活動銀河核の降着流からのニュートリノ放射

東北大学　（学振PD）

木村成生

References
1) SSK, Murase, Meszaros, 2019, PRD, 100, 083014
2) SSK, Murase, Meszaros in preparation
3) Murase, SSK, Meszaros, arXiv:1904.04226
see also: SSK, Murase, Toma, 2015, ApJ, 806, 159

Collaborators
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TOHOKU UNIVERSITY

Theoretical Astrophysics
Tohoku University

HEAP 2019@ 蔵王温泉　　December 2019

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- IceCube Neutrinos
- Accretion Flow in AGN
- AGN Corona model   Murase, SSK, Meszaros, arXiv:1904.04226
- LLAGN RIAF model   SSK, Murase, Meszaros, 2019, PRD, 100, 083014
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- Summary

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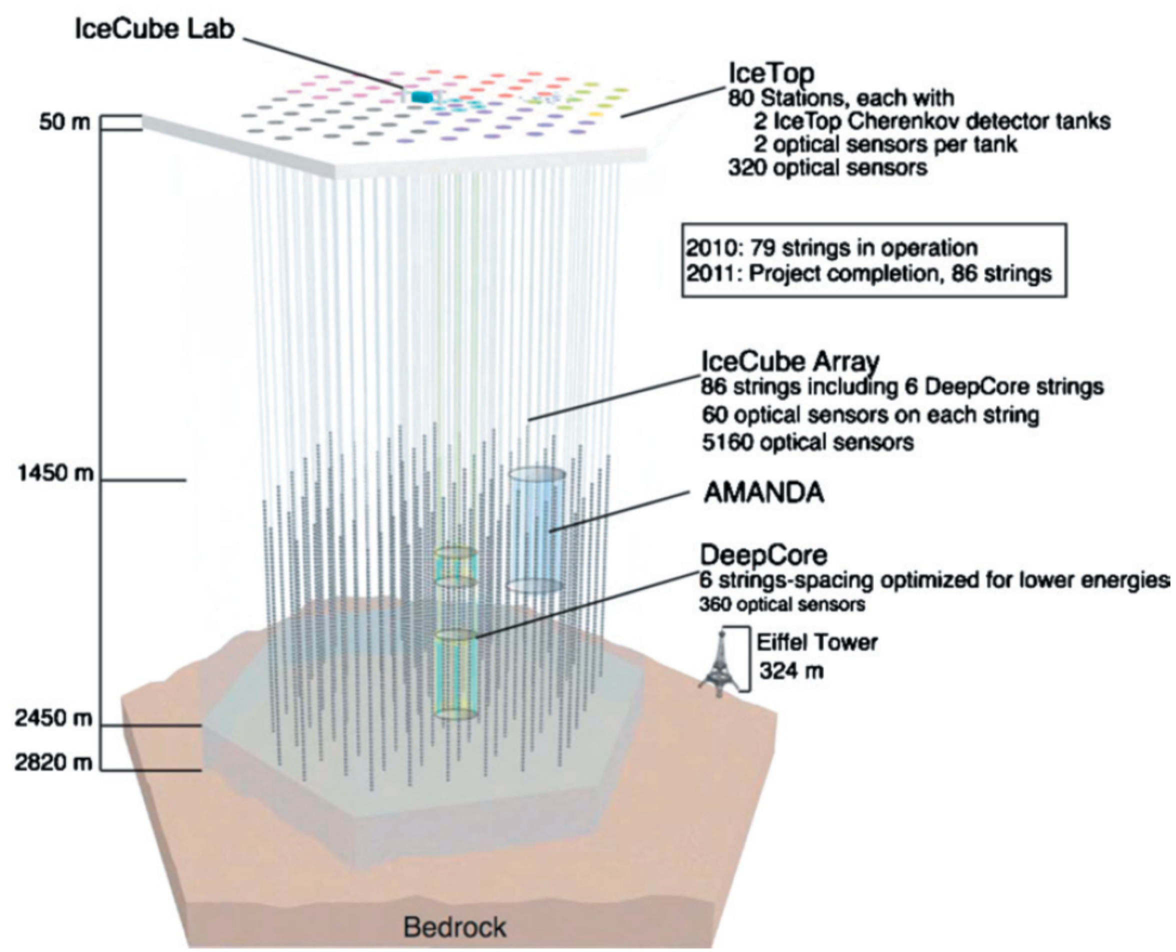
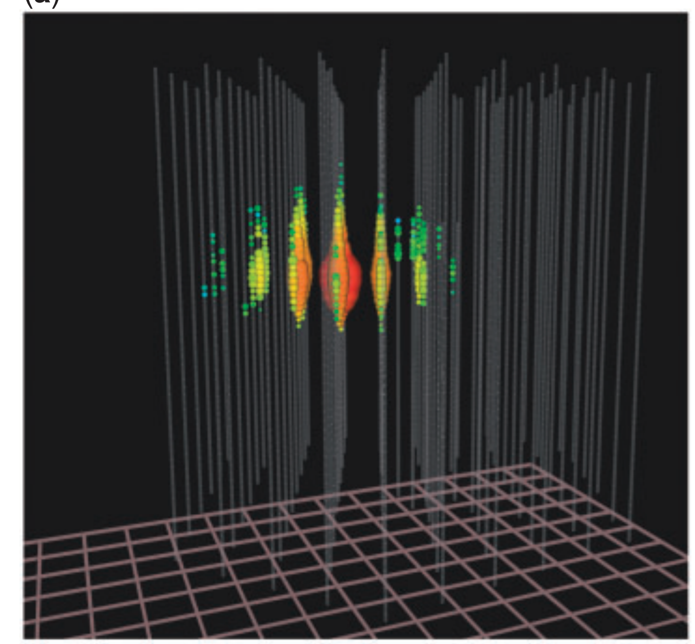
Detection of Astrophysical Neutrinos



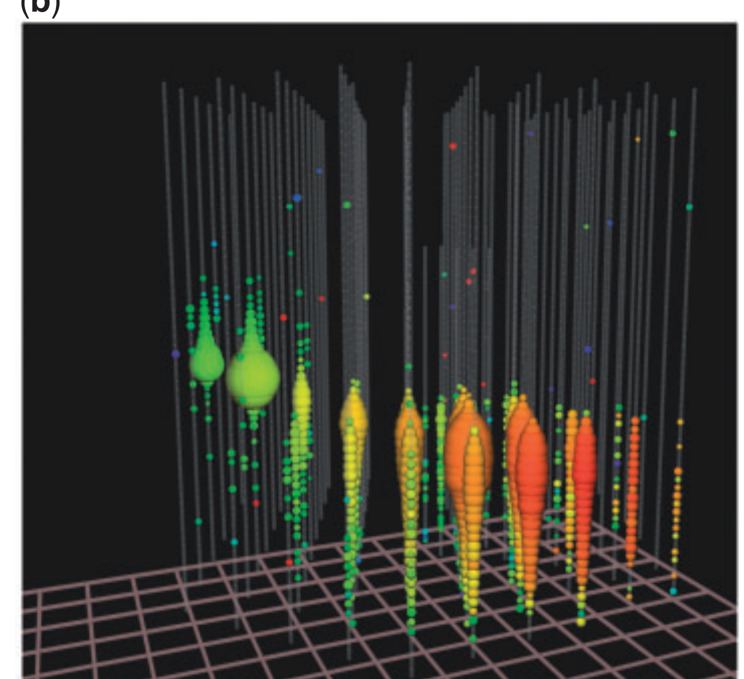
Shower or Cascade (ν_e)

(a)



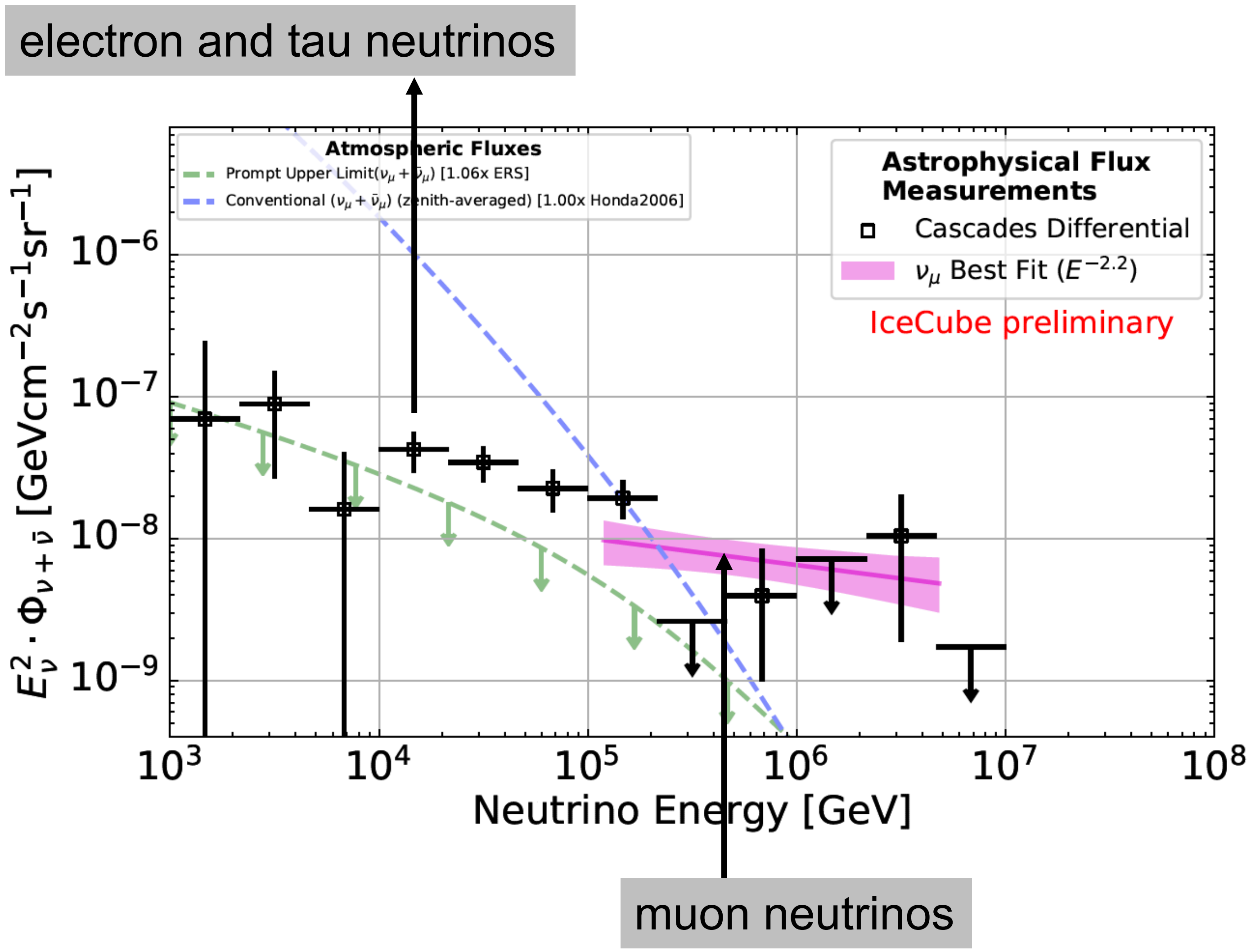
Track (ν_μ)

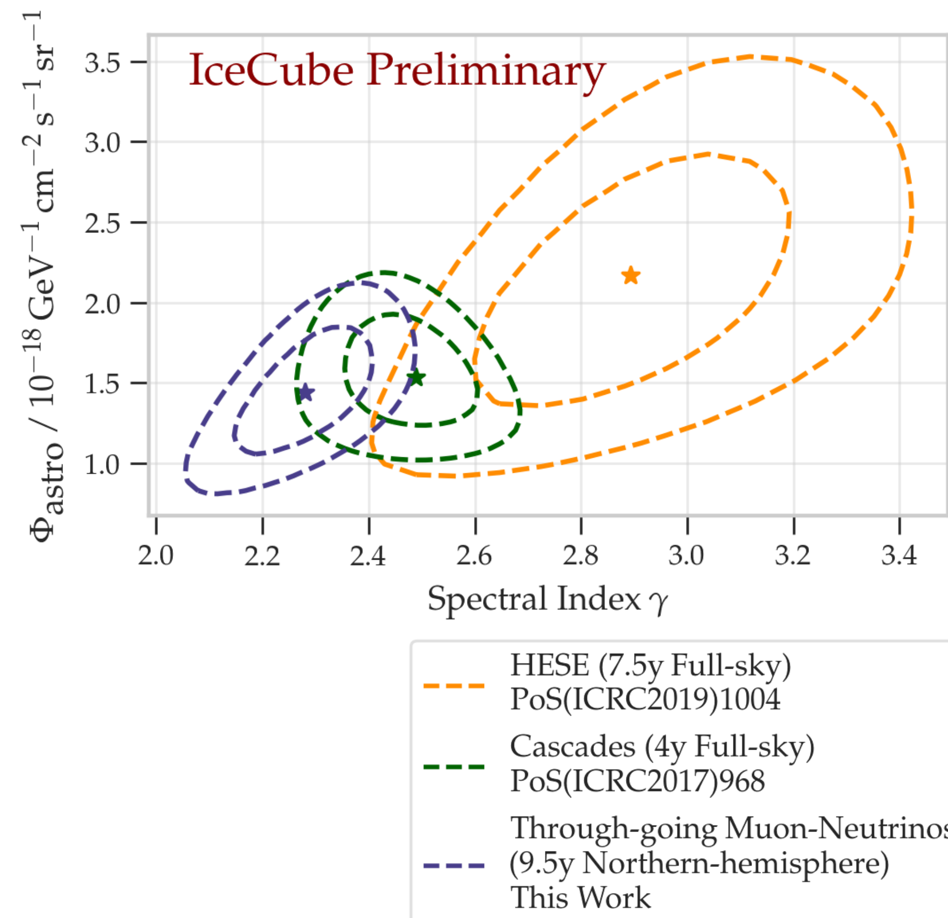
(b)



- IceCube experiment reported detection of astro-ν (E ~ PeV) in 2013
- Shower: good for spectrum
- Track: good for source search

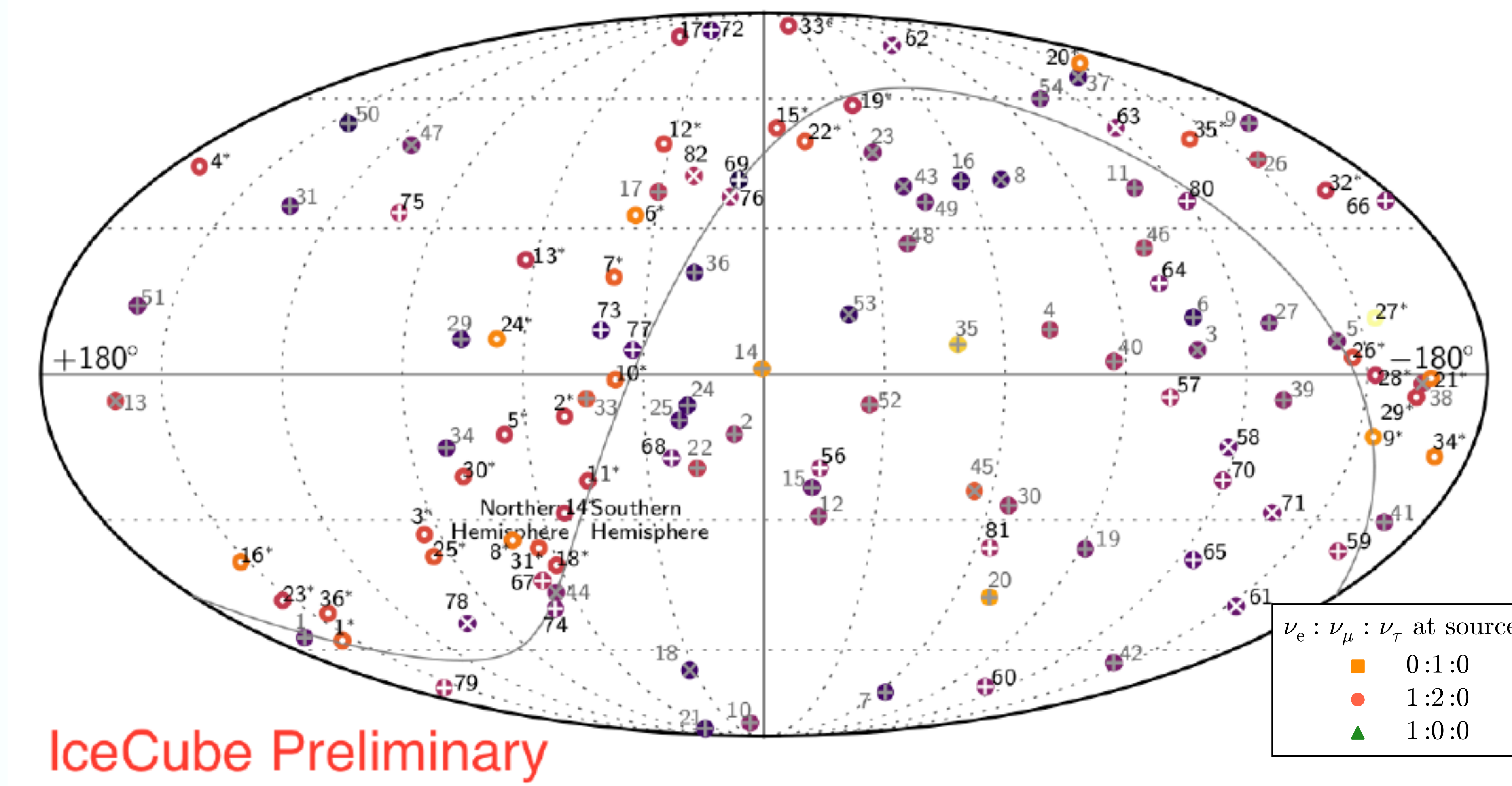
Neutrino Spectrum



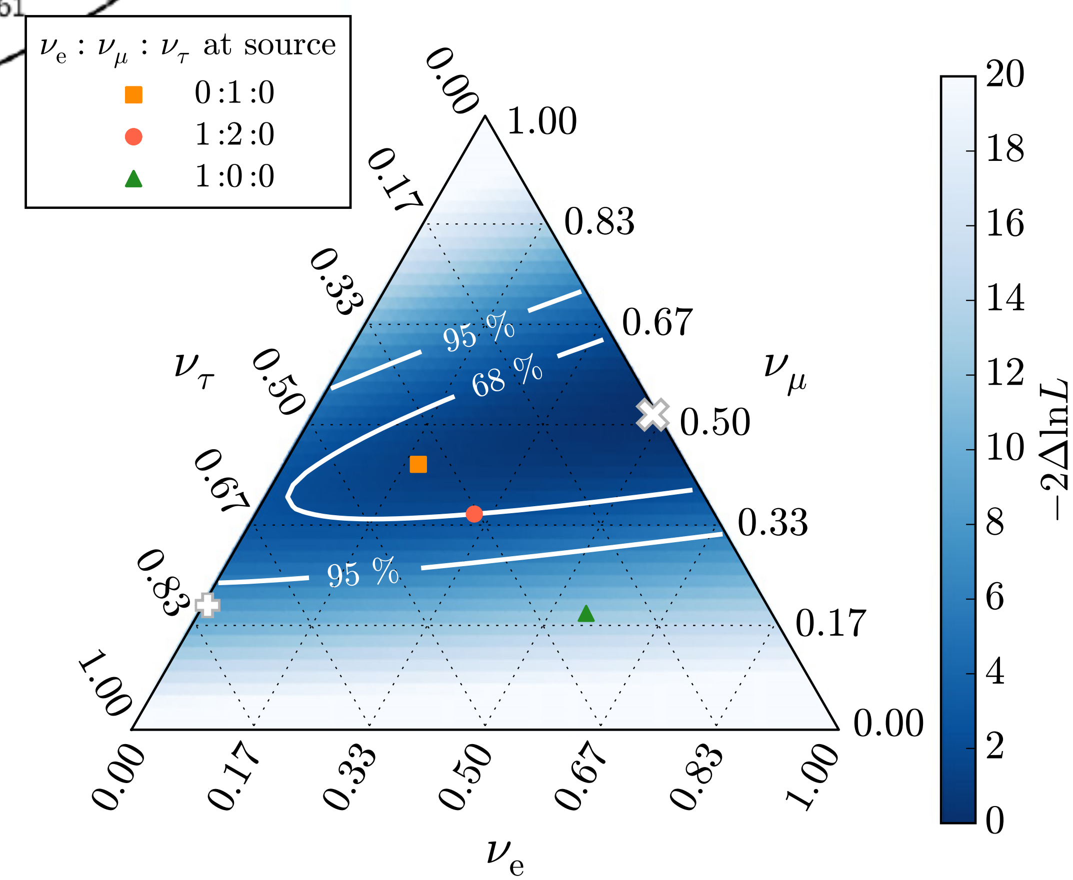


- Track analysis: flat spectrum (E > 200 TeV)
- Cascade analysis: soft spectrum (E > 1 TeV)
- Hint of 2 component??   Uncertainty of analyses??

Arrival Direction

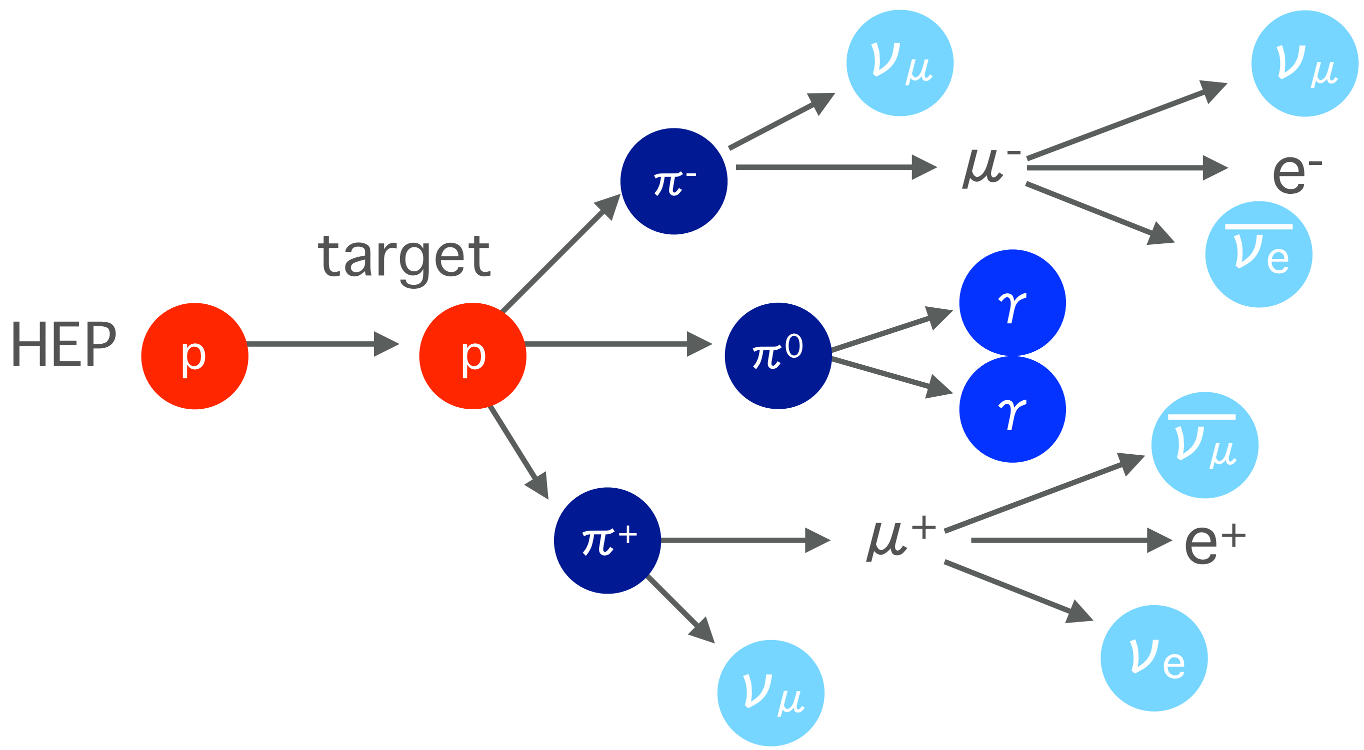


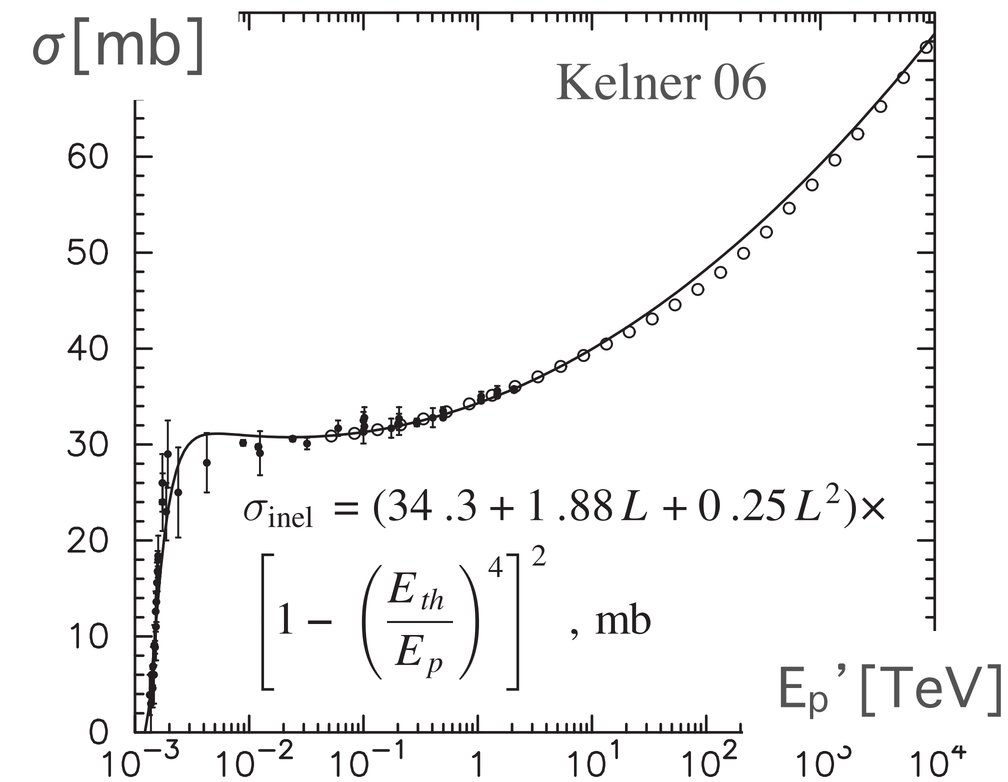
- Isotropic → Extragalactic origin
- No point-source detection so far
- Neutrino flavor ratio is consistent with pion decay
  [(1:2:0) at Source]



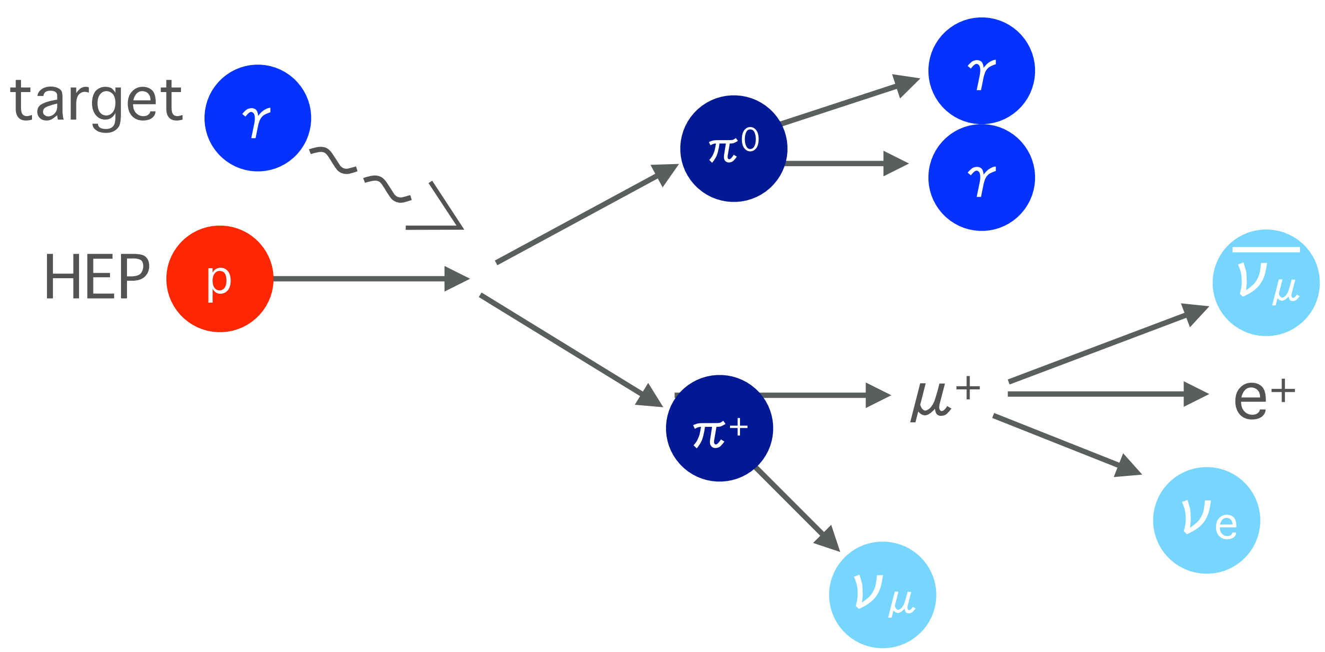
Neutrino Production Process

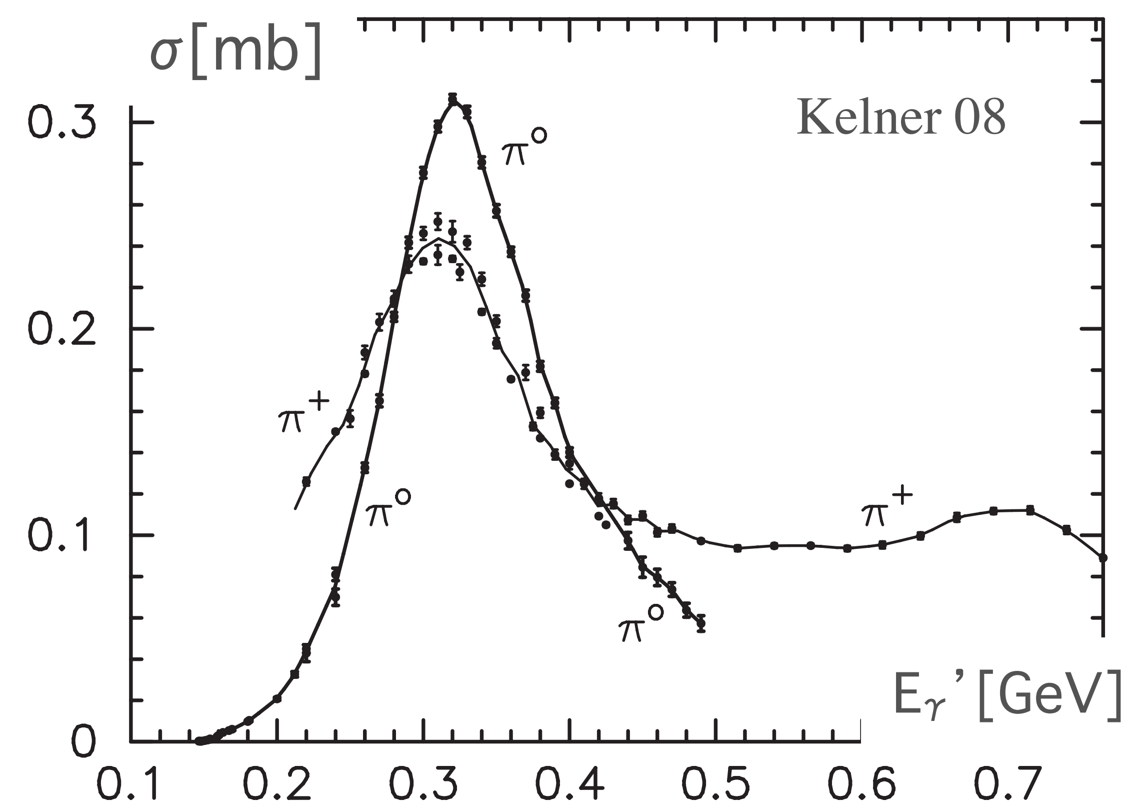
- pp inelastic collision





- Photomeson production (pγ)





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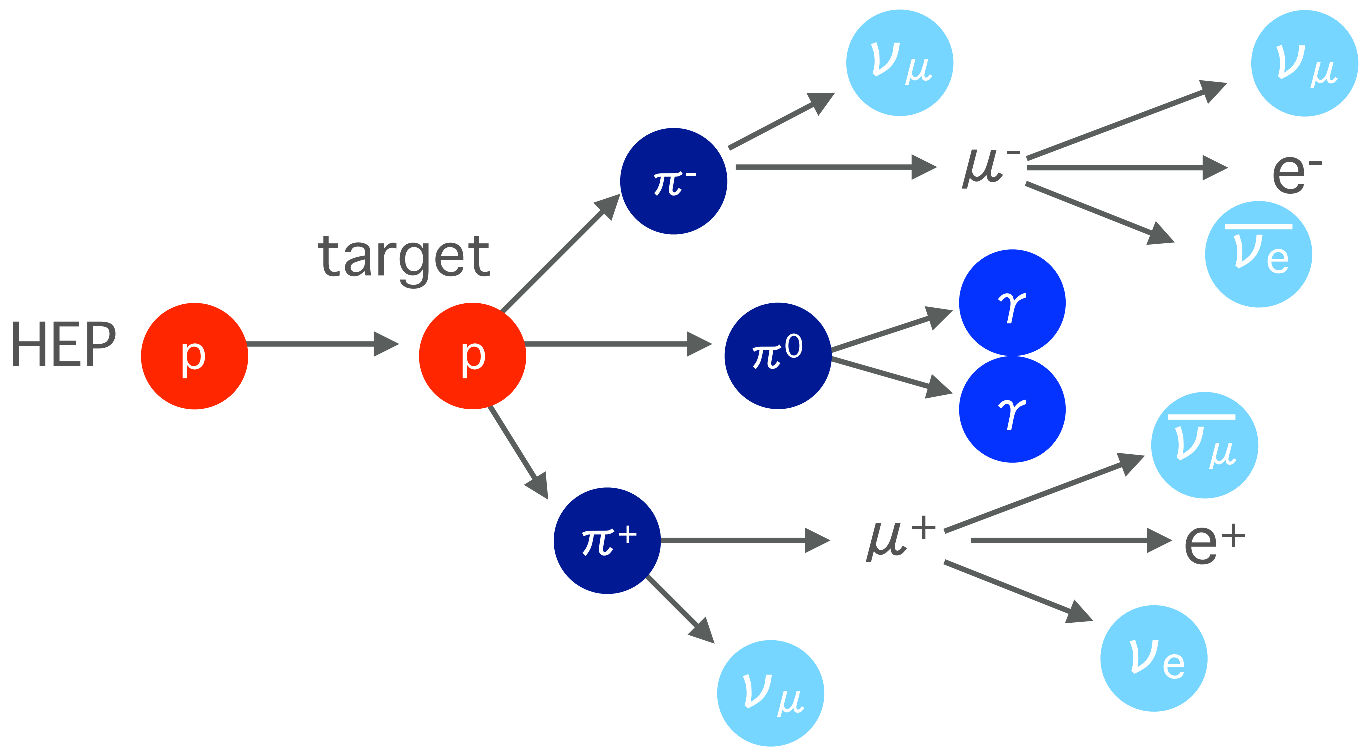
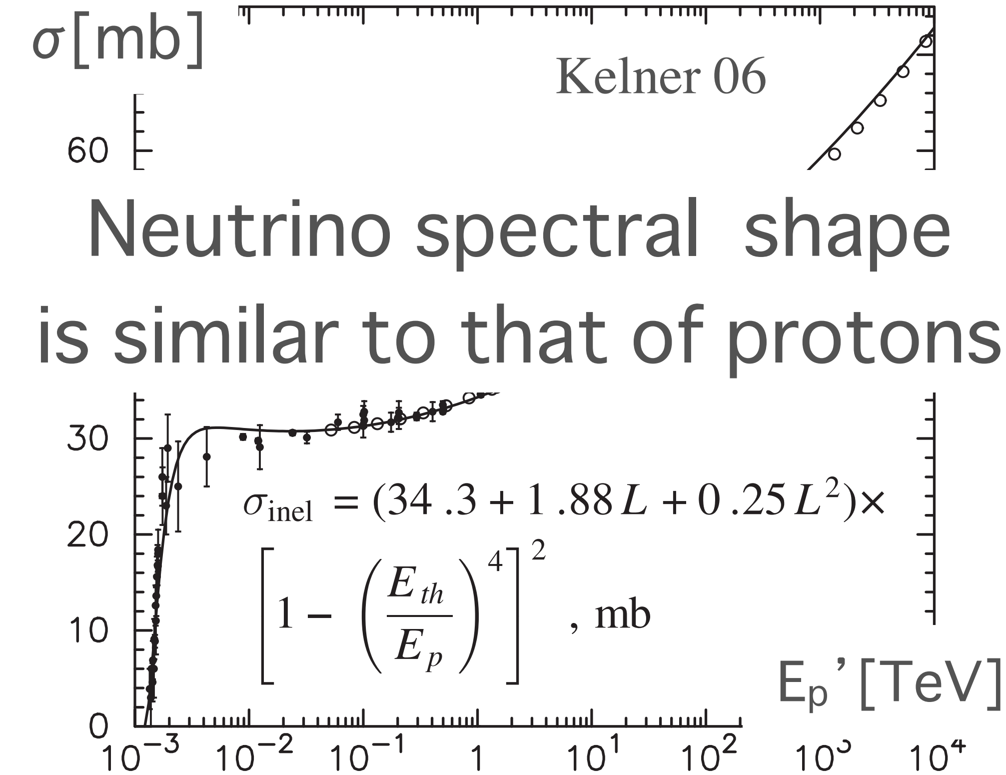
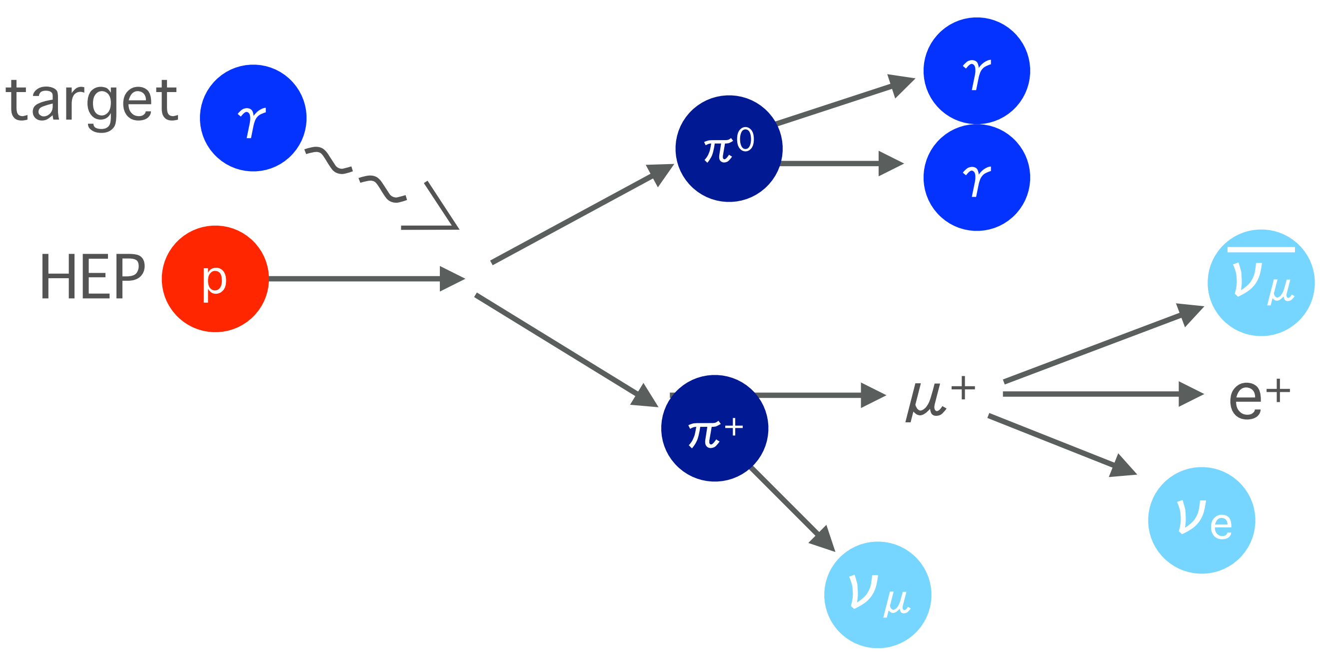
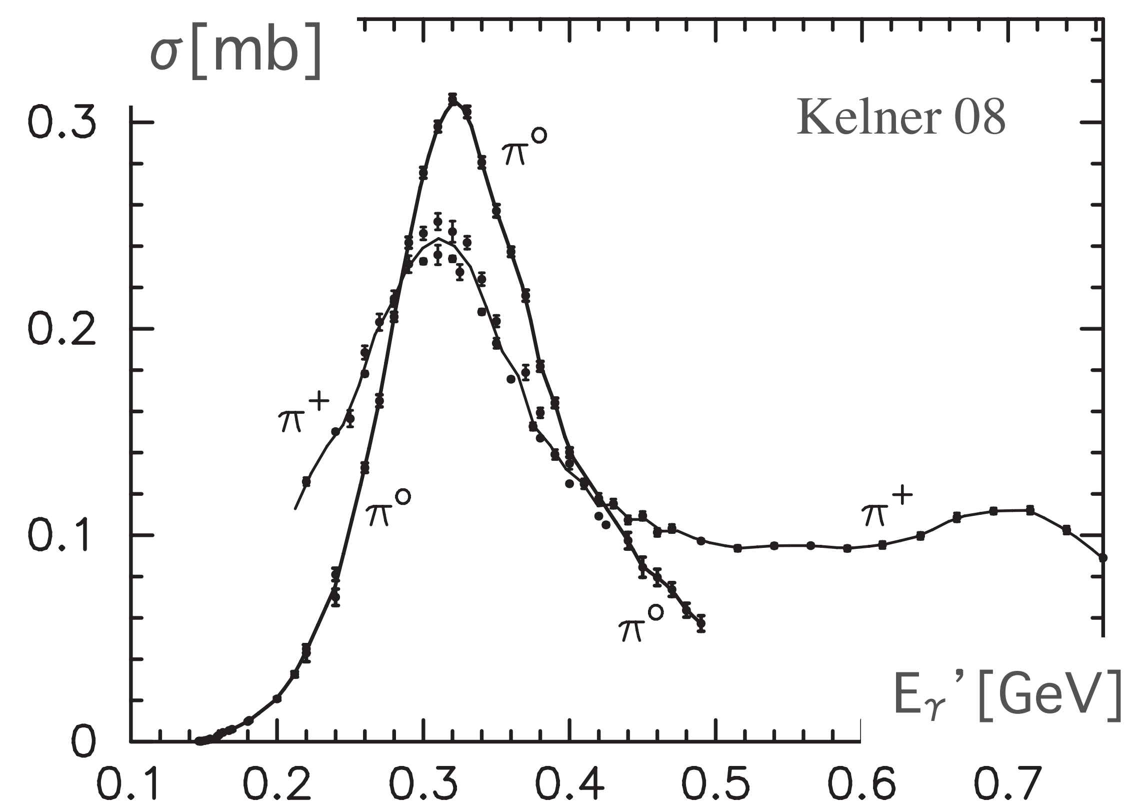




Neutrino spectral shape is similar to that of protons

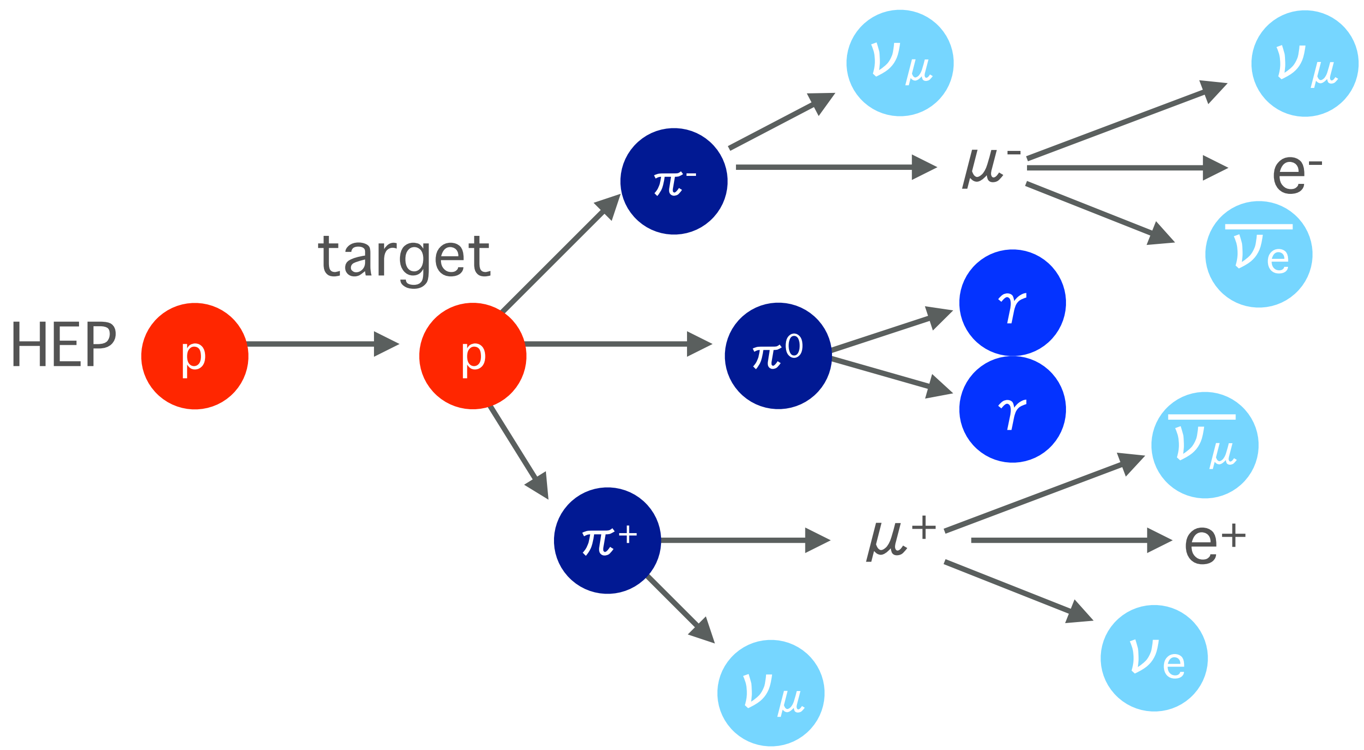
- Photomeson production (pγ)

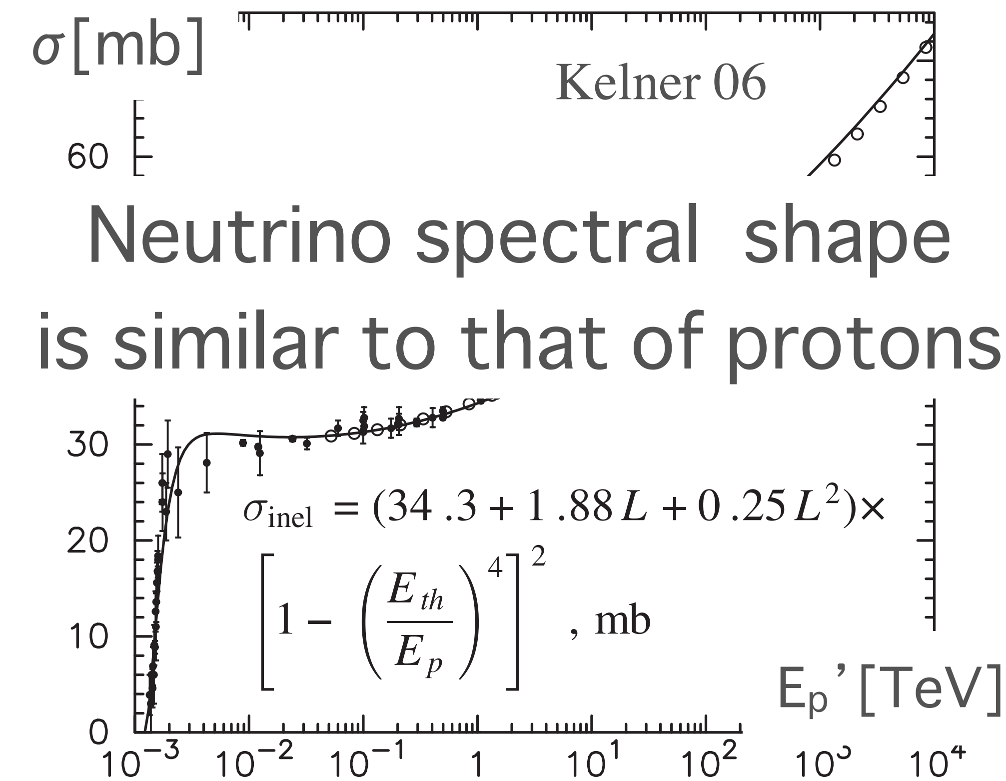




Neutrino Production Process

- pp inelastic collision





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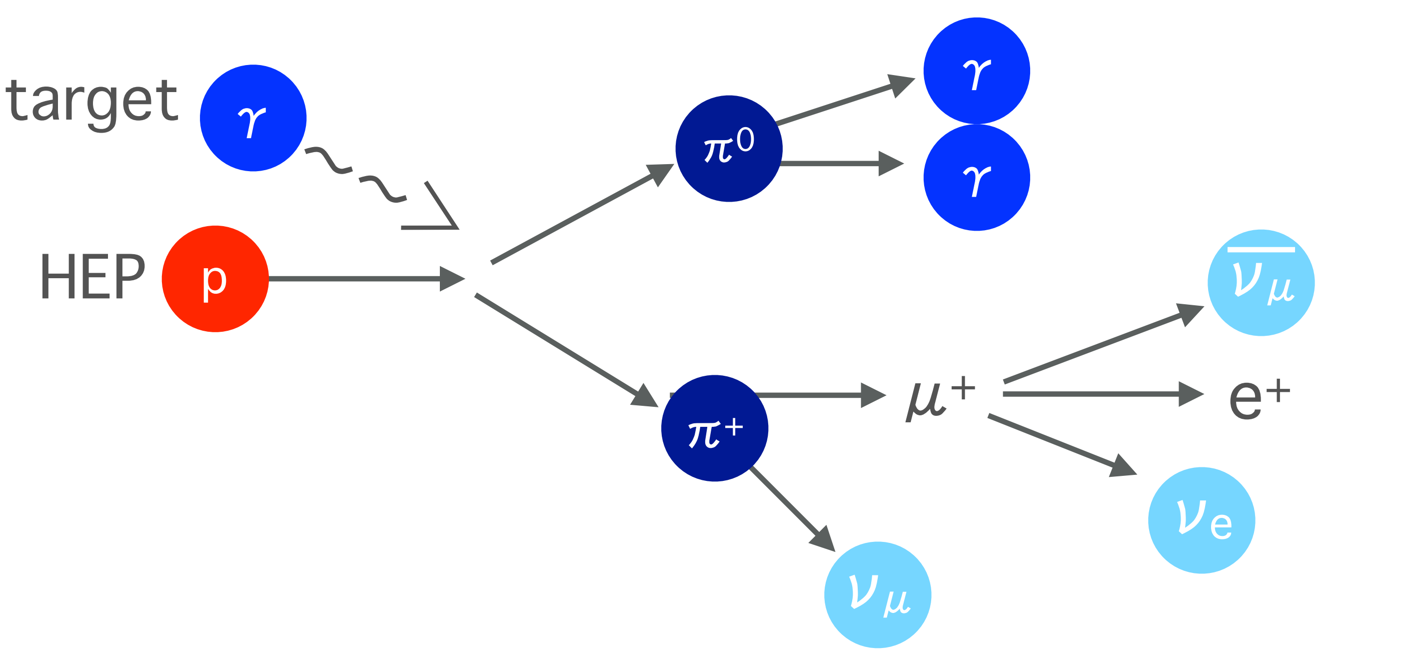
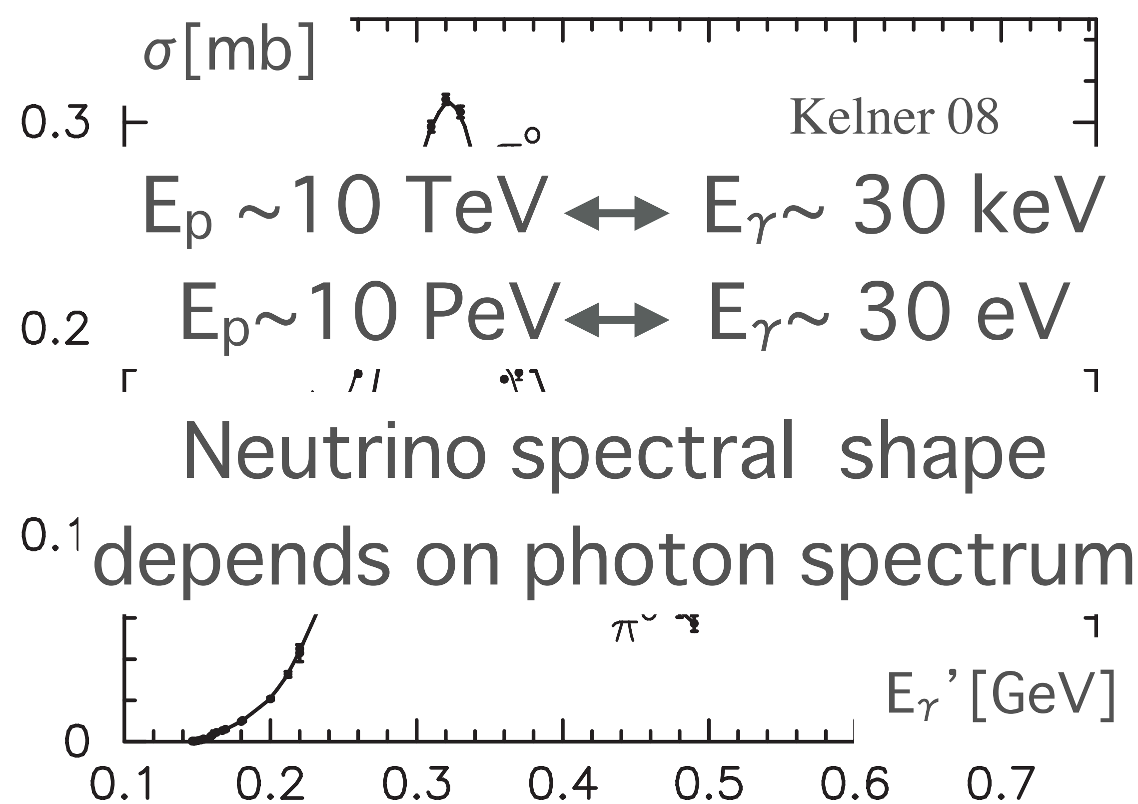




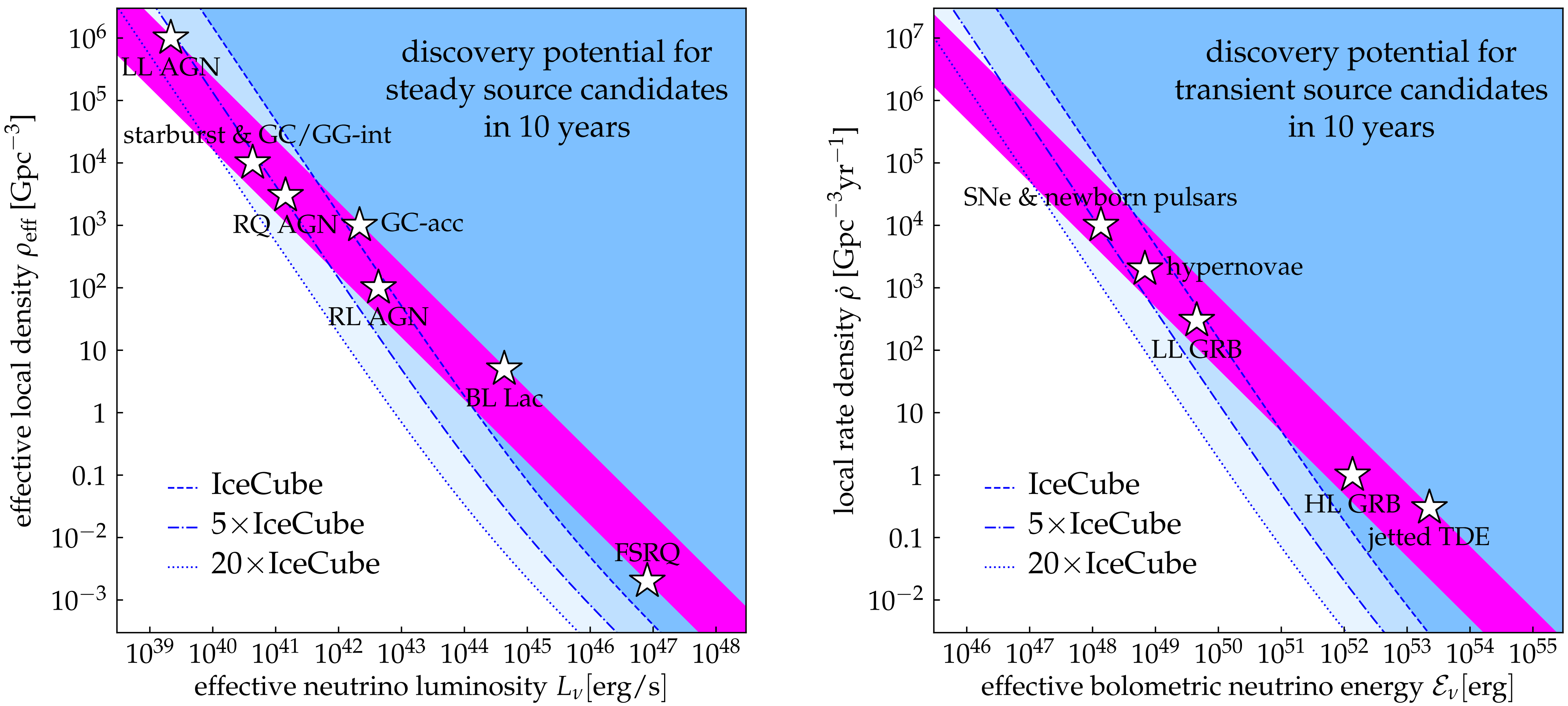
$E_p \sim 10$ TeV ↔ $E_\gamma \sim 30$ keV

$E_p \sim 10$ PeV ↔ $E_\gamma \sim 30$ eV

Neutrino spectral shape depends on photon spectrum

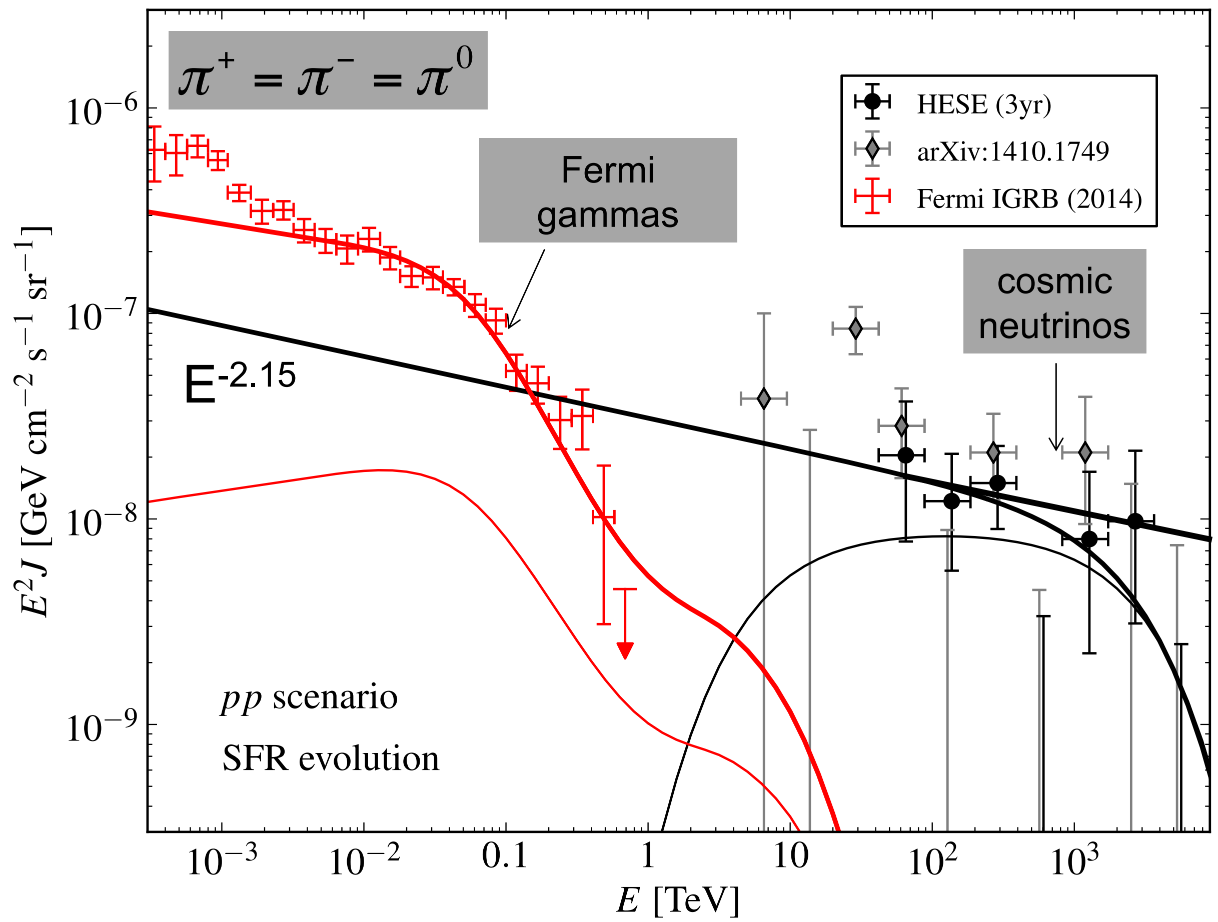
Point Source Constraint

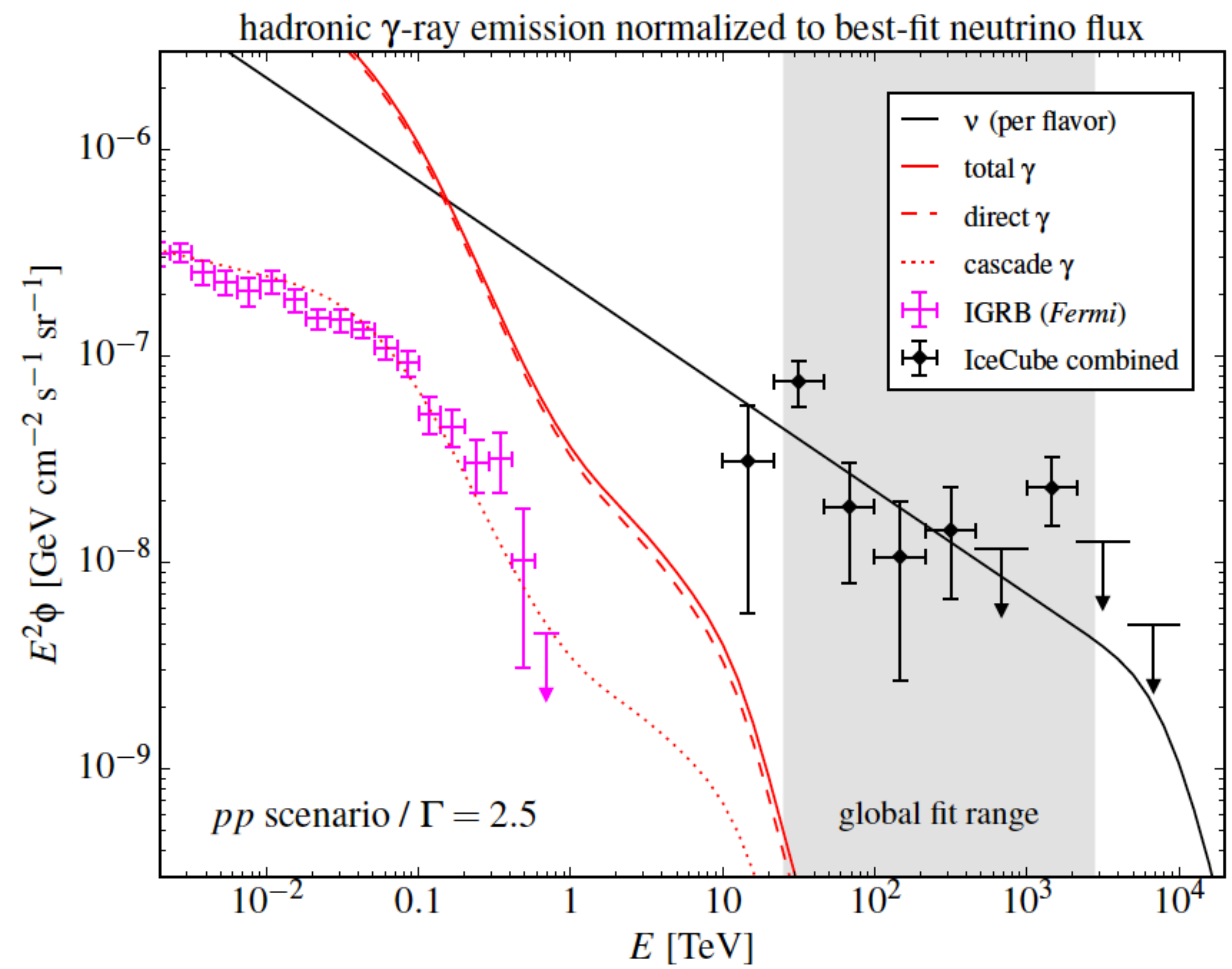
see Murase & Waxman 16



- No point-source detection
  → High number density of neutrino sources
- IceCube already disfavors luminous sources (GRBs, Blazars, Jetted TDEs)

Gamma-ray Constraints





- Astrophysical νs are accompanied with γ rays
- ν intensity at 10 TeV > γ-ray intensity at 100 GeV
  → accompanying γ rays overshoot Fermi data
  → ν sources should be opaque to γ rays

Murase et al. 2013, 2016
Ahler & Halzen 2017

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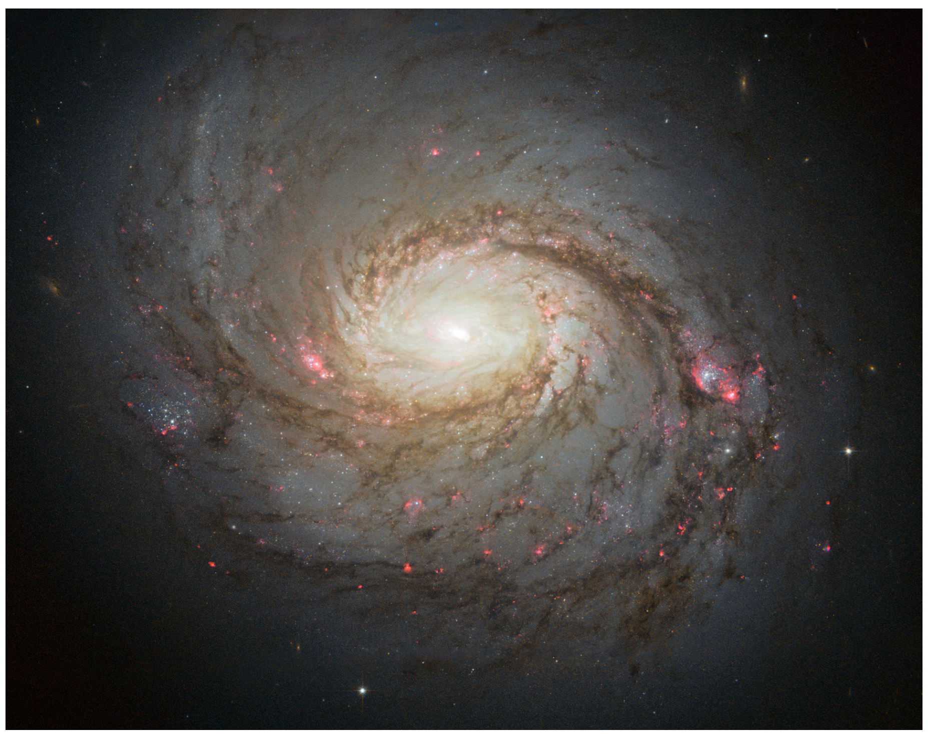
Active Galactic Nuclei (AGNs)

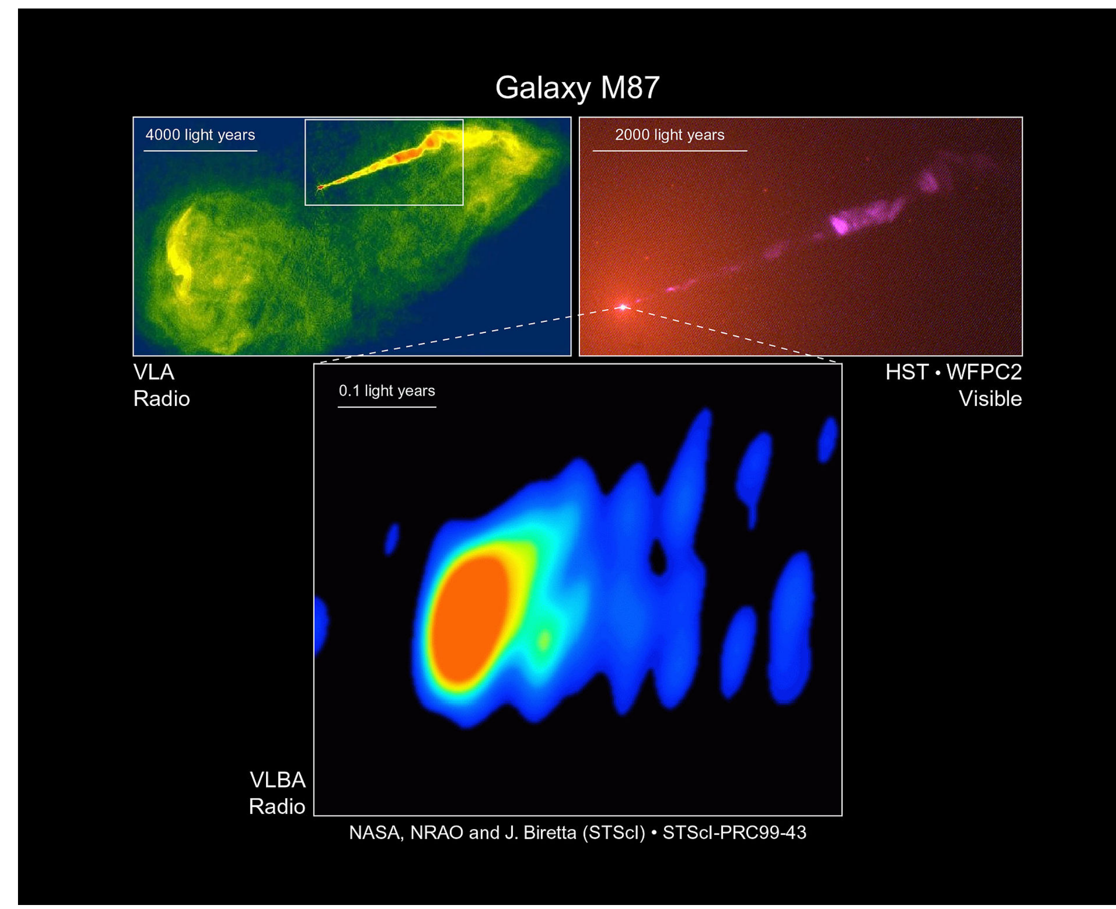
- Radio-quiet AGNs



M77 (NGC 1068): Wikipedia©

- No prominent jet
- 90% of AGNs

- Radio-loud AGNs



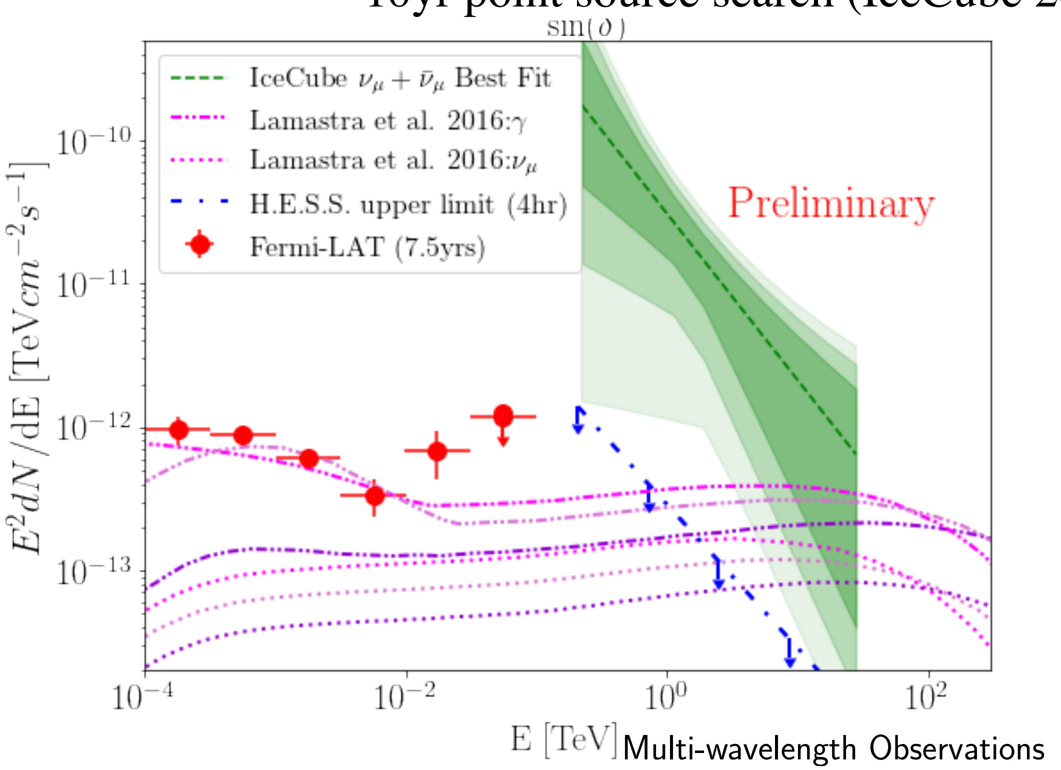
M87 (NGC 4486): Wikipedia©

- Powerful Jets
- 1-10 % of AGNs

Active Galactic Nuclei (AGNs)

- Radio-quiet AGNs

10yr point source search (IceCube 2019)



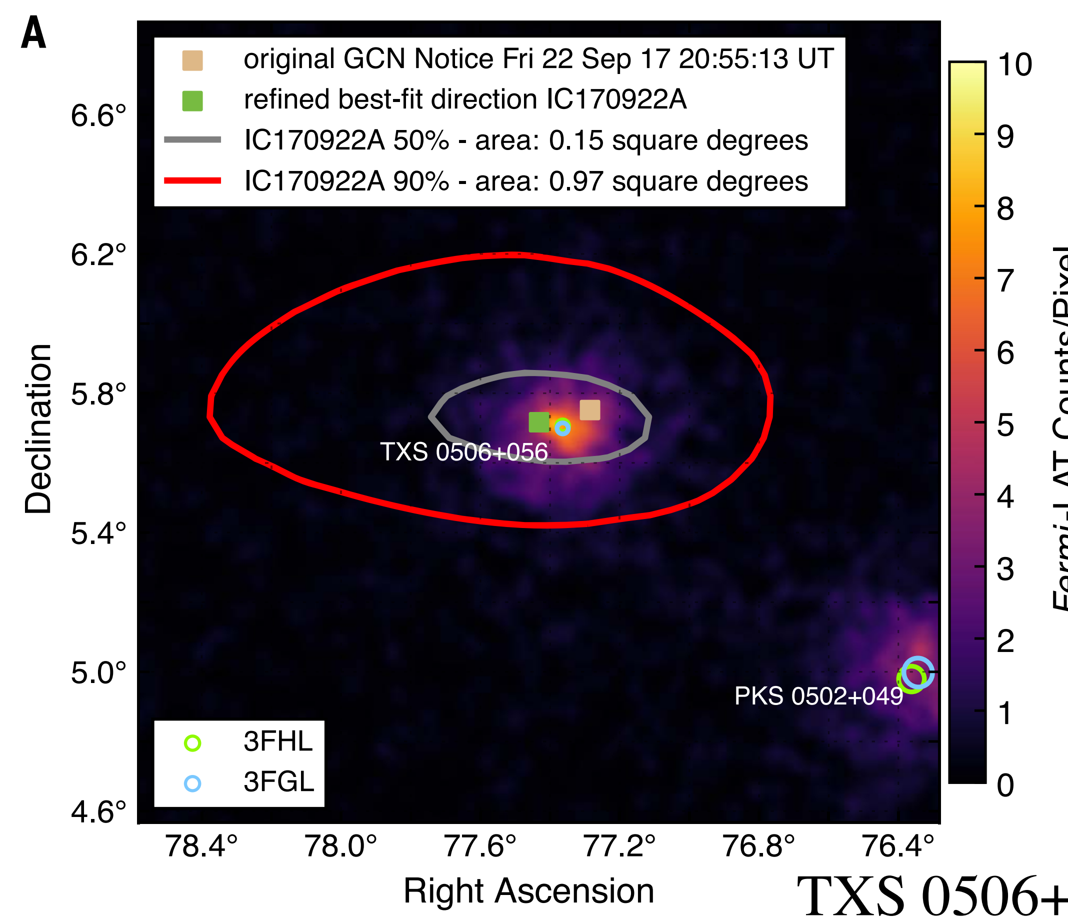
M77 (NGC 1068)

- Hottest Point in Northern Sky (2.9 σ)

- Radio-loud AGNs

Multi-messenger campaign

IceCube 2018



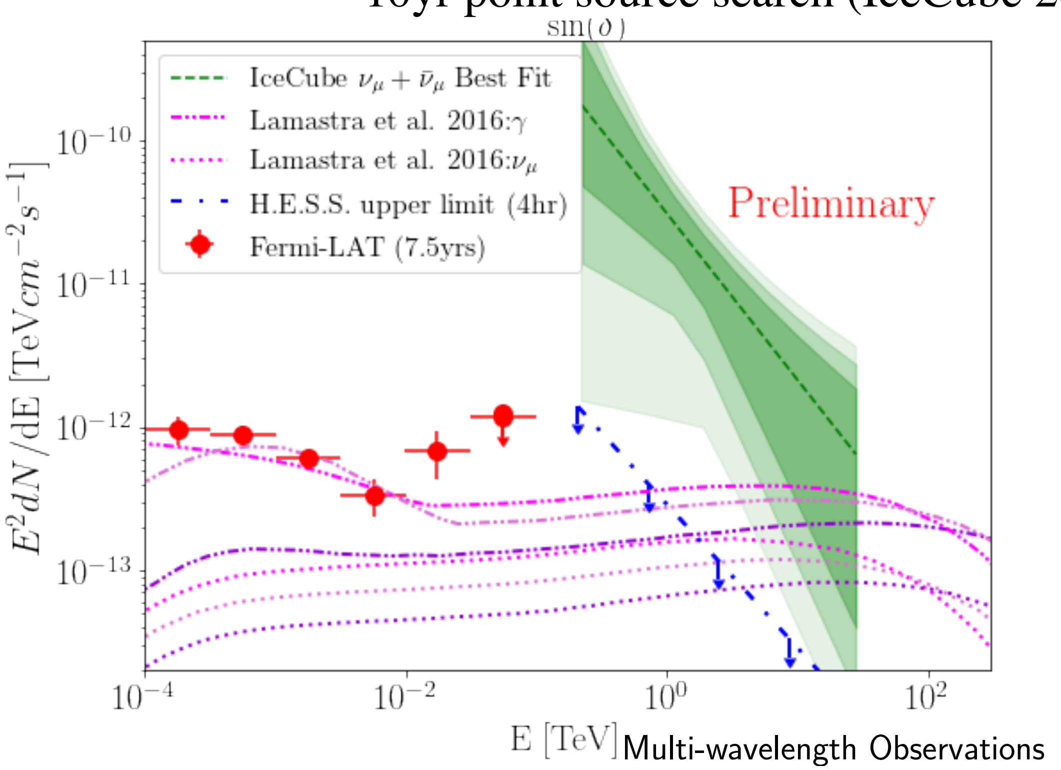
TXS 0506+056

- IC 170922 (3 σ)
- 2014-2015 Neutrino flare (3.5 σ)

Active Galactic Nuclei (AGNs)

- Radio-quiet AGNs

10yr point source search (IceCube 2019)



Multi-wavelength Observations

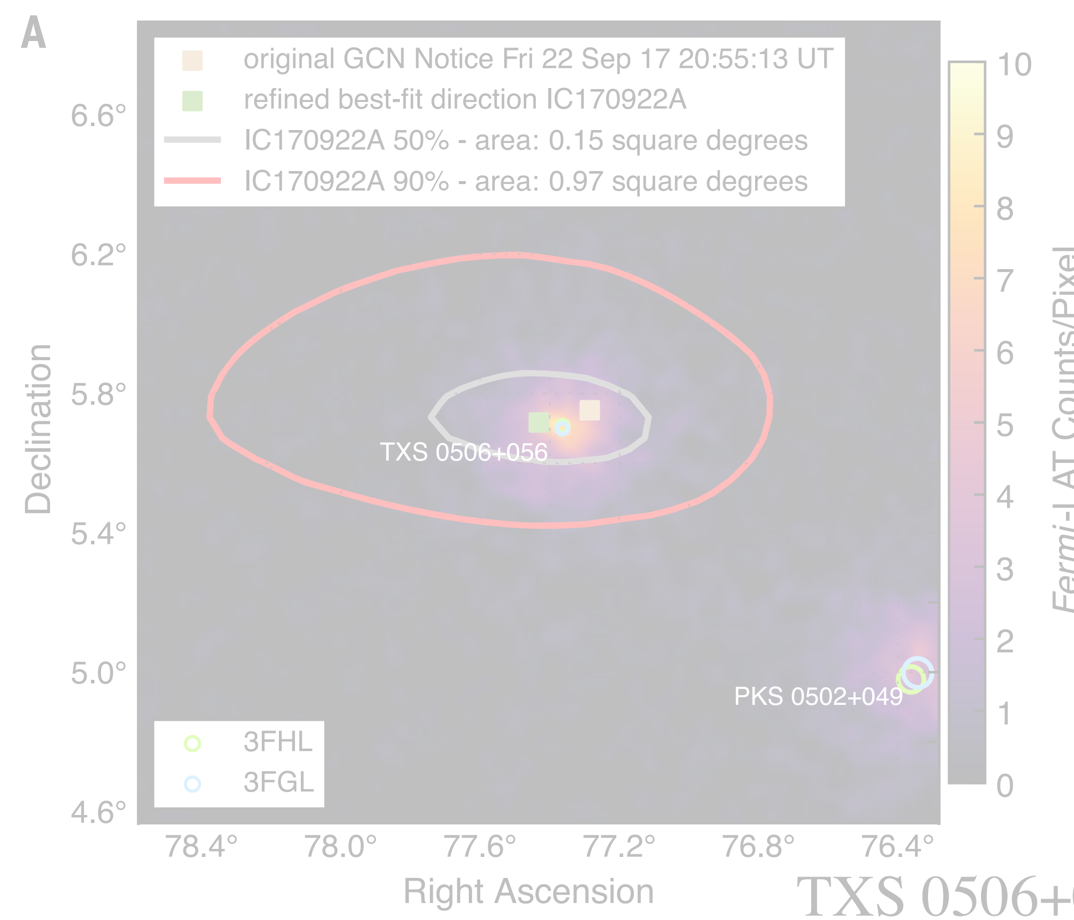
M77 (NGC 1068)

- Hottest Point in Northern Sky (2.9 σ)

- Radio-loud AGNs

Multi-messenger campaign

IceCube 2018



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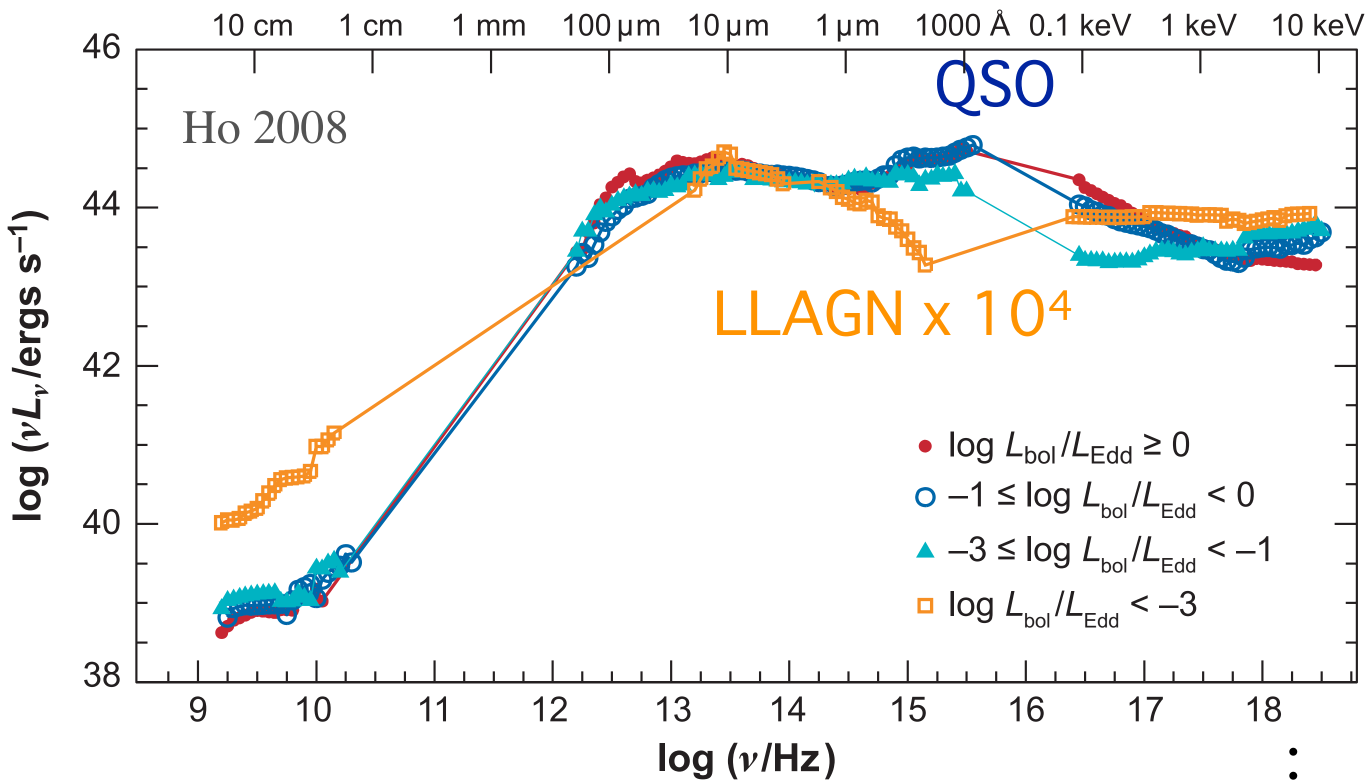
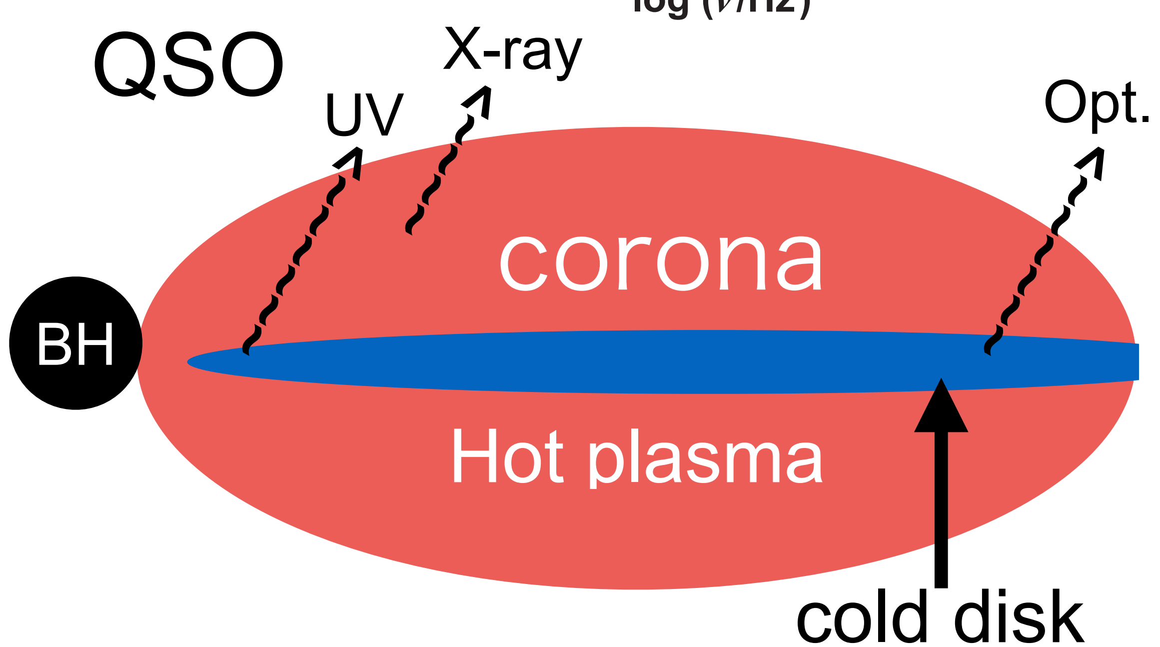
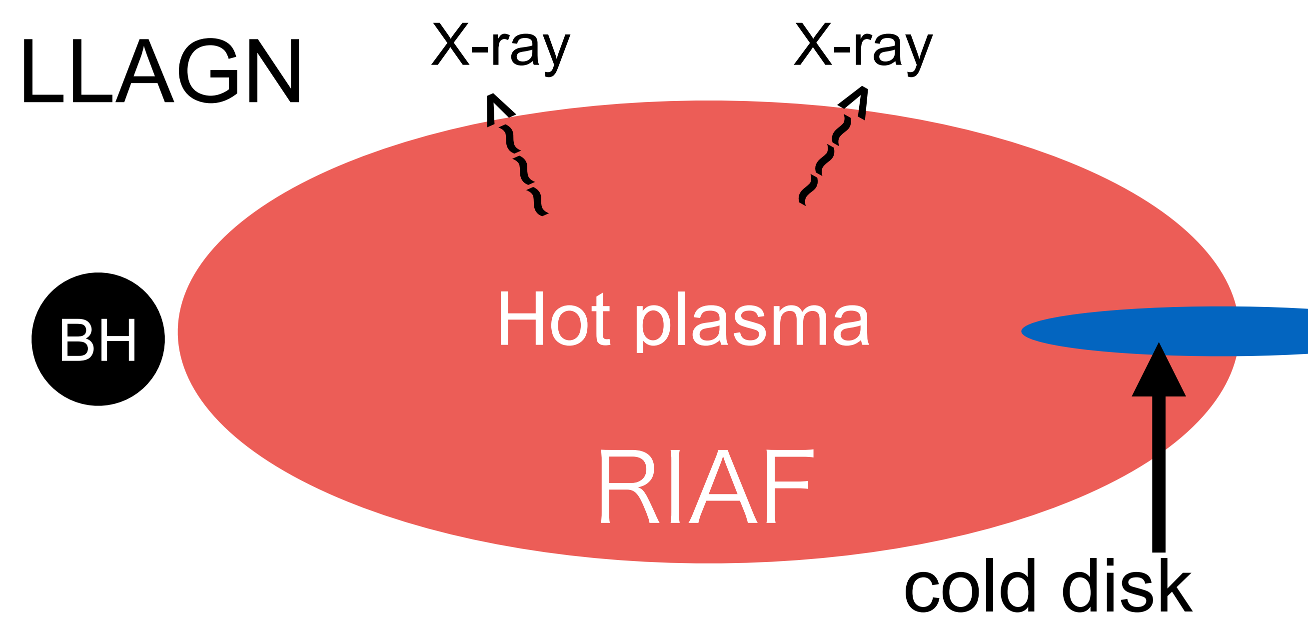
Radio-quiet AGNs

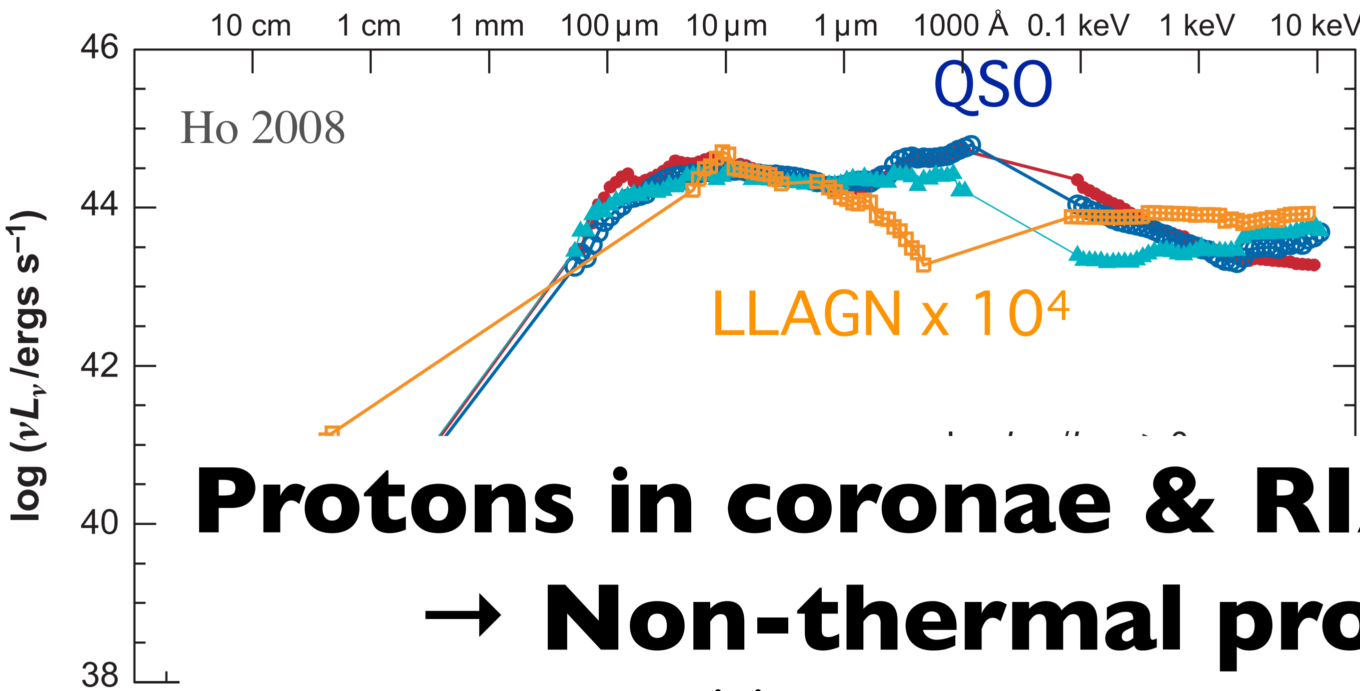


- QSO: Blue bump & X-ray
  →Optically thick disk + coronae
- LLAGN: No blue bump & X-ray
  →Optically thin flow
  [Radiatively Inefficient Accretion Flow (RIAF)]



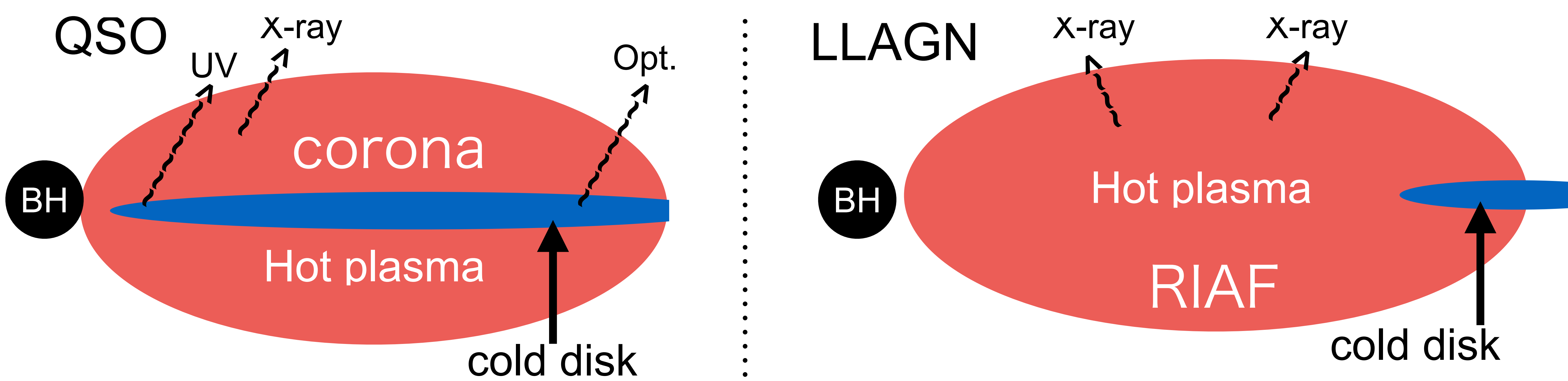


Radio-quiet AGNs



- QSO: Blue bump & X-ray →Optically thick disk + coronae
- LLAGN: No blue bump & X-ray →Optically thin flow

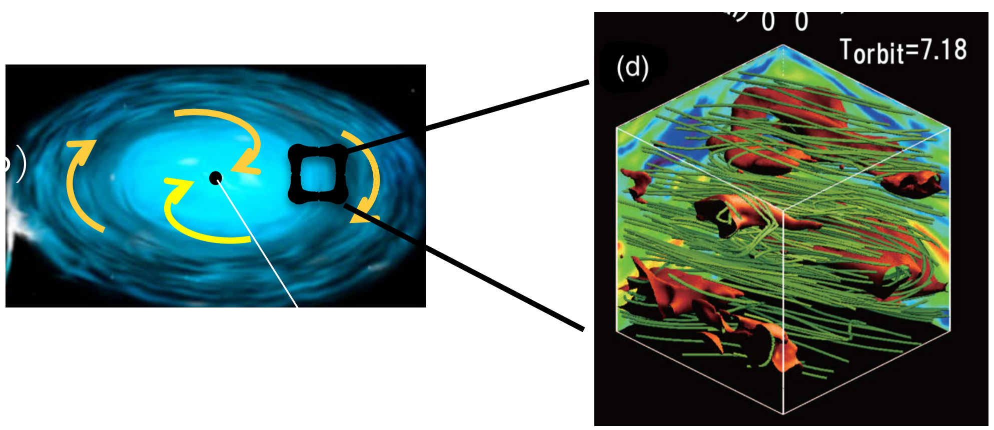
Protons in coronae & RIAFs are collisionless
→ Non-thermal proton production
** electrons are collisional **



Particle Acceleration in Accretion Flows

Particle-In-Cell Simulations

MHD + Test Particle Simulations

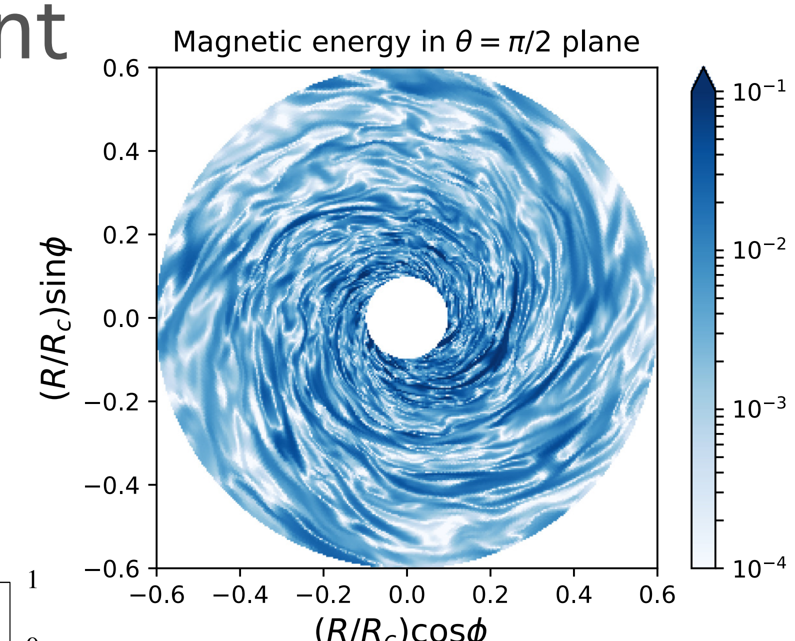


Numerical Simulations

turbulent

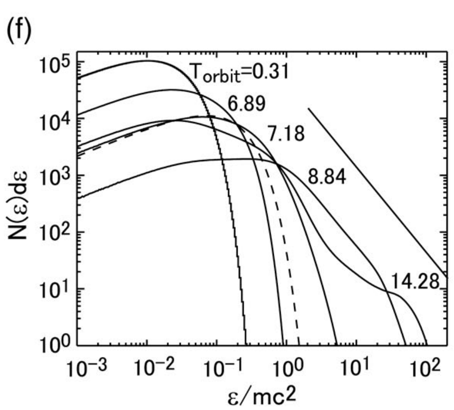
SSK et al. 2016; SSK et al. 2019

see also Lynn et al. 2014

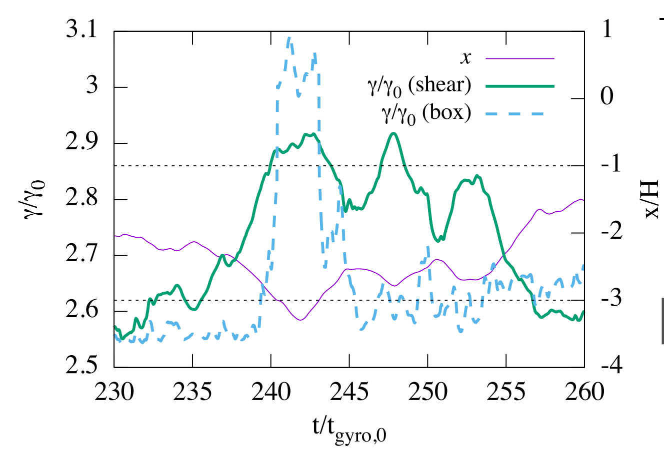


Hoshino 2013; Hoshino 2015
Riquelme et al. 2012; Kuntz et al. 2016

turbulent



Non-thermal



Energy change

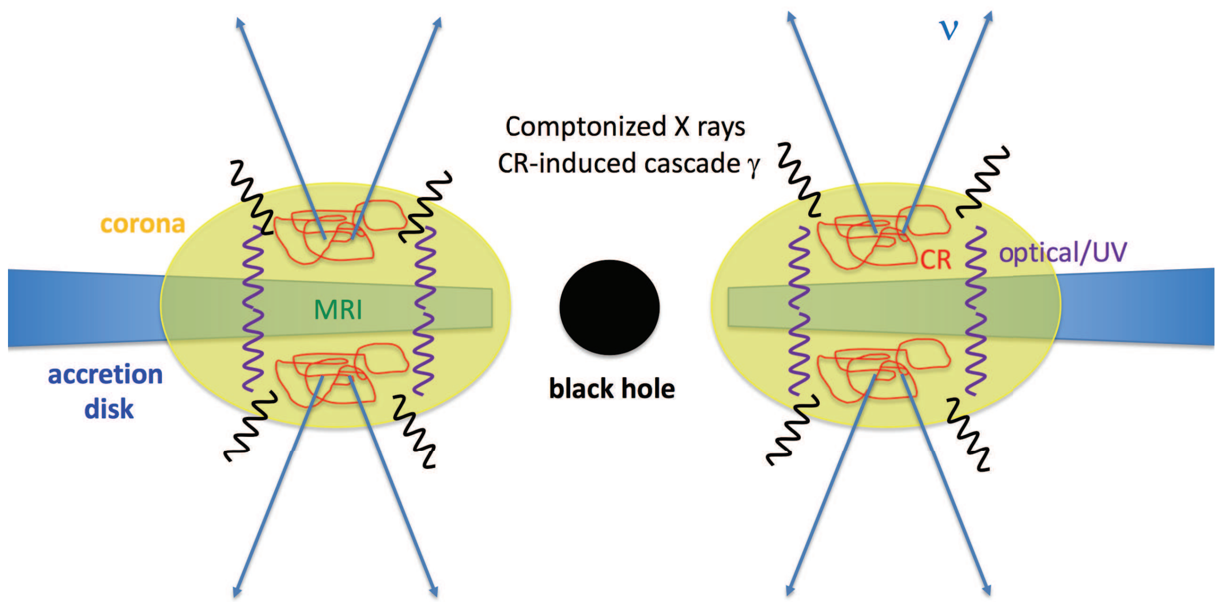
Magnetic reconnection or wave-particle interaction accelerates CRs,

High-Energy Emission

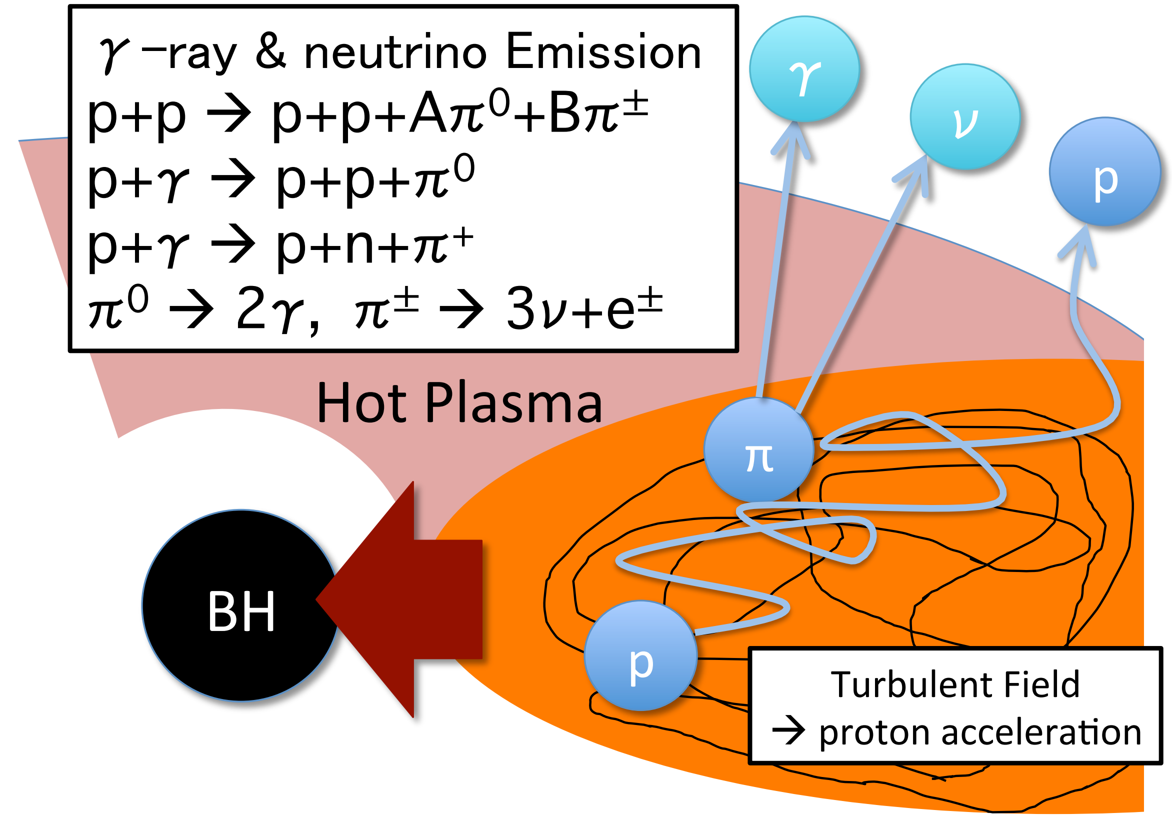
Mahadevan et al. 1997; SSK et al. 2015

Murase, SSK et al. 2019

Coronae in QSOs



RIAFs in LLAGNs



- Fairly high photon & proton densities in Coronae & RIAFs
- Interaction between CRs and matter/photons
  → neutrino & gamma-ray emission
- TeV-PeV γ-rays are reprocessed to MeV-GeV γ rays

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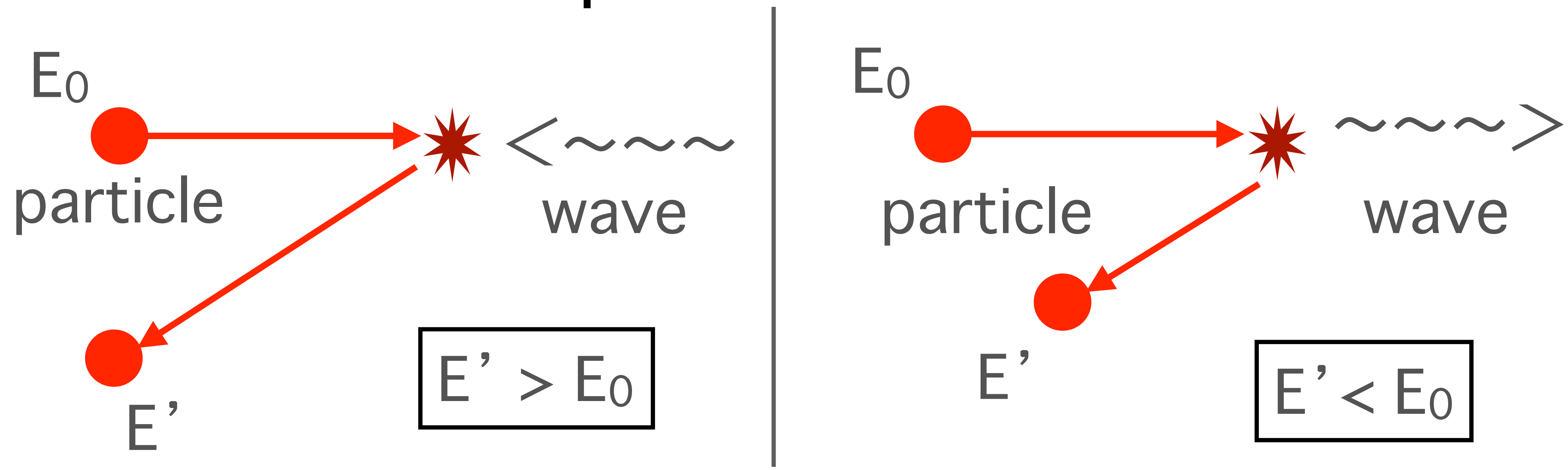
- Summary

Stochastic Acceleration

e.g.) Fermi 1949, Stawarz & Petrosian 2008, SSK et al. 2015

- Consider plasma with turbulent fields



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

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

According to quasi-linear theory,
gyro-resonant scattering results in

$D_p \propto p^q$ (power-spectrum $P_k = P_0 k^{-q}$)

Basic Equations

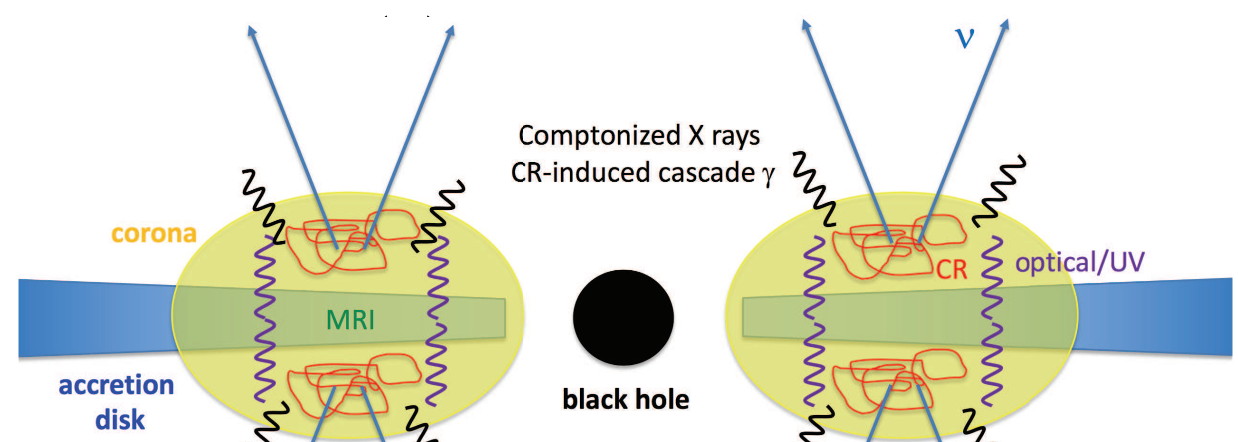
- Stochastic Acceleration (SA)

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

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

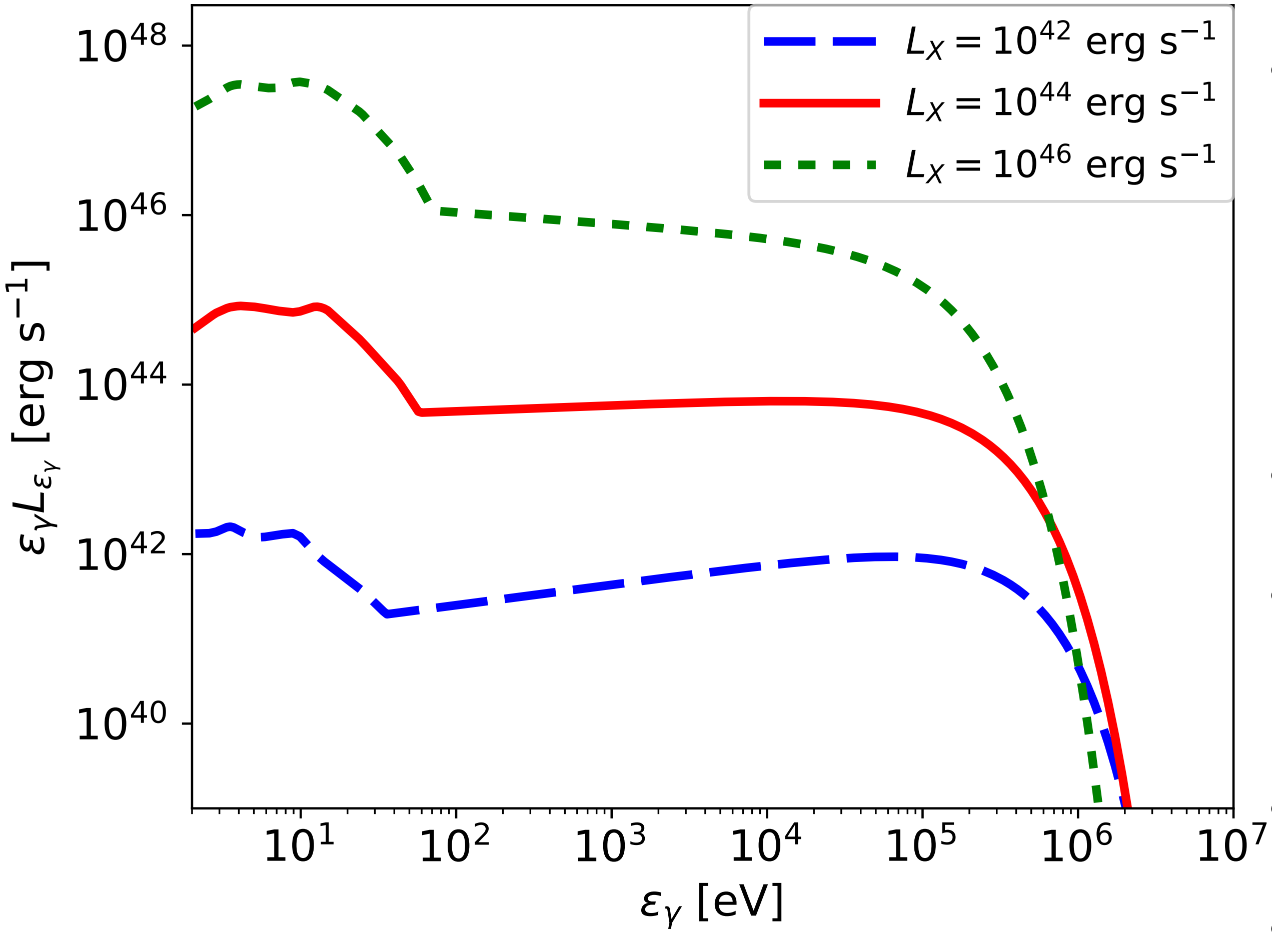
$$D_{\varepsilon_p} \approx \frac{\zeta c}{H}\left(\frac{V_A}{c}\right)^2\left(\frac{r_L}{H}\right)^{q-2}\varepsilon_p^2,$$

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



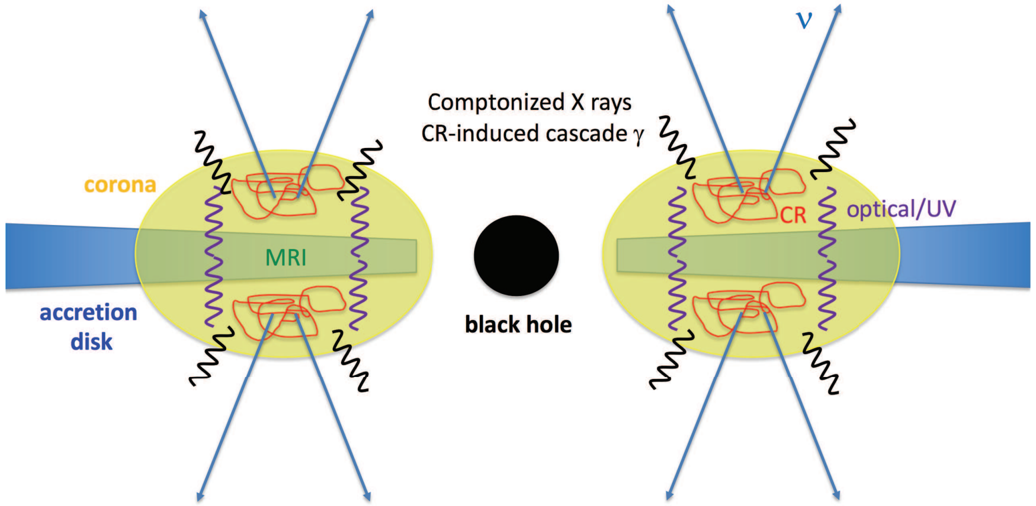
- Escape : Diffusive escape & infall to SMBH
- Coolings: pp inelastic collision, photomeson production
  proton synchrotron, Bethe-Heitler process ($p+\gamma \rightarrow p+e^{+}+e^{-}$)
- Muon & Pion Coolings are negligibly inefficient
- HE γ-rays are absorbed by target photons ($\gamma+\gamma \rightarrow e^{+}+e^{-}$)
  → electron & positron emit high-energy gamma-rays
  → Calculate electromagnetic cascades

Target Photon Field

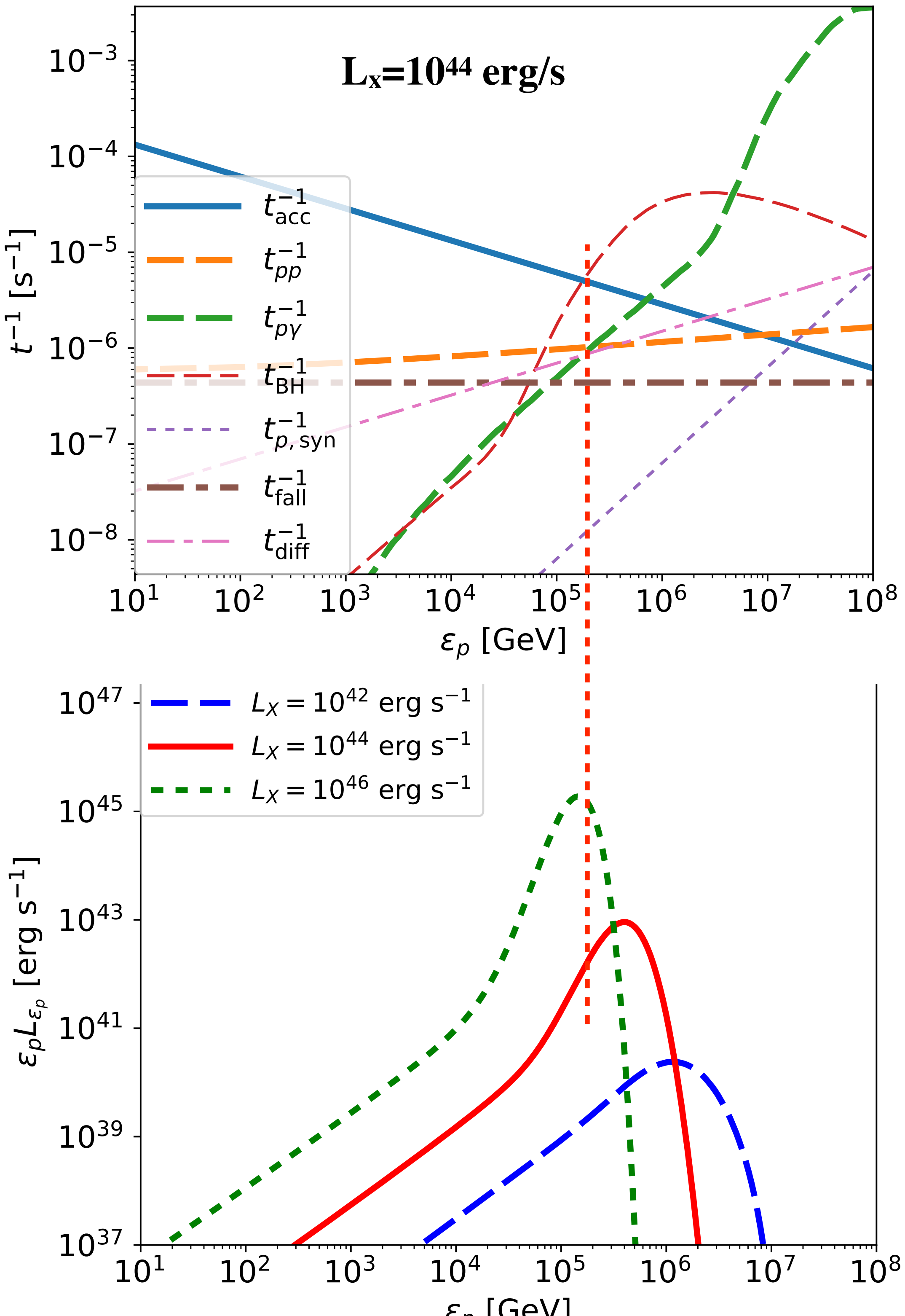


- Luminous objects
  → Rich observational data
  → **We can use empirical relation based on observations**
- Opt-UV photons from accretion disk
- X-rays from hot coronae above thin disk
- Higher L_{opt}/L_x for higher L_x AGNs
- Softer spectra for higher L_x AGNs

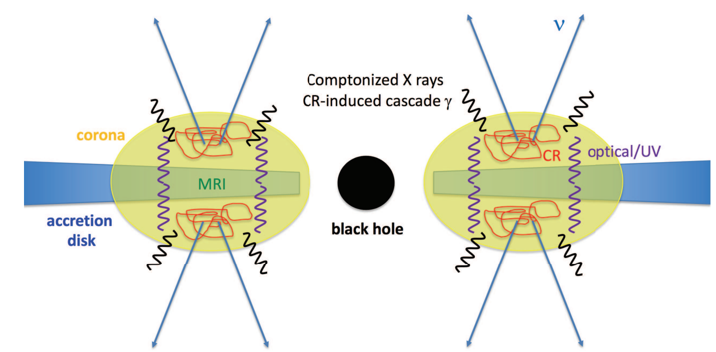
Pringle 1981, Ho 2008, Hopkins 2007
Bat AGN Spectroscopic Survey 2017, 2018,
Mayers et al. 2018



Rates & CR Spectrum

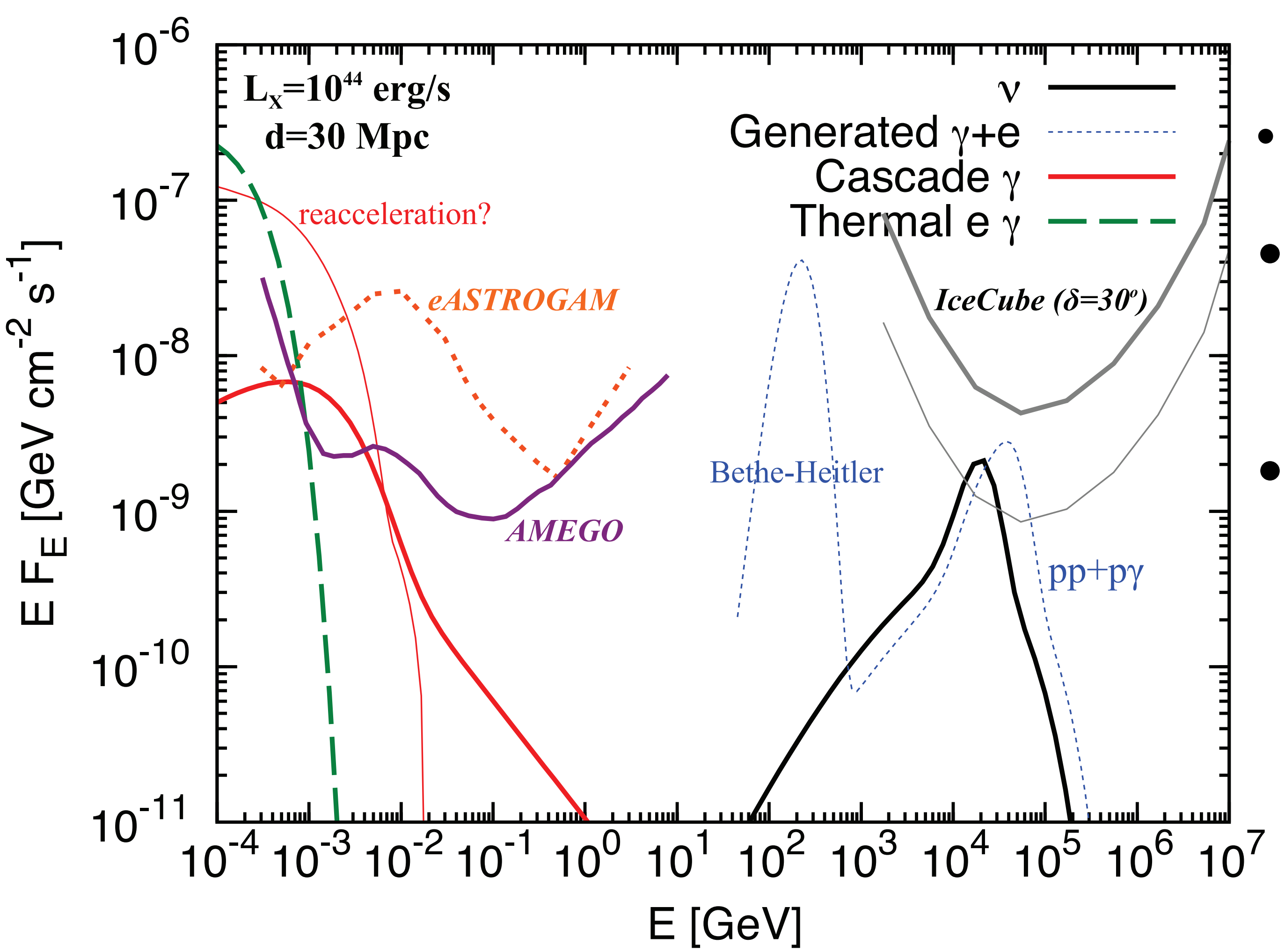


- $E_{p,max}$ ~ 10^5 GeV by $t_{acc} = t_{BH}$
- BH suppresses ν production at E_p ~ 3×10^4 - 3×10^6 GeV
- Escape is inefficient

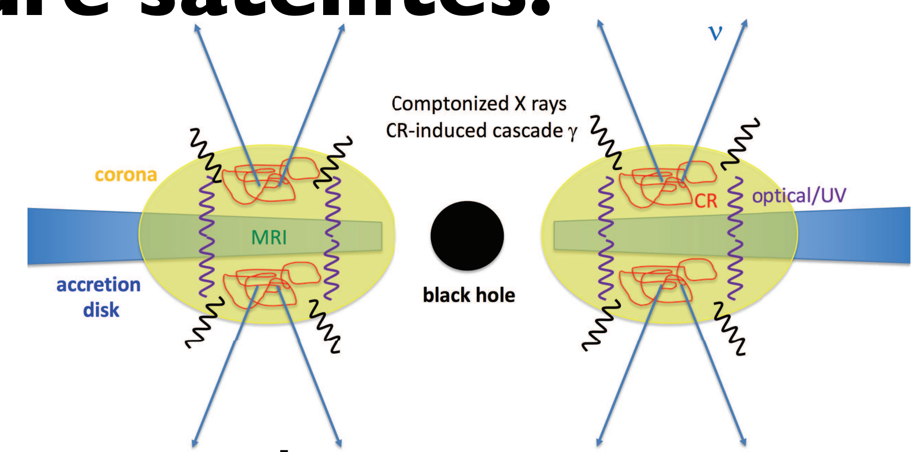


- Hard spectrum due to SA
- Pile up around E_{max}
- Higher L_x → lower E_{max} because of efficient cooling

HE particles from Nearby Seyfert Galaxies



- A typical Seyfert at 100 Mpc
- **pγ neutrinos are detectable by IceCube-Gen2**
- **MeV γ-rays can be detected by future satellites.**



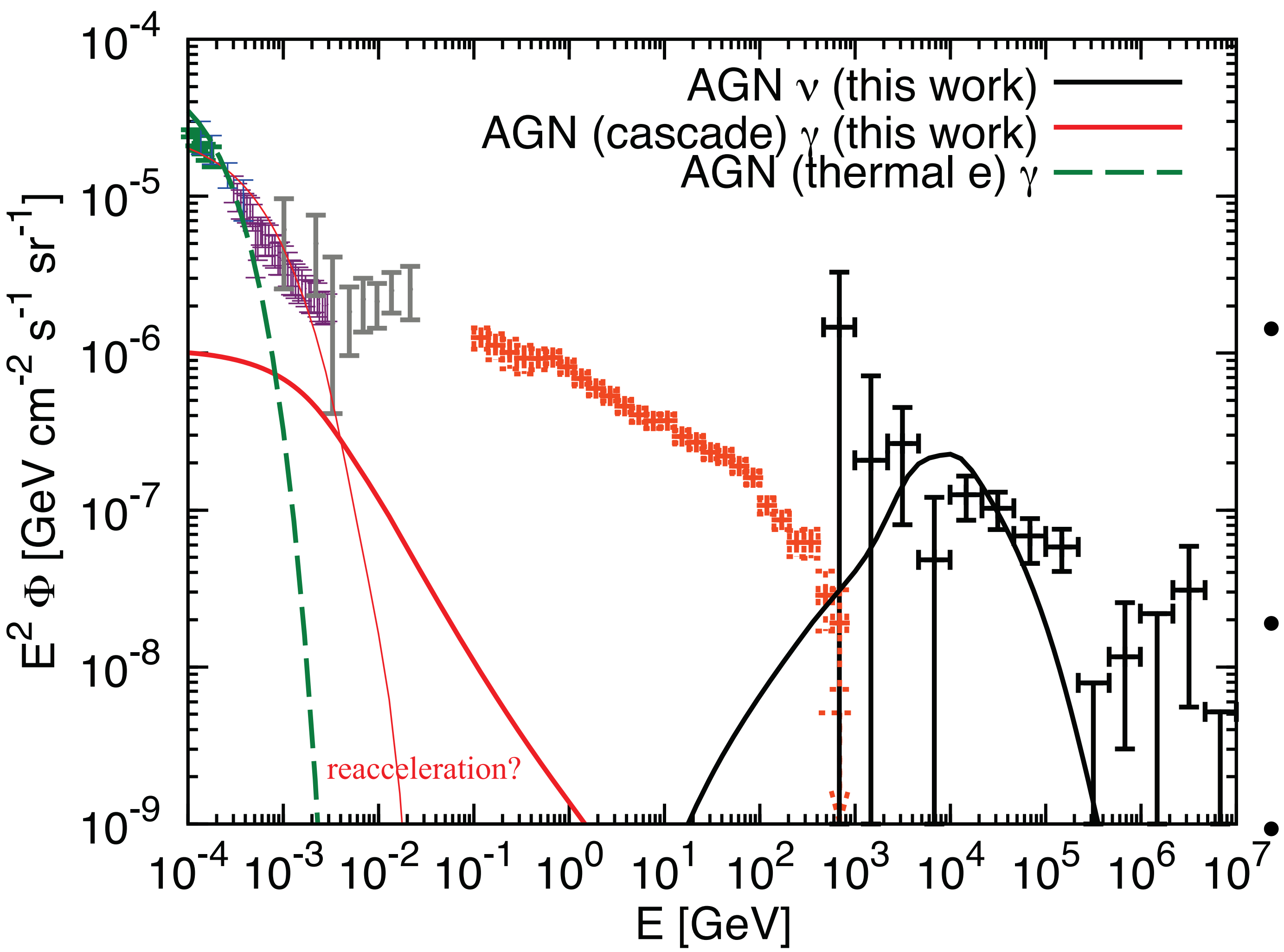
- MeV γ-ray luminosity is determined by B-H pair production
  → Ratio of γ to ν flux is fixed by the observed photon field
  → We can robustly test our model by future experiments

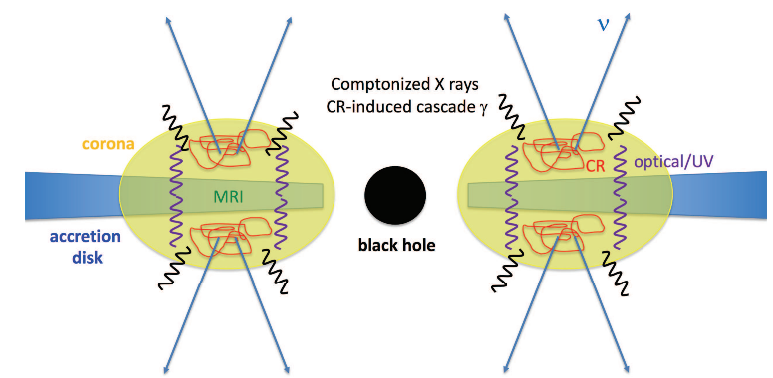
Extragalactic γ & ν Backgrounds

$$\Phi^{\rm diff}_{\nu,{\rm ob}}(E_{\nu,{\rm ob}}) = \frac{1}{4\pi}\int_{L_{\rm min}}^{L_{\rm max}} dL_{\rm X} \int_0^{z_{\rm max}} dz \frac{dn_0}{dL_{\rm X}} f(z) \frac{dV}{dz} \Phi_{\nu,{\rm ob}},$$

- AGNs with $L_X \sim 10^{44}$ erg/s provide the dominant contribution

e.g., Ueda et al. 2014





- We choose the injection efficiency so that our model can explain the MESE excess.
- **Energetically reasonable:** $P_{CR}/P_{th} \sim P_{CR}/P_B \sim 0.01$
- Cascade emission provides 10 - 30 % of MeV γ-ray background

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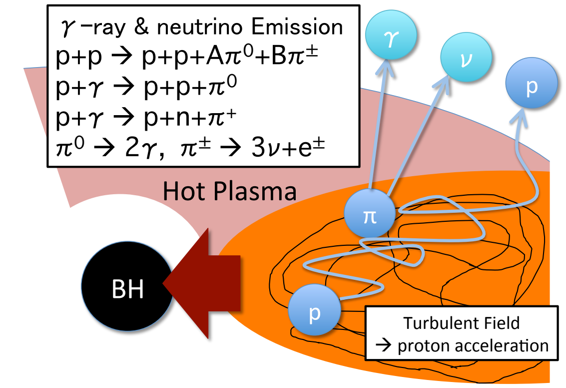


- Stochastic Acceleration (SA)

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

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

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

- Power-law Injection (PL)

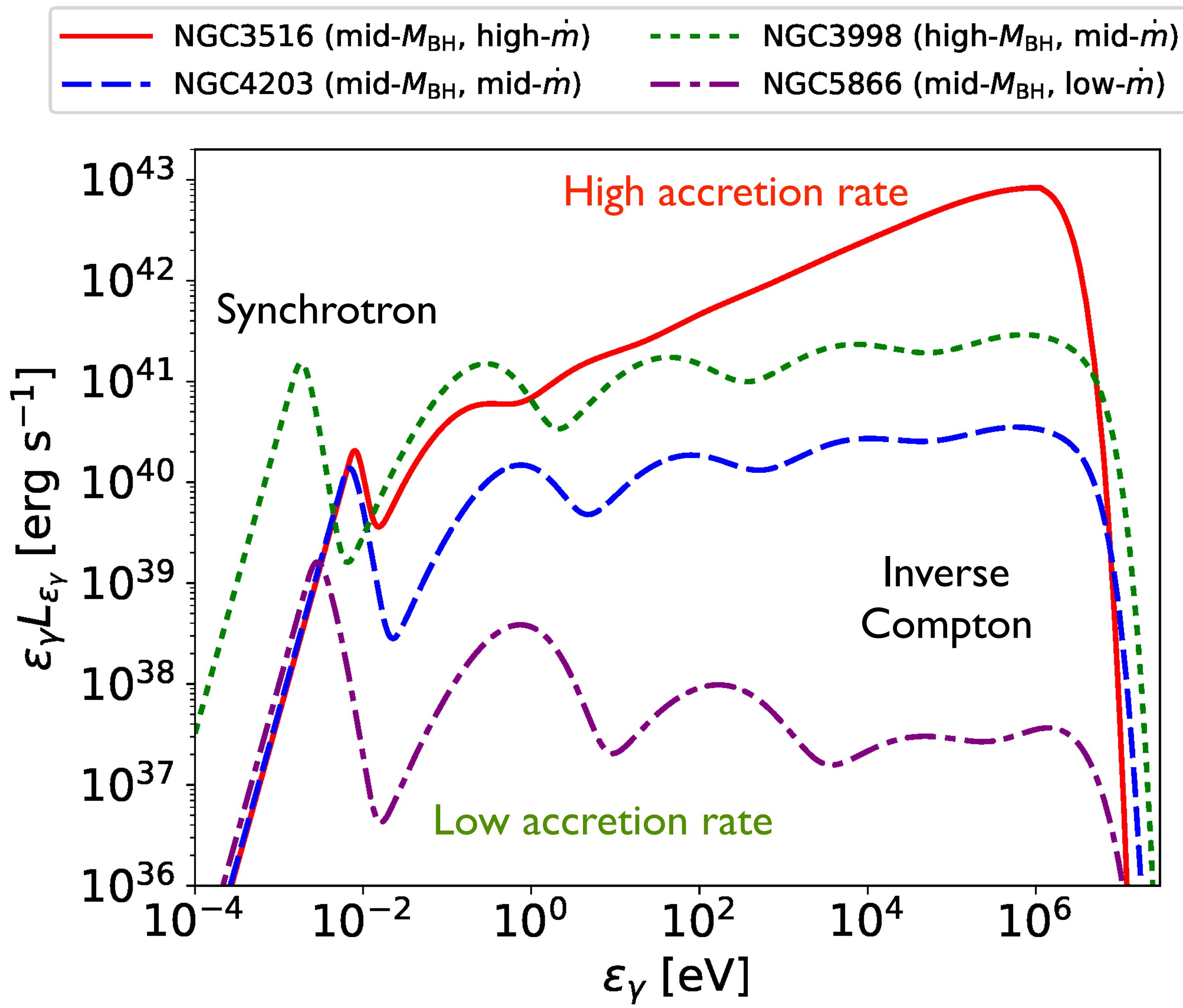
$$\frac{d}{d\varepsilon_p}\left(-\frac{\varepsilon_p}{t_{\mathrm{cool}}}N_{\varepsilon_p}\right) = \dot{N}_{\varepsilon_p,\mathrm{inj}} - \frac{N_{\varepsilon_p}}{t_{\mathrm{esc}}}$$

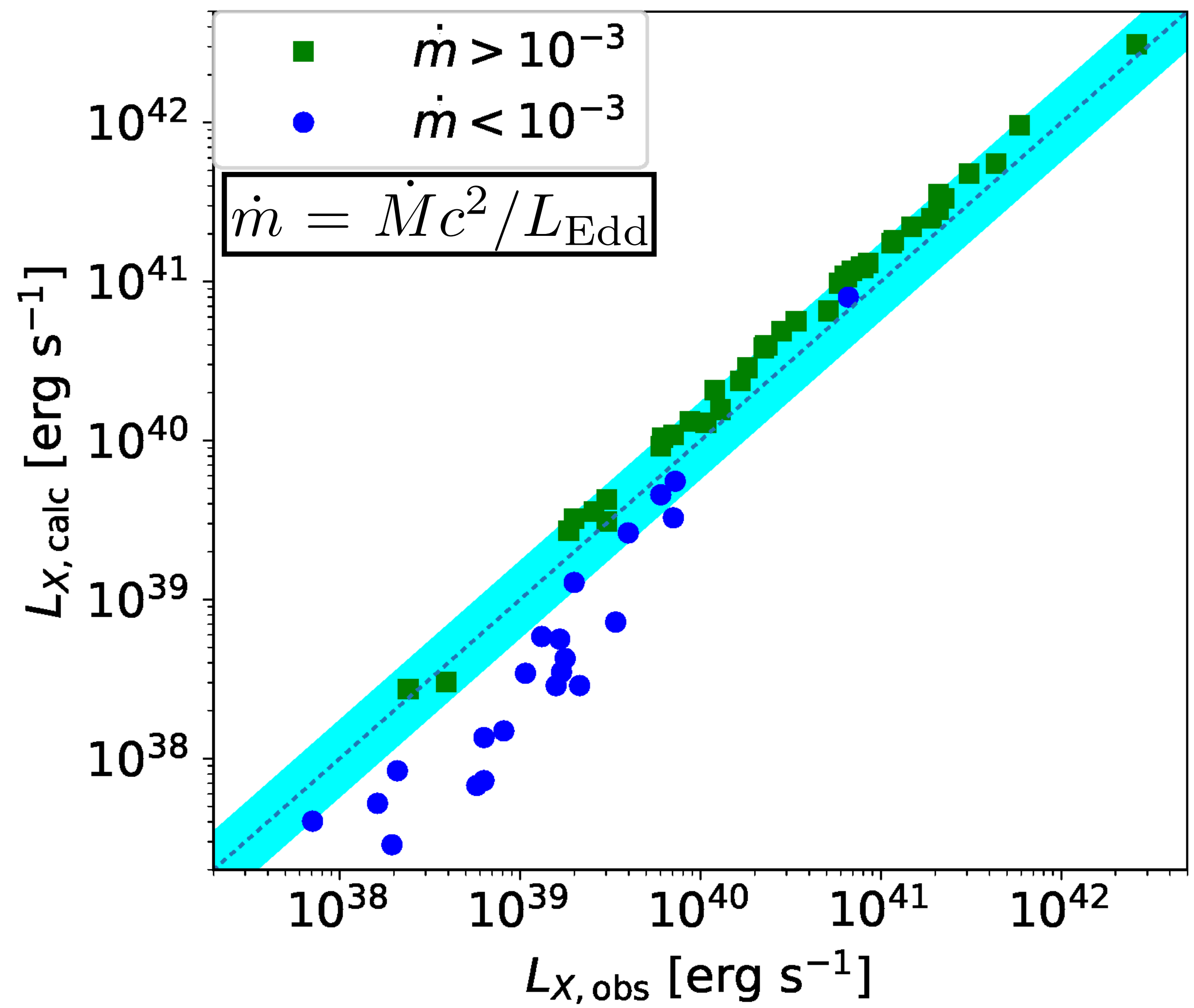
$$\dot{N}_{\varepsilon_p,\mathrm{inj}} = \dot{N}_0\left(\frac{\varepsilon_p}{\varepsilon_{p,\mathrm{cut}}}\right)^{-s_{\mathrm{inj}}}\exp\left(-\frac{\varepsilon_p}{\varepsilon_{p,\mathrm{cut}}}\right)$$

- Escape : Infall to SMBH
- Coolings: pp inelastic collision, photomeson production
  proton synchrotron, Bethe-Heitler process ($p+\gamma \rightarrow p+e^+ + e^-$)
- Muon & Pion Coolings are negligibly inefficient
- HE γ-rays are absorbed by target photons ($\gamma+\gamma \rightarrow e^+ + e^-$)
  → electron & positron emit high-energy gamma-rays
  → Calculate electro-magnetic cascades

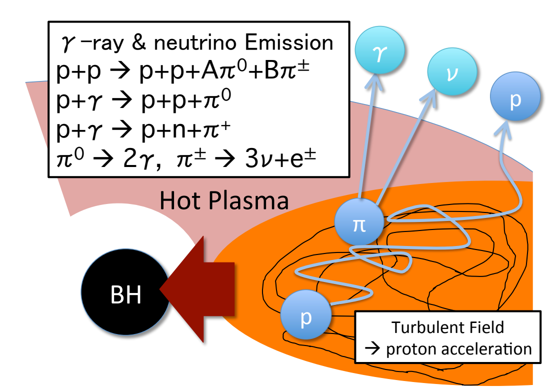
Target Photon Field

cf. SSK et al. 2015

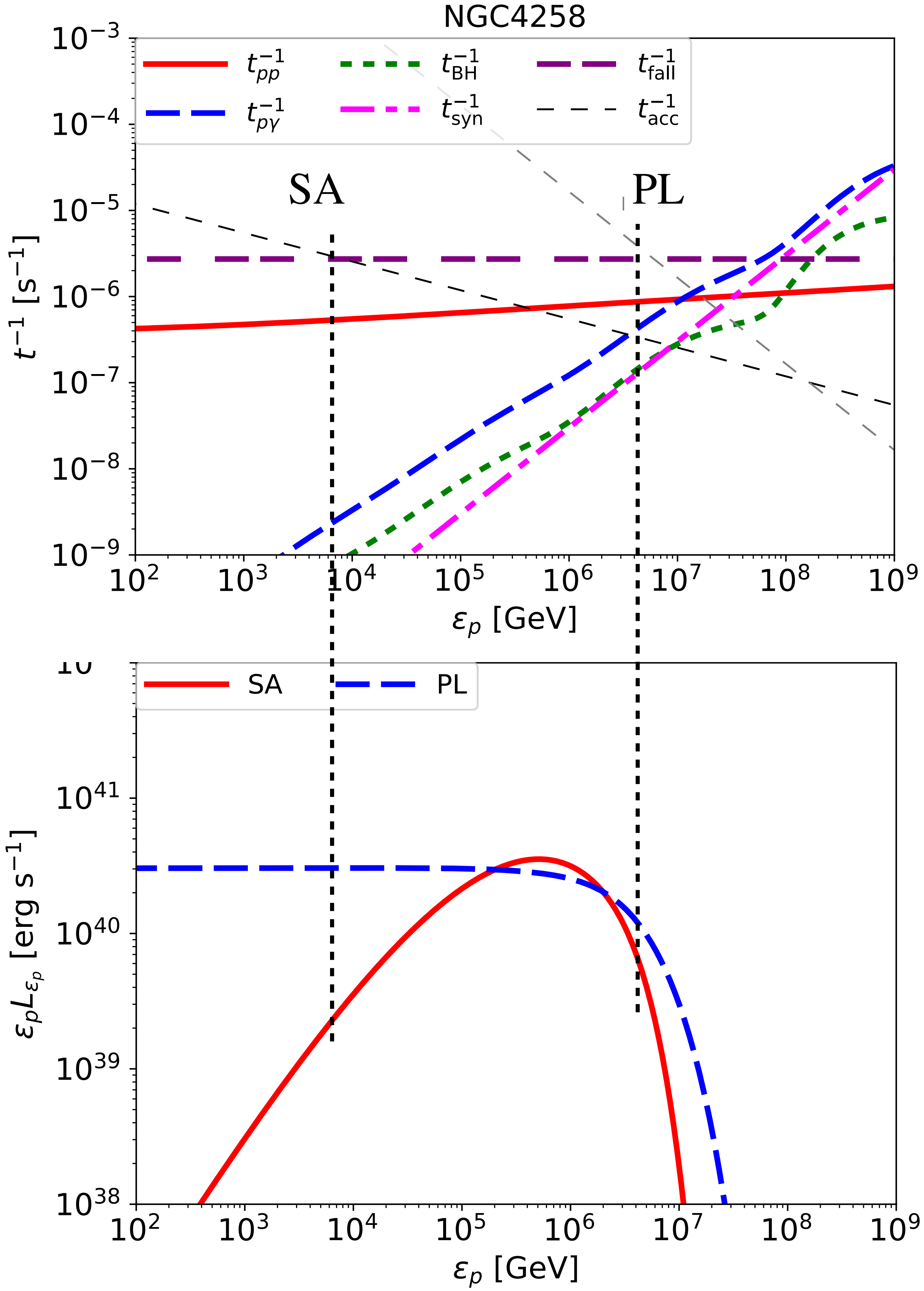




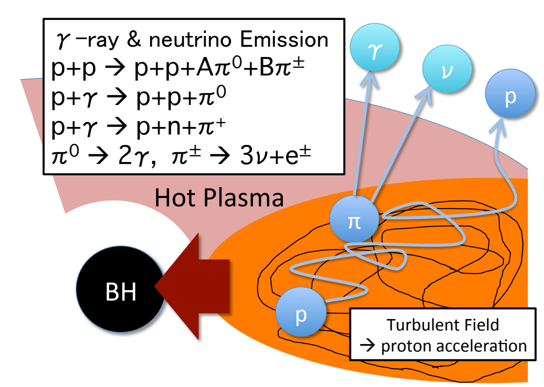
- Low-luminosity → Poor observational data
  → **Formulation based on theory**
- Thermal electrons in RIAFs emit seed photons
- Our results are consistent with X-ray observations



Rates & CR Spectrum



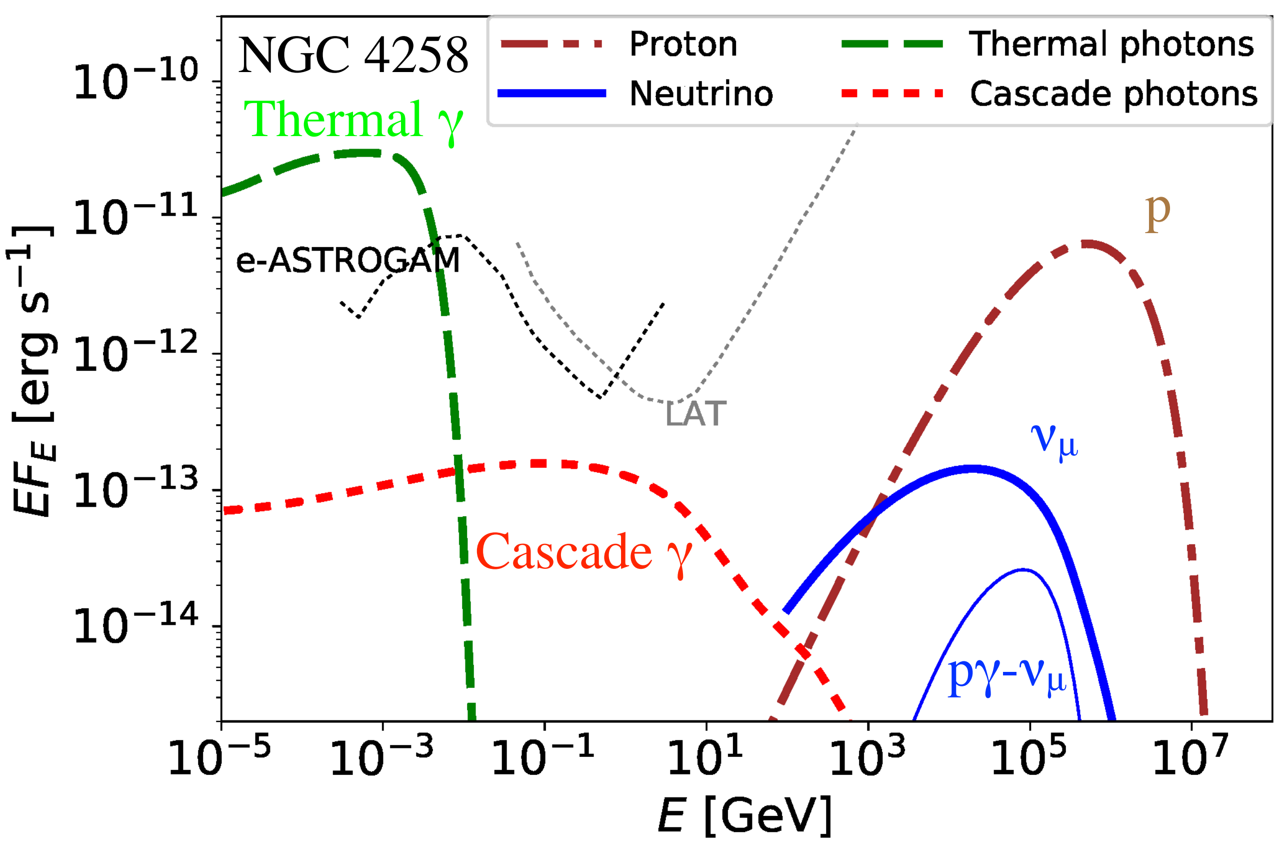
- **Infall is dominant**
- **Neutrino is mainly produced by pp**
- For SA, acceleration rate is much lower than PL model



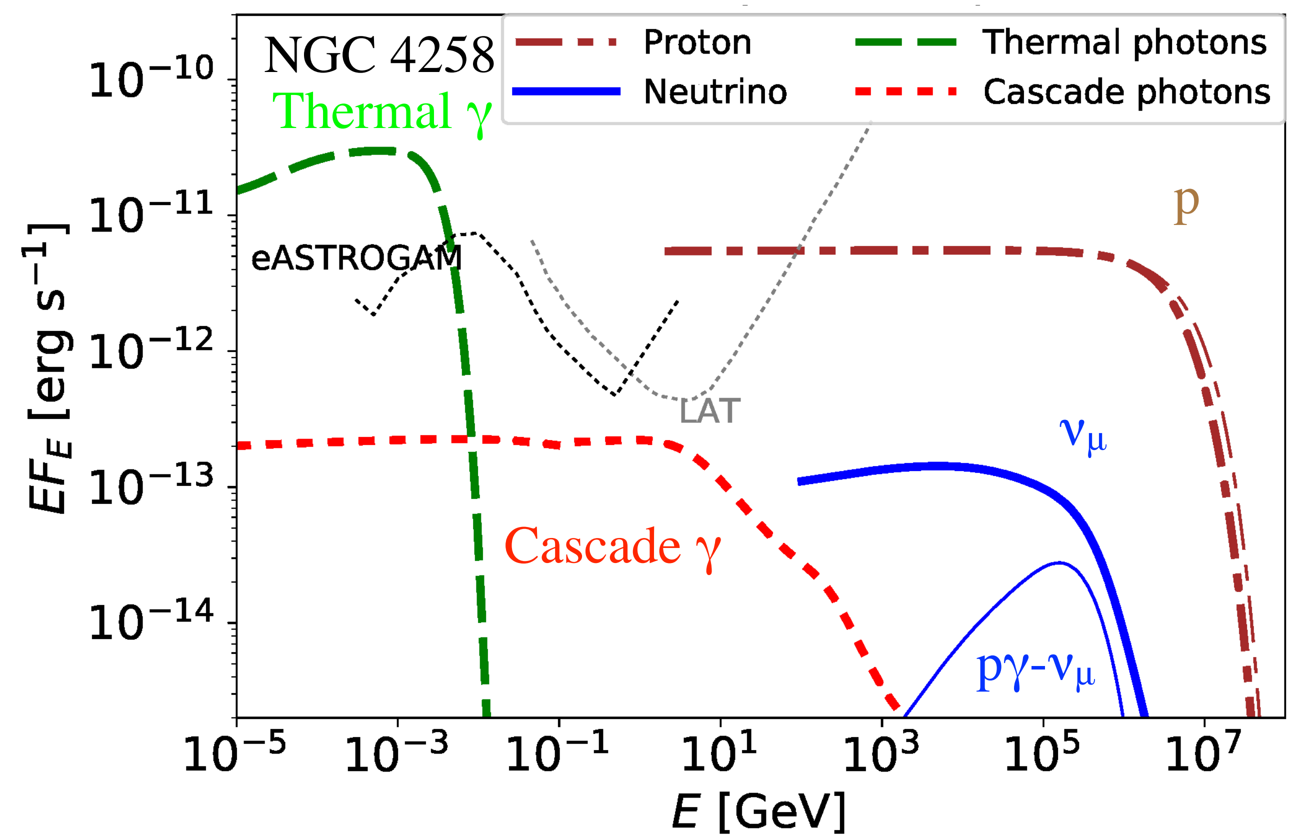
- Hard proton spectrum for SA
- Cutoff energy for SA is much higher than the critical energy (t_{acc} = t_{fall}) due to hard spectrum & gradual cutoff

HE Particle Spectrum

- Stochastic Acceleration (SA)



- Power-law Injection (PL)

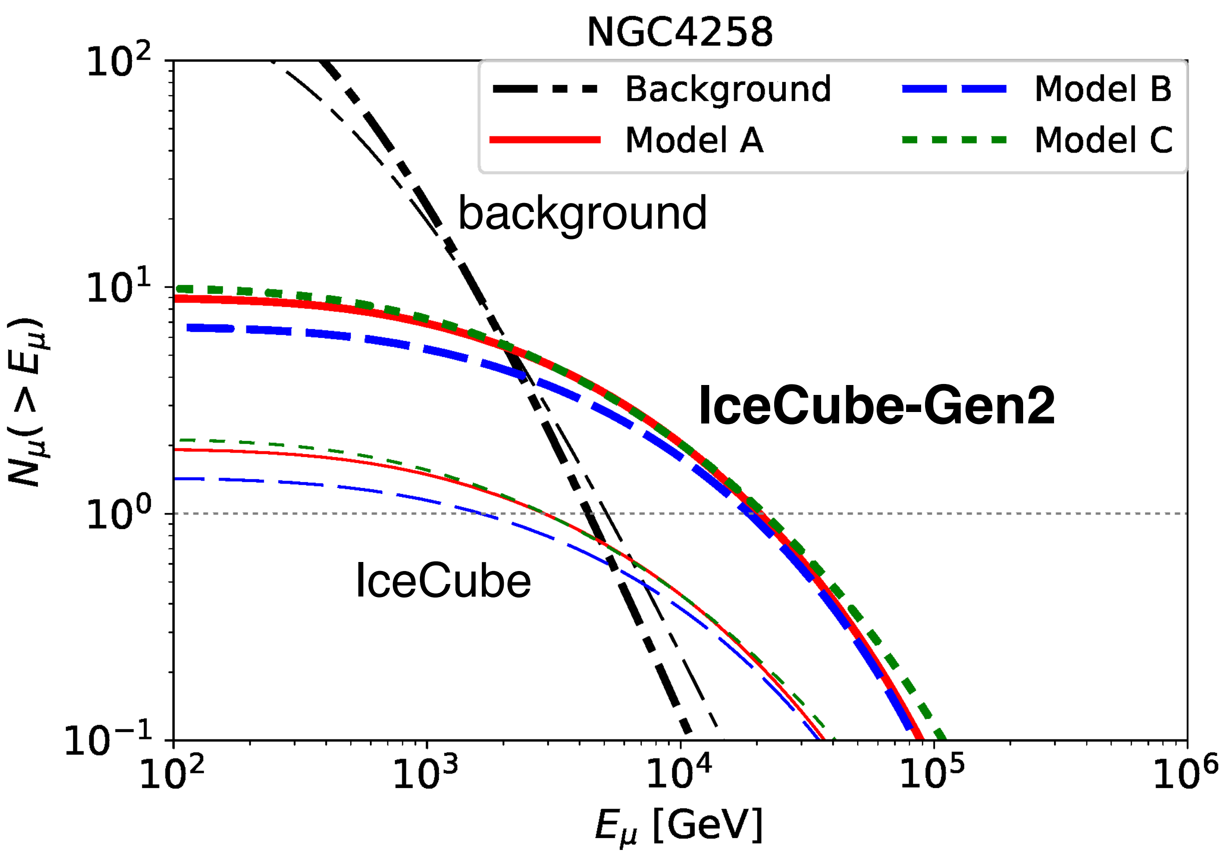


- pp-neutrino dominant, pγ contribution is comparable at high-energy
- Cascade γ-rays @ E<1 GeV: **too faint to detect** by LAT & CTA
- Thermal γ-rays @ E<MeV: **detectable** by future MeV satellites

Number of Muon Tracks

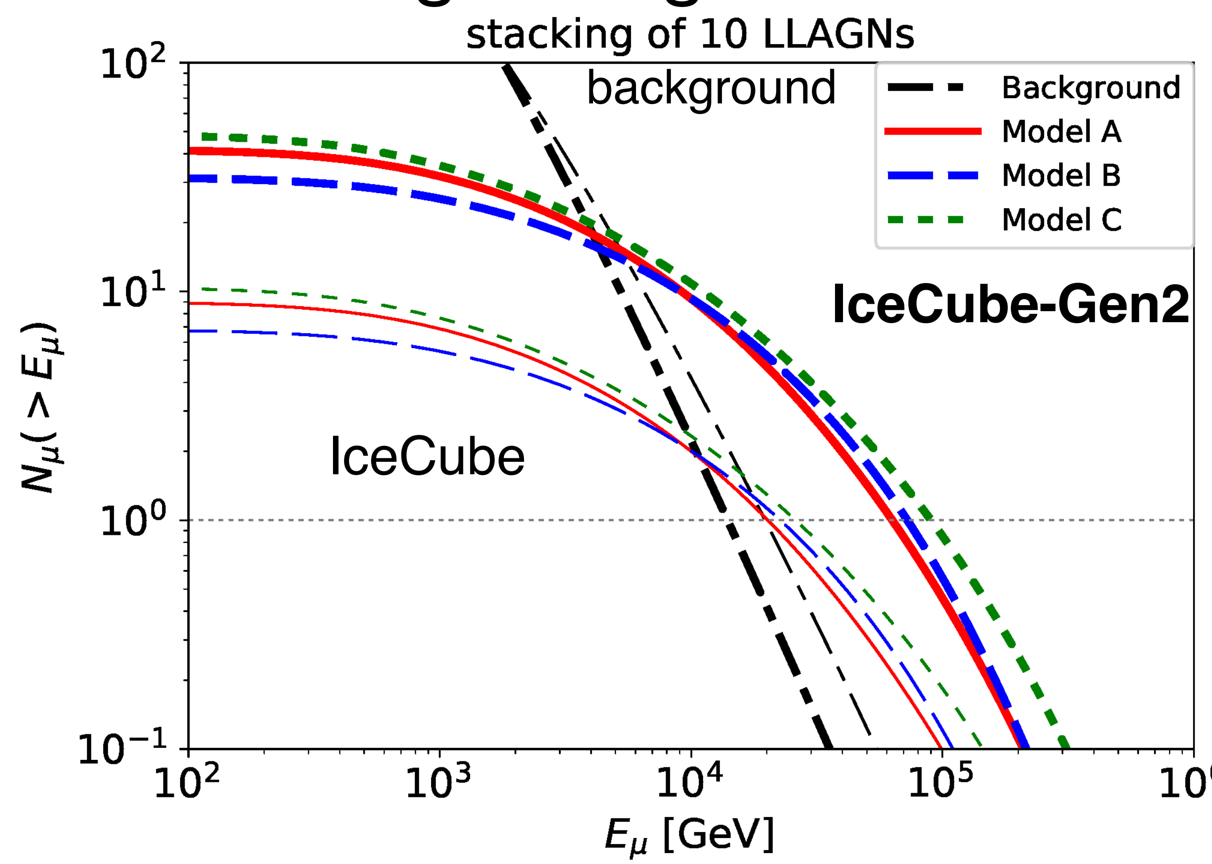
Murase & Waxman 2016

A Bright LLAGN (NGC 4258)



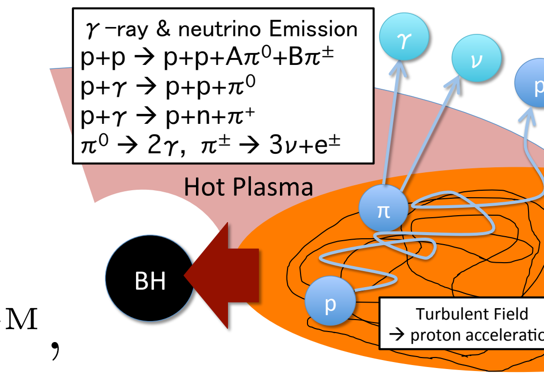
- IceCube cannot detect a neutrino
- **IceCube-Gen2 can detect** a few neutrinos of E > 10 TeV

Stacking 10 brightest LLAGNs



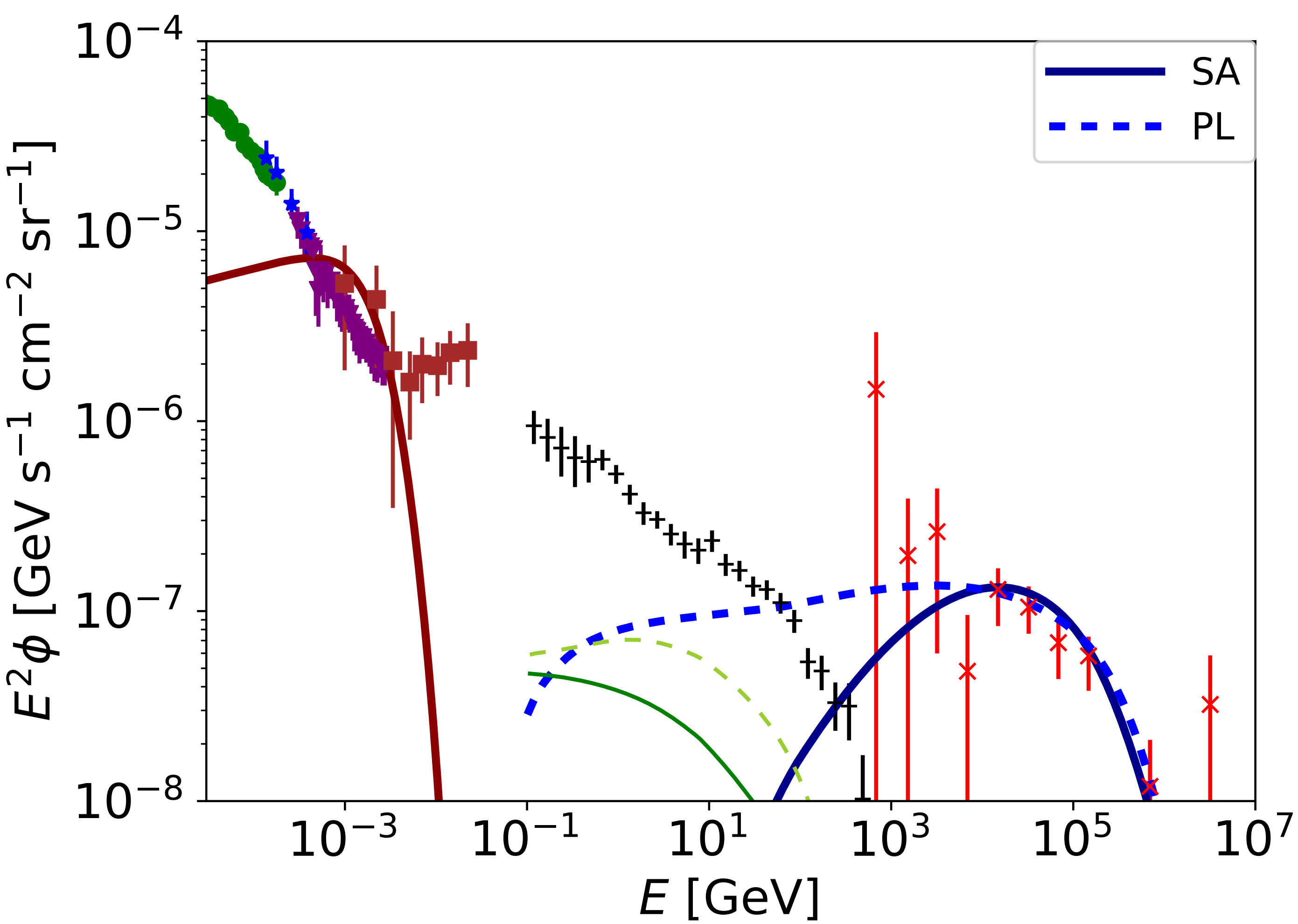
- IceCube cannot distinguish signals from the background
- **IceCube-Gen2 can detect** several neutrinos of E > 30 TeV

Extragalactic γ & ν Backgrounds



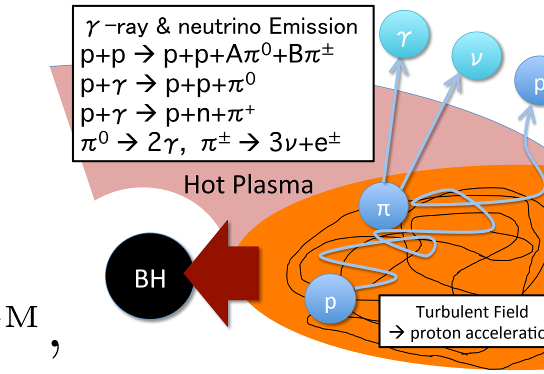
$$\Phi_i = \frac{c}{4\pi H_0}\int \frac{dz}{\sqrt{(1+z)^3\Omega_m+\Omega_\Lambda}}\int dL_{\mathrm{H}\alpha}\rho_{\mathrm{H}\alpha}\frac{L_{\varepsilon_i}}{\varepsilon_i}e^{-\tau_{i,\mathrm{IGM}}},$$

- AGNs with $\mathbf{L_{H\alpha}}$**< 4x10^{41} erg/s equally** contribute to ν
- LLAGNs with $\mathbf{L_{H\alpha}}$ **~ 4x10^{41} erg/s mainly** contribute to MeV



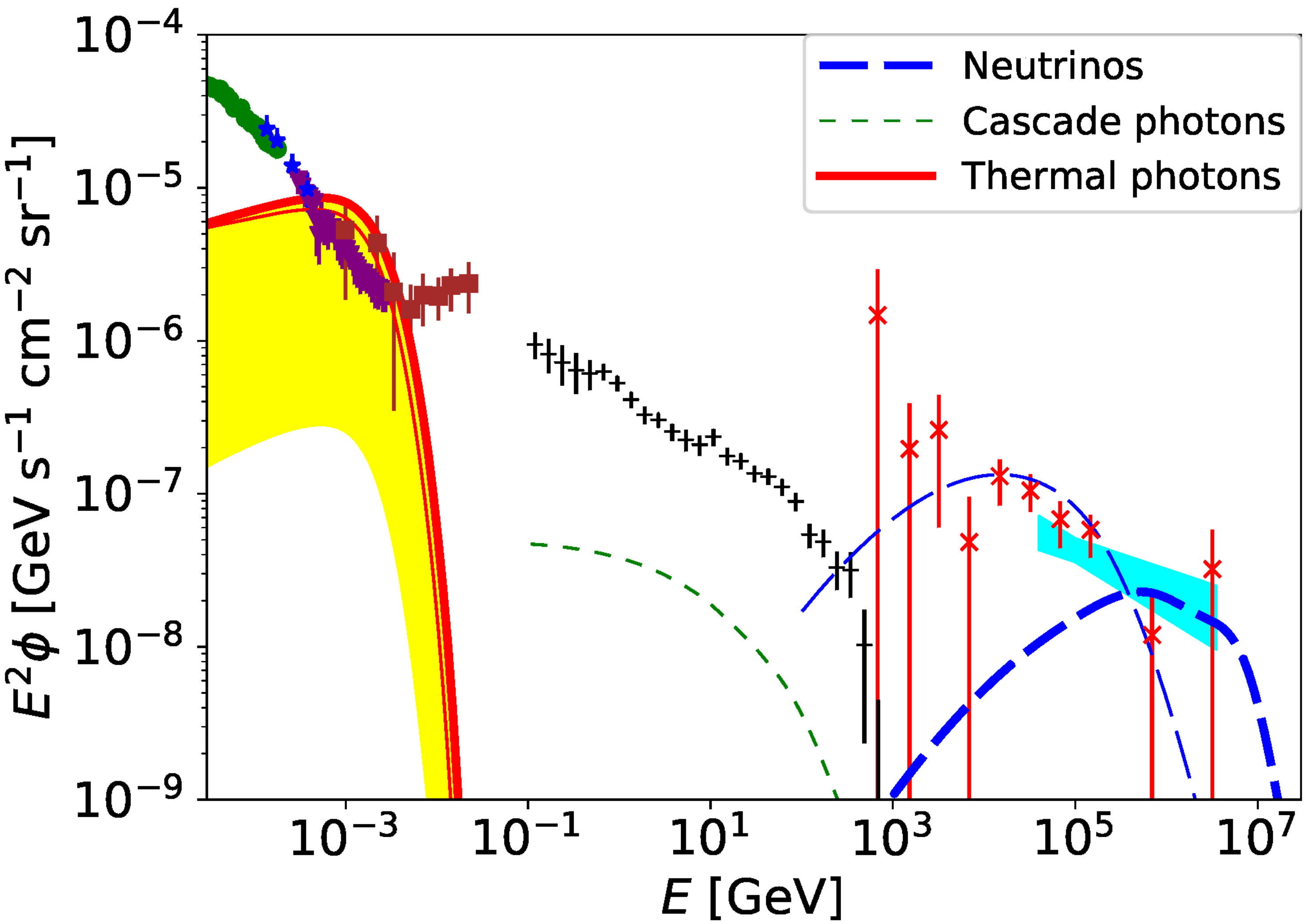
- **LLAGN can explain TeV-PeV ν and MeV γ bkgrds simultaneously**
- GeV γs are attenuated at RIAFs in LLAGNs
  → consistent with Fermi data
- P_{CR} ~ 0.1P_{th} for SA,
  P_{CR} ~ 0.4P_{th} for PL
  → **Need hard spectrum**

Extragalactic γ & ν Backgrounds



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

- LLAGNs with **$L_{H\alpha}$< 4x10^{41} erg/s equally** contribute to ν
- LLAGNs with **$L_{H\alpha}$ ~ 4x10^{41} erg/s mainly** contribute to MeV



- **LLAGN can explain TeV-PeV ν and MeV γ obs. simultaneously**
- GeV γs are attenuated at RIAFs in LLAGNs → consistent with Fermi data
- P_{CR} ~ 0.01P_{th} for PeV ν, P_{CR} ~ 0.1P_{th} for TeV ν

Index

- IceCube Neutrinos
- Accretion Flow in AGN
- AGN Corona model
- LLAGN RIAF model
- Summary

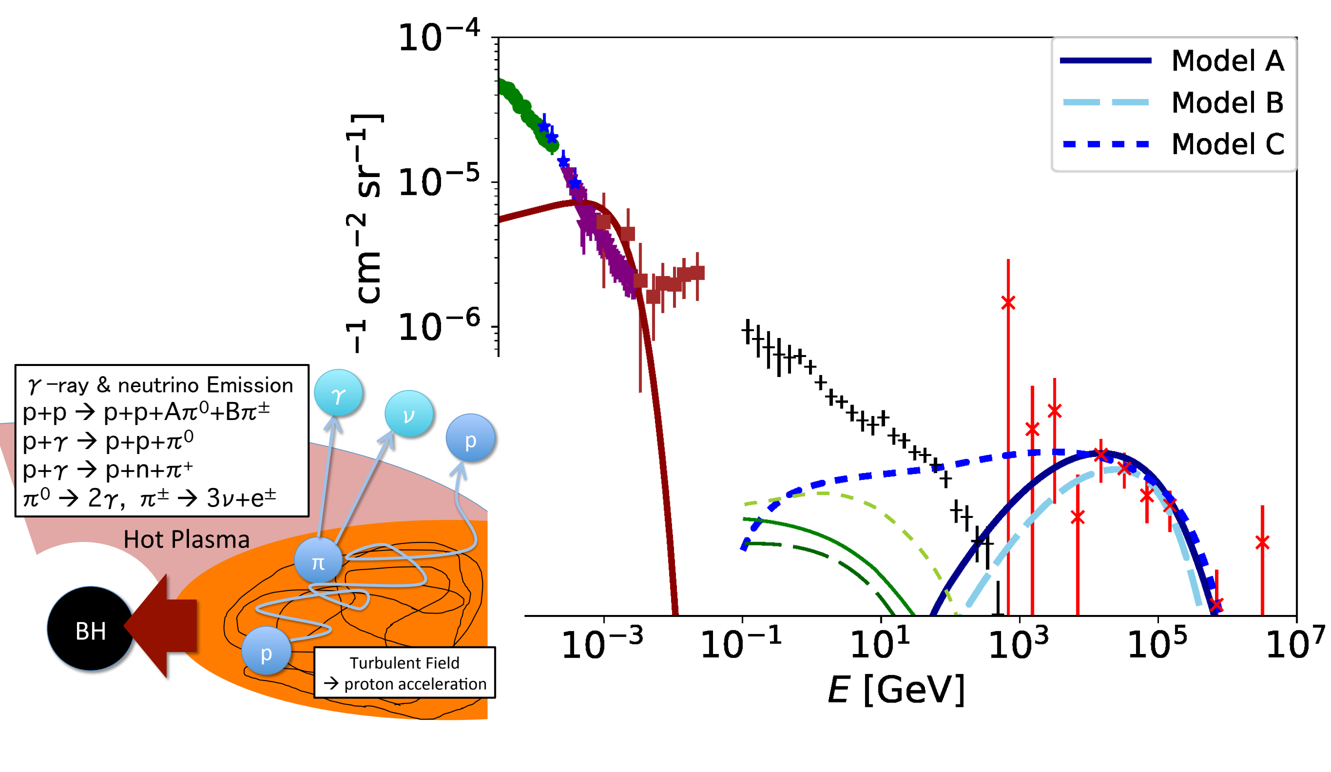
Murase, SSK, Meszaros, arXiv:1904.04226

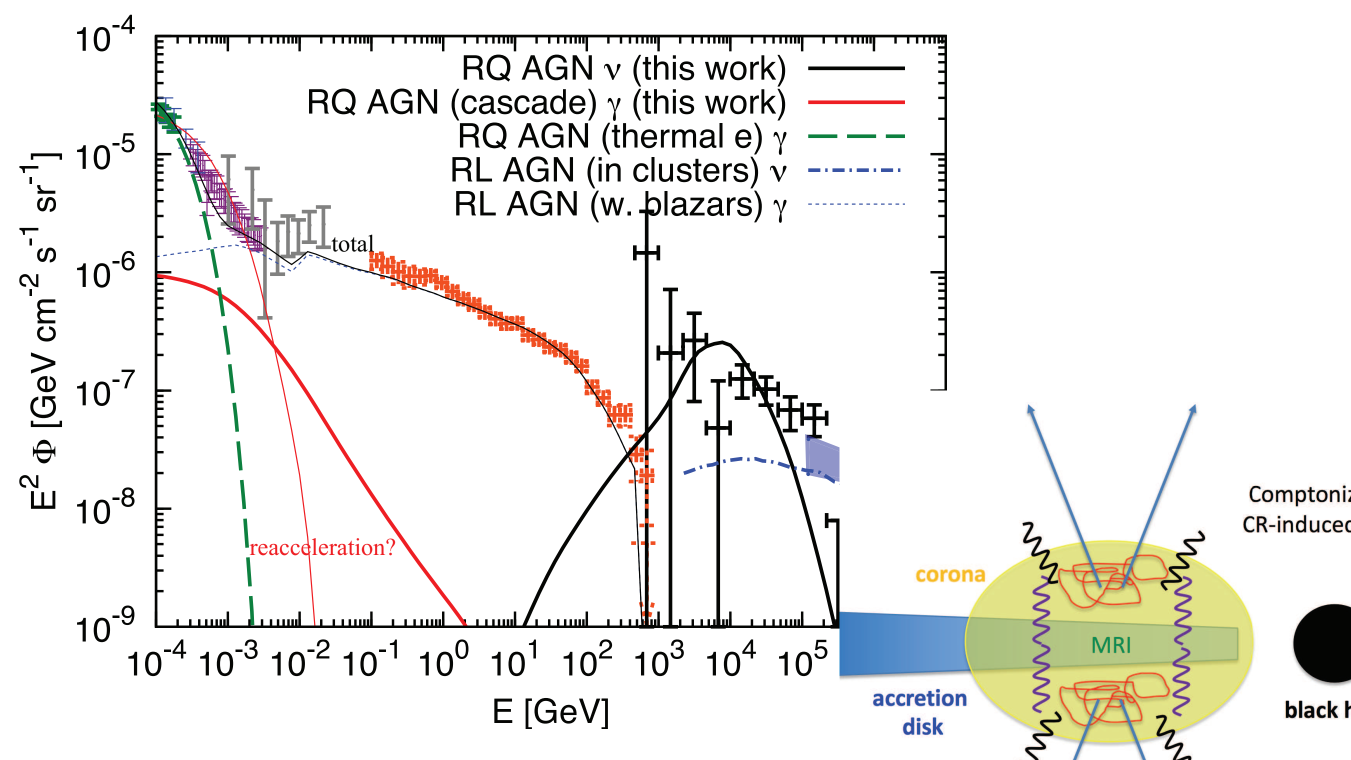
SSK, Murase, Meszaros, 2019, PRD, 100, 083014

SSK, Murase, Meszaros in prep.

Summary

- Accretion flows in AGNs are a feasible neutrino source
- **Seyfert galaxies can reproduce TeV-PeV νs** without violating Fermi constraints with observation based parameters.
- **RIAFs in LLAGNs can explain MeV γ & TeV-PeV ν backgrounds simultaneously** without violating Fermi constraints
- Future multi-messenger observations can robustly test both models:
  - IceCube-Gen2 can detect AGNs as point sources
  - AMEGO can detect MeV γ rays from AGNs

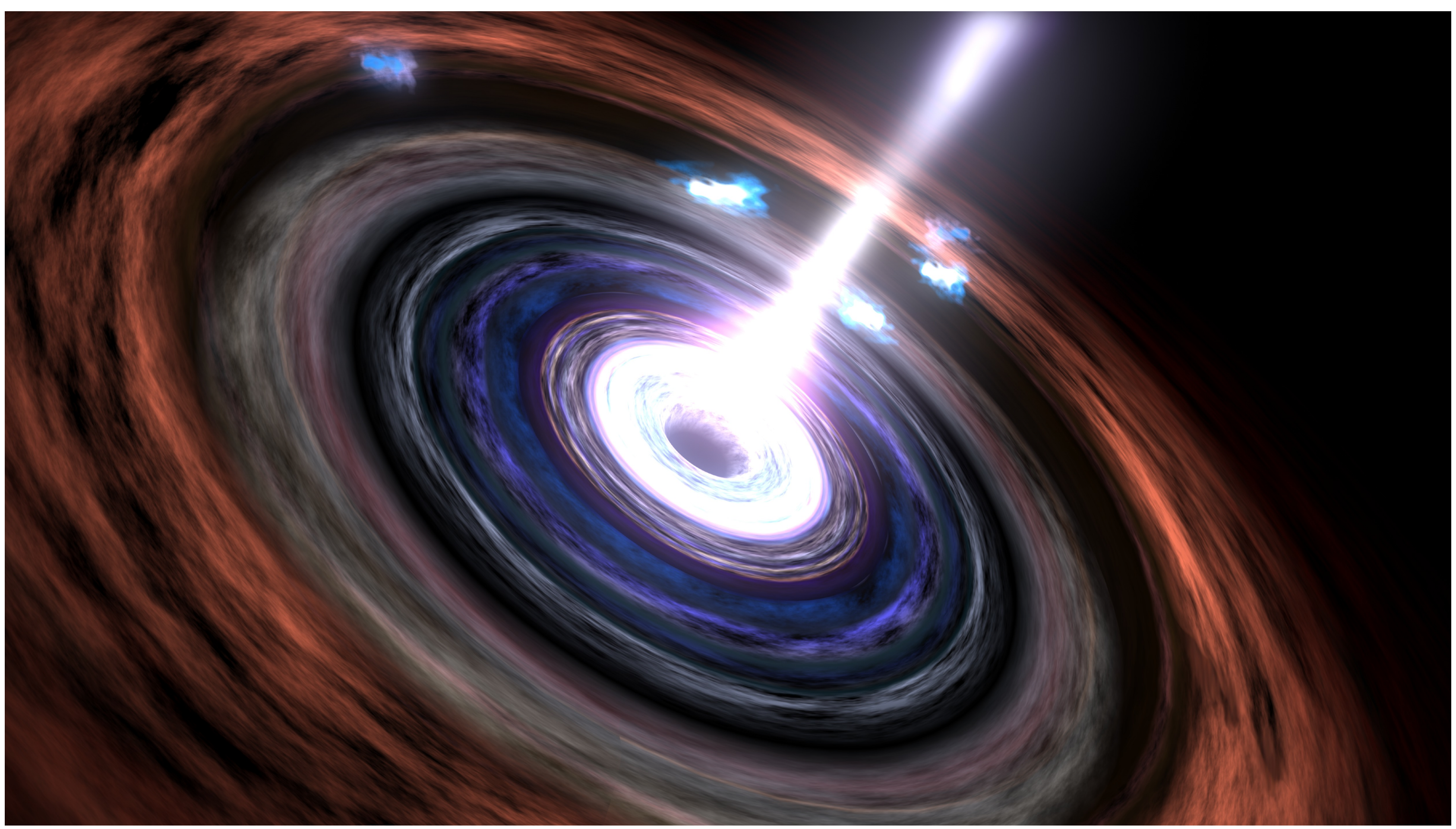


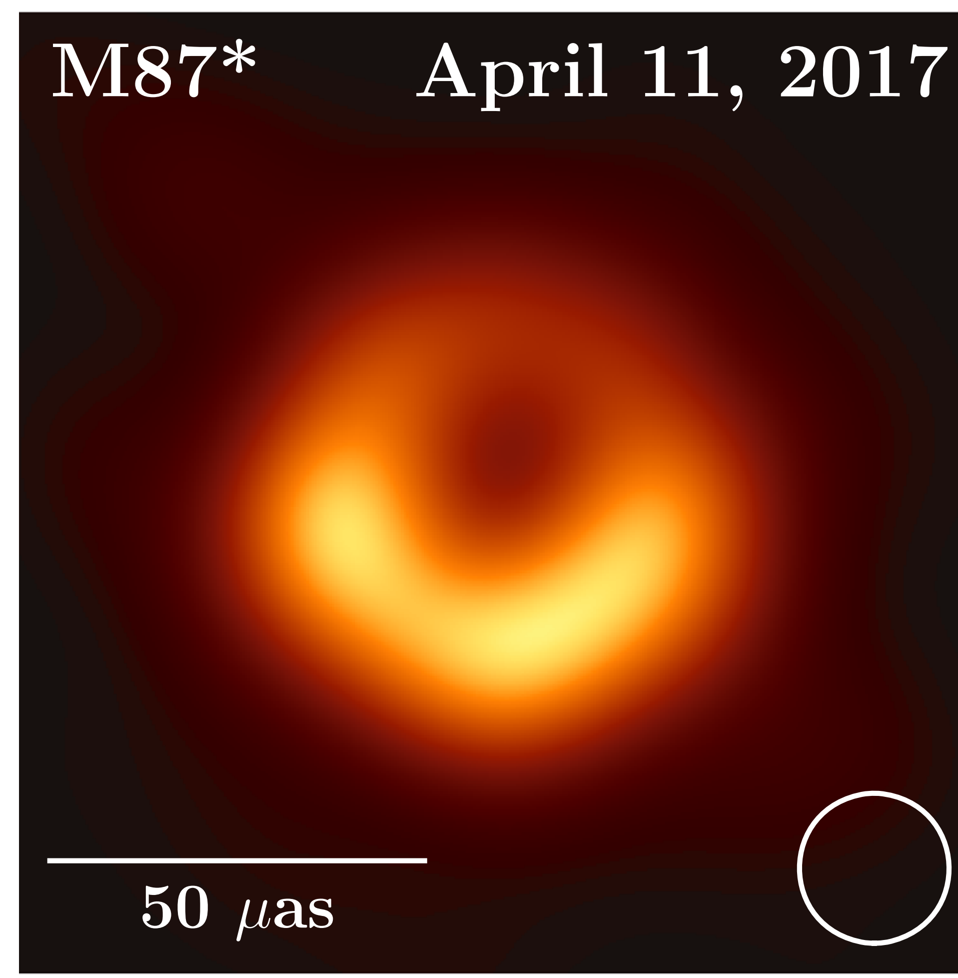


Thank you
for your attention

Active Galactic Nuclei (AGNs)

- Accretion onto Supermassive black hole (M_{BH}~$10^8 M_{sun}$)
  gravitational energy → radiation or thermal energy
- SMBH paradigm is proved by Event Horizon Telescope





EHT 2019

Plasma Conditions in Accretion Flow

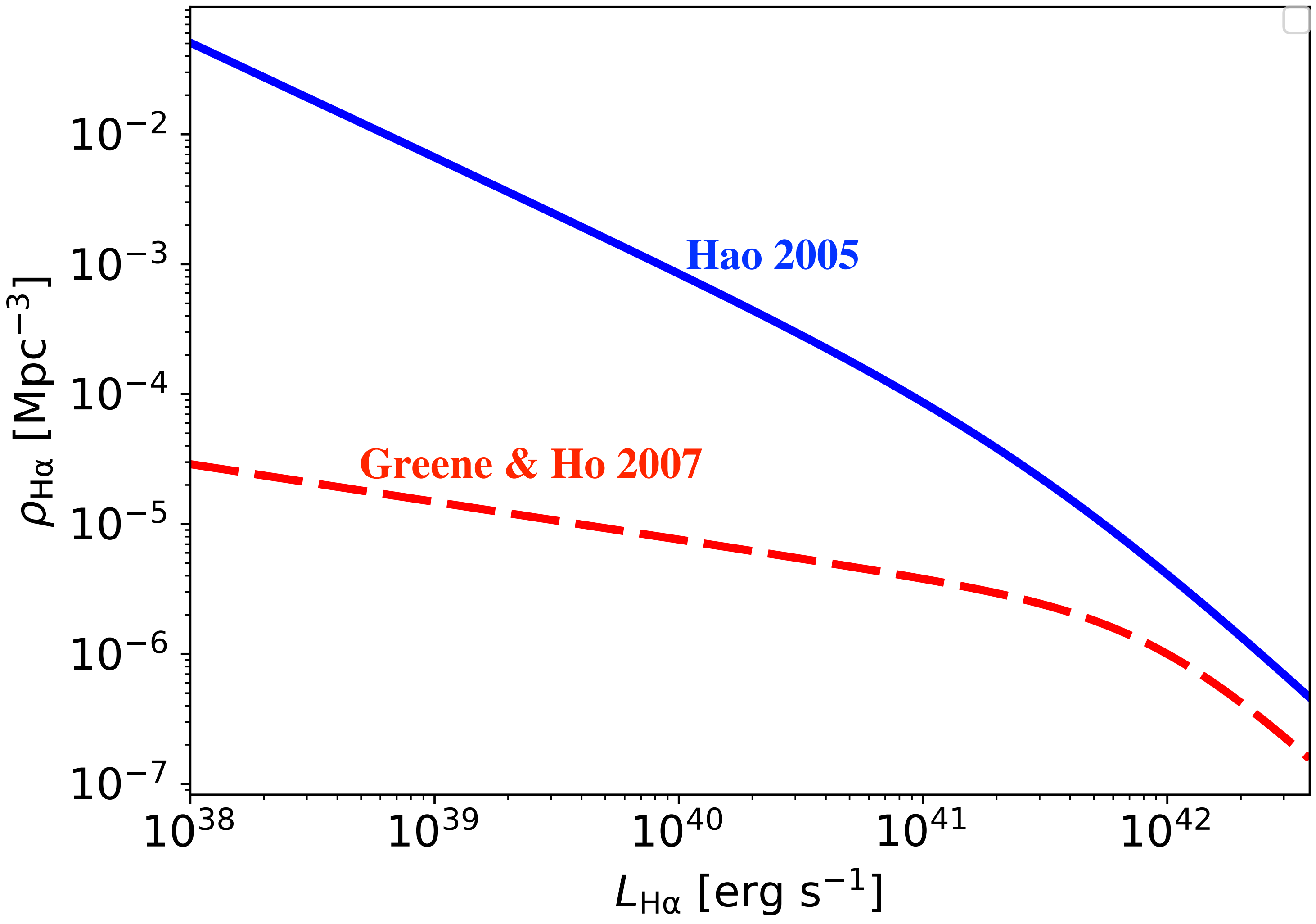
- To accelerate non-thermal particles, relaxation time > dissipation time
- For RIAFs in LLAGNs, $t_{dis} \sim t_{dyn} \sim R/V_{fall}$
- For Coronae in QSO, $t_{dis} \sim H/V_A$
- **Protons are collisionless** for both cases
  → **Non-thermal Proton**
- **Electrons are collisional** for both cases
  → **Thermal electrons only**

Luminosity Function

- ν & γ intensities from LLAGNs

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

- $\rho_{H\alpha}$: Hα line Luminosity function



We use higher LF

Target Photon Field

- Low-luminosity → Poor observational data
  → **Theory driven formulation**
- Thermal electrons in RIAFs emit seed photons
- Provide X-ray luminosity by observation
  → Bolometric correction based on AGN survey
  → Estimate mass accretion rate
  → Obtain physical quantities (ρ, B, n, Te) in RIAFs
  → Calculate target photon spectrum by one-zone approximation
- **We do not adjust X-ray luminosity**

EM Cascades in IGM

- Cutoff energy by $\gamma\gamma$ pair production in RIAFs
  E_{cut} ~ 0.1 - 100 GeV
- $\tau_{\gamma\gamma,IGM}$ ~1 for E_γ =100 GeV @ z=0.5
  → **We need to consider attenuation**
- $\gamma\gamma$ pair production: e^+e^- of γ_e~10^5 for E_γ~100 GeV
  →E_{ic} ~ $4\gamma_e^2 E_{CMB}/3$ ~ 10 MeV
  → **we can ignore EM cascade in IGM**
- τ << 1 for ν & MeV γ
  → we can ignore attenuations

Implications & Caveats

- **Multi-messenger tests are promising:**
  Nearby LLAGNs are detectable by IC-Gen2 & e-ASTROGAM
- High source number density (~10^{-3} Mpc^{-3})
  → LLAGNs can **avoid the point-source constraints**
- Luminosity Function (LF) is very uncertain
  - LF by Hao et al. (2005) >> Greene & Ho (2007)
  - If we use Greene & Ho (2007), neutrino flux becomes too low to explain TeV-PeV neutrinos