Possibility of High Energy Neutrino Production in Super-Eddington Accreting Black Holes

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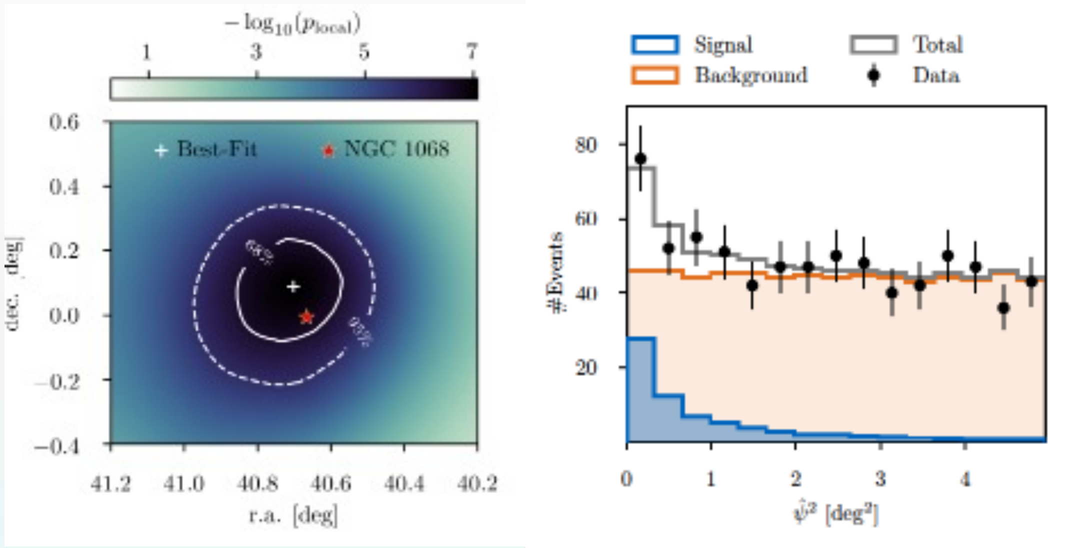
High Energy Neutrinos from Seyfert Galaxies

- NGC 1068: $\sim 4.2\sigma$ evidence for TeV neutrino emission
  - Seyfert 2, starburst galaxy
  - no corresponding γ-ray emission
  - one of the (extinction-corrected) X-ray-brightest AGN in the sky
  - NGC 4151, NGC 7469,⋯
- pp or $p\gamma$ interactions in the vicinity of the black hole?
  - the photon density is high → associated γ-ray photons would be absorbed via $\gamma\gamma \to e^- e^+$
- How to produce HE protons?
  - bright AGN → dense accretion disk → collisional → non-thermal acceleration is impossible



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X-ray Corona Model

Liang & Nolan 1984; Haardt & Maraschi 1991

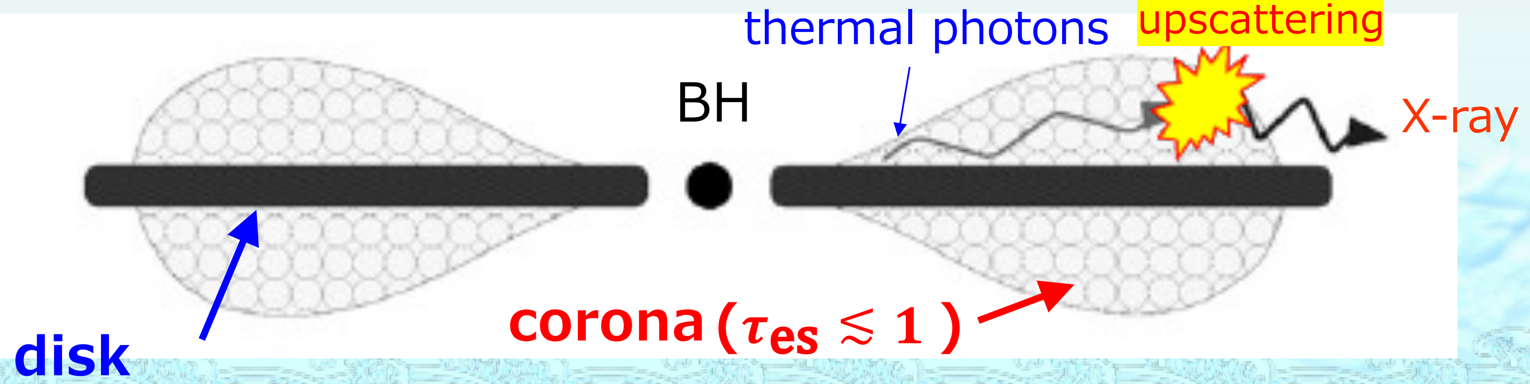
BH accretion flow = (1) dense, cool disk (~ 10^5 K)
+ (2) tenuous, hot corona (~ 10^9 K)

(1) ··· emit thermal soft photons (optical – UV)

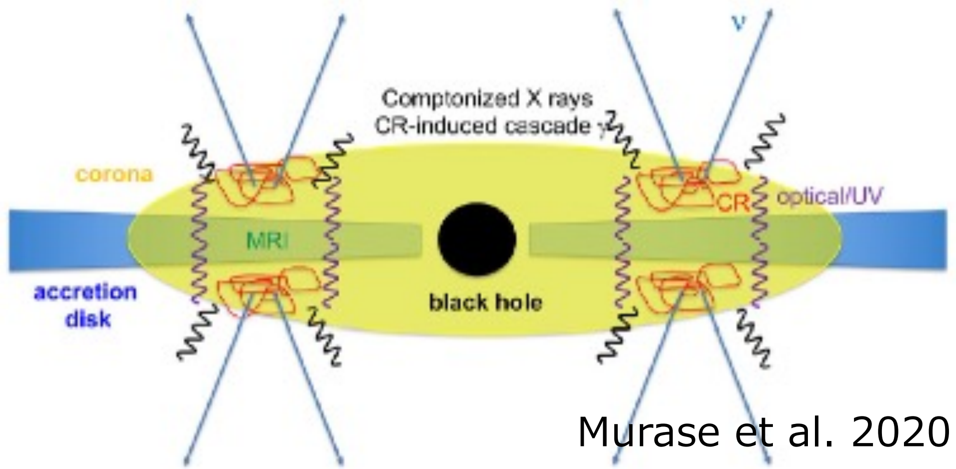
(2) ··· produce hard power-law photons via Comptonization (X-ray)

→ **account for the spectra of typical AGNs (and X-ray binaries)**

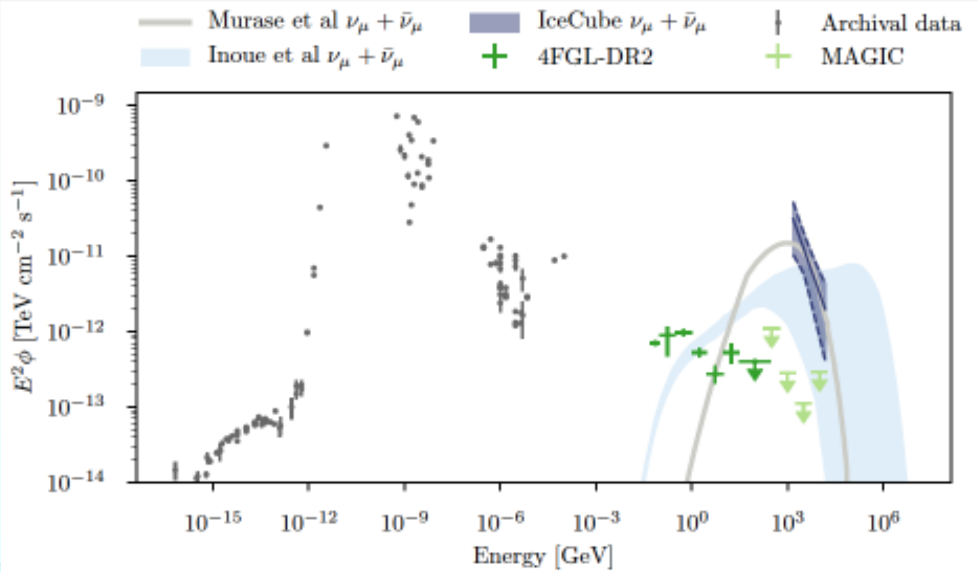
- plasma loading : disk evaporation? (Liu et al. 1995 etc.)
- heating process: magnetic reconnection? (Liu et al. 2003 etc.)



Corona as a particle accelerator/neutrino emitter



Murase et al. 2020



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Murase et al. 2020; Kheirandish et al. 2021 etc.

- corona ~ collisionless plasma
- being turbulent due to magnetorotational instability (MRI)

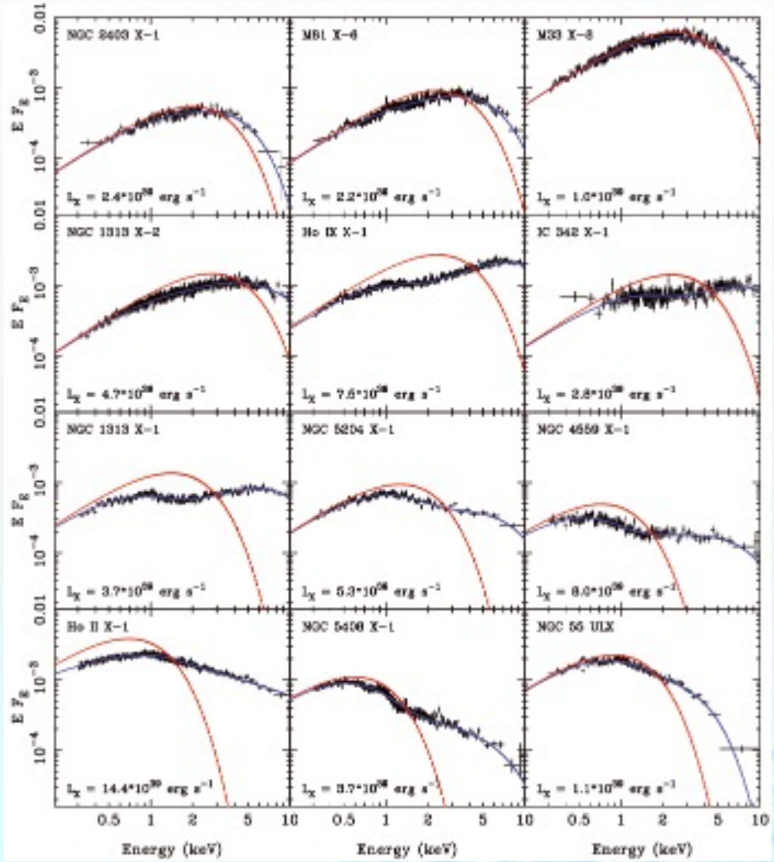
→ Non-thermal particle acceleration is possible

→ HE neutrino production via $p\gamma$ interaction is expected

- fairly consistent with the neutrino emission from NGC 1068 reported by IceCube

X-ray spectra of super-Eddington accreting BHs

X-ray spectra of ULXs (Gladstone+ 09)



e.g., Ultraluminous X-ray sources:

(1) thermal + Comptonized

(2) Comptonizing plasma (corona) should be <u>relatively cool (T_c ~ 10^7K) and optically-thick (τ_c ~ 5-30)</u>

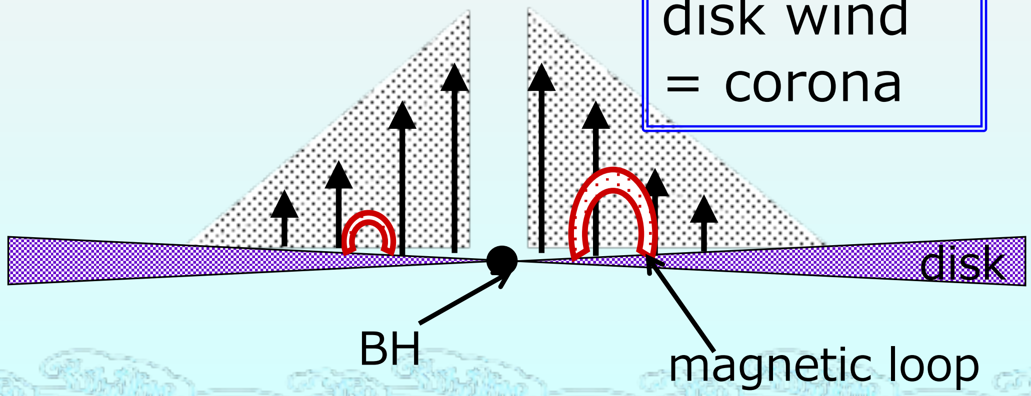
similar trends for GRS 1915+105 (Vierdayanti et al. 2010) and some narrow-line Seyfert 1 galaxies (Idogaki+ 2018 etc.)

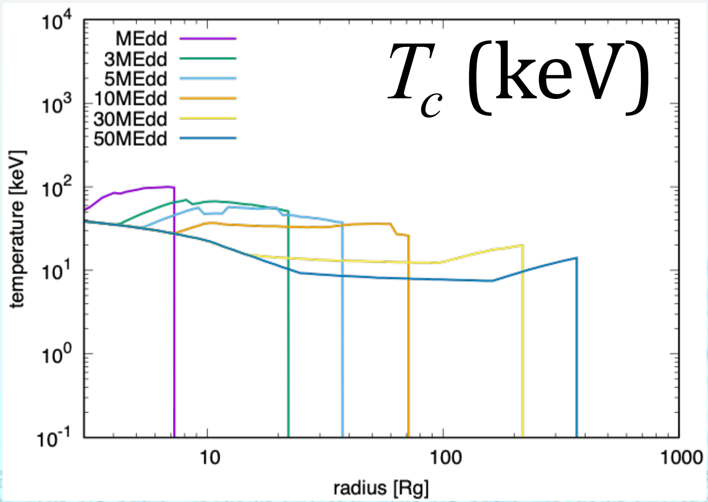
➡ Common to super-Eddington BHs ?

wind-fed corona model for super-Eddington BHs

NK & Mineshige 2021

- radiation force > gravity → radiation-driven disk wind
  → **efficient coronal plasma loading from the wind**
- disk mass loss: $\dot{M}_{\rm disk} \propto r^s$ $(0 < s < 1)$ → **corona density**
- magnetic reconnection-heating → **corona temperature**
  (Liu et al. 2002)
- One can reproduce optically-thick and cool corona (∵ Comptonization), as well as typical ULX spectra.

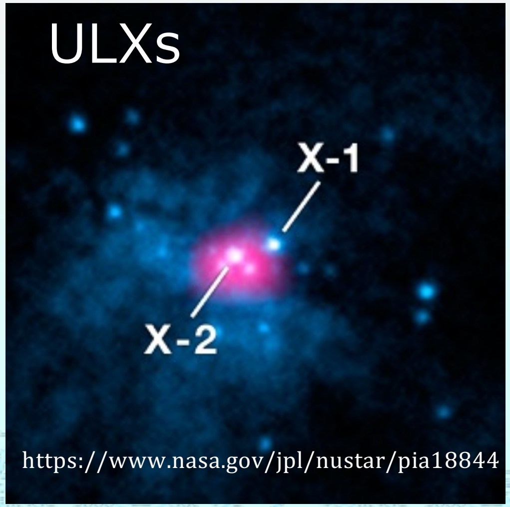


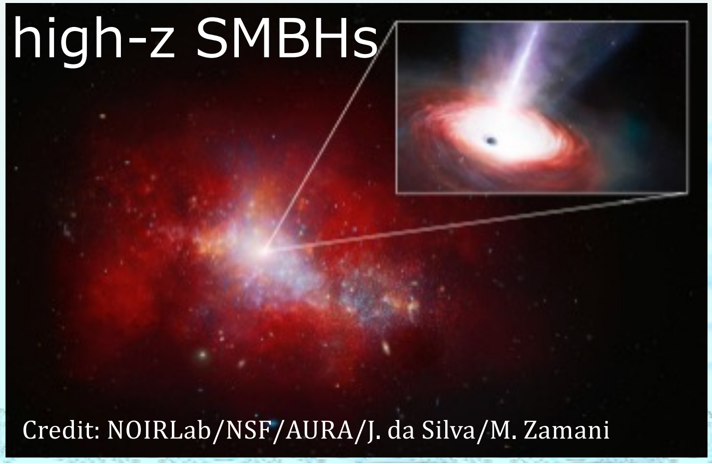


HE neutrinos from super-Eddington BHs?

- Previous works: HE neutrino production has been discussed mainly in RIAFs (LLAGNs) or coronae of standard disks
- But··· super-Eddington accretors are also common:
  - ULXs, bright microquasars, Narrow Line Seyfert 1s,···
  - high-z AGNs are often supposed to be super-Eddington
  - **Their coronae are physically different**

→ Let's investigate HE neutrinos from super-Eddington BHs





Methods

- corona model: NK & Mineshige 2021
  - $n_c(r), T_c(r), H_c(r), U_{\rm ph}(r)$ → re-modeling into the one-zone corona

- neutrino spectrum calculations: Kimura et al. 2015
  - 2nd order Fermi acceleration of CR protons in the turbulent corona
    → Fokker-Planck equation for CR p distribution function $\mathcal{F}_p$:

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

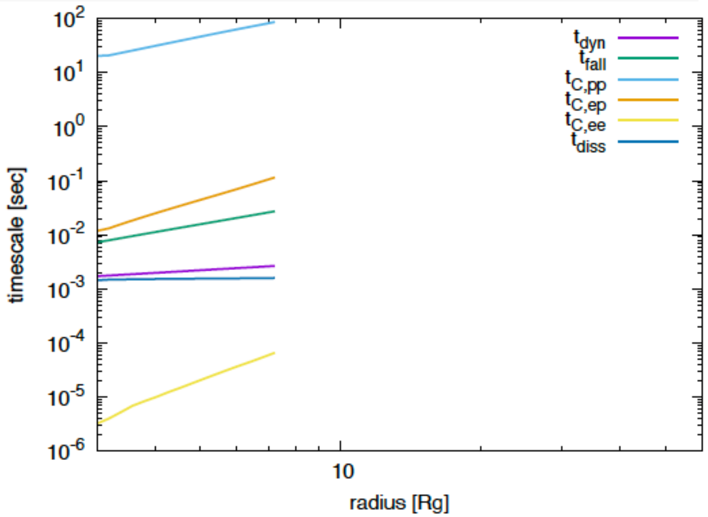
  - consider both pp and $p\gamma$ interactions
  - cooling processes: pp, $p\gamma$, p-synchrotron, Bethe-Heitler

- parameters:
  - $M_{\rm BH} = 10 M_\odot$ ($L_{\rm Edd} = 1.26\times10^{39}$ erg s^{-1})
  - $\dot{M} = \dot{M}_{\rm Edd}, 3\dot{M}_{\rm Edd}, 5\dot{M}_{\rm Edd}, 10\dot{M}_{\rm Edd}$

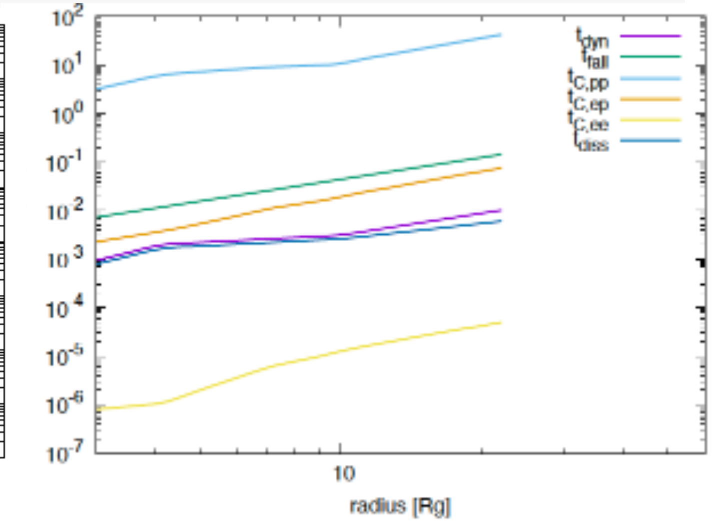
Is the corona collisionless?

$$t_{C,pp} = \frac{\sqrt{2\pi}}{n_p \sigma_\mathrm{T} c \ln \Lambda} \left(\frac{m_p}{m_e}\right)^2 \theta_p^{3/2}$$: Coulomb relaxation timescale

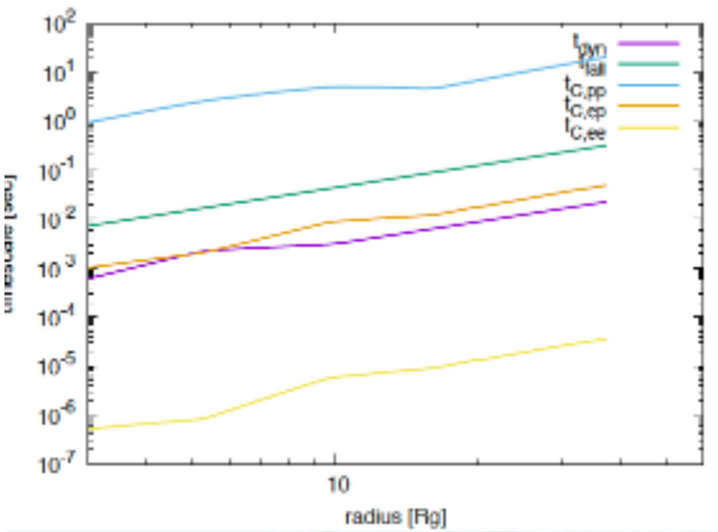
$\dot{M} = \dot{M}_\mathrm{Edd}$



$\dot{M} = 3\dot{M}_\mathrm{Edd}$

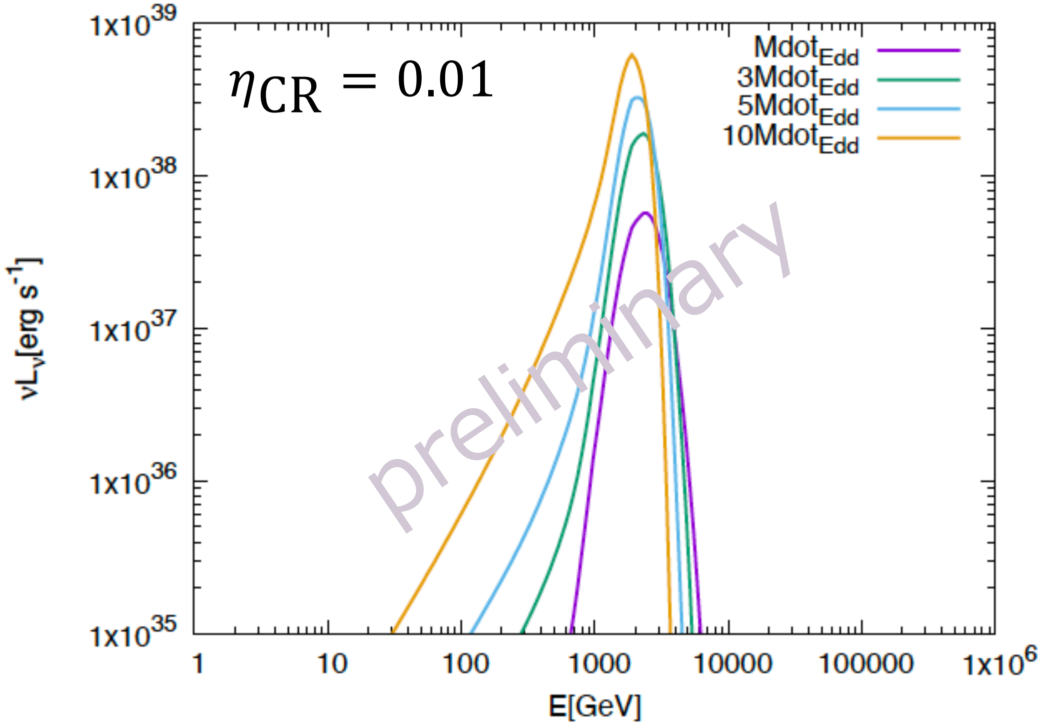


$\dot{M} = 5\dot{M}_\mathrm{Edd}$



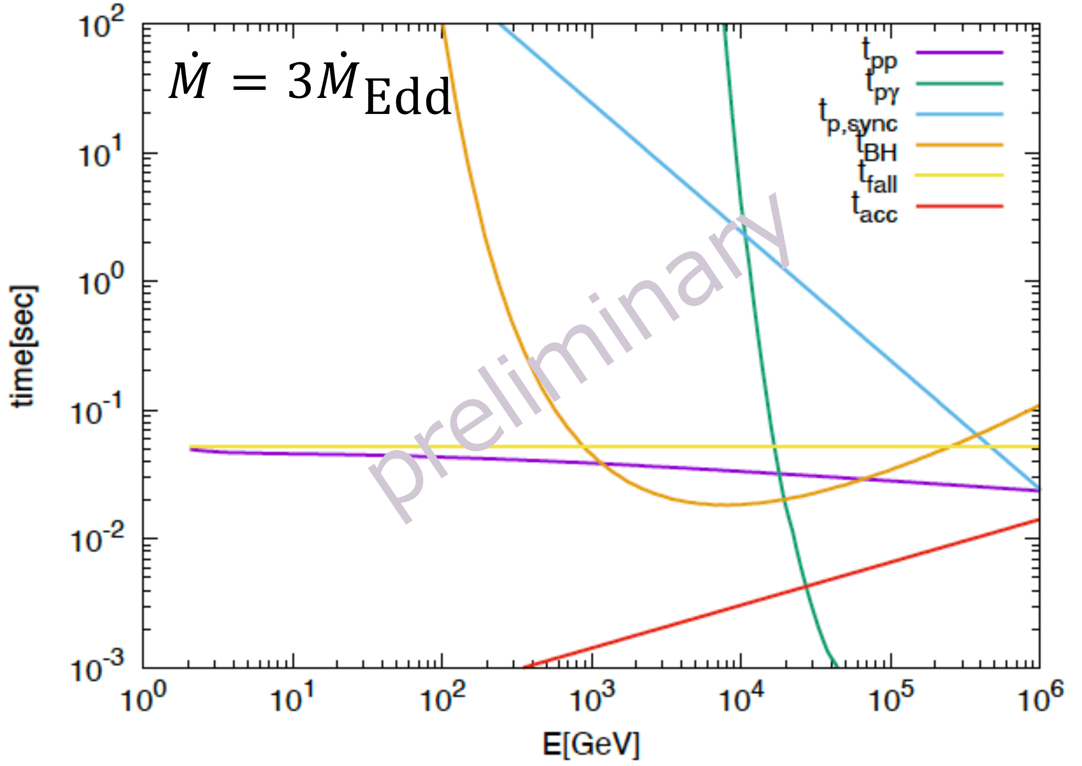
$t_{C,pp} \gg t_\mathrm{fall}, t_\mathrm{dyn}$ → the corona can be regarded as collisionless

Results: HE neutrino spectra



- $\varepsilon_\nu L_\nu(\varepsilon_\nu) \gtrsim 10^{38}\ \mathrm{erg\ s^{-1}}$
- Sharp peak and steep cutoff at $\gtrsim$ TeV
- Lower peak energy for larger $\dot{M}$
- The peak becomes broader for larger $\dot{M}$

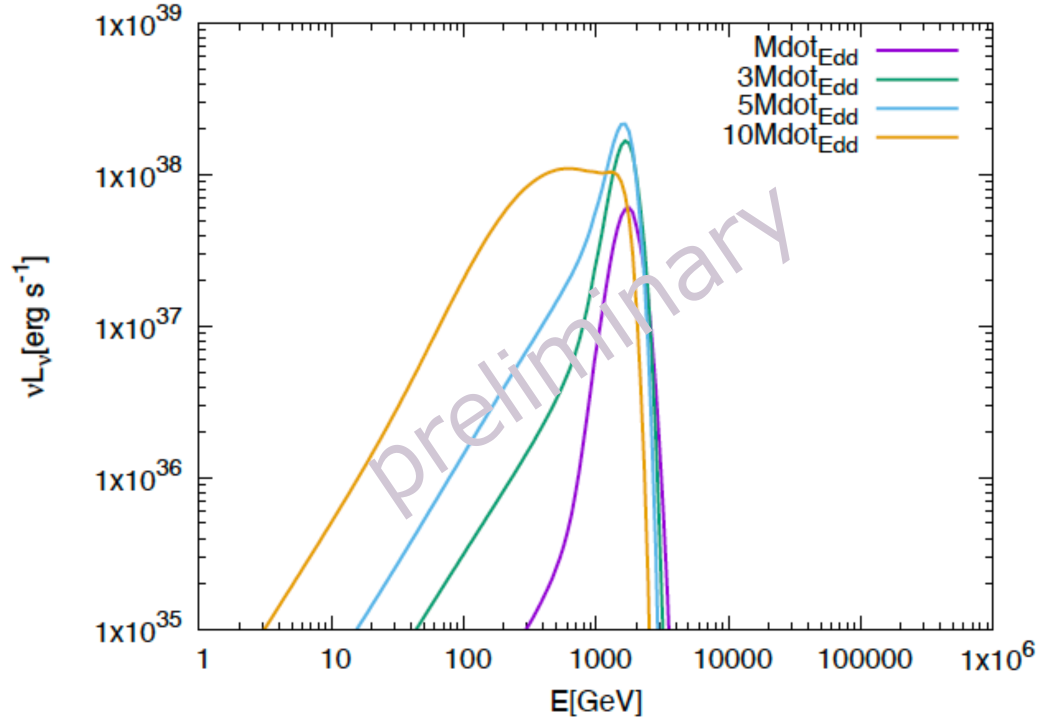
timescales



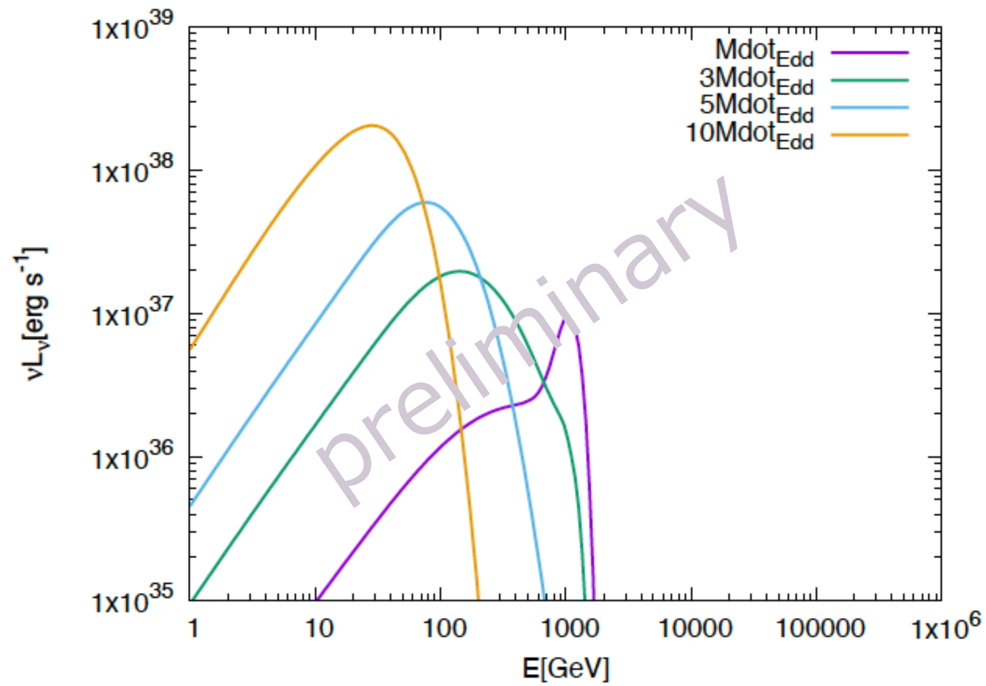
- $p\gamma$ interaction timescale becomes steeply efficient at $\gtrsim 10$ TeV
- $t_{\rm acc} \sim t_{p\gamma}$ at $\gtrsim 10$ TeV
- due to the high corona density, pp interaction is also effective for high $\dot{M}$

Cases with weaker magnetic fields

1/3 of the fiducial value



1/15 of the fiducial value



Discussions

- HE neutrino spectra from ULXs have sharp cutoffs at $\sim \mathrm{TeV}$ (or lower when B being weaker)
  - optically-thick compared to the corona in sub-Edd BHs → higher X-ray photon density → efficient $p\gamma$ cooling
  - $\dot{M}\uparrow$ → higher photon density & denser corona → $p\gamma/pp$ cooling → lower and broader peak
  - weaker B → longer t_{acc} → lower and broader peak

- detectable?
  - fiducial: $\varepsilon_\nu L_\nu(\varepsilon_\nu) \gtrsim 10^{38}\,\mathrm{erg\,s^{-1}}$ at $\sim \mathrm{TeV}$ → $F_\nu \sim 10^{-11}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ @ 10 Mpc
  - $\sim$ 500 ULXs (including candidates) in $D < 10\,\mathrm{Mpc}$ (Bernadich+ 2022) → marginally detectable by IceCube (10 yrs) by stacking?

Summary

- **Accretion disk coronae in active galactic nuclei are the promising high energy neutrino emitters**
  - collisionless & turbulent plasma → non-thermal particle acceleration → HE ν production via pp or $p\gamma$
- **How about the coronae in super-Eddington BHs?**
  - ULXs, microquasars, NLS1s, high-z AGNs, etc.
  - plasma loading by radiation-driven wind → optically-thick and cool corona (different from sub-Edd BHs)
  - collisionless condition → OK!
  - particle acceleration & neutrino production in ULX coronae → $\varepsilon_\nu L_\nu(\varepsilon_\nu) \sim 10^{38}\ \mathrm{erg\ s^{-1}}$ at ~ TeV with a sharp cutoff
  - detectable by stacking?
  - What about other super-Edd BHs (NLS1s, high-z AGNs)?