Energetic Particle Acceleration in Relativistic Shearing Flows

Frank M. Rieger

HEPRO VIII @ IAP Paris

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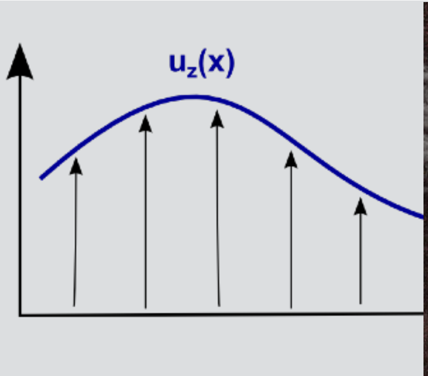

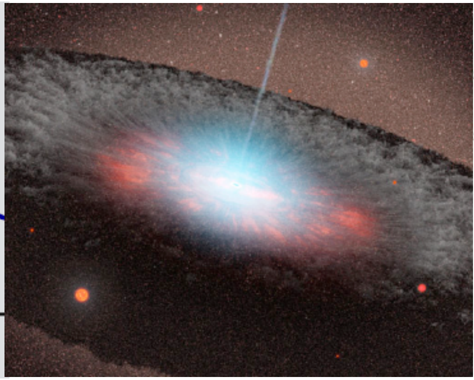
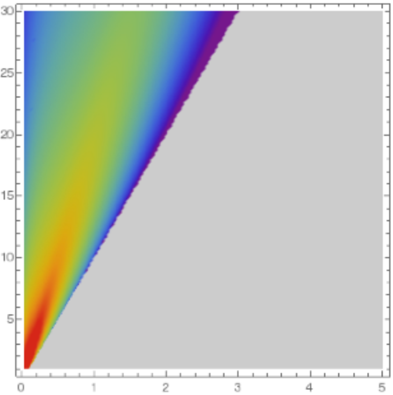

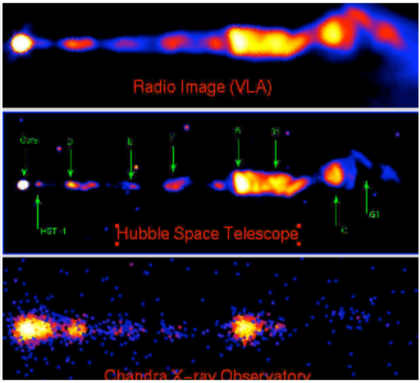

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Outline

- **Astrophysical Motivation & Exemplary Context**
  - Extended high-energy emission in large-scale AGN jets
  - Ubiquity of shearing flows

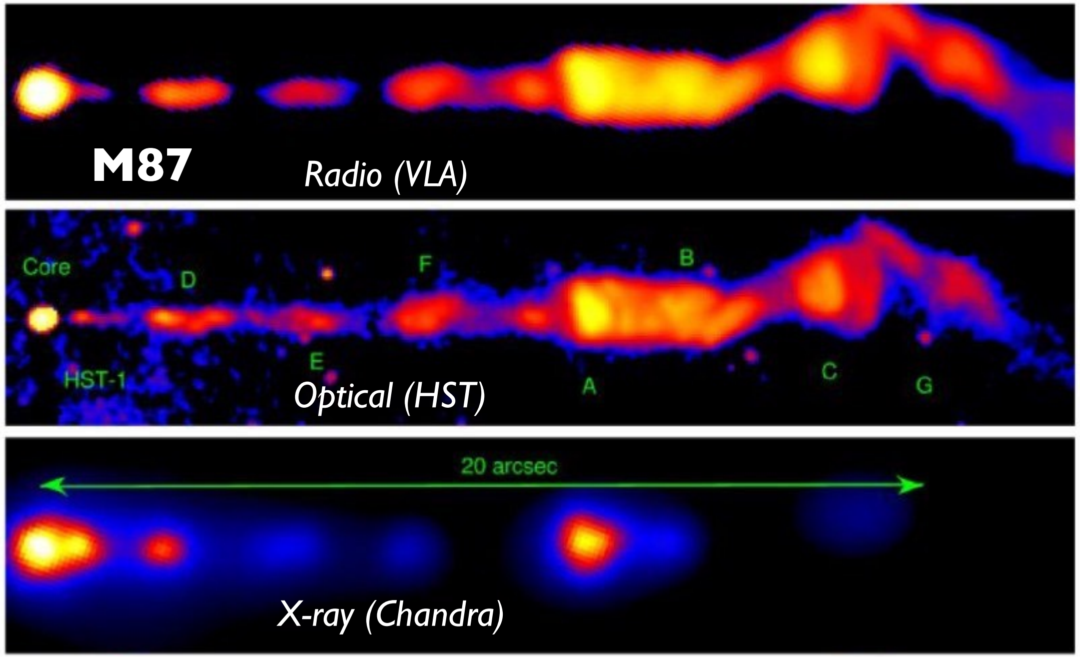
- **Shear Particle Acceleration**
  - Focus on stochastic Fermi-type acceleration (basic idea)
  - Particle transport, acceleration and power-law formation
  - Modelling electron shear acceleration in large-scale jets
  - On UHECR acceleration in shearing AGN flows
  - Summary

On ultra-relativistic electrons in AGN Jets I

_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)

$$\nu \propto \gamma^2 B$$

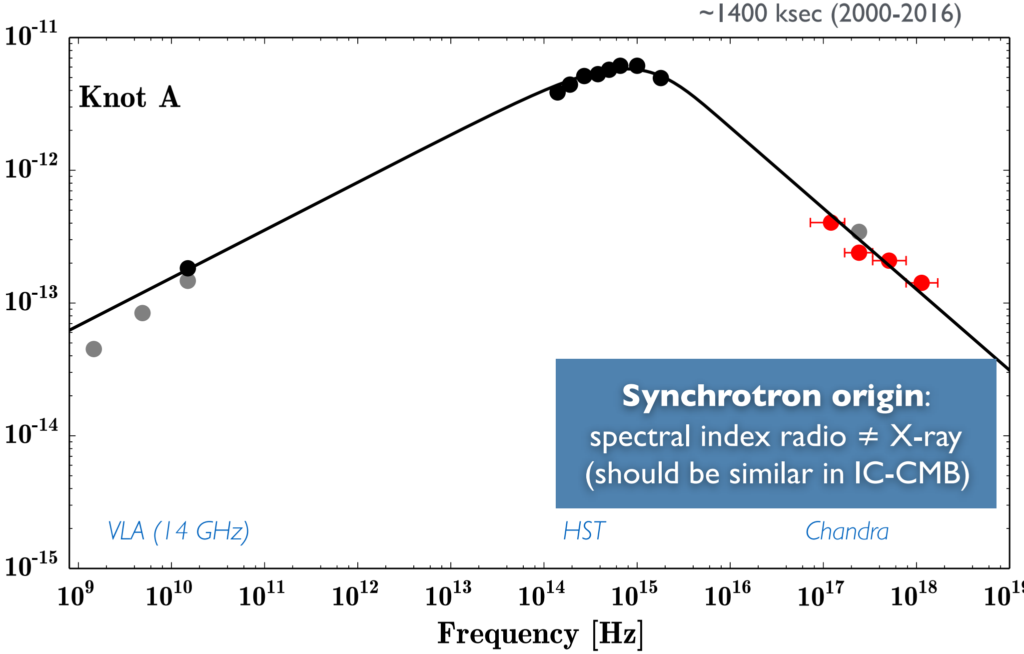


1 arcsec ~ 0.1 kpc (0.081 kpc)

Marshall+ 2002

Relativistic particles throughout whole jet

~1400 ksec (2000-2016)

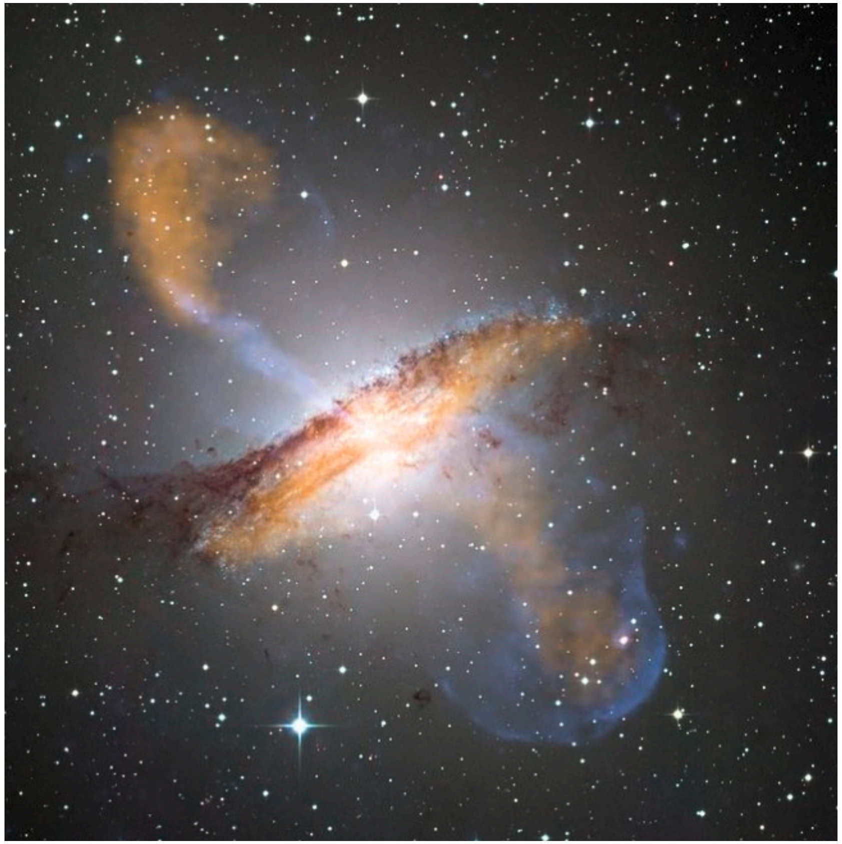


Synchrotron origin:
spectral index radio ≠ X-ray
(should be similar in IC-CMB)

SED can be fitted by broken power-law

($B = 3\times10^{-4}$ G, $\gamma_b \sim 10^6$, $\gamma_{max} \sim 10^8$, $P_{jet} \sim 10^{43}$ erg/s, $\Delta\alpha \sim 2$)

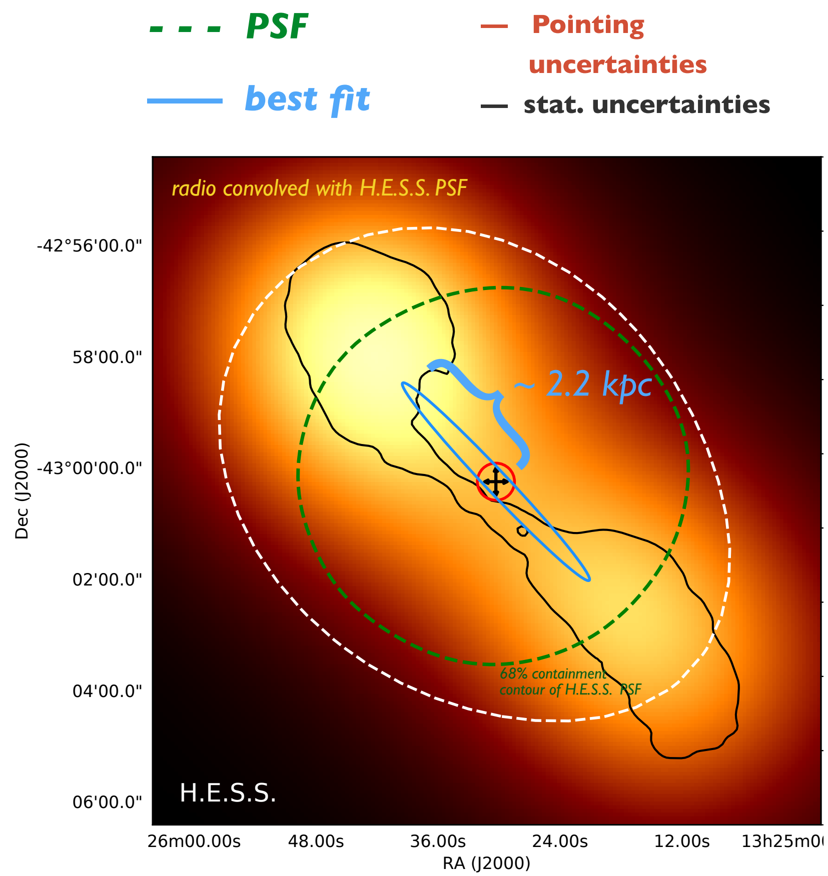
On ultra-relativistic electrons in AGN Jets II



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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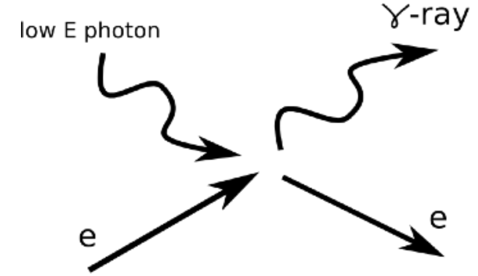
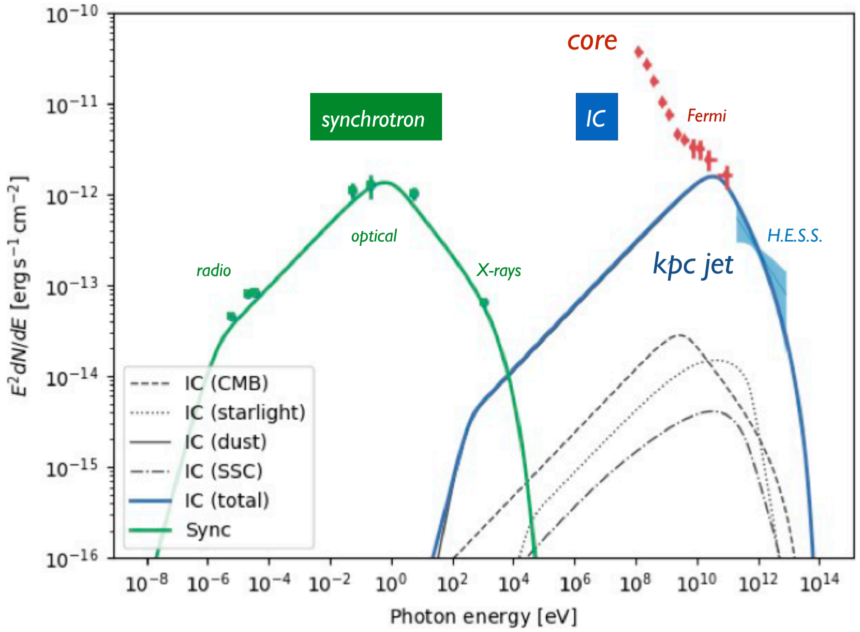


Inverse Compton emission

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

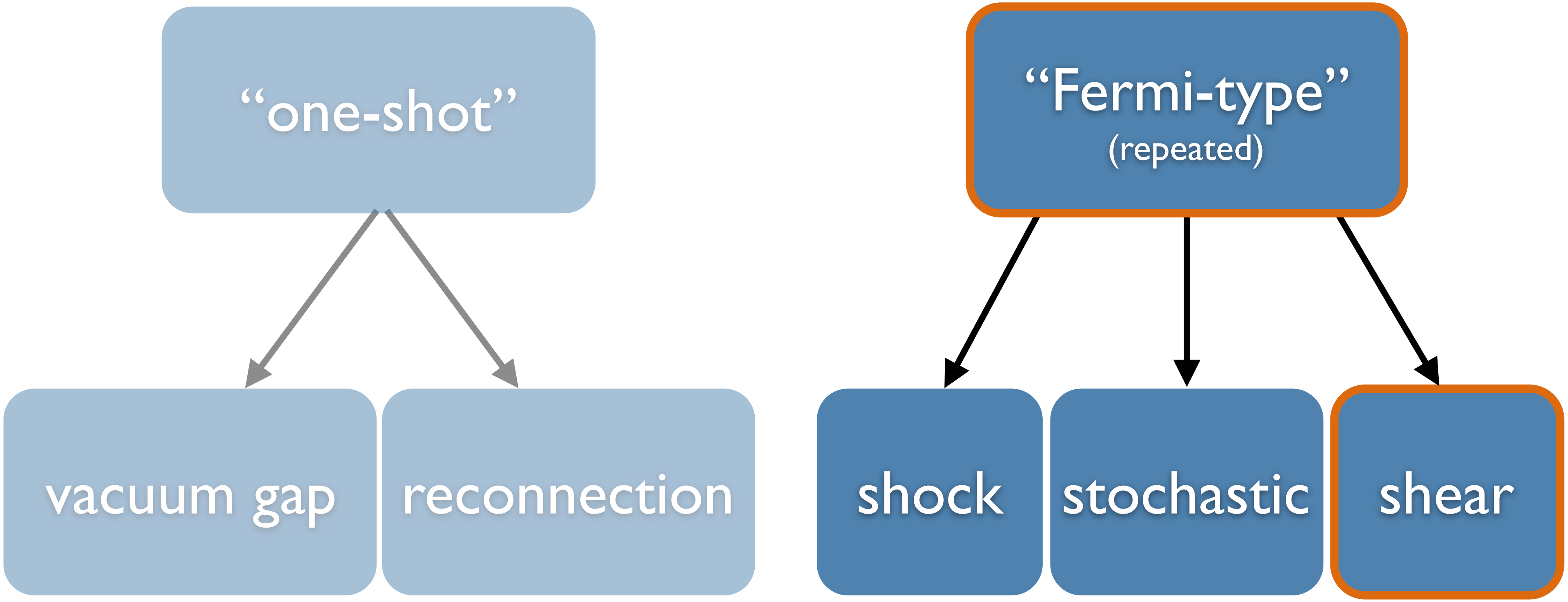
(H.E.S.S. Collab. 2020, Nature)



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

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

A possible scenario…



“one-shot”

vacuum gap

reconnection

“Fermi-type”
(repeated)

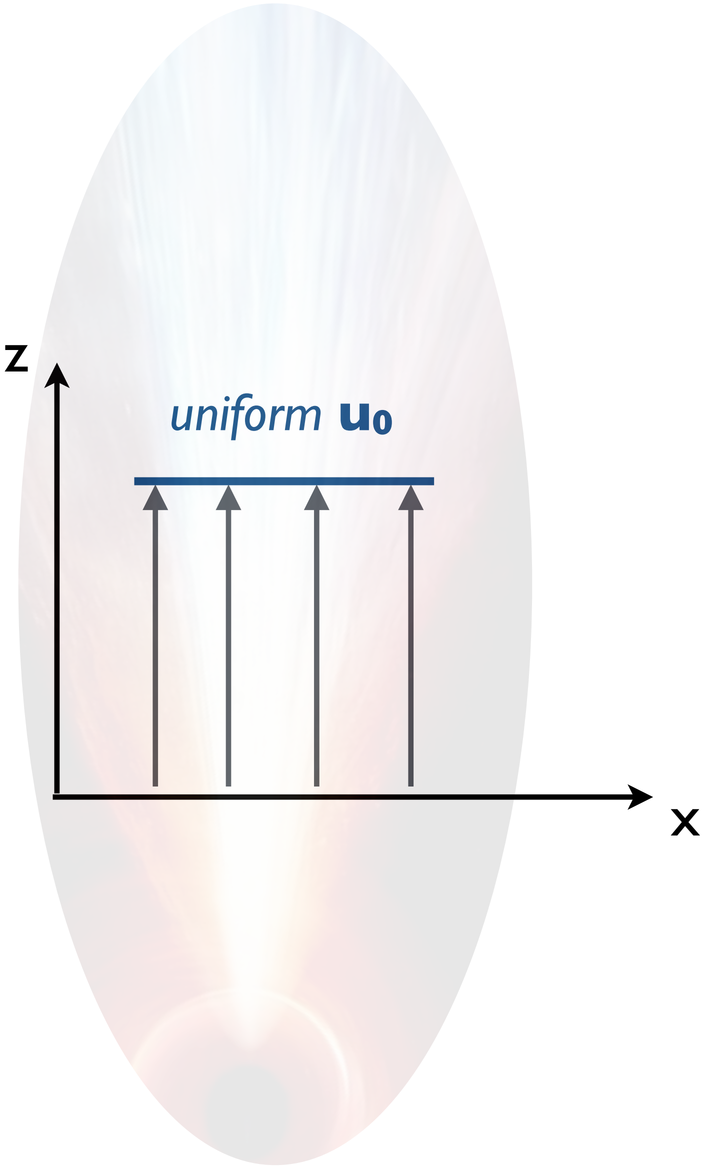
shock

stochastic

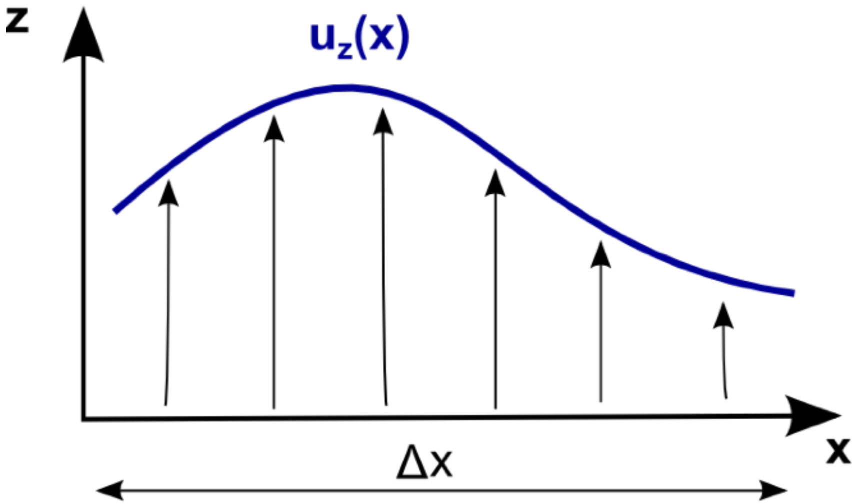
shear

vacuum gap	reconnection	shock	stochastic	shear
BH magnetosphere	*inner jet*	*jet, hot spots*	*jet, lobes*	*jet*
charge density? *topology?* *transparency?*	*limited in size?* *luminosity output?* *spectral shape?*	*efficiency* *(Γ_s, σ)?* *localized?*	*efficiency?* *spectral shape?*	*efficiency?* *energetic seeds?*

What are shearing flows ?

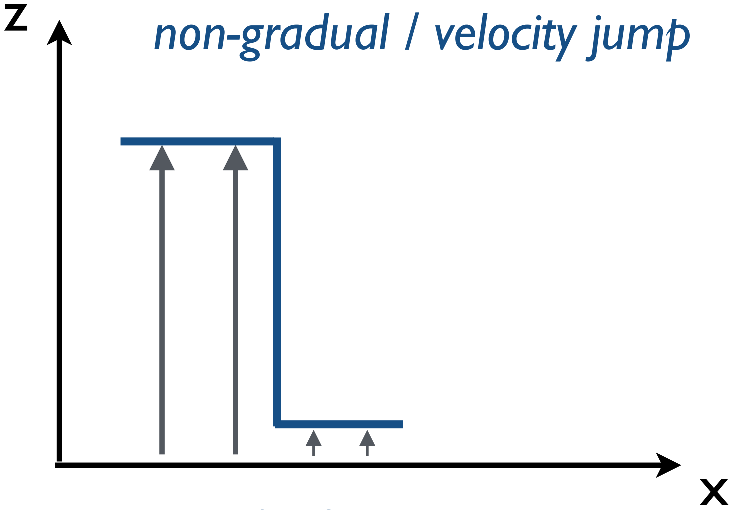


gradual shear



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

non-gradual / velocity jump



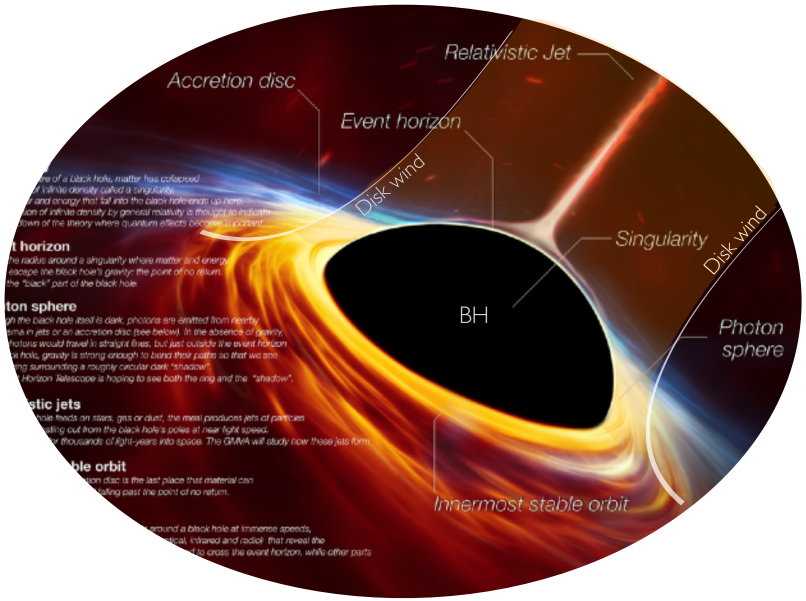
Jokipii & Morfill; Ostrowski; Kimura+….

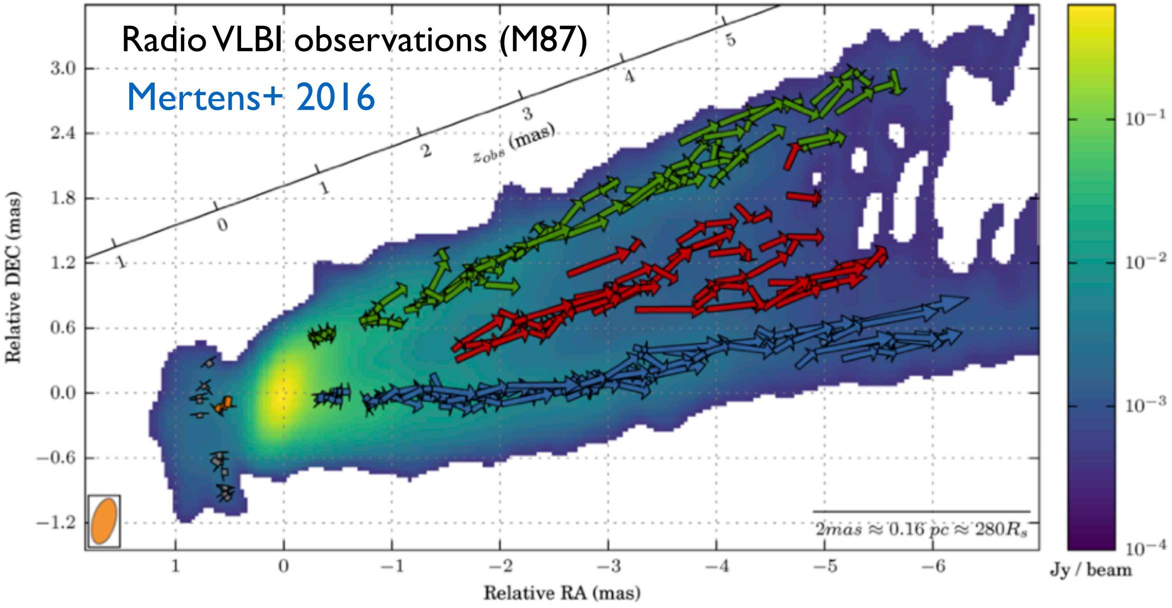
On the naturalness of velocity shears in AGN…

- **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

    ⇒ *presence of both slow (~0.5c) and fast (~0.92c) components….*

    [similar indications in Cen A, cf. EHT observations in Janssen+ 2021]



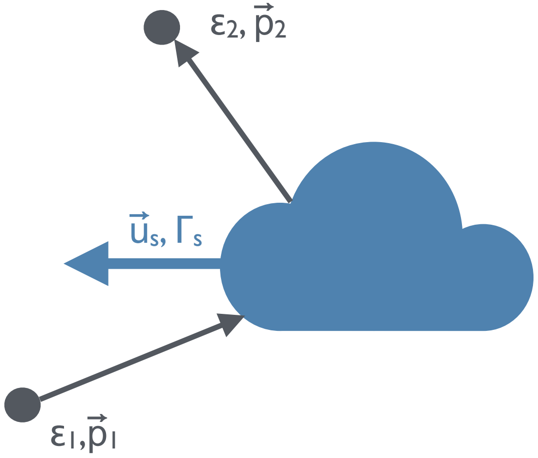

Radio VLBI observations (M87)

Mertens+ 2016

Fermi-type Particle Acceleration

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:

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

$p_1 \simeq \epsilon_1/c$

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

- 1. **stochastic**: average energy gain <u>2nd order:</u> $< \Delta\epsilon > \propto \Gamma_s^2\,(u_s/c)^2\,\epsilon_1$

Non-Gradual Shear Particle Acceleration

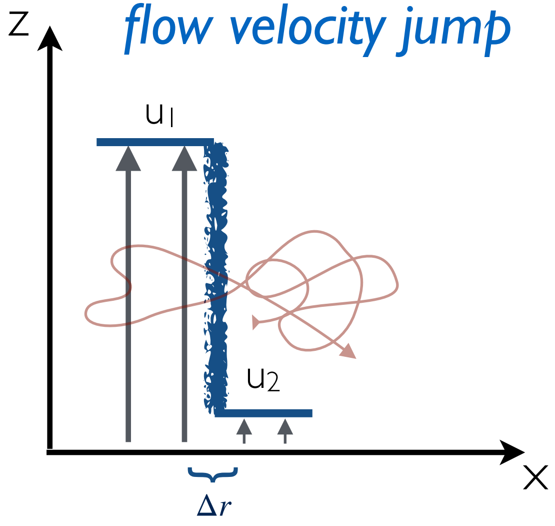
- II. ***Non-gradual*** **shear flow**
  - like 2nd Fermi, stochastic process with average gain per cycle (crossing and recrossing):

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

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

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

flow velocity jump



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

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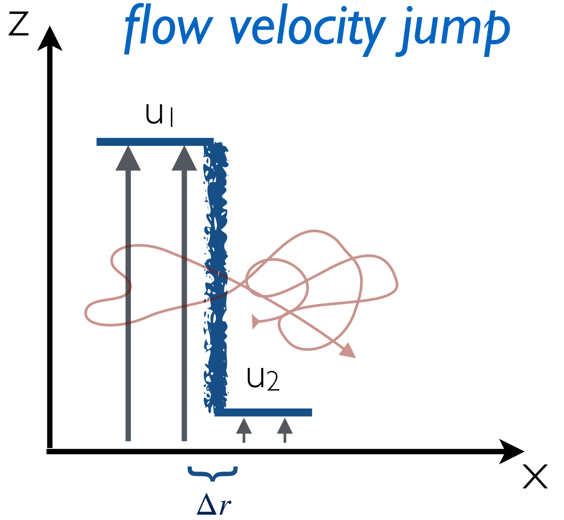


flow velocity jump

- 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

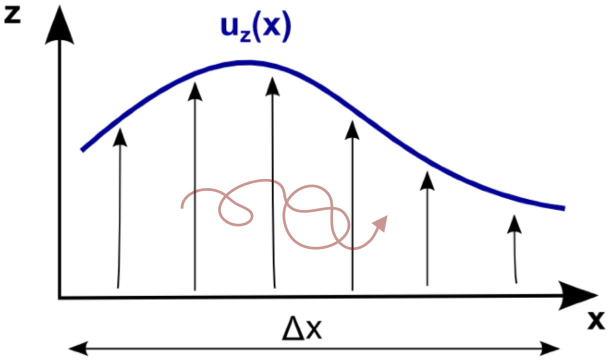
Jokipii & Morfill 1990; Ostrowski 1998, 2000; Stawarz & Ostrowski 2002; FR & Duffy 2004; Kimura+2018…

Stochastic Shear Particle Acceleration (basic idea) I

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

non-relativistic

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



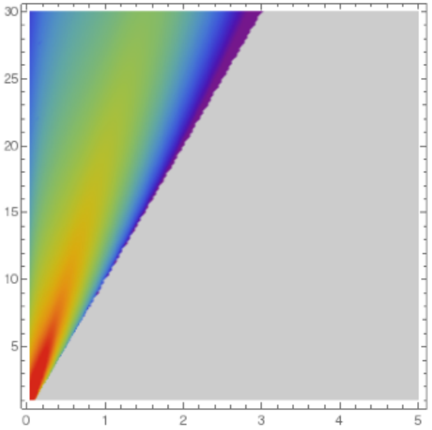
  - like 2nd Fermi, stochastic process with average gain:

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

using *characteristic* *effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right) \lambda$$

, where $\lambda = c\tau$ *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….

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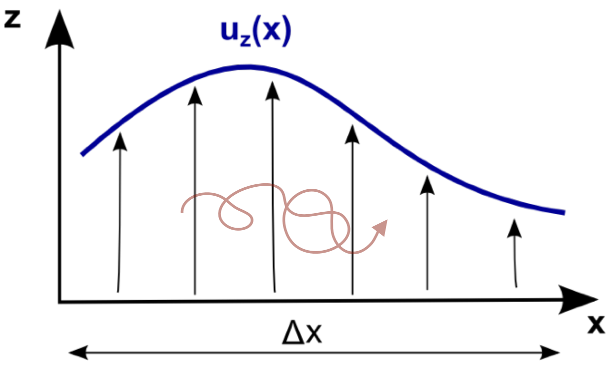

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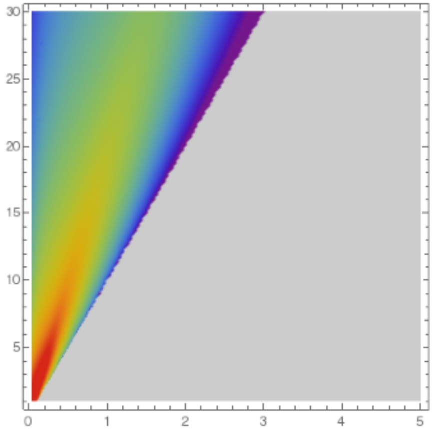
- leads to:

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

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

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



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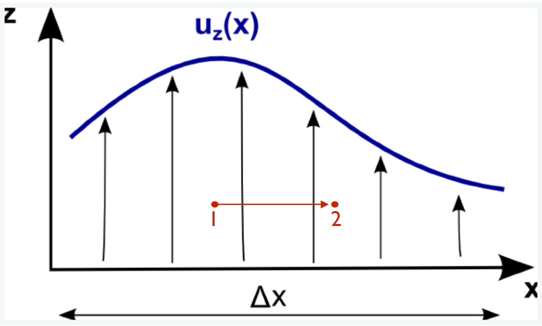
Stochastic Shear Particle Acceleration (basic idea) II

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 $\delta x = v_x\, \tau$, $\tau = \lambda/c$

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



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

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

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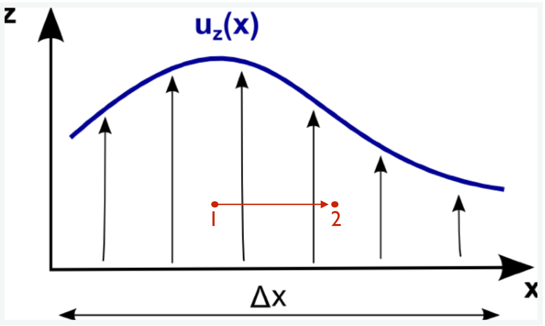

⇒ detailed balance satisfied [scattering being reversible P(p, -Δp) = P(p-Δp, Δp)]

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)

Incorporating spatial transport…

Relativistic 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 $\mathring{u}_\alpha = u^\beta u_{\alpha;\beta}$)

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

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

shear term

Γ relativistic shear coefficient

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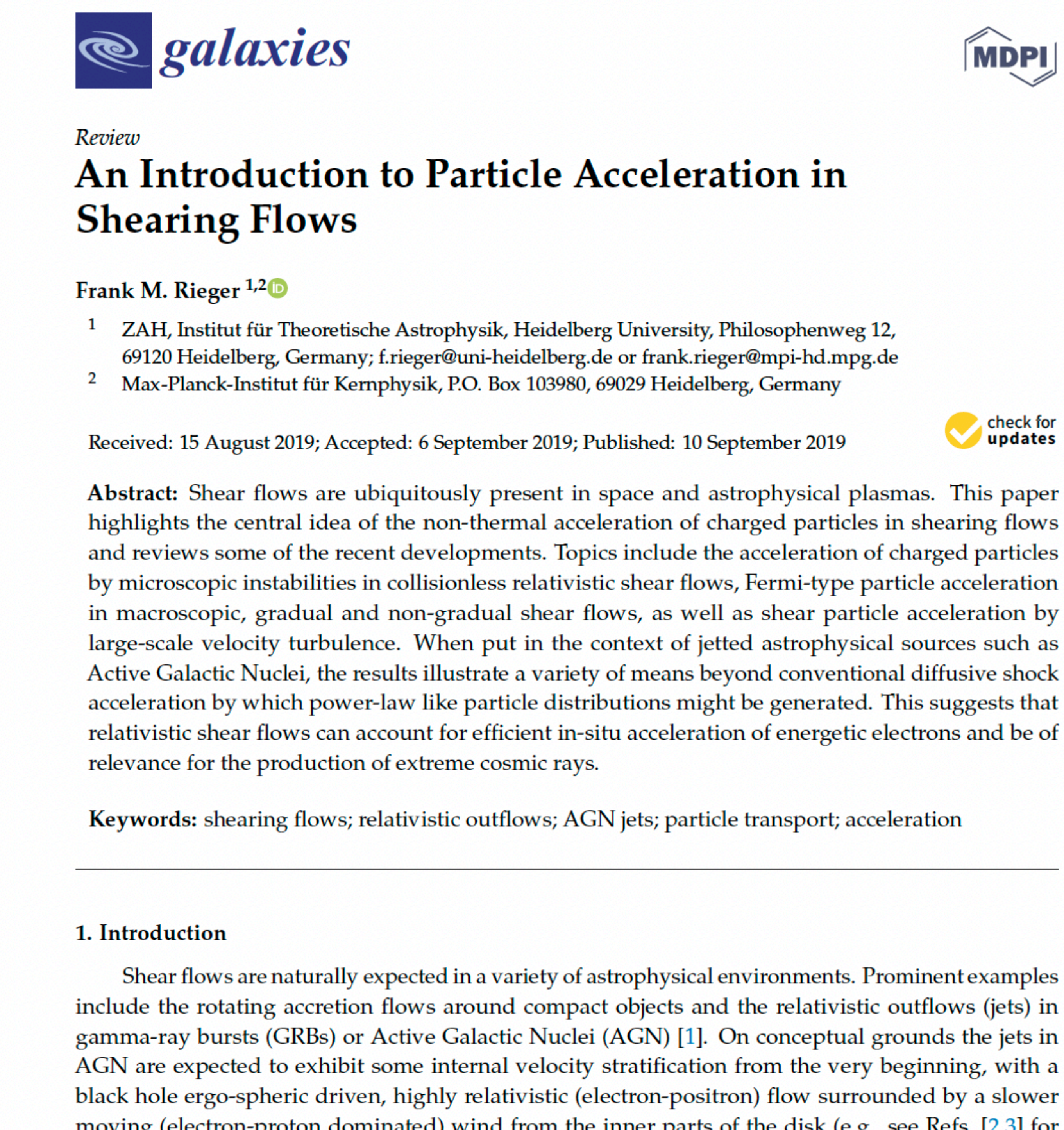
(Webb 1989; cf. also FR & Mannheim 2002; Webb+ 2018)

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

shear term

Γ relativistic shear coefficient

For introduction & overview…



galaxies

MDPI

Review

An Introduction to Particle Acceleration in Shearing Flows

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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

Galaxies 7 (2019), 78
[review]

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

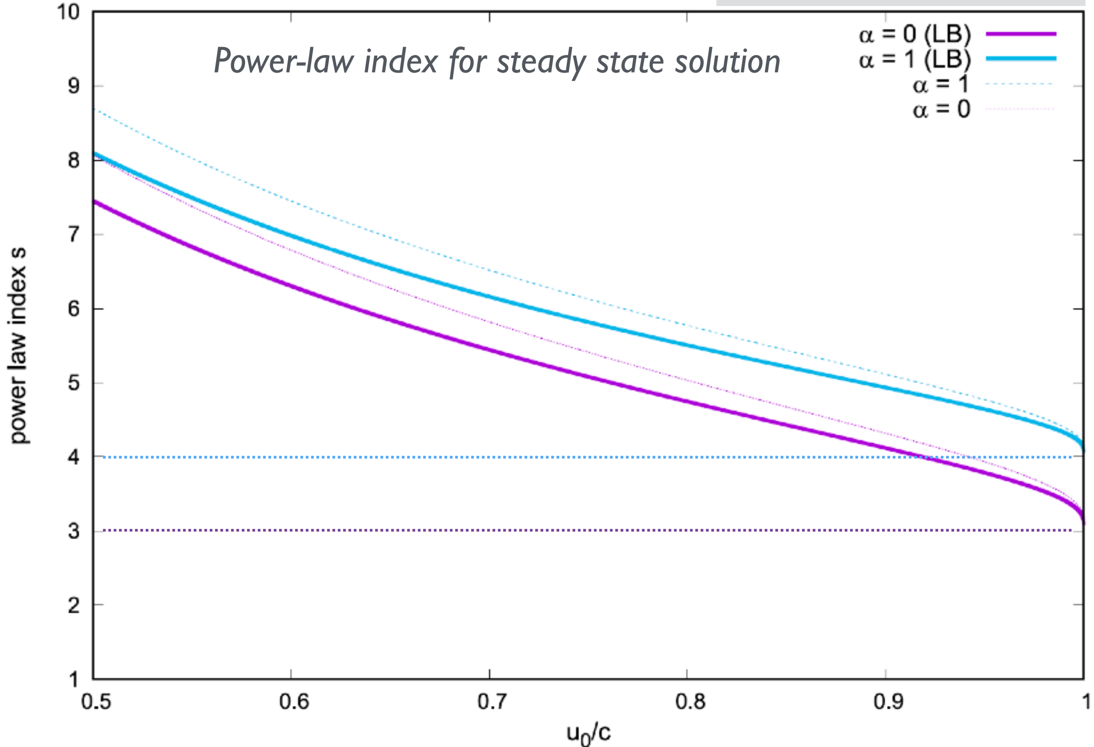
$\Gamma = (c^2/15)\,\gamma_b(r)^4\,(d\beta/dr)^2$

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.* [$n(p) \propto p^2 f \propto p^{-(1+\alpha)}$]

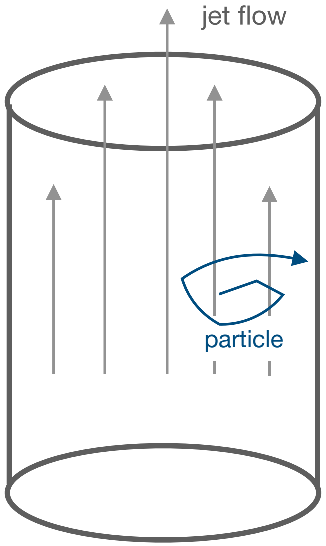
linear velocity shear



(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 stochastic and shear, and losses due to synchrotron and escape 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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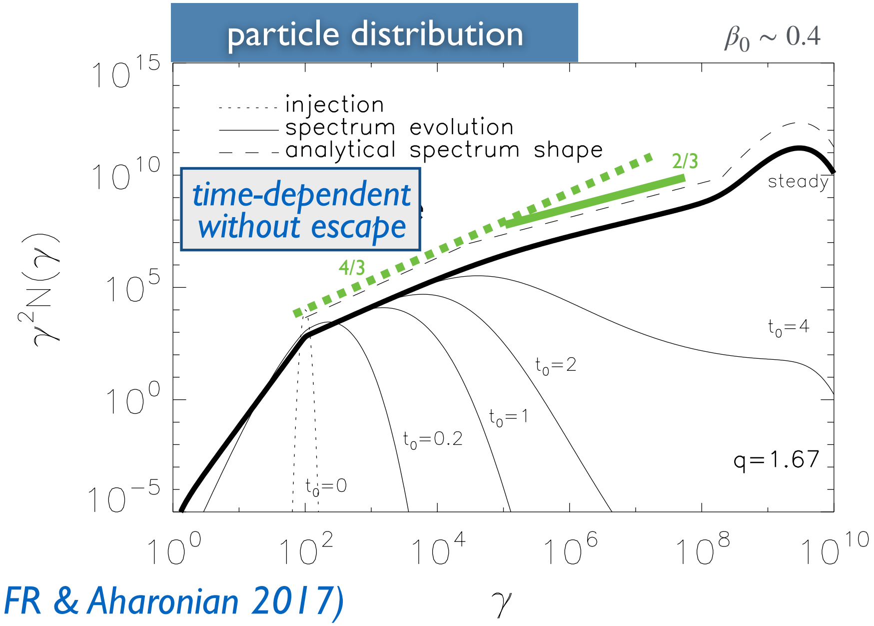
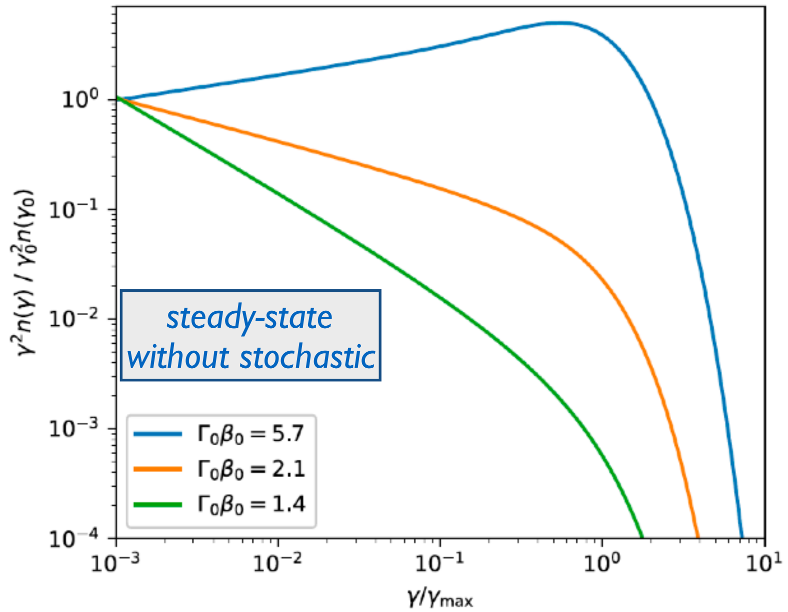

particle distribution

time-dependent without escape

(Liu, FR & Aharonian 2017)


steady-state without stochastic

(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.

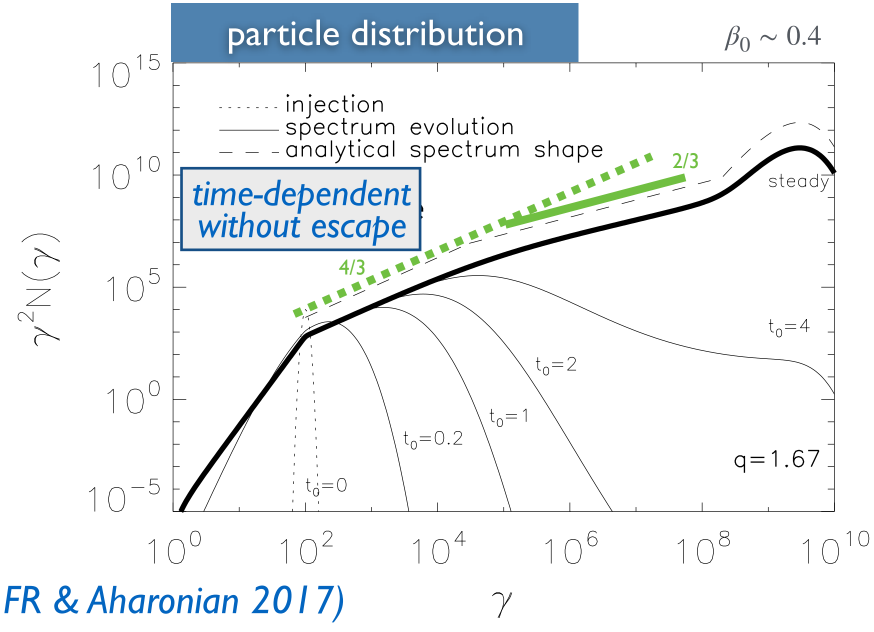
- from 2nd Fermi to shear…
- electron acceleration beyond $\gamma \sim 10^8$ possible
- formation of multi-component particle distribution
- incorporation of escape softens the spectrum

Parameters I: B = 3μG, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ 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), ξ=0.1

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

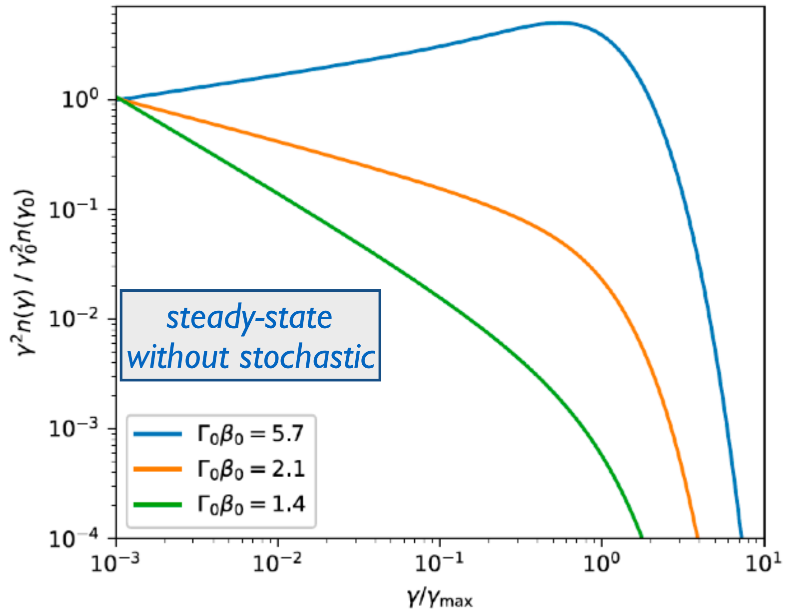
On continuous electron acceleration in large-scale AGN jets

Radiative-loss-limited electron acceleration in mildly relativistic flows



time-dependent without escape

(Liu, FR & Aharonian 2017)



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

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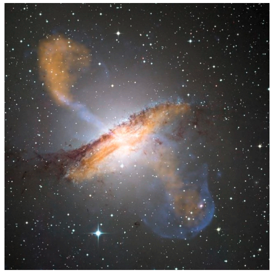
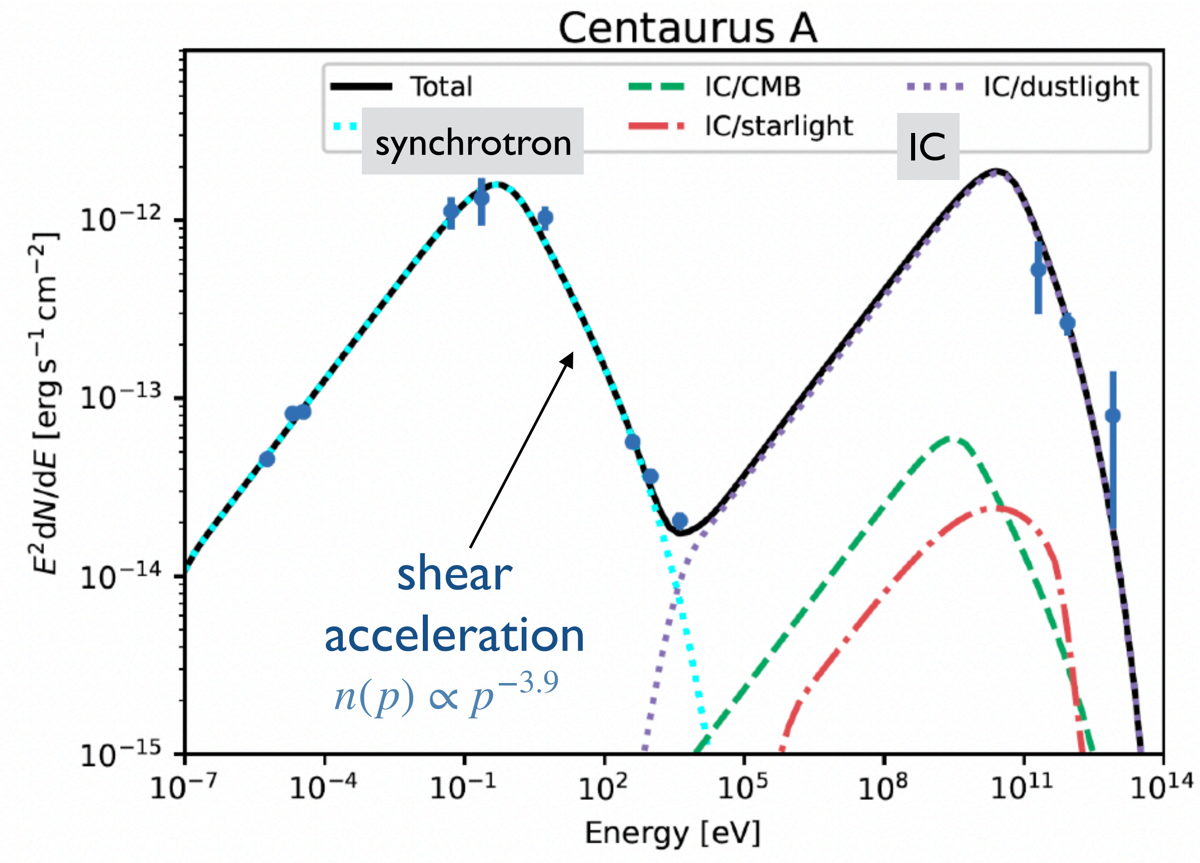
Exemplary application I



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

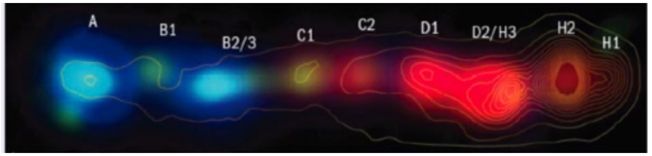


(Wang, Reville, Liu, FR & Aharonian 2021)

estimated (kinetic) jet power $L_j \sim 4 \times 10^{42}$ erg/s

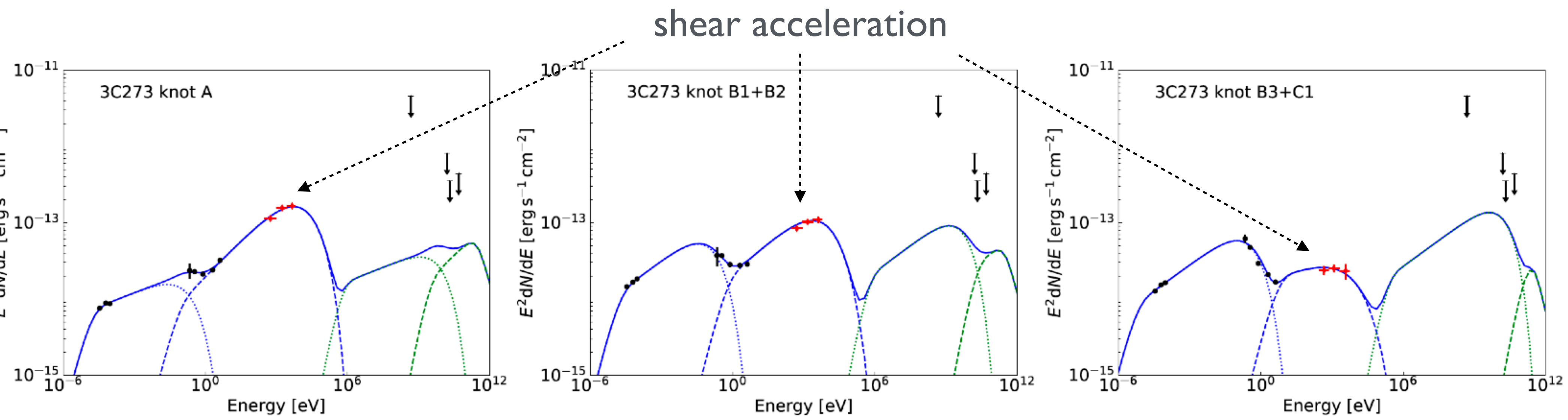
- SED reproduction with shear-related broken power-law & shock-accelerated seeds
- Kolmogorov turbulence description $\lambda \propto \gamma^{1/3}$
- quasi-linear velocity shear
- parameters: $\Delta r = 100$ pc, $B=17\ \mu G$, $\beta_0=0.67$
- electron acceleration up to $\gamma_e \approx 10^8$
- UHE proton acceleration to $>10^{18}$ eV

Exemplary application II



Modelling the X-ray emission in the FR II galaxy 3C 273

- SED reproduction with shear-related 2nd SED component
- Kolmogorov turbulence description $\lambda \propto \gamma^{1/3}$, electrons reaching $\gamma_e \sim 3 \times 10^8$
- inferred parameters: B ~ (a few -10) μG, $\beta_0 \sim (0.79 - 0.88)$
- **parameters consistent with large-scale jets being mildly relativistic $\Gamma_\mathrm{j} \lesssim 3$**

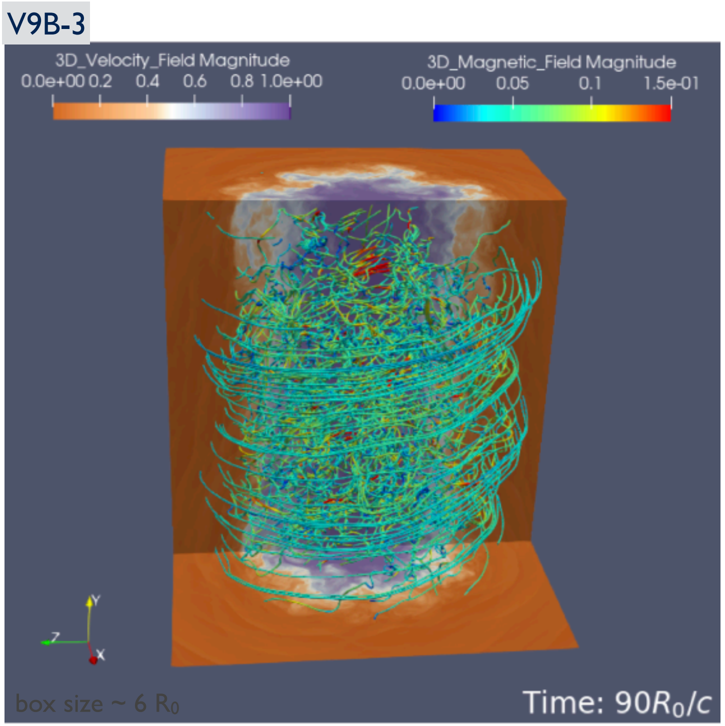

shear acceleration

(He…+ FR 2023)

Developments I

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

- employ 3D relativistic MHD jet simulations (PLUTO) for $v_j/c \,\varepsilon\, [0.6 , 0.99]$
- study KHI sheath formation for kinetically dominated jets ($\sigma < 0.2$) in stationary cocoon
- explore shear flow profile & turbulence spectrum for particle acceleration…
    - *typically $W_{sh}/R_j \sim 0.2 - 0.5$ (transition stage) and $\sim 0.5 - 0.8$ (deep saturation)…*
    - *Kolmogorov-type ($q \sim 5/3$) turbulence spectra…*



jet structure and KHI evolution

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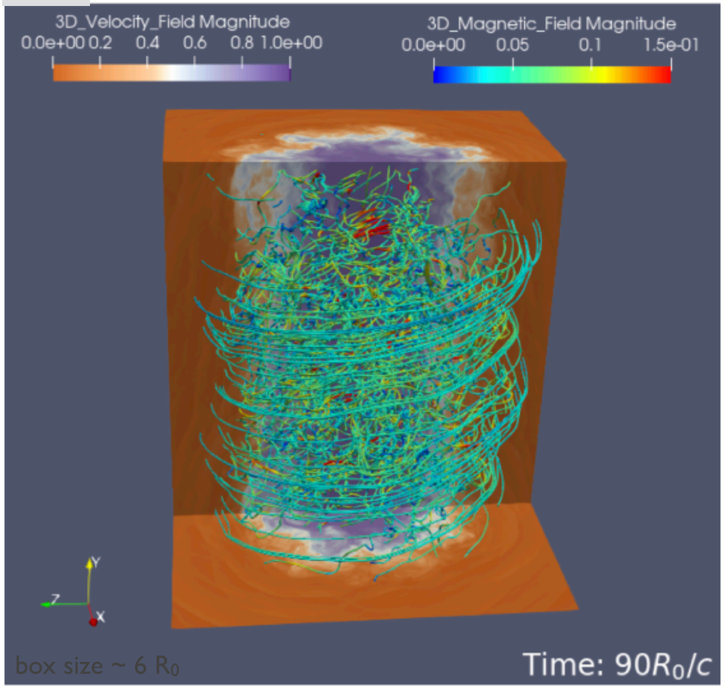
V9B-3



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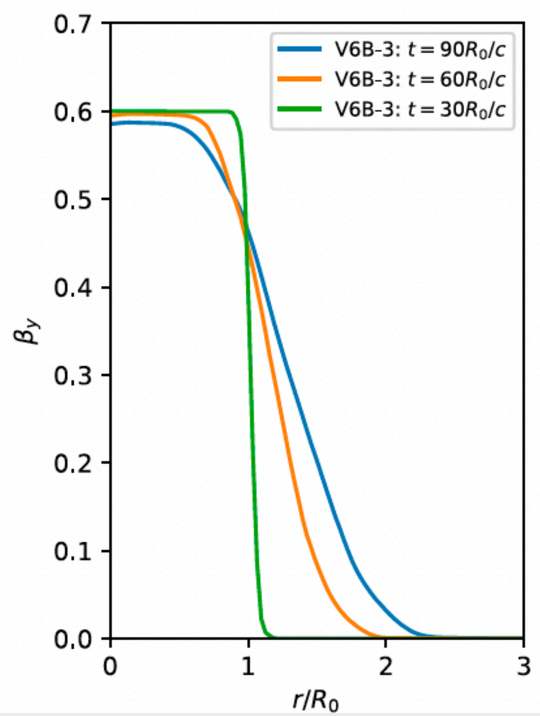


Parameters:

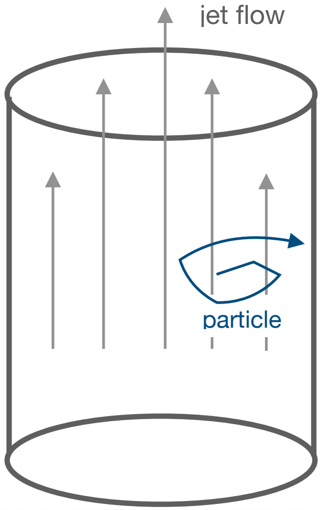
$v_j = 0.6c$, $\sigma = 0.002$,
$R_0 = 0.1$ kpc
$L_j \approx 1E43$ erg/s

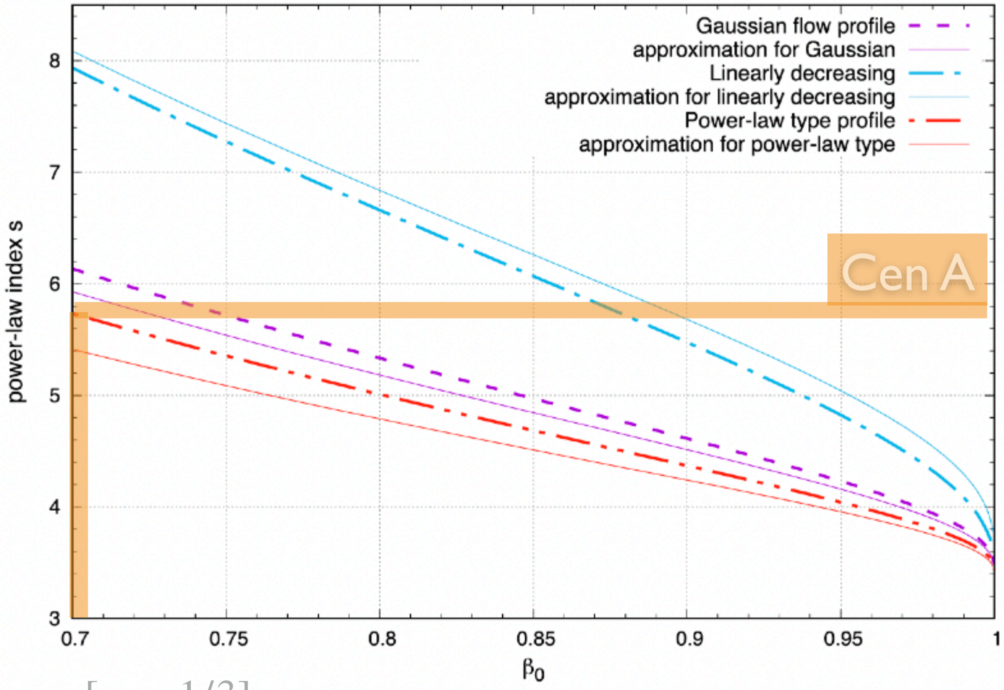
$$\sigma_{l,t} = \langle B_{l,t}^2 \rangle / 8\pi\rho_o c^2$$

(azimuthally) averaged flow velocity profiles

Developments II

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
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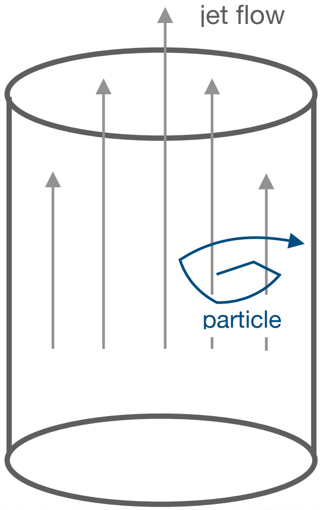

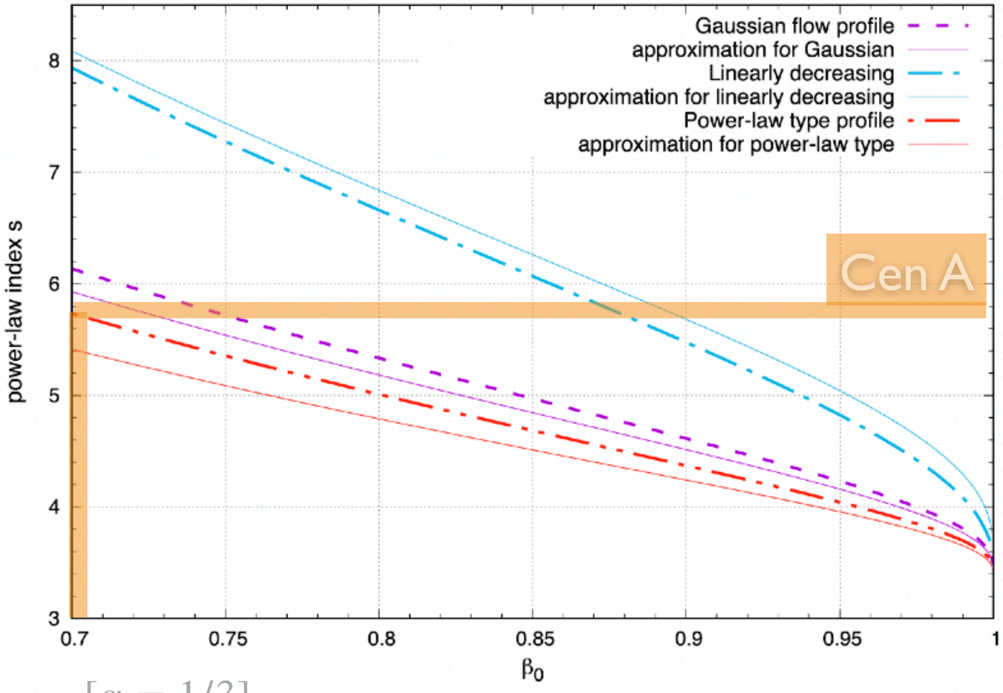

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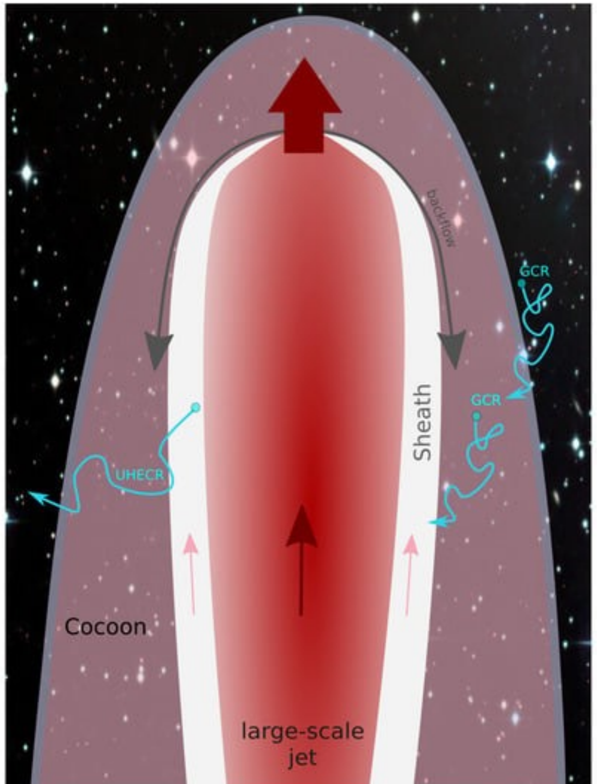
allows to constrain flow profile through observed PL index….

On UHECR acceleration in shearing large-scale AGN jets



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

(FR & Duffy 2019)

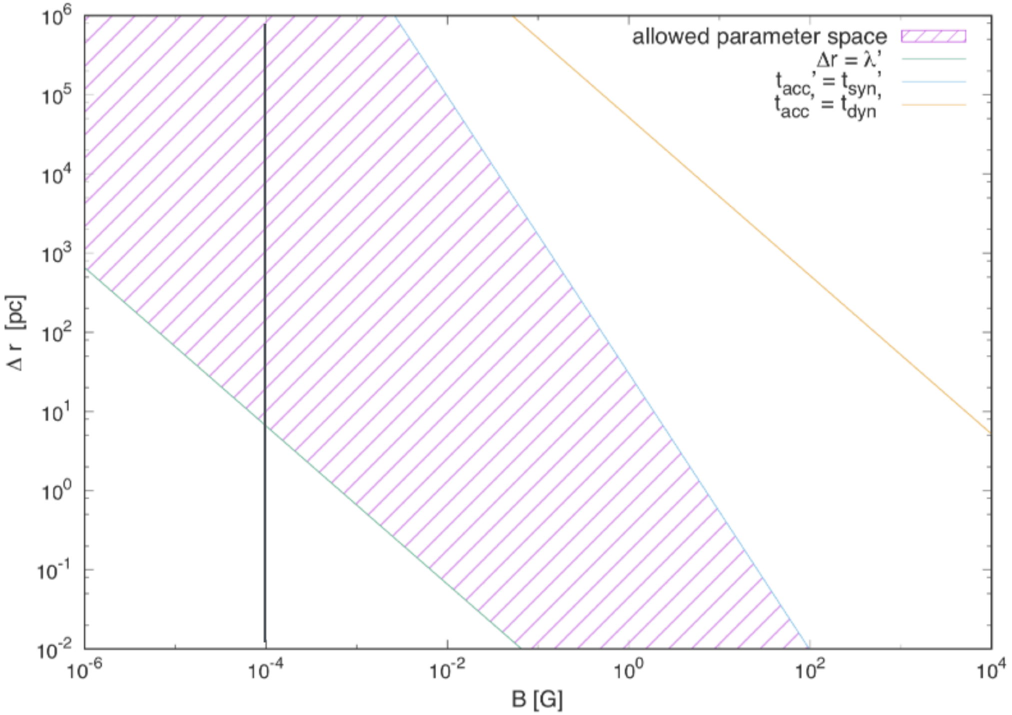


Figure 2. Allowed parameter range (shaded) for shear acceleration of CR protons to energies $E_p' = 10^{18}$ eV for a particle mean free path $\lambda' \propto p'^{\alpha}$ with $\alpha = 1/3$ (corresponding to Kolmogorov type turbulence $q = 5/3$). A flow Lorentz factor $\gamma_b(r_0) = 3$ has been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

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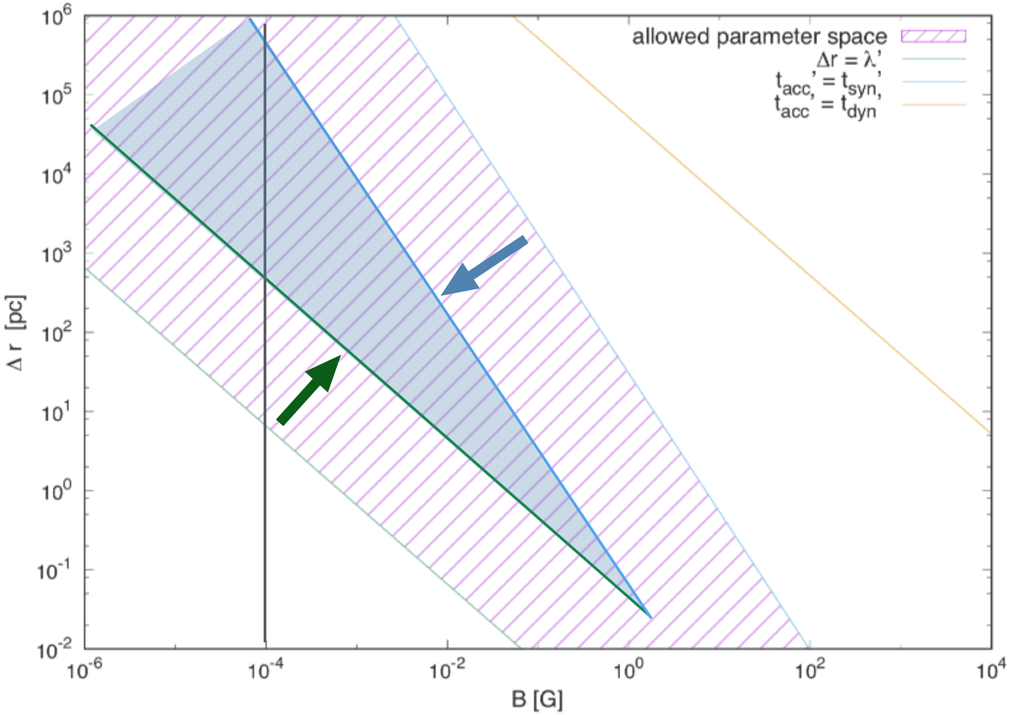

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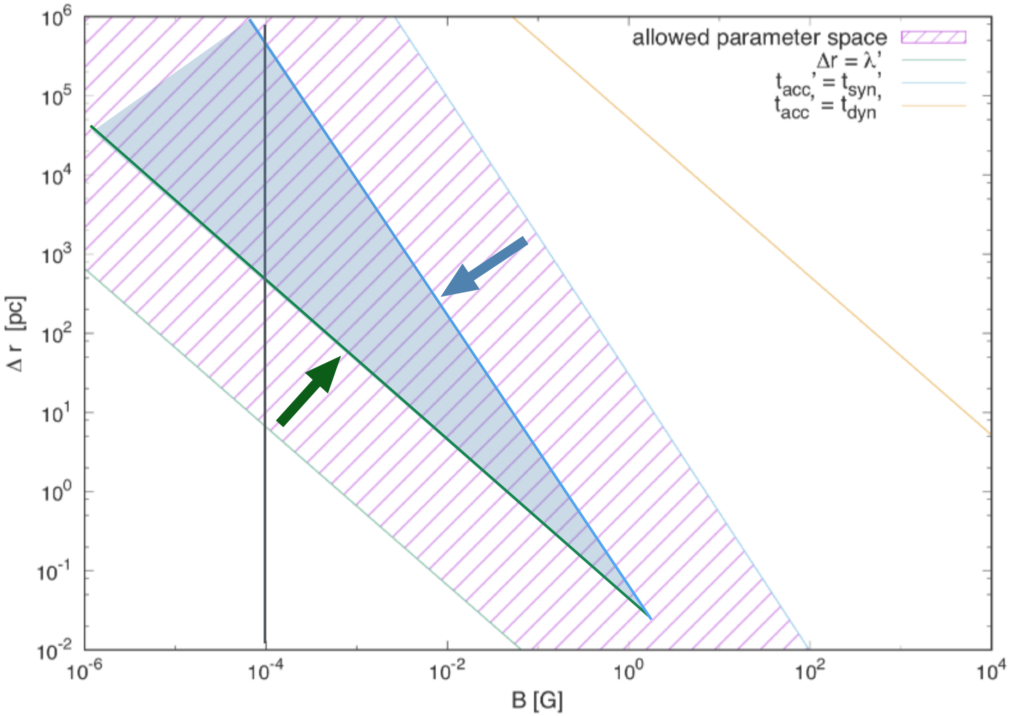

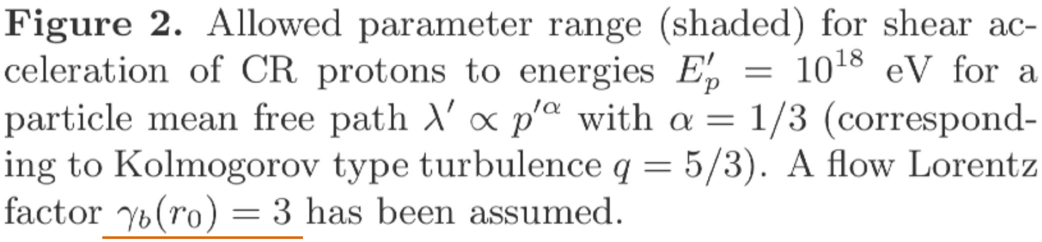

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caveat:
simplification of spatial transport

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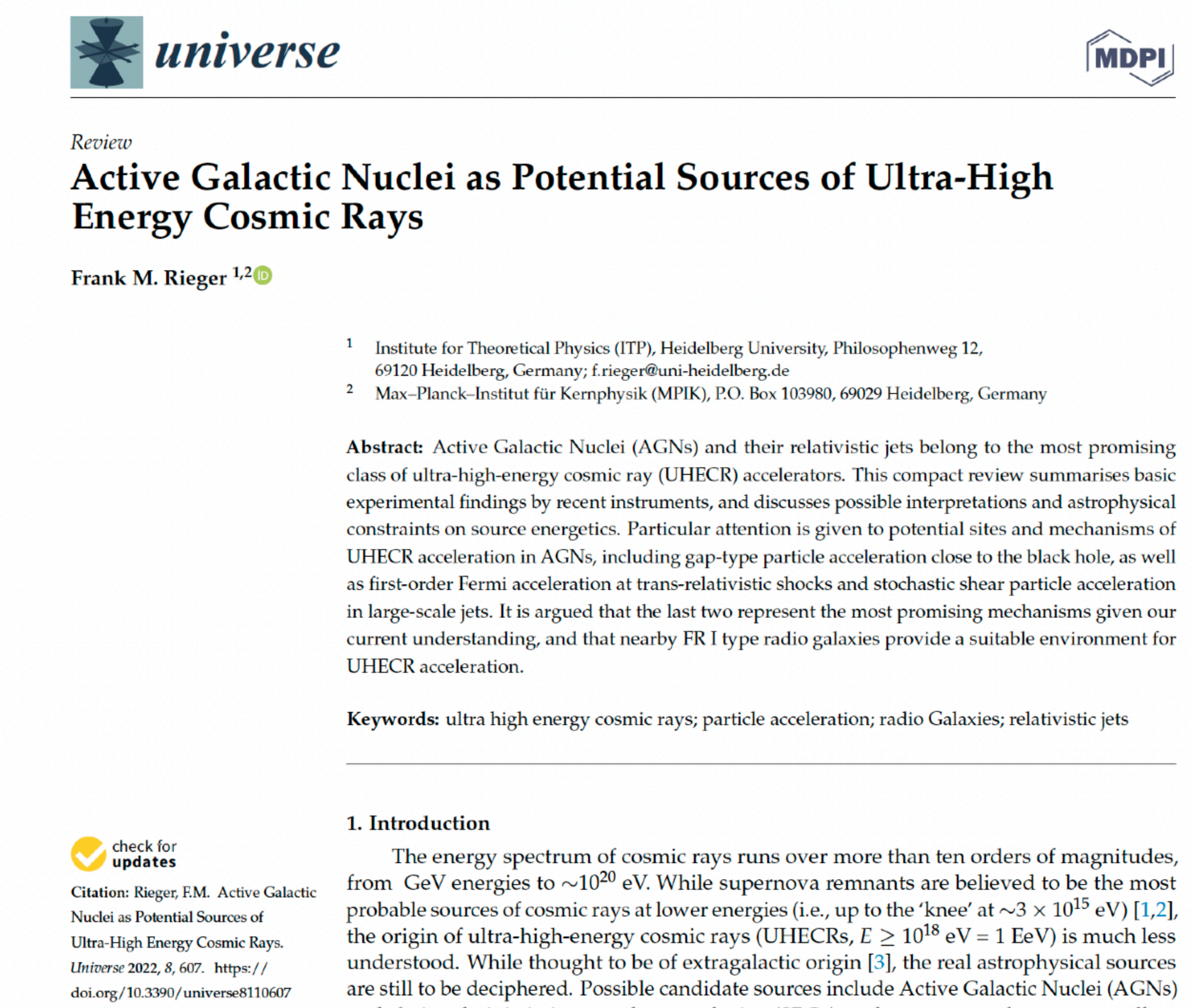
For overview & discussion of shear acceleration of UHECRs

Universe 8 (2022), 607
[review]



universe

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

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)

check for updates

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

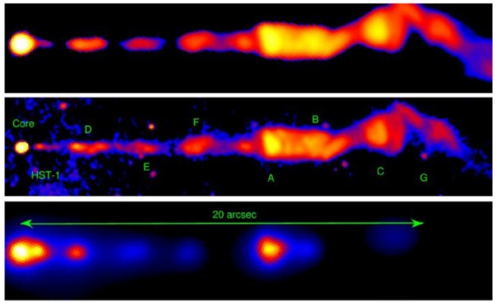
non-gradual:
Ostrowski+, Kimura+…

Espresso type:
Mbarek & Caprioli…

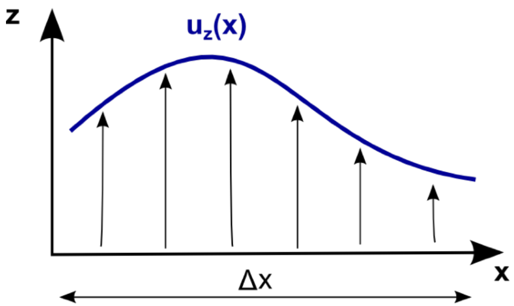
see also talk by H. Kang

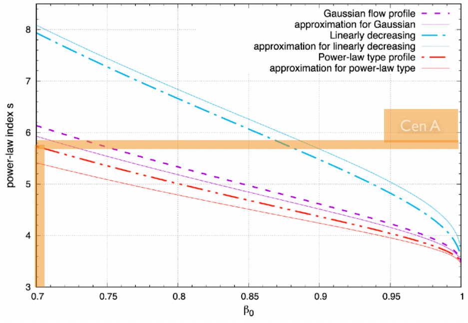
Summary

Particle Acceleration in Astrophysical Shear Flows:



- needs relativistic flow speeds to be efficient (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 (PL index) indicative of flow profile…
  - large-scale AGN jets as possible UHE accelerators….





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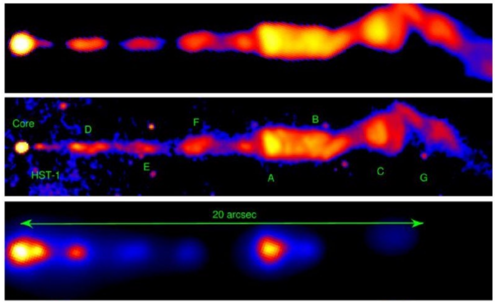
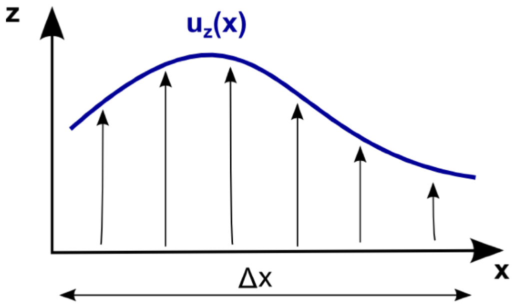
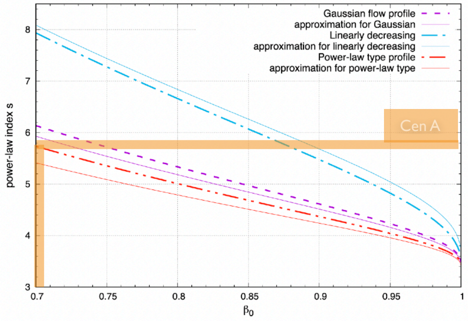
Thank you ! & Questions ?







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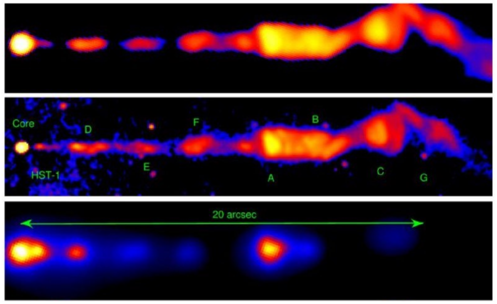
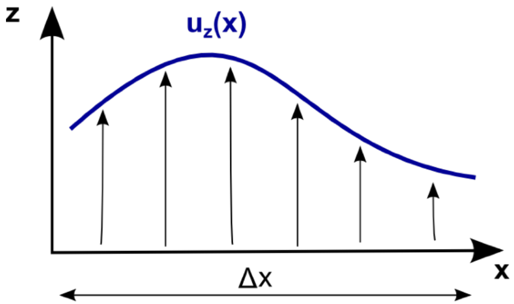
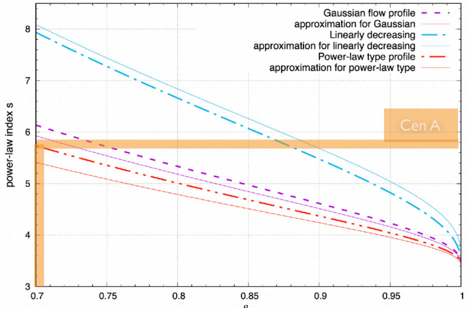
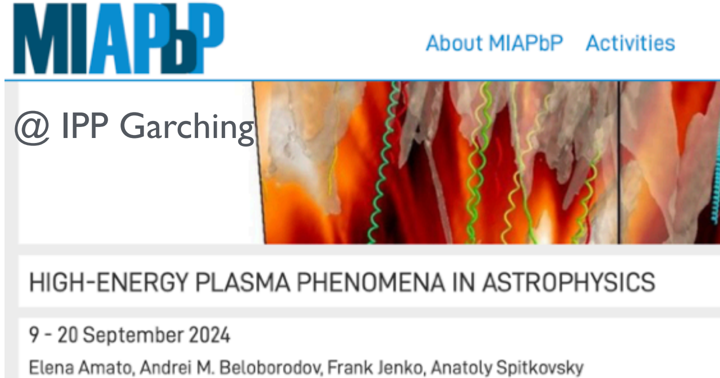






Thank you ! & Questions ?

MIAPbP Workshop @ IPP Sept 23



@ IPP Garching

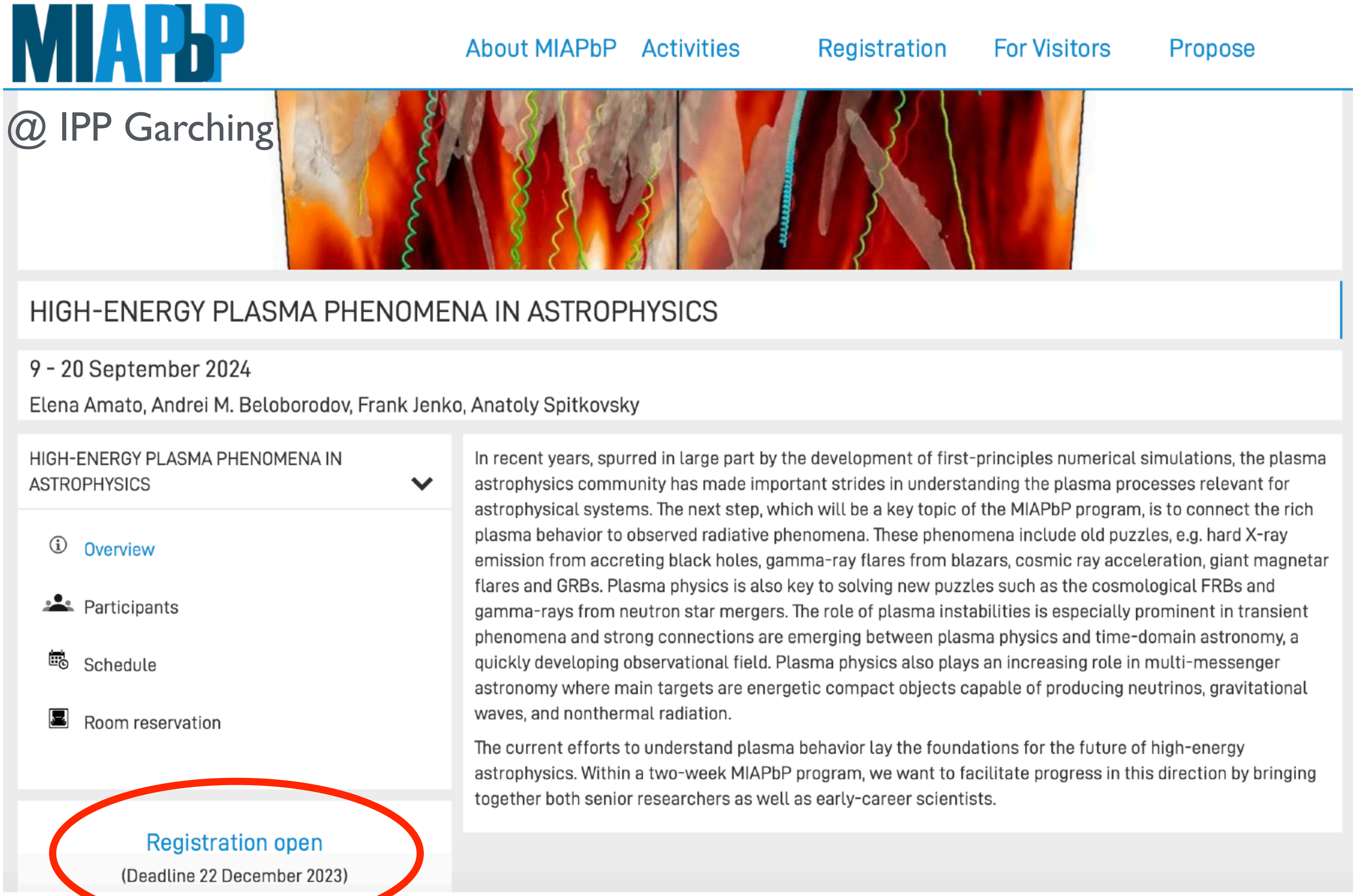
HIGH-ENERGY PLASMA PHENOMENA IN ASTROPHYSICS

9 - 20 September 2024

Elena Amato, Andrei M. Beloborodov, Frank Jenko, Anatoly Spitkovsky

MIAPbP Workshop Sept. 2024

@ IPP Garching



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In recent years, spurred in large part by the development of first-principles numerical simulations, the plasma astrophysics community has made important strides in understanding the plasma processes relevant for astrophysical systems. The next step, which will be a key topic of the MIAPbP program, is to connect the rich plasma behavior to observed radiative phenomena. These phenomena include old puzzles, e.g. hard X-ray emission from accreting black holes, gamma-ray flares from blazars, cosmic ray acceleration, giant magnetar flares and GRBs. Plasma physics is also key to solving new puzzles such as the cosmological FRBs and gamma-rays from neutron star mergers. The role of plasma instabilities is especially prominent in transient phenomena and strong connections are emerging between plasma physics and time-domain astronomy, a quickly developing observational field. Plasma physics also plays an increasing role in multi-messenger astronomy where main targets are energetic compact objects capable of producing neutrinos, gravitational waves, and nonthermal radiation.

The current efforts to understand plasma behavior lay the foundations for the future of high-energy astrophysics. Within a two-week MIAPbP program, we want to facilitate progress in this direction by bringing together both senior researchers as well as early-career scientists.

Registration open

(Deadline 22 December 2023)