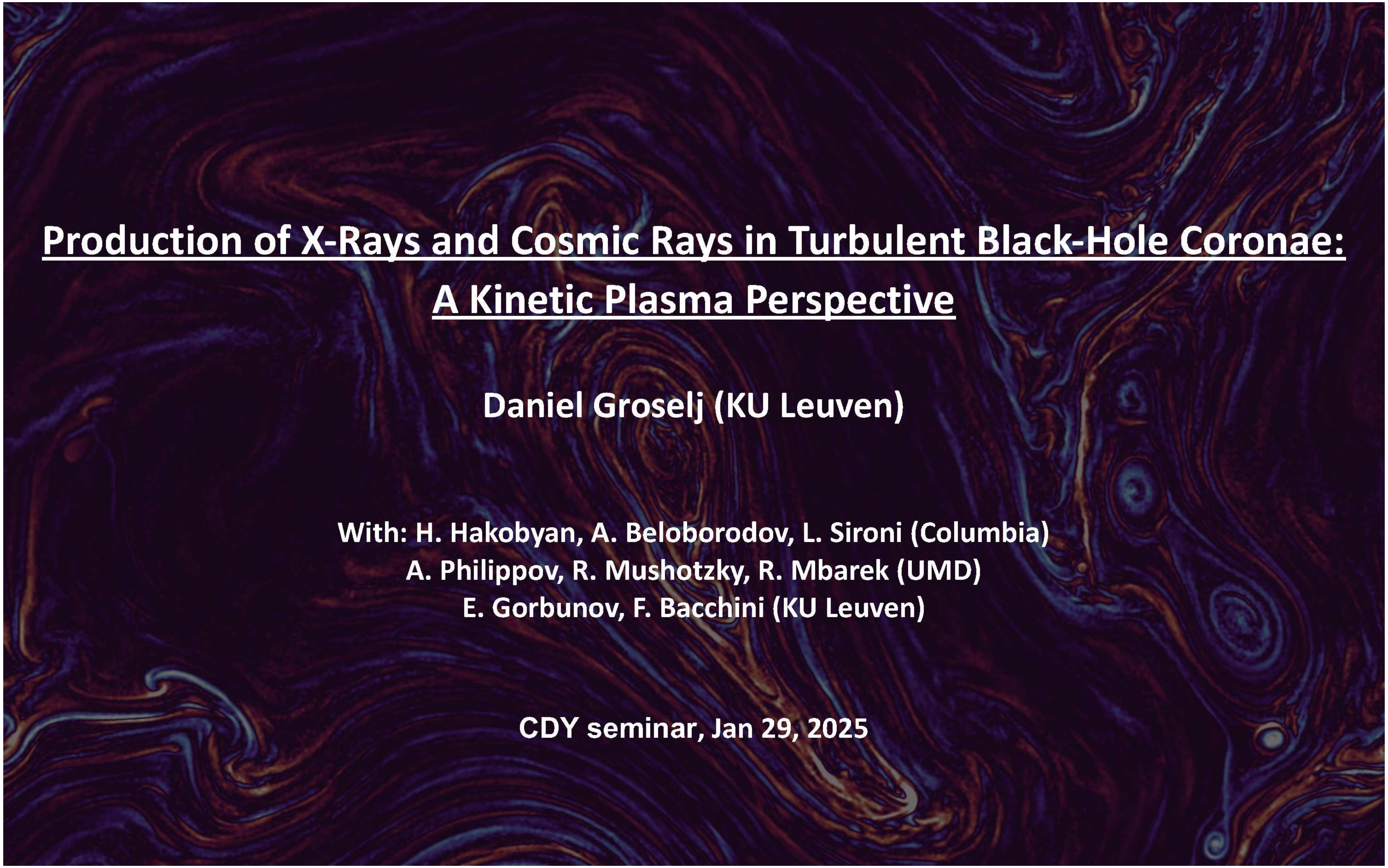

# Production of X-Rays and Cosmic Rays in Turbulent Black-Hole Coronae: A Kinetic Plasma Perspective

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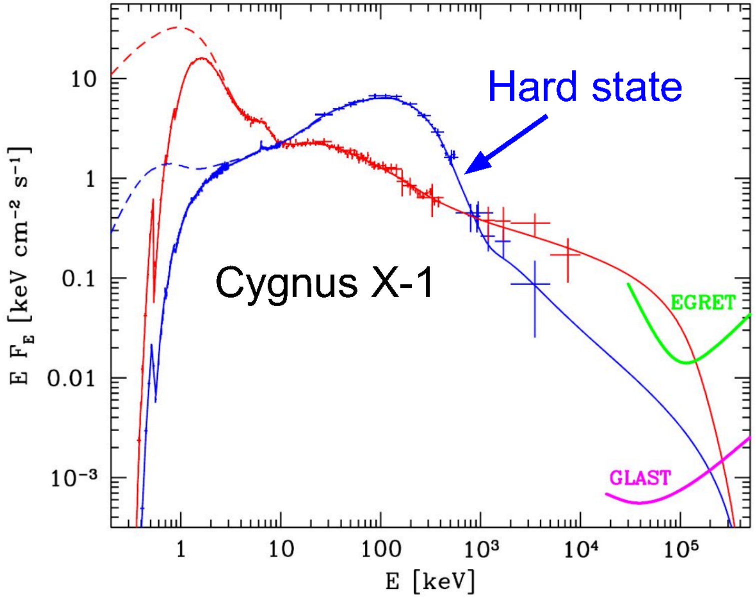
# Origin of bright emission of hard X-rays from black-hole (BH) coronae?

## Hard state in X-ray binaries (XRBs):

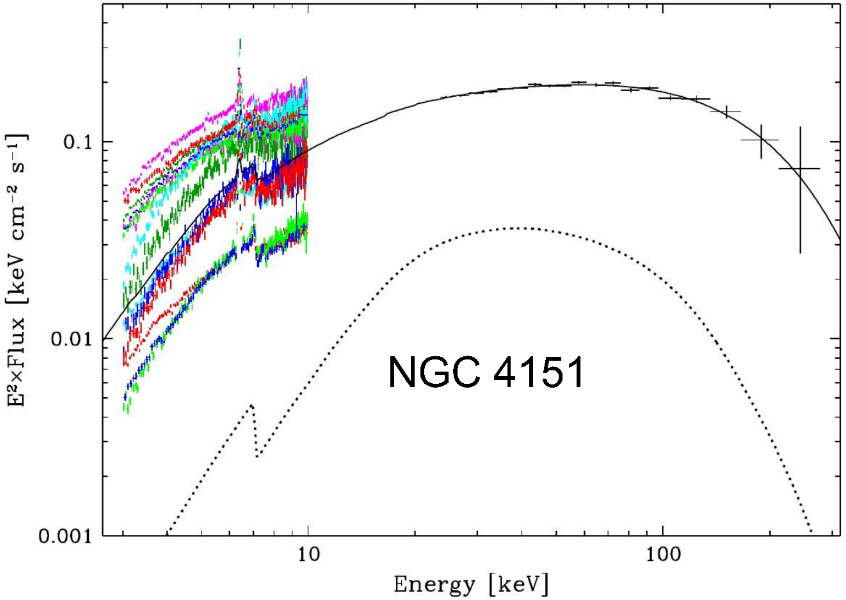
Zdziarski & Gierlinski (2004)



- Nonthermal emission spectra peaked at around ~ 100 keV (i.e., in hard X-rays)

## Luminous cores of active galaxies :

Lubinski et al. (2016)

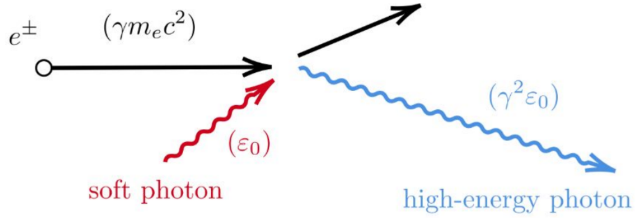


- X-ray spectra similar to hard state in XRBs
- Cores of active galaxies may be also sources of high-energy neutrinos [e.g., Murase et al. (2020)]

# Origin of bright emission of hard X-rays from black-hole (BH) coronae?

<u>Physics picture</u>:

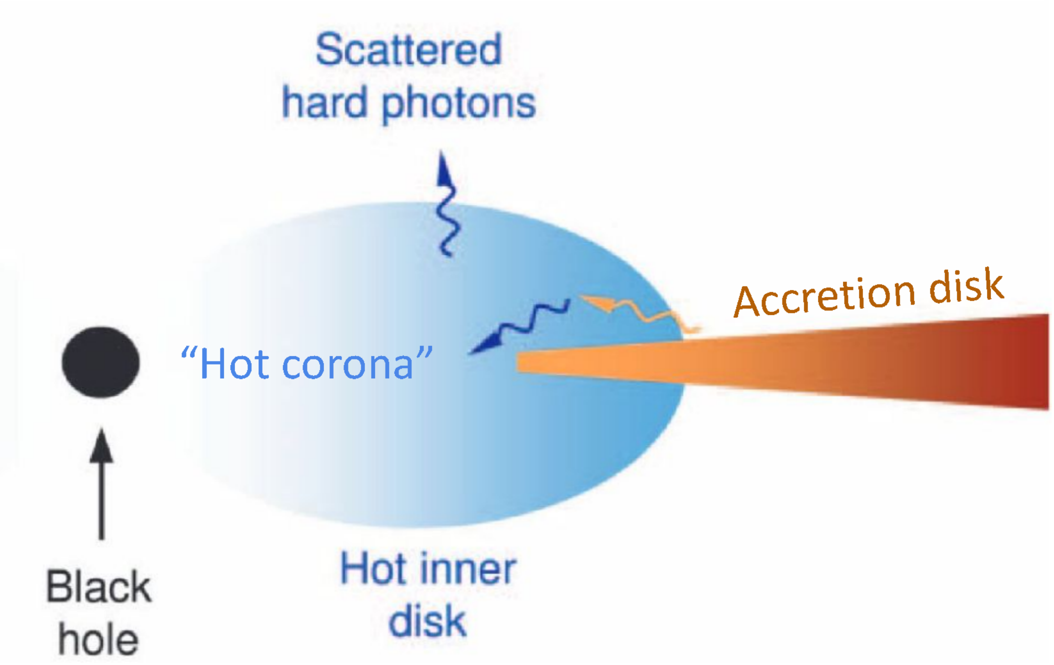
- Comptonization of soft photons in a "hot corona" of moderate optical depth



<u>Some open questions</u>:

- How are coronal electrons energized?
- Energy partitioning between escaping photons, protons, and electrons?
- Proton acceleration & production of high-energy neutrinos?

⇒ this can be now studied with *radiative* particle-in-cell (PIC) plasma simulations (self-consistent coupling of plasma kinetics & radiative transfer)



# Emission of hard X-rays via turbulence mediated Comptonization

## Why turbulence?

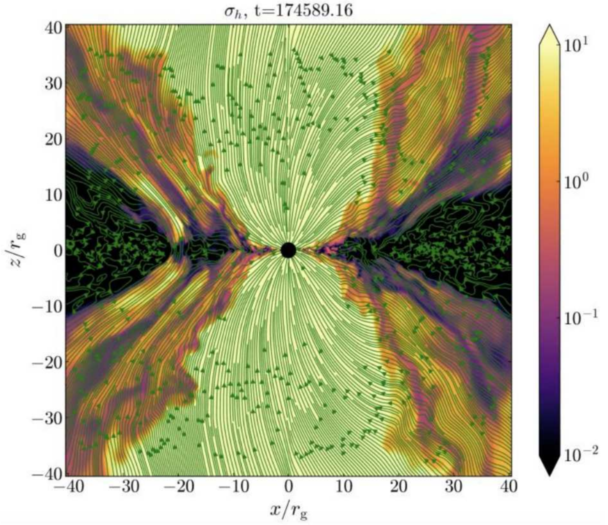
- Instabilities in accreting flow can lead to turbulence
- Large separation between global scales of the flow and the dissipative/kinetic scales
- Support in global MHD simulations

## Reconnection and/or turbulence?

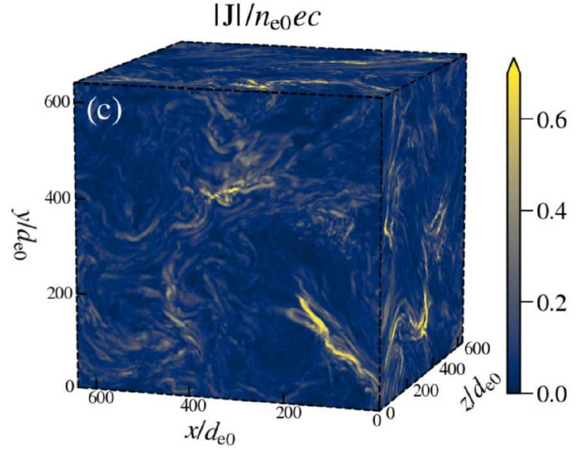
- Turbulence can form reconnecting sheets, similarly isolated current layers evolve into turbulent state
  ⇒ reconnection and turbulence are not mutually exclusive
- Key difference is in volume filling fraction of dissipation regions
  ⇒ turbulence is more volume-filling, reconnection setups feature isolated sheets in a quiescent upstream plasma

[see also Beloborodov (2017), Sironi & Beloborodov (2020), Sridhar et al. (2021, 2022)]

Musoke et al.



Groselj et al. (PRL 2024)



# Regime(s) of turbulence in BH coronae

- Large radiative compactness & moderate optical depth

$$\ell \sim 4\pi(m_\mathrm{p}/m_\mathrm{e})(L/L_\mathrm{E})(R/R_\mathrm{g})^{-1} \gg 1 \qquad \tau_\mathrm{T} \sim 1$$

⇒ strong coupling between the radiation & plasma:
rapid cooling of particles, electron-positron pair creation

- Large electron magnetization

$$\sigma_\mathrm{e} = B^2/4\pi n_\mathrm{e} m_\mathrm{e} c^2 \gg 1$$

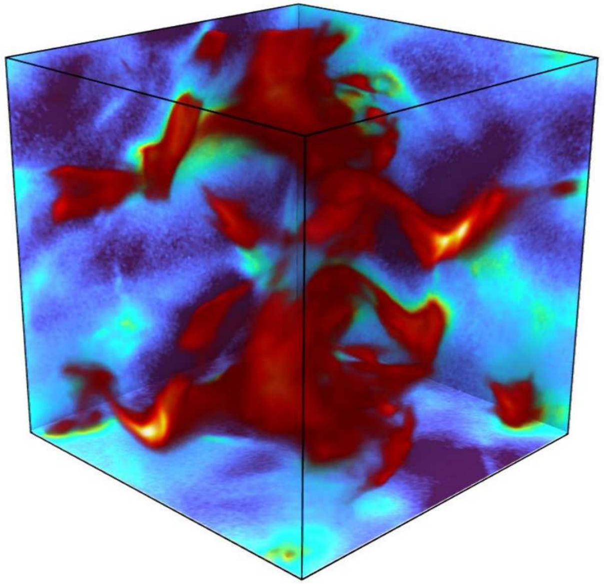
- Outer scale fluctuations may be large (<u>this talk</u>) *or* small compared to the guide magnetic field

- Composition may be pair (<u>PART I of this talk</u>) *or* electron-ion (<u>PART II</u>) dominated

⇒ <u>We use particle-in-cell (PIC) simulations /w radiative transfer:</u>

- Injection of seed photons from a thermal bath
- Diffusive photon & charged particle escape
- Spatially resolved Compton scattering (Monte-Carlo method) with QED (Klein-Nishina) cross-sections

X-ray photon energy density
(Tristan-MP v2 radiative PIC simulation
on a $1280^3$ grid)

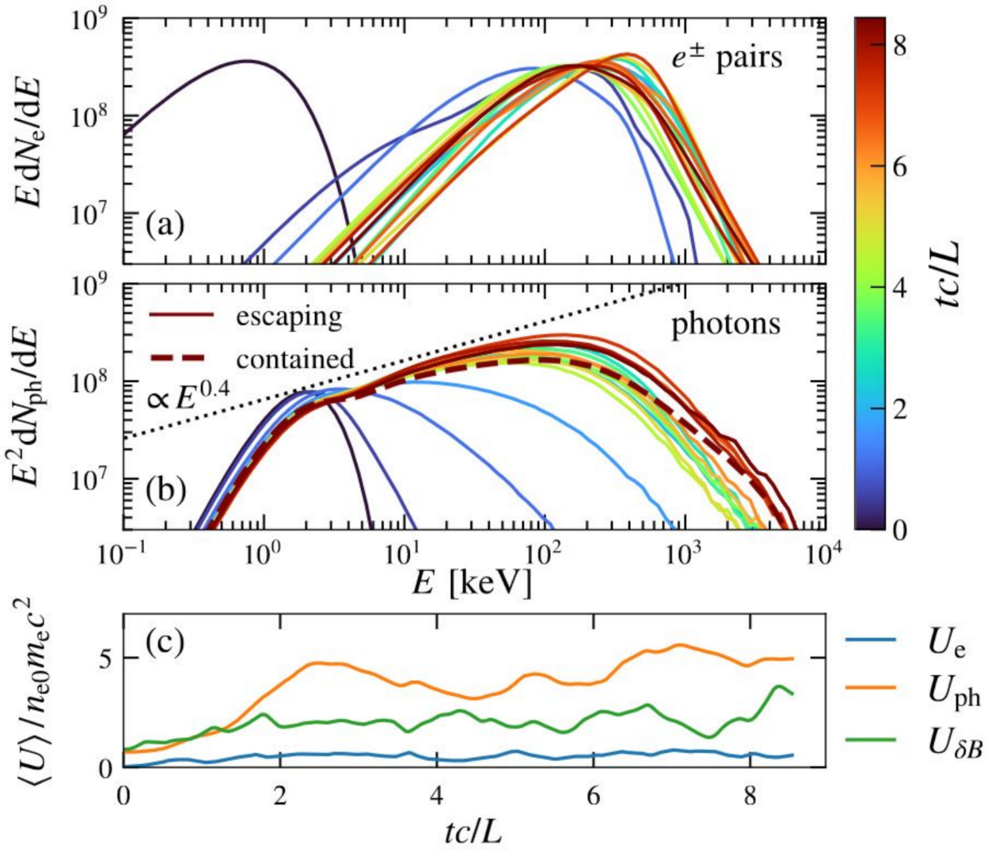


Groselj et al. (PRL 2024)

# Proof of principle: 3D local turbulent box w/ pair plasma composition

- Electron-positron plasma used for simplicity [for self-consistent pair balance see Nattila (2024)]
- Steady state reached when power input from (external) turbulence forcing matches escaping photon luminosity
- Energy budget dominated by radiation and magnetic fields

1st PIC turbulence simulations with self-consistent Compton scattering at moderate optical depth:



Groselj et al. (PRL 2024)

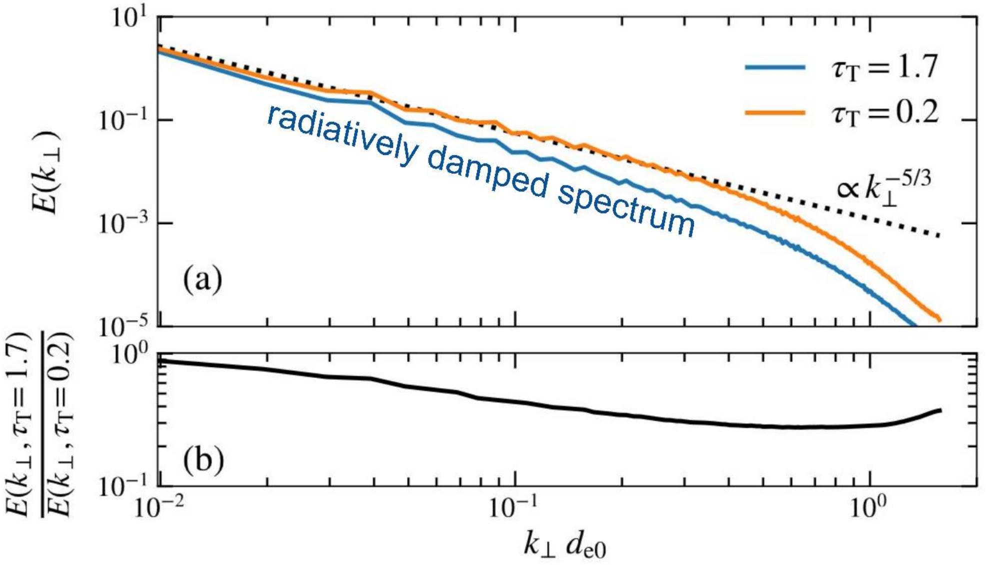
# Emission mechanism: Comptonization via turbulent motions & intermittent hotspots

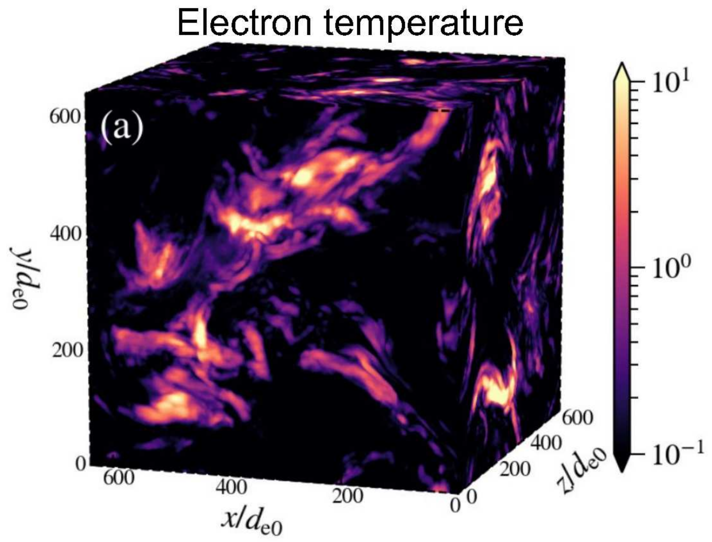
- Comptonization leads to radiative damping of turbulent cascade
  => non-universal turbulence spectra

- Large fraction of the turbulence power is passed directly to photons

- Anisotropic emission w.r.t. mean magnetic field: $I\left(\hat{\mathbf{n}}\perp\mathbf{B}_0\right)\approx 3\,I\left(\hat{\mathbf{n}}\parallel\mathbf{B}_0\right)$

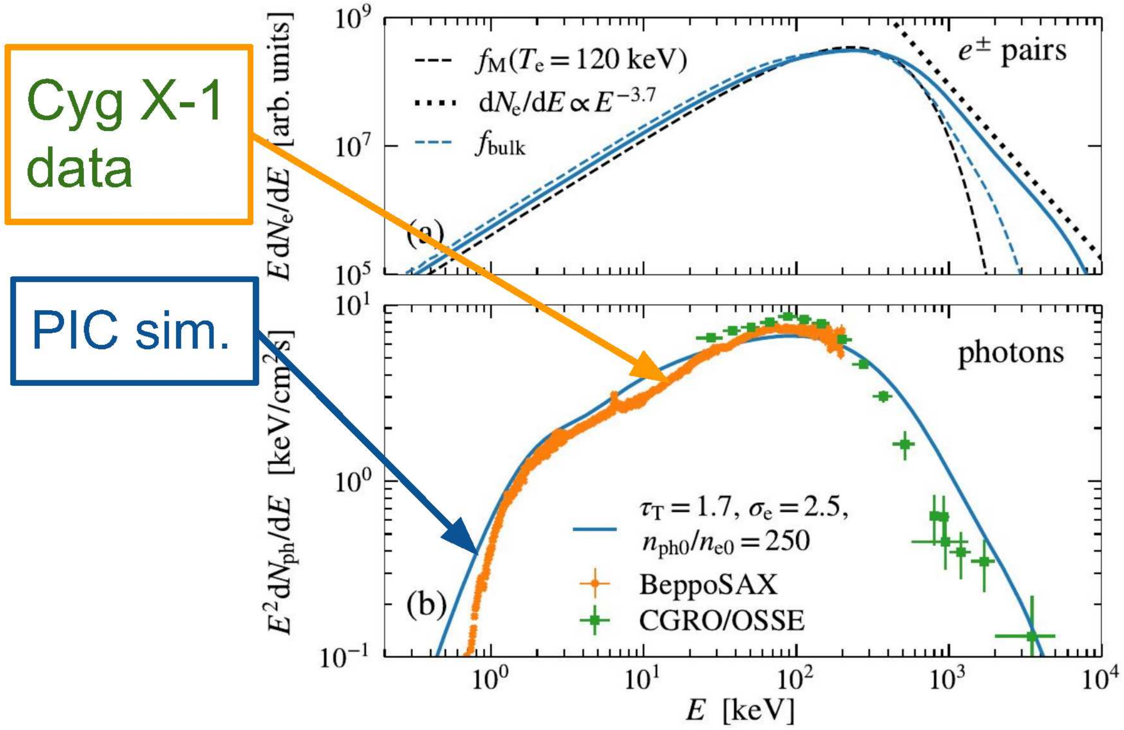
- Fraction of power that arrives at microscales channeled into nonthermal electrons at intermittent “hotspots”





# Contact with observations of Cygnus X-1

- Electron spectrum ~ quasi-thermal part contributed by bulk motions (dashed blue line) + nonthermal tail from localized “hotspots”
- Peak of Comptonized emission mainly shaped by bulk motions w/ *effective* temperature ~ 100 keV
- Nonthermal electron tail shapes the MeV emission

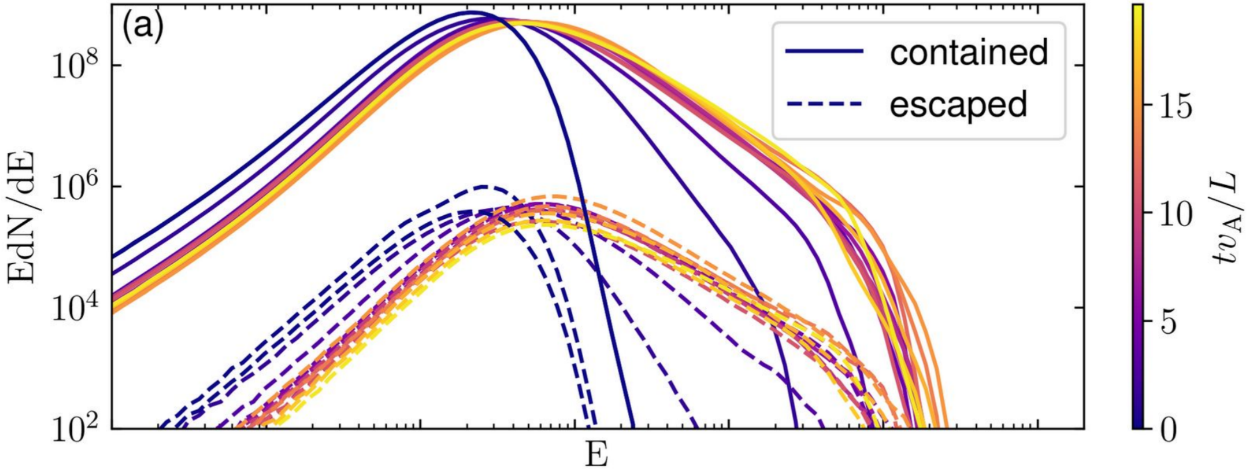


# Electron-ion turbulent corona & application to AGNs

- Released power partitioned between X-rays and ions as quantified by the *ion heating fraction*
  ⇒ a well-known plasma parameter but unexplored in regime applicable to BH coronae

- Coronal turbulence with large-amplitude fluctuations is *nominally* (i.e., w/o efficient ion heating) supersonic & trans-Alfvenic! ⇒ expect shocks

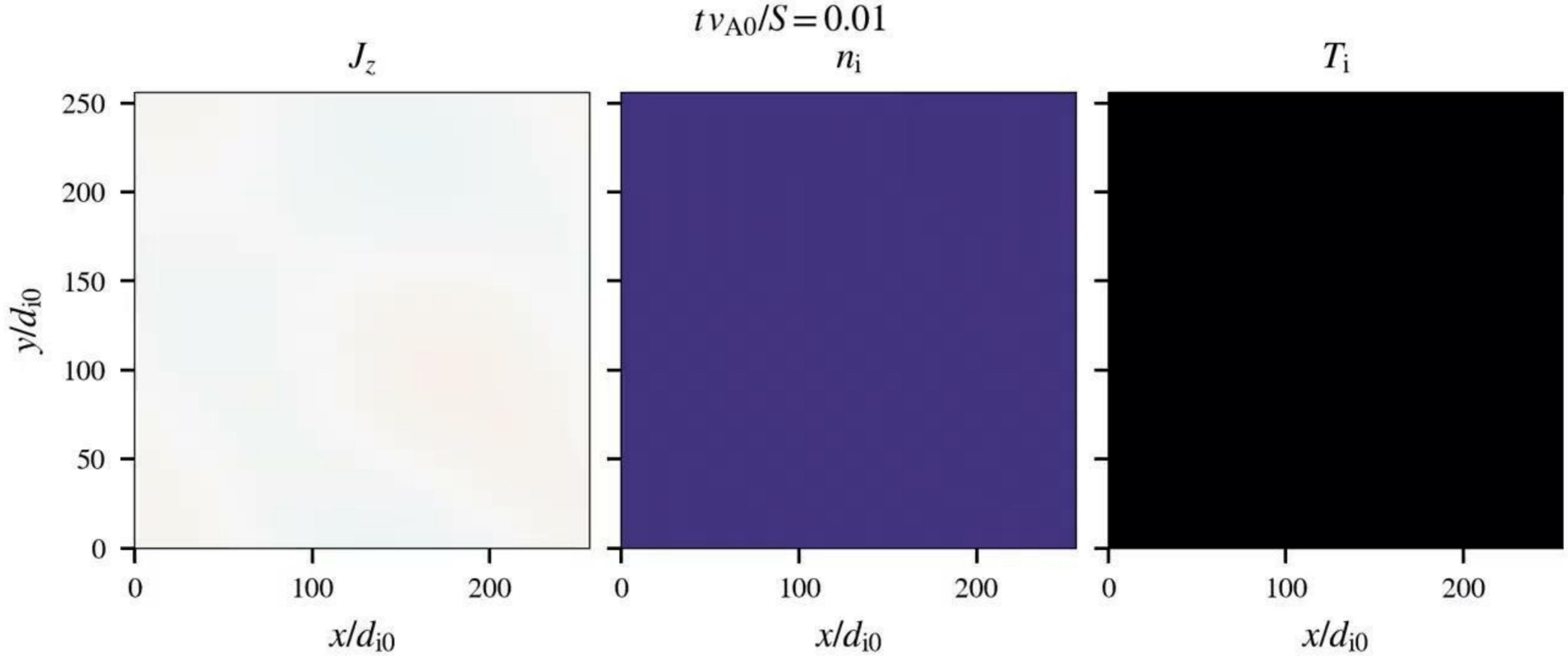
- Preventing (ion) energy accumulation requires *open systems* with escape of charged particles!
  ⇒ escape gives steady state nonthermal spectra of kinetic turbulence even w/o radiative cooling



Gorbunov, Groselj, & Bacchini (in prep.)

# Particle energization at turbulent shocks & current sheets

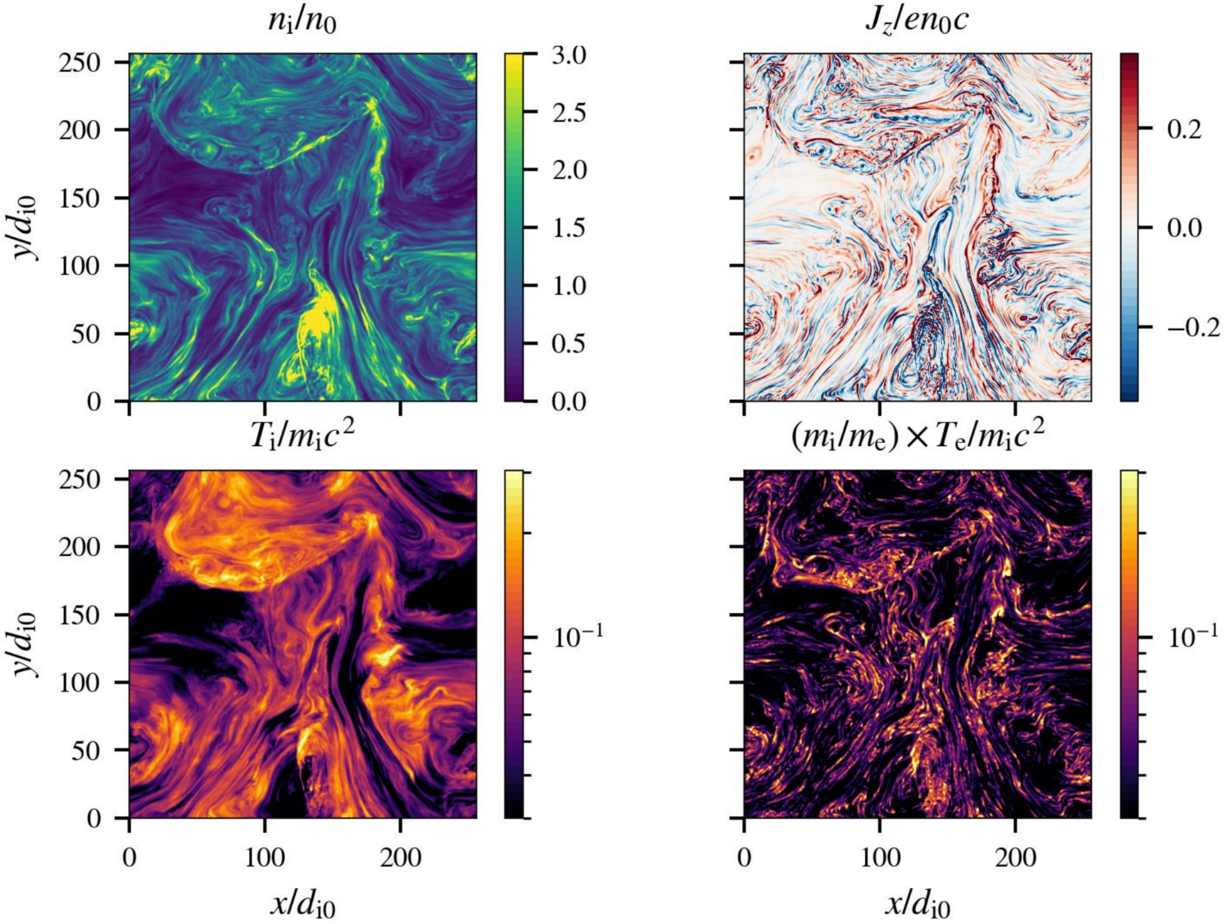
2D radiative PIC simulations ($7680^2$ box, $m_i/m_e = 144$):



Groselj et al. (in prep.)

# Particle energization at turbulent shocks & current sheets

- Coronal turbulence maintains a two-temperature state, with ions much hotter than electrons
- Electrons are intermittently energized near current sheets, ions at both shocks and current sheets

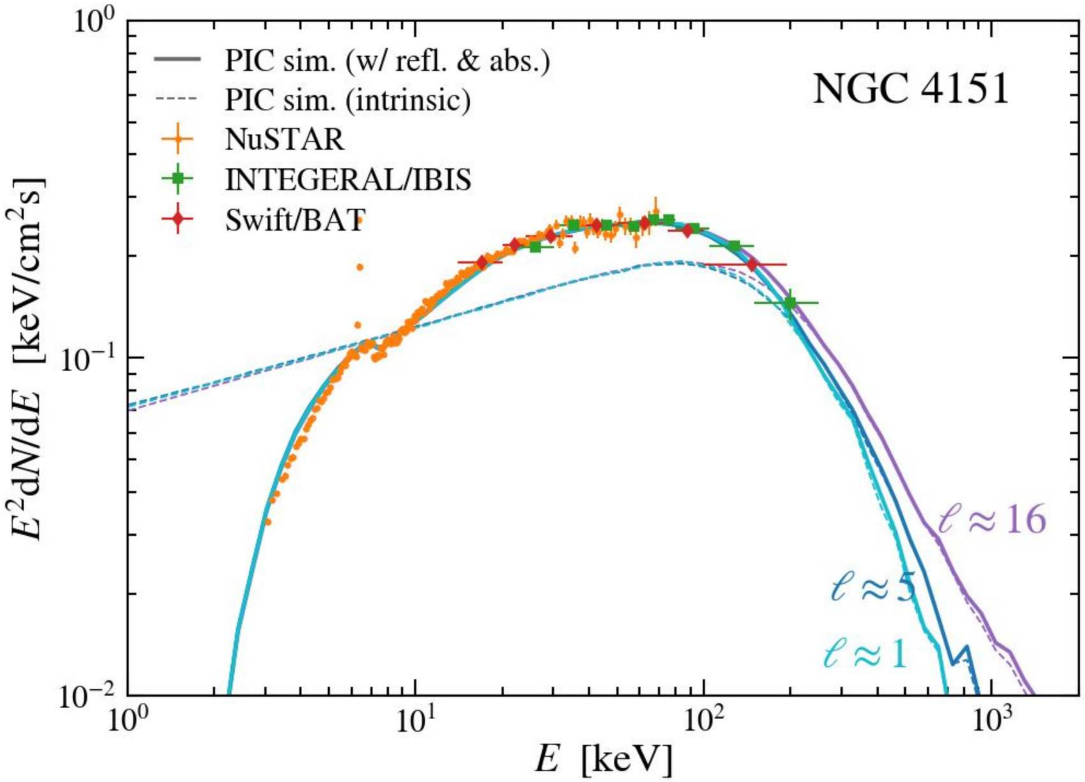


Groselj et al. (in prep.)

# Contact with X-ray observations of NGC 4151

- Excellent agreement between direct predictions from radiative PIC simulations & X-ray observations

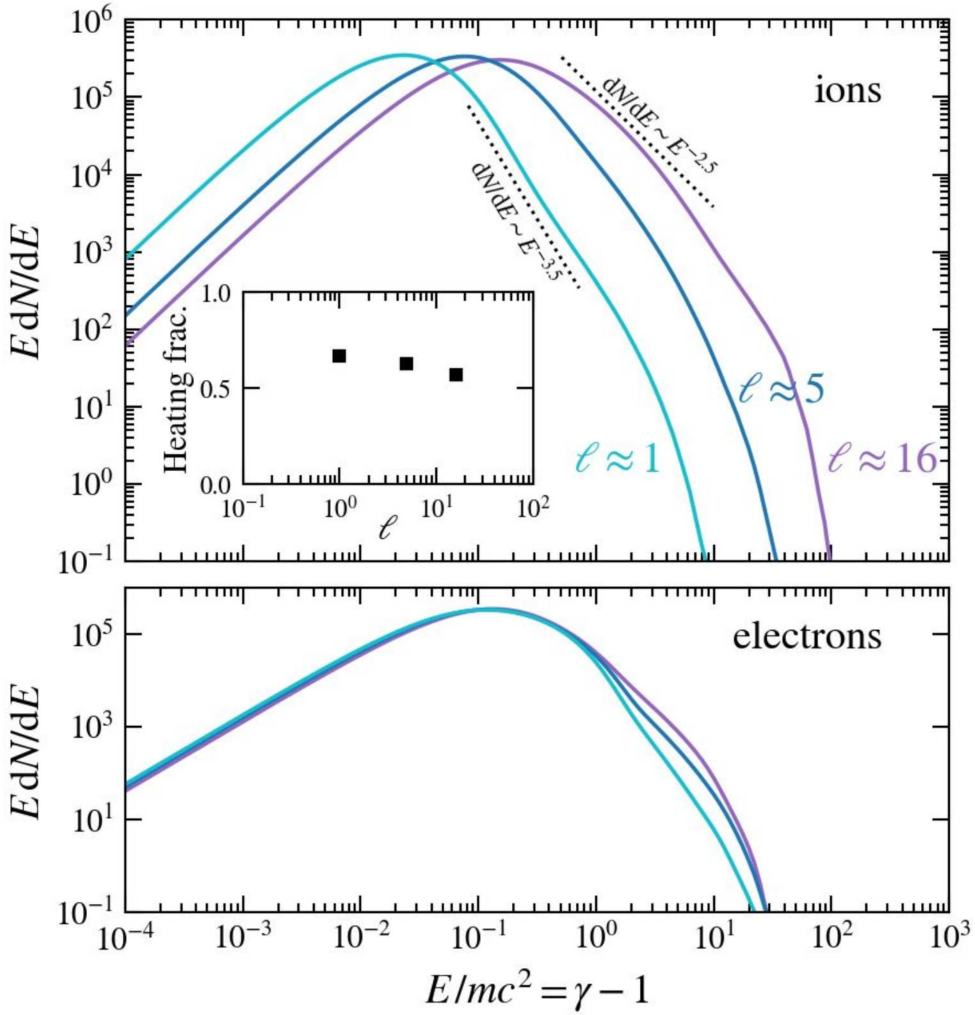
- The compactness affects primarily the MeV range, which is shaped by the nonthermal electron tail



Groselj et al. (in prep.)

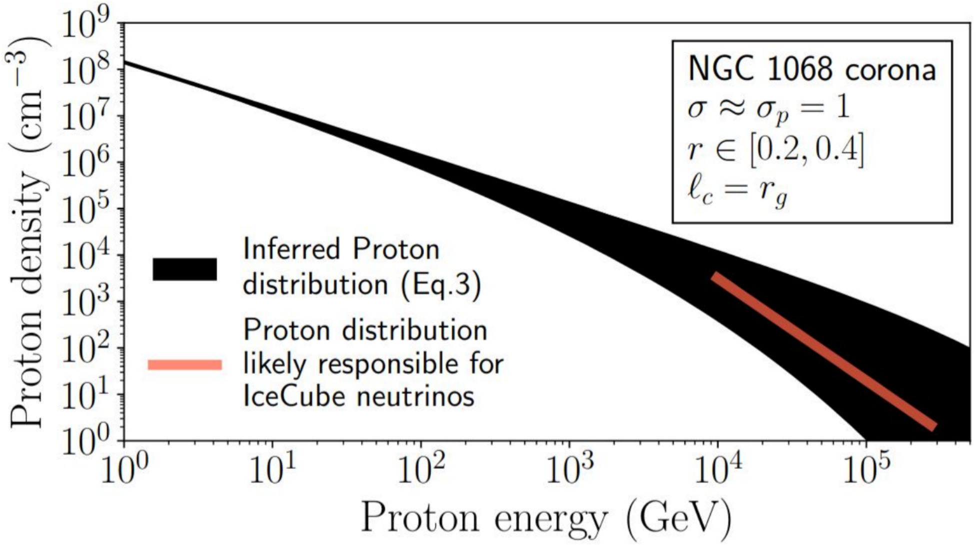
# Efficient production of non-thermal ions at high compactness

- Ion spectrum hardens with growing compactness and extends to higher energies
- Spectrum of (cooled) electrons depends weakly on compactness ℓ
- Significant fraction of turbulence power goes to ions, i.e. the ion “heating” fraction is ≳ 50%



# Implications for multi-messenger emission

- Predicting neutrino emission requires extrapolations of PIC simulation results to (much) larger domains
- Estimates suggest that turbulence can power both the observed X-ray and neutrino emission [see also, e.g., Murase et al. (2024), Mbarek et al. (2024), Fiorillo et al. (2024)]
- Ion heating fraction limits amount of power in CR protons, and in turn the resulting neutrino emission (models favor large heating fraction, consistent with our results)



Mbarek et al. [incl. Groselj] (in prep.)

# Summary

- Now possible to study the microphysics of particle energization and emission in BH coronae from first principles using radiative PIC simulations (plasma kinetics + radiative transfer)
- Turbulence is a viable mechanism for powering high-energy multi-messenger emission of BH coronae
- Dissipated power is partitioned approximately evenly between X-rays and (nonthermal) ions
- Similar models could be applied to other radiatively dense environments (e.g., GRBs)