Turbulent plasmas as high-energy particle accelerators: (some) theory and applications

Martin Lemoine

Astroparticule & Cosmologie (APC)

CNRS – Université Paris Cité

Outline/summary:

→ Theoretical modeling of stochastic particle acceleration:

… generalized Fermi mechanism in sharp field bends and compression regions

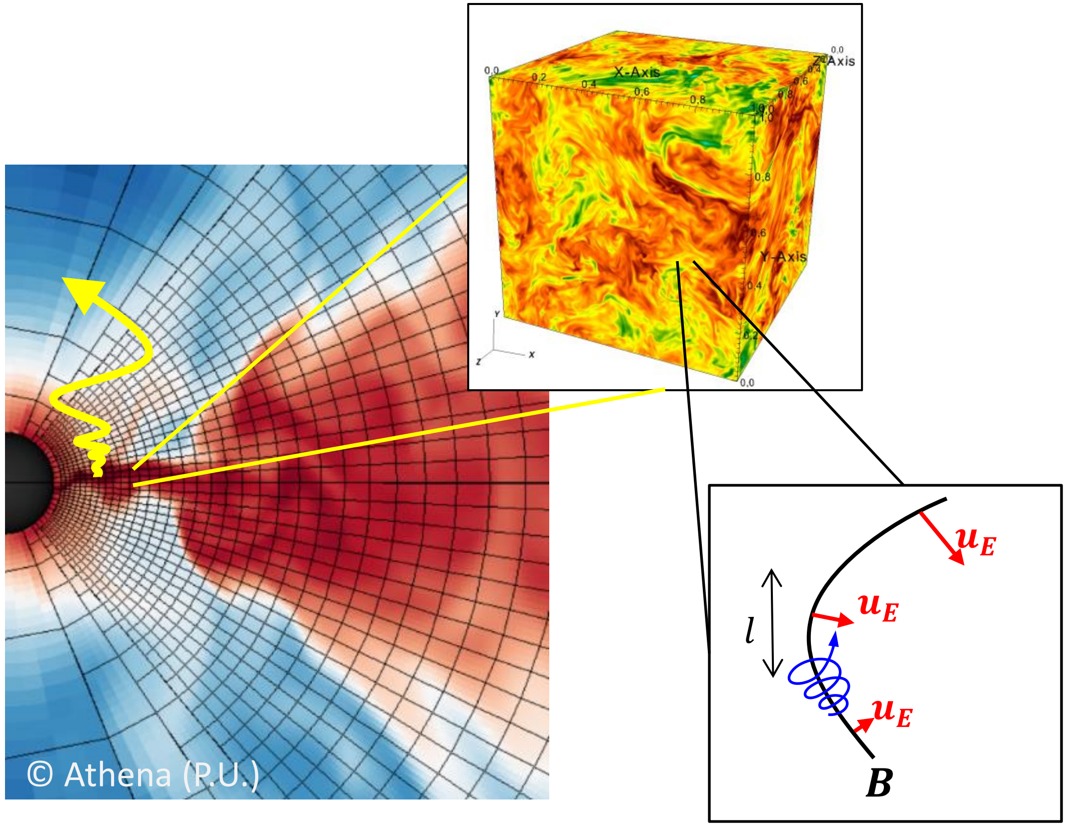
→ Application to PWNe and Crab flares

… relativistic turbulence as an extreme particle accelerator, radiation at synchrotron burn-off limit

→ Application to AGN coronae as neutrino sources

… turbulent co-energization of electrons and protons in BH corona

→ natural account of X-ray (leptonic) and neutrino (TeV) spectra



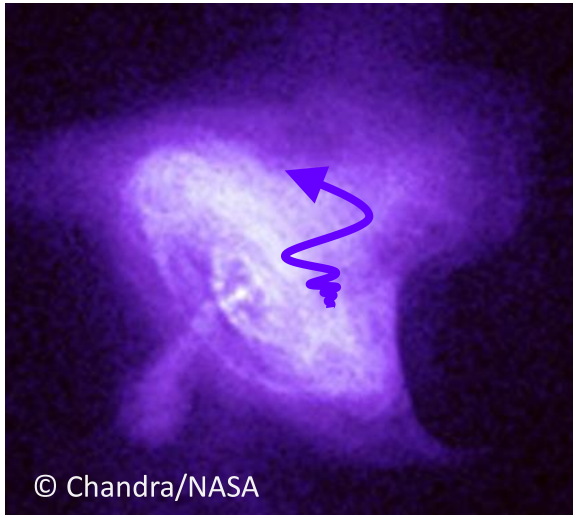
Stochastic particle acceleration in turbulence: a universal scheme in astrophysics

→ dissipation/acceleration in any turbulent plasma,
with efficient acceleration at large magnetization σ, large amplitude $\delta B/B$

<u>magnetization:</u> σ = magnetic energy dens. / plasma energy dens.
$\sim$ (rms eddy velocity/c)^2

e.g, ISM: $\sigma \sim 10^{-9}$... but in VHE sources, $\sigma \gtrsim 0.01$

here: relativistic turbulence: $\sigma \gtrsim 0.1$ meaning eddy velocity $\sim c$



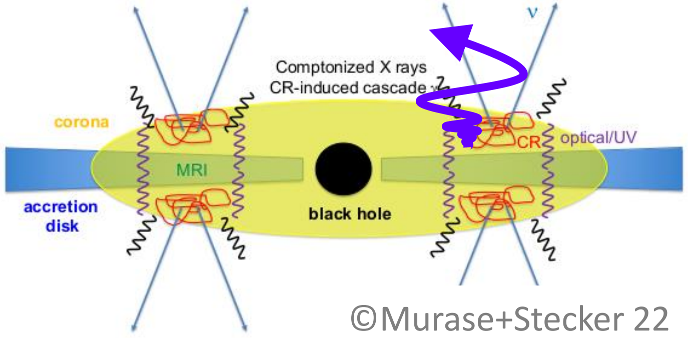
… in pulsar wind nebulae

→ a stochastic process of acceleration:

… particles move in energy space by energy gain- or loss- interactions in randomly oriented electric fields

… specific virtues: efficient over broad range of σ + hard spectra expected

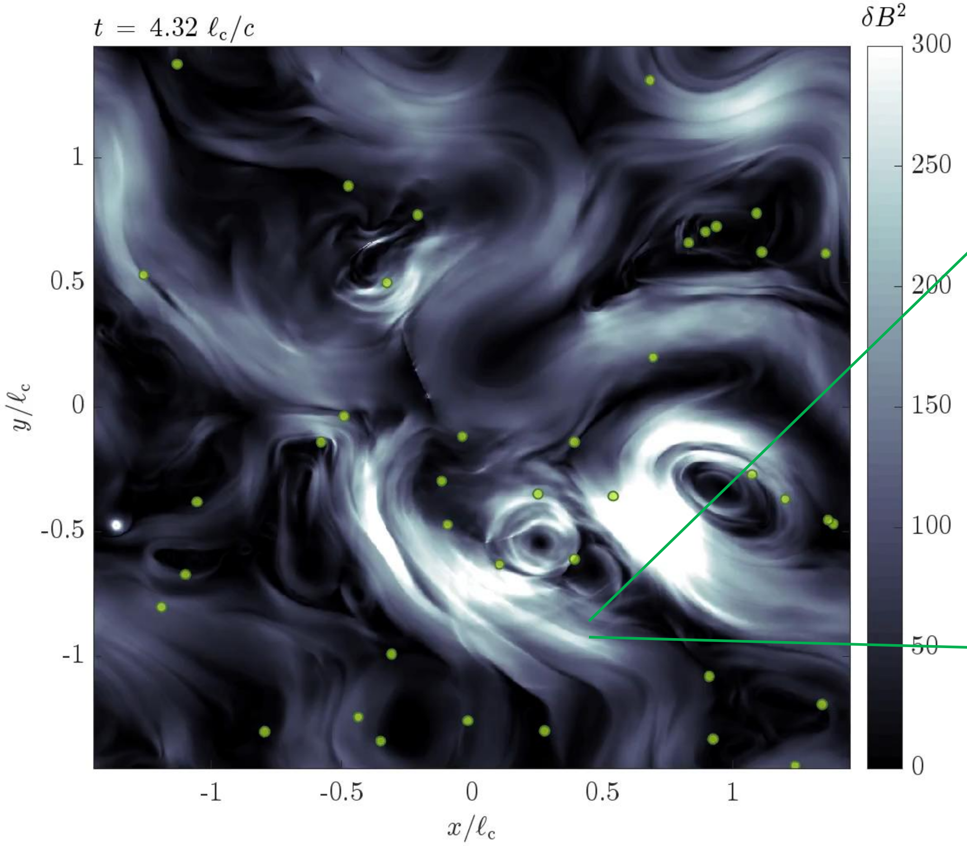
… long-standing question: acceleration physics?



… in black hole environments

Microphysics of particle in turbulent plasmas: simulations & theory

→ **recent progress:** MHD + kinetic (PIC) numerical simulations[1] offer direct probes of particle acceleration in turbulence… raising new questions and a direct measurement of acceleration rate (diffusion coefficient)



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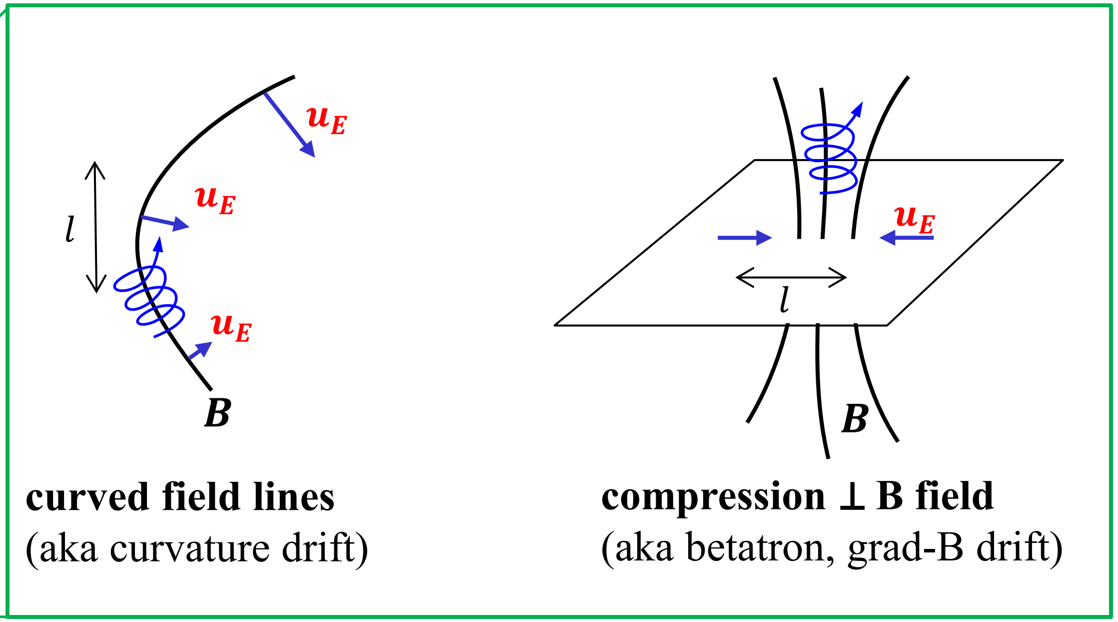


→ **important:** PIC simulations remain limited to small spatio-temporal scales relative to astrophysical phenomena… theoretical extrapolation needed: theory[2]

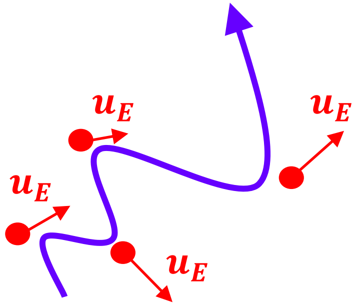
Refs: 1. Dmitruk+03, …, Isliker+17, Pecora+18, Zhdankin+2017, Comisso+Sironi 18,19, Wong+20, Trotta+20, Pezzi+22, Pugliese+23, Wong+25,…
2. M.L. 19 [PRD 99, 083006 (2019)], 21 [PRD 104, 063020 (2021)], 22 [PRL 129, 215101 (2022)], 25 [PRE 112, 015205 (2025)];
+ previous works by Webb 85, Bykov+Toptygin 83, Ptuskin 88, Chandran+Maron 04, Cho+Lazarian 06, Petrosian 12, Ohira 13, Brunetti+Lazarian 16, …

Standard implementation of stochastic acceleration in VHE sources... + outline

→ **standard modeling:** Fokker-Planck approximation for diffusive processes, fully characterized by diffusion coefficient $D_{\varepsilon\varepsilon}$

$$\partial_t n_\epsilon = \partial_\varepsilon \left(D_{\varepsilon\varepsilon} \partial_\varepsilon n_\varepsilon \right) + \ldots \qquad \text{with } n_\varepsilon \equiv \mathrm{d}n/\mathrm{d}\varepsilon$$

→ functional form of $D_{\varepsilon\varepsilon}(\varepsilon, v_A, \delta B/B, \ell_c, \ldots)$ ← acceleration theory… but, which theory?



the Fermi pinball[1]?

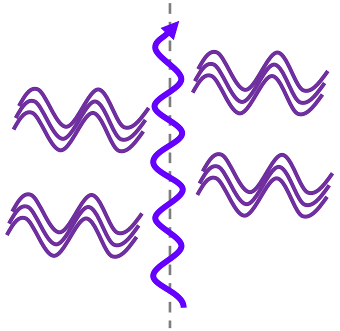
… discrete, point-like interactions
… $\mathbf{E} = \mathbf{0}$ in scattering center rest frame
… net gain: head-on vs tail-on (?)

… however, generalization to turbulence?

resonant wave-particle interactions[2]?

… perturbative calculation of $D_{\varepsilon\varepsilon}$

… however, waves or structures?



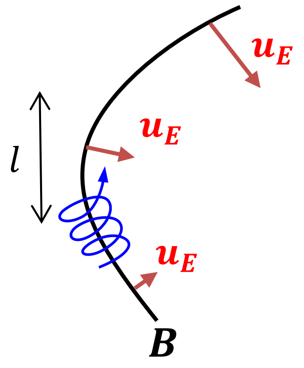
→ here: all about "generalized Fermi" = generalizing Fermi idea to continuous random flow for turbulent plasmas
→ new, interesting phenomenological signatures tested on simulations
+ applications to cases of interest

Refs: 1. e.g., Fermi 49, 54, … 2. e.g. Schlickeiser 84, ….

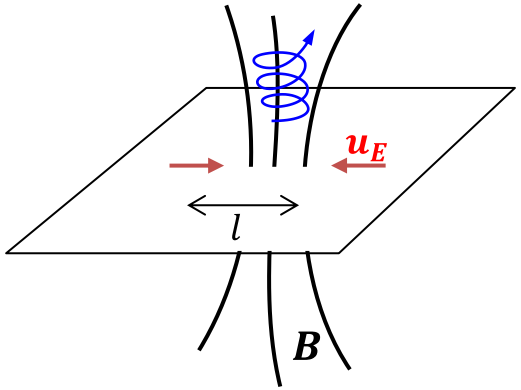
Generalized Fermi acceleration: stochastic acceleration in a continuous random flow

→ an effective theory, covariant & non-perturbative, for modelling stochastic particle acceleration

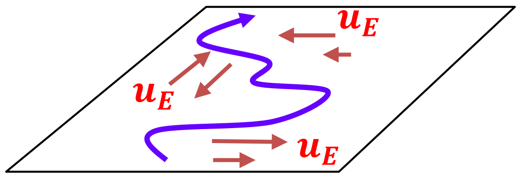
⇒ main interaction diagrams:



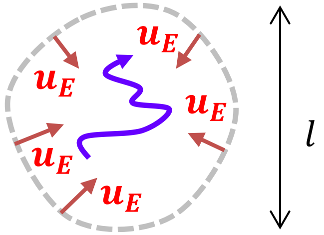
dynamic, curved field line
(aka curvature drift)



dynamic compression ⊥ B field
(aka betatron)



turbulent sheared flow



large-scale compressions
(aka magnetic pumping)

close to original intuition by Fermi!
(cf Fermi 1949)

in large-amplitude turbulence $\delta B/B \gtrsim 1$, curvature + ⊥ compression provides dominant contribution to acceleration due to strong non-gaussianity (intermittency) of random forces

Refs: 1. M.L. 19 [PRD 99, 083006 (2019)], M.L. 21 [PRD 104, 063020 (2021)], M.L. 22 [PRL 129, 215101 (2022)], M.L. 25 [PRE 112, 015205 (2025)]
based on previous work by G. Webb (1985, 1989)

Application to large-amplitude turbulence: $\delta B \sim B$

→ key features:

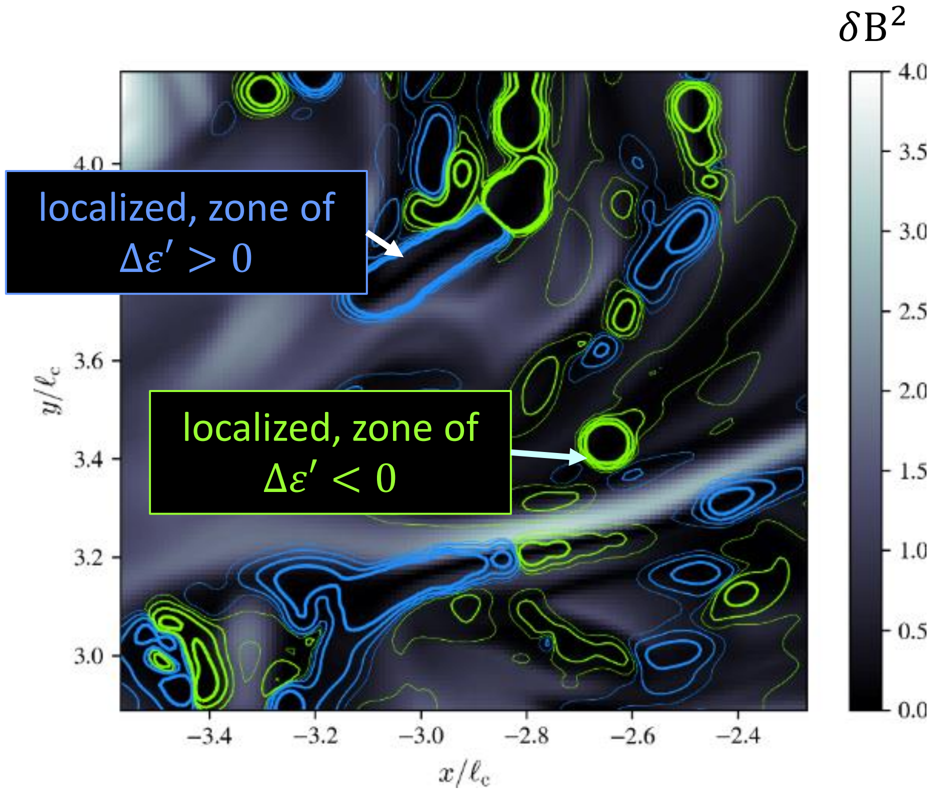
… energy loss/gain from localized regions of strong gradients of $\boldsymbol{u_E}$ (on some scale l)

… exponential energy loss/gain while in an accelerating/decelerating structure

$$\frac{\mathrm{d}\varepsilon'}{\mathrm{d}t'} \approx \pm\Gamma_l\,\varepsilon' \quad \text{with} \quad \Gamma_l \sim \mathcal{O}(\Delta u_E/l)$$

⇒ acceleration = non-Brownian diffusion, succession of intense episodes of gain/loss

⇒ diffusion coefficient = insufficient statistics for predicting particle energy distribution[1]



→ remarks:

… a generalized transport equation accounting for pdf(Γ_l): Ref.[2] + comparison to test particles in MHD sim.

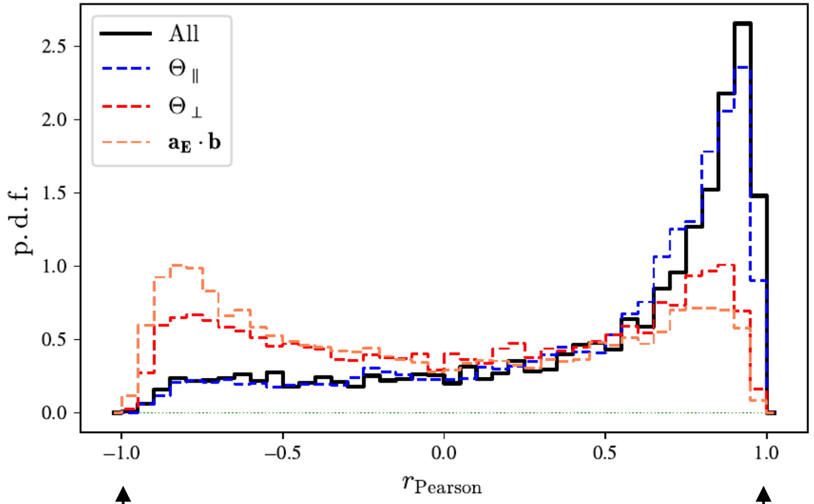
… role of field line curvature in acceleration (+transport) supported by other studies[3]

Refs: 1. M.L. + Malkov 20 2. M.L. 22 [PRL 129, 215101 (2022)] 3. e.g., M.L. 23, Kempski+23, 25, Boldyrev+25, Mbarek+26, Golant+26

Generalized Fermi acceleration: test on numerical experiments (PIC + MHD)

→ test[1]: for each particle history in a simulation, reconstruct $\varepsilon'_{\rm th}(t)$ using theoretical model and velocity gradients measured in the simulation at $\boldsymbol{x}, t$…
… then measure degree of correlation $r_{\rm Pearson}$ between the observed $\varepsilon'_{\rm obs}(t)$ and reconstructed $\varepsilon'_{\rm th}(t)$

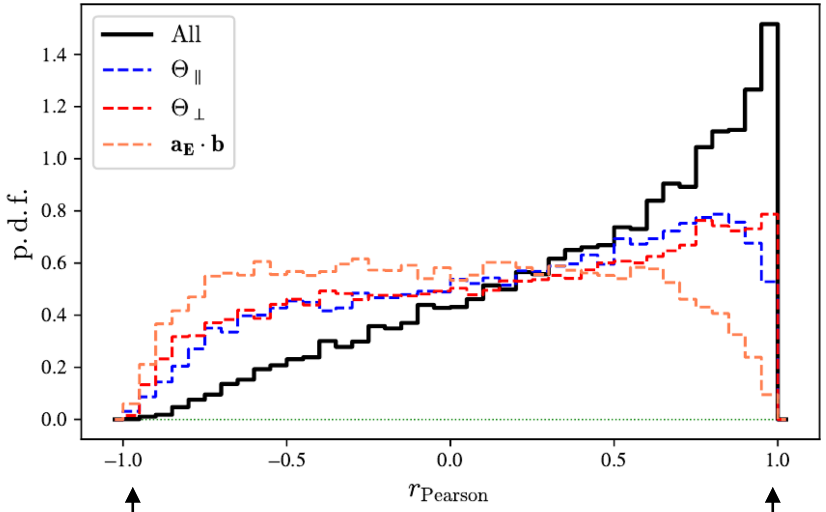
PIC simulation: 3D, $1\,080^3$, e^-e^+, $\delta B/B \sim 3$, $\sigma \sim 1$



100% anti-correlation

100% correlation

incompressible MHD, 3D, 1024^3, $v_A = 0.4c$



100% anti-correlation

100% correlation

[Note: $\Theta_\parallel$ = field line curvature, $\Theta_\perp$ = perp. gradient (mirror), $\boldsymbol{a_E}\cdot\boldsymbol{b}$ = field line acceleration]

⇒ model captures the dominant contribution to particle energization

+ note: in wave turbulence w/ resonant wave-particle interactions, no apparent correlation seen (as expected)

Refs: 1. V. Bresci+ 22

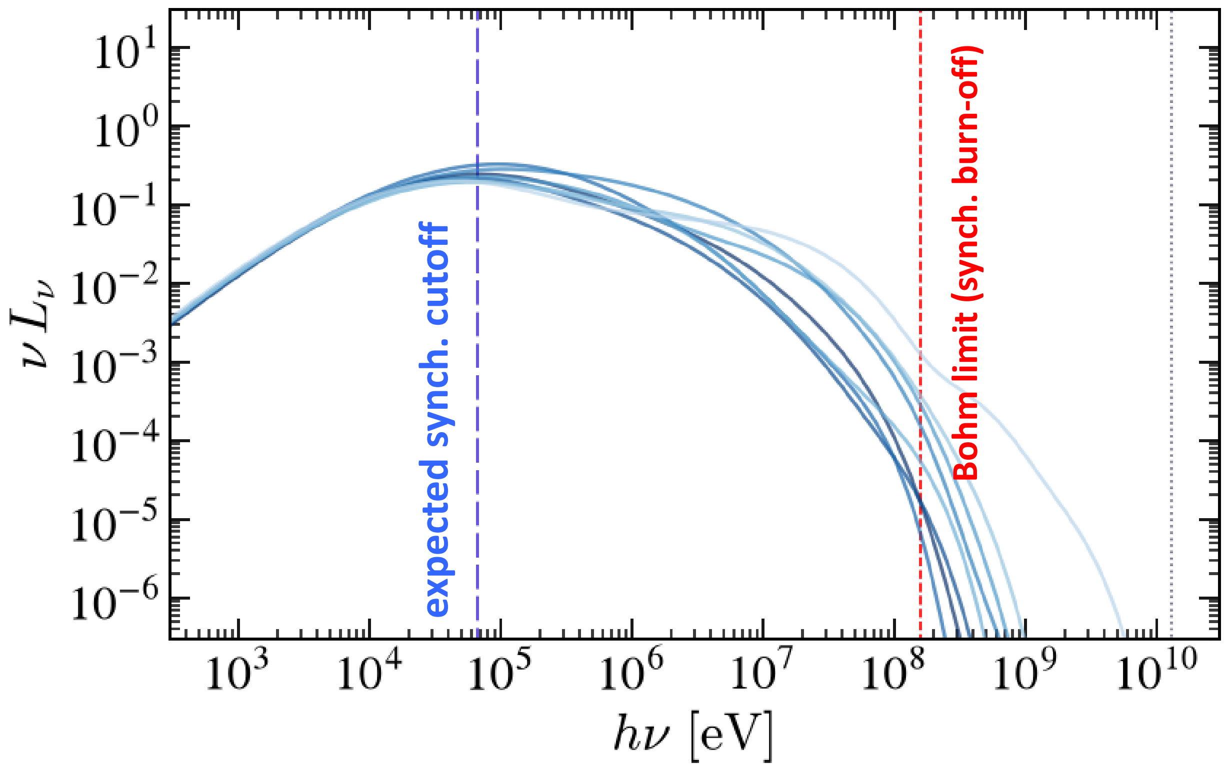
Impact of energy losses: turbulence as an extreme particle accelerator?

→ maximum energy w/ synchrotron cooling:

… on average, turbulence is a slow accelerator[1]: $D_{\varepsilon\varepsilon} \simeq 0.1\,\sigma\,\varepsilon^2 c/\ell_c \quad \Rightarrow \quad \boldsymbol{t_{acc} \sim l_c/c}$ **(turn-around time!)**

… vs Bohm limit: $t_B \sim r_g/c \quad \ll \quad t_{acc}$ ⇒ expect sharp cut-off ε_{cut} well below Bohm limit?

radiated synchrotron spectral power



… intermittency → particles are accelerated at different rates in different regions[2]

⇒ extension of spectrum beyond expected ε_{cut}, up to Bohm limit[3]

… ε_{cut} particles: exponential acc. in gradient $\Delta u_E \sim c$ on scale r_g (generalized Fermi type)

+ characteristic features: steepening of spectrum, strong time variability at radiative limit ($\sim$ 100MeV)

→ a specific radiative signature of relativistic, large-amplitude turbulence

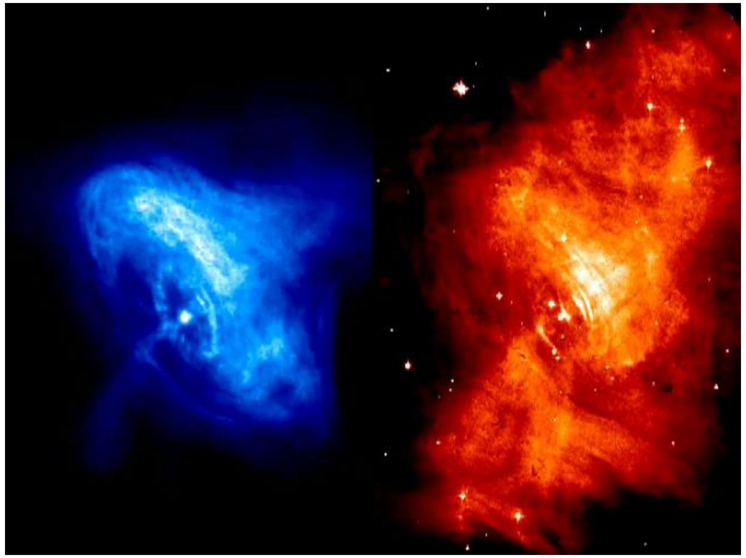
Refs: 1. Wong, Zhdankin, Uzdensky + 20, 25 2. Nättilä+Beloborodov 21 3. M.L., Bresci, Gremillet 25 [PRD 112, 123028]

Turbulence in the Crab nebula as an extreme particle accelerator

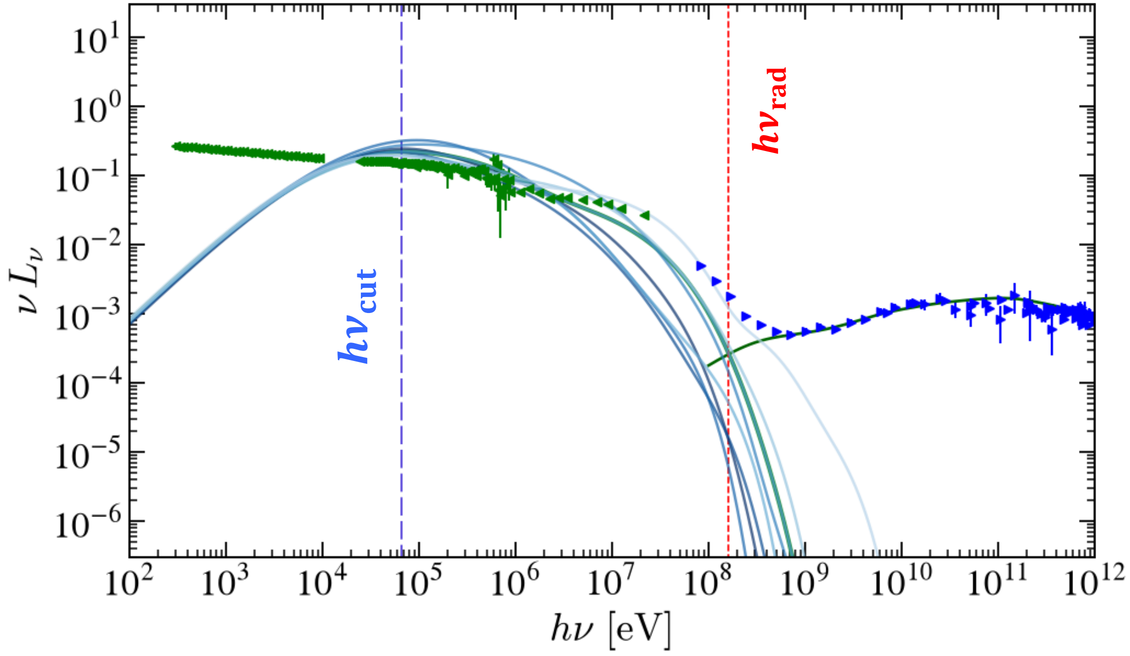
→ application to the Crab nebula, and its flaring behavior?

… assuming a region of relativistic turbulence downstream of the termination shock, e.g.[1] , reasonable estimates indicate that turbulence can produce PeV particles: $B \sim 200\mu\text{G}$, $\ell_c \sim 0.1\text{pc}$, $\sigma \sim 1$

$\Rightarrow h\nu_{\text{cut}} \sim 100\text{keV}, \quad h\nu_{\text{rad}} \sim 100\text{MeV}$



direct overlay (no tuning beyond flux norm.) of simulation to Crab



→ additional motivations:

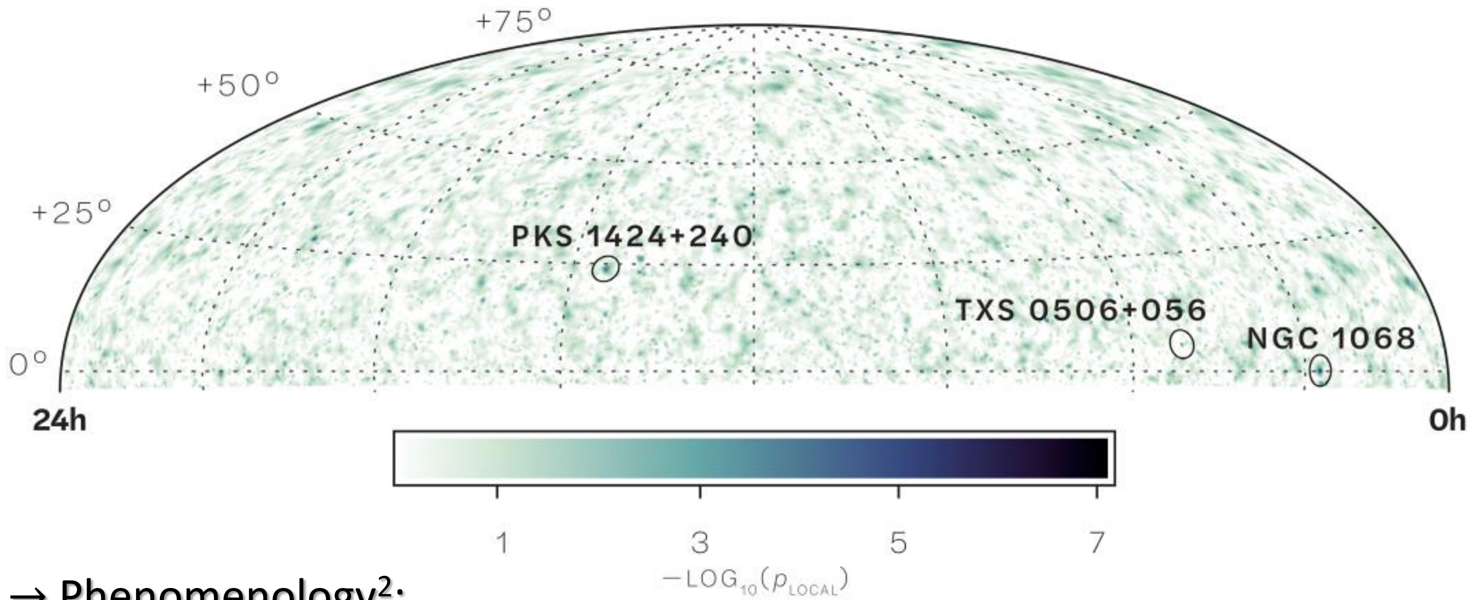
… Crab flux at 100MeV is variable in time[2] → here interpreted as fluctuating energy cut-off

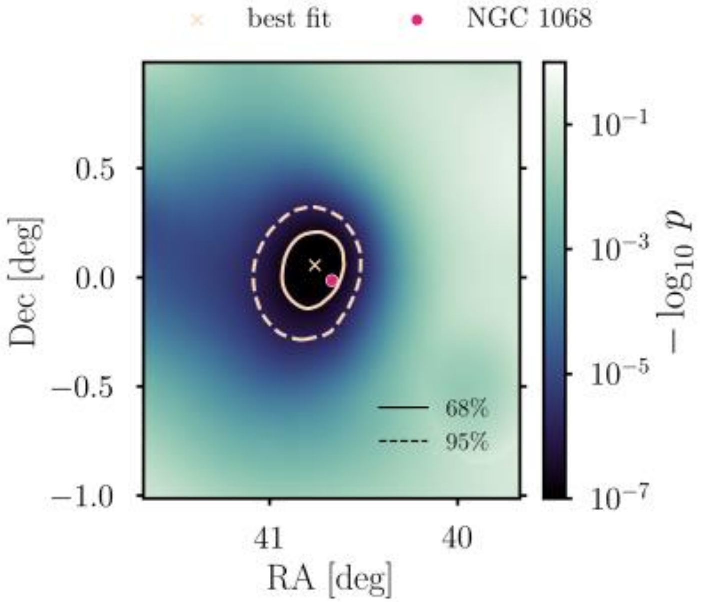
… Crab flares: rare events of stochastic acceleration at/above synchrotron burn-off?

Refs: 1. Porth+13, Zrake 16, M.L. 16, Zrake+Arons 17, Tanaka+18, Lyutikov+19,… 2. Pshirkov+20, Dieter+Horns 20

Application to BH coronae: stochastic proton acceleration & IceCube neutrinos

→ IceCube 22… 26[1]: excess of high-energy (3 – 30 TeV) neutrinos from nearby AGN (Seyfert) NGC 1068… and possibly NGC4151, NGC7469, CGCG 420-015





→ Phenomenology[2]:

… origin of neutrinos: proton acceleration to $\gtrsim 30$TeV + hadronic interactions

… lack of (comparable) gamma-ray flux requires compact zone for reprocessing through $\gamma\gamma \to e^+e^-$

⇒ likely region: BH corona, within $\lesssim 30r_g$

⇒ likely acceleration agent: strong, semi-relativistic turbulence ($\sigma \sim 0.1$) energizing electrons, accelerating protons

i.e., IceCube opening a window on hadronic counterpart of leptonic dissipation channels seen in X-ray?

Refs.: 1. IceCube Coll. 2022 [Science], 2024; Padovani+24, Neronov+24 2. Inoue+19, Murase+20, 22, Keirandish+21, Eichmann+22 …

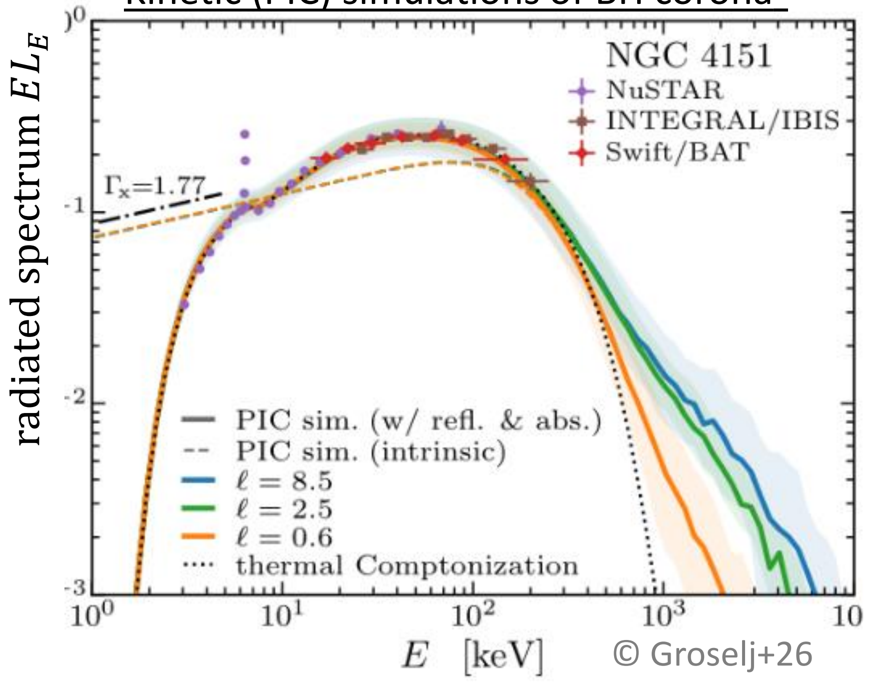
IceCube neutrinos = window on hadronic processes in black hole coronae

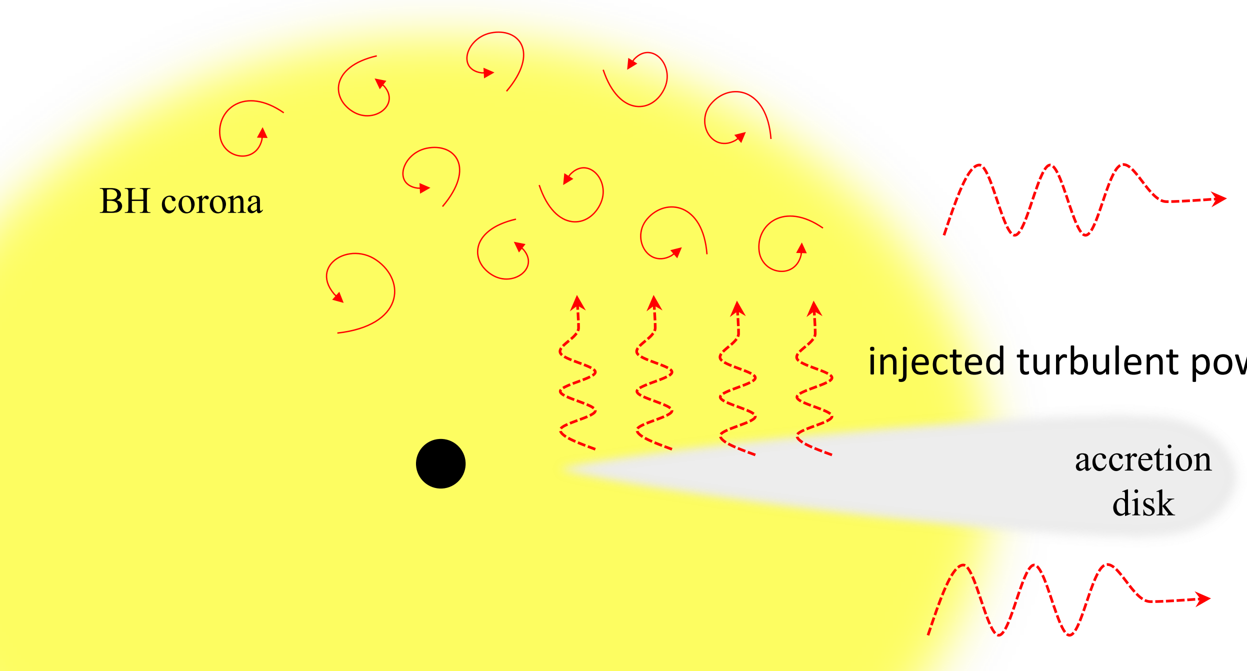
→ corona: $B \sim O(\mathrm{kG}), v_A \sim O(0.3c), R_c \sim O(10\, r_g)$

… electron energization through turbulent heating:
$kT_e \sim 100\mathrm{keV}$ → hard X-ray continuum by Comptonization
on short times scales $\ll R_c/c$!
recent first-principles modelling through PIC simulations[1]

… proton acceleration: long timescales $\gg R_c/c$ (beyond PIC!)

Kinetic (PIC) simulations of BH corona[1]





turbulent heating in electrons: Q_e

injected turbulent power Q_{turb}

injected power in VHE protons: Q_p

note: p-acceleration acts as a sink for turbulence!

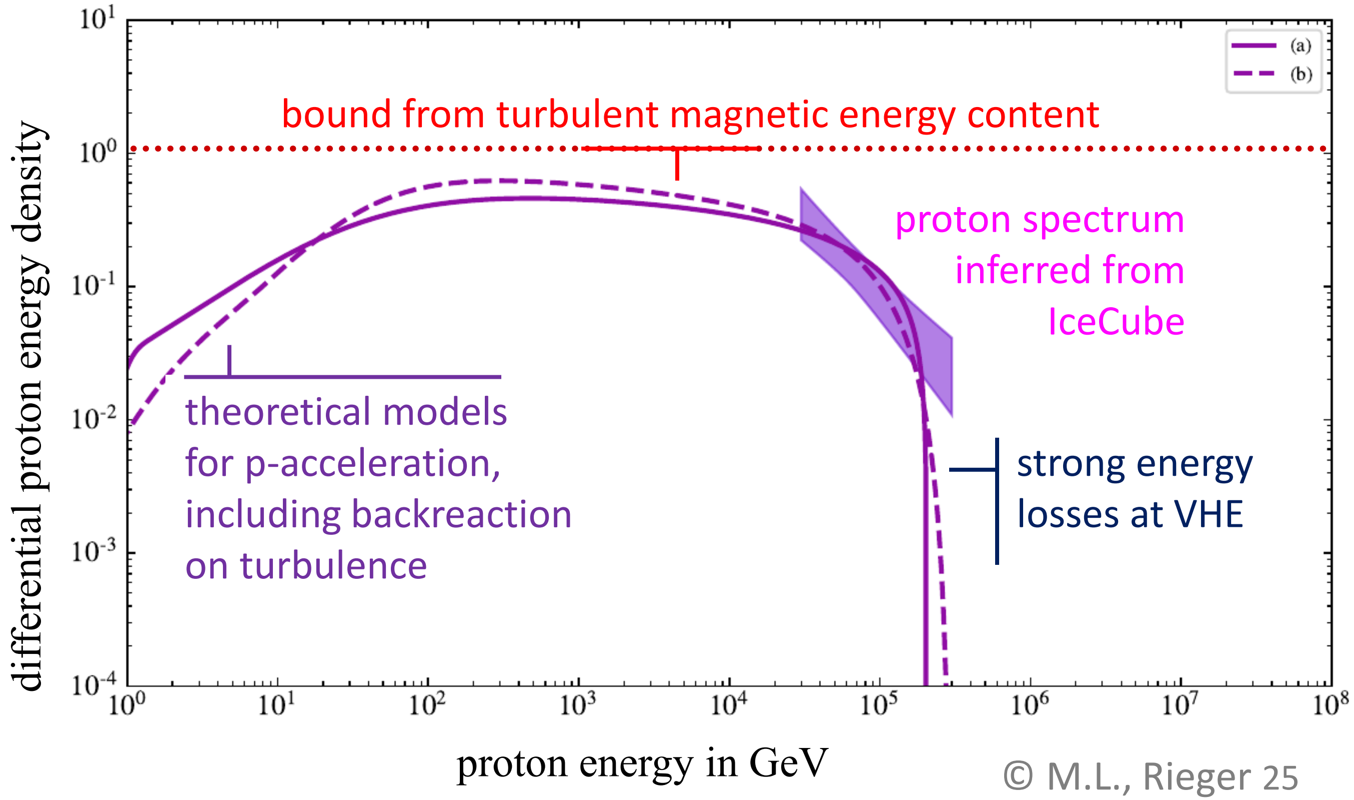
Refs.: 1. Nättilä 24, Groselj+ 24, 26

Nonlinear stochastic acceleration: p energy budget dictated by turbulence driving

→ energy budget:

… for NGC1068: $L_\nu \sim 10^{42}$ erg/s $\sim 10^{-3} L_{\rm edd}$ $\Rightarrow$ $u_p \sim L_\nu\, t_{\rm loss}/V_{\rm cor} \sim O(10^5)\ {\rm ergs/cm^3} \sim O(u_B) \sim O(p_{th})$

⇒ a natural explanation for observed L_ν: proton energy fraction limited by rate at which turbulence is driven [1,2]
(then, damping of turbulence self-regulates acceleration process, shaping flat energy spectrum[1])



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Refs: 1. M. L., Rieger, Murase (2024) 2. M.L. + Rieger (2025)

Detailed modeling of hadronic processes in AGN cores by Sébastien Le Bihan et al.

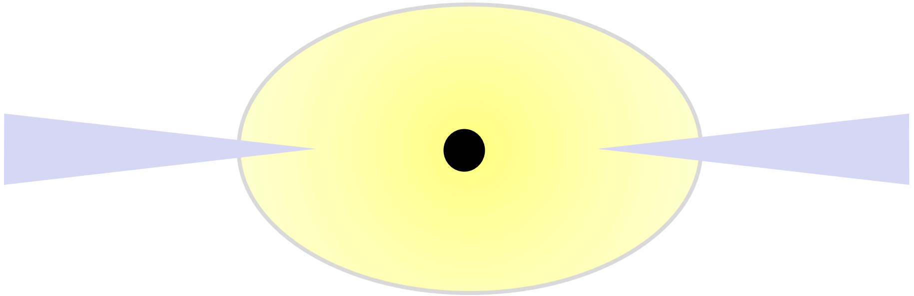
→ Simplified model:

spherical, size $R_{co} = 15\, r_g$

… note, key parameters are:

advection through the corona (here, std radial inflow)

diffusive escape from corona (here, std diffusion coefficient)



→ Transport equations:

$$\partial_t n_s(p,\,t) = \left[\mathcal{L}_{\text{stoch. acc.}} n_p(p,\,t)\right]_{s=p} + -\partial_\varepsilon\left(\varepsilon\, \nu_{\text{loss}} n_s\right) - \frac{n_s}{\tau_{\text{esc}}} + Q_s$$

… for species: protons (s=p), pairs, photons, pions, neutrinos

… describing stochastic acceleration of protons, electromagnetic cascades, escape processes, Comptonization

$$\partial_t \mathcal{E}_{B_k}(t) = \text{cascade}(k) - \text{acceleration}(k) - \text{heating}$$

… describing evolution of turbulent magnetic energy in k-space, including damping from accelerated protons

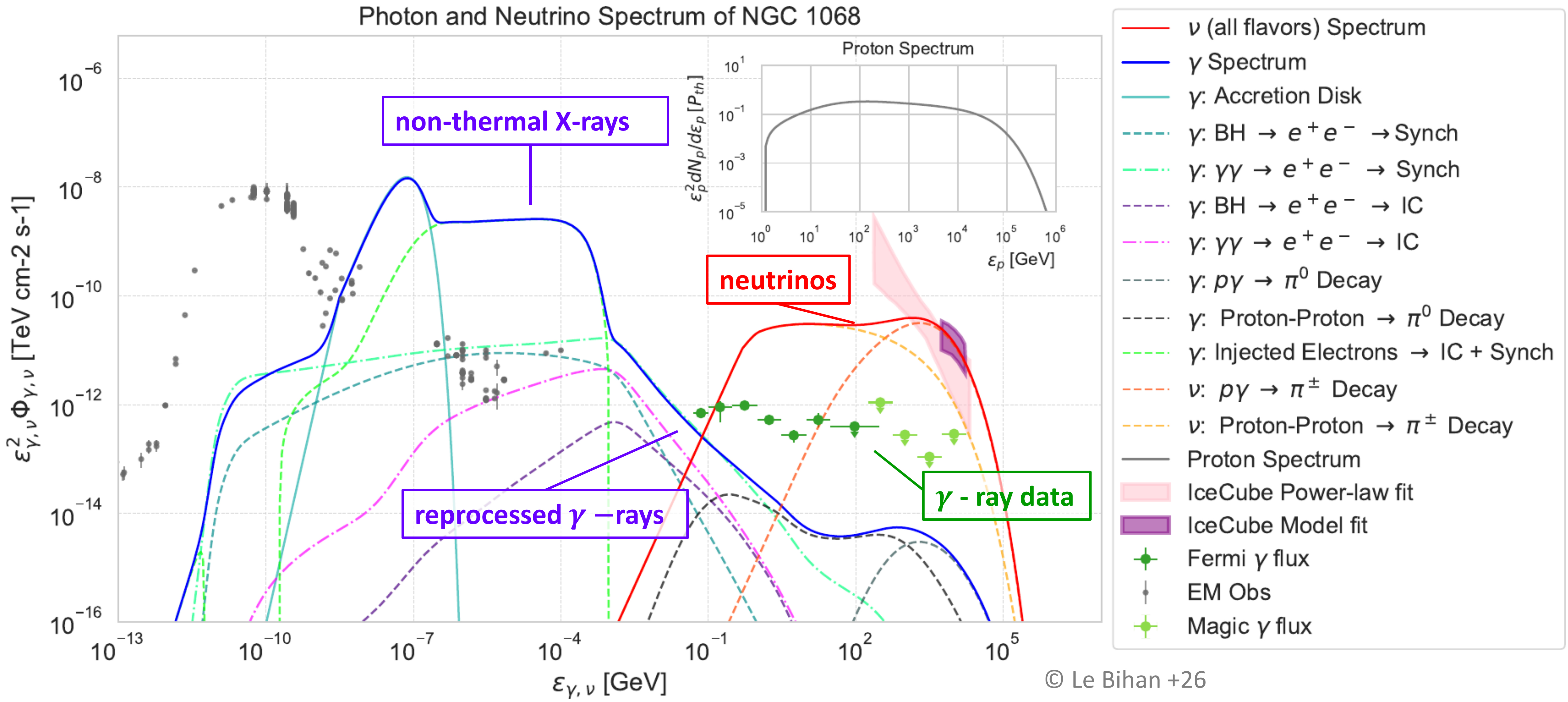
→ Numerical code (developed by S. Le Bihan):

Turb-AM3[1]: couples stochastic acceleration solver + turbulence feedback with AM3 (multi-messenger radiative code[2])

… NB: applicable to various other types of sources!

Refs.: 1. Le Bihan, M. L., Rieger 26 [A&A 712, A218 (2026)] 2. Guo + 17, Klinger + 24

Detailed model (S. Le Bihan et al.): multi-messenger (stationary) spectrum for NGC1068



⇒ **standard coronal + turbulence parameters provide a natural fit to IceCube (+photon) data**

Summary

→ Turbulent plasmas as a modern particle acceleration scheme in VHE multi-messenger astrophysics

… the Fermi picture is well alive: a generalized Fermi effective theory for modelling acceleration

… main energization agents (large-amplitude): sharp field line bends, compression $\perp B$, acceleration of field lines

… satisfactory tests on simulations

→ Many open questions on microphysics of particle acceleration:

… extension to low $\delta B/B$ and role of intermittency, structures, waves?

… extension to low v_A (requires long timescales)?

… impact of turbulence anisotropy at gyroradius $\ll$ outer scale?

→ Signatures and applications to VHE multi-messenger astrophysics:

… w/ synchrotron cooling: extension beyond expected cut-off due to non-homogeneity of acceleration rates + acceleration up to synchrotron burn-off: an origin for Crab flares?

… on long timescales, in BH coronae: p-spectra self-regulated by feedback on turbulence, provides natural account of observed IceCube neutrino flux