Particle Acceleration by Magnetized Turbulence in Coronae of Active Galactic Nuclei

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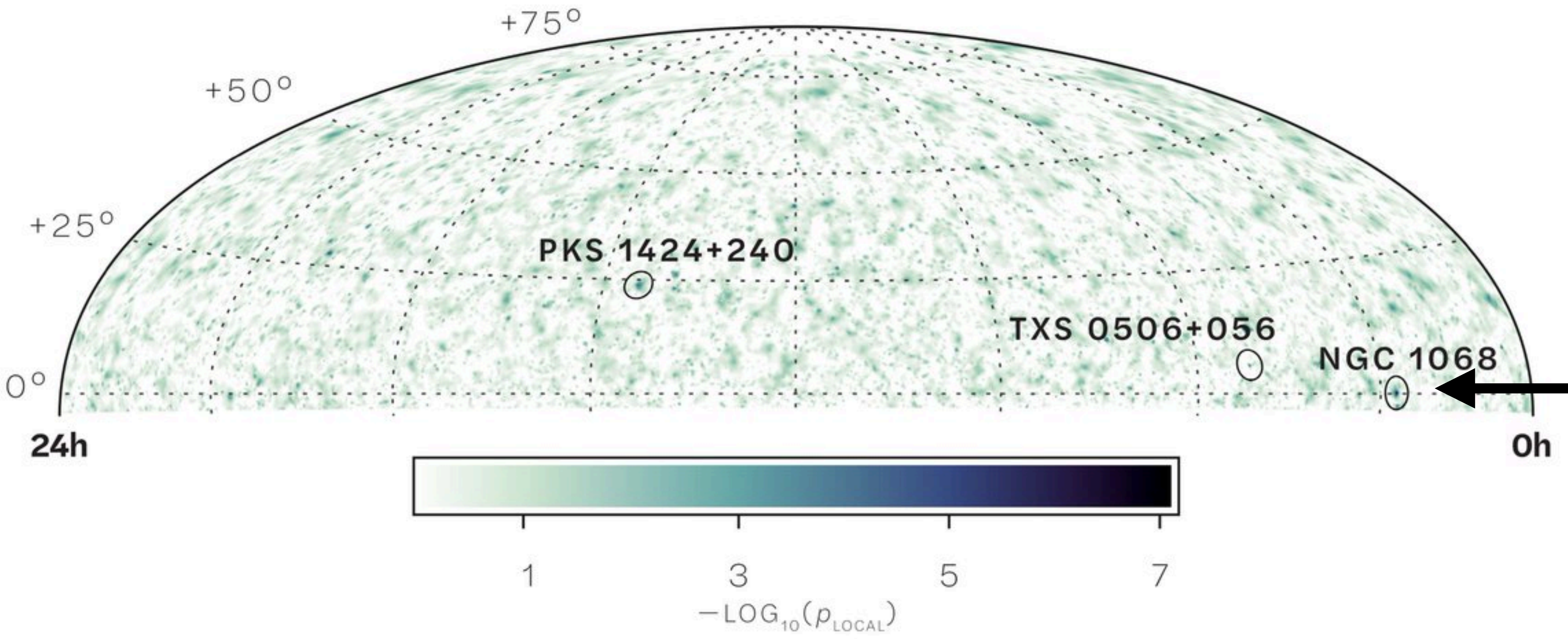
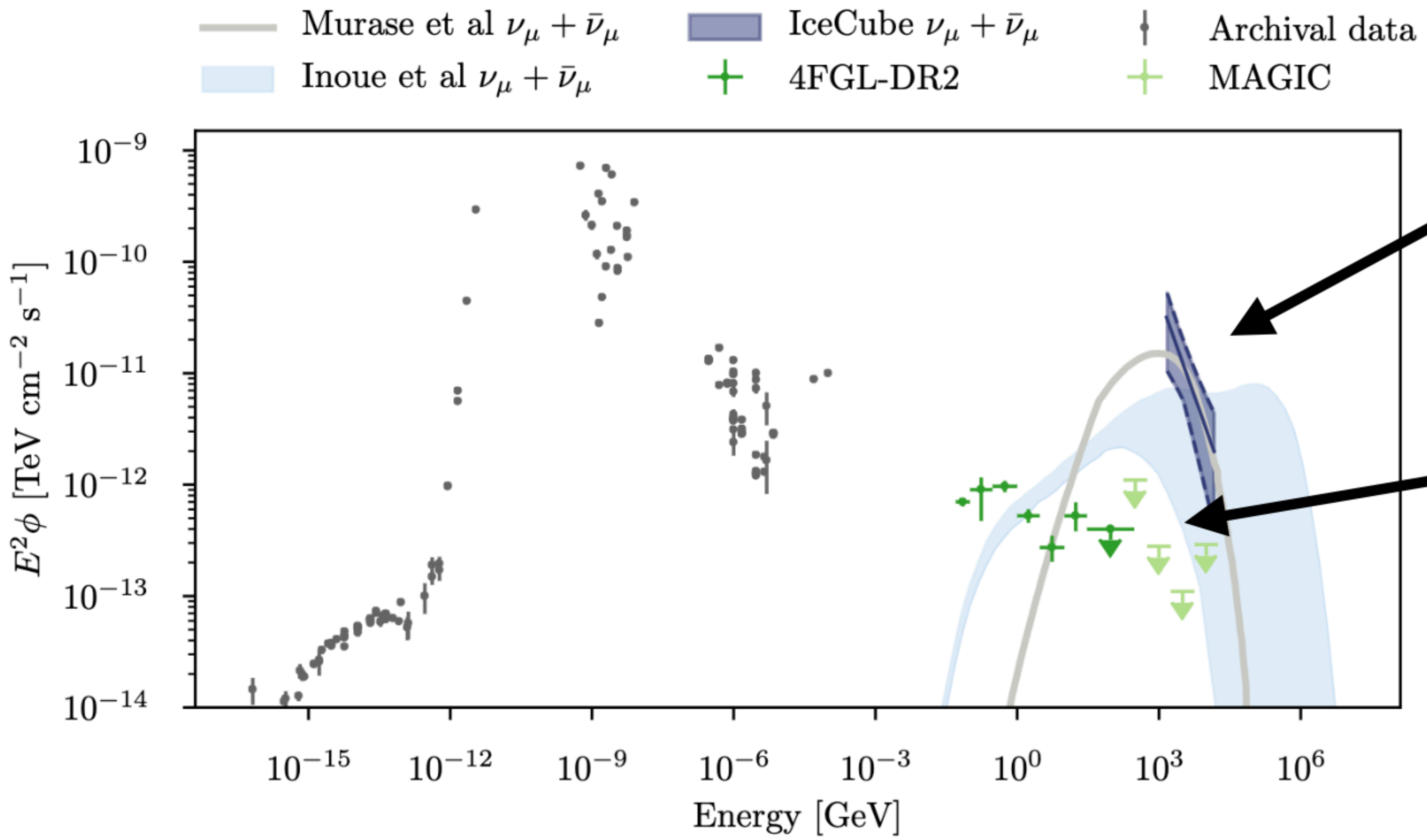
Plan of the talk

- Particle acceleration in AGN coronae: neutrinos as probes
- Turbulence-driven particle acceleration in AGN coronae
- Tackling particle acceleration via magnetized turbulence from first principles
  - Fully kinetic modeling of plasma turbulence
- Two stages of particle acceleration
  - Injection (via magnetic reconnection)
  - Stochastic particle acceleration
- Predicted proton and neutrino spectra from the corona of NGC1068

Localized sources of high-energy neutrinos





Soft ν production ($\propto E_\nu^{-3}$?)

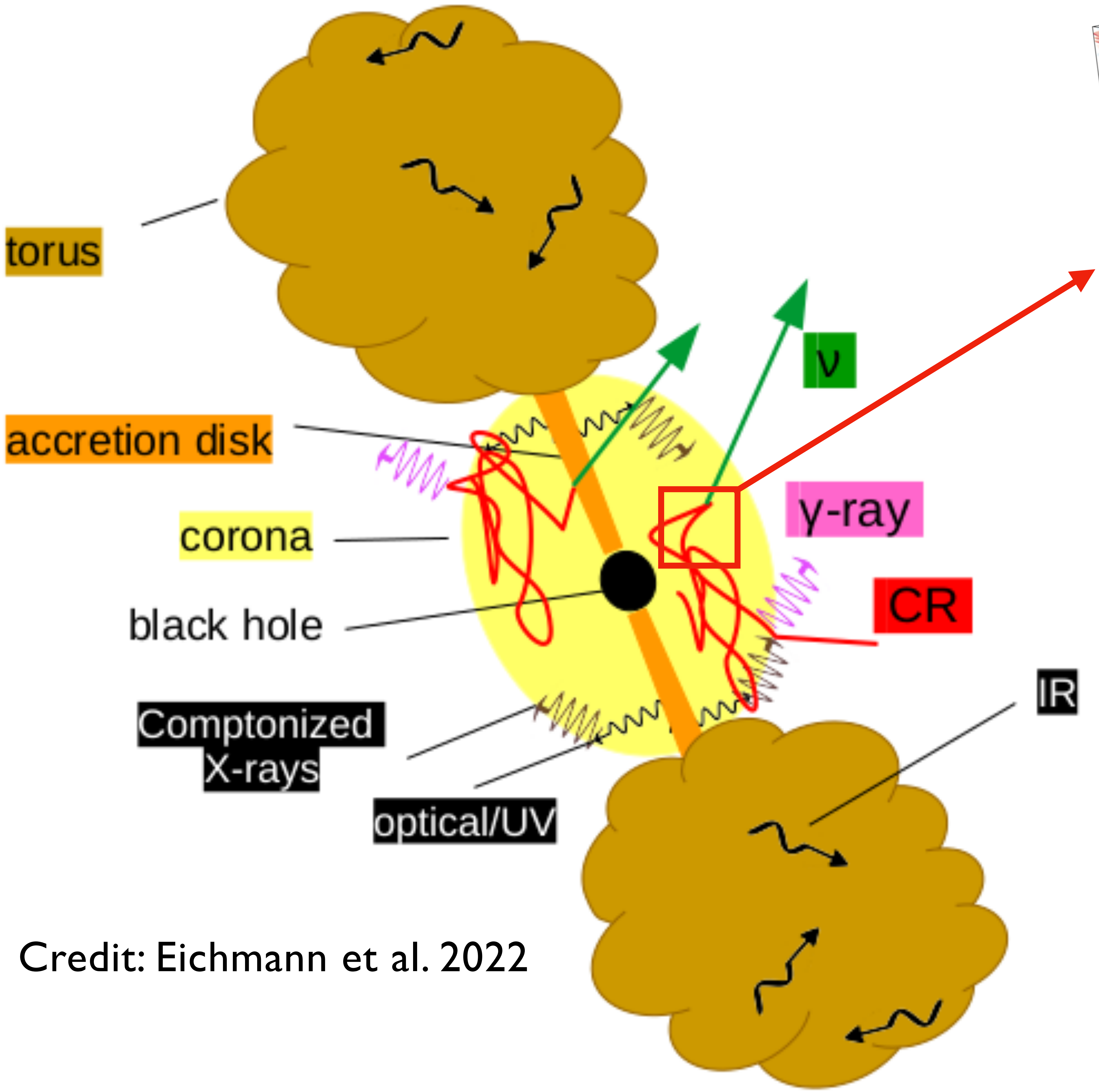
No associated γ

Figures from IceCube, 2022

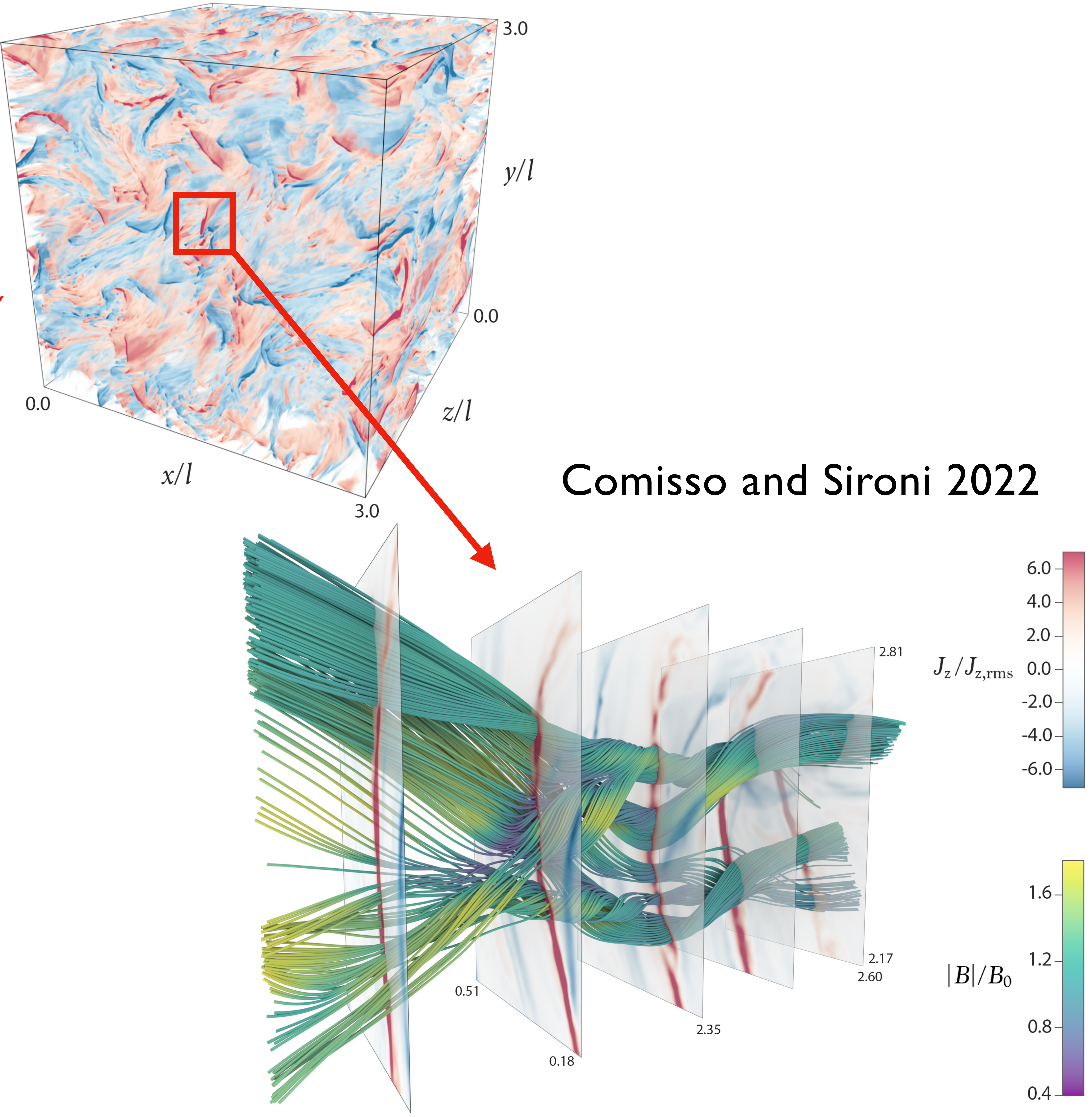
Active galactic nucleus: a complex environment

Credit: Eichmann et al. 2022

Active galactic nucleus: a complex environment



Credit: Eichmann et al. 2022



Comisso and Sironi 2022

Fully kinetic treatment of the plasma

- The evolution of the particle density $f_s(\boldsymbol{x}, \boldsymbol{p}, t)$ of species s in a collisionless plasma is described by the Vlasov equation

$$\frac{\partial f_s}{\partial t} + \frac{\boldsymbol{p}}{m_s \gamma_s} \cdot \nabla_{\boldsymbol{x}} f_s + \boldsymbol{F} \cdot \nabla_{\boldsymbol{p}} f_s = 0$$

where $\gamma_s^2 = 1 + \frac{|\boldsymbol{p}|^2}{m_s^2 c^2}$ and $\boldsymbol{F} = q_s \left(\boldsymbol{E} + \frac{\boldsymbol{p}}{\gamma_s m_s c} \times \boldsymbol{B} \right)$.

- $\boldsymbol{E}(\boldsymbol{x}, t)$ and $\boldsymbol{B}(\boldsymbol{x}, t)$ are determined from Maxwell's equations

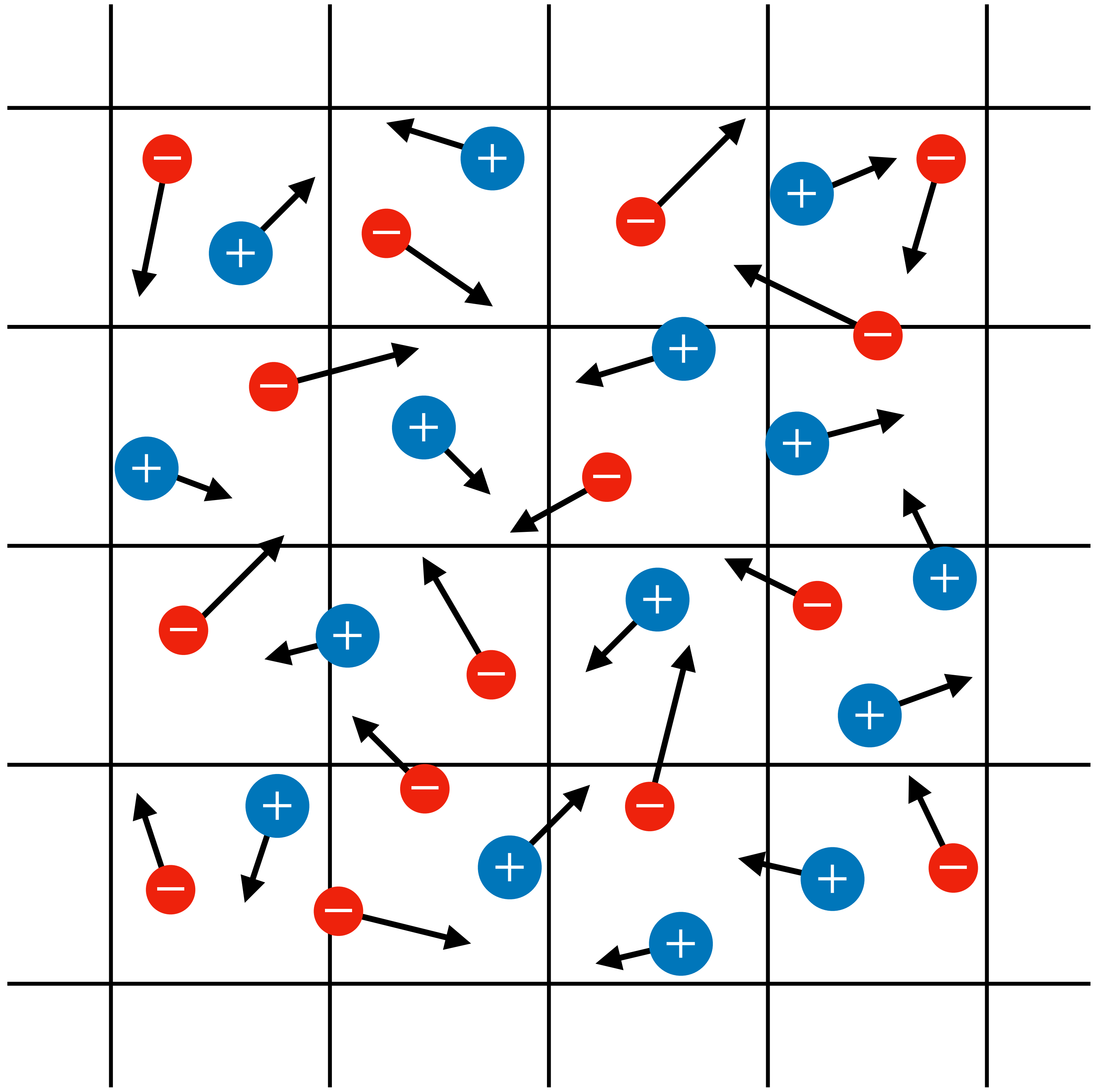
$$\frac{\partial \boldsymbol{E}}{\partial t} - c\,\mathrm{curl}\boldsymbol{B} = -4\pi \boldsymbol{J}\,, \qquad \mathrm{div}\boldsymbol{E} = 4\pi\rho\,,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + c\,\mathrm{curl}\boldsymbol{E} = 0\,, \qquad \mathrm{div}\boldsymbol{B} = 0\,,$$

where the source terms are computed by

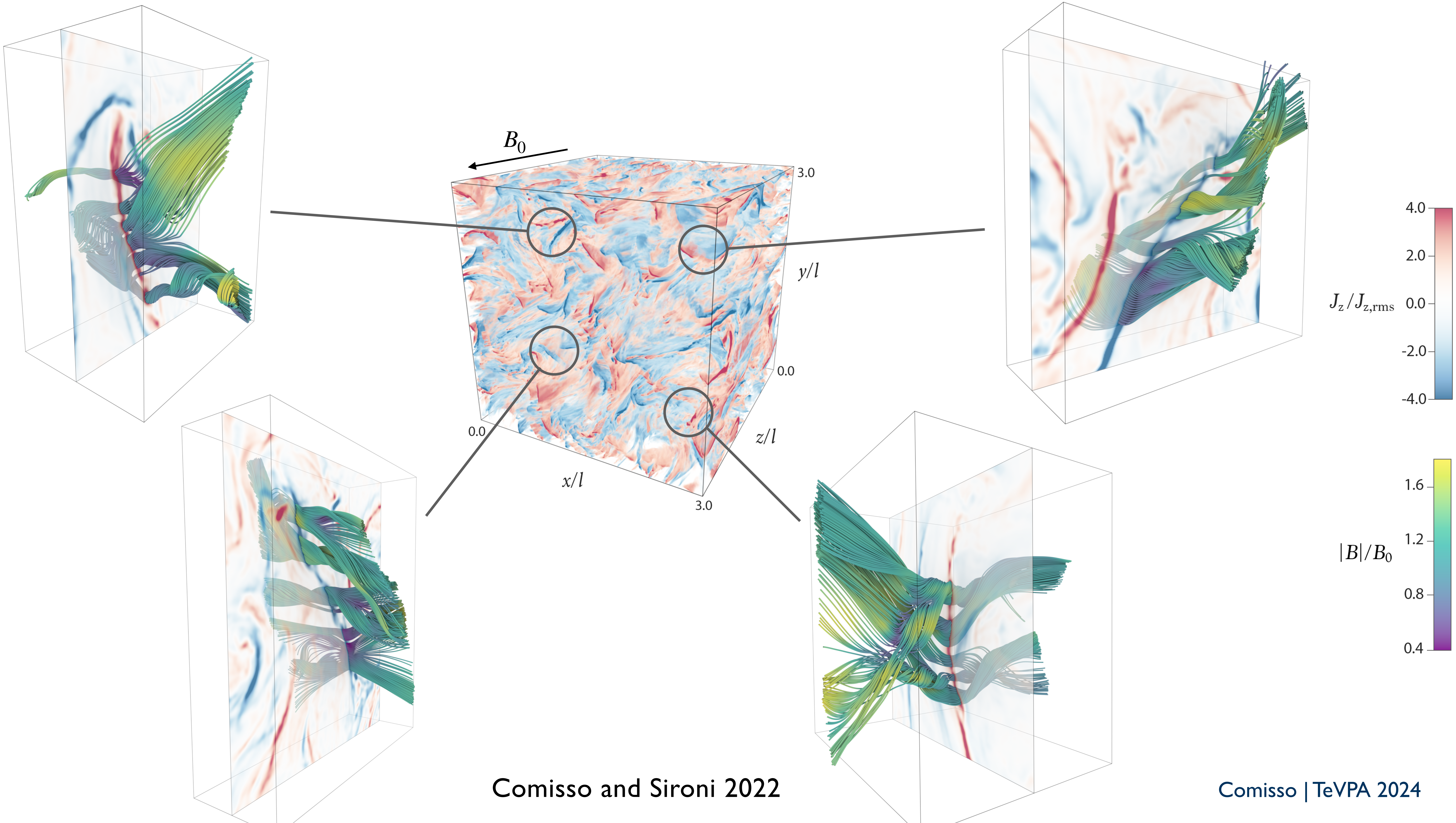
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\boldsymbol{p}\,, \qquad \boldsymbol{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\boldsymbol{p}}{\gamma_s} d\boldsymbol{p}\,.$$

- Solution via particle-in-cell method



PIC code: TRISTAN-MP
(Spitkovsky 2005)

Rendering of electric current density and reconnection in the turbulent cascade



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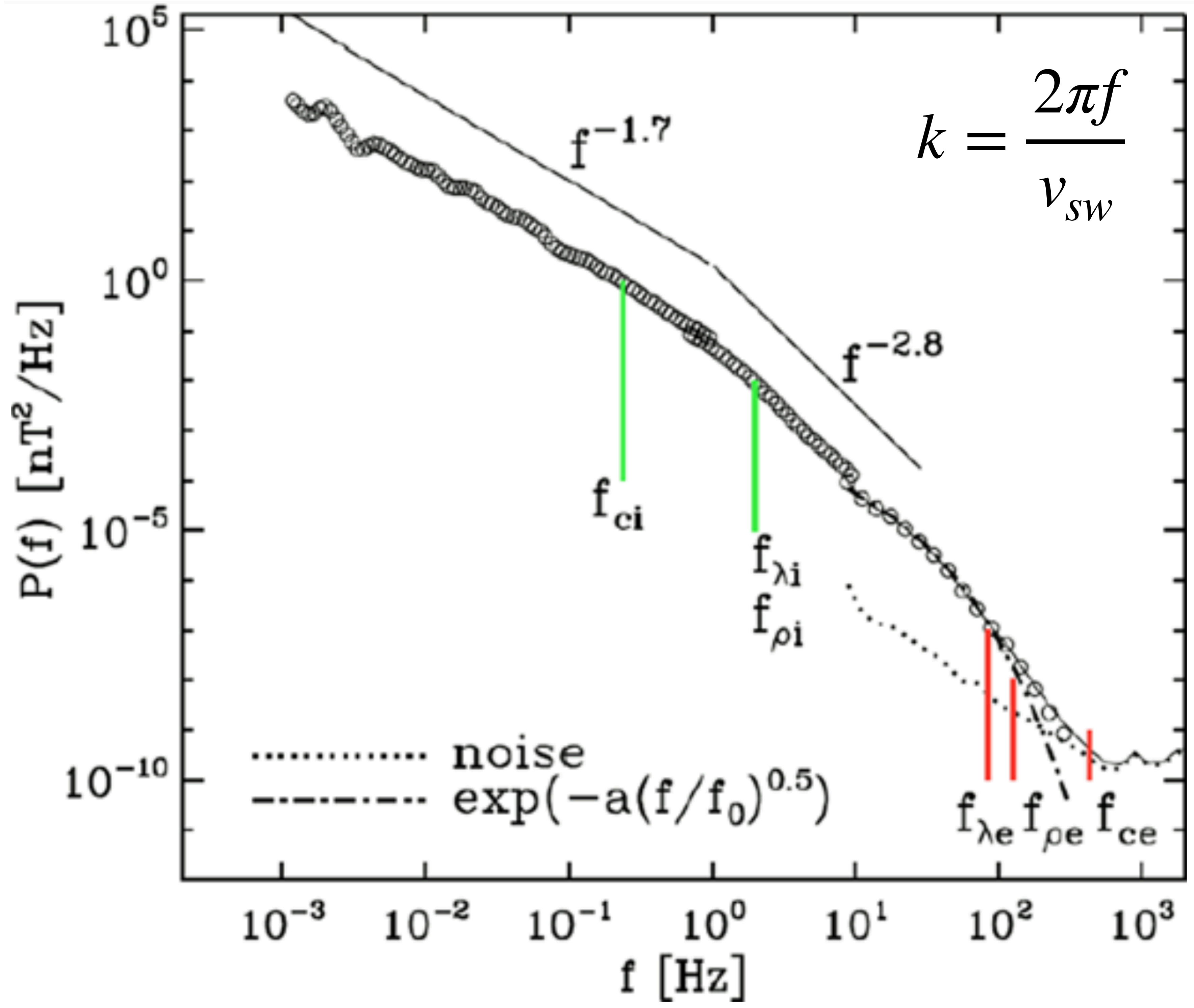
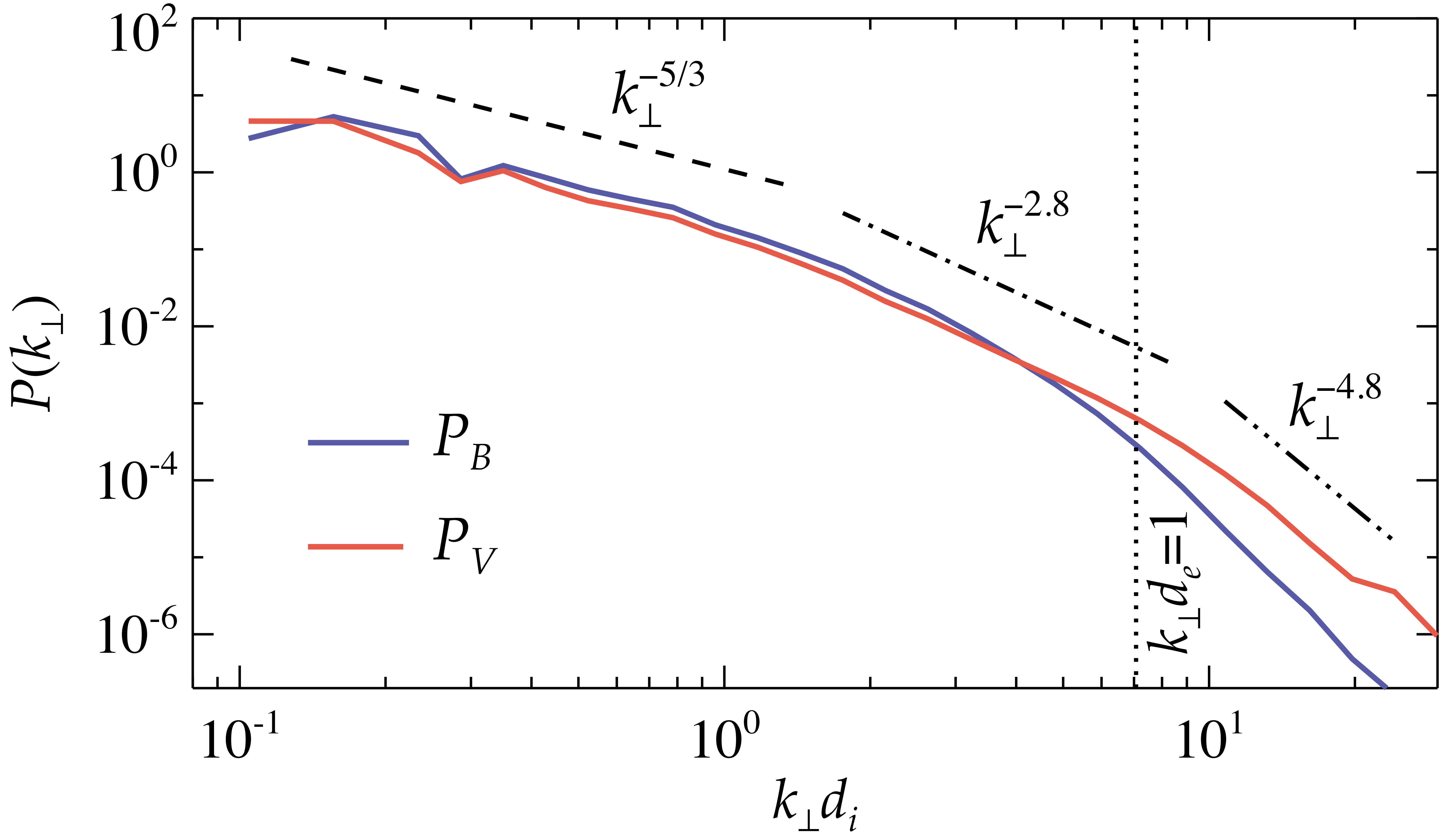
Turbulent cascade from MHD to kinetic scales

Magnetic power spectrum of Solar Wind



Alexandrova et al. 2013

Power spectra from low-β PIC simulation



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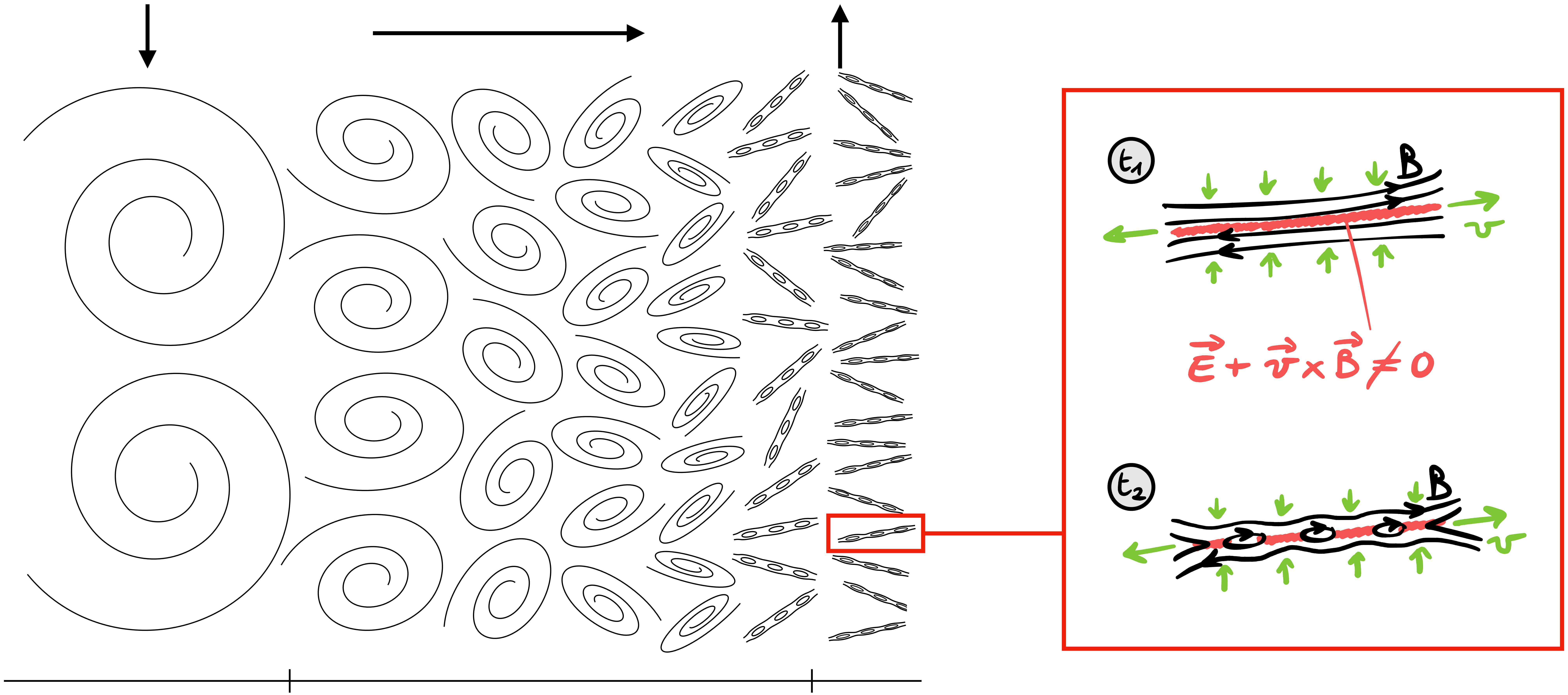
Turbulent energy cascade in large magnetized systems



injection of energy

flux of energy

dissipation of energy

$l = 2\pi / k_f$

$\lambda_d = 2\pi / k_d$

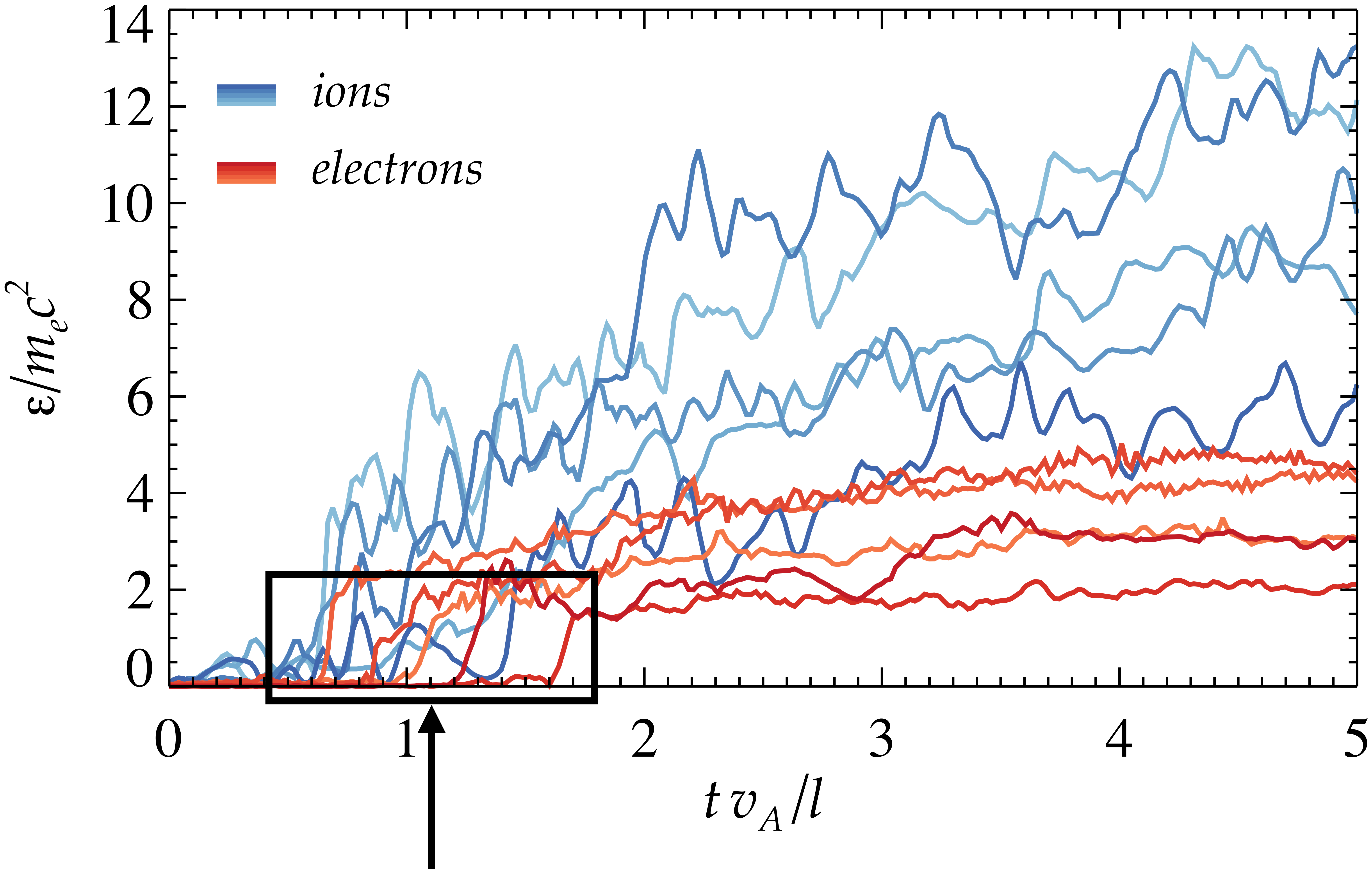
energy-containing range

inertial range

dissipation range

$\vec{E} + \vec{v} \times \vec{B} \neq 0$

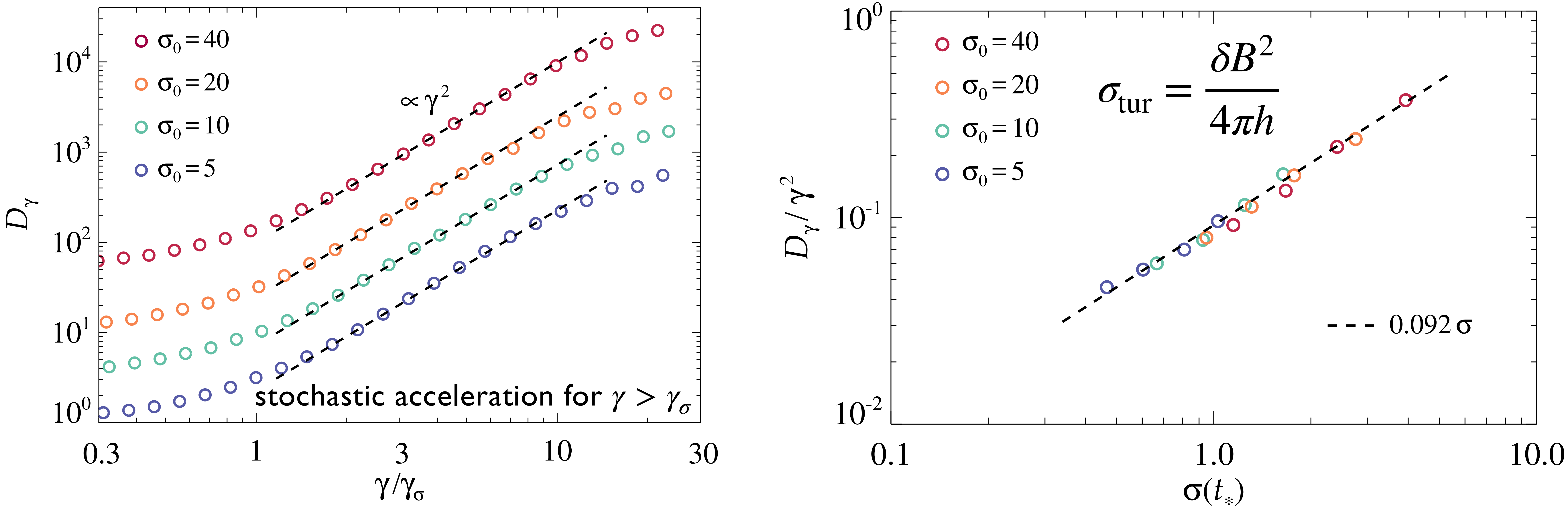
1st acceleration stage ("injection" via magnetic reconnection)



"Injection"

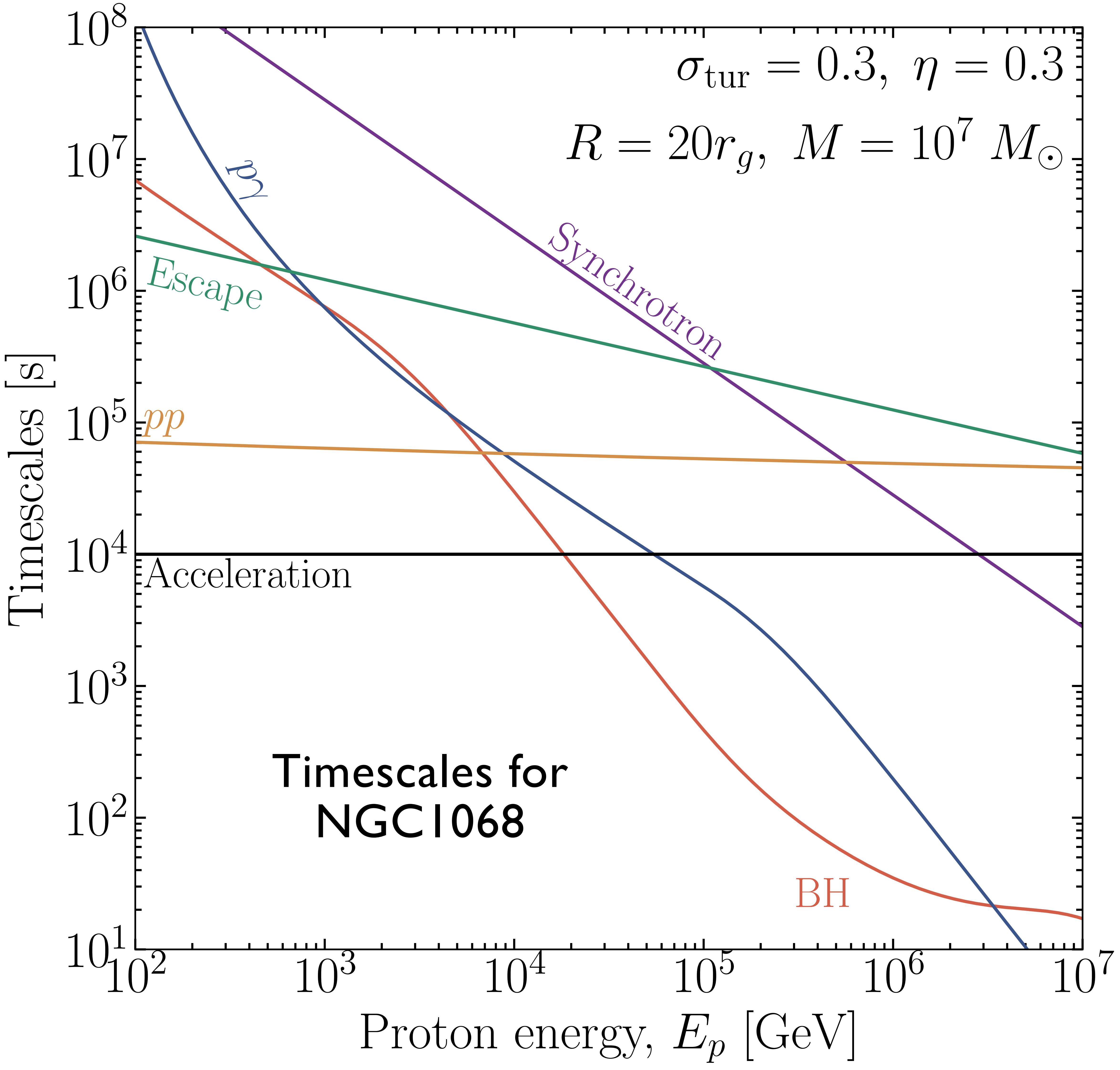
Particles accelerated at reconnection layers

2nd acceleration stage (stochastic particle acceleration)



- Fokker-Planck for stochastic acceleration: $$\frac{\partial f(\gamma,t)}{\partial t} = -\frac{\partial}{\partial \gamma}\left(A_\gamma f(\gamma,t)\right) + \frac{\partial^2}{\partial \gamma^2}\left(D_\gamma f(\gamma,t)\right)$$
- Mean rate of change of γ due to stochastic acceleration: $$A_\gamma = \frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2}\frac{\partial}{\partial\gamma}\left(\gamma^2 D_\gamma\right)$$
- PIC simulations give: $$D_\gamma \sim 0.1\sigma_{\rm tur}\left(\frac{c}{\ell_c}\right)\gamma^2 \longrightarrow t_{\rm acc} = \frac{\gamma^2}{D_\gamma}$$

Stochastic proton acceleration with cooling in the AGN corona

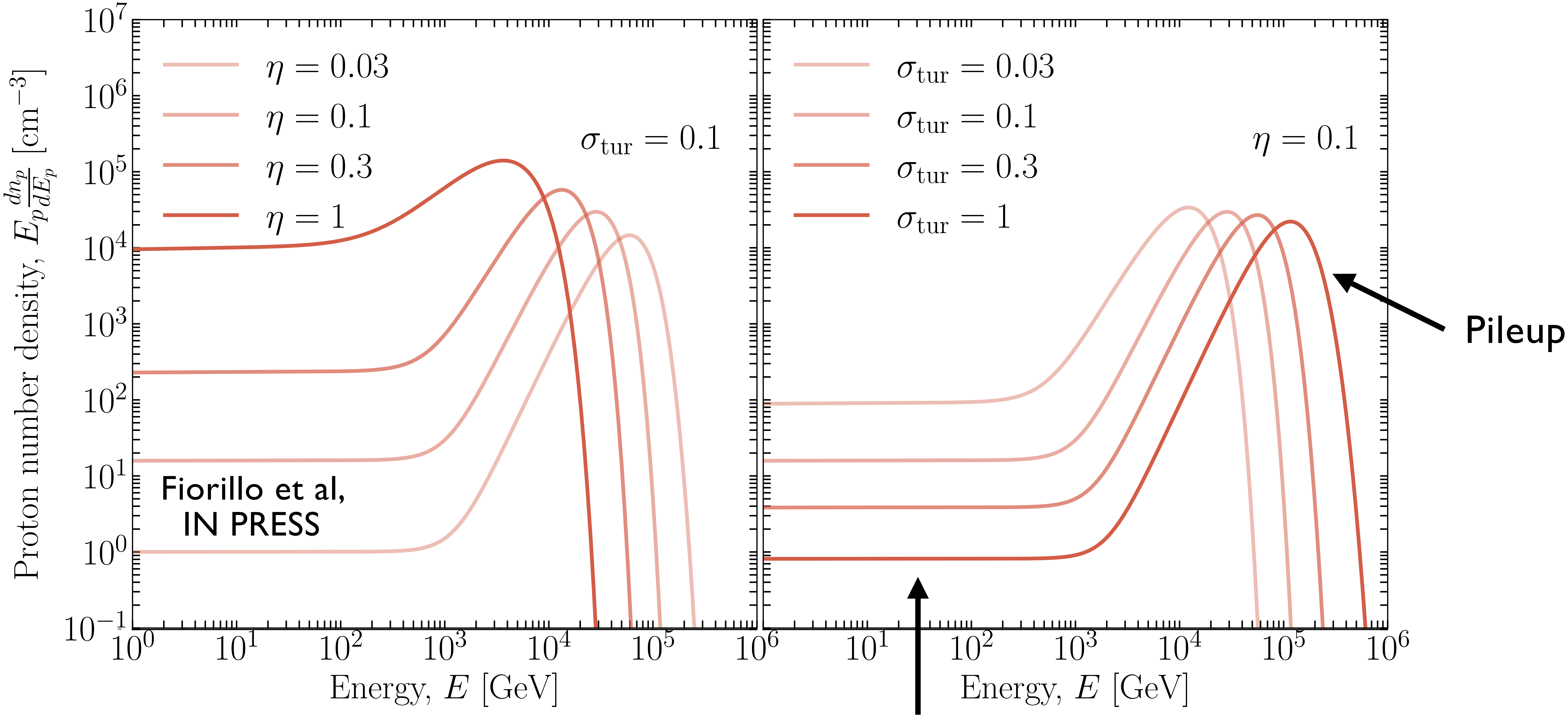


$$\left(\eta = \frac{\ell_c}{R}\right)$$

- $t_{\rm acc}$ is energy-independent
- Bethe-Heitler cooling limits proton energy to 20 TeV (requires sufficiently compact corona)
- electron-proton corona: $n_e/n_p \sim 1$

See also earlier model by Murase et al. '20

Proton energy spectrum in the AGN corona

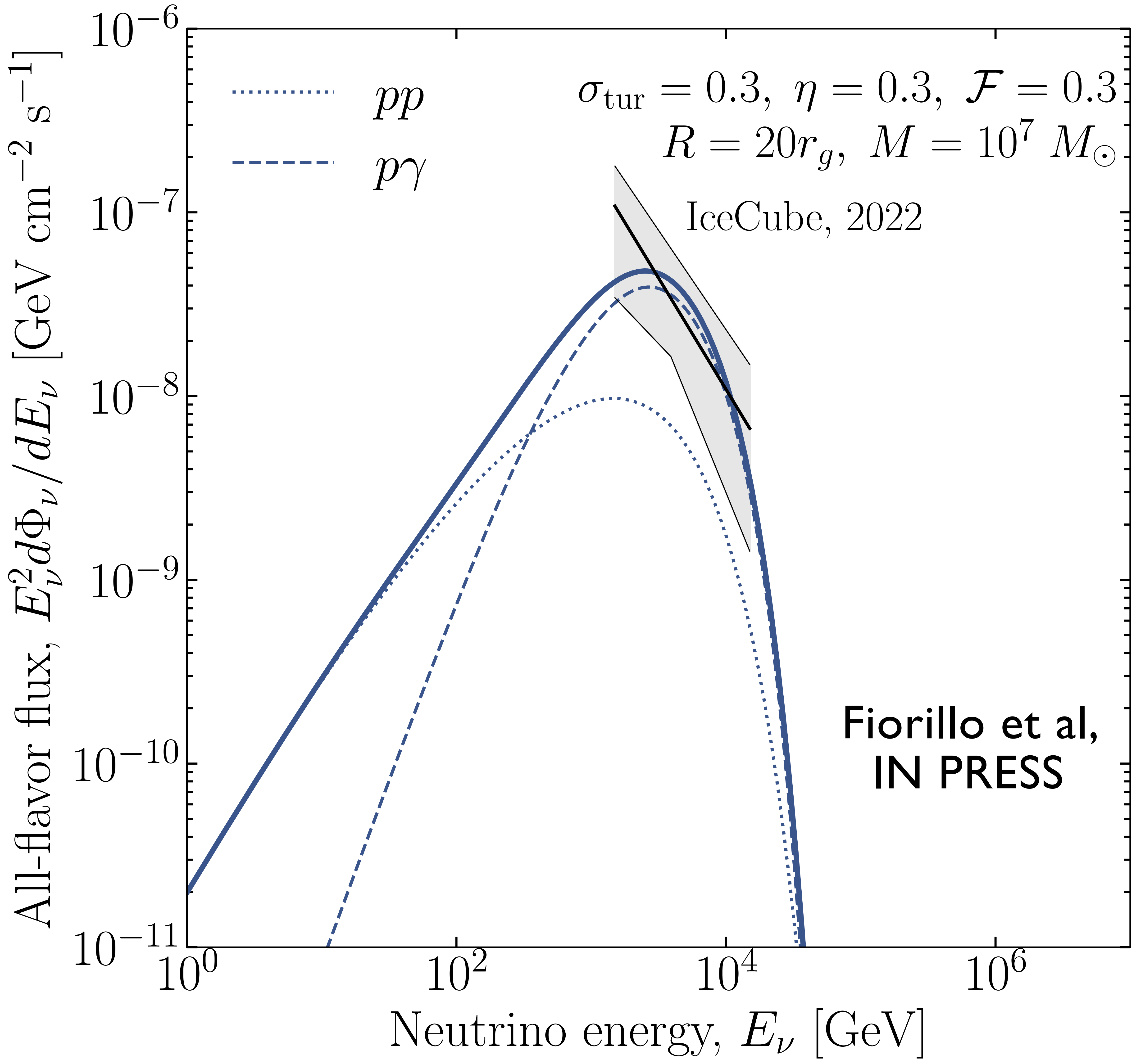


Fiorillo et al,
IN PRESS

Pileup

$dn_p/dE_p \propto E_p^{-1}$ range

Predicted neutrino spectrum for NGC1068

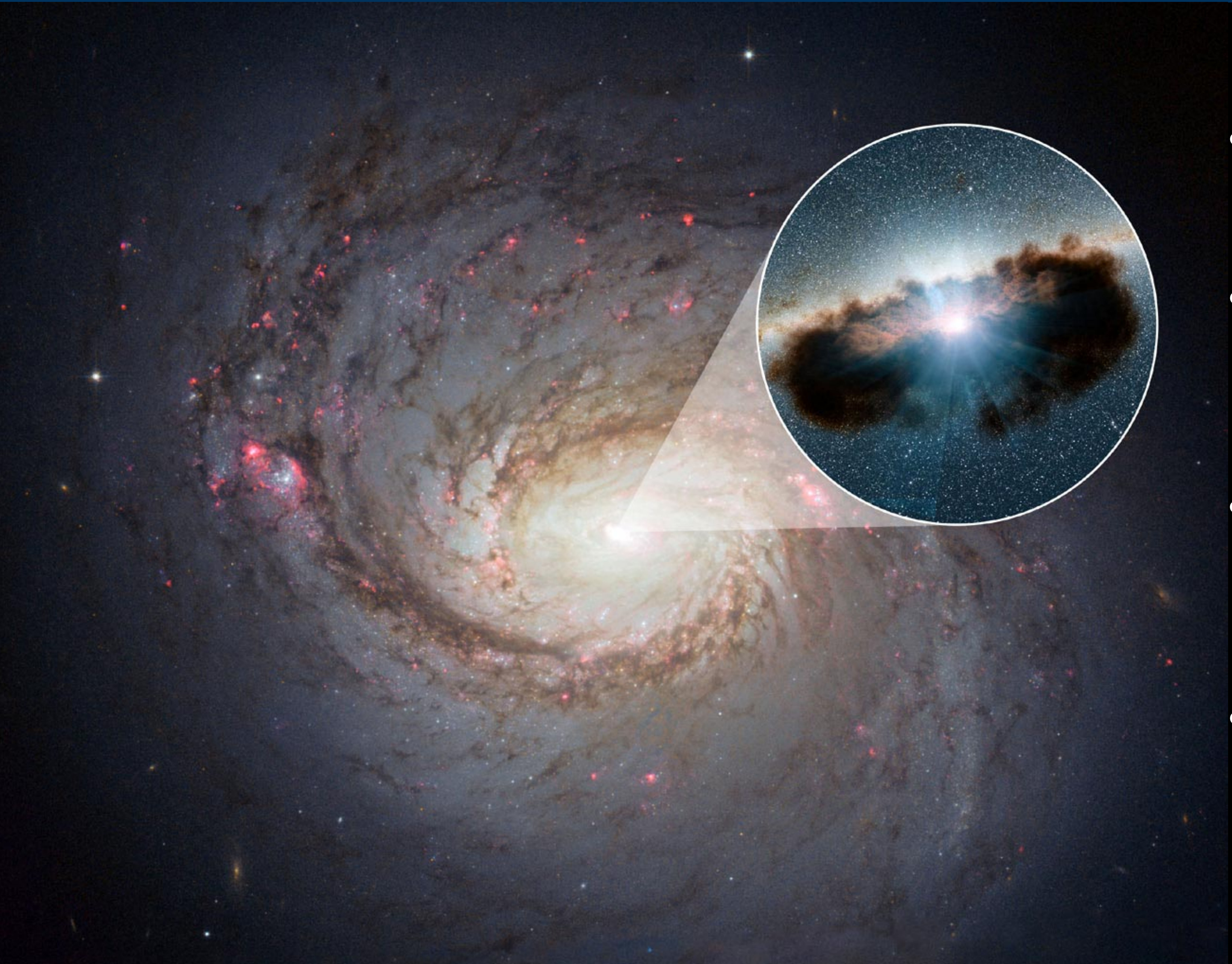


Fiorillo et al,
IN PRESS

- $p\gamma$ and pp production processes compete
- Exponential cutoff rather than power-law suppression (inferred by reconnection-based models*)
- The neutrino signal constrains the allowed range of $\sigma_{\rm tur} = \delta B^2 / 4\pi n_p m_p c^2$ and $\eta = \ell_c / R$
- Neutrino signal provides a testbed for particle acceleration

* Kheirandish et al. '21, Fiorillo et al '24, Mbarek et al. '24

Key takeaways



- Fully kinetic (first principles) treatment of turbulent plasma
- Turbulence self-consistently produces reconnection layers (which inject particles)
- Particle acceleration to highest energy propelled by stochastic scattering off turb. fluctuations
- Turbulence-driven particle acceleration can explain the neutrino signal from NGC1068