Shear acceleration in large scale AGN jets and possible application in explaining X-ray emissions

Ruo-Yu Liu (MPIK)

Collaborators: Frank Rieger, Felix Aharonian, Nayantara Gupta

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Outline

- A brief introduction to shear acceleration

- Accelerated particle spectrum by this mechanism
  Fokker-Planck coefficient
  time-dependent spectrum
  the role of stochastic acceleration plays
  UHECR acceleration

- Possible application in explaining kpc-Mpc scale X-ray emissions from AGN jets
  IC/CMB model v.s. synchrotron model
  An example: knots of 3C 273 (two-component synchrotron)

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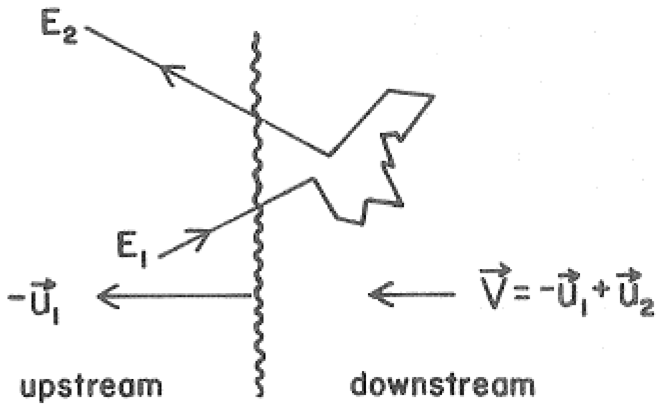
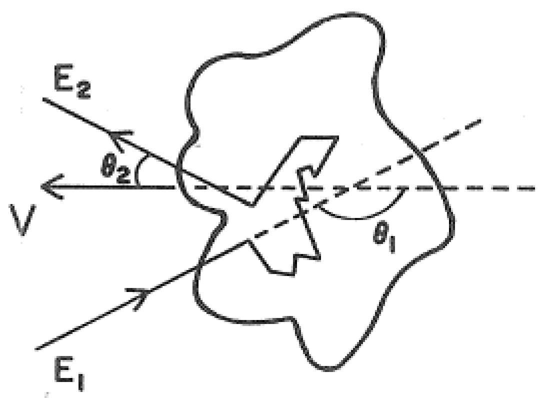
Fermi-type acceleration

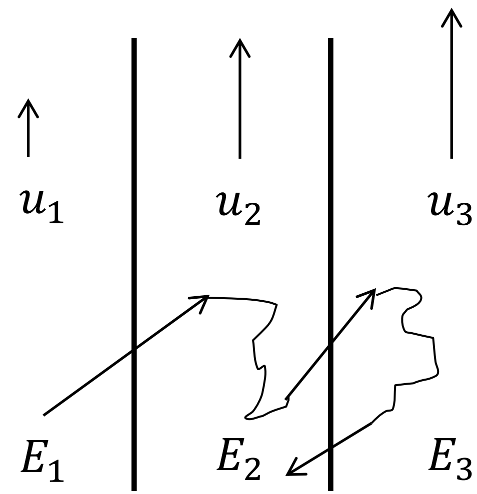


Shock acceleration (1st-order Fermi acc.)



Stochastic acceleration (2nd-order Fermi acc.)

(Figure from T.K. Gassier's book)



Shear acceleration

Different geometry of the scattering center

A historical review

A kinetic analysis of the charged-particle acceleration process in collisionless plasma shear flows

E. G. Berezhko and G. F. Krymskiĭ

Institute of Cosmological Research and Aeronomy, Siberian Branch, USSR Academy of Sciences, Yakutsk

(Submitted April 28, 1981)

Pis'ma Astron. Zh. **7**, 636–640 (October 1981)

The friction mechanism for accelerating particles in interplanetary space

E. G. Berezhko

Institute of Cosmophysical Research and Aeronomy, Siberian Branch, USSR Academy of Sciences, Yakutsk

(Submitted February 8, 1982)

Pis'ma Astron. Zh. **8**, 747–750 (December 1982)

$$v_\alpha \frac{\partial f^u}{\partial r_\alpha} - p_\alpha \frac{du_\beta}{\partial r_\alpha}\left(\frac{\partial f^u}{\partial p}\Omega_\beta + \frac{1}{p}\frac{\partial f^u}{\partial \Omega_\beta}\right) = \frac{1}{\tau}(\overline{f^u} - f^u),$$

$$n(y,p) = Cp^{-\gamma}\left[1 - \frac{\gamma+2}{2}\left(\frac{u}{c}\right)^2 + \frac{(\gamma+2)(\gamma-1)}{6}\left(\frac{u}{v}\right)^2 + \frac{\gamma+2}{15}\tau^2 u\frac{d^2u}{dy^2}\left(1-\gamma+\frac{v^2}{c^2}\right)\right], \qquad (11)$$

non-relativistic gradual shear flow,

particle's direction randomized in each scattering event

COSMIC-RAY VISCOSITY[1]

J. A. Earl,[2,3] J. R. Jokipii,[4] and G. Morfill[5]

Received 1988 January 19; accepted 1988 May 19

An independent derivation

THE DIFFUSION APPROXIMATION AND TRANSPORT THEORY FOR COSMIC RAYS IN RELATIVISTIC FLOWS

G. M. Webb
University of Arizona, Department of Planetary Sciences, Lunar and Planetary Laboratory

Received 1988 July 15; accepted 1988 October 27

Extension to relativistic flow

COSMIC RAYS AT FLUID DISCONTINUITIES[1]

J. R. Jokipii
University of Arizona
J. Kóta
Central Research Institute for Physics, Budapest
and
G. Morfill
Max-Planck-Institut für Extraterrestrische Physik, Garching

Received 1989 May 24; accepted 1989 July 12

Extension to non-gradual shear flow

Acceleration of ultra-high energy cosmic ray particles in relativistic jets in extragalactic radio sources

M. Ostrowski

Observatorium Astronomiczne, Uniwersytet Jagielloński, ul.Orla 171, PL-30-244 Kraków, Poland

Application in specific cases

Particle acceleration in rotating and shearing jets from AGN

F. M. Rieger[1,2] and K. Mannheim[1]

and etc (can not list all of them)

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A complementary method

PARTICLE ACCELERATION IN STEP FUNCTION SHEAR FLOWS: A MICROSCOPIC ANALYSIS

J. R. JOKIPII[1] AND G. E. MORFILL[2]

Received 1988 September 16; accepted 1989 October 11

$$\delta x = \frac{p_1}{m} \cos\theta\tau \,, \qquad (1)$$

in the x-direction. If $\delta x(\partial U_z/\partial x) \ll u_z$, the fluid velocity has changed by an amount $\delta u = (\partial U_z/\partial x)\delta x$, and the particle momentum relative to the fluid has changed to

$$p_2^2 = p_1^2\left(1 + 2\,\frac{m\delta u}{p_1}\sin\theta\cos\phi + \frac{m^2\delta u^2}{p_1^2}\right). \qquad (2)$$

$$\left\langle \frac{\Delta p^2}{\Delta t} \right\rangle = \frac{1}{15}\, p^2 \left(\frac{\partial U_z}{\partial x}\right)^2 \tau \,,$$

$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle = \frac{2}{15}\, p \left(\frac{\partial U_z}{\partial x}\right)^2 \tau \,,$$

A MICROSCOPIC ANALYSIS OF SHEAR ACCELERATION

FRANK M. RIEGER AND PETER DUFFY

UCD School of Mathematical Sciences, University College Dublin, Belfield, Dublin 4, Ireland; frank.rieger@ucd.ie, peter.duffy@ucd.ie

Received 2006 May 18; accepted 2006 July 28

$$\tilde{\tau} = \tau_c + \frac{1}{2}\frac{\partial\tau_c(p_1)}{\partial p_1}\Delta p = \tau_c\left(1 + \frac{1}{2}\alpha\,\frac{\Delta p}{p_1}\right)$$

$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle \equiv \frac{2\langle p_2 - p_1\rangle}{\tau_c} = \frac{4+\alpha}{15} p \left(\frac{\partial u_z}{\partial x}\right)^2 \tau_c,$$

$$\left\langle \frac{(\Delta p)^2}{\Delta t} \right\rangle \equiv \frac{2\langle (p_2 - p_1)^2\rangle}{\tau_c} = \frac{2}{15} p^2 \left(\frac{\partial u_z}{\partial x}\right)^2 \tau_c,$$

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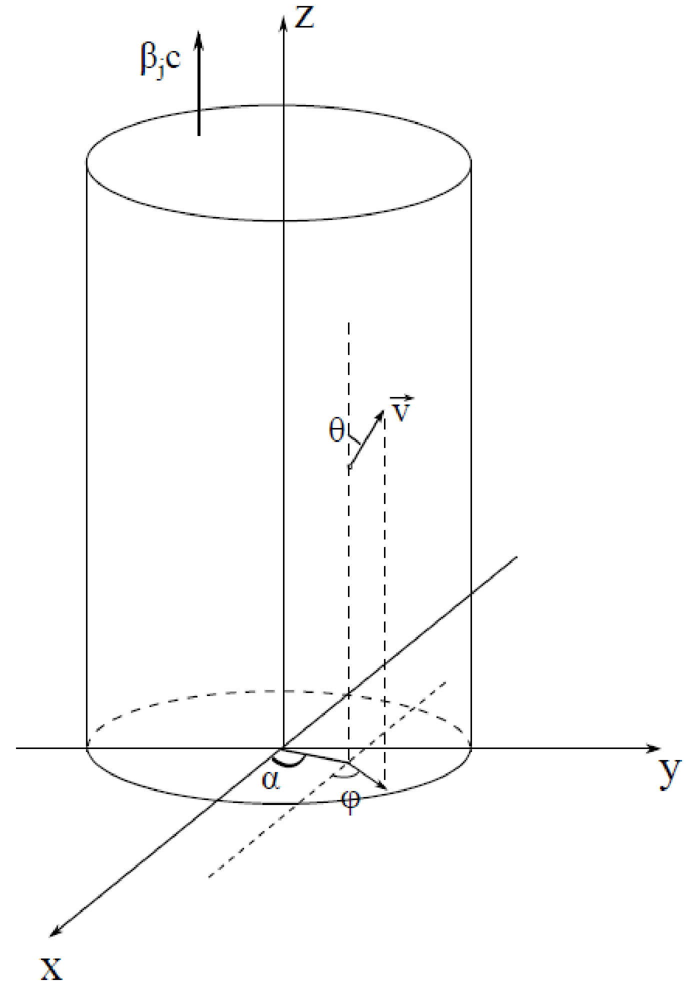
3D mildly-relativistic flow with gradual shear



$$\begin{cases} \Delta x = \beta_x c\tau(p) \\ \Delta y = \beta_y c\tau(p) \\ \Delta z = \beta_z c\tau(p), \end{cases}$$

$$\Delta r = \sqrt{(r\cos\alpha + \Delta x)^2 + (r\sin\alpha + \Delta y)^2} - r$$

$$\Delta\beta_j \equiv \beta_j' - \beta_j \simeq \frac{\partial \beta_j}{\partial r}\Delta r \qquad <<1$$

Lorentz transformation

$$\gamma' = \Gamma_\Delta \gamma (1 - \beta\beta_\Delta \cos\theta)$$

$$\gamma' \simeq \gamma\left(1 + \frac{1}{2}A^2\beta^2\tau^2\sin^2\theta\cos^2\alpha - A\beta^2\tau\sin\theta\cos\theta\cos\alpha - A^2\beta_j\beta^3\tau\sin^2\theta\cos\theta\cos^2\alpha\right)$$

$$\langle\frac{\Delta\gamma^2}{\Delta t}\rangle \equiv \frac{2\langle(\gamma' - \gamma)^2\rangle}{\tau} = 2\int\int\int(\gamma' - \gamma)^2\sin\theta d\theta\ d\phi d\alpha/(8\pi^2\tau) \simeq \frac{2}{15}A^2\gamma^2\tau \propto \gamma^{4-q}\,.$$

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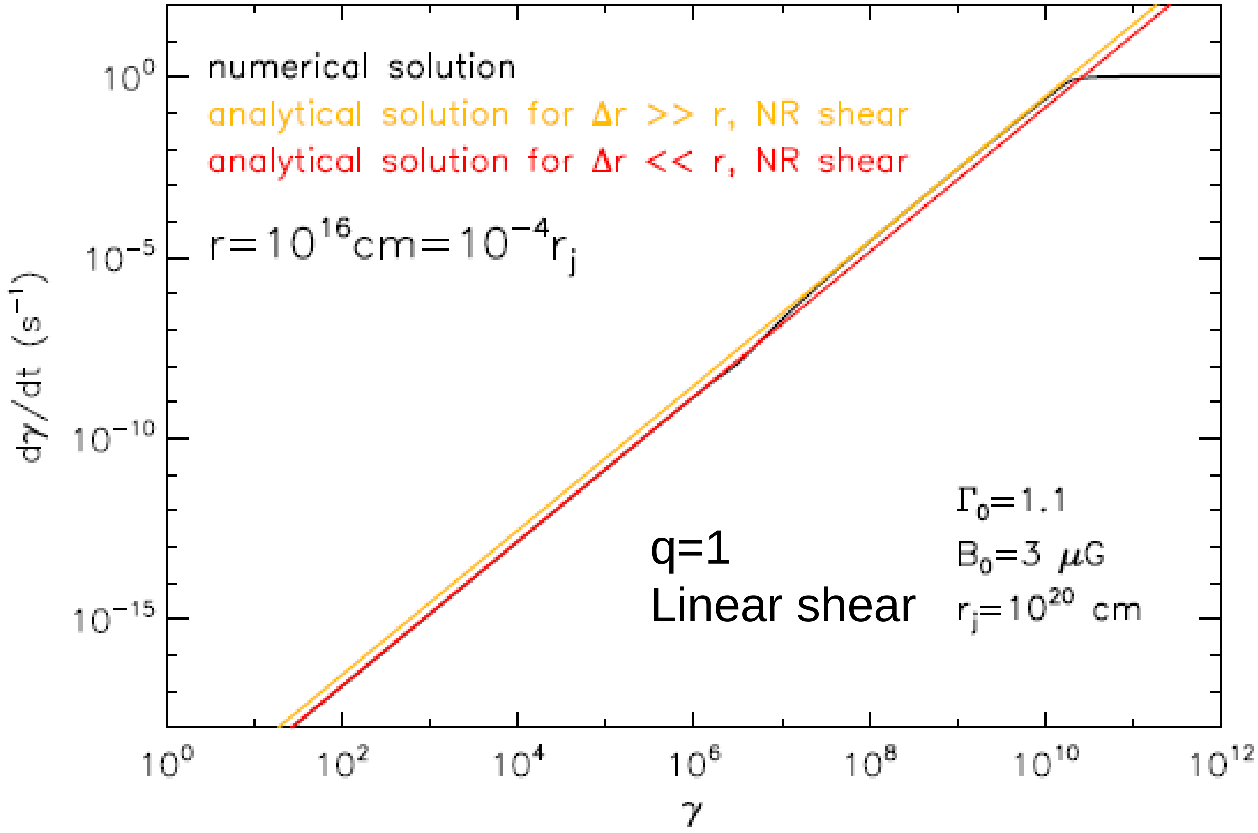
Average acceleration rate

$$\langle\frac{\Delta\gamma}{\Delta t}\rangle = \frac{1}{2\gamma^2}\frac{\partial}{\partial\gamma}\left[\gamma^2\langle\frac{\Delta\gamma^2}{\Delta t}\rangle\right] = \frac{6-q}{15}A^2\gamma\tau \propto \gamma^{3-q}$$

Under the condition of detailed balance



Acceleration rate increases with particle energy!

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Fokker Planck equation

(assume isotropic distribution in momentum space)

$$\frac{\partial f(p,t)}{\partial t} = \underbrace{\frac{1}{2p^2}\frac{\partial^2}{\partial p^2}\left[p^2\left\langle\frac{\Delta p^2}{\Delta t}\right\rangle f(p,t)\right]}_{\text{Momentum dispersion}} - \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\left\langle\frac{\Delta p}{\Delta t}\right\rangle + \langle\dot{p}_c\rangle\right) f(p,t)\right]}_{\text{Systematic change of momentum}} - \underbrace{\frac{f(p,t)}{t_{\mathrm{esc}}(p)}}_{\text{Diffusive escape}} + \underbrace{q(p,t)}_{\text{Particle injection}}$$

$$n(\gamma,t)d\gamma = 4\pi p^2 f(p,t)dp$$

$$\frac{\partial n(\gamma,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial\gamma}\left[\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle\frac{\partial n(\gamma,t)}{\partial\gamma}\right] - \frac{\partial}{\partial\gamma}\left[\left(\left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle - \frac{1}{2}\frac{\partial}{\partial\gamma}\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle + \langle\dot{\gamma}_c\rangle\right) n(\gamma,t)\right] - \frac{n}{t_{\mathrm{esc}}} + Q(\gamma,t)$$

$$\left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle = \left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle_{\mathrm{st}} + \left\langle\frac{\Delta\gamma^2}{\Delta t}\right\rangle_{\mathrm{sh}}$$

$$\left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle = \left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle_{\mathrm{st}} + \left\langle\frac{\Delta\gamma}{\Delta t}\right\rangle_{\mathrm{sh}}$$

Scattering of particles in different part of the flow is essentially due to the scattering by turbulent waves

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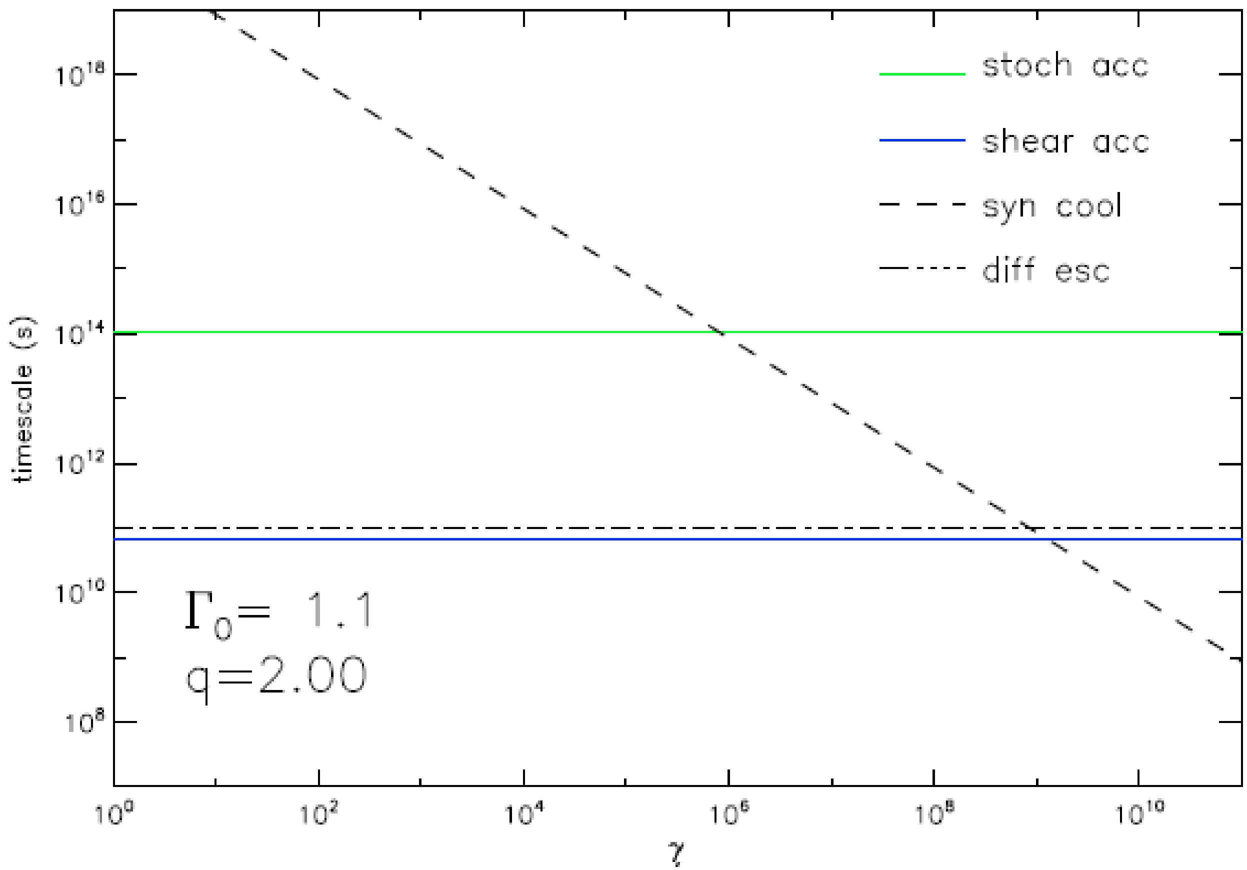
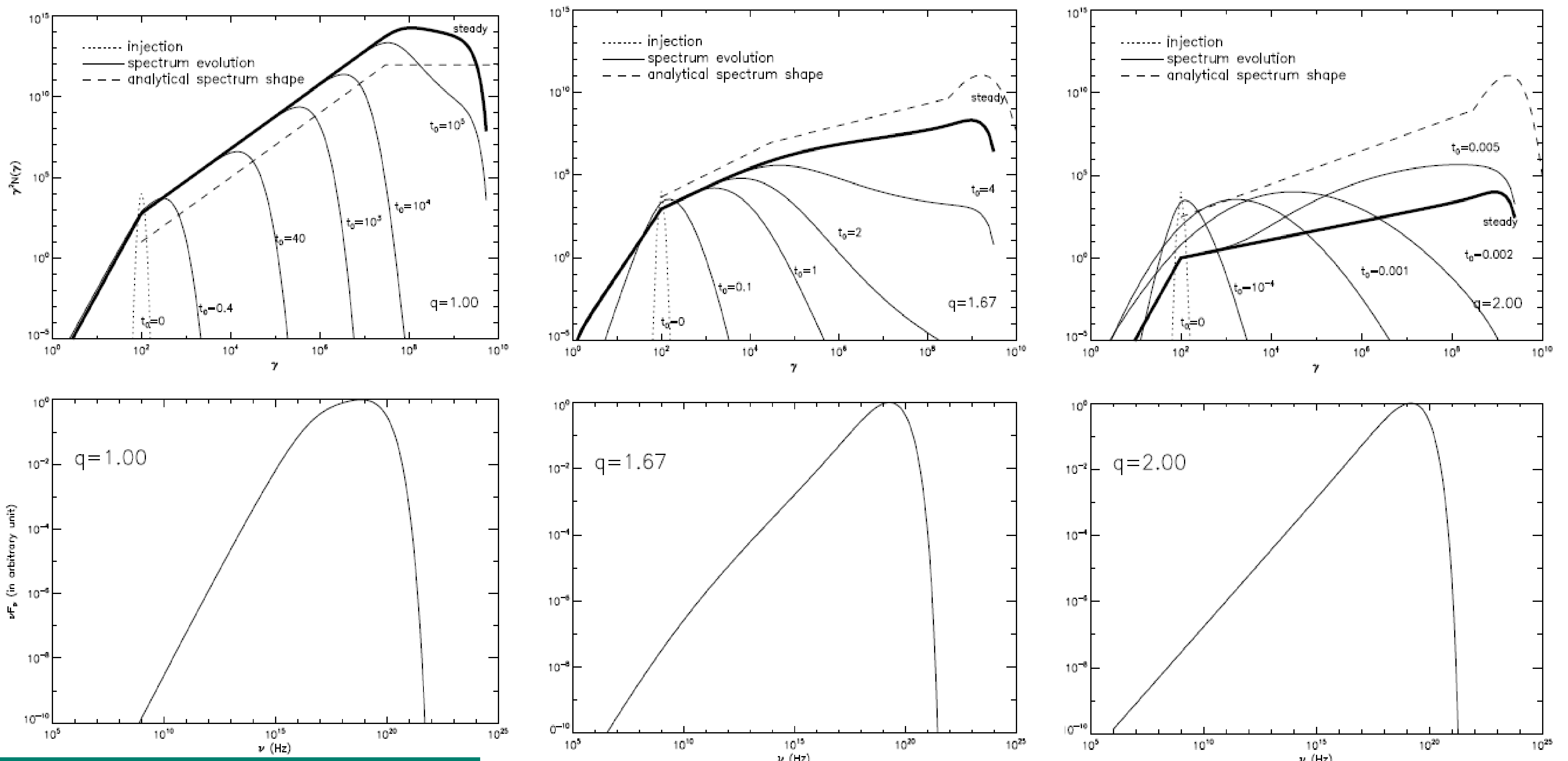
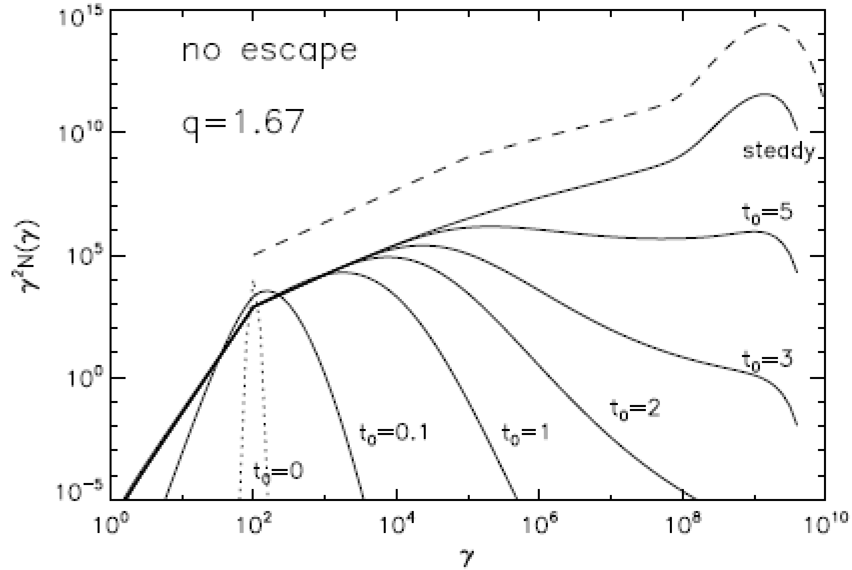
Timescales of different processes



Analytic solution (Steady state, escape ignored)

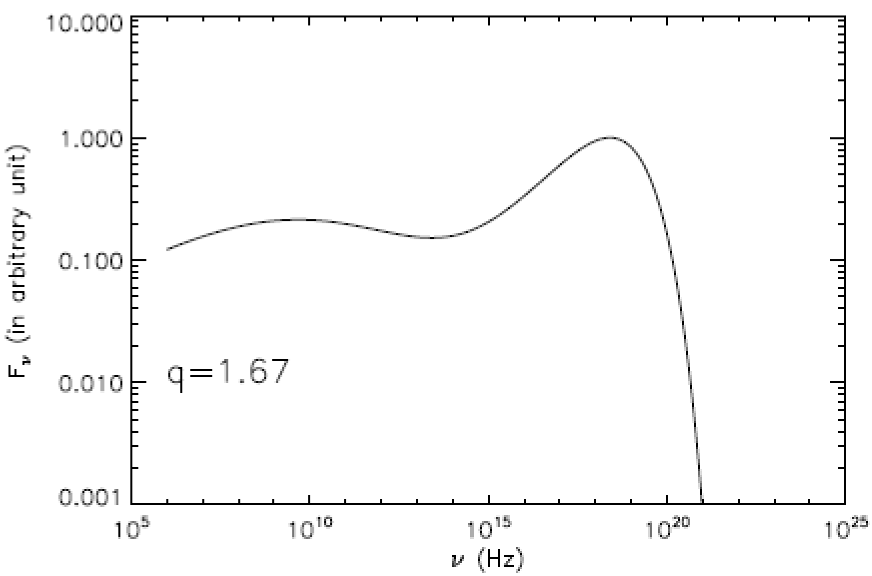
$$n(\gamma) \propto \begin{cases} \gamma^{1-q}, & \gamma_0 < \gamma < \gamma_{\rm eq} \\ \gamma^{q-3}, & \gamma_{\rm eq} \le \gamma < \gamma_{\rm max} \\ \gamma^2 \exp\left[-\frac{6-q}{q-1}\left(\frac{\gamma}{\gamma_{\rm max}}\right)^{q-1}\right] & \gamma_{\rm max} < \gamma. \end{cases}$$

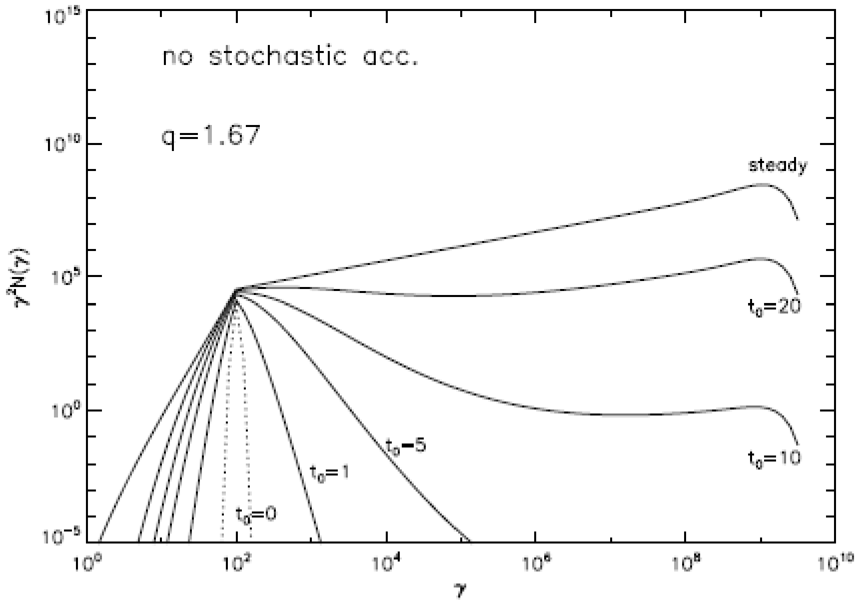




Diffusive escape softens the spectrum

Stochastic acceleration provide seed particle for shear acceleration



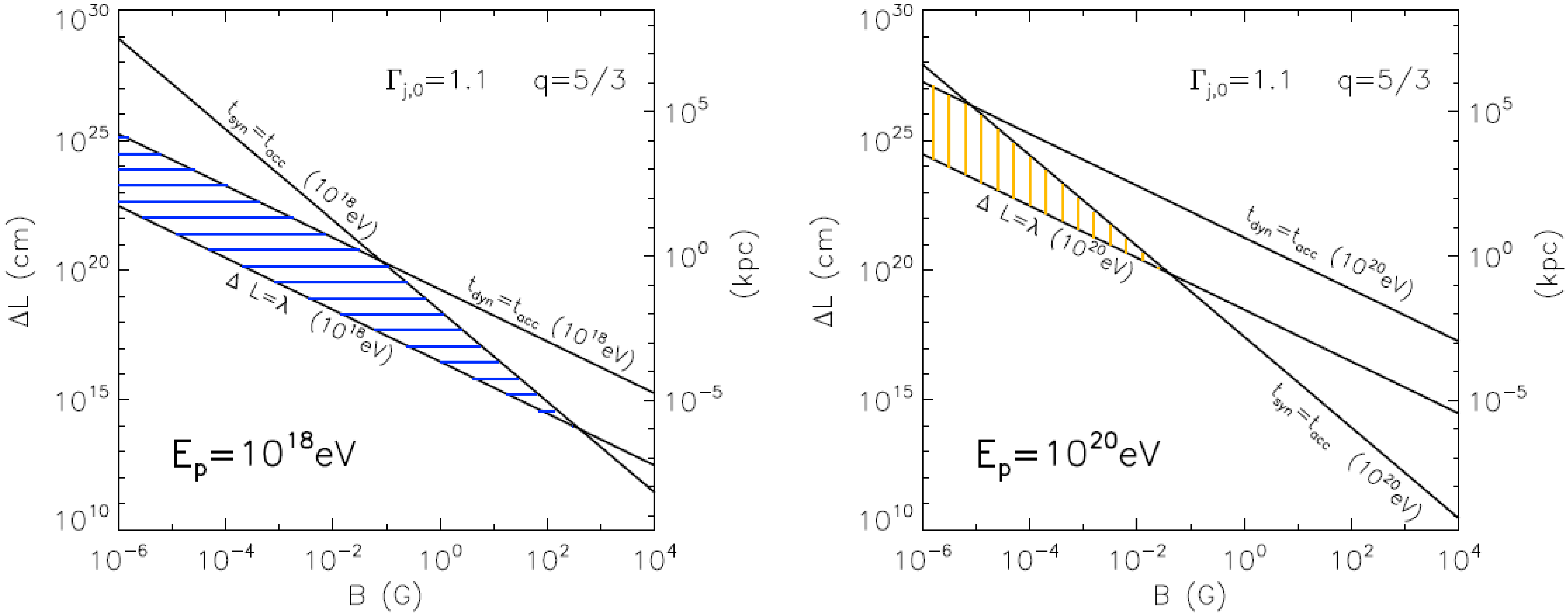


Proton acceleration

constraints $\Delta L > \lambda$ (>r_g, stricter than Hillas condition)

$$t_{\rm acc} < t_{\rm syn}$$

$$t_{\rm acc} < t_{\rm dyn}$$



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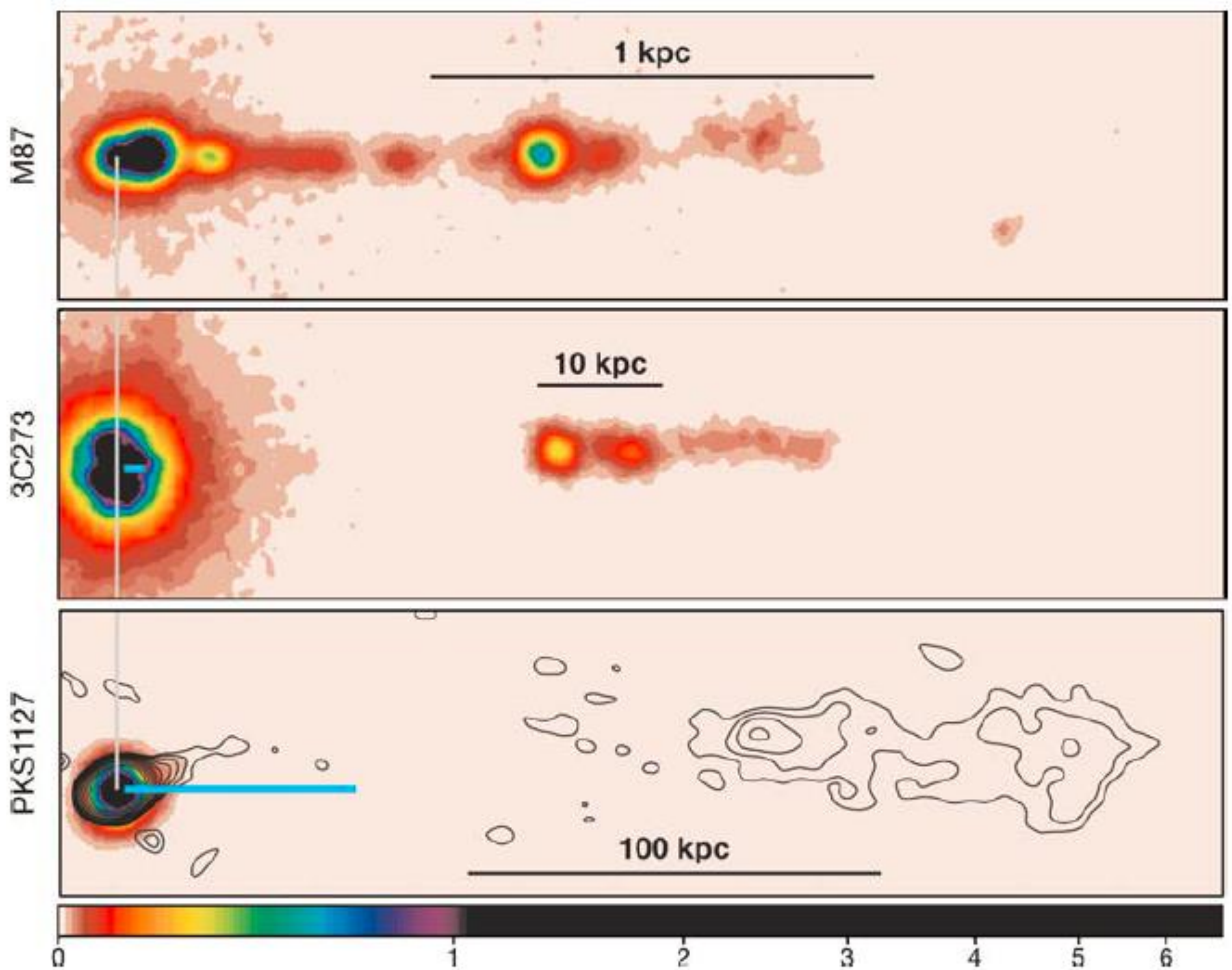
Large-scale X-ray jet (>kpc scale)



Harris & Krawczynski 2006

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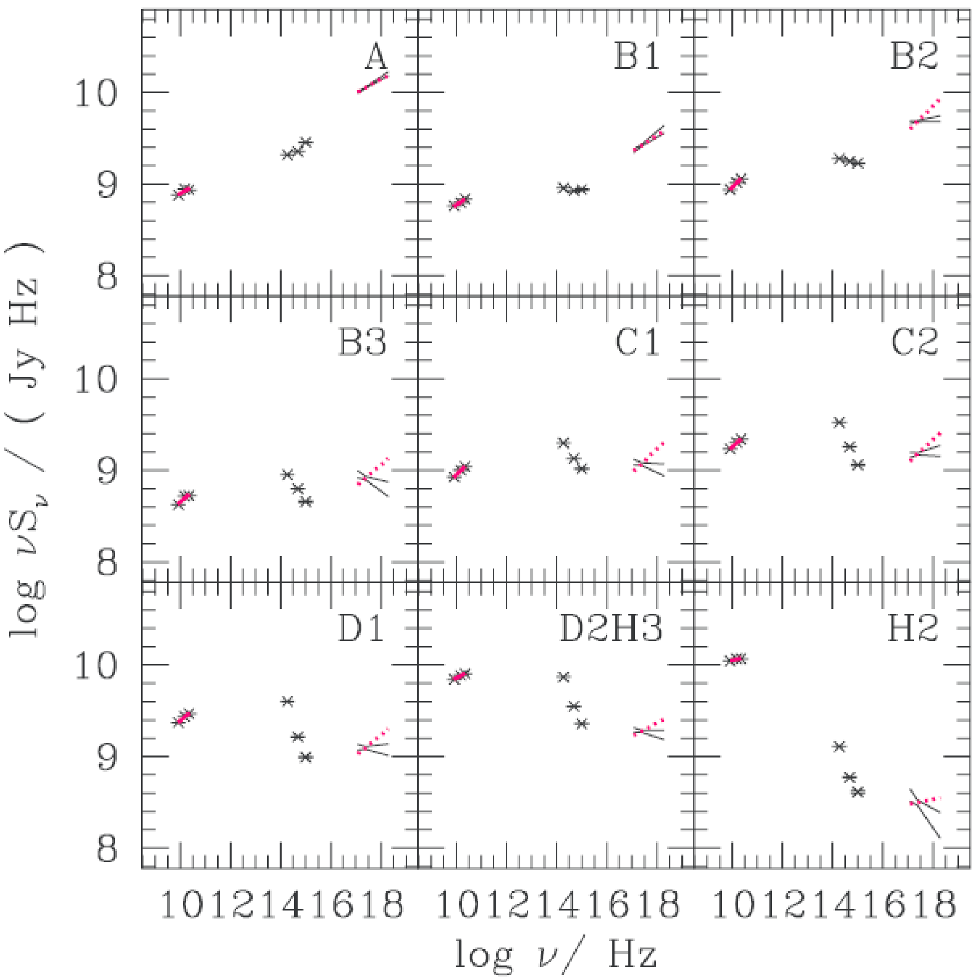
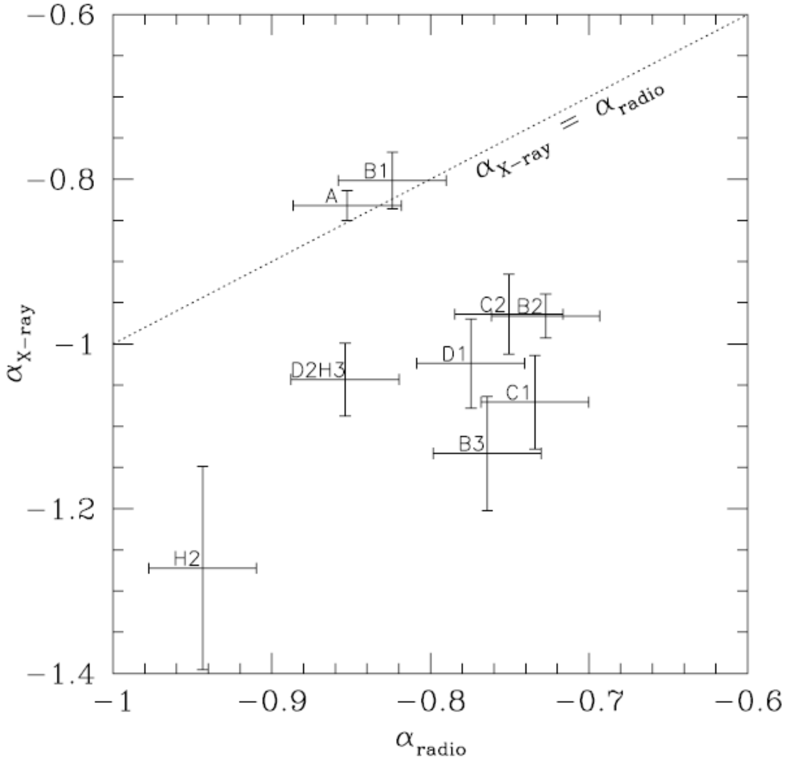
One emission models ✗





X-ray softer than radio

Spectrum of different knots in 3C 273 jet
and some other sources disfavor this model…

Jester et al. 2006

Two emission models

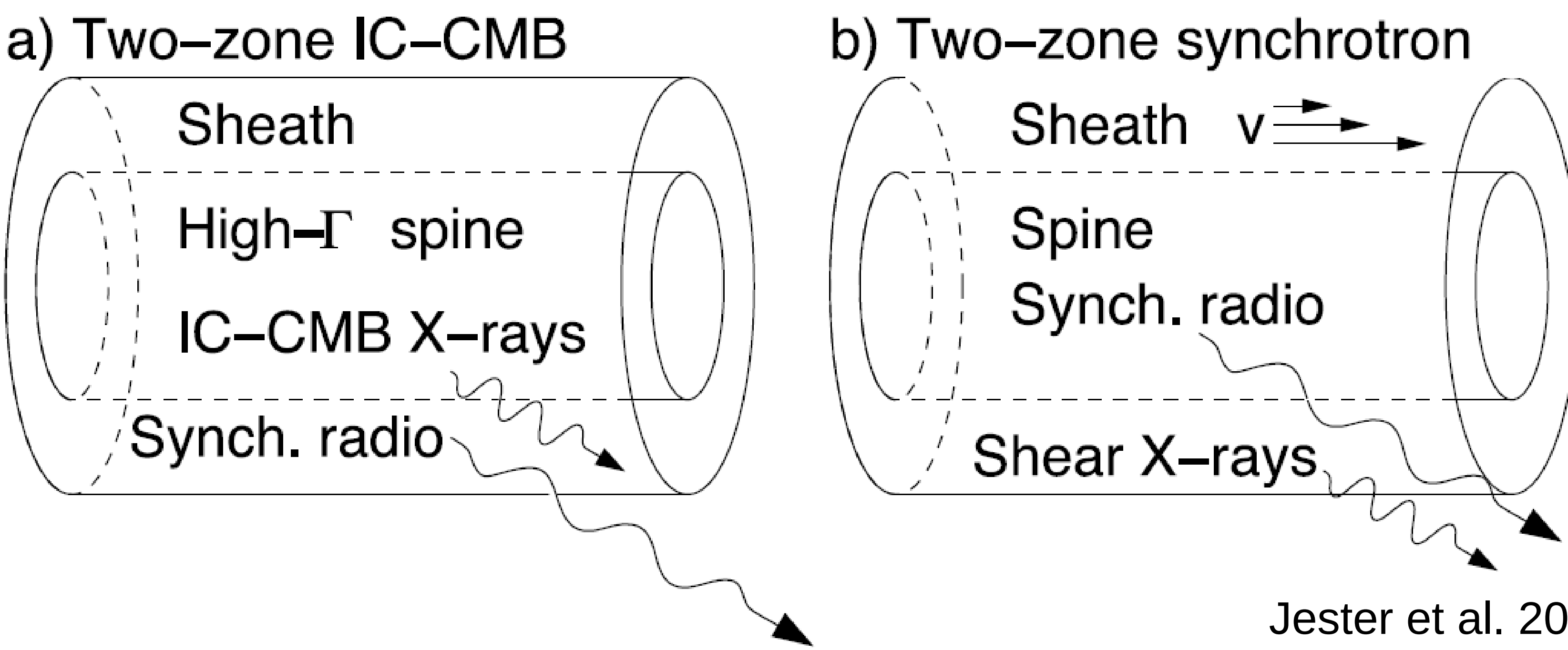
Size of the X-ray bright region (knots >kpc; extended jet; kpc-Mpc)

Cooling time of X-ray emitting electrons << kpc

Proton synchrotron
(e.g. Aharonian 2002)

Low-energy electrons with strong Lorentz boost

Distributed acceleration



Jester et al. 2006

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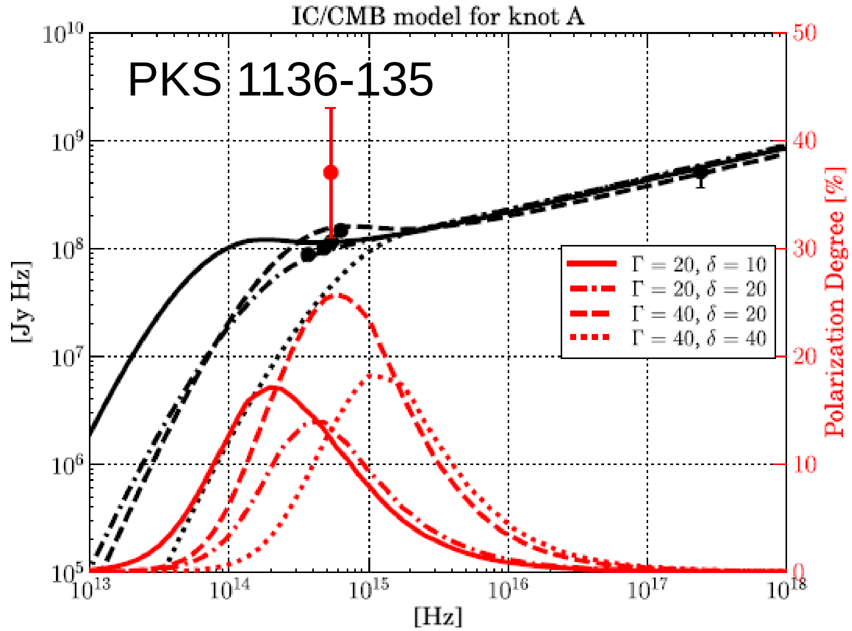
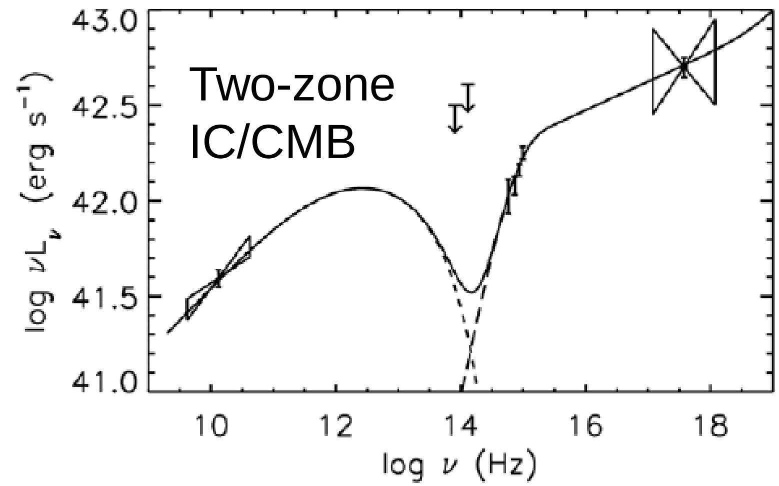
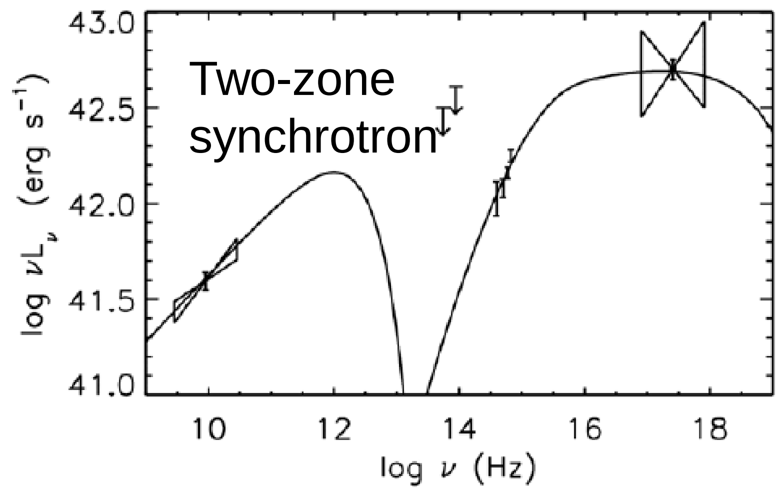
IC/CMB model may be already ruled out in some sources…

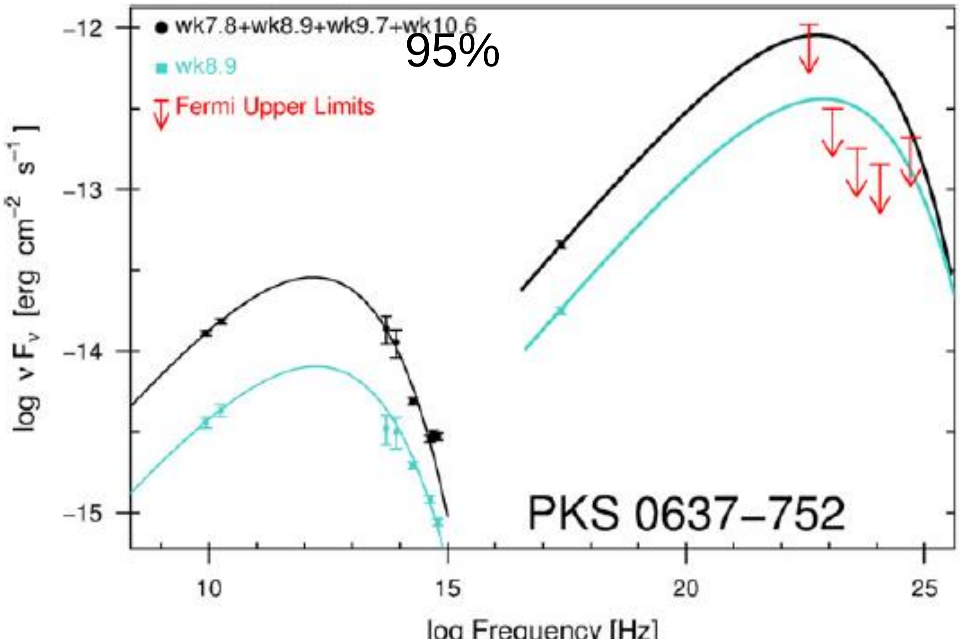


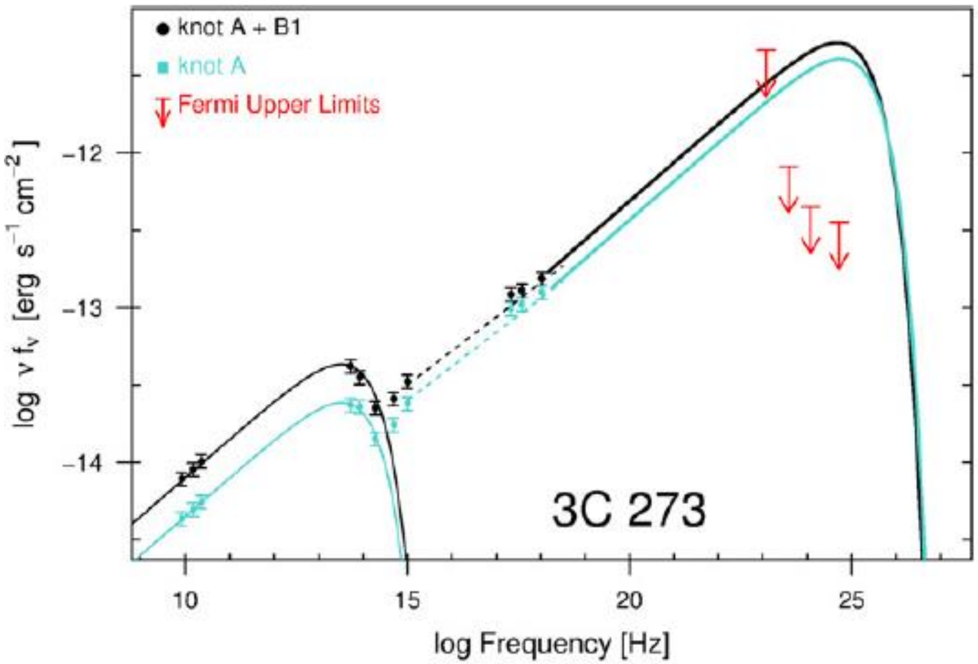




While IC/CMB model can explain the SED, it can not explain the polarization

Cara et al. 2013





IC/CMB model overproduces gamma-ray flux

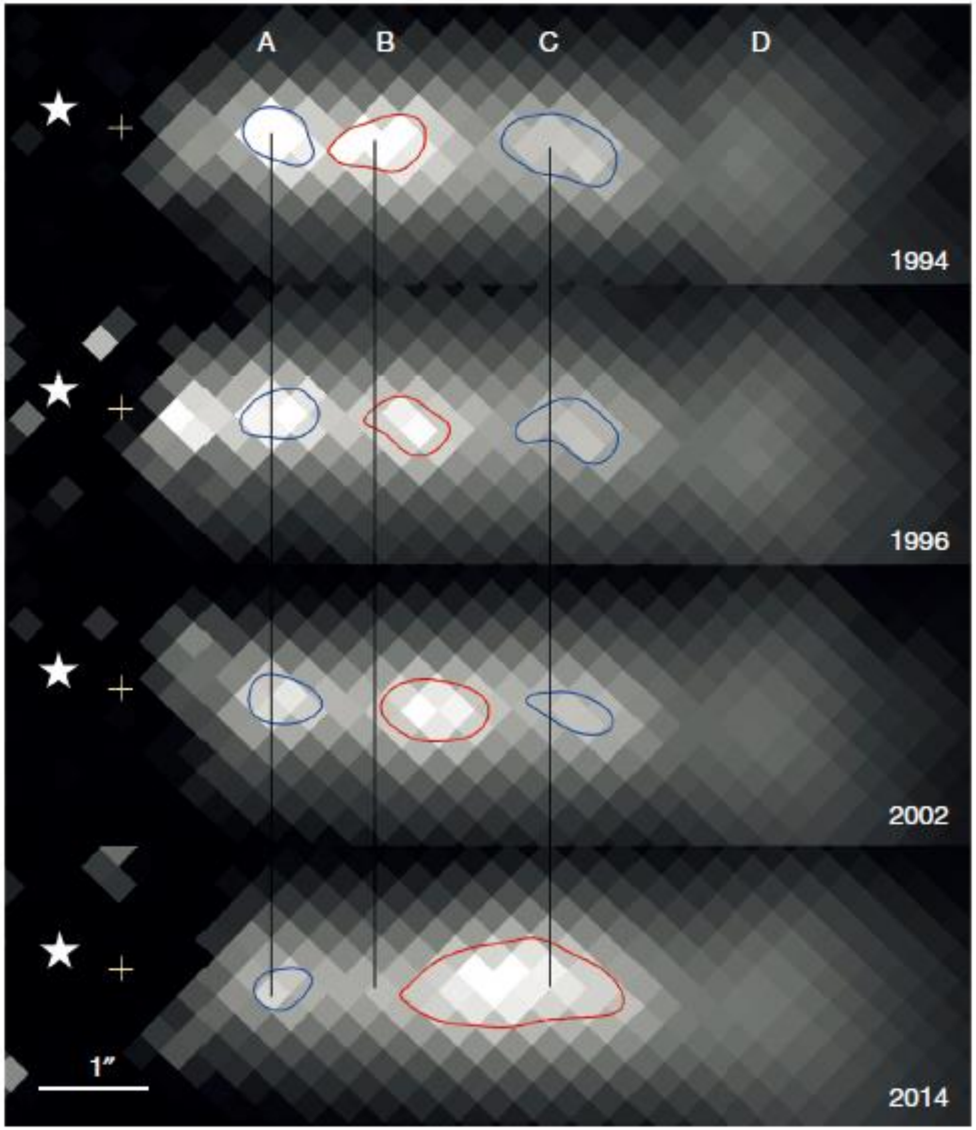
Meyer et al. 2014, 2015

Other potential problems:

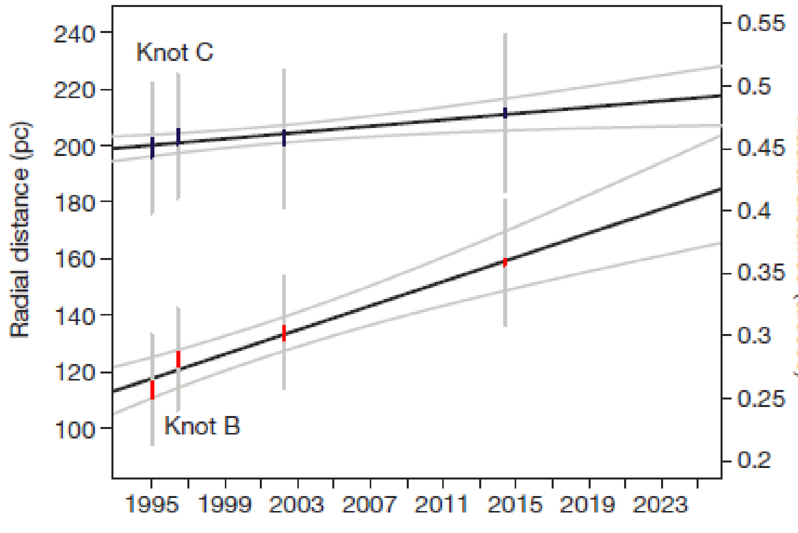
- too long physical length of the jet
- Too much energy required for the jet
- Too many expectation at high z

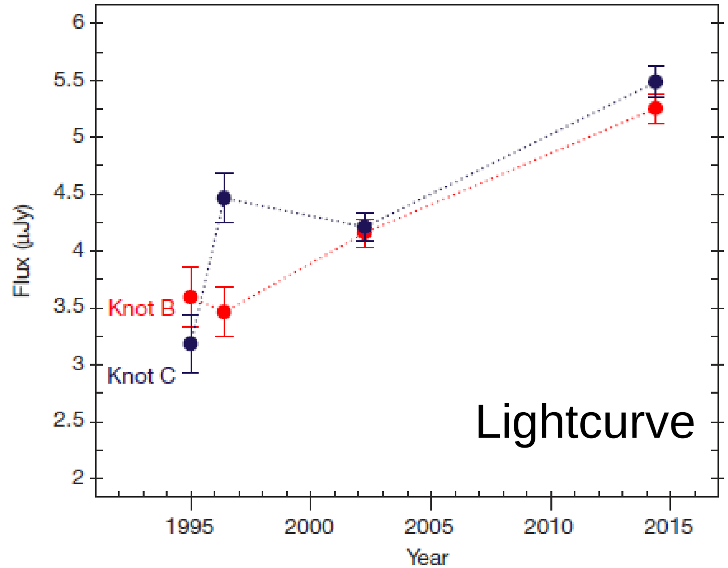
(Harris & Krawczynski 2006; Atoyan & Dermer 2004; Schwarz 2002 and etc)

Internal collision in kpc scale jet (3C 264)



HST image





Meyer et al. 2016

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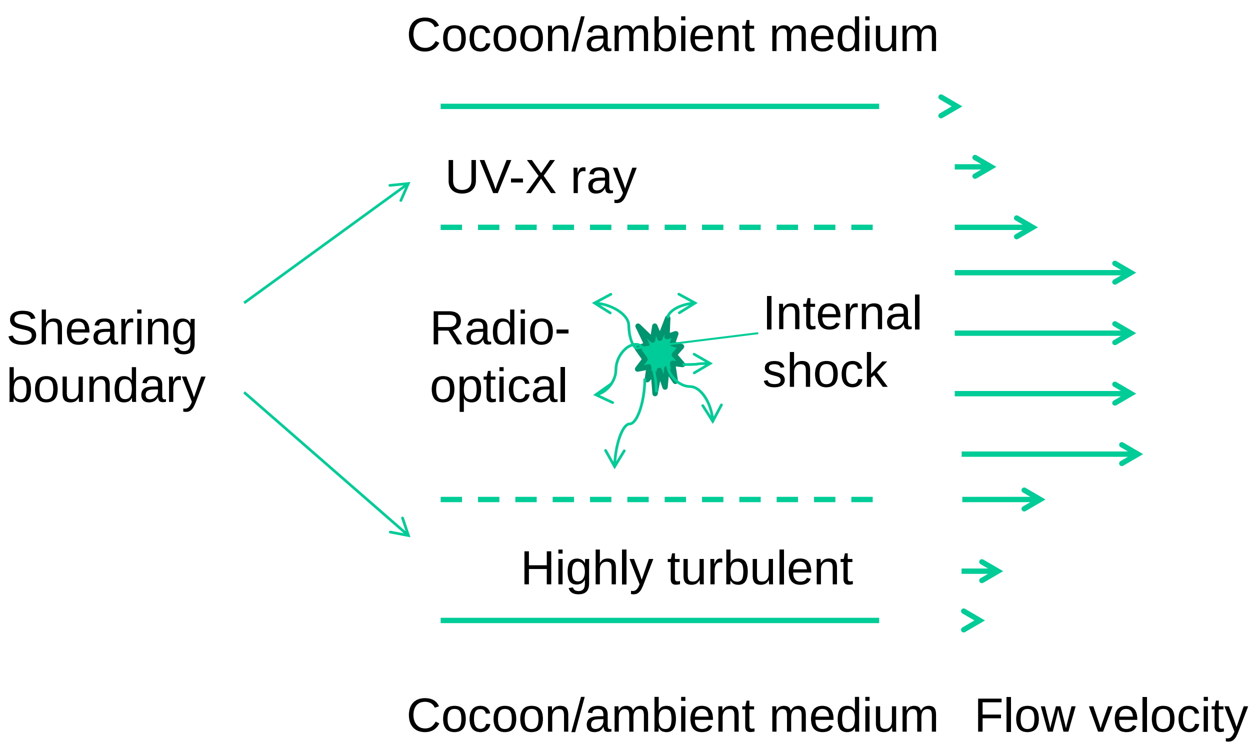
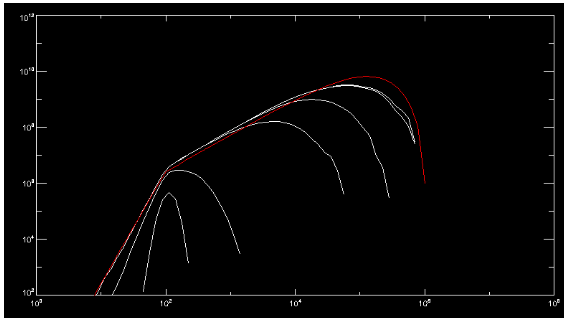
A toy model based on two-zone synchrotron emission

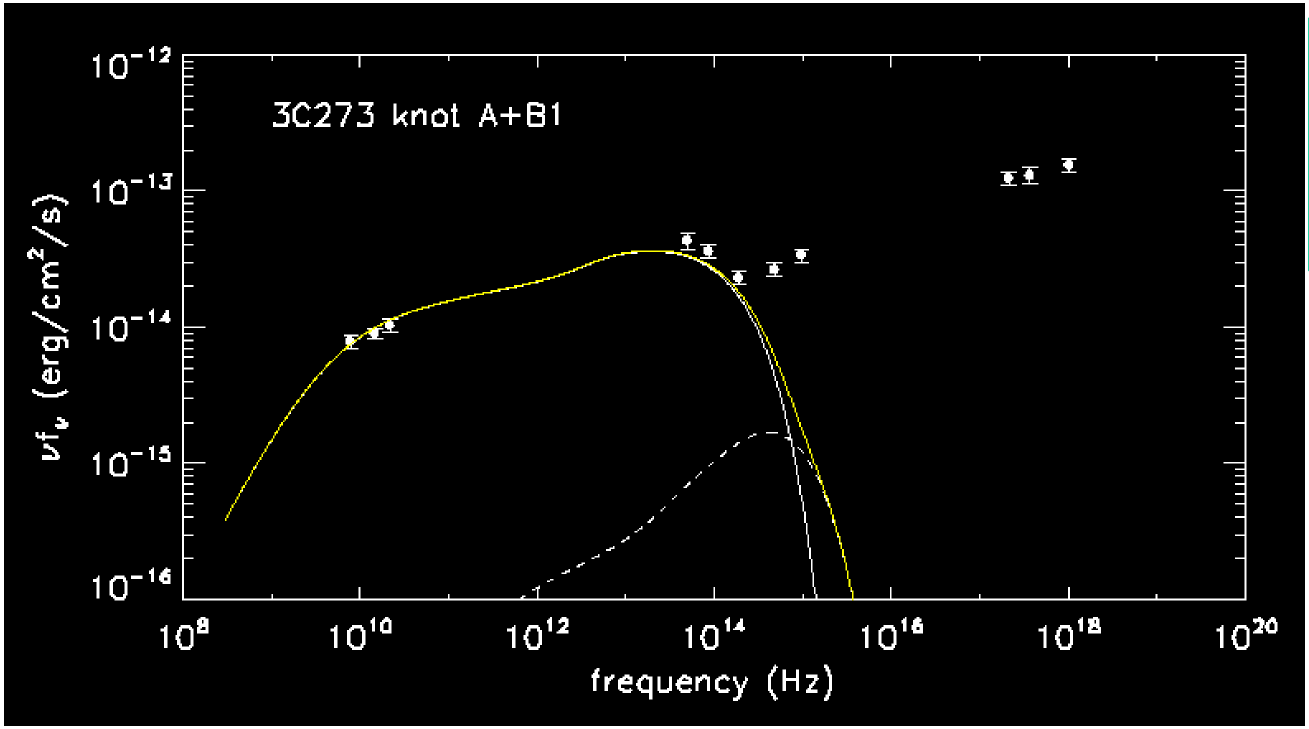


Not scaled!

A preliminary result

Based on a simple Monte-Carlo simulation of particle's propagation/scattering





Internal shock injects electrons of a power-law distribution with a -2.4 index

Snapshot at 10^4yr after Particle injection

Jet radius: 150pc

Shearing boundary: 30pc

Parameters: B_in = 100muG, n_in=0.01cm^-3, \Gamma_0=3
B_out=10 muG, n_out=10^-5cm^-3, \delta=3

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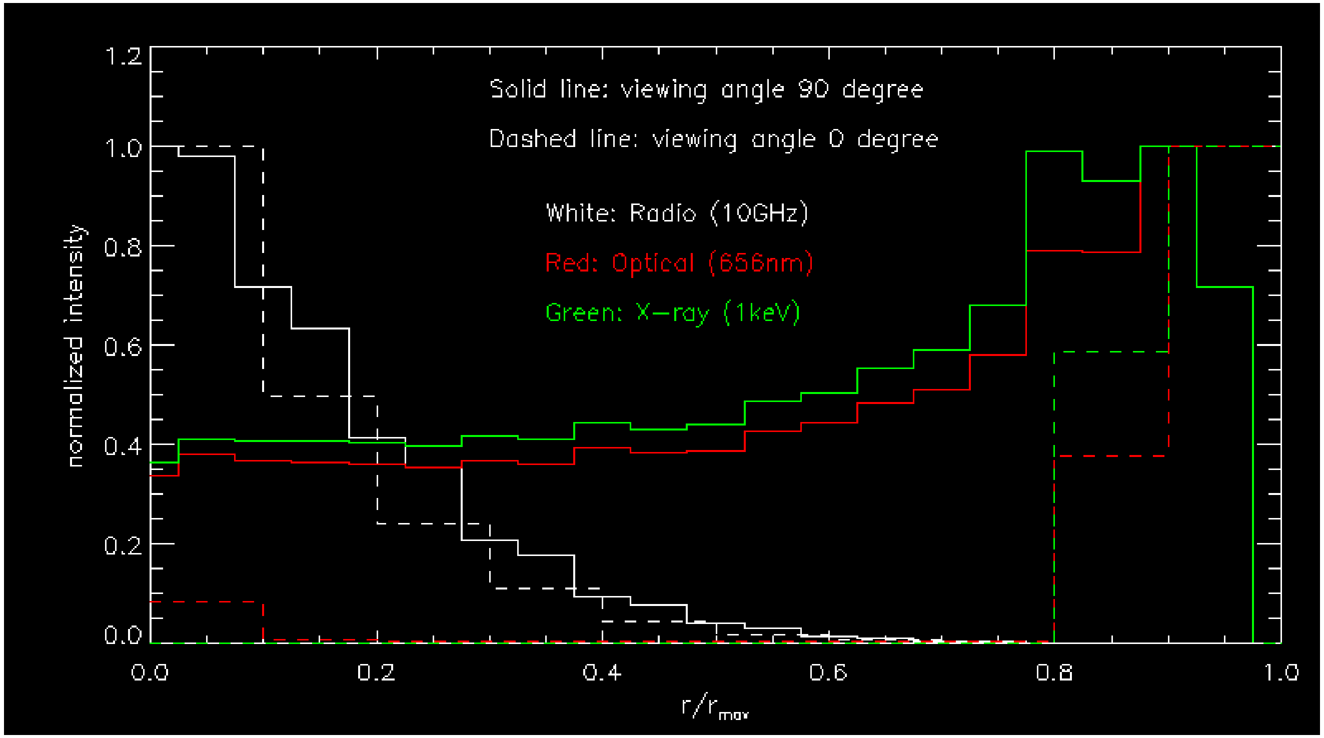
Transverse profile of brightness in different band

Solid lines: 90 degree viewing angle
Dashed lines: 0 degree viewing angle



PSF:
Chandra ~ 0.5”
HST ~ 0.06”
VLA ~ 0.35”

3C 273 distance: 650Mpc

1” ~ 3kpc

Jet width: 300 pc

Limb brightening in Optical-X ray

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Summary

- Shear acceleration naturally appears in the presence of shearing background flow and turbulent waves
- Shear acceleration is efficient in accelerating high energy particles
- Stochastic acceleration always accompanies with shear acceleration and provide high-energy “seed” particles
- Under the joint operation of shear acceleration, stochastic acceleration and cooling, the accelerated spectrum may have a multi component
- Possible application in explaining X-ray emissions in large scale AGN jets

Thanks for your attention!

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