Gamma-ray and neutrino emissions from radiatively inefficient accretion flows

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References:
1)SSK, Murase, Meszaros, arXiv:2005.01934
2)SSK, Murase, Meszaros, 2019, PRD, 100, 083014
3)Murase, SSK, Meszaros, 2020, PRL, 125, 011101

Connecting high-energy astroparticle physics
for origins of cosmic rays and future perspectives
@ Kyoto University (Online)

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Theoretical Astrophysics
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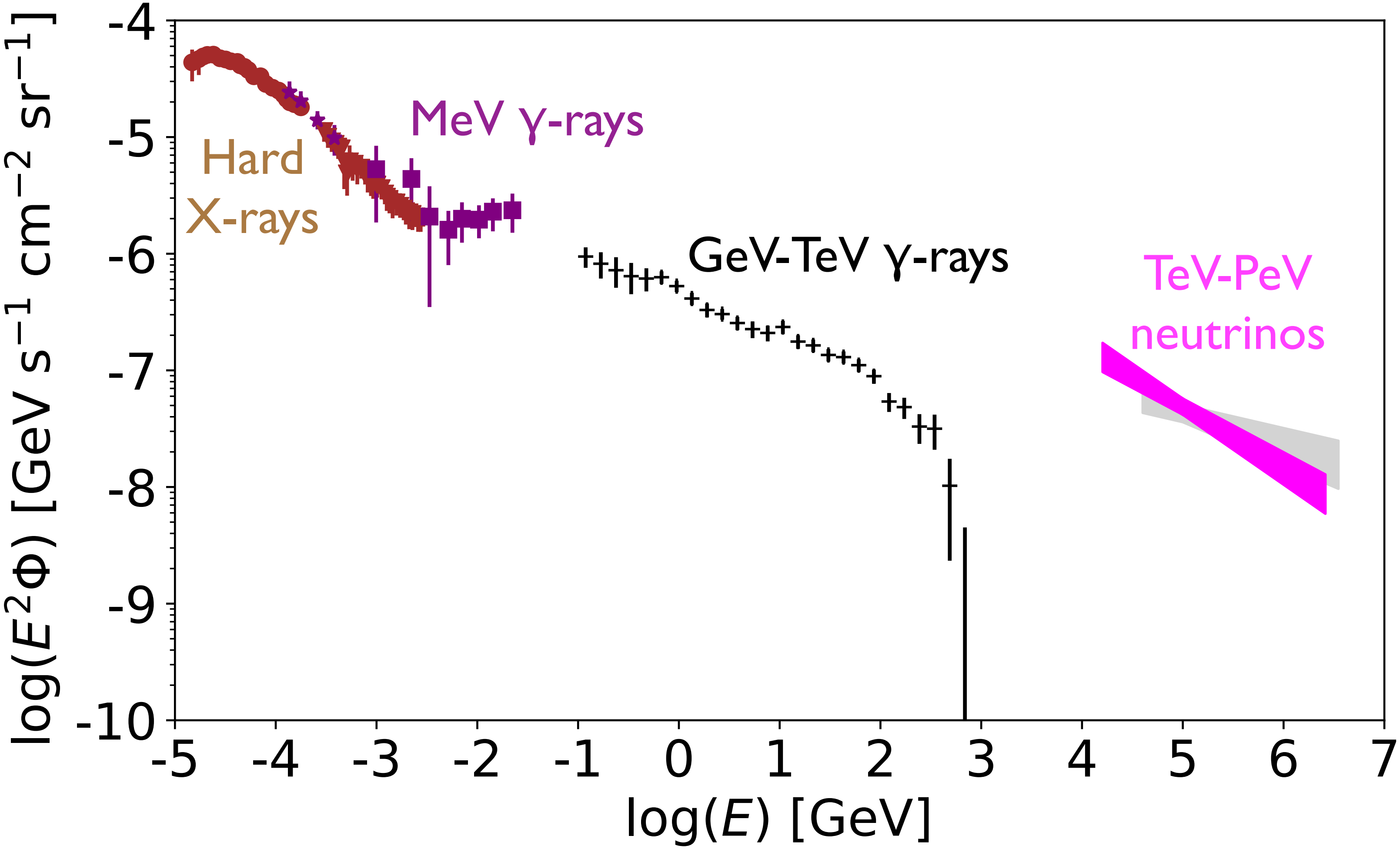
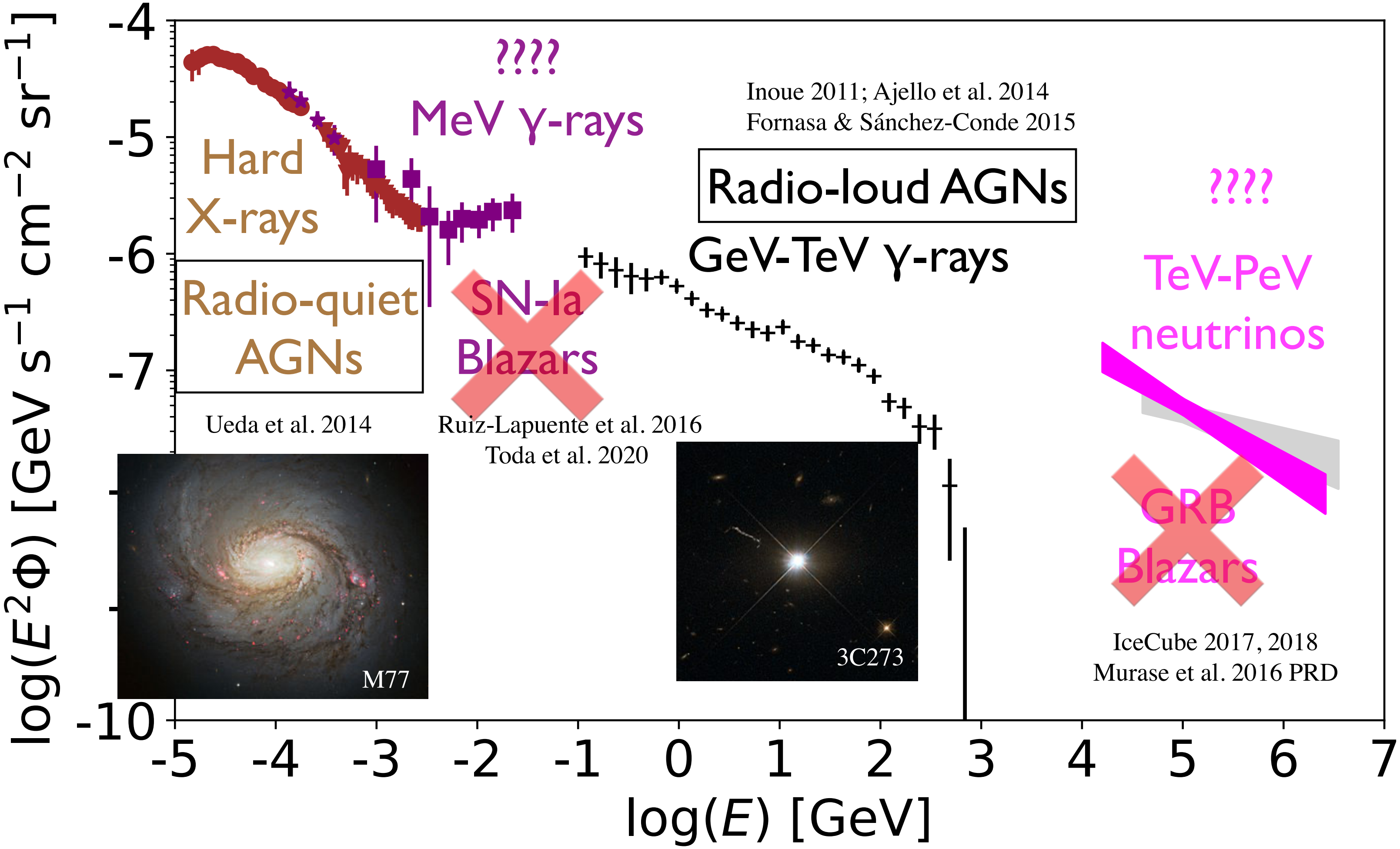
- Introduction
- Photons from Thermal Electrons
- Non-thermal components
- Summary

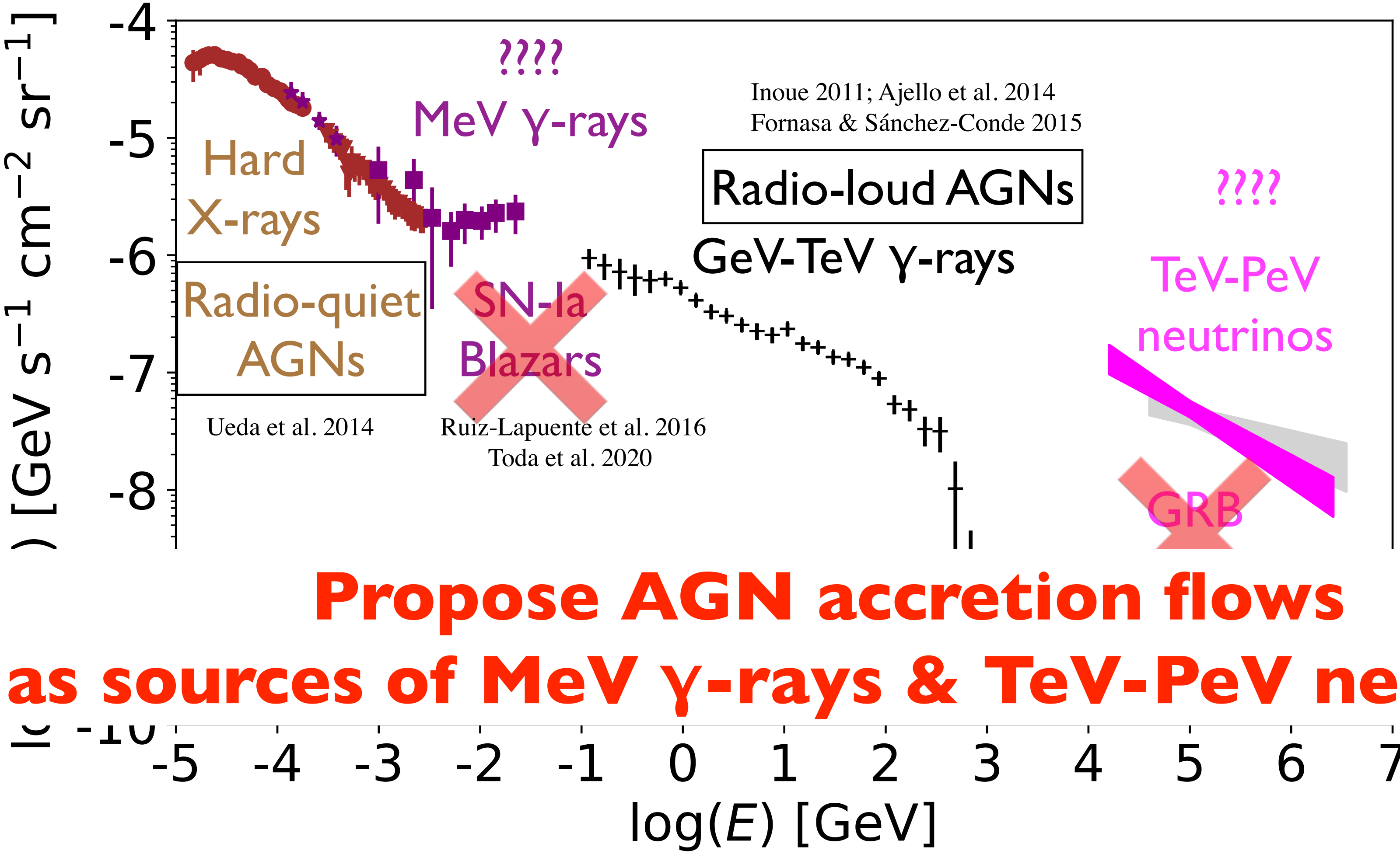
Cosmic High-energy Backgrounds



Cosmic High-energy Backgrounds

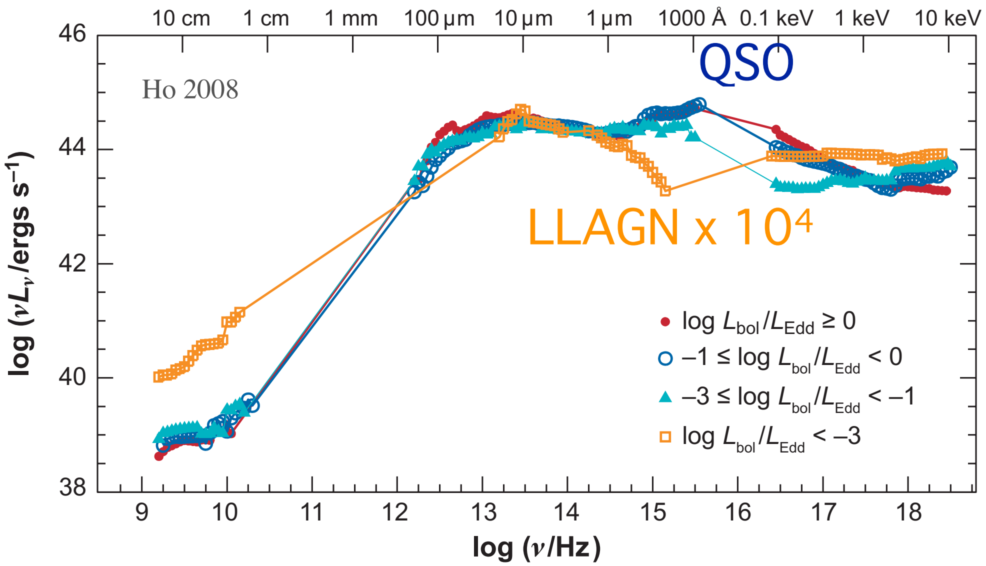


Cosmic High-energy Backgrounds

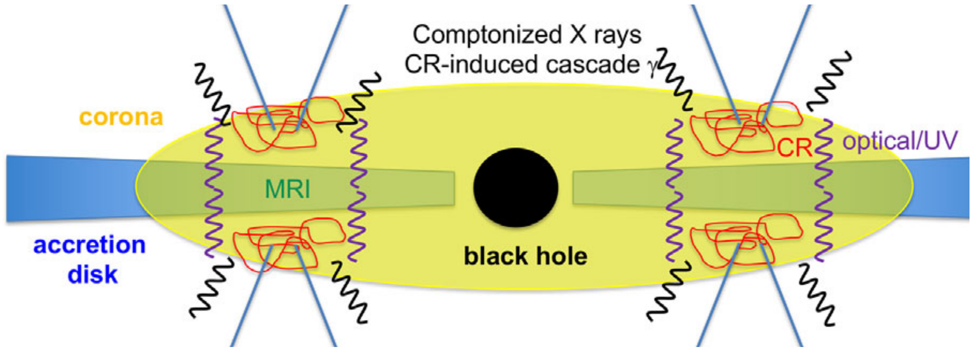


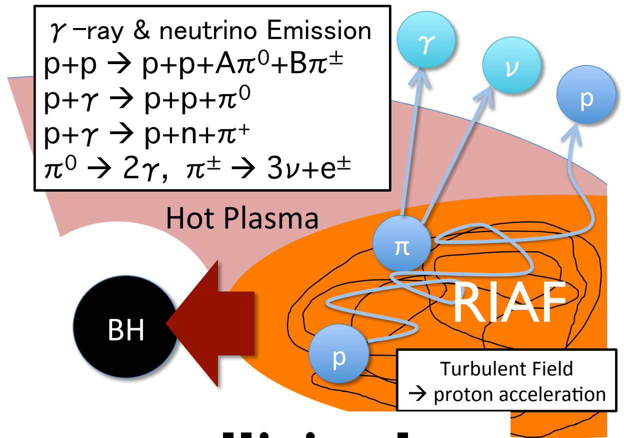
Propose AGN accretion flows
as sources of MeV γ-rays & TeV-PeV neutrinos

AGN Accretion Flows



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



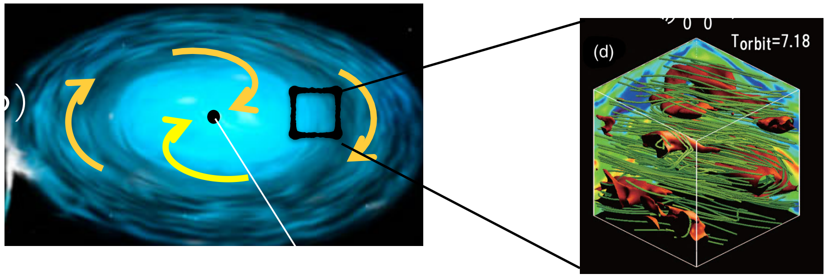


Protons in coronae & RIAFs are collisionless
→ Non-thermal proton production

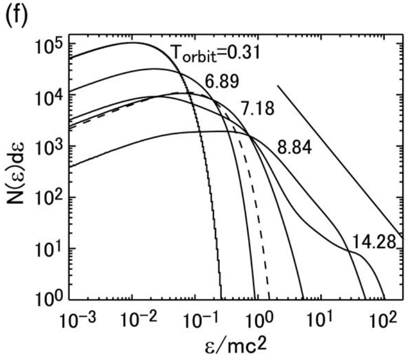
Particle Acceleration in MRI Turbulence

Particle-In-Cell Simulations

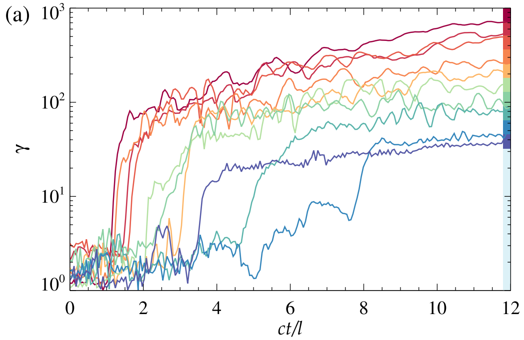
turbulent



Hoshino 2013, 2015; Riquelme et al. 2012; Kuntz et al. 2016; Comisso & Sironi 2018



Non-thermal

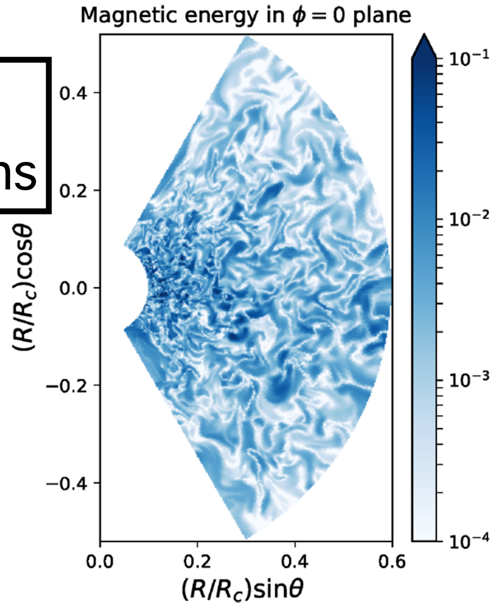


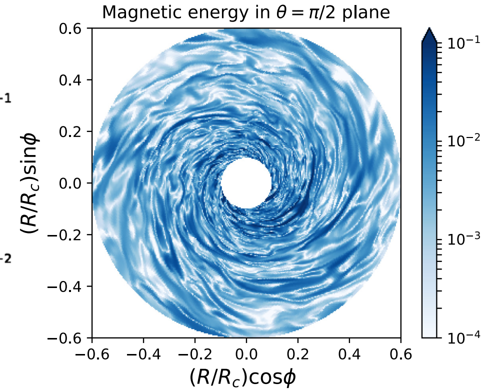
Numerical Simulations

MHD + Test Particle Simulations

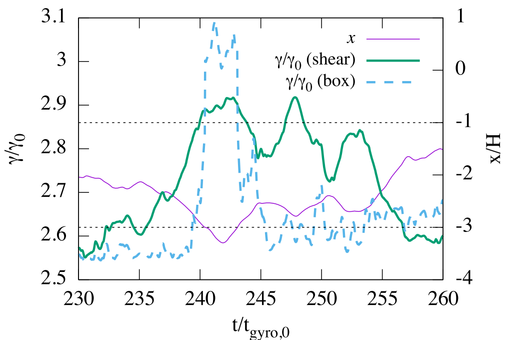
SSK et al. 2016, 2019

MHD turbulence





Energy change



Magnetic reconnection and MHD turbulence accelerates CRs

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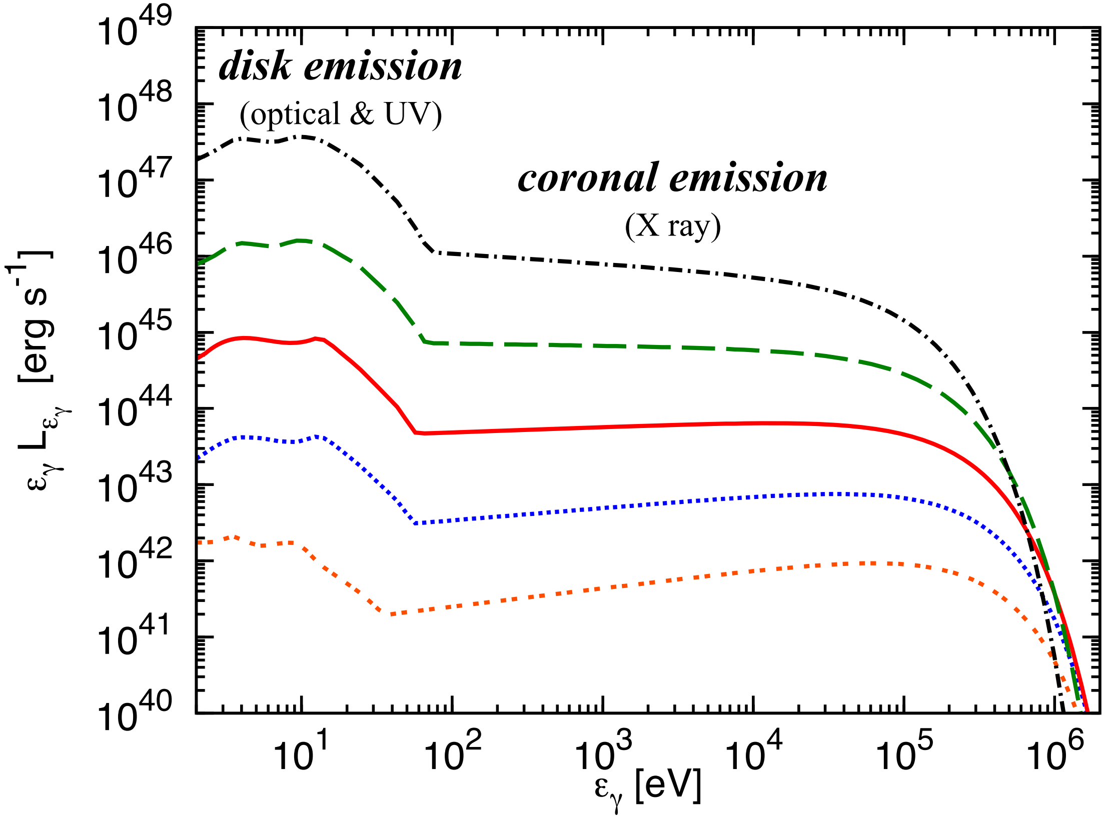
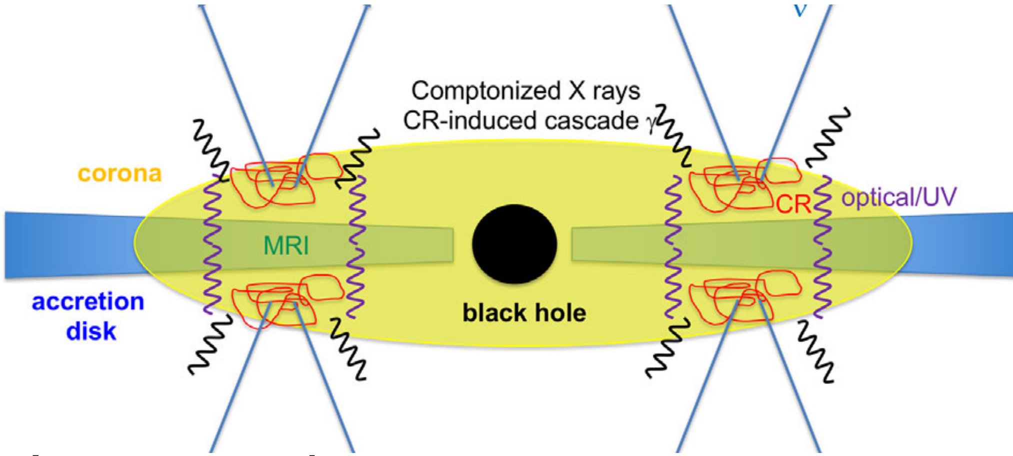
UV - MeV photons from QSO

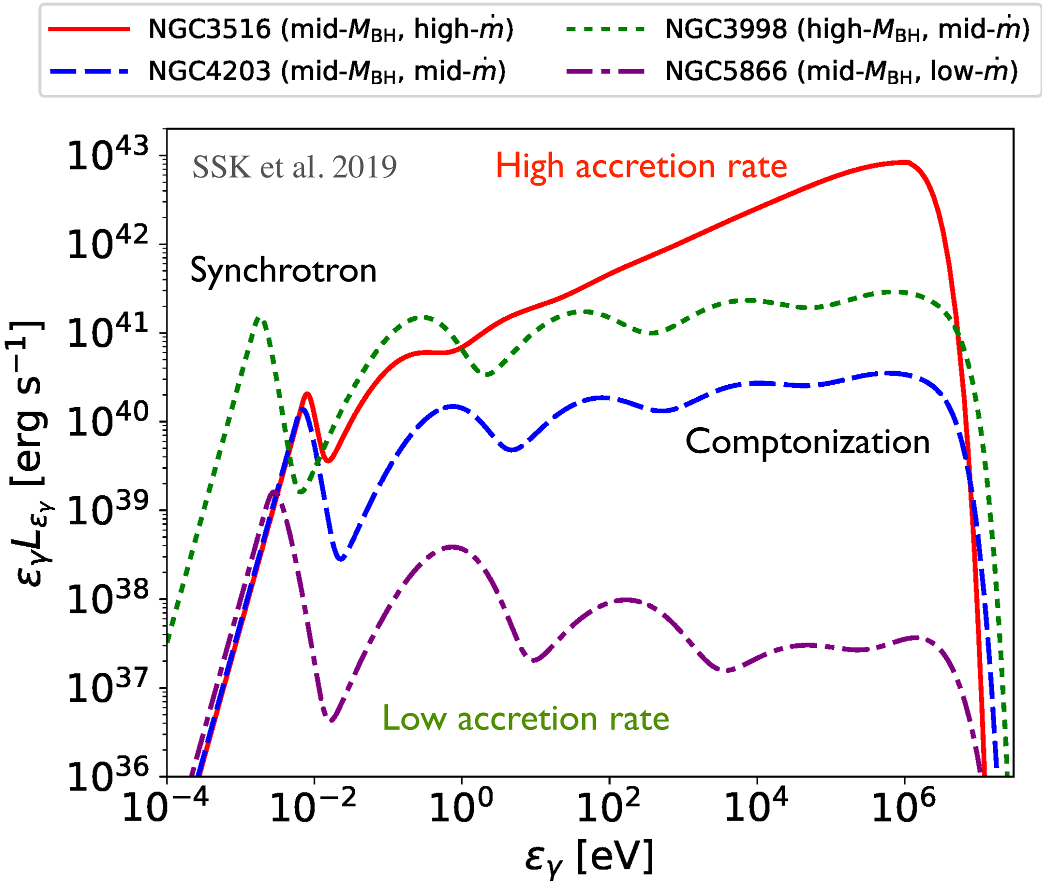


Pringle 1981, Ho 2008, Hopkins 2007, Mayers et al. 2018
Bat AGN Spectroscopic Survey 2017, 2018,

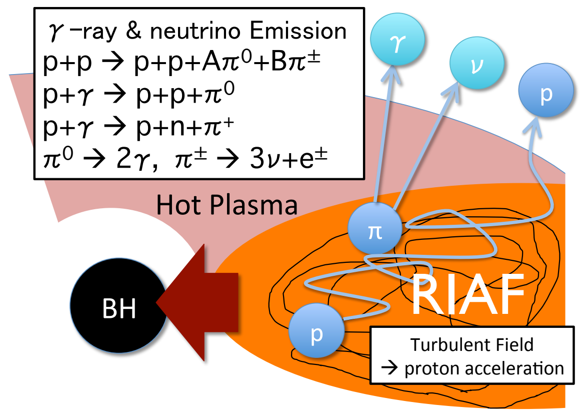


- Luminous objects
  → Rich observational data
  → **We can use empirical relation based on observations**
- Opt-UV photons from accretion disk
- X-rays from coronae above thin disk
- Higher L_{opt}/L_x for higher L_x AGNs
- Softer spectra for higher L_x AGNs
- Free parameters:
  viscous α, plasma β, corona size R

Radio-MeV photons from RIAFs



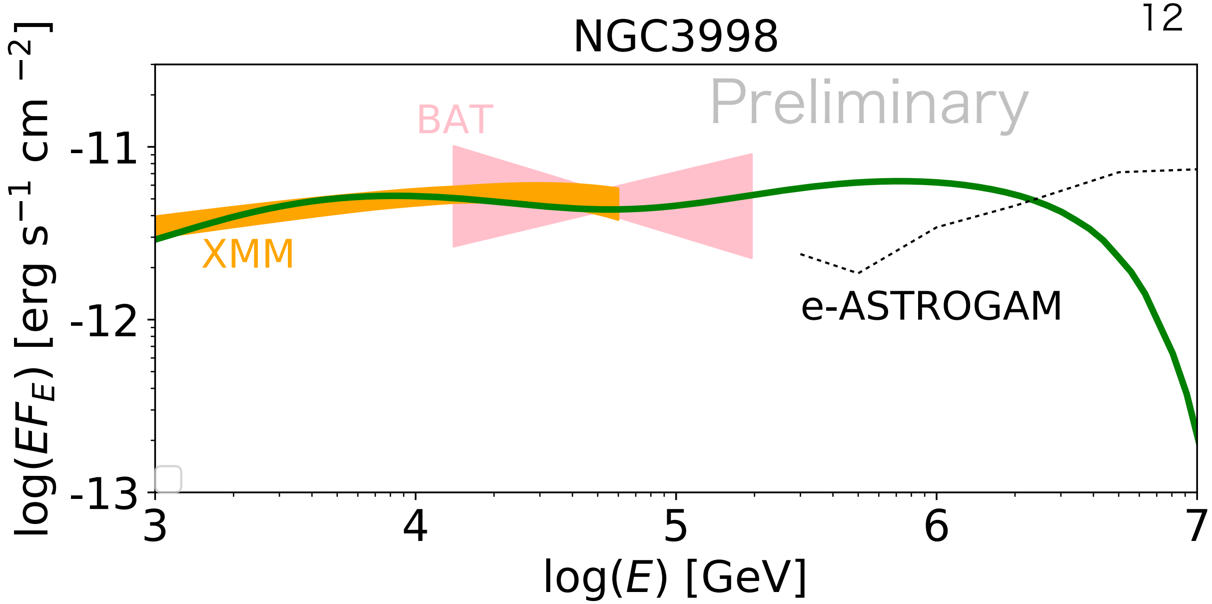
- Low-luminosity
  → Poor observational data
  → Formulation based on theory
- Thermal electrons in RIAFs emit photons through Synchrotron & Comptonization
- Photon cutoff energy is always around MeV because $L_\gamma \propto T_e^\chi$
  * $\chi = 7$ for synchrotron SSK et al. 2020
  * $\chi = 6 - (\ln \tau_T / \ln[16kT_e/m_e c^2]) > 6$ for Comptonization

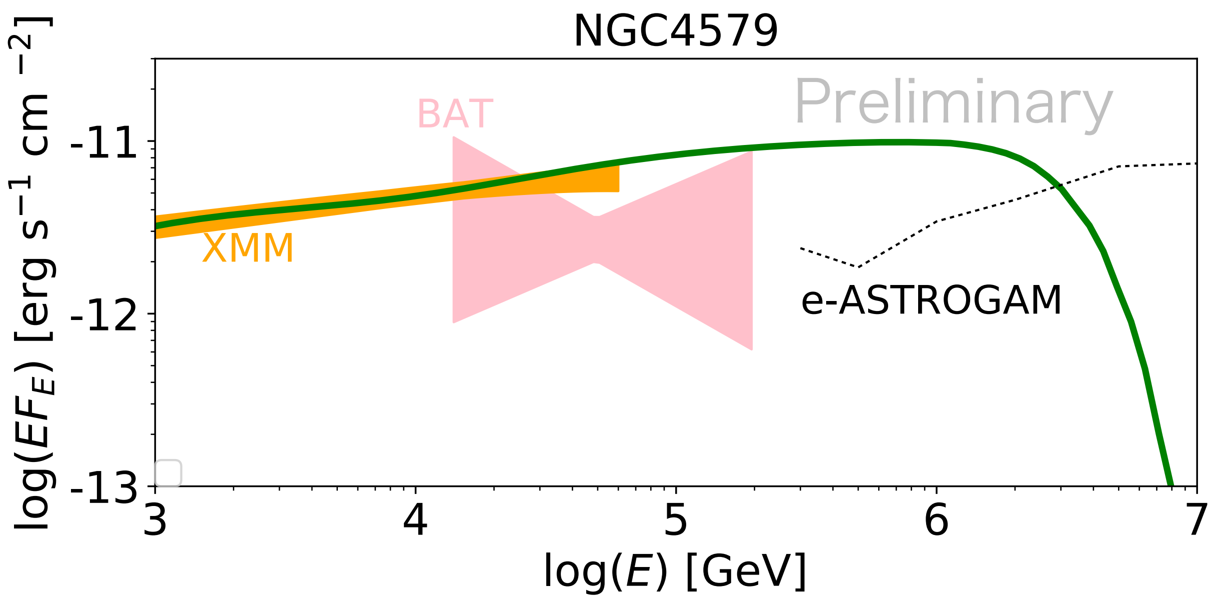


SSK et al. 2015

Comparisons to X-ray Obs.

- Our model nicely reproduce the X-ray datas for nearby objects, which allows us to calibrate parameters in our RIAF model
- **Most of nearby bright LLAGNs should be detected by future MeV satellites,** such as e-ASTROGAM, AMEGO, GRAMS





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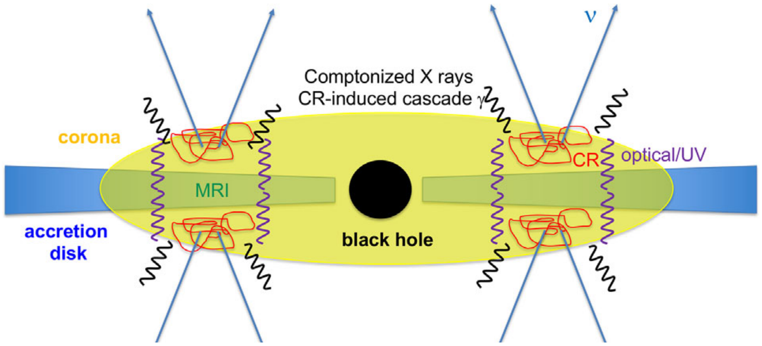
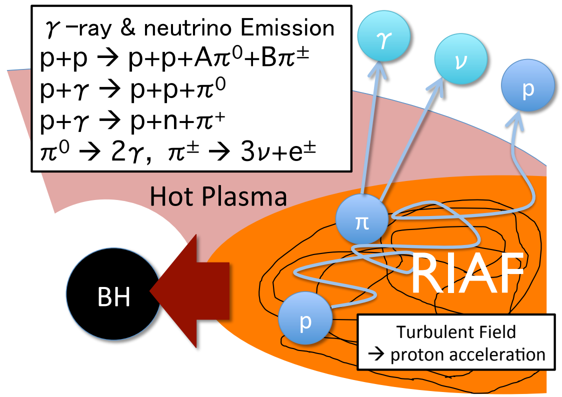
cf.) Dermer et al. 2012, SSK et al. 2015

Non-thermal Components





- Stochastic Acceleration (SA)

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

$$D_{\varepsilon_p} \approx \frac{\zeta c}{H}\left(\frac{V_A}{c}\right)^2\left(\frac{r_L}{H}\right)^{q-2}\varepsilon_p^2,$$

$$\dot{F}_{p,\mathrm{inj}} = \dot{F}_0\delta(\varepsilon_p - \varepsilon_{p,\mathrm{inj}})$$

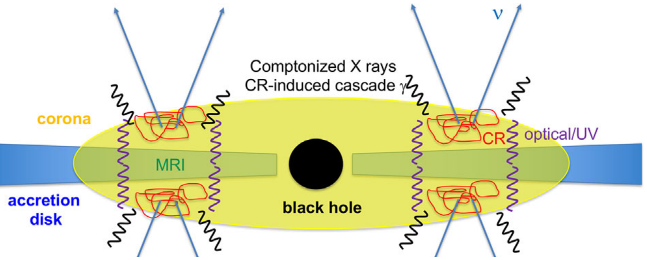
- Electromagnetic cascades

$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\mathrm{esc}}} + \dot{n}^{(\mathrm{IC})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{ff})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{syn})}_{\varepsilon_\gamma} + \dot{n}^{\mathrm{inj}}_{\varepsilon_\gamma},$$

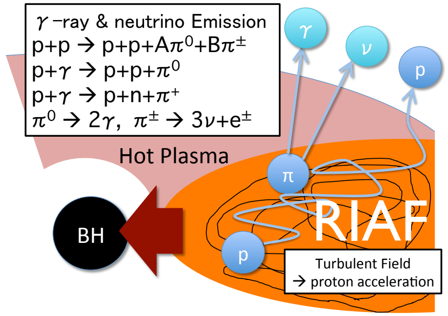
$$\frac{\partial n^e_{\varepsilon_e}}{\partial t} + \frac{\partial}{\partial \varepsilon_e}[(P_{\mathrm{IC}} + P_{\mathrm{syn}} + P_{\mathrm{ff}} + P_{\mathrm{Cou}})n^e_{\varepsilon_e}] = \dot{n}^{(\gamma\gamma)}_{\varepsilon_e} - \frac{n^e_{\varepsilon_e}}{t_{\mathrm{esc}}} + \dot{n}^{\mathrm{inj}}_{\varepsilon_e},$$

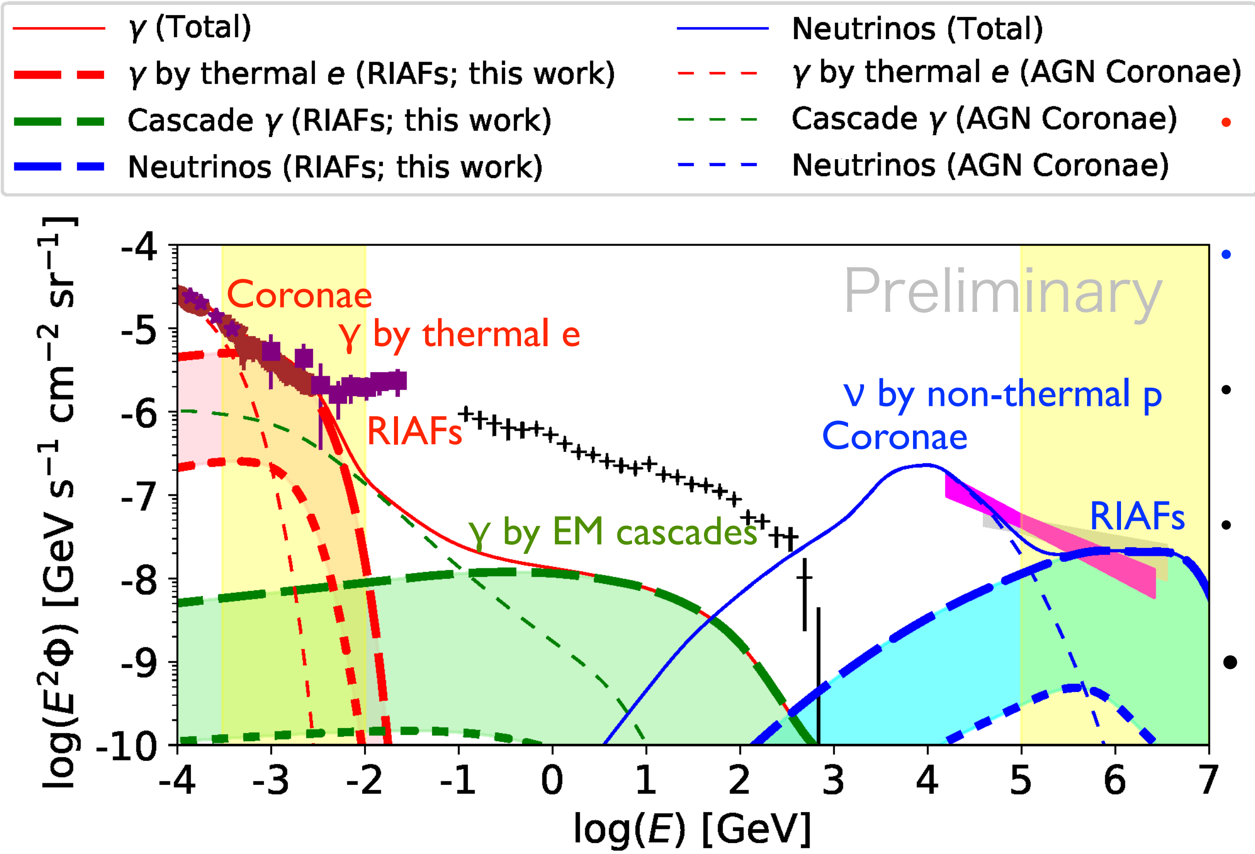
- Gyro-resonant wave-particle interactions in Kolmogorov-like MHD turbulence
- Escape : Diffusion & advection (to SMBH)
- Coolings:
  i) p+p → p + p (n) + π
  ii) p+γ → p (n) + π,
  iii) p+γ → p + e^+ + e^-
  iv) proton synchrotron
- Muon & Pion Coolings are negligible

Extragalactic γ & ν Backgrounds



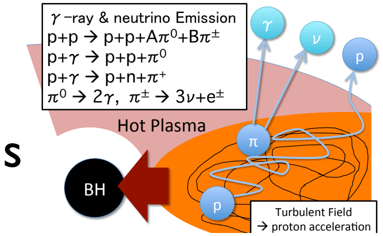
$$\Phi_i = \frac{c}{4\pi H_0}\int \frac{dz}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}\int dL_{\mathrm{H}\alpha}\rho_{\mathrm{H}\alpha}\frac{L_{\varepsilon_i}}{\varepsilon_i}e^{-\tau_{i,\mathrm{IGM}}},$$





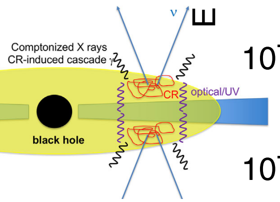
- Luminous AGNs can account for X-ray and 10 TeV neutrino backgrounds
- LLAGN can explain PeV ν and MeV γ backgrounds
- GeV γs are attenuated inside accretion flows → well below the Fermi data
- $P_{CR} \sim 0.01 P_{th}$ → reasonable in the sense that CR energy < Magnetic energy
- **AGN cores can account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

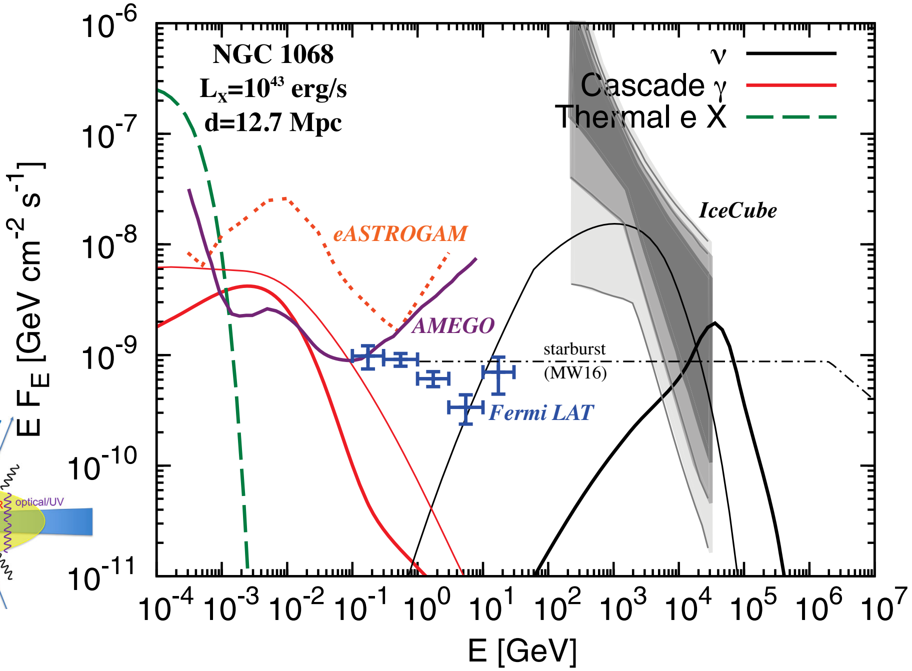
HE particles from Nearby AGNs



- M77 (NGC 1068)

Murase, SSK, Meszaros 2020
See also Inoue Y. et al. 2020

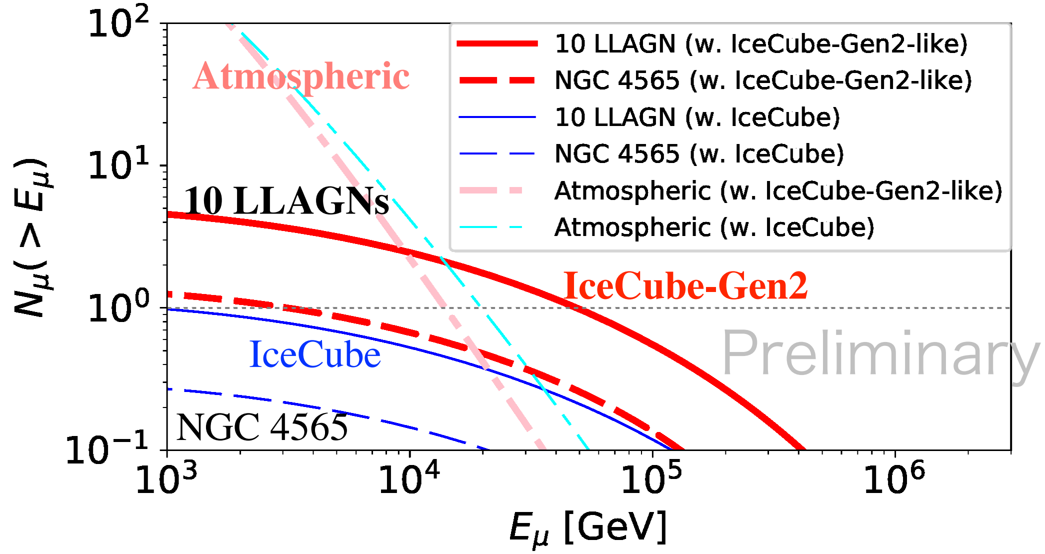




- Possible to explain IceCube data without overshooting γ-ray data
- γ to ν flux ratio is fixed by observed spectrum
  → **We can robustly test our model by future experiments**

- Stacking nearby LL AGNs

SSK, Murase, Meszaros 2020



- We cannot detect single LL AGN even with IceCube-Gen2
- IceCube **cannot detect any** νs
- **IceCube-Gen2 will detect a few νs above atmospheric background**

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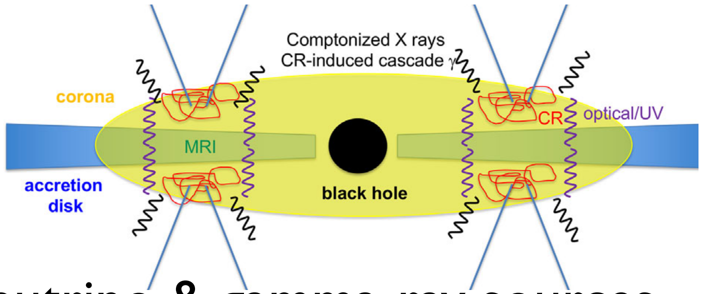
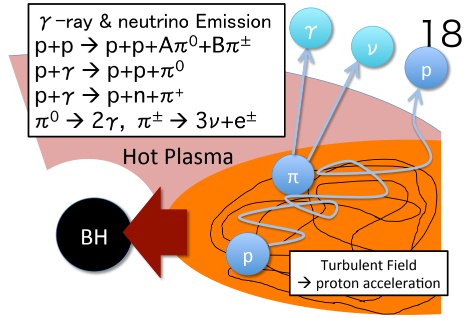
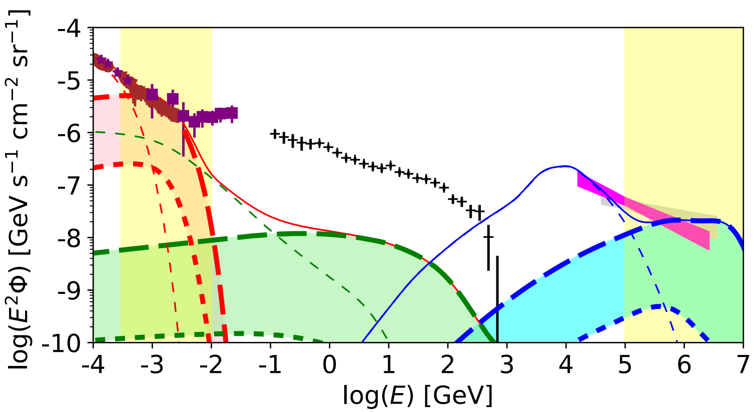
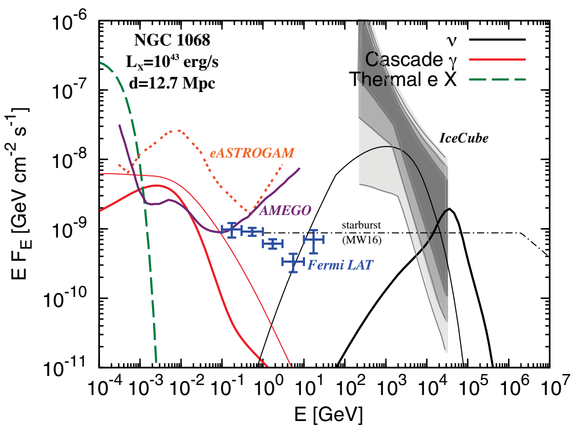


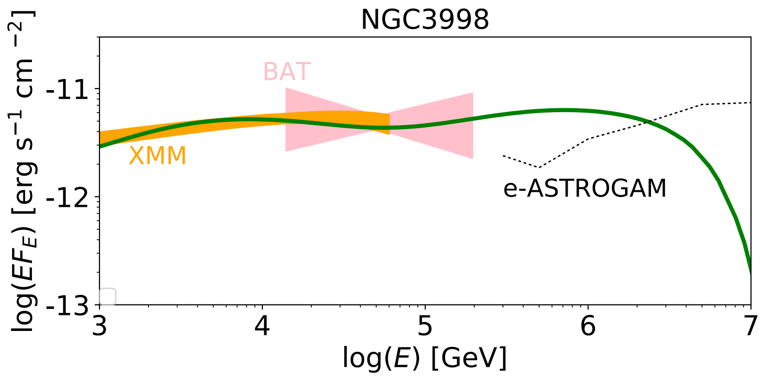


- Accretion flows in AGNs are feasible neutrino & gamma-ray sources
  - Coronae in Seyfert galaxies can reproduce X-ray & 10-100 TeV ν backgrounds
  - RIAFs in LLAGNs can explain MeV γ & PeV ν backgrounds

  → **Combining these two, AGN accretion flows can explain a wide energy range of γ & ν backgrounds**
- **Future multi-messenger observations can robustly test our models:**
  - IceCube-Gen2 can detect AGNs as point sources
  - Proposed MeV satellites can detect MeV γ rays from AGNs







Thank you
for your attention