Diffuse gamma-ray emission from the Galactic center and implications of its past activities

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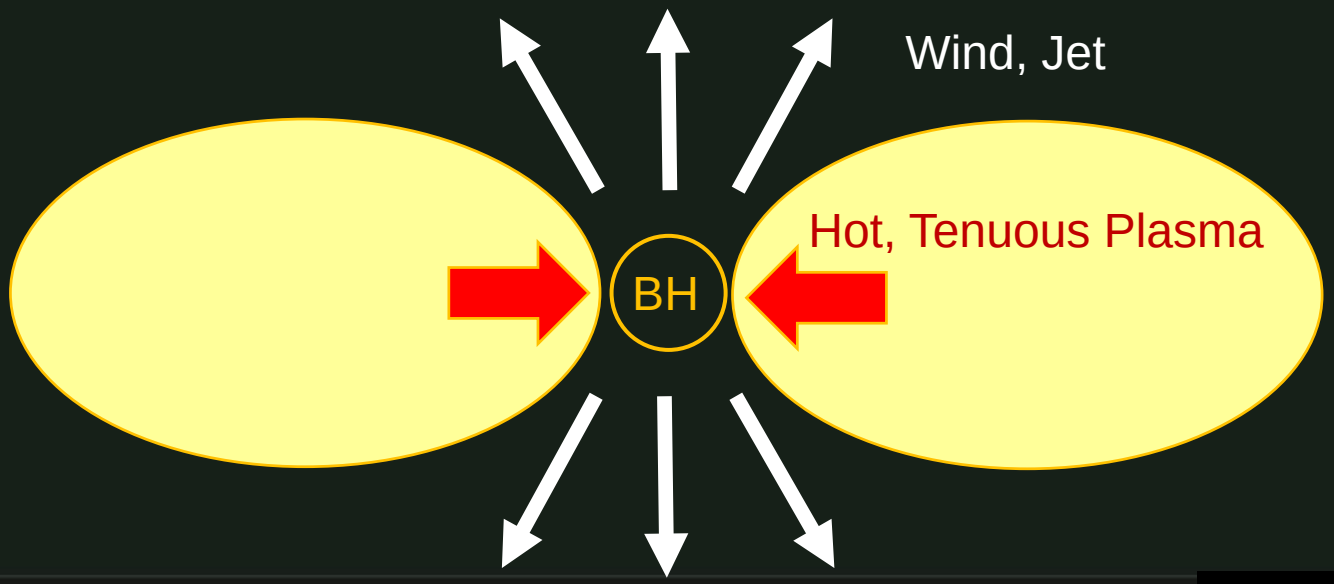
    - Sgr A* is an LLAGN
- Diffusion of CR protons in the CMZ
- Diffuse TeV gamma rays from the Galactic center
- Sgr A* as a PeVatron
- Summary

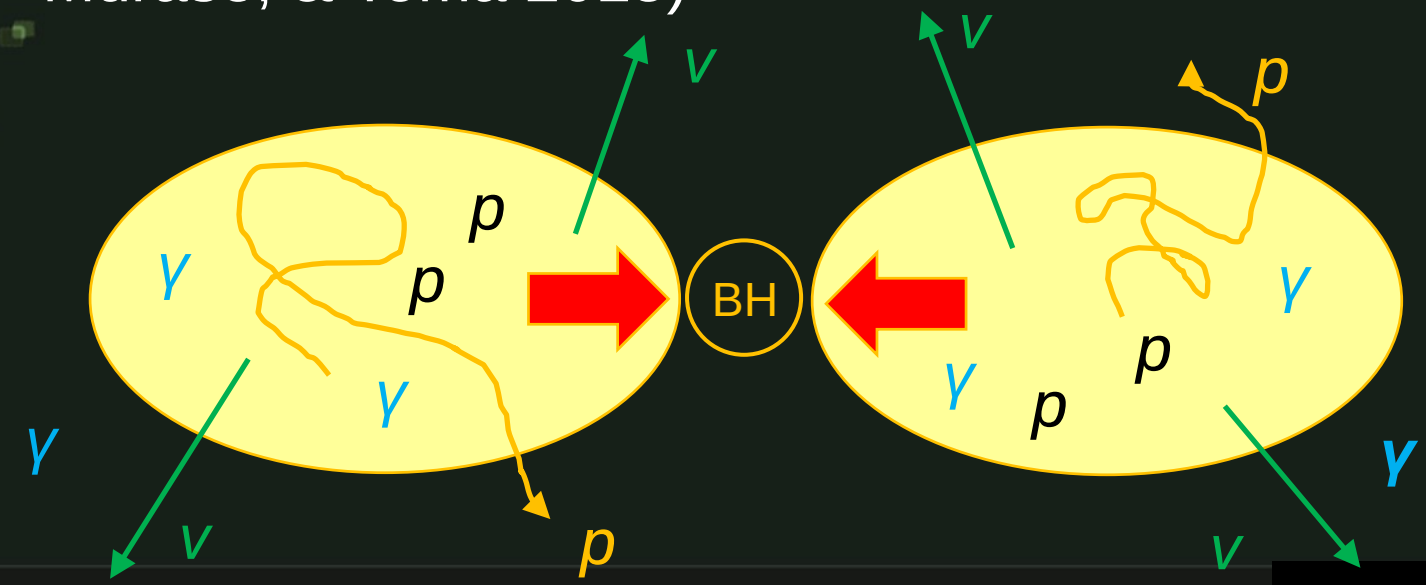
CR acceleration in a RIAF

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



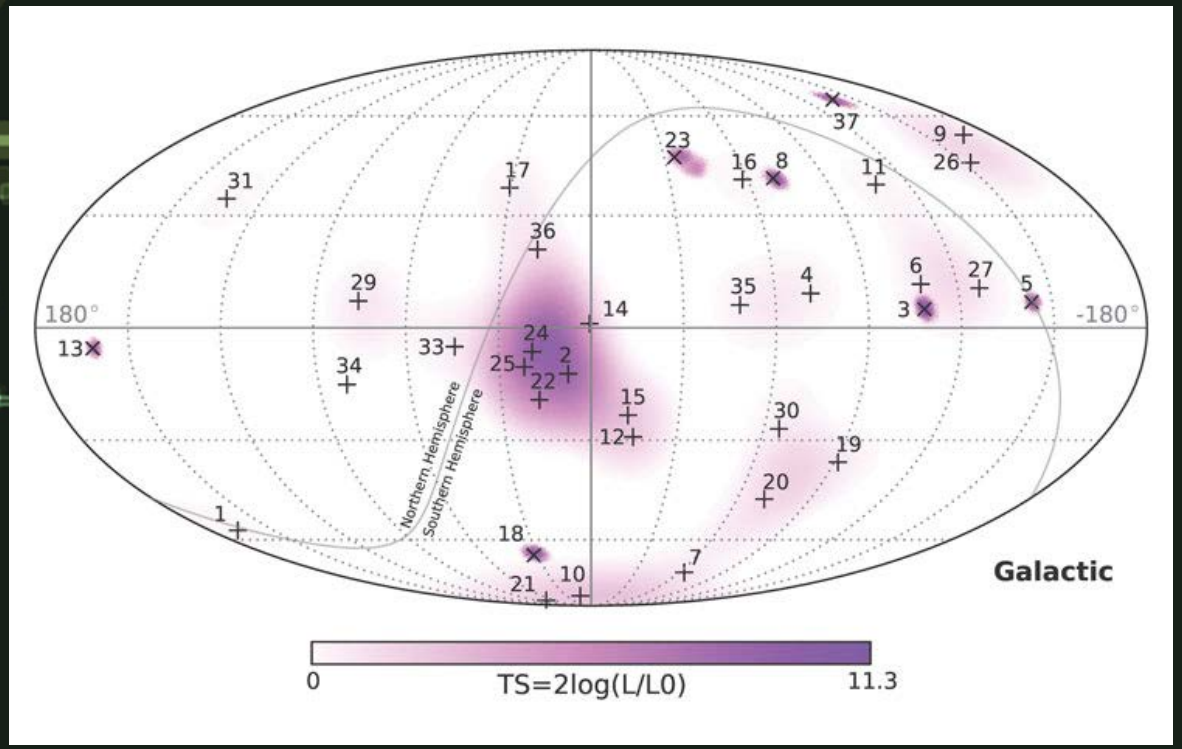
CR acceleration in RIAF

- Protons are stochastically accelerated in turbulence in a RIAF
  - Neutrinos and γ-rays are created via *pγ* and *pp*-interaction
    - Neutrinos detected by IceCube (Kimura, Murase, & Toma 2015)



IceCube Observations

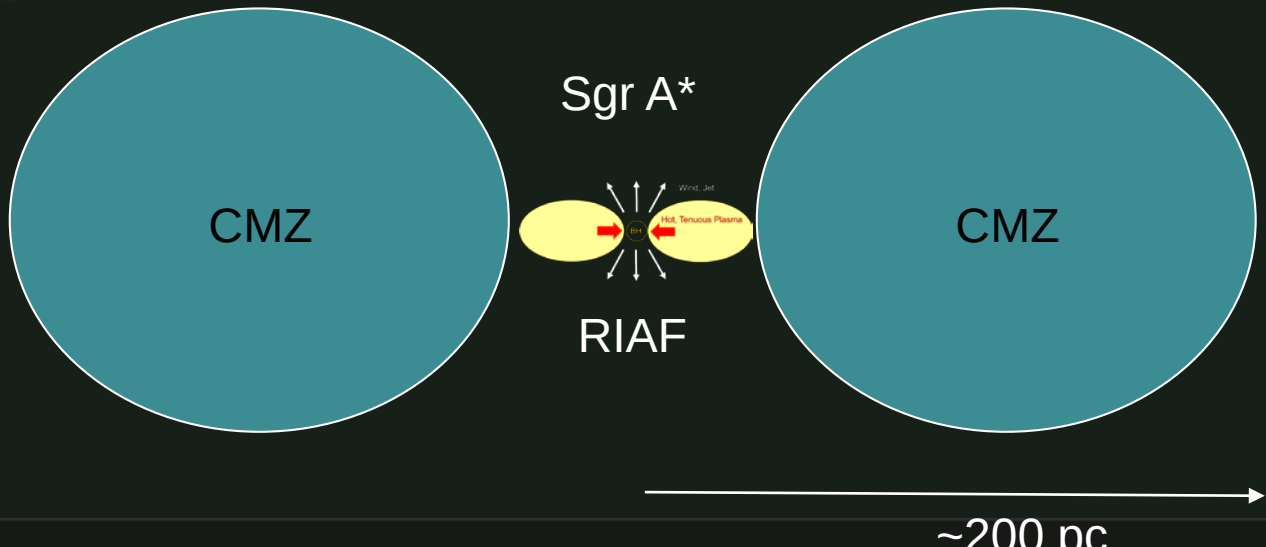
- Uniform distribution of neutrinos
  - Neutrinos have extragalactic origin



IceCube home page

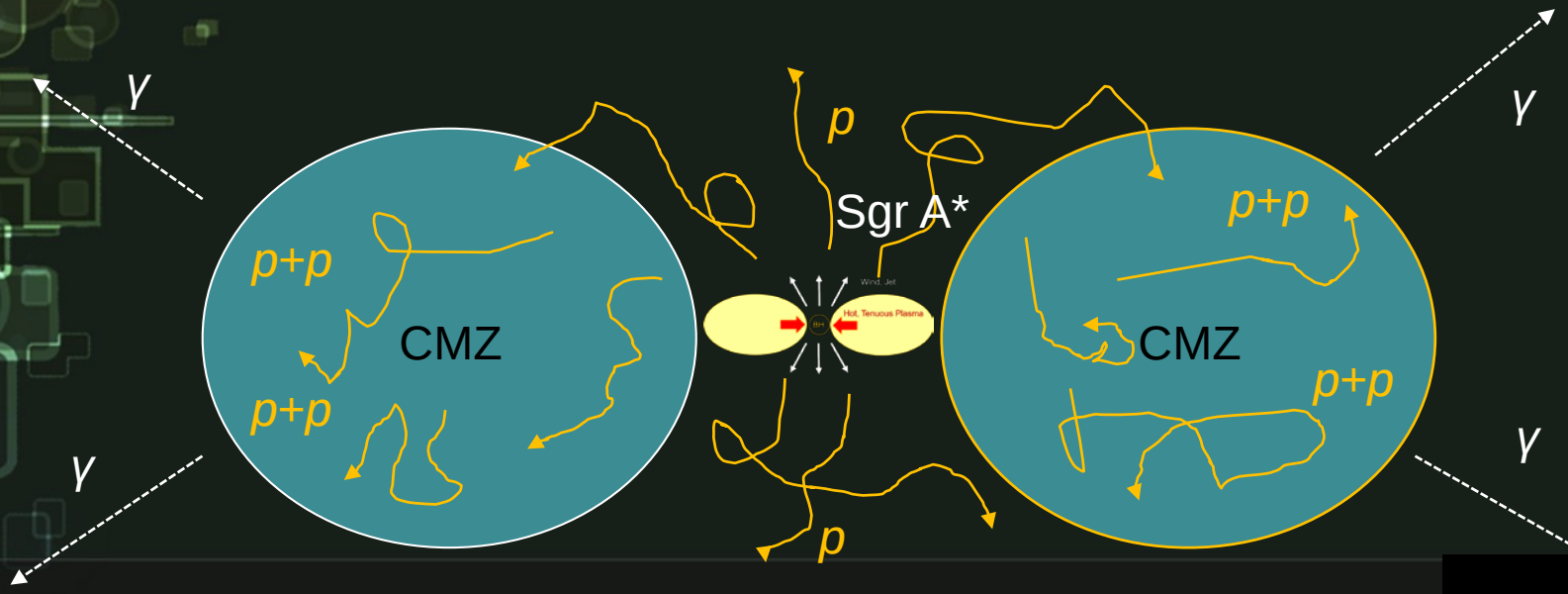
Sgr A* and CMZ

- 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 $M_\odot$



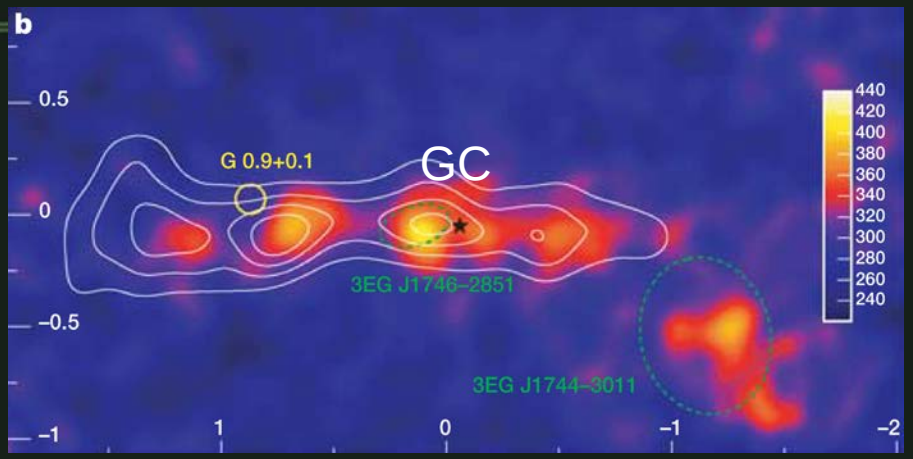
CR protons in CMZ

- 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
    - CMZ is filled with CRs!
    - Those CRs have diffused from the GC (HESS collaboration 2016)
  - We investigate this TeV γ-ray emission



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

Model

- We solve a diffusion equation
  - Spherically symmetric
    - We are interested in diffusion in the direction of CMZ

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

  - 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 $t_{\rm acc} = t_{\rm diff,RIAF}$

$$\frac{E_{p,\rm eq}}{m_p c^2} \sim 1.4\times10^5 \left(\frac{\dot{m}}{0.01}\right)^{1/2} \left(\frac{M_{\rm BH}}{1\times10^7\,M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{1/2} \left(\frac{\zeta}{0.1}\right)^{3} \left(\frac{\beta}{3}\right)^{-2} \left(\frac{R_{\rm acc}}{10\,R_S}\right)^{-7/4}$$

- 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*

- The CR spectrum depends on RIAF parameters
  - 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)

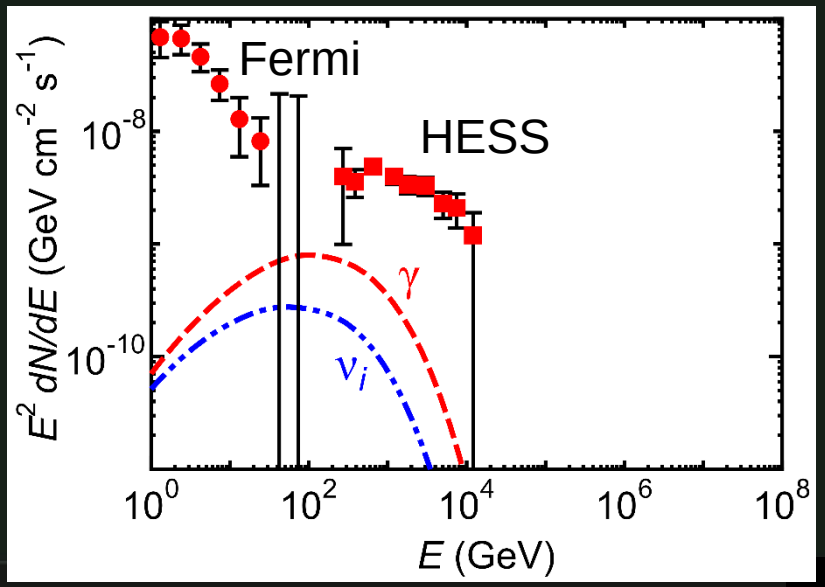
Results

- Current accretion rate on Sgr A* is very small

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

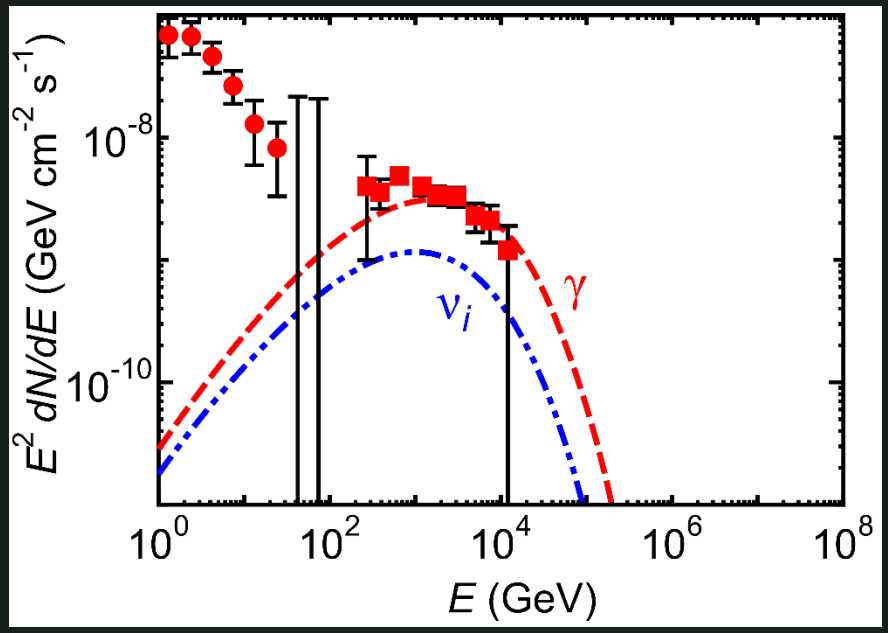
- If $\dot{m}$ is constant, γ-ray luminosity is much smaller than the Fermi and HESS observations

Spectrum
Red: γ-ray
Blue: neutrino



Past activity of Sgr A*

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



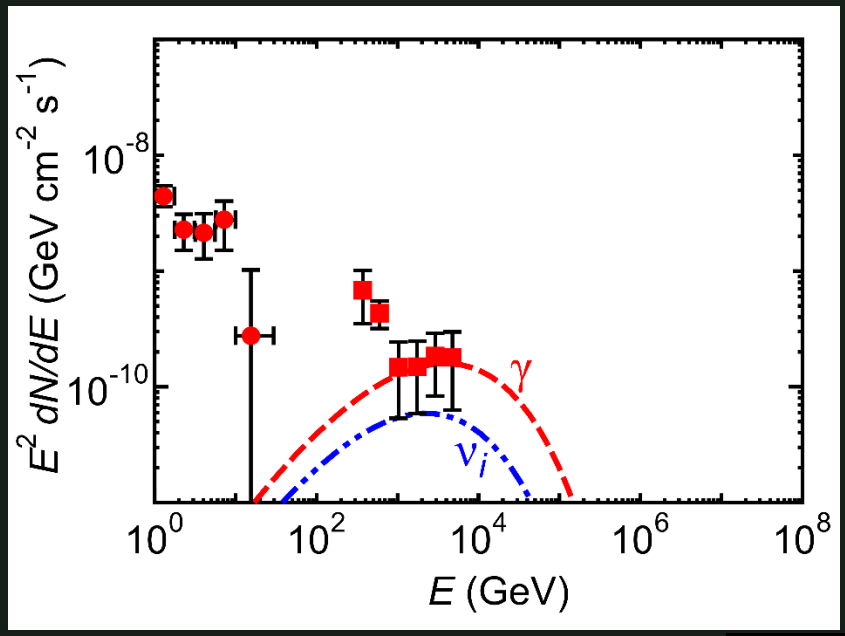
History of CR Acceleration

- Current γ-ray spectrum of Sgr A* does not have to coincide with that of the CMZ
  - It takes some time for CRs to diffuse from Sgr A*
  - γ-ray spectrum of the CMZ reflects the past activity of Sgr A*

Other galaxies

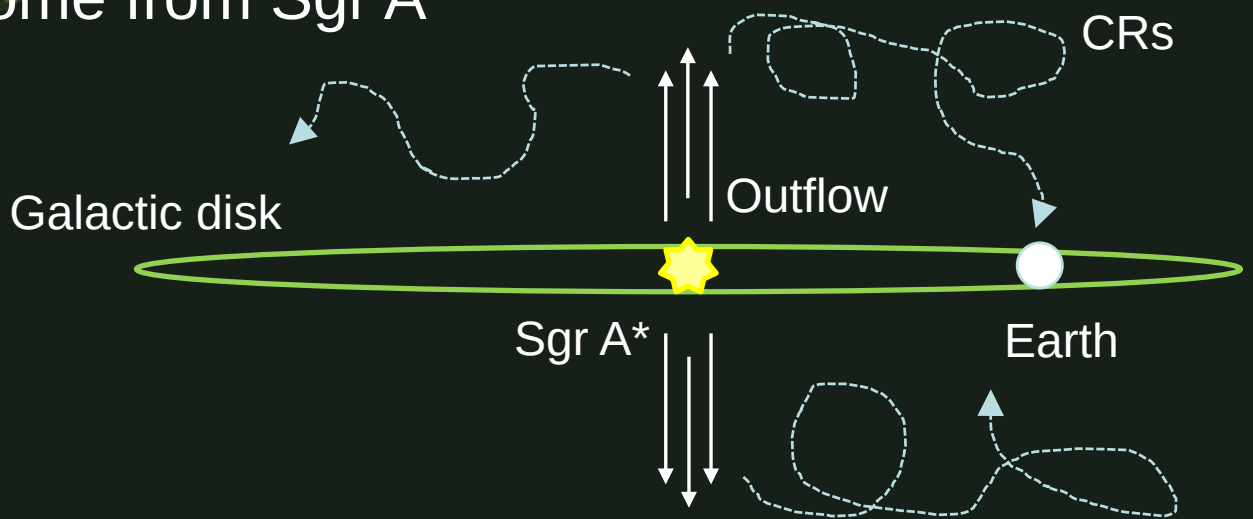
- Centaurus A
  - Nearby radio galaxy (3.84 Mpc)
  - TeV γ-ray emission can be explained if the AGN is well covered by molecular gas
    - $\lambda \sim 0.02$

(by ESO)



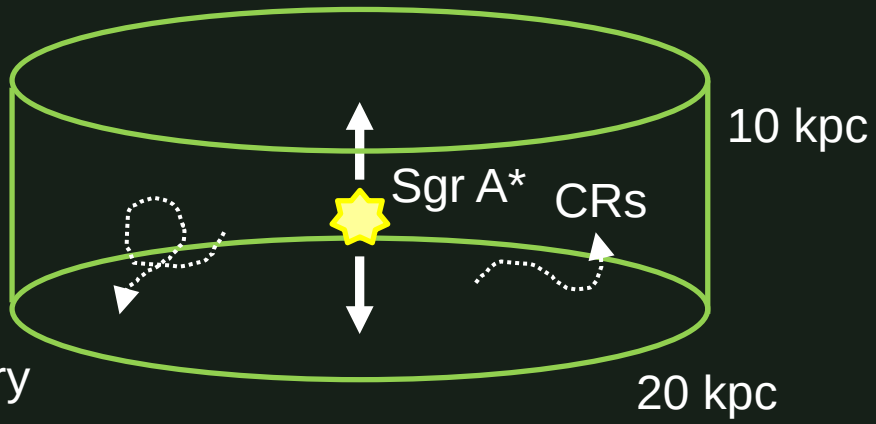
Sgr A* as a PeVatron?

- The origin of Galactic PeV CRs is unknown
- Our model predicts that Sgr A* can accelerate PeV CRs (PeVatron)
  - Most of the CRs (>99.9%) go to the Galactic halo through outflows
  - Some of the PeV CRs observed on the Earth may come from Sgr A*



Model

- We consider Sgr A* as a single source of TeV-PeV CRs
  - Injected into the Galactic halo

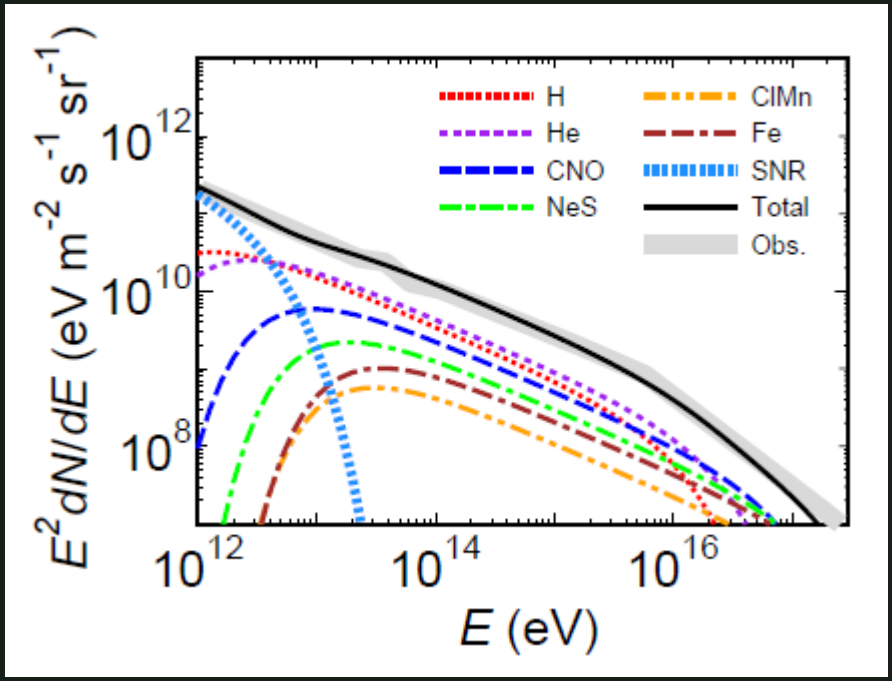


CRs escape from the boundary

- Lower-energy CRs are provided by supernova remnants (SNRs)
- We assume simple forms of CR spectra at Sgr A*

Results

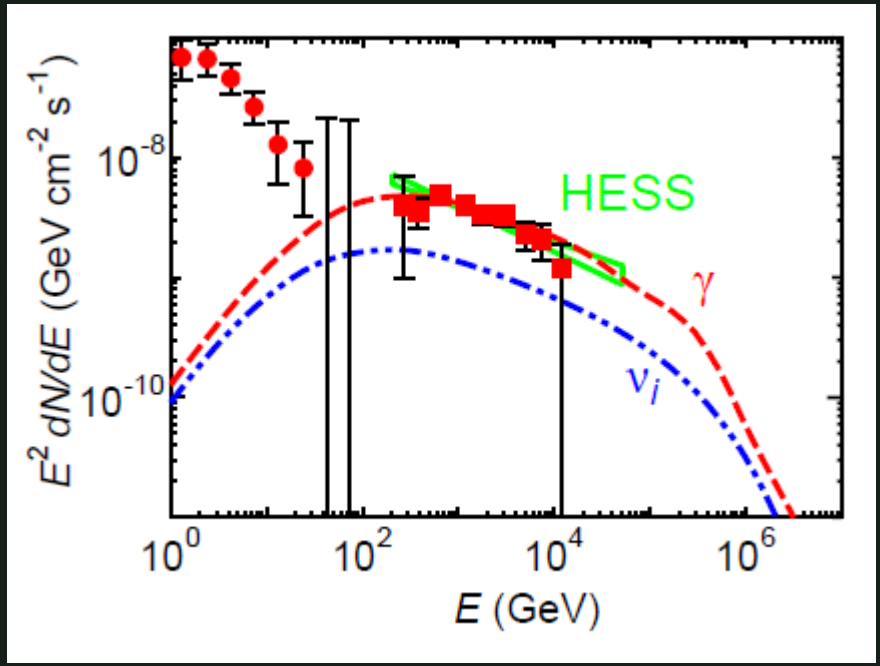
- CR spectrum on the Earth



– The observed spectrum can be reproduced

γ-rays from the CMZ

- TeV-PeV emissions can be reproduced



  - – Extended to $\gtrsim$50 TeV
    - Consistent with recent HESS observations
      - – HESS collaboration (2016)

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

Summary

- We solved a diffusion equation for the CRs and calculated γ-ray spectra
  - The results are consistent with TeV γ-ray observations if Sgr A* was more active in the past
- Sgr A* may be providing PeV CRs observed on the Earth