Construction of the Very High Energy Gamma-Ray Spectrum in Centaurus A Based on Filamentary Jet Model

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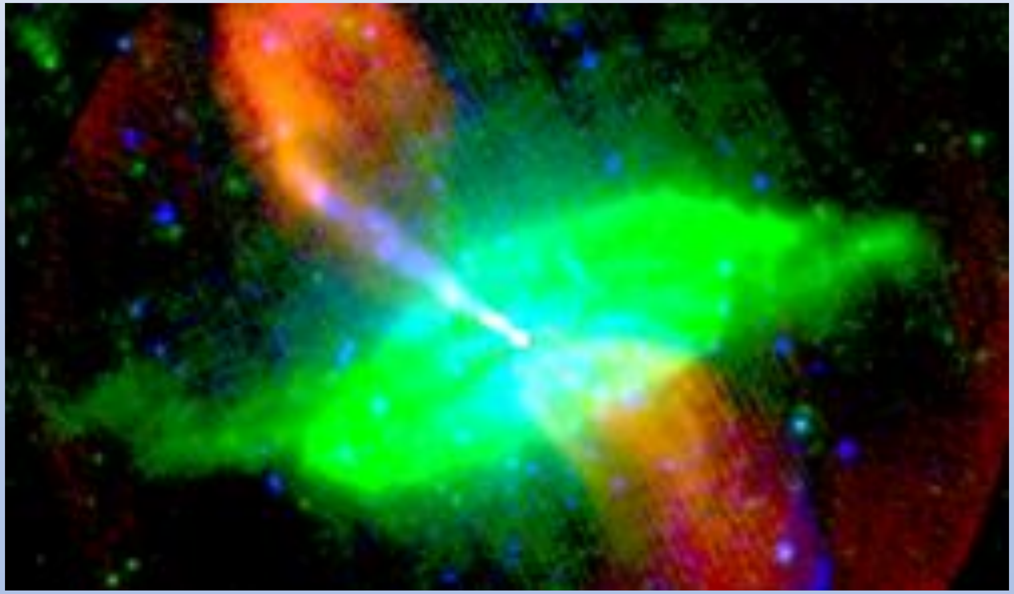
Centaurus A (NGC5128) ① Feature

- The nearest active galaxy

  (d=3.8 Mpc: Harris et al. 2006)

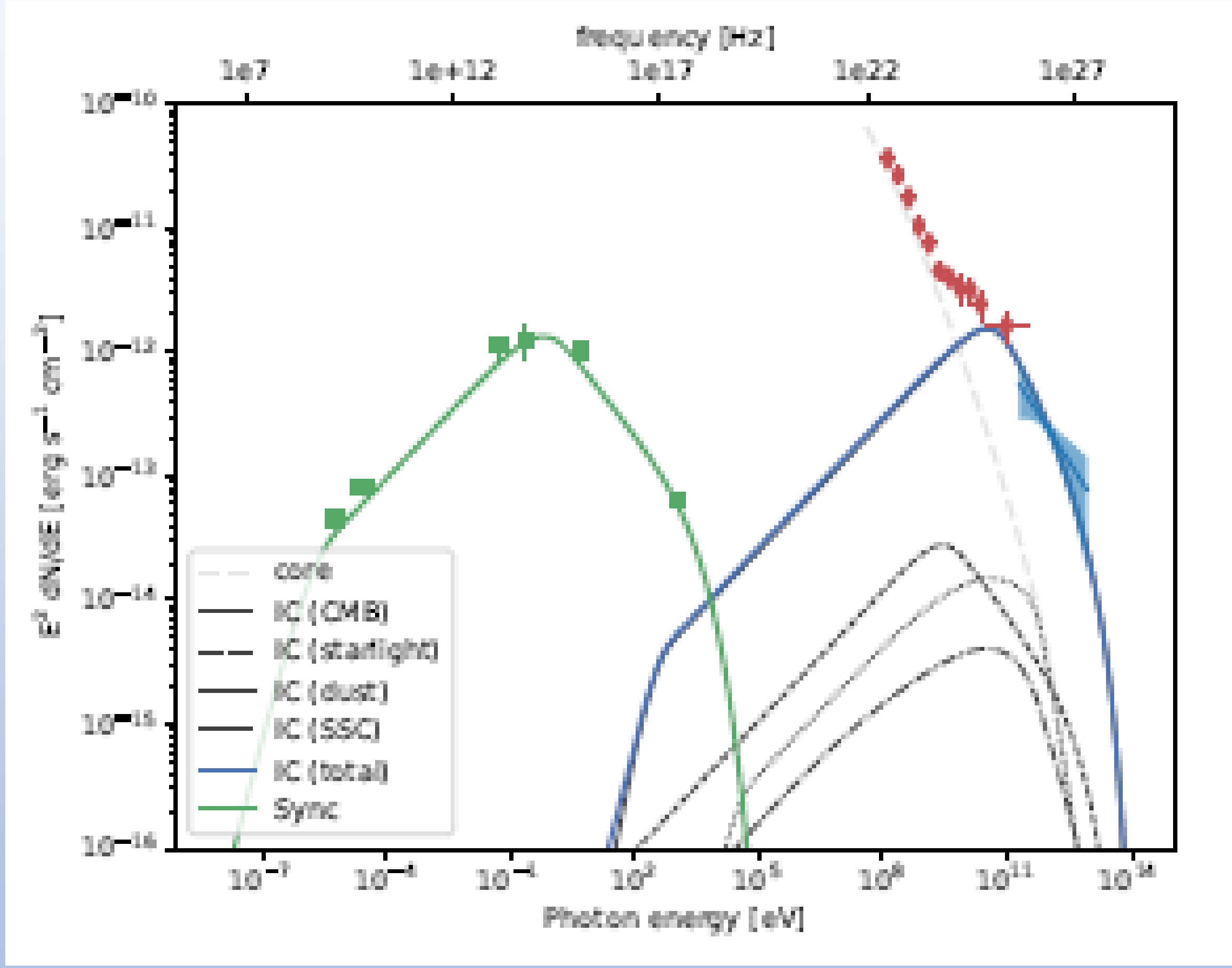
- resolved in the range from radio to gamma-rays
  - radio emitting core: < 10^{-2} pc
  - jet and counter-jet: ～ pc
  - jet and inner lobes: ～ kpc
  - giant outer lobes: hundreds of kpc

Optical image（ ESO, WFI ）



Red: radio Green: infrared Blue: X-ray（ M. Hardcastle ）

Centaurus A ② Unnatural hardening of VHE



H.E.S.S. Collaboration, 2020

- VHE (> 100 GeV) γ-rays has been detected with H.E.S.S.

The origin of the **unnatural hardening** of the VHE gamma-rays remains still controversial!

Centaurus A ③ Model of the spectrum

■ Fanaroff-Riley Class I (FR-I) Radio Galaxy

← mis-aligned BL Lac

➡ SSC (Synchrotron Self-Compton) Model

Conventional single-zone SSC cannot explain the hardening of VHE gamma-rays

(e.g.) Chiaberge et al. (2001)

→ *not* favored !

➡ EC (External Compton) Model

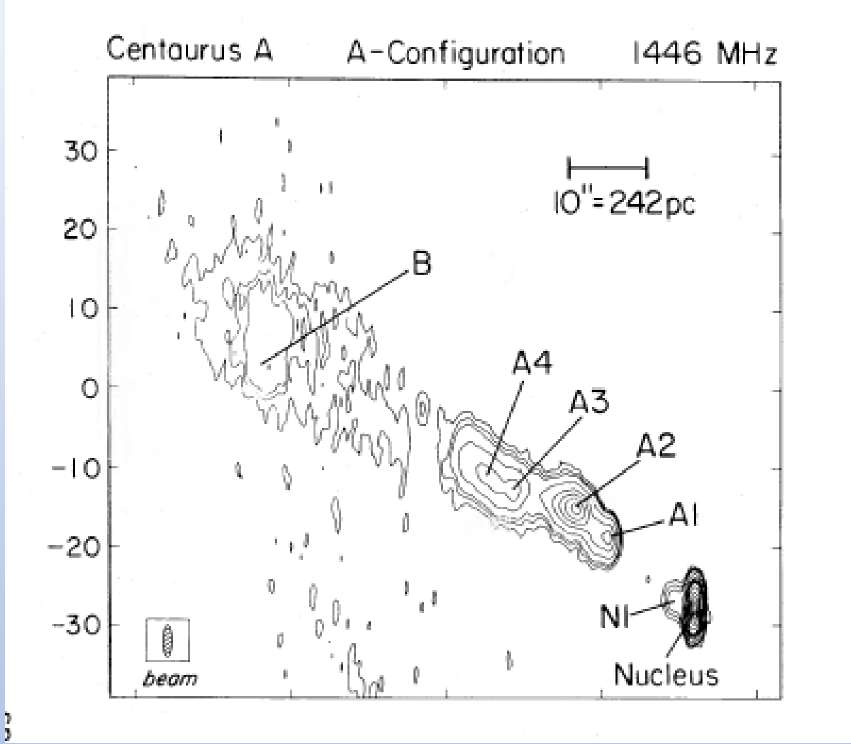
dust, starlight, …

(e.g.) Tanada et al. (2019)

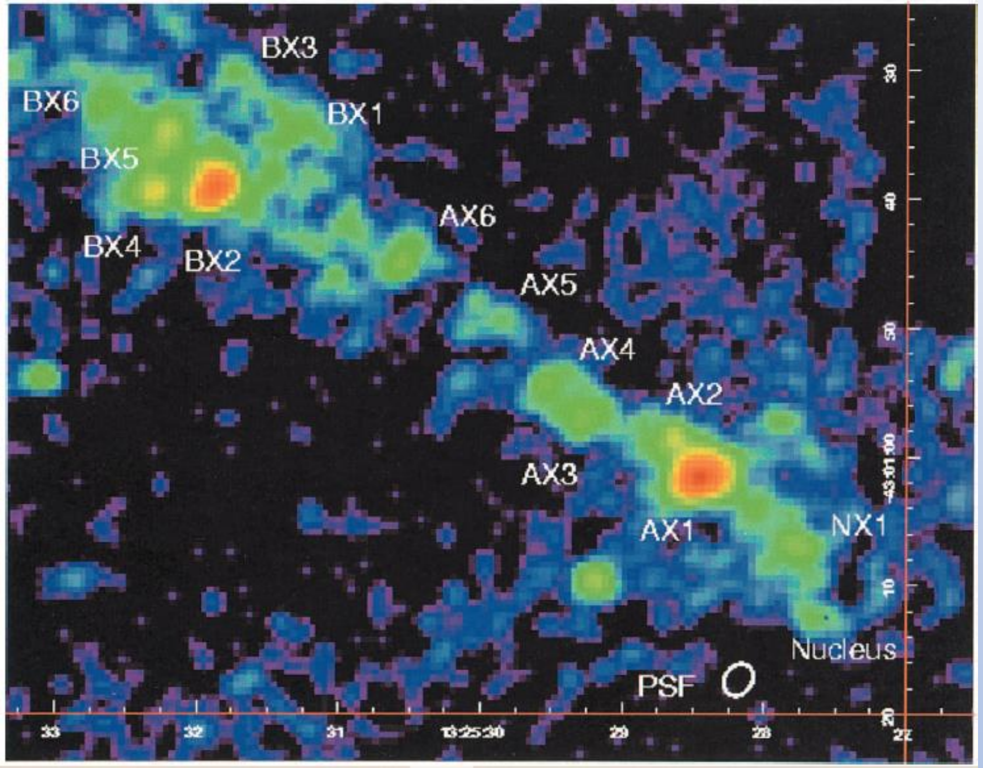
→ candidate

Jet Morphology (Radio and X-rays)

- Knot-like Structure detected by radio and X-rays



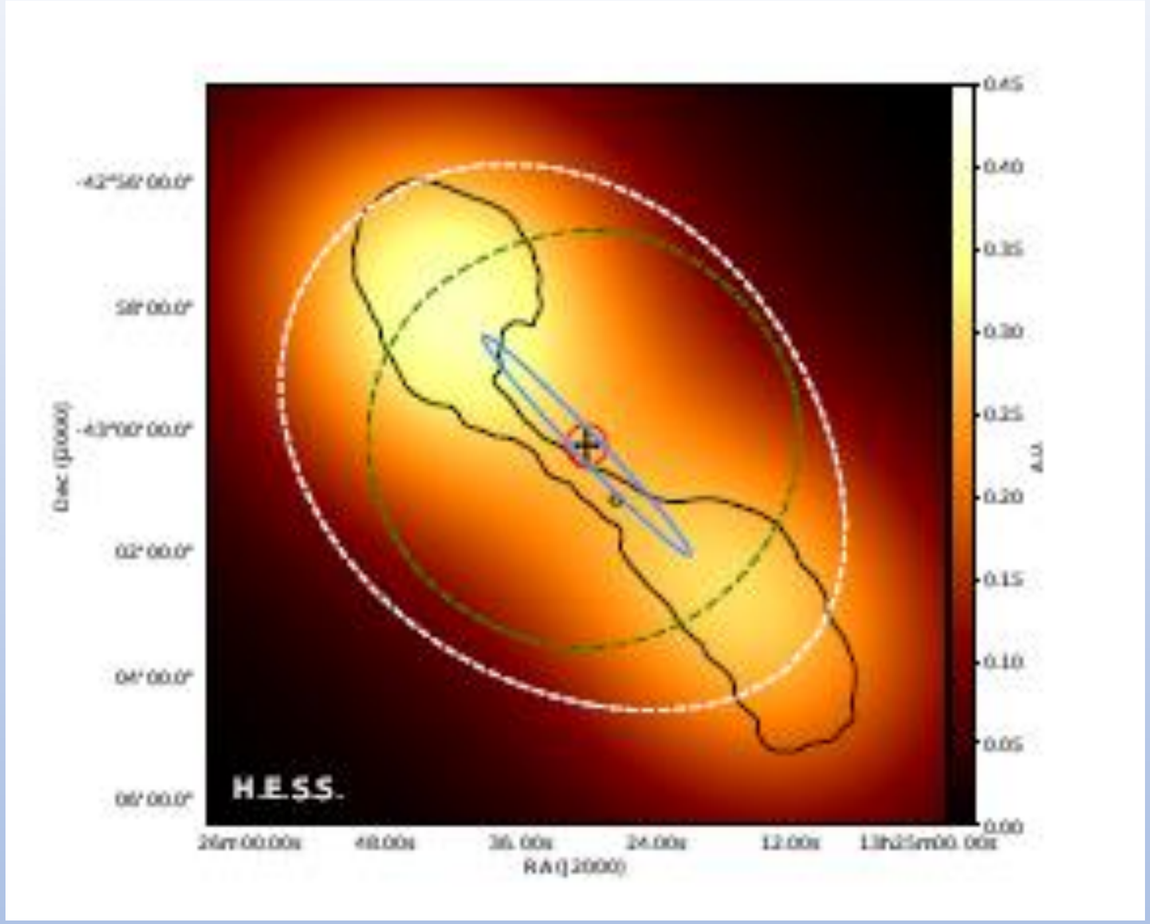
Radio (VLA)
Burns et al. (1983)



X-rays (Chandra)
Kraft et al. (2002)

Jet Morphology (Gamma-Rays)

- Gamma-rays are detected at the extended region of the jet.



H.E.S.S. Collaboration 2020

The source of particle acceleration is distributed within the quite wide range.

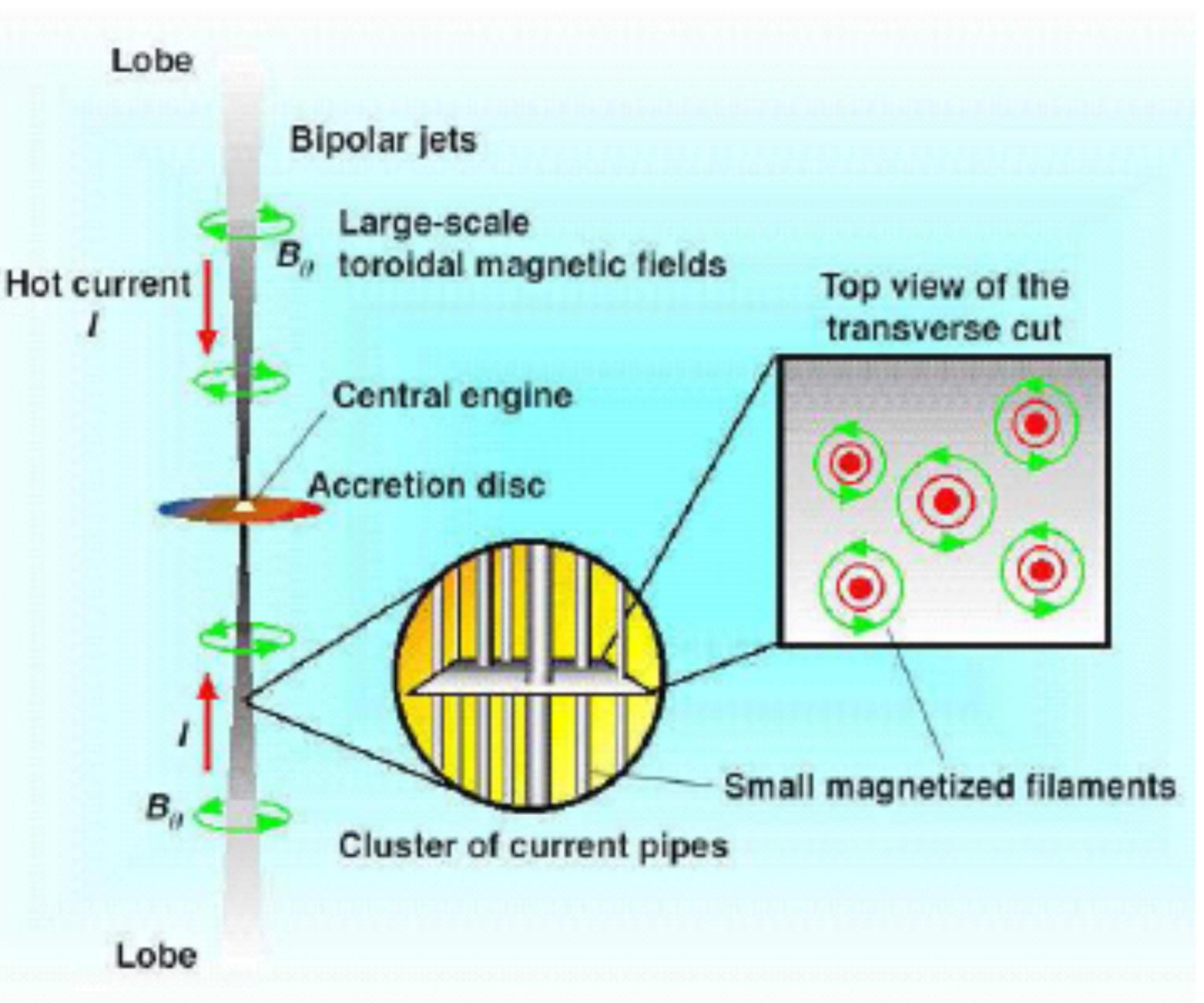
- Stochastic acceleration
- Shear acceleration

Contour ： Radio (VLA)

Color-scale ： Gamma-rays (H.E.S.S.)

Filamentary jet model

■ **Jet is comprised of the bunch of current filaments.**



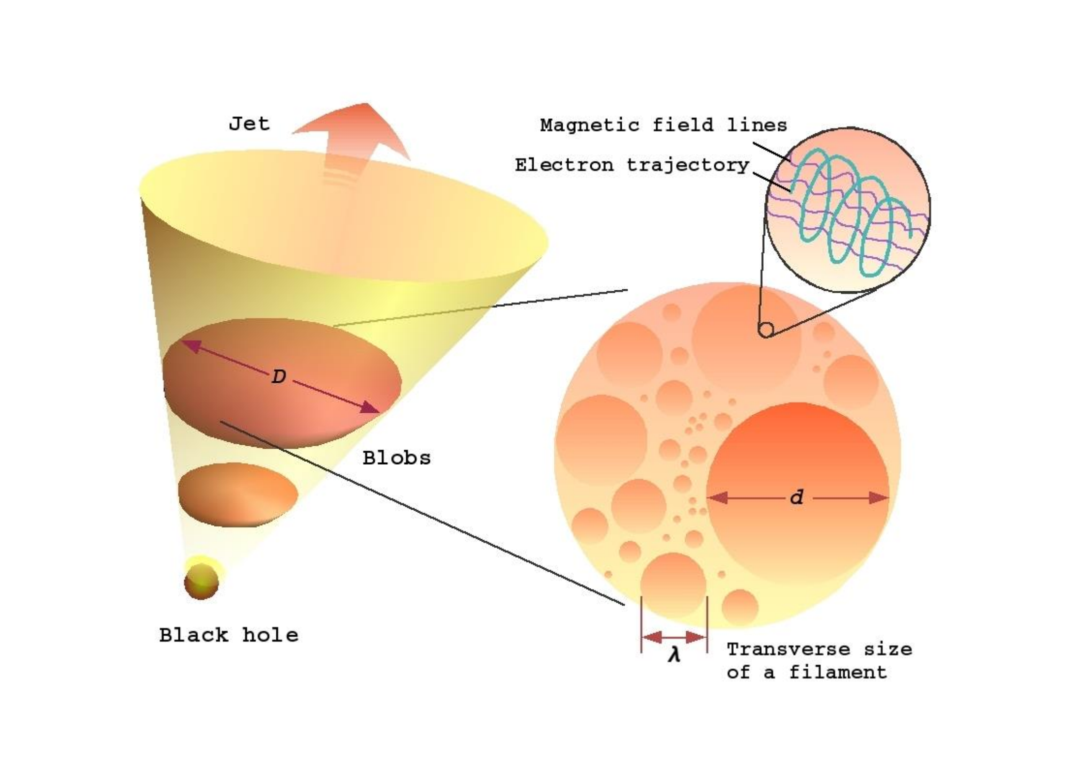
- □ **Filamentation**
  - ● **Collision of shocks, Instabilities**
- □ **magnetic field generation**
  - ● **Toroidal magnetic field is induced around the filaments with various transverse sizes.**

$$B = B_m \left(\frac{\lambda}{D}\right)^{(\beta-1)/2}$$

λ : width of a filament
β : turbulent spectral index

Acceleration Processes

■ **Electrons are trapped with the magnetic field of each filament.**



Cutting edge of the jet

□ **Numerous filaments with various sizes are present in a knot.**

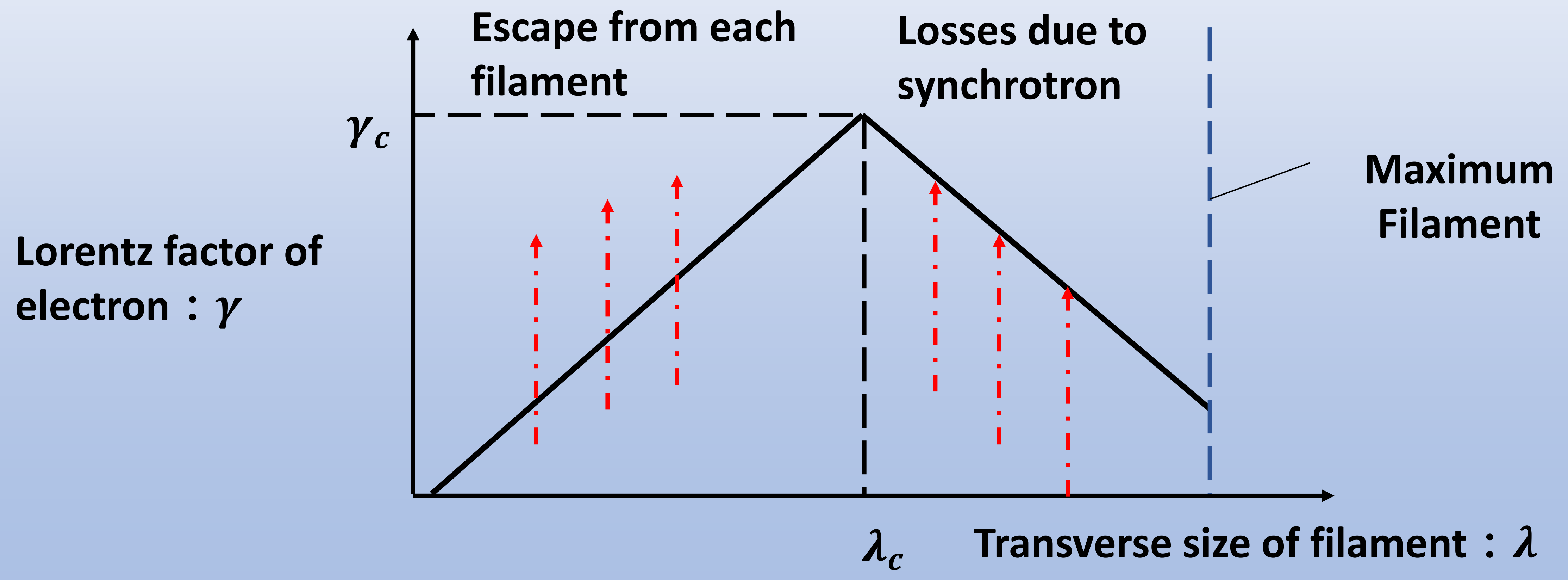
□ **Shock wave passes through the jet.**

→ **observed as knots (or blobs)**

□ **Electrons are accelerated stochastically being back and forth across the shock (DSA).**

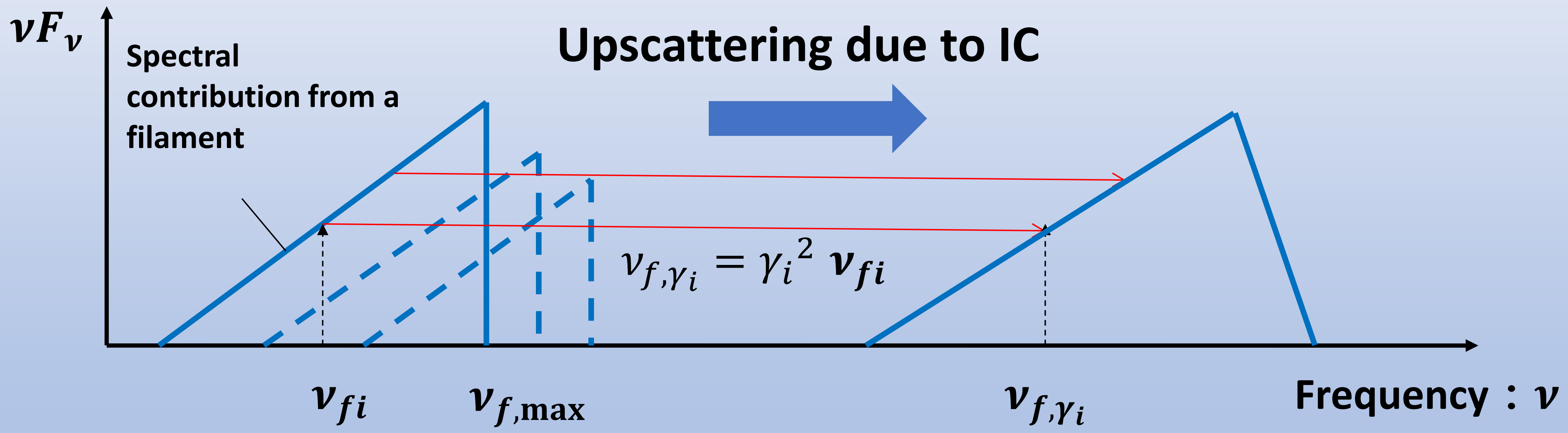
Acceleration and Energy Restriction

- **Maximum energy of accelerated electrons is determined by the temporal or spatial limit.**



A multi-zone SSC Scenario

- Superposing synchrotron spectra by the accelerated electrons from the filaments with various sizes



Schematic view of constructing spectrum

Effects of Radiative Cooling

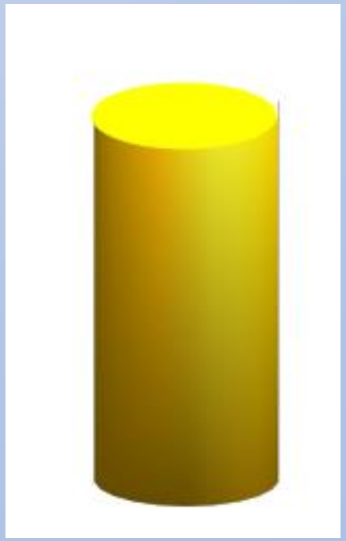
- It is more natural to consider some kind of radiative losses in filamentary jet model.

large ← $\dfrac{emitting\ surface}{emitting\ volume}$ → small

$$\frac{u_{\rm rad}}{u_{\rm m}} = a\left(\frac{\lambda}{D}\right)$$

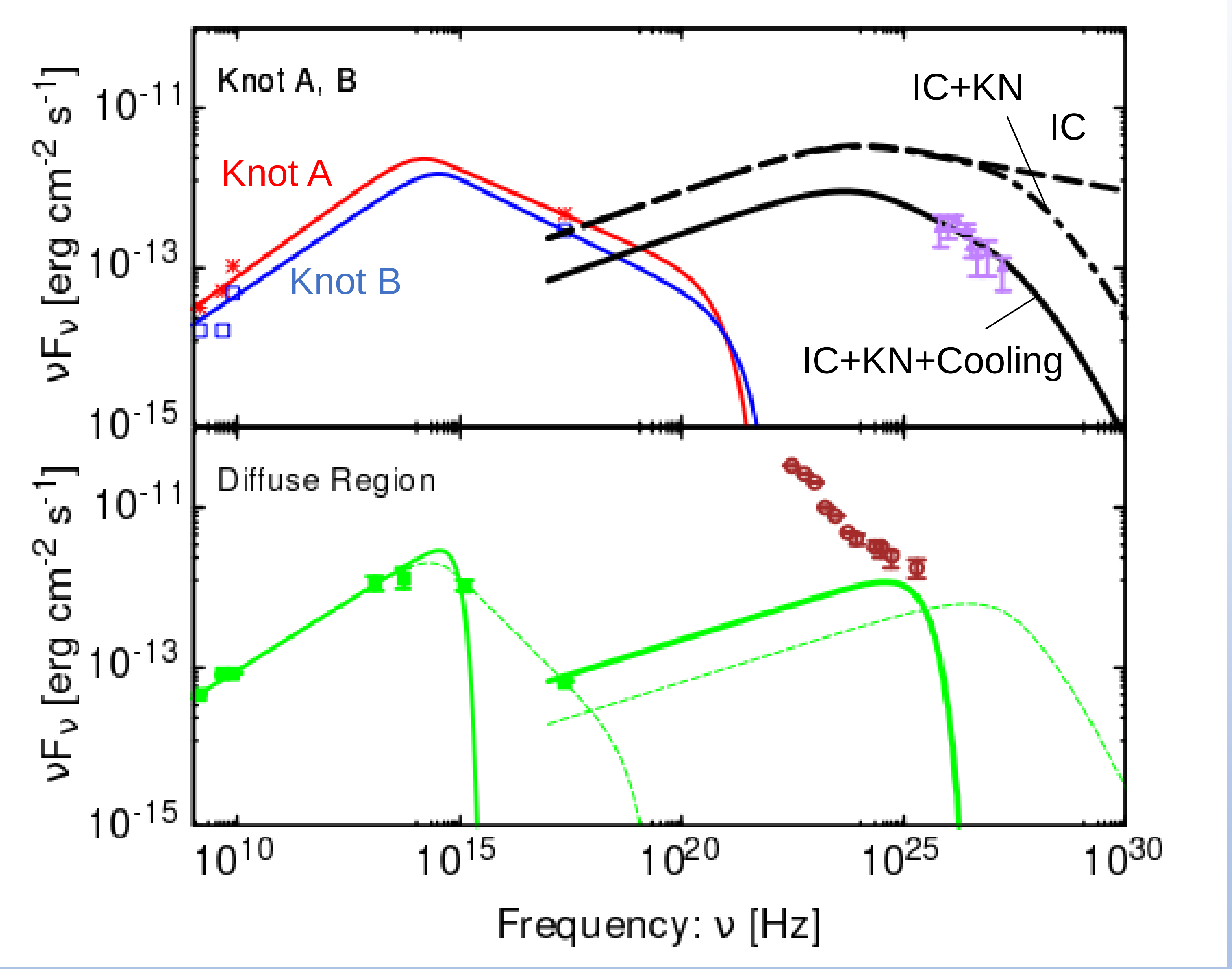
$a < 1$: constant
λ : filament width
D: Maximum Size of filament

cooled
(radiator effect)



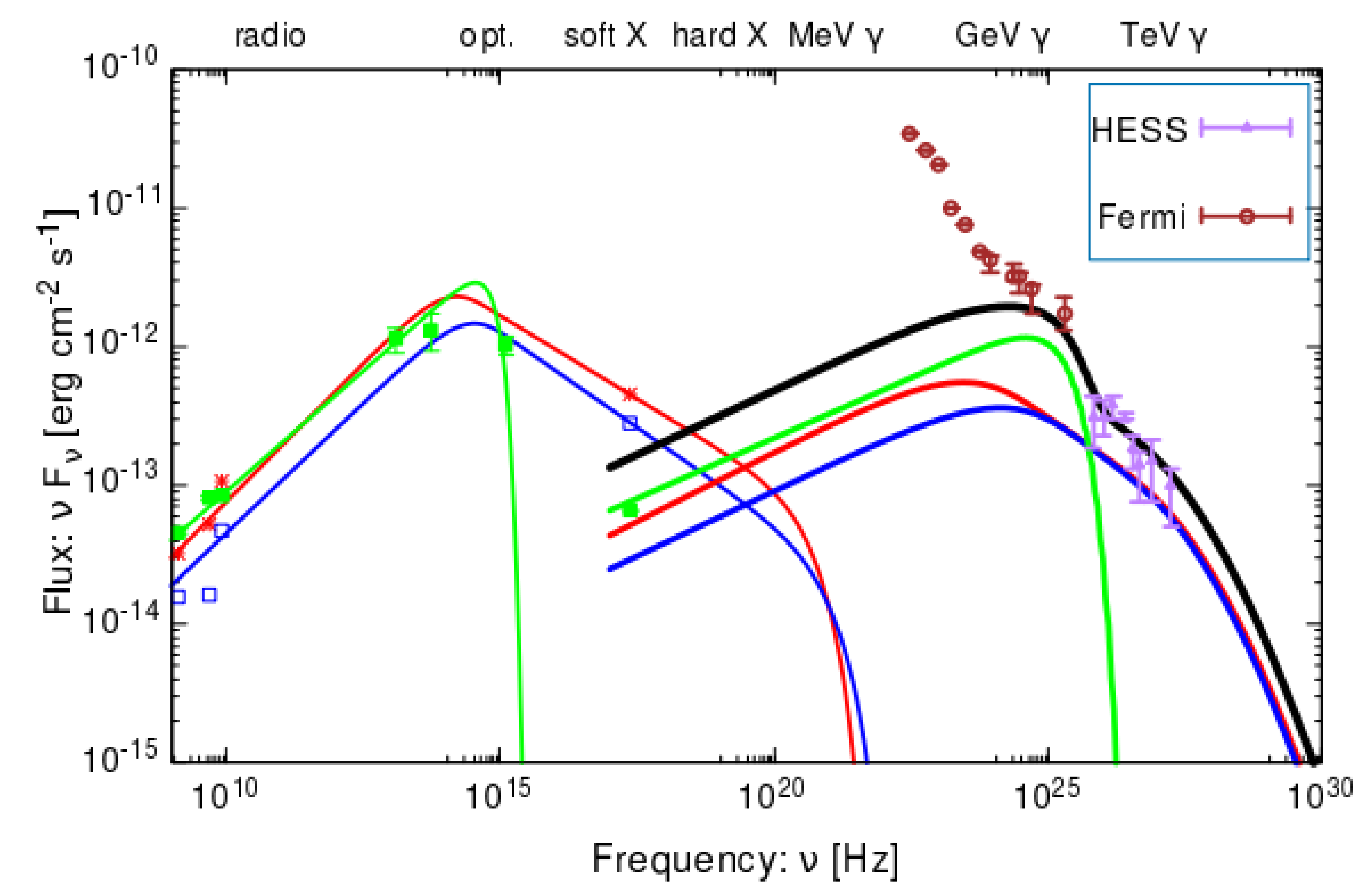
Spectral fitting① knots and diffuse region

Knots: Filamentary model
+KN+Cooling
Diffuse Region:
Fully developed
turbulence
⇒ one-zone SSC



Spectral Fitting ② Total

Black solid curve is sum Of the knot A, B, and Diffuse region.
All of them are including IC+KN+cooling effects.
It is well accommodated with the H.E.S.S. and Fermi fluxes > 100 GeV.



Summary

■ **The major origin of the spectral hardening of the VHE fluxes is ascribed to the DSA + SSC + filament model within the reasonable parameter range.**

■ **The maximum Lorentz factor of electrons reaches $\sim 10^9$.**

■ **The γ-ray variability can be estimated as**

$\tau = t_{syn} \sim 4.2\ \mathrm{yr}$ (at 20 GeV)

might be resolved by CTA in future …