Diffuse High-energy Neutrino Flux & Models

FRIS, Tohoku University (JSPS Research Fellow)

Shigeo S. Kimura

References
1) Murase, SSK, Meszaros, arXiv:1904.04226
2) SSK, Murase, Meszaros, 2019, PRD, 100, 083014
3) SSK, Murase, Meszaros in preparation

see also: SSK, Murase, Toma, 2015, ApJ, 806, 159

TOHOKU UNIVERSITY

Collaborators
Peter Meszaros (Penn State)
Kohta Murase (Penn State; YITP)
Kenji Toma (Tohoku Univ.)

Theoretical Astrophysics Tohoku University

Theory Meeting Experiment 2020 @ Quy Nhon, Vietnam

Contents

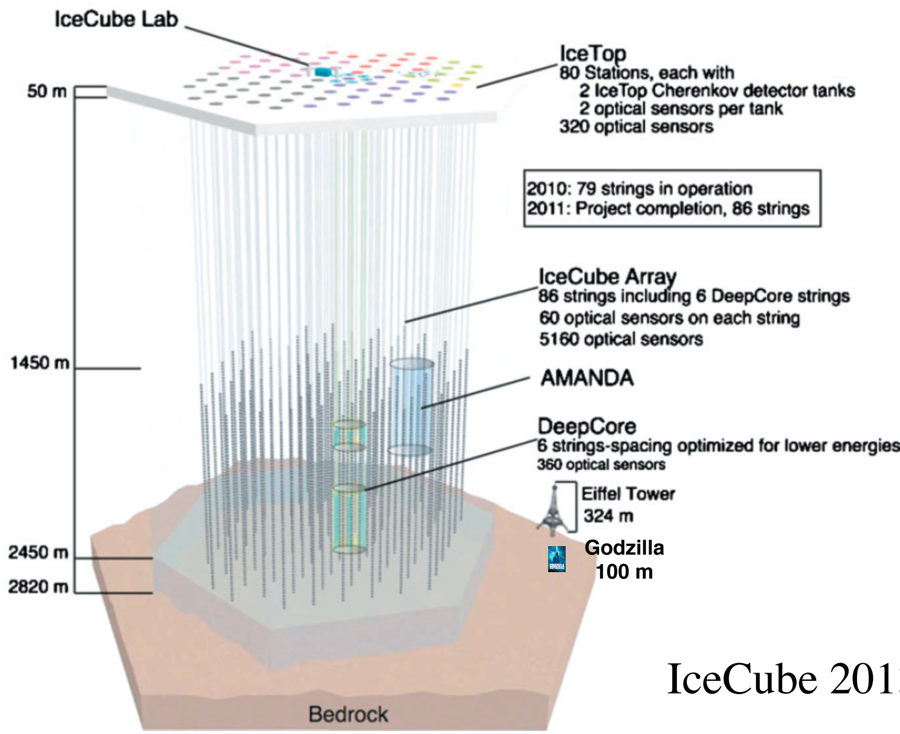
- Introduction
- Models and Constraints
- AGN Core Model
- Summary

Murase, SSK, Meszaros, arXiv:1904.04226
SSK, Murase, Meszaros, 2019, PRD, 100, 083014
SSK, Murase, Meszaros in prep.

Contents

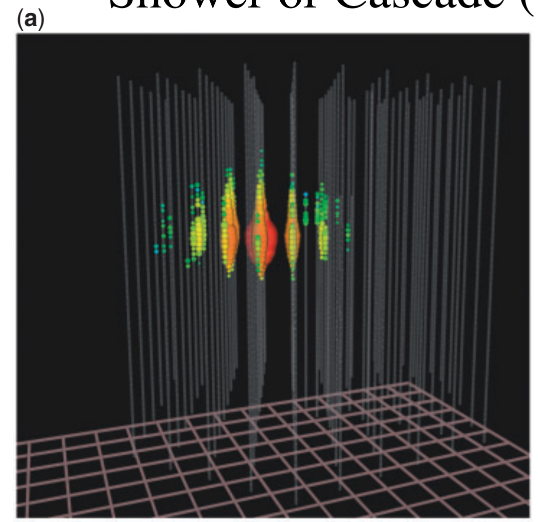
Murase, SSK, Meszaros, arXiv:1904.04226
SSK, Murase, Meszaros, 2019, PRD, 100, 083014
SSK, Murase, Meszaros in prep.

Detection of Astro-Neutrinos

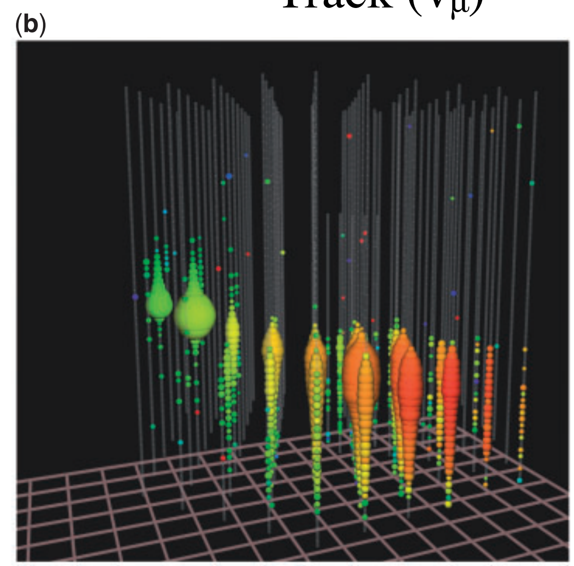


IceCube 2013

Shower or Cascade (ν_e)



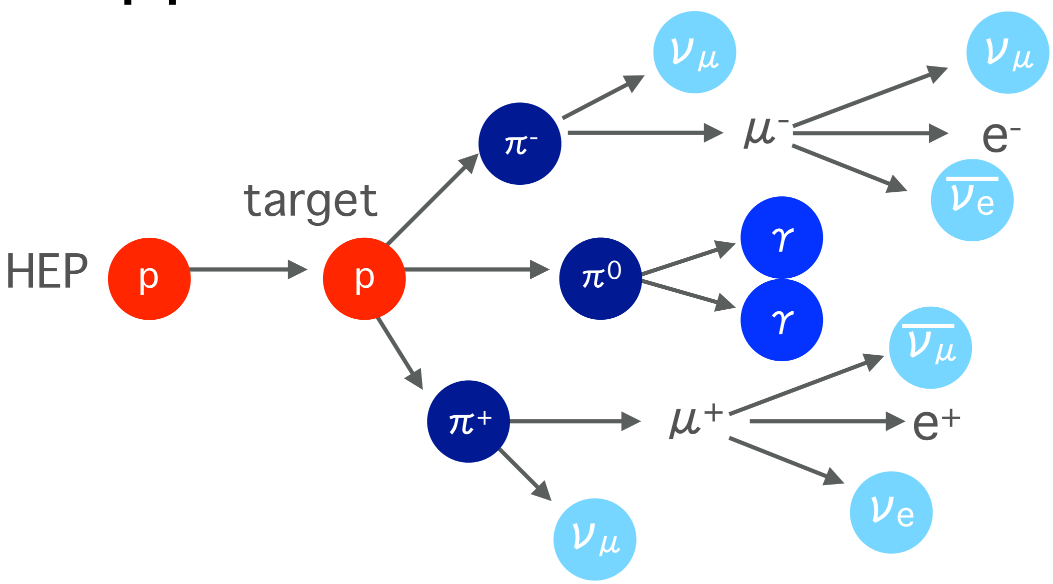
Track (ν_μ)

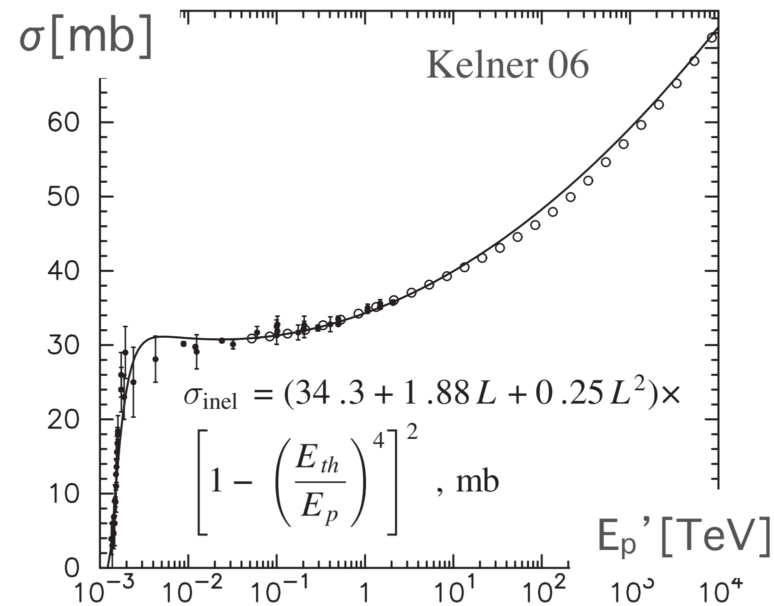


- IceCube experiment reported detection of astro-ν (E ~ PeV) in 2013
- Shower: good for spectrum
- Track: good for source search
- **Origin has yet to be determined**

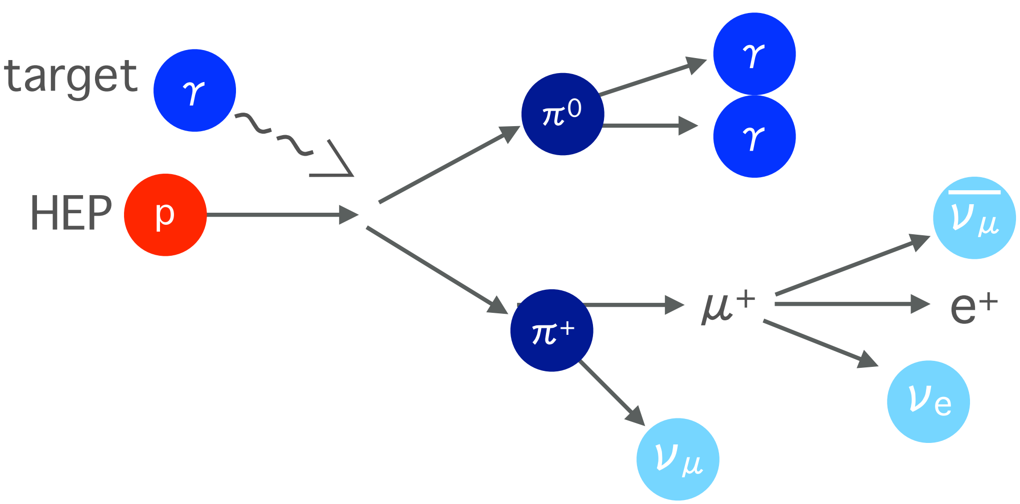
Products of Hadronic Interactions

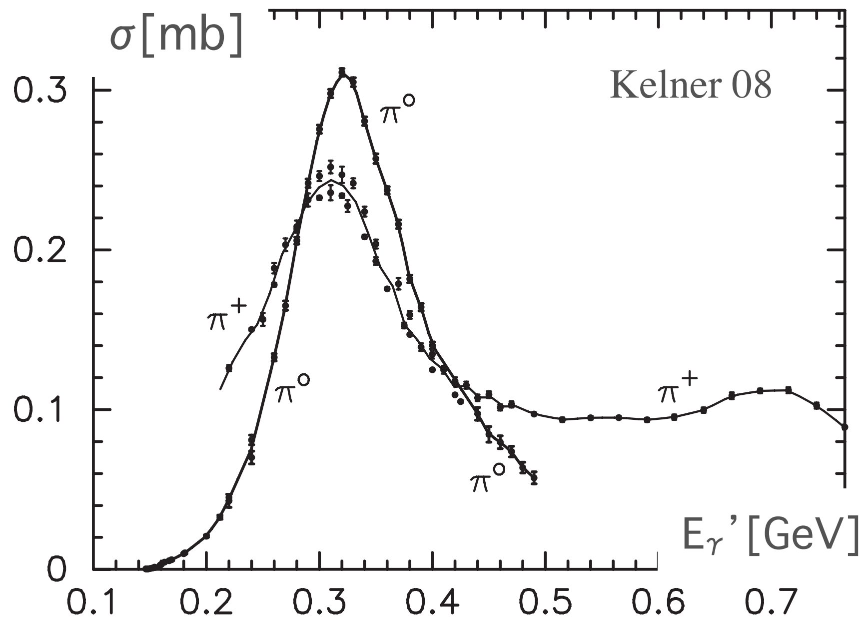
- pp inelastic collision



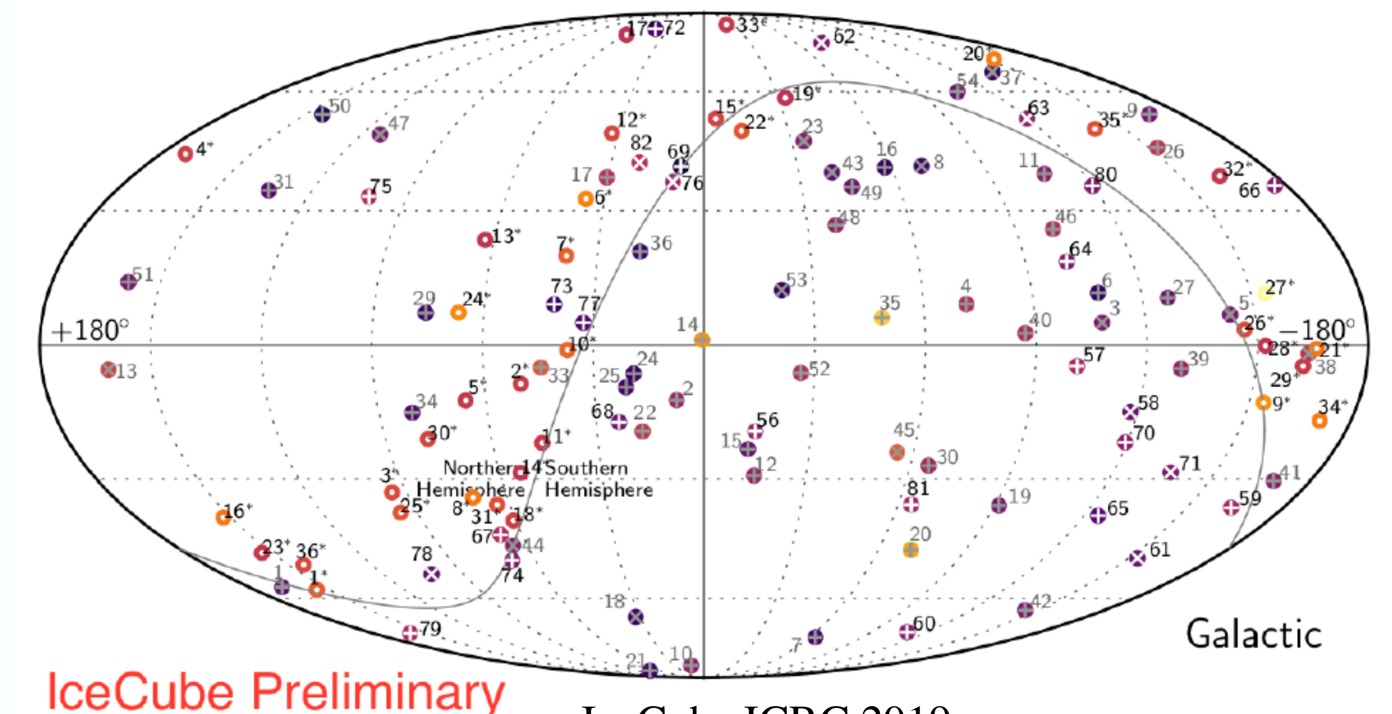


- Photomeson production (pγ)



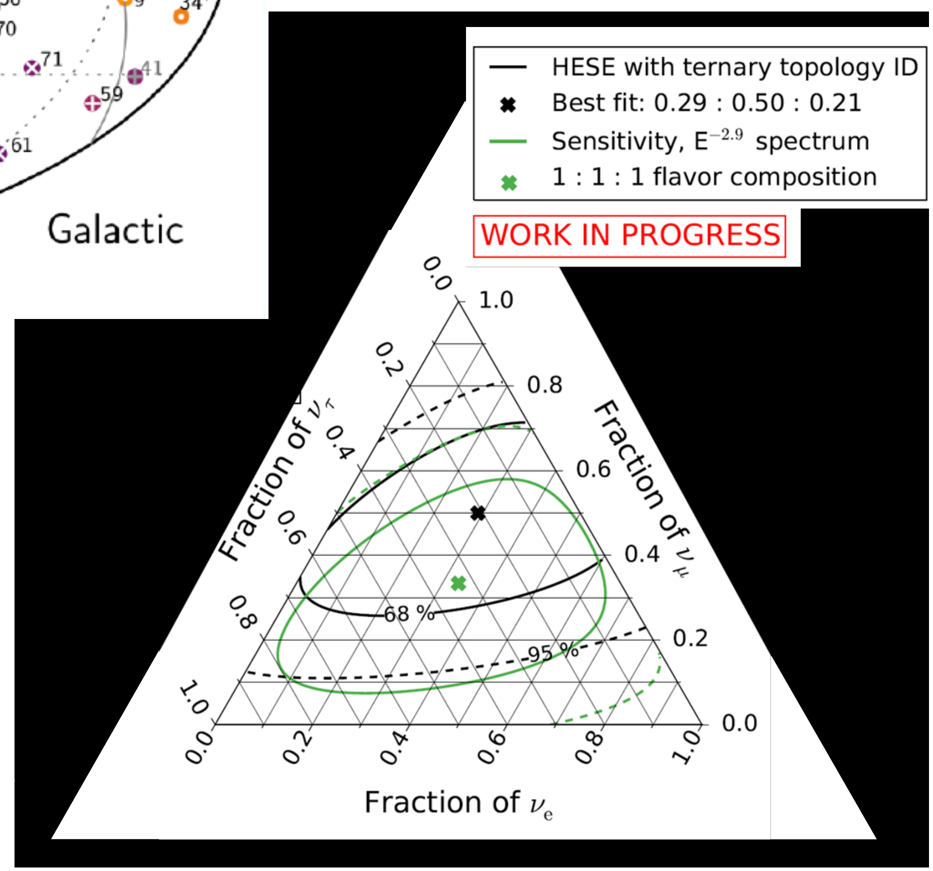


Arrival Direction



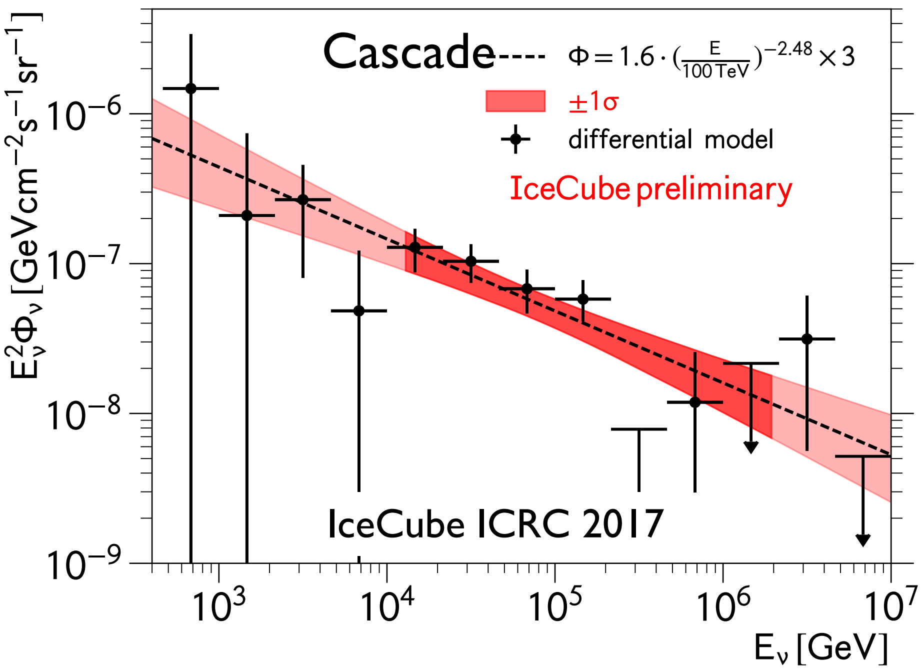
IceCube ICRC 2019

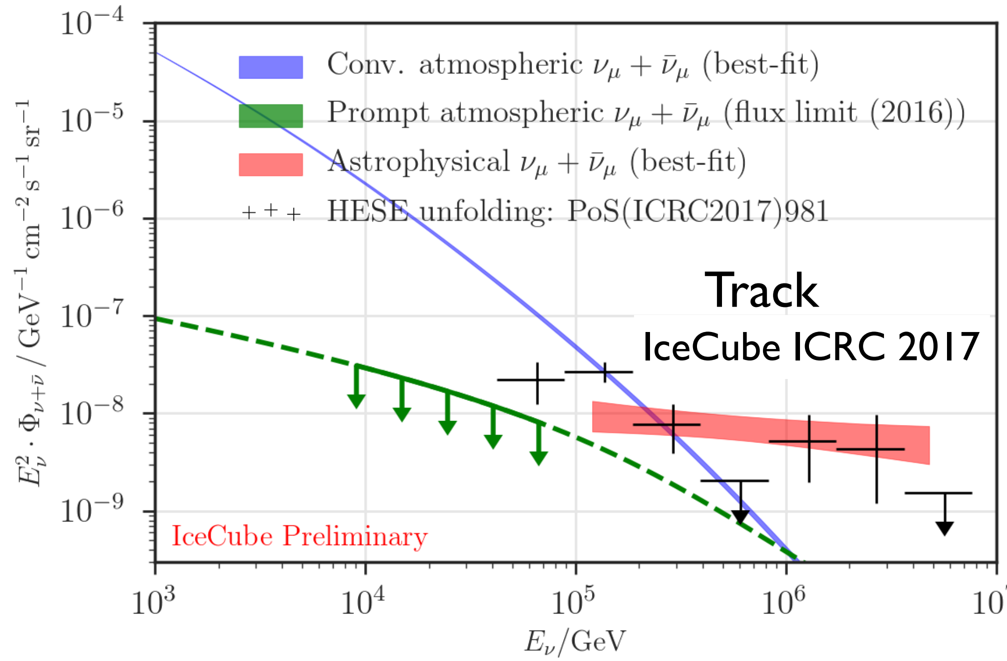
IceCube ICRC 2019



- Isotropic → Extragalactic origin
- No point-source/clustering detection
  → Galactic contribution: < 10%
- Neutrino flavor ratio is consistent with pion decay [(1:2:0) at Source]

Neutrino Spectrum





- Soft spectrum by the cascade analysis
  → **Medium energy excess (High intensity @~10 TeV)**
- Flat spectrum by the track analysis
  →**Hint of two component??**

Discuss models that can explain medium energy excess

Contents

- High-energy Neutrino Observations
- Models and Constraints
- AGN Core model
- Summary

Murase, SSK, Meszaros, arXiv:1904.04226
SSK, Murase, Meszaros, 2019, PRD, 100, 083014
SSK, Murase, Meszaros in prep.

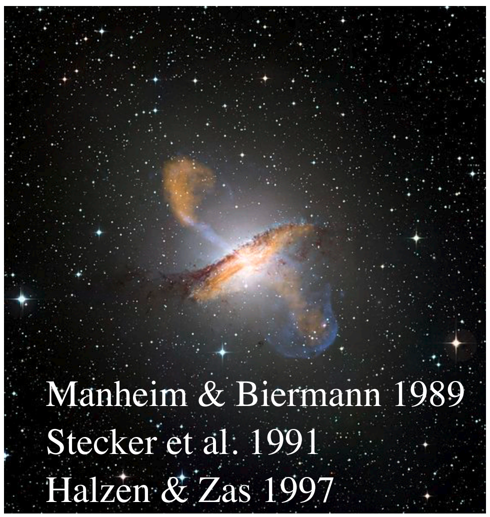
Pre-IceCube Models

- **Cosmic-ray accelerators**

  mainly pγ interaction

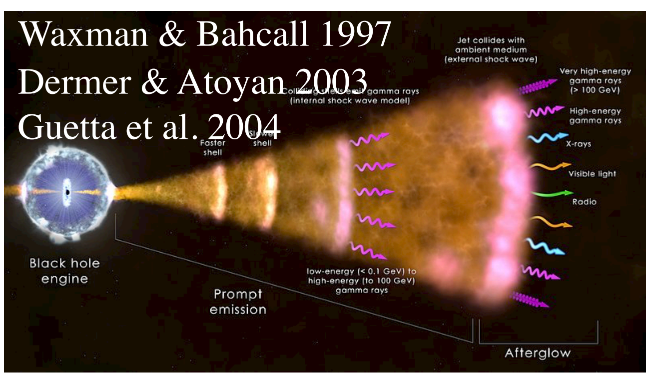
  - Active Galactic Nuclei (AGN)

    Blazars & luminous Seyfert galaxies



Manheim & Biermann 1989
Stecker et al. 1991
Halzen & Zas 1997

  - Gamma Ray Bursts (GRBs)

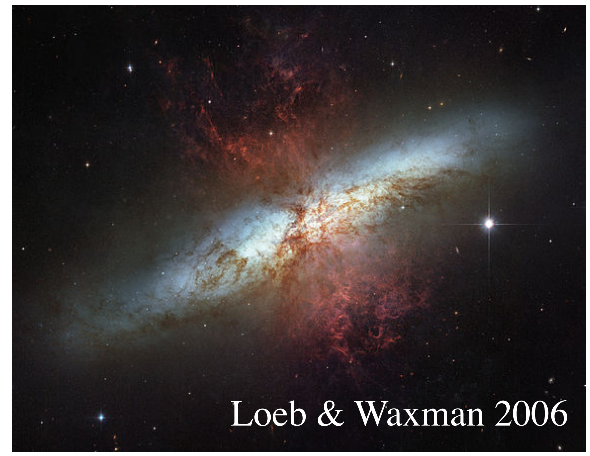


Waxman & Bahcall 1997
Dermer & Atoyan 2003
Guetta et al. 2004

- **Cosmic-ray reservoirs**

  mainly pp interaction

  - Star Forming Galaxies (SFG)



Loeb & Waxman 2006

  - Galaxy Group / Galaxy Cluster

Murase et al. 2008
Kotera et al. 2009

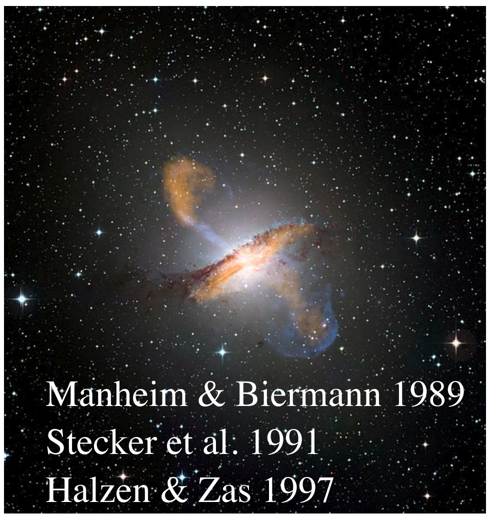
Pre-IceCube Models

- **Cosmic-ray accelerators**

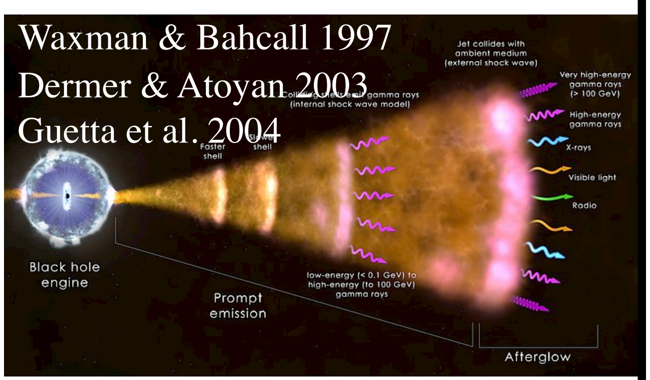
  mainly pγ interaction

  - Active Galactic Nuclei (AGN)

    Blazars & luminous Seyfert galaxies



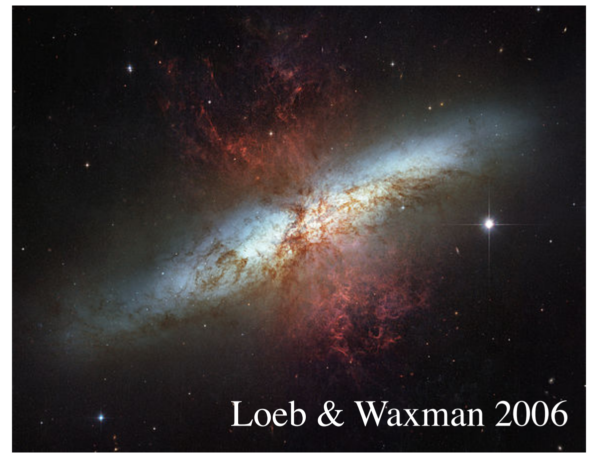
  - Gamma Ray Bursts (GRBs)



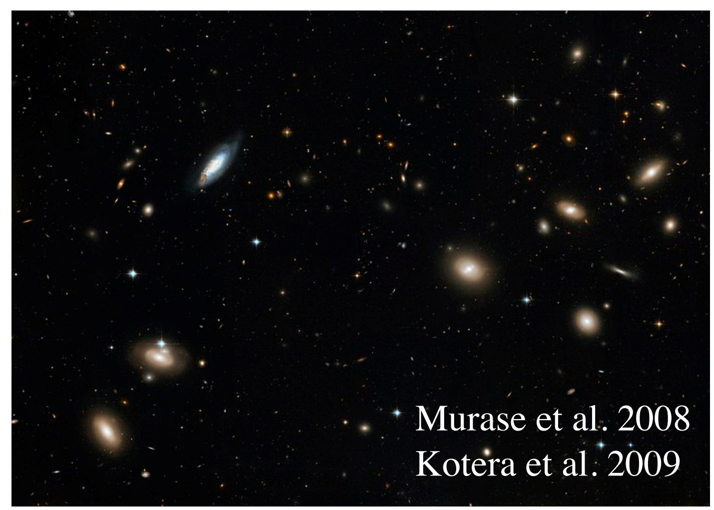
- **Cosmic-ray reservoirs**

  mainly pp interaction

  - Star Forming Galaxies (SFG)



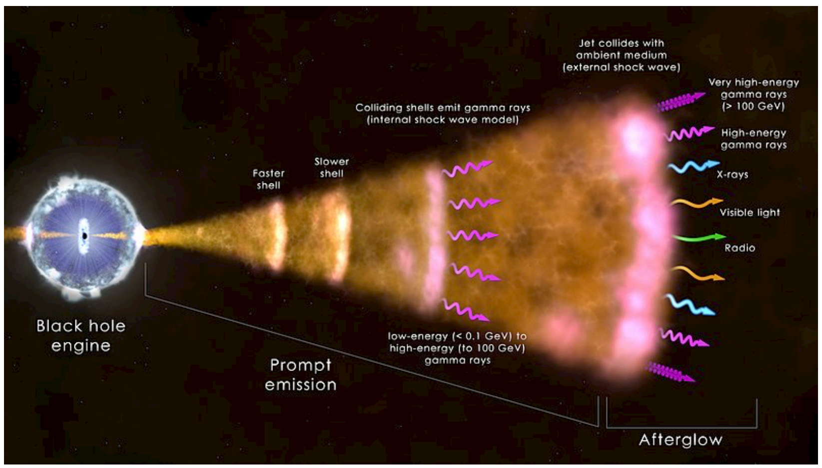
  - Galaxy Group / Galaxy Cluster

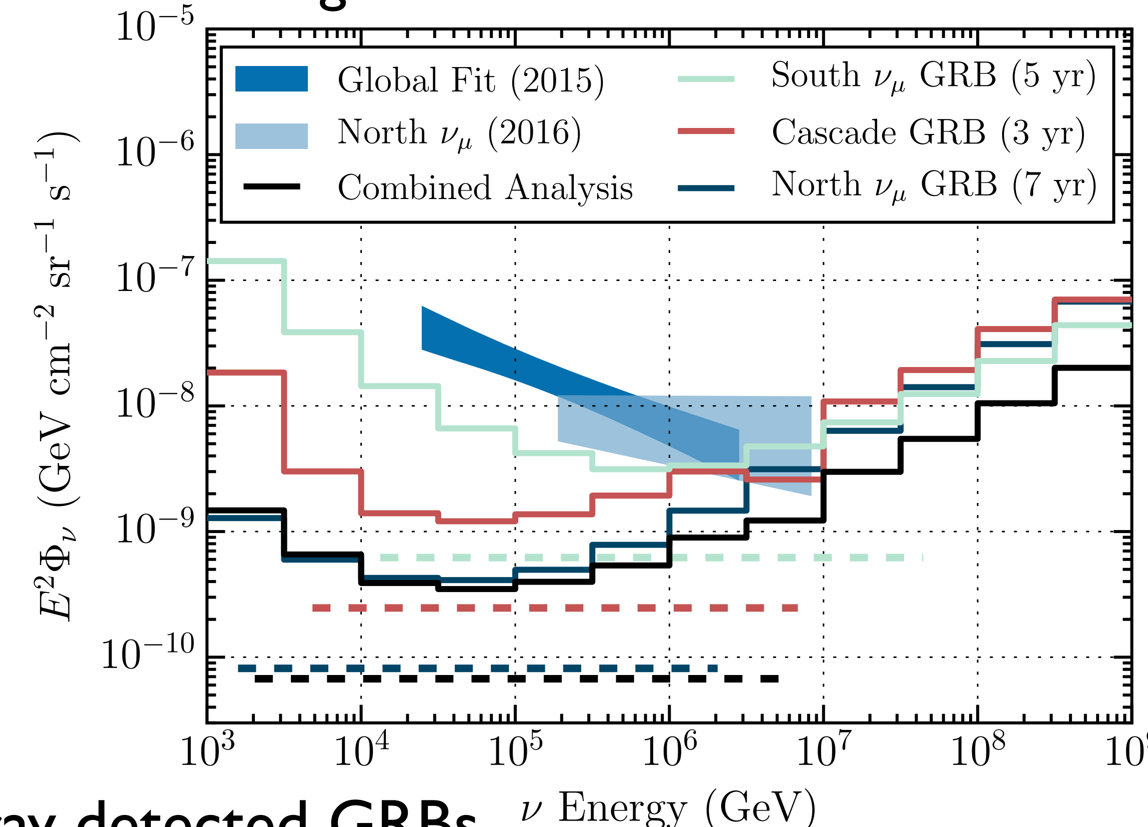


High-Luminosity GRBs

IceCube 2012, 2015, 2017

- GRBs: explosion related to death of massive star
- The most luminous explosion in electromagnetic waves





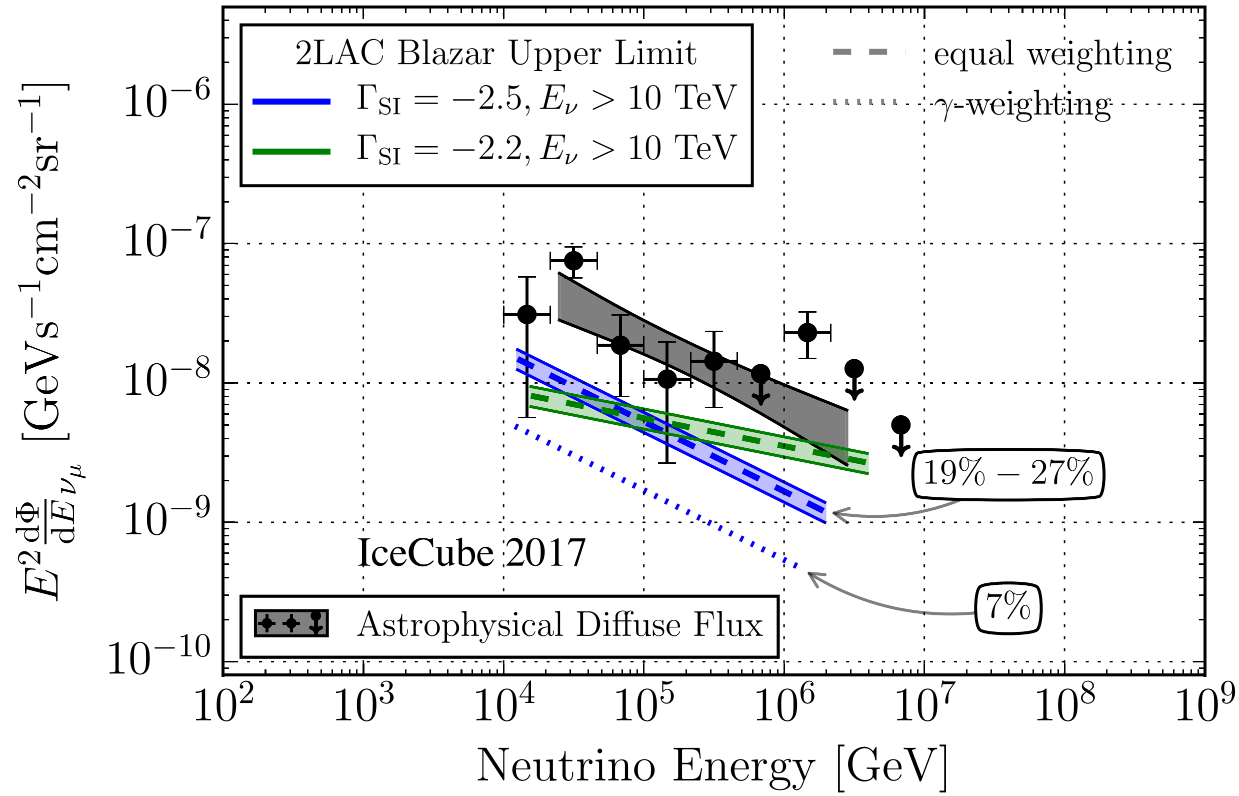
- Stacking analysis of gamma-ray detected GRBs

→ No associated neutrinos so far

→ **Less than 1 % of detected neutrinos**

Blazars

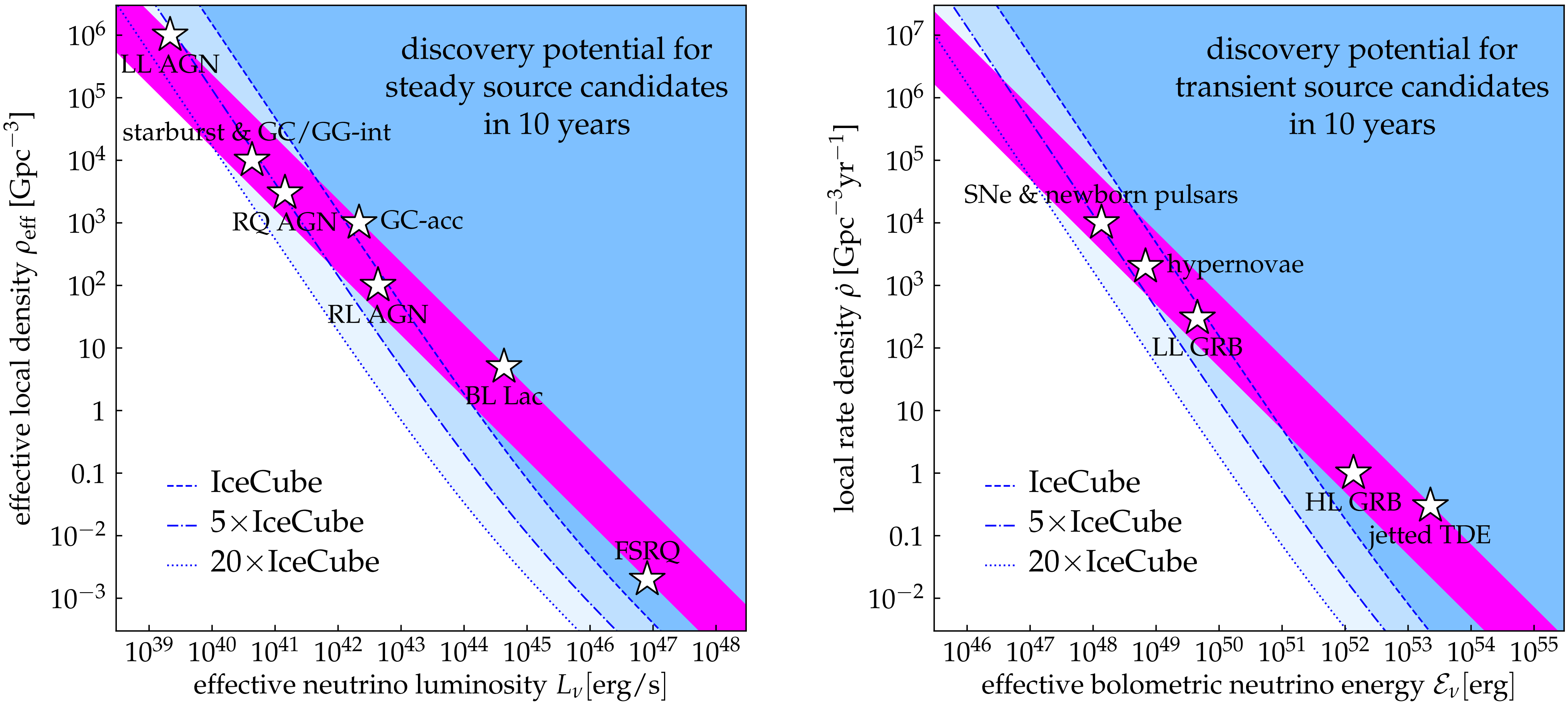
- AGNs whose jets are directed to us
- The most luminous steady objects



- Stacking analysis of blazars detected by Fermi LAT
  → No associated neutrinos so far
  → **Less than 27 % of detected neutrinos**

see also Yuan et al. 2019

Point-source constraint



- Diffuse intensity ~ (Source number density) x (Luminosity)
- **No point-source detection disfavors luminous sources** (GRBs, Blazars, Jetted TDEs)

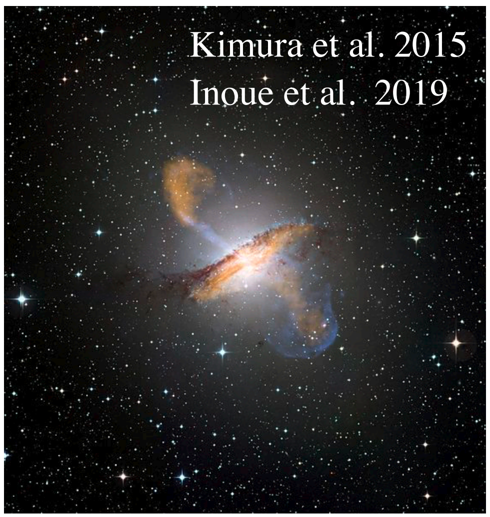
Murase & Waxman 2016

PeV Neutrino Models

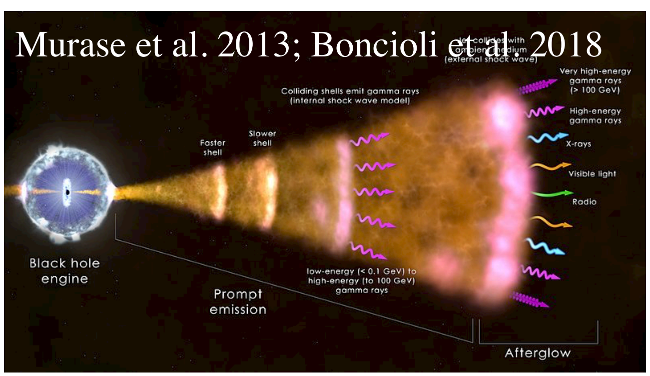
- **Cosmic-ray accelerators**

  mainly pγ interaction

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



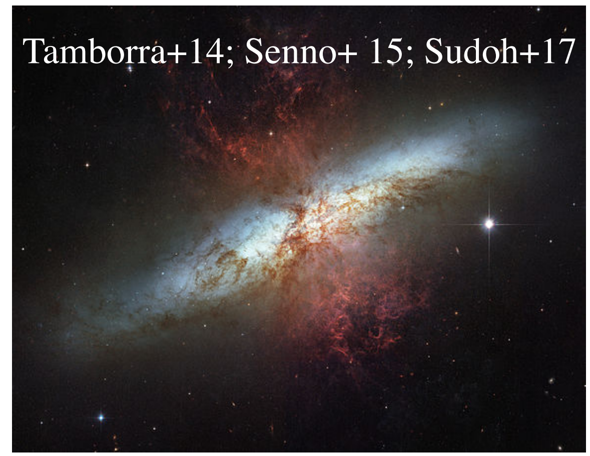
  - Gamma Ray Bursts (GRBs)
  - LLGRBs



- **Cosmic-ray reservoirs**

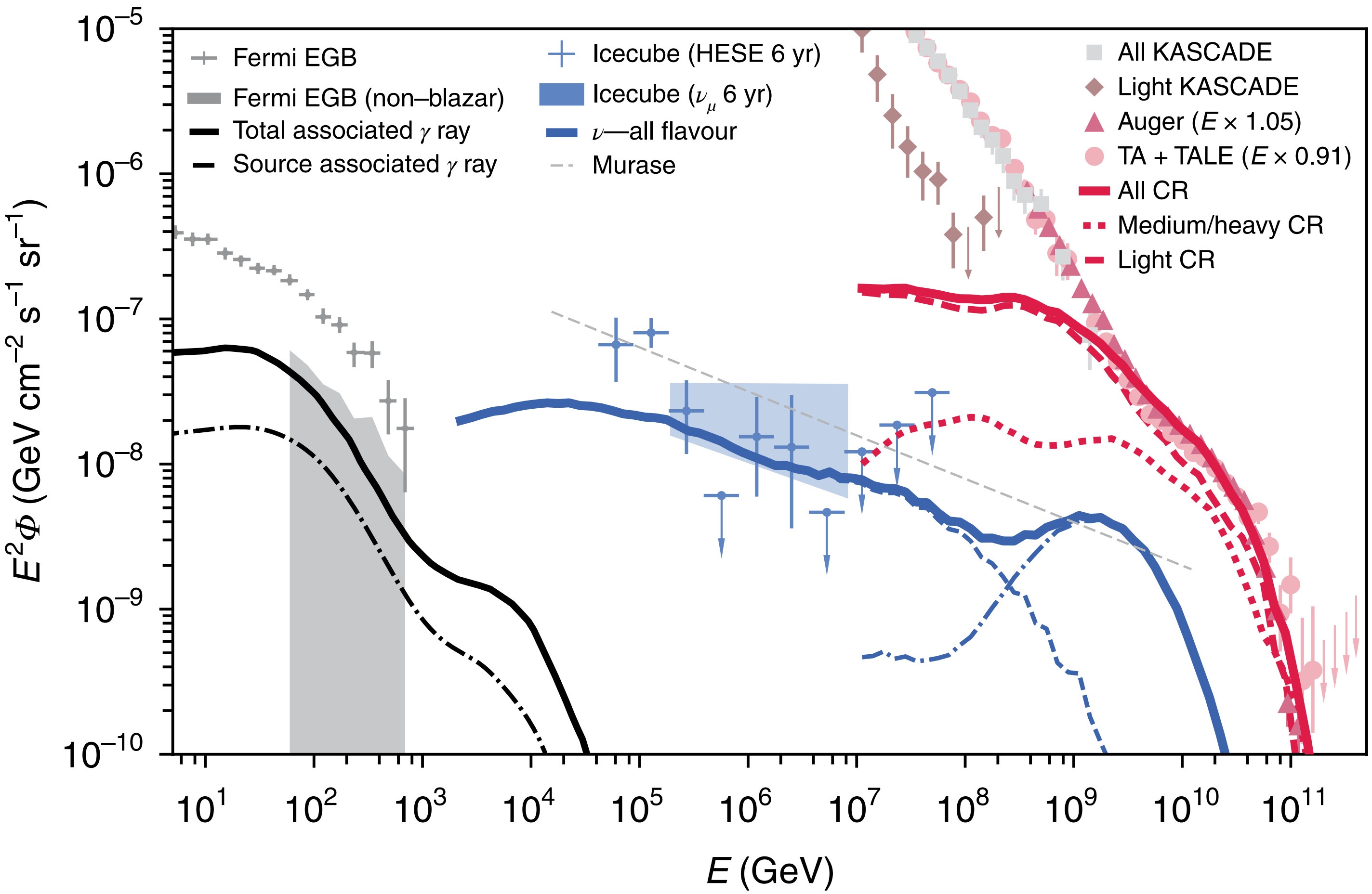
  mainly pp interaction

  - Star Forming Galaxies (SFG)



  - Galaxy Group / Galaxy Cluster

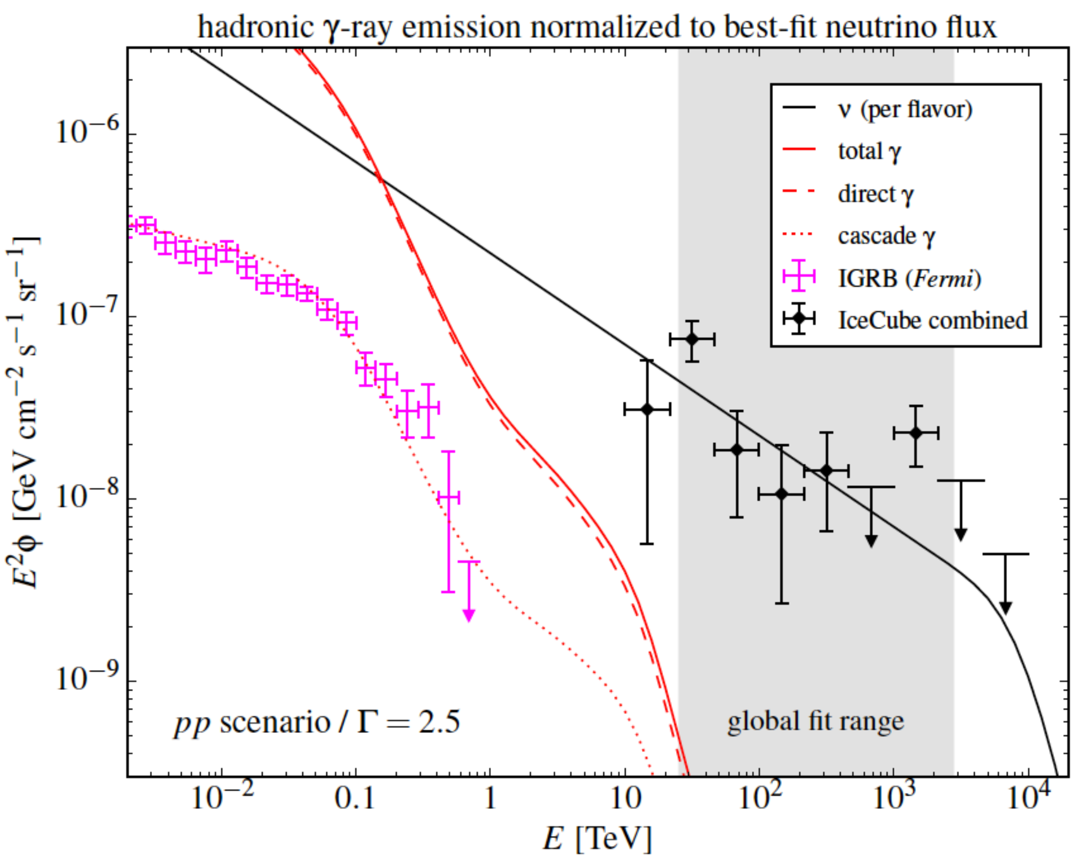
Grand-unified Picture

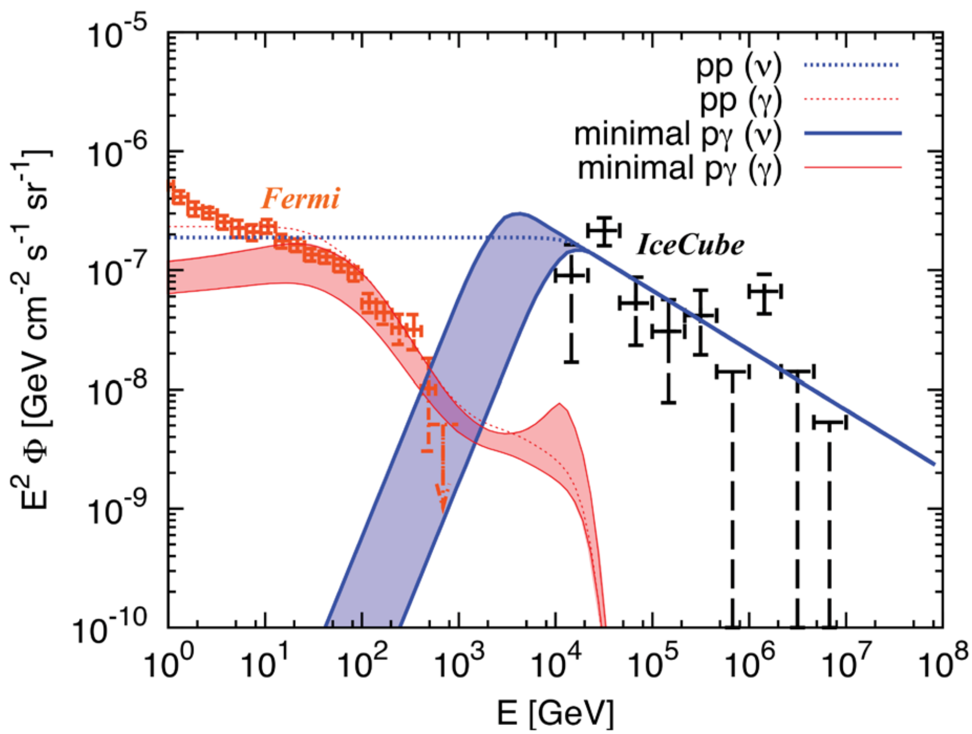


Fang & Murase 18

- AGN jets create UHECRs
  →UHECRs are confined and produce neutrinos in galaxy clusters
  →Accompanied γ-rays are cascaded down to sub-TeV γ-rays
  →**A common origin of sub-TeV γ, PeV ν, & UHECRs**

Gamma-ray Constraint





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

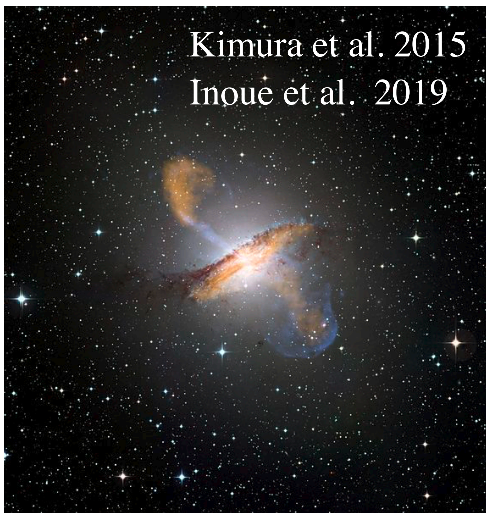
- ν flux@10 TeV > γ flux@100 GeV
  → accompanying γ overshoot Fermi data
  → **ν sources should be opaque to TeV γ rays**

Models for 10 TeV Neutrinos

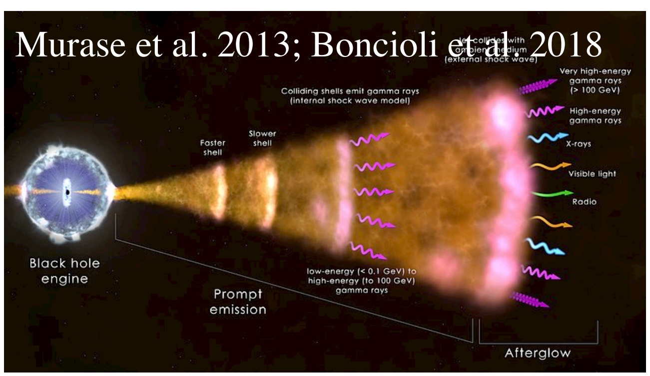
- **Cosmic-ray accelerators**

  mainly pγ interaction

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



  - Gamma Ray Bursts (GRBs)
    - LLGRBs



- **Cosmic-ray reservoirs**

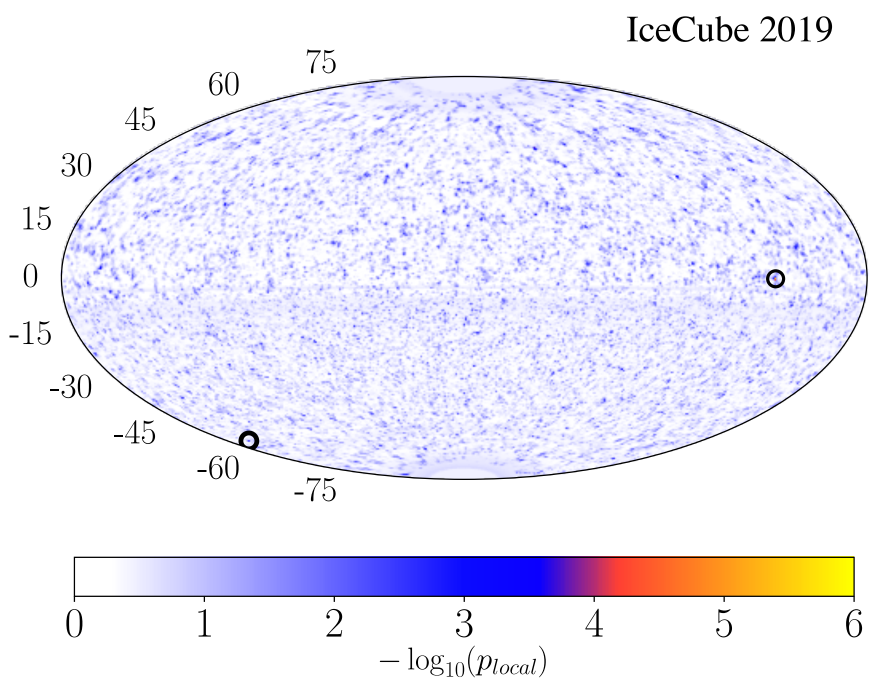
  mainly pp interaction

  - Star Forming Galaxies (SFG)

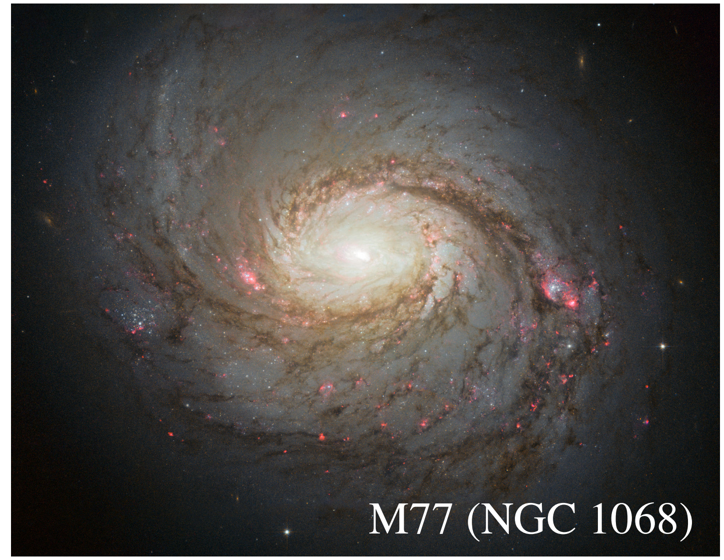
  - Galaxy Group / Galaxy Cluster

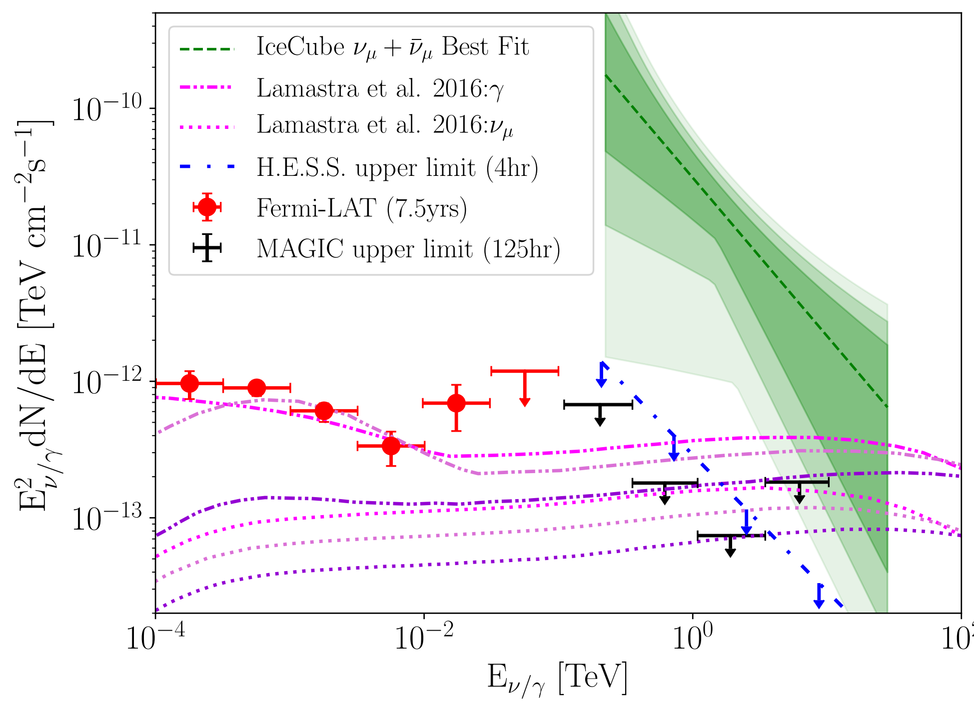
Hint of ν point sources

- Point source search with 10-year data set



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



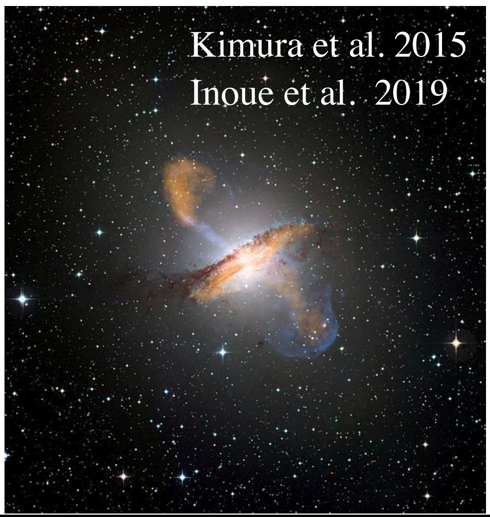


Models for 10 TeV Neutrinos

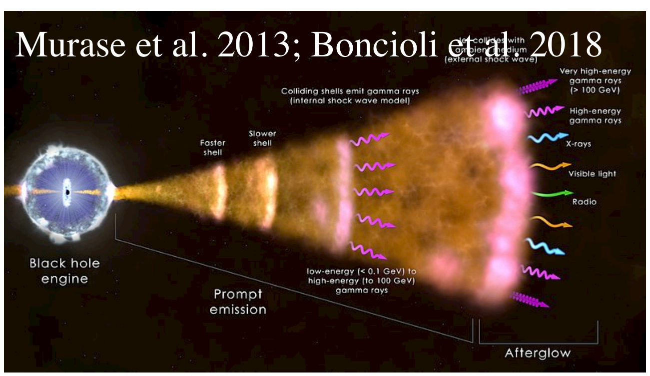
- **Cosmic-ray accelerators**

  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

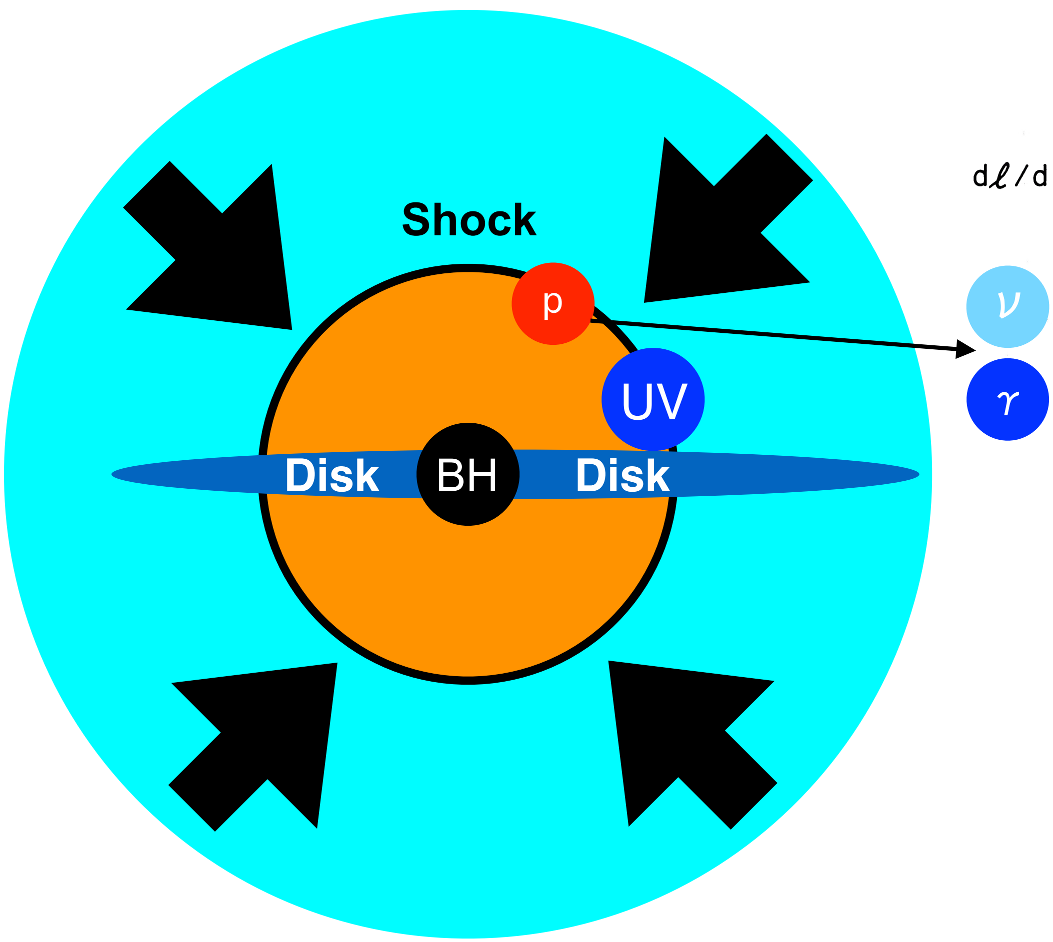
Contents

Murase, SSK, Meszaros, arXiv:1904.04226
SSK, Murase, Meszaros, 2019, PRD, 100, 083014
SSK, Murase, Meszaros in prep.

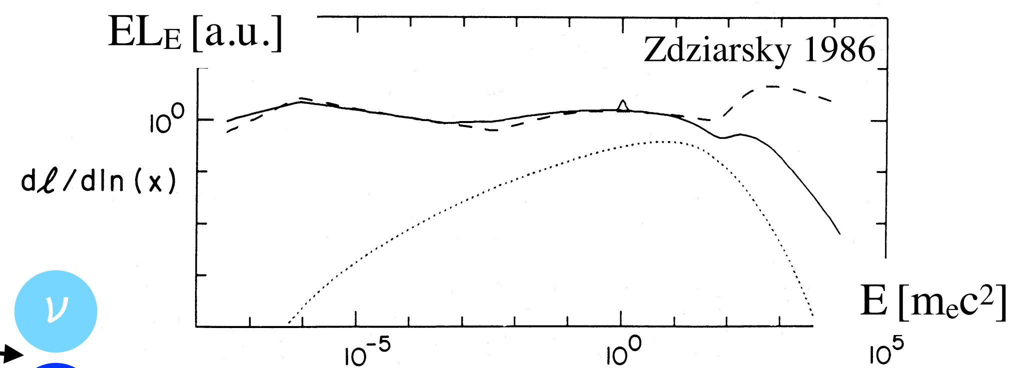
Classical AGN Core Model

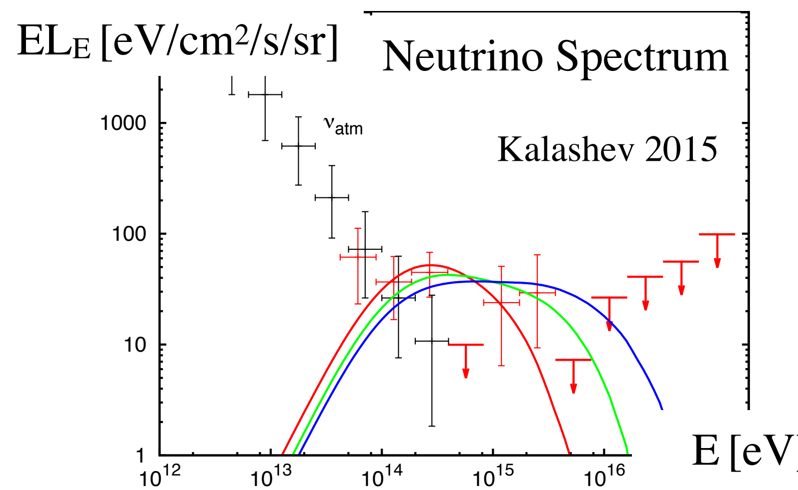
Berezinsky & Ginzburg 1981; Begeleman et al. 1990; Stecker et al. 1991

- Proton acceleration in accretion shocks
  → **X-ray emission by proton-induced EM cascades**
- Photomeson production using UV photons
  → **Hard spectrum in 100 TeV range**

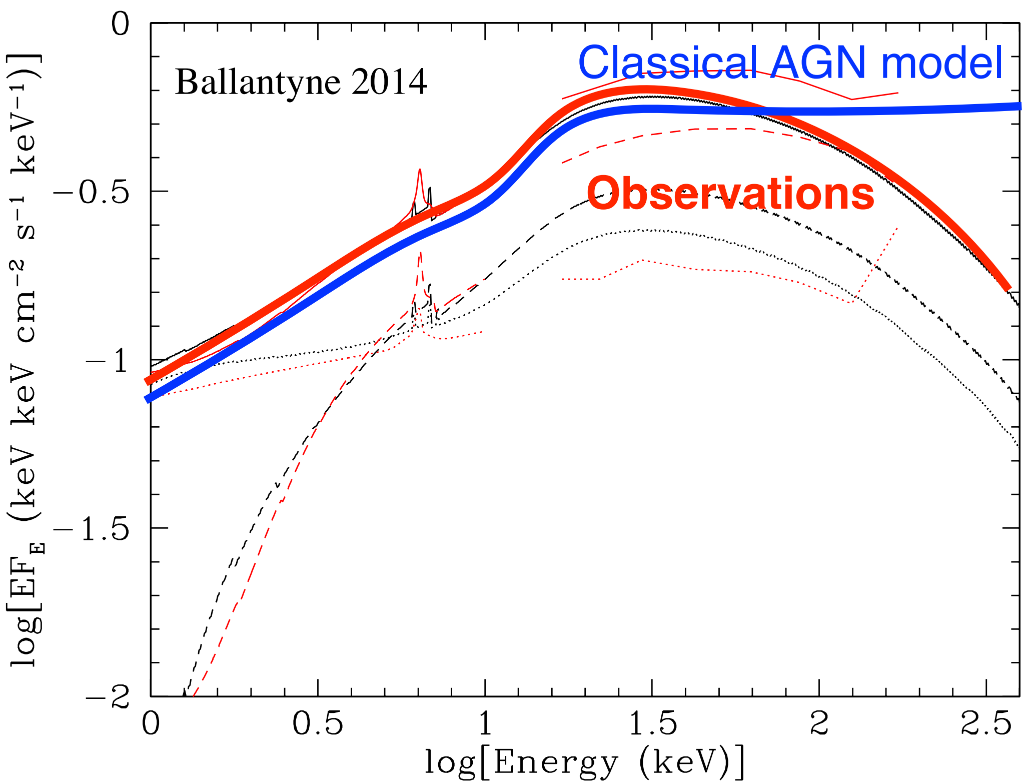


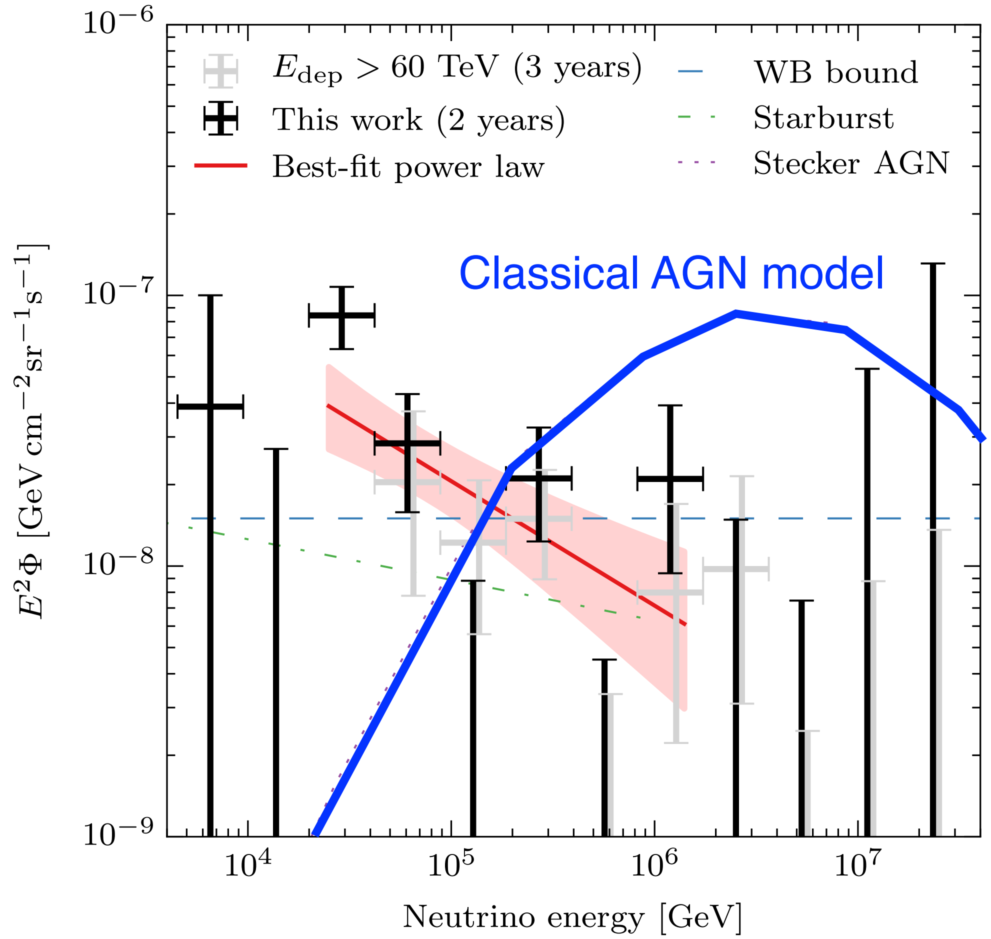
Photon Spectrum





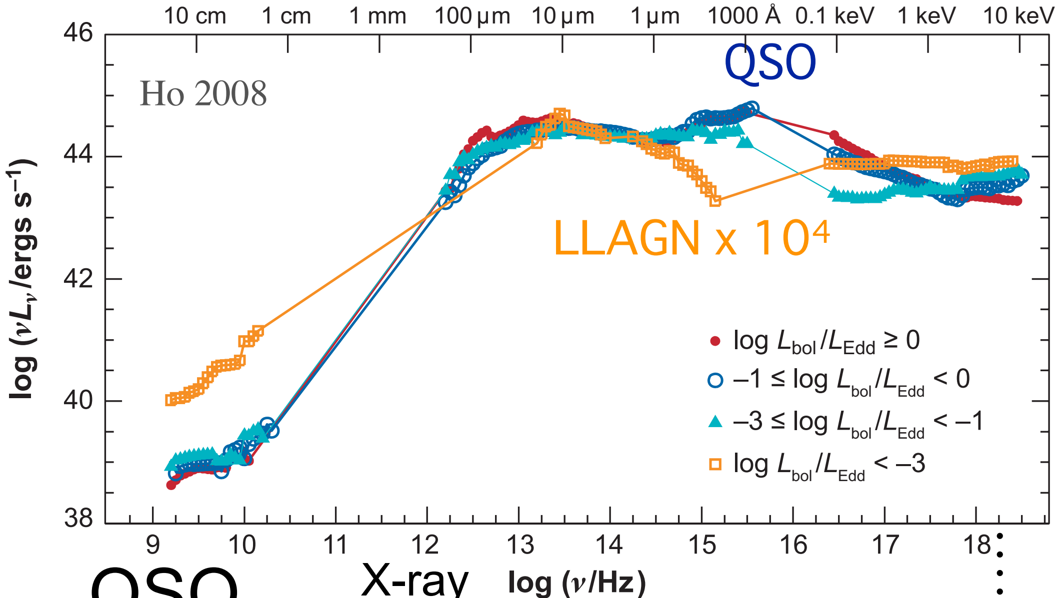
Classical AGN Core Model



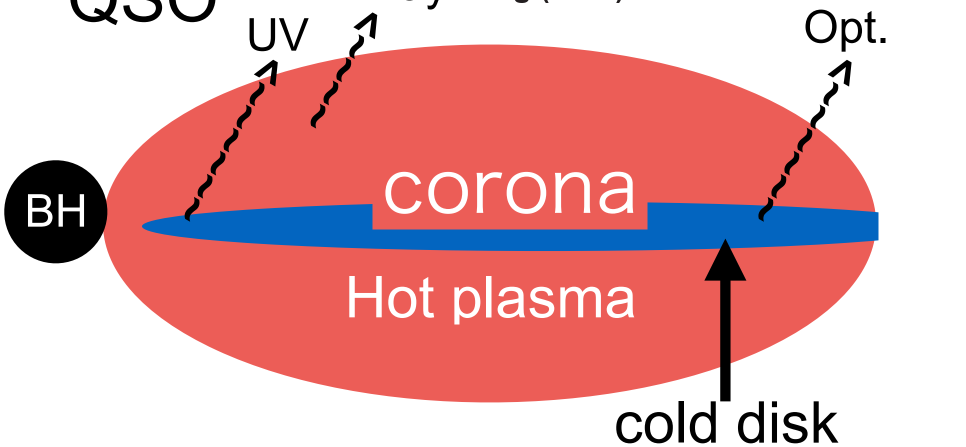


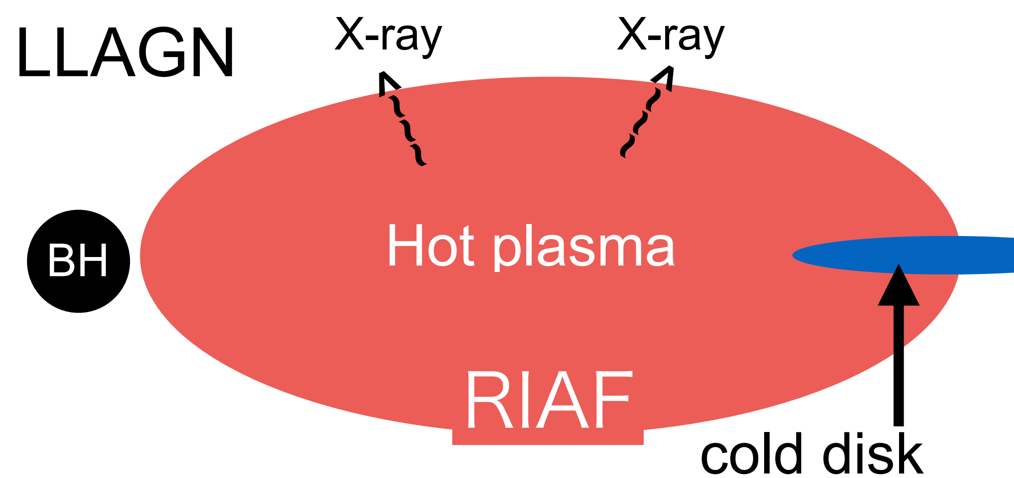
- Observations of softening in hard X-ray range
  → **Accretion shock models are disfavored**
- Observed spectrum is soft in 0.1-1 PeV range
  → **inconsistent with UV target photons**

Modern AGN Core Picture



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



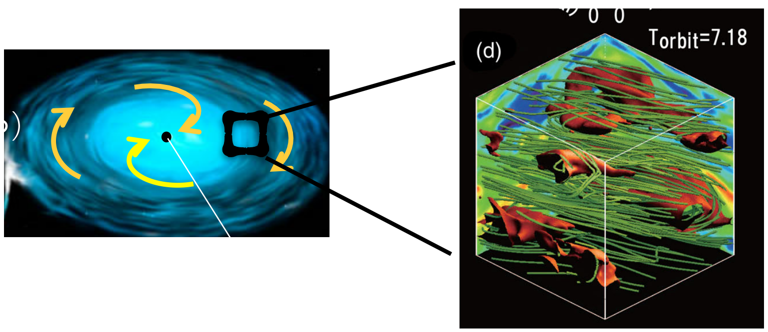


Protons in coronae & RIAFs are collisionless

→ Non-thermal proton production

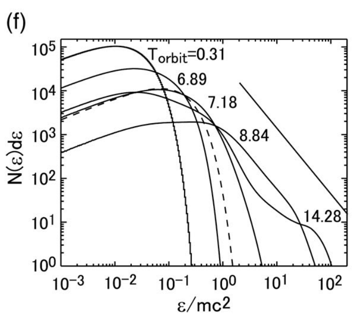
Particle Acceleration in Accretion Flows

Particle-In-Cell Simulations



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

turbulent

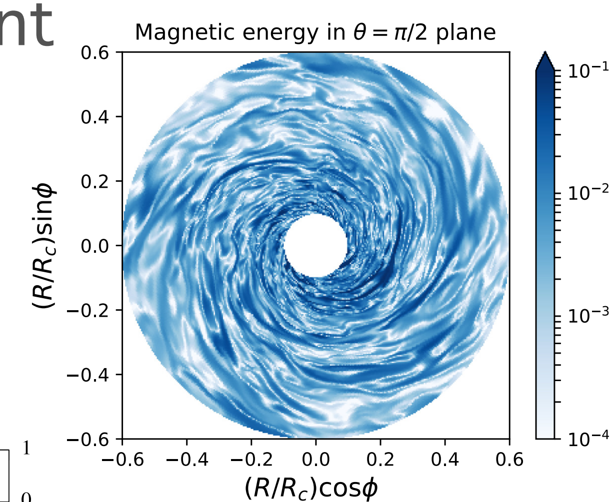


Non-thermal

Numerical Simulations

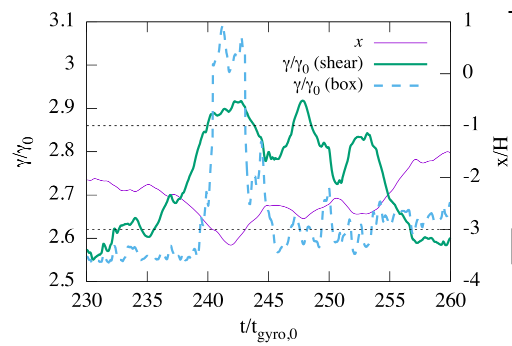
MHD + Test Particle Simulations

turbulent



SSK et al. 2016; SSK et al. 2019

see also Lynn et al. 2014



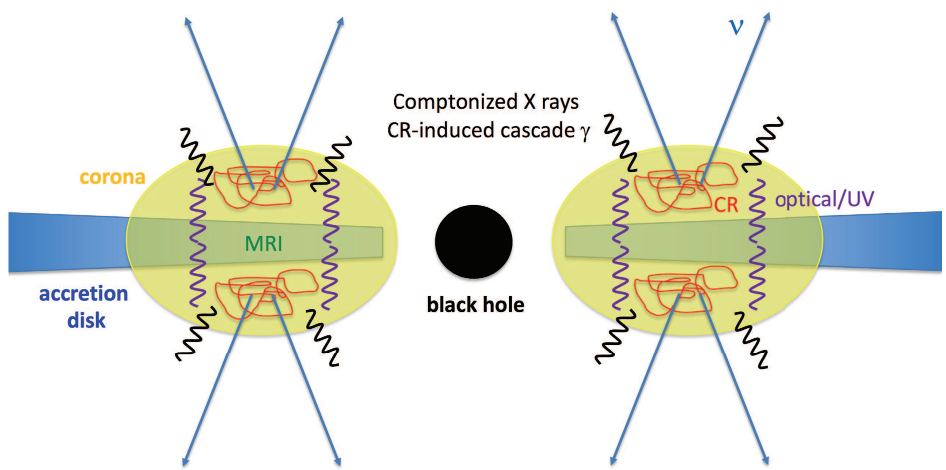
Energy change

Magnetic reconnection or MHD turbulence accelerates CRs

Non-thermal Particles

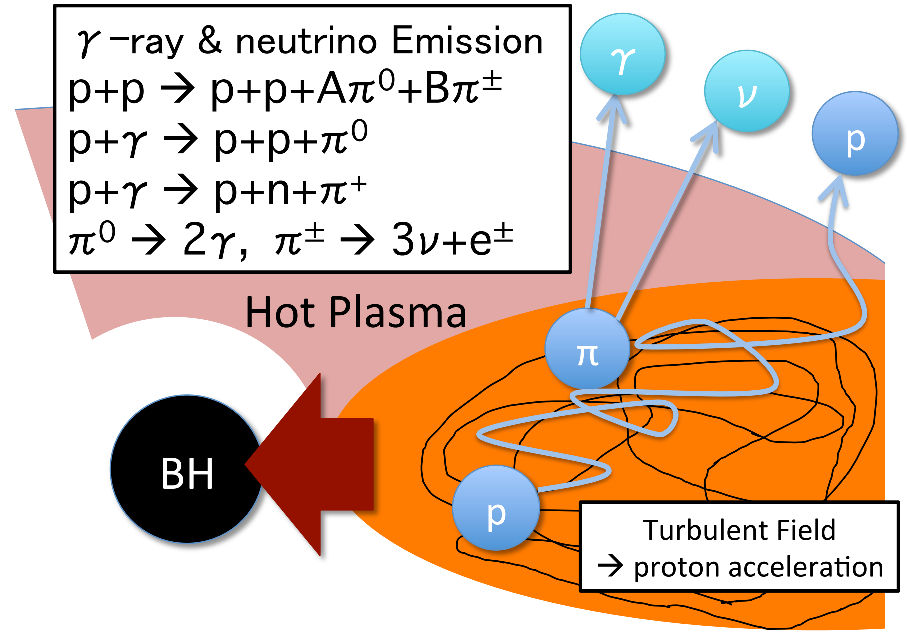
Murase, SSK et al. 2019

- Coronae in QSOs



Mahadevan et al. 1997; SSK et al. 2015; SSK et al. 2019

- RIAFs in LLAGNs



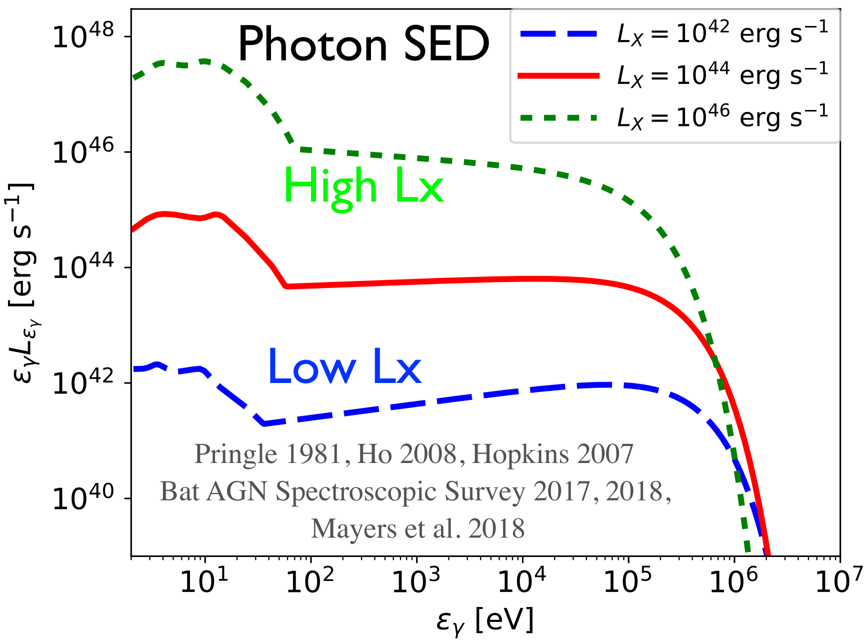
- Transport equations for primary protons and secondary e⁺e⁻ & γ

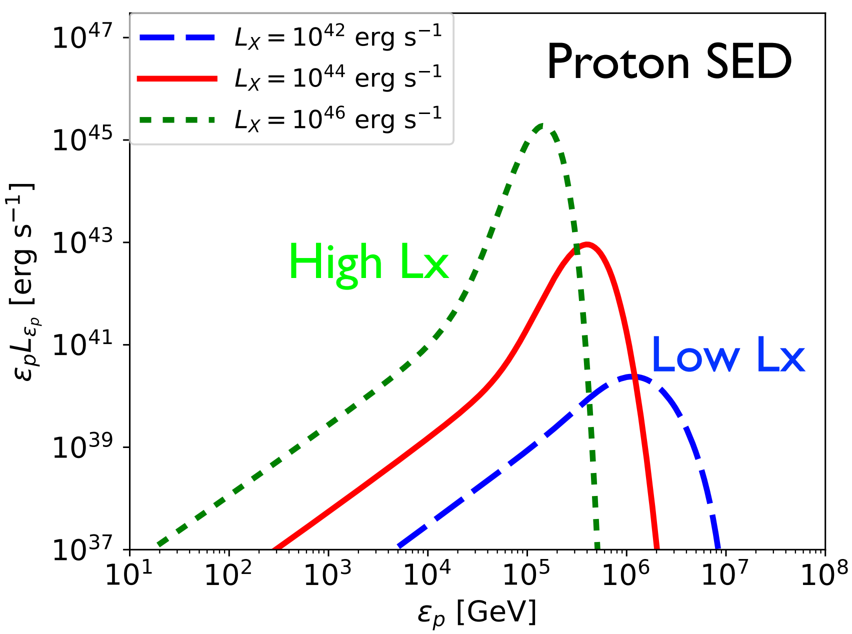
$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\mathrm{cool}}}F_p\right) - \frac{F_p}{t_{\mathrm{esc}}} + \dot{F}_{p,\mathrm{inj}}$$

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

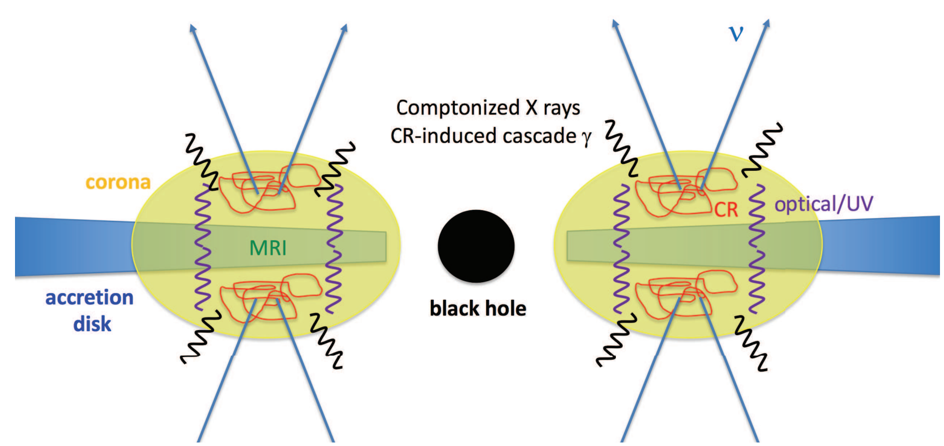
$$\frac{\partial n_{\varepsilon_\gamma}^\gamma}{\partial t} = -\frac{n_{\varepsilon_\gamma}^\gamma}{t_{\gamma\gamma}} - \frac{n_{\varepsilon_\gamma}^\gamma}{t_{\mathrm{esc}}} + \dot{n}_{\varepsilon_\gamma}^{(\mathrm{IC})} + \dot{n}_{\varepsilon_\gamma}^{(\mathrm{ff})} + \dot{n}_{\varepsilon_\gamma}^{(\mathrm{syn})}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

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
- Softer spectra for higher L_X AGNs
- Low proton cutofff energy for high L_X AGNs

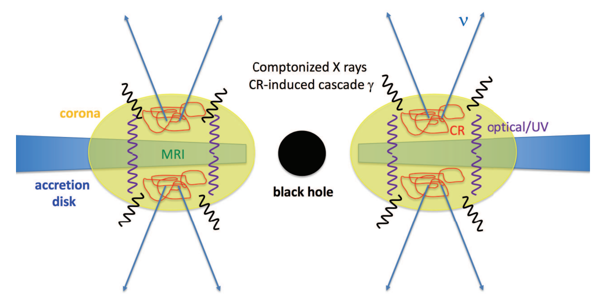


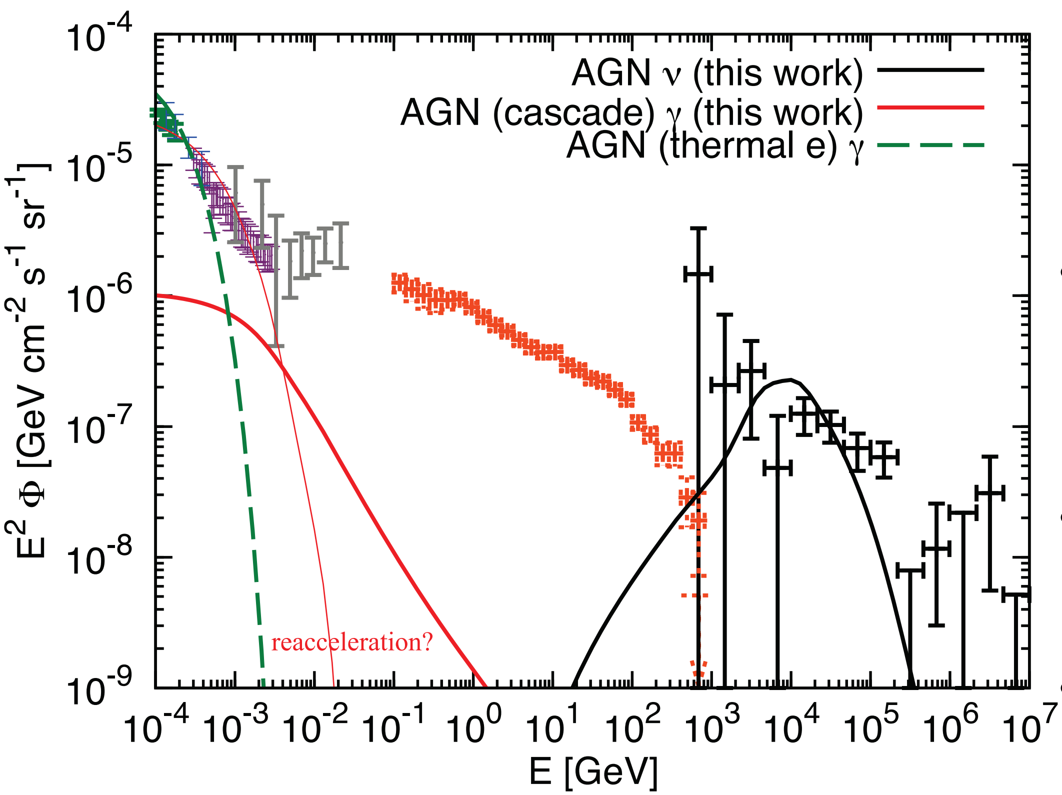
Extragalactic γ & ν Backgrounds

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

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

e.g., Ueda et al. 2014



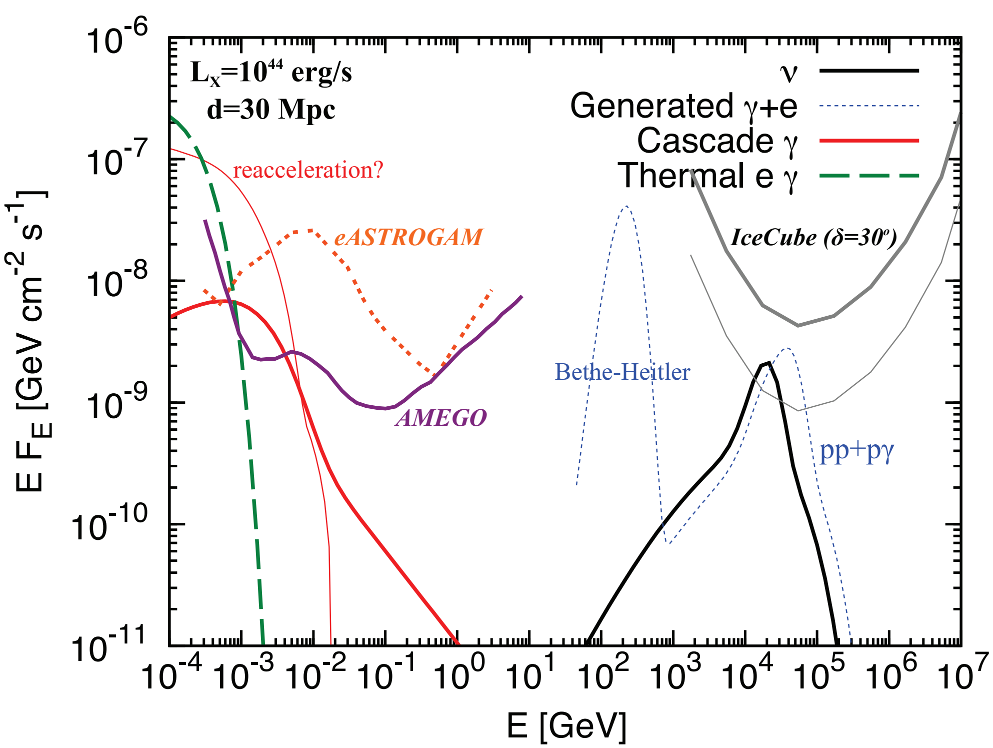


- We choose the injection efficiency so that our model can explain the MESE excess.
- **Energetically reasonable:** $P_{CR}/P_{th} \sim P_{CR}/P_B \sim 0.01$
- Cascade emission provides 10 - 30 % of MeV γ-ray background

HE particles from Nearby AGNs

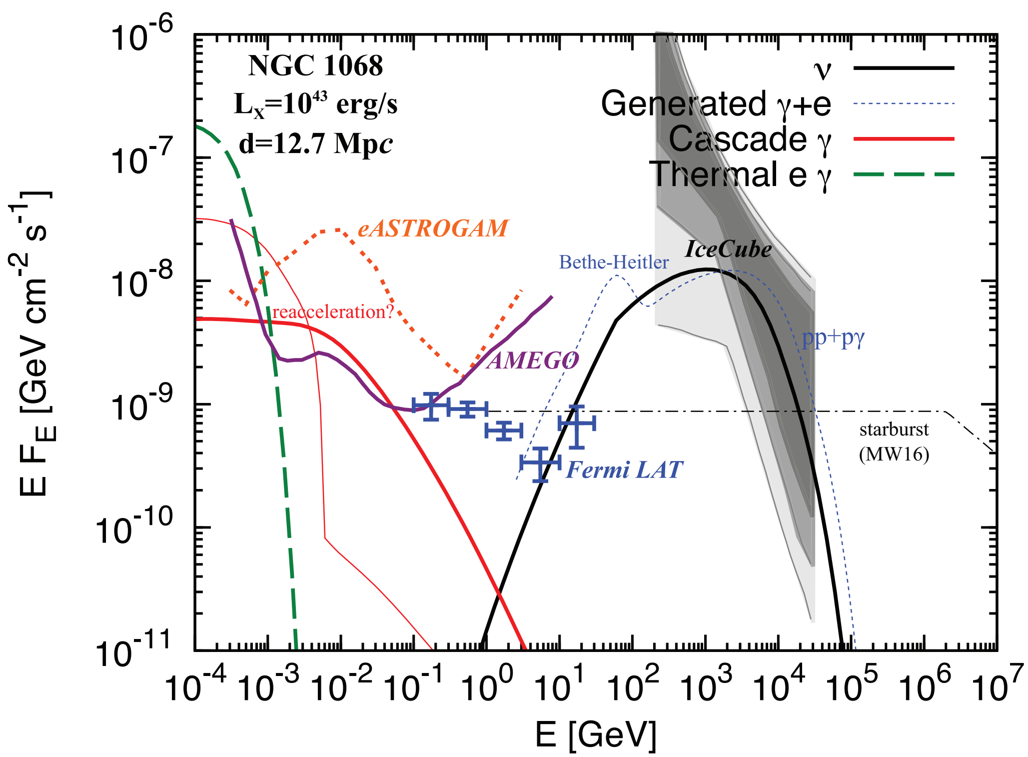
- Ratio of γ to ν flux is fixed by the observed photon field
  → **We can robustly test our model by future experiments**

- A typical Seyfert at 30 Mpc



- Neutrinos & MeV γ-rays can be detected by Future facilities

- NGC 1068

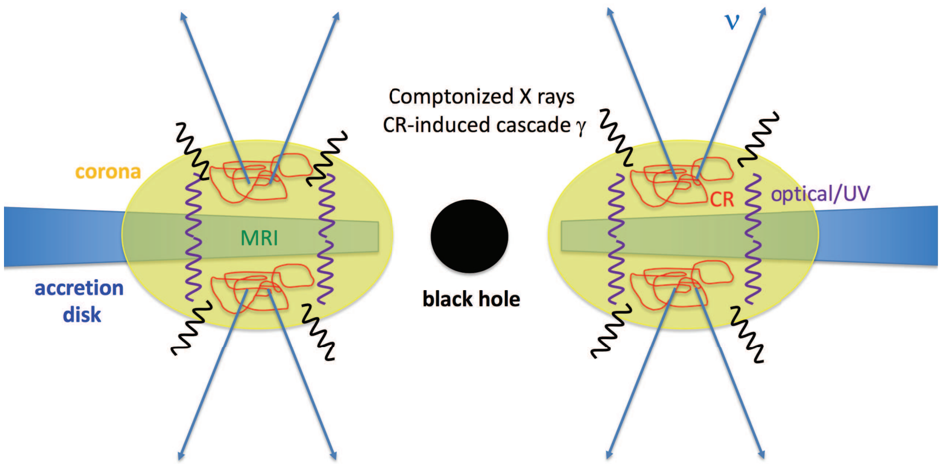


- Possible to explain IceCube data without overshooting γ-ray data

Non-thermal Particles

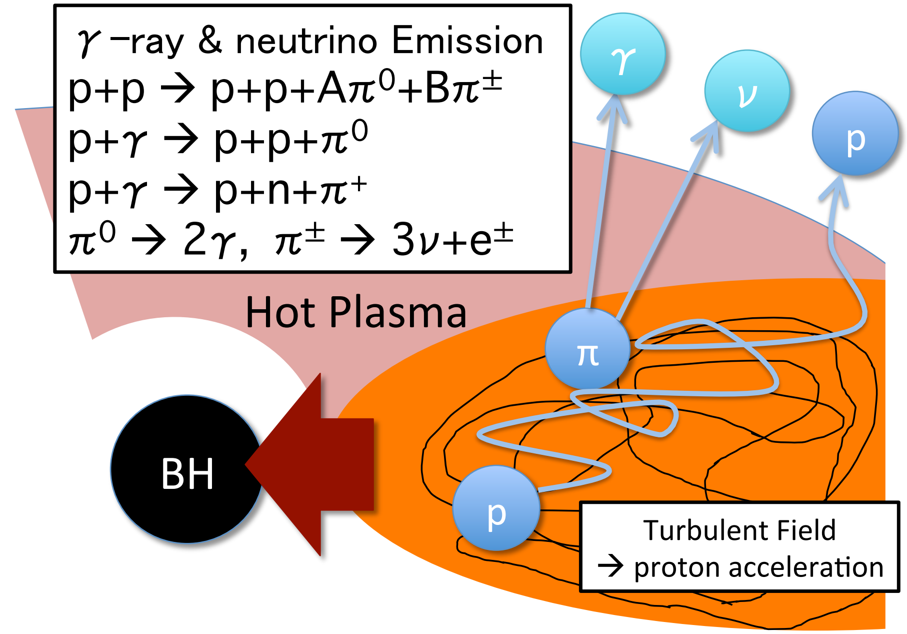
Murase, SSK et al. 2019

- Coronae in QSOs



Mahadevan et al. 1997; SSK et al. 2015; SSK et al. 2019

- RIAFs in LLAGNs



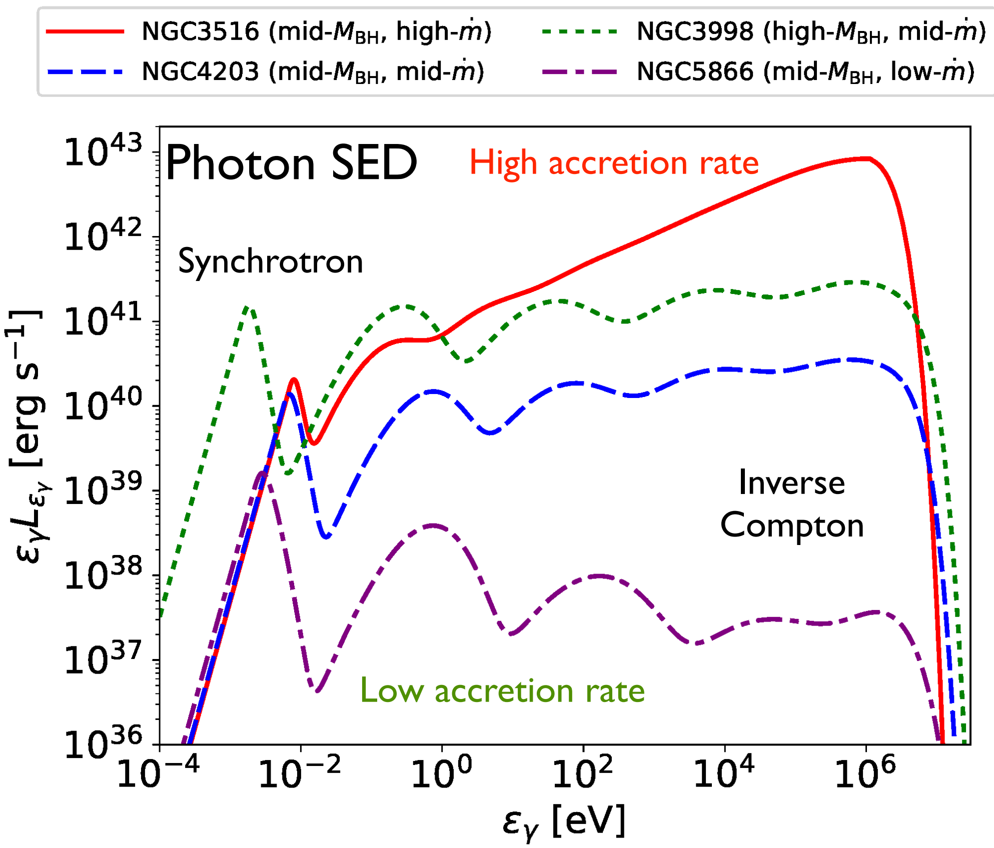
- Transport equations for primary protons and secondary e^+e^- & γ

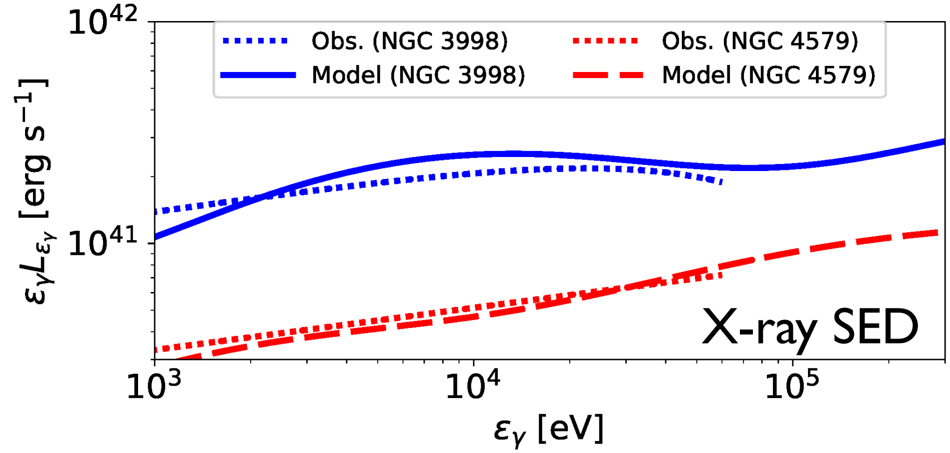
$$\frac{\partial F_p}{\partial t} = \frac{1}{\varepsilon_p^2}\frac{\partial}{\partial \varepsilon_p}\left(\varepsilon_p^2 D_{\varepsilon_p}\frac{\partial F_p}{\partial \varepsilon_p} + \frac{\varepsilon_p^3}{t_{p-\mathrm{cool}}}F_p\right) - \frac{F_p}{t_{\mathrm{esc}}} + \dot{F}_{p,\mathrm{inj}}$$

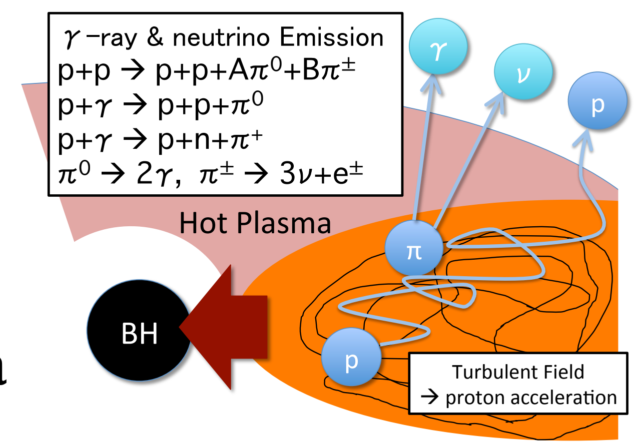
$$\frac{\partial n^e_{\varepsilon_e}}{\partial t} + \frac{\partial}{\partial \varepsilon_e}\left[(P_{\mathrm{IC}} + P_{\mathrm{syn}} + P_{\mathrm{ff}} + P_{\mathrm{Cou}})n^e_{\varepsilon_e}\right] = \dot{n}^{(\gamma\gamma)}_{\varepsilon_e} - \frac{n^e_{\varepsilon_e}}{t_{\mathrm{esc}}} + \dot{n}^{\mathrm{inj}}_{\varepsilon_e},$$

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

Target Photon Field



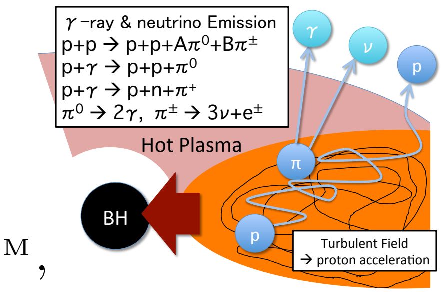


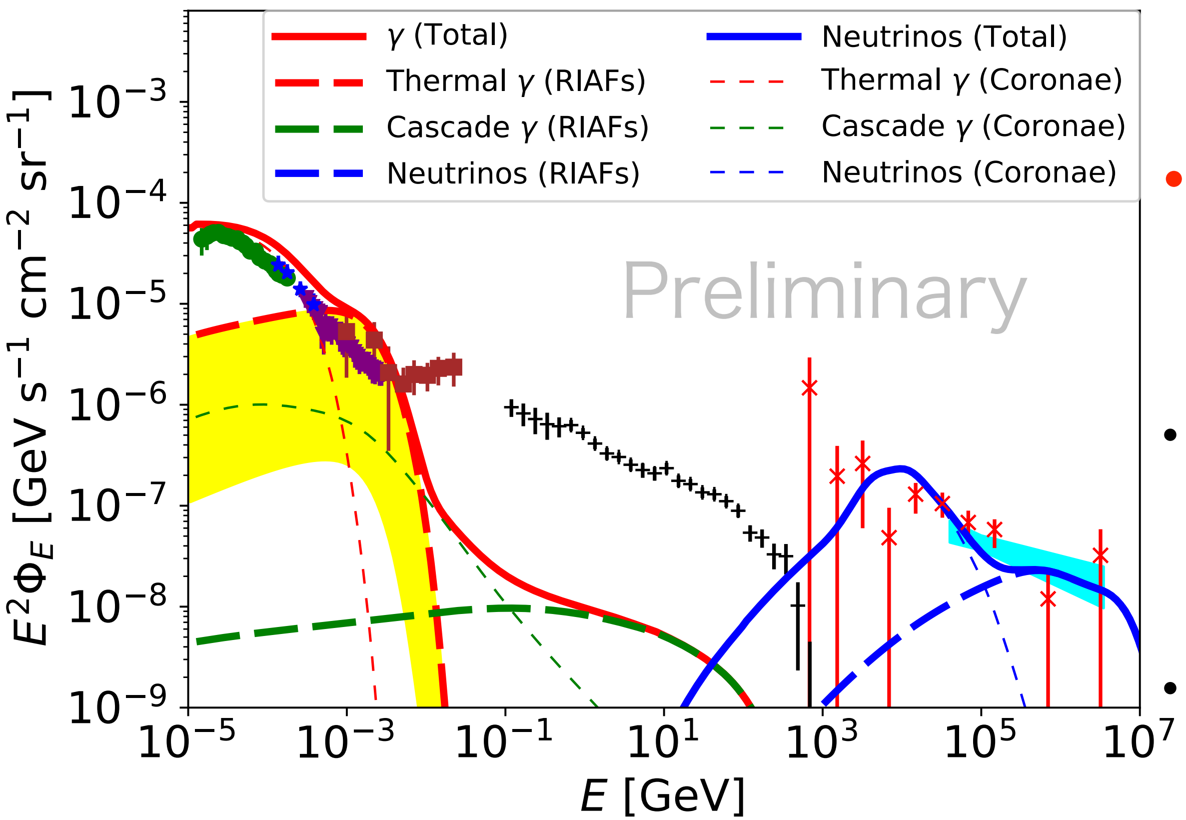


- Low-luminosity → Poor observational data → **Formulation based on theory**
- Thermal electrons in RIAFs emit seed photons
- Our results are consistent with X-ray observations

Extragalactic γ & ν Backgrounds

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



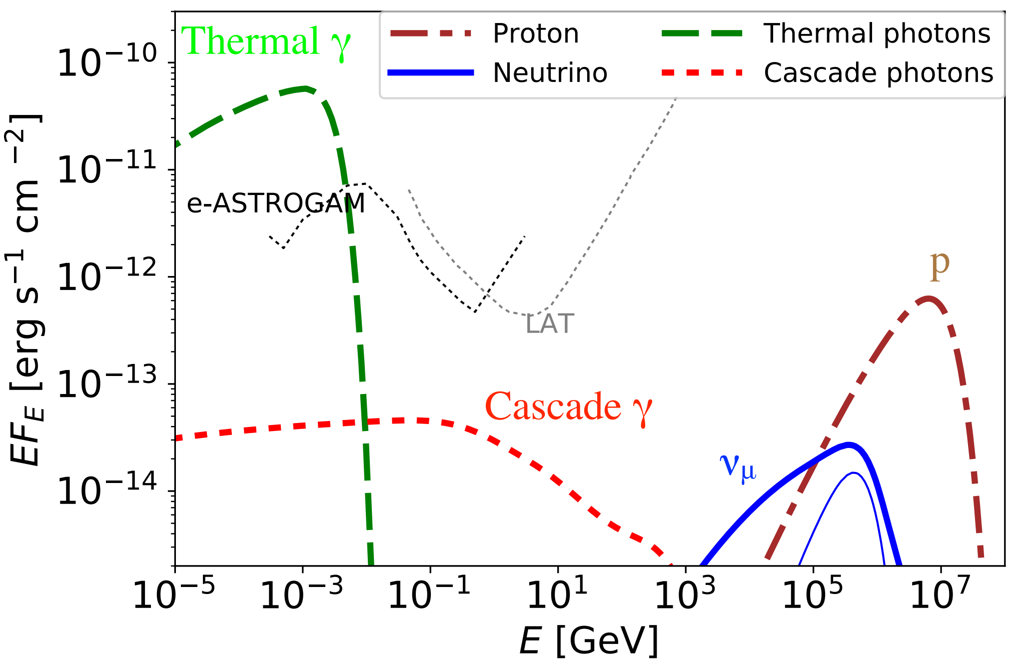


- **LLAGN can explain PeV ν and MeV γ bkgd simultaneously**
- GeV γs are attenuated at RIAFs in LLAGNs
  → consistent with Fermi data
- $P_{CR} \sim 0.01 P_{th}$

- With a similar parameter set, Seyfert contribute to TeV-PeV ν
  → AGN cores can account for a broad range of γ & ν background

Detectability

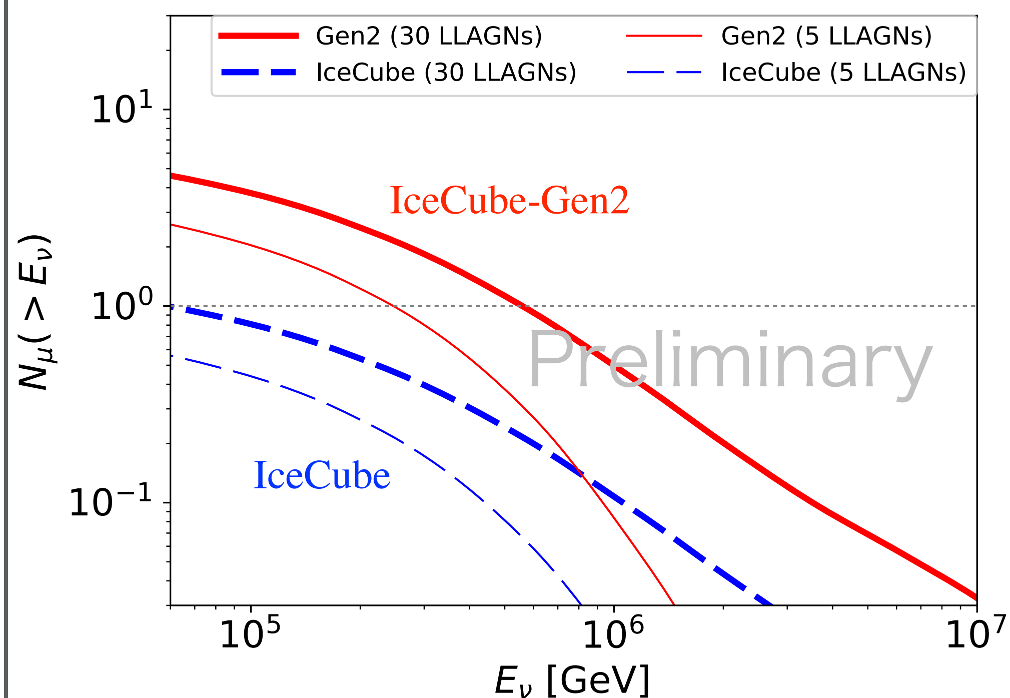
- NGC 4565



- Cascade γ-rays @ E<1 GeV: **too faint to detect** by LAT or CTA
- Thermal γ-rays @ E~MeV: **detectable** by future MeV satellites

- Prospects for stacking analysis

$$\overline{\mathcal{N}_\mu} = \int \phi_\nu A_{\rm eff}(\delta,\ E_\nu) dE_\nu,$$



- Atmospheric background is negligible @ E > 100 TeV
- IceCube **cannot detect** νs
- **IceCube-Gen2 will detect νs**

Contents

- High-energy Neutrino Observations
- Models and Constraints
- AGN Core model
- Summary

Murase, SSK, Meszaros, arXiv:1904.04226
SSK, Murase, Meszaros, 2019, PRD, 100, 083014
SSK, Murase, Meszaros in prep.

Summary

- Two model independent constraints:
  - Multiplet & stacking analyses disfavors GRBs & blazars
  - Gamma-ray constraint disfavors coscmi-ray reservoir models
- Accretion flows in AGNs are feasible neutrino sources
  - **Seyfert galaxies can reproduce TeV-PeV ν background** without violating Fermi constraints with observation based parameters.
  - **RIAFs in LLAGNs can explain MeV γ &PeV ν backgrounds simultaneously**
- Future multi-messenger observations can robustly test both models:
  - IceCube-Gen2 can resolve both AGNs as point sources
  - Proposed MeV satellites can detect MeV γ rays from AGNs