Hadronic Gamma Rays from the Hot Accretion Flow in M87

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References
SSK, Toma in preparation

see also:
SSK, Murase, Toma, 2015, ApJ, 806, 159
SSK, Murase, Meszaros in preparation
SSK, Toma, Suzuki, Inutsuka, 2016, ApJ, 822, 88
SSK, Tomida, Murase, 2019, MNRAS, 485, 163

Collaborators
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Tohoku University

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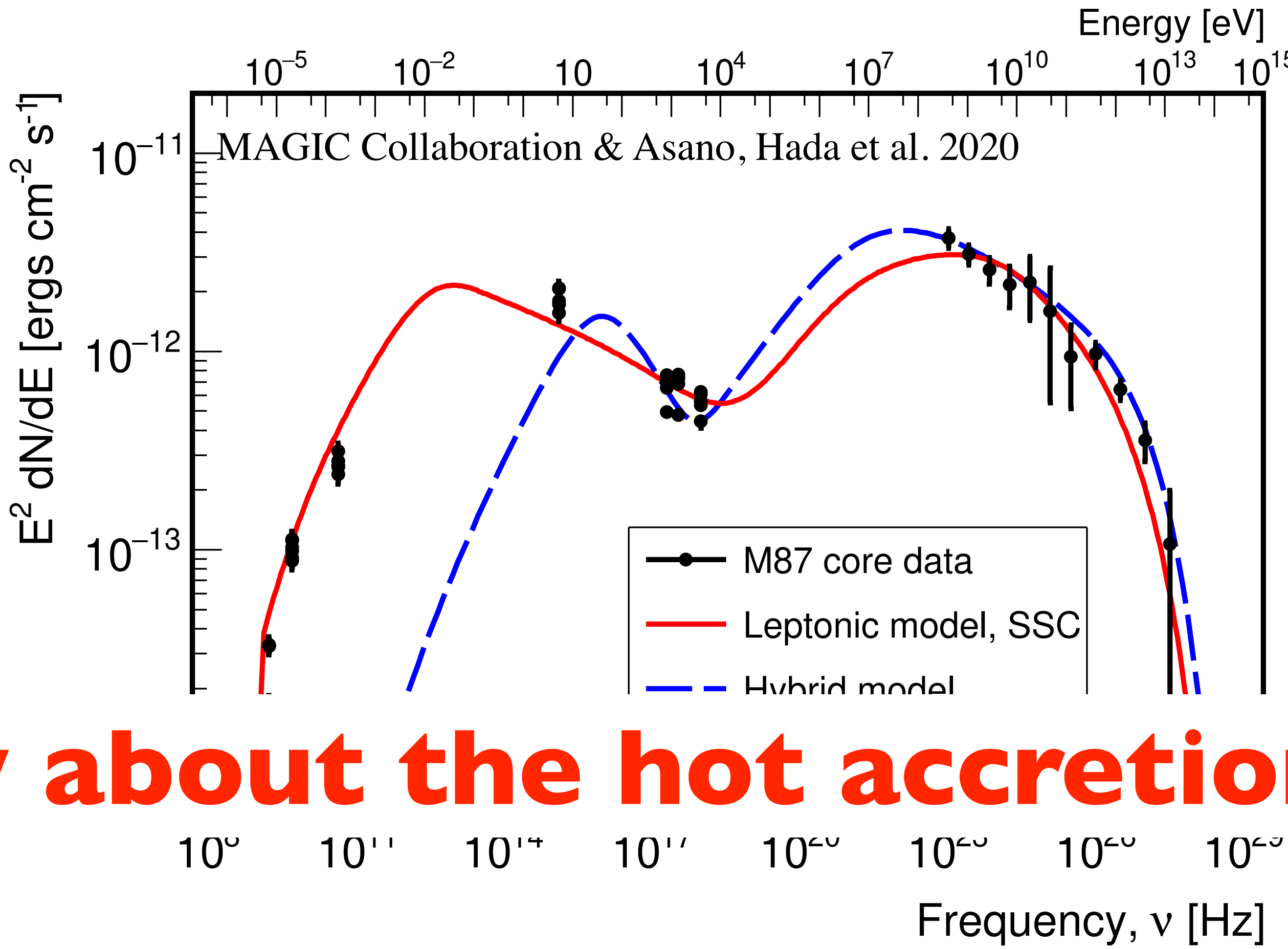
M87 Observations



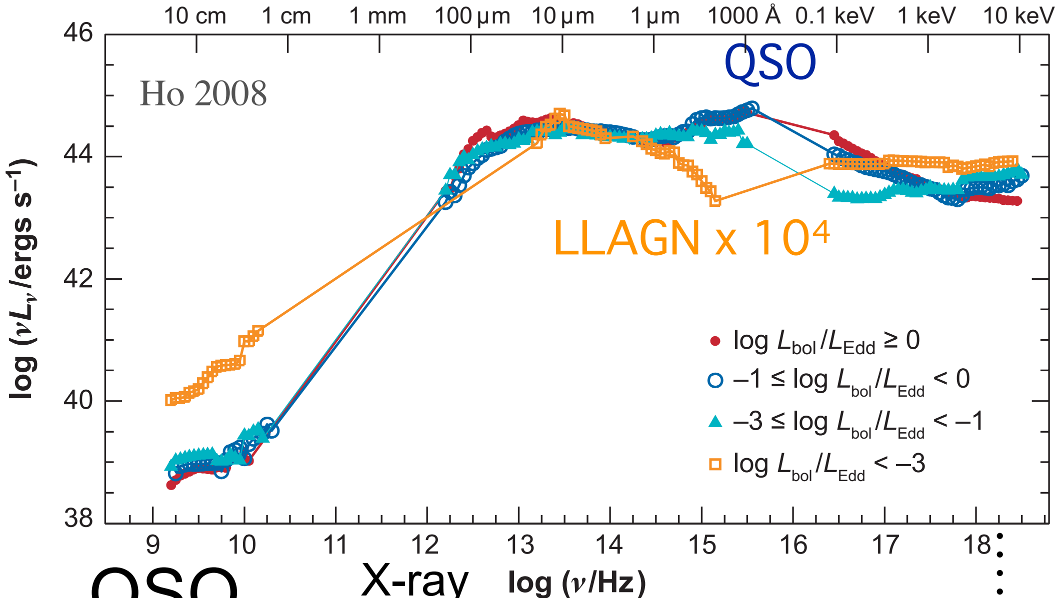
How about the hot accretion flow?

- HE & VHE γ-rays are observed, but **emission region & mechanism are not known**
- Leptonic jet model: too weak magnetic field (mG)
- Hadronic jet model: very high power (>10^{45} erg/s)

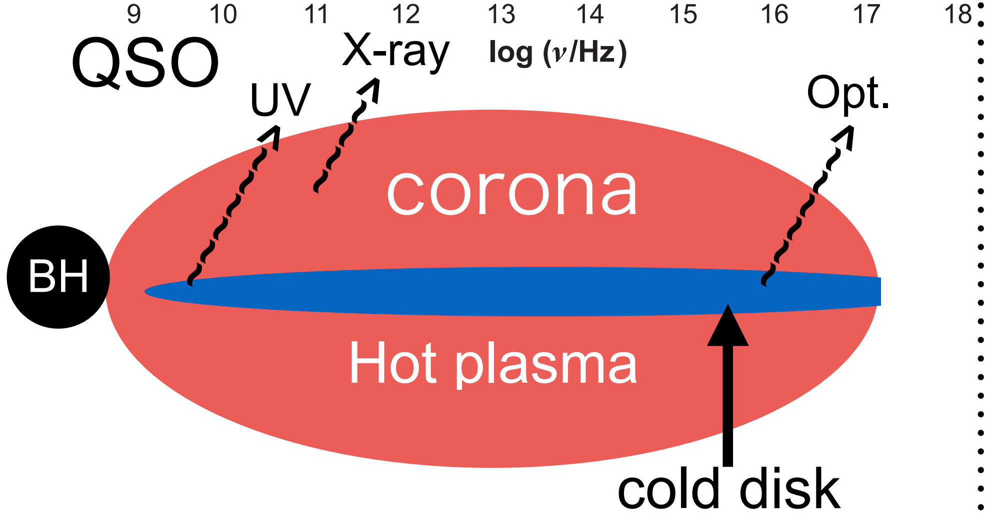
Contents

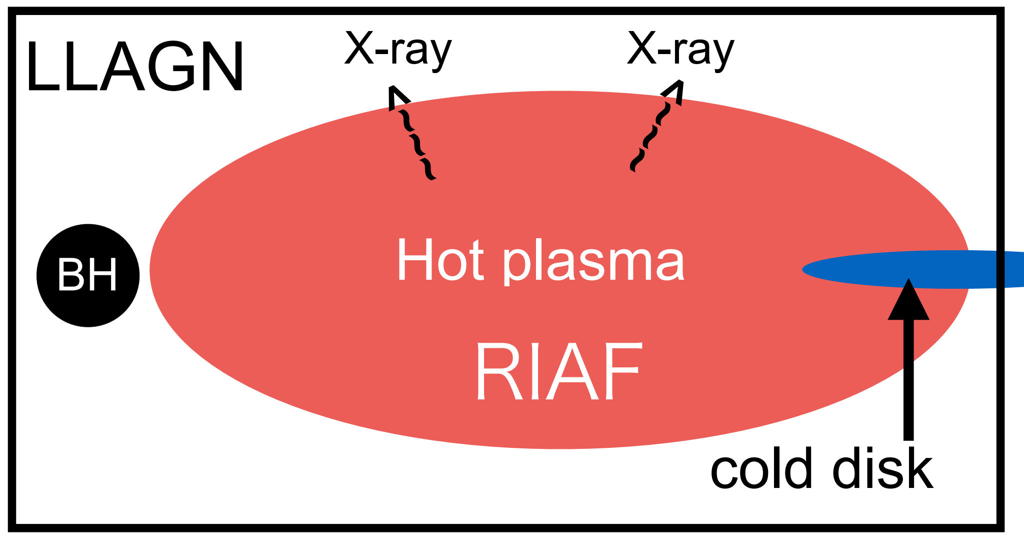
- Motivation for hadronic emission from RIAFs
  - Particle Acceleration in RIAFs
  - RIAFs as Neutrino Sources
- Hadronic Emission from MADs in Radio Galaxies
- Summary

Accretion flows in AGNs



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

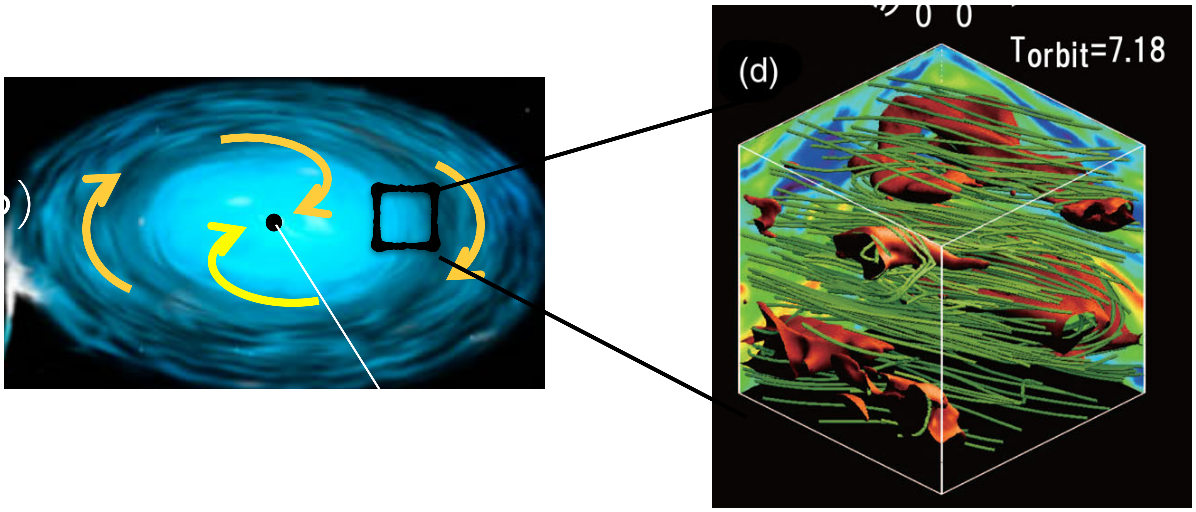




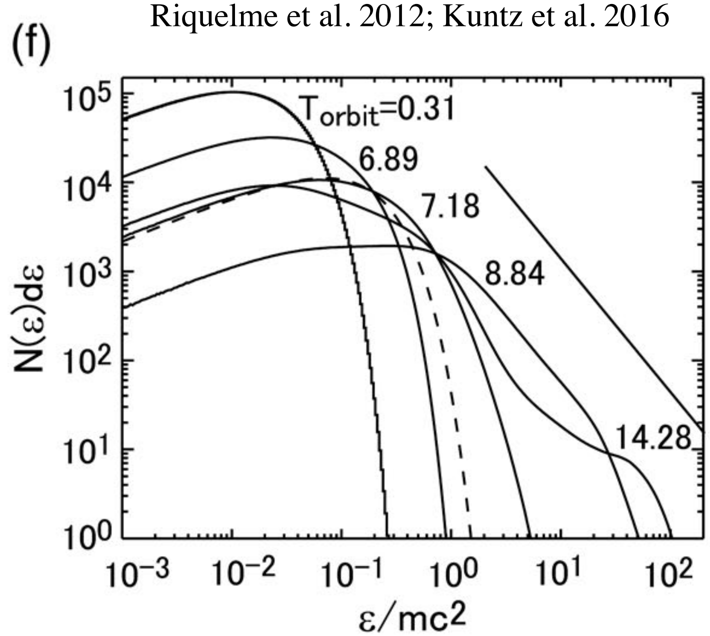
Coronae and RIAFs are collisionless
→ protons are naturally accelerated

Particle Acceleration in Accretion Flows

Particle-In-Cell Simulations



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

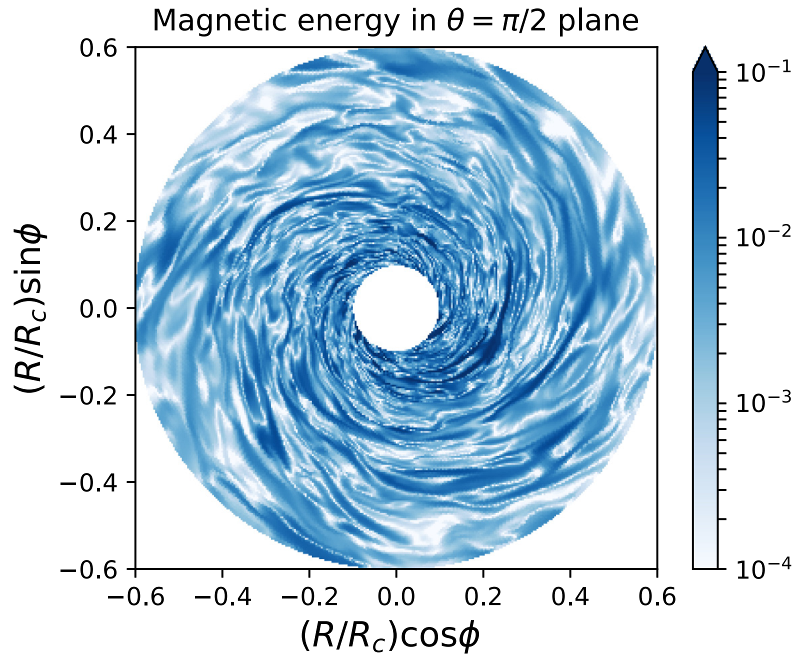


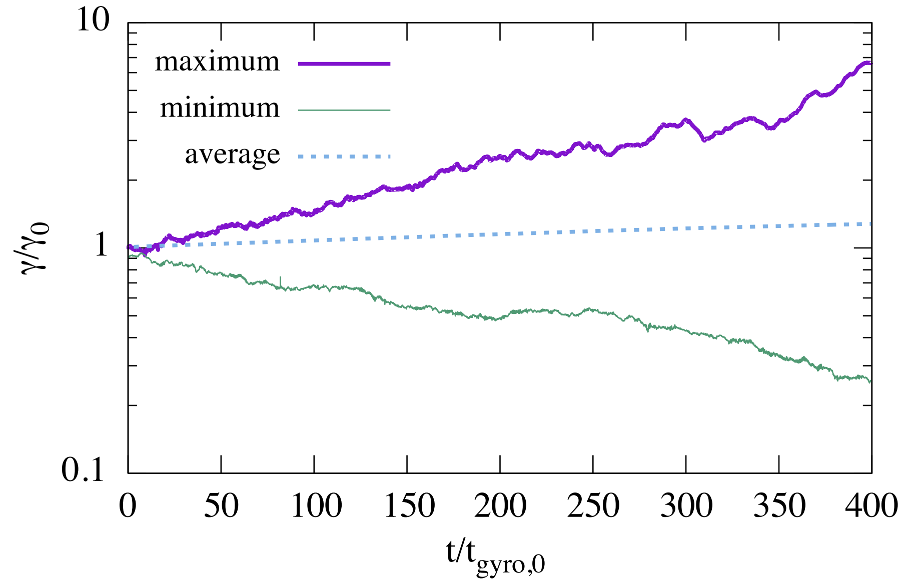
- Magneto-rotational instability (MRI) drives turbulence
- Turbulence triggers magnetic reconnection
- Distribution function: Thermal → Non-thermal tail
- **Magnetic reconnection accelerates CRs in plasma scale**

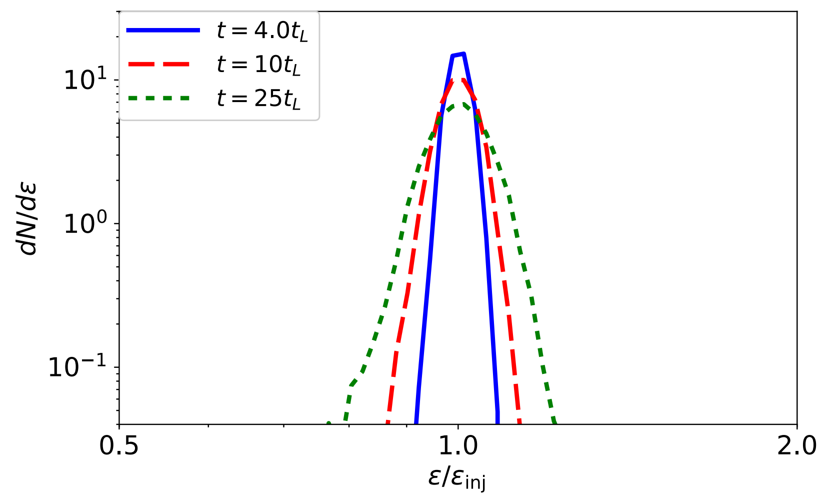
Particle Acceleration in Accretion Flows

SSK et al 2016; SSK et al. 2019
see also Lynn et al. 2014

MHD + Test Particle Simulations

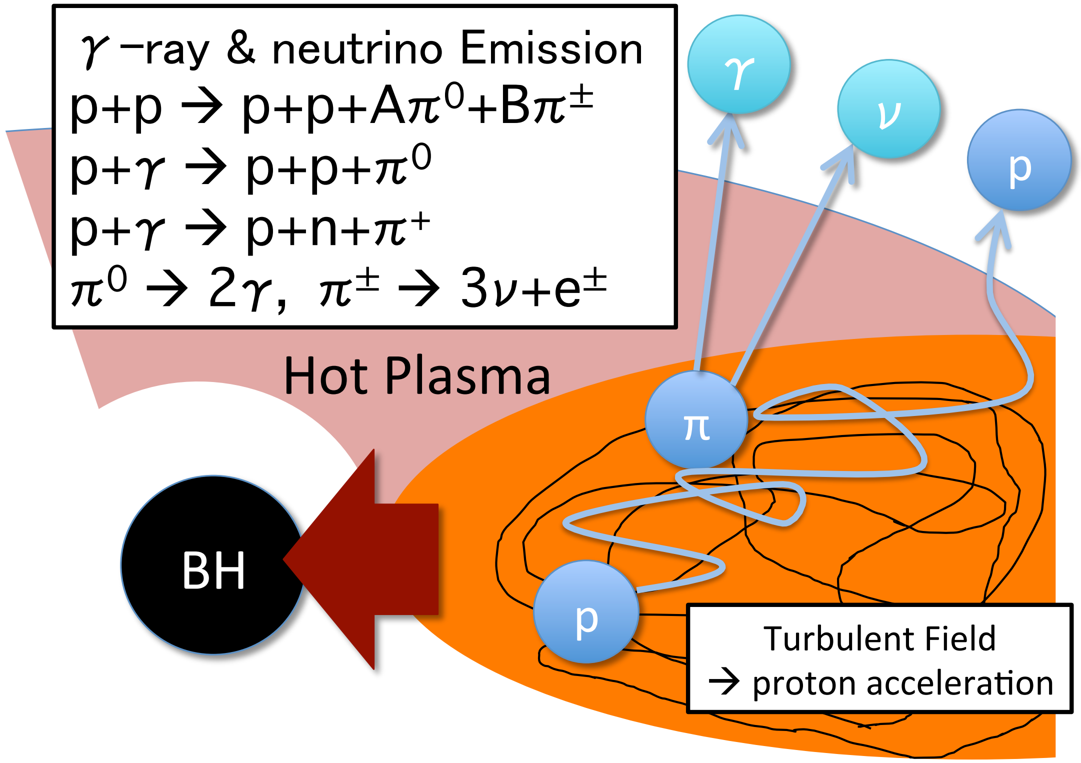






- MRI drives turbulence
- Turbulence interacts with CRs
- Distribution function: broadened due to wave-particle interaction
- **MHD turbulence further accelerates CRs**

High-Energy Emission

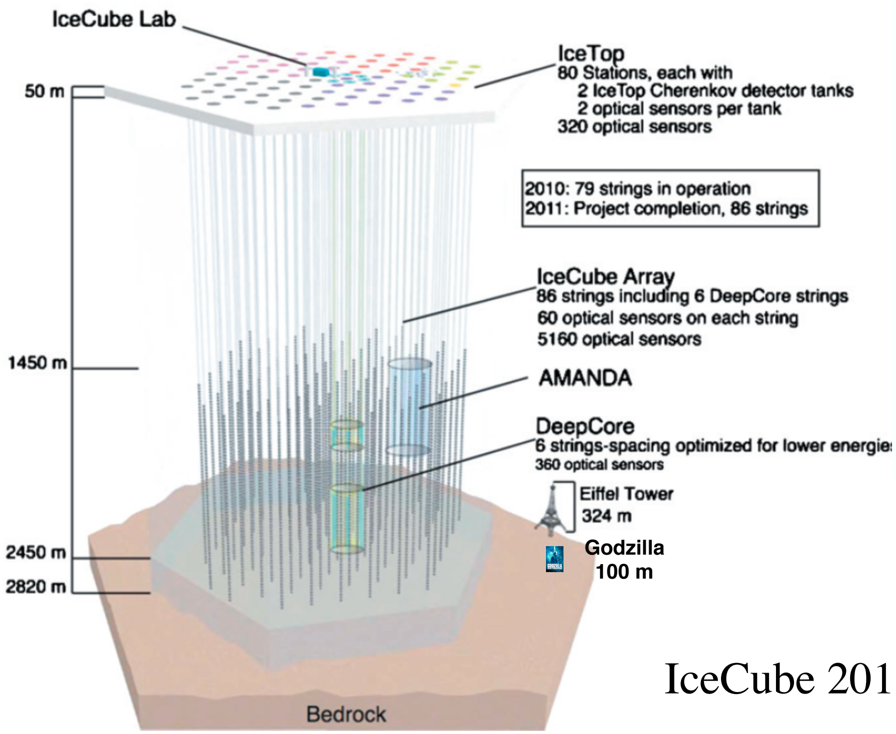


Mahadevan et al. 1997; SSK et al. 2015

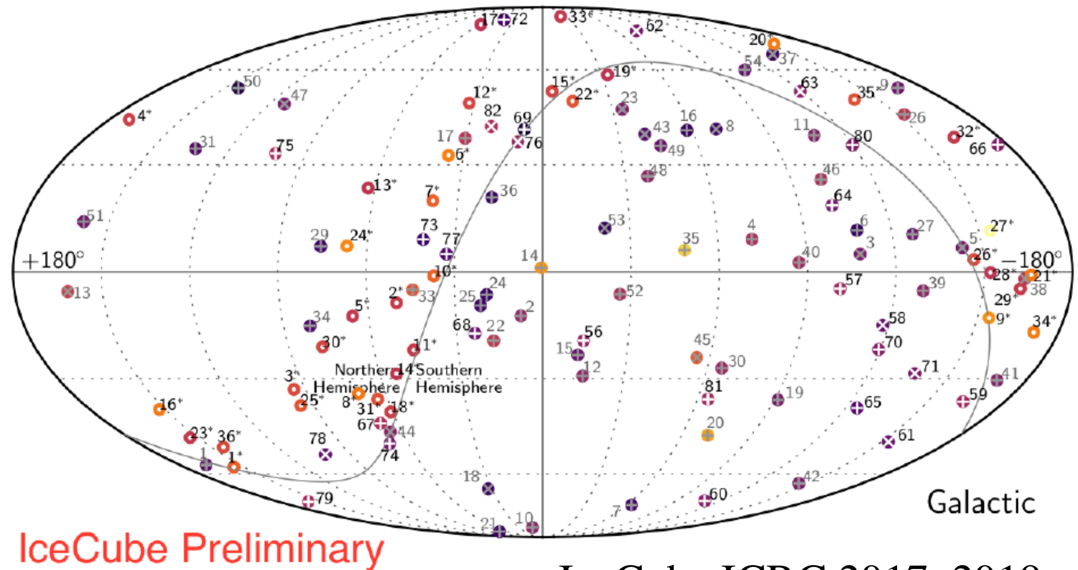
- Interaction between CRs and matter/photons
  → **efficient neutrino & gamma-ray emissions**
- TeV-PeV γ-rays are absorbed by γγ pair production
  → **MeV-GeV photons from the RIAF**

Contents

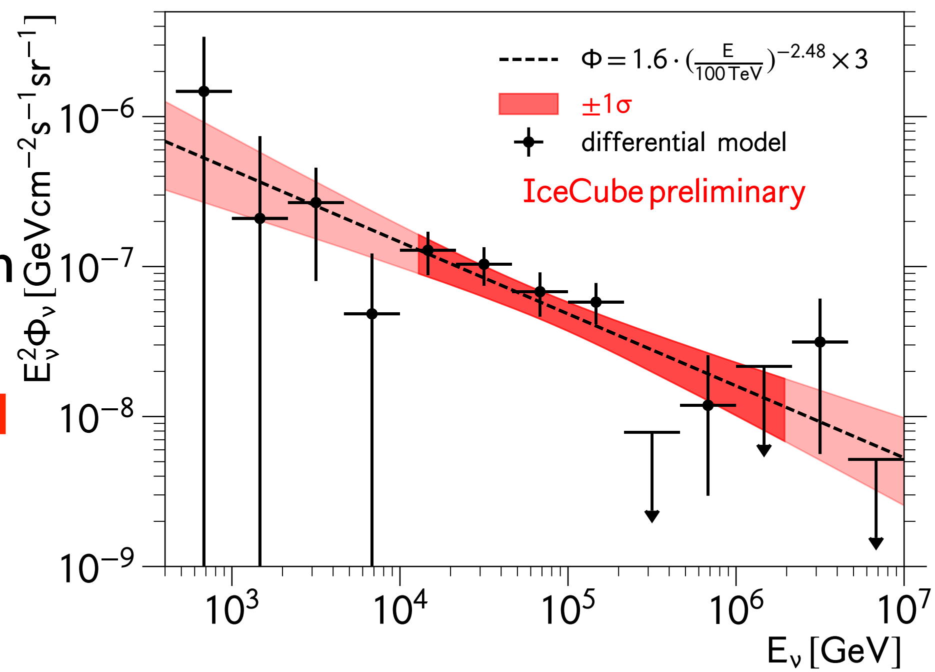
Detection of Astro-Neutrinos



IceCube 2013



IceCube ICRC 2017, 2019



- IceCube experiment reported detection of astro-ν (E ~ PeV) in 2013
- **Origin has yet to be determined**
- Isotropic → extragalactic origin
- Soft spectrum in TeV-PeV range

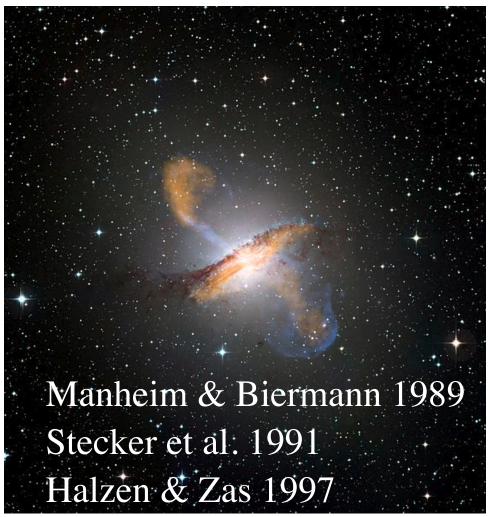
Pre-IceCube Models

- **Cosmic-ray accelerators**

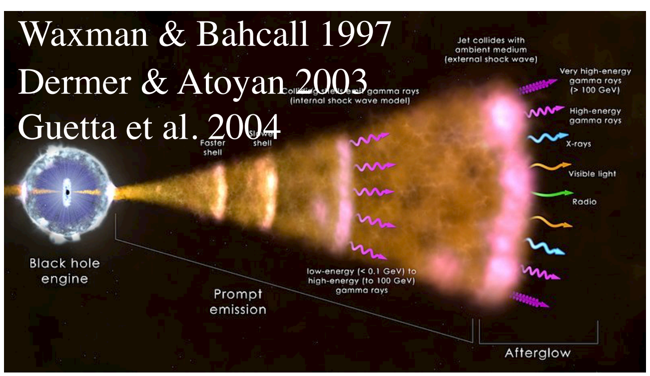
  mainly pγ interaction

  - Active Galactic Nuclei (AGN)

    Blazars & luminous Seyfert galaxies



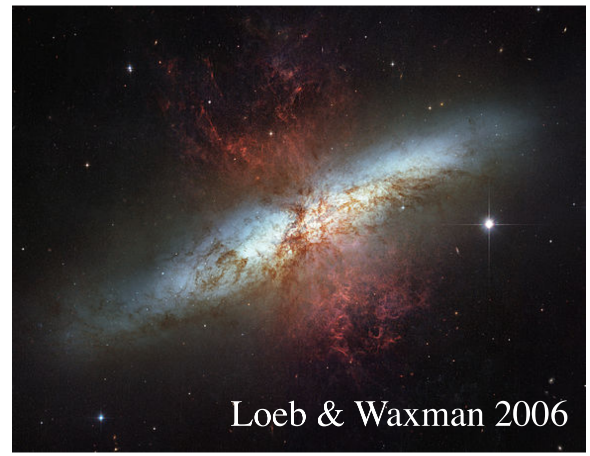
  - Gamma Ray Bursts (GRBs)



- **Cosmic-ray reservoirs**

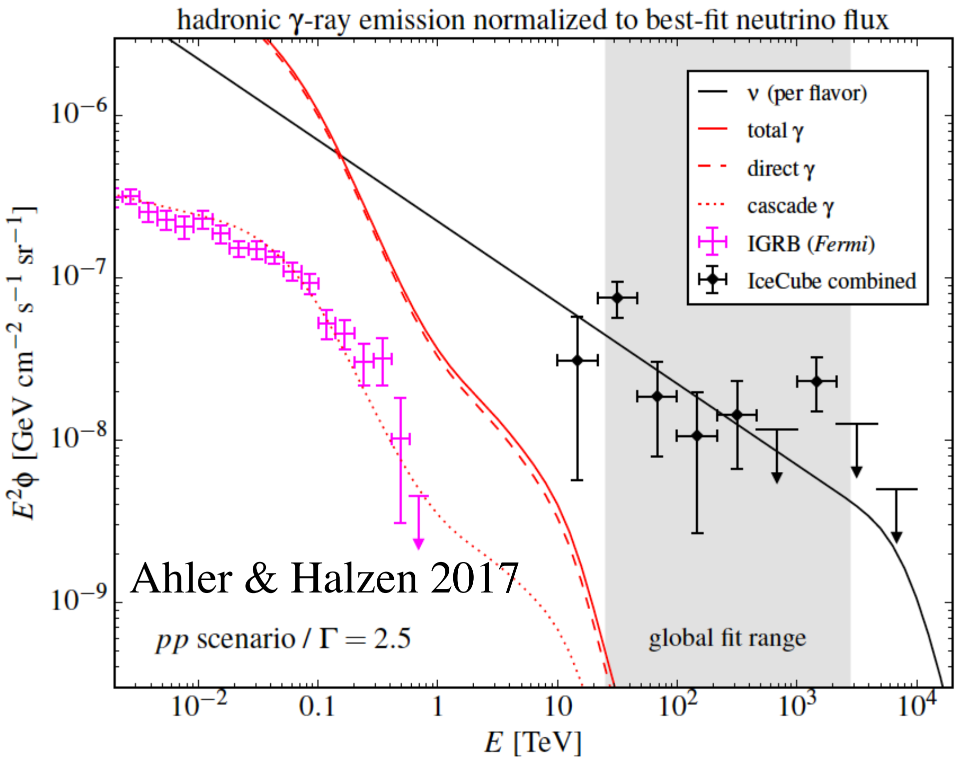
  mainly pp interaction

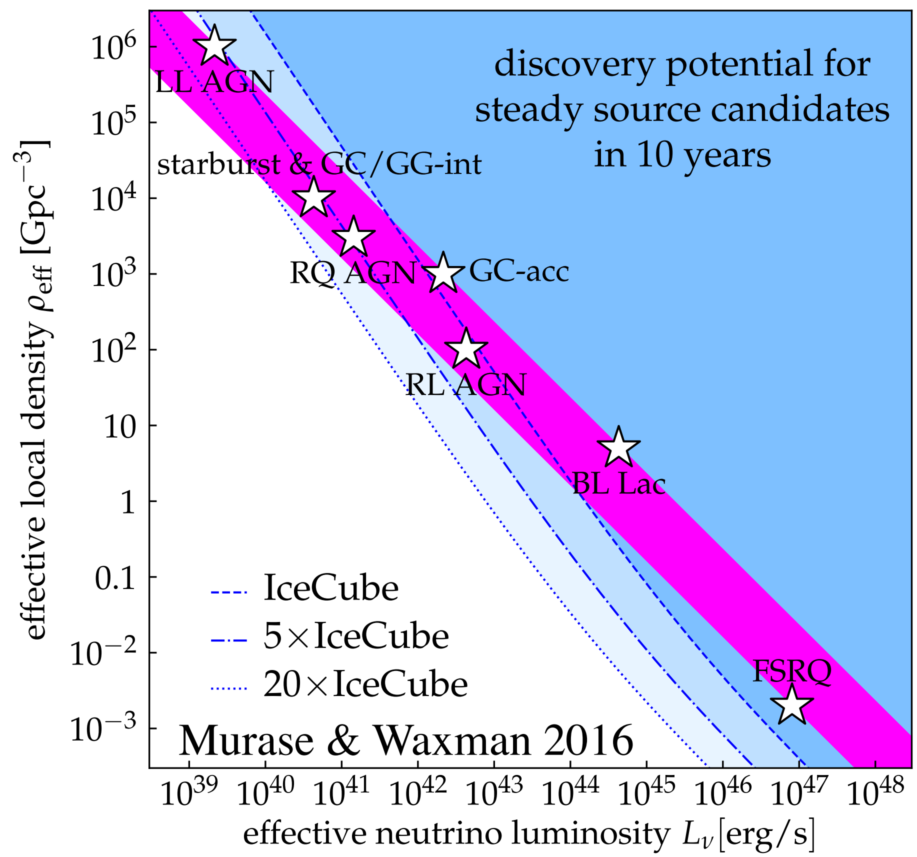
  - Star Forming Galaxies (SFG)



  - Galaxy Group / Galaxy Cluster

Model-independent Constraints





- ν flux@10 TeV > γ flux@100 GeV
  → accompanying γ overshoot Fermi data
  → **ν sources should be opaque to TeV γ rays**

Murase et al. 2013, 2016; Ahler & Halzen 2017

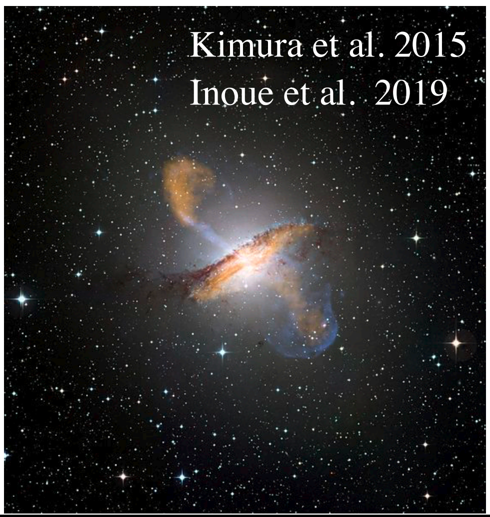
- **No point-source detection disfavors luminous sources** (GRBs, Blazars, Jetted TDEs)

Models for 10 TeV Neutrinos

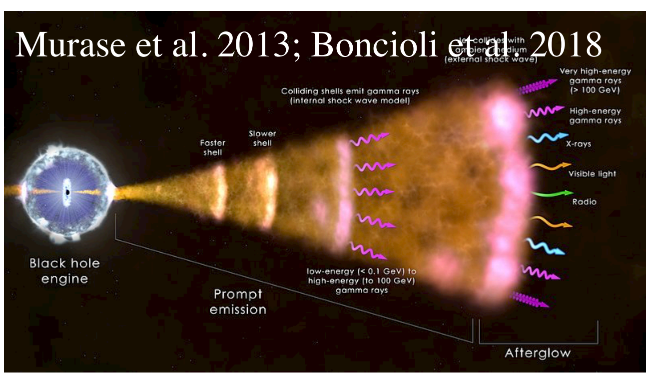
- **Cosmic-ray accelerators**

  mainly pγ interaction

  - Active Galactic Nuclei (AGN)
    - Non-beamed AGN



  - Gamma Ray Bursts (GRBs)
    - LLGRBs



- **Cosmic-ray reservoirs**

  mainly pp interaction

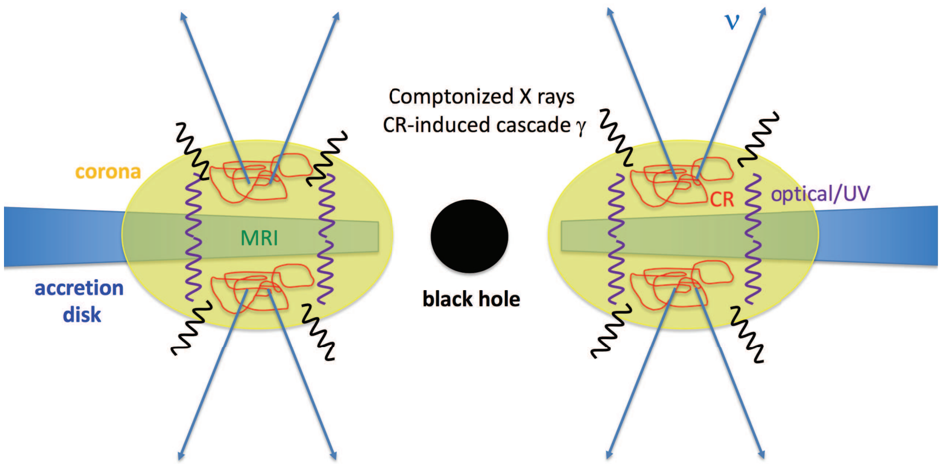
  - Star Forming Galaxies (SFG)

  - Galaxy Group / Galaxy Cluster

AGN Core Model

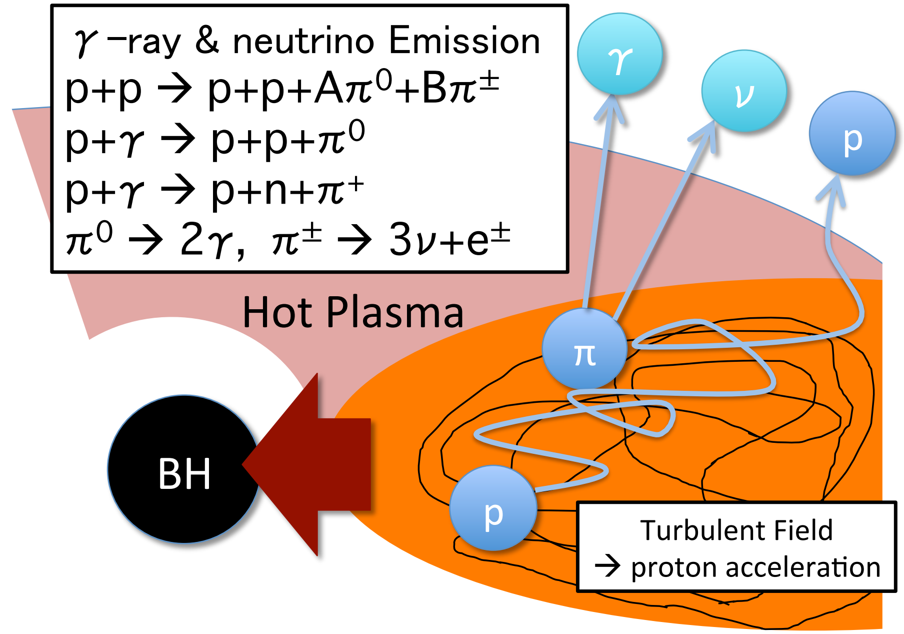
Murase, SSK et al. 2019

- Coronae in QSOs



Mahadevan et al. 1997; SSK et al. 2015, 2019, in prep.

- RIAFs in LLAGNs



- Transport equations for primary protons and secondary e^+e^- & γ

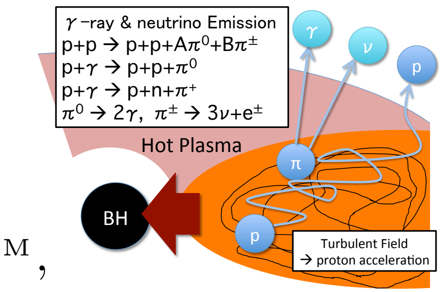
$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\rm cool}}F_p\right) - \frac{F_p}{t_{\rm esc}} + \dot{F}_{p,\rm inj}$$

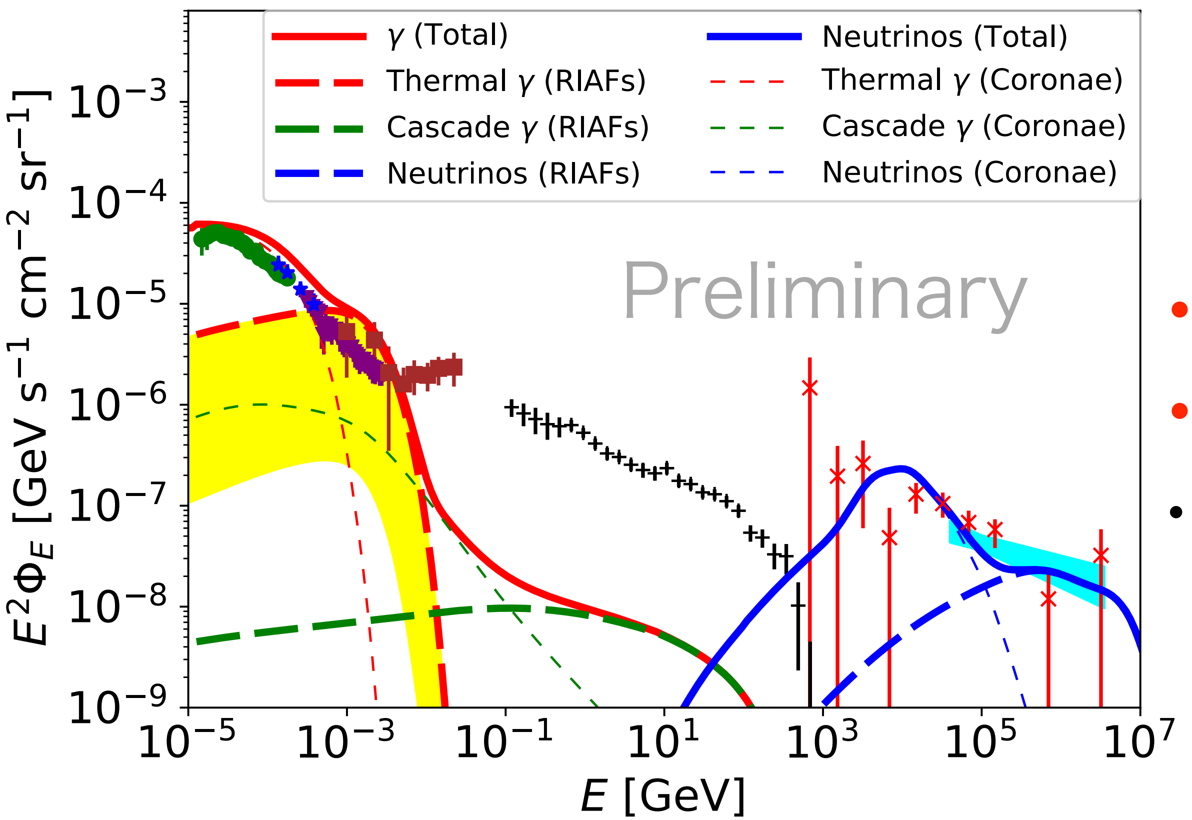
$$\frac{\partial n^e_{\varepsilon_e}}{\partial t} + \frac{\partial}{\partial \varepsilon_e}[(P_{\rm IC} + P_{\rm syn} + P_{\rm ff} + P_{\rm Cou})n^e_{\varepsilon_e}] = \dot{n}^{(\gamma\gamma)}_{\varepsilon_e} - \frac{n^e_{\varepsilon_e}}{t_{\rm esc}} + \dot{n}^{\rm inj}_{\varepsilon_e},$$

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

Extragalactic γ & ν Backgrounds

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





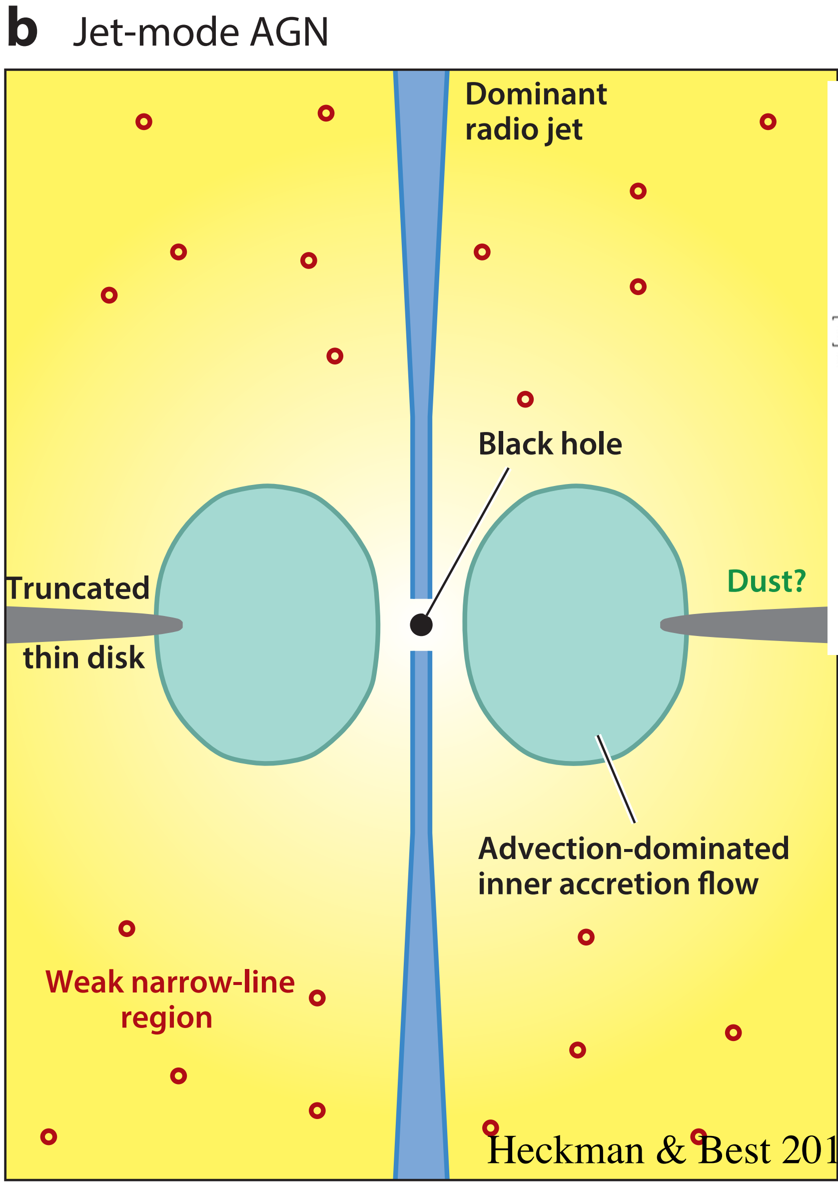
SSK, Murase, Meszaros in prep.
see also SSK, Murase, Toma 2015;
SSK, Murase, Meszaros 2019;
Murase, SSK, Meszaros 2019

- **Seyfert: X-ray & TeV ν**
- **LLAGN: MeV γ & PeV ν**
- GeV γs are attenuated in the source
  → consistent with Fermi data

- **AGN cores can account for a broad range of γ & ν bkgd.**

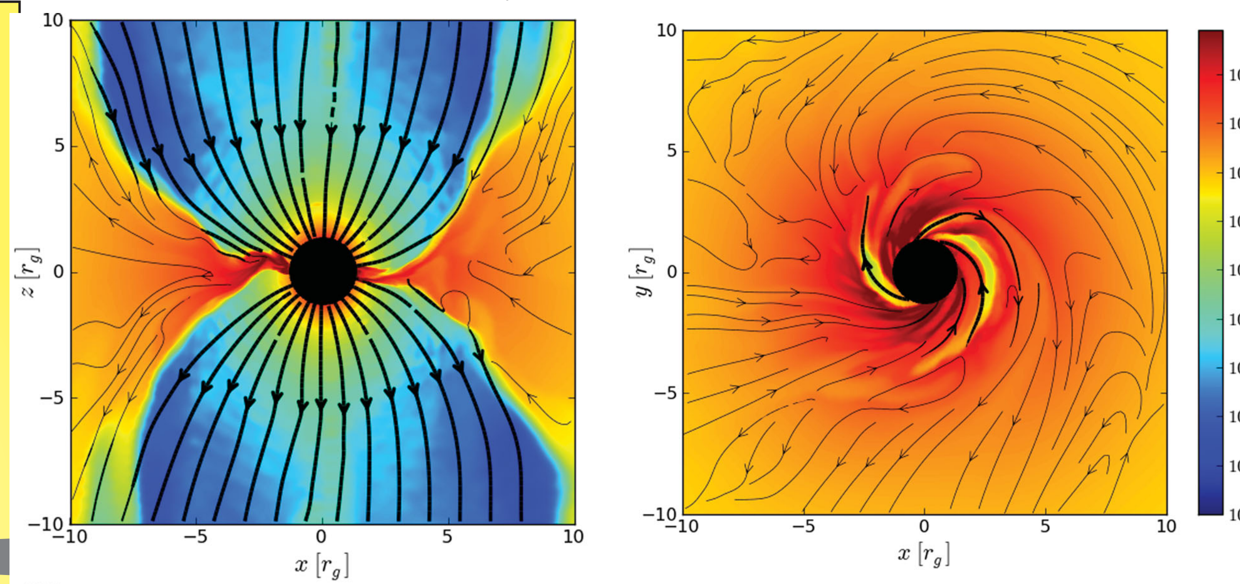
Contents

Accretion Flow in FR-I Galaxies



Heckman & Best 2014

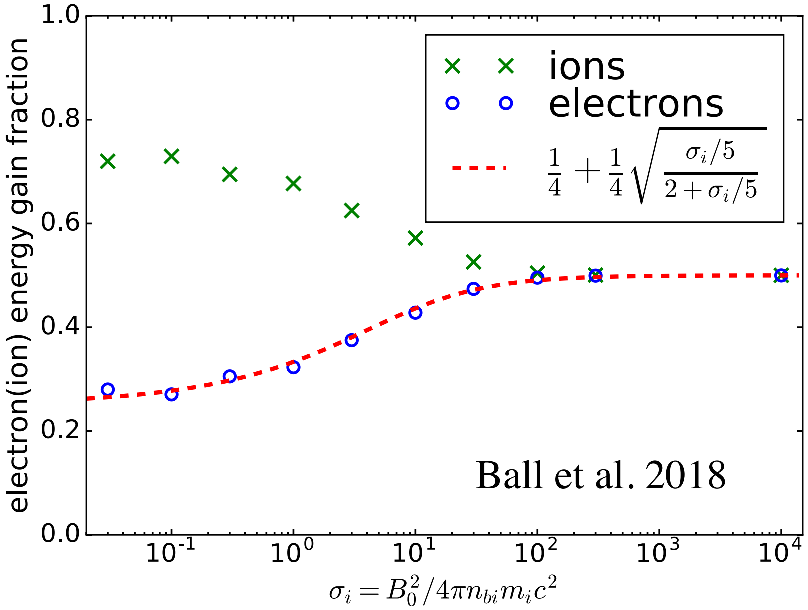
Talks by Mizuno-san, Nakamura-san, Kino-san

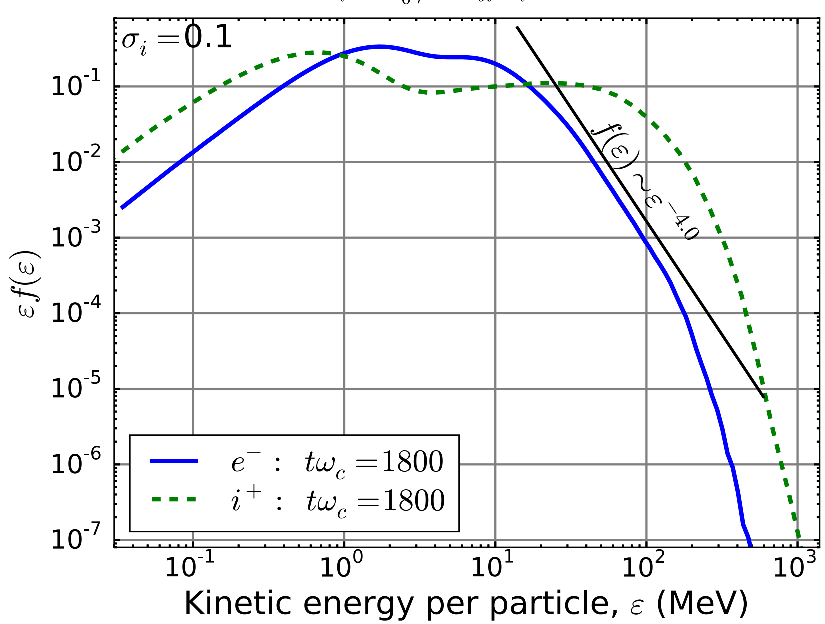


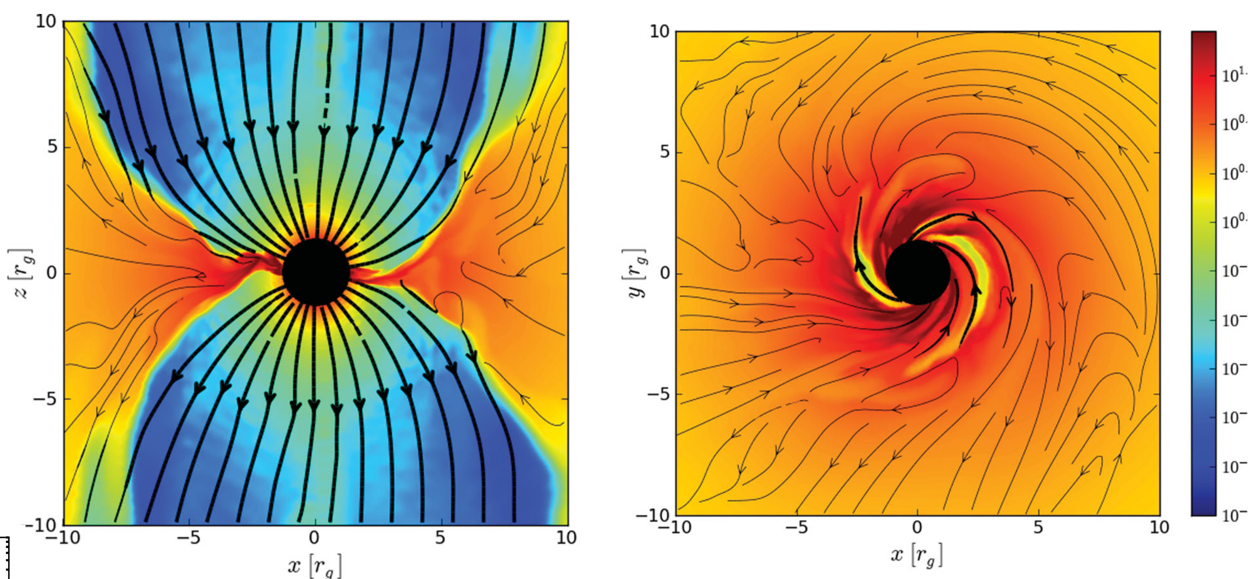
McKinney et al. 2012

- Powerful jet → Strong magnetic field → Magnetically Arrested Disks (MAD)

Accretion Flow in FR-I Galaxies







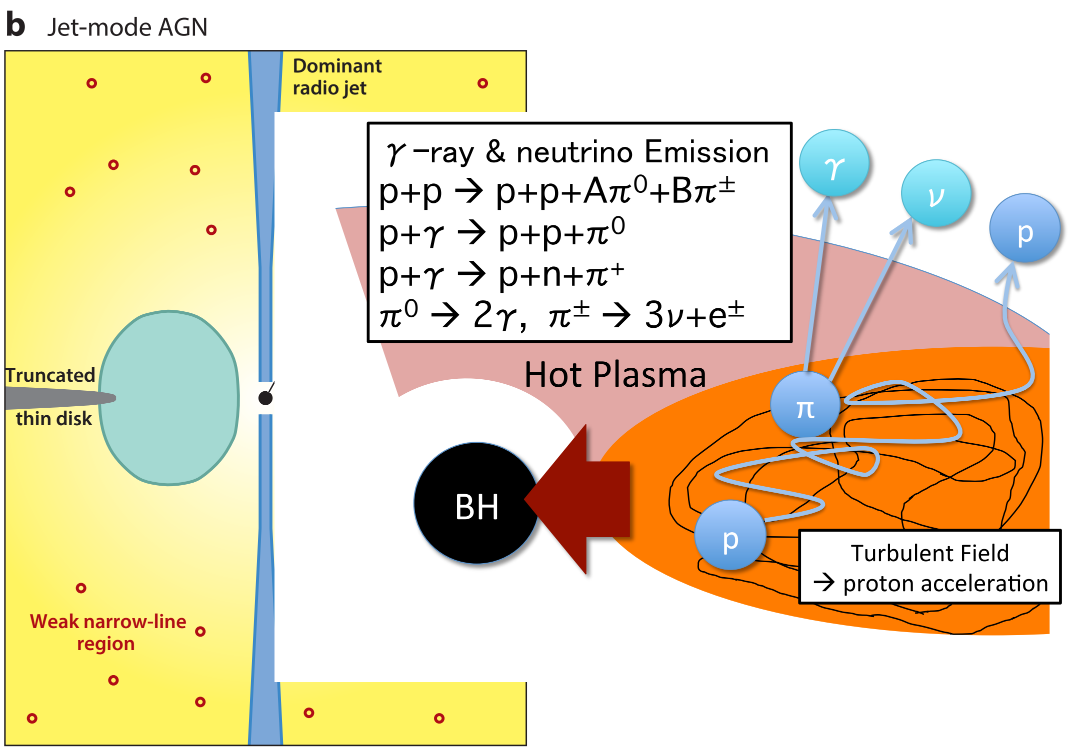
McKinney et al. 2012

- Powerful jet → Strong magnetic field → Magnetically Arrested Disks (MAD)
- Reconnection with strong magnetic field → **most of released energy may go to non-thermal protons**

Model

c.f.) Mahadevan et al. 1997;
SSK et al. 2015, 2019, in prep

- Consider Steady & one-zone accreting plasma
- Non-thermal protons emit gamma-rays through hadronic interactions
- Thermal electrons emit soft photons through Synchrotron & SSC
  → take γγ attenuation by soft photons into account
- Secondary e+e- pairs emit soft radiations through Synchrotron



$$V_R \approx \frac{1}{2}\alpha V_K \simeq 3.4\times 10^8 \mathcal{R}_1^{-1/2}\alpha_{-1}\ \mathrm{cm\,s^{-1}},$$

$$C_s \approx \frac{1}{2}V_K \simeq 3.4\times 10^9 \mathcal{R}_1^{-1/2}\ \mathrm{cm\,s^{-1}},$$

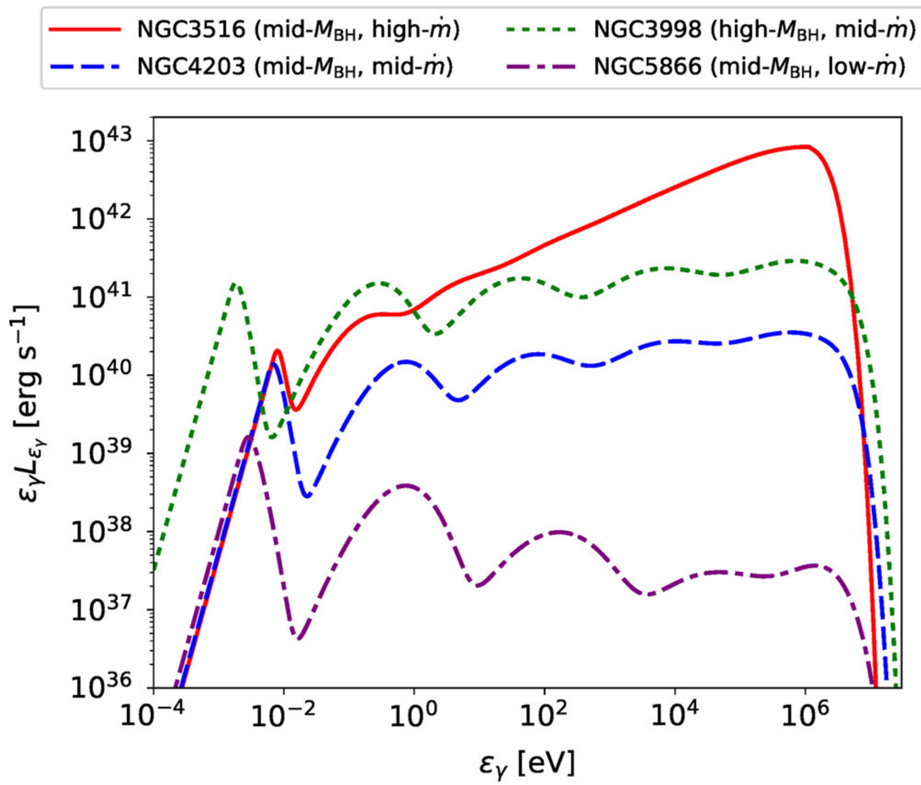
$$H \approx \frac{1}{2}R \simeq 1.5\times 10^{14}\mathcal{R}_1 M_8\ \mathrm{cm},$$

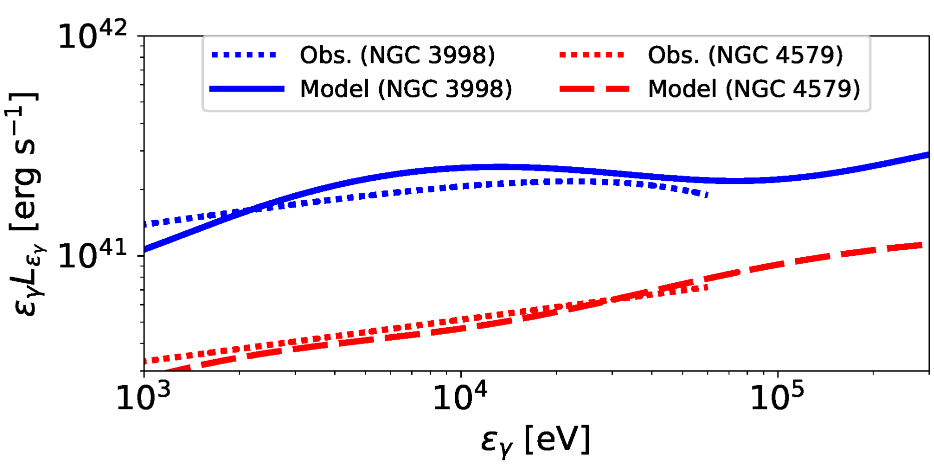
$$n_p \approx \frac{\dot{M}}{4\pi m_p R H V_R} \simeq 4.6\times 10^8 \mathcal{R}_1^{-3/2}\alpha_{-1}^{-1}M_8^{-1}\dot{m}_{-2}\ \mathrm{cm^{-3}},$$

$$B \approx \sqrt{\frac{8\pi P_g}{\beta}} \simeq 2.6\times 10^2 \mathcal{R}_1^{-5/4}\alpha_{-1}^{-1/2}M_8^{-1/2}\dot{m}_{-2}^{1/2}\beta_{0.5}^{-1/2}\ \mathrm{G},$$

$$V_A \approx \frac{B}{\sqrt{4\pi m_p n_p}} \simeq 2.7\times 10^9 \mathcal{R}_1^{-1/2}\beta_{0.5}^{-1/2}\ \mathrm{cm\,s^{-1}},$$

Soft photons in RIAFs





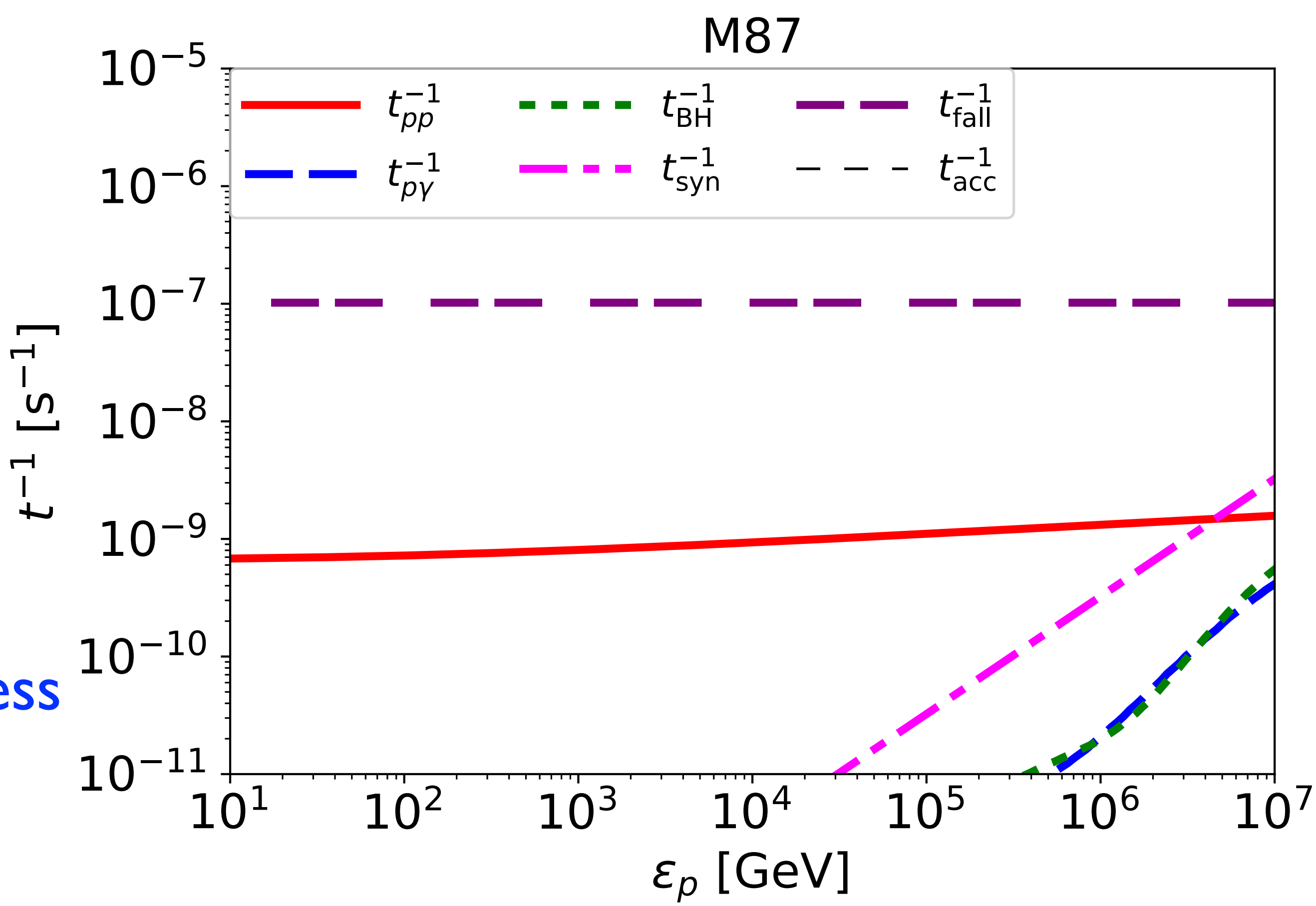
c.f.) Kawashima-san's talk
Mahadevan et al. 1997;
SSK et al. 2015, 2019, in prep

- Synchrotron peak at radio
- SSC for IR to MeV gamma
- high accretion rate
  → luminous & hard
- higher black hole mass
  → luminous
- Electron temperature: always MeV range
- Our model is consistent with X-ray observation in terms of
  - softening in hard X-ray range
  - anti-correlation of λ_{Edd} - Γ_x

Non-thermal Protons

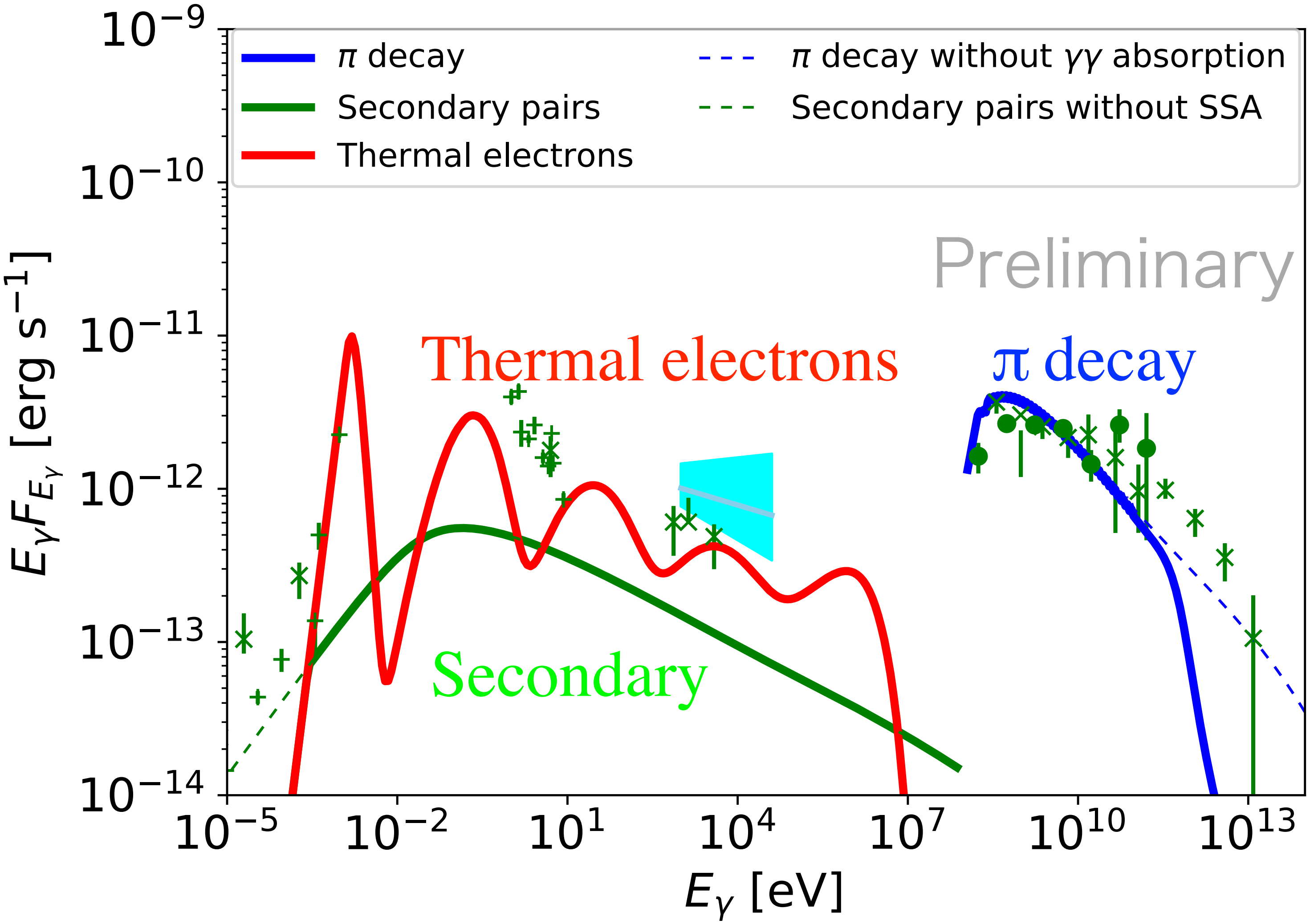
- Transport equation: $$\frac{d}{d\varepsilon_p}\left(-\frac{\varepsilon_p}{t_{\rm cool}}N_{\varepsilon_p}\right) = \dot{N}_{\varepsilon_p,{\rm inj}} - \frac{N_{\varepsilon_p}}{t_{\rm esc}},$$
- Power-law injection: $$\dot{N}_{\varepsilon_p,{\rm inj}} = \dot{N}_0\left(\frac{\varepsilon_p}{\varepsilon_{p,{\rm cut}}}\right)^{-s_{\rm inj}}\exp\left(-\frac{\varepsilon_p}{\varepsilon_{p,{\rm cut}}}\right)$$
- Normalization:

$$\int \varepsilon_p \dot{N}_{\varepsilon_p,{\rm inj}} d\varepsilon_p = \epsilon_p \dot{m} L_{\rm Edd},$$



- Infall loss is dominant
- pp interaction is the dominant cooling process

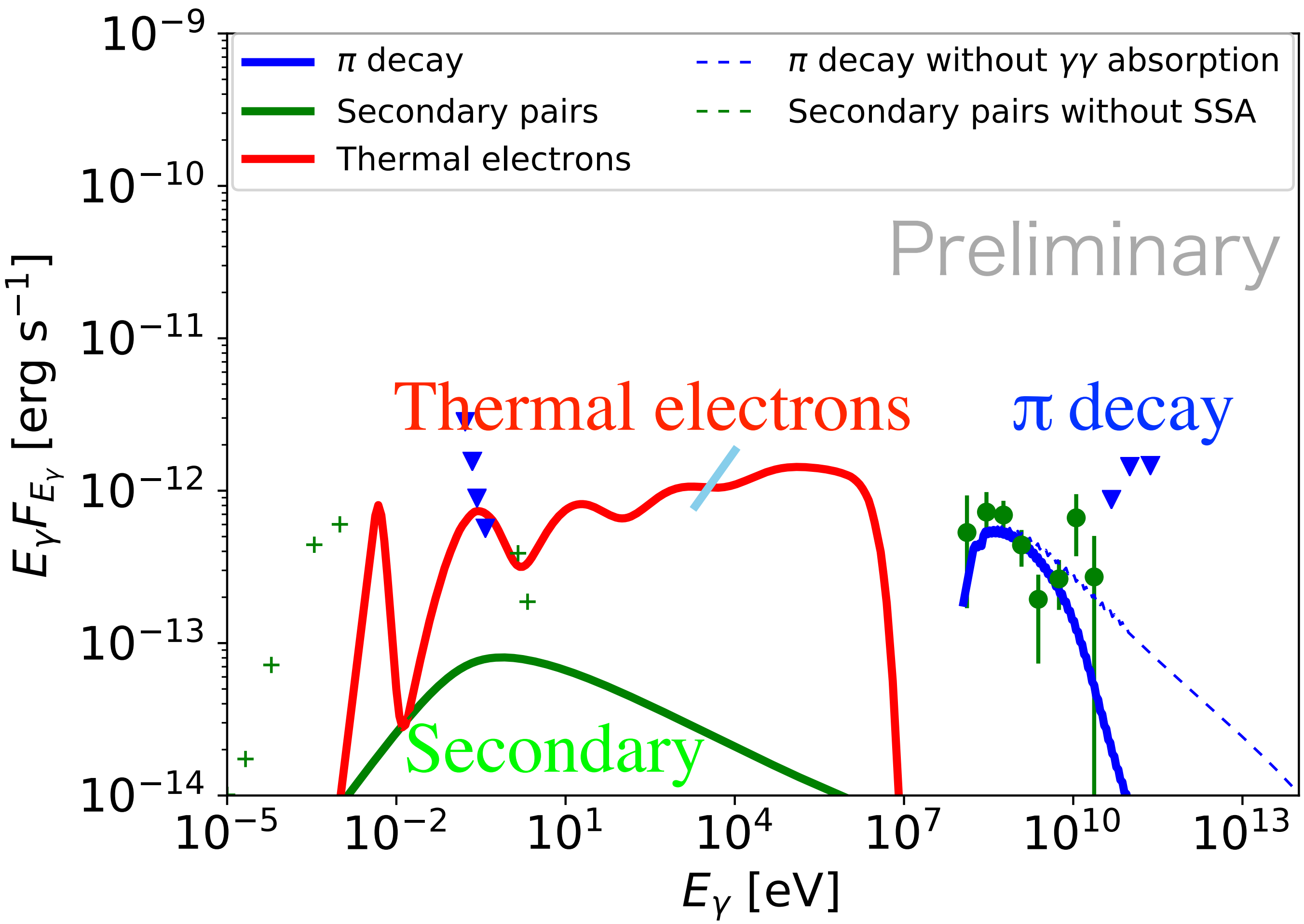
SED for M87



SSK & Toma in prep.

- Roughly consistent with observed broadband spectrum
- $L_{CR} = 0.1\dot{M}c$ → **MAD model achieves observed GeV flux**
- radio (<10 GHz) & TeV γ should be produced by other regions

SED for NGC 315



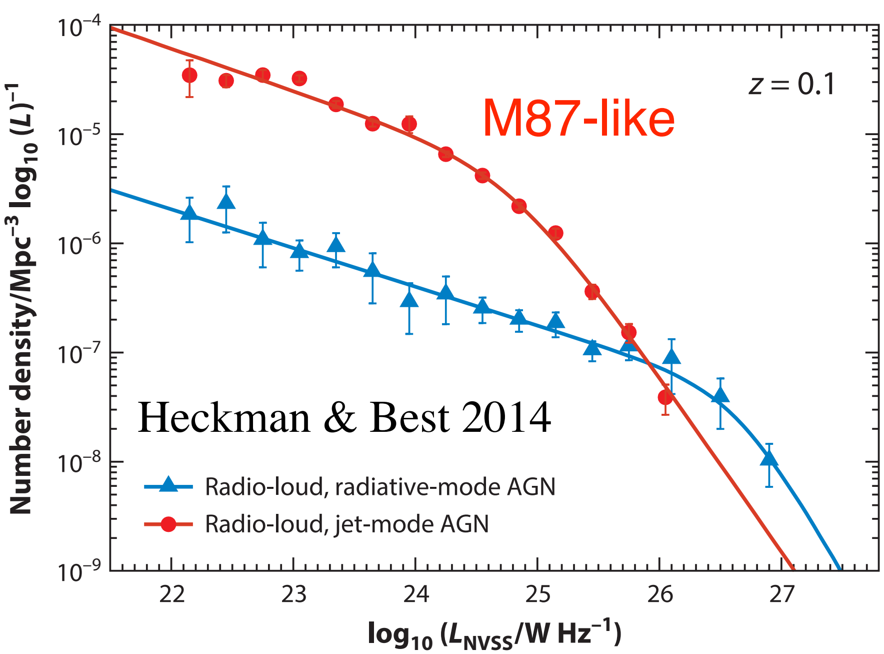
SSK & Toma in prep.

- Rough agreement with observed dat
  with the same parameter set of M87 except for M_{BH} & $\dot{M}$

High-Energy Backgrounds from MAD in Radio Galaxies

$$\frac{dF_\gamma}{dE_\gamma\, d\Omega} = \int dz \frac{d^2V}{dz\, d\Omega} \int \frac{dF_\gamma}{dE_\gamma} \frac{dL_\gamma}{L_\gamma \log(10)} \rho_\gamma(L_\gamma, z)(1-\omega(F_\gamma(L_\gamma, z))) \exp(-\tau_\gamma(E_\gamma, z)),$$

- Radio luminosity function for "jet-mode AGN"

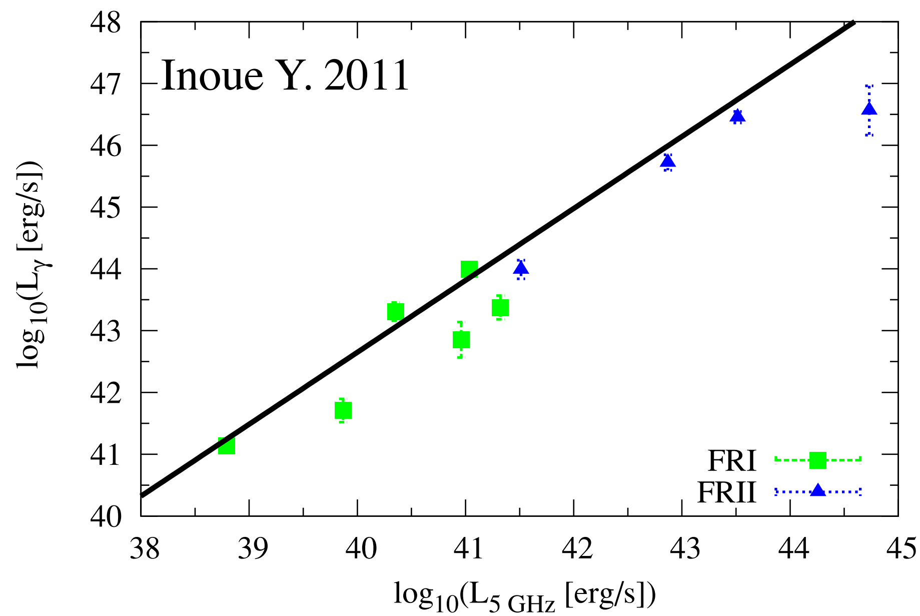


$$\rho = \rho_0 / \left[(P/P_0)^\alpha + (P/P_0)^\beta \right].$$

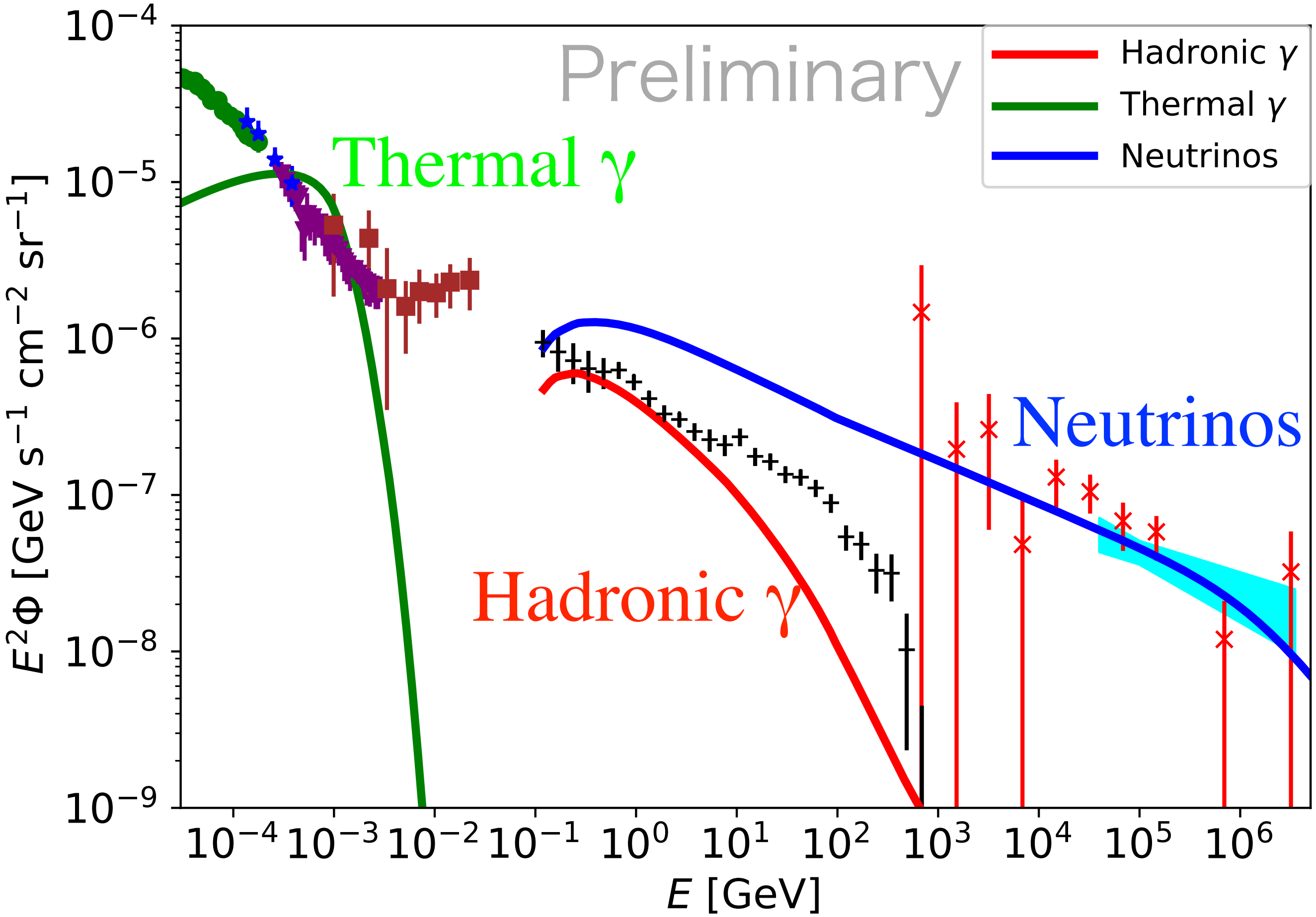
$P_0 = 10^{24.95}$ W/Hz, $\rho_0 = 10^{-5.33}$ Mpc^{-3}

- Convert Radio luminosity to γ-ray luminosity

$$\log_{10}(L_\gamma) = (-3.90 \pm 0.61) + (1.16 \pm 0.02) \log_{10}(L_{5\,\mathrm{GHz}}),$$



High-Energy Backgrounds from MAD in Radio Galaxies

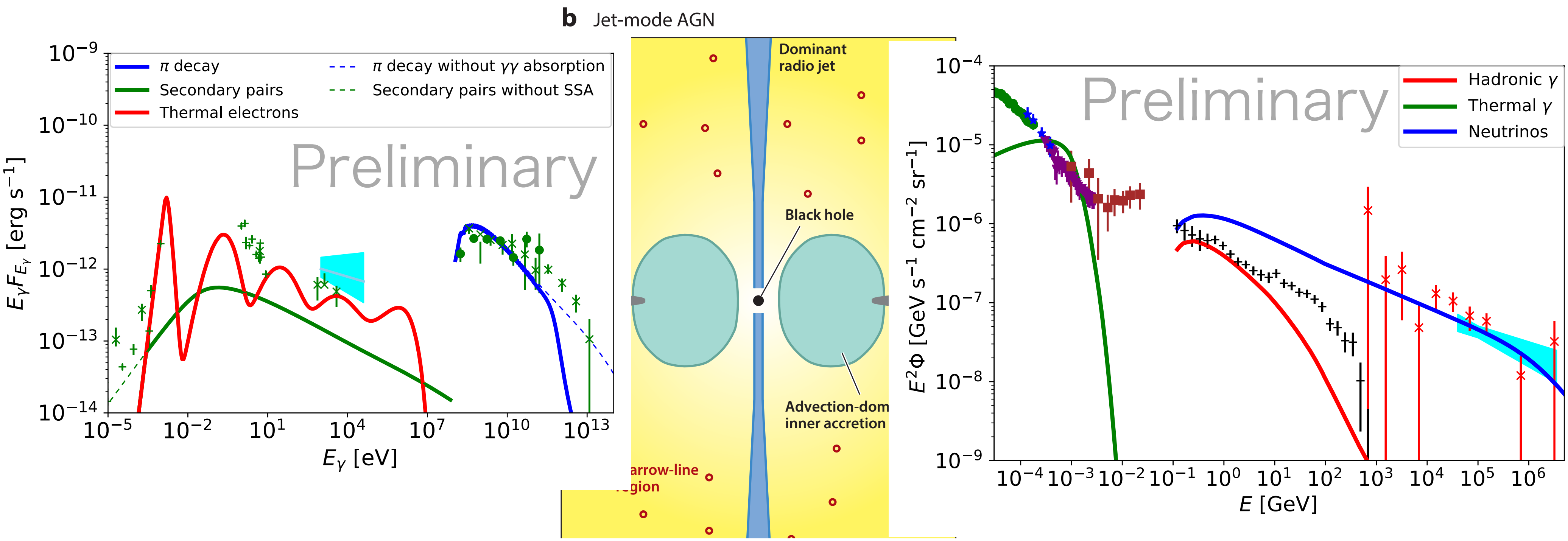


- **MeV gamma-rays, GeV gamma-rays, & TeV-PeV neutrinos can be explained simultaneously with the same parameter set**

Contents

Summary

- Cosmic-rays are naturally accelerated in hot accretion flows, especially in MADs by magnetic reconnection
- Radio-galaxies likely host MADs, leading to hadronic emissions
- With a one parameter set, **hadronic emission from MAD can reproduce the gamma-ray observations for M87 & NGC 315**
- With the same parameter sets, **hadronic emission from MADs will produce wide range of cosmic high-energy backgrounds**.



Thank you for your attention