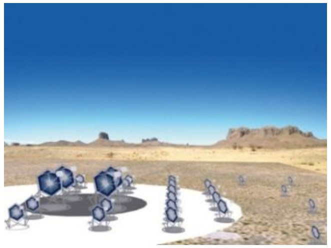
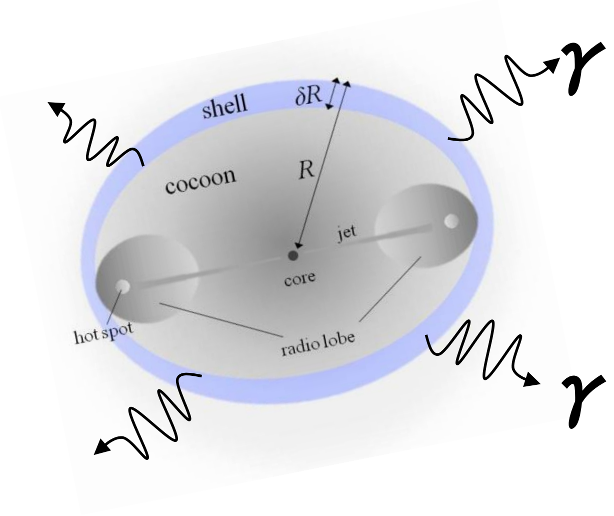
CTAで探る低光度AGN電波シェルからの超高エネルギーガンマ線放射



CTA



SKA

紀　基樹 (国立天文台)
10月からISAS/JAXA

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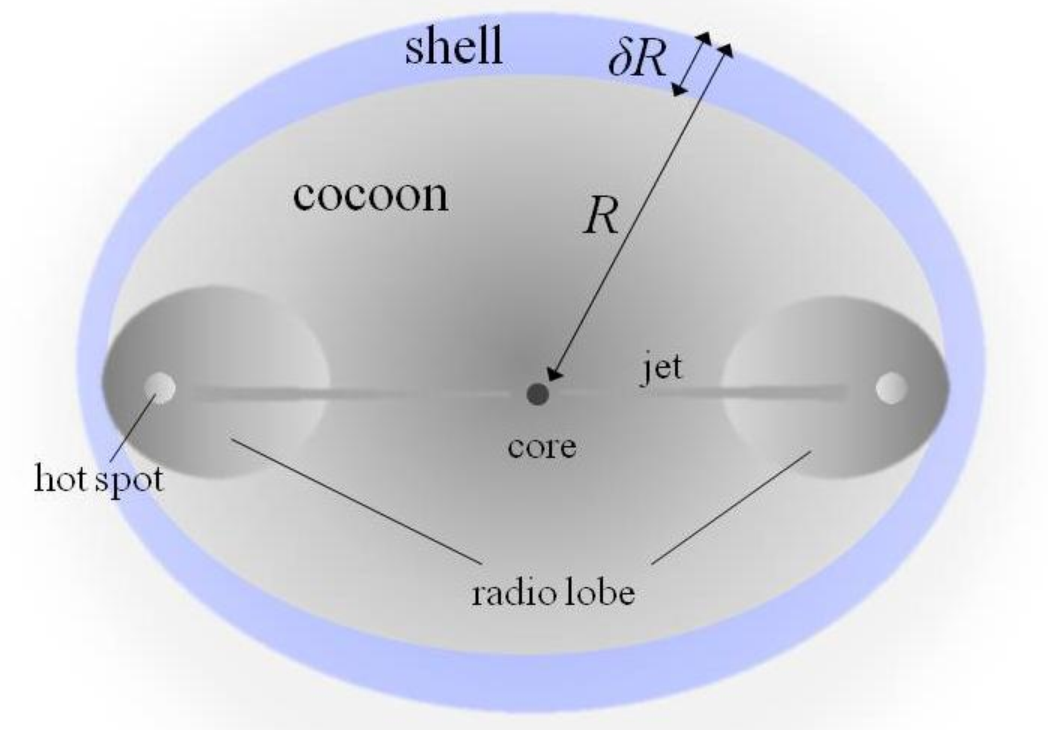
Introduction

What are shells & radio lobes?

Jets are enveloped in a cocoon consisting of shocked jet material and the cocoon is surrounded by shocked interstellar medium. The shocked ambient region is identical to the shell



AGN jets are known as powerful particle accelerators.

Shell is known as dark viewed in radio

DISCOVERY OF THE BOW SHOCK OF CYGNUS A

C. L. CARILLI
Department of Physics, Massachusetts Institute of Technology; and National Radio Astronomy Observatory[1]

R. A. PERLEY
National Radio Astronomy Observatory

AND

J. H. DREHER
Department of Physics, Massachusetts Institute of Technology

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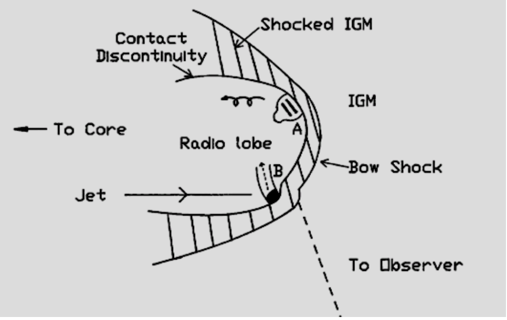


ABSTRACT

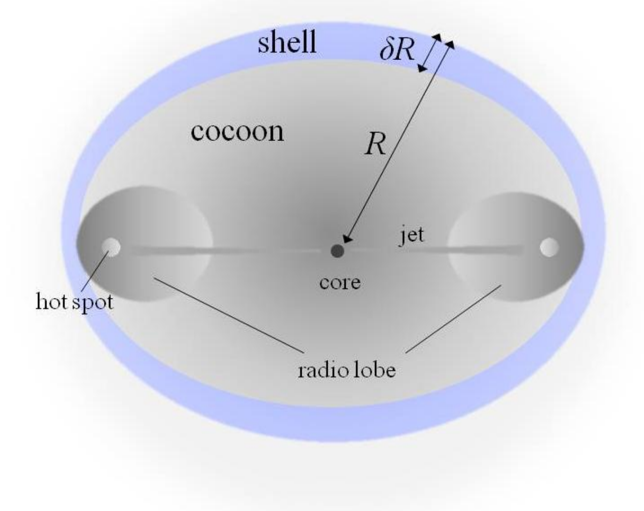
Rotation measure images of Cygnus A indicate that a bow shock precedes the supersonic advance of hot spot B into the intergalactic medium. The shock is radio quiet and is observed only by the rotation measure discontinuity which occurs at the point where the fields and particles in the IGM are compressed by the shock. The fact that this discontinuity is projected onto part of the source provides information on the three-dimensional structure of the radio source and supports models of extragalactic radio sources in which the jet varies direction on relatively short time scales. From the observed rotation measures, we calculate magnetic field strengths in the cluster gas of $\sim 7.5\ \mu G$.

Subject headings: galaxies: intergalactic medium — galaxies: jets — shock waves — radio sources: galaxies

Model

Shell Dynamics

Dynamics: we adopt well-established bubble model (Castor 1975; Ostriker & McKee 1988). The shell width at the bubble radius R is denoted as δR.



$$\begin{cases} R(t) = C \ \ R_0{}^{\alpha/(\alpha-5)} \left(\dfrac{L_\mathrm{j}}{\rho_0}\right)^{1/(5-\alpha)} t^{3/(5-\alpha)} \\ \rho_\mathrm{a}(R) = \rho_0 (R/R_0)^{-\alpha} \\ \delta R = (\hat{\gamma}_\mathrm{a} - 1)R/[(\hat{\gamma}_\mathrm{a} + 1)(3-\alpha)] \end{cases}$$

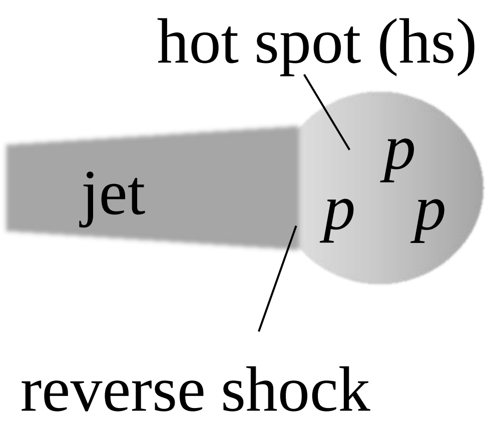
Non-thermal photons and electrons: We solve the following kinetic equation describing the electron energy distribution as follows:

$$\frac{\partial N_e(\gamma_e, t)}{\partial t} = \frac{\partial}{\partial \gamma_e}[\dot{\gamma}_{\mathrm{cool}}(\gamma_e, t) N_e(\gamma_e, t)] + Q_e(\gamma_e, t)$$

Regarding IC scattering, the following seed photons are included:
(1) UV photons from a standard accretion disk
(2) IR photons from a dust torus
(3) synchrotron photons from the radio lobes
(4) synchrotron photons from the shell

Proton Acceleration In Hot Spots

MK & Asano (2011)



Assuming proton-gyro factor $\xi_p \sim 10^2$,

Acceleration time

$$t_{p,\mathrm{acc,hs}} \approx 3.5\ \varepsilon_{p,18} B_{\mathrm{hs},-1}^{-1} \xi_{p,2}\ \mathrm{yr}$$

Cooling time

$$t_{p,\mathrm{syn,hs}} = \frac{6\pi m_p^4 c^3}{\sigma_T m_e^2 \varepsilon_p B_{\mathrm{hs}}^2} \approx 1.4 \times 10^4\ \varepsilon_{p,18}^{-1} B_{\mathrm{hs},-1}^{-2}\ \mathrm{yr}$$

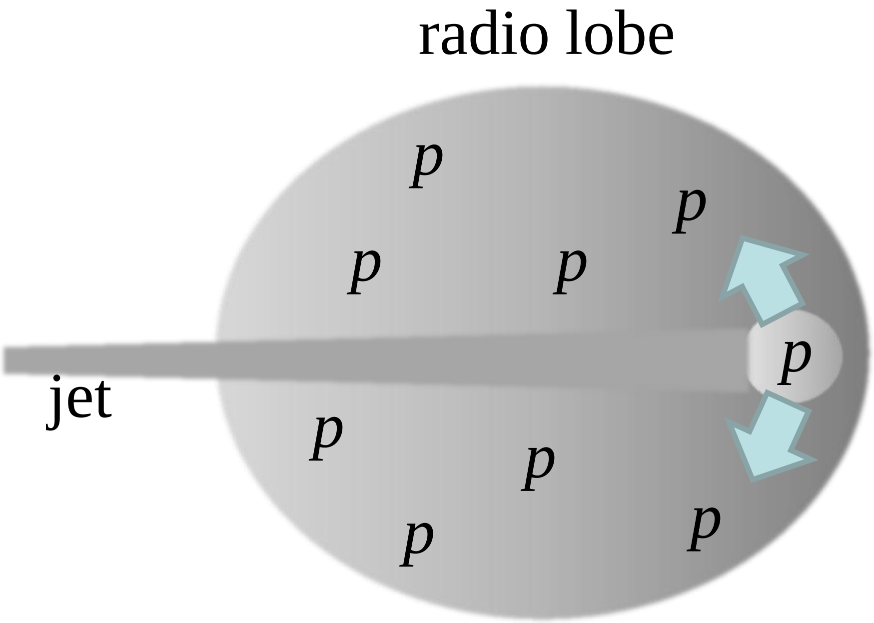
Confinement condition

$$R_{\mathrm{hs}} > r_{\mathrm{L,hs}} \approx 1 \times 10^{-2}\ \varepsilon_{p,18} B_{\mathrm{hs},-1}^{-1}\ \mathrm{pc}$$

Hot spots can accelerate protons up to ~10^18eV (when $\xi_p \sim 10^2$).

Proton injection into radio lobes

MK & Asano (2011)



Sideways escape velocity

$$v_{\rm esc,hs} \approx 0.3\ c$$

Sideways escape time

$$t_{\rm esc,hs} \approx 3\ R_{\rm hs,18}\ \text{years}$$

High energy protons produced at the hot spot are injected (escaped) into the radio lobes.

Application to nearby mini-bubbles

Targets: Nearby Compact Radio Sources (~a few pc size)

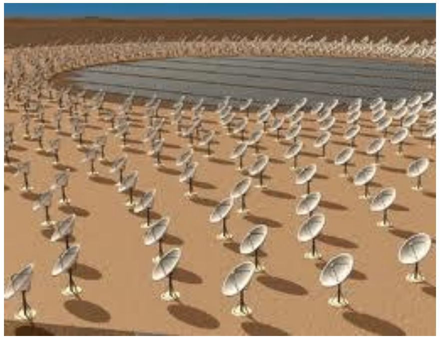
1. Compact RAdio sources in Low-Z (CORALZ)
Snellen+; de Vries+
0.005<z<0.16
Θ < 2 arcsec
S_1.4GHz >100 mJy in FIRST catalogue.

CORALZ list: De Vries+09

IAU Name	z	$S_{1.4\ \mathrm{GHz}}$ (mJy)	$L_{5.0\ \mathrm{GHz}}$ (W Hz^{-1})	ν_{peak} (MHz)	θ (mas)	LLS (pc)	Morph.
The CORALZ core sample							
J073328+560541	0.104	394	24.68	460	47	90	CSO
J073934+495438	0.054	107	23.63	950	2*	2*	U
J083139+460800	0.127	131	24.62	2200	9	20	CD
J083637+440109	0.054	139	23.66	<150	1600	1700	CSO?
J090615+463618	0.085	314	24.49	680	31	49	CSO
J102618+454229	0.153	105	24.55	180	17	45	CSO
J103719+433515	0.023	129	22.96	<150	19	9	CSO
J115000+552821	0.139	143	24.57	<230	41	100	U
J120902+411559	0.095	147	24.26	370	20	35	CSO
J131739+411545	0.066	249	24.37	2300	4	5	CX
J140051+521606	0.116	174	24.36	<150	150*	320*	U
J140942+360416	0.148	143	24.45	330	27	70	CJ?
J143521+505122	0.099	141	24.20	<150	150*	270*	U
J150805+342323	0.045	130	23.35	<230	170	150	CD?
J160246+524358	0.106	576	24.75	<150	180	350	CSO
J161148+404020	0.152	553	25.03	<150	1300	3400	CX
J170330+454047	0.060	119	23.54	<150			
J171854+544148	0.147	329	24.86	480	68	175	CSO?
Other nearby sources in the CORALZ sample							
J093609+331308	0.076	55	23.84	2200	1.5*	2*	U
J101636+563926	0.232	108	24.91	<150	240	890	CD?
J105731+405646	0.008	47	21.59	1250	0.5*	0.1*	U
J115727+431806	0.229	256	25.25	<150	630	2300	CJ?
J132513+395552	0.074	56	23.69	1900	10	14	CSO?
J134035+444817	0.065	82	23.89	2300	3.3	4.1	CJ?
J155927+533054	0.178	182	24.67	<150	1500	4500	CSO?

2. Less-Luminous CORALZ
•Deeper survey of CORALZ in the future
S _1.4GHz >1~100 mJy in FIRST catalogue

•A new (unbiased) survey by SKA in the future



Jet Power, Ambient matter density etc.

Jet power: Since the SSA turnover frequency, the flux and the size of the radio lobe are observationally determined, B_lobe is well constraint. Therefore, we can estimate the the jet power from these quantities.

$$\nu_{\rm ssa,lobe} \propto B_{\rm lobe}^{1/5} S_{\nu,\rm lobe}^{2/5} R_{\rm lobe}^{-4/5} \sim \text{a few} \times 100 \text{ MHz (de Vries et al. 2009)}$$

$$L_{\rm j}\epsilon_{\rm B,lobe} \equiv L_{\rm poy} = 4\pi R_{\rm lobe}^2 c/3 \times (B_{\rm lobe}^2/8\pi)$$

$$L_{\rm j} \sim 6 \times 10^{47} (R_{\rm lobe}/2 \text{ pc})^2 (\epsilon_{\rm B,lobe}/10^{-2})^{-1} \text{ erg s}^{-1}$$

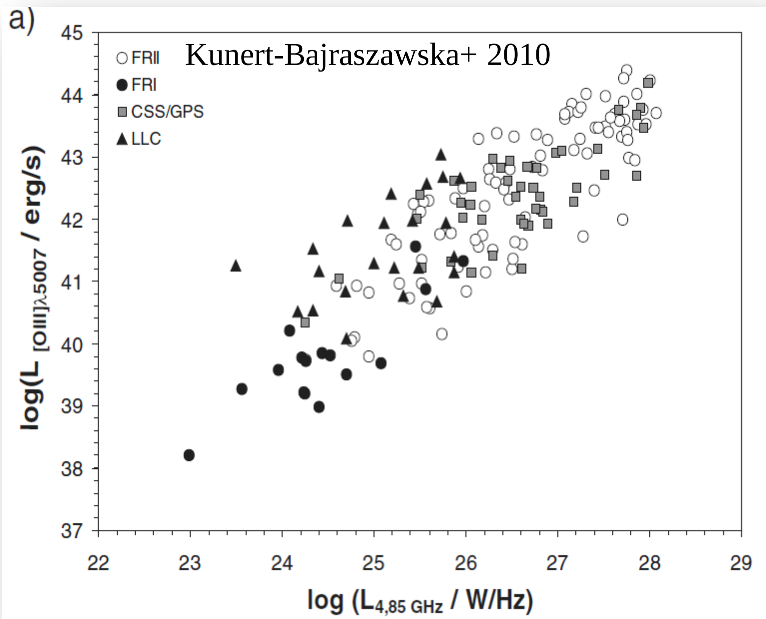
Shell and lobe parameters: Shell parameters can be well constrained by the well-studied supernovae remnants. Lobe parameters are determined by the various observations of the lobes.

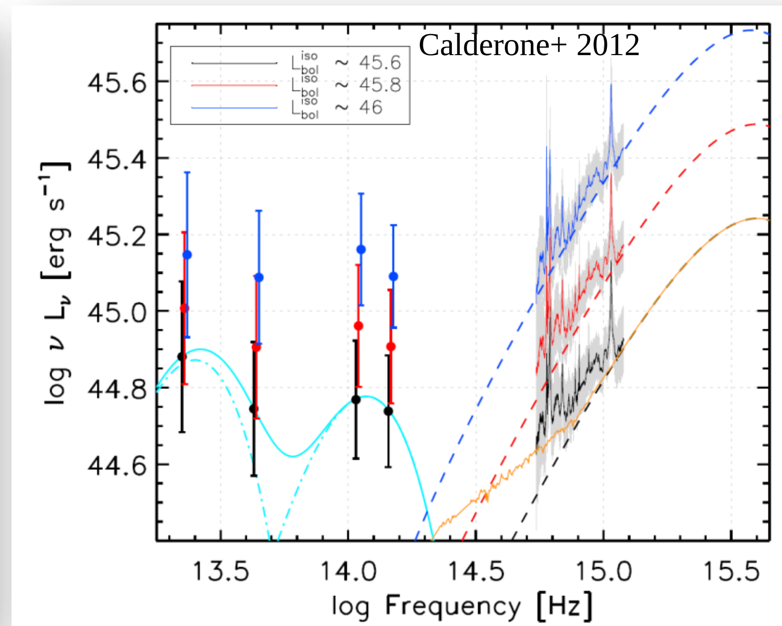
parameters	symbols	values
mass density of ambient matter	n_0	0.1 cm^{-3}
magnetic field strength	$B_{\rm shell}$	$10\ \mu$G
fraction of non-thermal electrons	$\epsilon_{\rm e,shell}$	0.05
power-law index of injected electrons (shell)	$p_{\rm shell}$	2
gyro-factor	$\xi_{\rm shell}$	10

$$\gamma_{\rm lobe,min} = \gamma_{\rm shell,min} = 1$$

Estimate of nucleus luminosity: L_{IR} & L_{UV}

Since disk's UV emission is likely a main source for the ionization of clouds in narrow line regions, it is reasonable to suppose that $L_{UV} > L_{[OIII]}$





$L_{[OIII]} \sim 10^{40\text{-}43}$ erg/s

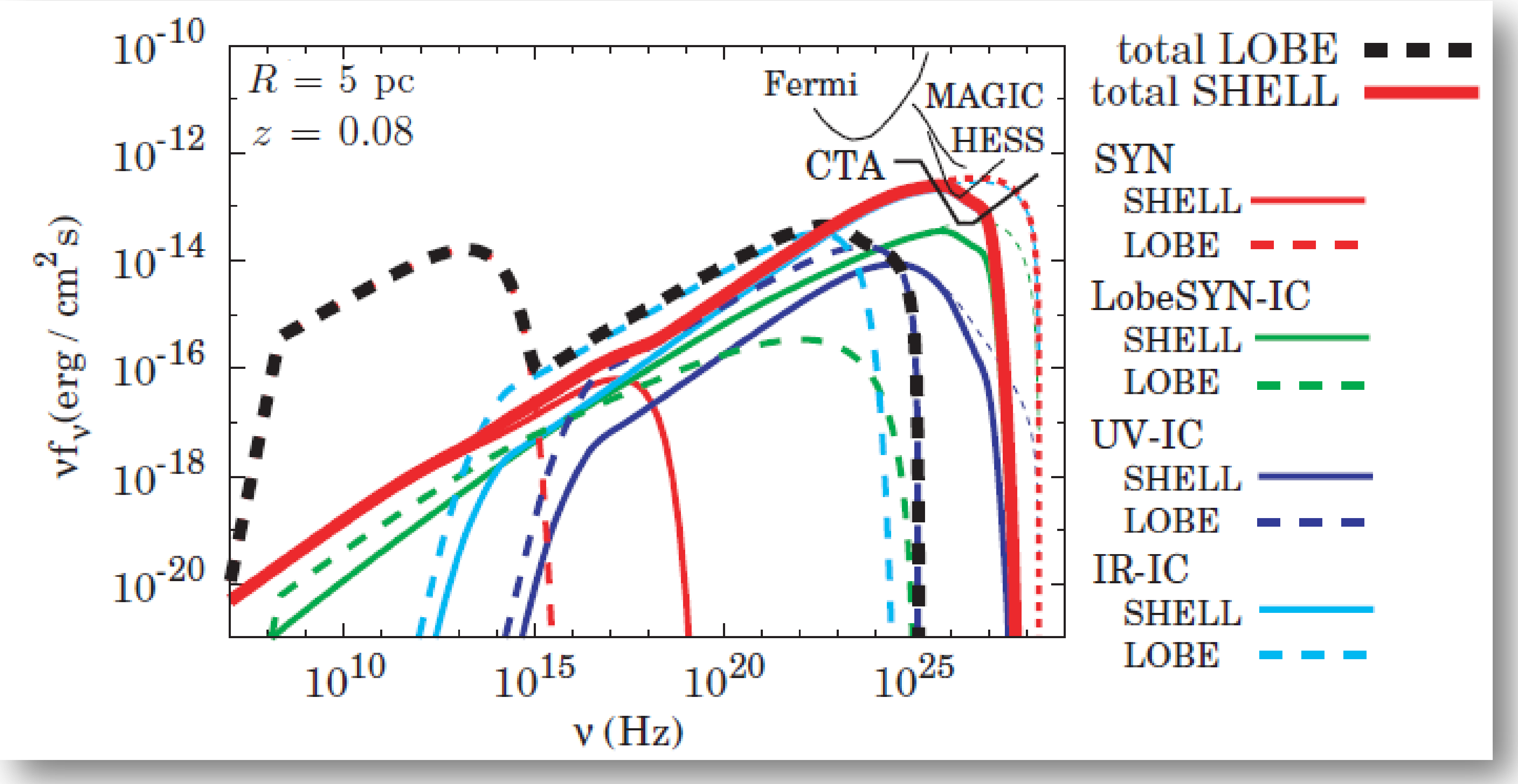
$L_{IR} \sim (1/3\text{-}1/2)\, L_{UV}$

We adopt

$$L_{UV} = 6 \times 10^{42}, 6 \times 10^{43}, 6 \times 10^{44} \ \mathrm{erg\ s^{-1}}$$

Results: VHE γ from mini-shell

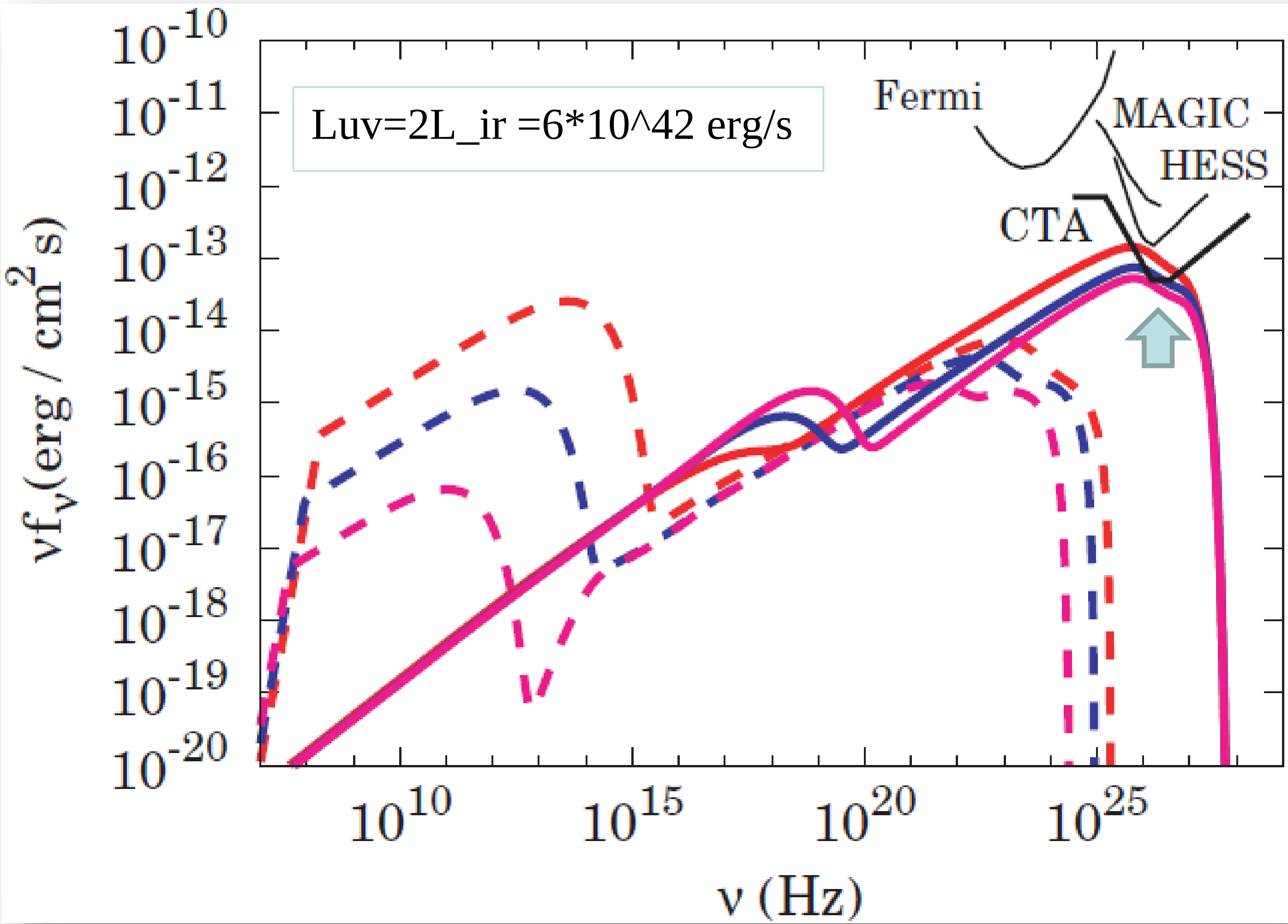
Resultant Spectra



We find that the non-thermal emission from the mini-shells can be detectable by CTA and they become a potential new class of VHE gamma-ray emitters.

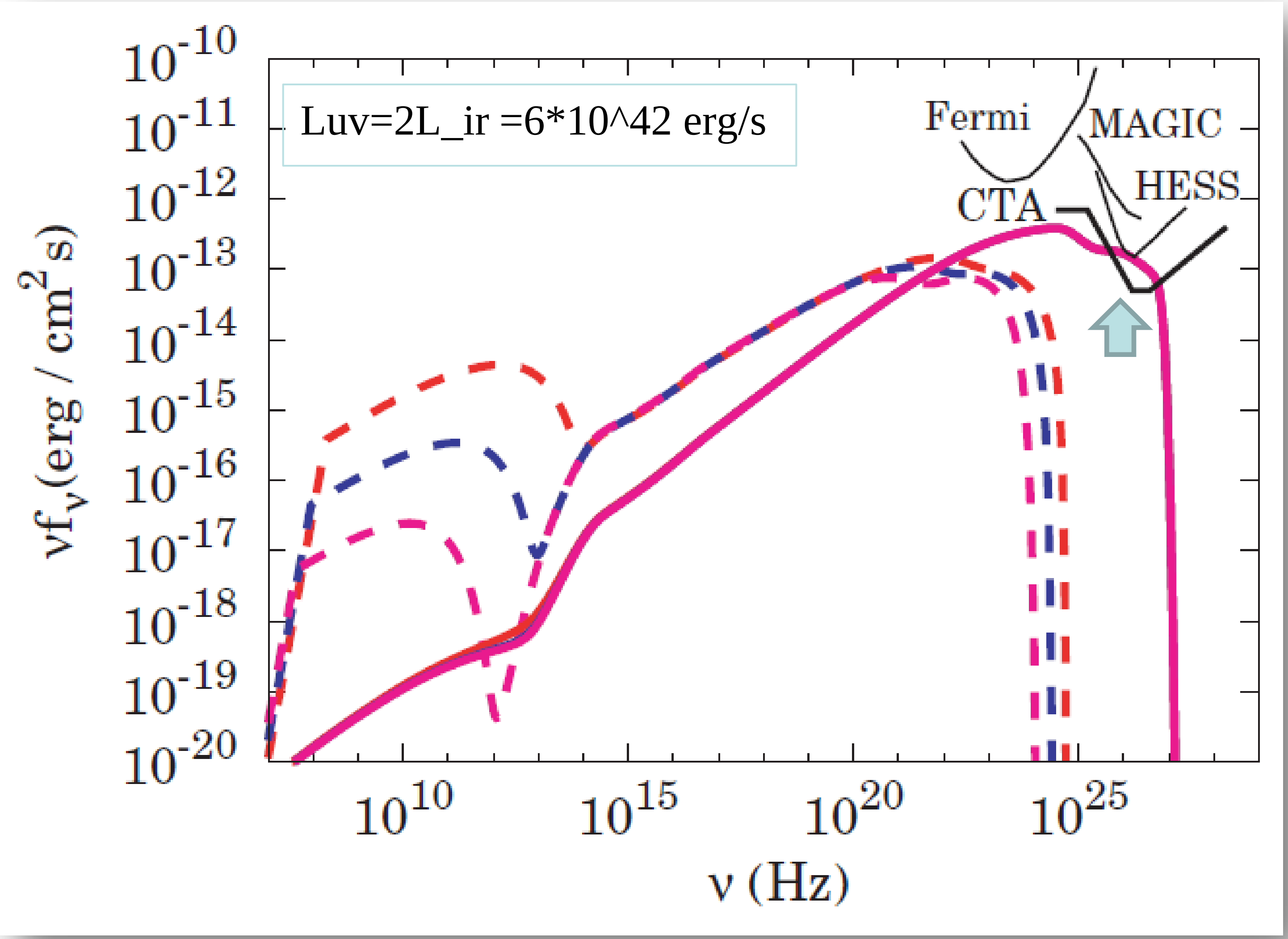
IC seed: lobe-synchrotron-dominated

The shell luminosity at TeV range becomes slightly brighter when synchrotron emission of radio lobes become brighter.



IC seed: nucleus-dominated

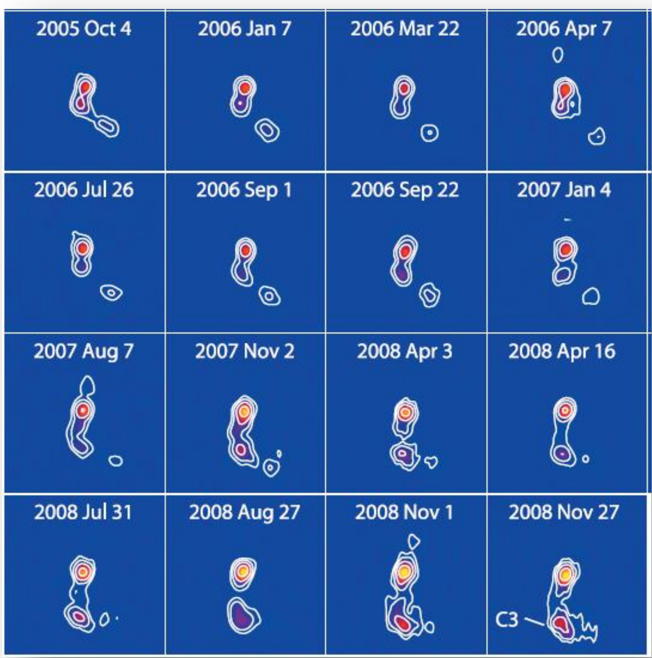
The shell luminosity at TeV range remains constant because IC scattering is dominated by nucleus emission .



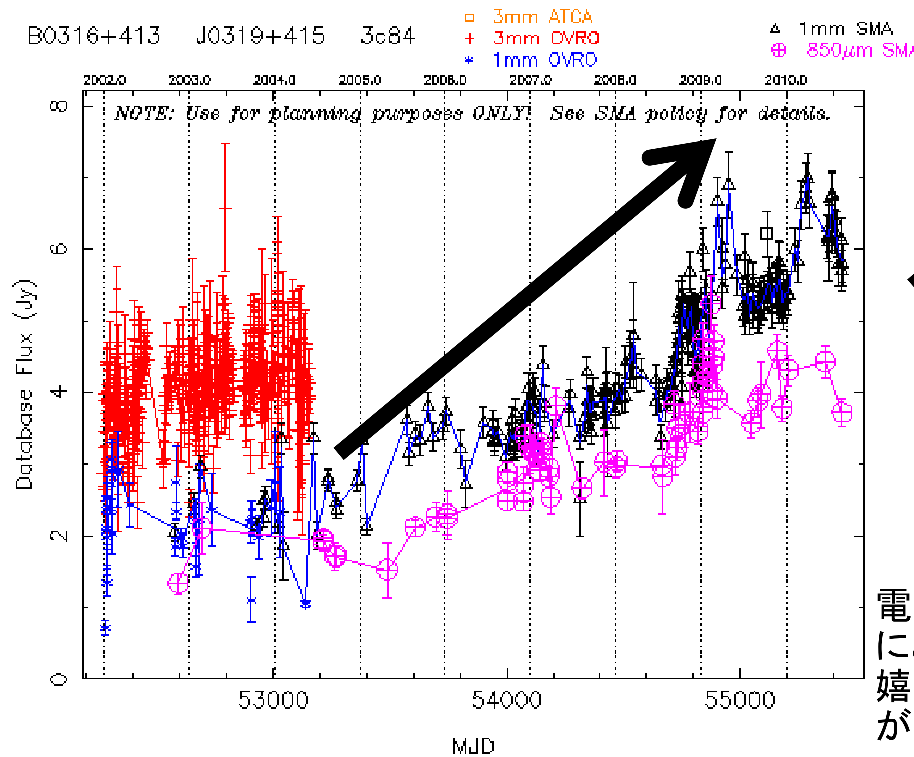
Results: VHE γ from mini-radio lobes

What if the a jet stops within a few ten years?

Suzuki, Nagai, MK+ 2012



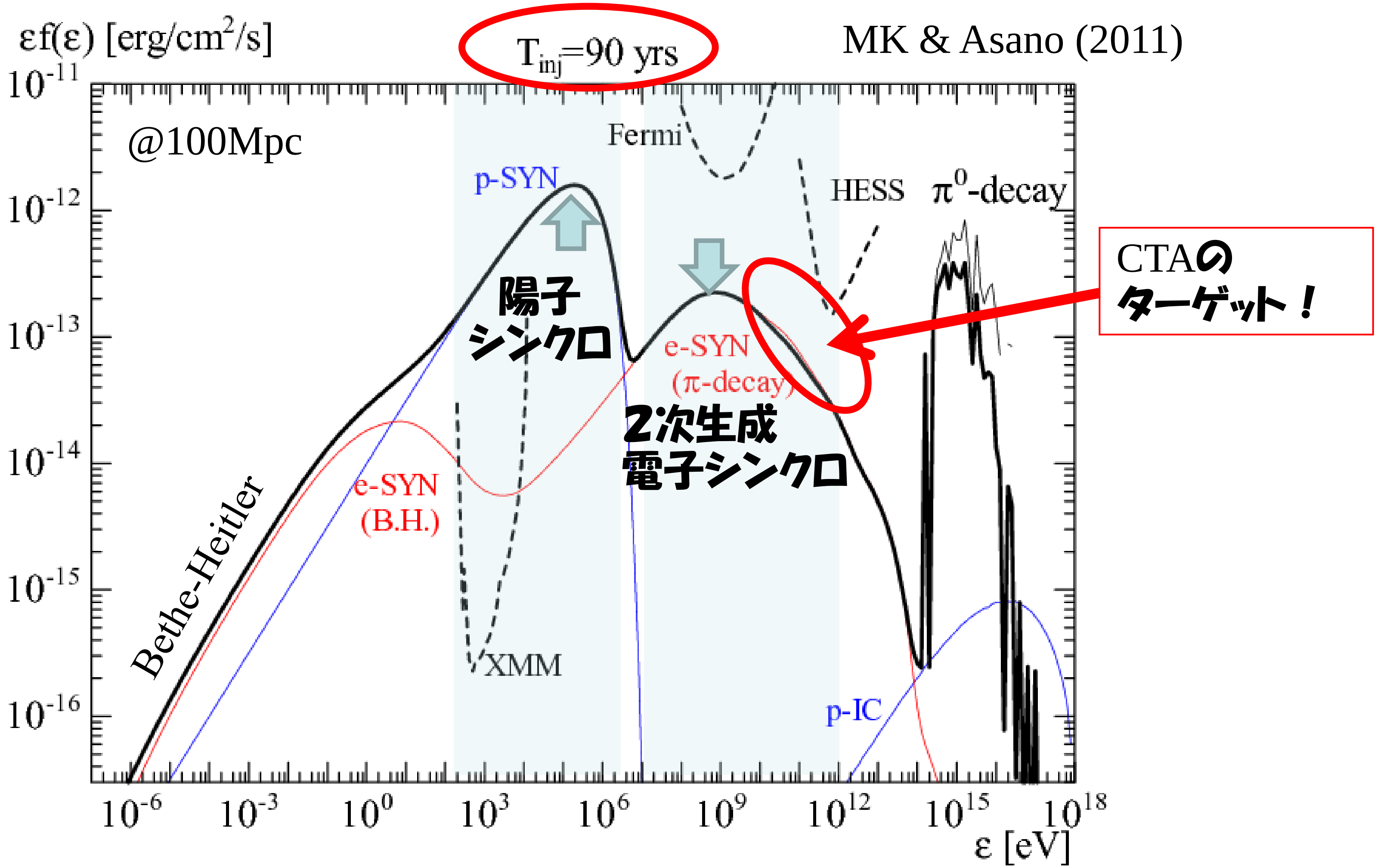
New-born lobe: NGC1275



?

電波観測屋
にとっては
嬉しくない
が. .

Hadronic Afterlight



電波ダークなローブ。CTAでの検出可能性有。

Summary

We have studied non-thermal emissions from mini radio lobes and shells (CORALZs & less luminous CORALZs). Since the energy densities of soft photons from AGN nucleus and synchrotron photons from the radio lobe are large, emissions both from the mini-shells and mini-lobe can be detectable by CTA and can be new class of VHE emitters.

- IC emission from the mini-shell overwhelms the emission from the radio lobe in VHE range.

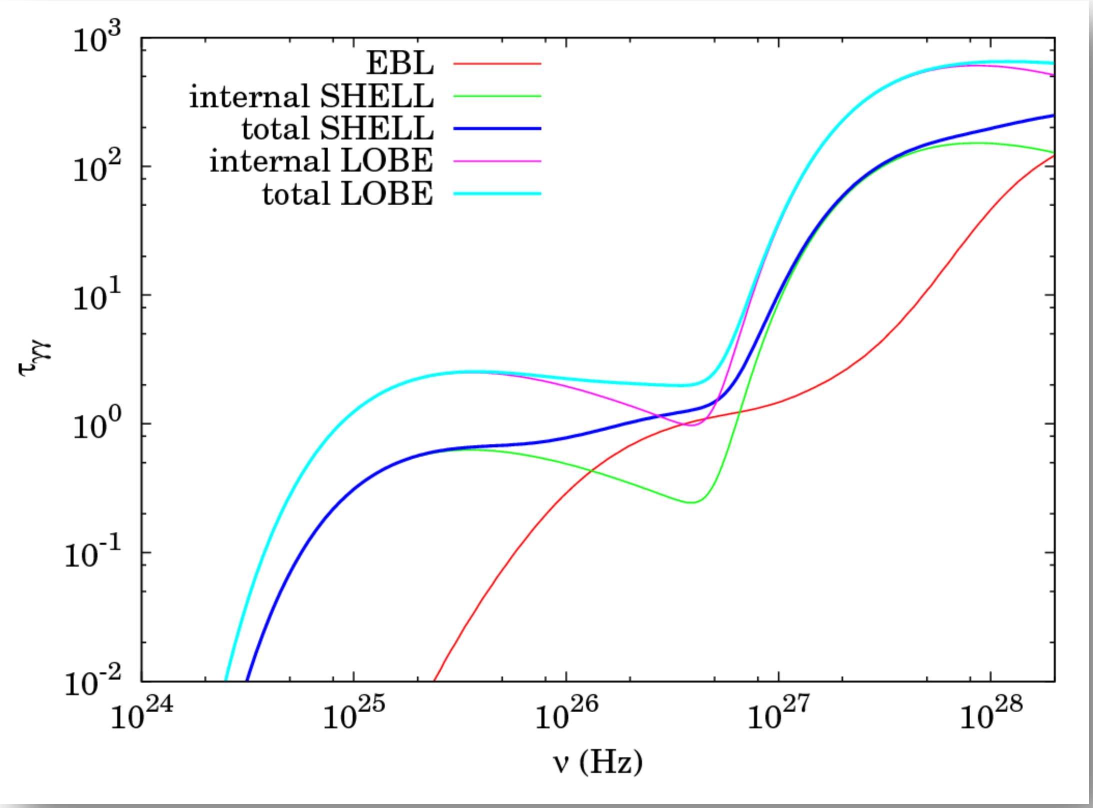
  MK, Ito, Kawakatu & Orienti (2012), ApJ Letters, submitted

- When the jet stops within ~100years, hadronic (pγ) afterlight emission from the mini radio lobe can be seen in VHE range.

  MK & Asano (2011) MNRAS Letters

Buck up

$\gamma\gamma \Rightarrow e^+ e^-$ absorption (R=5pc)



We include the effect of absorption via gamma gamma ->e+e- interaction.VHE photons suffer from the gamma/gamma absorption via interaction with various soft photons.
The γγ absorption opacity against the intrinsic photons (tau_{gamma-gamma}) can be calculated by summing up all of the photons from

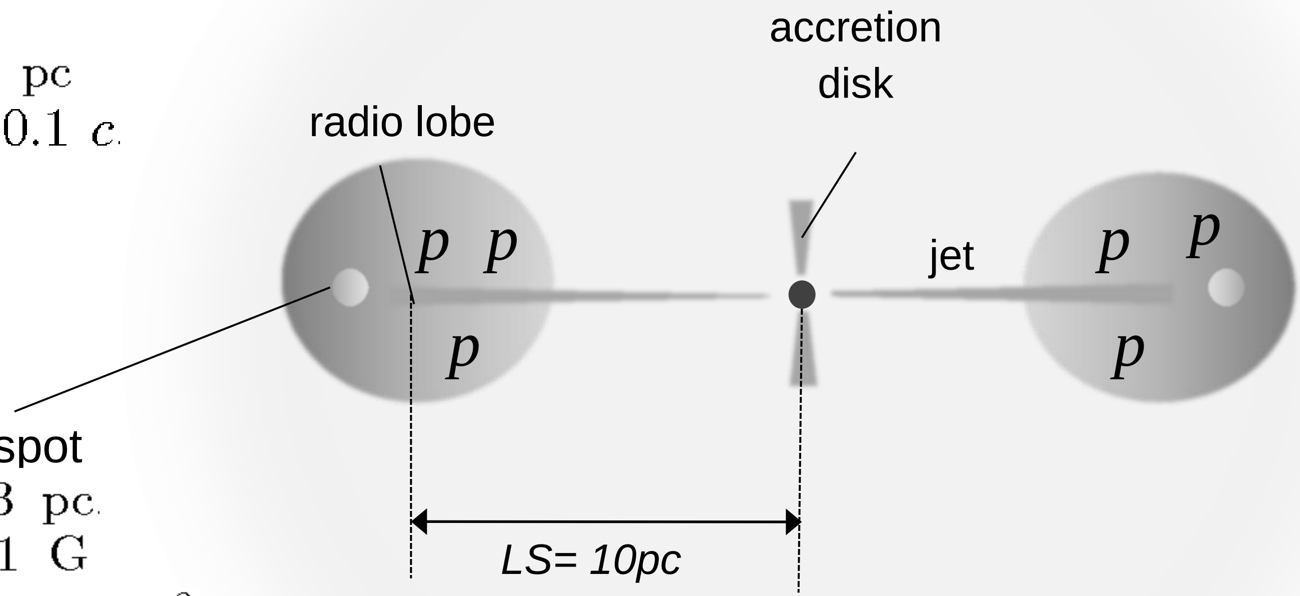
(1) the shell (negligibly small),
(2) the radio lobes,
(3) the dusty torus, and
(4) the accretion disk

and we multiply the γγ absorption factor of exp (-τ_γγ) to the unabsorbed flux. We adopt the model of Franceschini et al. (2008).

At the frequency below ~10^26 Hz, the number density of target photons from radio lobes is larger than that from the shell, therefore the lobe photons govern the absorption opacity.

What happens for C.R.-filled lobes?

$$R_{\rm lobe} = 2 \ {\rm pc}$$
$$v_{\rm exp,lobe} = 0.1 \ c$$



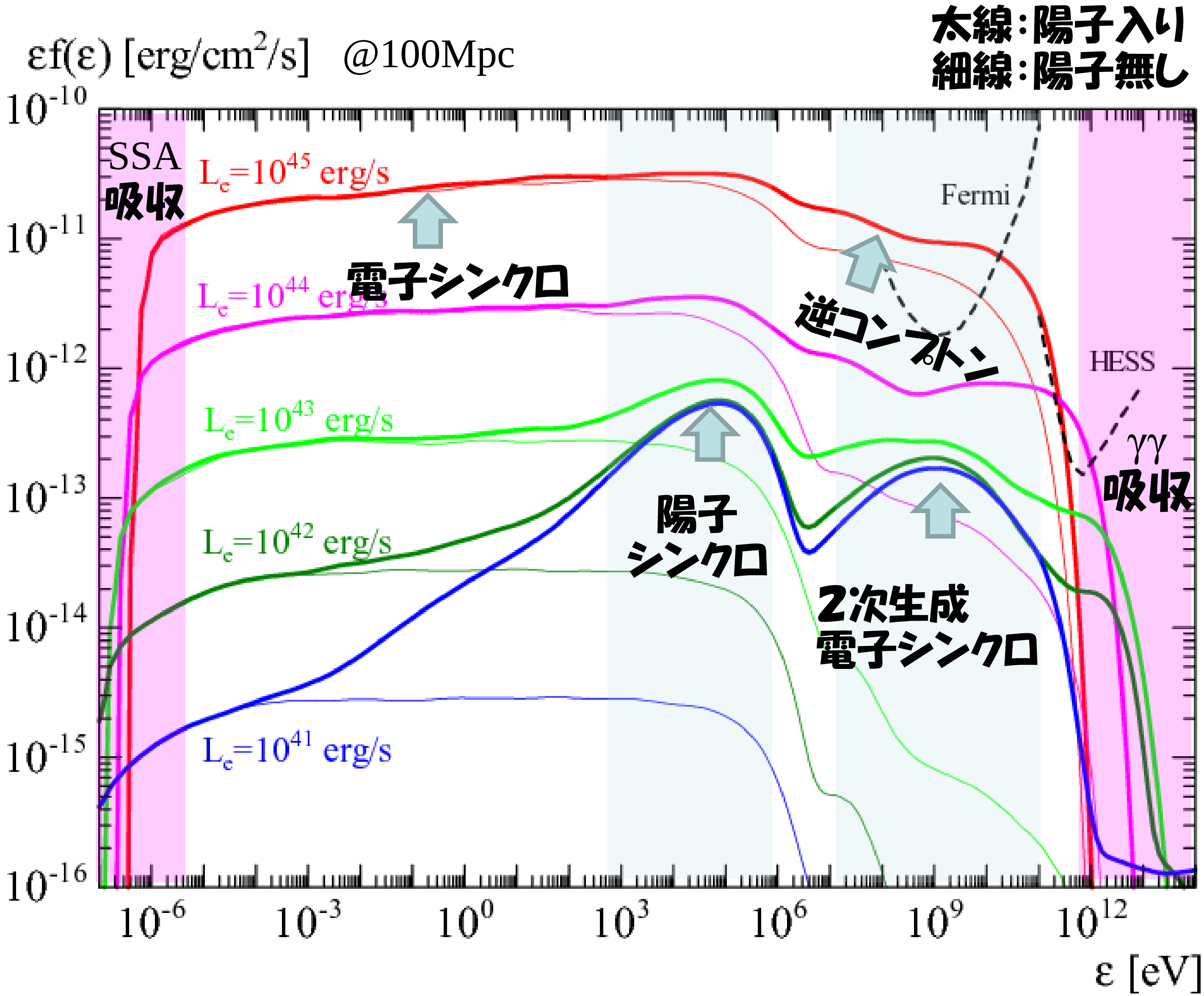
hot spot

$$R_{\rm hs} = 0.3 \ {\rm pc}$$
$$B_{\rm hs} = 0.1 \ {\rm G}$$
$$\xi_p = \xi_e = 1 \times 10^2$$
$$s_p = s_e = 2$$
$$L_p = 5 \times 10^{46} \ {\rm erg \ s^{-1}}$$

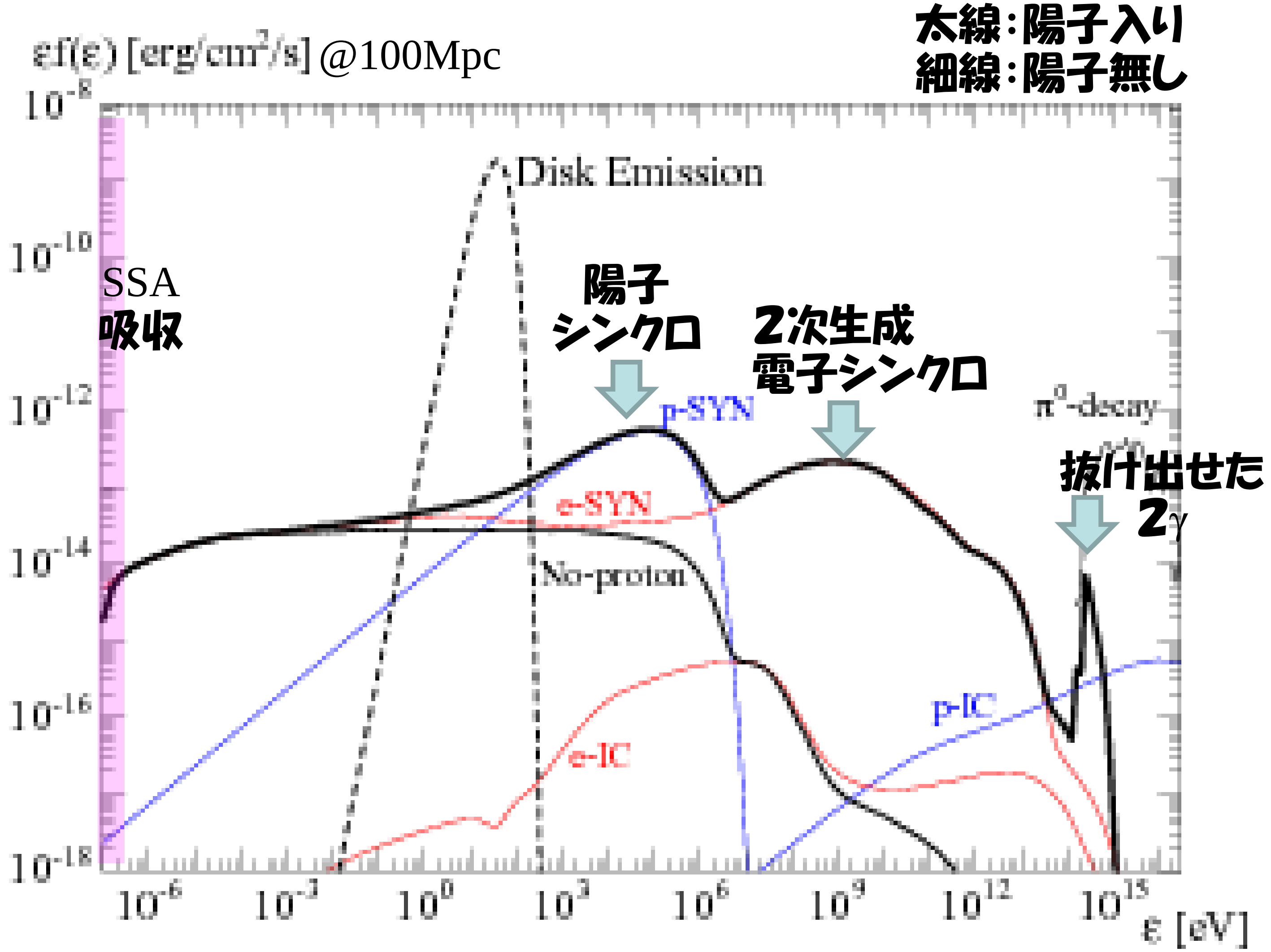
$$L_{\rm disk} = 3 \times 10^{45} \ {\rm erg \ s^{-1}}$$

$p\gamma$ cascade in the mini radio lobe!

Predicted photon spectra



Predicted photon spectra



Cascade and cooling process

$p + \gamma \longrightarrow p/n + \pi^0/\pi^+$ （π 中間子生成）

$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$ （π 中間子崩壊）

$\pi^0 \longrightarrow 2\gamma$

$\gamma + \gamma \longrightarrow e^+ + e^-$ （γ γ 吸収）

$p + \gamma \longrightarrow p + e^+ + e^-$ (Bethe-Heitler過程)

Synchrotron and Inverse-Compton of charged particles

Synchrotron-Self-Absorption (SSA)