Diffuse TeV gamma-rays from the Galactic center and Sgr A*

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  - Radiatively inefficient accretion flows (RIAFs)
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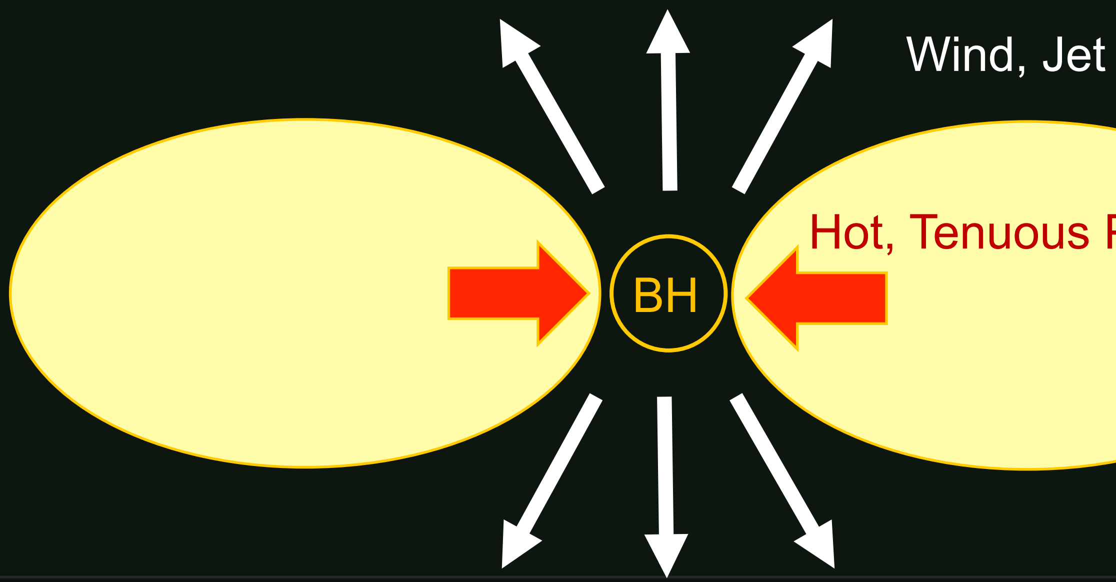
    - Sgr A* is an LLAGN
- Diffusion of CR protons in the CMZ
- Diffuse TeV gamma rays from the Galactic center
- Sgr A* as a PeVatron (preliminary)
- Summary

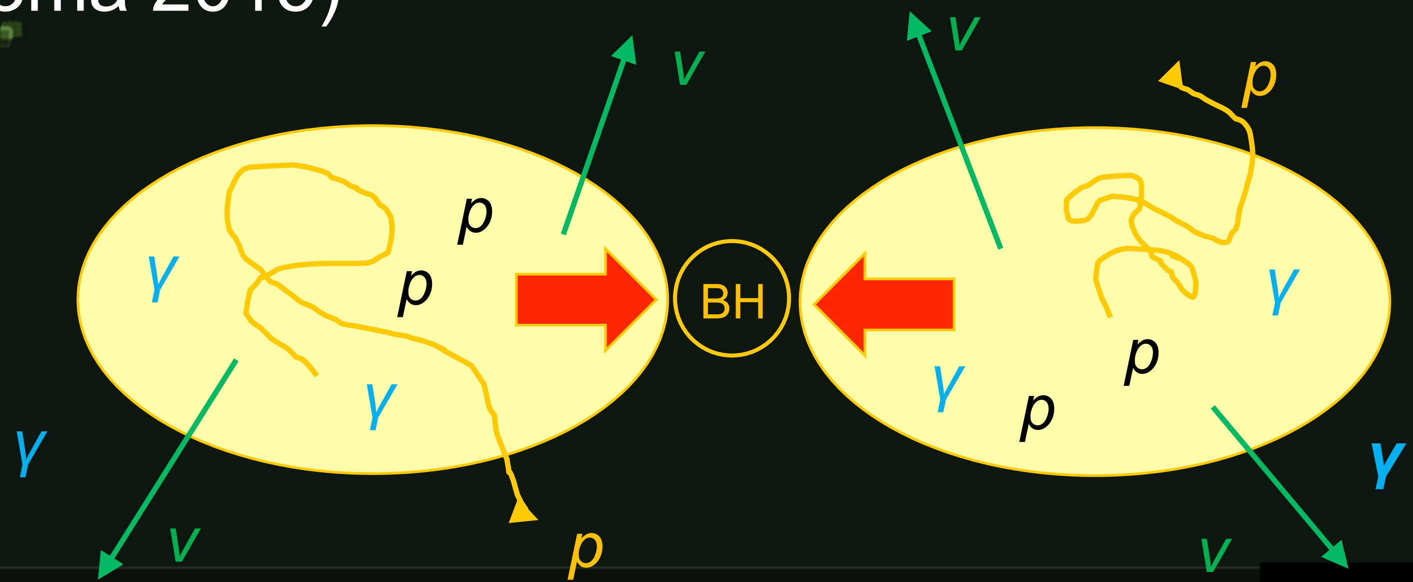
CR acceleration in a RIAF

- Accretion flows for LLAGNs are thought to be RIAFs
  - Hot and tenuous
  - Coulomb collision is inefficient (collisionless)
    - Insufficient thermalization → particle acceleration



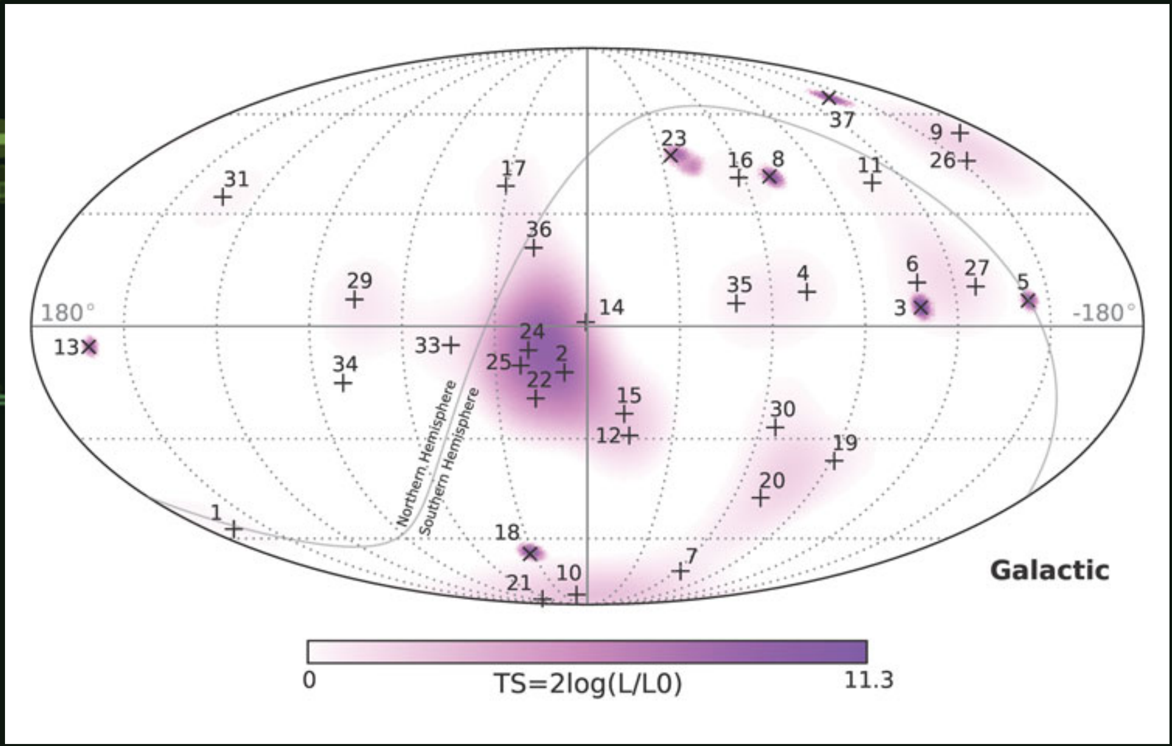
CR acceleration in RIAF

- Protons are stochastically accelerated in turbulence in a RIAF
  - *pγ* and *pp*-interaction in the RIAFs may be responsible for production of the neutrinos detected by IceCube (Kimura, Murase, & Toma 2015)



IceCube Observations

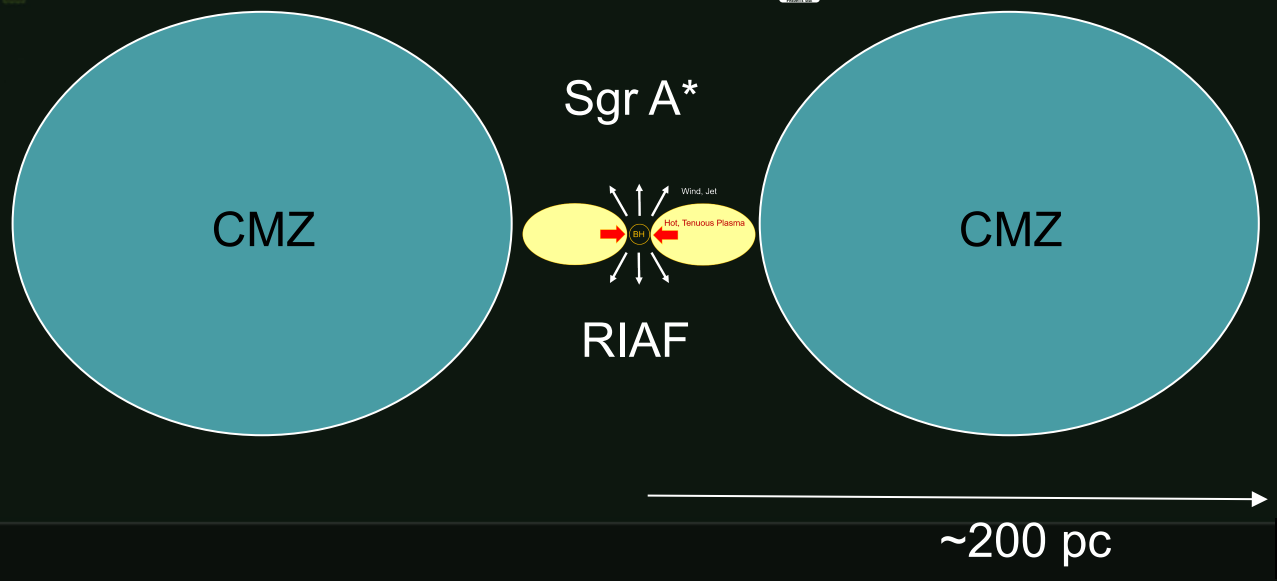
- Uniform distribution of neutrinos
  - Neutrinos have extragalactic origin



IceCube home page

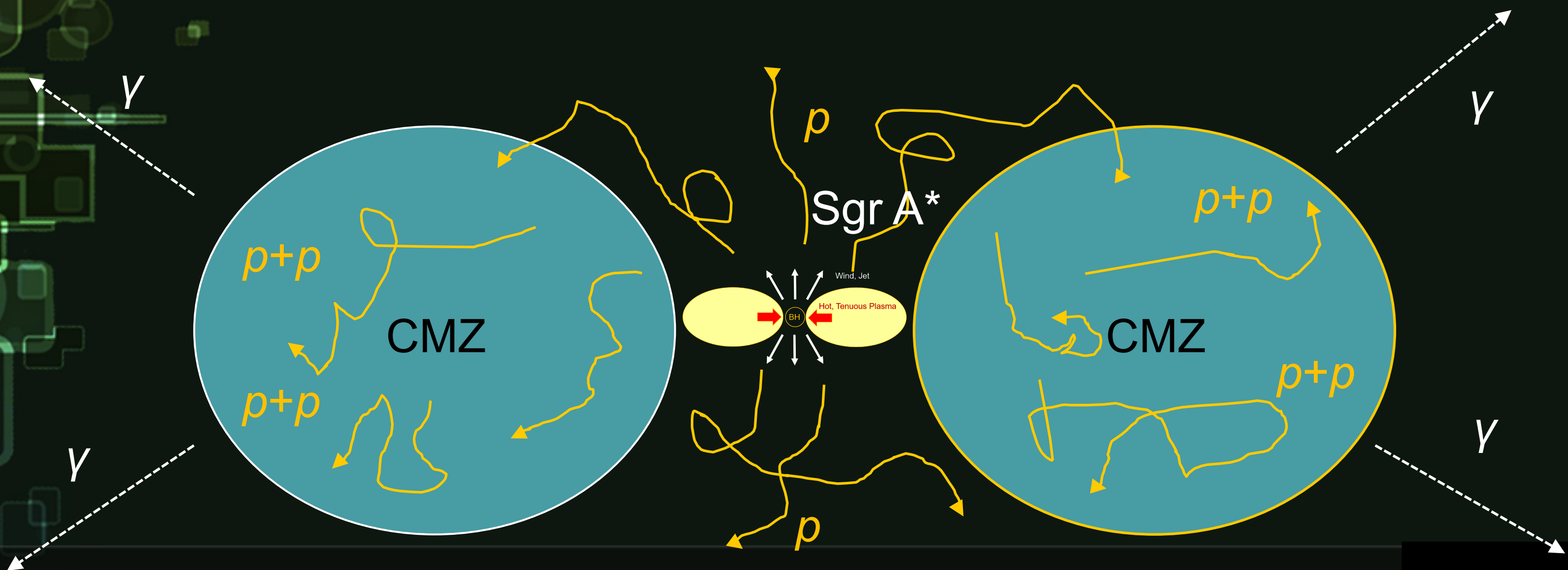
Sgr A* and CMZ

- Sgr A* is the supermassive black hole at the Galactic center
  - It is a LLAGN and has a RIAF
    - CRs may be accelerated
  - Surrounded by molecular gas (CMZ)
    - Mass of CMZ is ~ 10^7 M



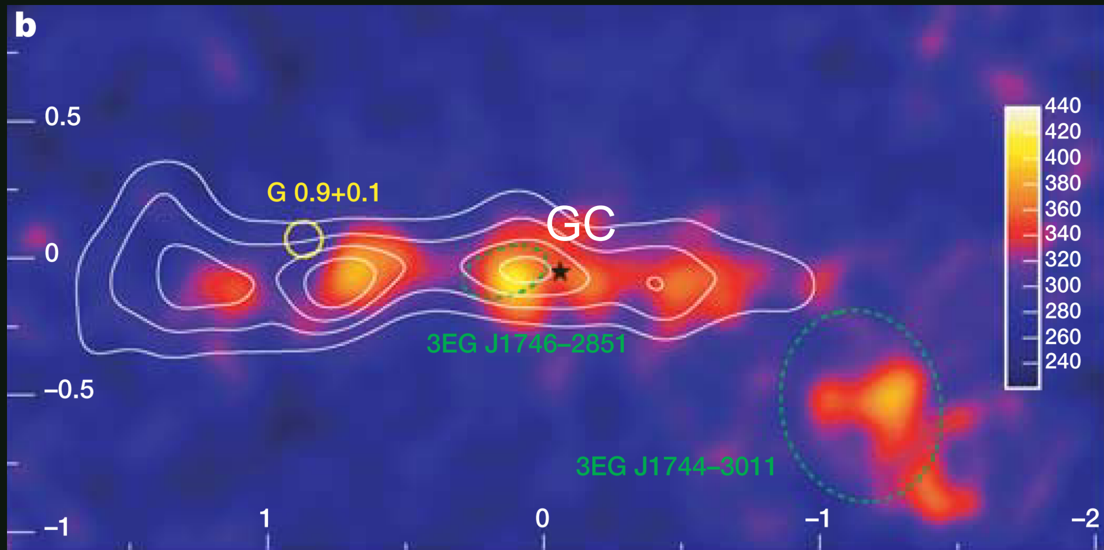
CR protons in CMZ

- Some of the protons accelerated in the RIAF should plunge into the CMZ
  - They produce γ-rays through *pp*-interaction
  - We calculate the diffusion of CR protons in the CMZ and the γ-ray emission



Diffuse γ-rays from the CMZ

- HESS observation around the Galactic center (GC)
  - CMZ radiates γ-rays
    - CRs have diffused from the GC (HESS collaboration 2015)
  - We investigate this TeV γ-ray emission



Color: γ-ray
Contour: molecular gas
(Aharonian+ 06)

Model

- We solve a diffusion equation
  - Spherically symmetric
    - We ignore the outflow perpendicular to the Galactic disc

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial f}{\partial r}\right) + Q$$

  - Diffusion coefficient (κ)
    - Typical Galactic value (e.g. Gabici+ 09)

$$\kappa = 10^{28}\left(\frac{E_p}{10\ \mathrm{GeV}}\right)^{0.5}\left(\frac{B}{3\ \mu\mathrm{G}}\right)^{-0.5}\ \mathrm{cm^2 s^{-1}},$$

    - B ~ mG in CMZ
  - Source (Q)
    - CRs accelerated in Sgr A* (Kimura+ 13)
    - Only a tiny fraction of CRs plunge into the CMZ

      $\lambda \sim 10^{-3}$

Spectrum of CRs Injected at Sgr A*

- The typical energy of CRs accelerated in a RIAF is determined by the condition of $t_{\rm acc} = t_{\rm diff,RIAF}$

$$\frac{E_{p,\rm eq}}{m_p c^2} \sim 1.4 \times 10^5 \left(\frac{\dot{m}}{0.01}\right)^{1/2} \left(\frac{M_{\rm BH}}{1\times 10^7\, M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{1/2} \left(\frac{\zeta}{0.1}\right)^{3} \left(\frac{\beta}{3}\right)^{-2} \left(\frac{R_{\rm acc}}{10\, R_S}\right)^{-7/4}$$

- Functional form
  - 2nd Fermi acceleration (Becker+ 06)

$$\dot{N}(x)dx \propto x^{(7-3q)/2} K_{(b-1)/2}((x/x_0)^{2-q})dx$$

K_ν: Bessel func.

- Normalization

$$\propto \dot{M} c^2$$

Spectrum of CRs Injected at Sgr A*

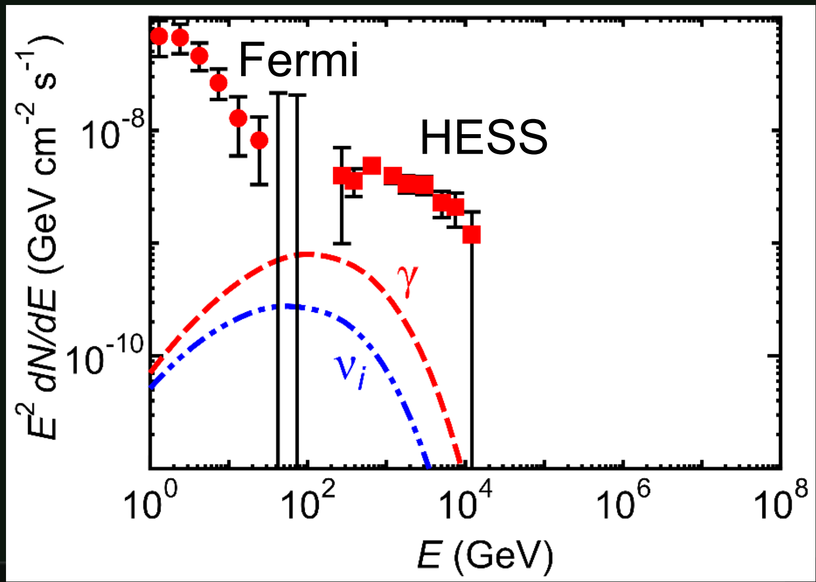
- RIAF parameters determine the CR spectrum
  - Accretion disc size, magnetic fields, turbulence ….
  - We chose these RIAF parameters so that they are consistent with the IceCube observations (flux, spectrum)
    - IceCube neutrinos are coming from numerous LLAGNs in the Universe
      - Kimura et al. (2015)

Results

- Current accretion rate on Sgr A* is very small

  $\dot{m} = \dot{M}/\dot{M}_{Edd} = 4.2 \times 10^{-6}$

- If $\dot{m}$ is constant, γ-ray luminosity is much smaller than the Fermi and HESS observations



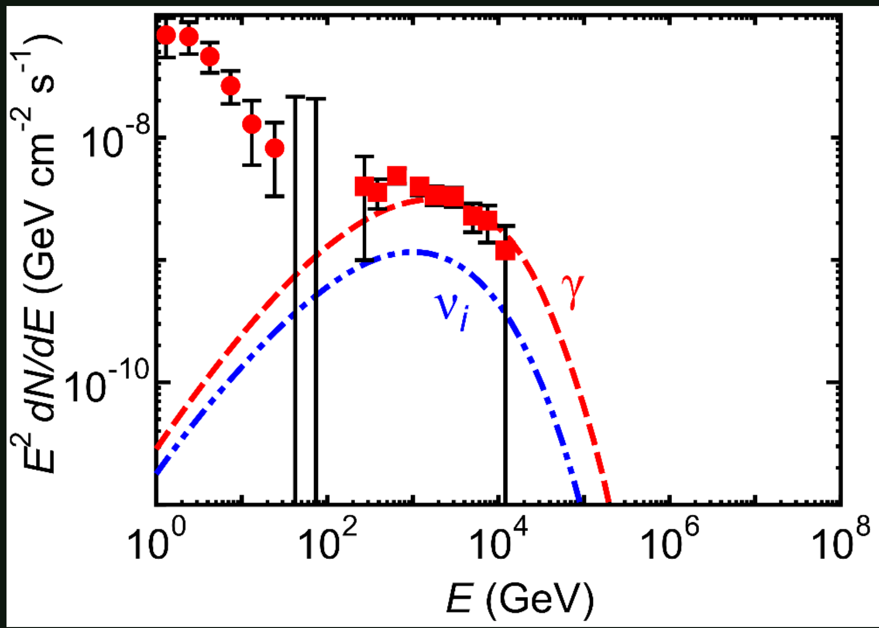
Spectrum

Red: γ-ray

Blue: neutrino

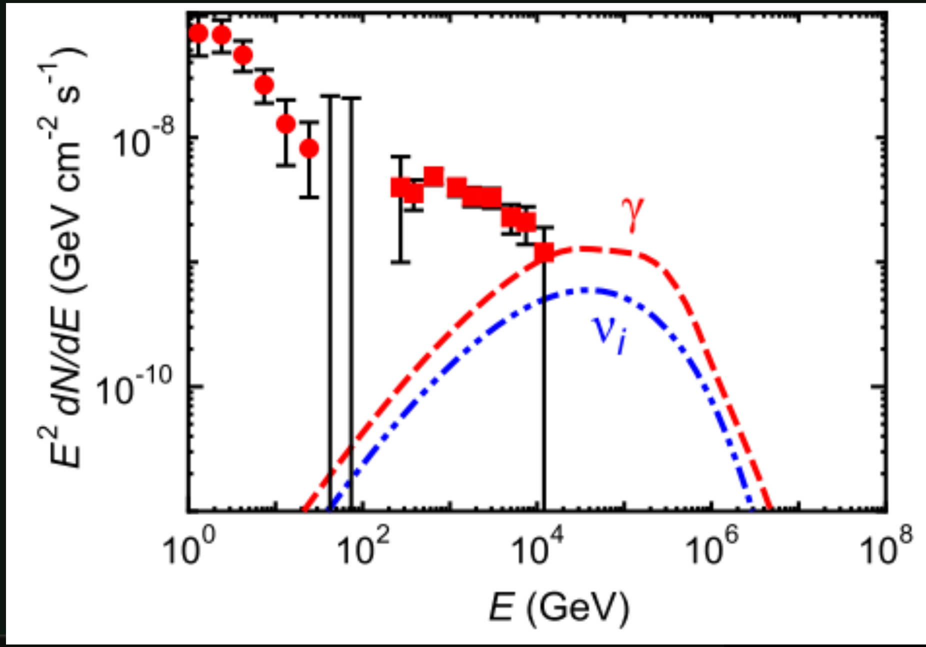
Past activity of Sgr A*

- Observations have indicated that Sgr A* was much more active in the past
  - Sunyaev+1993, Koyama+96, Murakami +00, Totani+06, Ryu+13
    - $\dot{m} \sim 0.001$ (100 yrs ago)
- TeV γ-ray observations can be explained
  - GeV emission has another origin



Uncertainty

- Since our model is rather simple, there are uncertainties in parameters
  - Increase the typical energy of protons assuming more efficient acceleration
  - CTA can discriminate models with different parameters

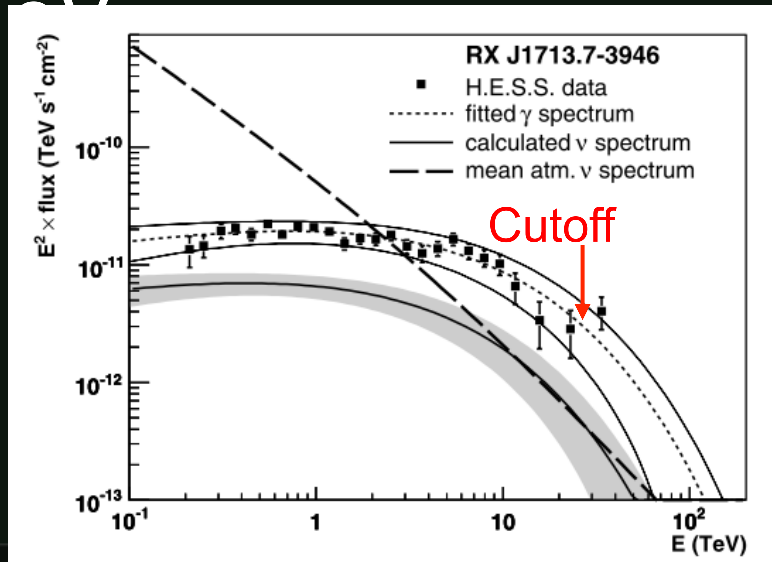


History of CR Acceleration

- Current γ-ray spectrum of Sgr A* does not have to coincide with that of the CMZ
  - γ-ray spectrum of the CMZ reflects the past activity of Sgr A*

PeV cosmic rays

- Supernova remnants (SNRs) are often thought to be the source of CRs for $E < 10^{15.5}$ eV
  - PeV=10^{15} eV
- However, observational evidence is scarce for E [illegible] 10^{14} eV
  - Cutoff at E [illegible] 10^{14} eV



Kappes et al. (2007)

Summary

- LLAGNs may accelerate CRs and may be the source of neutrinos detected by IceCube
  - If so, Sgr A* should produce a lot of CR protons
  - Some of them should enter the Central Molecular Zone and generate γ-rays
- We solved diffusion equation of the CRs and calculated γ-ray spectra
  - The results are consistent with TeV γ-ray observations if Sgr A* was active in the past

Summary

- Sgr A* may be providing PeV CRs observed at the Earth
  - The problem of anisotropy must be solved