Spectral and Dynamical Constraints on Kinetic Power and Age of SS 433 Jets

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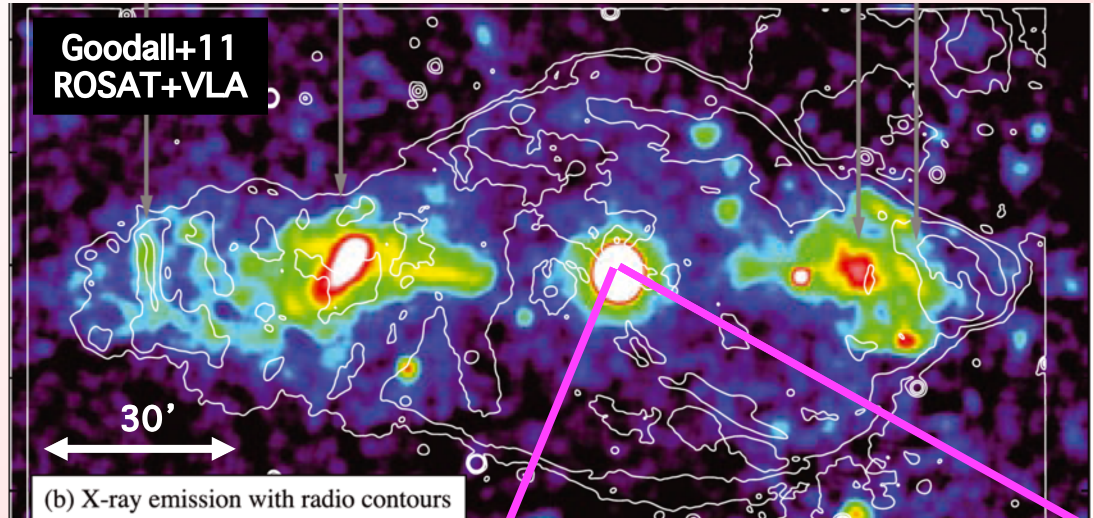
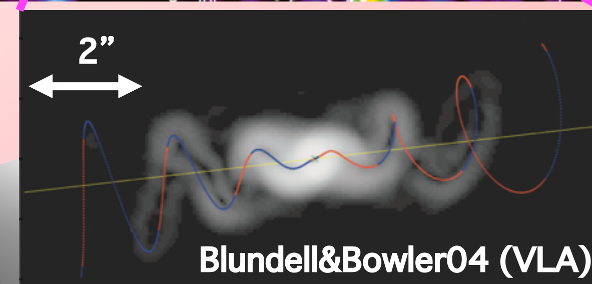
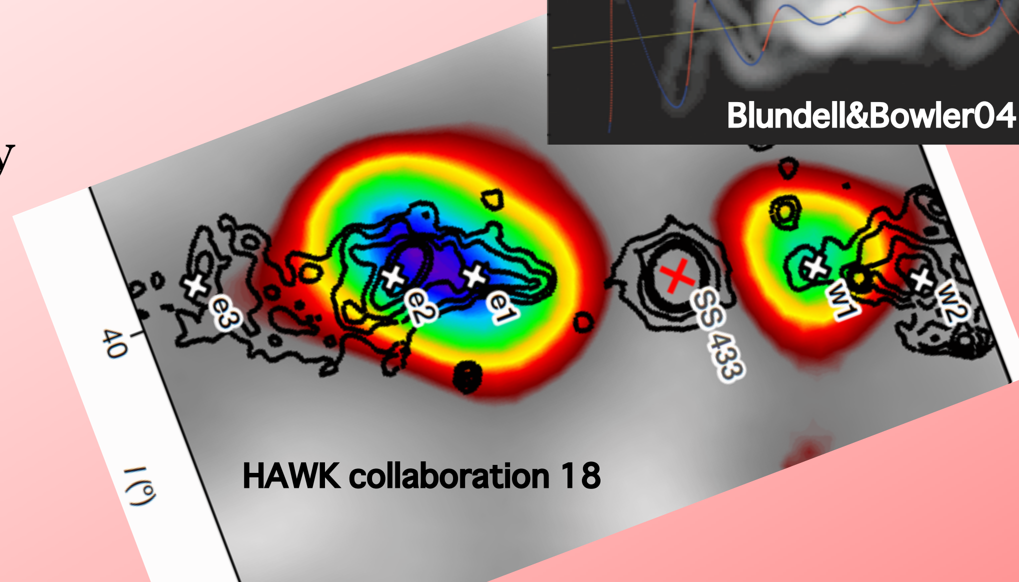
Introduction

SS 433/W 50

- ~ 10M$_\odot$ black hole & ~10M$_\odot$ supergiant X-ray binary system (SS 433) @ ~5.5kpc
- Radio Supernova Remnant + cocoon of SS 433's jet (W 50)
- ~0.26c precessing jets & X-ray hot spots
- Non-thermal radio, X-ray & TeV γ-ray emission.



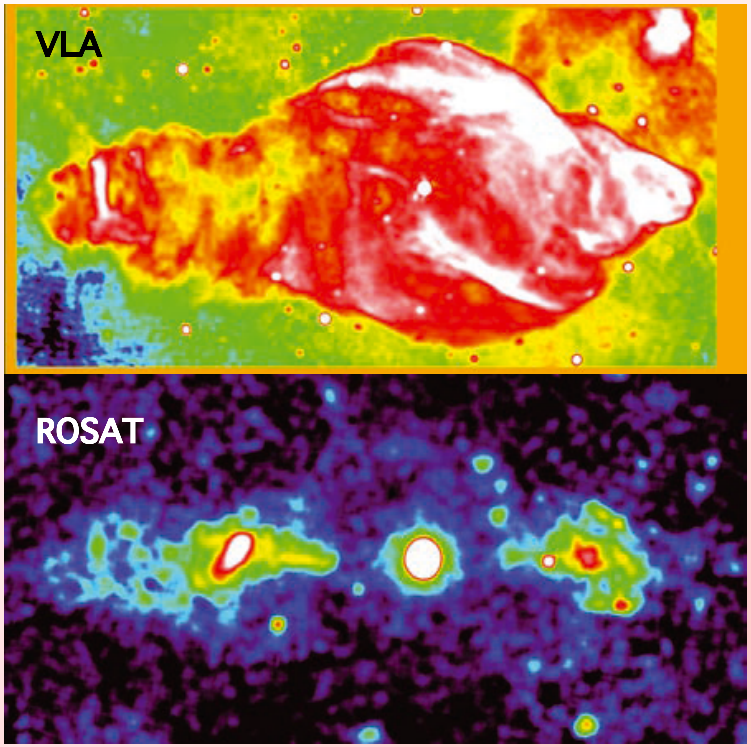


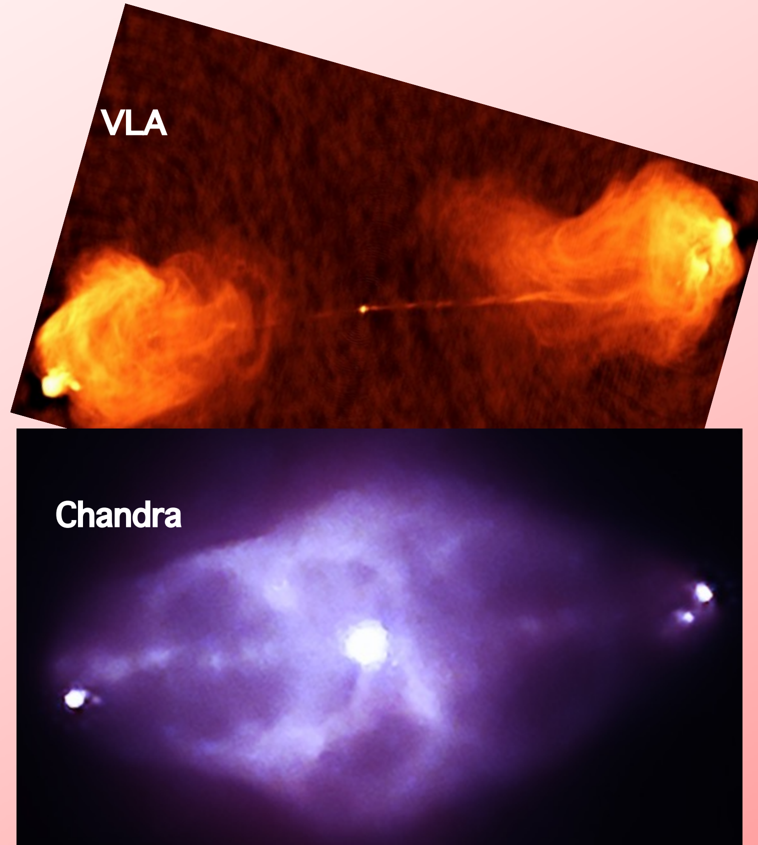


First microquasar with TeV emission

Motivation

Jets of stellar-mass vs. supermassive black holes





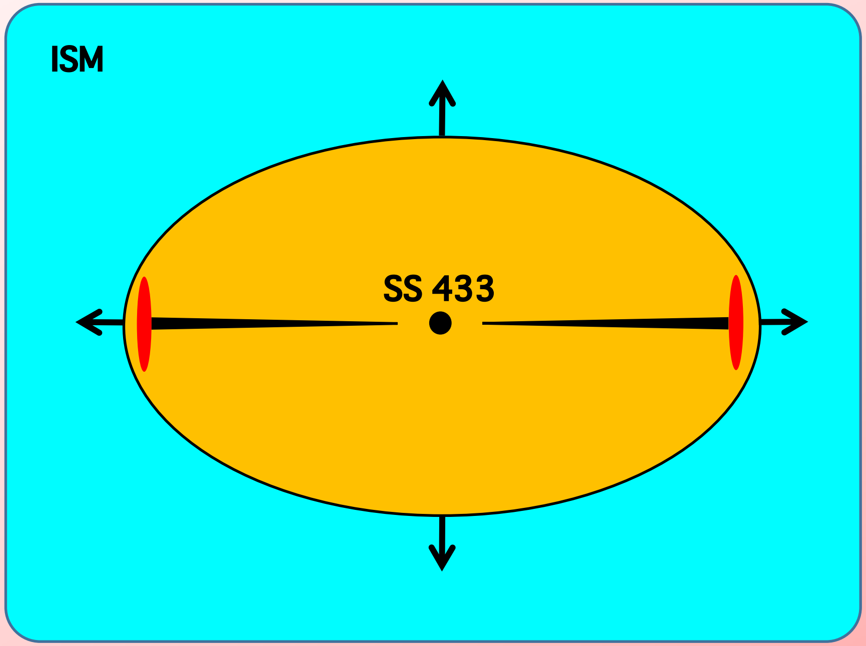
Common physics in relativistic jets from black holes

Model

One-zone Model

One-zone time-evolution model of cocoon

- Expanding elliptical cocoon surrounded by uniform interstellar medium
- Expansion is supported by kinetic energy of relativistic jet powered by SS 433
- Supplying accelerated particles & B-field from the relativistic jet and they are confined inside the cocoon
- Leptonic emission model from the reverse shocked cocoon materials



$$L_{\mathrm{jet}} = (\eta_{\mathrm{e}} + \eta_{\mathrm{B}} + \eta_{\mathrm{p}}) L_{\mathrm{jet}}$$

$$\eta_{\mathrm{p}} = 1 - \eta_{\mathrm{e}} - \eta_{\mathrm{B}}$$

thermal energy for cocoon expansion and (non-radiating) cosmic-ray protons

Dynamics

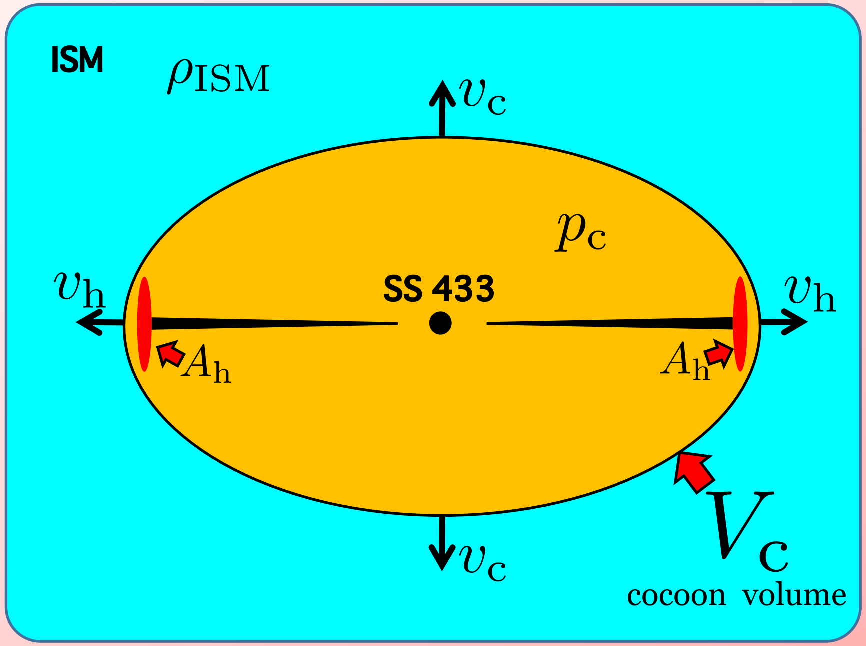
Cocoon expansion model c.f. Kino&Kawakatu04

EOM$_{\rm head}$ $$\frac{L_{\rm jet}}{2v_{\rm jet}A_{\rm h}} = \rho_{\rm ISM}v_{\rm h}^2$$

EOM$_{\rm side}$ $$p_{\rm c} = \rho_{\rm ISM}v_{\rm c}^2$$

energy cons. $$\frac{p_{\rm c}V_{\rm c}}{\Gamma_{\rm c}-1} = L_{\rm jet}t_{\rm age}$$

$$+\ v_{\rm c} \propto t^X$$



assuming self-similar expansion

$$v_{\rm c} \propto v_{\rm h} \propto t^{-2/5}$$

We look for $L_{\rm jet}$ (jet power) & $t_{\rm age}$ (system age)

$L_{\rm jet}$ & $v_{\rm jet}$ = 0.26c are const. with time

major/ minor axis $2r_{\rm h}$ / $2r_{\rm c}$ ~ 200 / 100

pcadiabatic index of cocoon $\Gamma_{\rm c}$ = 4/3

observed $A_{\rm h}$ & aspect ratio $R = r_{\rm c}/r_{\rm h}$

determines ranges of $L_{\rm jet}$ - $t_{\rm age}$

Spectrum

$$\frac{\partial}{\partial t}N(\gamma,t)+\frac{\partial}{\partial \gamma}\dot{\gamma}_{\rm cool}(\gamma,t)N(\gamma,t)=Q_{\rm jet}(\gamma)$$

syn. + IC + ad. cooling

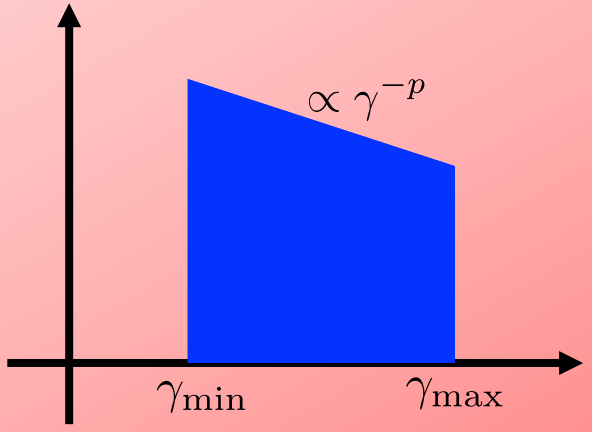
single-PL injection

- Synchrotron + inverse Compton (CMB) model
- B-field inside cocoon ($\eta_{\rm B}$)

$$\frac{B^2(t)}{8\pi}V_{\rm c}=\eta_{\rm B}\int_0^t L_{\rm jet}(t')dt'$$

- Single power-law injection ($\gamma_{\rm min}$, $\gamma_{\rm max}$, p, $\eta_{\rm e}$)

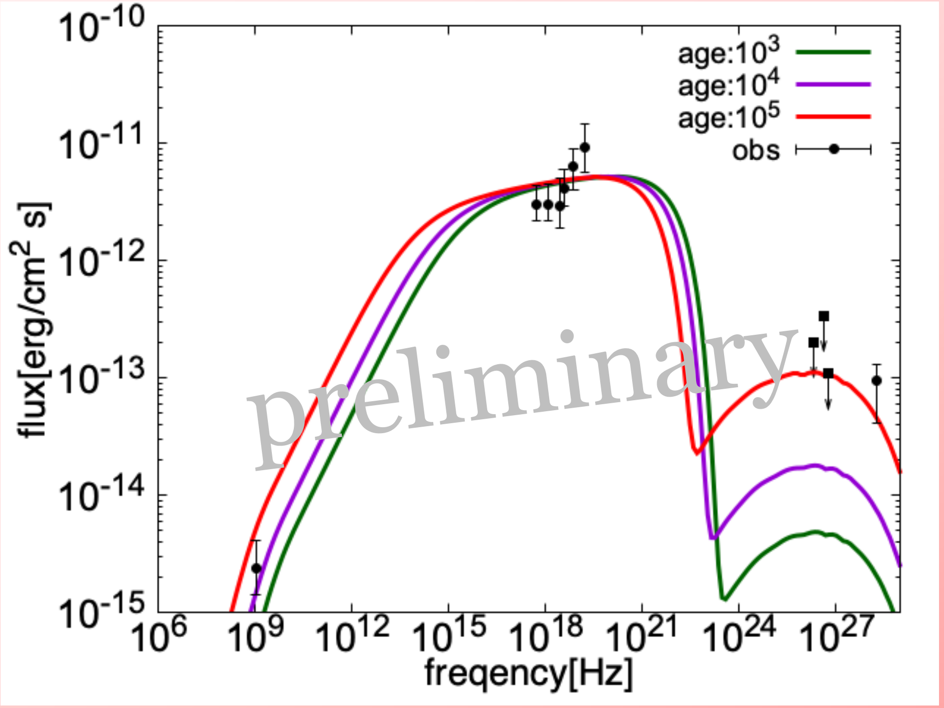
$$\int_{\gamma_{\rm min}}^{\gamma_{\rm max}}\gamma m_{\rm e}c^2 Q_{\rm jet}d\gamma=\eta_{\rm e}L_{\rm jet}$$



Results & Conclusion

Results: SED

- $p \sim 2$, $\gamma_{\rm min} < 10^{3.5}$, $\gamma_{\rm max} > 10^{9.5}$
- X-ray is cooling regime
- radio flux increases with time
- γ-ray flux strongly depends on electron energy content ($\eta_{\rm e} L_{\rm jet} t_{\rm age}$)
- magnetic field ~ 16μG



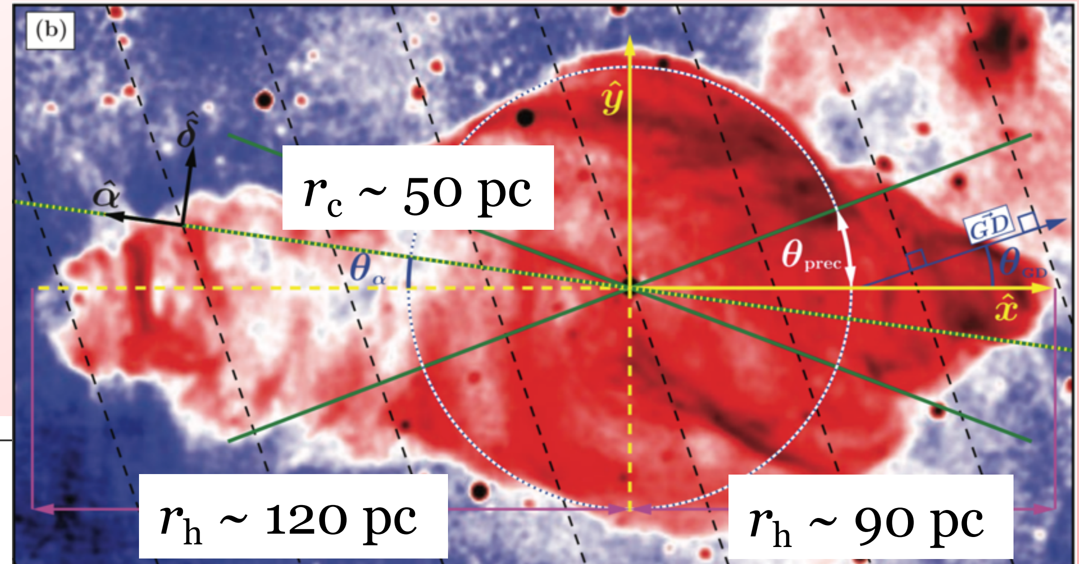
$u_{\rm e}/u_{\rm B} \sim 10$ for Cyg A

Kino&Takahara04

$$\Rightarrow \; L_{\rm jet} t_{\rm age} \gtrsim 10^{51} {\rm erg}, \;\; u_{\rm e}/u_{\rm B} \sim 10^{-3.5} \ll 1$$

Results: L_{jet} - t_{age}

- Adopting
  - $A_{\mathrm{h}} \sim \pi(10\mathrm{pc})^2$
  - $R \sim 0.4 \sim 0.6$
  - $n_{\mathrm{ISM}} \sim 1\ \mathrm{cc}^{-1}$



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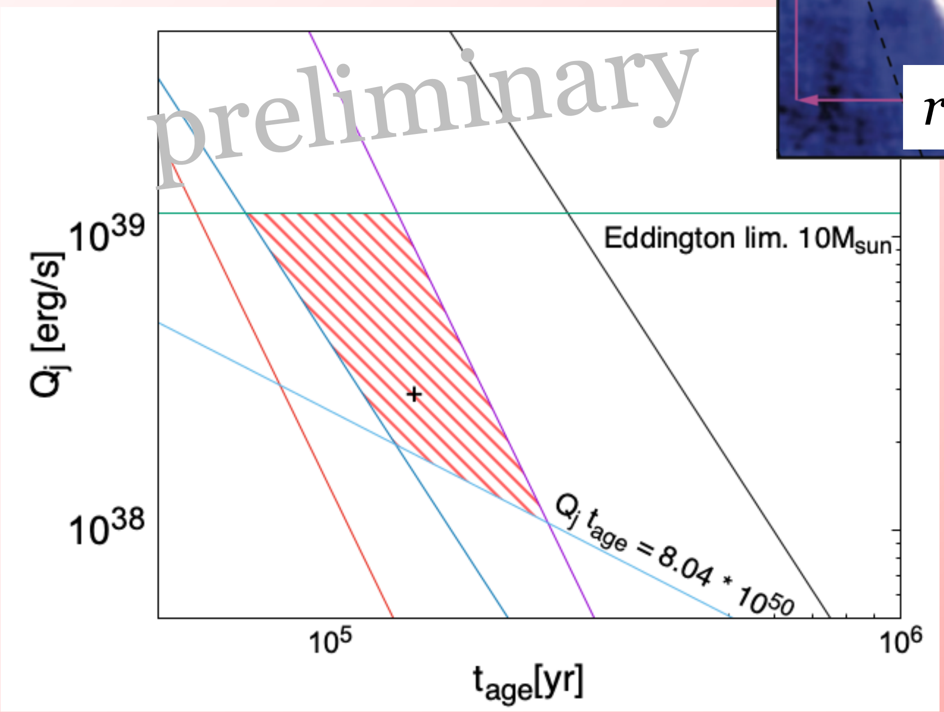
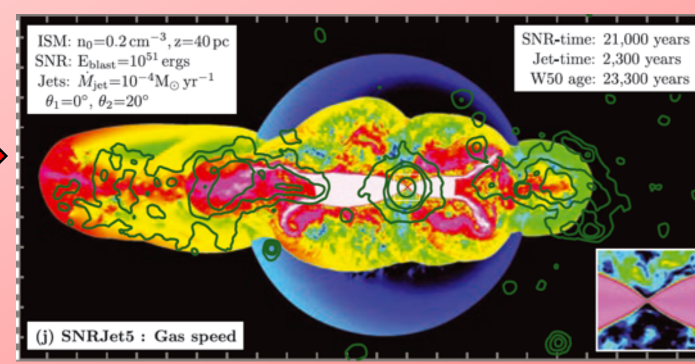


$t_{\mathrm{age}} \sim 20$ kyr, $n_{\mathrm{ISM}} \sim 0.2\ \mathrm{cc}^{-1}$



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Conclusions

- One-zone time-evolution model of SS 433
- Kinetic power and the age of the system are constrained independently from spectral and dynamical study
- Broadband emission modelling, especially γ-ray flux, constrains the total energy content supplied from the jet
- Ratios of electron to magnetic energy inside are very different for Cyg A and SS 433 cocoons