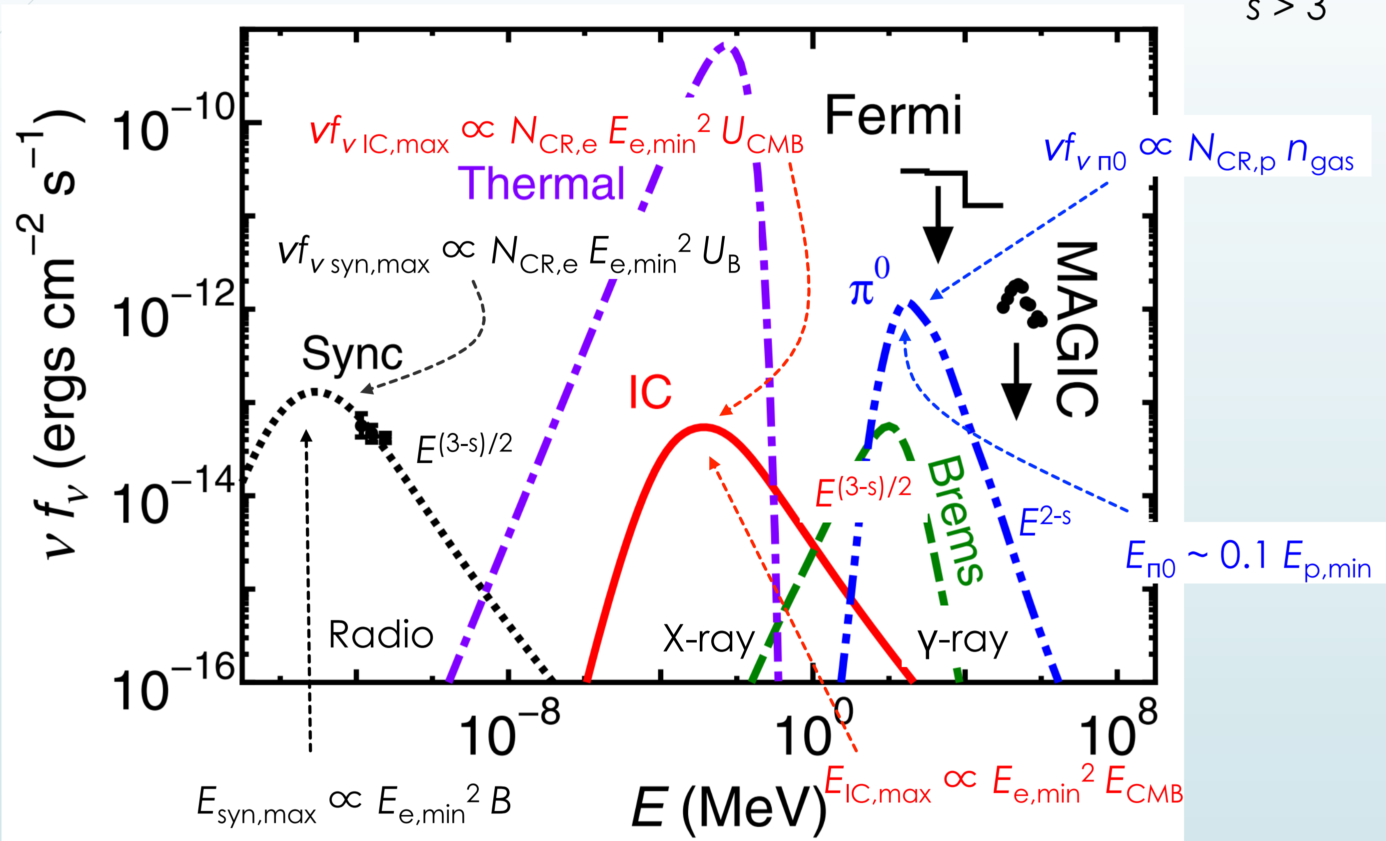
Second electrons are also created
→ Synchrotron, IC

Non-thermal emissions from cores

- Fujita & Ohira (2012, 2013)

$dN_{CR,e,p}/dE \propto E^{-s}$

$s > 3$



What do the observations mean?

- No detection of gamma-rays
  - Number of cosmic-ray protons is not large
- No detection of hard X-rays
  - Weak IC emission
  - $U_B = U_{CMB}\, \nu f_{\nu\, \mathrm{syn,max}} / \nu f_{\nu\, \mathrm{IC,max}}$
    - Strong Magnetic fields ([illegible] μG)
- It would be difficult to detect hard X-rays with Astro-H
  - It is unlikely that $B <$ μG in cores
- It would be difficult to detect TeV gamma-rays with CTA
  - It is unlikely that cosmic-ray spectrum is hard in clusters
  - Shocks are weak, and turbulent acceleration is not so efficient
- SKA observations are important to know $E_{e,\mathrm{min}}$

What is the origin of synchrotron emission?

- Electron energy ($E_e = \gamma\, m_e\, c^2$)

$$\gamma \approx 10^4 \left(\frac{B}{5\mu\mathrm{G}}\right)^{-1/2} \left(\frac{\nu}{1.4\mathrm{GHz}}\right)^{1/2}$$

- Primary electrons
  - Electrons directly (re)accelerated at shocks or turbulence
- Secondary electrons
  - Pions are created via *p-p* interaction, and electrons are generated

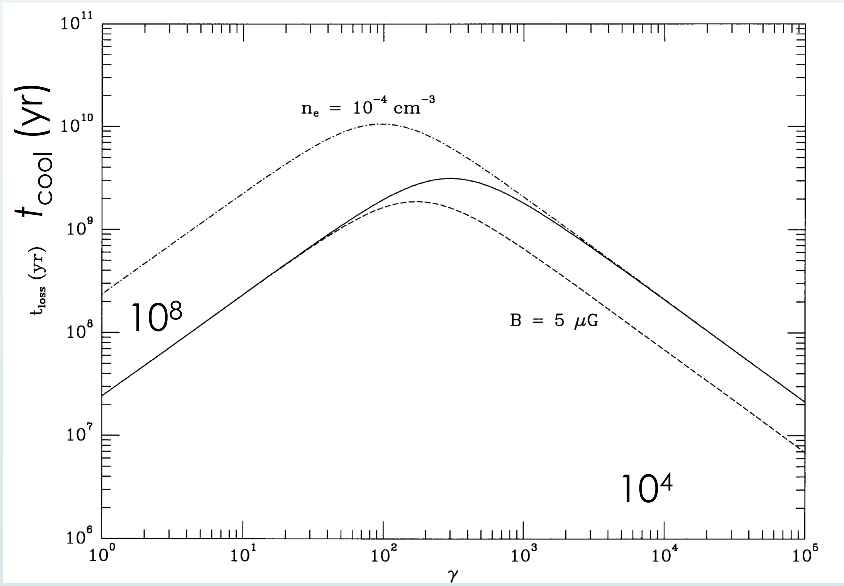
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \rightarrow e^{\pm} + \nu_e/\bar{\nu}_e + \nu_{\mu} + \bar{\nu}_{\mu}$$

  - Protons must have been accelerated
  - Lower energy cutoff ($m_{\pi}c^2$ = 140 MeV) → SKA

Cooling time of electrons

- Cooling time of cosmic-ray elections is much shorter than the age of clusters ($\sim 10^9$ yr)
  - $t_{cool} \sim 10^8$ yr

Cooling time of electrons



Sarazin (1999)

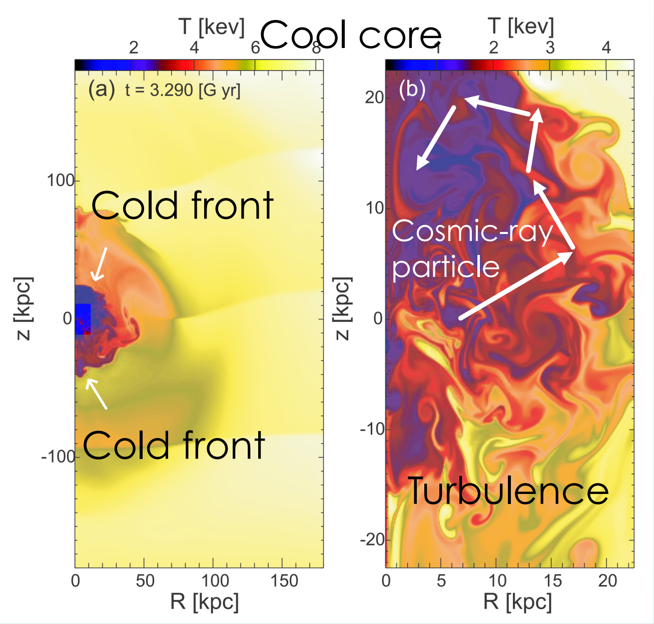
$\gamma = E_e/m_e c^2$

Cooling time of electrons

- The short cooling time constrains the acceleration of the electrons
- If the central AGN is the source of the electrons, the diffusion scale of the elections is
  - $r_{\rm diff} = \sqrt{t_{\rm cool}\, L\, V}$ ~ 20 kpc < mini-halo size (~100 kpc)
    - Diffusion by turbulence
    - *L*: Eddy size, *V*: Eddy velocity
    - $t_{\rm cool}=10^8$ yr, L=10 kpc, V=300 km s^{-1}
  - The electrons cannot cover the mini-halo
- In situ acceleration model (for primary electrons) or secondary electron model are required
  - Cosmic-ray protons do not cool

In situ acceleration

- Elections are reaccelerated by turbulence developing in a core (e.g ZuHone et al. 2013)
  - Second order Fermi acceleration
    - Slow acceleration

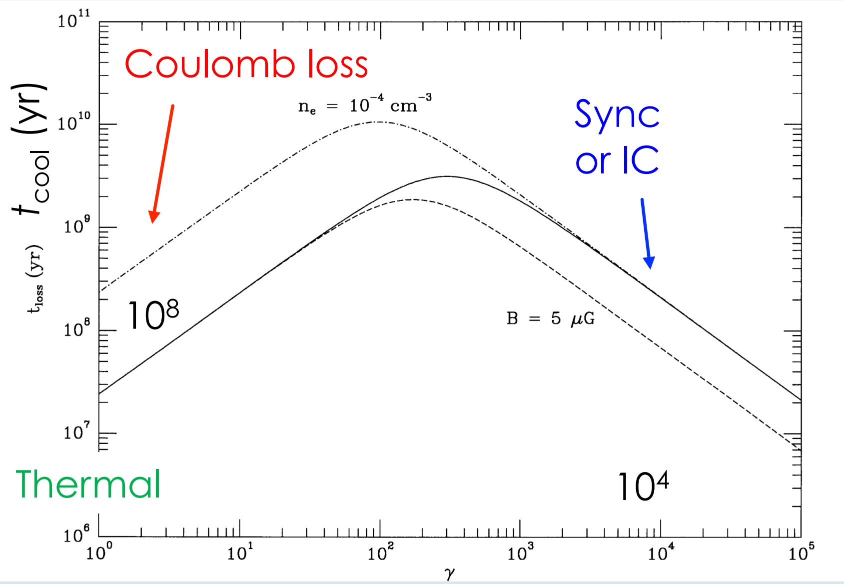


Fujita, Matsumoto, & Wada (2004)
c.f. Ascasibar & Markevitch (2006)

Why 're'acceleration?

- If thermal electrons are accelerated, they have to break through the 'Coulomb loss barrier'
  - Coulomb interaction with thermal electrons cause energy loss
  - It is generally difficult to overcome it for turbulent acceleration

Cooling time of electrons



Sarazin (1999)

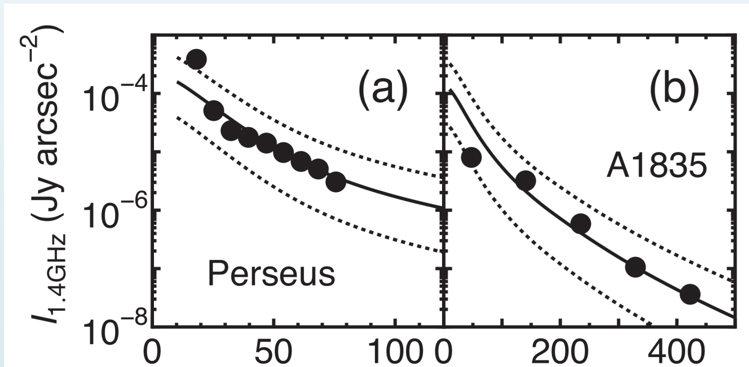
$\gamma = E_e/m_ec^2$

Seed electrons

- Turbulent acceleration models assume the existence of seed cosmic-ray elections
  - $\gamma \sim 100$
  - $t_{\rm cool} \sim 10^9$ yr
    - They tend to accumulate in clusters
- The origin of the seeds has not be considered in detail
  - Electrons accelerated at shocks generated by cluster mergers?
  - Secondary electrons?

Secondary electron models

- Electrons are created via *p-p* interaction
- Since proton cooling can be ignored, protons accumulated in a core keep creating the electrons
- Proton accelerators
  - AGNs
    - Jets may include protons
    - Interaction between jets and ICM
  - Cluster mergers

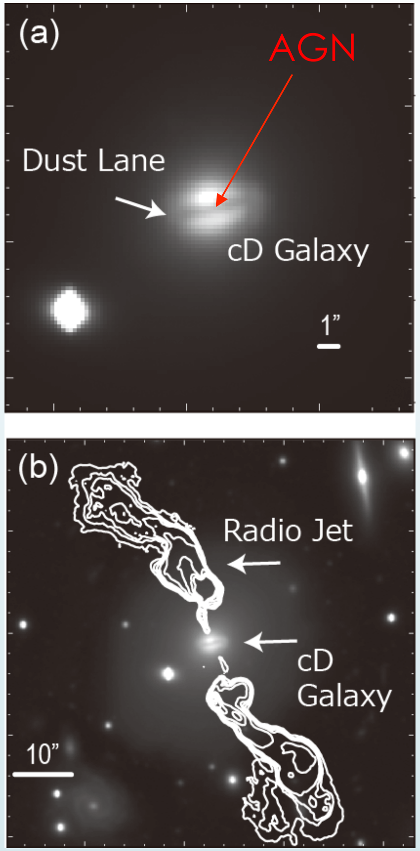


Fujita & Ohira (2013)

Turbulence and heating of cluster cores

AGN Heating

- Cluster cores must have been heated by something
  - AGNs are the most popular candidate of the heating source
- Energy transfer from the AGN to the ICM
  - Mechanical heating?
    - Shocks, sound waves…
    - It has a serious problem



Hydra A
(Fujita et al. 2013)

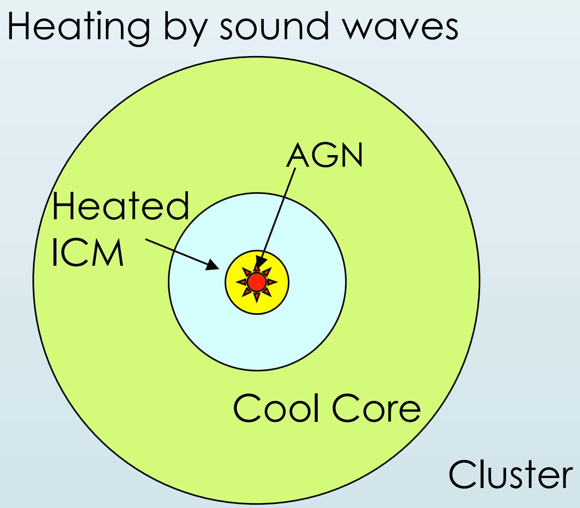
Formation of Weak Shocks

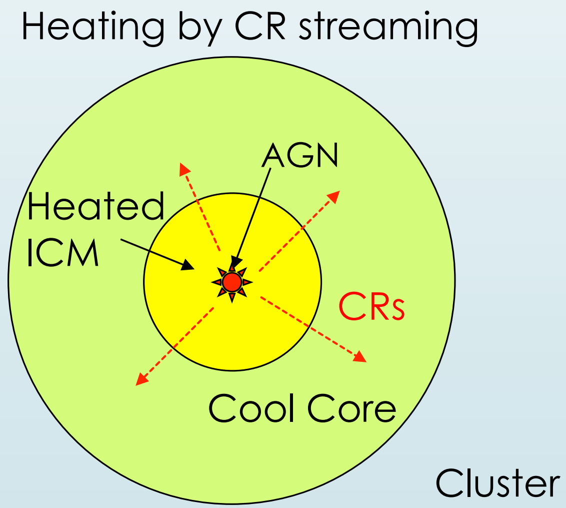
- If the amplitude of waves is large (δv [illegible] $0.1 \times$ sound velocity), the waves rapidly (within a few wave lengths) steepen, and become nonlinear weak shocks
  - e.g. Fluid Mechanics (Landau and Lifshitz)

- Once weak shocks are formed, the wave energy is dissipated at the shock fronts
  - This dissipation is very fast (~10 kpc << core size)
  - In the case of the Perseus cluster, the observed sound waves should soon become weak shocks or they have already become weak shocks.
- Solar corona (Stein & Schwartz 1972; Suzuki 2002)

Localness of Heating

- Heating by sound waves is unstable
  - Heating is localized (Fujita & Suzuki 2005)
- We consider another solution
  - Cosmic-ray (CR) streaming
    - Heating is not localized
      - Rephaeli 1979; Böhringer & Morfill 1988; Loewenstein et al. 1991; Guo & Oh 2008





How to revive the mechanical heading

- Cool cores are unstable
  - However, cooling flows are suppressed in almost all cores
    - Probably, heating is stable
- Strong turbulence in the whole core
  - Mix the ISM and prevent local heating and cooling

Summary

- Observations of non-thermal emissions from cluster cores
  - Radio mini-halos are observed
  - Hard X-rays and gamma-rays have not been confirmed
- Origin of non-thermal emissions
  - Electrons (primary, secondary)
    - Synchrotron radio emission
    - Inverse Compton scattering (Hard X-rays)
  - Protons
    - π^0-decay gamma-rays (*p*-*p* interaction)
    - Production of secondary electrons

Summary

- Short cooling time of CR electrons constrain CR acceleration models
  - Turbulent acceleration
    - Seed electrons are required
  - Secondary electrons (proton origin)
- Turbulence is related to core heating