Particle Acceleration Simulations in Hot Accretion Flows

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Shigeo S. Kimura

References

1) SSK, Murase, Meszaros, 2019, PRD, 100, 083014
2) SSK, Murase, Meszaros, arXiv:2005.01934
3) Murase, SSK, Meszaros, 2020 PRL, 125, 011101
4) SSK, Tomida, Murase, 2019, MNRAS, 485, 163
see also: SSK, Toma, Suzuki, Inutsuka, 2016, ApJ, 822, 88
SSK, Murase, Toma, 2015, ApJ, 806, 159
SSK & Toma, 2020, ApJ, 205, 978

TOHOKU UNIVERSITY

Black Hole Astrophysics with VLBI: Multi-Wavelength and Multi-Messenger Era
2020 December 9-11

Theoretical Astrophysics
Tohoku University

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- Summary

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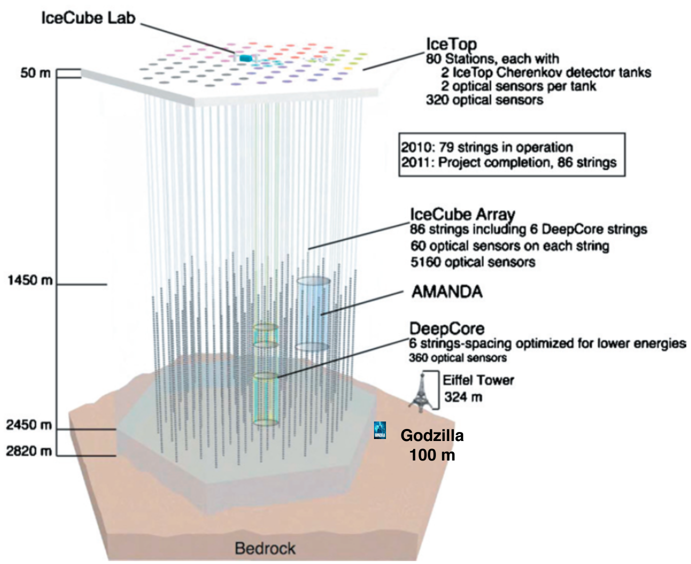
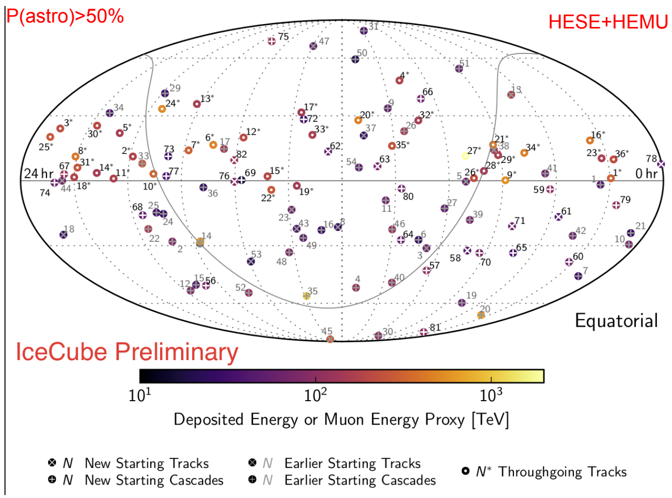
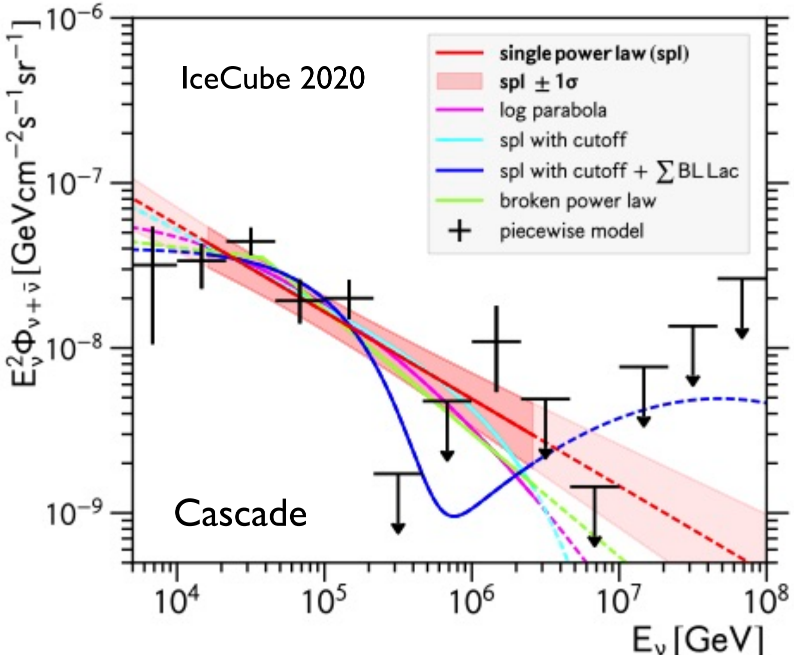
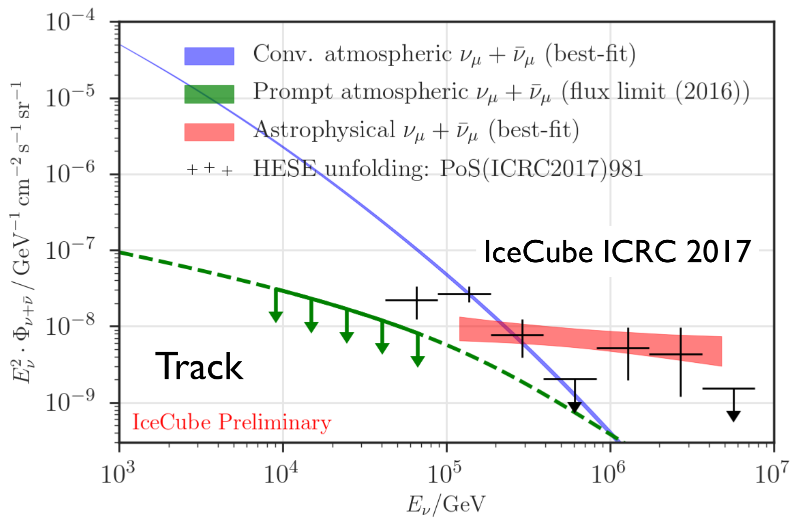
Astrophysical Neutrinos

IceCube 2013





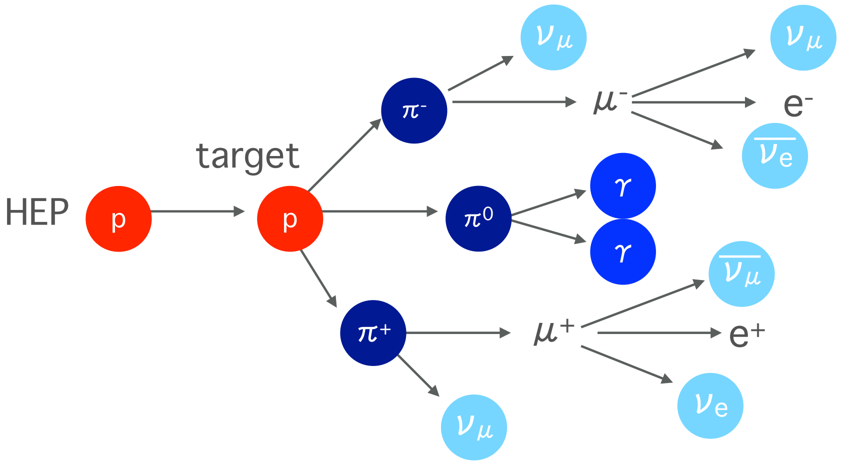


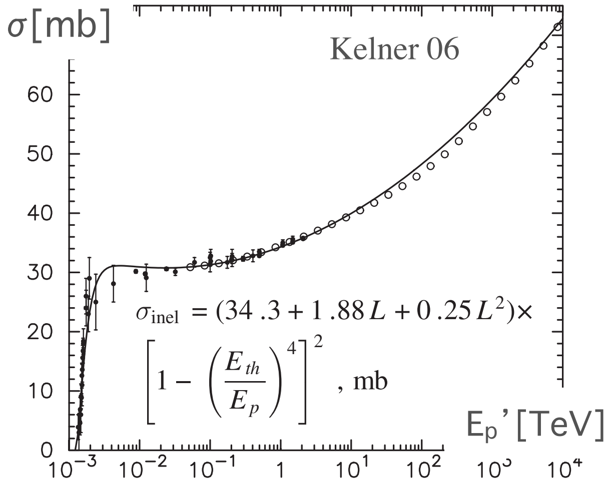


- IceCube has been detecting astrophysical νs (TeV-PeV)
- Isotropic arrival distribution → Extragalactic origin
- Soft spectrum by the cascade analysis
  → Medium energy (~10 TeV) excess ?
- Flat spectrum by the track analysis→two component ?
- **Origin has yet to be determined**

Neutrino Production Process

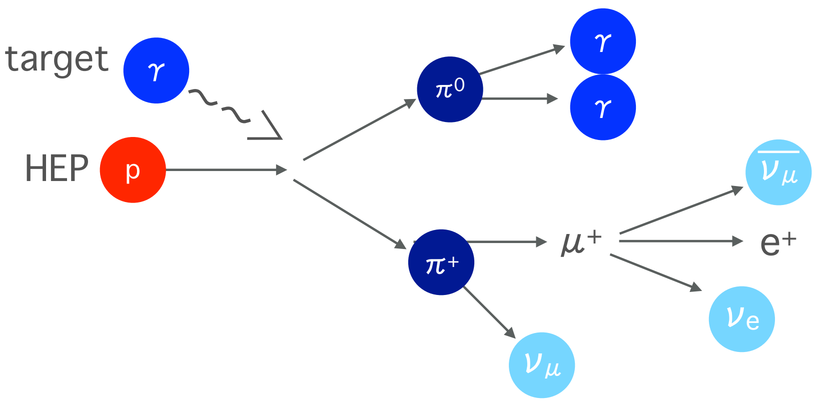
- pp inelastic collision

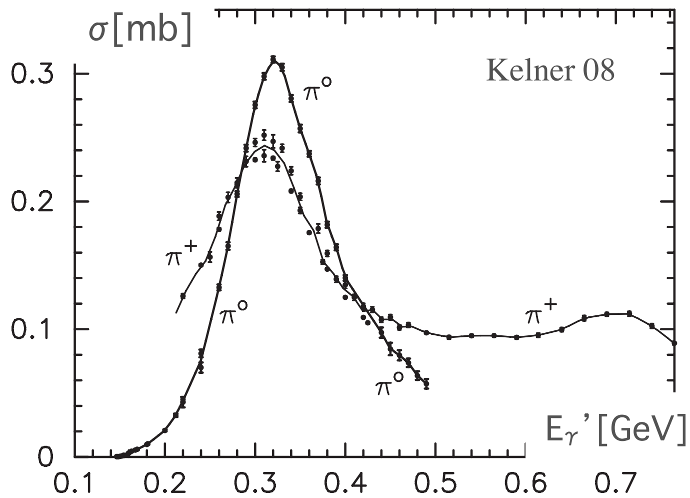




σ_{pp} weakly depends on E_p
→ ν spectra ~ p spectra

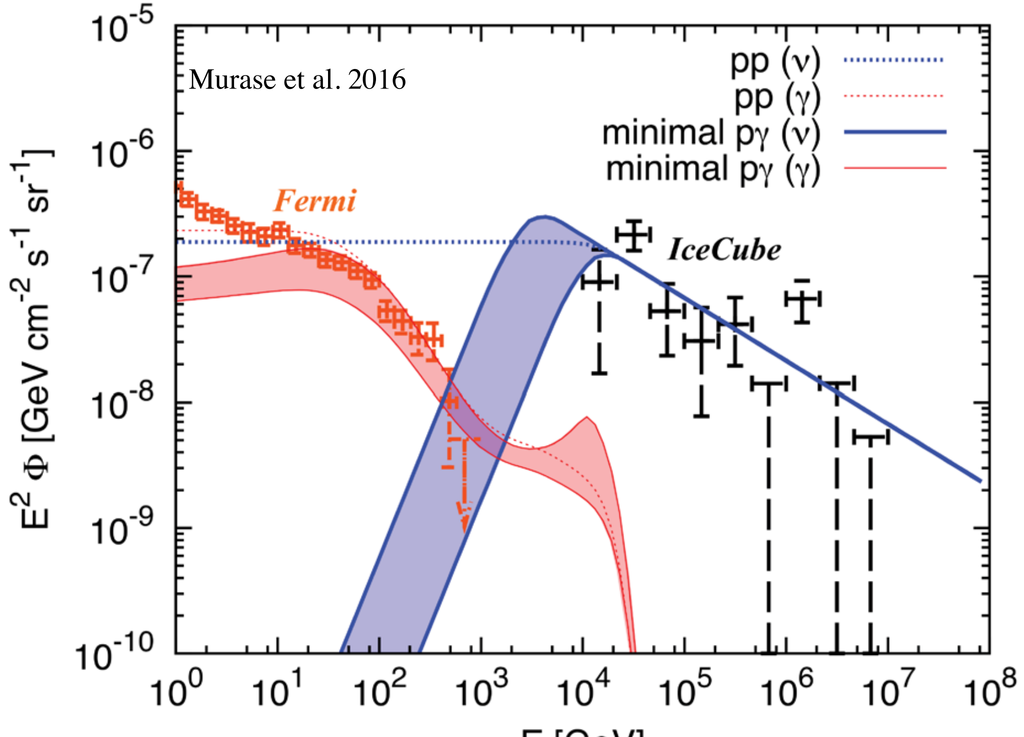
- Photomeson production (pγ)



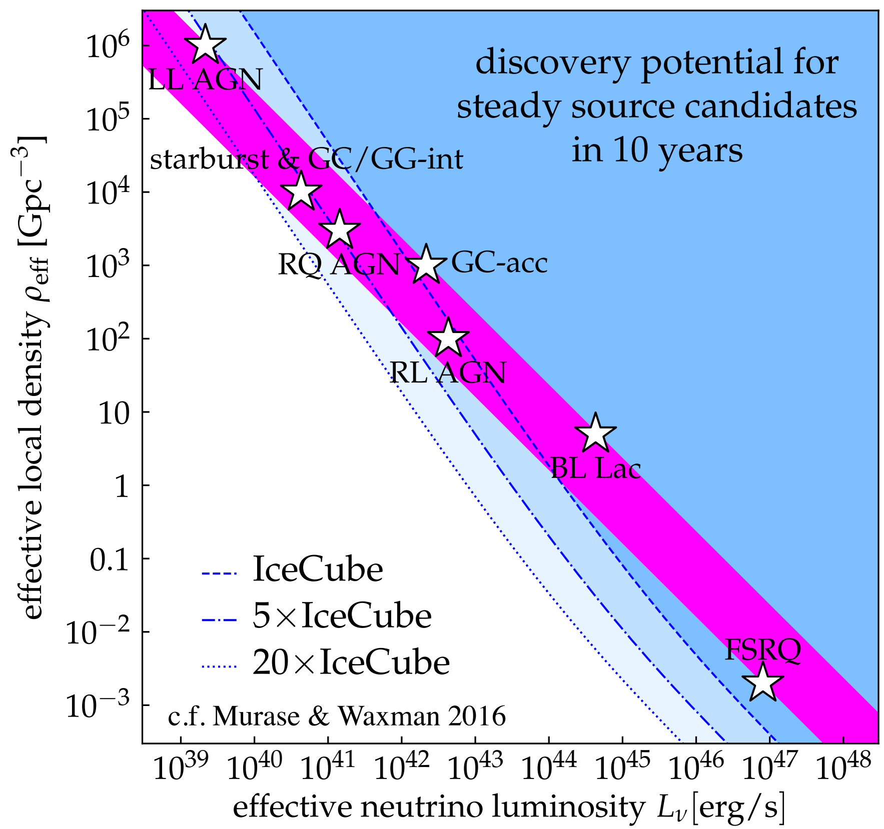


$\sigma_{p\gamma}$ is peaky function of E_p
→ target photon spectra affect ν spectra
e.g.
E_ν ~ 1 PeV ⇄ E_γ~10 eV

Gamma-ray & point-source constraints

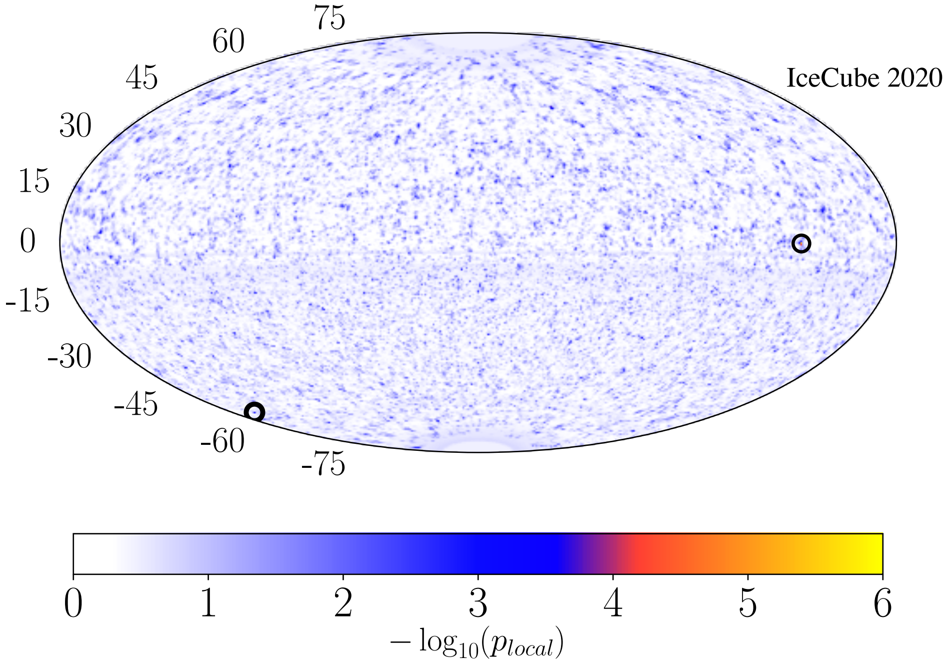


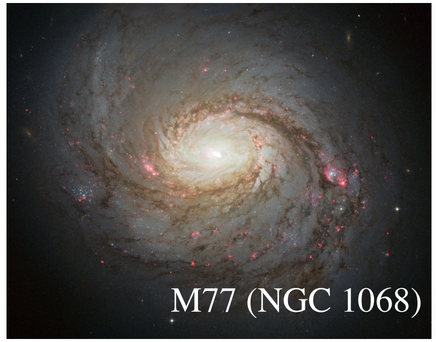
Murase-san's talk

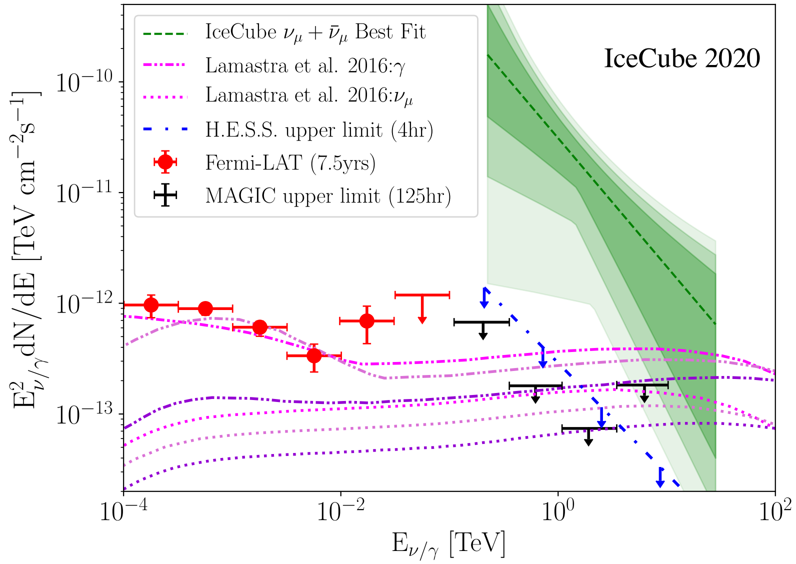


- Neutrino source should be
  i) **opaque to γ-rays**, otherwise the accompanied γ-rays overshoot the Fermi data
  ii) **Abundant,** otherwise the nearest source should be detected as a point source

Hint of ν from Accretion flows





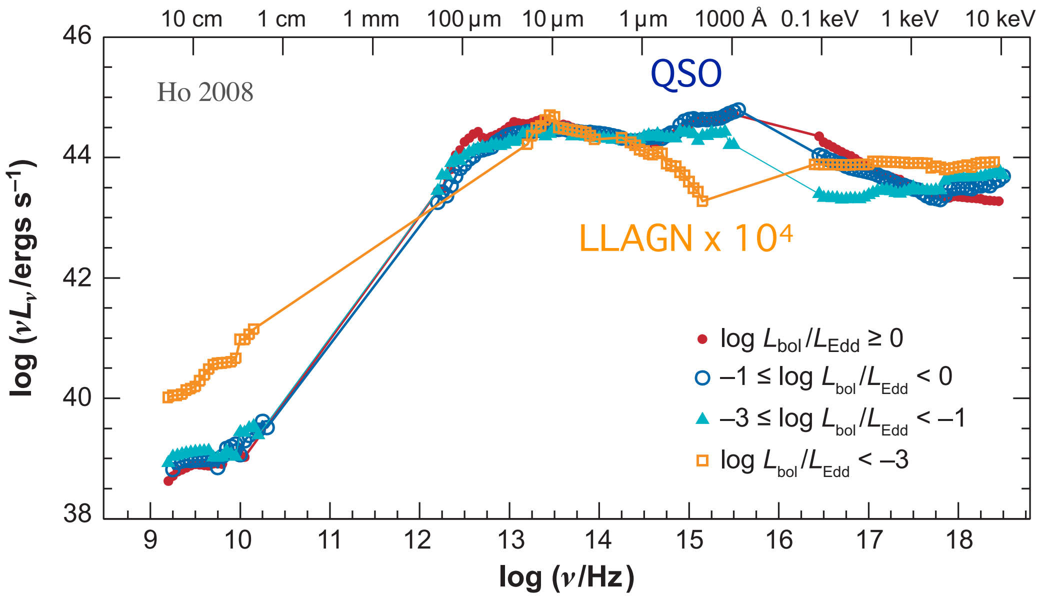


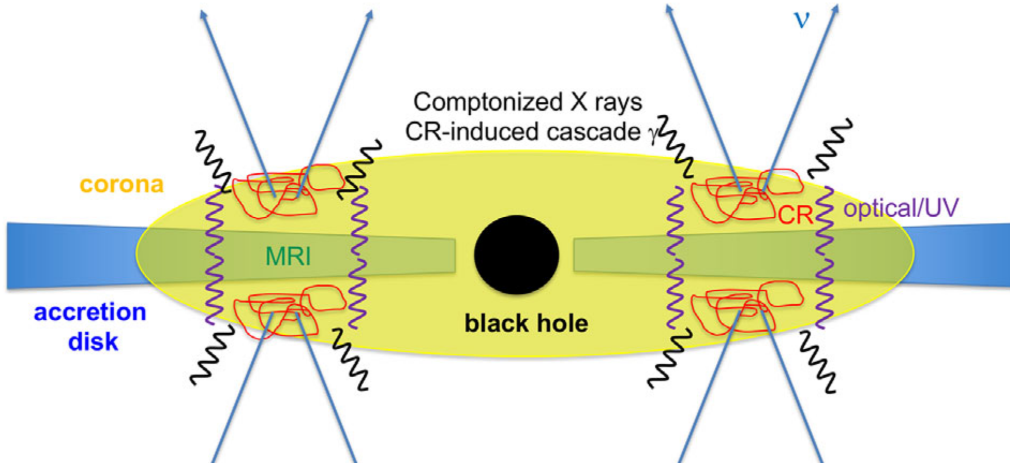
- Point source search with 10-year data set
- Hottest Point (2.9σ) : M77 (NGC 1068; Seyfert 2)
- $L_\nu > L_\gamma$ → "Hidden Source"

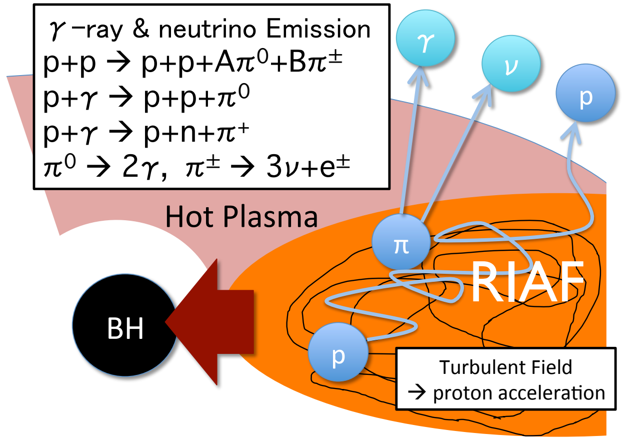
Let us discuss non-thermal process in accretion flows

Luminous & Low-luminosity AGN

UV-luminosity dichotomy by mass accretion rates







- QSO: Blue bump & X-ray →Optically thick disk + coronae
- LLAGN: No blue bump & X-ray →Optically thin flow [Radiatively Inefficient Accretion Flow (RIAF)]

Protons in coronae & RIAFs are collisionless

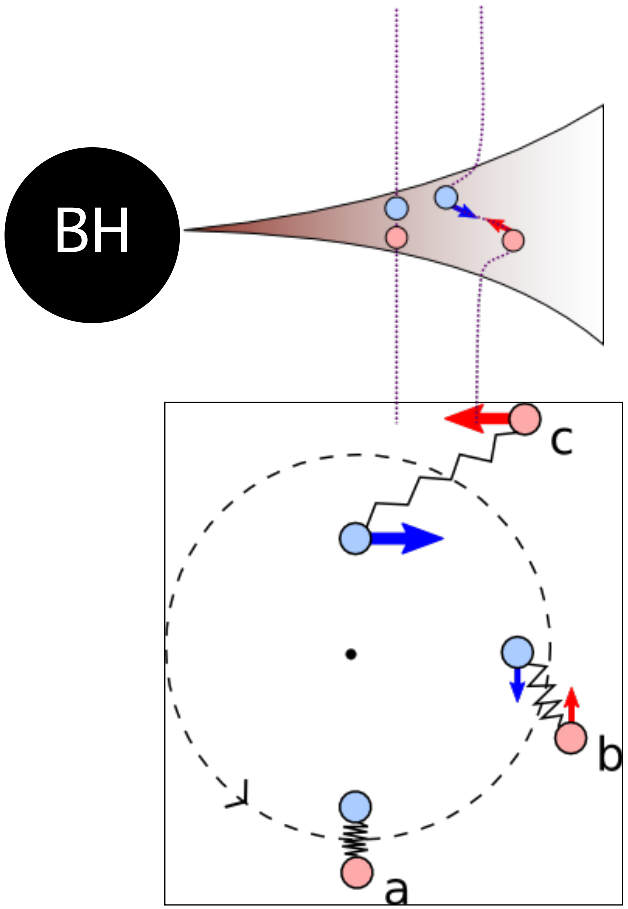
→ Non-thermal proton production

Magneto-Rotational Instability (MRI)

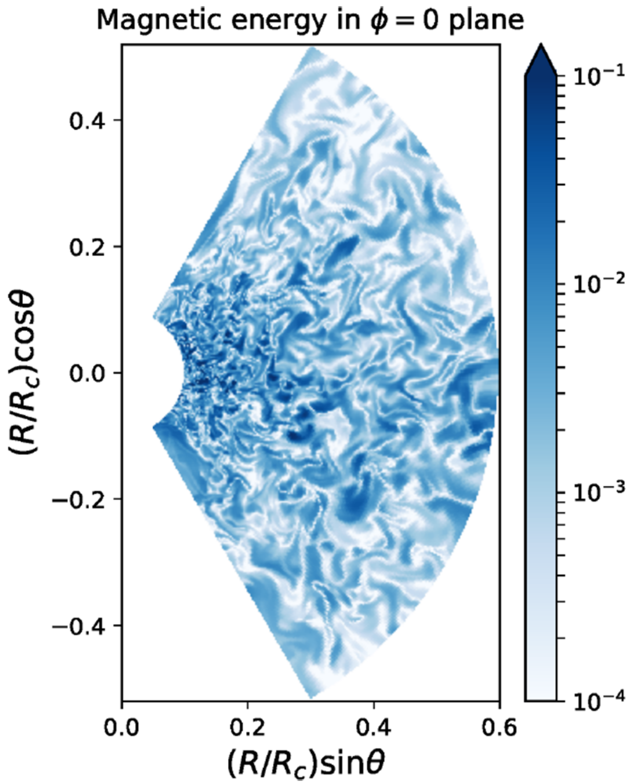
Gas accretion with angular momentum
→ formation of rotationally supported disks

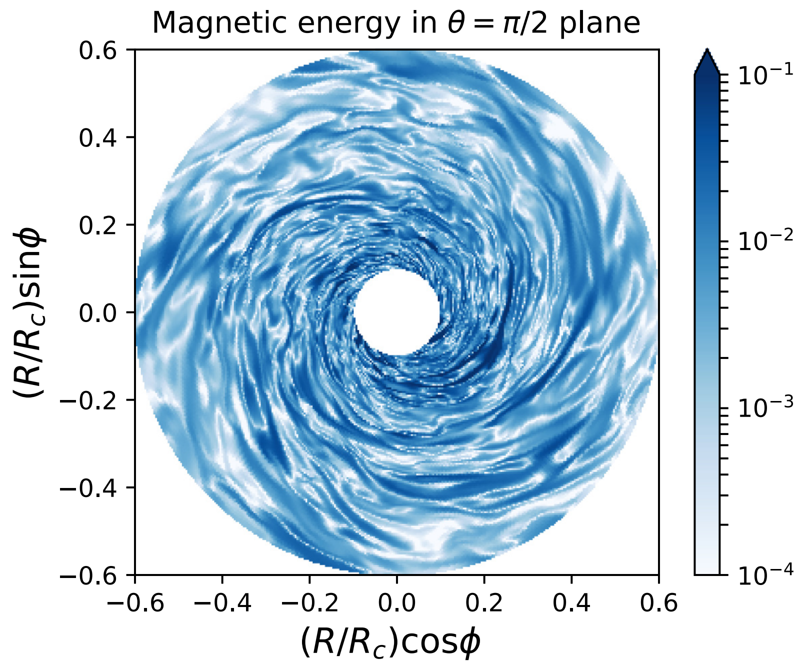
Machida-san's talk
Hoshino-san's talk

Velikhov '59; Balbus & Hawley '91



SSK et al. 2019, MNRAS



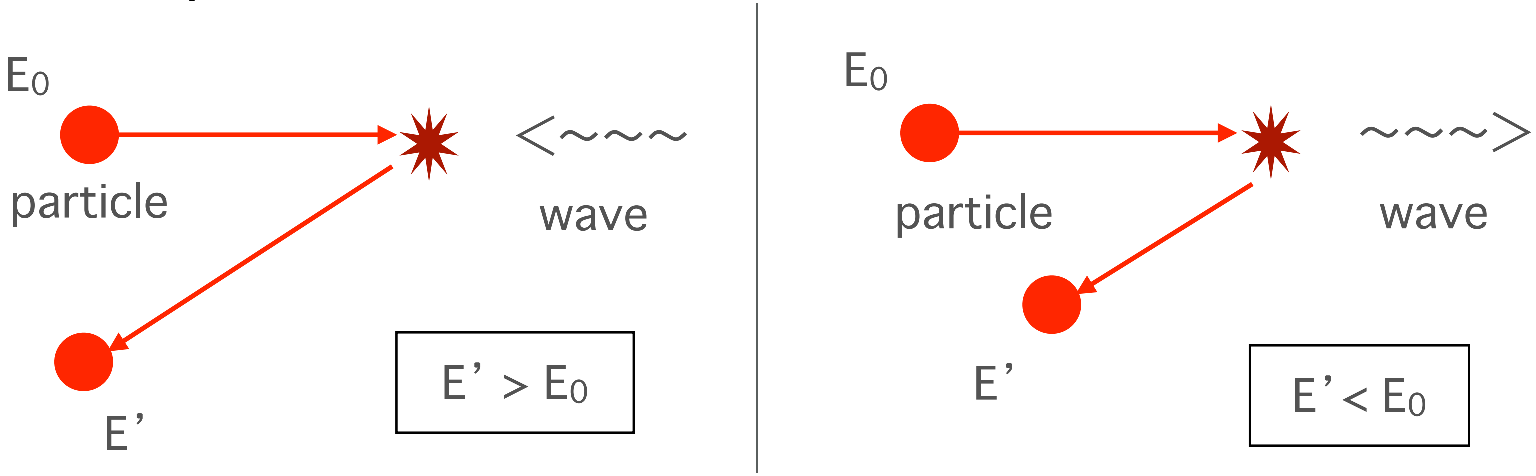


Accretion flows develop MHD turbulence by MRI

Stochastic Acceleration by Turbulence

e.g.) Fermi 1949, Petrosian 2012

- Consider plasma with turbulent fields



Some gain E, others lose E →diffusion in E space

$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

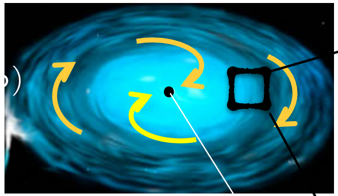
D_E depends on the particle-wave interaction processes

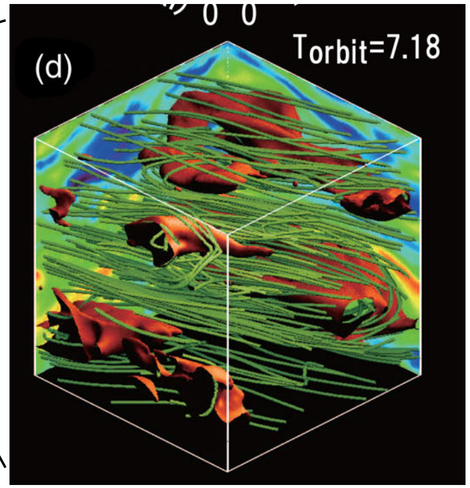
gyro-resonance in Kolmogorov turbulence : $D_E \propto E^{5/3}$

Particle Acceleration in Turbulence

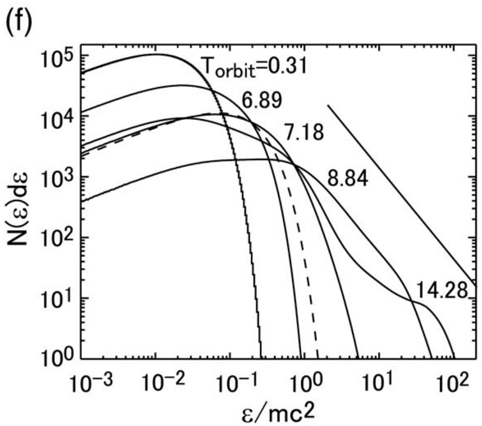
PIC in Shearing Box

Hoshino-san's talk





Hoshino 2013, 2015
Riquelme et al. 2012;
Kuntz et al. 2016

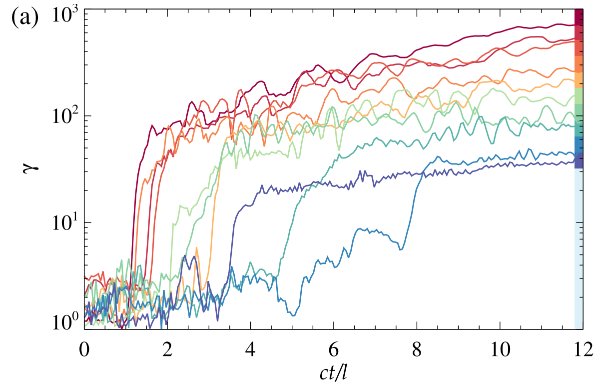


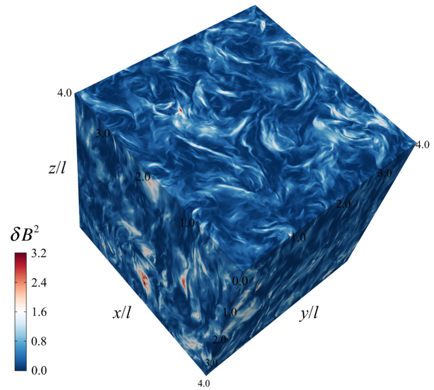
MRI turbulence

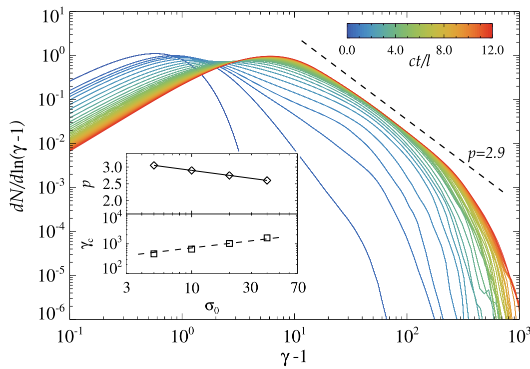
Non-thermal particle distribution

Particle-In-Cell Simulations with turbulence

Comisso & Sironi 2018, 2019
Zhdankin et al. 2018

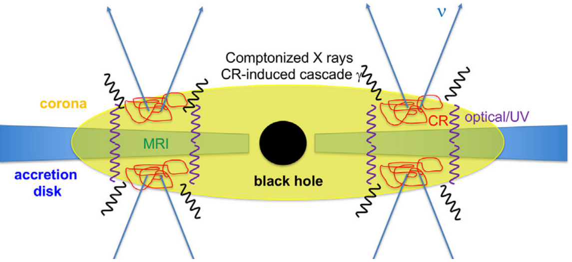






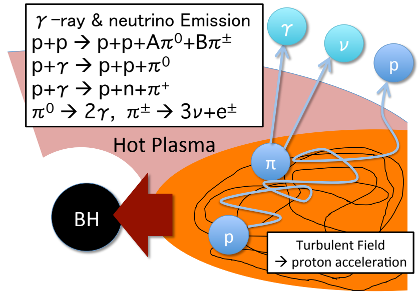
Magnetic reconnection produce relativistic particles
→ Higher energy particles interact with larger scale turbulence

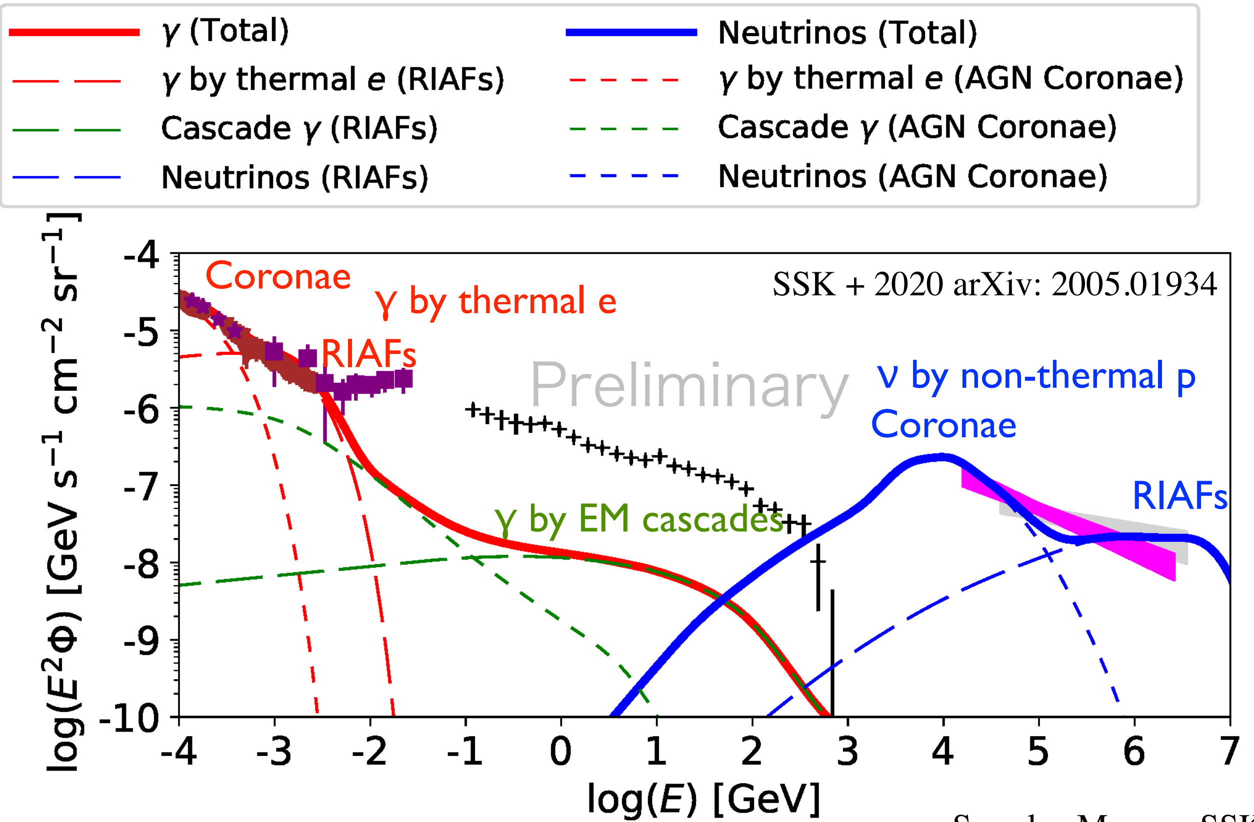
Cosmic High-energy Background from RQ AGNs



$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\rm cool}}F_p\right) - \frac{F_p}{t_{\rm esc}} + \dot{F}_{p,\rm inj}$$

$$\Phi_i = \frac{c}{4\pi H_0}\int \frac{dz}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}\int dL_{\rm H\alpha}\rho_{\rm H\alpha}\frac{L_{\varepsilon_i}}{\varepsilon_i}e^{-\tau_{i,\rm IGM}},$$





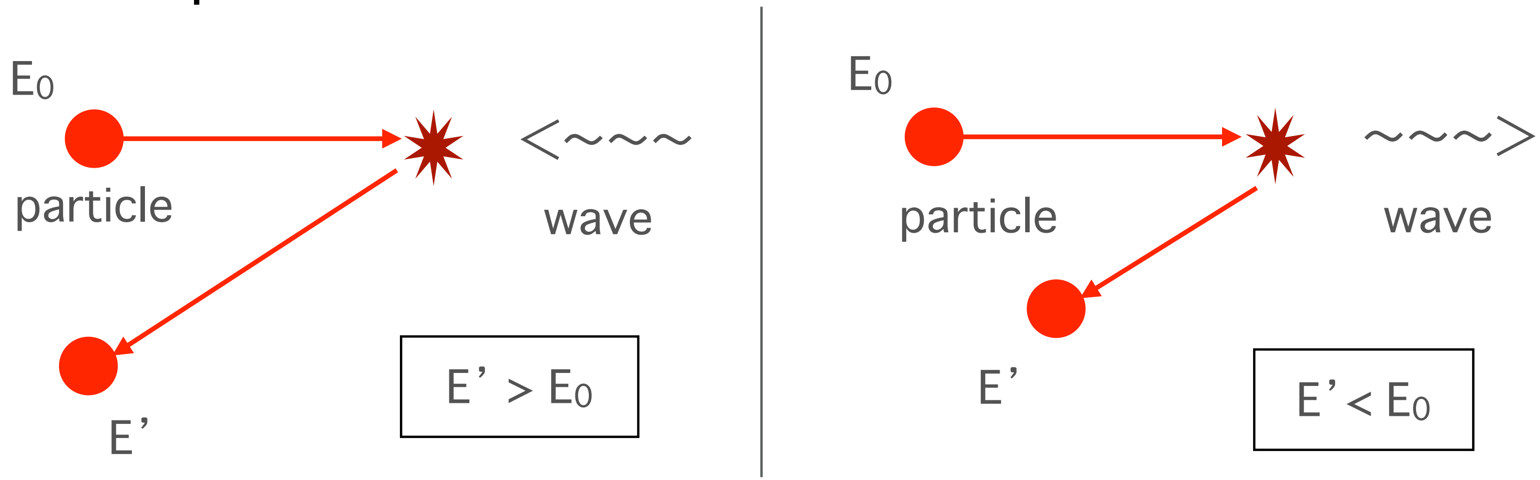
- Luminous AGNs can account for X-ray and 10 TeV neutrino backgrounds
- LLAGN can explain PeV ν and MeV γ backgrounds
- GeV γs are attenuated inside accretion flows → well below the Fermi data
- $P_{\rm CR} \sim 0.01 P_{\rm th}$ → reasonable in the sense that CR energy < Magnetic energy
- **AGN cores can account for a broad range of γ & ν bkgd**

See also Murase, SSK, Meszaros 2020; SSK et al. 2019, PRD; SSK et al. 2015

Stochastic Acceleration by Turbulence

e.g.) Fermi 1949, Petrosian 2012

- Consider plasma with turbulent fields



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D_E **depends on the particle-wave interaction processes**

gyro-resonance in Kolmogorov turbulence : $D_E \propto E^{5/3}$

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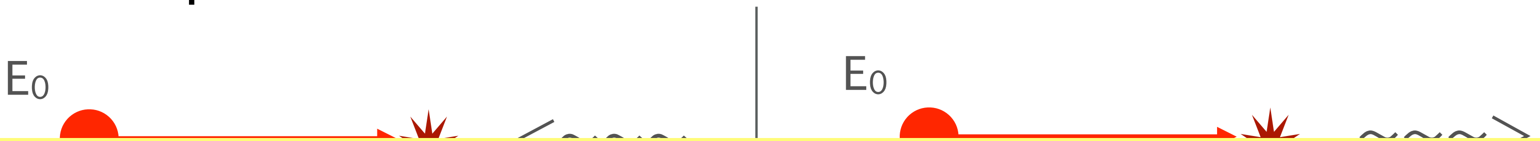

- In non-linear stage of MRI turbulence, turbulence energy is injected in multiple scales
  → **we need high-resolution MHD simulations**
- The dominant wave-particle interaction process depends on the characteristics of turbulence & pitch angle distribution of particles
  → **we need particle simulations in MRI turbulence**

D_E **depends on the particle-wave interaction processes**

gyro-resonance in Kolmogorov turbulence : $D_E \propto E^{5/3}$

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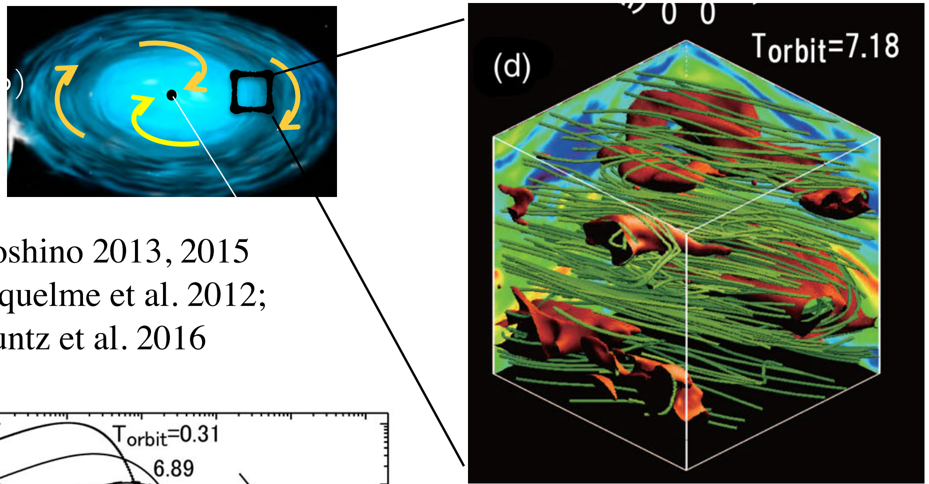

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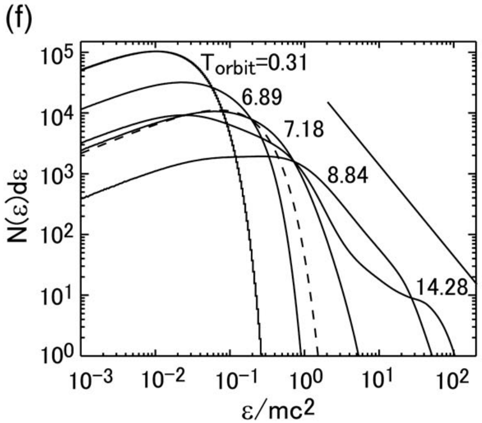

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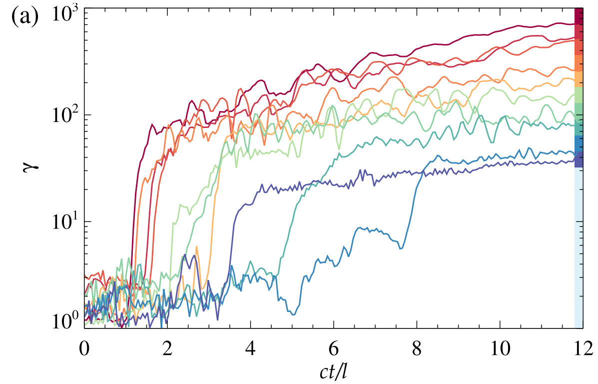

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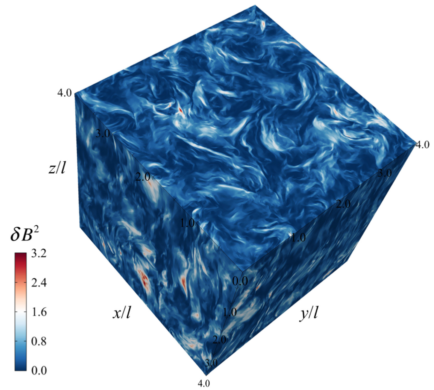

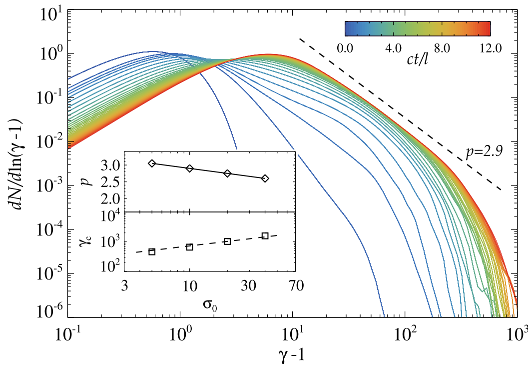

Magnetic reconnection produce relativistic particles
→ Higher energy particles interact with larger scale turbulence

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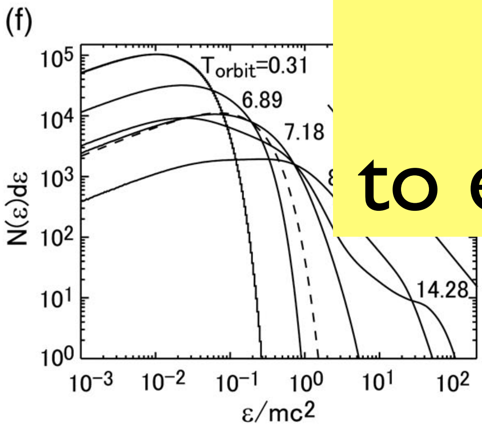

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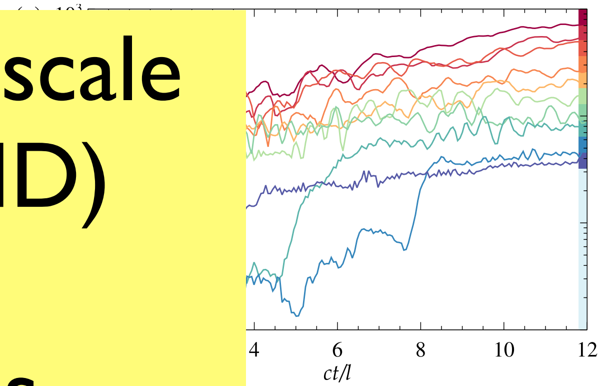
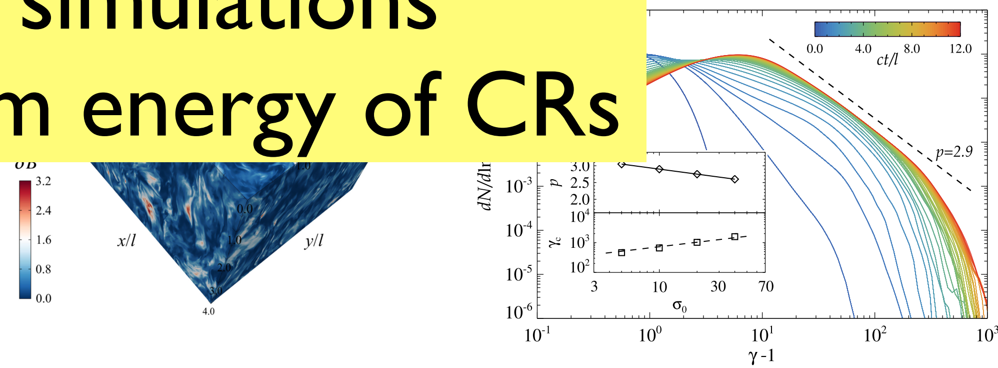




plasma scale << astrophysical scale
(PIC) (MHD)

We need MHD simulations
to estimate maximum energy of CRs

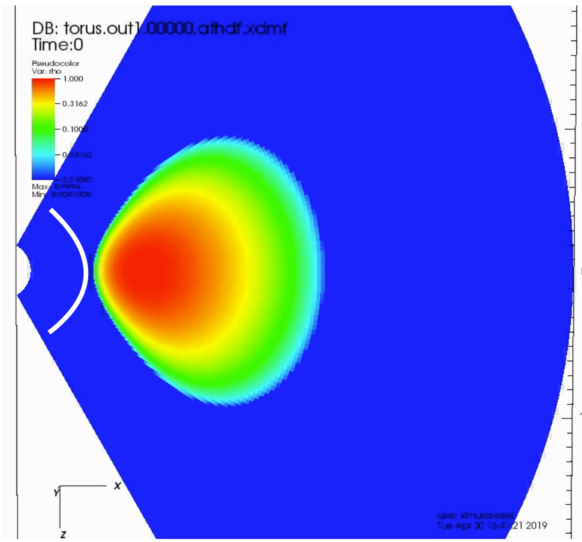
Magnetic reconnection produce relativistic particles
→ Higher energy particles interact with larger scale turbulence

MHD simulations + Test Particle Simulations

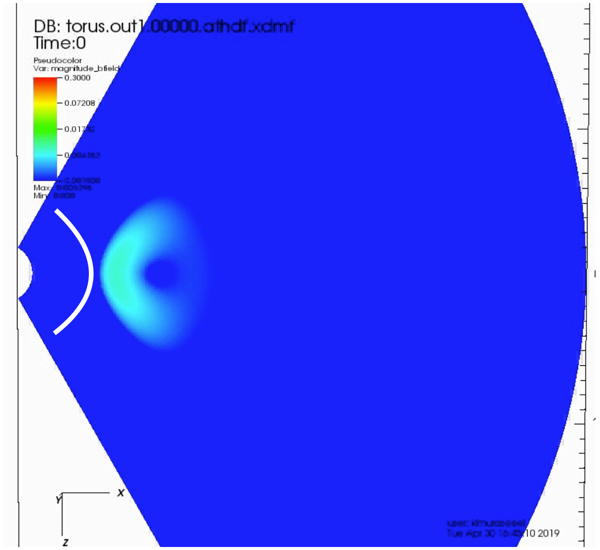
- We used **Athena++ & ATERUI II** (XC 30, XC50) @ CfCA, NAOJ for MHD sim.

Stone et al. 2020

Density



Magnetic field



$$\frac{\partial \rho}{\partial T} + \nabla \cdot (\rho \boldsymbol{V}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{V})}{\partial T} + \nabla \cdot \left(\rho \boldsymbol{V}\boldsymbol{V} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} + P^{*}\mathbb{I} \right) = -\rho \nabla \Phi,$$

$$\frac{\partial E_{\rm tot}}{\partial T} + \nabla \cdot \left[\left(E_{\rm tot} + P^{*} \right) \boldsymbol{V} - \frac{\boldsymbol{B} \cdot \boldsymbol{V}}{4\pi} \boldsymbol{B} \right] = -\rho \boldsymbol{V} \cdot \nabla \Phi,$$

$$\frac{\partial \boldsymbol{B}}{\partial T} - \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) = 0,$$

Highest resolution run: $(N_r, N_\theta, N_\varphi) = (640, 320, 768)$]

SSK et al. 2019 MNRAS

- Calculate orbits of ~ 2×10^4 particles by solving their equations of motion in snapshot data of MHD simulations
- We focus on very high energy particles.

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = \mathrm{e} \left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} \right),$$

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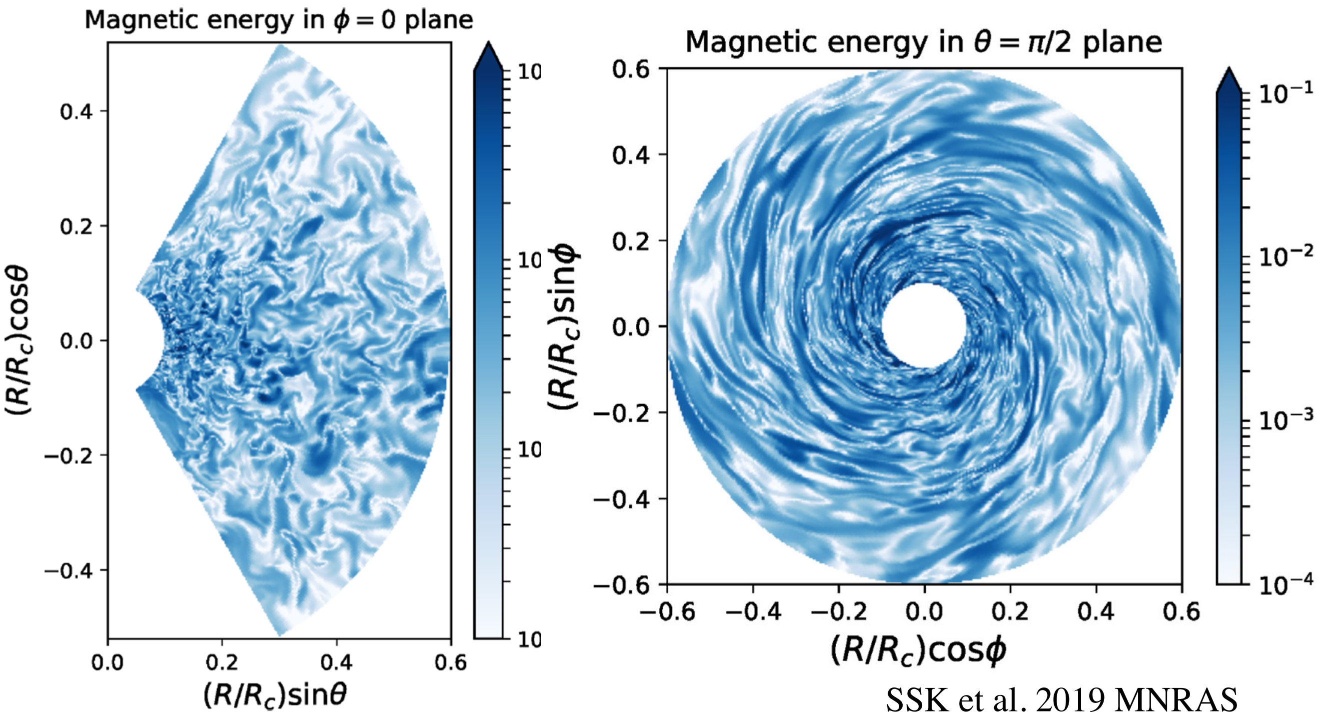

SSK et al. 2019 MNRAS

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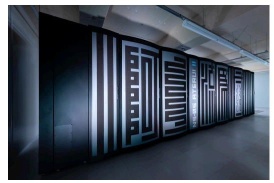

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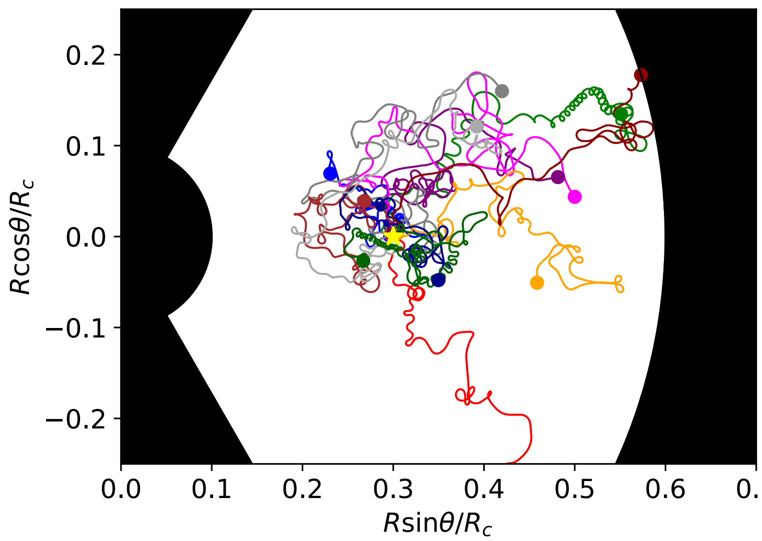
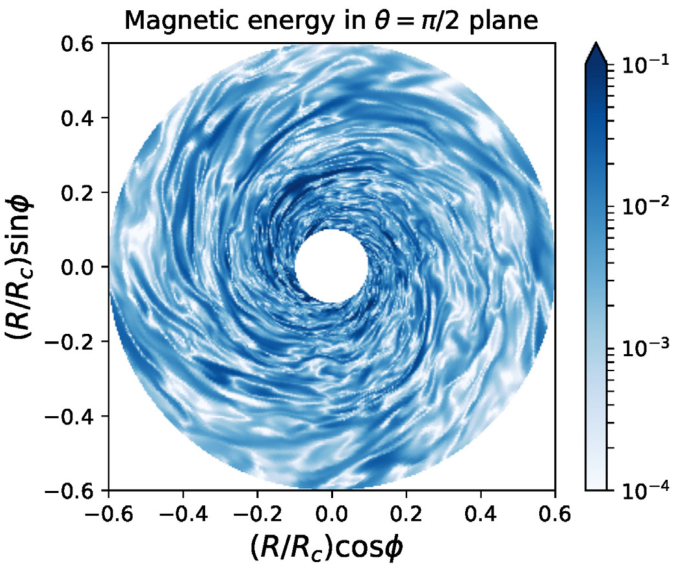
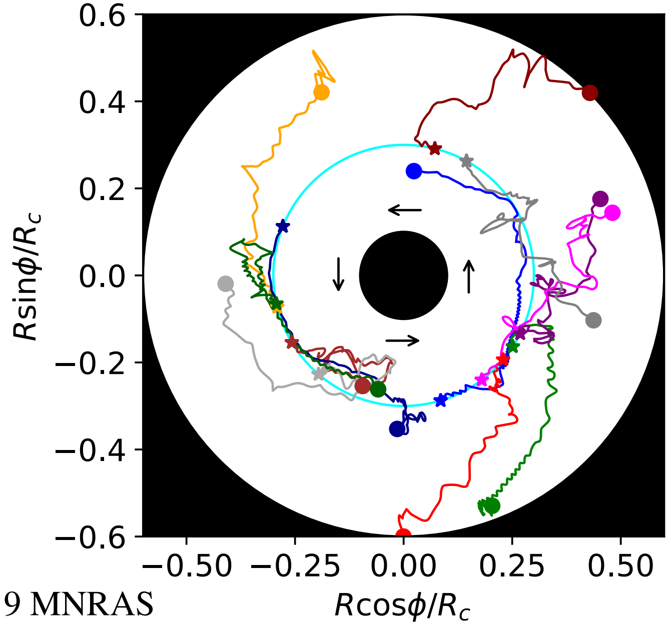
Particle orbits

- Put mono-energetic ultra-relativistic particles on a ring at (R, θ) = (0.3, π/2) with random momentum directions
- Magnetic fields are directed to azimuth direction with a spiral due to shear & accretion motions
- Inner regions have stronger magnetic fields →magnetic mirror forces acts outward



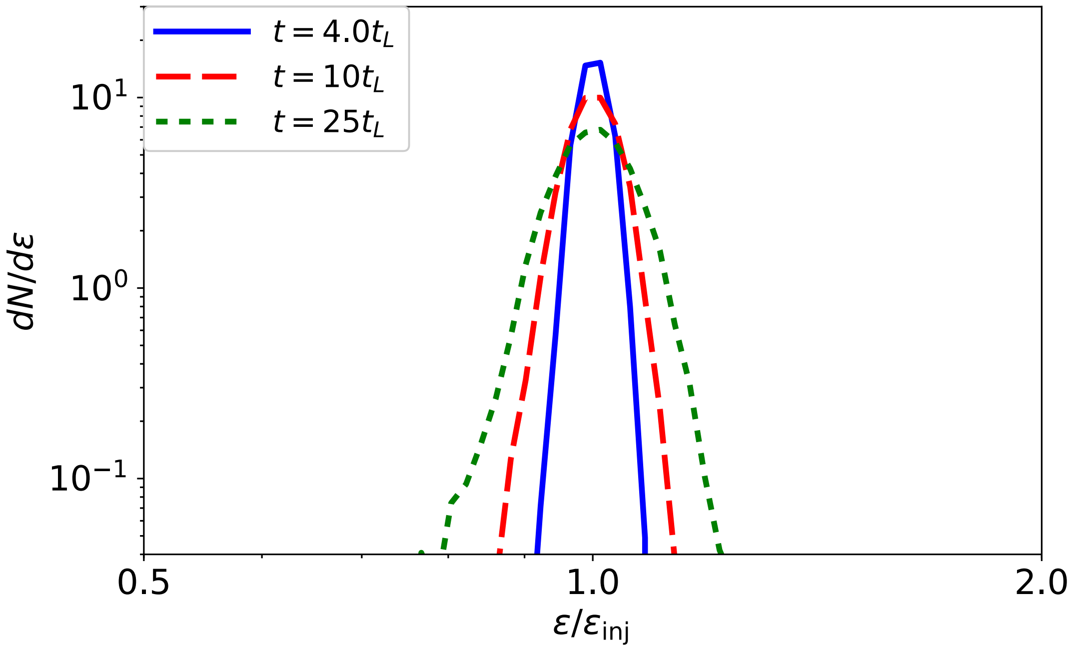


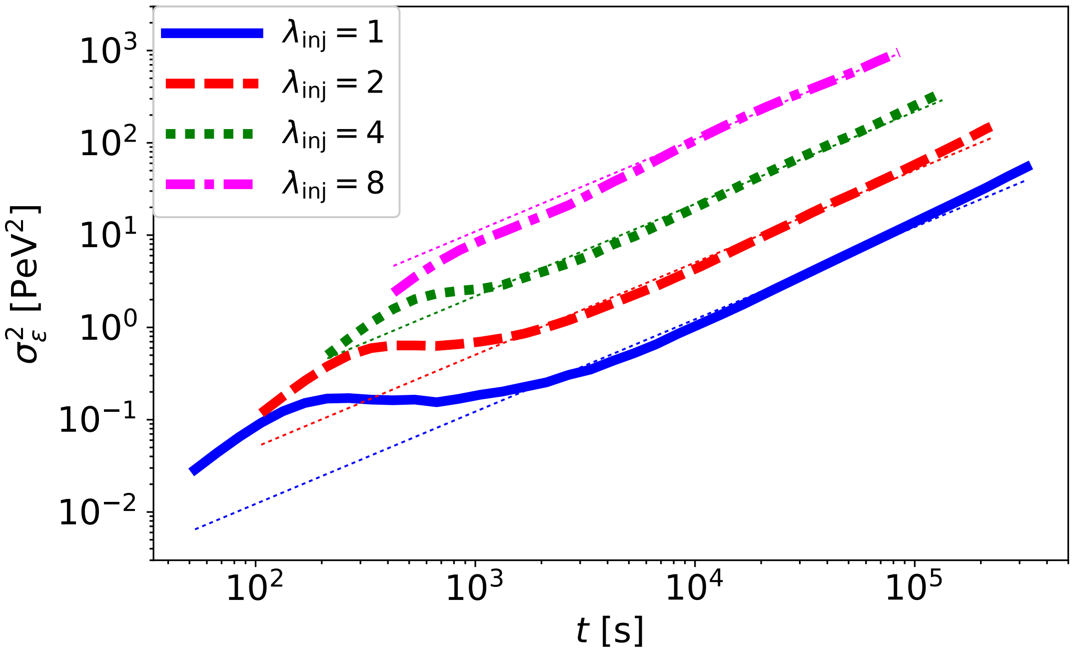
- Particles mainly move along magnetic fields → azimuthal & radially outward directions



SSK et al. 2019 MNRAS

Diffusion in Energy Space





SSK et al. 2019 MNRAS

- Evaluate particle energy in fluid rest frame
- Energy distribution function diffuses in energy space
- The dispersion of the energy distribution is proportional to time
  → **diffusion in energy space**

Diffusion Coefficient

- If evolution is written by

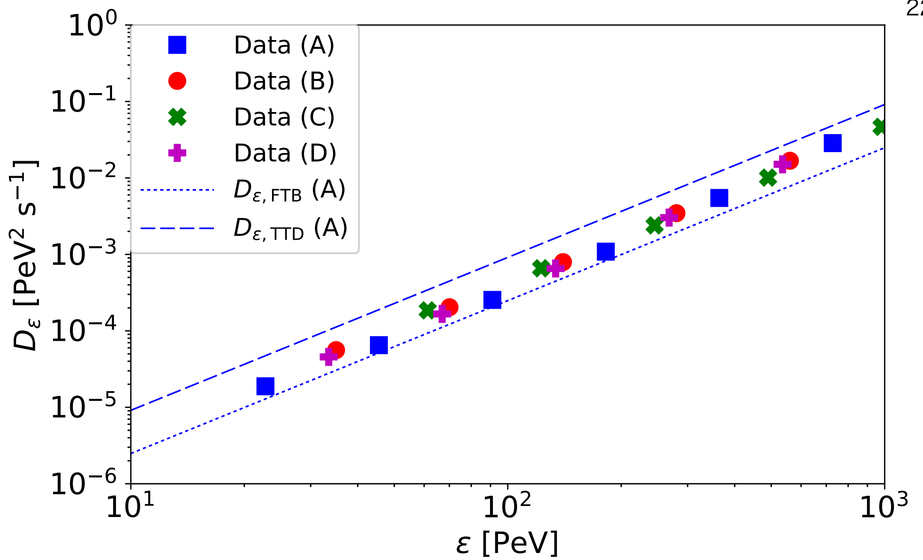
$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right)$$

we can obtain the relation: $\sigma_\epsilon^2 \approx 2D_{\epsilon_{\rm ini}} t.$

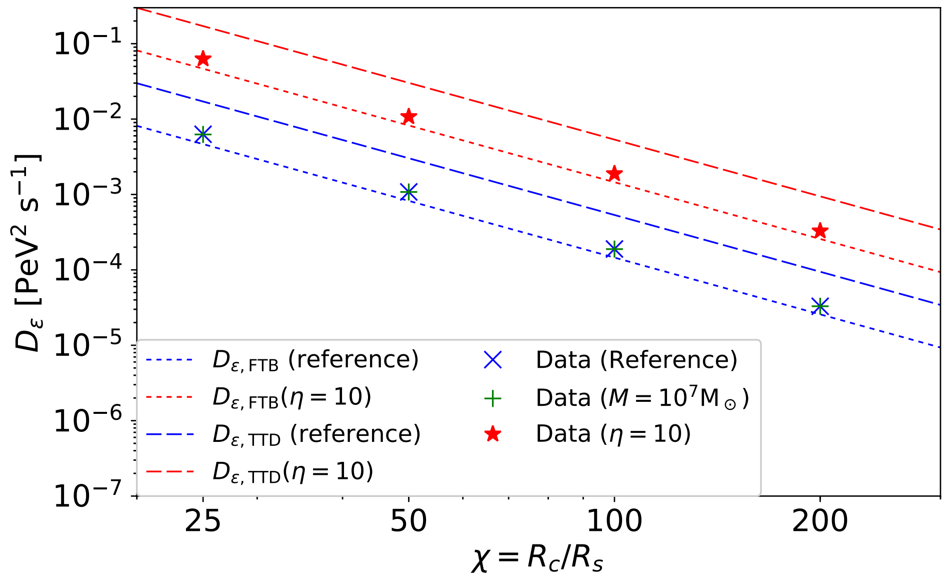
- From the power spectrum of MHD simulation, the largest eddy has most of the turbulent power
→ interaction timescale $t_{\rm int} \sim H/c$
& energy change rate $\Delta\epsilon \sim (V_{\rm turb}/c)^2\epsilon$
↓

$$D_{\epsilon,\rm FTB} \approx \frac{1}{3}\frac{\Delta\epsilon^2}{t_{\rm int}} \sim \frac{4\epsilon^2}{3}\frac{c}{L_{\rm tur}}\left(\frac{V_{R,\rm tur}}{c}\right)^2 \propto \epsilon^2 M^{-1}\chi^{-2}$$

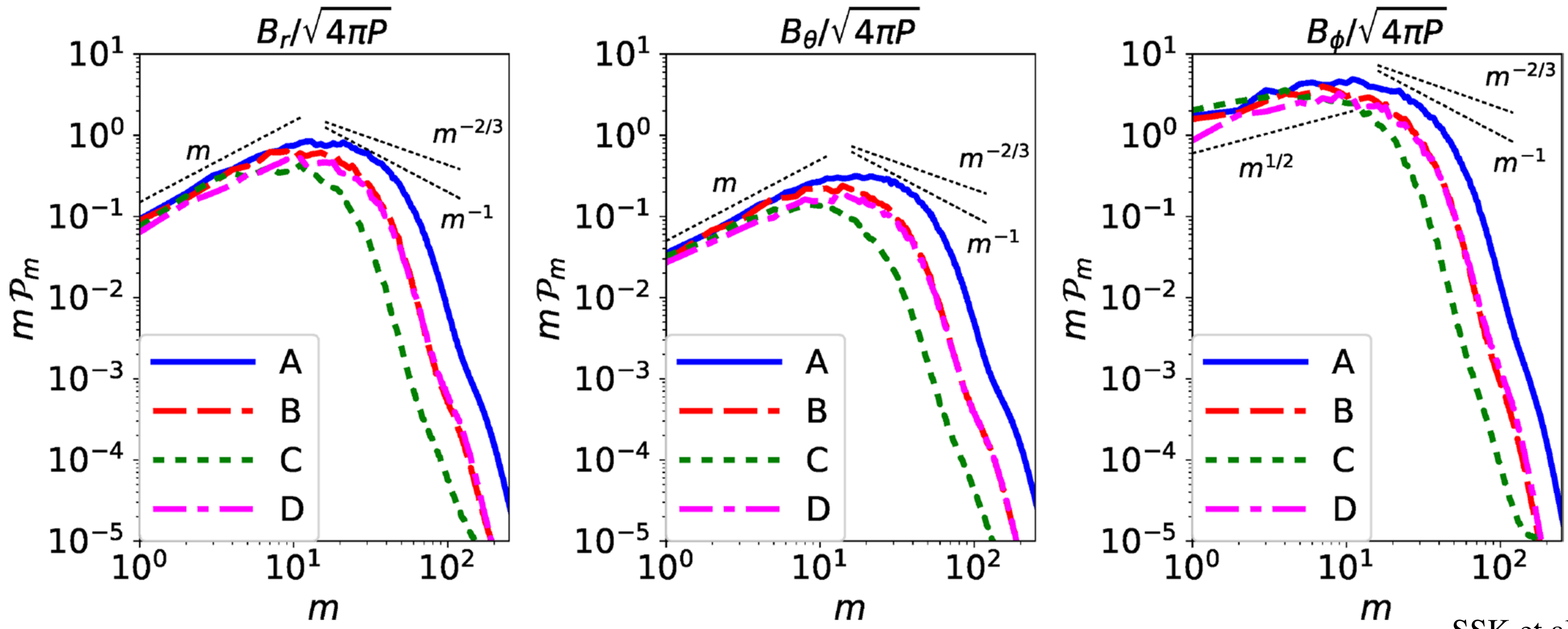
All the CR particles interact with eddies of largest scale



SSK et al. 2019 MNRAS



Magnetic Field Power Spectrum in φ direction

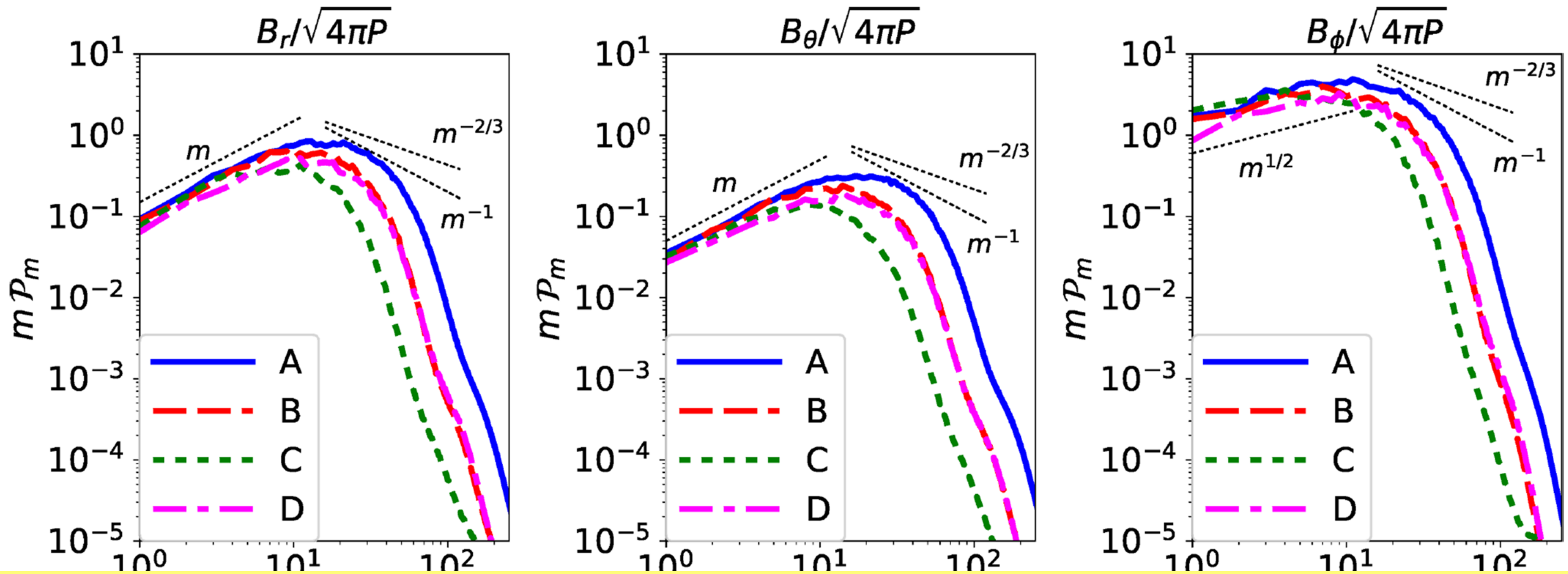


SSK et al. 2019 MNRAS

$$X_m = \frac{1}{\sqrt{2\pi}} \int X \exp(-im\phi) d\phi, \qquad \mathcal{P}_m = \frac{\int |X_m|^2 R dR d\theta}{\int R dR d\theta},$$

- $m\mathscr{P}_m$ peaks at m~10 - 20, which is consistent with scale height $H = C_s/\Omega_K$
- Inertial range is too narrow to see the power-law index
  → power in smaller-scale waves are underestimated due to numerical dissipation

Magnetic Field Power Spectrum in φ direction



Higher resolution & Higher order accuracy simulations are necessary in order to understand particle acceleration in MHD scales

- $m\mathscr{P}_m$ peaks at m~10 - 20, which is consistent with scale height $H = C_s/\Omega_K$
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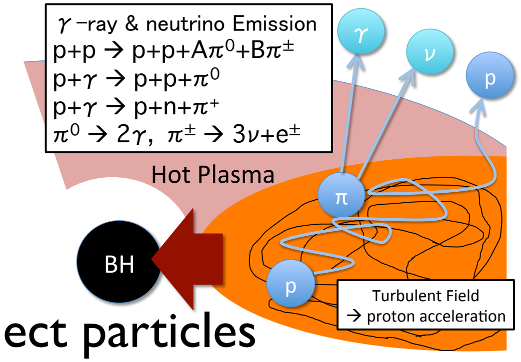
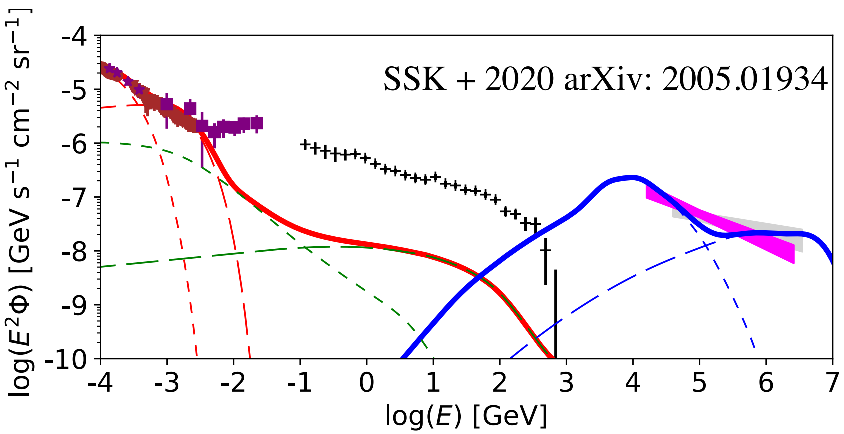
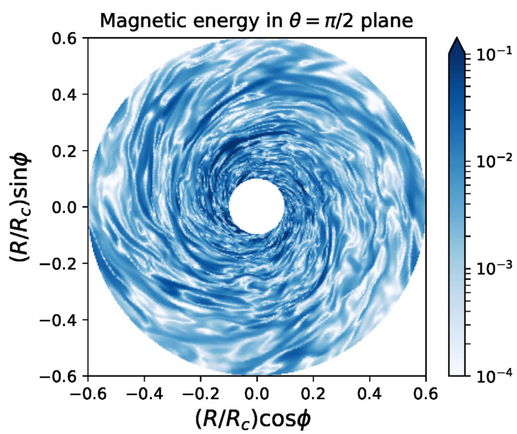
Contents

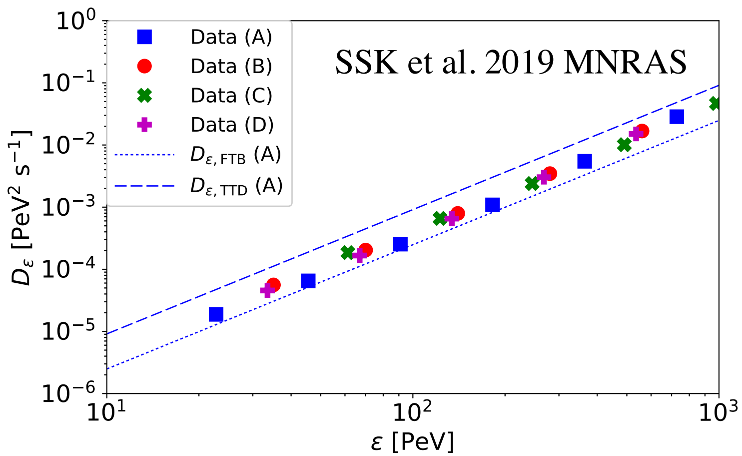
Summary



- Accretion flows in AGNs are feasible neutrino & gamma-ray sources
  - RQ AGNs can explain X - MeV γ-ray & TeV - PeV ν backgrounds
- Particle acceleration processes in RIAFs are under investigation
  - PIC simulations demonstrated that the magnetic reconnection process inject particles
  - **MHD + test particle simulations demonstrate the diffusion nature of the stochastic particle acceleration process in MHD turbulence**
  - Future higher resolution & higher order accuracy simulations are necessary to reveal the maximum achievable energy of CRs in accretion flows







Thank you
for your attention