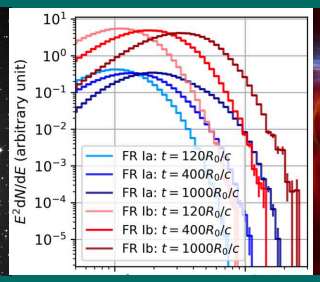
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

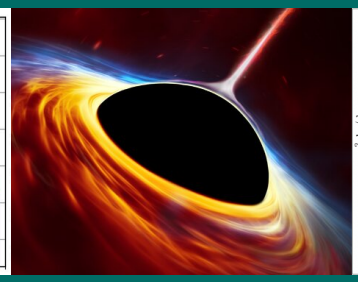
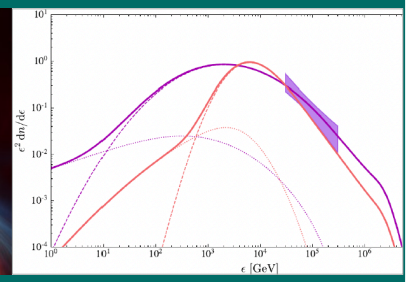
High Energy Particle Acceleration in Shearing Flows

PLASMA ASTRO

Frank M. Rieger

@ Illuminating the Active Universe
(ESO September 14-17, 2026)

Collaborators: *Peter Duffy, Martin Lemoine, Felix Aharonian, Brian Reville, Jieshuang Wang, Jia-Xing Wang…*

Basic properties and the physics of AGN

from PhD times…😀

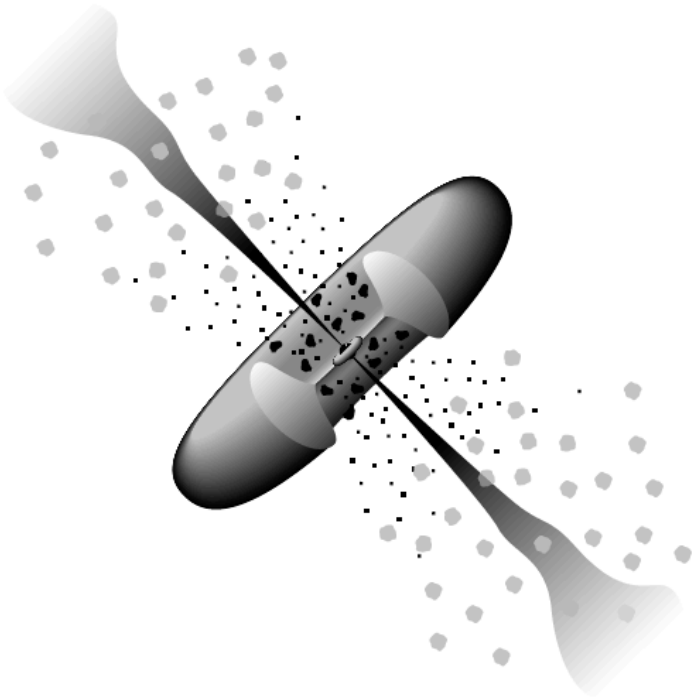


Figure 1.3: Sketch illustrating the current paradigm of (radio-loud) AGN (adopted from Urry & Padovani 1995).

to recent times….

A&A, 706, A351 (2026)
https://doi.org/10.1051/0004-6361/202556986
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Astronomy & Astrophysics

Hillas meets Eddington: The case for blazars as ultra-high-energy neutrino sources

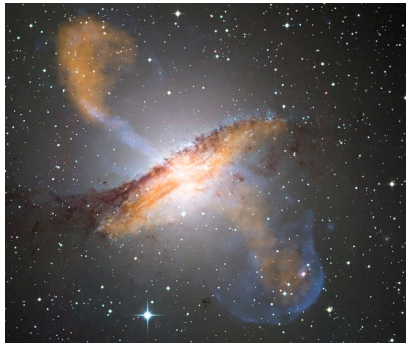
X. Rodrigues[1,2,⋆], F. Rieger[3,4], A. Bohdan[3], and P. Padovani[1]

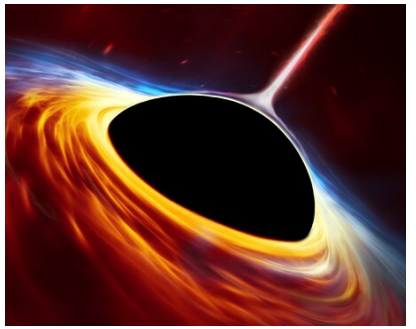
[1] European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching bei München, Germany
[2] Excellence Cluster ORIGINS, Boltzmannstr. 2, D-85748 Garching bei München, Germany
[3] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, DE-85748 Garching, Germany
[4] Institute for Theoretical Physics, Heidelberg University, Philosophenweg 12, 69120 Heidelberg, Germany

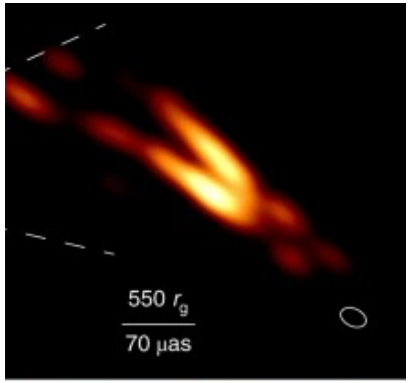
Received 25 August 2025 / Accepted 17 December 2025

Short Overview

- **Basics on Shear Acceleration in AGN** *(intro & context)*
- **(i) On Particle Acceleration in the kpc-scale jet of Cen A**
- **(ii) On Extended VHE emission in M87**
- **(iii) On Cosmic-Acceleration in Seyfert Galaxies (NGC1068)**
- **Conclusions**

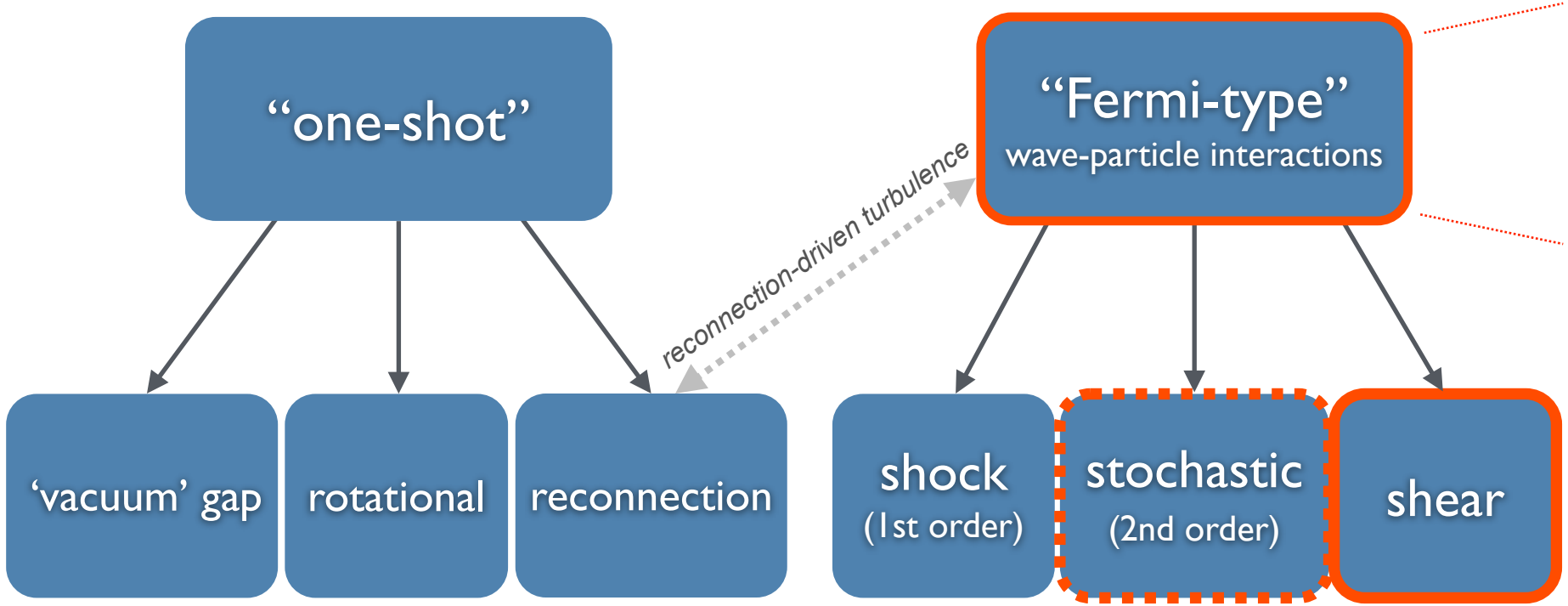






Basics: Possible Acceleration Processes in AGN *(not exhaustive)*





Where:	*BH vicinity*	*BH vicinity*	*Accretion & Inner Jet*	*Jet*	*Jet & Lobes*	*Jet*
Caveats:	charge density? topology? transparency?	efficiency? topology? transparency?	limited in size? efficiency (σ, B_g)? spectral shape?	efficiency (Γ_s, σ)? localized?	efficiency? spectral shape?	efficiency? energetic seeds?

Basics: On Fermi-Shear Particle Acceleration

FR 2019 [review]

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

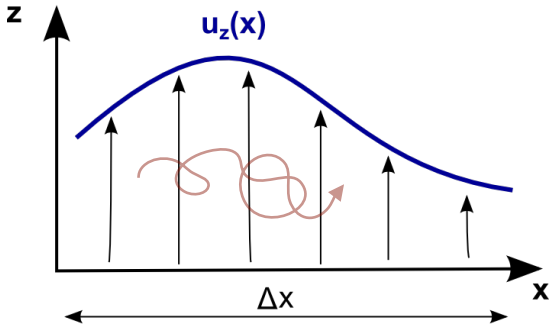
$$< \Delta E > \propto \left(\frac{u_{\rm eff}}{c}\right)^2 E = \frac{1}{c^2}\left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2 E$$

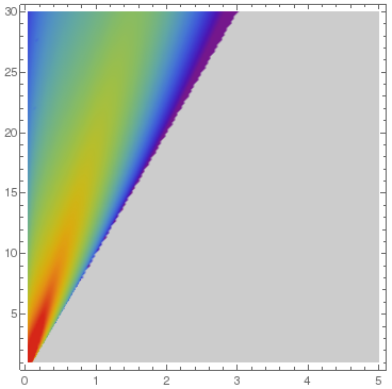
using *characteristic effective velocity*:

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

non-relativistic

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





(Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004ff…)

Basics: On Fermi-Shear Particle Acceleration

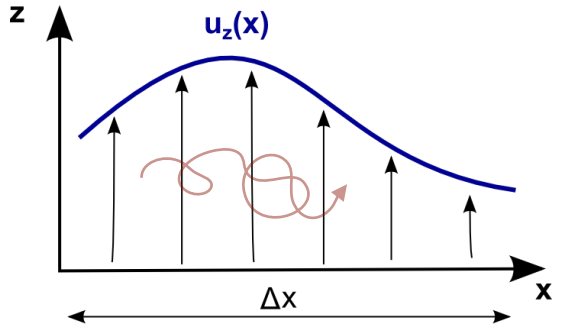
FR 2019 [review]

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

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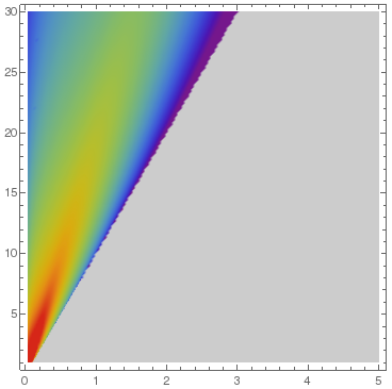


using *characteristic effective velocity*:

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

- leads to:

$$t_{\rm acc} = \frac{E}{(dE/dt)} \sim \frac{E}{< \Delta E >} \cdot \frac{\lambda}{c} \propto \frac{1}{\lambda}$$



⇒ *seeds* from acceleration @ shock or 'classical' stochastic…

⇒ easier for protons…(⇨ UHECR)

(Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004ff…)

Basics: Simplified leaky-box model for shear acceleration

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

(FR & Duffy 2019)

momentum-diffusion coefficient: $D_p \propto (d\beta/dr)^2\, p^2\, \tau_s$ and $\tau_{\rm esc} \propto (\Delta r)^2/\kappa$

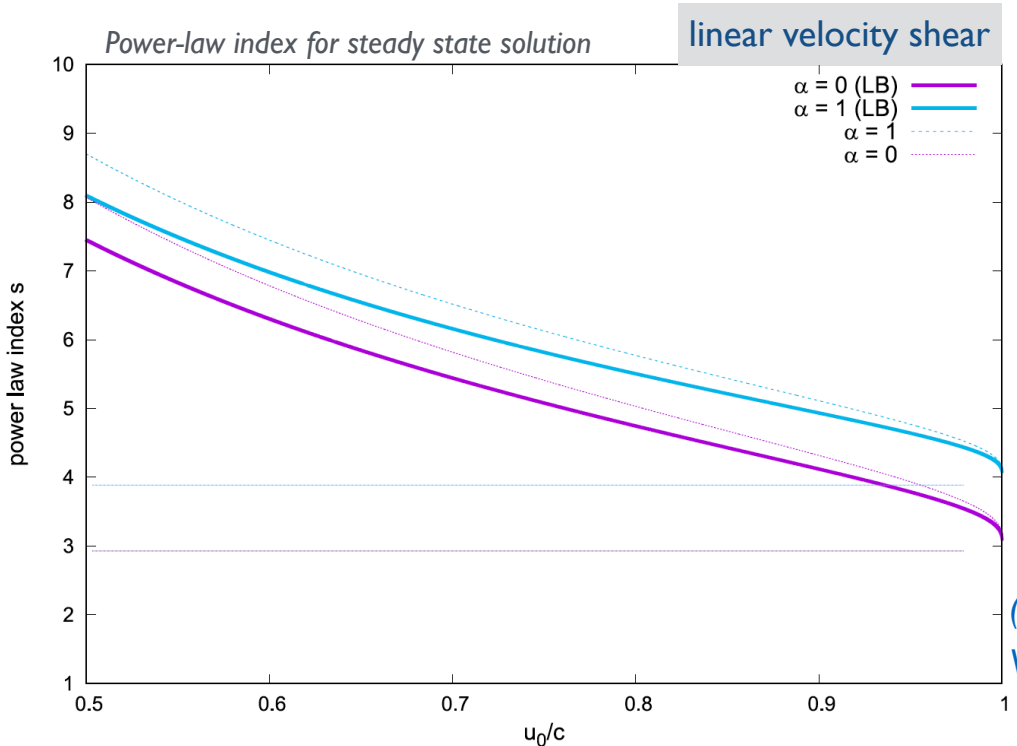
Power-law solution:

$$f(p) \propto p^{-s}$$

- *PL index s sensitive to maximum flow speed*
  ⇒ diagnostics of jet (spine) speed
- *for relativistic flow speeds approximating:*

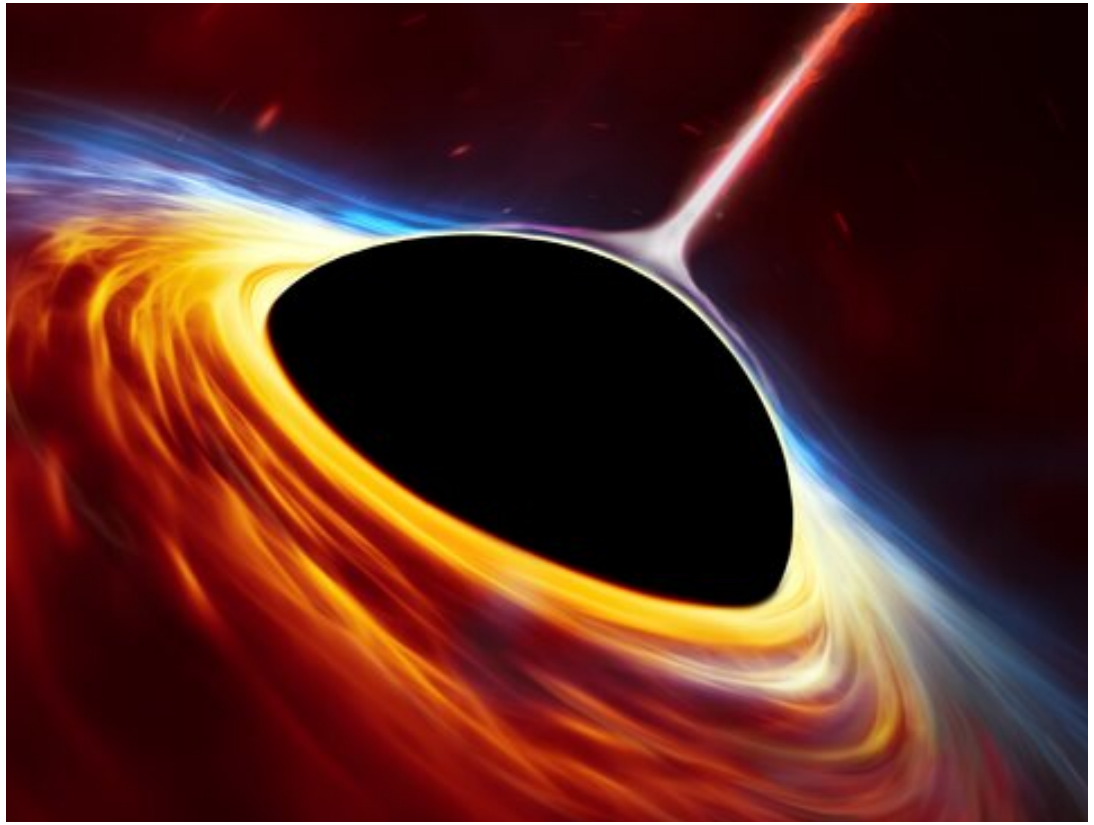
$$n(p) \propto p^2 f(p) \propto p^{-(1+\alpha)}$$

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



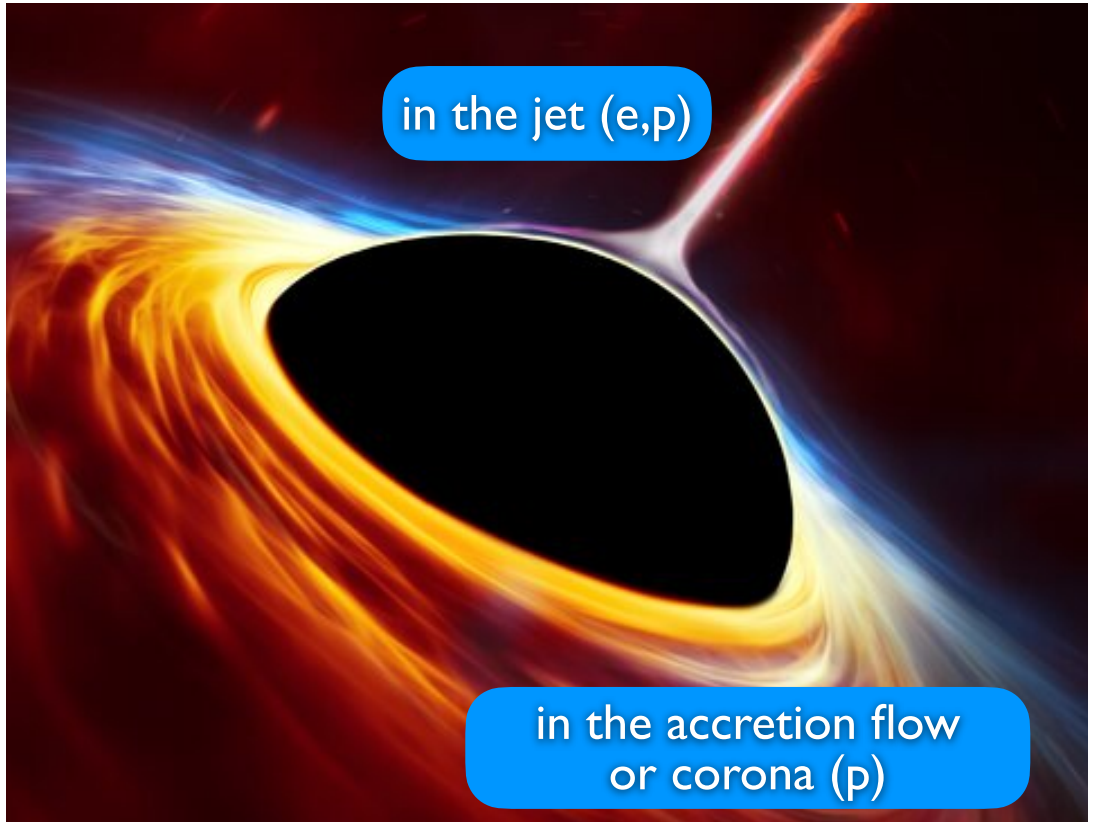
(see also Webb+ 2018)

Fermi-type Particle Acceleration in AGNs



For favourable conditions, Fermi-type particle acceleration known to produce power-laws: $n(p) \propto p^{-\alpha}$

Fermi-type Particle Acceleration in AGNs



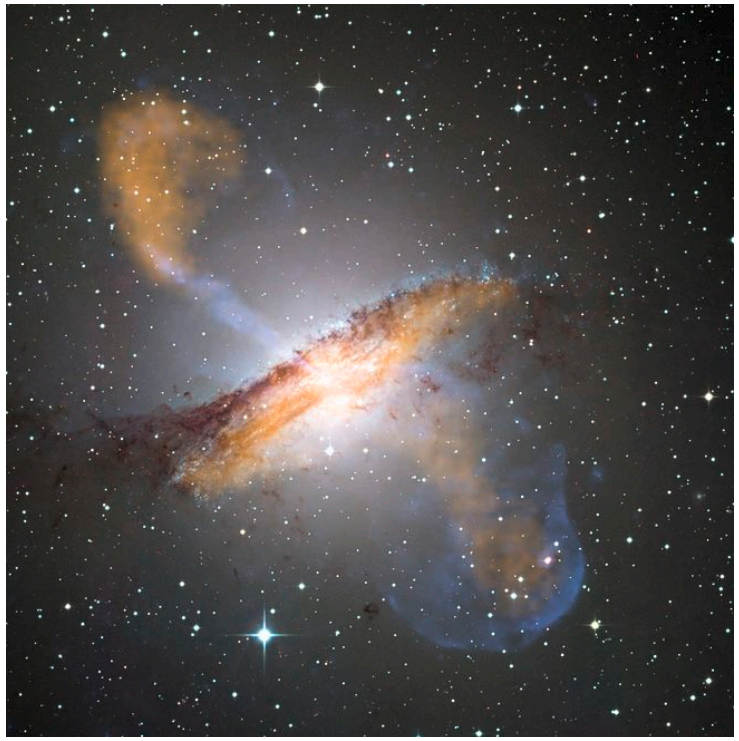
For favourable conditions, Fermi-type particle acceleration known to produce power-laws: $n(p) \propto p^{-\alpha}$

- *shock - power-law:* $\alpha \simeq 2$
- *"shear" - power-law index depends on flow speeds*
  - ➡ $\alpha \to 1$ for highly relativistic flows
  - ➡ $\alpha \gg 1$ for sub-relativistic flows
- *"classical" - can be as hard as spectra* $n(p) \sim p^{-1}$
  - ➡ energy content $\epsilon_p \propto p^2 n(p)$ keeps growing
  - ➡ expect non-linear feedback to set-in

    (Lemoine, Murase & FR 2024)

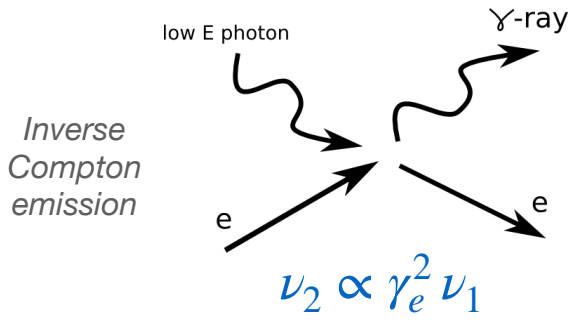
I. On Particle Acceleration in the (kpc-scale) Jet of Centaurus A

(I.) On ultra-relativistic electrons in large-scale AGN jets

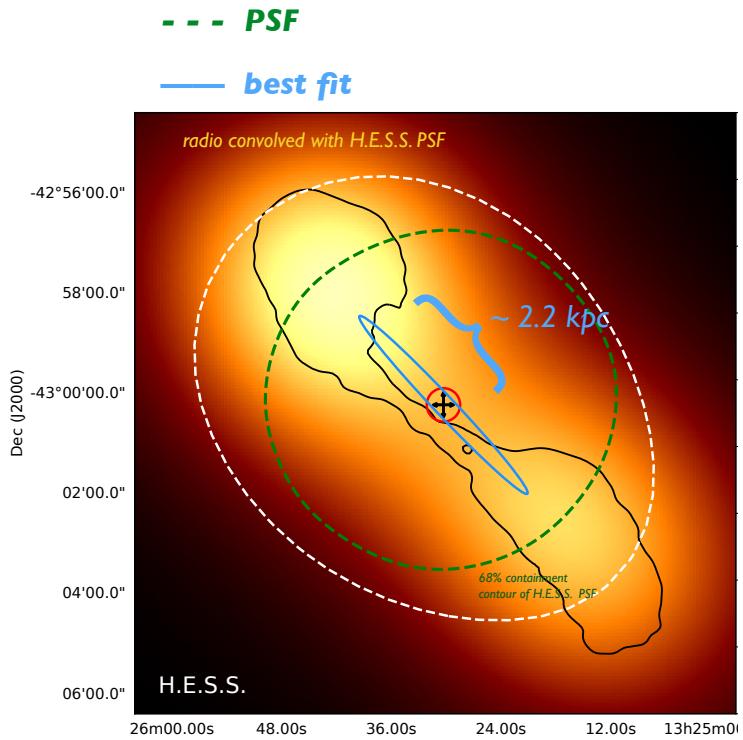


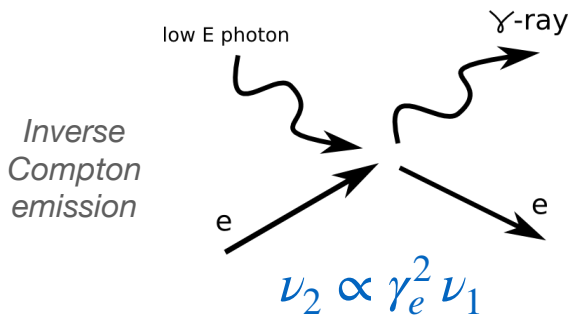
VHE (>240 GeV) **emission along kpc-jet of Cen A**

- 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



(I.) On ultra-relativistic electrons in large-scale AGN jets

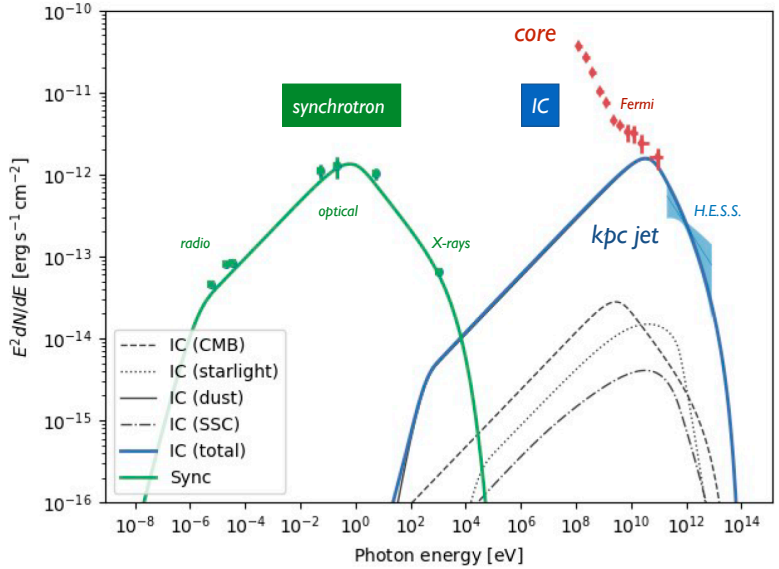




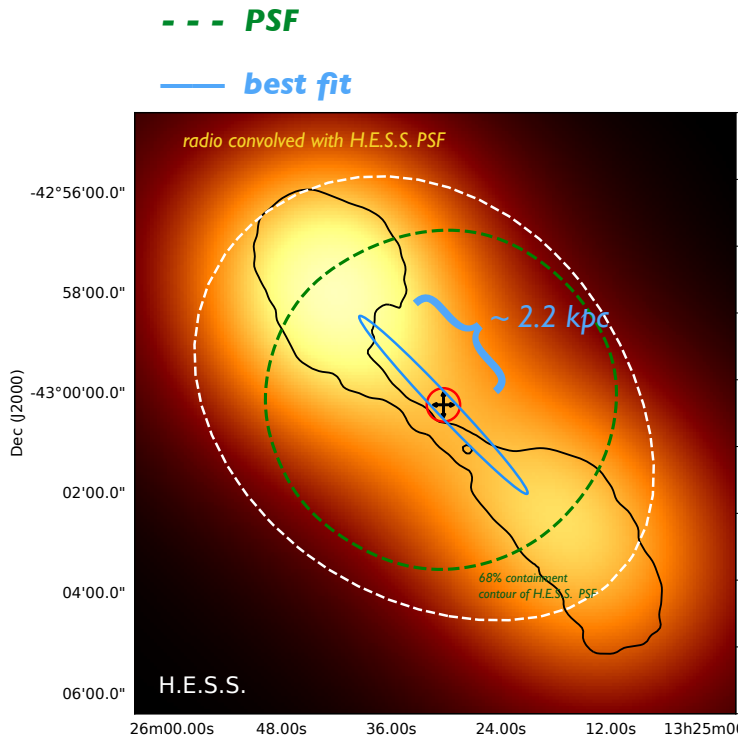
VHE (>240 GeV) emission along kpc-jet of Cen A

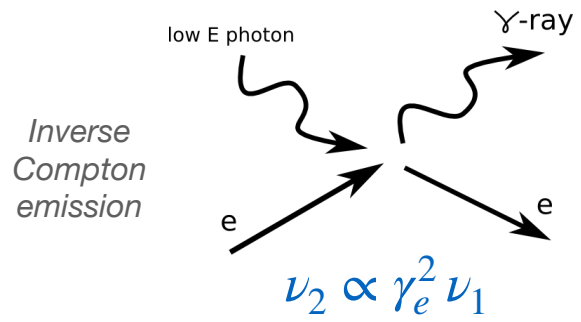
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(H.E.S.S. Collab. 2020, Nature)



(I.) On ultra-relativistic electrons in large-scale AGN jets

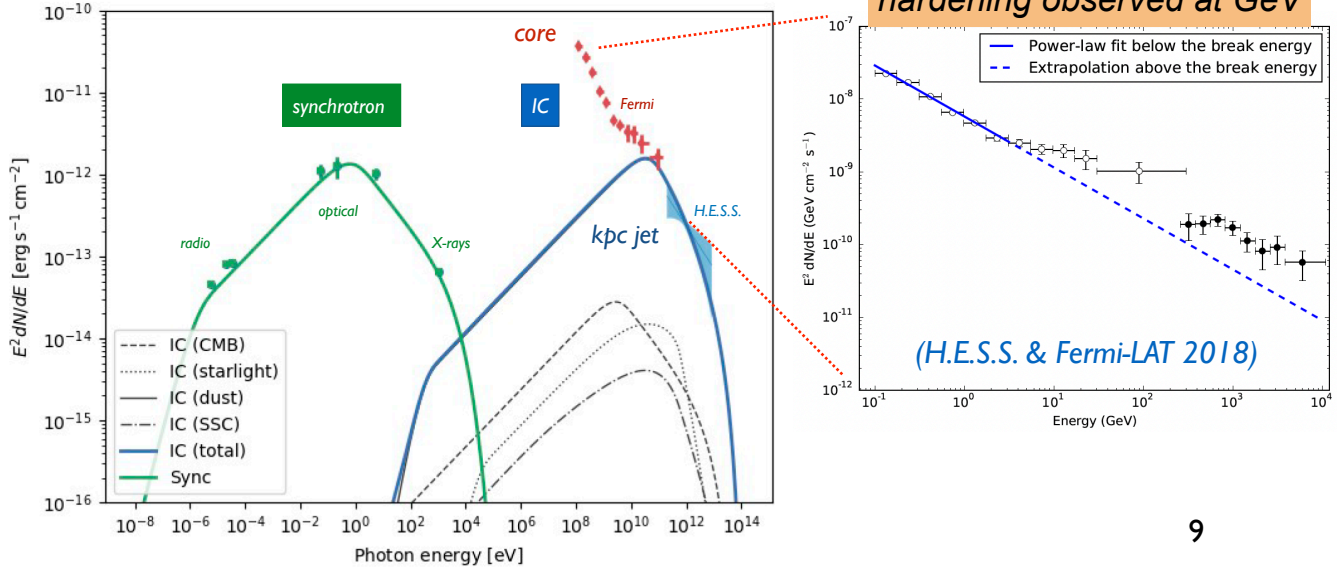




VHE (>240 GeV) emission along kpc-jet of Cen A

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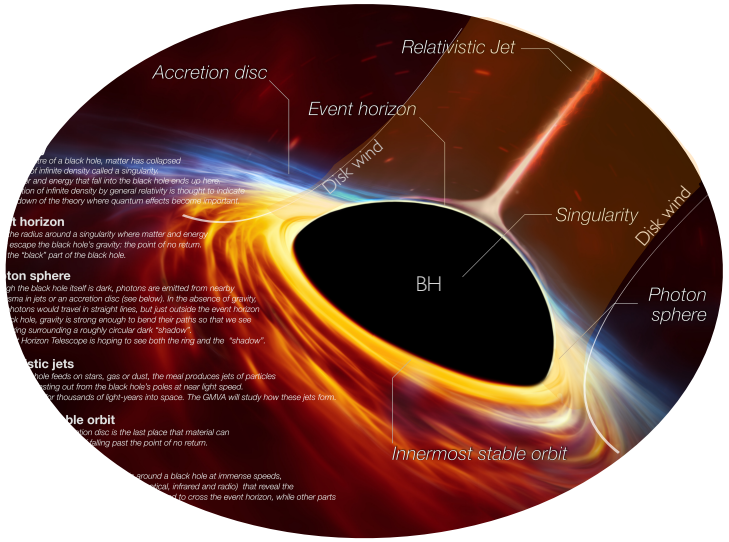


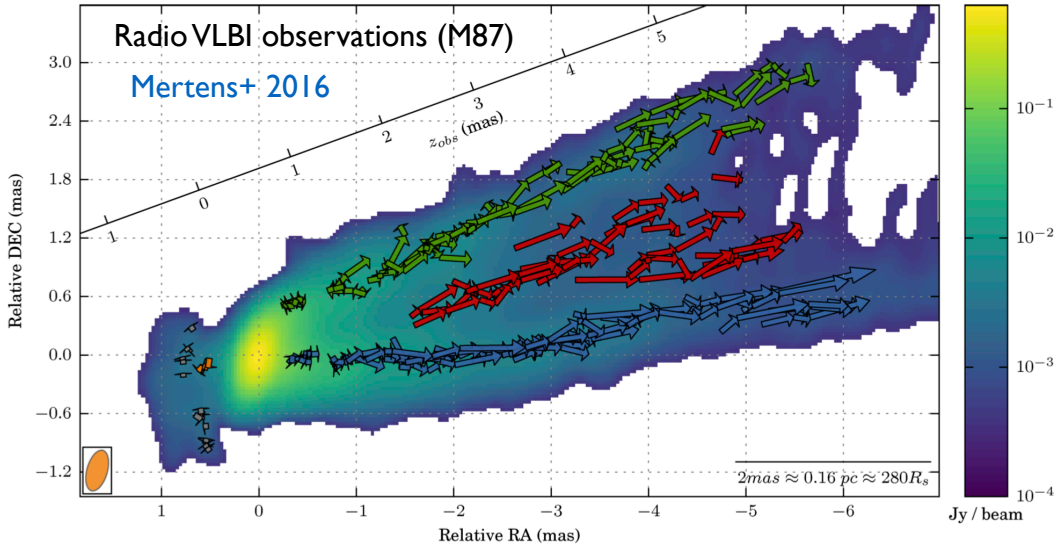
explains unusual spectral hardening observed at GeV

(H.E.S.S. & Fermi-LAT 2018)

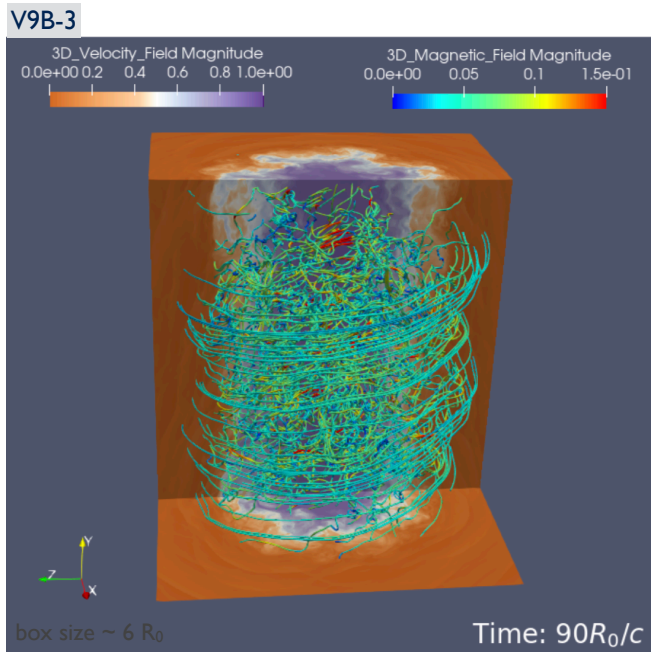
(II.) On the naturalness of velocity shears in AGN jets…

- **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]

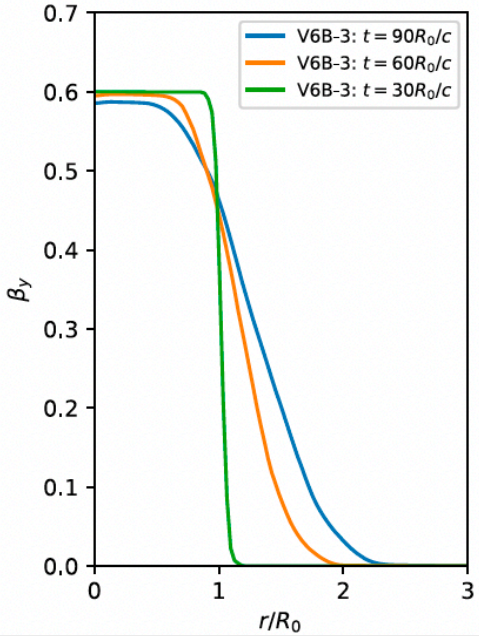




(III.) Self-consistent formation of macroscopic shear layers



jet structure and KHI evolution



(azimuthally) averaged flow velocity profiles

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

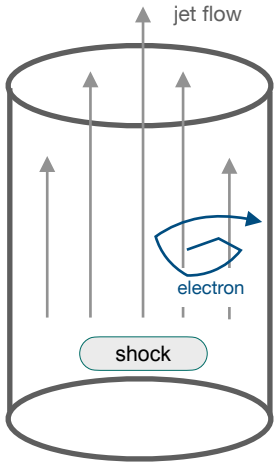
$\sigma_{l,t} = \langle B_{l,t}^2 \rangle / 8\pi\rho_o c^2$

(Wang, Reville, Mizuno, FR & Aharonian 2023)

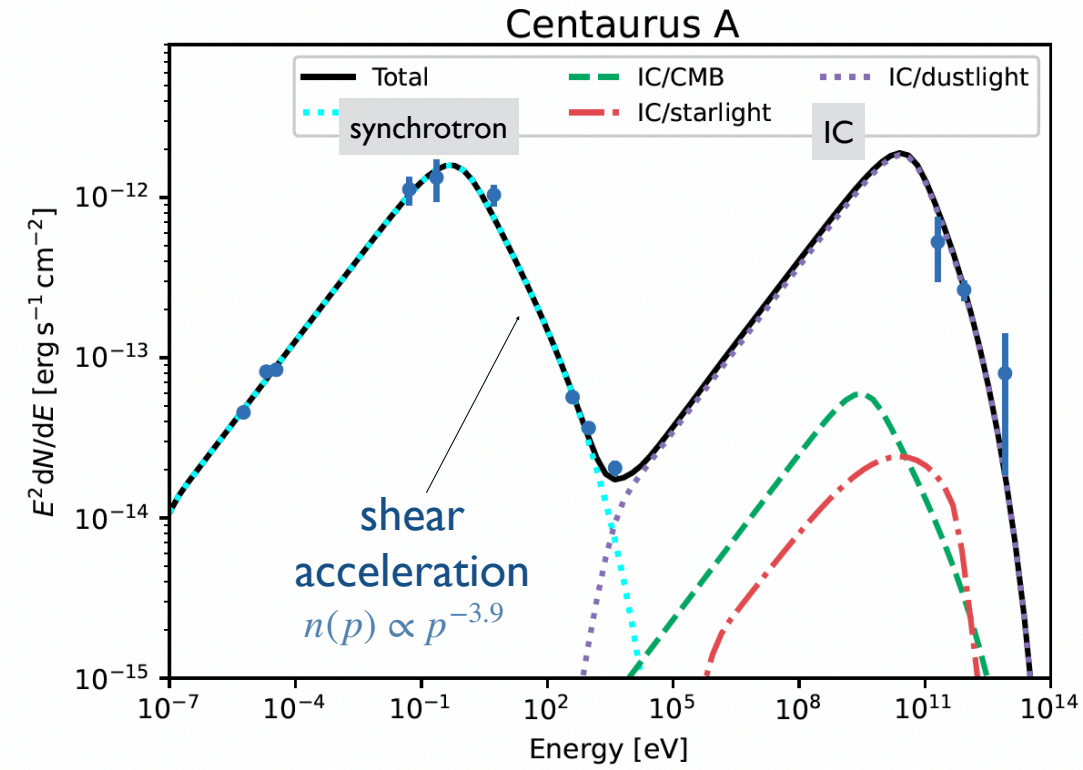
- 3D relativistic jet sims (PLUTO, $v_j/c \in [0.6, 0.99]$) probe KHI sheaths in kinetically dominated flows ($\sigma \in [0.002, 0.2]$)
- study shear flow profile & turbulence spectrum for particle acceleration…
  - *typically* $W_{sh}/R_j \sim 0.2 - 0.5$ *(transition stage) and* $\sim 0.5 - 0.8$ *(deep saturation)…*
  - *Kolmogorov-type (q ~ 5/3) turbulence spectra…*

(IV.) Accelerating electrons to ultra-relativistic energies





Shear Acceleration in Cen A: Fokker-Planck Model $n(p)$ (synchrotron-limited)



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

- SED reproduction with shear - related power-law & shock-accelerated seeds
- Kolmogorov turbulence description $\lambda \propto \gamma^{1/3}$
- quasi-linear velocity shear, with: $\Delta r = 100$ pc, $B = 17$ μG, $\beta_0 = 0.67$
- electron acceleration up to $\gamma_e \approx 10^8$
- estimated (kinetic) jet power $L_j \sim 4 \times 10^{42}$ erg/s
- UHECR acceleration ($E_p \gtrsim 10^{18}$eV)

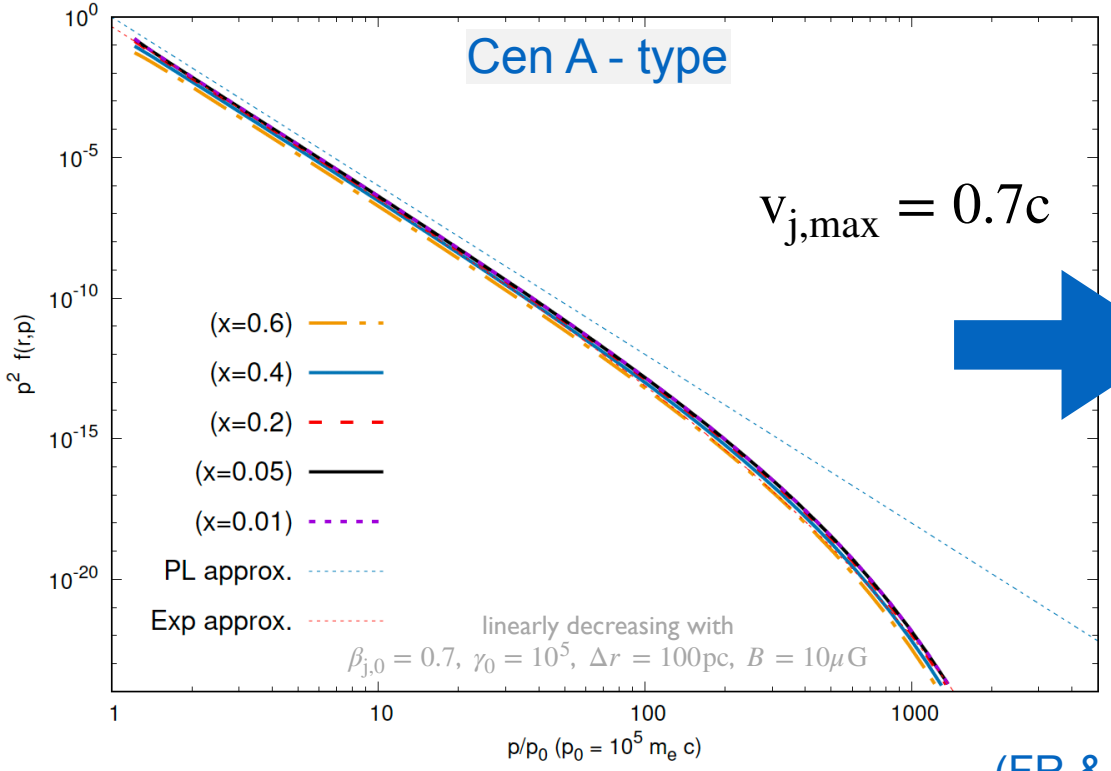
(V.) Accelerating <u>electrons</u> to ultra-relativistic energies



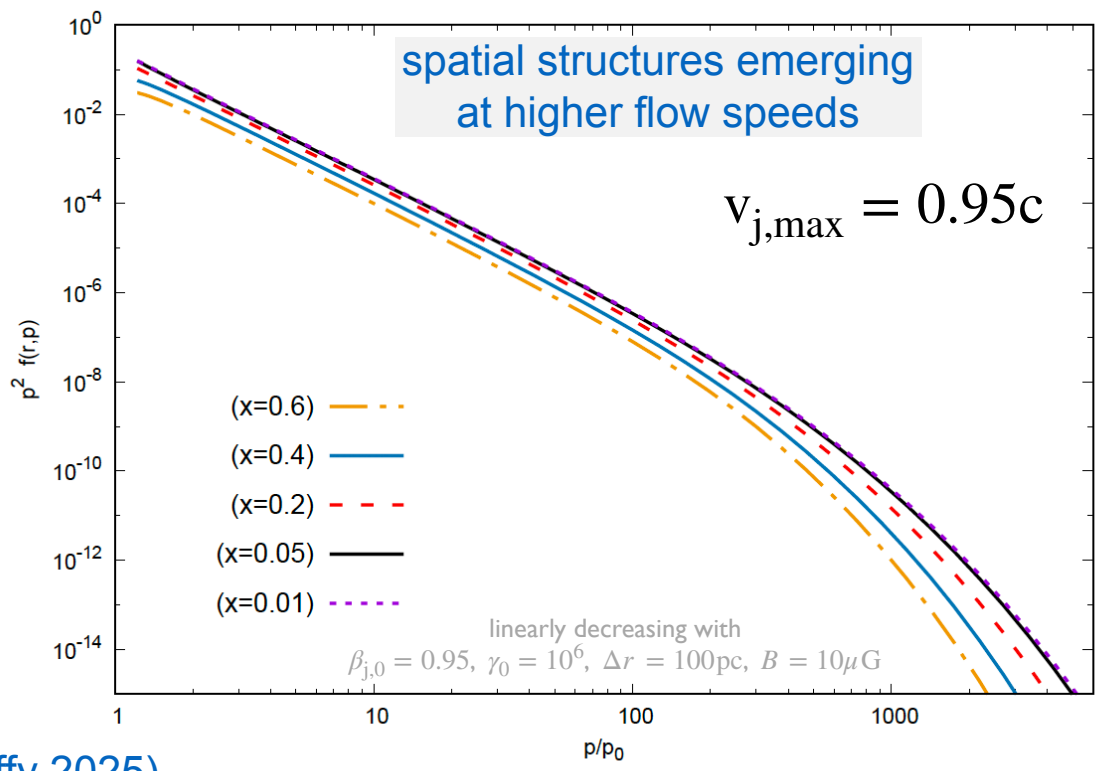
Shear Acceleration in Cen A: Full Transport Theory $n(r,p)$ (synchrotron-limited)

- ➡ **general support for FP modelling approach ($\gamma_{e,max} \sim 10^8$)**
- ➡ sensitivity to jet flow speed & profile

Particle distribution *- numerical solution of relativistic transport equation*

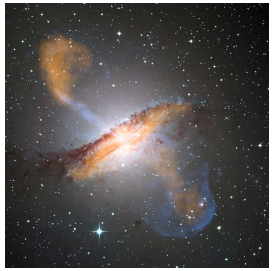


Particle distribution *- numerical solution of relativistic transport equation*



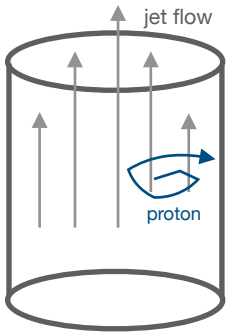
(FR & Duffy 2025)

(VI.) Accelerating protons in kpc-scale radio galaxy jets



High-resolution MHD jet + test-particle simulations

- ➡ *time-integrated particle-spectra mostly peak at ~ 10% Hillas ($E \sim q\beta BR_j$)*
- ➡ *"current" Cen A (FRIc) may account for UHECR (8-32 EeV) dipole anisotropy*



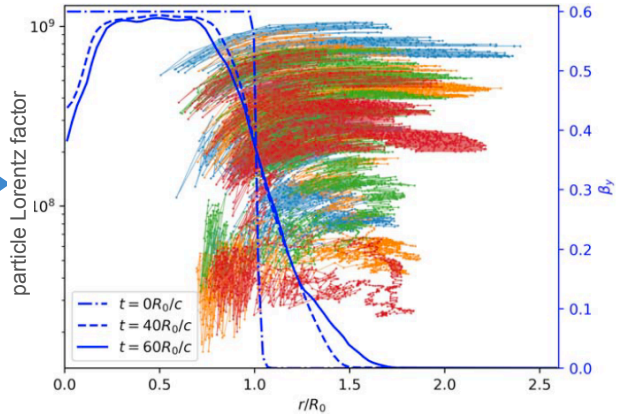
simulations parameters

Runs	β_0	$t_{\rm frozen}$ (R_0/c)	R_0 (kpc)	l_0 (R_0)	Δl (pc)	$\bar{B}_0$ (μG)	Θ_0	$\gamma_{\rm inj}$
FR Ia	0.6	120	0.1	2.6	0.5	27.4	0.05	5×10^7
FR Ib	0.6	60	0.1	2.6	0.5	27.4	0.05	5×10^7
FR Ic	0.6	160	0.1	2.6	0.5	86.9	0.05	9×10^7
FR II	0.9	60	1	3.0	6.0	27.4	0.09	3×10^8

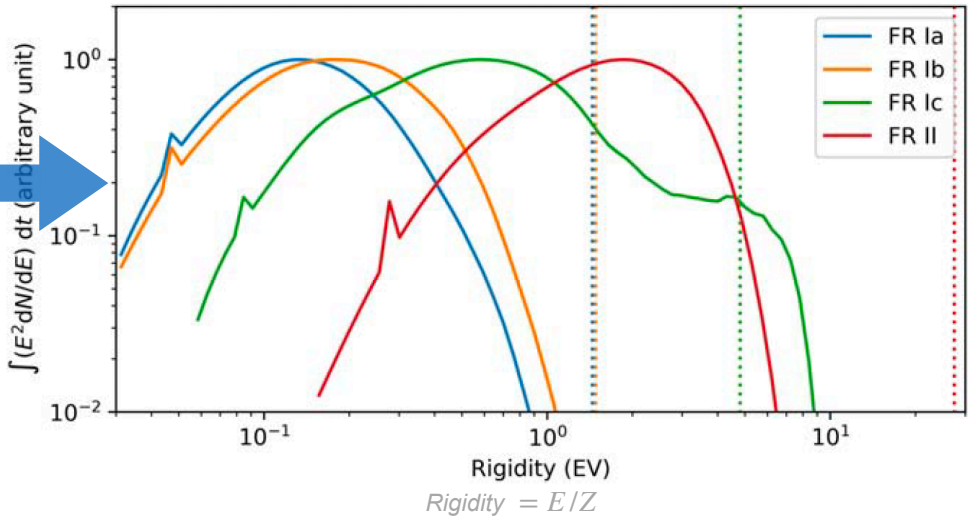
low sigma ($\sigma \sim 0.02 - 0.2$)

(Wang, Reville, FR & Aharonian 2024)

localisation of acceleration



time-integrated particle spectra



Rigidity $= E/Z$

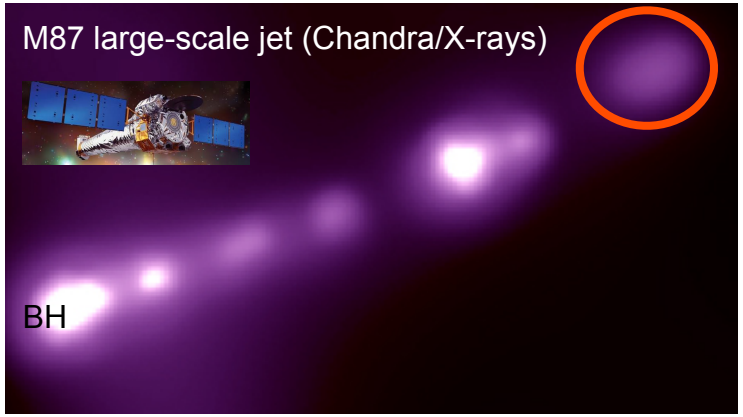
II. On extended VHE emission in M87

High-energy emission from the kpc-scale knots in M87

Wang, +FR , A&A 708 [2026]

High-energy emission from the kpc-scale knots in M87

- **Background**: Comprehensive Chandra re-analysis of FR I jets including M87.

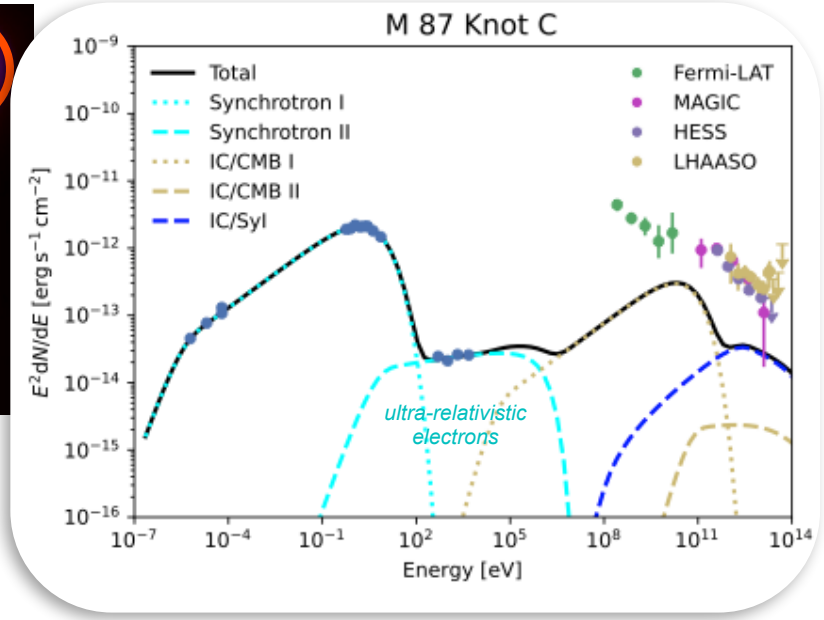


Wang, +FR , A&A 708 [2026]

High-energy emission from the kpc-scale knots in M87

- **Background**: Comprehensive Chandra re-analysis of FR I jets including M87.
- **Trend:** Two e$^-$-populations needed to fit radio-X-ray knot SEDs via synchrotron $(B \sim 10\mu\mathrm{G})$.

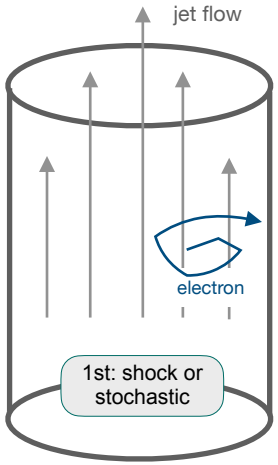




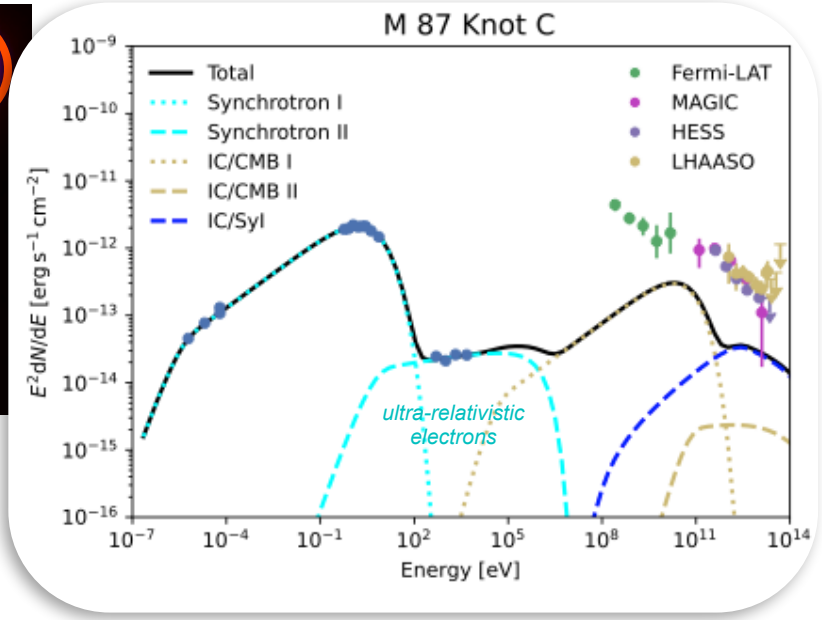
Wang, +FR , A&A 708 [2026]

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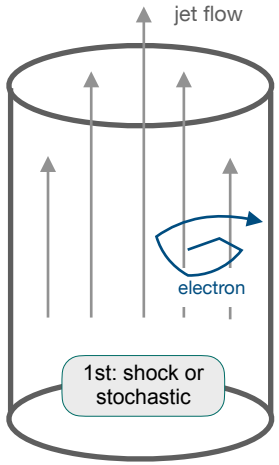




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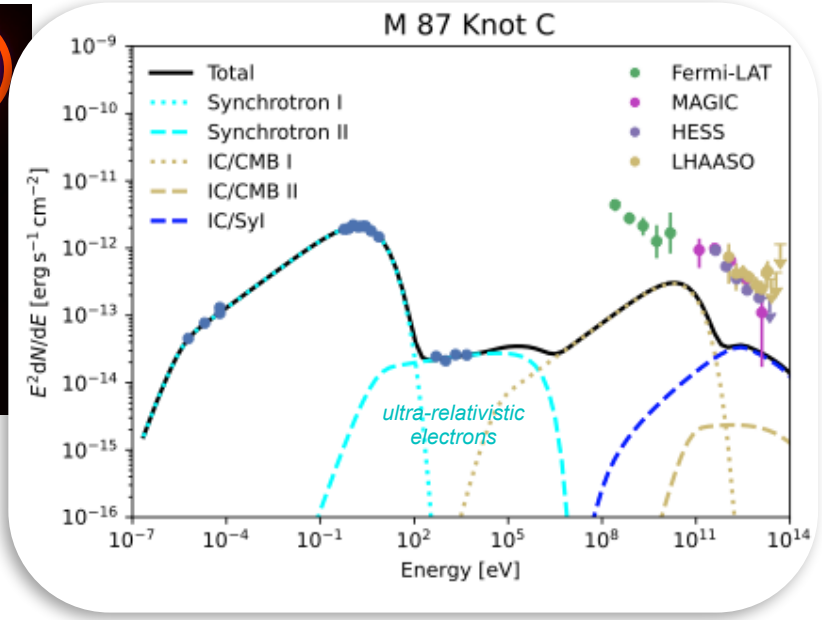
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- **Implication:** IC-(CMB**+**Syn) of all components in M87 ~ VHE low-state emission

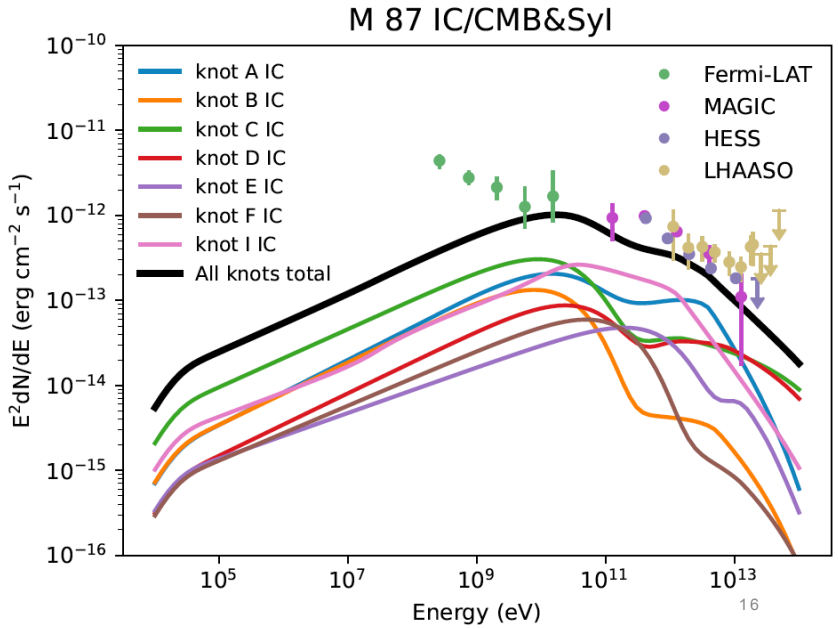


⇒ ***IC emission from large-scale jets may account for (steady) VHE low states*** (cf. Tavecchio 2025 for 3C273)



Wang, +FR , A&A 708 [2026]





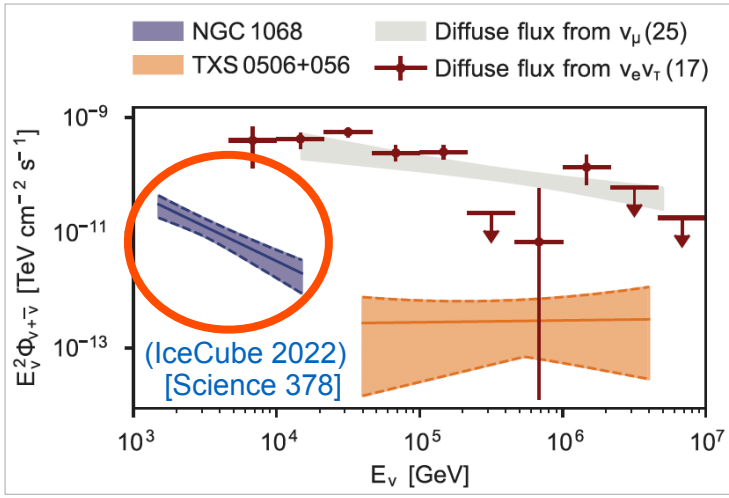
III. On Cosmic-Ray Acceleration in Seyfert Galaxies

I. Cosmic-ray acceleration in Seyfert (jetted) coronas

(Lemoine & FR 2025)

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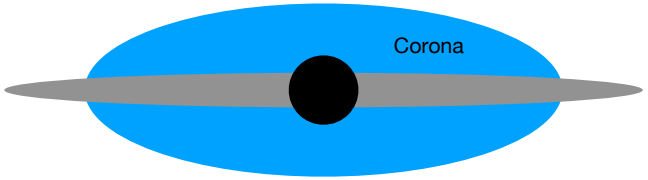
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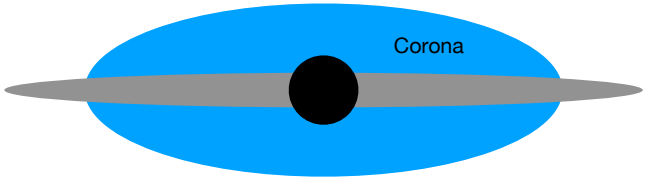
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TOY MODEL: couple diffusive Fokker-Planck model:

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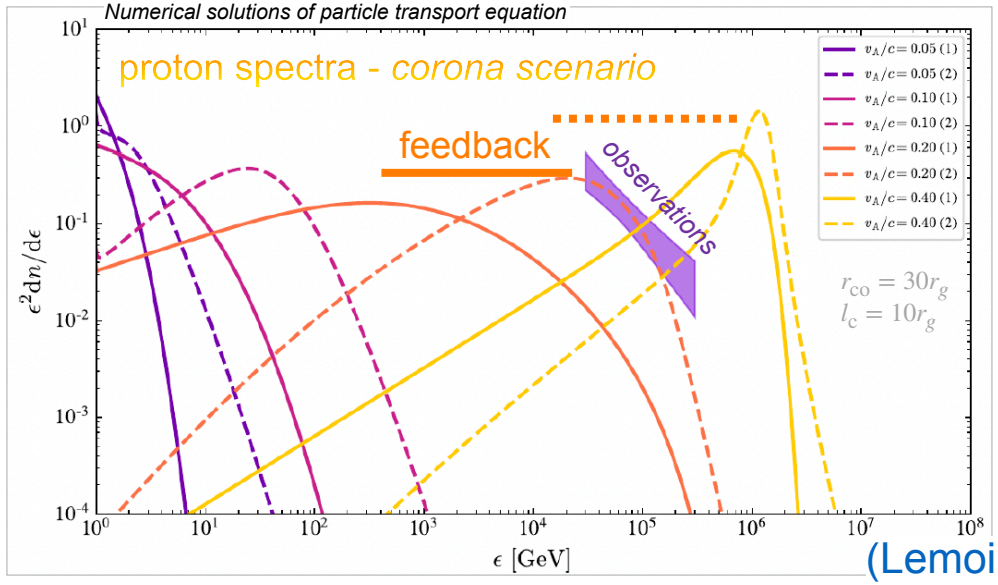
with $\epsilon_p \propto p^2 n(p) \propto p^4 f(p)$ particle energy spectrum

+

to turbulent energy cascade model

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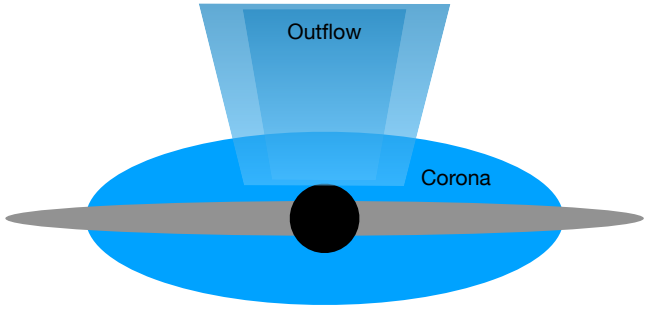
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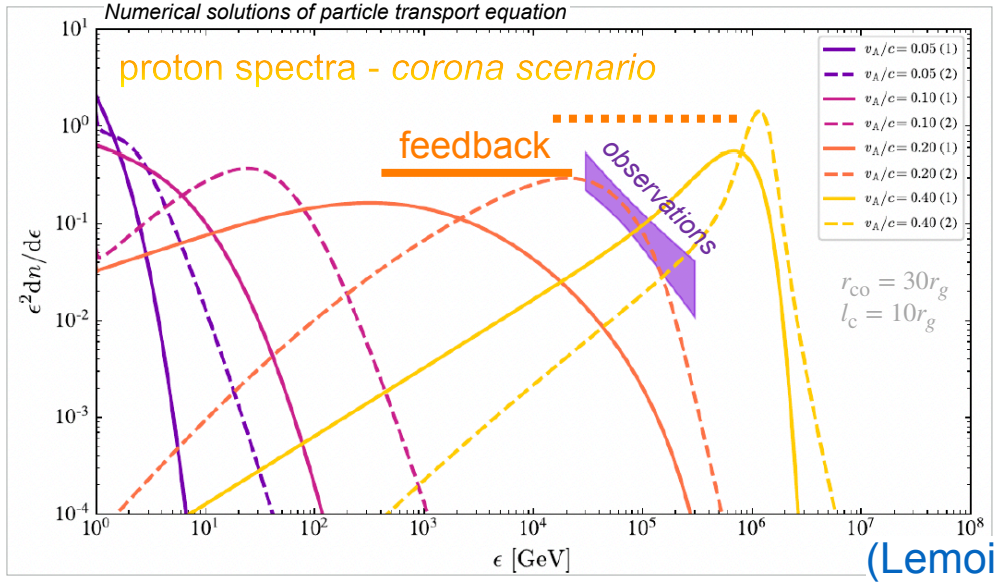
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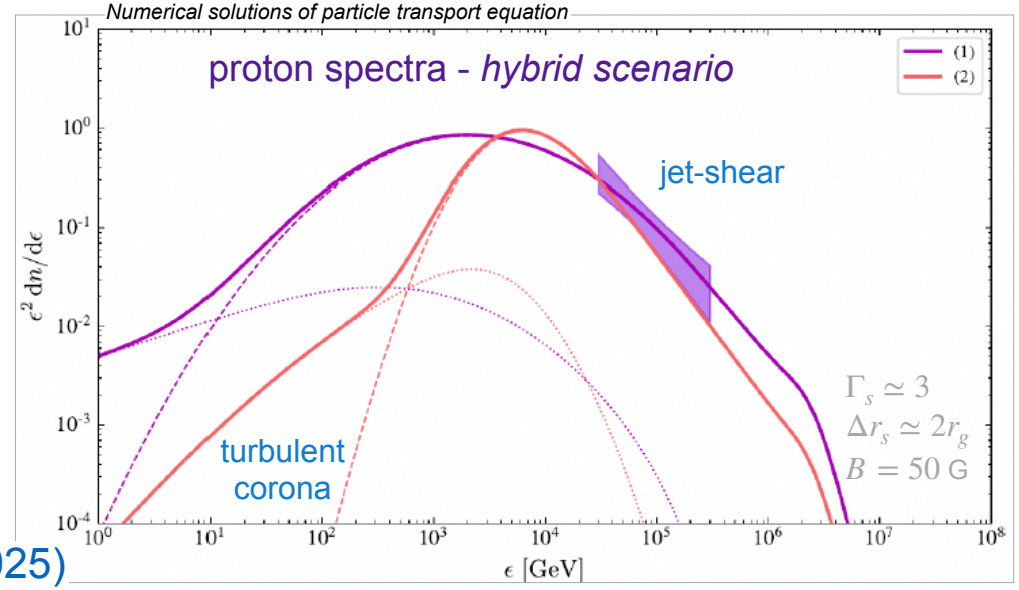
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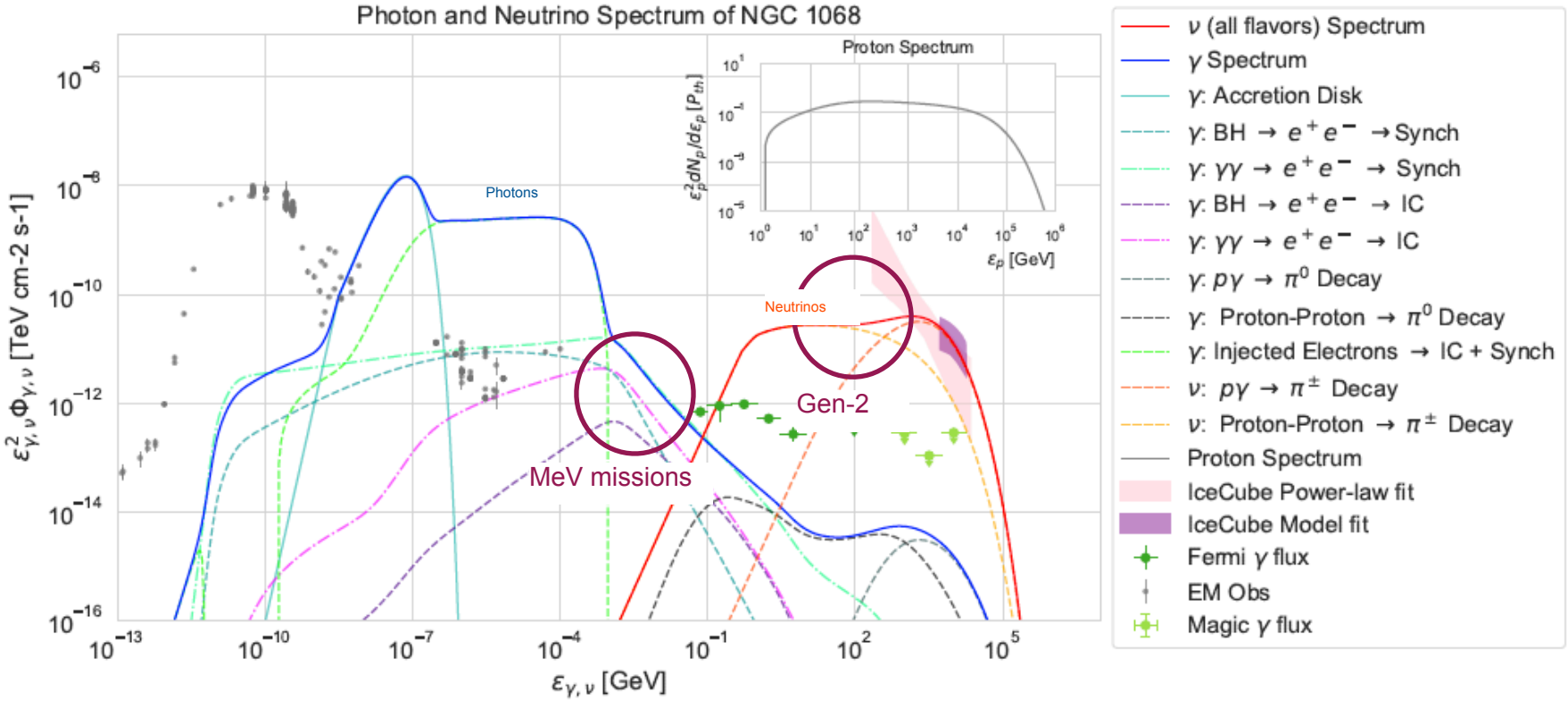
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II. *Example:* Cosmic-ray acceleration by strong turbulence

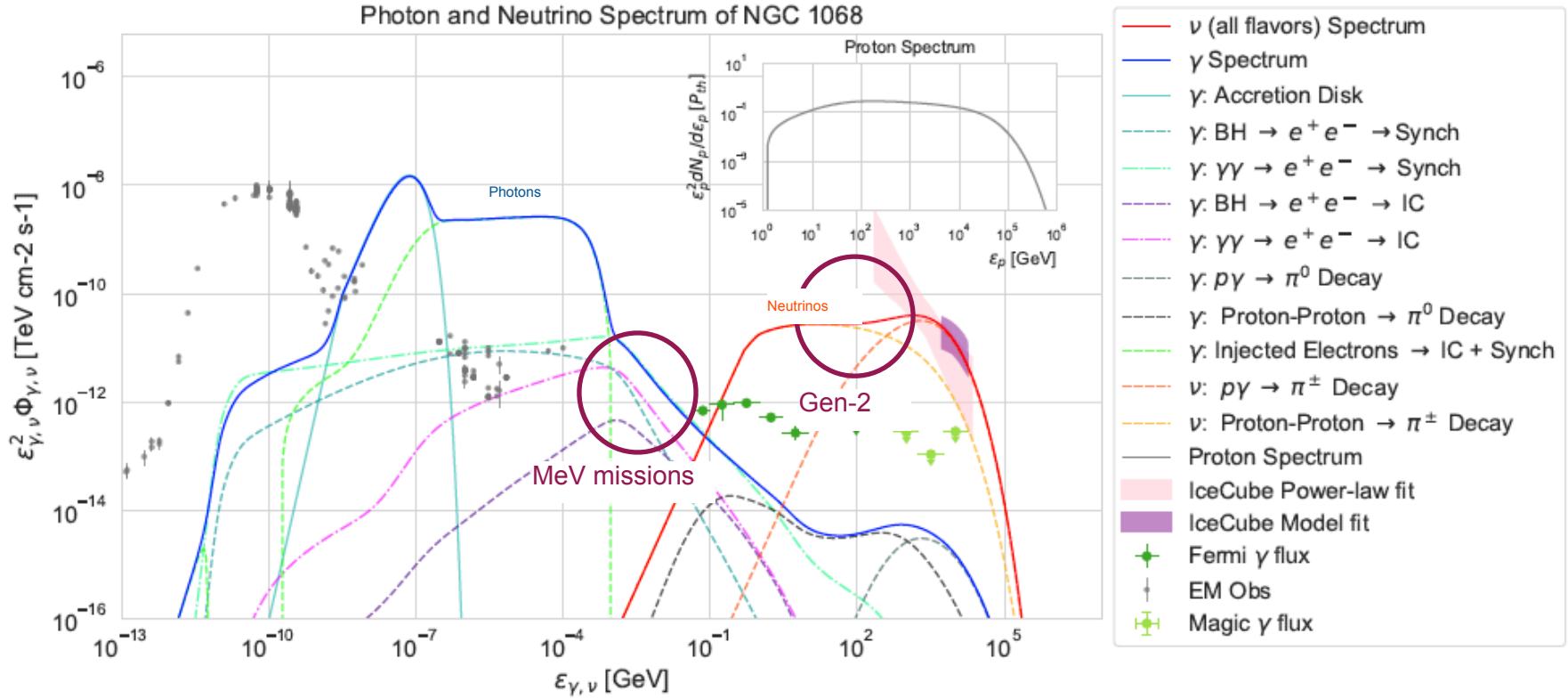


(Le Bihan, Lemoine & FR 2026)

$L_d = 5 \times 10^{44}$ erg/s, $r_{\rm co} = 15 r_g$, $\xi_p = 0.3$; $l_c = r_{\rm co}/3.5$, $v_{\rm adv} = 0.03c$, $v_{\rm A} = 0.25c$,

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- **Enables:** Predictive broadband modelling across energy bands.



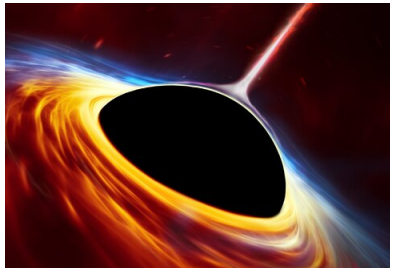
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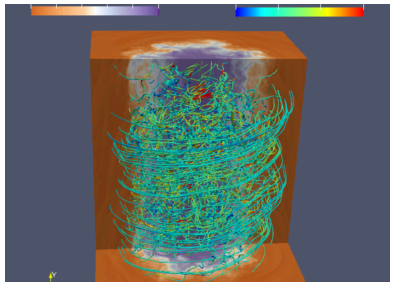
Turbulent shearing flows are ubiquitous in astrophysics

⇒ ***fast*** *(jetted) flows facilitate* ***efficient stochastic-shear*** *particle acceleration*



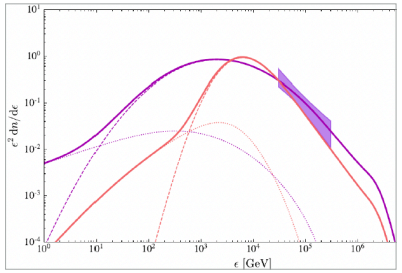
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  ⇒ *up to ~ 'Hillas' for sufficiently high magnetization ~ UHECR dipole anisotropy*



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- **In general:** ⇒ *may in reality see hybrid acceleration at work*

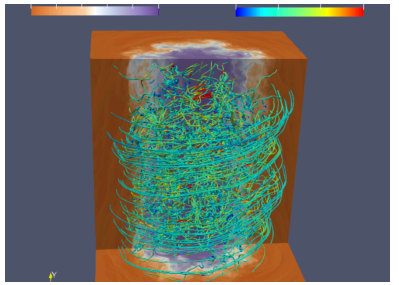
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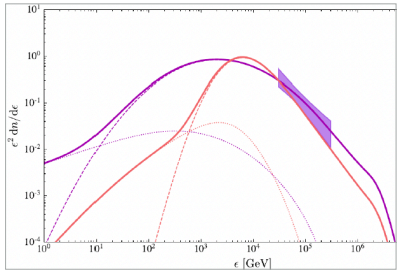
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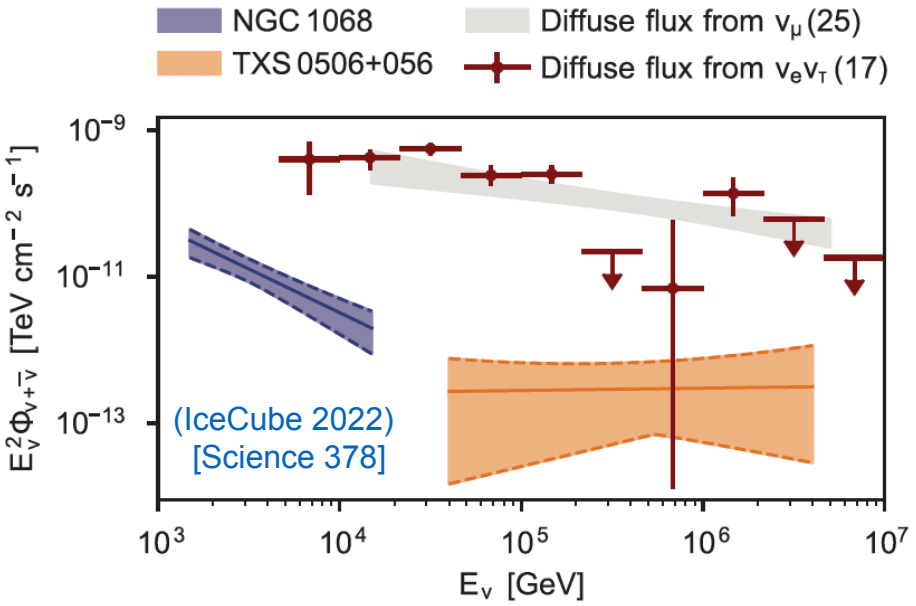
Thank you! Questions =)

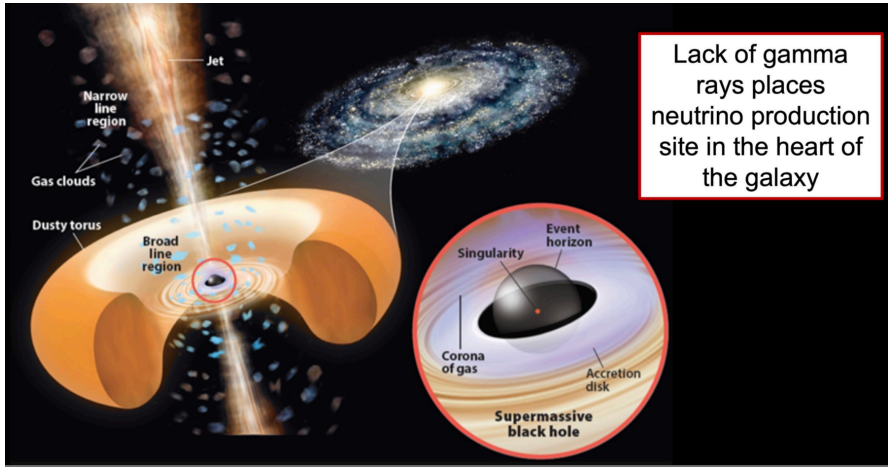
BONUS

Stochastic Particle Acceleration in (jetted) BH corona

IceCube Neutrino (Candidate) Source NGC 1068:

- ~80 HE neutrinos from direction of NGC 1068
- nearby (10 Mpc), X-ray bright ($L_x \sim 10^{44}$ erg/s) Seyfert AGN
- BH mass ~10^7 M_{sun},, weak jet L_{jet} ~10^{43} erg/s ~ $L_{acc}/10^{2\text{-}3}$
- *isotropic* equivalent: $L_\nu(1.5-15\ \mathrm{TeV}) \sim 3\times10^{42}$ erg/s
- steep neutrino spectrum: $n_\nu(\epsilon) \propto \epsilon^{-3}$
- absence of VHE γ-rays (MAGIC) points to compact region
  ⇒ BH environment ⇒ turbulent (jetted) corona?
- *would need to accelerate protons to ~ (30-300) TeV*





Stochastic Particle Acceleration - Nonlinear Aspects

Toy Model:

- couple common diffusive Fokker-Planck model

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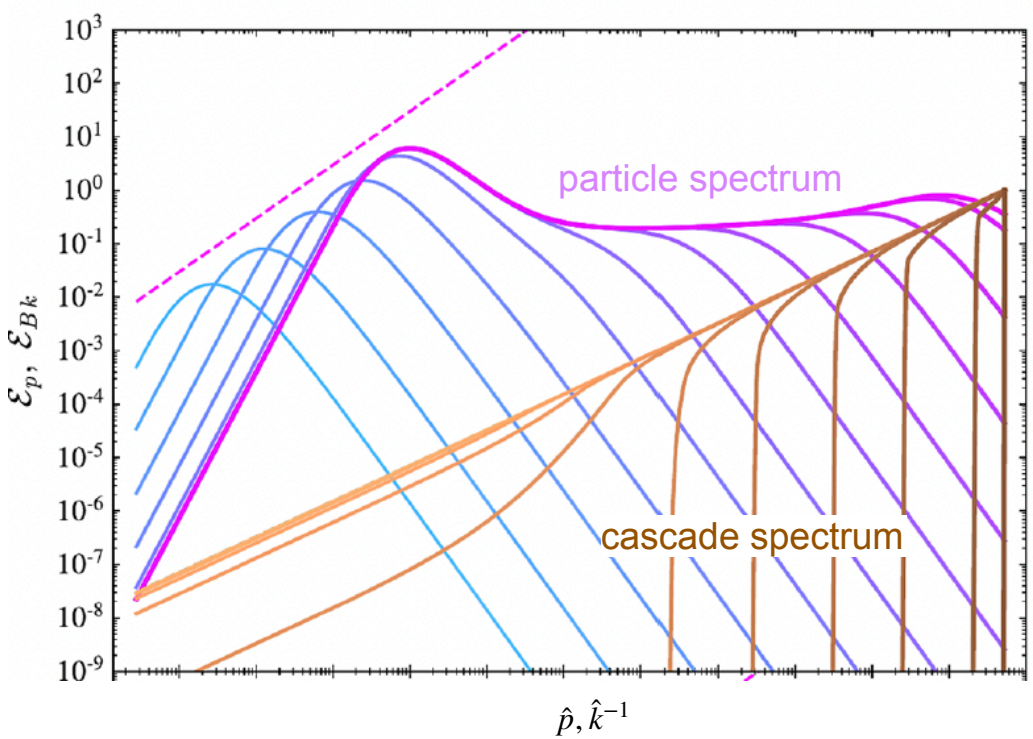
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$\gamma_k = k\delta v_k$ turbulent energy transfer rate ($\delta v_k \propto \epsilon_{Bk}^{1/2}$)…
considering gyro-resonance type conditions ($r_\mathrm{L} = pc/cB \sim k^{-1}$)

➡ **feedback** (damping at all scales $k \gg (1/\hat{p}_{max})$)
when energy flow along cascade integrated over time ~ peak energy → shapes $n_{\mathrm{nl}}(p) \propto p^{-2}$

(Lemoine, Murase & FR 2024)



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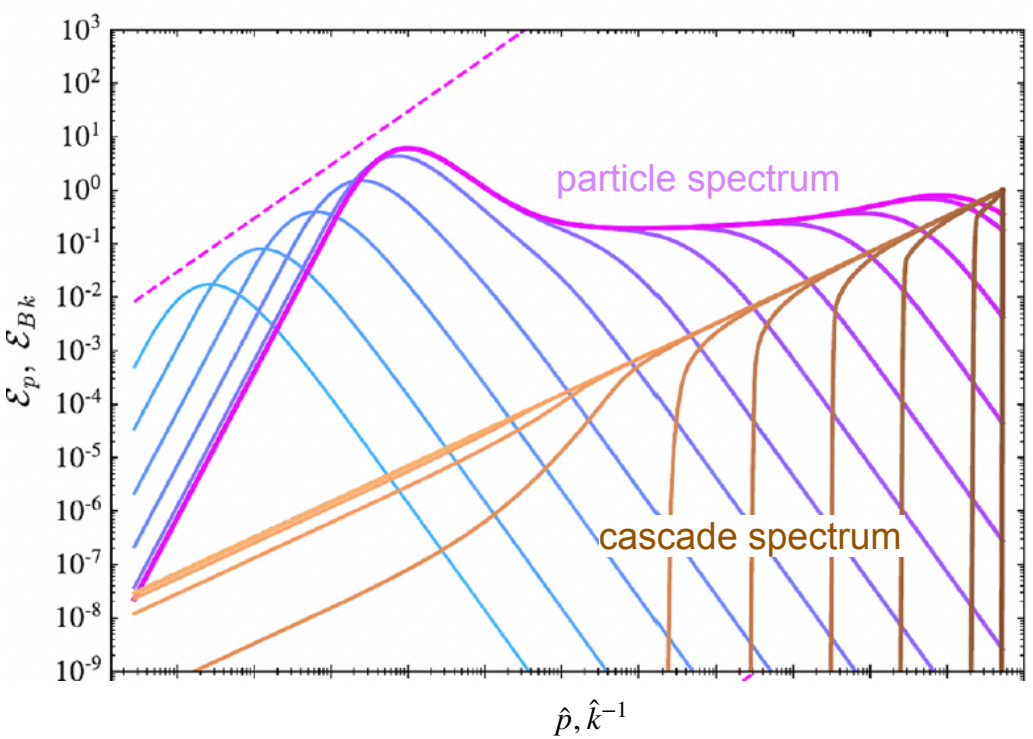
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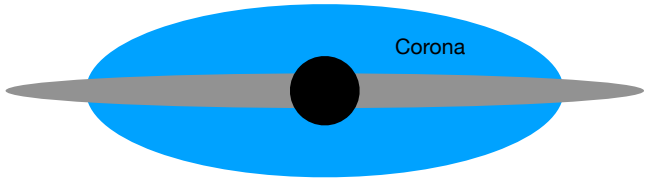
(Lemoine, Murase & FR 2024)



relevance for Neutrino - AGN (Seyfert) where substantial amount of energy needs to go into acceleration of protons

Stochastic Particle Acceleration in (jetted) BH corona

(I) Acceleration in the BH Corona of NGC 1068



expect non-linearity when

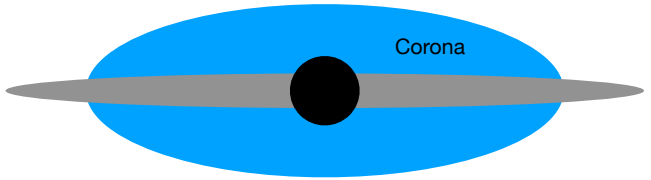
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with $t_{\rm acc} \sim (c/v_A)^2\,(\ell_c/c)$ for strong MHD turbulence, ℓ_c coherence length…

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- can reproduce spectrum with reasonable set of parameters
- no ad-hoc normalisation (self-regulation)
- close to (radiation-limited) cut-off region, ⇒ expect increasing curvature
- *more complex shapes possible if r-distribution of Alfven speeds…*

(Lemoine & FR 2025)

Numerical solution of particle transport equation

