Particle Acceleration in (relativistic) Shearing Flows

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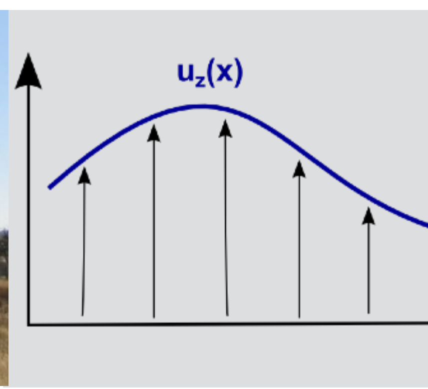
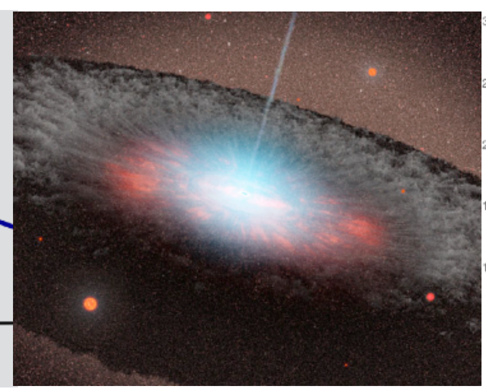
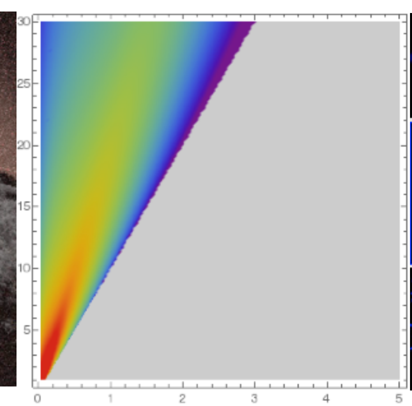
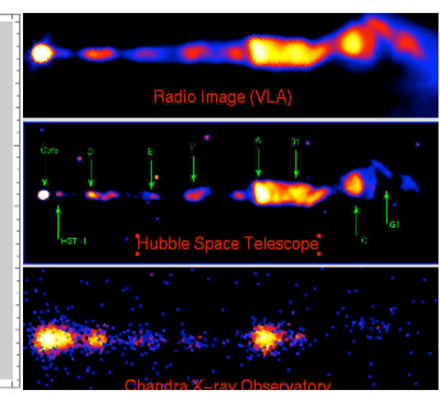
CDY Spring Series

February 8, 2023









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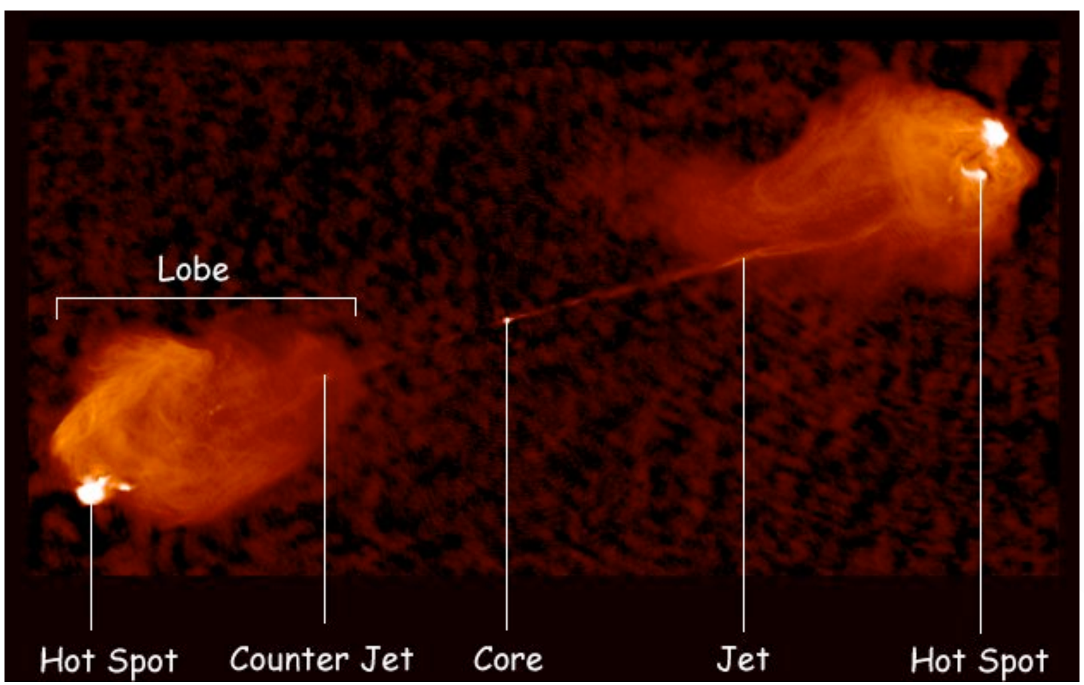
Outline: *Particle Acceleration in (relativistic) Shearing Flows*

- **Astrophysical Motivation & Exemplary Context**
  - Large-scale Jets in AGN
  - Origin of extended high-energy emission
  - Ubiquity of Shearing flows

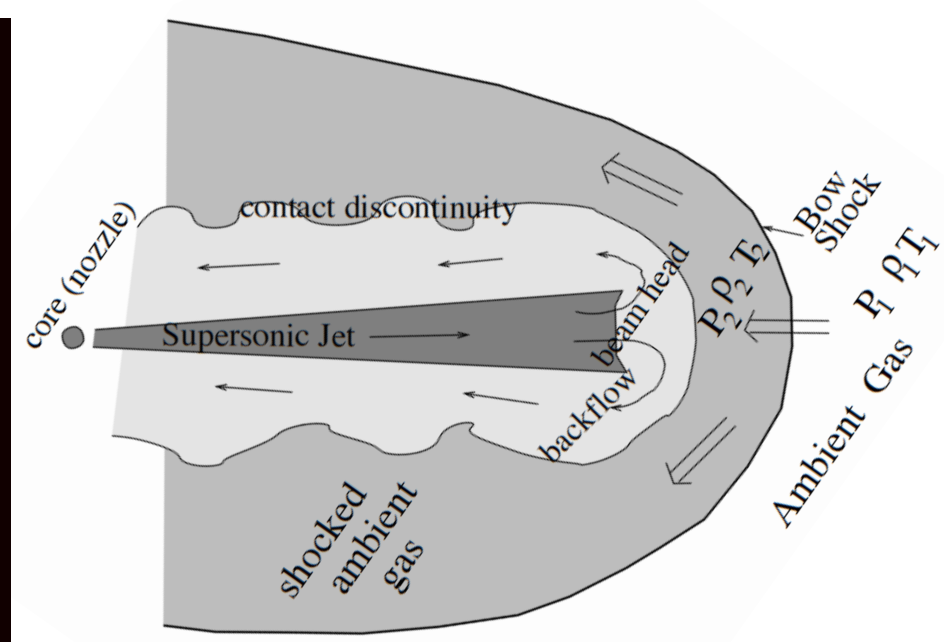
- **Shear Particle Acceleration**
  - Focus on stochastic Fermi-type acceleration (basic idea)
  - Particle transport, acceleration and power-law formation
  - Modelling electron shear acceleration in large-scale jets
  - On UHECR acceleration in shearing AGN flows
  - Summary

_Large-scale Jets in *Active Galaxies*

- relativistic jets & hot spots & back flows
- flow Lorentz factors $\Gamma \sim (1.5 - 10)$
- spatial dimension up to several 100 kpc ~ 10^6 lyr
- laminar appearance (though high fluid Reynolds numbers, Re = ρ u L/μ > 10^{10})



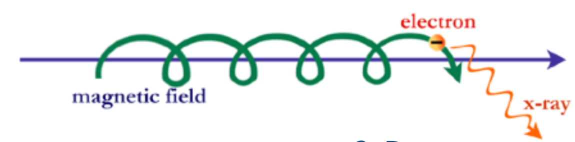
FR II radio galaxy **Cygnus A** at 5 GHz , d ~ 220 Mpc (z=0.056), extension ~120 kpc (credits: NRAO/AUI, A. Bridle)



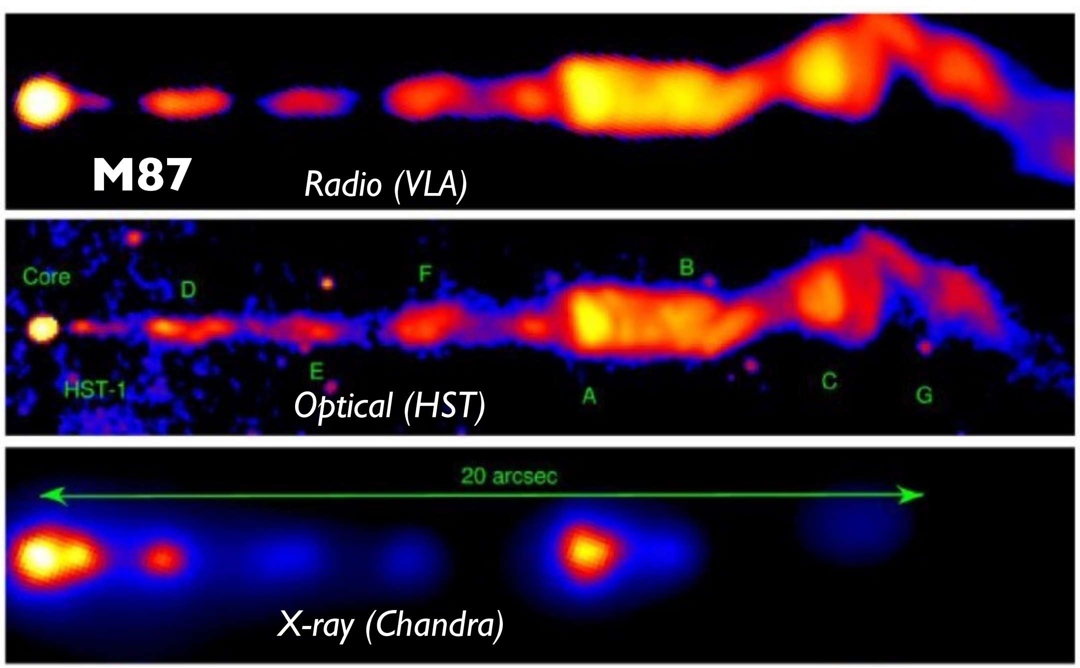
Worrall & Birkinshaw 2006

_Example: High-Energy Emission from large-scale jets

- extended X-ray electron synchrotron emission
- needs electron Lorentz factors $\gamma_e \sim 10^8$
- short cooling timescale $t_{cool} \propto 1/\gamma_e$; cooling length $c\, t_{cool} \ll$ kpc
- distributed acceleration mechanism required (Sun,Yang, FR, Liu & Aharonian 2018 for M87)



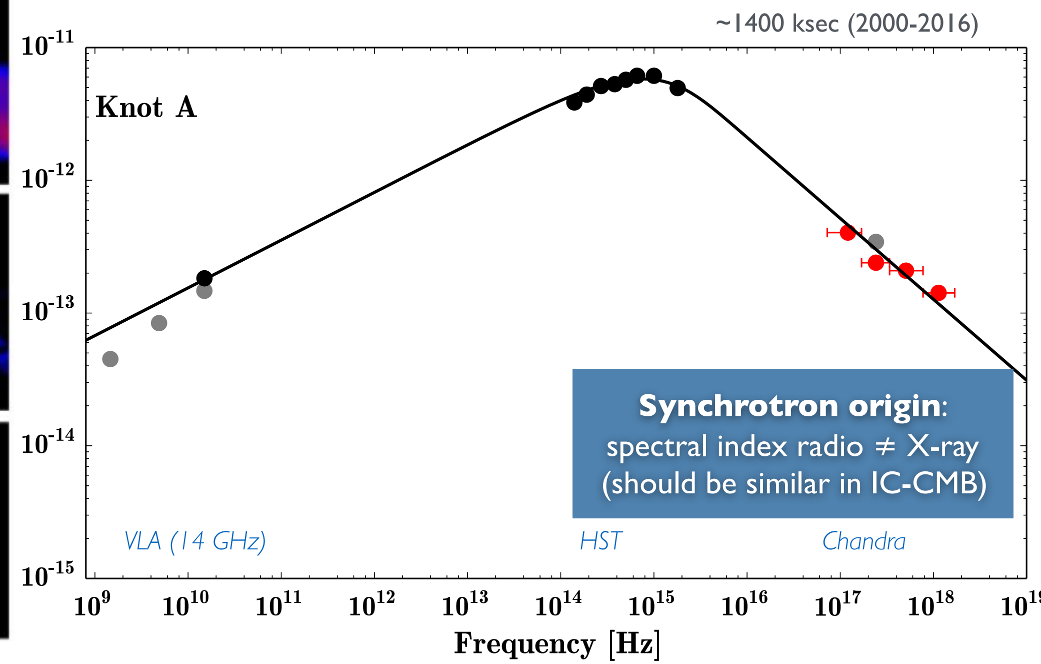
$\nu \propto \gamma^2 B$



1 arcsec ~ 0.1 kpc (0.081 kpc)

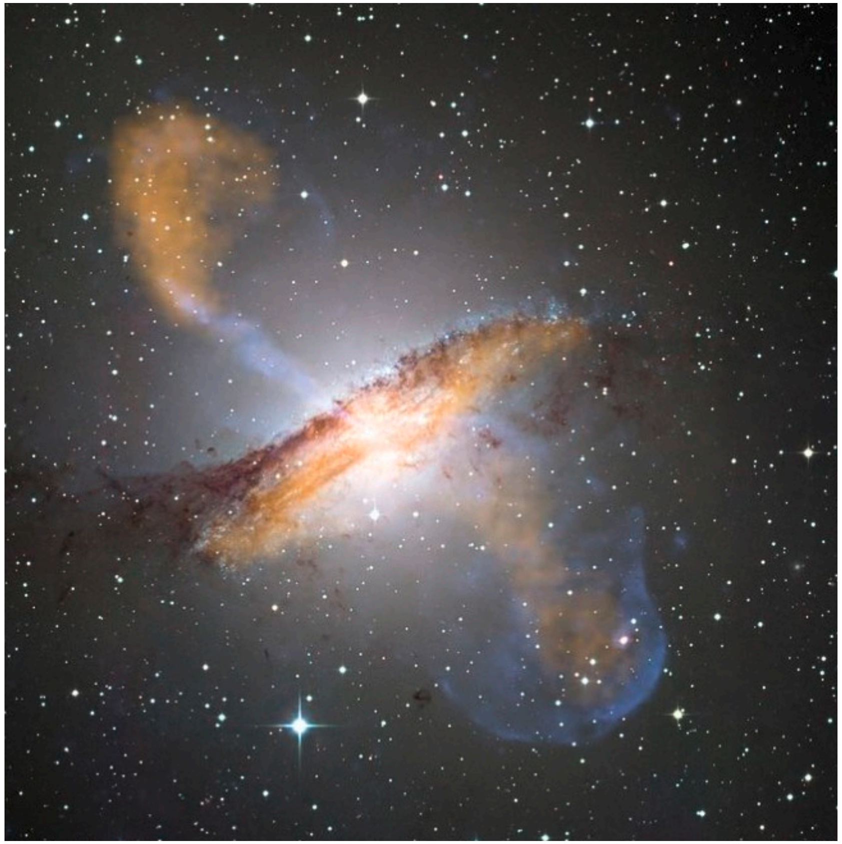
Marshall+ 2002

Relativistic particles throughout whole jet



SED can be fitted by broken power-law

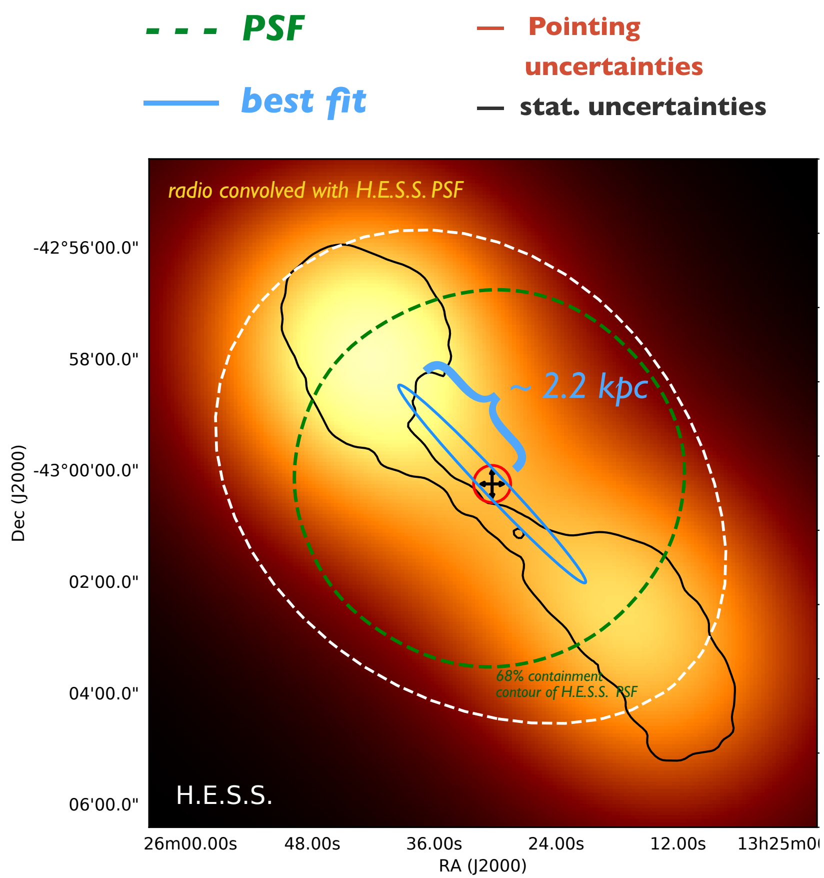
(B = 3x10^{-4} G, $\gamma_b \sim 10^6$, $\gamma_{max} \sim 10^8$, $P_{jet} \sim 10^{43}$ erg/s, $\Delta\alpha \sim 2$)



VHE emission along the kpc-jet of Cen A

- Inverse Compton up-scattering of dust by ultra-relativistic electrons with $\gamma_e = 10^8$
- verifies X-ray synchrotron interpretation
- continuous re-acceleration required to avoid rapid cooling

On ultra-relativistic electrons in AGN Jets II



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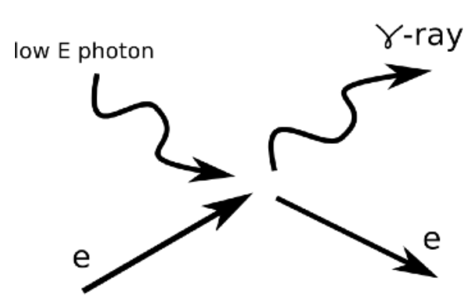
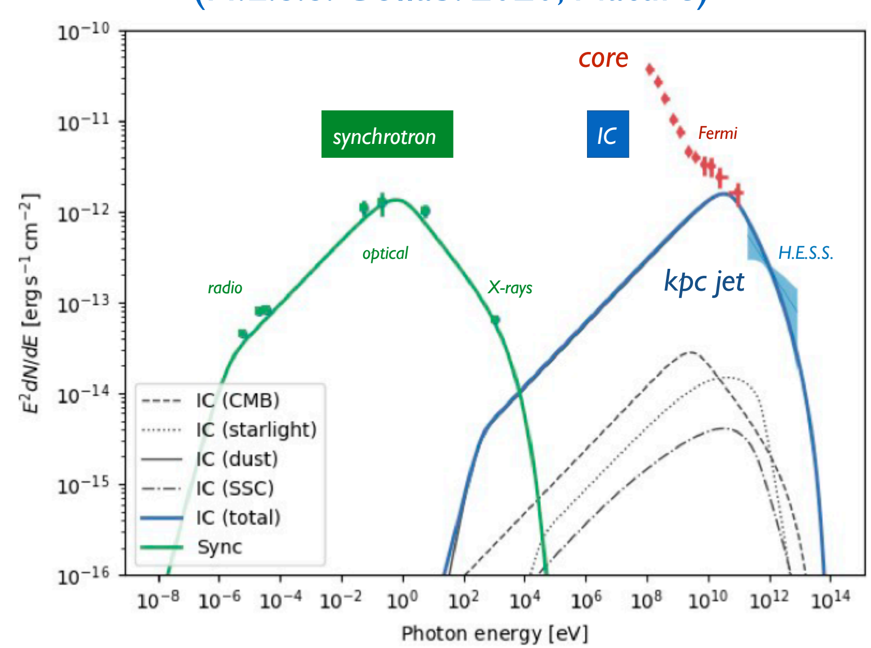
Inverse Compton emission



$$\nu_2 \propto \gamma_e^2\ \nu_1$$

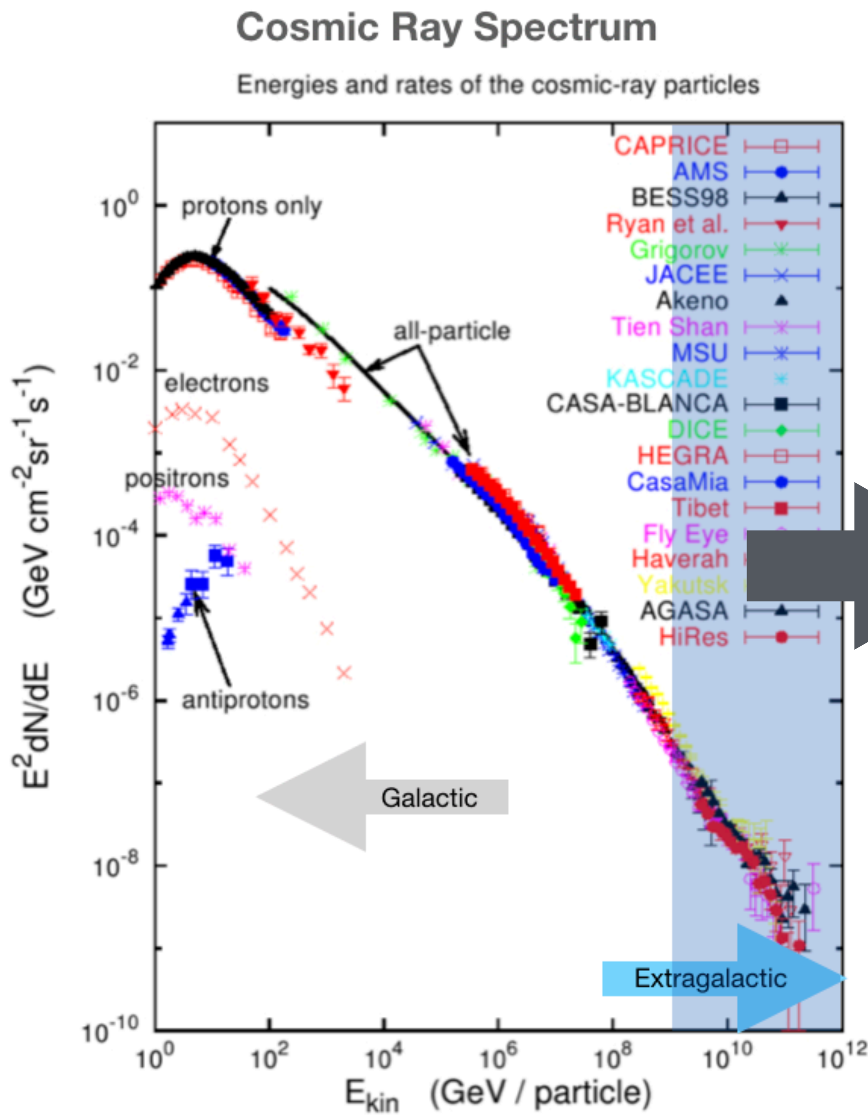
(H.E.S.S. Collab. 2020, Nature)

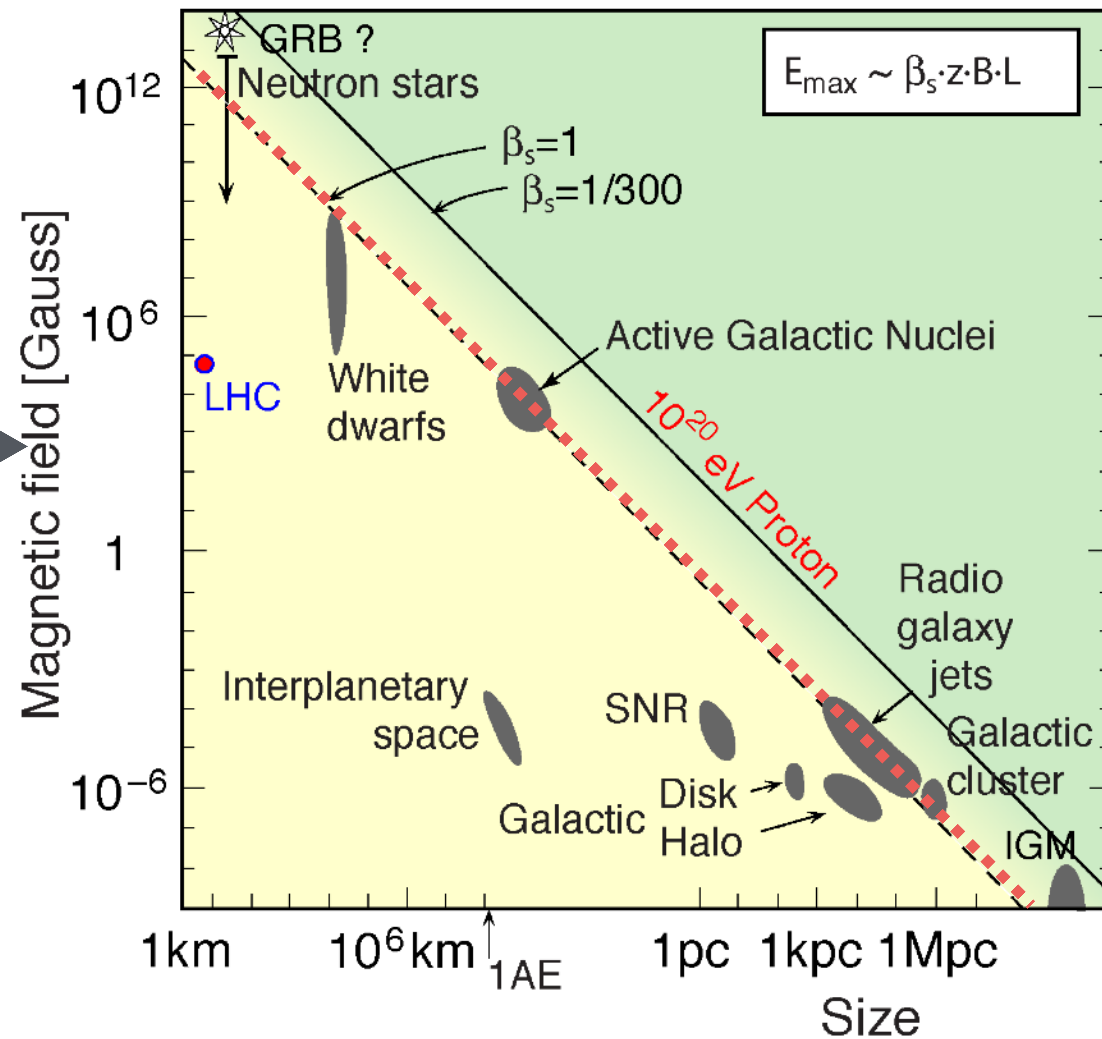


Parameters: ECBPL: α_1=2.30, α_2=3.85 , γ_b =1.4 x 10^6, γ_c=10^8, B=23μG, W_{tot} = 4 x 10^{53} erg

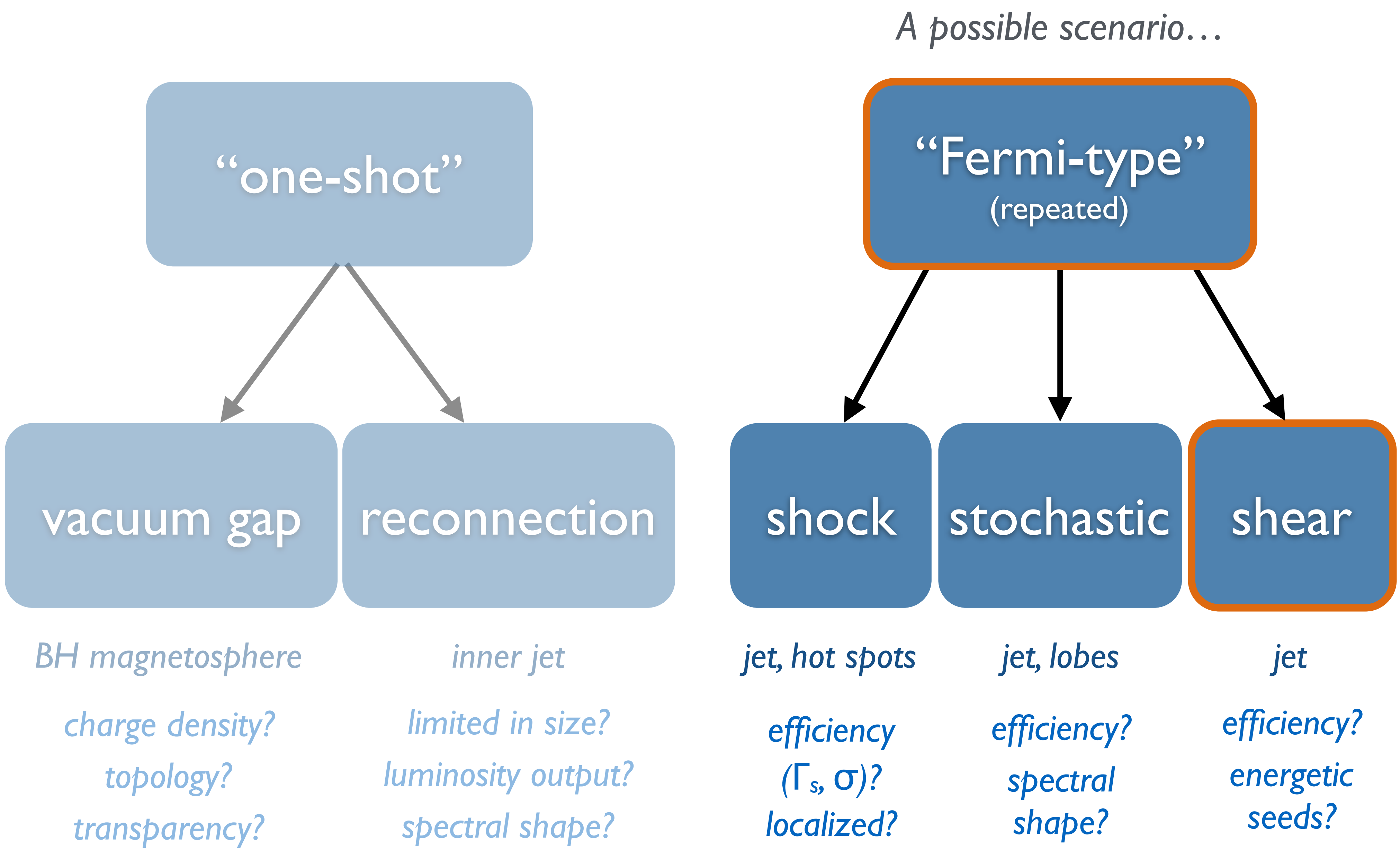
_large-scale jets as possible UHECR accelerators (Hillas)

(e.g., Aharonian, Belyanin, Derishev+ 2002)

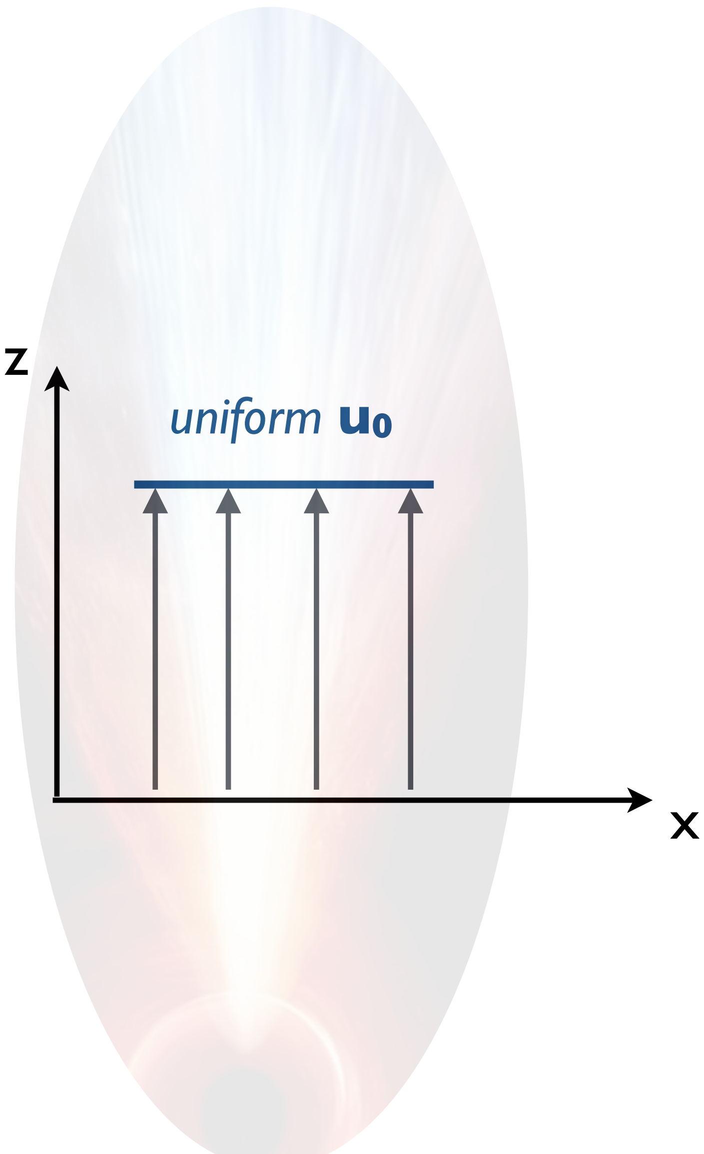




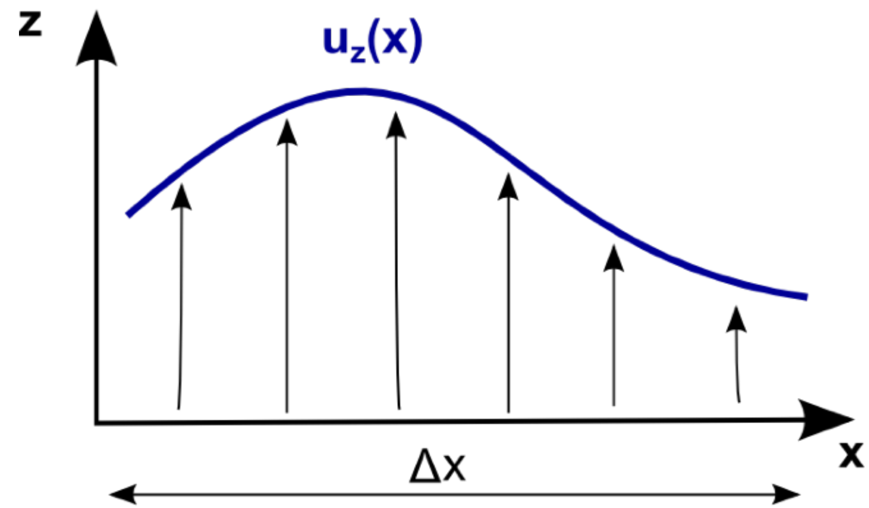
How to accelerate electrons to $\gamma_e \sim 10^8$ and keep them energized ?



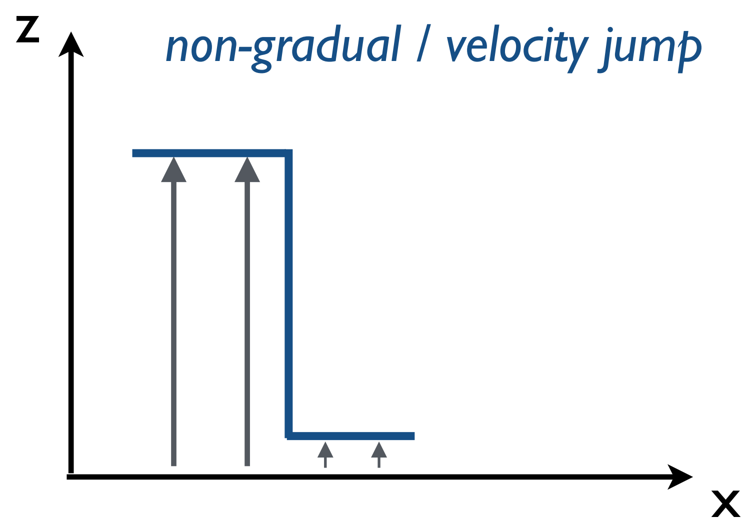
What are shearing flows ?



gradual shear



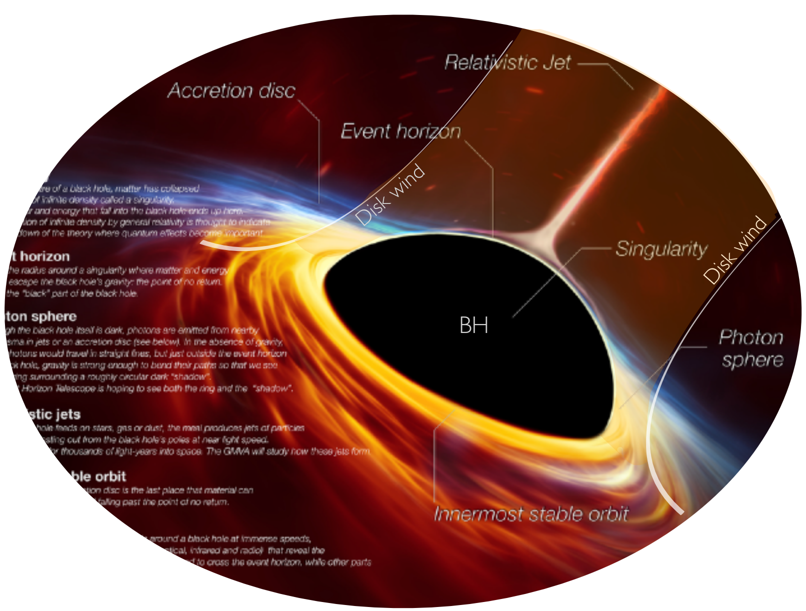
Berezhko & Krymsky; Earl, Jokipii & Morfill; Webb+ ; FR & Duffy…

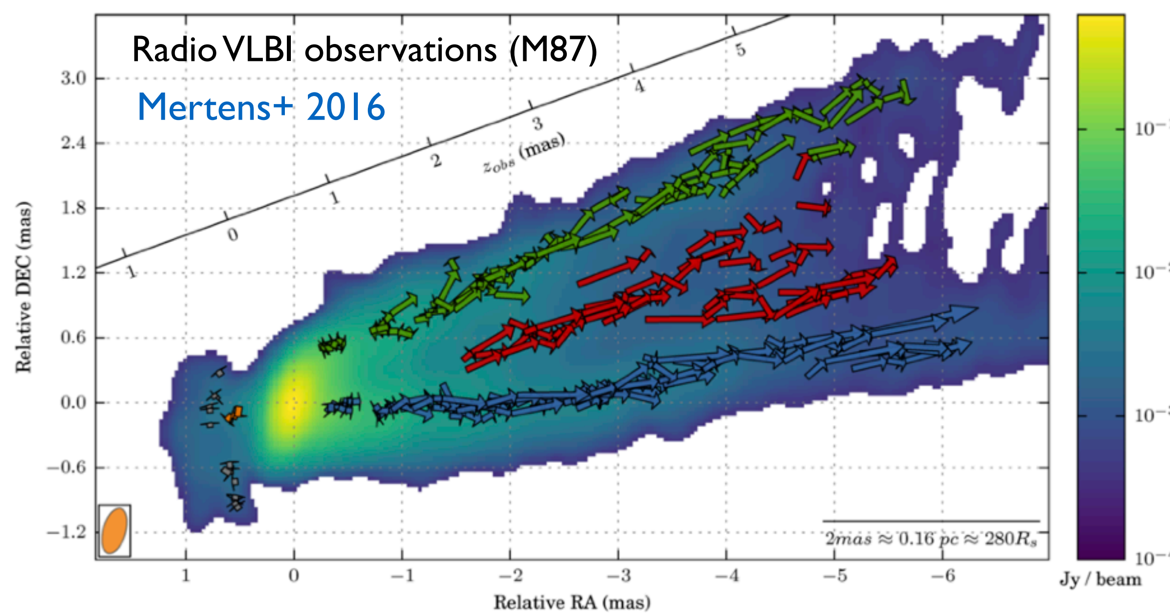


Jokipii & Morfill; Ostrowski; Kimura+….

On the naturalness of velocity shears in AGN…

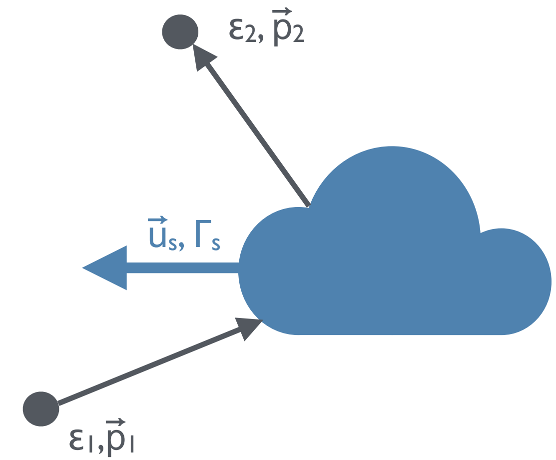
- **Jet origin:** BH-driven (BZ) jet & disk-driven (BP) outflow… (e.g., Mizuno 2022)
- **Jet propagation:** instabilities, mixing, layer formation… (e.g., Perucho 2019)
- **Jet observations:** limb-brightening & polarisation signatures… (e.g., Kim+ 2018)
  - M87: significant structural patterns on sub-pc scales
    $\Rightarrow$ *presence of both slow (~0.5c) and fast (~0.92c) components….*
    [similar indications in Cen A, cf. EHT observations in Janssen+ 2021]





Kinematic effect resulting from *scattering off magnetic inhomogeneities*

E. Fermi, Phys. Rev. 75, 578 [1949]



_Ingredients: in frame of scattering centre

- momentum magnitude conserved
- particle direction randomised

_Characteristic energy change per scattering:

$$\boxed{\Delta\epsilon = \epsilon_2 - \epsilon_1 = 2\,\Gamma_s^2\left(\epsilon_1\, u_s^2/c^2 - \overrightarrow{p_1}\cdot\overrightarrow{u_s}\right)}$$

$p_1 \simeq \epsilon_1/c$

➡ *energy gain for head-on* ($\vec{p}_1 \cdot \vec{u}_s < 0$), *loss for following collision* ($\vec{p}_1 \cdot \vec{u}_s > 0$)

- I. **stochastic**: average energy gain 2nd order: $\langle\Delta\varepsilon\rangle \propto (u_s/c)^2\, \varepsilon$
- II. **shock**: spatial diffusion, head-on collisions, gain 1st order: $\langle\Delta\varepsilon\rangle \propto (u_s/c)\, \varepsilon$

Stochastic Shear Particle Acceleration

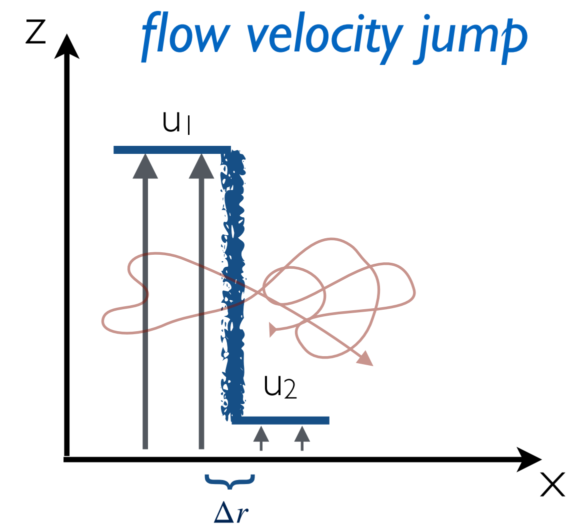
- III. ***Non-gradual* shear flow**

  - like 2nd Fermi, stochastic process with average gain per cycle (crossing and recrossing):

$$\boxed{< \Delta\epsilon > \sim \Gamma_\Delta^2\, \beta_\Delta^2\, \epsilon}$$

with relative velocity $\beta_\Delta = (u_1 - u_2)/[(1 - u_1 u_2/c^2)\, c]$

provided particle mean free path $\lambda > \Delta r$



Jokipii & Morfill 1990; Ostrowski 1998, 2000; Stawarz & Ostrowski 2002; FR & Duffy 2004; Kimura+2018…

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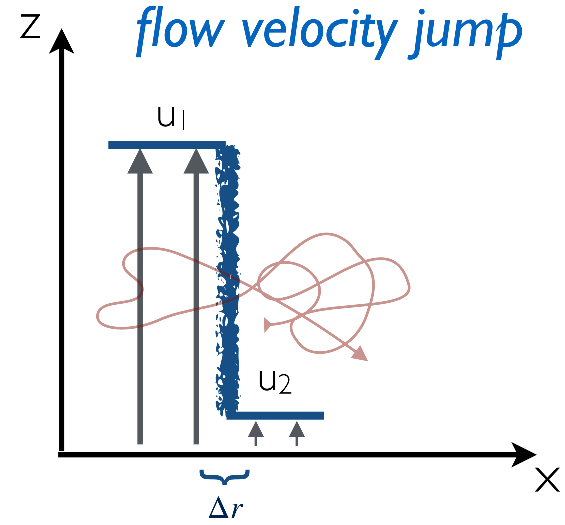
flow velocity jump



  - characteristic acceleration timescale:

$$\boxed{t_{\rm acc} \simeq \frac{\epsilon}{(d\epsilon/dt)} \simeq \frac{\epsilon}{\langle\Delta\epsilon\rangle}\, t_c \propto \lambda}$$

with cycle time t_c

Jokipii & Morfill 1990; Ostrowski 1998, 2000; Stawarz & Ostrowski 2002; FR & Duffy 2004; Kimura+2018…

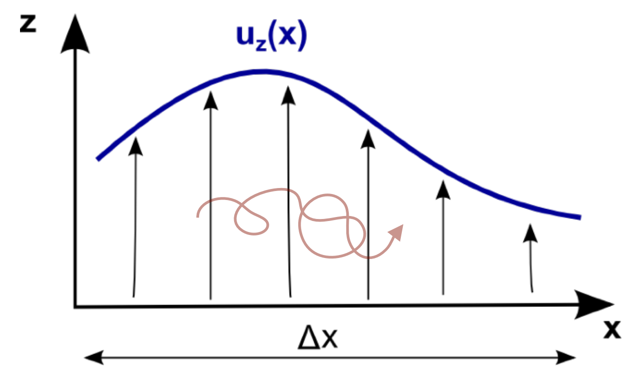
- IV. ***Gradual* shear flow** with frozen-in scattering centres:

non-relativistic

$$\vec{u} = u_z(x)\ \vec{e}_z$$

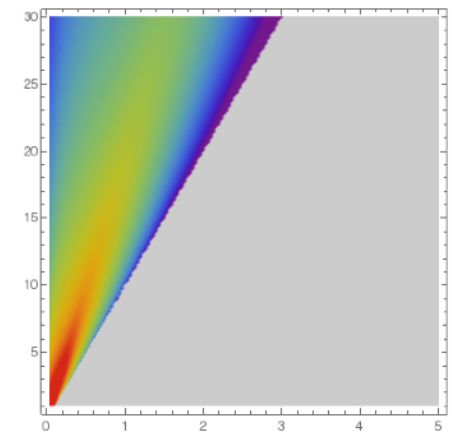
  - like 2nd Fermi, stochastic process with average gain:

$$\boxed{< \Delta\epsilon > \propto \left(\frac{u}{c}\right)^2 \epsilon = \frac{1}{c^2}\left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2\ \epsilon}$$



using *characteristic* *effective velocity*:

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda \quad \text{, where } \lambda = c\tau \quad \textit{particle mean free path}$$



Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004, 2006, 2016; Liu, FR & Aharonian 2017; Webb+ 2018, 2019; Lemoine 2019; FR & Duffy 2019, 2021….

Stochastic Shear Particle Acceleration (basic idea) I

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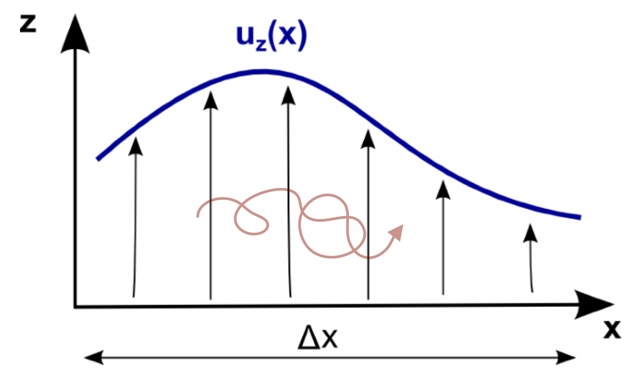
$$\vec{u} = u_z(x)\ \vec{e}_z$$



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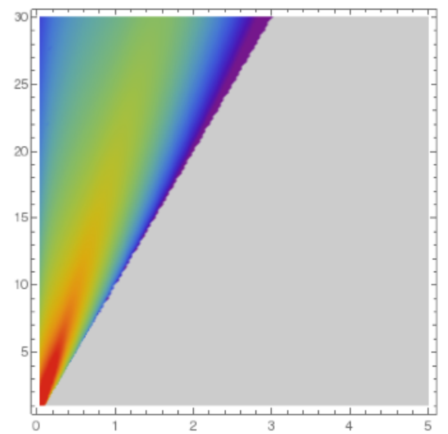
using *characteristic effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda$$, where $\lambda = c\tau$ *particle mean free path*

  - leads to:

$$\boxed{t_{acc} = \frac{\epsilon}{(d\epsilon/dt)} \sim \frac{\epsilon}{< \Delta\epsilon >} \times \frac{\lambda}{c} \propto \frac{1}{\lambda}}$$



$\Rightarrow$ *seeds* from acceleration @ shock or stochastic…

$\Rightarrow$ easier for protons…(➪ UHECR)

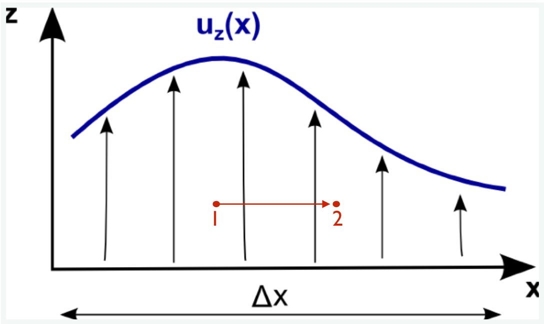
Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004, 2006, 2016; Liu, FR & Aharonian 2017; Webb+ 2018, 2019; Lemoine 2019; FR & Duffy 2019, 2021….

Stochastic Shear Particle Acceleration (basic idea) II

Calculate Fokker Planck coefficients for particle travelling across shear $\mathbf{u}_z(x)$ with

$\mathbf{p}_2 = \mathbf{p}_1 + m\,\boldsymbol{\delta}\mathbf{u}$ where $\delta u = (du_z/dx)\,\delta x$ and $\delta x = v_x\,\tau$, $\tau = \lambda/c$

$$\Delta p := p_2 - p_1 \;\Rightarrow\; \begin{cases} \left\langle \dfrac{\Delta p}{\Delta t} \right\rangle \propto p \left(\dfrac{\partial u_z}{\partial x} \right)^2 \tau \\[2ex] \left\langle \dfrac{(\Delta p)^2}{\Delta t} \right\rangle \propto p^2 \left(\dfrac{\partial u_z}{\partial x} \right)^2 \tau \end{cases}$$



⇒ detailed balance satisfied [scattering being reversible P(p, -Δp) = P(p-Δp, Δp)]

(cf. Jokipii & Morfill 1990; FR & Duffy 2006)

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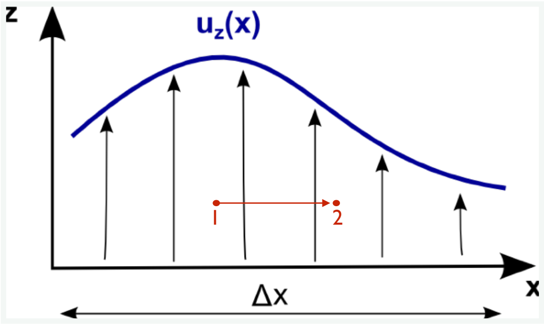

$\Rightarrow$ detailed balance satisfied [scattering being reversible $P(p, -\Delta p) = P(p-\Delta p, \Delta p)$]

Fokker Planck eq. reduces to momentum diffusion equation:

$$\boxed{\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D \frac{\partial f}{\partial p}\right)}$$

$$D = \frac{1}{15}\left(\frac{\partial u_z}{\partial x}\right)^2 p^2 \tau \;\propto\; p^{2+\alpha} \quad \text{for} \quad \tau := \tau_0 p^\alpha$$

(cf. Jokipii & Morfill 1990; FR & Duffy 2006)

Stochastic Shear Particle Acceleration (basic idea) III

- Momentum-dependent part of the phase space distribution function f(t,p) obeys diffusion equation in momentum space:

$$\boxed{\frac{\partial f(t,p)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D(p)\frac{\partial f(t,p)}{\partial p}\right) + \ldots}$$

with $D(p) \propto \, < (\Delta p)^2 > \, = D_0\, p^{2+\alpha}, (\alpha \geq 0)$ momentum-space diffusion coefficient

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$$\frac{\partial f(t,p)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D(p)\frac{\partial f(t,p)}{\partial p}\right) + \ldots = \underbrace{(4+\alpha)\frac{D(p)}{p}\frac{\partial f(t,p)}{\partial p}}_{\text{change of mean energy}} + \underbrace{D(p)\frac{\partial^2 f(t,p)}{\partial p^2}}_{\text{broadening of distribution}} + \ldots$$

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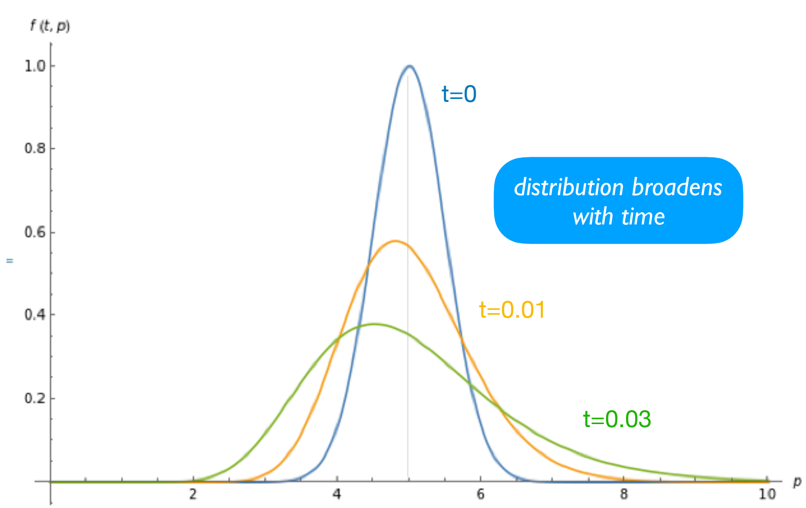
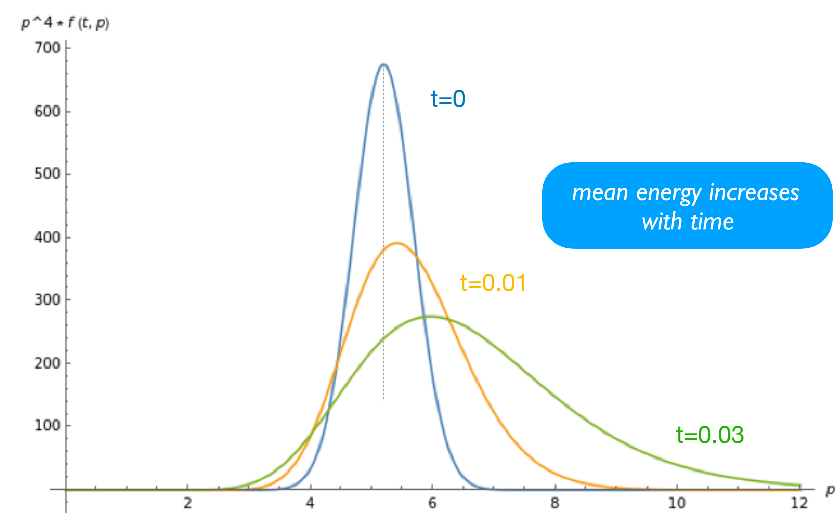
Example: Instantaneous injection at time t = 0 with $p_0 = 5$ for $\alpha = 0$



Phase-space distribution function *f(t,p)*



Energy distribution n(p) $p^2 \propto p^4 f(t,p)$

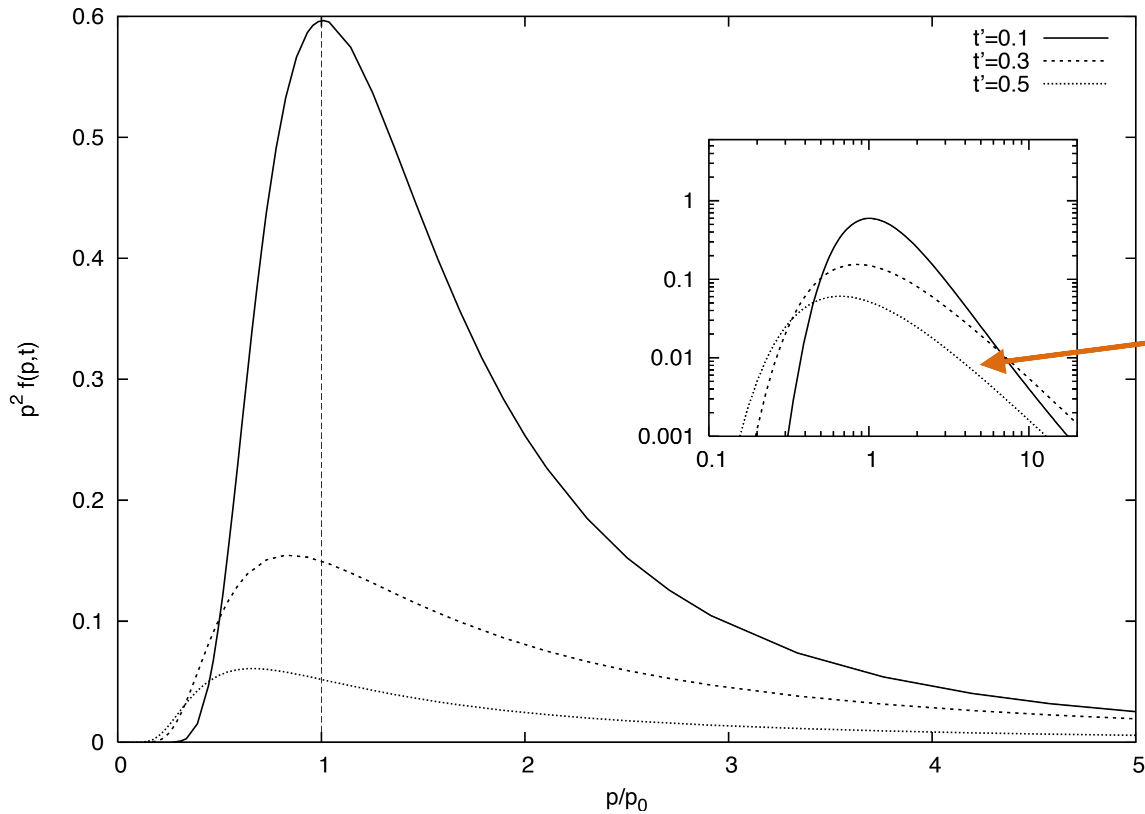
Stochastic Shear Particle Acceleration (basic idea) IV

Local power law formation above injection p_0 with index depending on scaling of particle mean free path:

$$\boxed{n(p) \propto p^2 f(p) \propto p^{-(1+\alpha)}}$$

for $\alpha > 0$

- with $\tau = \tau_0\, p^\alpha$, e.g. $\alpha = 1/3$ for Kolmogorov, or $\alpha = 1$ for Bohm-type
- characteristic for time-independent (steady-state) solution

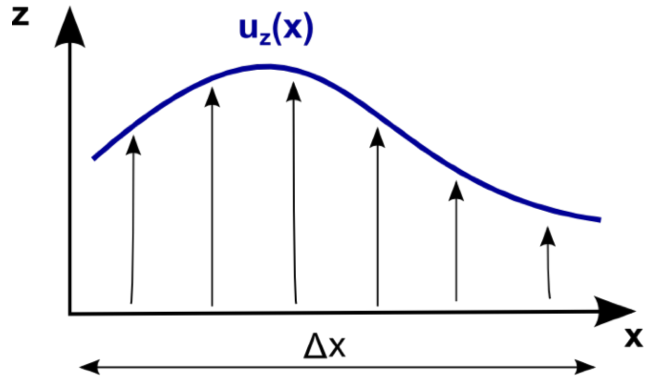


Time-dependent solution of Fokker-Planck equation for non-relativistic shear using impulsive injection with p_0 at $t_0 = 0$ for $\alpha = 1$

power law formation

(e.g., Berezhko 1982; FR & Duffy 2006)

Diffusive Particle transport



Full non-relativistic Particle Transport Equation (PTE)

Start from non-relativistic Boltzmann equation with simple BKG-type collision term

- use mixed system of phase-space coordinates
- Galilean trafo $p_i = p_i' + m\, u_i$ (background flow speed u_i, comoving p_i')
- diffusion approximation $f = f_0 + f_1$, with $\langle f_1 \rangle = 0$

$$\frac{\partial f_0}{\partial t} + u_i \frac{\partial f_0}{\partial x_i} - \frac{p'}{3}\frac{\partial u_i}{\partial x_i}\frac{\partial f_0}{\partial p'} - \frac{\partial}{\partial x_i}\left(\frac{\tau}{3}\frac{p'^2}{m^2}\frac{\partial f_0}{\partial x_i}\right)$$

$$+ \frac{2\,\tau\, p'}{3} A_i \frac{\partial^2 f_0}{\partial x_i \partial p'} + \frac{1}{3\, p'^2}\frac{\partial\left(\tau\, p'^3\right)}{\partial p'} A_i \frac{\partial f_0}{\partial x_i}$$

shear term

$$\boxed{- \frac{\Gamma}{p'^2}\frac{\partial}{\partial p'}\left(\tau\, p'^4 \frac{\partial f_0}{\partial p'}\right)} + \frac{p'}{3}\frac{\partial(\tau A_i)}{\partial x_i}\frac{\partial f_0}{\partial p'} = 0$$

$$\Gamma = \frac{1}{30}\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)^2 - \frac{2}{45}\frac{\partial u_i}{\partial x_i}\frac{\partial u_k}{\partial x_k}$$

$$A_i = \frac{\partial u_i}{\partial t} + u_l \frac{\partial u_i}{\partial x_l}$$ *"inertial drifts"*

(Earl, Jokipii & Morfill 1988;
cf. also Williams & Jokipii 1991; FR 2001)

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$$\frac{\partial f_0}{\partial t} + u_i \frac{\partial f_0}{\partial x_i} - \frac{p'}{3}\frac{\partial u_i}{\partial x_i}\frac{\partial f_0}{\partial p'} - \frac{\partial}{\partial x_i}\left(\frac{\tau}{3}\frac{p'^2}{m^2}\frac{\partial f_0}{\partial x_i}\right) + \frac{2\,\tau\, p'}{3} A_i \frac{\partial^2 f_0}{\partial x_i \partial p'} + \frac{1}{3\,p'^2}\frac{\partial\left(\tau\, p'^3\right)}{\partial p'} A_i \frac{\partial f_0}{\partial x_i} \boxed{- \frac{\Gamma}{p'^2}\frac{\partial}{\partial p'}\left(\tau\, p'^4 \frac{\partial f_0}{\partial p'}\right)} + \frac{p'}{3}\frac{\partial(\tau A_i)}{\partial x_i}\frac{\partial f_0}{\partial p'} = 0$$

shear term

$$\Gamma = \frac{1}{30}\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)^2 - \frac{2}{45}\frac{\partial u_i}{\partial x_i}\frac{\partial u_k}{\partial x_k}$$

$$A_i = \frac{\partial u_i}{\partial t} + u_l \frac{\partial u_i}{\partial x_l}$$ *"inertial drifts"*

(Earl, Jokipii & Morfill 1988;
cf. also Williams & Jokipii 1991; FR 2001)

for steady shear flow $\mathbf{u} = u_z(x)\, \mathbf{e}_z$, adiabatic and inertial terms vanish; space-independent part equivalent to shear-diffusion equation

Full non-relativistic Particle Transport Equation (PTE)

Start from non-relativistic Boltzmann equation with simple BKG-type collision term

- use mixed system of phase-space coordinates
- Galilean trafo $p_i = p_i' + m\,u_i$ (background flow speed u_i, comoving p_i')
- diffusion approximation $f = f_0 + f_1$, with $\langle f_1 \rangle = 0$

$$\frac{\partial f_0}{\partial t} + u_i \frac{\partial f_0}{\partial x_i} - \cancel{\frac{p'}{3}\frac{\partial u_i}{\partial x_i}\frac{\partial f_0}{\partial p'}} - \frac{\partial}{\partial x_i}\left(\frac{\tau}{3}\frac{p'^2}{m^2}\frac{\partial f_0}{\partial x_i}\right)$$

$$+ \cancel{\frac{2\,\tau\,p'}{3} A_i \frac{\partial^2 f_0}{\partial x_i \partial p'}} + \frac{1}{3\,p'^2}\cancel{\frac{\partial(\tau\,p'^3)}{\partial p'} A_i \frac{\partial f_0}{\partial x_i}}$$

shear term

$$\boxed{- \frac{\Gamma}{p'^2}\frac{\partial}{\partial p'}\left(\tau\,p'^4 \frac{\partial f_0}{\partial p'}\right)} + \cancel{\frac{p'}{3}\frac{\partial(\tau A_i)}{\partial x_i}\frac{\partial f_0}{\partial p'}} = 0$$

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Relativistic PTE Generalisation

Particle Transport Equation (PTE) - mixed frame - for isotopic distribution function $f_0(x^\alpha,p)$, with $x^\alpha = (ct,x,y,z,)$ and metric tensor $g_{\alpha\beta}$

(fluid four velocity u^α and fluid four acceleration $\mathring{u}_\alpha = u^\beta u_{\alpha;\beta}$)

$$\boxed{\begin{aligned}\nabla_\alpha\left[cu^\alpha f_0 - \kappa(g^{\alpha\beta}+u^\alpha u^\beta)\left(\frac{\partial f_0}{\partial x^\beta} - \dot{u}_\beta\frac{(p^0)^2}{p}\frac{\partial f_0}{\partial p}\right)\right] \\ + \frac{1}{p^2}\frac{\partial}{\partial p}\left[-\frac{p^3}{3}cu^\beta_{;\beta}f_0 + p^3\left(\frac{p^0}{p}\right)^2\right. \\ \left.\times\,\kappa\dot{u}^\beta\left(\frac{\partial f_0}{\partial x^\beta} - \dot{u}_\beta\frac{(p^0)^2}{p}\frac{\partial f_0}{\partial p}\right) - \boxed{\Gamma\tau p^4\frac{\partial f_0}{\partial p}}\right] = Q.\end{aligned}}$$

(Webb 1989; cf. also FR & Mannheim 2002; Webb+ 2018)

shear term

Γ relativistic shear coefficient

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Note: for steady shear flow profile $\vec{u} = u(r)\vec{e}_z$, fluid four acceleration $\dot{u}_\beta = 0$ and divergence $\nabla_\beta u^\beta = 0$

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For introduction & overview…

Galaxies 7 (2019), 78 [review]

galaxies

MDPI

Review

An Introduction to Particle Acceleration in Shearing Flows

Frank M. Rieger [1,2]

1 ZAH, Institut für Theoretische Astrophysik, Heidelberg University, Philosophenweg 12, 69120 Heidelberg, Germany; f.rieger@uni-heidelberg.de or frank.rieger@mpi-hd.mpg.de

2 Max-Planck-Institut für Kernphysik, P.O. Box 103980, 69029 Heidelberg, Germany

Received: 15 August 2019; Accepted: 6 September 2019; Published: 10 September 2019

check for updates

Abstract: Shear flows are ubiquitously present in space and astrophysical plasmas. This paper highlights the central idea of the non-thermal acceleration of charged particles in shearing flows and reviews some of the recent developments. Topics include the acceleration of charged particles by microscopic instabilities in collisionless relativistic shear flows, Fermi-type particle acceleration in macroscopic, gradual and non-gradual shear flows, as well as shear particle acceleration by large-scale velocity turbulence. When put in the context of jetted astrophysical sources such as Active Galactic Nuclei, the results illustrate a variety of means beyond conventional diffusive shock acceleration by which power-law like particle distributions might be generated. This suggests that relativistic shear flows can account for efficient in-situ acceleration of energetic electrons and be of relevance for the production of extreme cosmic rays.

Keywords: shearing flows; relativistic outflows; AGN jets; particle transport; acceleration

1. Introduction

Shear flows are naturally expected in a variety of astrophysical environments. Prominent examples include the rotating accretion flows around compact objects and the relativistic outflows (jets) in gamma-ray bursts (GRBs) or Active Galactic Nuclei (AGN) [1]. On conceptual grounds the jets in AGN are expected to exhibit some internal velocity stratification from the very beginning, with a black hole ergo-spheric driven, highly relativistic (electron-positron) flow surrounded by a slower moving (electron-proton dominated) wind from the inner parts of the disk (e.g., see Refs. [2,3] for

For introduction & overview…

galaxies

MDPI

Galaxies 7 (2019), 78 [review]

Review

An Introduction to Particle Acceleration in Shearing Flows

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Kinetic/PIC:

Alves, Grismayer+, Liang+, Sironi+…

turbulence:

Bykov & Toptygin, Ohira…

On electron shear acceleration in large-scale jets

Simplified leaky-box model for shear acceleration

$$\boxed{\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right) - \frac{f}{\tau_{\rm esc}}}$$

(FR & Duffy 2019)

Momentum-diffusion: $D_p = \Gamma p^2 \tau_s \propto p^{2+\alpha}$

mean free path: $\lambda = c\,\tau_s \propto p^{\alpha}$

[$\alpha = 1/3$ for Kolmogorov]

Escape time: $\tau_{\rm esc}(p) \simeq \dfrac{(\Delta r)^2}{2\,\kappa(p)} \propto p^{-\alpha}$

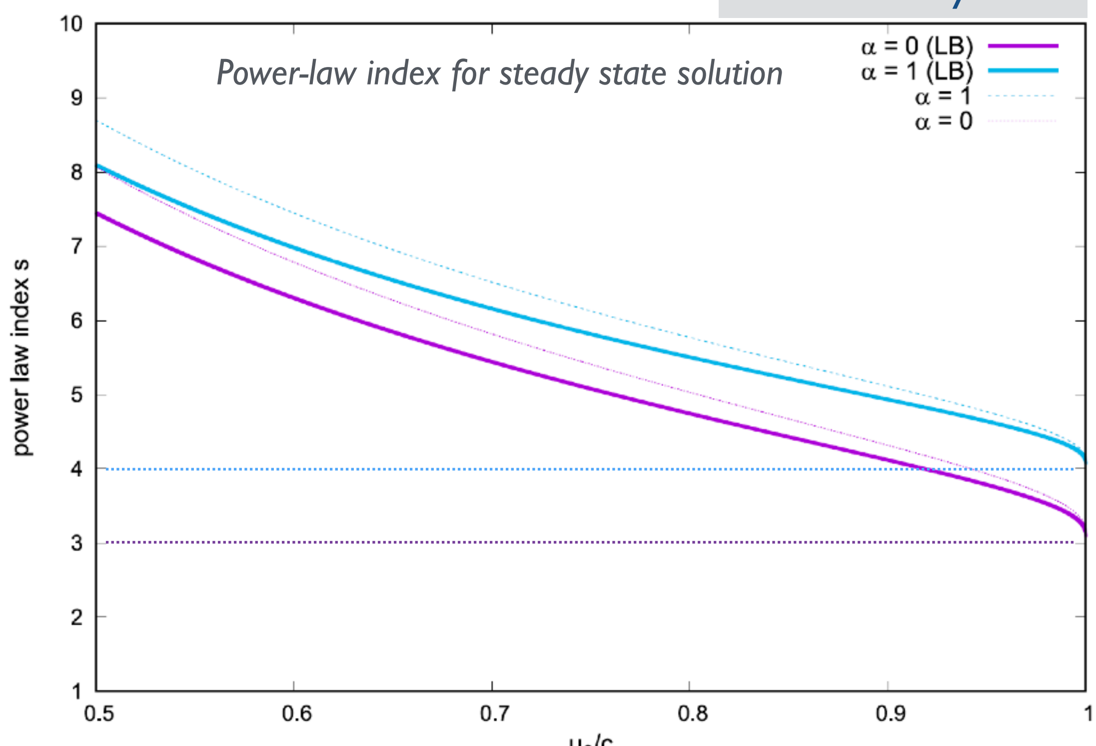
$\Gamma = (c^2/15)\,\gamma_b(r)^4\,(d\beta/dr)^2$

Power-law solution:

$$\boxed{f(p) = f_0\, p^{-s}}$$

- *PL index s sensitive to maximum flow speed*
- *only for relativistic flow speeds is classical index s = 3 + α obtained.*

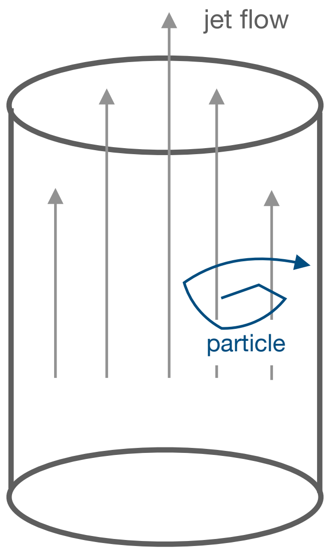
linear velocity shear



(see also Webb+ 2018)

On continuous electron acceleration in large-scale AGN jets

Radiative-loss-limited electron acceleration in mildly relativistic flows



Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by <u>stochastic</u> and <u>shear</u>, and losses due to <u>synchrotron</u> and <u>escape</u> for cylindrical jet.

Parameters I: $B = 3\mu G$, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ pc, $\beta_A \sim 0.007$, $\Delta r \sim r_j/10$,
mean free path $\lambda = \xi^{-1}\, r_L\, (r_L/\Lambda_{max})^{1-q} \propto \gamma^{2-q}$, $q=5/3$ (Kolmogorov), $\xi=0.1$

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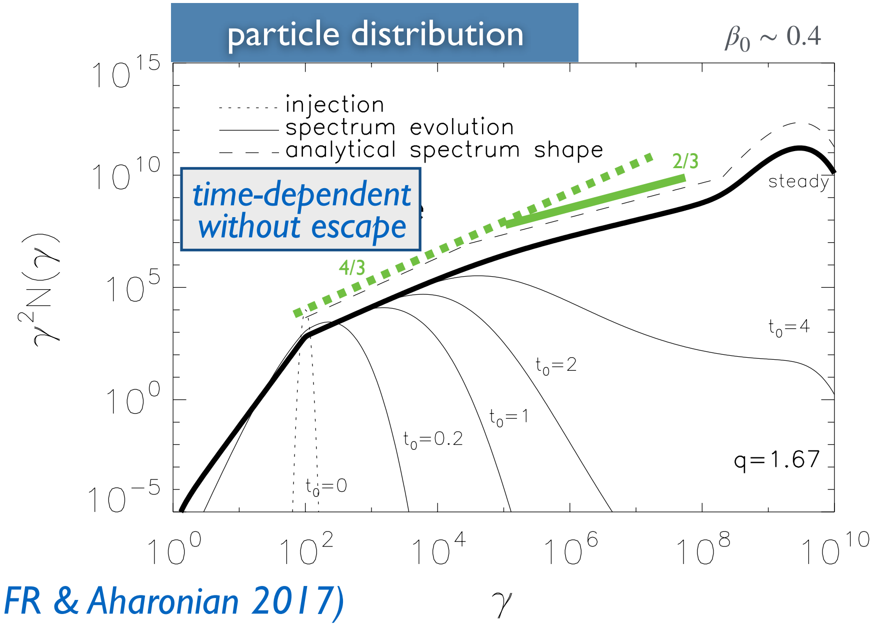
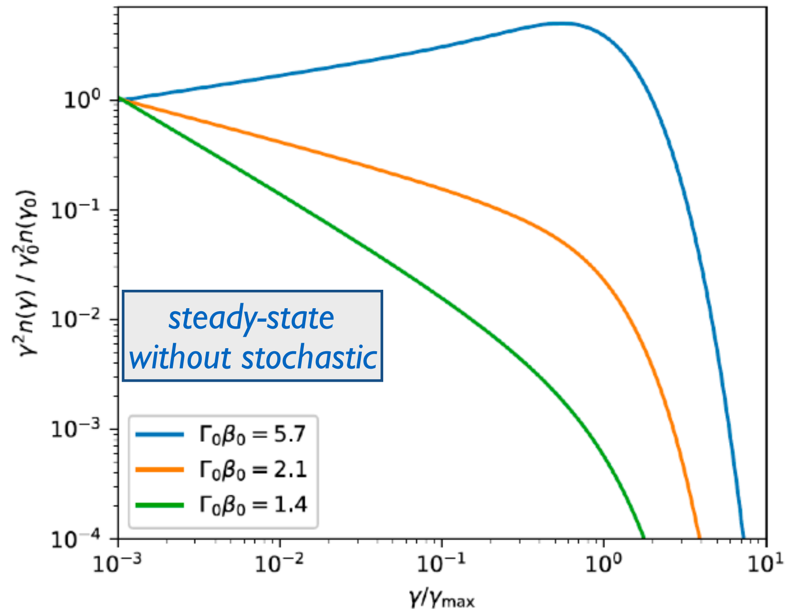


(Liu, FR & Aharonian 2017)



(Wang, Reville, Liu, FR & Aharonian 2021)

Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by stochastic and shear, and losses due to synchrotron and escape for cylindrical jet.

- from 2nd Fermi to shear…
- electron acceleration beyond $\gamma \sim 10^8$ possible
- formation of multi-component particle distribution
- incorporation of escape softens the spectrum

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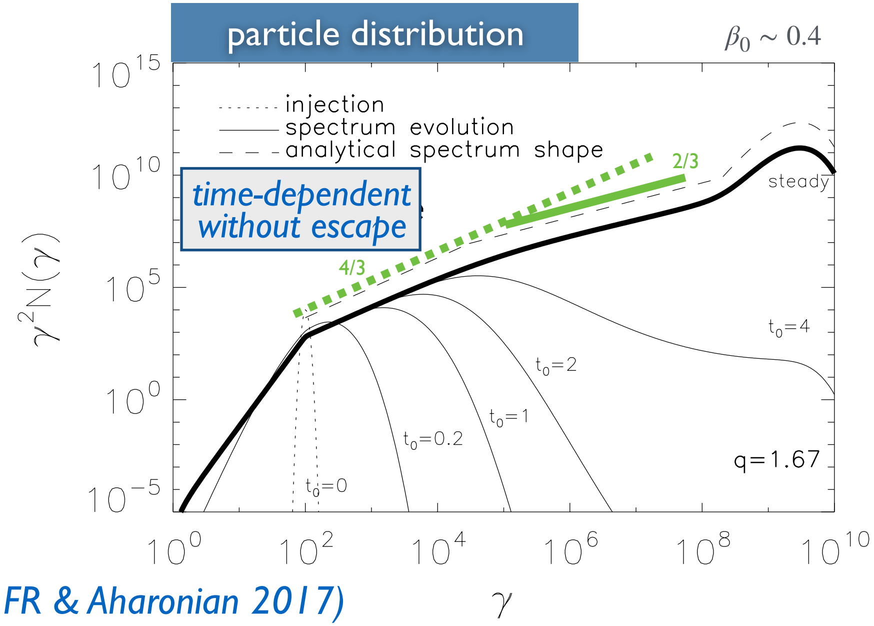

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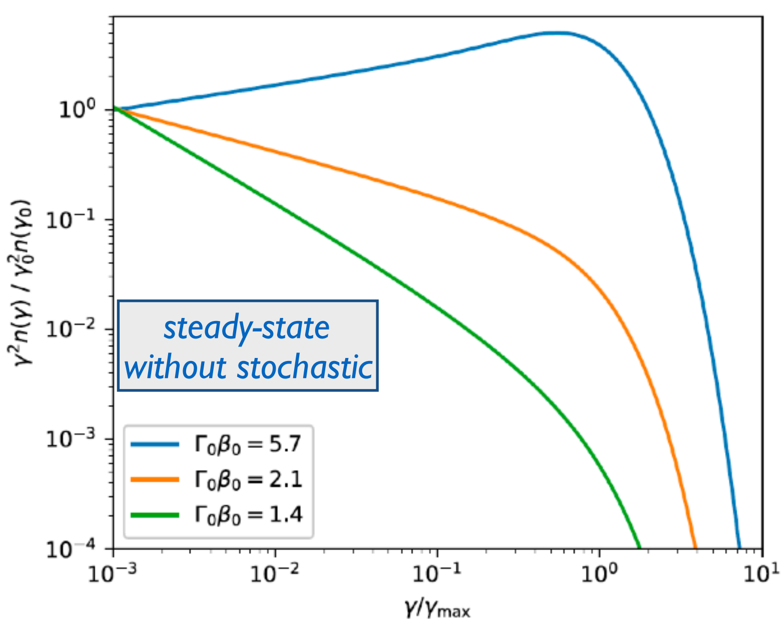

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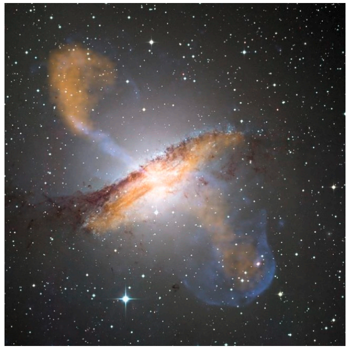
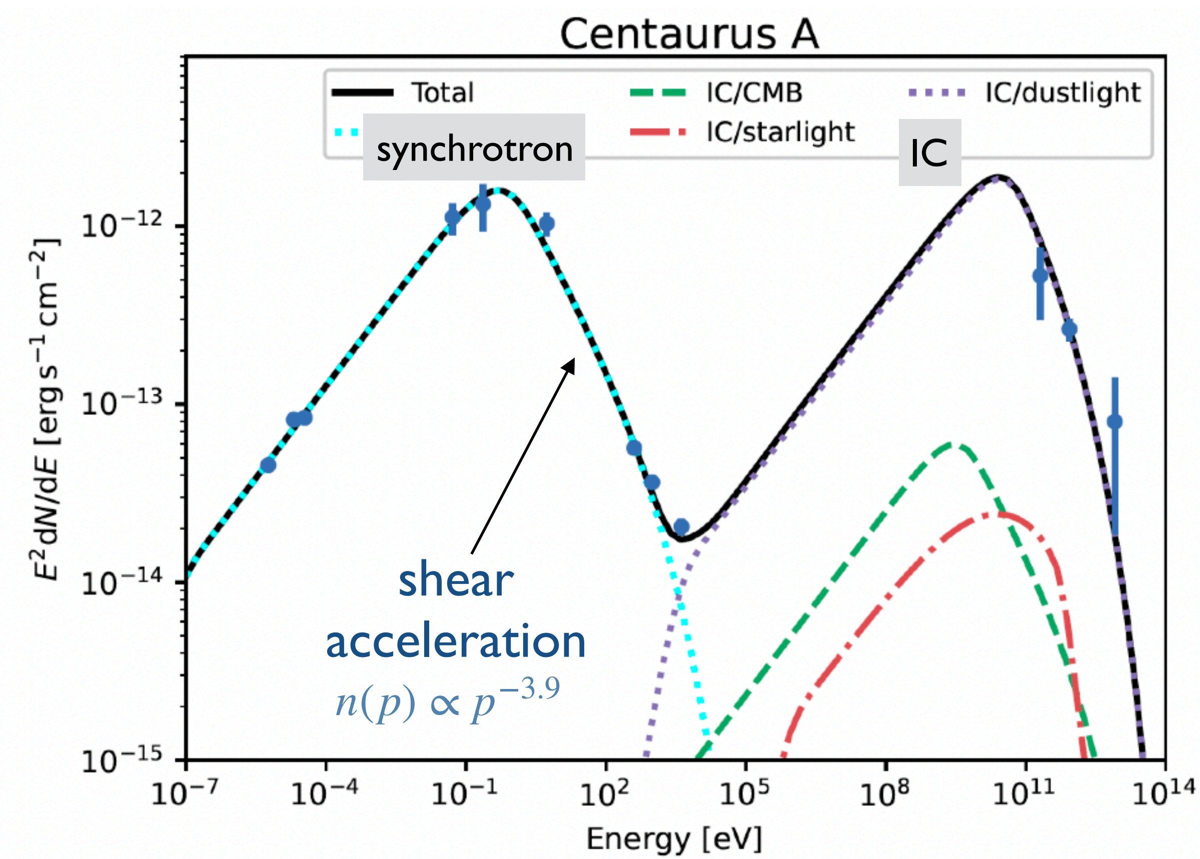
caveat: simplification of spatial transport; in general, high jet speeds needed.

(cf . also FR & Duffy 2019, 2022; Tavecchio 2021)

Radiative-loss-limited electron acceleration in mildly relativistic flows



On continuous shear acceleration in the kpc-scale jet of Cen A



(Wang, Reville, Liu, FR & Aharonian 2021)

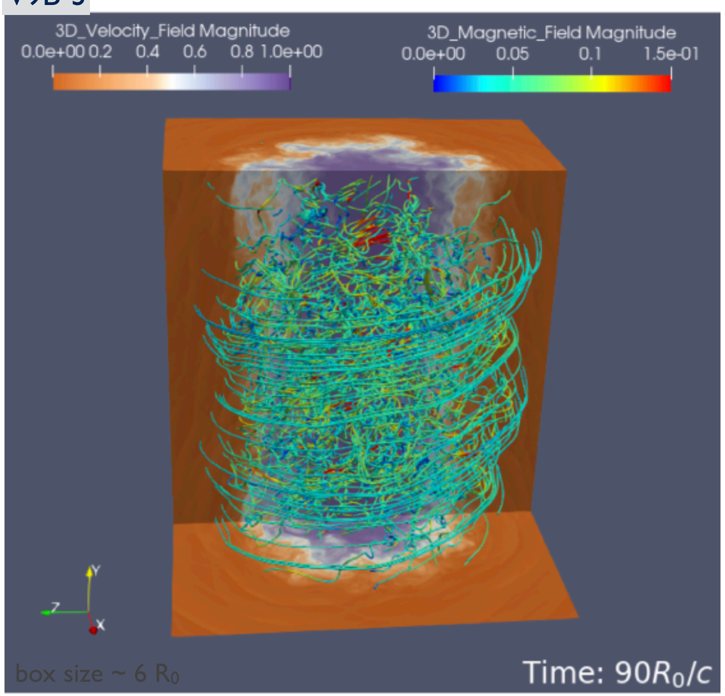
- SED reproduction with shear-related broken power-law & shock-accelerated seeds
- Kolmogorov turbulence description $\lambda \propto \gamma^{1/3}$
- quasi-linear velocity shear
- parameters: Δr = 100 pc, B=17 μG, β_0=0.67
- electron acceleration up to $\gamma \approx 10^8$
- estimated (kinetic) jet power $L_j \sim 4 \times 10^{42}$ erg/s

Developments I

Characterising velocity shears in large-scale jets *(Wang, Reville, Mizuno, FR & Aharonian 2023)*

- employ 3D relativistic MHD jet simulations (PLUTO) for $v_j/c \in [0.6\ ,0.99]$
- examine sheath formation in kinetically dominated jets (KHI) with $0.002 < \sigma < 0.2$
- study shear flow profile & turbulence spectrum for particle acceleration…
    - *typically $W_{sh}/R_j \sim 1/4 - 1/2$ (transition stage) and $\sim 1/2 - 4/5$ (deep saturation)…*
    - *Kolmogorov-type ($q \sim 5/3$) turbulence spectra…*

V9B-3



jet structure and KHI evolution

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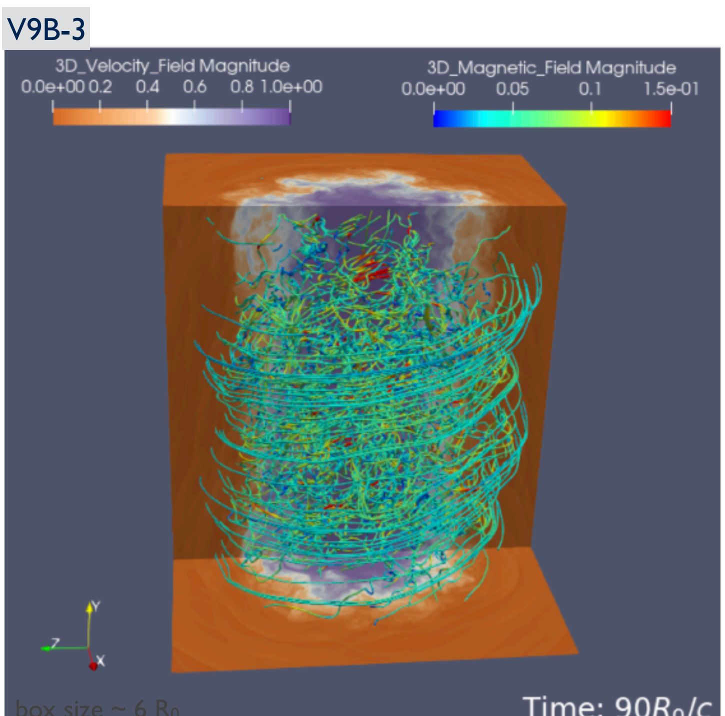

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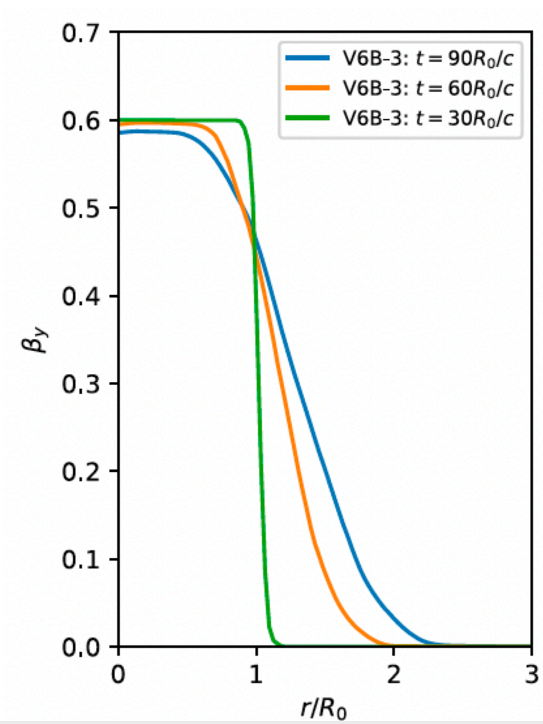
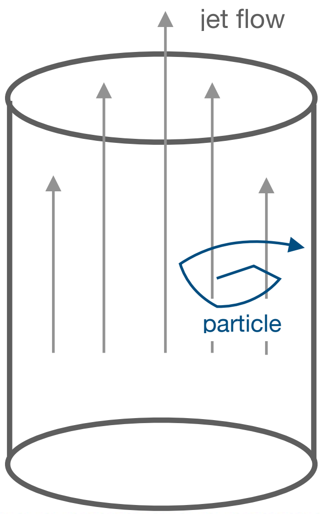


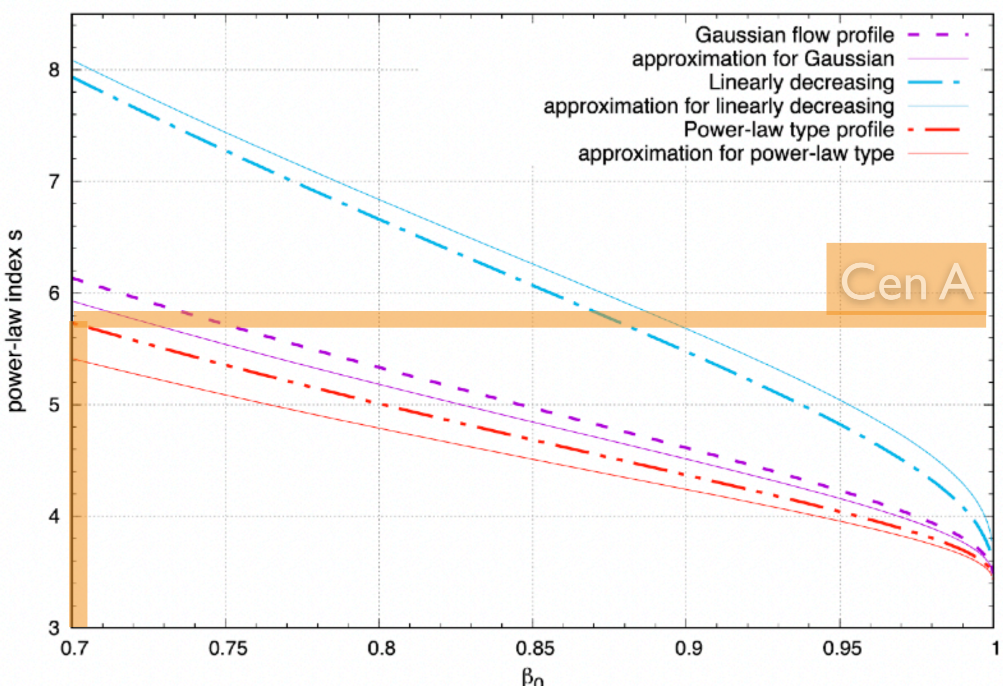
(azimuthally) averaged flow velocity profiles

Parameters:
$v_j = 0.9c$, $\sigma = 0.002$,
$R_0 = 0.1$ kpc
$L_j \approx 1E43$ erg/s

$$\sigma_{l,t} = \langle B_{l,t}^2 \rangle / 8\pi \rho_o c^2$$

On continuous electron acceleration in large-scale AGN jets *(FR & Duffy 2022)*





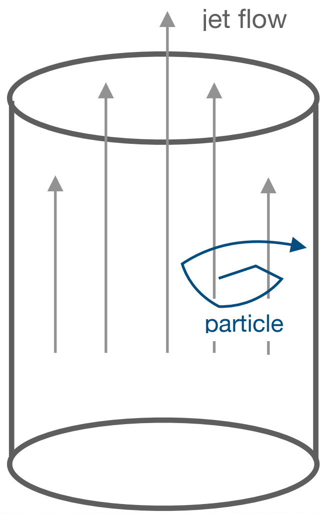
$[\alpha = 1/3]$

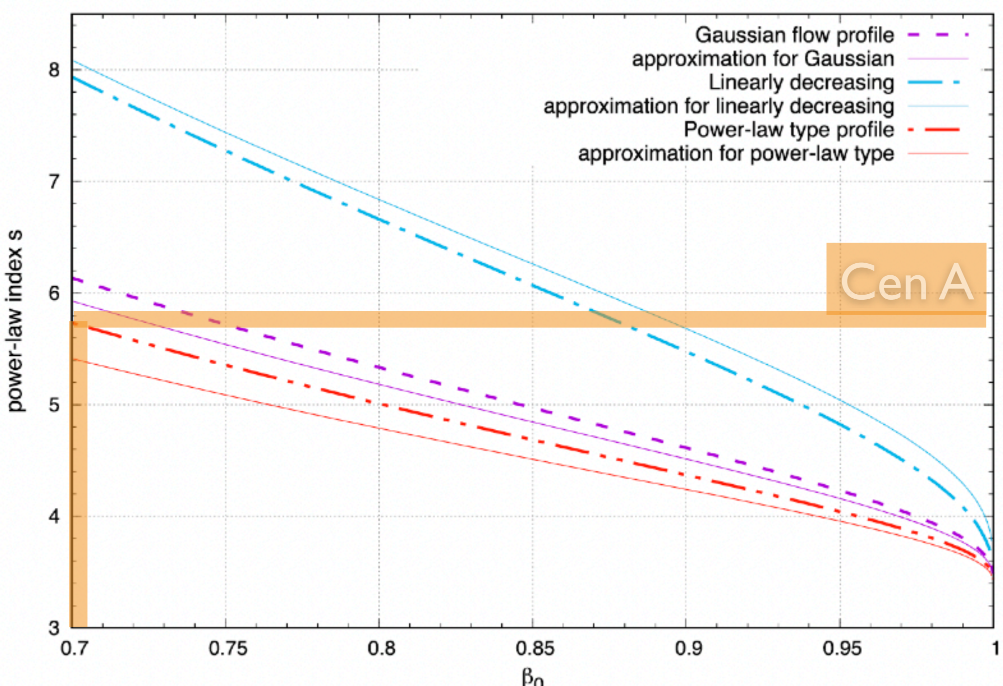
Solve full PTE for cylindrical shear flow without radiative losses

- at ultra-relativistic flow speeds, universal PL index recovered: $f \propto p^{-s}$ with $s \to (3 + \alpha)$
- at mildly relativistic flow speeds, PL index gets softer & becomes sensitive to flow profile
- 1st-order FP-type approximation possible…

Developments II

On continuous electron acceleration in large-scale AGN jets *(FR & Duffy 2022)*





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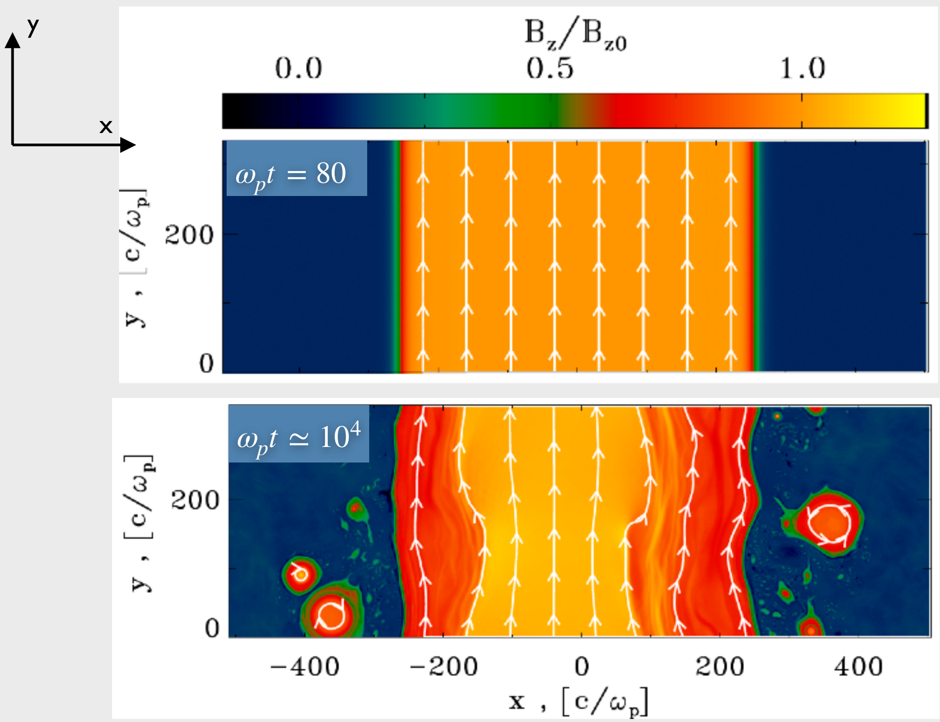
allows to constrain flow profile through observed PL index….

Example: 2D **PIC** of relativistic ($\Gamma_y \sim$ 1.3-3) highly-magnetized ($\sigma \sim 100$) **e⁺e⁻** - jet and stationary, weakly-magnetized ($\sigma \sim 0.1$) ambient **e⁻p** - plasma (Sironi+2021)

- focus on wide(r) shear layers with $\Delta \gg c/\omega_p$ (typical model setup: $\Delta = 64\,c/\omega_p$)
- initialize with out-plane B_z ($\sigma_z \sim 90$) and in-plane B_y ($\sigma_y \equiv B_{j,y}^2/4\pi n_0 m_e c^2 \simeq 7$)
- as a result of KHI, field lines get twisted and significant B_x ($\sigma_x \sim 4$) develops…



shear & magnetic field evolution

Interlude - On highly magnetized shear flows…

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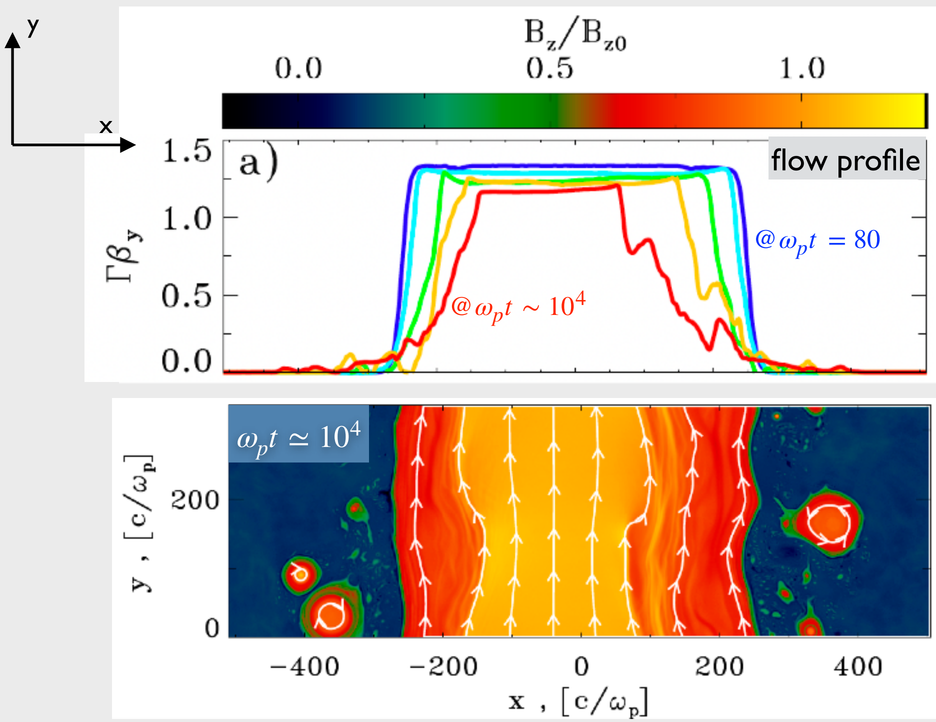

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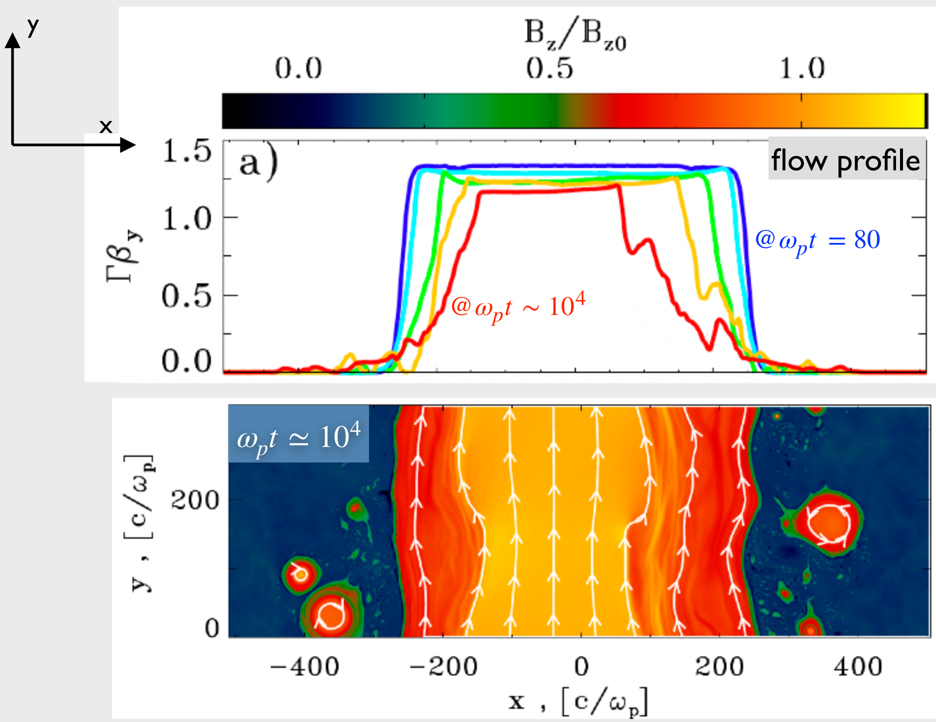
- as a result of KHI, field lines get twisted and significant B_x ($\sigma_x \sim 4$) develops…
- *electron acceleration in reconnection layers to $\gamma_e \sim 30 \Rightarrow$ seeds for further shear acceleration*



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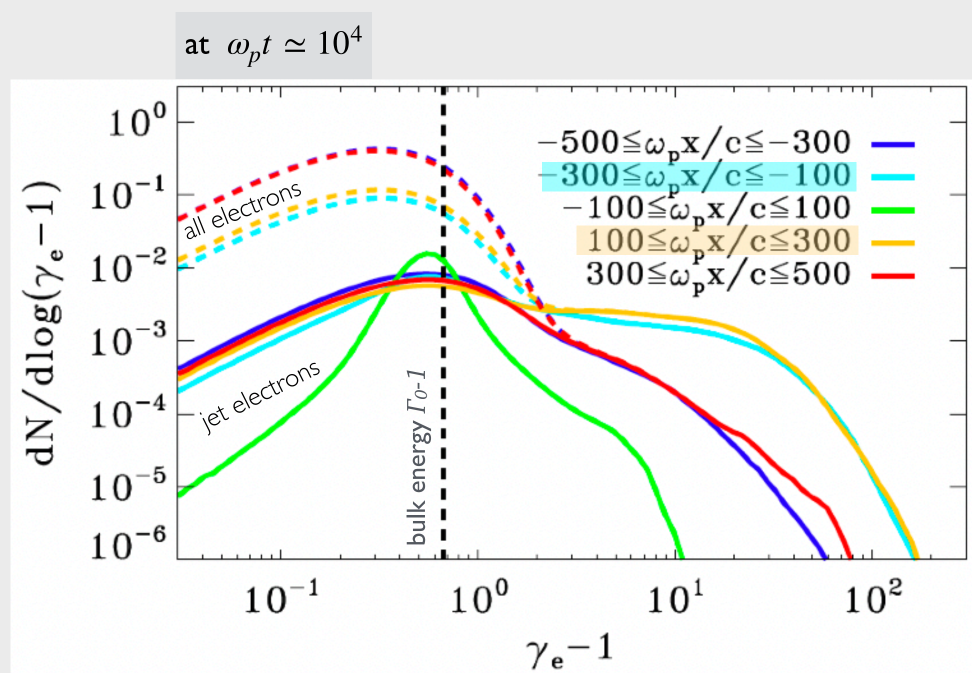
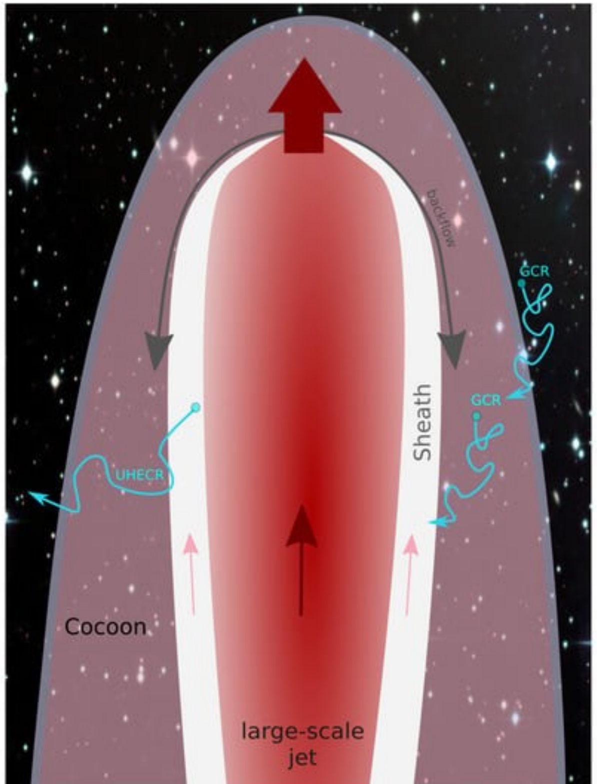


spatial dependence of electron spectrum

On UHECR acceleration in shearing large-scale AGN jets



On gradual shear in mildly relativistic, large-scale AGN jets

(FR & Duffy 2019)

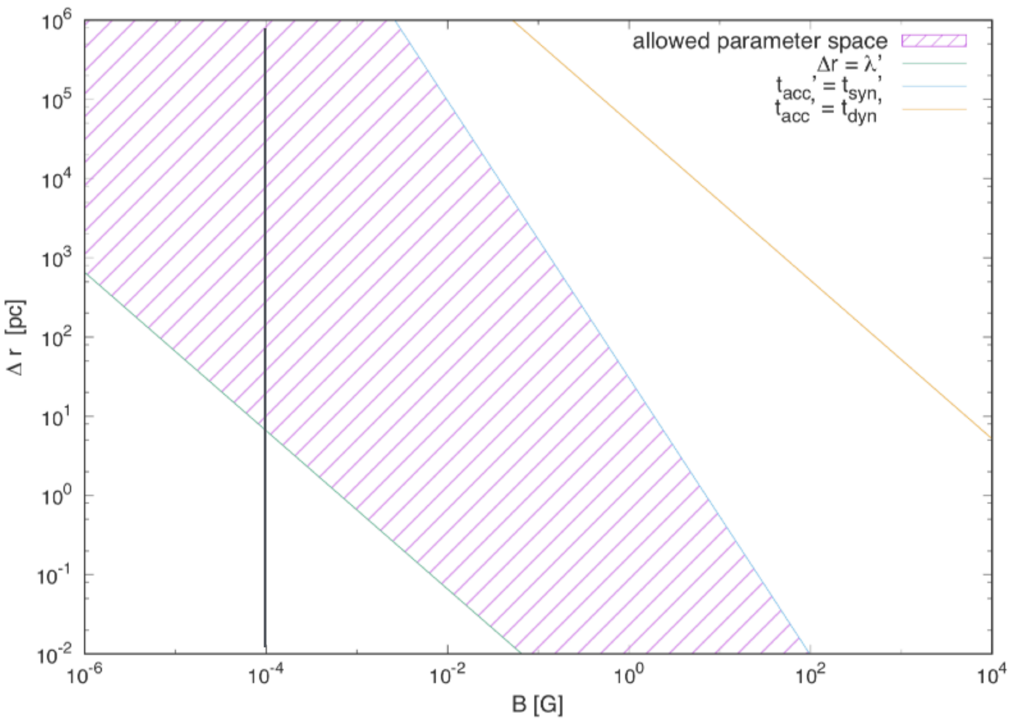


Figure 2. Allowed parameter range (shaded) for shear acceleration of CR protons to energies $E_p' = 10^{18}$ eV for a particle mean free path $\lambda' \propto p'^{\alpha}$ with $\alpha = 1/3$ (corresponding to Kolmogorov type turbulence $q = 5/3$). A flow Lorentz factor $\gamma_b(r_0) = 3$ has been assumed.

($t_{acc,shear} \propto \gamma^{q-2}$)

Potential for UHECR acceleration:

need jet widths such as to

(1) *laterally confine particles,*

(2) *beat synchrotron losses,*

(3) *operate within system lifetime*

– expect KHI-shaped shear width $\Delta r > 0.1 r_j$ (FR & Duffy 2021)

- for protons ~10^{18} eV achievable in jets with relatively plausible parameters (i.e., lengths 10 kpc – 1 Mpc, B ~ [1– 100] μG)
- escaping CRs may approach $N(E) \propto E^{-1}$

(cf. also Liu+ 2017; Wang+2021; Webb+ 2018, 2019)

On gradual shear in mildly relativistic, large-scale AGN jets

(FR & Duffy 2019)

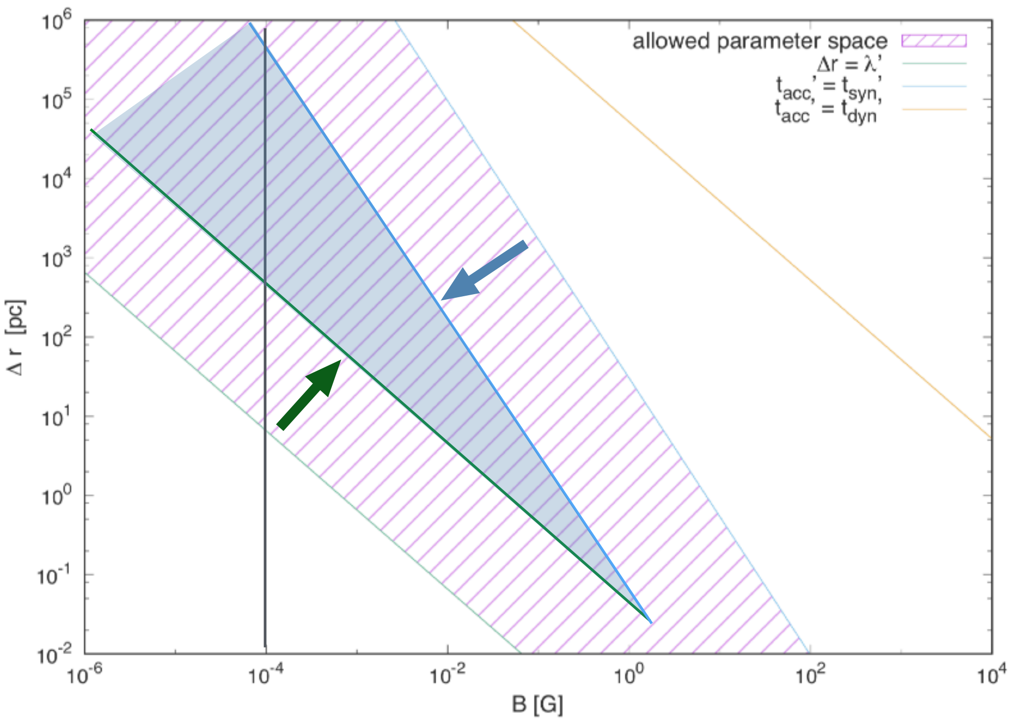


Figure 2. Allowed parameter range (shaded) for shear acceleration of CR protons to energies $E_p' = 10^{18}$ eV for a particle mean free path $\lambda' \propto p'^{\alpha}$ with $\alpha = 1/3$ (corresponding to Kolmogorov type turbulence $q = 5/3$). A flow Lorentz factor $\gamma_b(r_0) = 3$ has been assumed.

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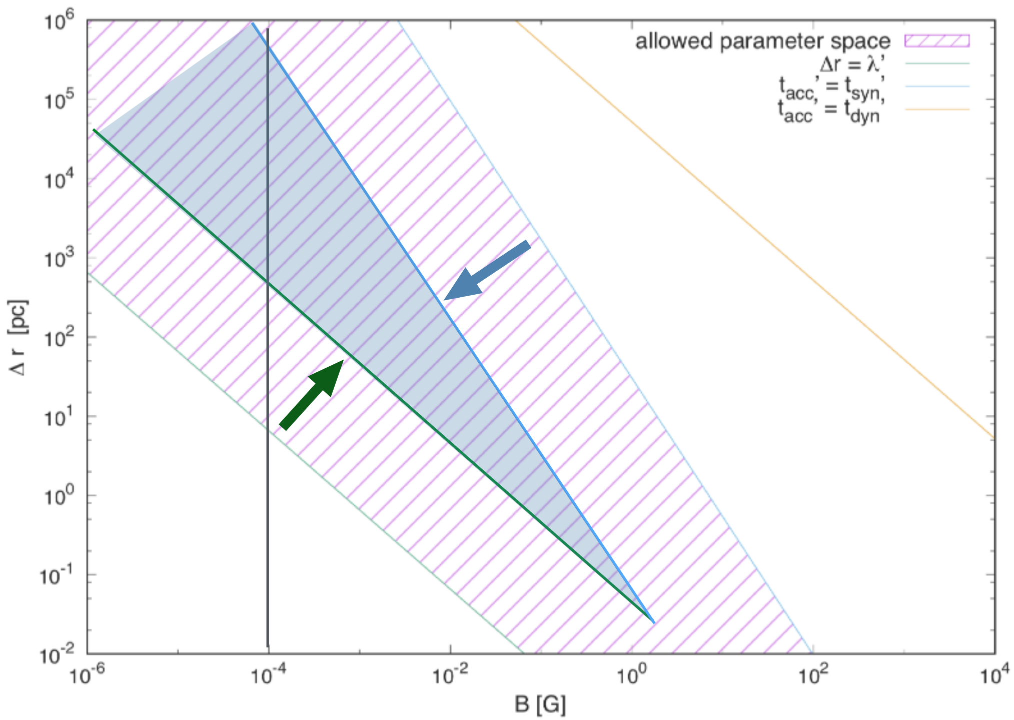

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caveat:
simplification of spatial transport

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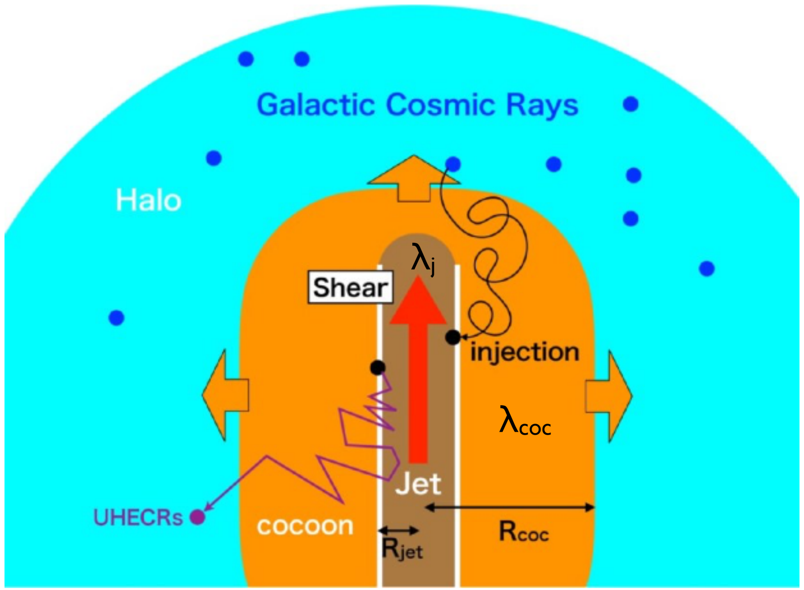
On non-gradual shear in large-scale FR I type jets



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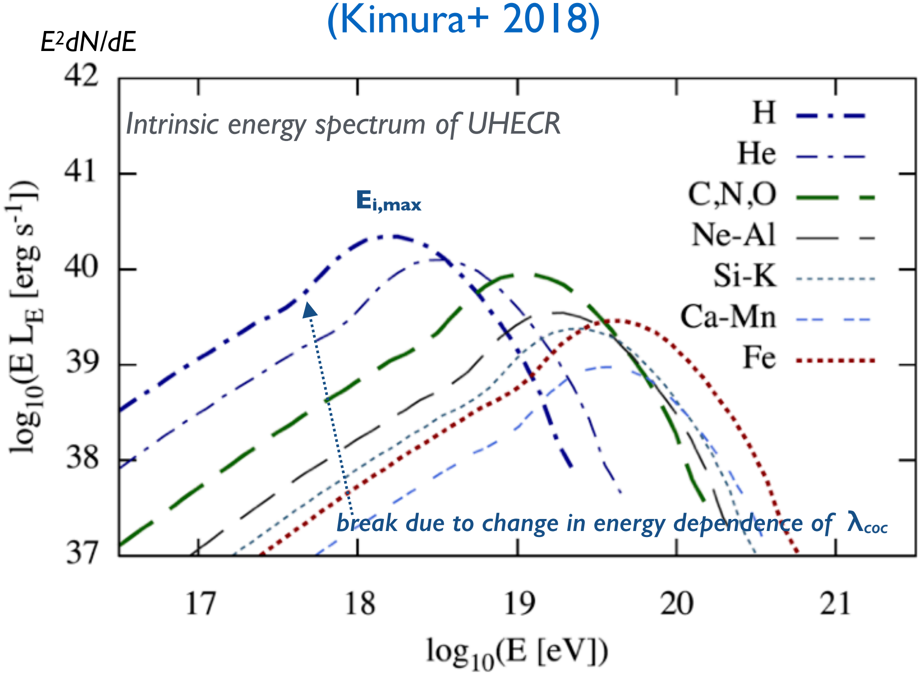

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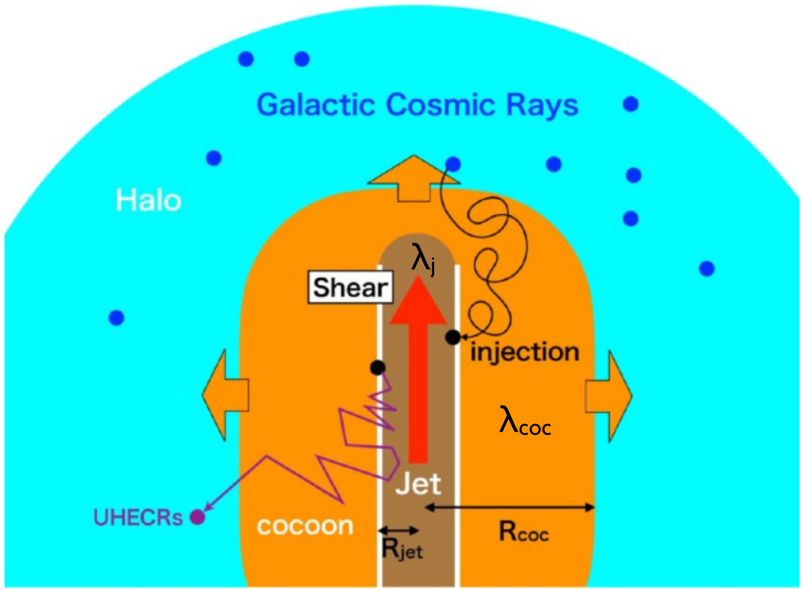
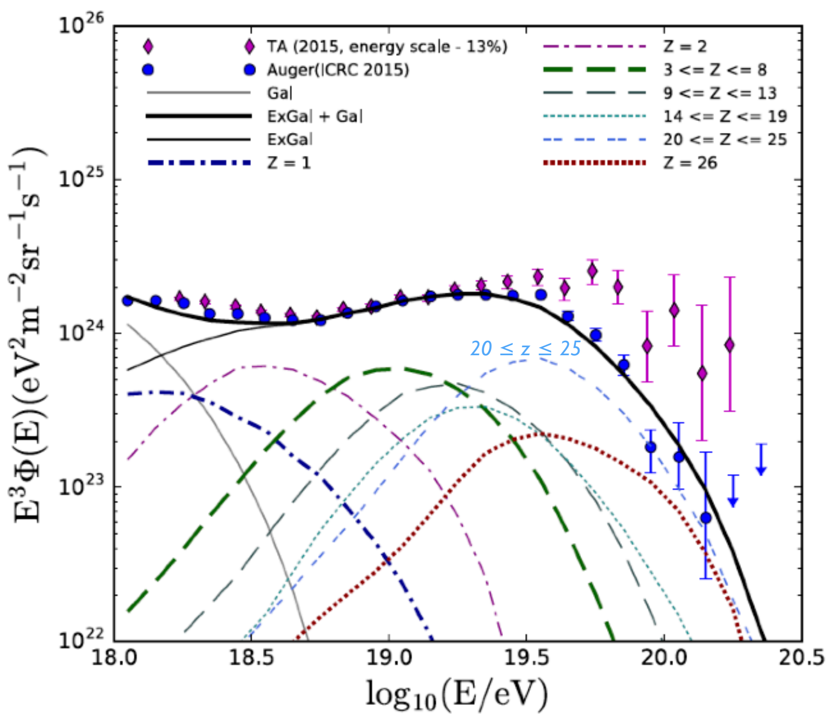
- more complex UHECR abundance due to injections at TeV-PeV energies, @ $E_{inj,i} = 15\,Z_i$ TeV
- diffusion in cocoon (residence time) determines max. energy $E_{i,max} \propto Z_i$

(via $t_{acc} = t_{conf}$, with cycle time in t_{acc} dominated by $\lambda_{i,coc}$ and "confinement" time by accelerator region ~ R_{jet}/c)

Bohm diffusion $\lambda_j \sim r_L$ inside jet, in cocoon $\lambda_{coc} \propto (E/Z)^2$ at high energies (non-resonant scattering), and $\lambda_{coc} \propto (E/Z)^{1/3}$ at lower ($< 5 \times 10^{17}$ eV) energies (resonant scattering)

Model parameters: jet length l_j =5 kpc, R_{jet}= 0.5 kpc, B_j =300 μG, B_{coc}=3μG, v_j = 0.7 c, $v_{exp,coc}$=3000 km/s, thin velocity shear of 0.01 R_{jet}.....





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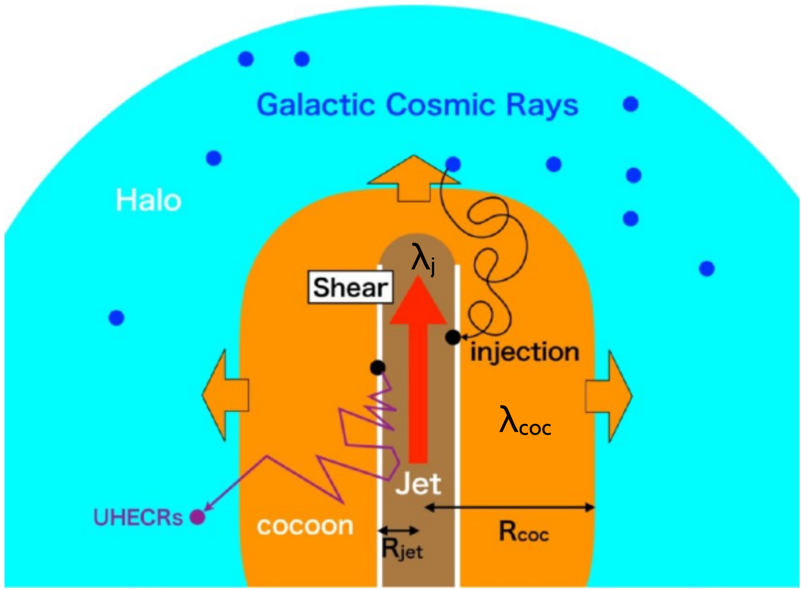

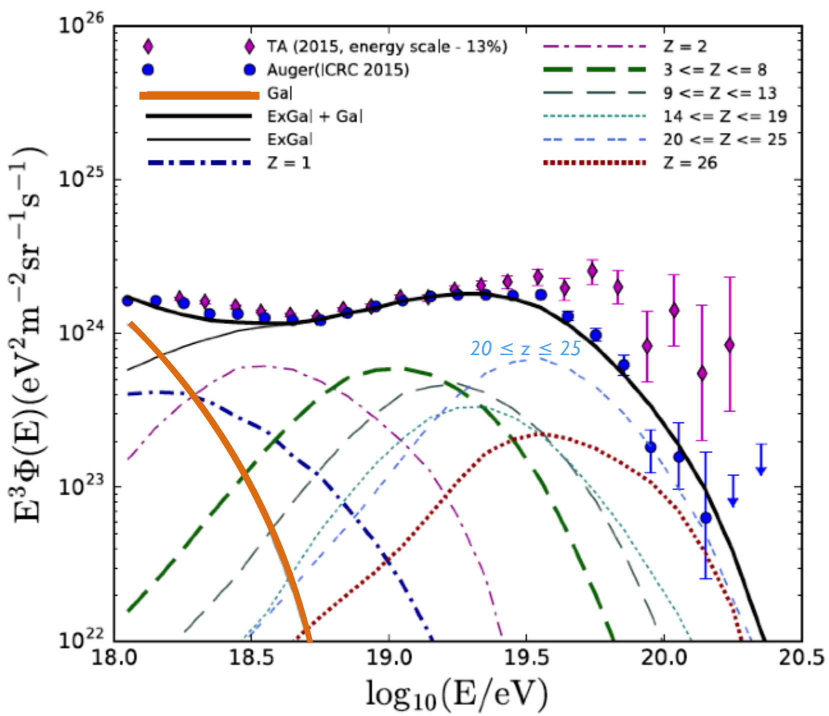

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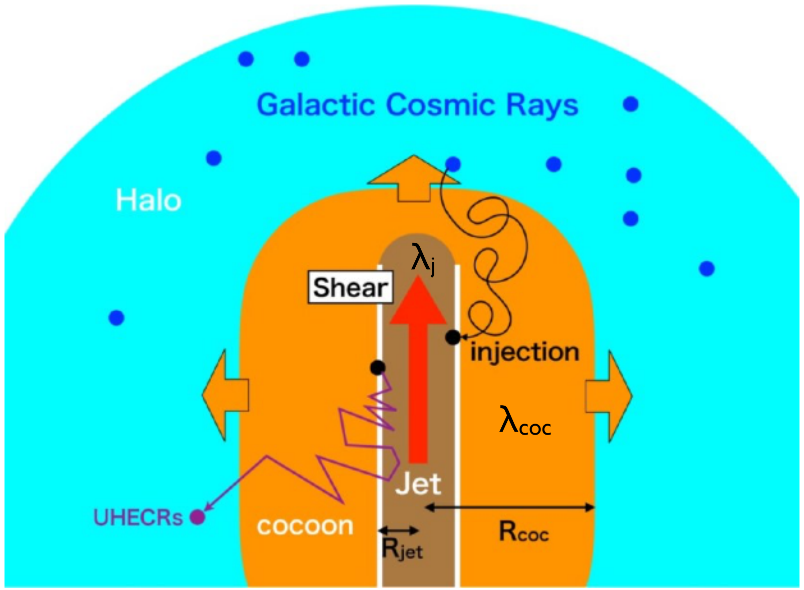

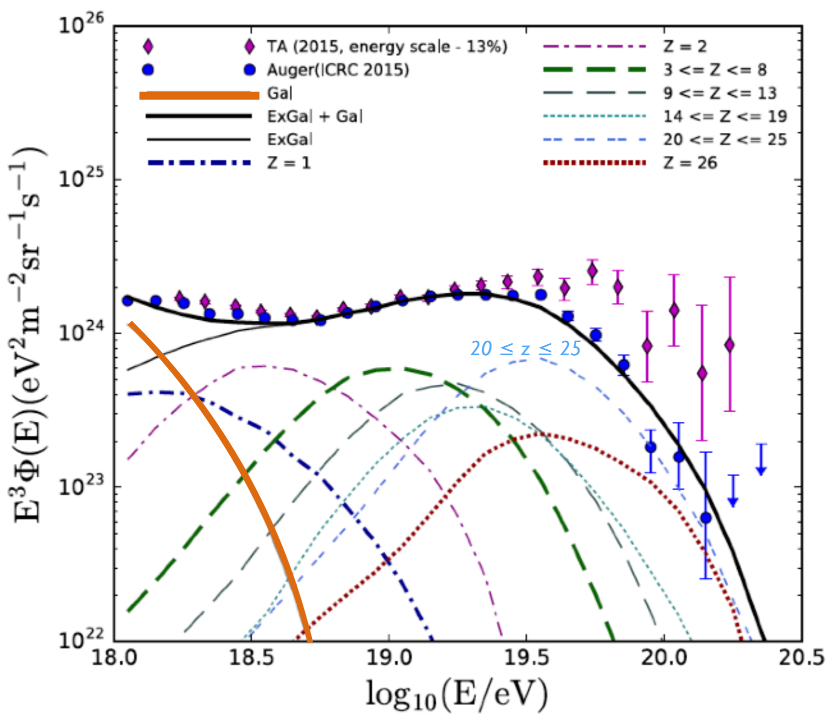

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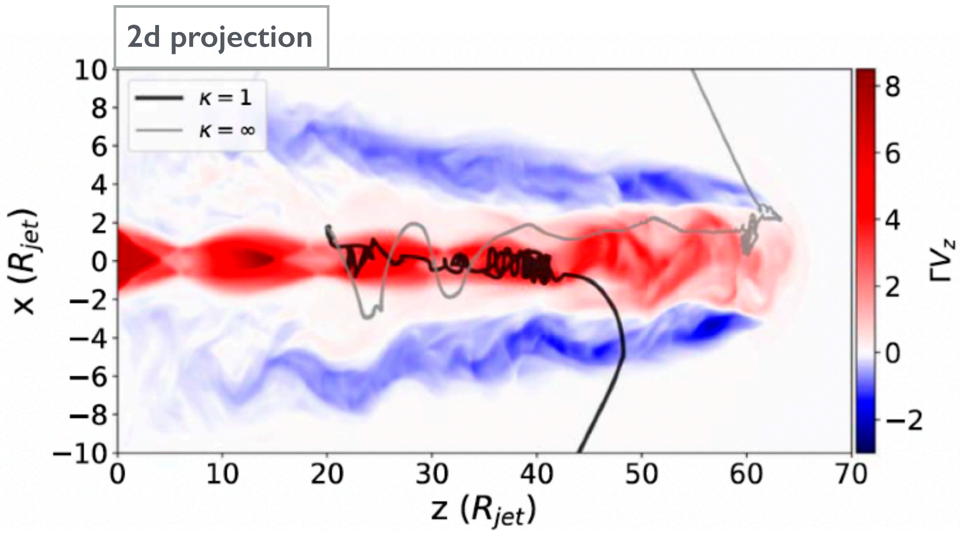
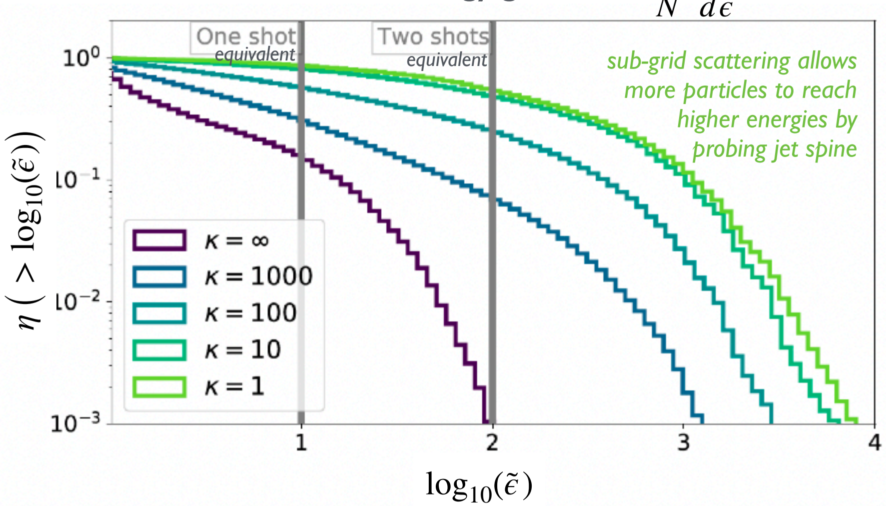
caveat:
all sources assumed to be the same, sensitive to turbulence description, narrow shear layer…



for injected $r_{L,i}$ =0.075 R_{jet}; $B(r \geq R_{jet}) \propto 1/r$; $B(z) \propto 1/z$

Cumulative distribution of energy gains: $\eta = \frac{\tilde{\epsilon}}{N}\frac{dN}{d\tilde{\epsilon}}$ with $\tilde{\epsilon} \simeq E_f/E_i$



for particle injection spectrum with $r_L \sim (0.0002 - 0.2)\, R_{jet}$

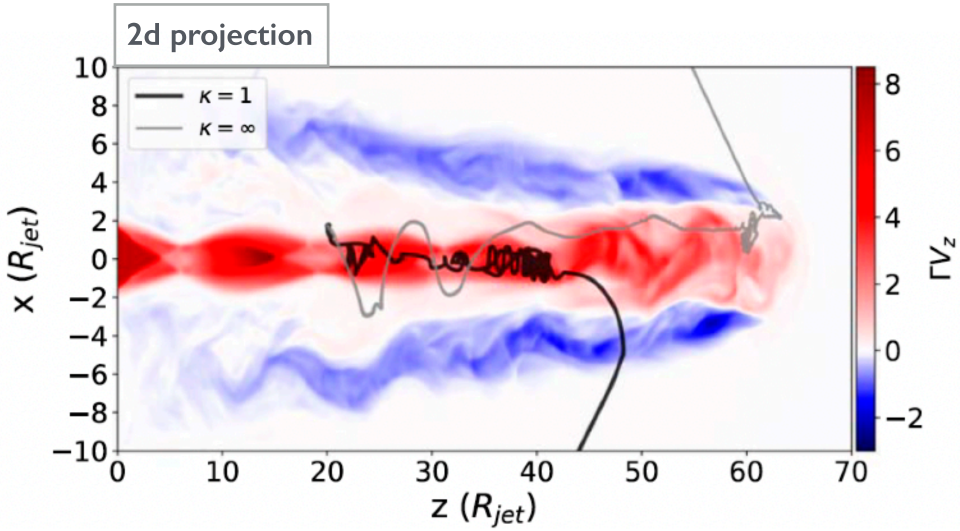
"**Non-gradual**" shear particle acceleration:

recycling of GCR in relativistic (Γ~10) large-scale jets (Mbarek & Caprioli 2019, 2021):

- Γ^2 boost possible $\Rightarrow$ only few cycles ('espresso shots') needed
- following test particles in simulated MHD jets (3d, PLUTO)
- particle injection spectrum $dN_i/dE_i \propto E_i^{-1}$, spanning gyro-radii range $r_{L,i} \sim (10^{-4} - 10)\, R_{jet}$
- modelling effect of unresolved turbulence via gyro-dependent diffusion where $D = \kappa\, r_L\, c/3$ with $\kappa = 1{,}10{,}100{,}1000 \Rightarrow$ spectral hardening $dN/dE \propto E^{-\alpha}, \alpha \sim 0.5$ for low κ…

Resolution of jet simulations ~ $R_{jet}/10$

Model reference parameters: R_{jet} = 100 pc, B_j =100 μG, Γ_0=7…..



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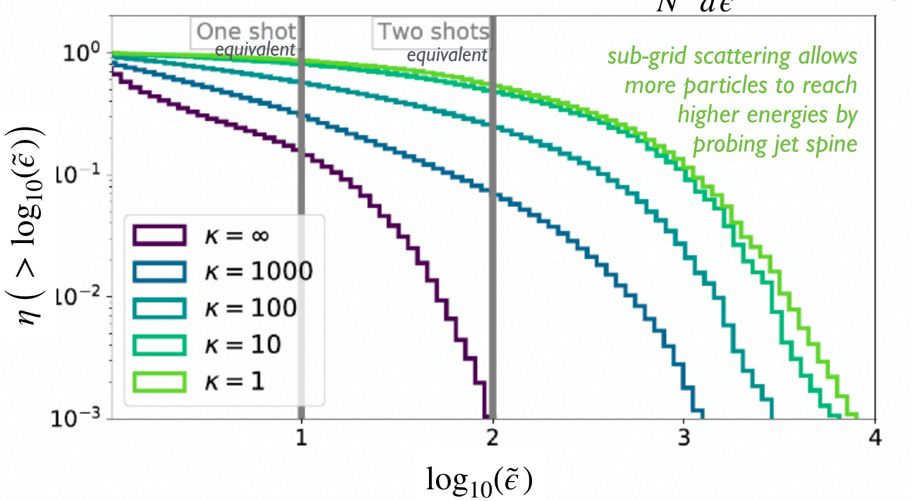

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caveat:
jet resolution; gyro-dependent diffusion;
requires strongly magnetized (σ~0.6),
high-power jets (L ≳10^{44} erg/s)…

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For overview & discussion of shear acceleration of UHECRs

Universe 8 (2022), 607
[review]

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MDPI

Review

Active Galactic Nuclei as Potential Sources of Ultra-High Energy Cosmic Rays

Frank M. Rieger [1,2]

[1] Institute for Theoretical Physics (ITP), Heidelberg University, Philosophenweg 12, 69120 Heidelberg, Germany; f.rieger@uni-heidelberg.de
[2] Max–Planck–Institut für Kernphysik (MPIK), P.O. Box 103980, 69029 Heidelberg, Germany

Abstract: Active Galactic Nuclei (AGNs) and their relativistic jets belong to the most promising class of ultra-high-energy cosmic ray (UHECR) accelerators. This compact review summarises basic experimental findings by recent instruments, and discusses possible interpretations and astrophysical constraints on source energetics. Particular attention is given to potential sites and mechanisms of UHECR acceleration in AGNs, including gap-type particle acceleration close to the black hole, as well as first-order Fermi acceleration at trans-relativistic shocks and stochastic shear particle acceleration in large-scale jets. It is argued that the last two represent the most promising mechanisms given our current understanding, and that nearby FR I type radio galaxies provide a suitable environment for UHECR acceleration.

Keywords: ultra high energy cosmic rays; particle acceleration; radio Galaxies; relativistic jets

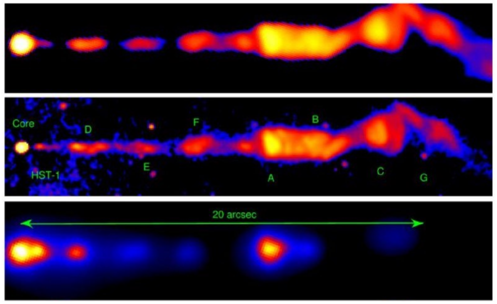
Citation: Rieger, F.M. Active Galactic Nuclei as Potential Sources of Ultra-High Energy Cosmic Rays. *Universe* **2022**, *8*, 607. https://doi.org/10.3390/universe8110607

1. Introduction

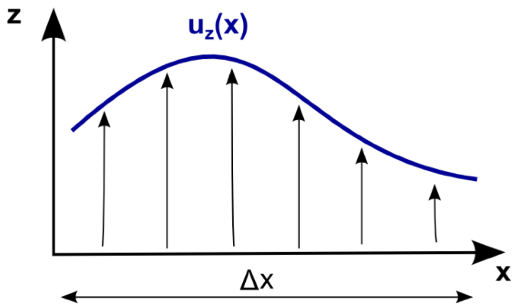
The energy spectrum of cosmic rays runs over more than ten orders of magnitudes, from GeV energies to $\sim 10^{20}$ eV. While supernova remnants are believed to be the most probable sources of cosmic rays at lower energies (i.e., up to the 'knee' at $\sim 3 \times 10^{15}$ eV) [1,2], the origin of ultra-high-energy cosmic rays (UHECRs, $E \geq 10^{18}$ eV = 1 EeV) is much less understood. While thought to be of extragalactic origin [3], the real astrophysical sources are still to be deciphered. Possible candidate sources include Active Galactic Nuclei (AGNs)

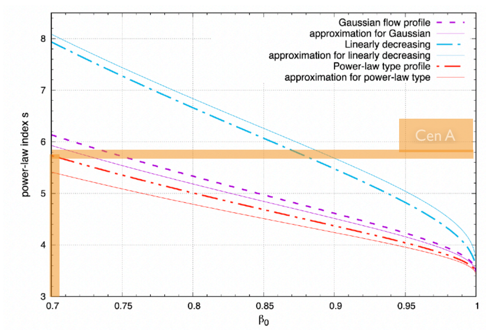
Summary

Particle Acceleration in Astrophysical Shear Flows:



- needs relativistic flow speeds to work efficiently (hard spectra)
- depends on seed injection for electrons (➪ e.g., shocks)
- represent a ‘natural’ mechanism in AGN jets
  - origin of ultra-relativistic electrons & extended emission
  - multiple power-law formation possible…
  - spectral shape (power-law index) indicative of flow profile…
  - large-scale AGN jets as possible UHE accelerators….





Outlook & tasks ahead:

- incorporation in jet simulations…
- UHECR characteristics for AGNs…
- and many more…

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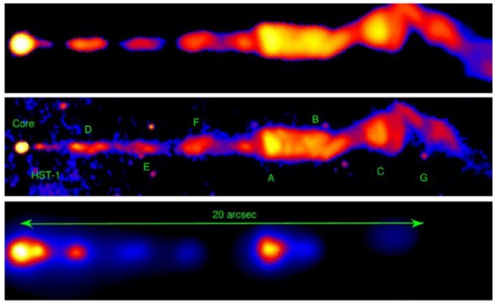

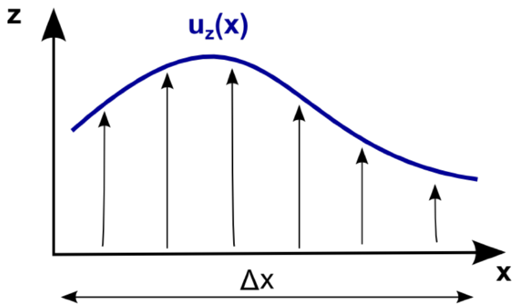

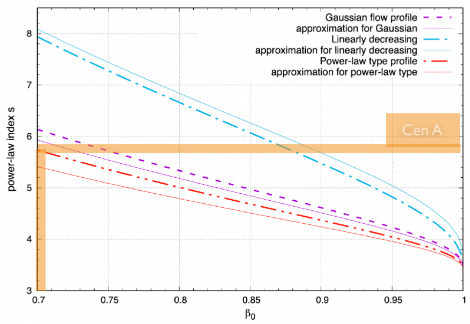

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Thank you!
&
Questions ?