Neutrinos and gamma rays from beta decays in an active galactic nucleus NGC 1068 jet

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Based on the collaboration work with
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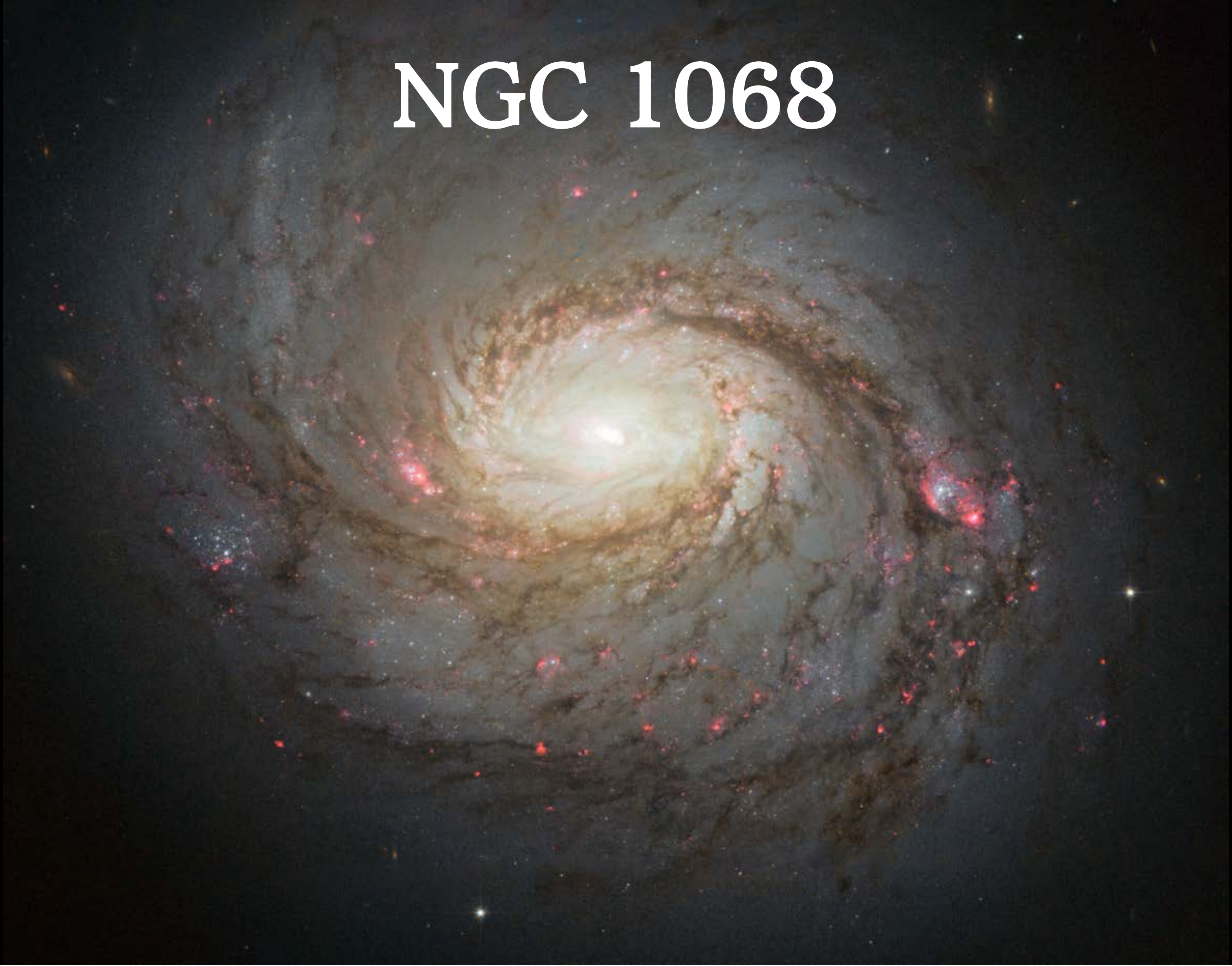
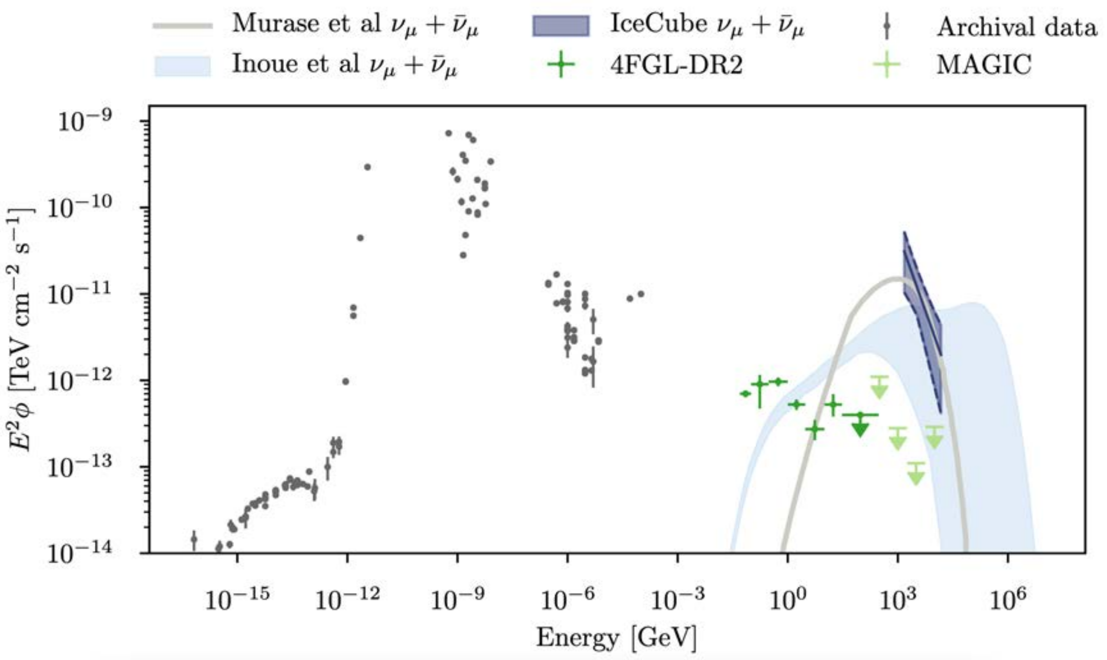

NGC 1068

Big Puzzles from IceCube

- ➢ **Neutrino point sources**
- → active galaxy NGC 1068
- → Jet & Disk ⇨ gamma rays & $\nu's$
- ➢ **TeV Neutrino power**
- → $\sim 10^{42}$ erg/sec
- ➢ **GeV-TeV gamma rays**
- → Fermi LAT & MAGIC data
- → significantly less than ν's



[Abbasi et al. (2022) from IceCube collaboration]

Possible sources for neutrinos

- $pp/p\gamma$ **interactions**

→ series of pion decays

$\pi^0 \to 2\gamma, \quad \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu_\mu} + \nu_\mu$

[Eichmann et al. (2022), Inoue et al. (2022), Murase et al. (2022) etc]

- **Leptonic interactions**

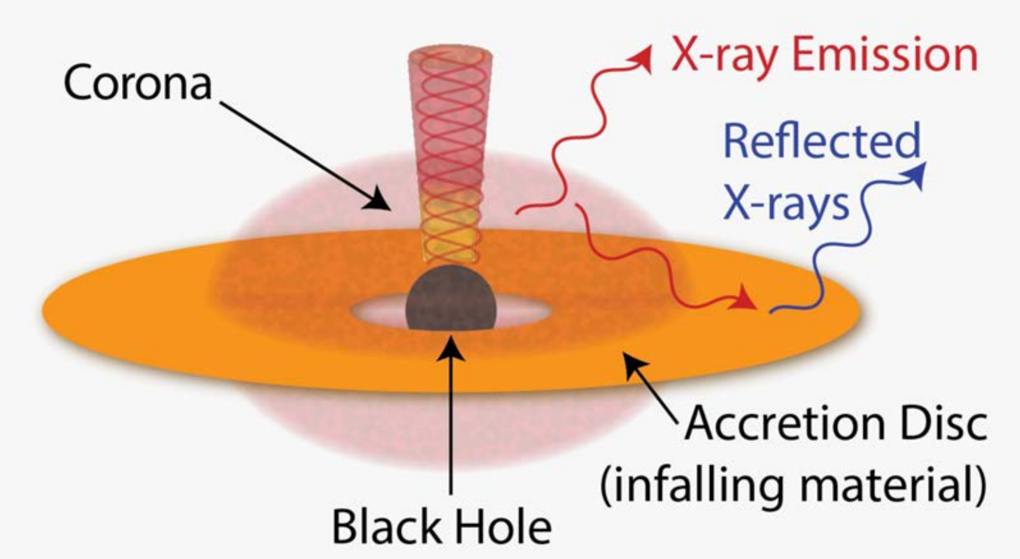
→ $\mu + \bar{\mu}$ pair creation makes ν_μ's

[Bhattacharjee, Sigl (2000), Hooper, Plant (2023) etc]

- **AGN disk-corona model**

→ Hypothetical Central energetic engine [Zdziarski (1986), Kalashev et al. (2015) etc]

(still some uncertainty exists [Inoue Takasao Khangulyan (2024)])



[https://danwilkins.net/research]

- **We pose another scenario without corona!**

Summary of our work

- Neutrino emissions from active galaxy

→ Photodisintegration of ^{4}He

→ β decay of neutrons

- Gamma ray emissions

→ β decay electrons + Bethe-Heitler pairs

→ Inverse Compton scattering of disk photons + Synchrotron

- Magnetic field strength

→ Required strength from GeV data is consistent with ALMA survey

- Neutrino flavor ratio study can probe this scenario

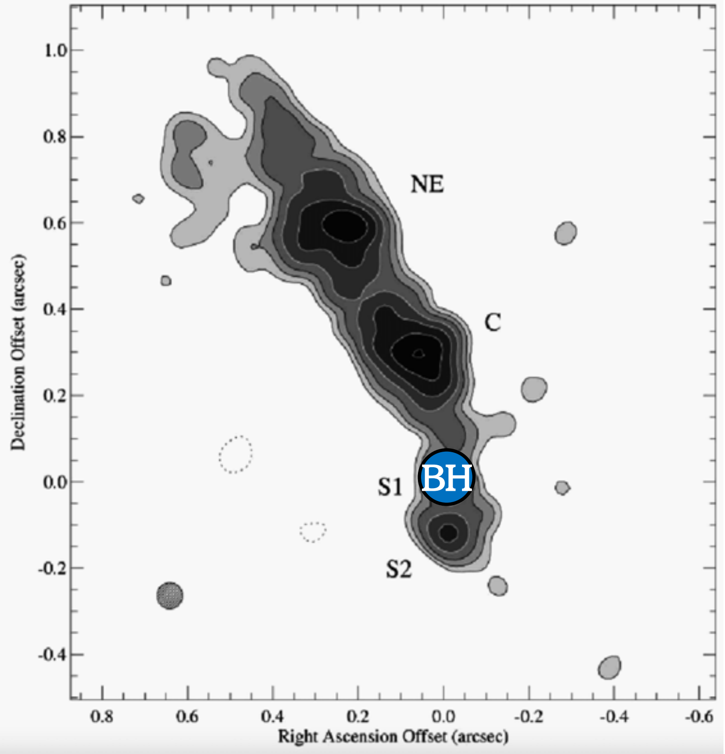
Our Disk & Jet Models

- **standard disk model (No corona)**

→ $L_{bol} \sim (0.4 - 4.7) \times 10^{45}$ erg/sec [Pfuhl et al. from GRAVITY]

- **maximum jet power**

→ $L_{jet} \approx 10 \times L_{bol} \sim 10^{46}$ erg/sec



[Gallimore et al. (2004)]

Our Disk & Jet Models

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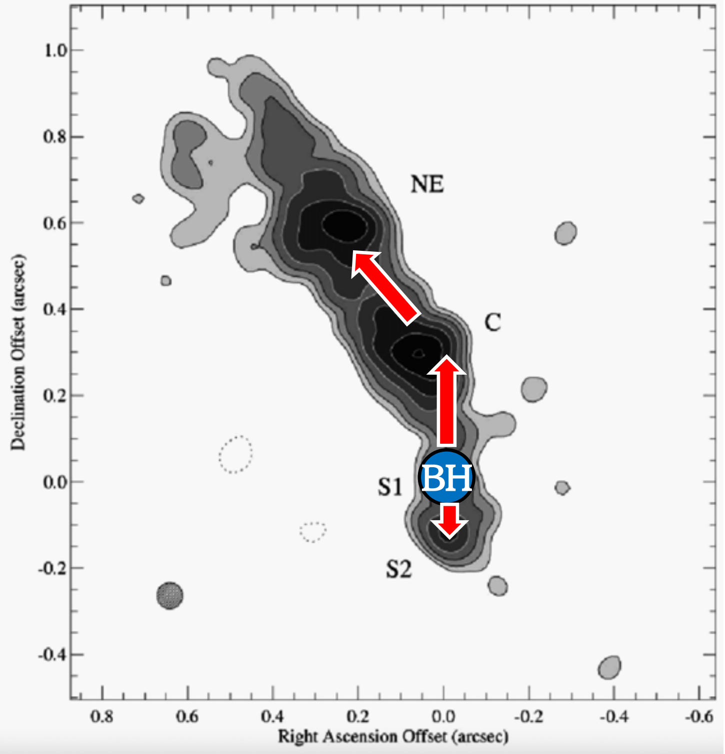
- emission radius

→ set $R_{emission}$ = 0.8 pc (before molecular cloud)

- magnetic field

→ ALMA implies ~ 100 μG at 10 pc

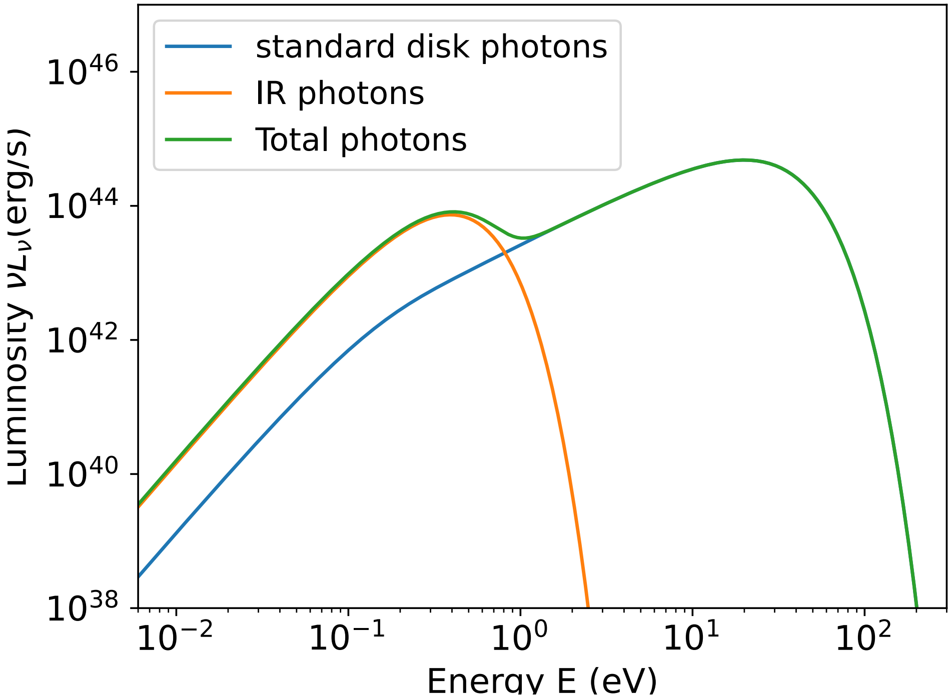
→ It can go as high as ~ 0.1-1.0 G at 1 pc scale



[Gallimore et al. (2004)]

Disk photons

- **standard disk photons**
→ geometrically thin
→ optically thick
- **temperature gradient**
→ multicolor blackbody radiation
→ peaks around UV
- **IR photons from dust torus**
→ simple blackbody with $T \sim 10^3$ K
→ $L_{IR} = 10^{44}$ erg/sec



Protons & ^{4}He in the Jet

- **Dual cutoff power law model**

→ E^{-p} between lower/higher cutoffs

- power-law index: p = 2.4
- proton lower cutoff: 1 PeV
- proton lower cutoff: 10^3 PeV

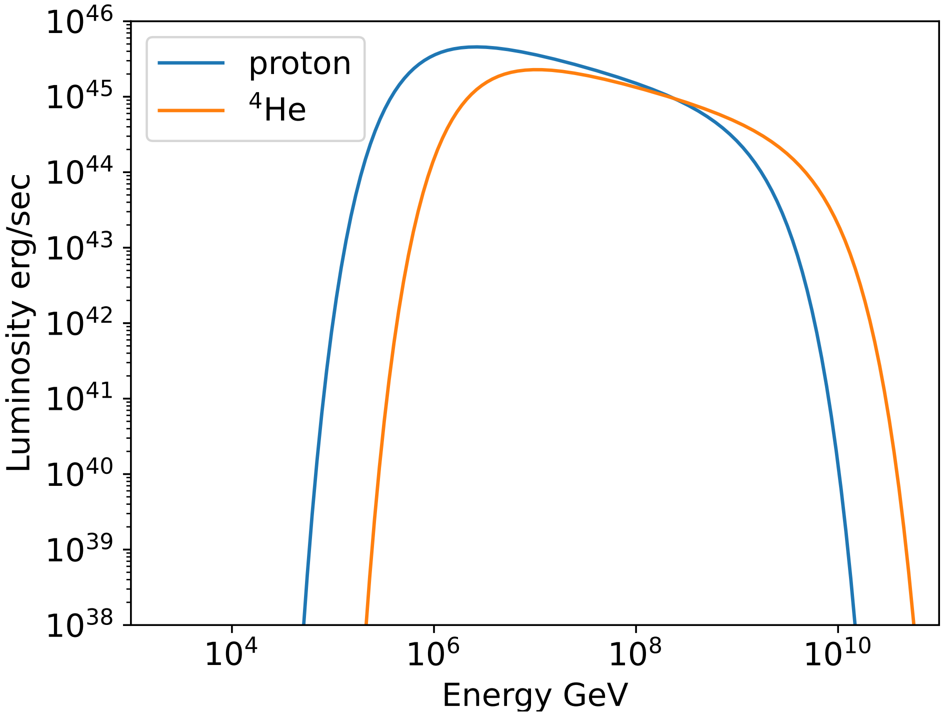
→ Consistent with the Hillas condition

$\mathrm{E_{max}} \sim qBr \gg 1\,\mathrm{PeV} \quad (\mathrm{for}\ q = 2)$

(^{4}He cutoffs) = 2 × (proton cutoffs)

- **Energy range of p & ^{4}He**

→ Bulk Lorentz factors are the same



Photodisintegration of ^{4}He

- **Subsequent β decays**

$$^{4}\text{He} + \gamma \rightarrow 2\text{p} + 2\text{n}$$

$$\text{n} \rightarrow \text{p} + e^{-1} + \bar{\nu}_e$$

- **PeV ^{4}He in the jet**

→ $\gamma_{He} \geq 10^{6}$

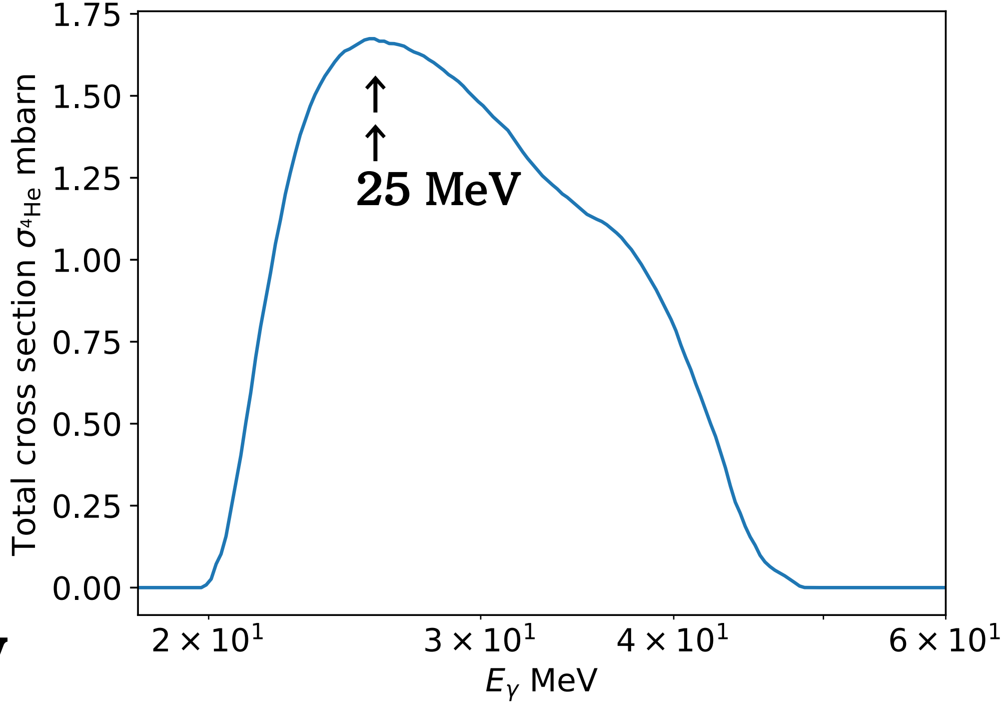
- **Photons in ^{4}He rest frame**

→ original UV photons: 10-40 eV

→ disk photons are boosted

→ boosted energy: $E_{\text{boosted}} > 10$ MeV

[Horiuchi, Suzuki, Arai (2012)]



Interections of the Jet Protons

- Bethe-Heitler pair production

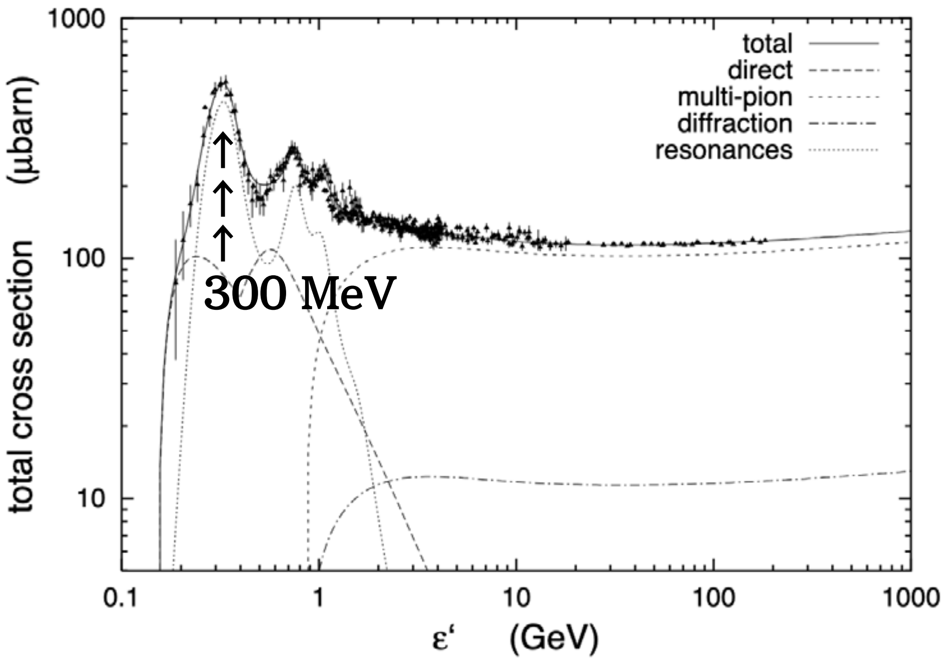
$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

- photo-pion process

$$p + \gamma \rightarrow p + \pi^{0} \text{ or } n + \pi^{+}$$

$$\pi^{0} \rightarrow 2\gamma$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}} + \nu_{\mu}$$



[Rachen, Stanev (1998)]

Optical Depths

- **Mean free path**

→ Using n_{photon} & cross section σ

$$\lambda_{\text{free}} = \frac{1}{n_{\text{photon}}\sigma}$$

- **Optical depth at $\mathrm{R}_{\text{emission}}$**

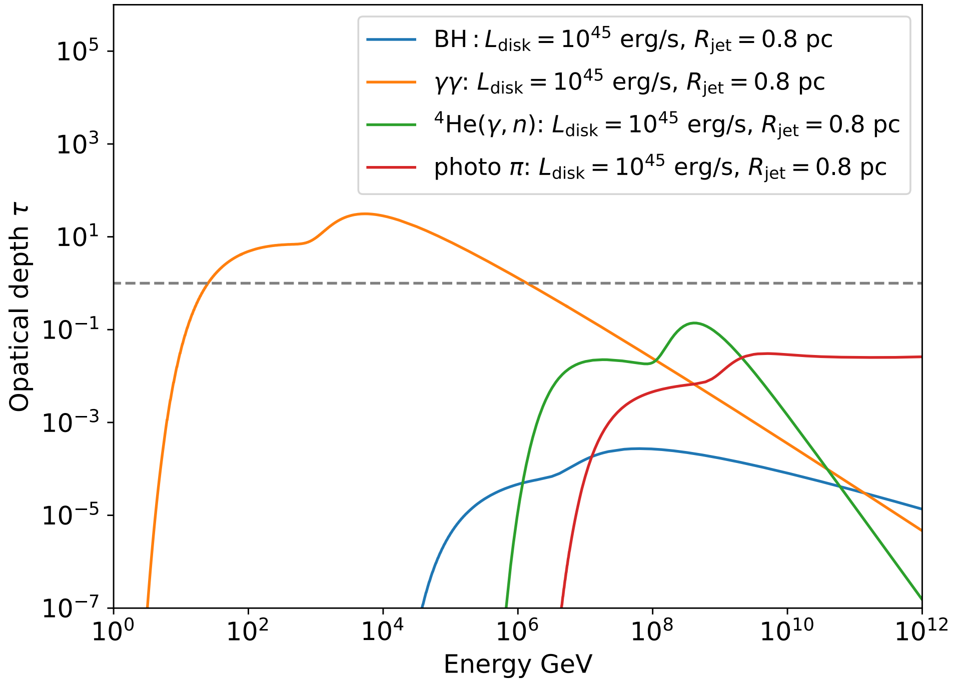
→ Take ratio:

$$\tau = \frac{\mathrm{R}_{\text{emission}}}{\lambda_{\text{free}}} = \frac{0.8\ \text{pc}}{\lambda_{\text{free}}}$$

- **Flux calculation**

$$\Phi_{\text{escaped}} \equiv e^{-\tau}\,\Phi_{\text{initial}}$$

$$\Rightarrow \Phi_{\text{converted}} = (1 - e^{-\tau})\Phi_{\text{initial}}$$



Gamma rays from electrons

- Inverse Compton (IC)

→ electrons upscatter soft photons

→ suppressed at higher energies (Klein-Nishina effect)

- Synchrotron

→ spiral emission by B field

- naima

→ Open python package

→ relativistic particle distribution

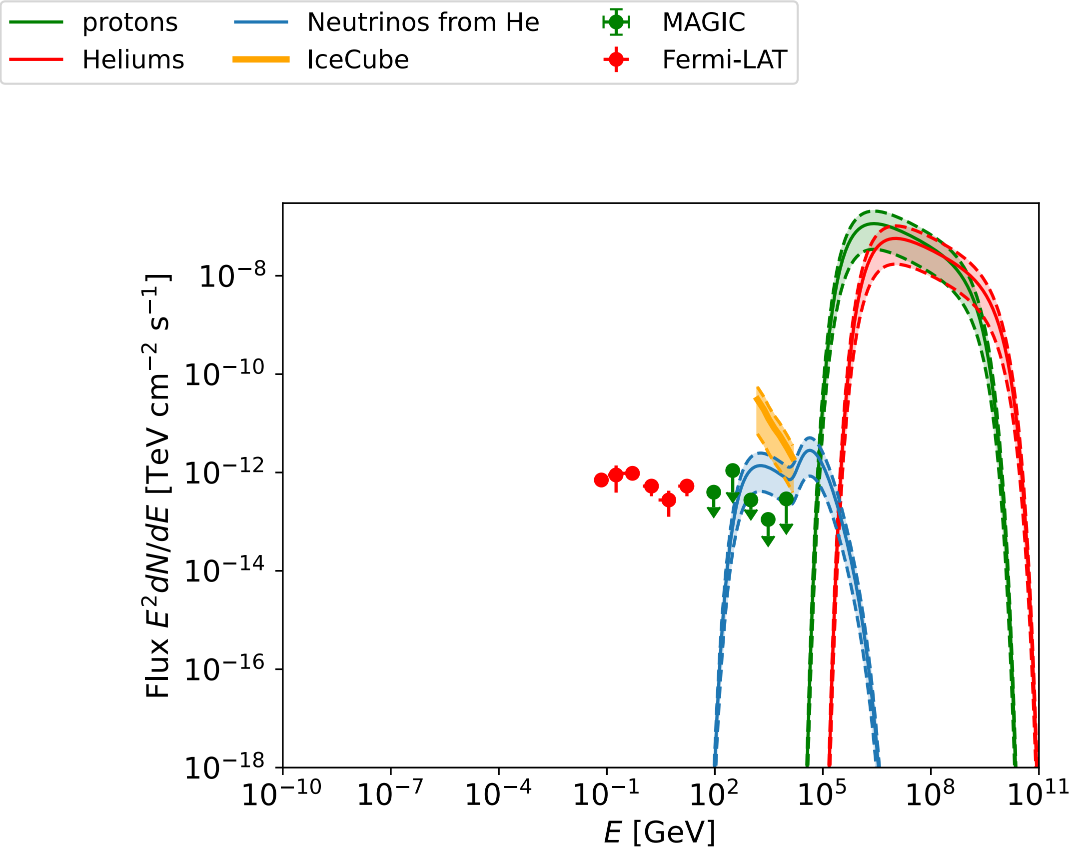
→ Synchrotron + IC

Summary Plots

- **Neutrino emissions**

→ Photodisintegration of ^{4}He

→ Compatible with IceCube data



Summary Plots

➢ Neutrino emissions

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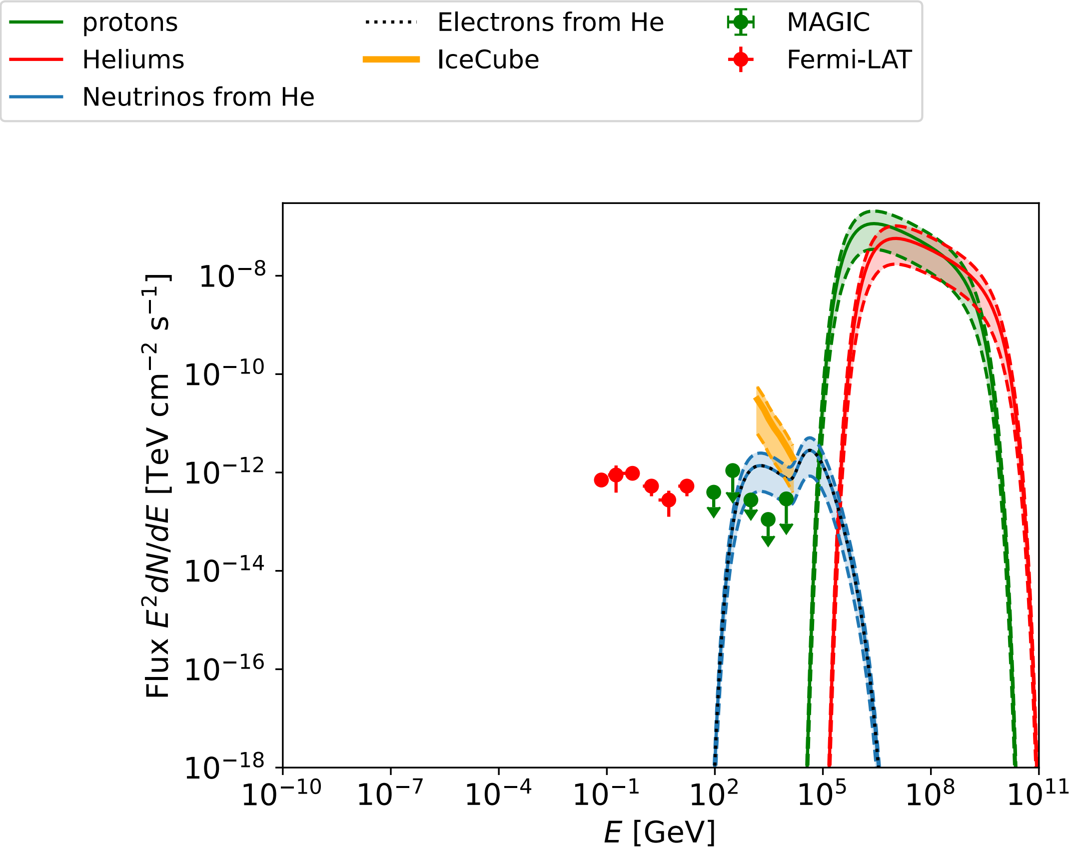
➢ Electrons from β decay



Summary Plots

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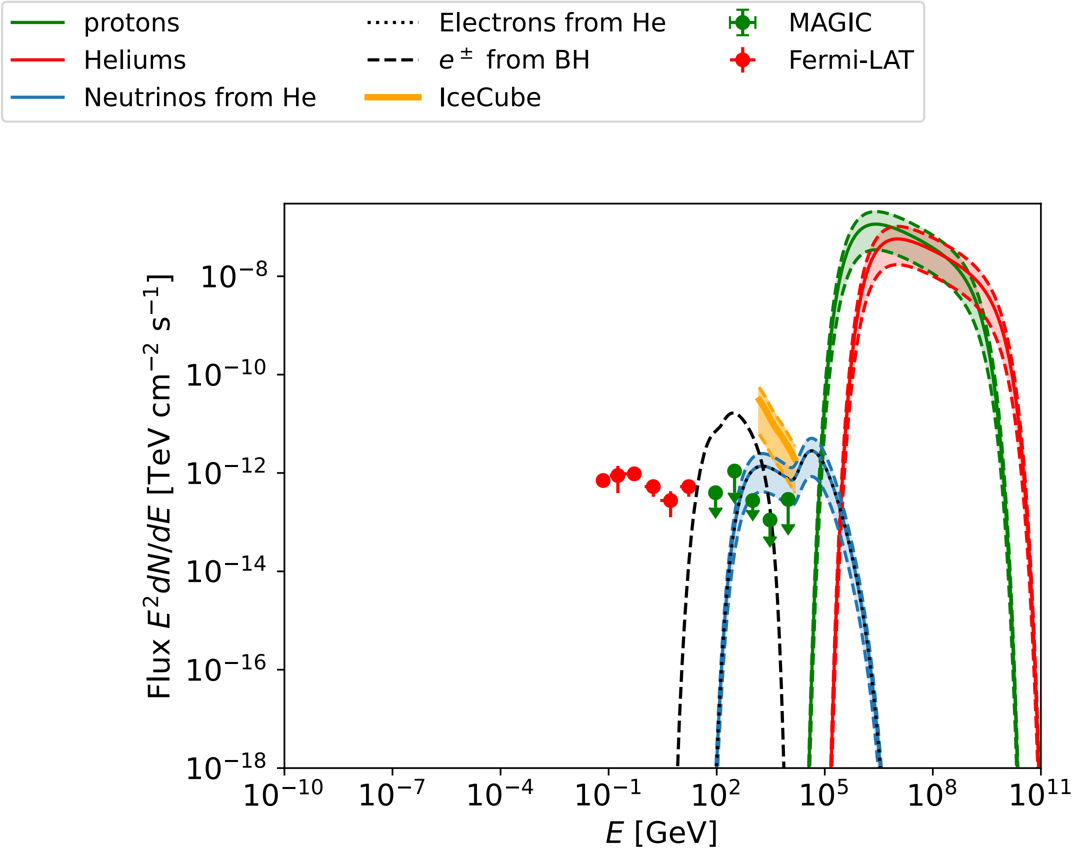
- ➢ Electrons from β decay, BH



Summary Plots

- Neutrino emissions

→ Photodisintegration of ^{4}He

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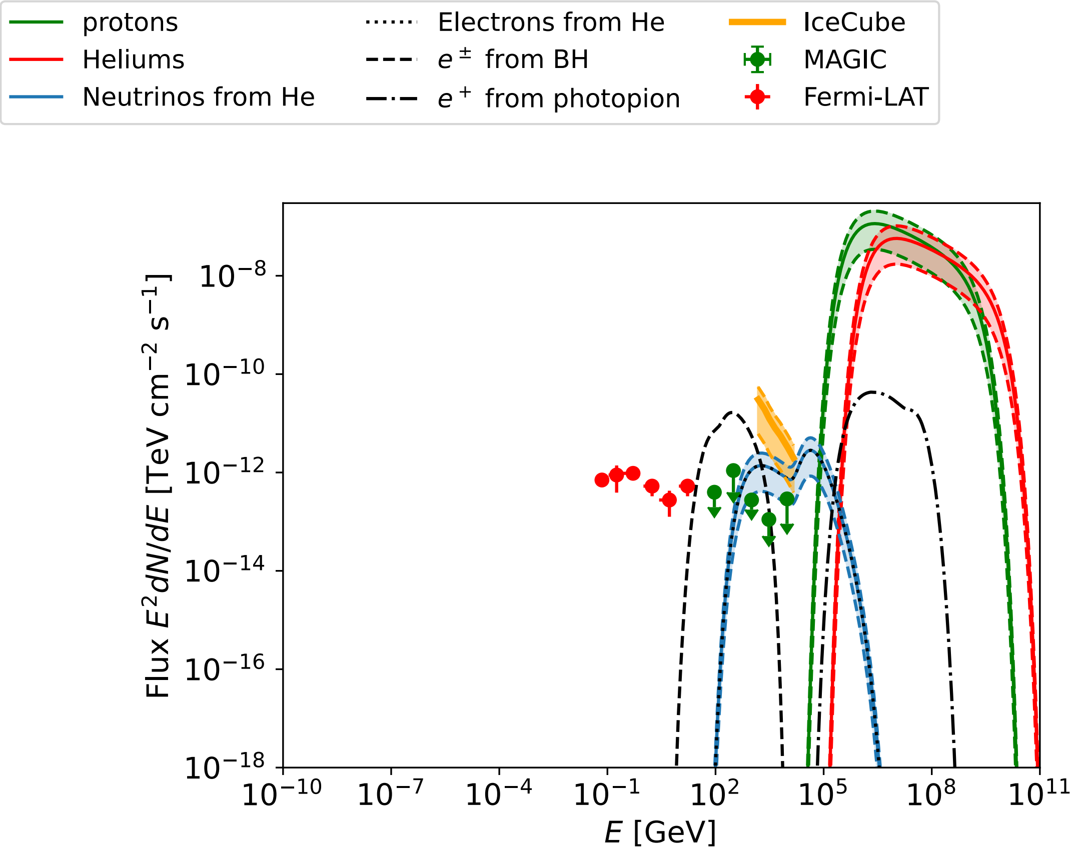
- Electrons from β decay, BH & $p\gamma$



Summary Plots

- **Neutrino emissions**

→ Photodisintegration of ^{4}He

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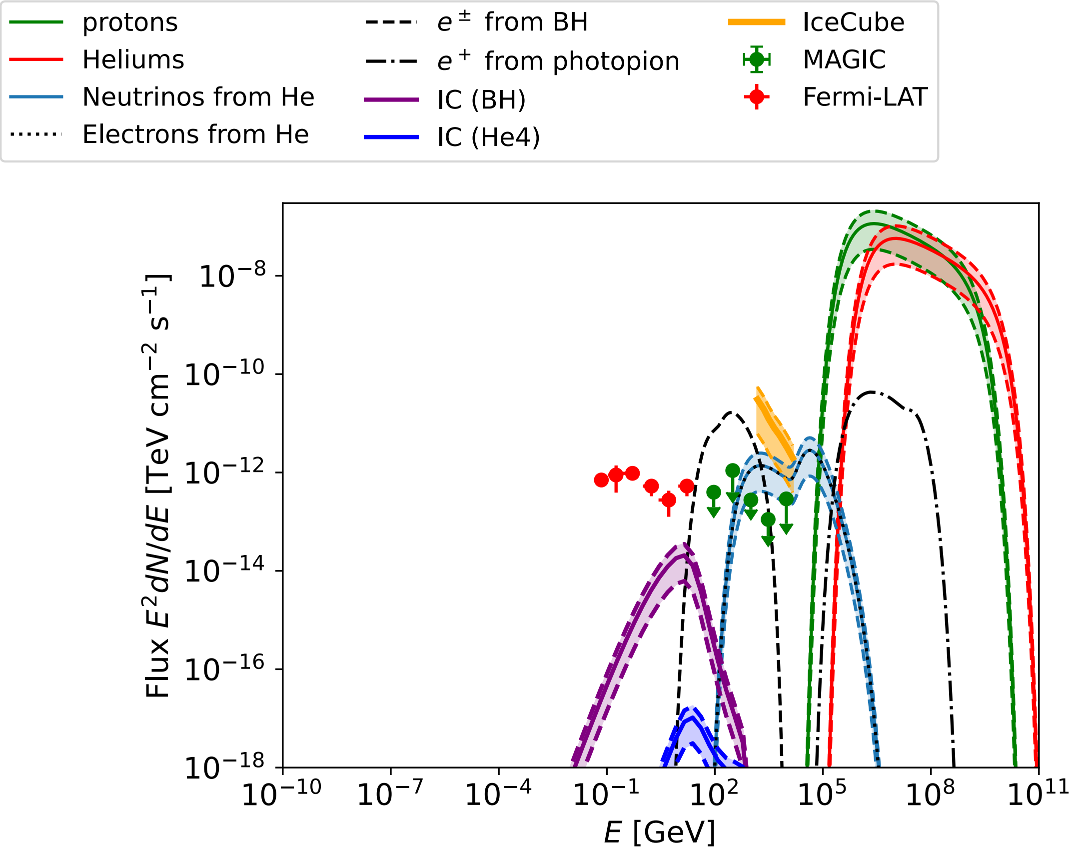
- **Electrons from β decay, BH & $p\gamma$**

- **Gamma ray emissions from $e^{\pm}$'s**

→ Inverse Compton emission



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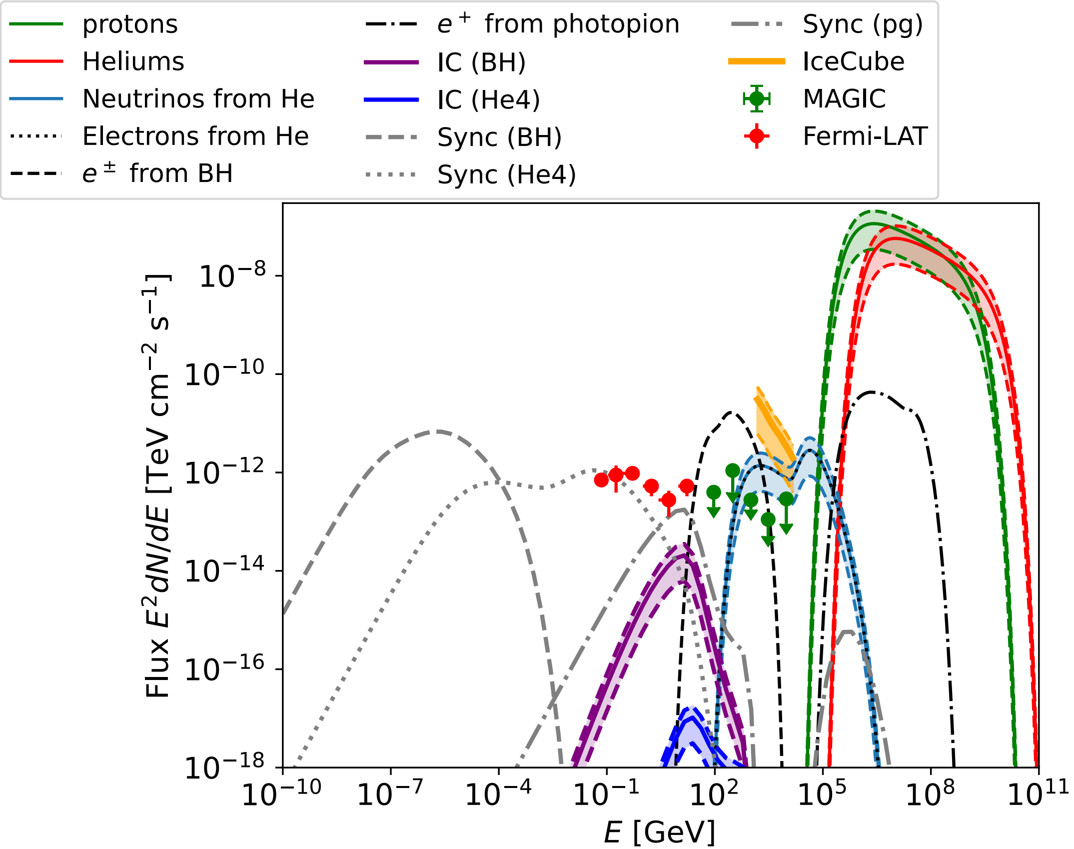
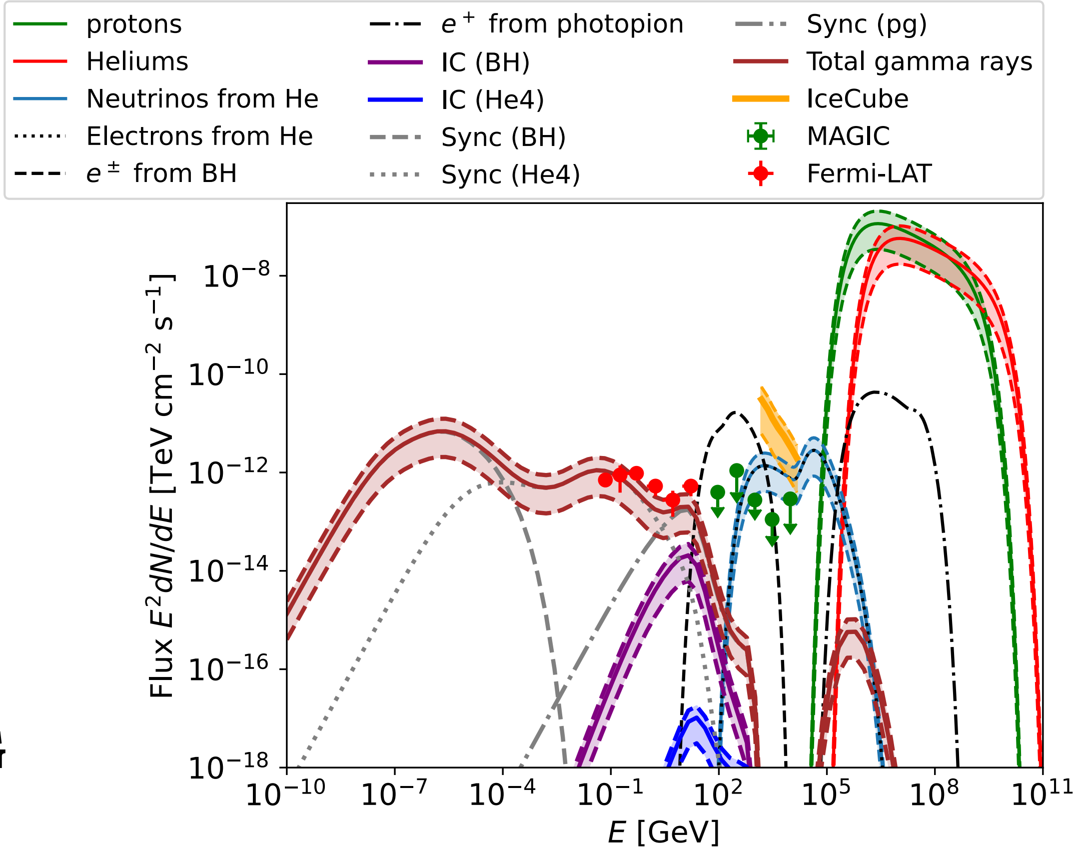
→ Synchrotron emissions



Summary Plots

- ➢ Neutrino emissions
  → Photodisintegration of ^{4}He
  → Compatible with IceCube data
- ➢ Electrons from β decay, BH & $p\gamma$
- ➢ Gamma ray emissions from $e^{\pm}$'s
  → Inverse Compton emission
  → Synchrotron emissions
- ➢ Magnetic field strength
  → Fermi GeV data is explained by B~0.4 G



Outlooks

➢ Initial neutrino flavor ratio

→ $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$ (β decay)

↔ $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ (photopion)

➢ IceCube flavor study

→ Observed/Oscillated flavor ratio can probe our scenario [Bustamante, Ahlers (2019)]

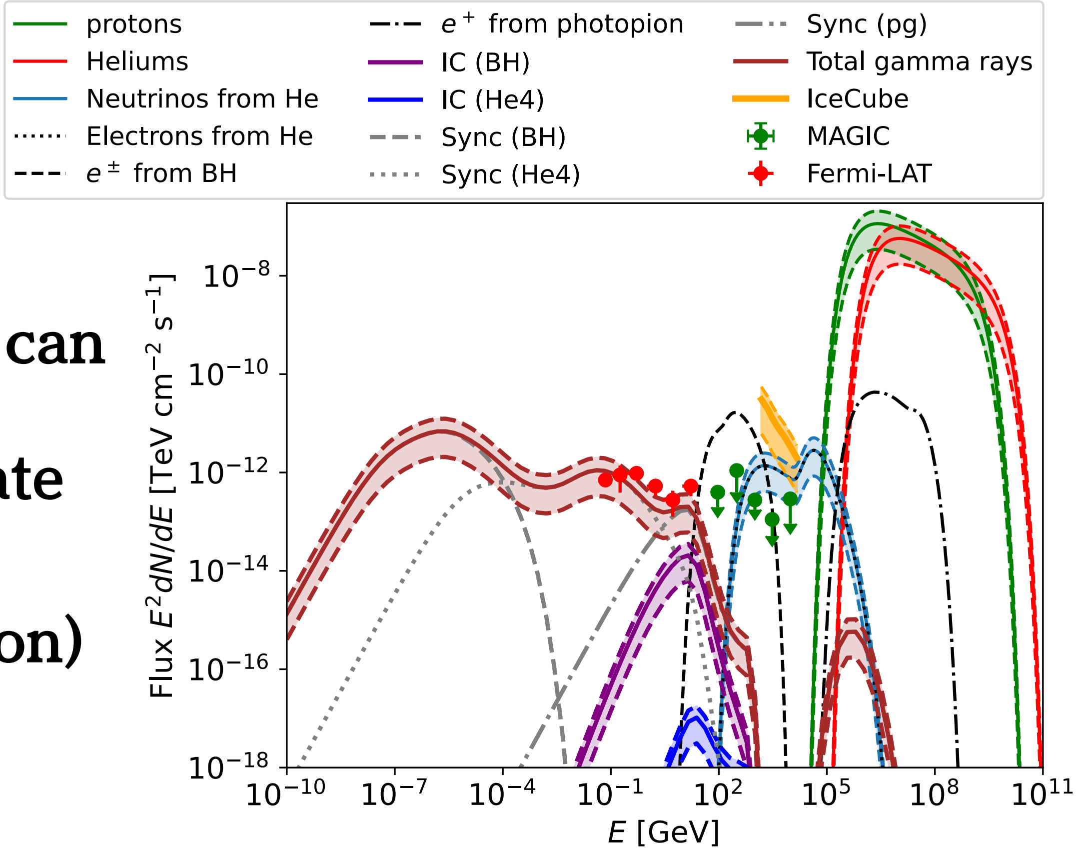
→ Simple QM time evolution estimate

$$\nu_e : \nu_\mu : \nu_\tau \simeq 5 : 2 : 2 \ (\beta \text{ decay})$$

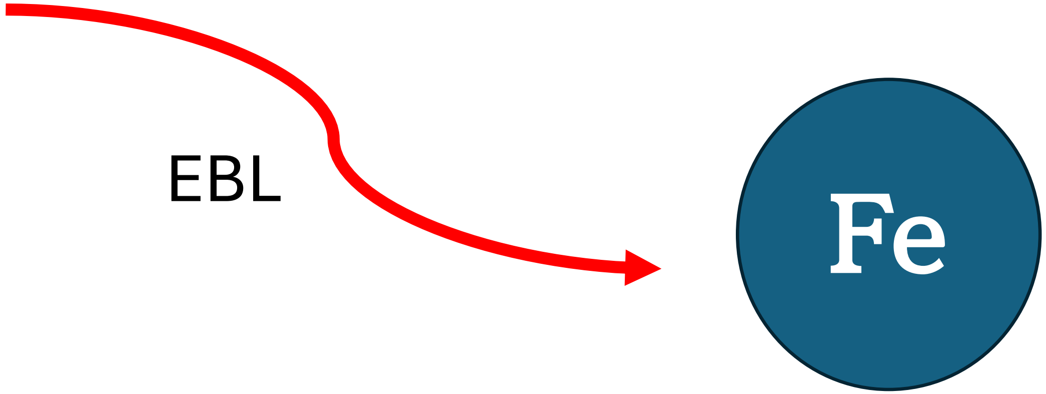
$$\leftrightarrow \nu_e : \nu_\mu : \nu_\tau \simeq 1 : 1 : 1 \ (\text{photopion})$$

➢ Precise jet/torus structure

→ to explain GeV-TeV wiggles



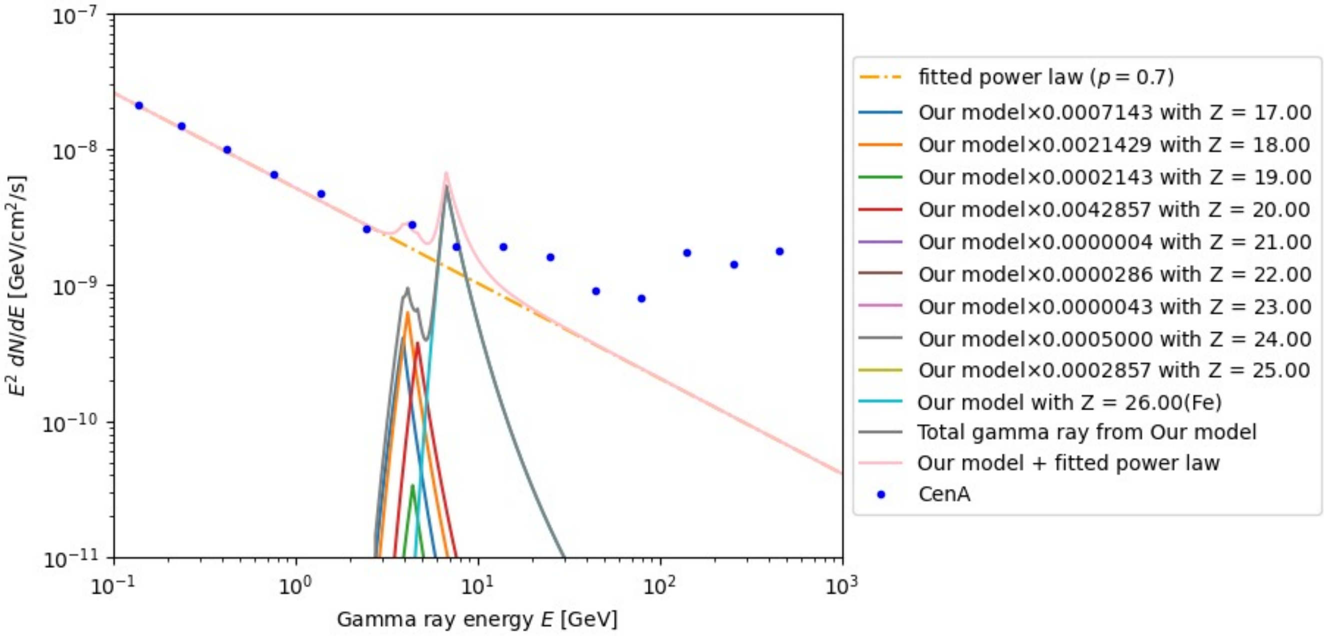
Another application of CR photodisintegration



[Kusenko, Voloshin (2011)]

- Excitation & deexcitation of escaped CR (Fe etc...) with CMB

Another application of CR photodisintegration



Preliminary work result with
Alexander Kusenko,
Shigehiro Nagataki,
Jirong Mao

- Excitation & deexcitation of escaped CR (Fe etc…) with CMB
- Possible explanation of Cen A gamma ray "Shoulder"

Conclusion

- Neutrino emissions

→ Photodisintegration of ^{4}He

→ β decay of neutrons

- Gamma ray emissions

→ IC & synchrotron of β decay electrons + Bethe-Heitler pairs

- Magnetic field strength

→ Required strength from GeV data is consistent with ALMA survey

- Neutrino flavor ratio study can probe this scenario