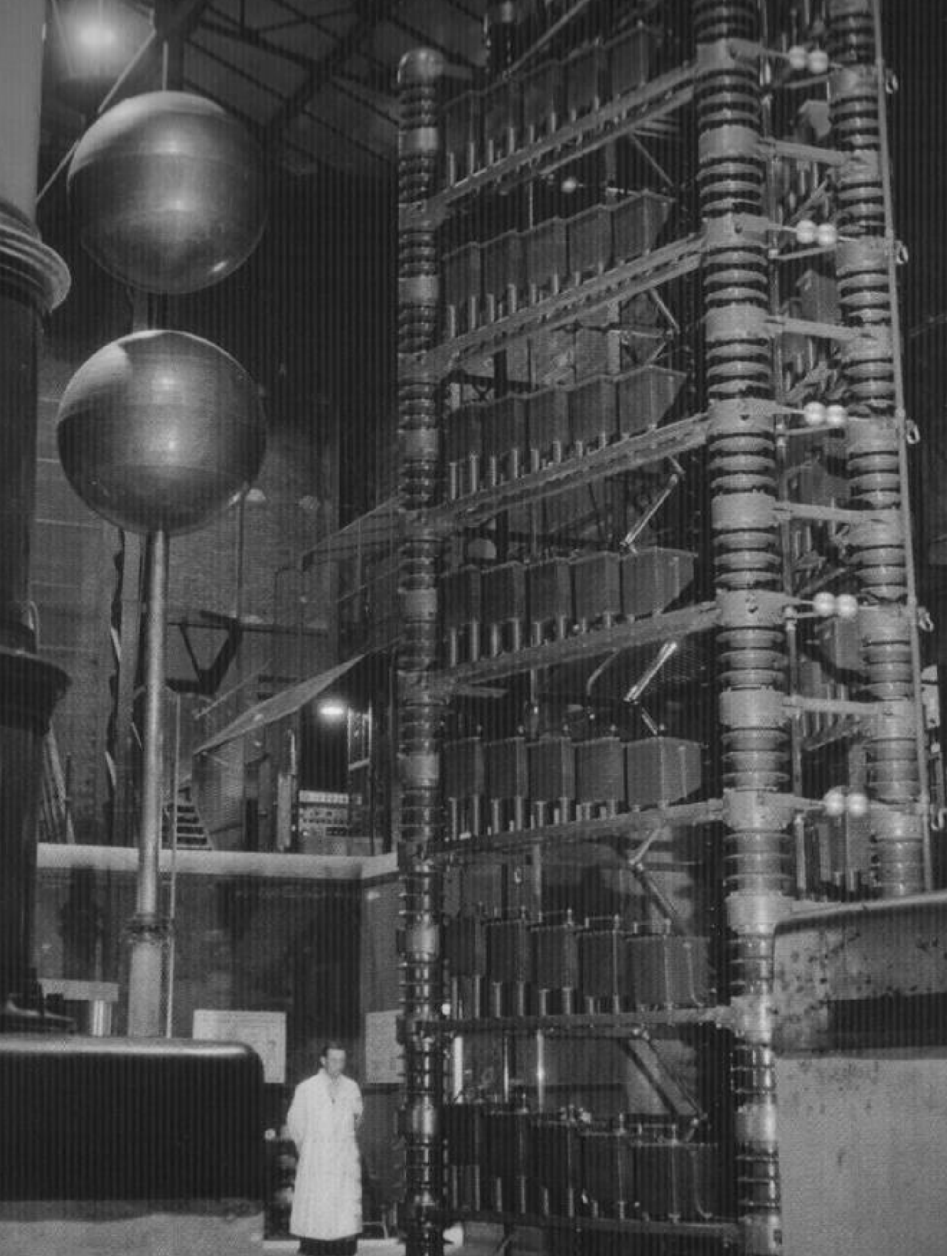

particle acceleration on Earth, ca. 1937

Plasmas around black holes – Dissipation and supra-thermal particles

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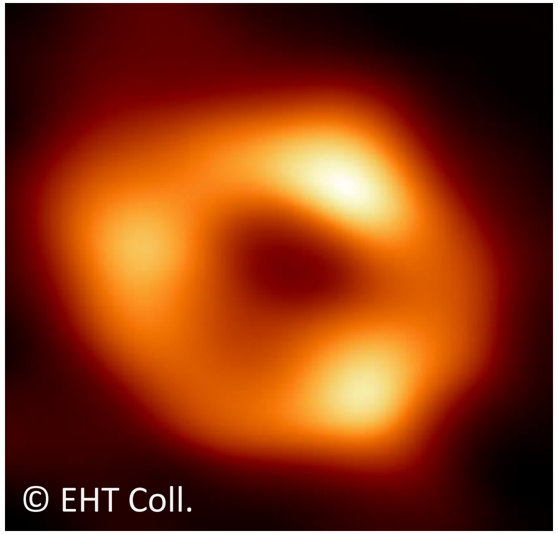
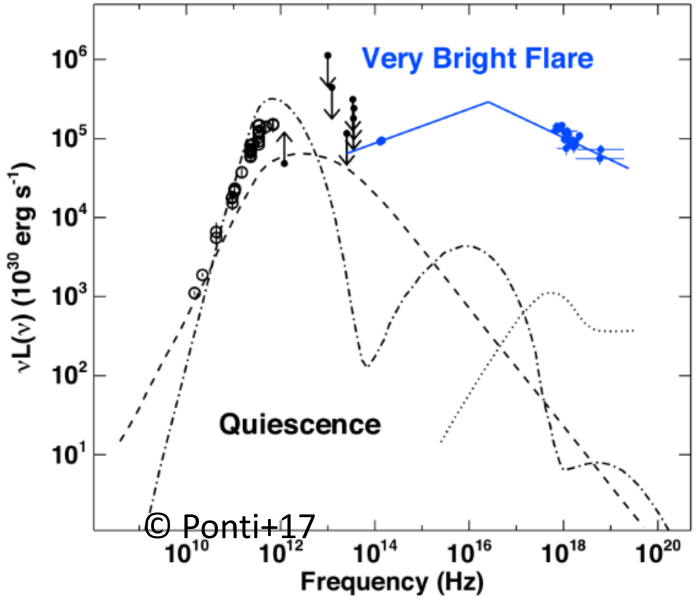
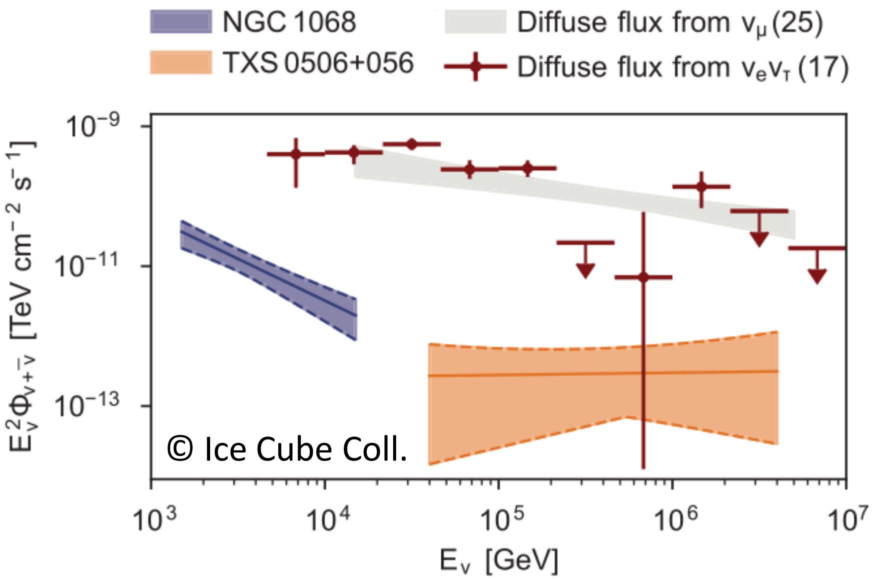
Heating and particle acceleration in plasmas around black holes

… radiative signatures of collisionless plasmas…

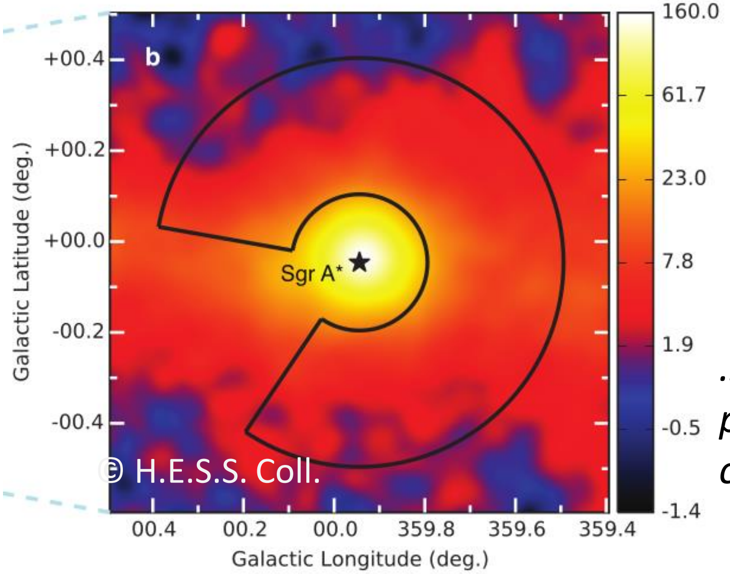


… electron acceleration at the origin of flares …



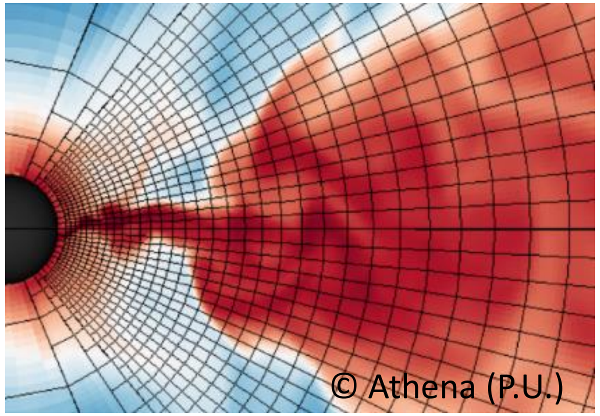


… VHE neutrinos from proton acceleration in BH vicinity (?)…



… origin of PeV protons in the Galactic center …

Kinetic plasma physics in collisionless astrophysical sources: an issue of scale separation



→ radiatively inefficient accretion flows (e.g. SgrA*):

… a collisionless system (m.f.p. collisions ≫ size of system), out of equilibrium,
… two-temperature: $T_i \sim 10^{12}$K ∼ virial, $T_e \sim 10^{10}$K $\ll T_i$: why, how?

→ plasma behavior vs scales:

… on large scales, plasma ∼ fluid behavior (turbulent e.m. fields ∼ agent of collision),
[more precisely, near MHD behavior with frozen-in magnetic field, no dissipation]

… on kinetic scales, non-trivial distribution function + dissipative effects (heating)
[acceleration: particles extracted from thermal pool, pushed to high energies]

→ role of turbulence:

… in accretion flows, turbulence ∼ agent of viscosity → transport of angular momentum + heating through dissipation of turb. energy

… turbulence sourced by instabilities: e.g. magnetorotational (disk), Kelvin-Helmholtz (boundary layers), Rayleigh-Taylor (e.g. flux ejection events), Rossby wave, …

BH gravitational radius
$r_{\rm g} \sim 10^{12}\,{\rm cm}$

≈

plasma ion gyroradius
$r_{\rm L,i} \sim 10^{5}\,{\rm cm}$

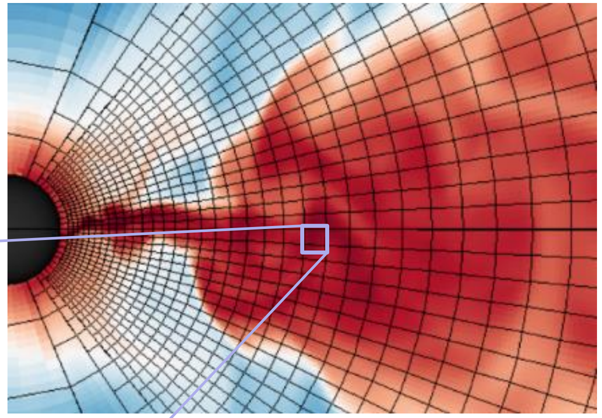
ion skin depth
$d_{\rm i} \sim 10^{4}\,{\rm cm}$

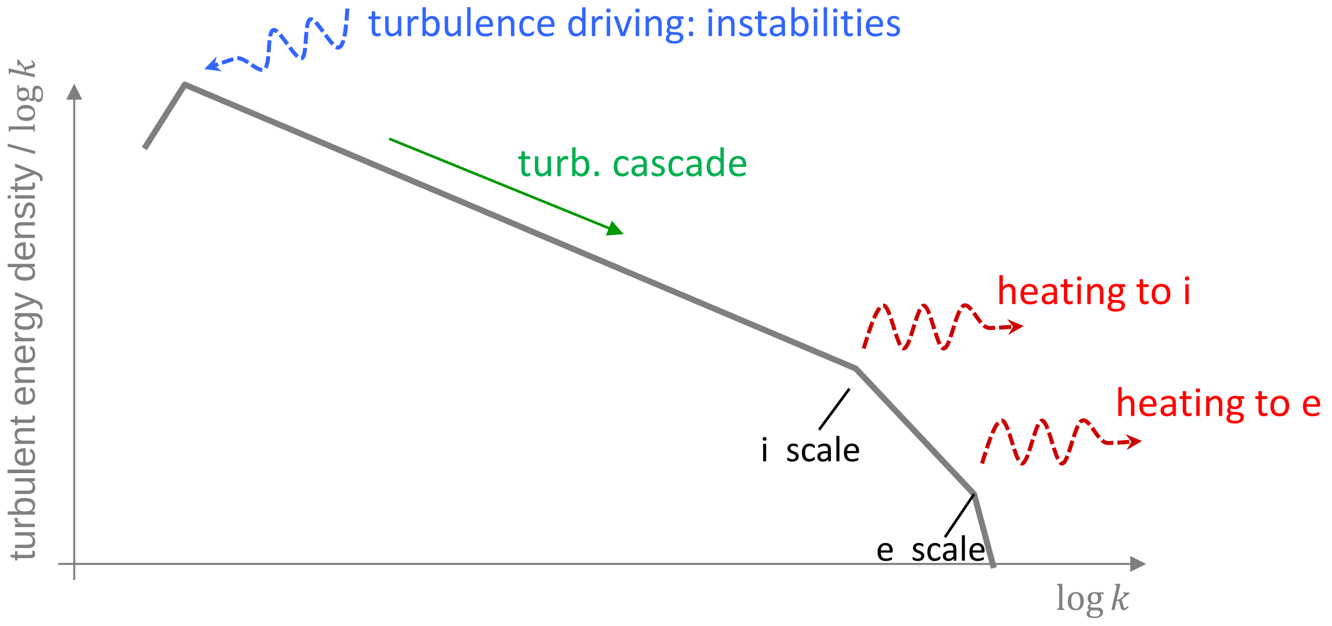
electron gyroradius
$r_{\rm L,e} \sim 10^{2}\,{\rm cm}$

Turbulence in accretion flows: plasma heating with partition of energy

→ radiatively inefficient accretion flows (e.g. SgrA*):

... two-temperature: $T_i \sim 10^{12}$K ~ virial, $T_e \sim 10^{10}$K $\ll T_i$: why, how?



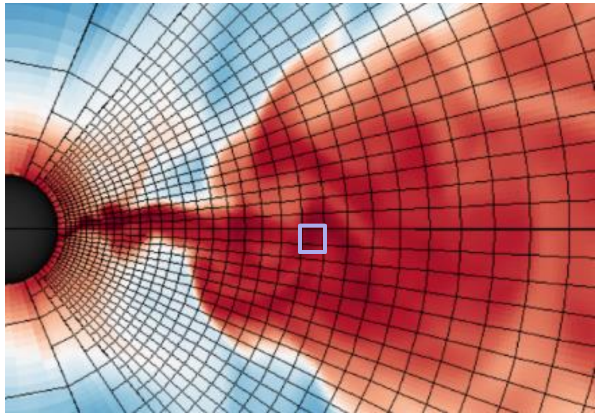


heating at small scales: through Landau damping, "stochastic heating" in small-scale electrostatic fields, wave-particle resonances, reconnection? ... debated[1] ...

⇒ in practice, insert local (=sub-grid) heating recipes in GRMHD simulations to track T_i, T_e hence radiative output[2]...
[additional complications: dynamical evolution of turbulence (dynamo), non-local cascade at high-beta…]

Refs: 1. e.g. research of Chandran, Howes, Kunz, Matthaeus, Quataert, Schekochihin, et al 2. e.g. Salas+24 and references

Turbulence in accretion flows and plasma heating

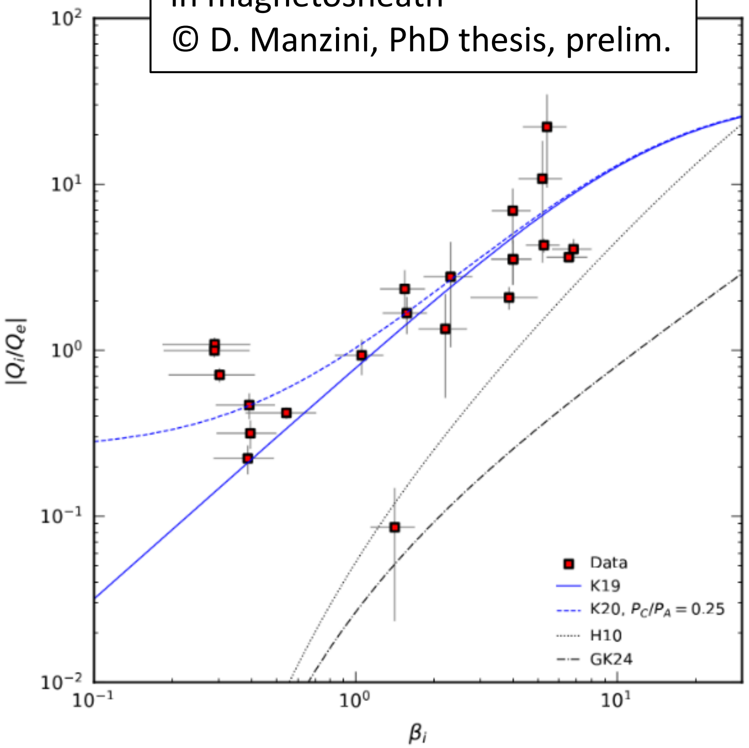


→ radiatively inefficient accretion flows (e.g. SgrA*):

... two-temperature: $T_i \sim 10^{12}$K ~ virial, $T_e \sim 10^{10}$K $\ll T_i$: why, how?

⇒ a broad field of study: driving of turbulence (instabilities), physics of turbulent cascade, physics of heating … with a strong connection to similar studies in the solar wind!

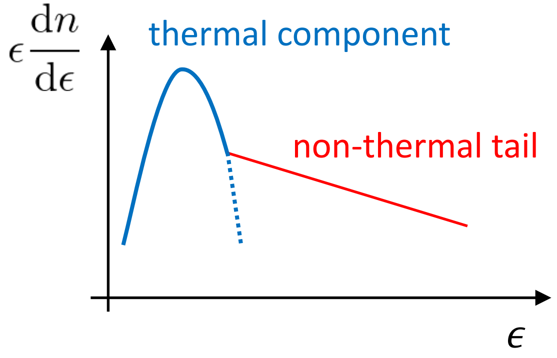
heating rate i/e vs plasma β
in magnetosheath
© D. Manzini, PhD thesis, prelim.



Workshop: Kinetic Physics of Astrophysical Plasmas, June 18-20, 2025, Jussieu
(cf A. Vanthieghem, M.L., A. Ciardi)

Astrophysical plasmas as particle accelerators – basic scenarios

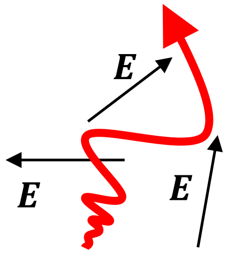
→ **particle acceleration:** origin of non-thermal populations ↔ high-energy radiation
… an essential duality: energy ↔ length, from gyroradius ∝ momentum

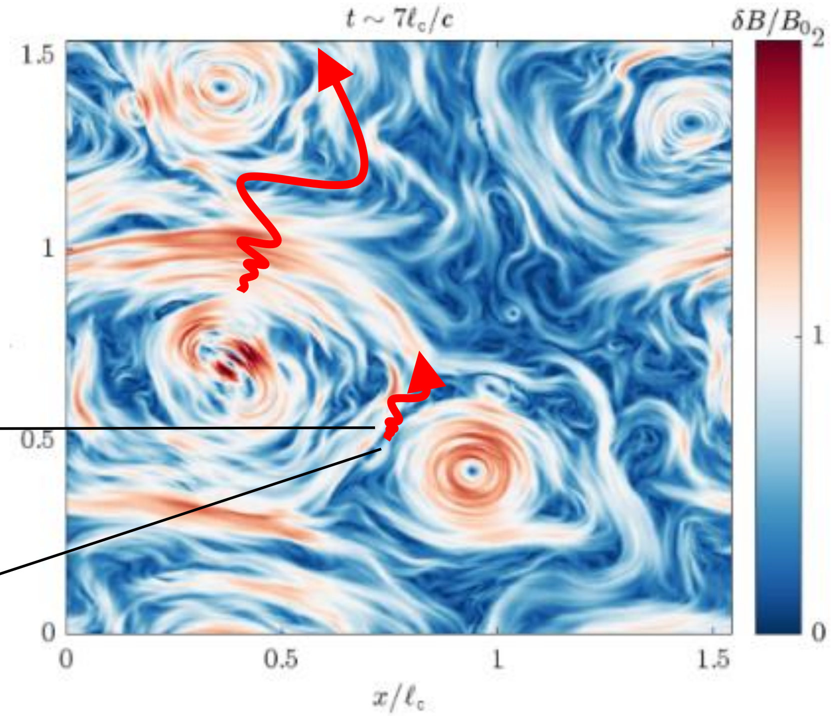


→ **on large scales: Fermi-type (Fermi 1949, 1954) acceleration**

↔ on MHD scales, Ohm's law: $\boldsymbol{E} = -\boldsymbol{v_E} \times \boldsymbol{B}/c$, with $\boldsymbol{v_E}$ plasma velocity

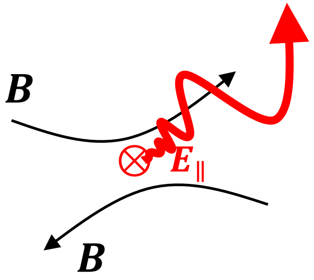
… shocks, …, **turbulence**



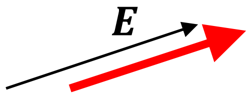


→ **on small scales:**

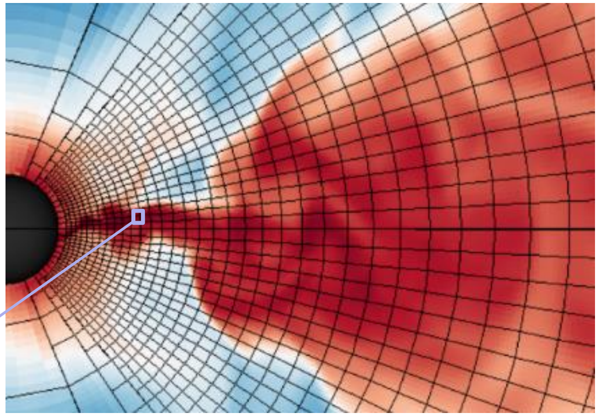
reconnection



… on kinetic scales or in localized patches: **electrostatic gaps (e.g. in BH magnetosphere)**



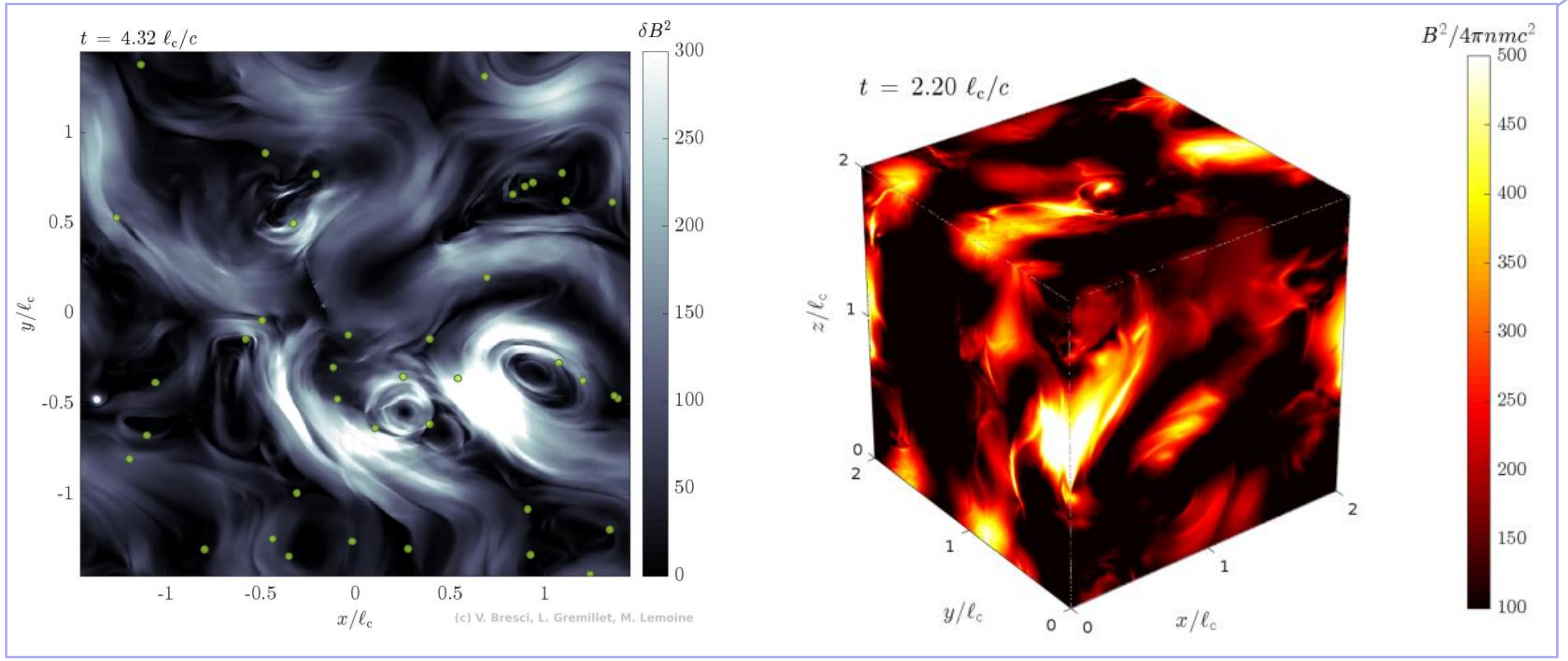
A long time challenge: modelling particle acceleration across scales in astrophysical sources

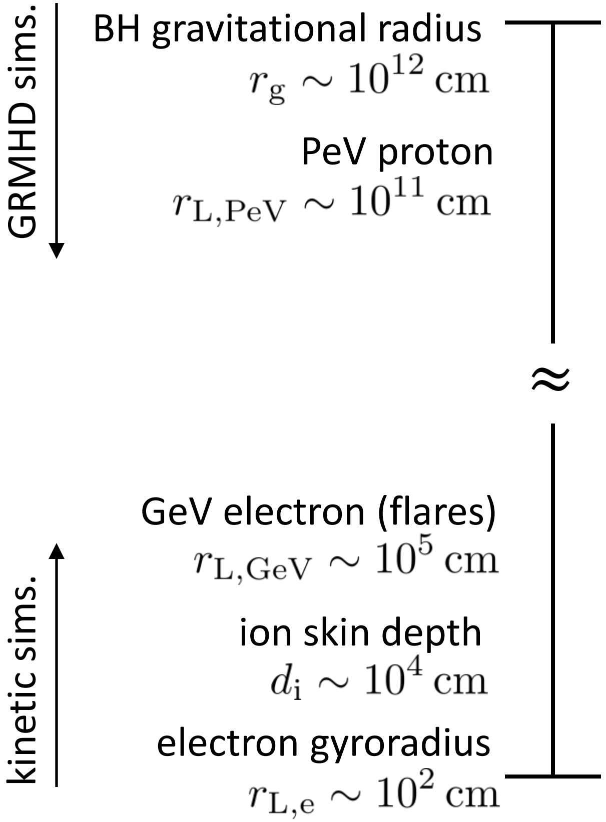


→ modelling:

(1) phenomenology: parametrize acceleration and compute radiative signatures[1] …

future: (2) direct implementation in GRMHD simulations[2]: need sub-grid recipes to model acceleration of particles with gyroradius below grid size… track particle acceleration in dynamic/unstable regions (disk, jet interface, flux ejection events etc)



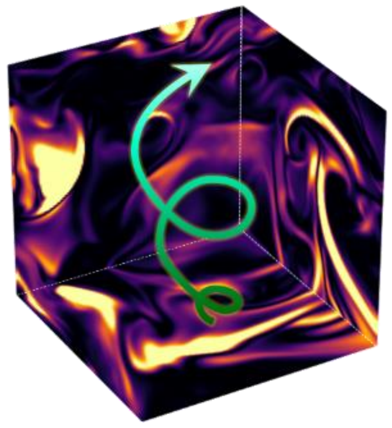


1. conduct kinetic simulations (small length & time scales) to study particle acceleration
2. derive analytical models, extrapolate to scales of interest, derive sub-grid recipes

Refs: 1. e.g. Aimar+23 2. e.g. Chael+17

Generalized Fermi acceleration in a random velocity flow

→ (covariant) implementation of Fermi acceleration in a non-uniform/random velocity flow $\boldsymbol{u_E}$:



… follow particle momentum along particle word line in the (non-inertial) frame where $\boldsymbol{E}=0$ moving at (4-velocity) $\boldsymbol{u_E}$

… in that frame, energy variation ∝ non-inertial forces ∝ velocity shear of $\boldsymbol{u_E}$

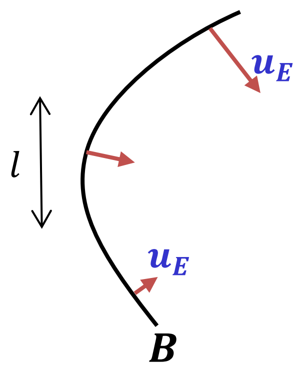
$$\frac{\mathrm{d}\epsilon'}{\mathrm{d}\tau} = -\Gamma^0_{\ a\, b}\,\frac{p'^a\,p'^b}{m}$$

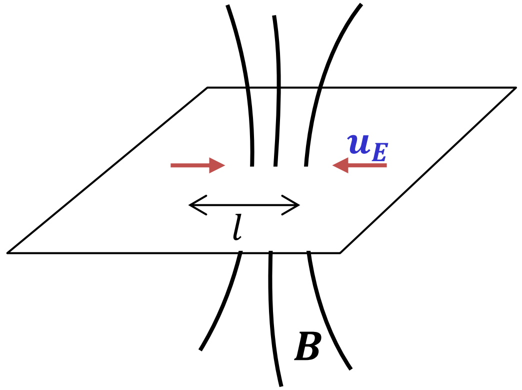
… inertial forces: $\Gamma^0_{\ a\, b} \propto \partial_a u_{E\,b}$

→ implementation in *(strong)* turbulence:

… main difficulty: characterize the statistics of $\partial_a u_{Eb}[\boldsymbol{x}(\tau),\tau]$ along the trajectory $\boldsymbol{x}(\tau)$ … scale by scale

⇒ dominant contribution from shear of velocity along and across magnetic field line on scales $l \gtrsim r_L$





Refs: M.L. 19 [PRD 99, 083006 (2019)], 21 [PRD 104, 063020 (2021)]; see also previous works by Webb 85, 89

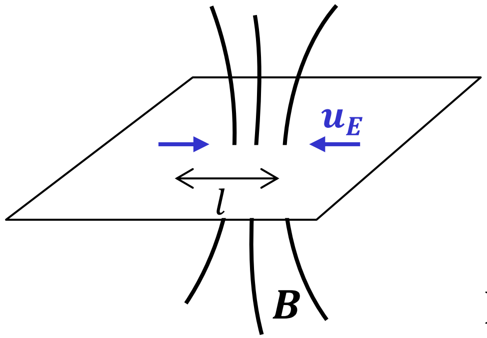
Generalized Fermi acceleration in magnetized turbulence

→ Theoretical model[1]: $\dot{\epsilon}' = \Gamma_l \, \epsilon'$ (simplified expression in comoving frame)

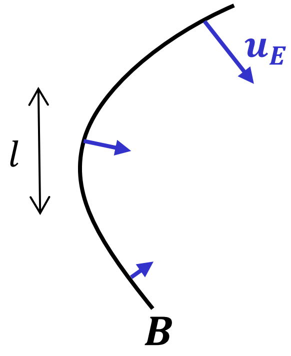
with Γ_l a random field: gradients of $\boldsymbol{u_E}$ coarse-grained on scale $l \gtrsim r_L$ ...

... Γ_l from dynamic curved field lines, or dynamic perp. gradients (mirrors), or acceleration of field lines

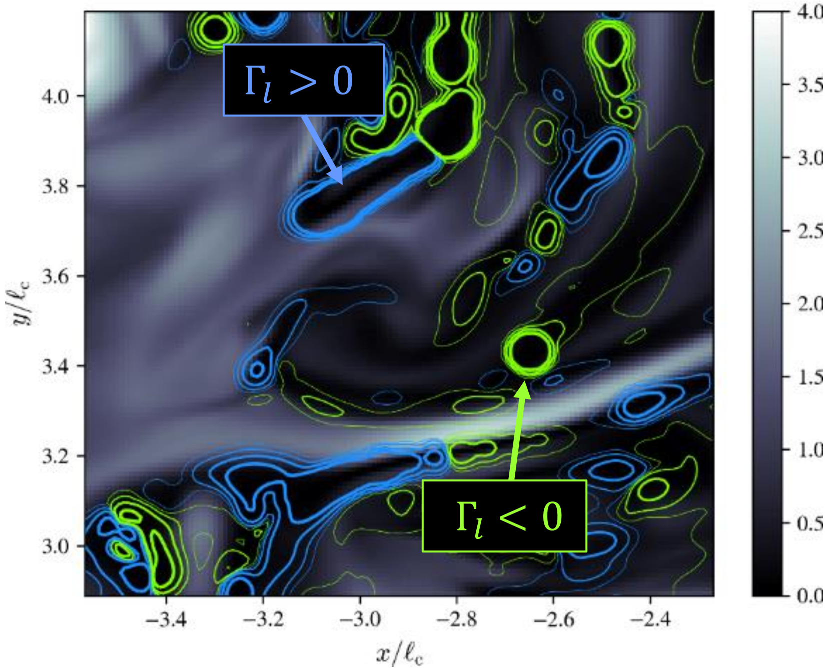
... Γ_l can be >0 or <0: particle undergoes random walk in energy space



$\Gamma_l \sim \Delta u_E / l$



Map of $\ln|\Gamma_l|$ in MHD 1024^3 sim.[2]
(no guide field: large-amplitude turb.)



→ Transport equation:

... model the probability distribution function of the random force, derive transport equation, integrate in time to obtain distribution function $f(\epsilon', \tau)$ of accelerated particles.

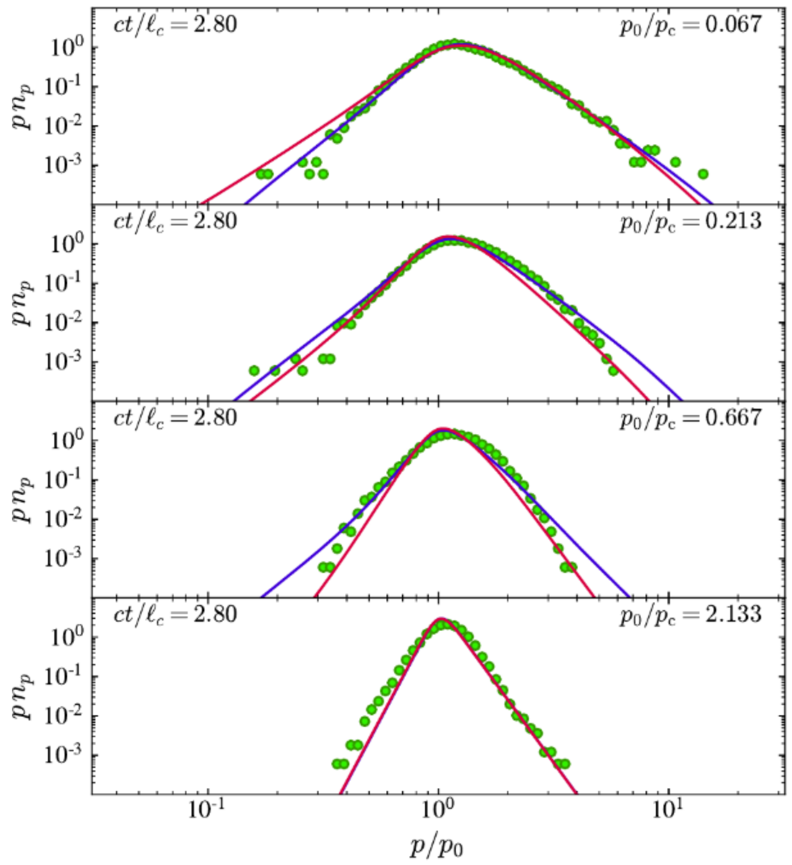
Refs.: 1. ML 21 [PRD 104, 063020 (2021)], ML 22 [PRL 129, 215101 (2022)]

A transport model reproducing spectra obtained by particle tracking in MHD simulation

→ comparison to numerical data:

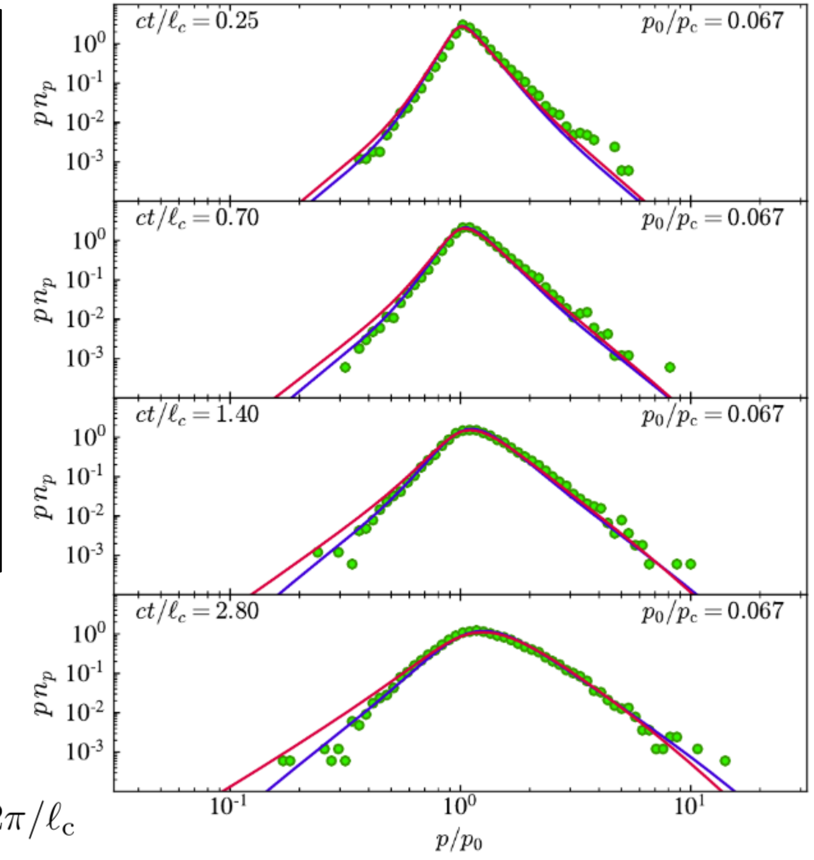
1. fit model (here 2: blue & red) to p.d.f. of forces (Γ_l)
2. integrate kinetic equation[1]
3. compare to distribution measured in MHD 1024^3 simulation[2] by time-dependent particle tracking…

← increasing initial particle momentum p_0



$$p_c : \quad r_L(p_c) = k_{\min}^{-1} = 2\pi/\ell_c$$

← increasing integration time



⇒ model reproduces time- and energy- dependent Green functions… + produces powerlaw spectra $dn/dp \propto p^{-4}$

Refs.: 1. ML 22 [PRL 129, 215101 (2022)] 2. no guide field - Eyink+13, JHU database

Evolution on ``long'' timescales: accelerated particles can modify the turbulence structure…

→ particle acceleration in turbulence, up to feedback[1]:

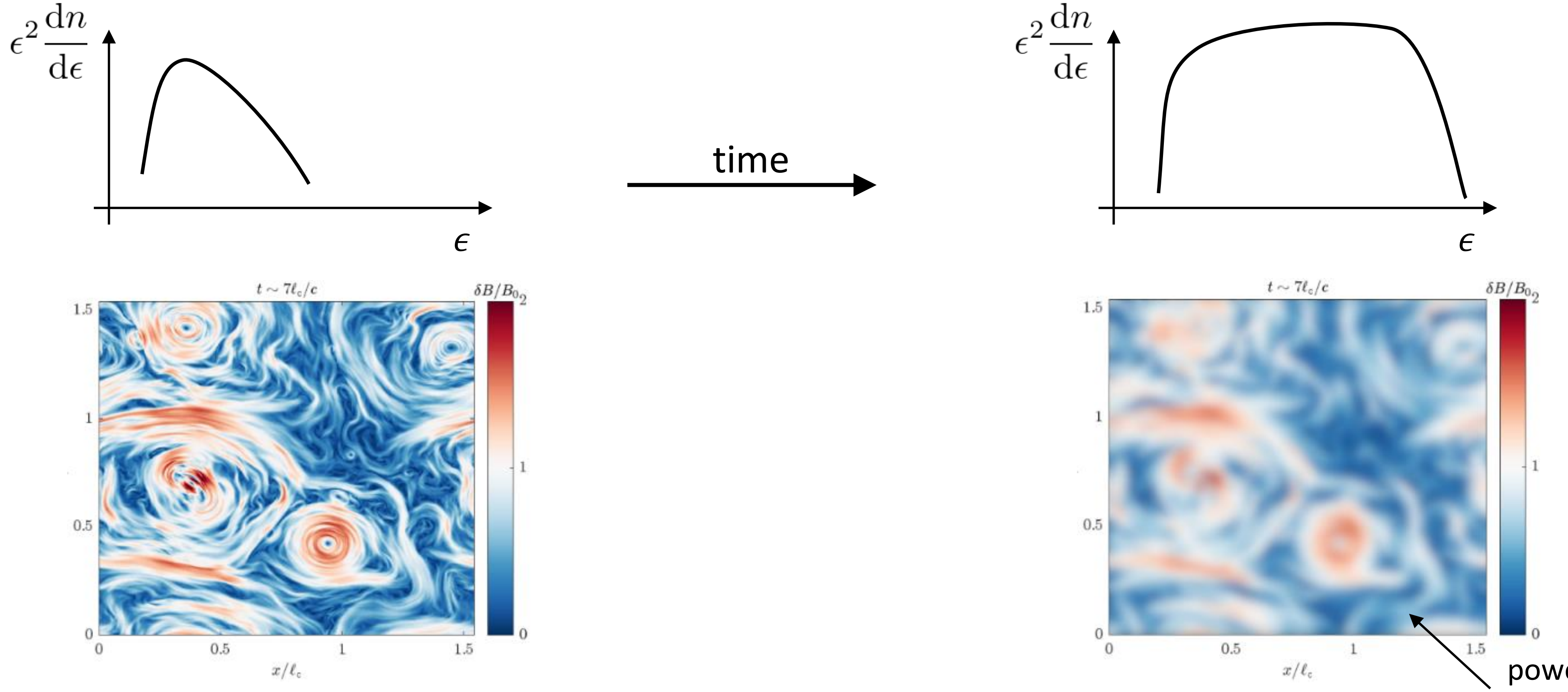
… acceleration = loss of energy for turbulence + most of energy given to highest energy particles

… higher energy particles ↔ larger mean free path ↔ source of viscosity + diffusivity

⇒ consequences: (1) self-regulation of acceleration impacts distribution function $f(\epsilon, t)$

(2) removes turbulent power on short scales, modifies plasma heating rate

(3) pressure in accelerated particles can become comparable to plasma pressure

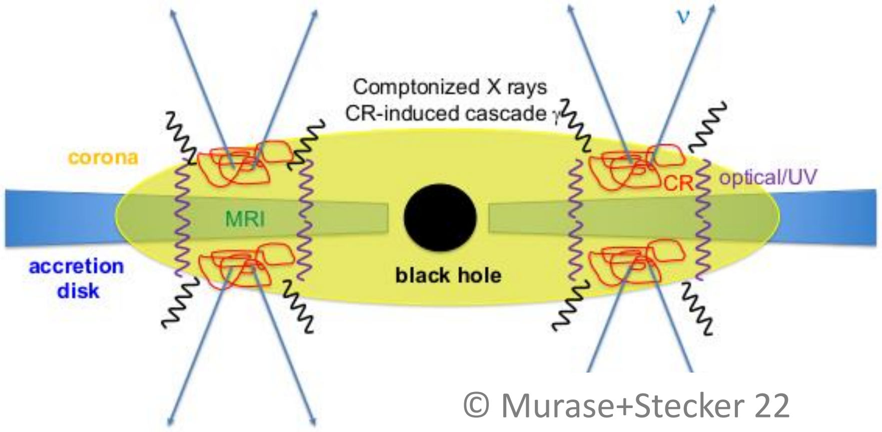


powerpoint version of turbulence damping

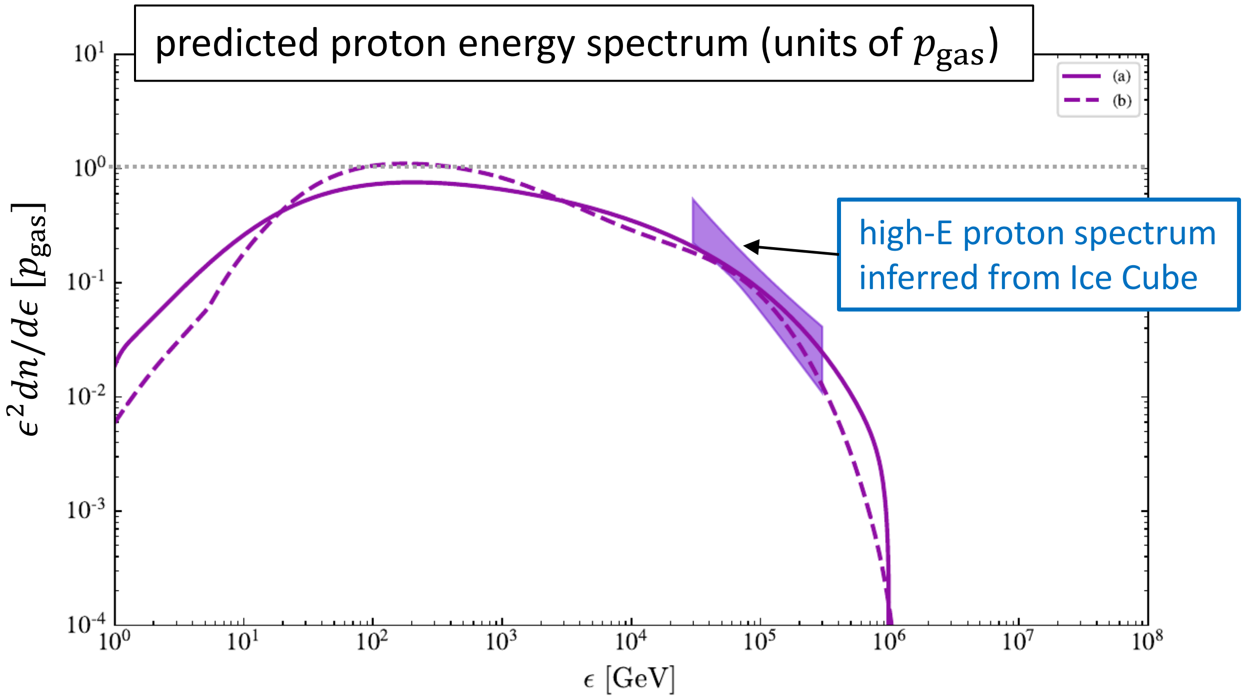
Refs.: 1. Eichler 79, Eilek 79, … Kakuwa 16 … M.L., Murase, Rieger 24

Application: origin of high-energy neutrinos from NGC 1068

→ **Ice Cube 22:** 4.2σ excess of high-energy (1-10 TeV) neutrinos from nearby AGN NGC 1068…
… a possible scenario: stochastic acceleration of protons to $\sim 30 - 300$ TeV in turbulent corona, then conversion to neutrinos through hadronic $p-p, p-\gamma$ interactions[1]



© Murase+Stecker 22



→ **model:** integrate spectra through transport eqns, including feedback on turbulence…
⇒ inclusion of feedback provides correct normalization of spectrum (for $v_A \simeq 0.2c$, $\ell_c \sim 10\, r_g$)…

… Ice Cube data suggest that high-energy particles are accelerated up to an energy content ~ gas pressure

Refs.: 1. e.g. Murase 22 + refs.,… Padovani+24 2. ML + Rieger, arXiv:soon

Summary

→ kinetic plasma physics = an essential ingredient of BH dynamics

… heating in collisionless environments regulated by turbulence cascade physics

… particle acceleration to high energies (non-thermal radiation) in reconnecting and/or turbulent regions

→ particle acceleration in magnetized turbulence

… a covariant generalized Fermi model… (non-resonant interactions prevail over wave-particle resonances)

… supported by kinetic and MHD simulations

→ perspectives for self-consistent implementation in BH physics

… strategy: elaborate semi-analytical recipes for sub-grid particles ($r_L < \Delta x$) for GRMHD simulations…

… for particles on grid, use PIC module of GRMHD codes

→ French community in critical need of GRMHD computational physicists (wrt US, Europe…)

… current faculty: Fabien Casse (APC), Peggy Varnière (APC) using/developing GR-AMRVAC (+PIC module)

… outstanding candidates competing for positions… hire!