# Multi-wavelength emission from Jets and Magnetically Arrested Disks in Radio galaxies

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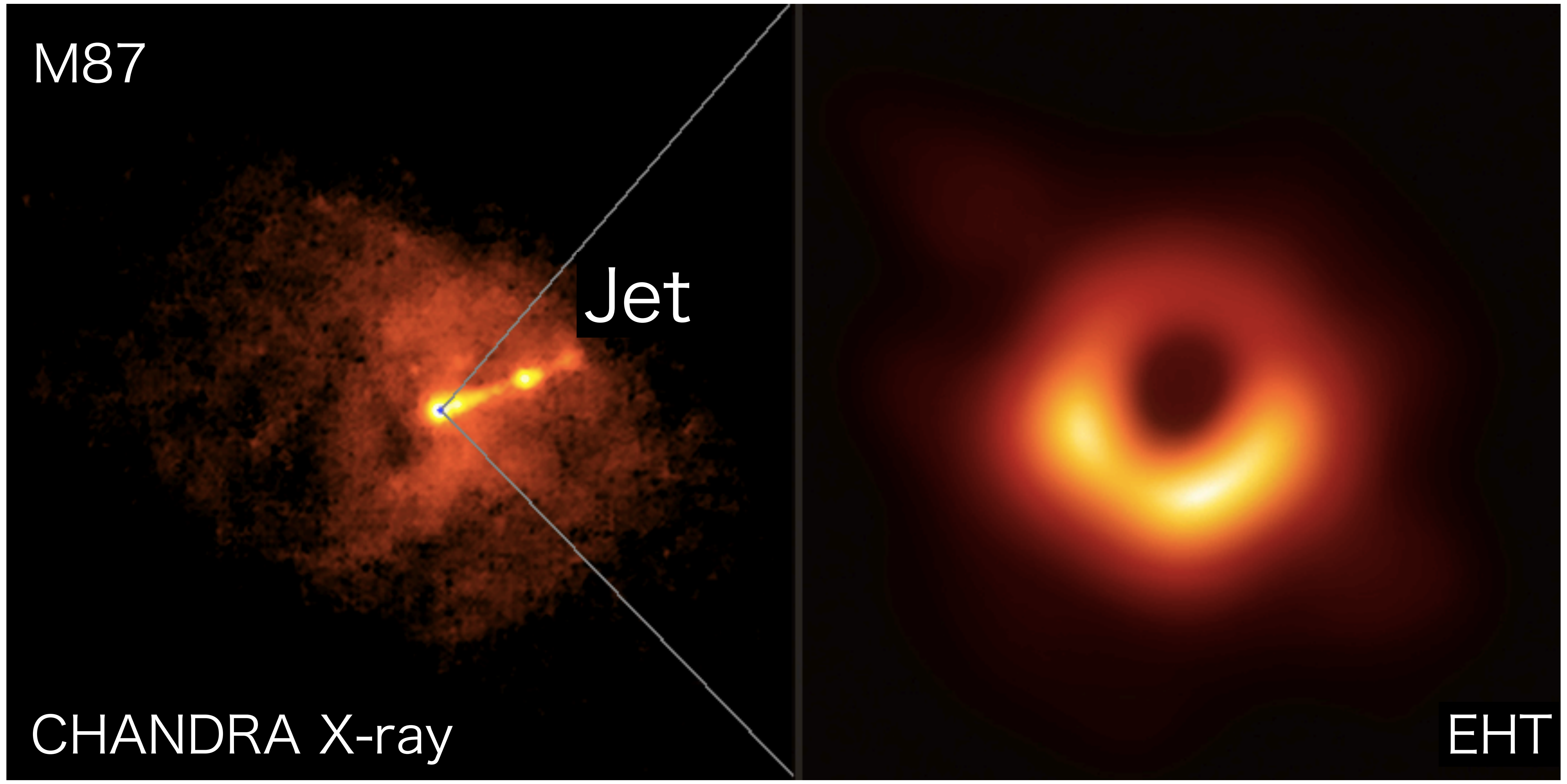
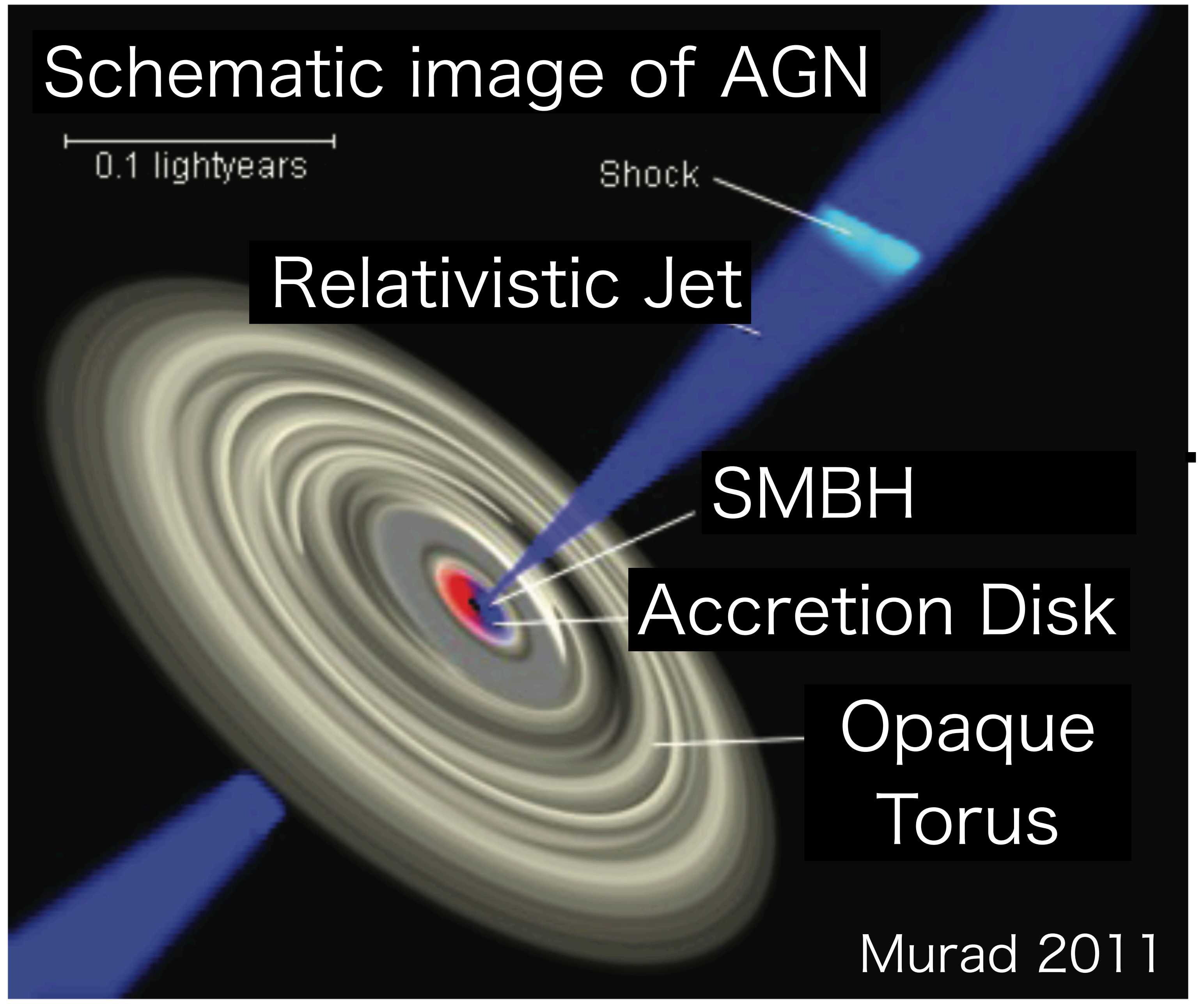
# Radio Galaxies






Blazar

Radio Galaxy

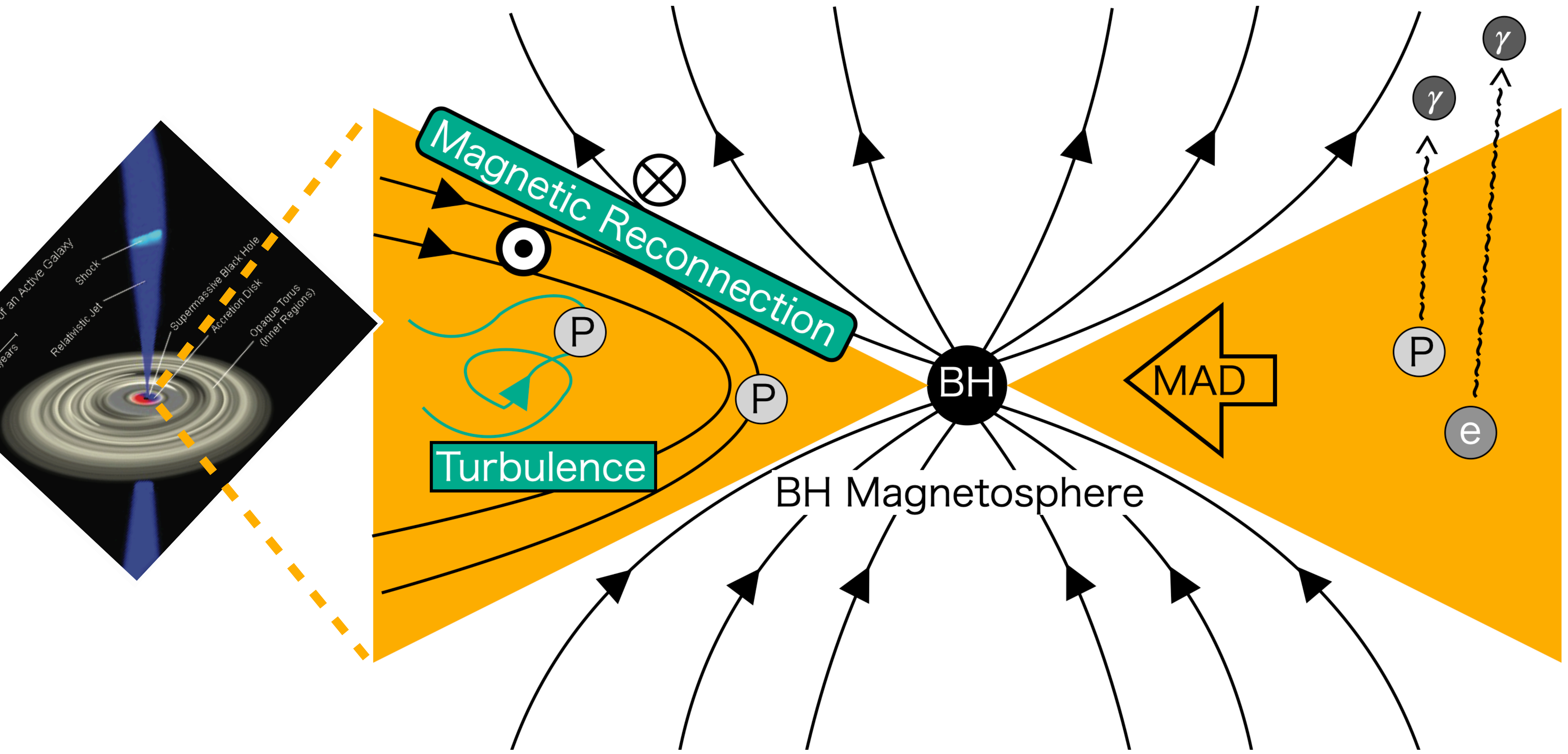
- ✔ Radio-loud AGNs (10% of all AGN) -> **Strong relativistic jet.**
- ✔ **Radio ~ GeV-TeV gamma-rays** are observed in nearby some radio galaxies.
- ✔ **Multi-wavelength emission mechanism and region are still unknown.**

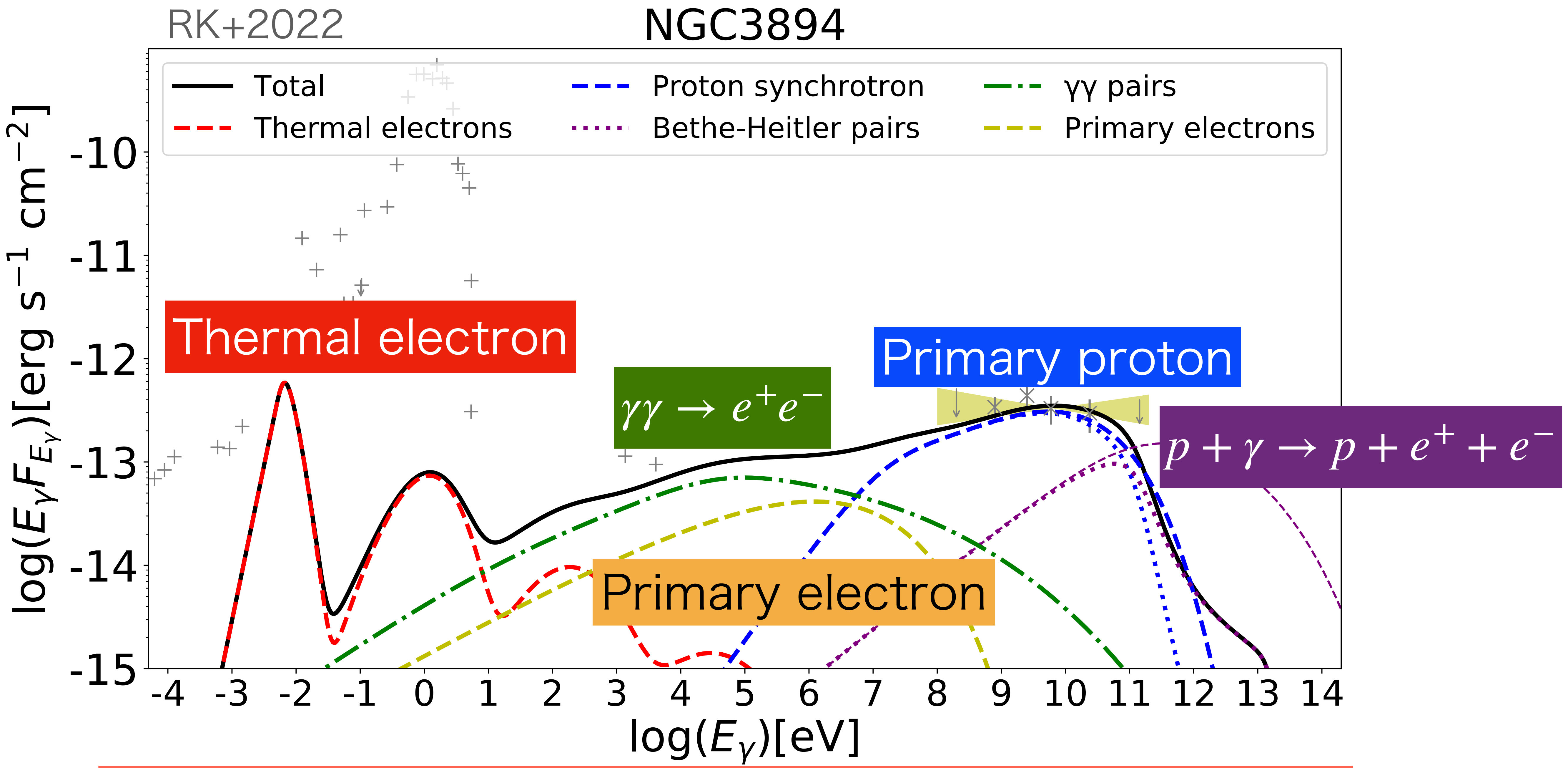
**Hadronic emission from the Magnetically Arrested Disks (MADs) is proposed.**

Kimura & Toma 2020

# MAD model

## Schematic image of MAD model




**Magnetic reconnection or MHD turbulence accelerates the CRs.**

**Synchrotron radiation produce the broadband photons.**

- 5 particle species

Thermal electron | Primary electron | Primary proton | $p+\gamma \to p+e^++e^-$ | $\gamma+\gamma \to e^++e^-$

- Steady & one-zone approximation

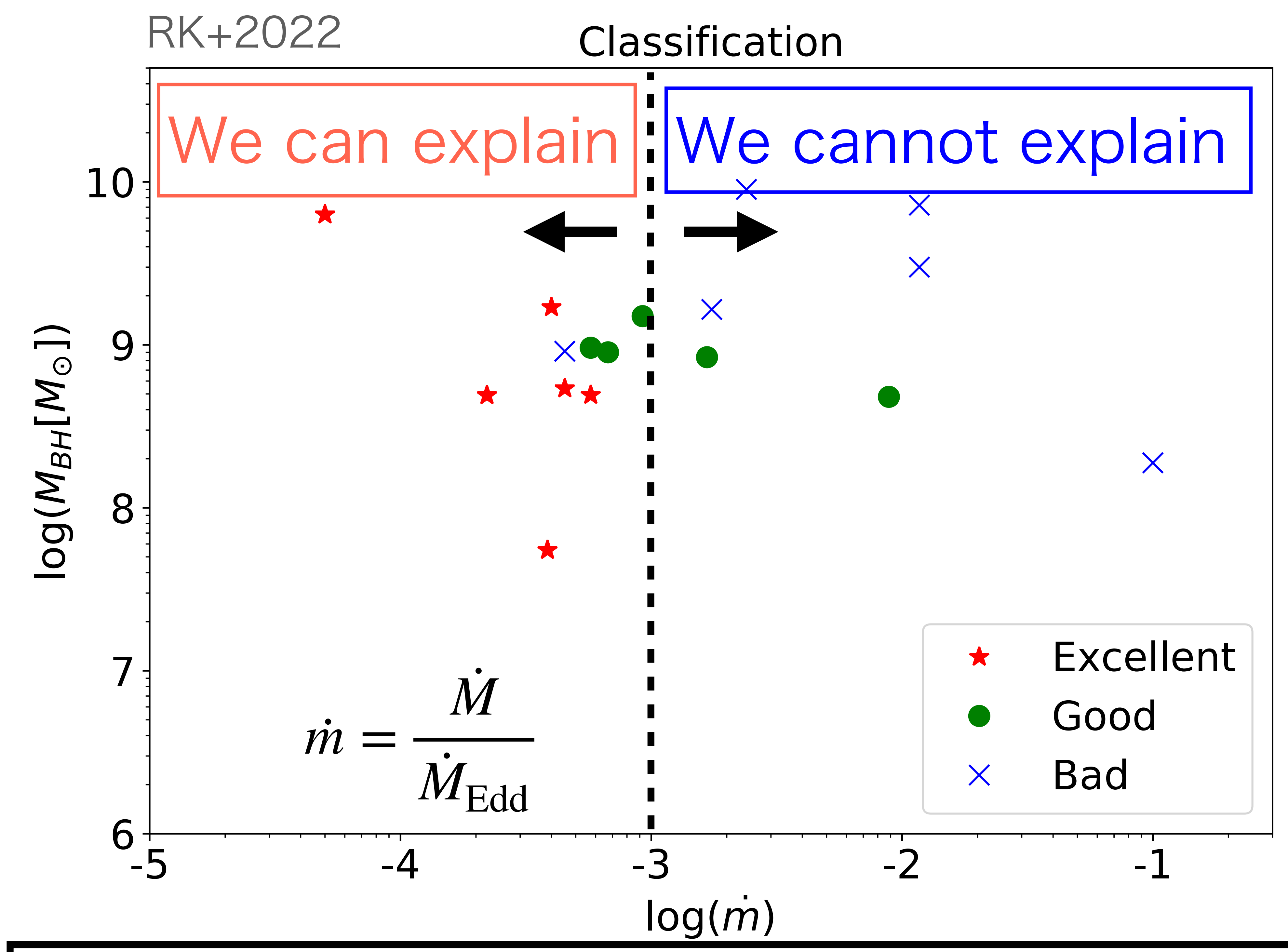
Equation of continuity in energy space

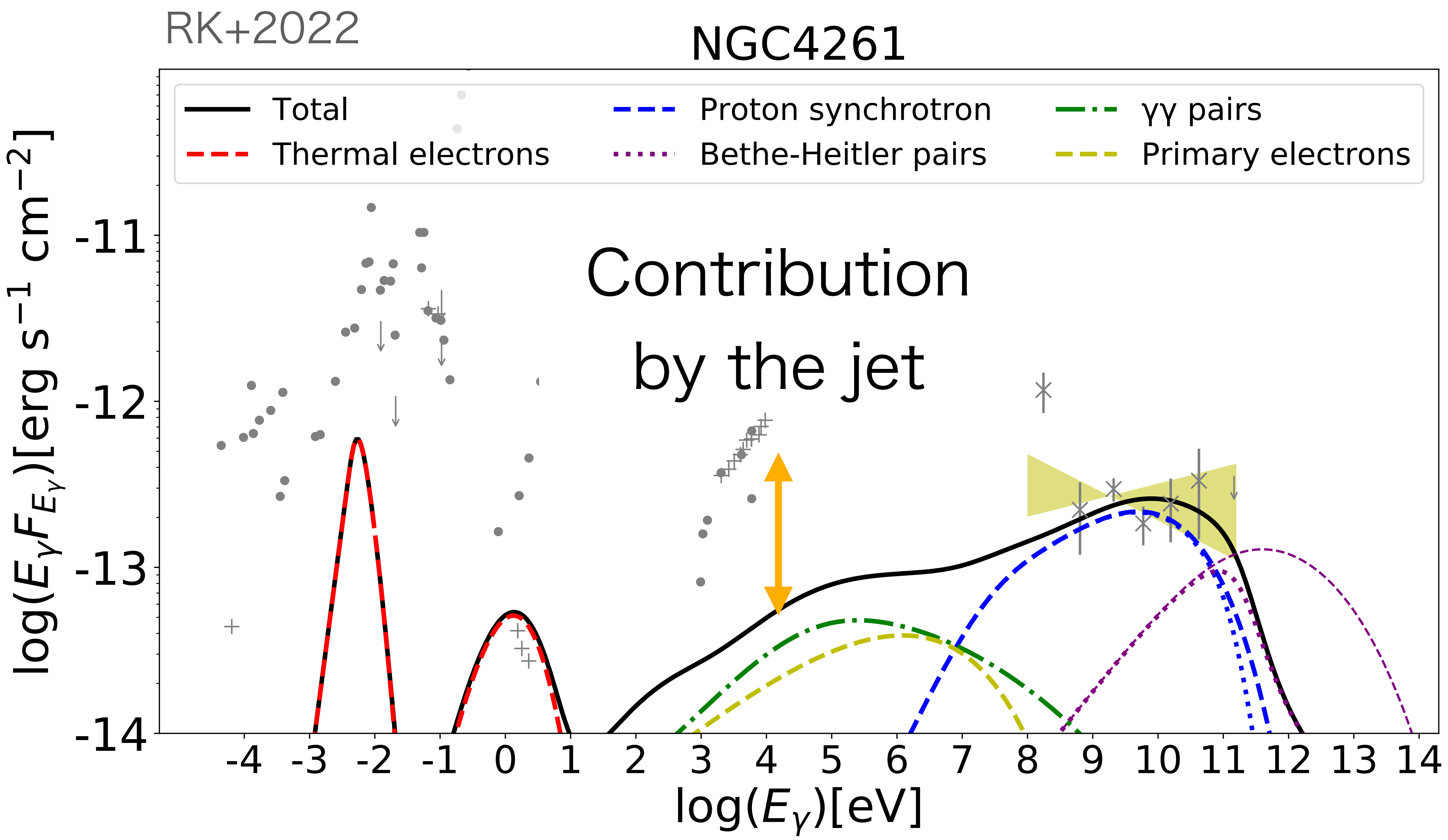
$$-\frac{d}{dE_i}\left(\frac{N_{E_i}E_i}{t_{i,\mathrm{cool}}}\right) = \dot{N}_{E_i,\mathrm{inj}} - \frac{N_{E_i}}{t_{\mathrm{esc}}}$$

Cooling Injection Escape

# Motivation of our study





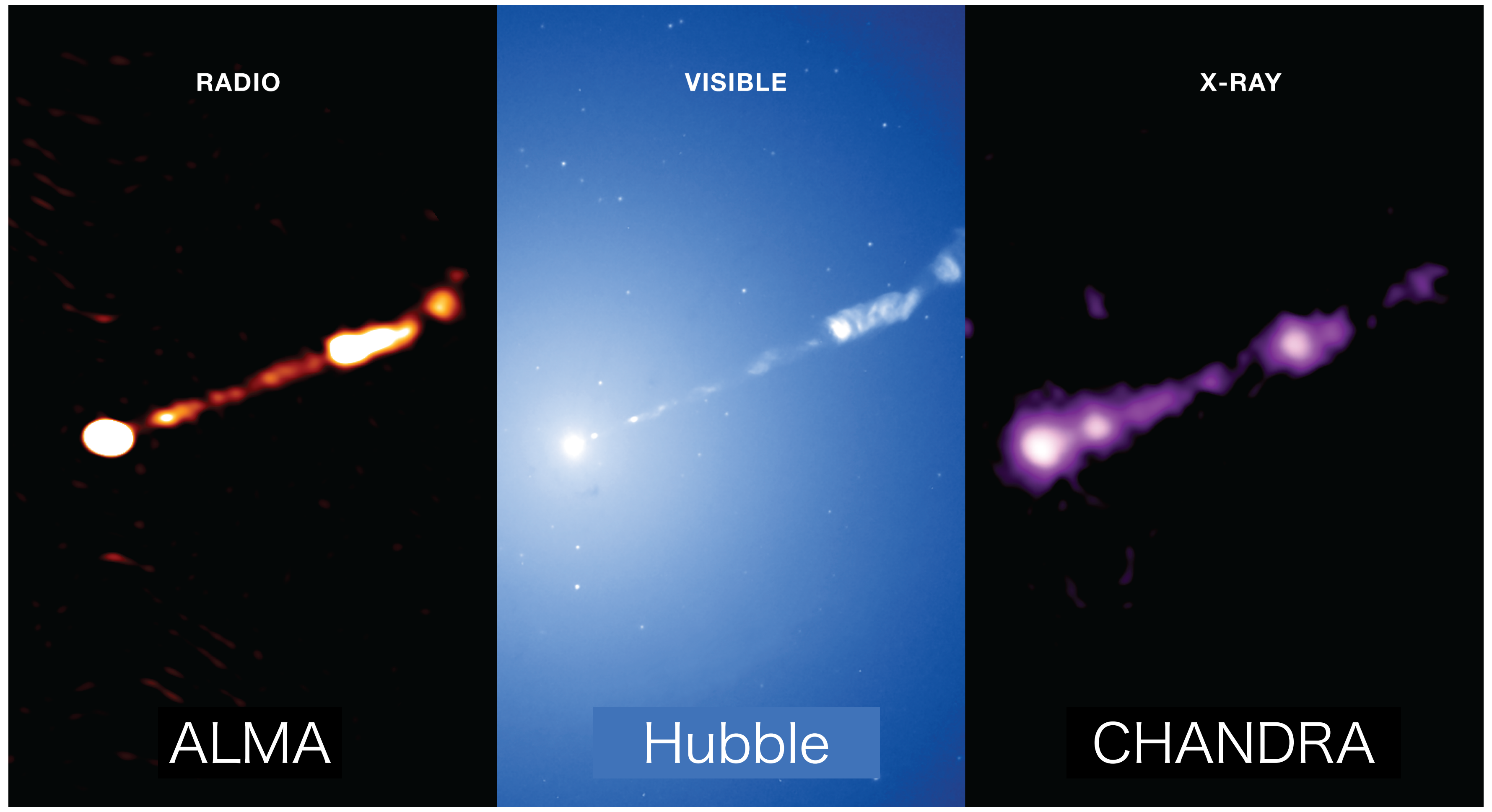

Apply MAD model to various RGs. → **MAD model can explain gamma-ray data, but cannot explain radio to X-ray data.**

**To understand the origin of the broadband photons from AGN -> Constructing the Jet-MAD model is required**

# Jet-MAD model -Radio Blob-

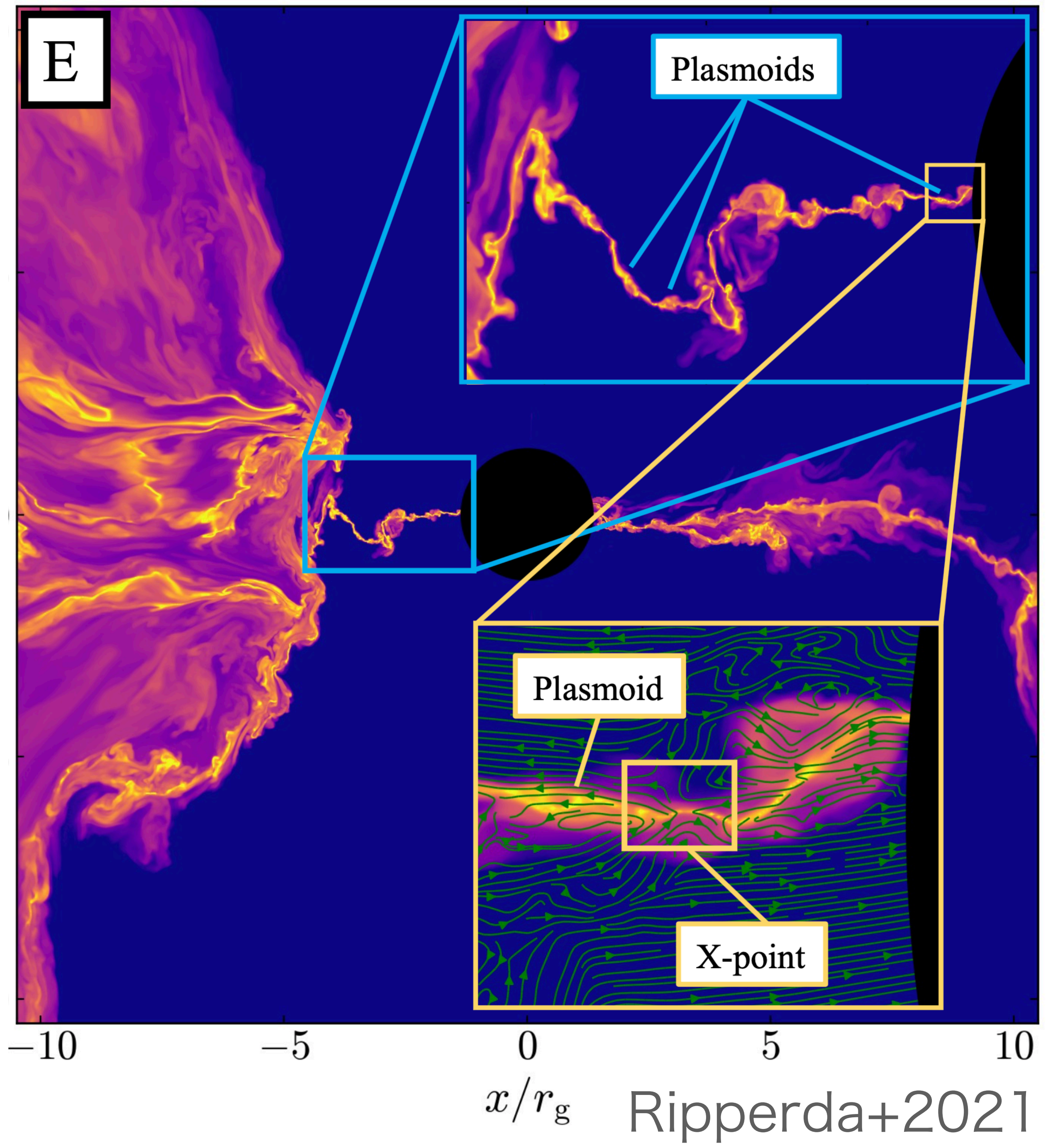


Multi-wavelength observation of jets



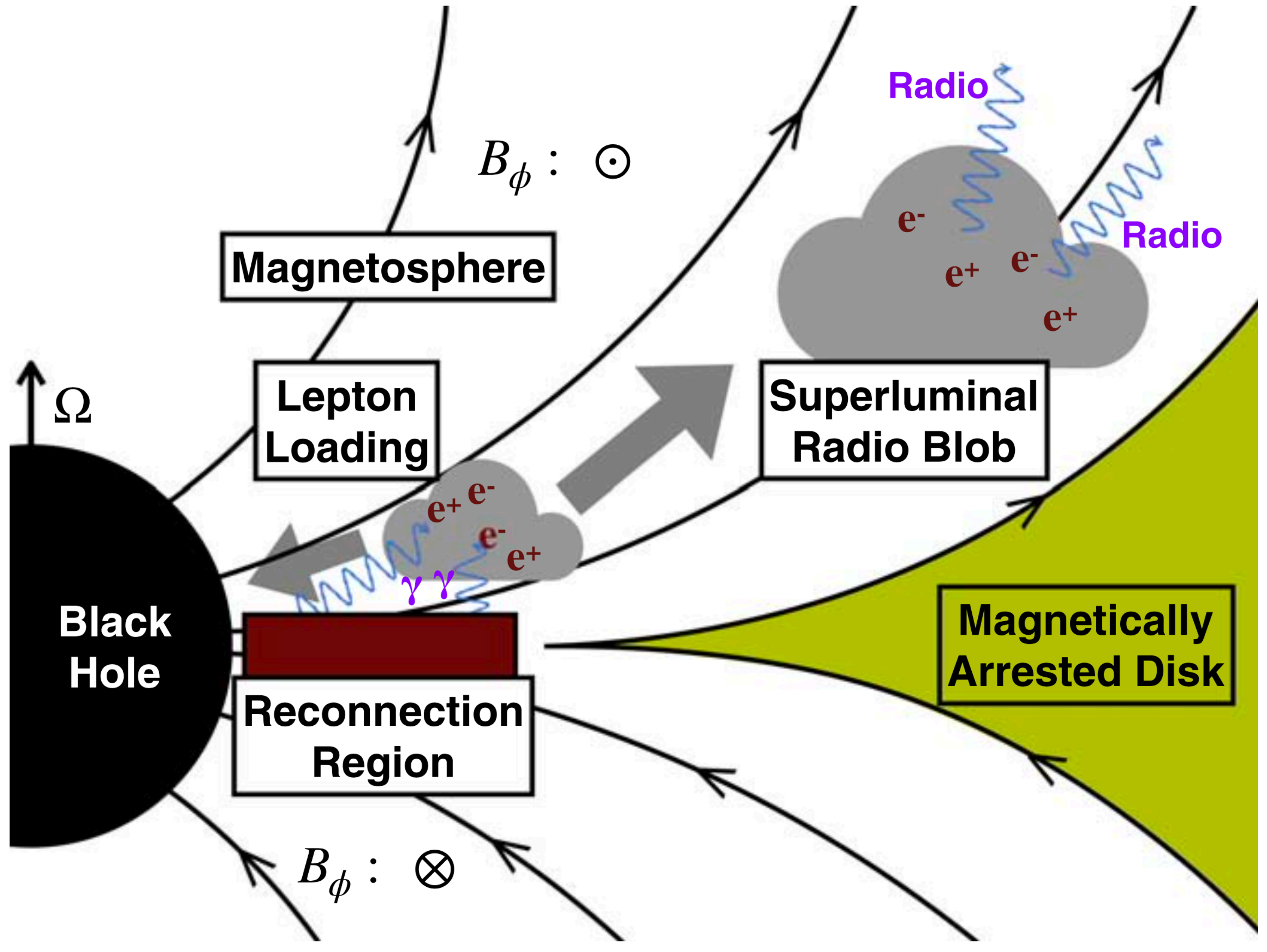

Magnetic Reconnection in the vicinity of BH

High resolution MHD simulation




Ripperda+2021

Particle Acceleration & Emission of HE photons -> $\gamma\gamma \to e^+e^-$ pair production




Kimura+2022

Injection mechanism -> **Unknown**

Kimura+2022

Radio Blob

-> $e^+e^-$ **pair plasma produced by** $\gamma + \gamma \to e^+ + e^-$

# Jet-MAD model -Disk & Blob-



**Magnetization parameter: $\sigma$**

$\sigma$ : Pair production rate = Escape rate

Cheng+2022

$$\sigma = \frac{B^2}{4\pi h} \sim 10^5$$

$h$: Enthalpy

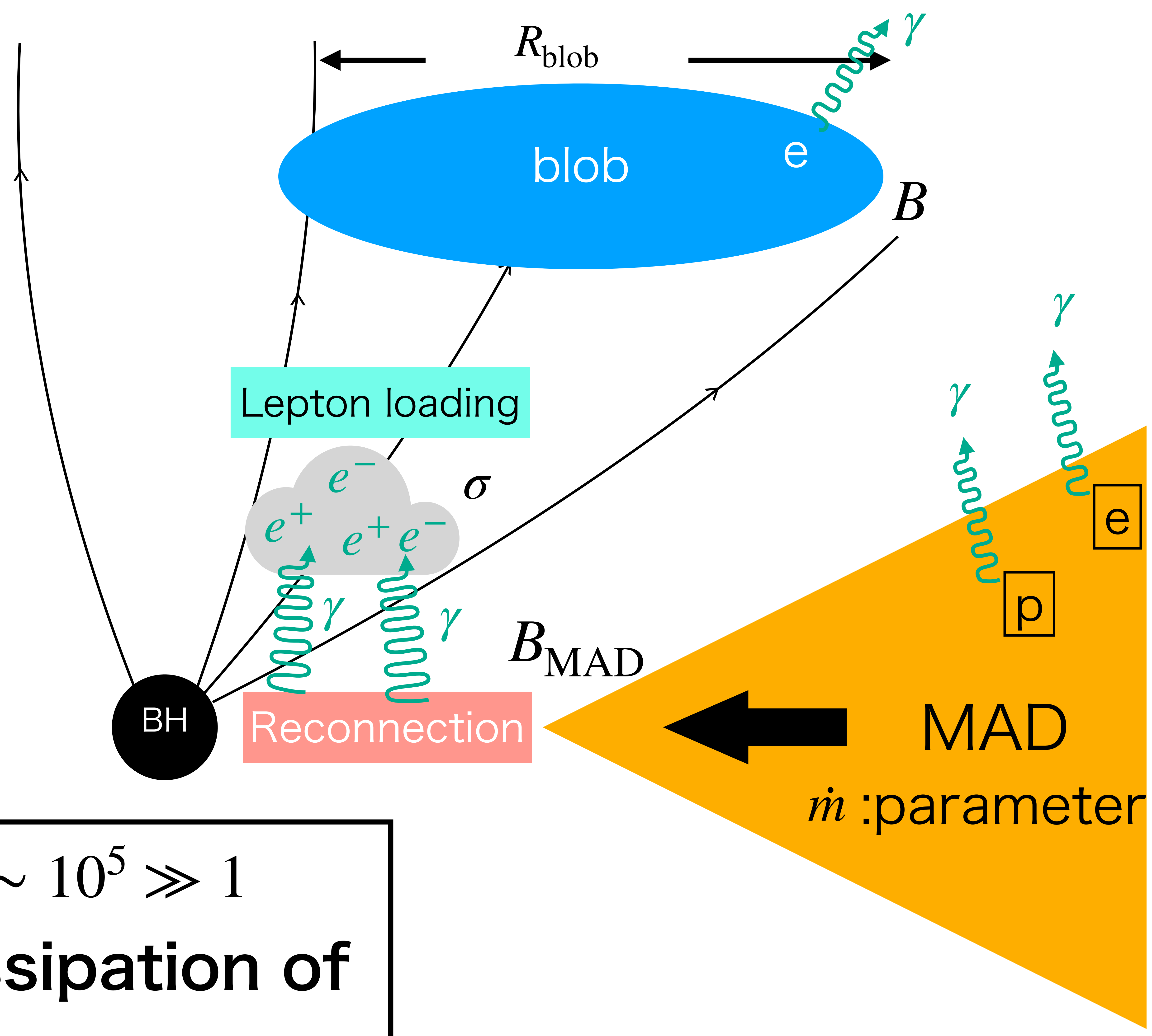
$\sigma$ -> Production rate

Production rate -> $B_{\rm MAD}$

$B_{\rm MAD}$ -> $\dot{m}$

$$B_{\rm MAD} = \sqrt{\frac{\dot{M} c \Phi_{\rm MAD}}{4\pi^2 R_g^2}}$$

Jet and Disk are related by the accretion rate, $\dot{m}$.




Magnetically dominated jet $\sigma \sim 10^5 \gg 1$
->Particle acceleration by the dissipation of the magnetic energy

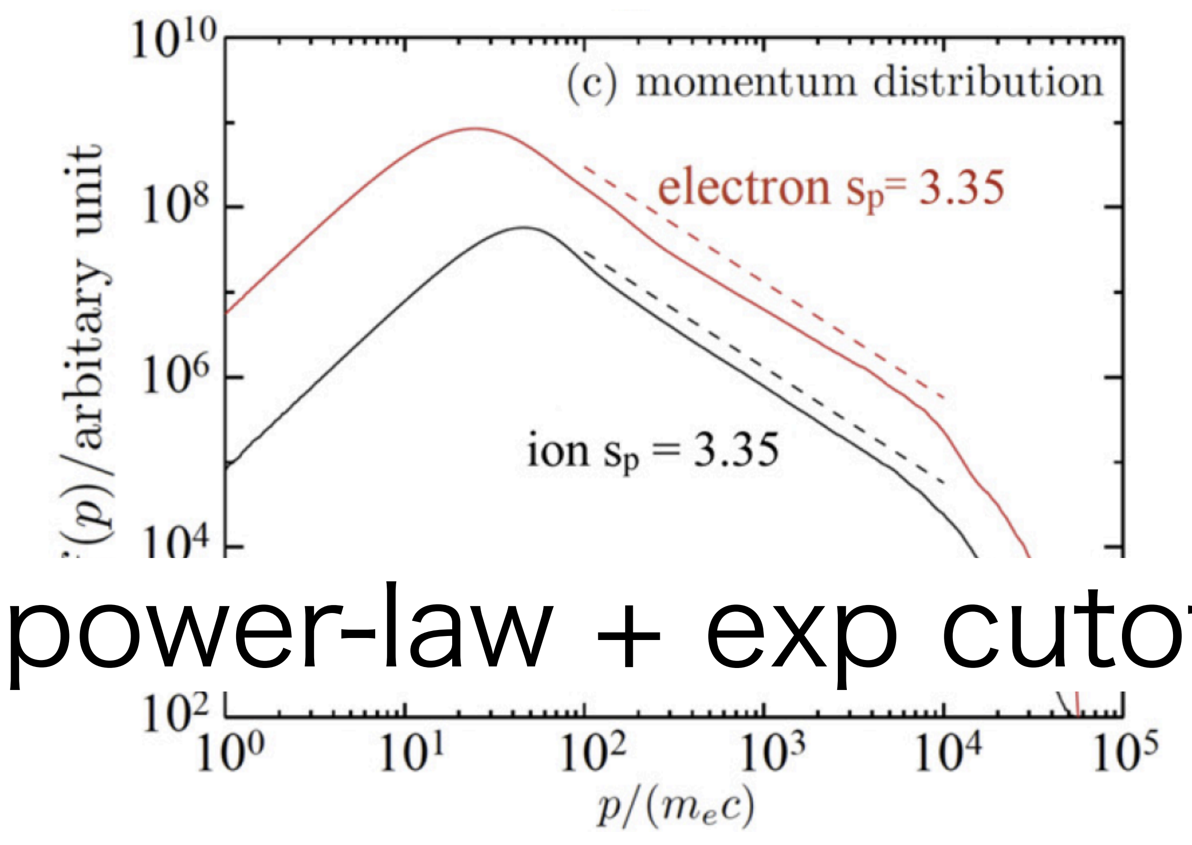
# Particle acceleration in Jets



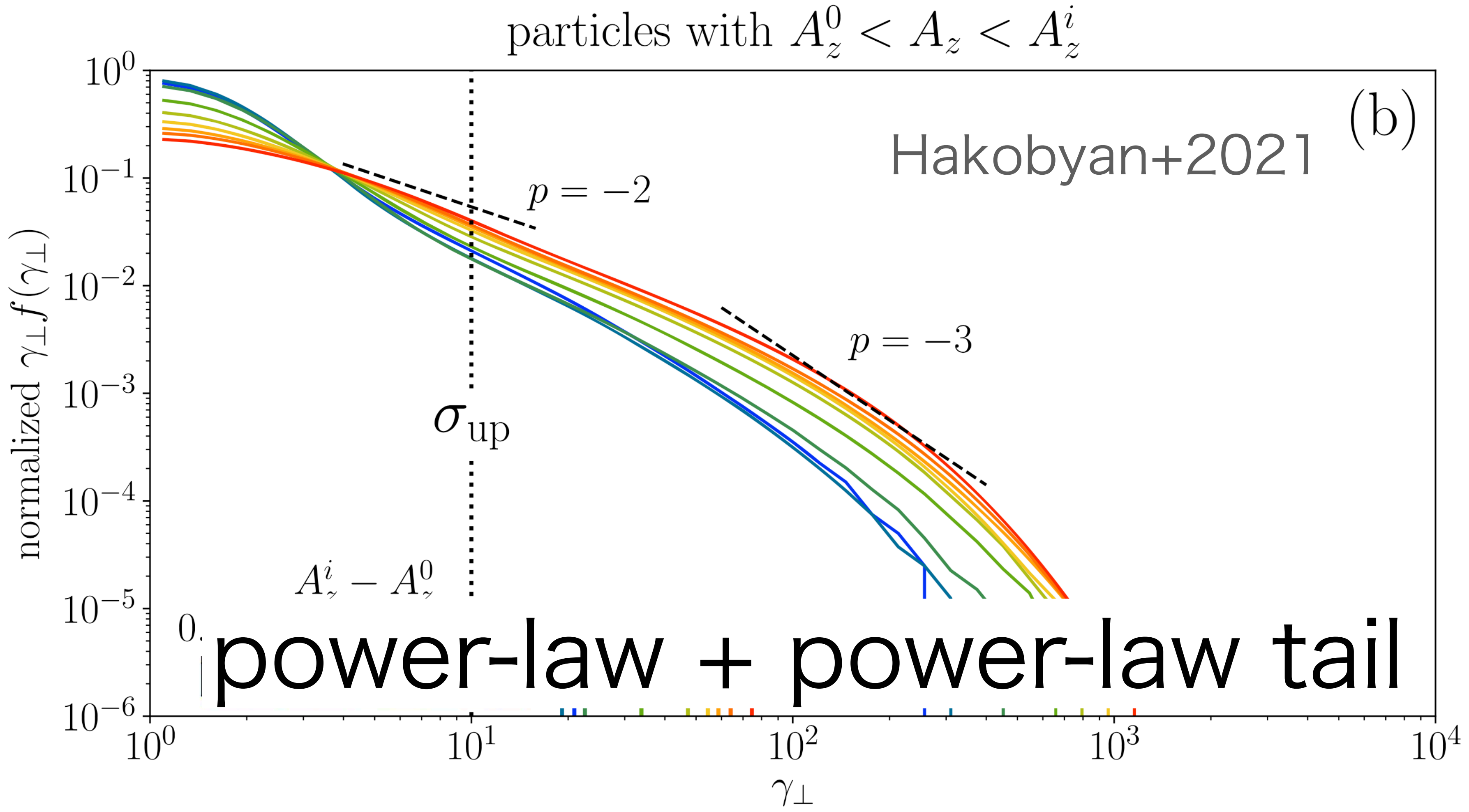
## (i) Magnetic Reconnection

Particle In Cell simulation

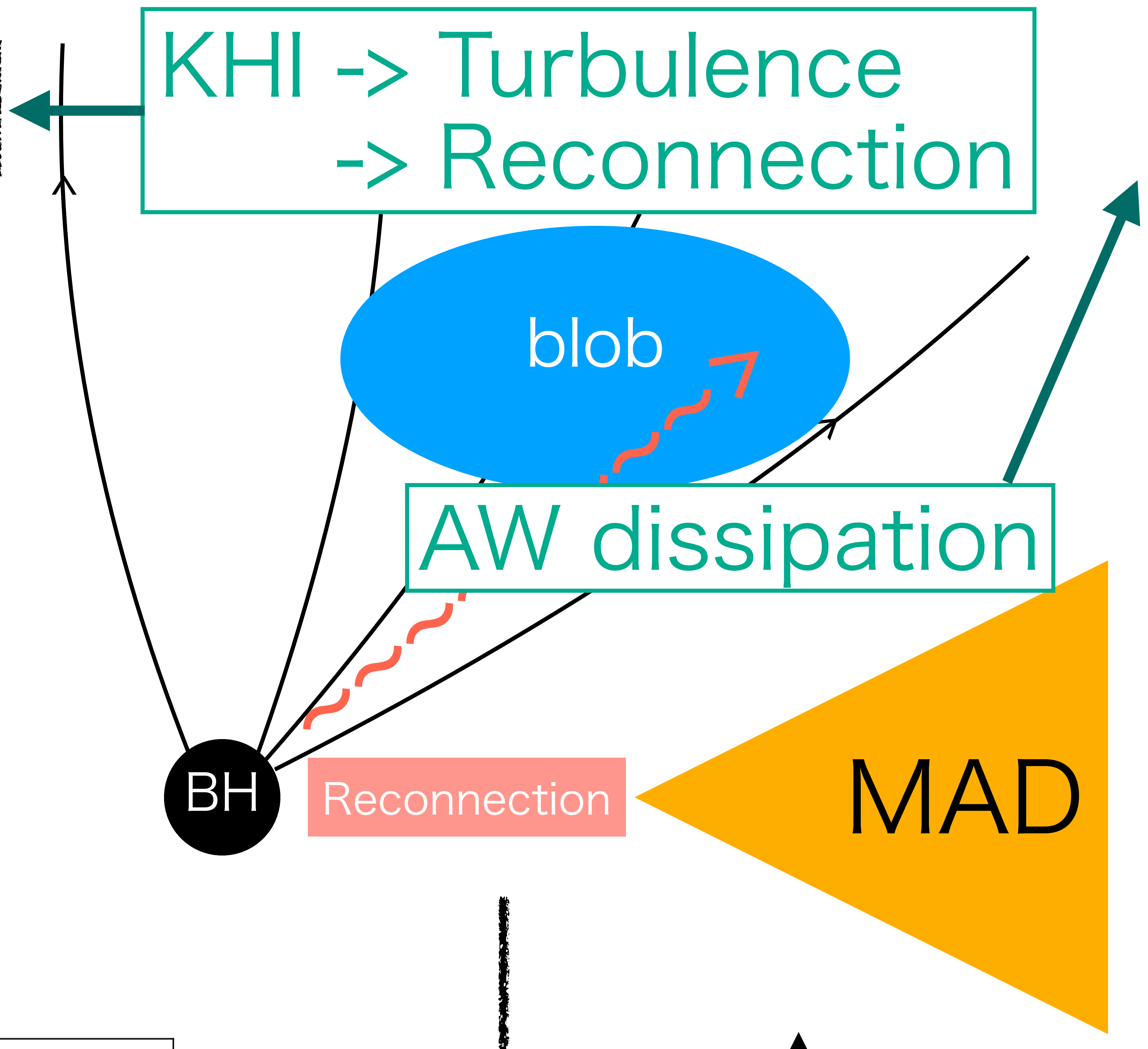
Guo+2016




power-law + exp cutoff

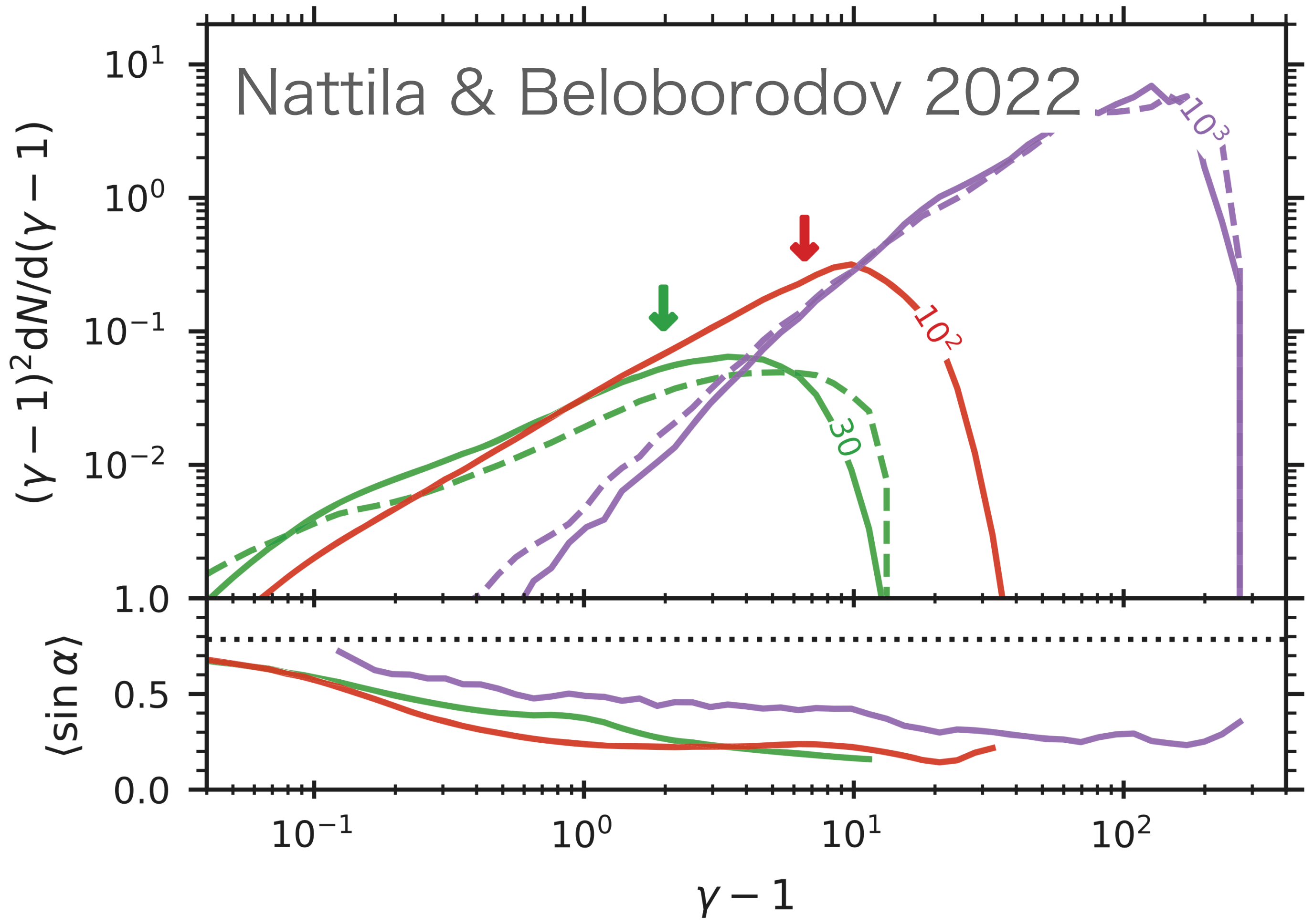


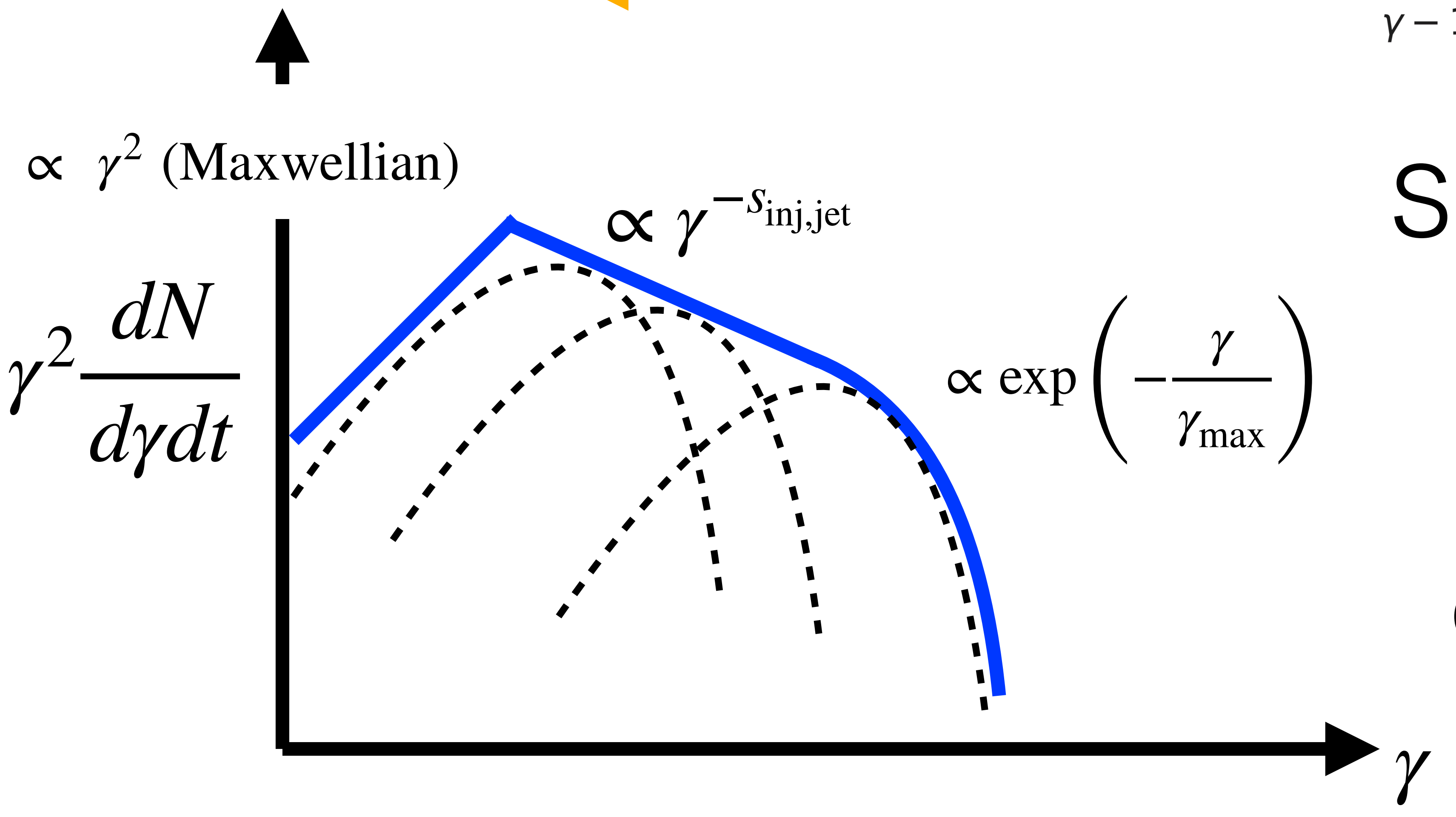

power-law + power-law tail




## (ii) Alfven Dissipation

Particle In Cell simulation




Superposition

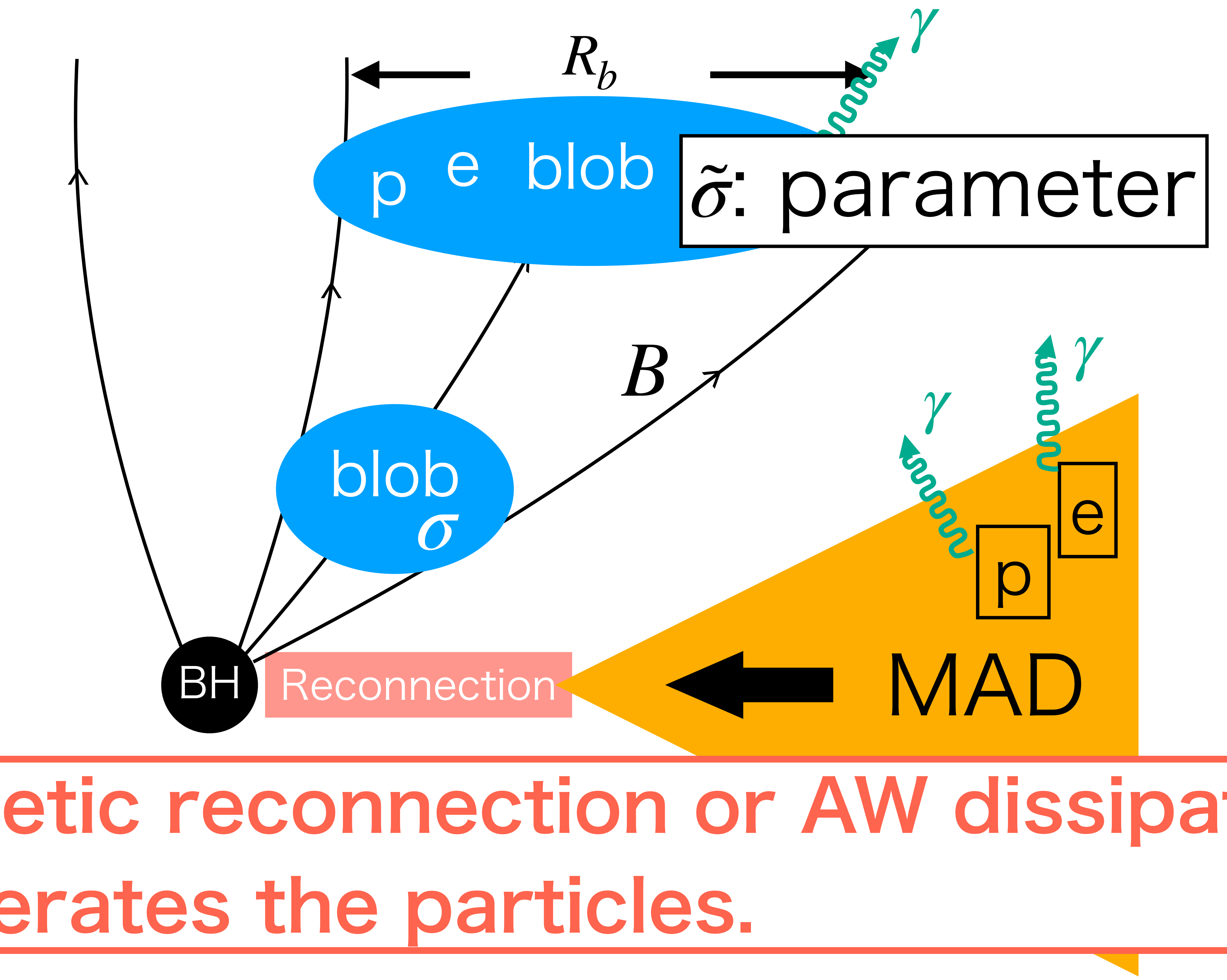
↓

Power law distribution

Magnetic reconnection or AW dissipation accelerates the particles

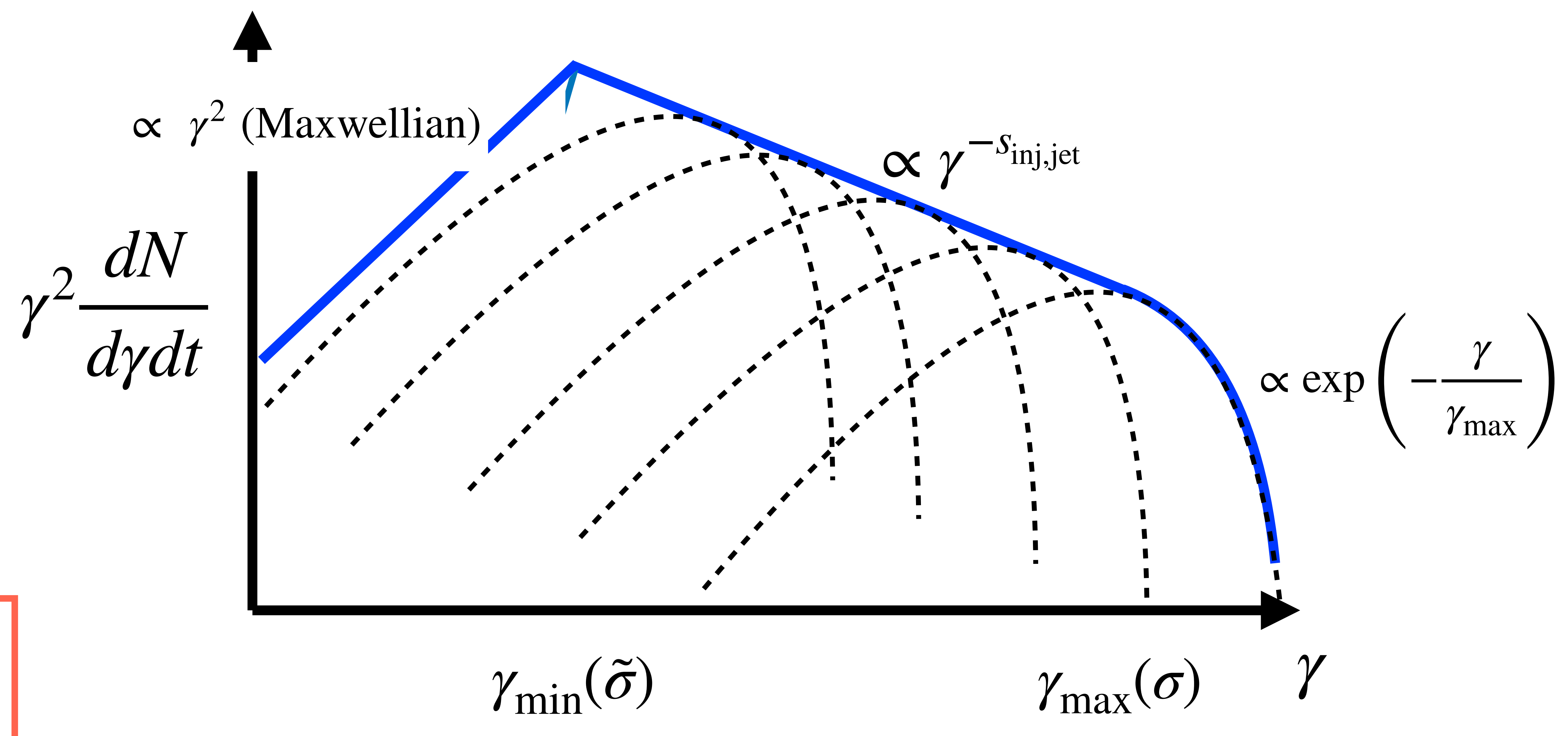
# Basic equation of Jet-MAD model

Schematic image of Jet-MAD model




**Magnetic reconnection or AW dissipation accelerates the particles.**

Differential number density of accelerated particle




- Two species of particle
  - Nonthermal Electrons
  - Nonthermal Protons

↑ Injected from ambient gas via KHI

- Steady & one-zone approximation

Transport Equation

$$-\frac{d}{dE_e}\left(\frac{N_{E_e}E_e}{t_{e,\rm cool}}\right) = \dot{N}_{E_e,\rm inj} - \frac{N_{E_e}}{t_{\rm esc}}$$

Cooling Injection Escape

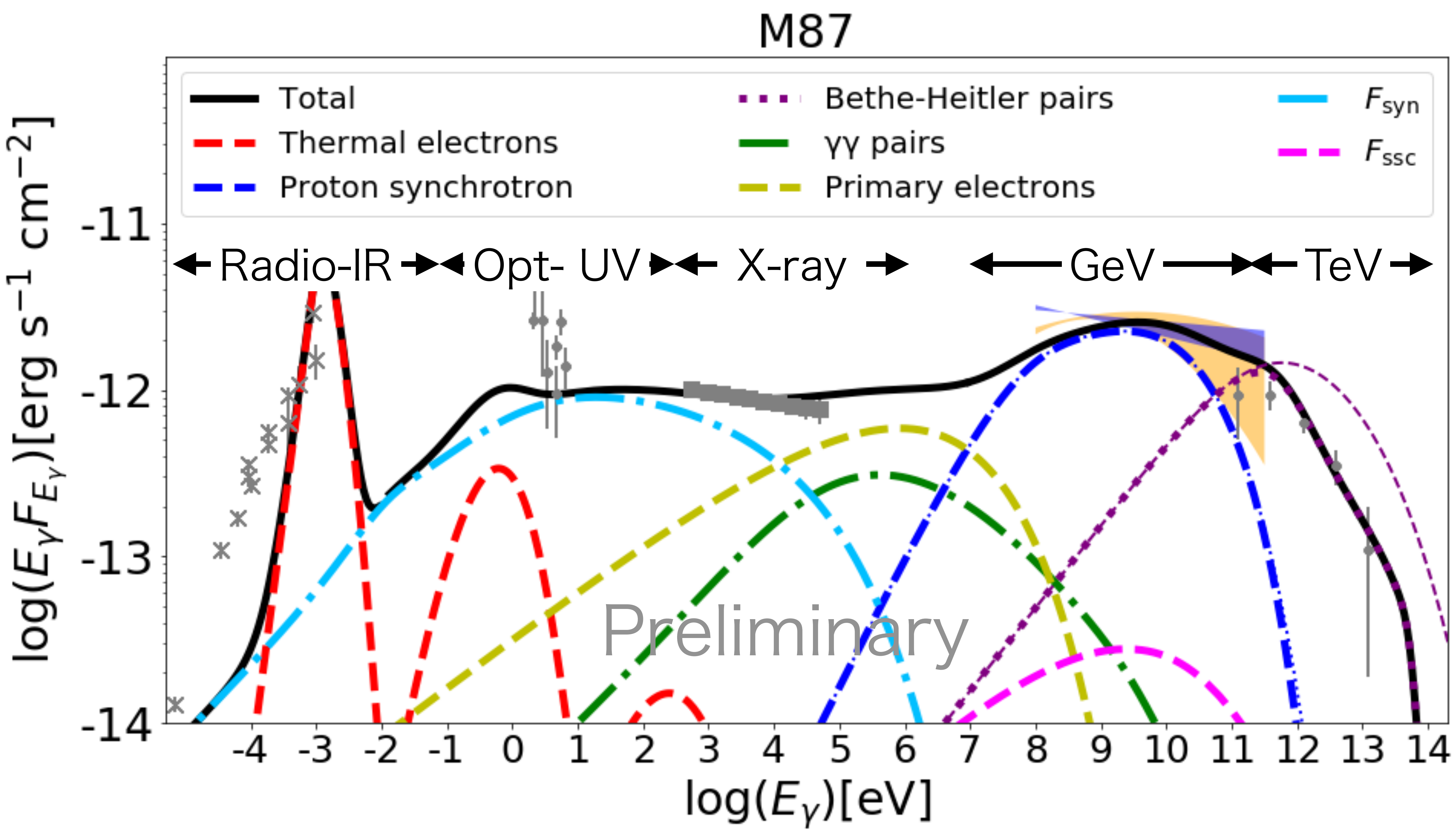
# Exponential cutoff



**Parameter：$\tilde{\sigma} \sim 0.01,\ \dot{m} \sim 6.0 \times 10^{-5}$** $B \simeq 0.05$ G

$R_b \simeq 100 R_g,\ \ Z \simeq 10^3 R_g$ $\delta_D = 1.9$

$\sigma \sim 1.0 \times 10^5$ $s_{\rm inj,MAD} = 1.4,\ s_{\rm inj,jet} = 2.18$



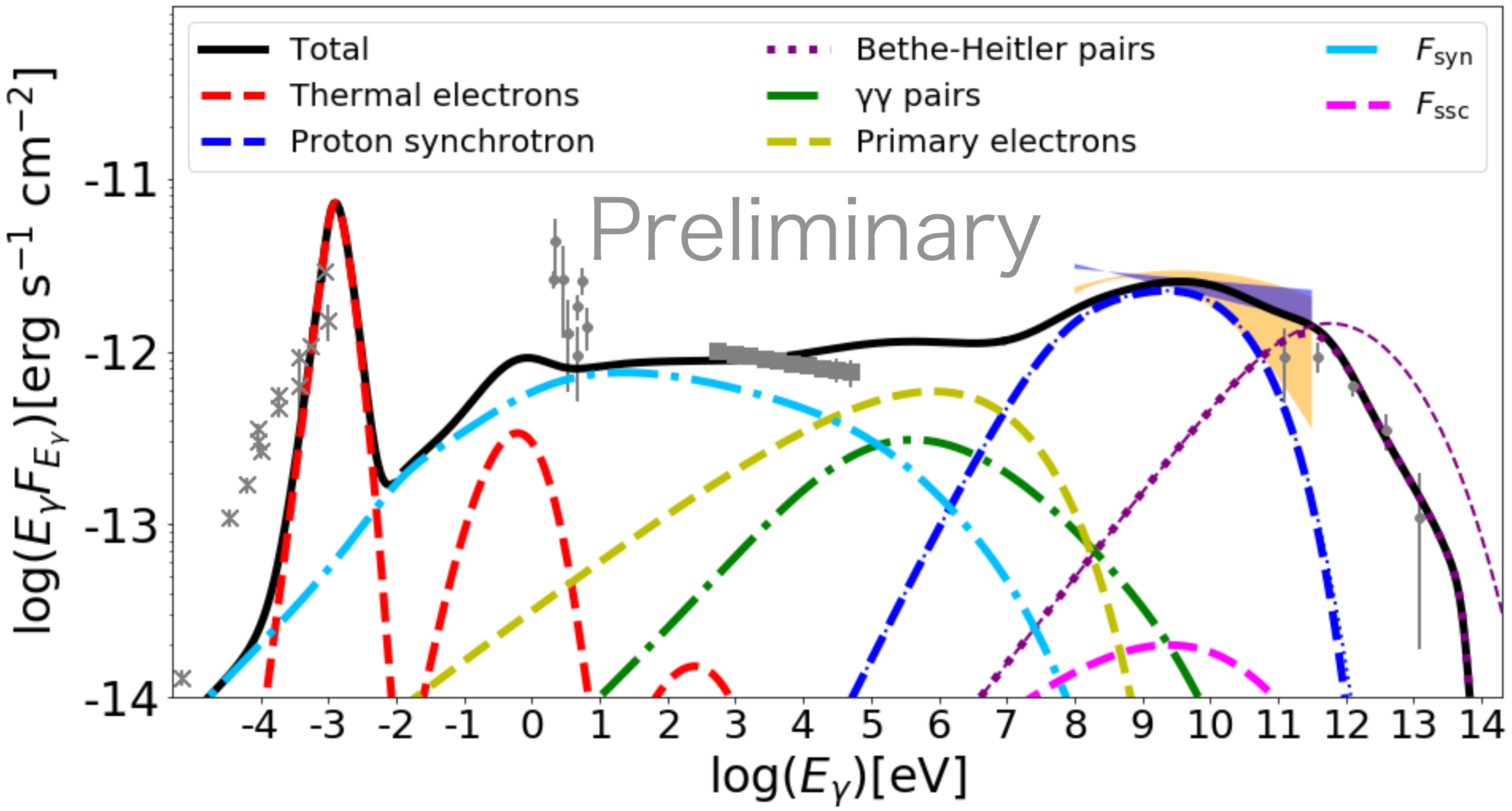

Multi-wavelength emission via Synchrotron radiation

| | MAD | Jet |
|---|---|---|
| **Radio - IR** | Thermal Electron | Electron |
| **Opt - UV** | | Electron |
| **X-ray** | **Nonthermal Electron** (>10keV) | Electron (<10keV) |
| **GeV** | Nonthermal Proton | |
| **TeV** | Secondary electron-positron pairs (Bethe-Heitler process) | |

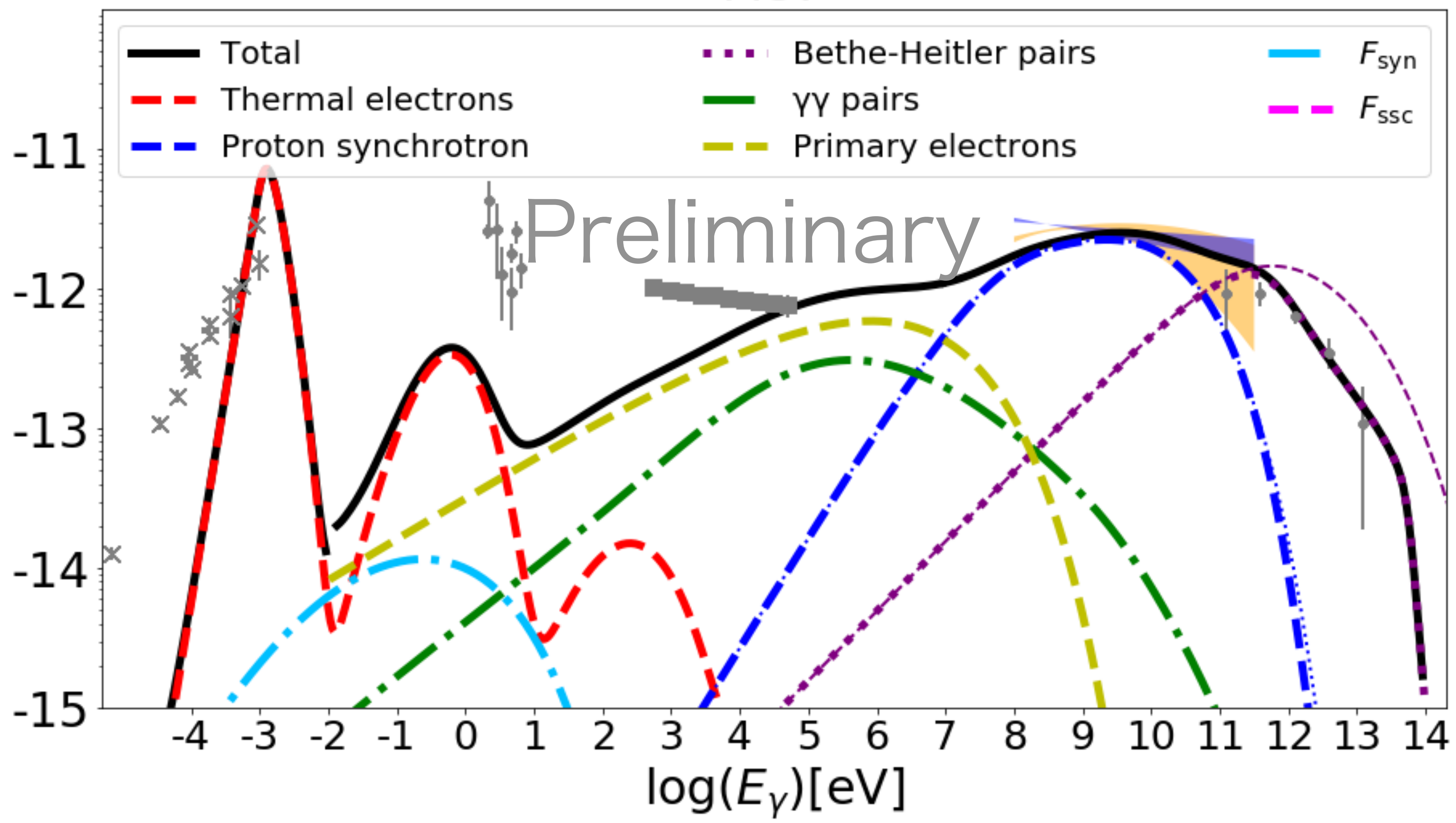
**Jet-MAD model can explain the multi-wavelength observational data**

# Different acceleration mechanisms 

Magnetic Reconnection ○




Alfven wave Dissipation ✕




We consider two different acceleration mechanisms:
**Magnetic reconnection**(exp cutoff or power-law tail) & **Alfven dissipation**

-> Jet-MAD model with the magnetic reconnection **can explain the observational data**, but the Alfven dissipation **cannot explain that**.

-> **The particle acceleration mechanism is likely the magnetic reconnection**.

# Summary

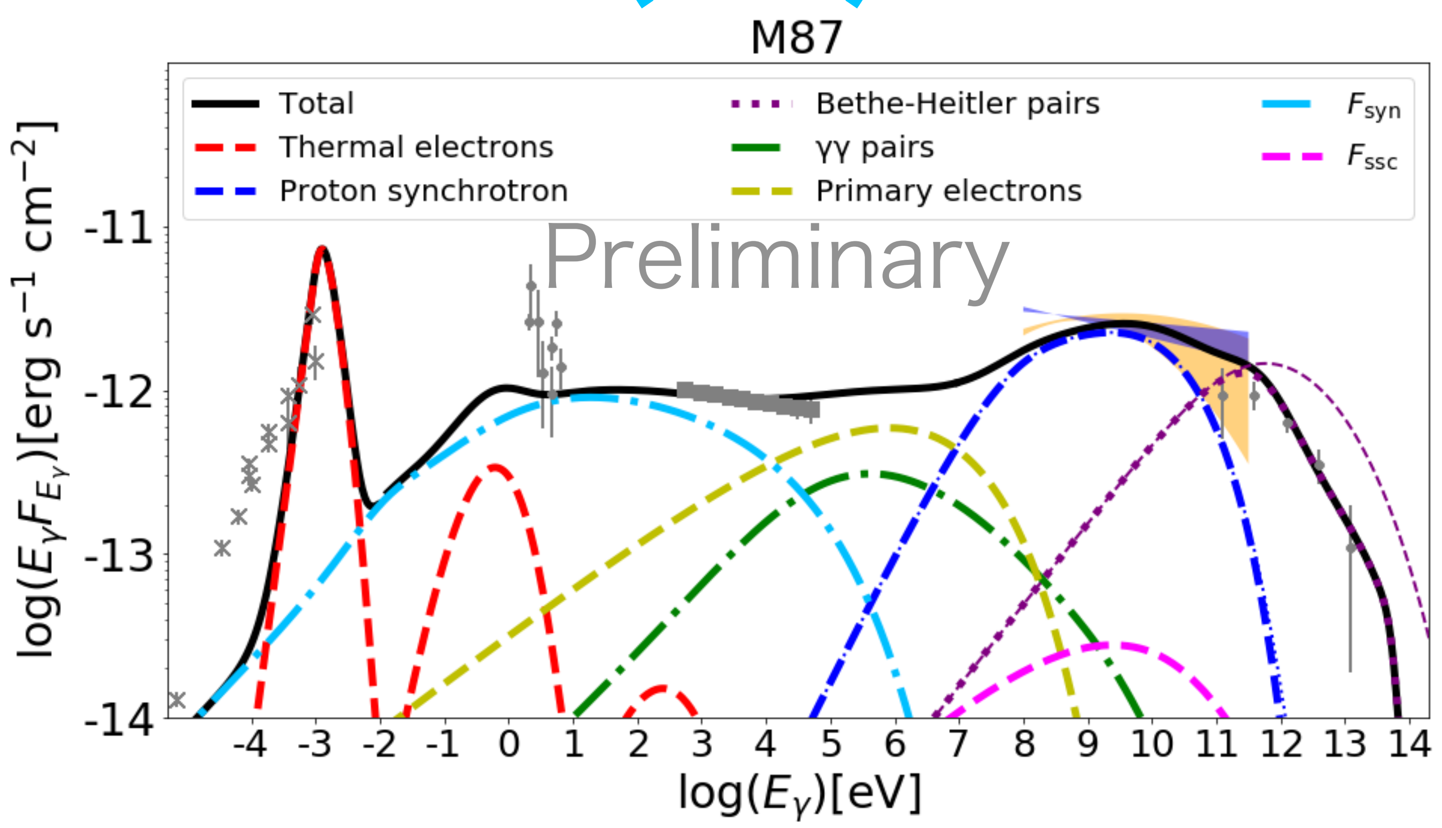


✔ Multi-wavelength emission mechanism in radio galaxies is still unknown

✔ MAD model cannot explain the radio to X-ray data.
-> **We construct the Jet-MAD model with particle injection model.**

✔ **Jet-MAD model can explain the observational data of M87**

- **Radio - IR: Thermal electron(MAD) + Nonthermal electron(Jet)**
- **Optical - X-ray: Nonthermal electron(Jet)**
- **X-ray: Nonthermal electron(MAD)** ( $> 10$**keV**)
  **+ Nonthermal electron(Jet)** ( $< 10$**keV**)



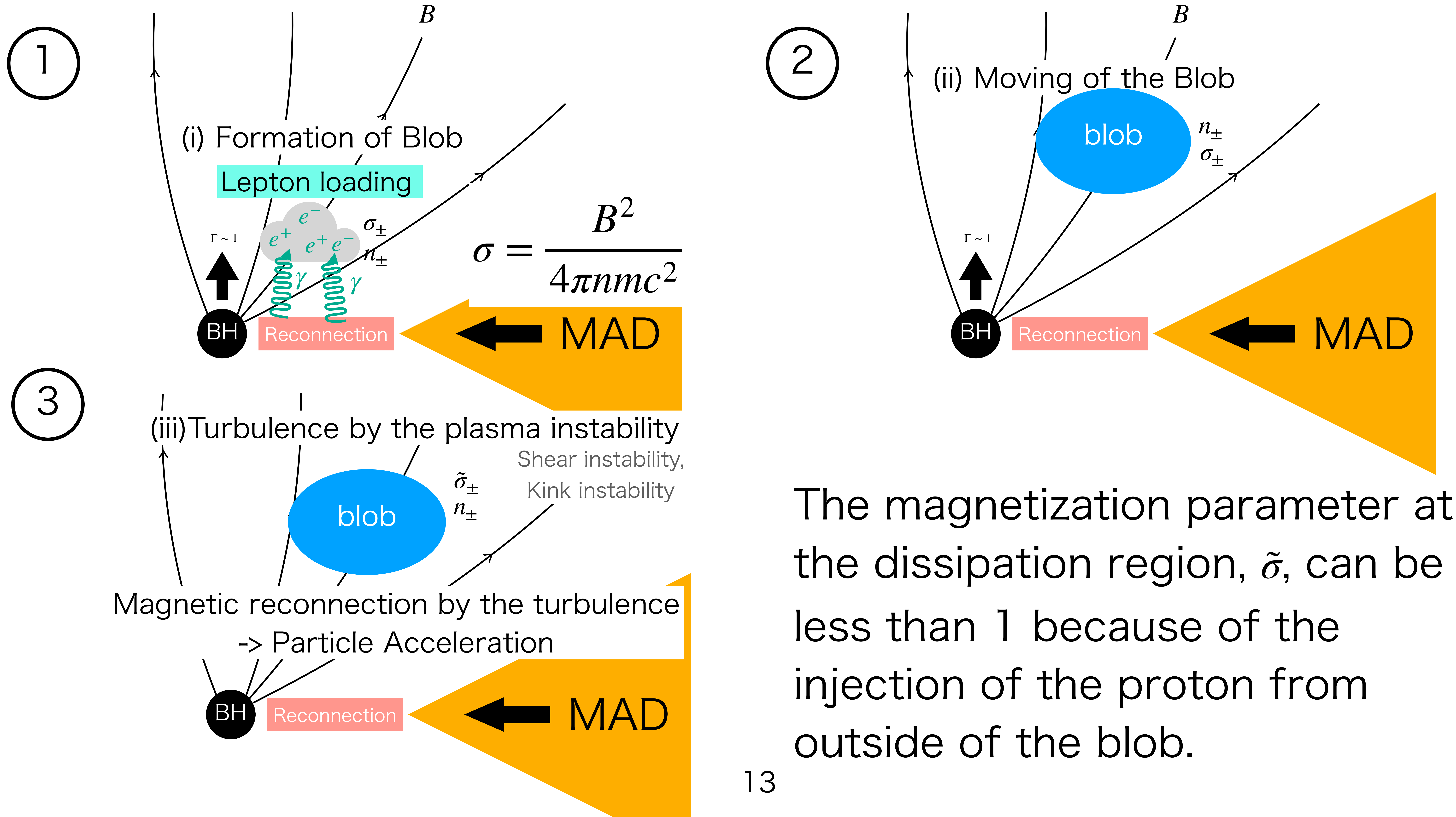

✔ We consider two different acceleration mechanisms:
-> **Magnetic reconnection** & **Alfven wave dissipation**

Magnetic reconnection **can explain the observational data**
**<->** Alfven wave dissipation **cannot explain that.**

-> **The particle acceleration mechanism is likely the magnetic reconnection**

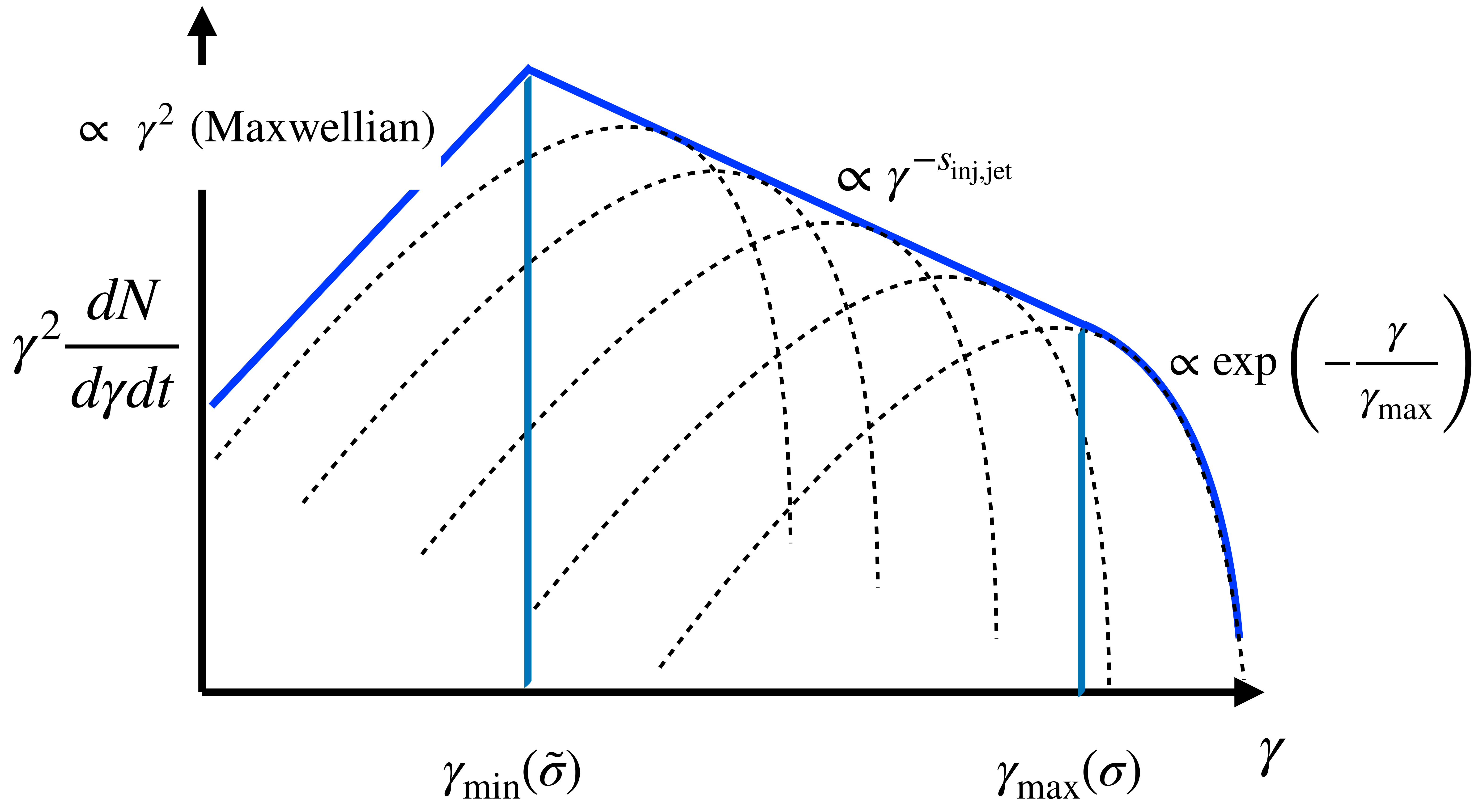
# Back Up Slide

# Scenario of the Jet-MAD model




The magnetization parameter at the dissipation region, $\tilde{\sigma}$, can be less than 1 because of the injection of the proton from outside of the blob.

# Particle distribution of Injection term




Maximum Energy

$$\gamma_{\rm max} = \xi \left(\frac{\delta_B}{B}\right)^2 \sigma$$

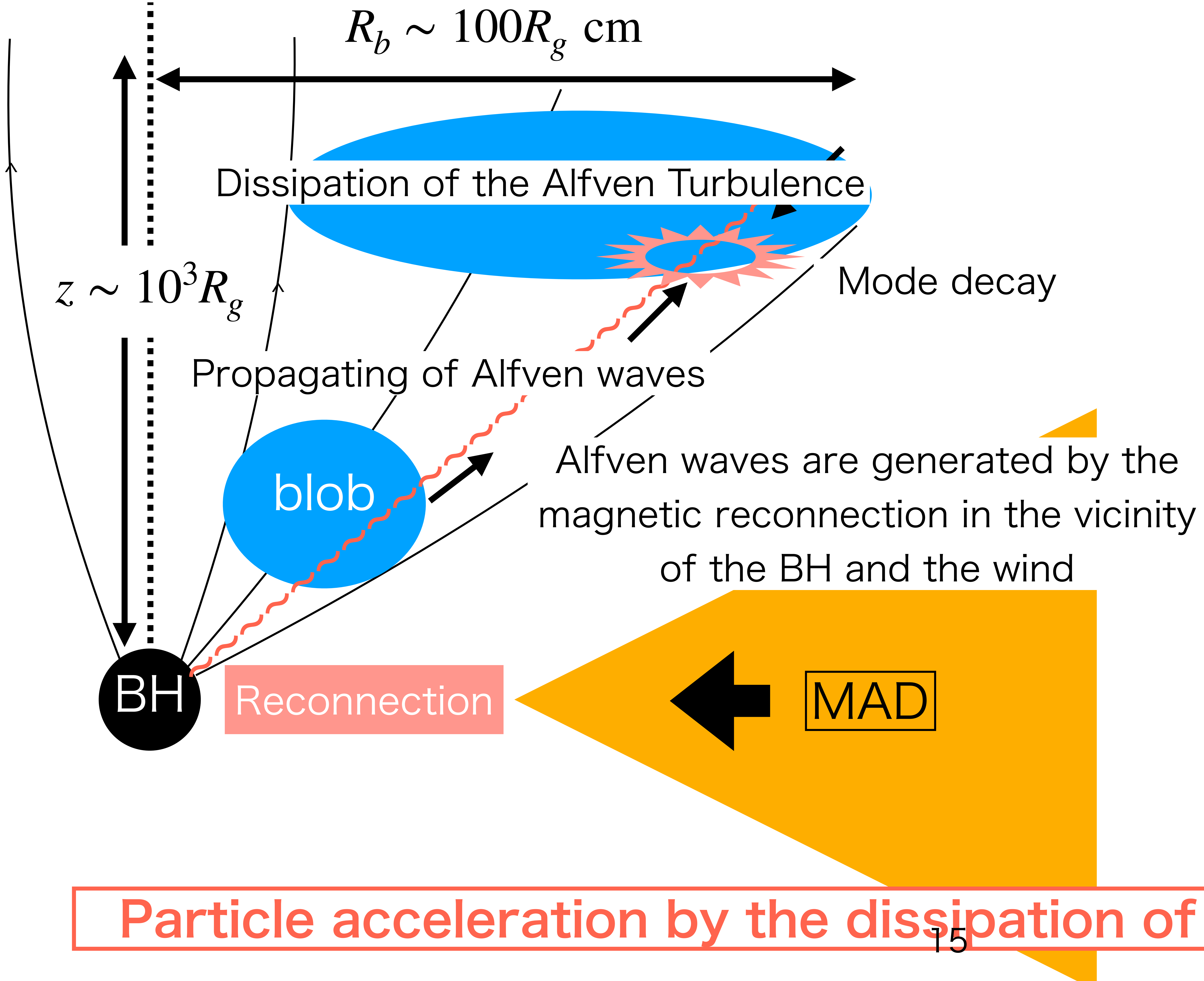
$\delta_B$: Amplitude of the perturbed magnetic field

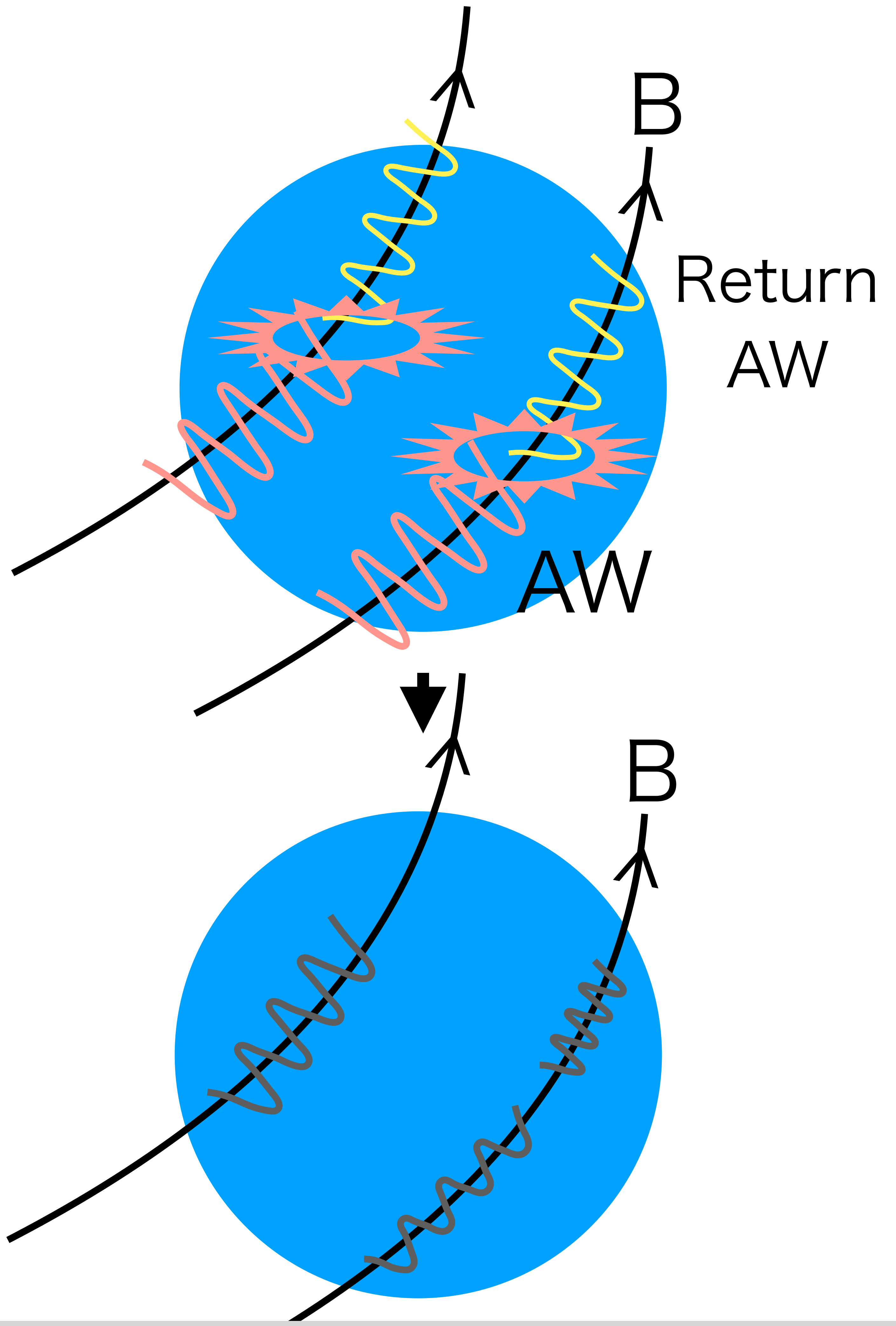
$\xi$ : The effect of the density reduction due to the expansion of the blob by the velocity dispersion of the blob

Minimum Energy

$$\gamma_{\rm min} = \left(\frac{\delta_B}{B}\right)^2 \frac{n_e m_e}{n_p m_p} \tilde{\sigma}$$

# The Other Scenario: Alfven Dissipation



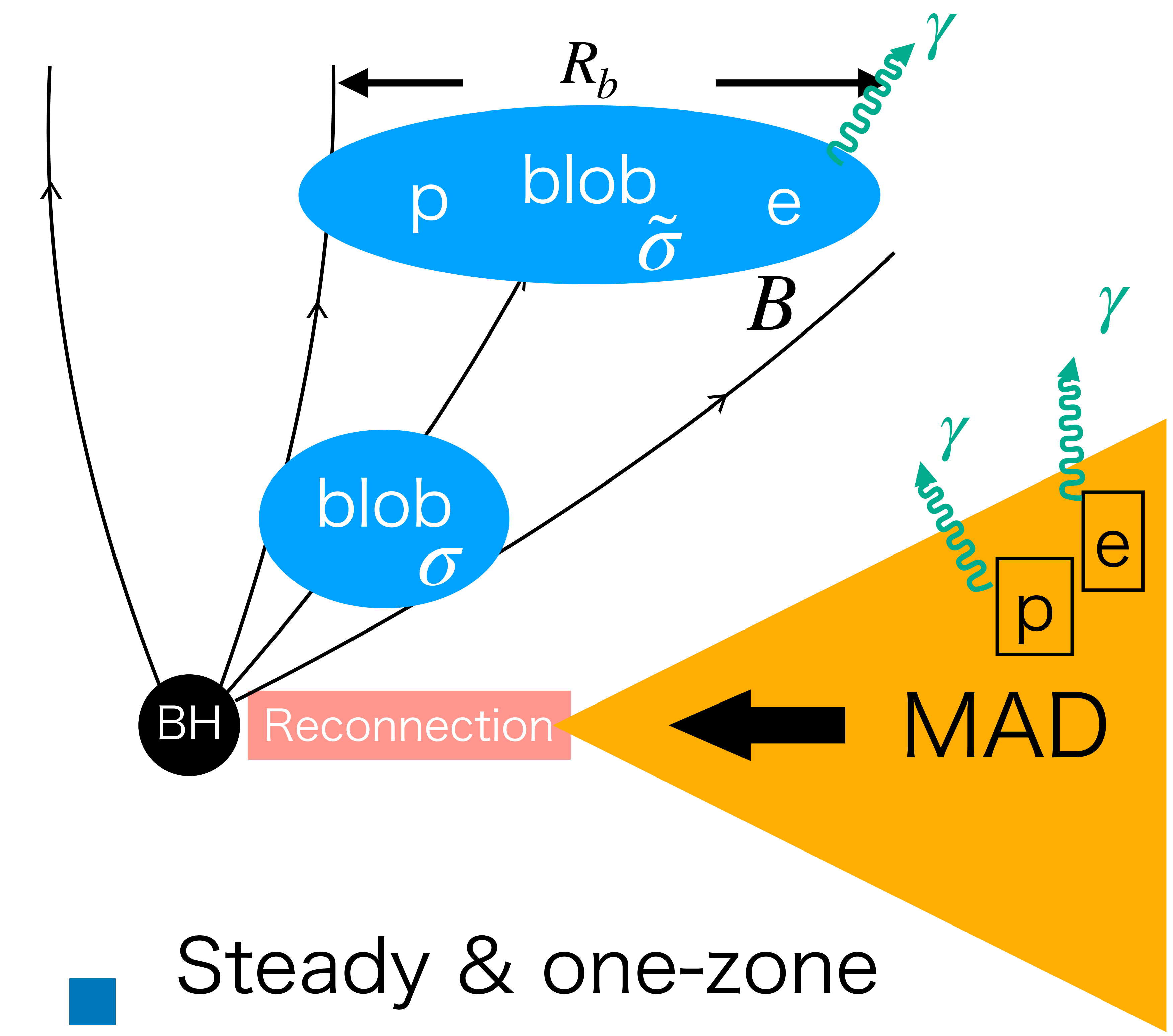




Turbulence inside the blob

**Particle acceleration by the dissipation of the Alfven turbulence**

# Basic equation of Jet-MAD model






- Steady & one-zone approximation
- Two species of particle
  - Nonthermal Electrons
  - Nonthermal Protons

↑ Injected from ambient gas via KHI

**Base of Jet ($\sigma = \sigma$)**

$$L_j = (1 + 0.5\sigma)\, n_e m_e c^2 \pi R_b^2 c$$

$$L_j \approx \eta \dot{M} c^2 = \eta \dot{m} L_{\rm Edd}$$

→

$$n_e = \frac{L_j}{1 + \frac{1}{2}\sigma} \frac{1}{m_e c^2} \frac{1}{\pi R_b^2 c}$$

**Dissipation region ($\sigma = \tilde{\sigma}$)**

$$L_j = \left( u_e + u_p + \frac{B^2}{8\pi} \right) \pi R_b^2 c$$

$$h = u_e + u_p \qquad \tilde{\sigma} = \frac{B^2}{4\pi h}$$

→

$$\tilde{n}_e \approx \frac{L_j}{1 + \frac{1}{2}\tilde{\sigma}} \frac{1}{\pi R_b^2 c} \frac{1}{m_p c^2}$$

$$B = \sqrt{4\pi h \tilde{\sigma}}$$

Transport Equation

$$-\frac{d}{dE_e}\left( \frac{N_{E_e} E_e}{t_{e,\rm cool}} \right) = \dot{N}_{E_e,\rm inj} - \frac{N_{E_e}}{t_{\rm esc}}$$

Cooling Injection Escape

# Simultaneous multi-wavelength observation by EHTMWL