Gamma-ray and neutrino emission from accretion flows

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References:

1) SSK, Murase, Meszaros, 2021, Nat. Comm., 12, 5615
2) Murase, SSK, Meszaros, 2020, PRL, 125, 011101

TeV Particle Astrophysics 2022 @ Kingston, Canada

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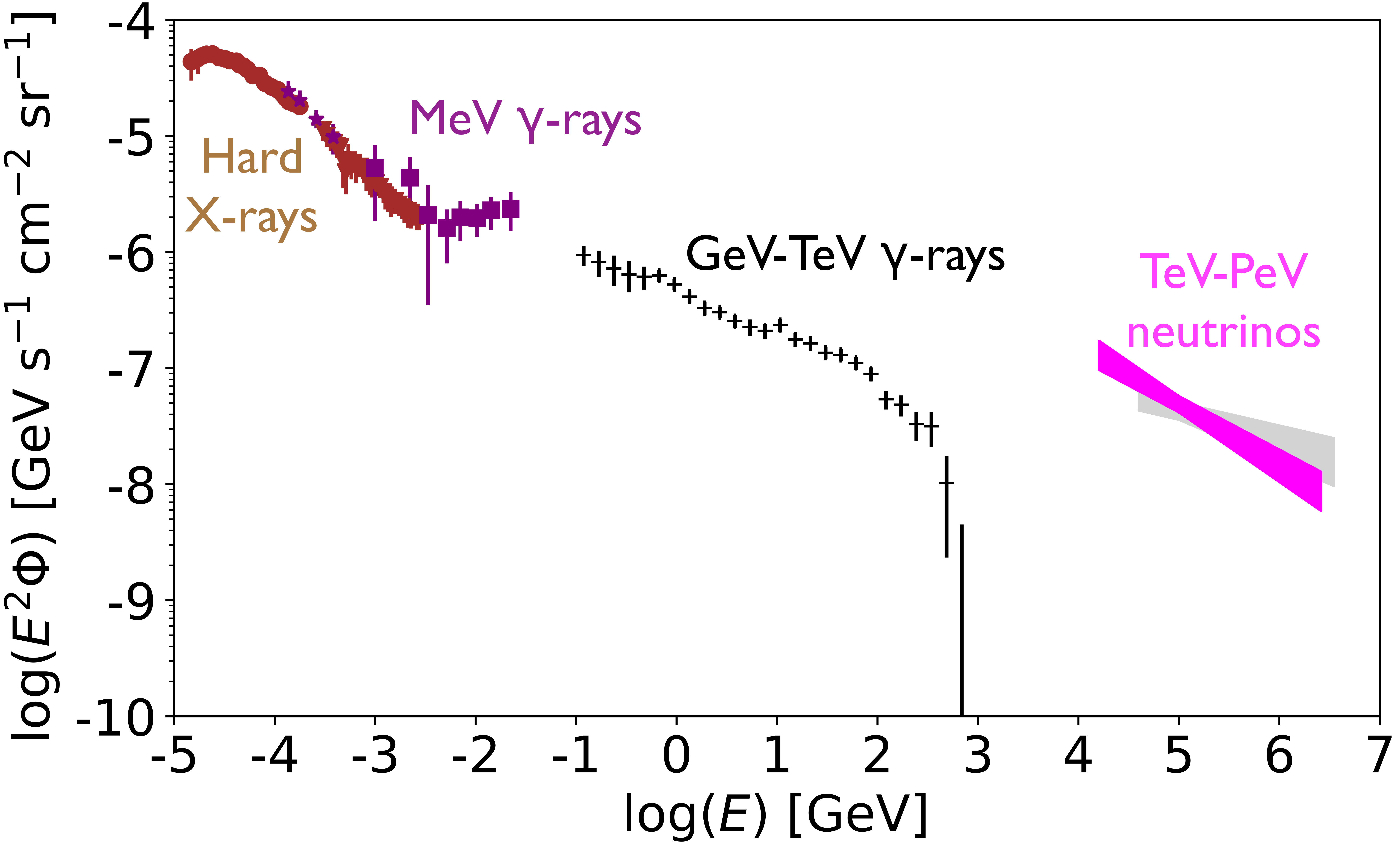
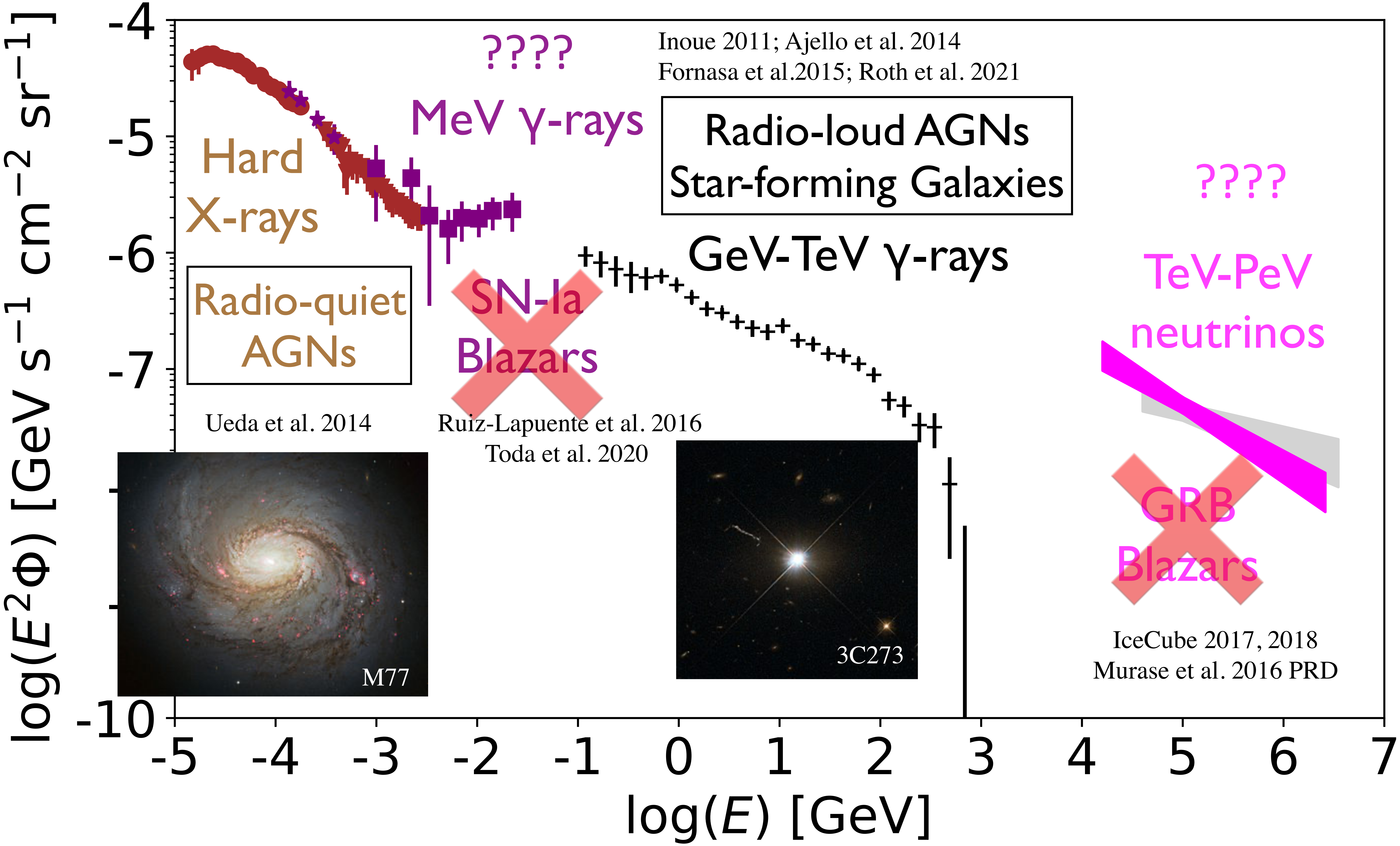
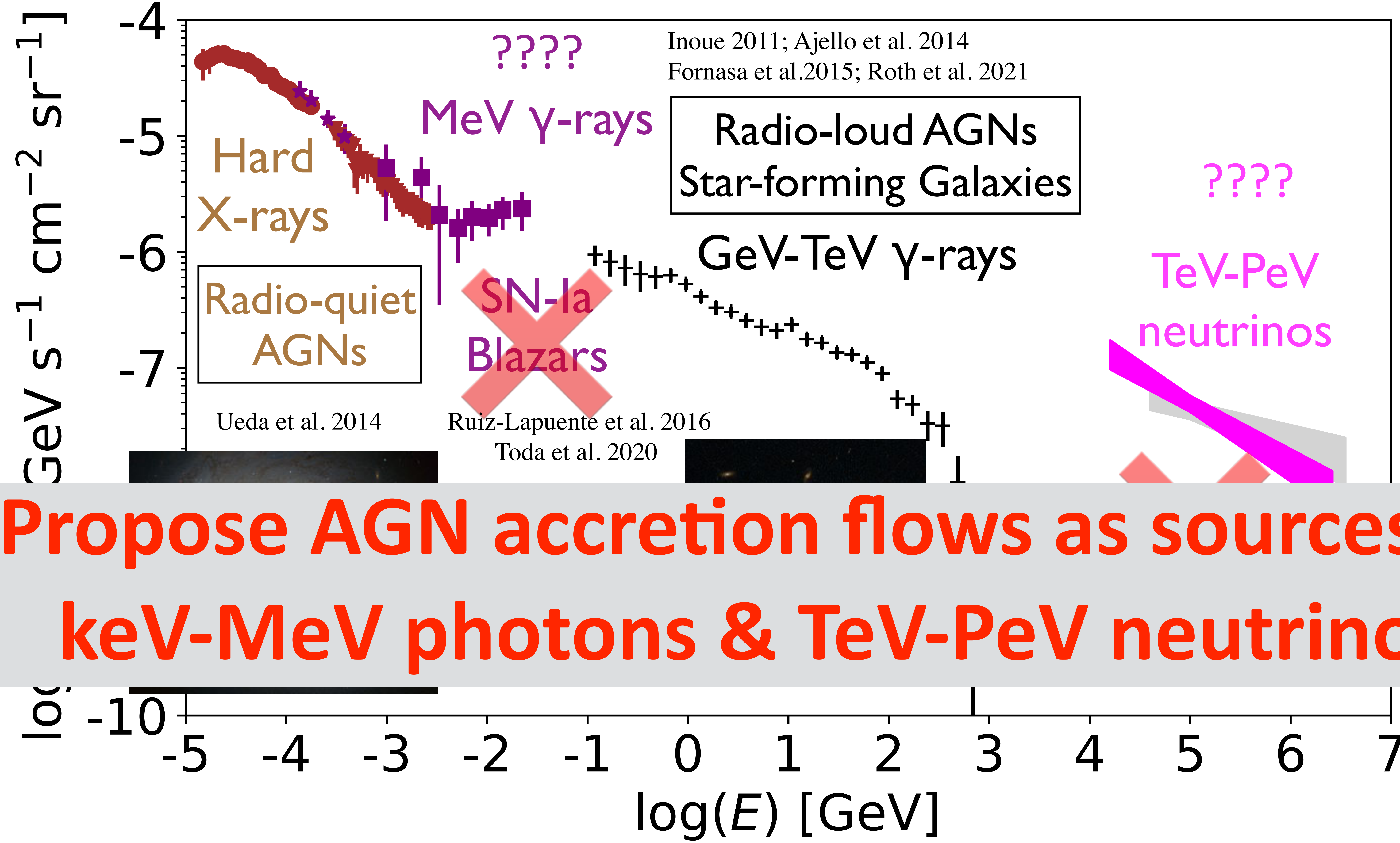
Cosmic High-energy Backgrounds



Cosmic High-energy Backgrounds



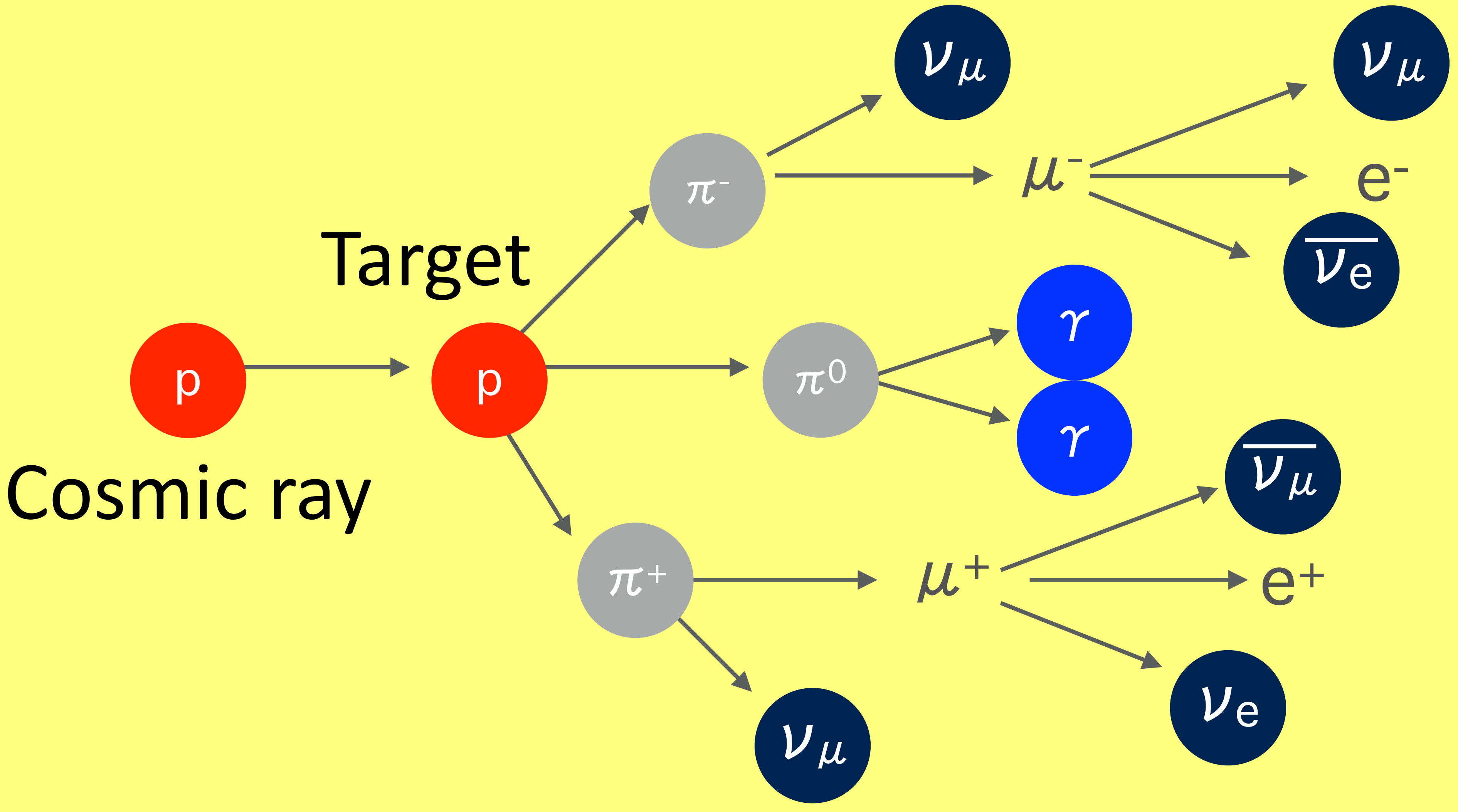
Cosmic High-energy Backgrounds



Propose AGN accretion flows as sources of keV-MeV photons & TeV-PeV neutrinos

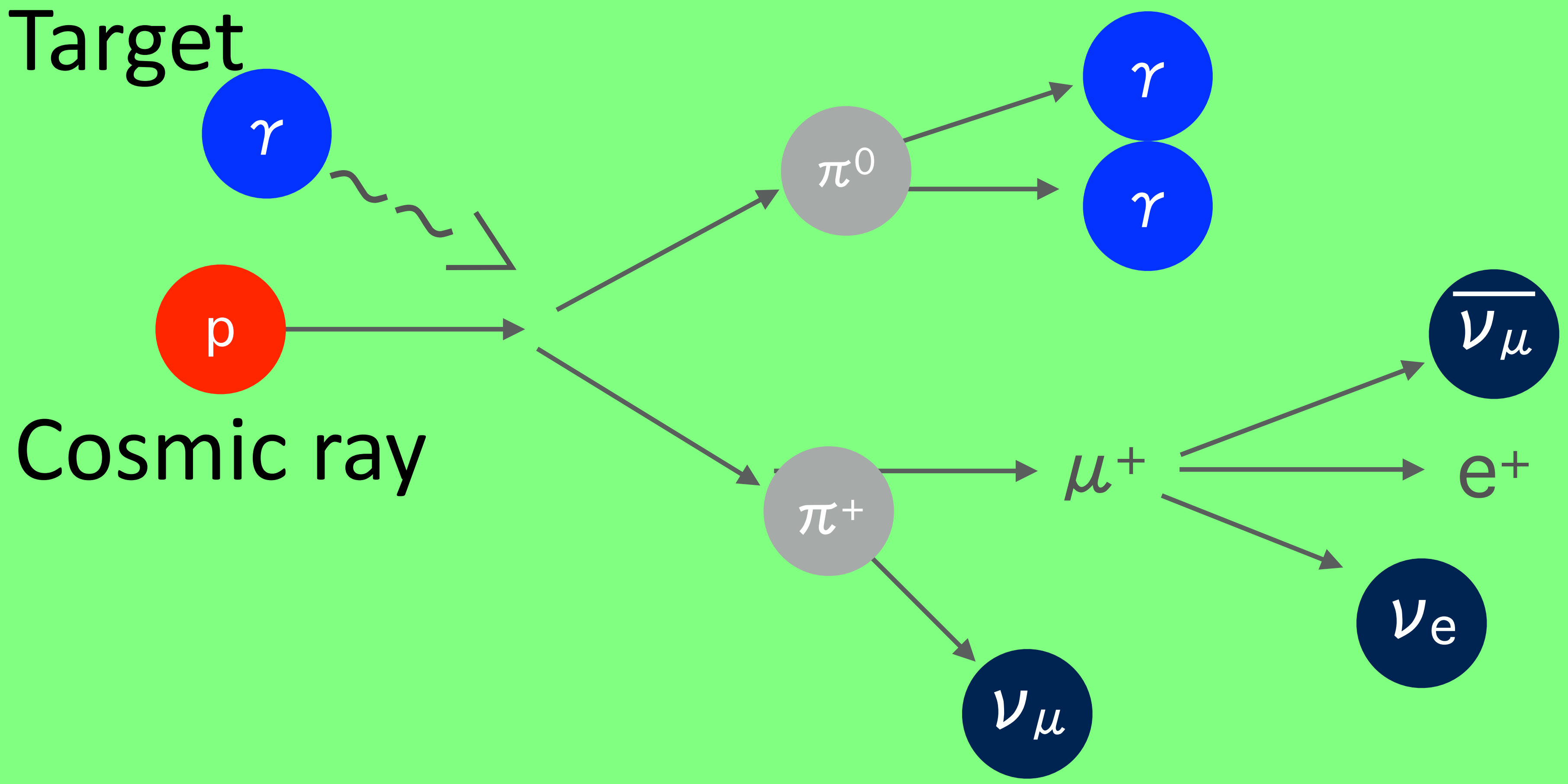
High-energy neutrino production

- pp inelastic collision



- $p+p \rightarrow p+p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

- Photomeson production (pγ)

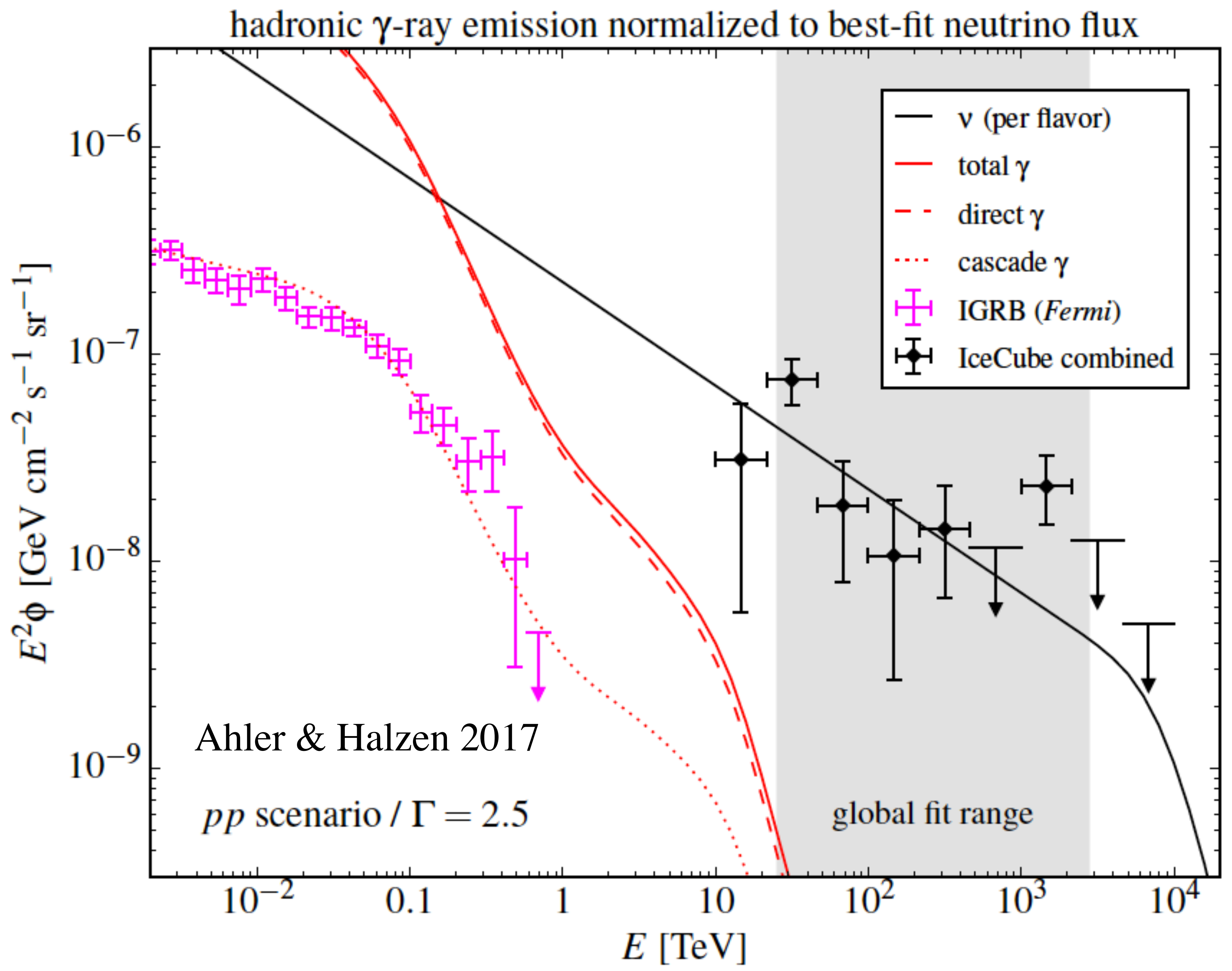


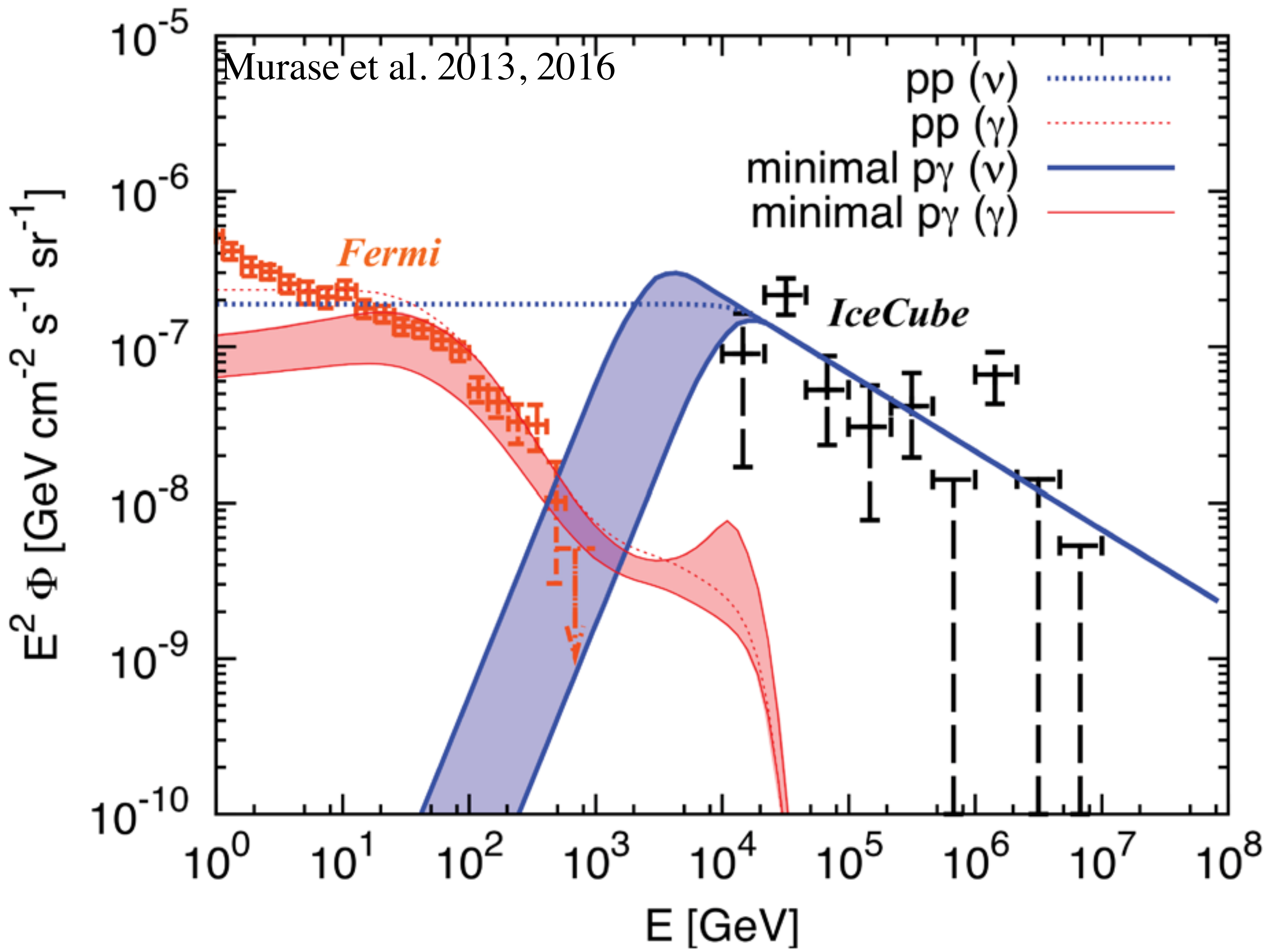
- $p+\gamma \rightarrow p+\pi$
- $\pi^{\pm} \rightarrow 3\nu+e$
- $\pi^0 \rightarrow 2\gamma$

Interaction between CRs & photons/nuclei → Neutrino production

Gamma-rays inevitably accompanied with neutrinos

Gamma-ray Constraint on Neutrino Sources





- Astrophysical neutrinos are always accompanied with gamma-rays
- ν flux@10 TeV > γ-ray flux@100 GeV
  → accompanying γ-rays overshoot Fermi data
  → **ν sources should be opaque to TeV γ rays**

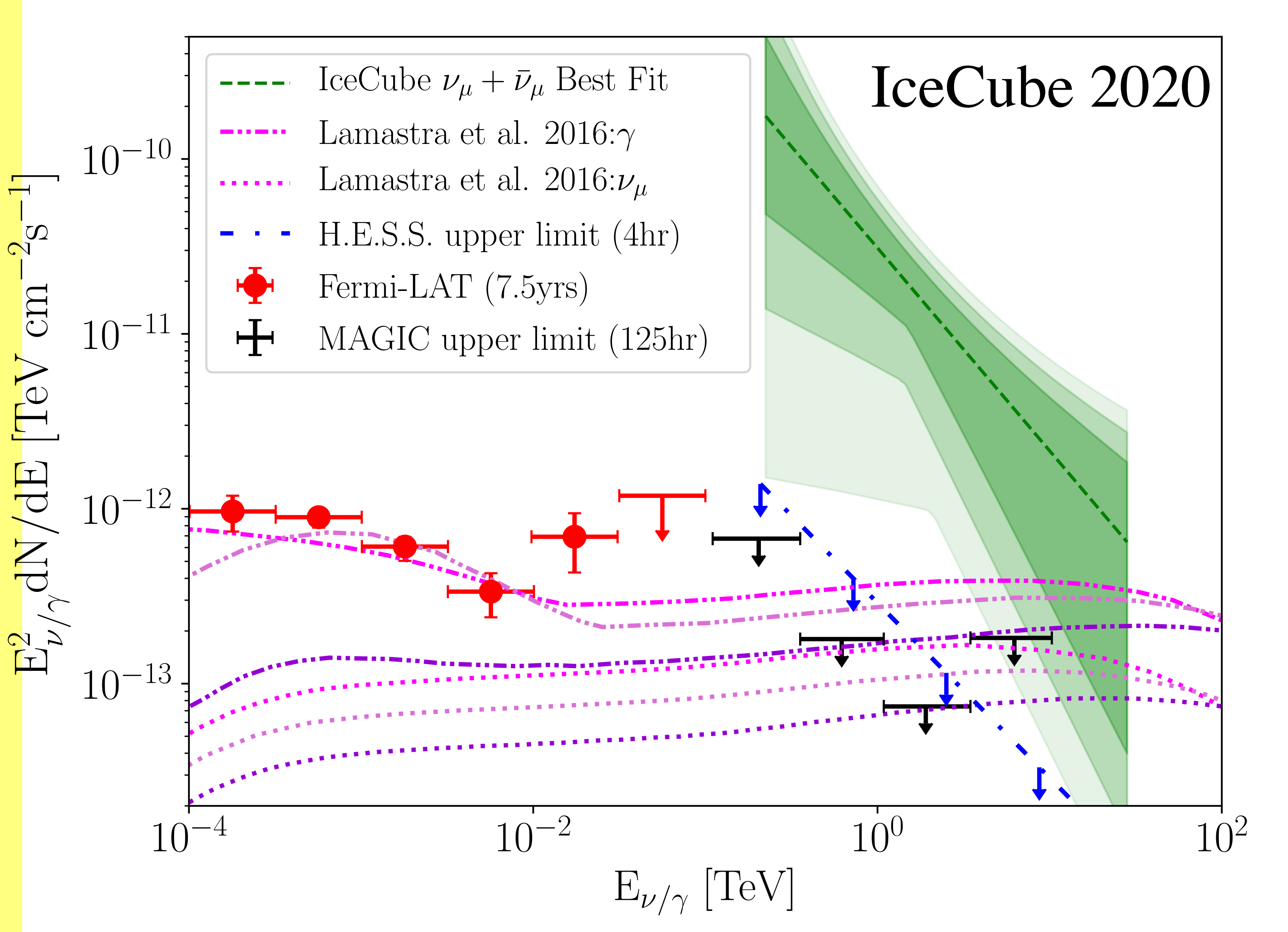
Hints of Neutrinos from Seyferts

- Point source search with 10-year data set

  -Hottest Point (2.9σ) : M77 (NGC 1068; Seyfert 2)

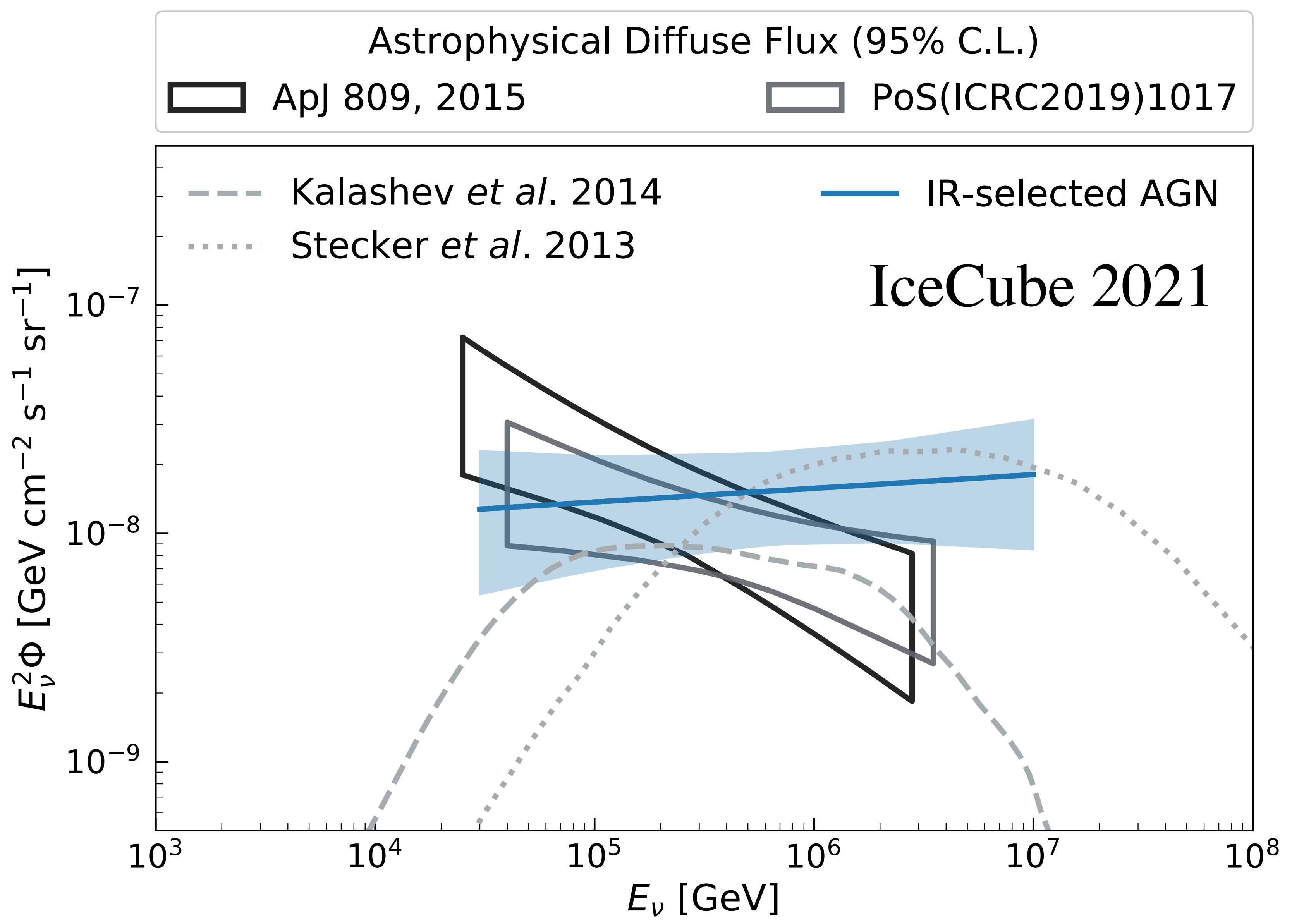
  $L_\nu > L_\gamma$ → "Hidden Source" (γ-rays are absorbed)

IceCube 2020



- Stacking analysis

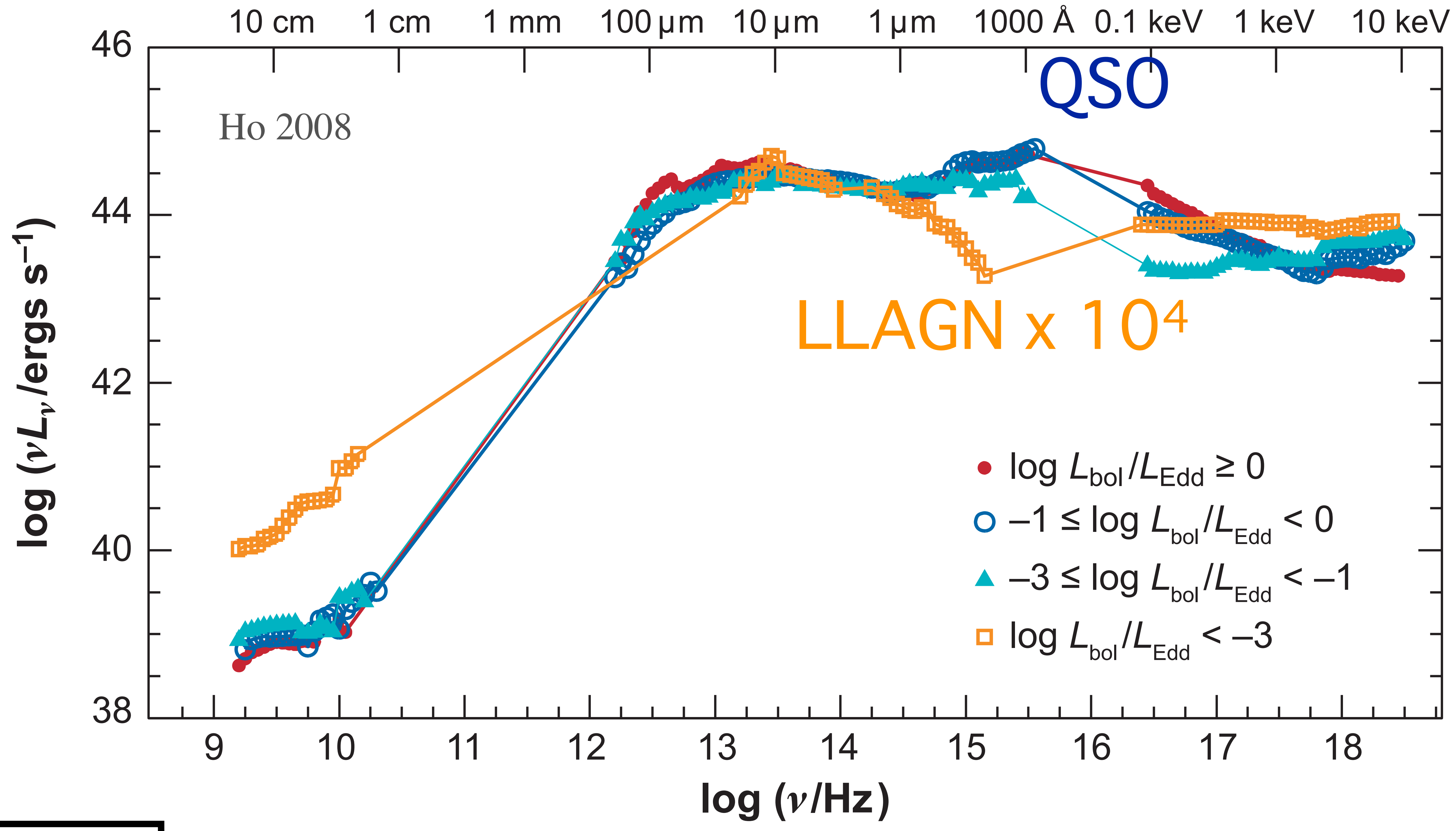
  - Association between ν events & AGN (2.6σ)

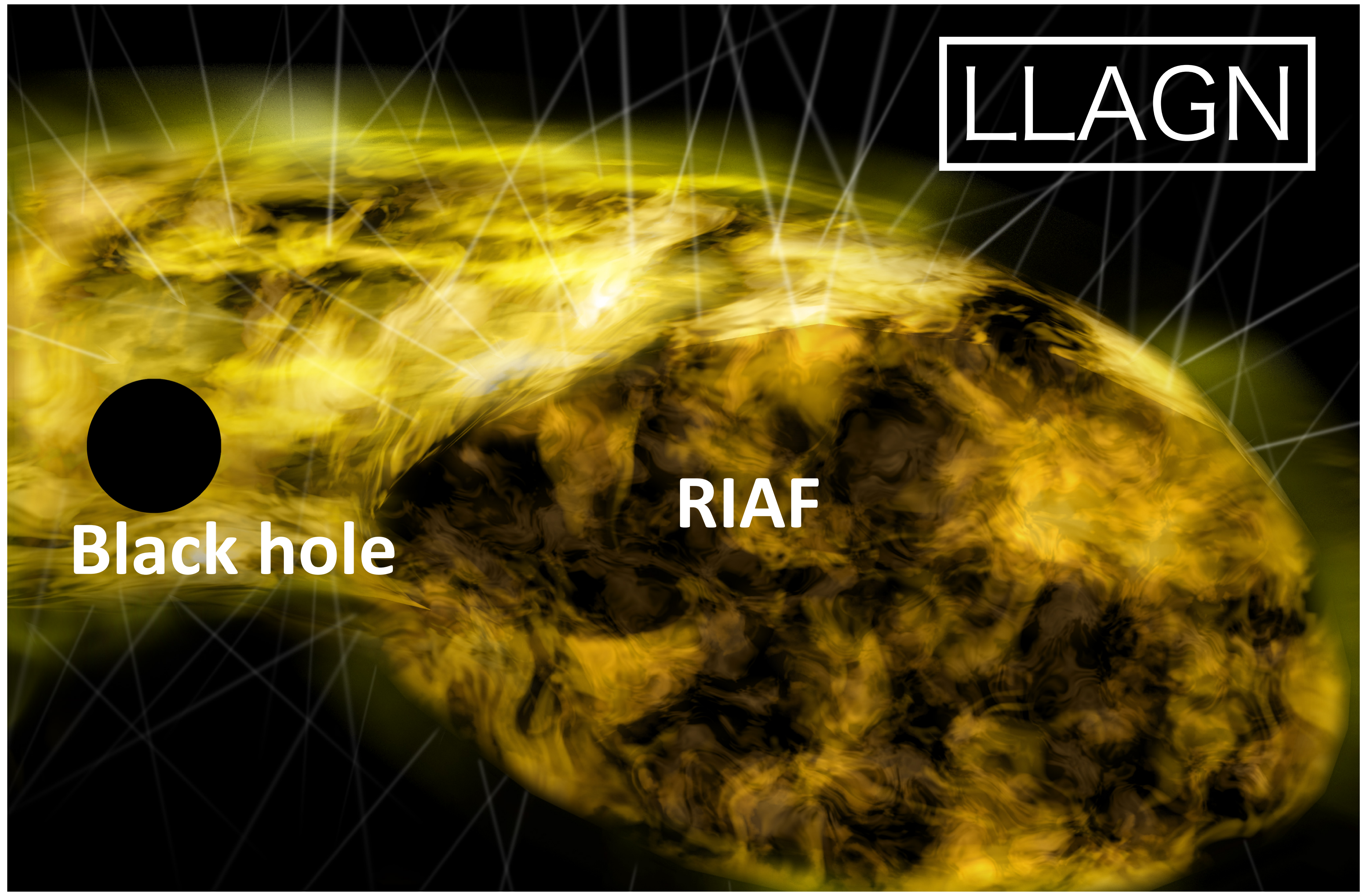


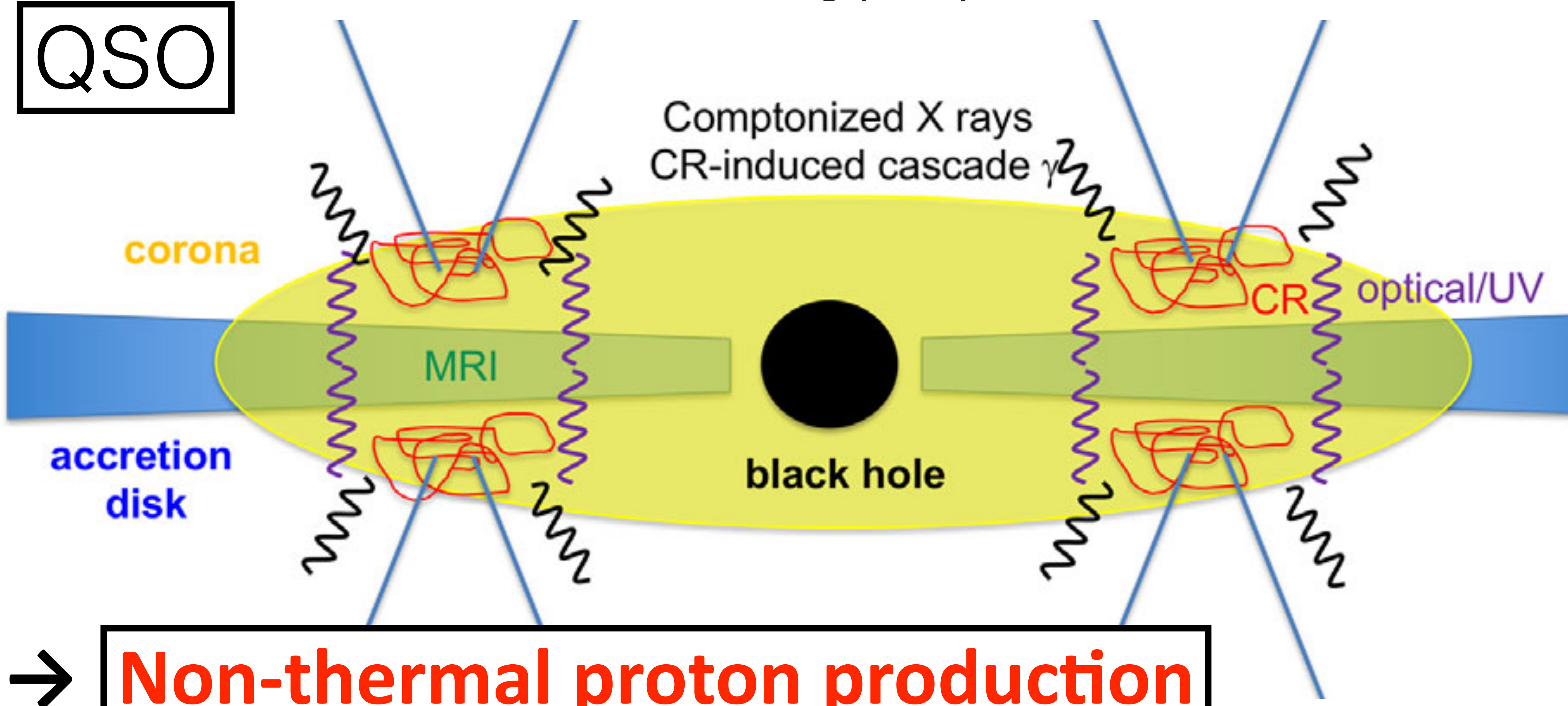
Let us discuss high-energy emission from accretion flows

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)





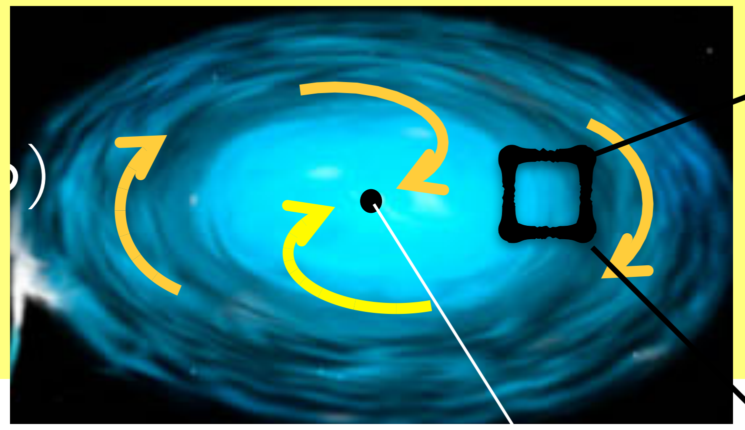


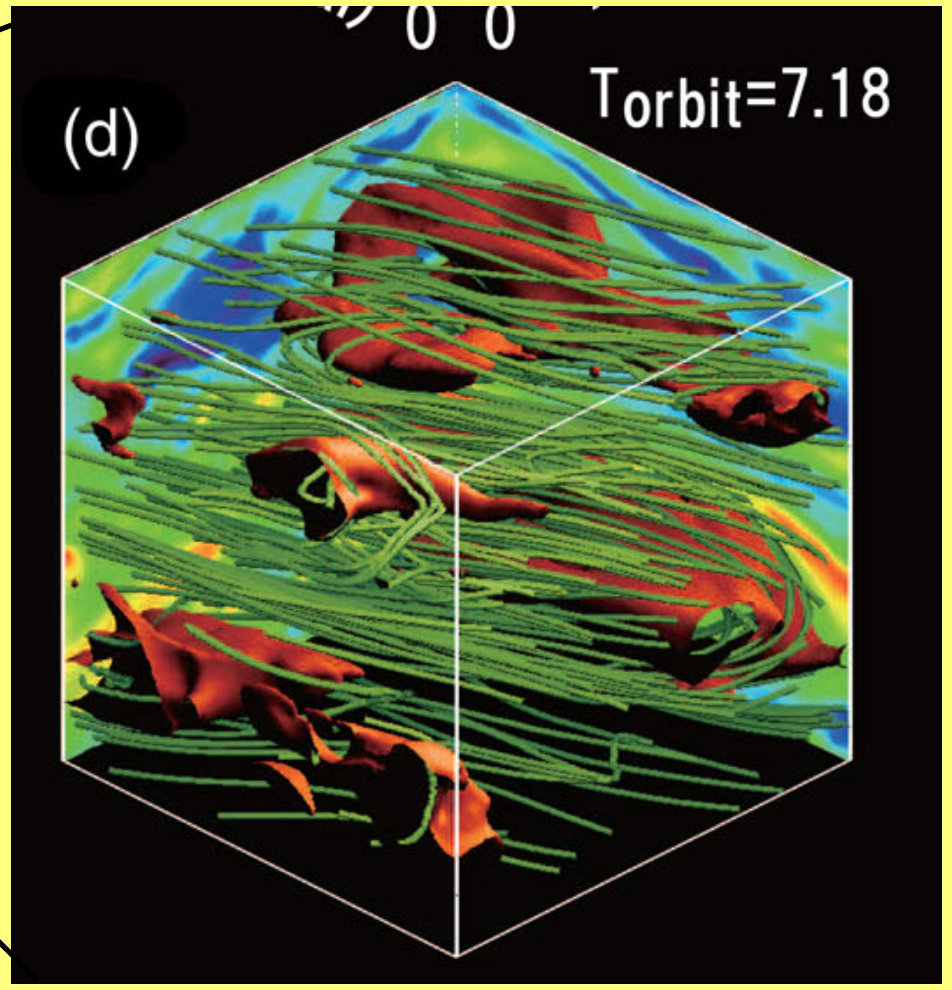
Protons in coronae & RIAFs are collisionless → Non-thermal proton production

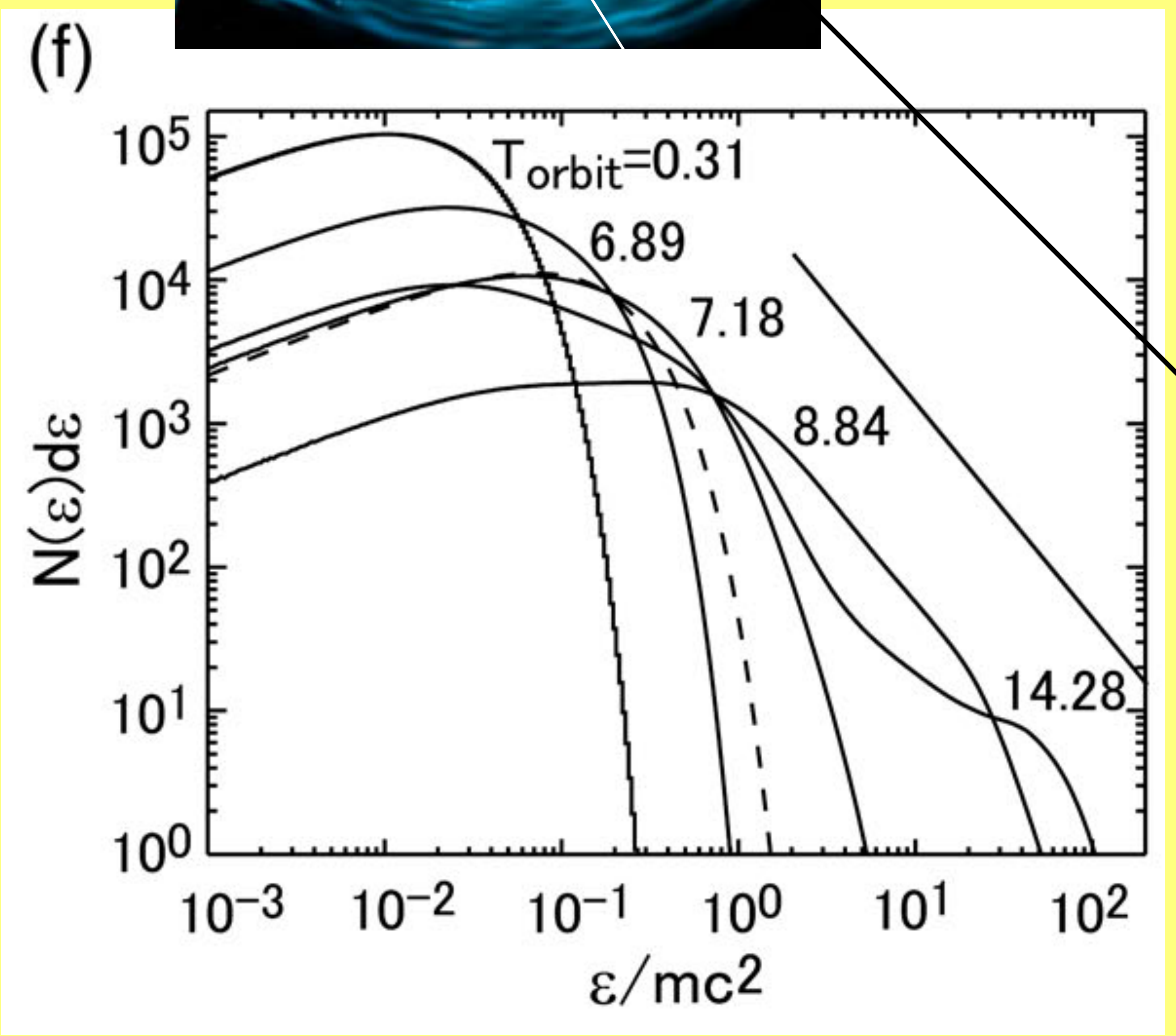
Particle Acceleration in Accretion Flows

Particle-In-Cell Simulations in shearing box

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





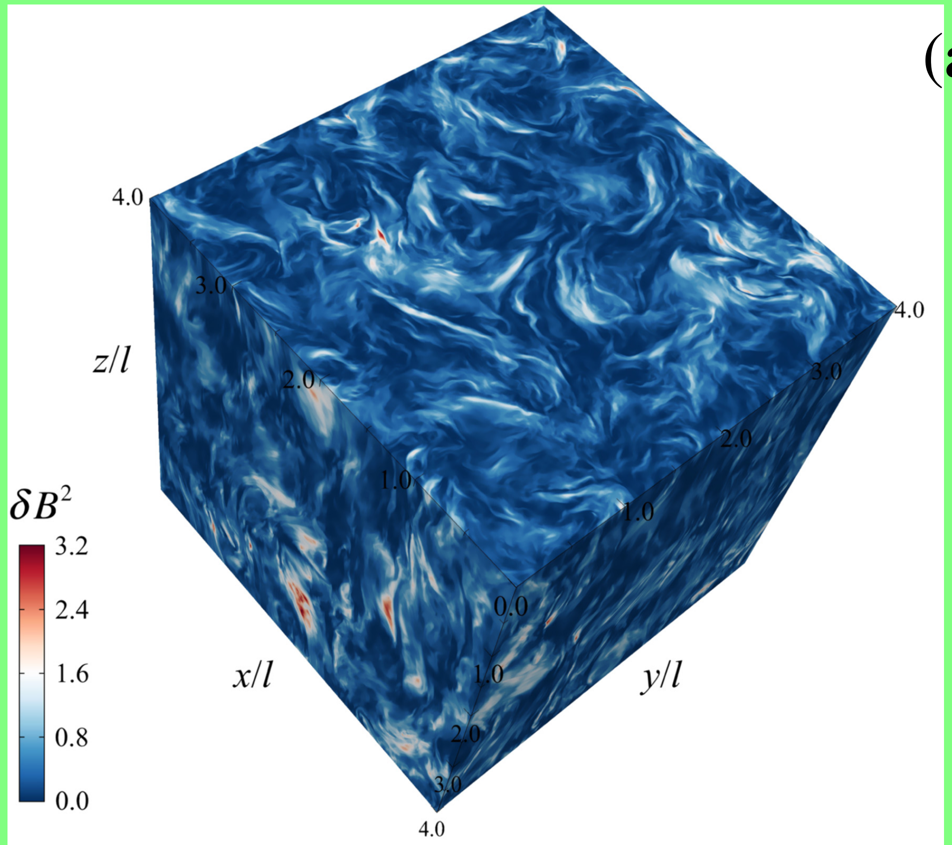


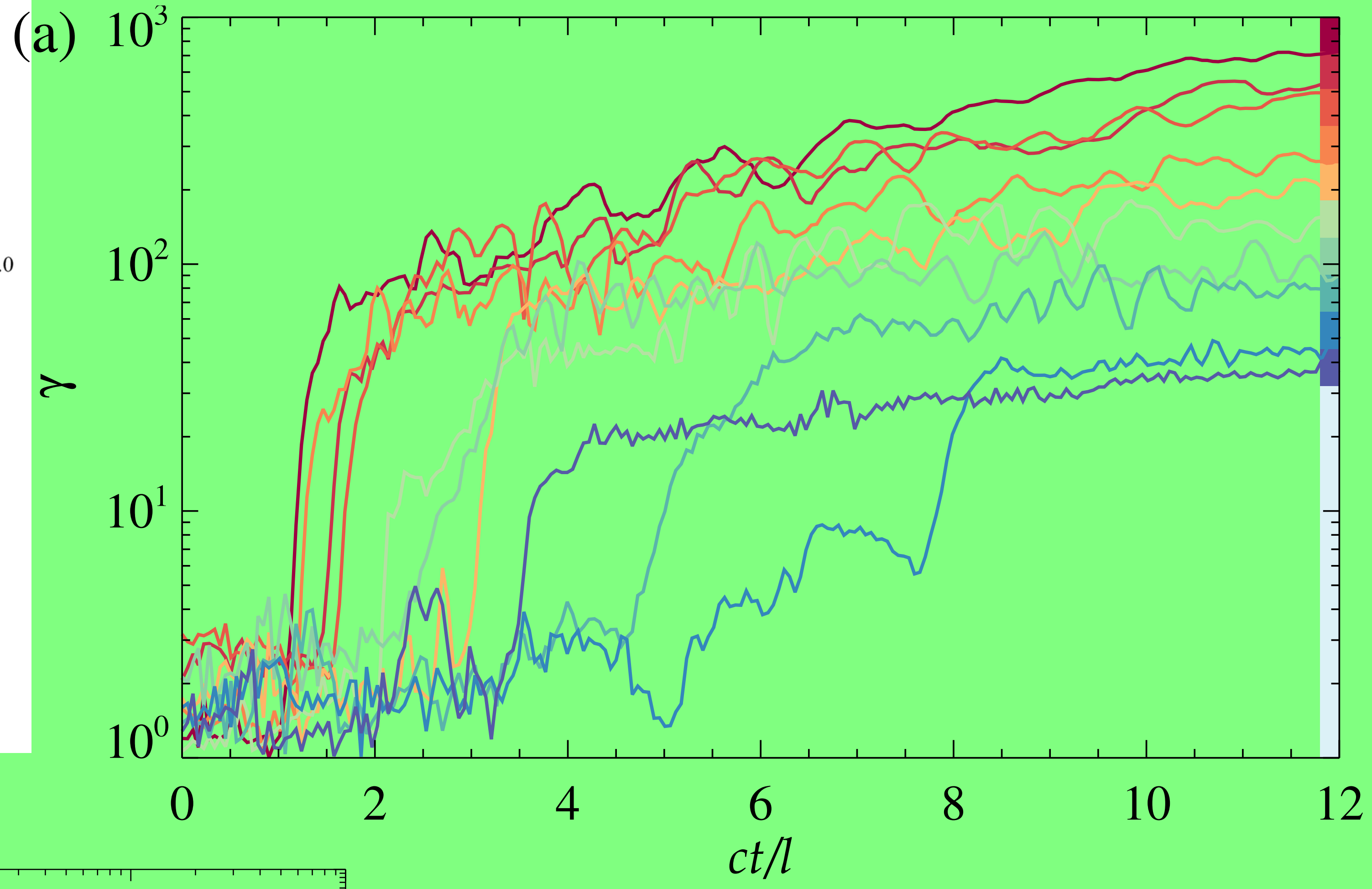
MRI turbulence

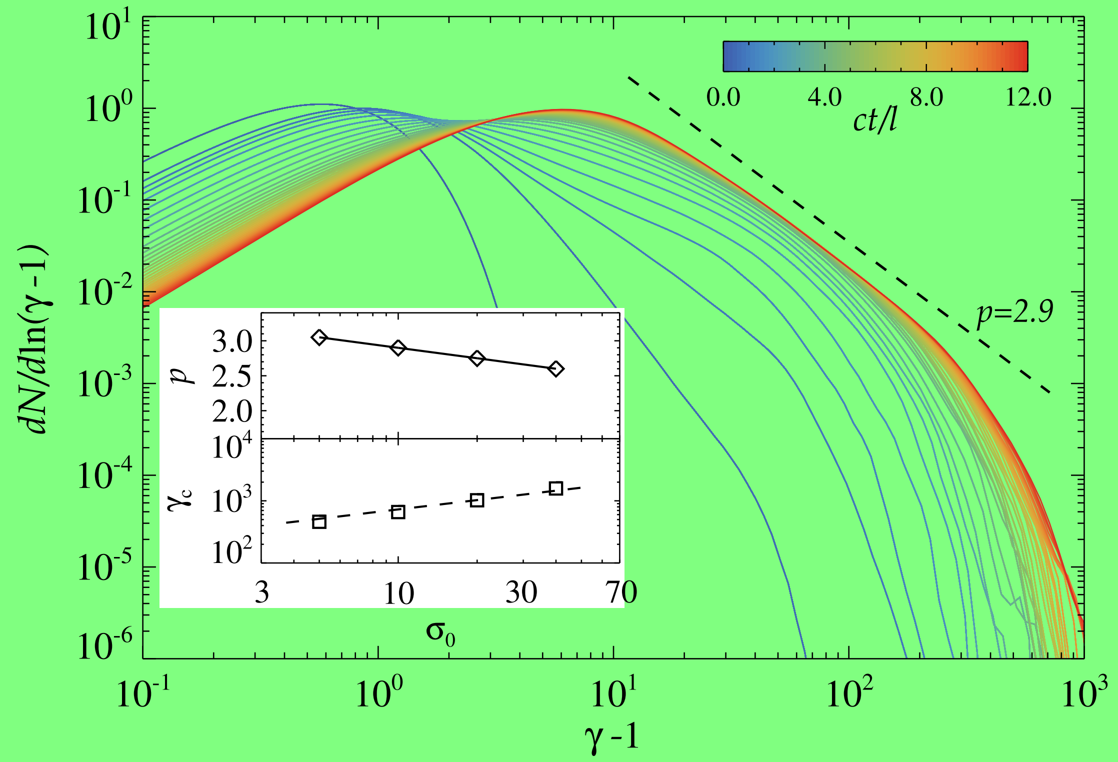
Non-thermal tail

Particle-In-Cell Simulations with turbulence

Comisso & Sironi 2018, 2019; Zhdankin et al. 2018







Stochastic acceleration

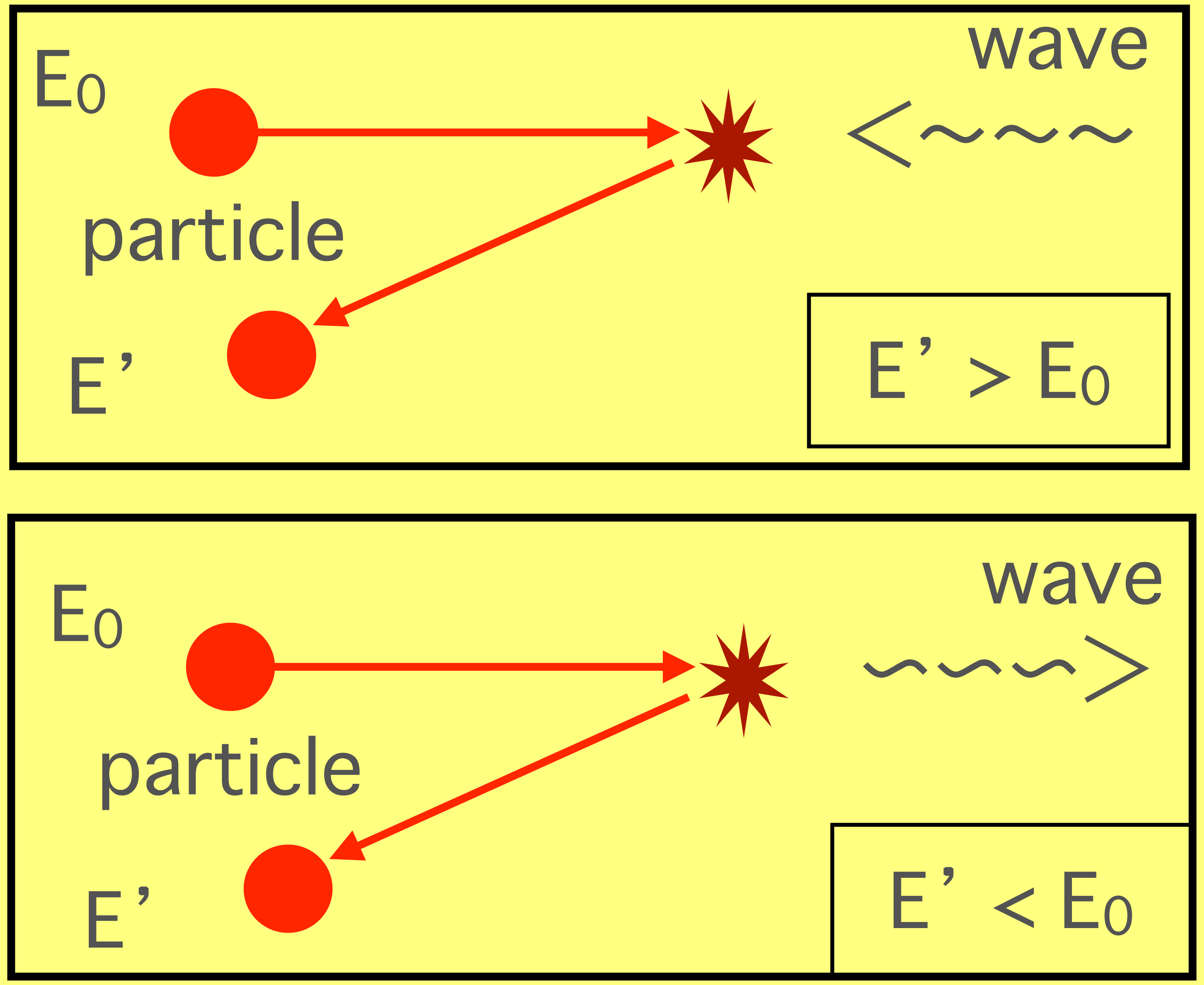
Power-law tail

Magnetic reconnection → relativistic particle production
Interaction with Turbulence → further energization

Stochastic Acceleration by MHD Turbulence

CR Acceleration Theory

e.g.) Fermi 1949



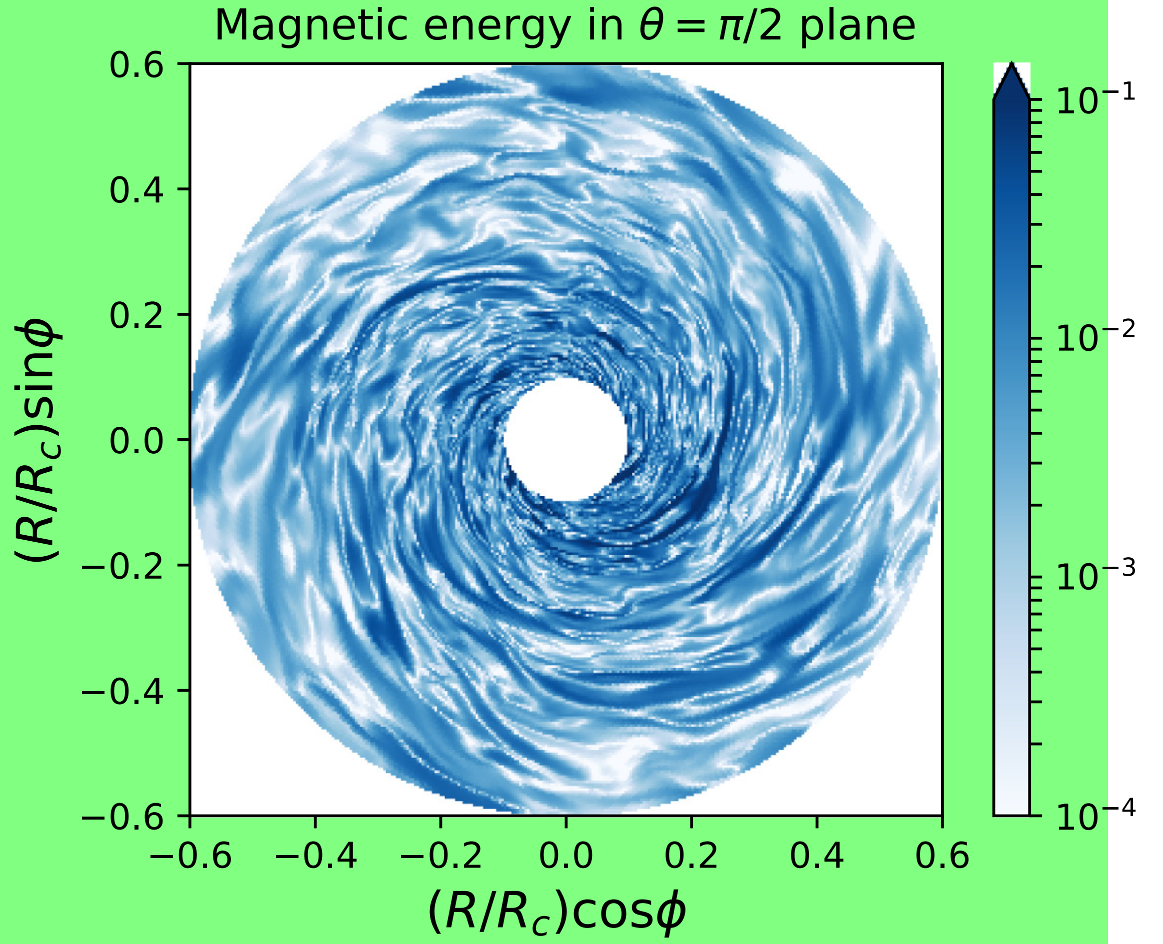
Some gain E, others lose E
→diffusion in E space

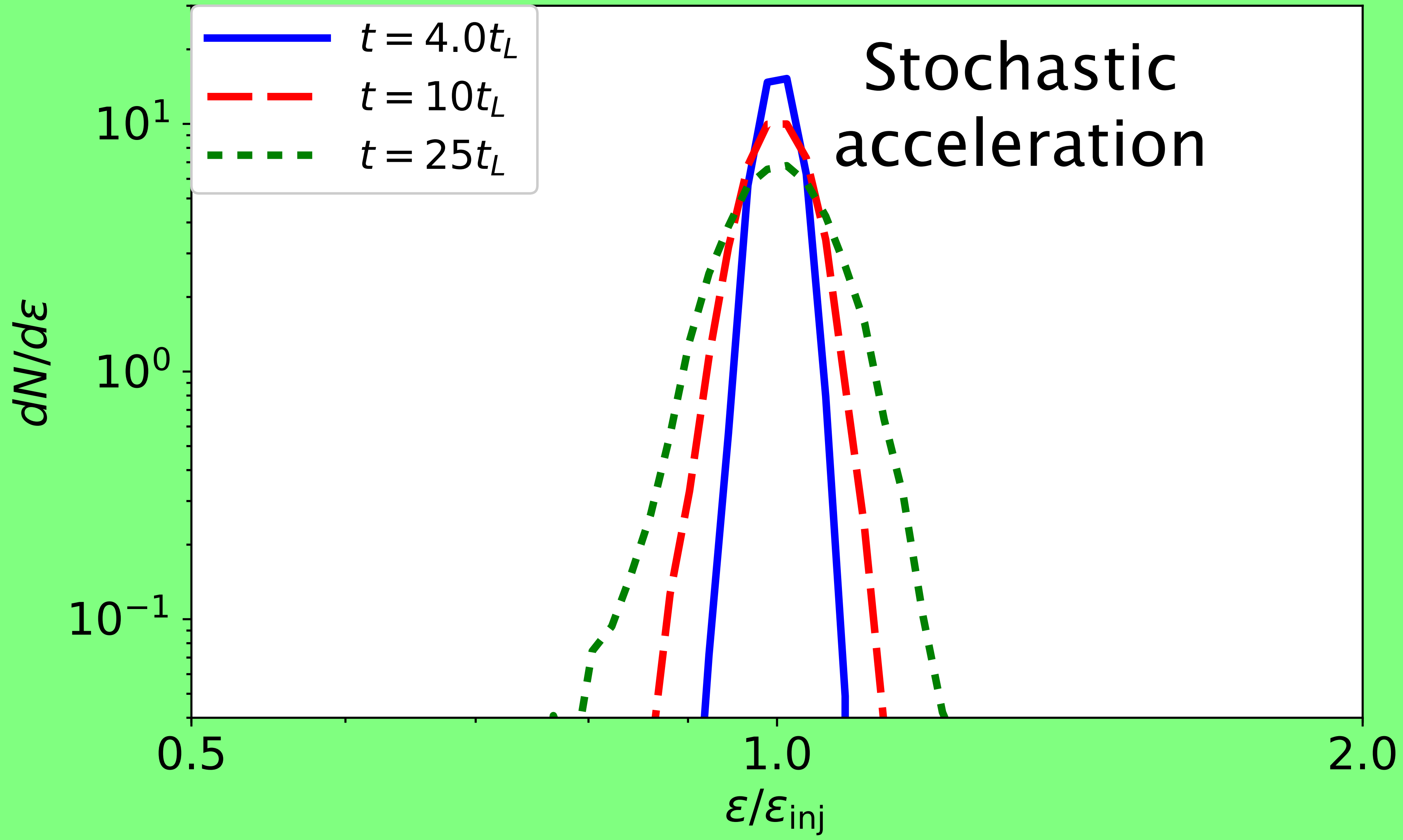
$$\frac{\partial F_p}{\partial t} = \frac{1}{E^2}\frac{\partial}{\partial E}\left(E^2 D_E \frac{\partial F_p}{\partial E}\right)$$

MHD + Test Particle Simulations

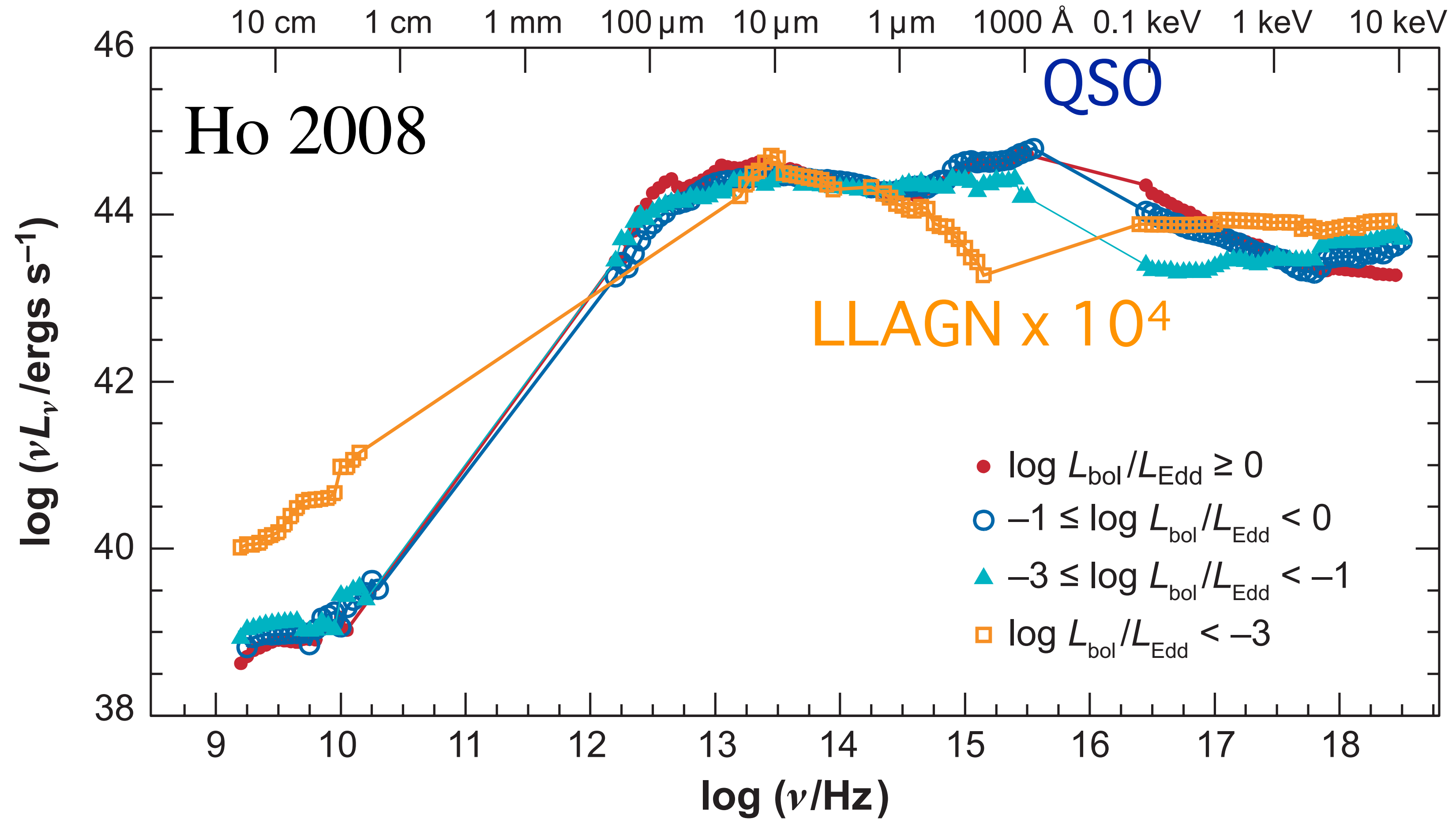
SSK+ 2016 ApJ, 2019 MNRAS; Sun & Bai 2021

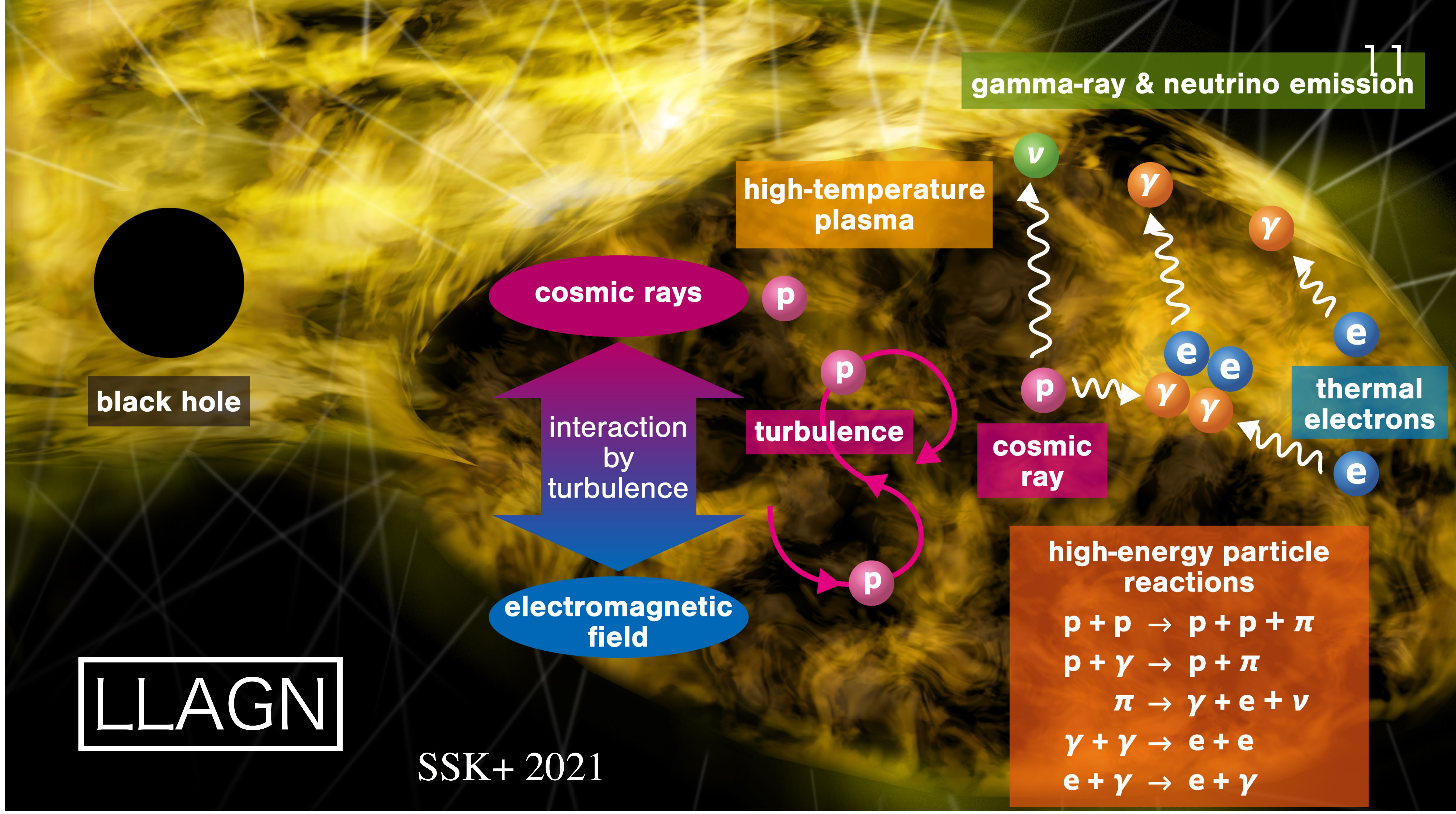
MRI turbulence

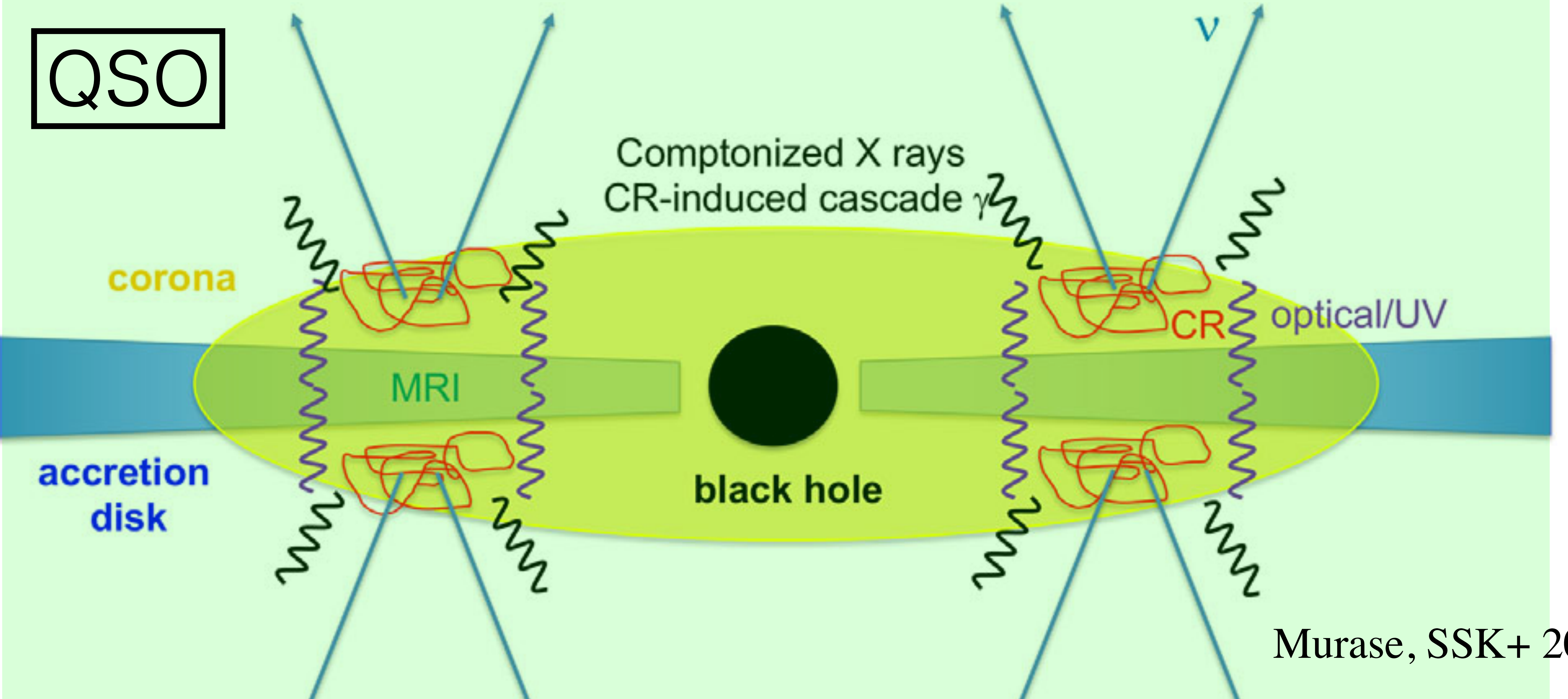




Schematic Picture



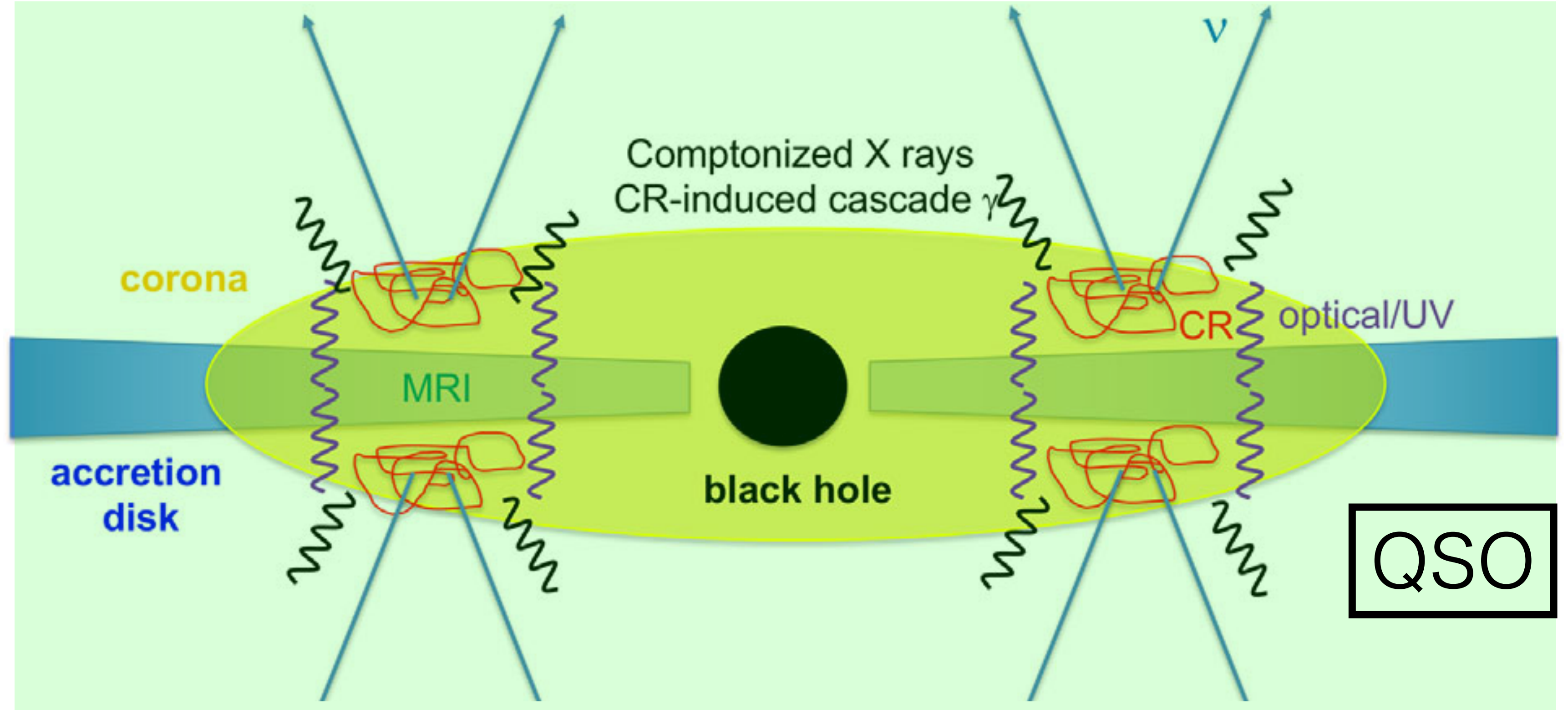


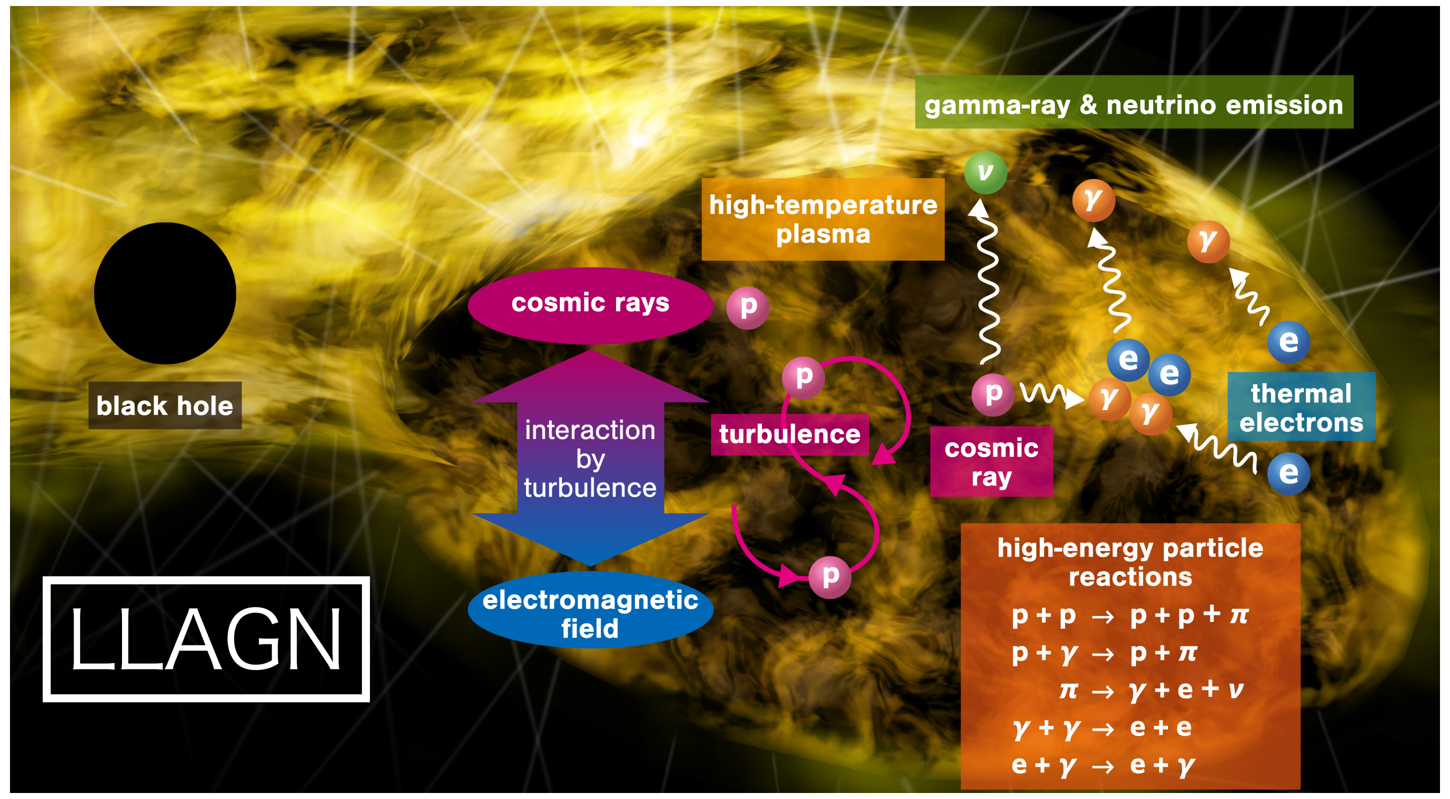


Murase, SSK+ 2020

- Separately model QSO & LLAGN
- Stochastic acceleration by MHD turbulence
- EM cascades taken into account

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 (EM cascades)

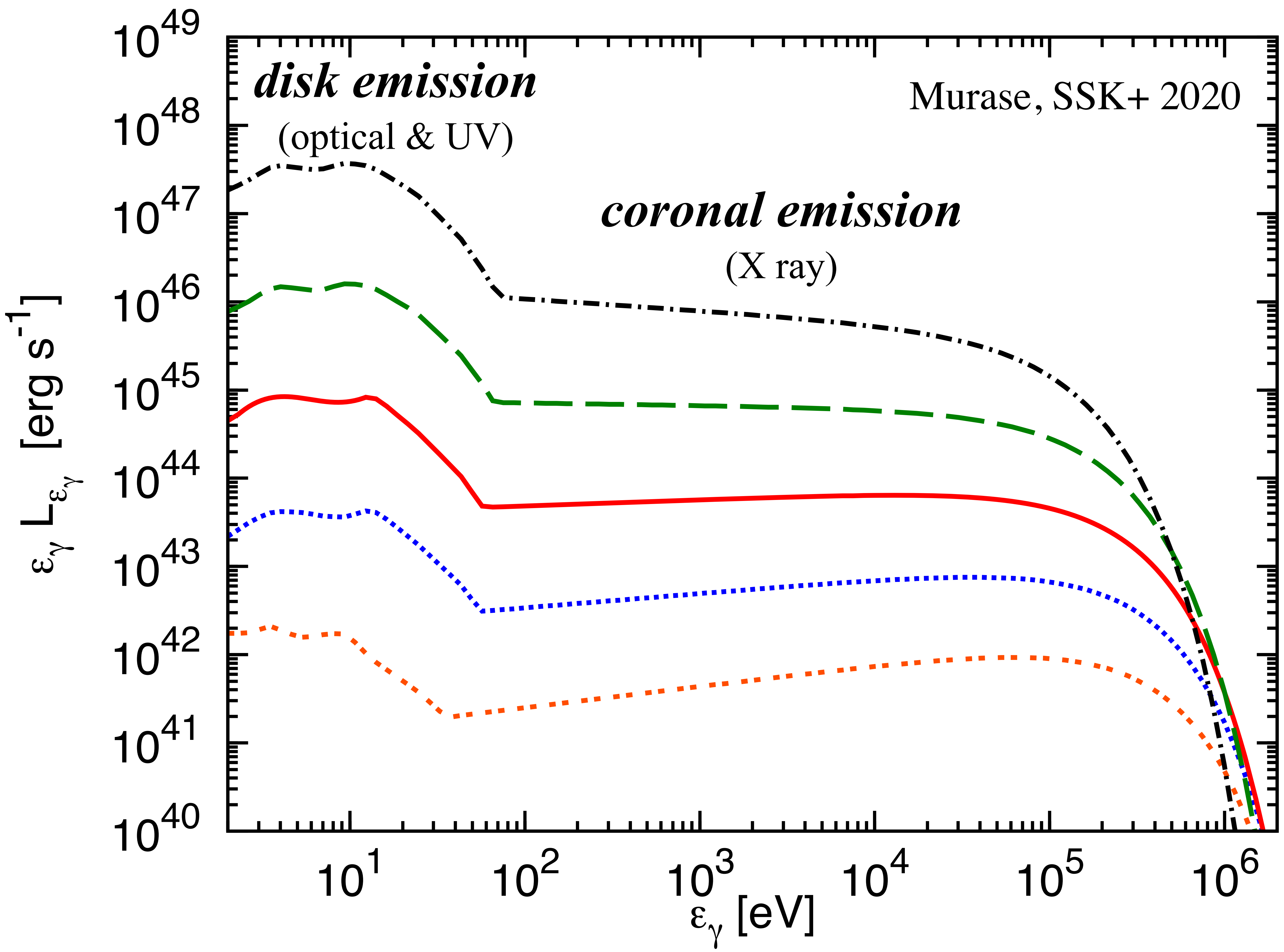
$$\frac{\partial n^\gamma_{\varepsilon_\gamma}}{\partial t} = -\frac{n^\gamma_{\varepsilon_\gamma}}{t_{\gamma\gamma}} - \frac{n^\gamma_{\varepsilon_\gamma}}{t_{\mathrm{esc}}} + \dot{n}^{(\mathrm{IC})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{ff})}_{\varepsilon_\gamma} + \dot{n}^{(\mathrm{syn})}_{\varepsilon_\gamma}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

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

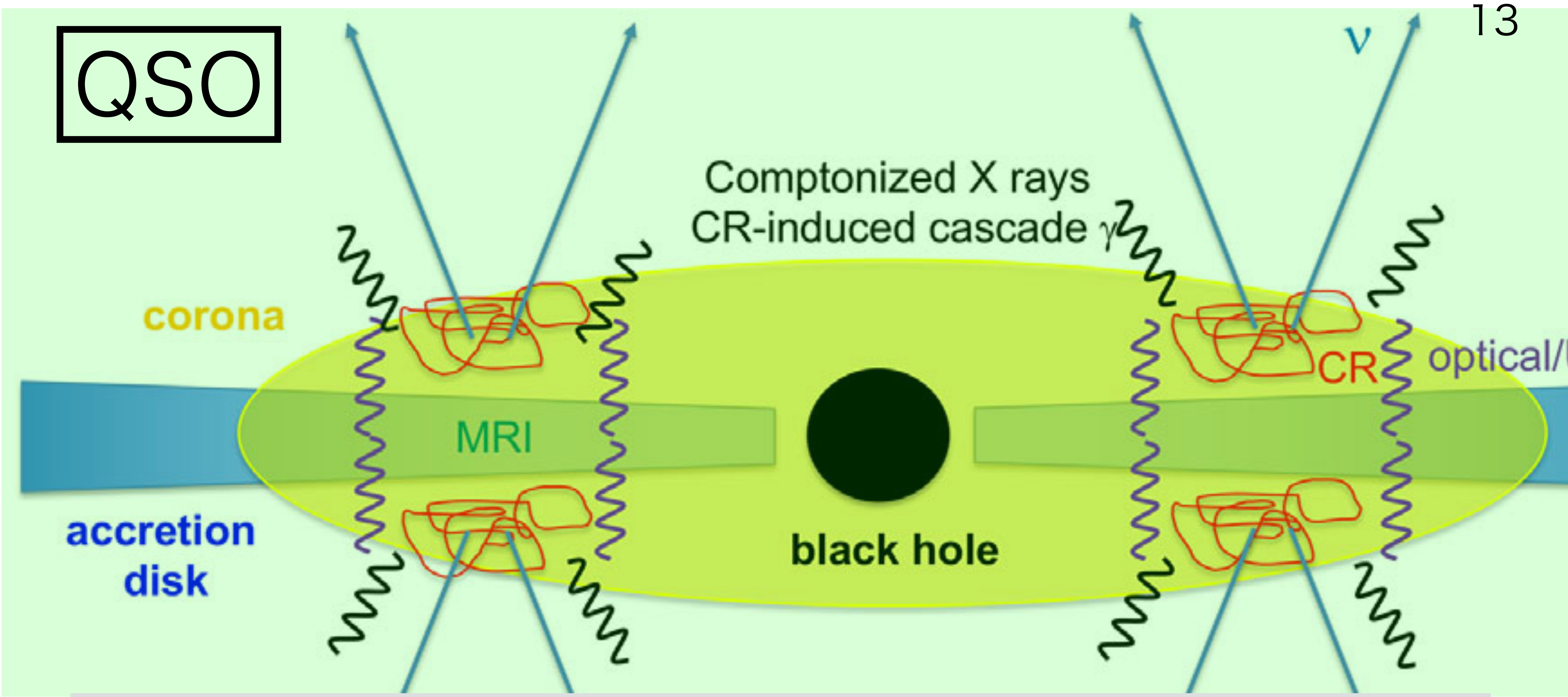
- Gyro-resonant wave-particle interactions in Kolmogorov-like MHD turbulence
- Escape : Diffusion & advection (to SMBH)
- Coolings:
  i) p+p —> p + p (n) + π
  ii) p+γ —> p (n) + π,
  iii) p+γ —> p + e^+ + e^-
  iv) proton synchrotron
- Muon & Pion decay before cooling
- γ+γ —> e+e- initiate EM cascade emission

SSK+ 2019; Murase, SSK+ 2020; SSK+ 2021

Target photons in QSO



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

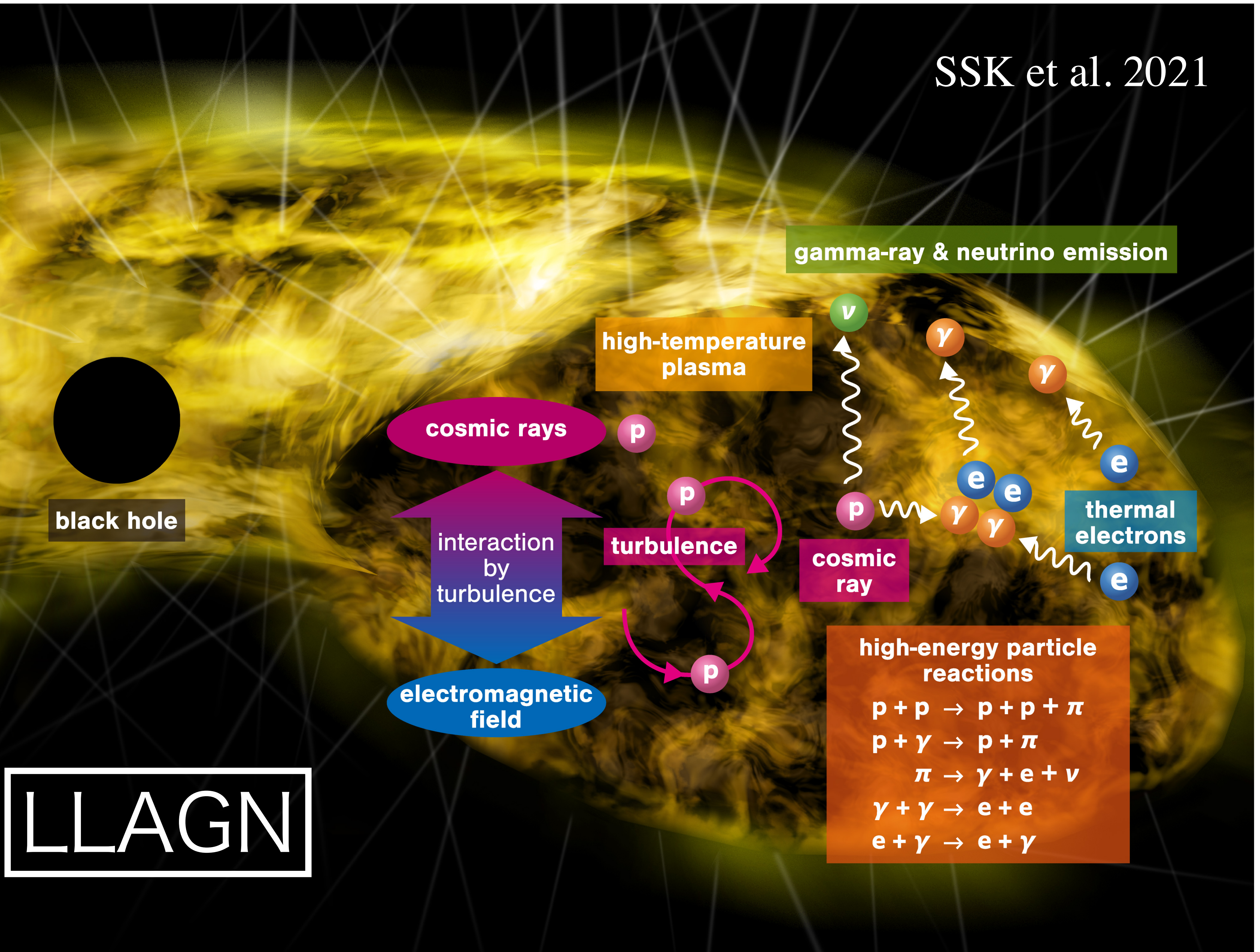


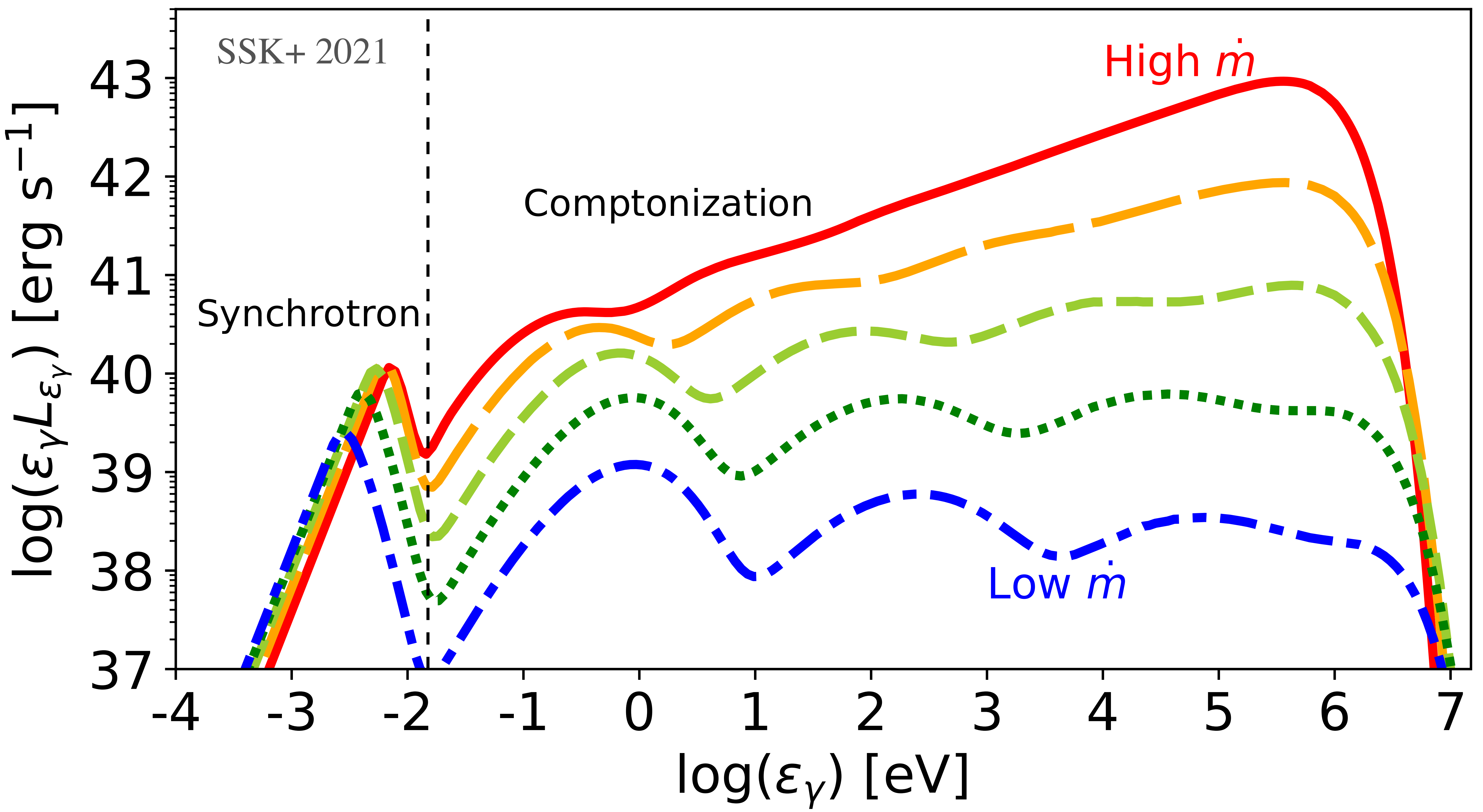
- Luminous objects
  → Rich observational data
  → **empirical relation based on observations**
- Opt-UV photons from accretion disk
- X-rays from hot coronae
- Higher L_{opt}/L_X for higher L_X AGNs
- Softer spectra for higher L_X AGNs

Target photons in LLAGN

See also SSK et al. 2015, 2019

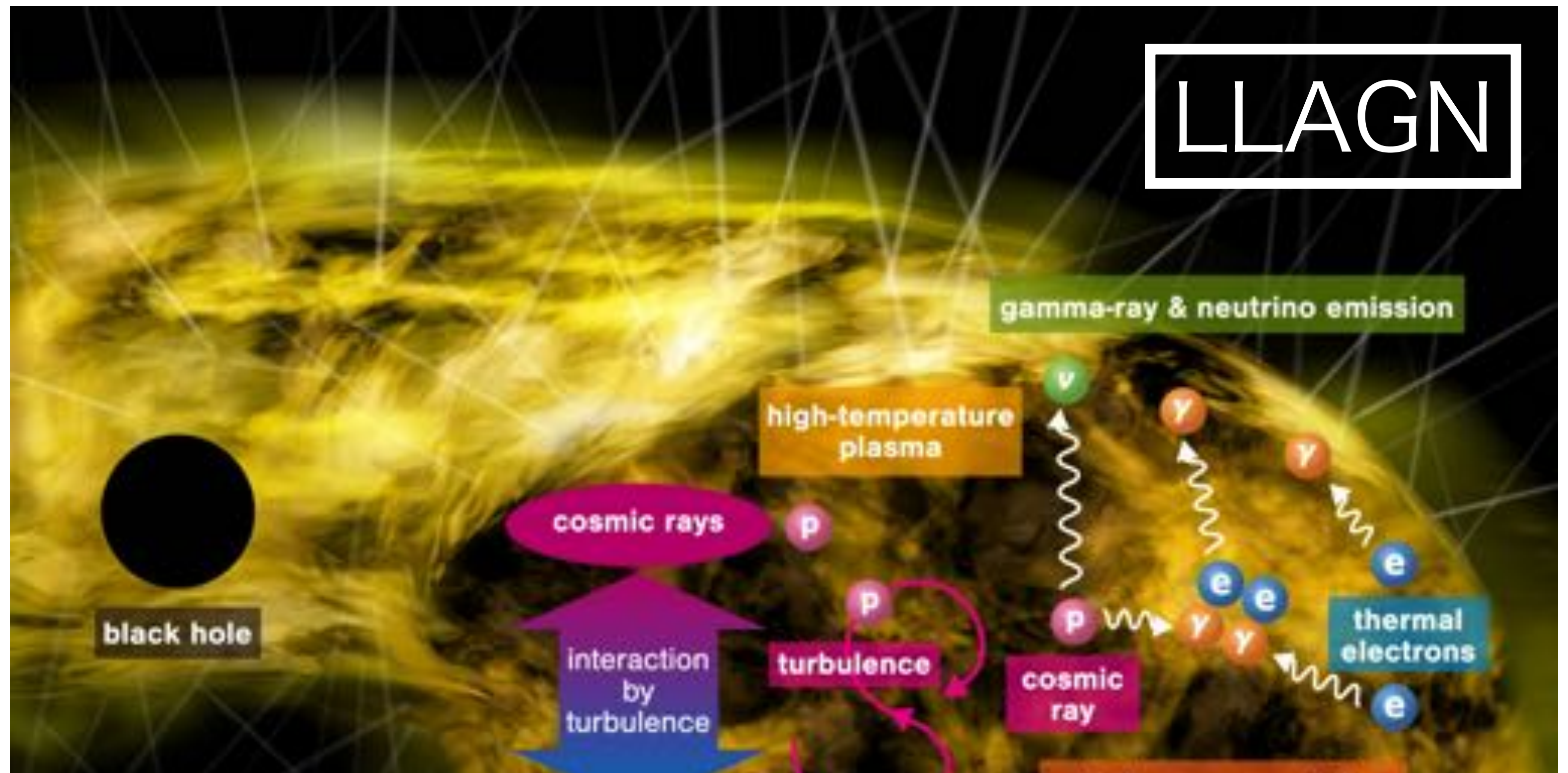
- Low-luminosity
  → Poor observational data
  → Formulation based on theory
- Thermal electrons in RIAFs emit photons through Synchrotron & Comptonization
- **Photon cutoff energy is always around MeV**

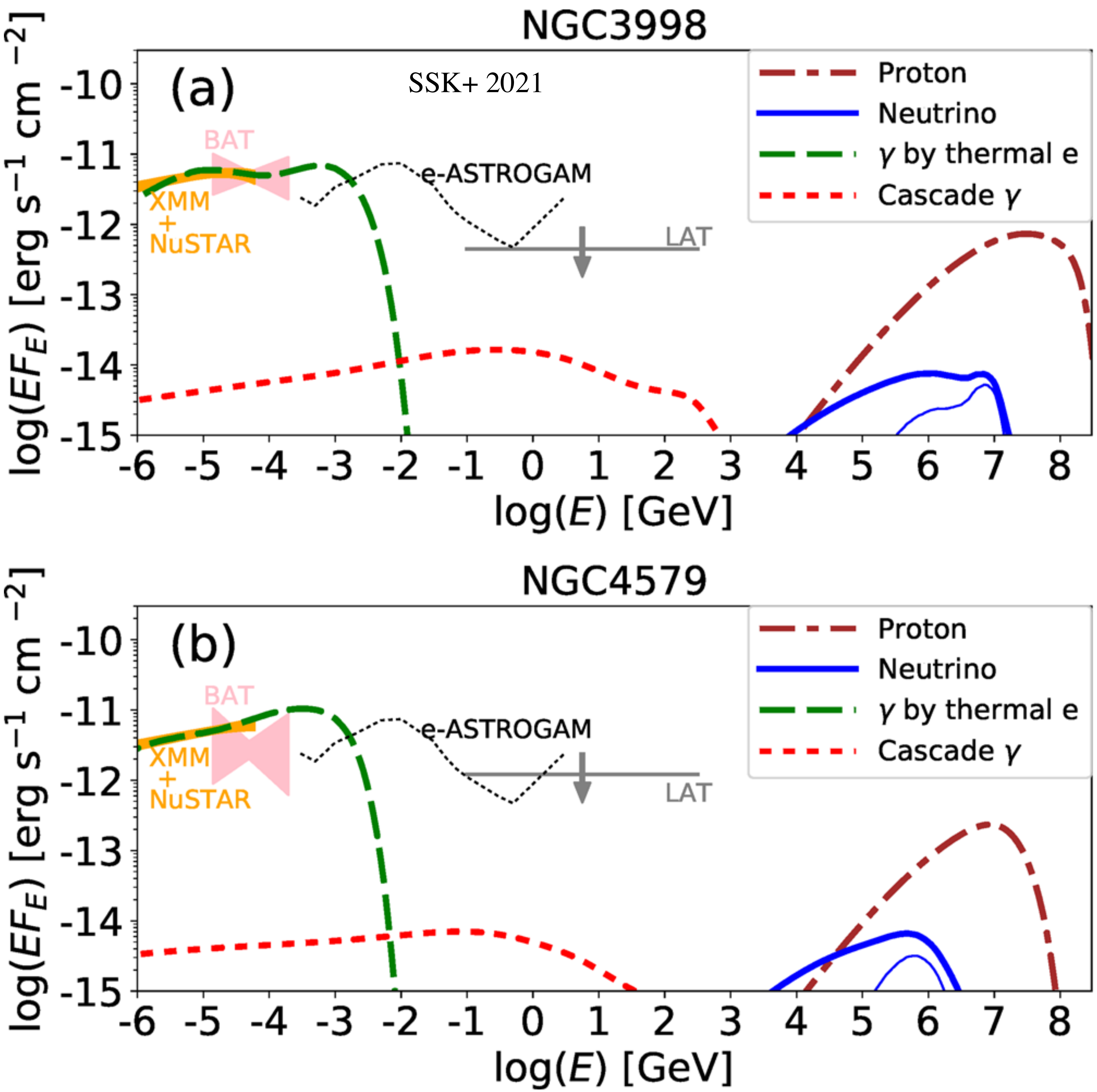




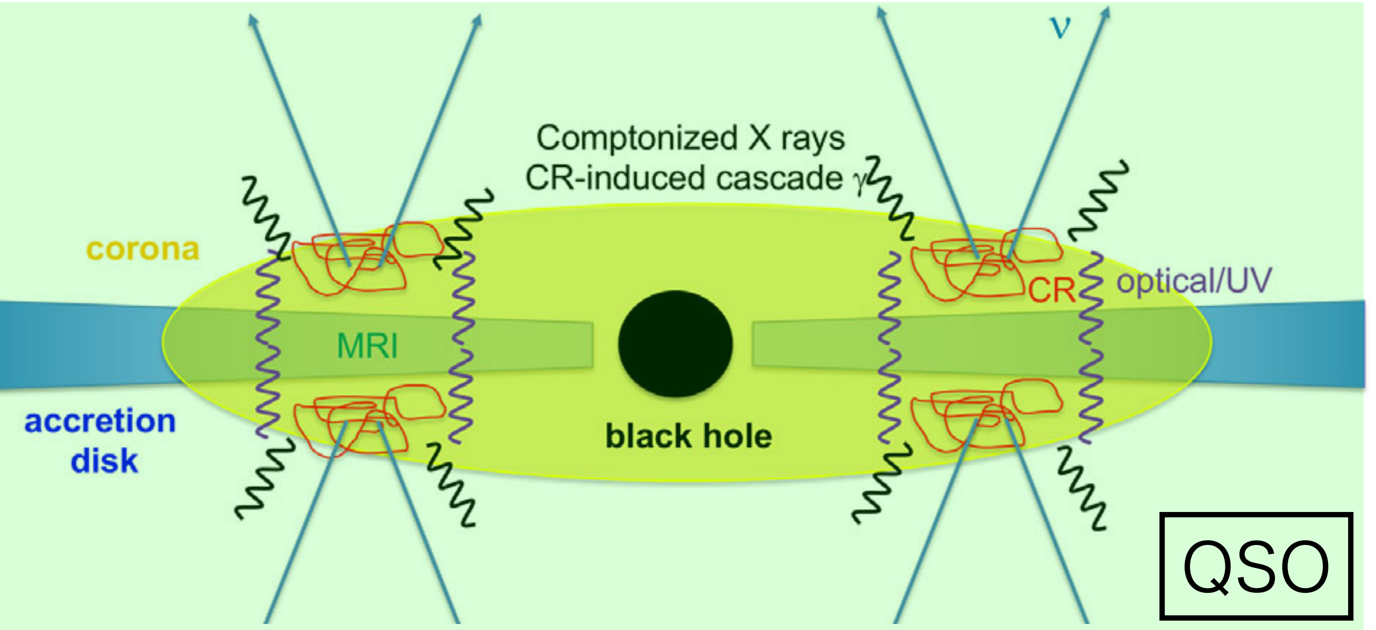
Multi-messenger SED for LLAGN

- Calibrating plasma parameters using X-ray data
- **Most of nearby bright LLAGNs should be detected by future MeV satellites**
- Hard proton CR spectra
- Neutrino energy: 0.1–10PeV

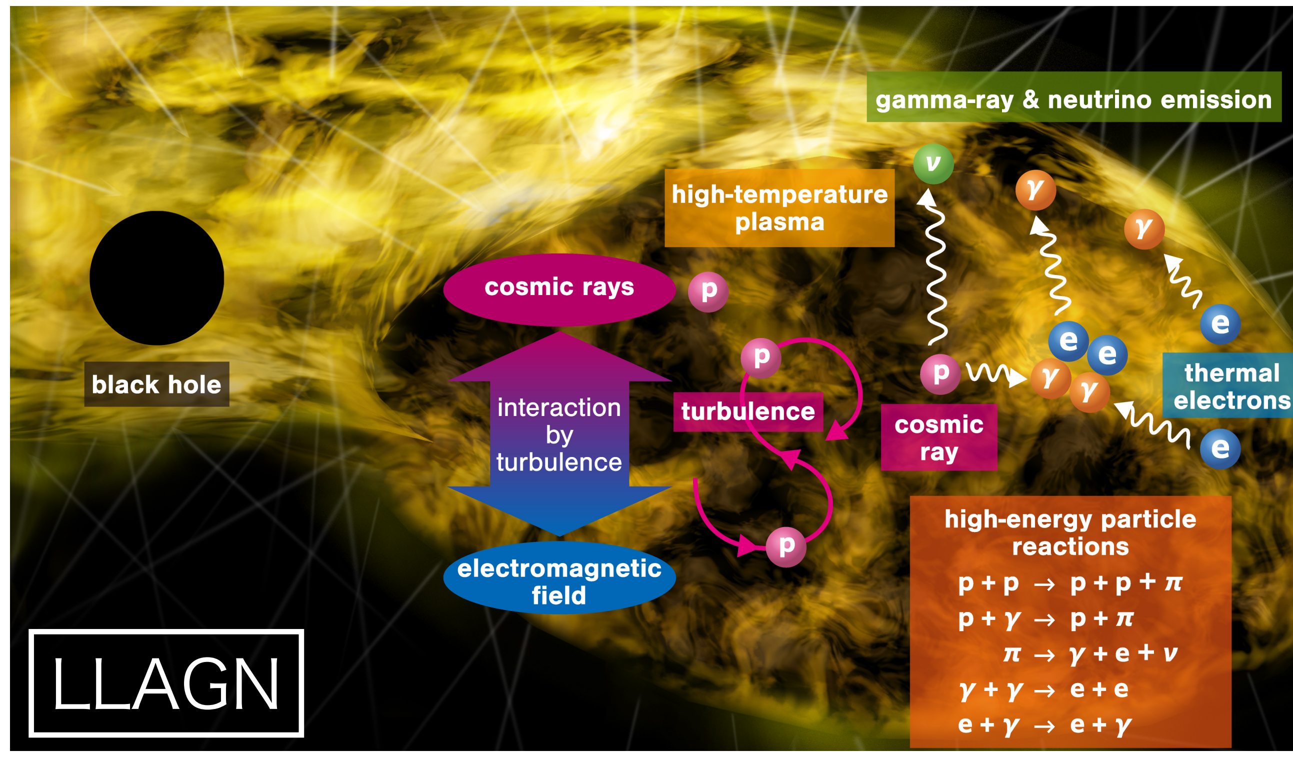


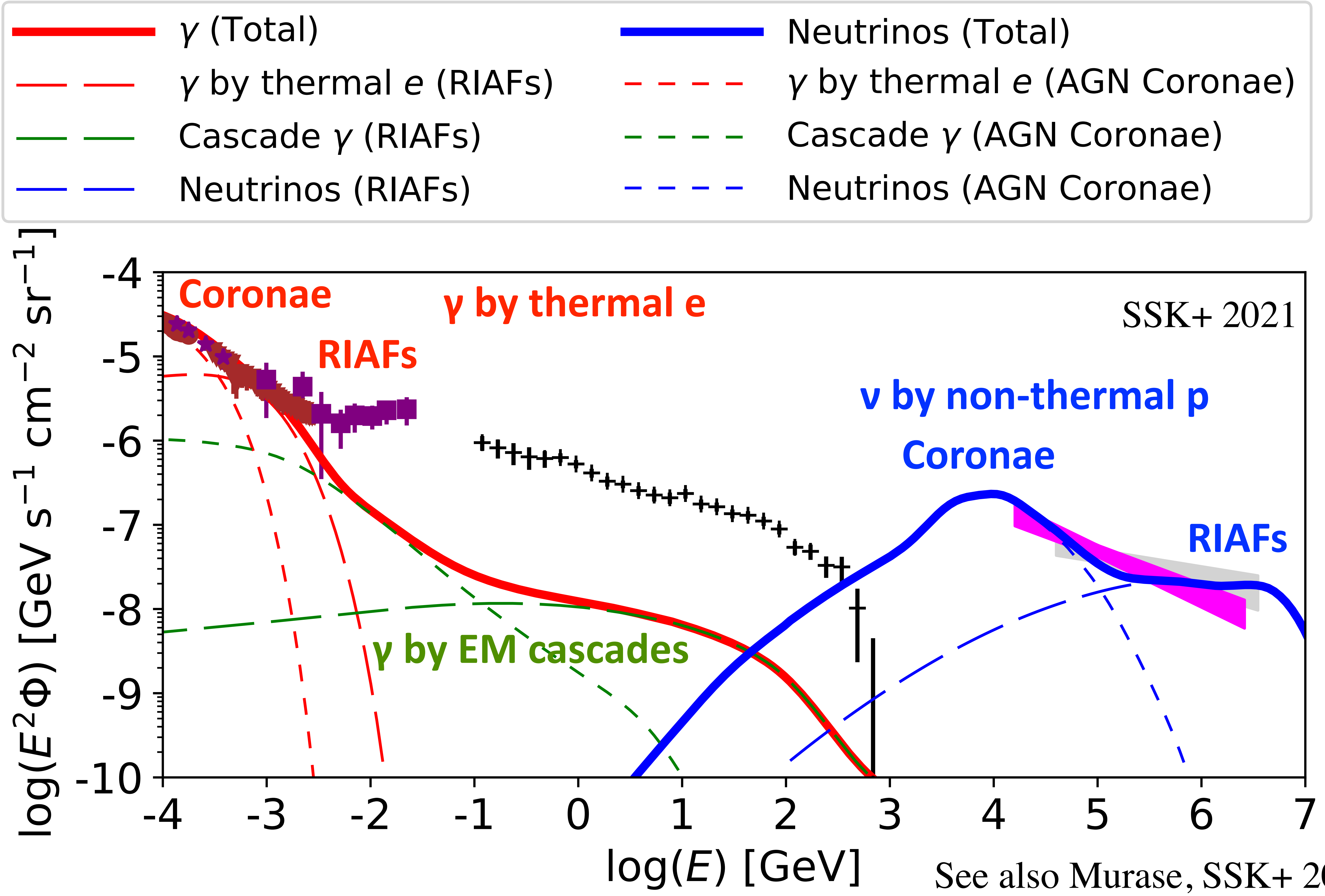


Cosmic High-energy Background from RQ AGNs



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





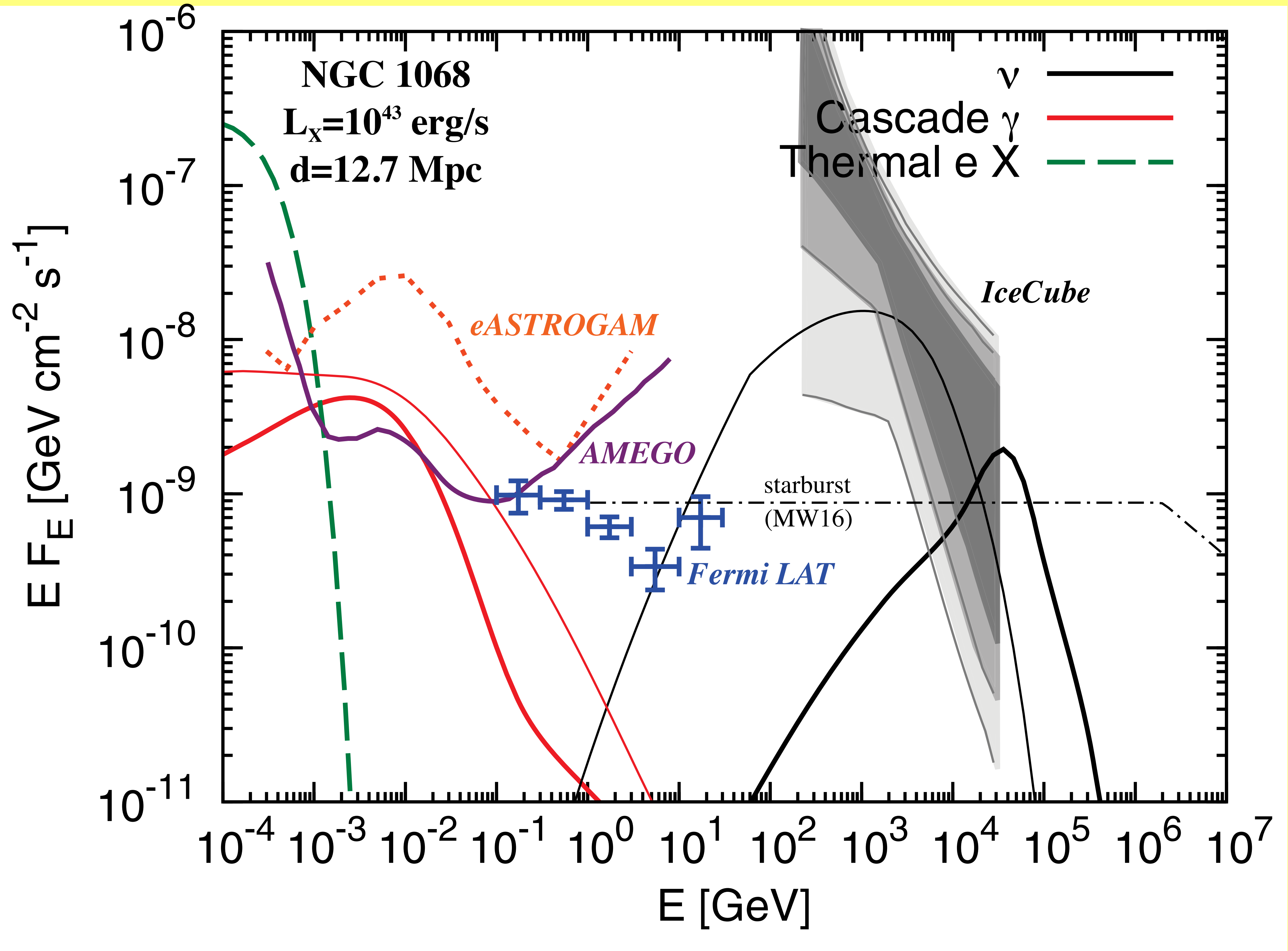
- QSO: X-ray & 10 TeV neutrinos
- LLAGN: MeV γ & PeV neutrinos
- Copious photons
  → efficient γγ —> e+e-
  → strong GeV γ attenuation
  → GeV flux below the Fermi data
- **AGN cores can account for keV-MeV γ & TeV-PeV ν background**

See also Murase, SSK+ 2020 PRL; SSK+ 2019, PRD; SSK+ 2015

HE particles from Nearby AGNs

- M77 (NGC 1068)

Murase, SSK+ 2020

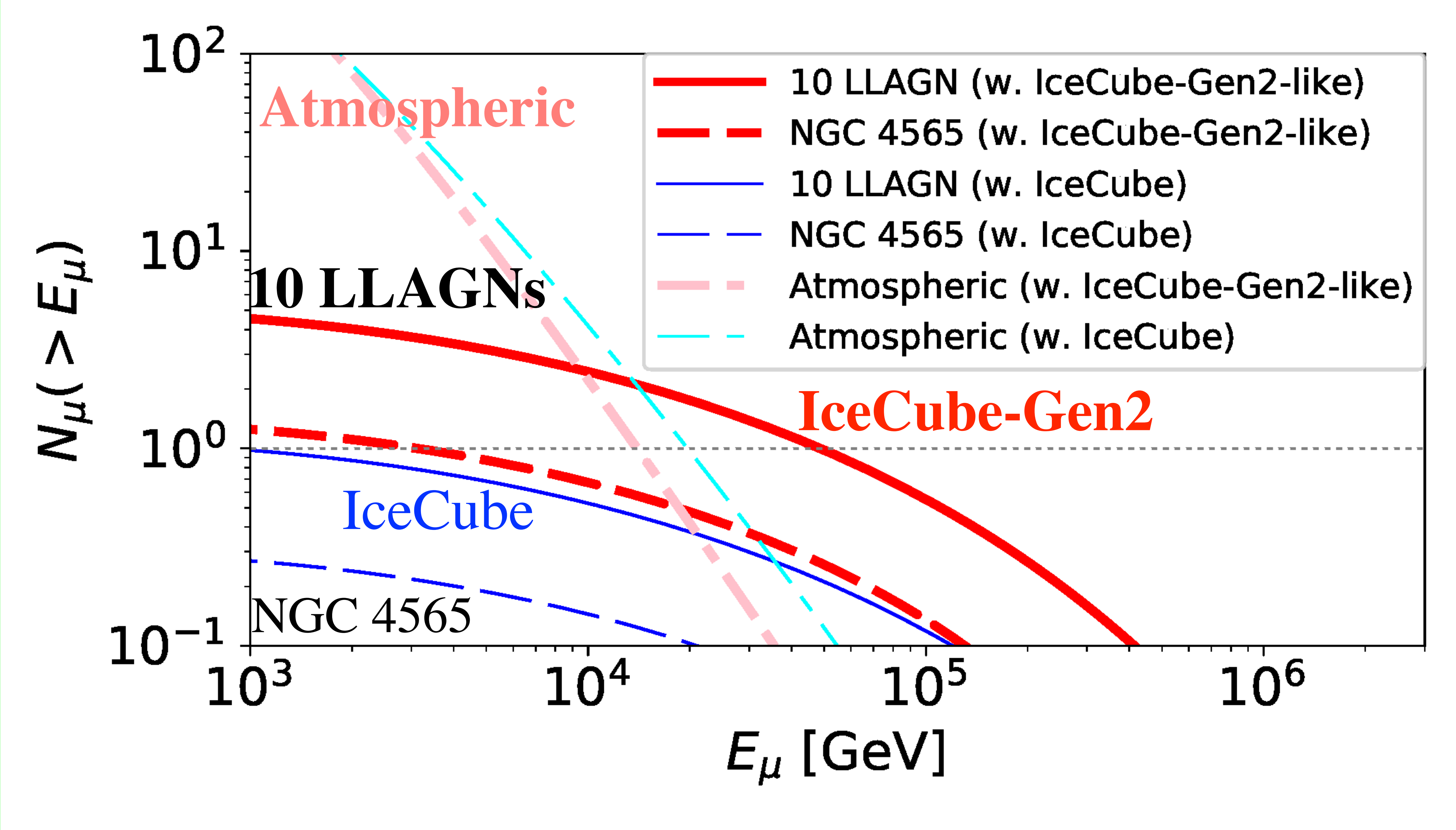


- Possible to explain IceCube data without overshooting γ-ray data
- γ to ν flux ratio is fixed by observed spectrum
  → robustly test model by future experiments

See also Kheirandish, Murase, SSK 2021

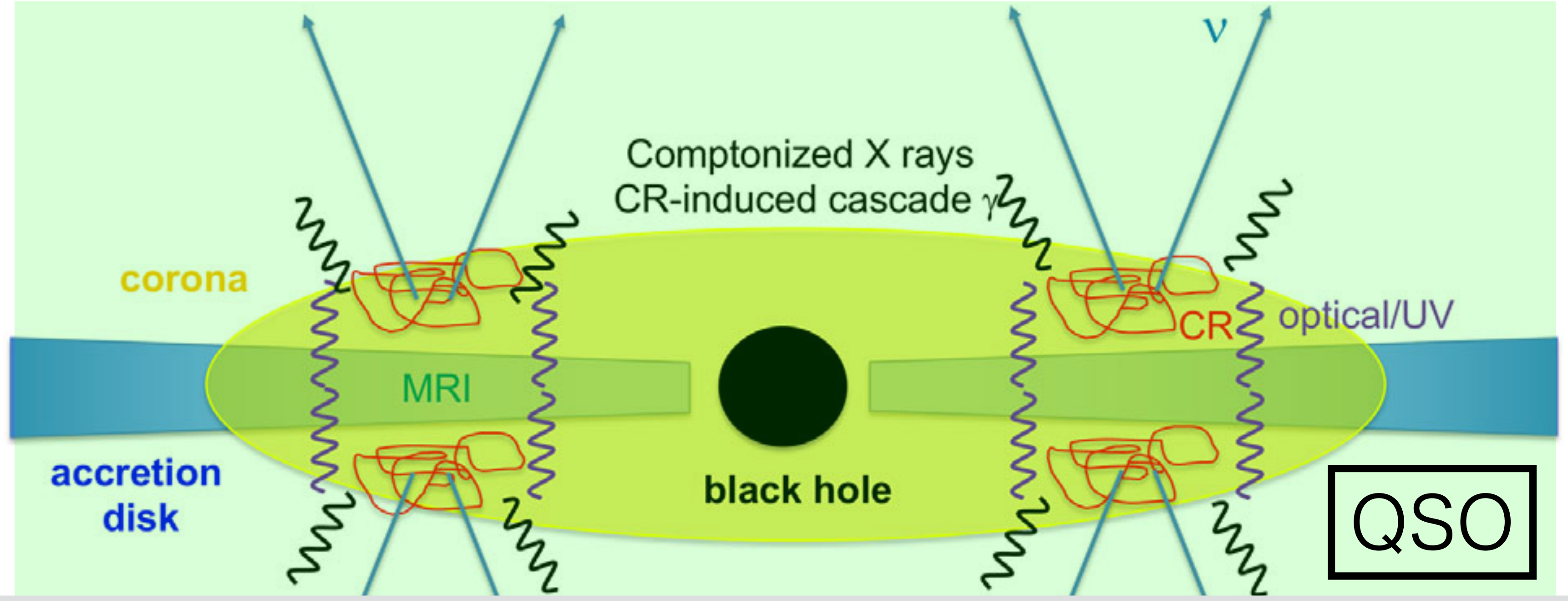
- Stacking nearby LL AGNs

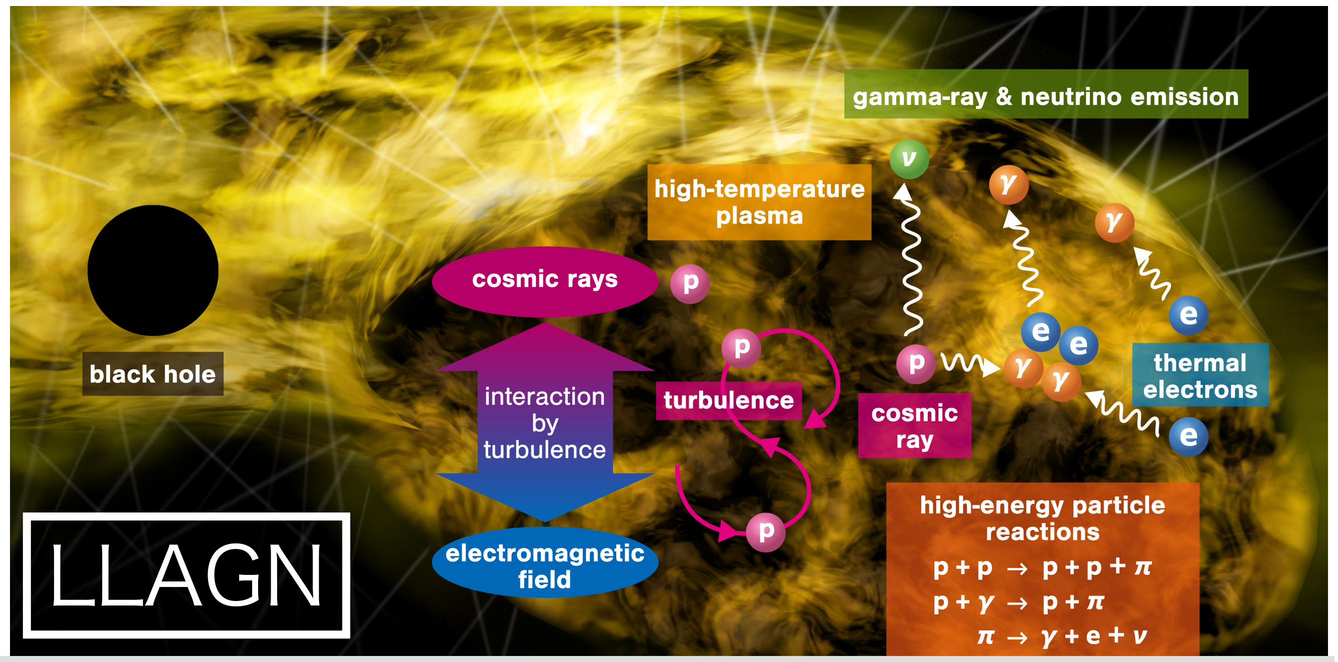
SSK et al. 2021



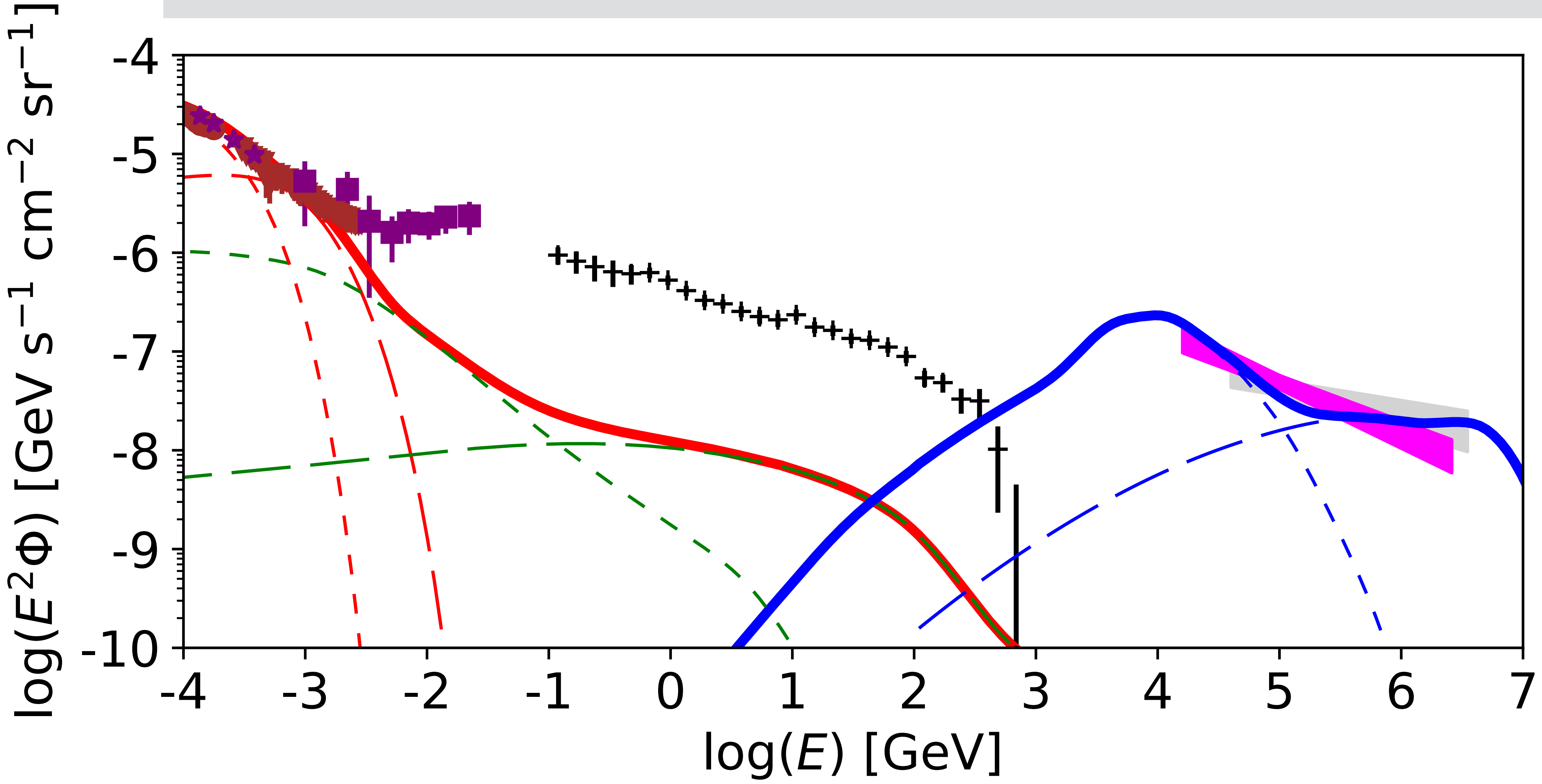
- IceCube **cannot detect any** neutrinos
- **IceCube-Gen2 will detect a few neutrinos above atmospheric background**

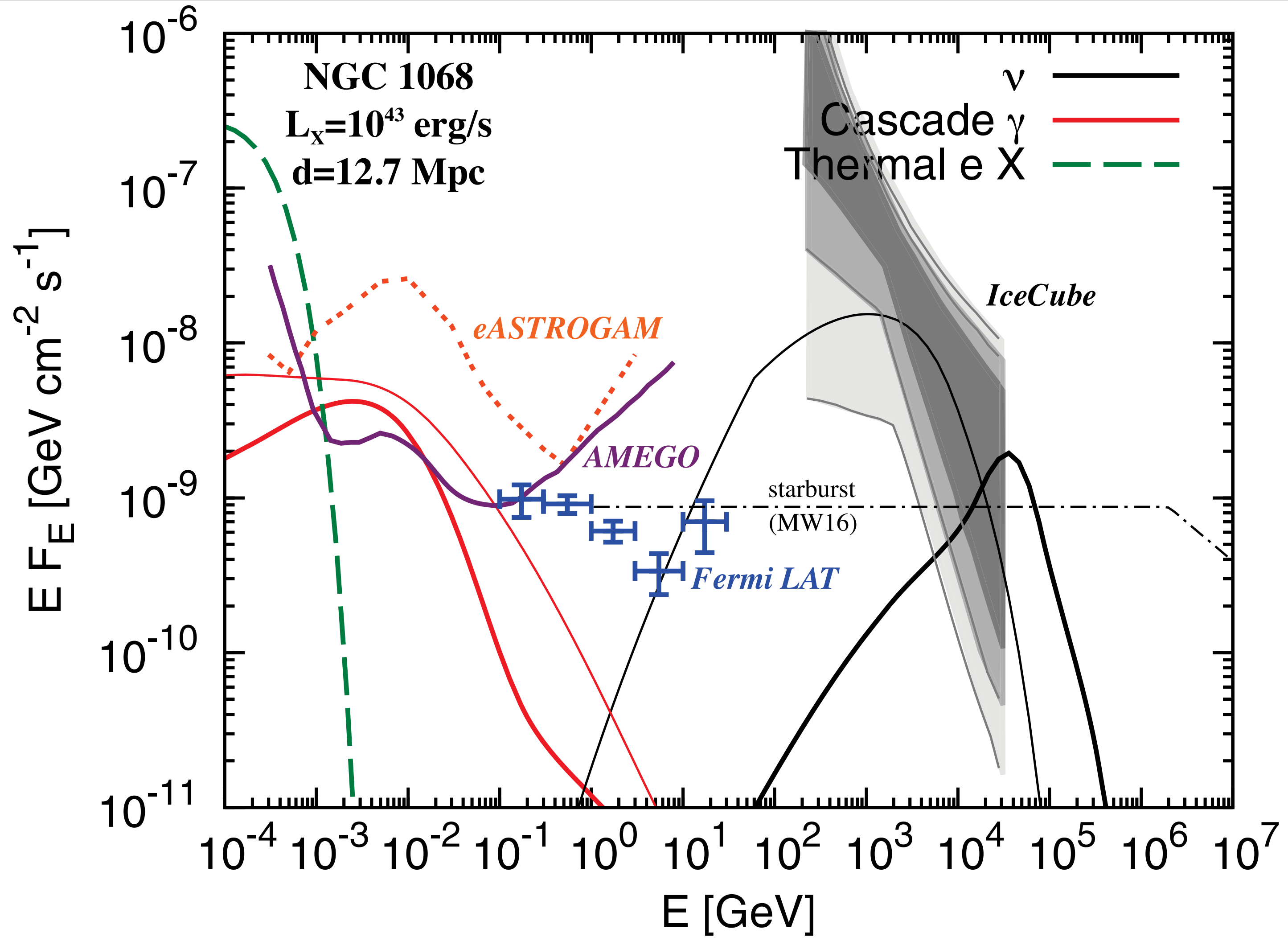
Summary

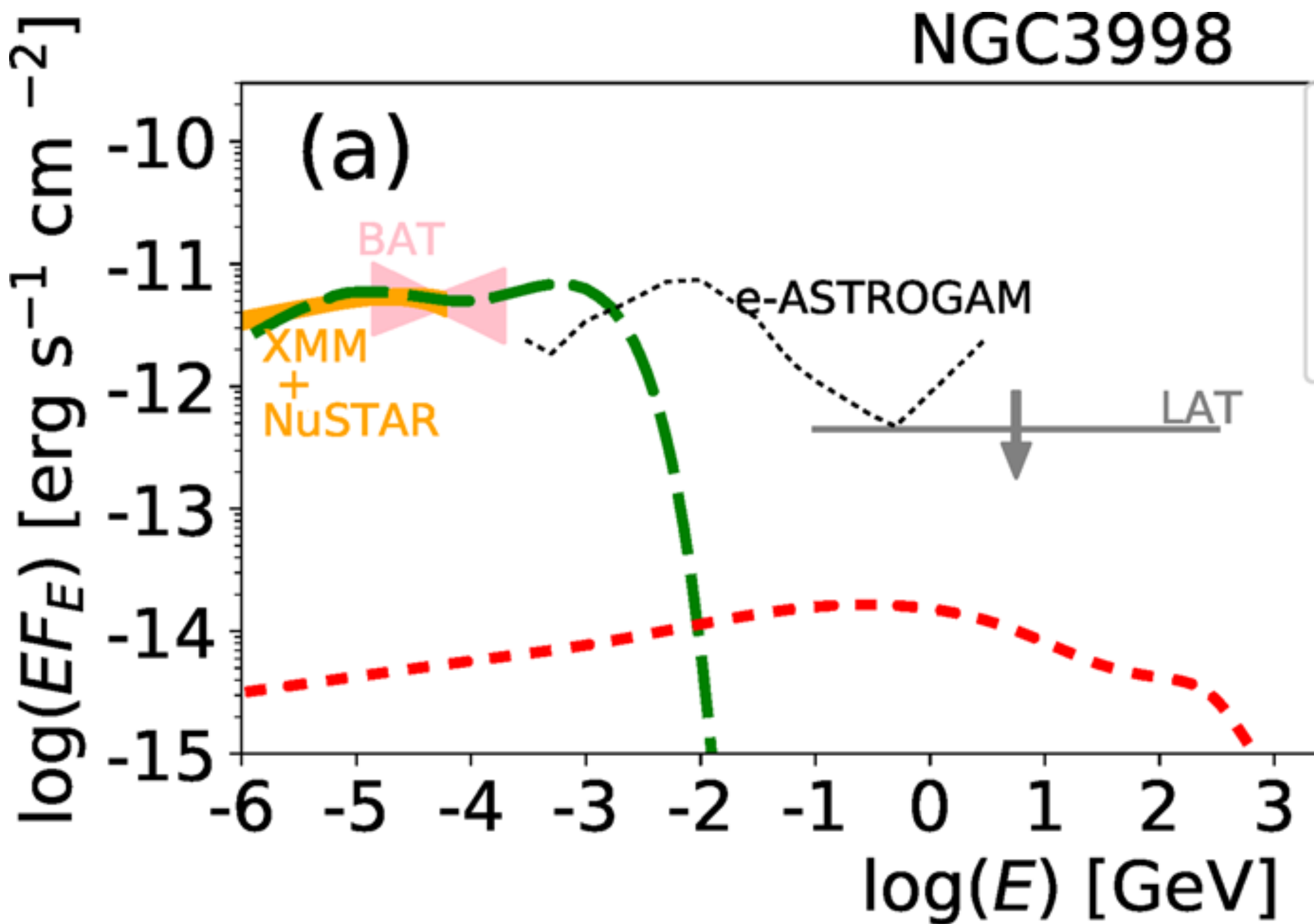




- Accretion flows in AGNs are feasible neutrino & gamma-ray sources
  - Coronae in Seyfert galaxies can reproduce X-ray & 10-100 TeV ν backgrounds
  - RIAFs in LLAGNs can explain MeV γ & PeV ν backgrounds
- **Combining these two, AGN accretion flows can explain keV-MeV photons & TeV-PeV neutrino backgrounds**
- Future multi-messenger observations can robustly test our models







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