H.E.S.S. observations of Seyfert–starburst galaxies

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Overview

Composite Seyfert-starburst galaxies

Observations, data analyses, and results

Discussion

Conclusion

Composite Seyfert-starburst galaxies

Seyfert vs starburst galaxies

Seyfert galaxies

- Subclass of AGN
- Found in spiral galaxies
- Viewing angle with respect to dusty torus
  - Obscured -> Seyfert 2
  - Unobscured -> Seyfert 1
- Jet/lobes can produce γ-ray emission
- Some detected by Fermi-LAT, none in VHE

Starburst galaxies

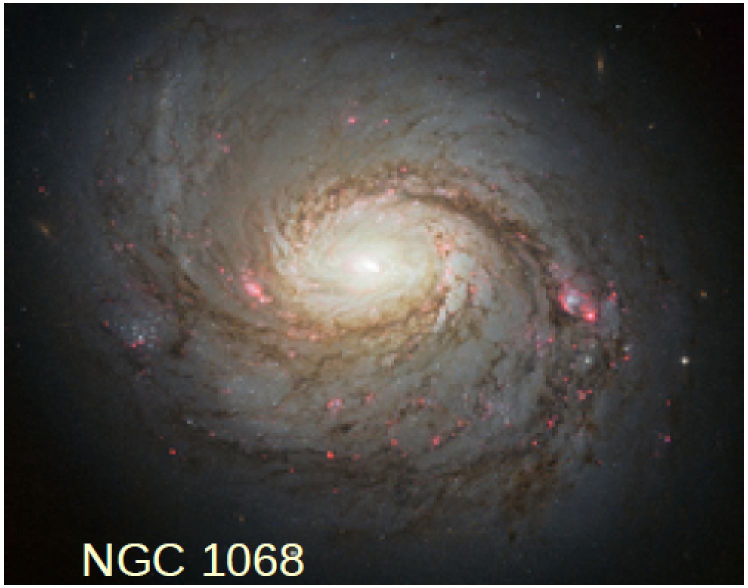
- Ongoing star formation
- Found in spiral galaxies
- Starburst phase lasts few hundred million years
- γ-ray emission from core-collapse supernovae & SNRs
- e.g. NGC 253 and M82 detected at VHE

Composite Seyfert-starburst galaxies

- The three nearest Seyfert galaxies (NGC 1068, Circinus, and NGC 4945) are also starburst galaxies
- All three show not only evidence of jet/lobe activity and star formation, but also circumnuclear superwind outflows which can accelerate charged particles
- Similar to scenarios for past activity creating Milky Way Fermi bubbles
- All three detected in GeV
  - Circinus and NGC 4945 similar to NGC 253
  - NGC 1068 one order of magnitude higher

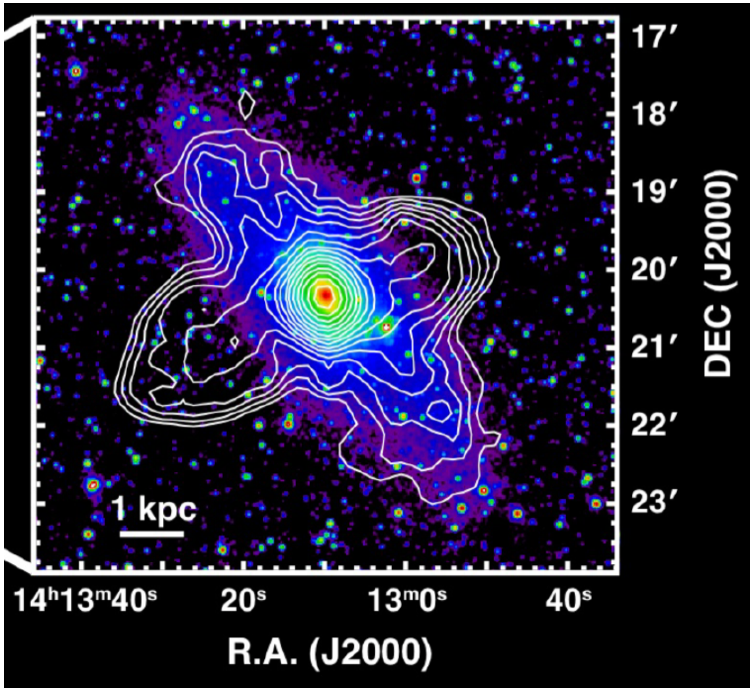
NGC 1068

- Face-on, early type, barred spiral galaxy
- Brightest Seyfert 2 galaxy (Seyfert 1 nucleus visible in polarized light)
- $M_{\rm BH} \sim 1.5 \times 10^7 M_\odot$
- Distance uncertain (10.1 - 16.7 Mpc)
- Circumnuclear disk, 200 pc + starburst ring, 2 kpc
- Reflection component from Compton thick layer in X-rays
- GeV luminosity one order of magnitude higher than NGC 253



Circinus galaxy

- Gas-rich spiral galaxy, distance 4.2 ± 0.7 Mpc
- 4° below the Galactic plane
- Seyfert 2 nucleus
- Circumnuclear gas/dust rings 80 and 430 pc
  - hosting immense starburst region
- Bipolar radio lobes inflated by kpc-scale outflows
- One-sided [O III] ionization cone
- Ionized filaments extending radially out to 1 kpc



Circinus galaxy

NGC 4945

- Barred spiral galaxy, nearly edge-on, distance 3.8 ± 0.3 Mpc
- Located in Centaurus constellation
- Highly obscured Seyfert 2 nucleus, $M_{\rm BH} \sim 10^6 M_\odot$
- Variable hard X-ray emission on hours timescale
- Very bright > 20 keV, only visible through reflected emission < 10keV due to large column density $(\log[N_H/\mathrm{cm}^{-2}] \sim 24.7)$
- Circumnuclear starburst disc 200 pc diameter
- Double conical ionized [N II] outflow

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Observations, data analyses, and results

H.E.S.S. Analysis

- `Model analysis` - semi analytical air shower model
  - Better angular resolution and sensitivity compared to Hillas parameter-based
- `Combined3 Standard` cut configuration
- Monoscopic vs steroscopic chosen depending on reconstructed direction uncertainty for events where both possible
- $0^\circ.12$ on-source radius (corresponding to point-like source)
- Reflected region background method with multiple off-source regions
- 95% confidence level, spectral index $\Gamma = 2.4$ assumed
- Cross-check with `gammapy` analysis

H.E.S.S. Observations of NGC 1068

- 431 good quality runs taken in wobble mode
  - 310 with 4 12-m telescopes
  - 69 with between 1 and 3 telescopes (most only 12-m)
  - 23 with only the 28-m
  - 29 with 5 telescopes
- 279 (65%) prior to MAGIC observations
- Zenith angles range from 23° to 38°, mean zenith angle 26°
- Most taken with offset $0^\circ.7$
- Total exposure 168.5 -> Acceptance-corrected exposure 144.3 hours

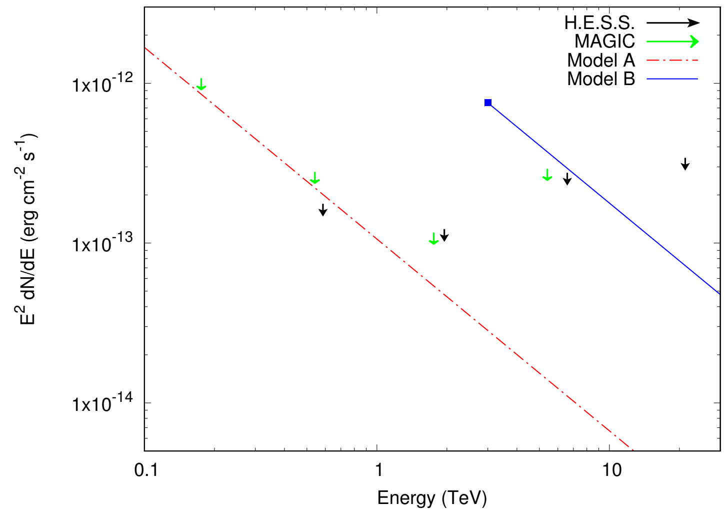
Year	Start (mm/dd)	End (mm/dd)
2004	10/09	10/17
2006	10/13	10/23
2008	08/27	09/08
2011	08/26	12/19
2012	10/13	12/11
2013	10/02	10/28
2014	08/23	10/16
2015	09/21	11/16
2016	07/05	10/29

Results: NGC 1068

- 6077 γ-ray like events on-source
  - 77660 γ-ray like events off-source
  - on-source/off-source exposure ratio $\alpha = 0.0762$
- γ-ray excess = 157 counts above background -> 2.0σ (no detection)
- Upper limit of $F(> 323\,\mathrm{GeV}) < 3 \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (95% confidence)

Results: NGC 1068

- H.E.S.S. upper limits comparable to MAGIC ULs
- Models A and B show γ-ray flux based on the IceCube ν flux for a $p-p(p-\gamma)$ neutrino source and further reduced by a factor of 4000 (8000) and 150 (300) due to absorption, respectively.
- Energy range for model B : IceCube scaled up 2x; for model A, extended to lower energies.
- Model A more tightly constrained



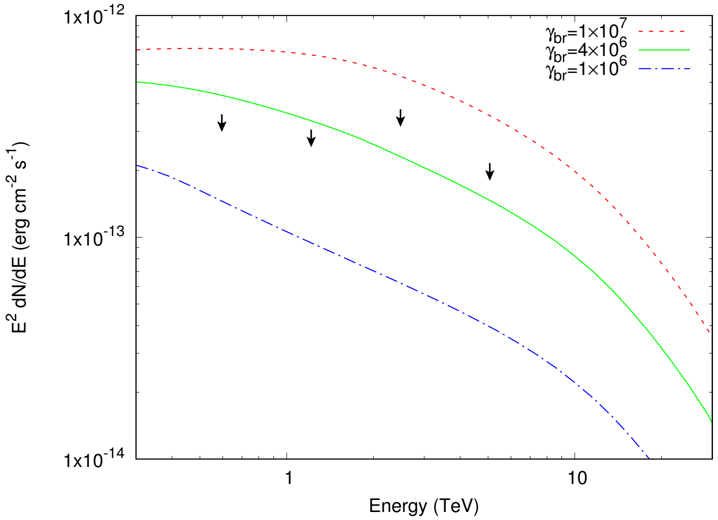
Flux upper limits obtained from H.E.S.S. observations shown along with those obtained from MAGIC. Models show the absorbed γ-ray flux

H.E.S.S. Observations of Circinus

- March 1-4 2014; 26 good quality runs in wobble mode
  - 5 with 3 12-m, 6 with 4 telescopes including 28-m, 15 with 5 telescopes
- Zenith angle $42^{\circ}.1 - 44^{\circ}.6$
- Offset angle $0^{\circ}.5$
- In addition, archival 12-m observations of nearby sources included
  - 12 in May 2006 of PSR J1537-6429
  - 6 in March 2007 of PWN HESS J1356-645
- Total exposure 18.4 hr -> acceptance-corrected 13.2 hr

Results: Circinus

- $b = -3^{\circ}.80 \rightarrow$ Galactic diffuse γ-ray background subdominant component of particle background
- Exclusion region around HESS J1356-645
- 213 γ-ray-like events on-source, 2923 off-source
- $\alpha = 0.06075 \rightarrow$ 35.4 excess counts $\rightarrow 2.5\sigma$ (no detection)



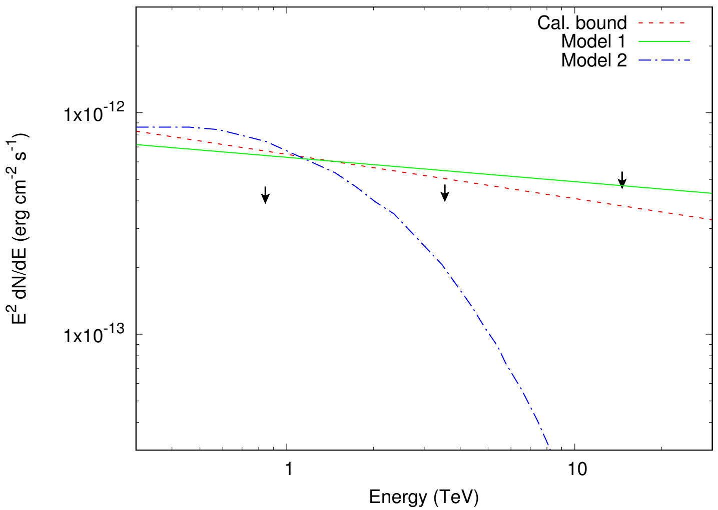
Flux upper limits obtained from H.E.S.S. observations of the Circinus galaxy. A model involving gamma-ray emitting lobes is shown for different values of a spectral break

H.E.S.S. Observations of NGC 4945

- 2012/3/17 - 2012/4/28, 2013/3/8, and 2015/2/15 - 2015/4/21
- 104 good quality runs in wobble mode
  - 8 with 3 12-m
  - 32 with 4 12-m
  - 60 with only 28-m
- Zenith angle $26^\circ.3 - 33^\circ.4$
- Offset $0^\circ.5$ for 12-m, $0^\circ.7$ for 28-m observations
- Total exposure 42.7 hr, acceptance-corrected 37.2 hr
- 92% of 12-m and 63% of 28-m runs taken during Swift-BAT 15-50 keV high state ($> 1.71 \times 10^{-3}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Results: NGC 4945

- 622 γ-ray-like events on-source, 7460 off-source
- $\alpha = 0.0821 \rightarrow 55.8$ excess events $\rightarrow 0.4\sigma$ (no detection)
- $F(> 320\,\mathrm{GeV}) < 5.8 \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (95% confidence)



Flux upper limits obtained from H.E.S.S. observations of NGC 4945 with 12-meter telescopes. Calorimetric bound from by Wang & Fields; Models 1 and 2 from Wojaczyński & Niedźwiecki and Xiang et al.

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Discussion

Comparison with GeV emission

- Circinus and NGC 4945 are at similar distances to NGC 253 and M82, starburst galaxies detected by both Fermi-LAT and H.E.S.S.
- NGC 1068 is $\sim$ 4 times more distant but significantly higher GeV luminosity
- NGC 1068 and NGC 4945: 4FGL-DR3 (Fermi-LAT 12-year) fluxes compatible with Lenain et al. (2010)
- Circinus: 4FGL-DR3 consistent with Ebrahim (2021) and Guo et al. (2019) but 2.5x lower than Hayashida et al. (2013)
- Extrapolation of Fermi-LAT spectra to H.E.S.S. energy range yields expected statistical significances of:
  - NGC 1068: 2.2 to 4.8 σ
  - Circinus: 1.0 to 3.6 σ
  - NGC 4945: 2.0 to 3.7 σ
- Lack of detection by H.E.S.S. consistent with extrapolation of Fermi-LAT spectra

Calorimeter model

- Requires energy injected in CR protons by SNe be lost to inelastic hadronic collisions before CR escape from starburst galaxies
- Neutral pion decay dominant γ-ray production mechanism
- Describes well NGC 253 and M82 γ-ray emission
- Wang & Fields found that GeV emission from NGC 1068 and NGC 4945 consistent with calorimetry assuming sufficiently high SN rates, but Circinus inconsistent
- Using W&F model, proton spectral index 2.2, H.E.S.S. limits imply 58% and 70% calorimetric efficiencies for NGC 1068 and NGC 4945 (assuming CR acceleration energy per SN of 3×10^{50} erg), higher than M82 (35%) and NGC 253 (39%), leaving room for contribution from other processes - viable explanation
- For Circinus, H.E.S.S. upper limits imply calorimetric efficiency upper limit above calorimetric bound (i.e. > 100%) due to low infrared luminosity and predicted VHE flux.

γ-ray emission due to AGN outflows

- Spectral curvature and/or variability
- TeV flux can be higher or lower than extrapolated GeV spectra
- According to Lenain et al. (2010) EIC model, VHE emisssion detectable by H.E.S.S. only if maximum electron energy $\gamma_{\text{max}} > 5 \times 10^6$
- For NGC 1068, characteristic frequency of a soft (external) photon field 1×10^{14} Hz $\rightarrow$ upscattering to TeV in Klein-Nishina regime and therefore suppressed wrt calorimeter model
- Adding additional hard ($\Gamma \simeq 2.0$) component to account for CR protons accelerated by AGN-driven shocks can exceed TeV flux produced by calorimeter model (Lamastra et al. 2016)
  - However, requires CR acceleration efficiencies larger than commonly assumed for SNR shocks
  - Constraints from Acciari et al. (2019) show that AGN outflow model fails to reproduce broadband γ-ray spectrum from NGC 1068.

Jet-driven bubbles: NGC 1068 and the Circinus galaxy

- Structures similar to Fermi bubbles
- kpc-scale lobes present in NGC 1068 and Circinus
- Kataoka et al. (2013) model + ISRF in addition to CMB
- Using radio band flux densities, for Circinus: $\sim 3.5\mu G$ while for NGC1068: NE lobe $87\mu G$, SW lobe $44\mu G$
- Broken power law electron spectra, index 2.2 below and 3.2 above γ_{brk}
- Maximum electron Lorentz factor 10^8
- Break energy only free parameter
- Comparing to H.E.S.S. limits, break energy must be lower than $\gamma_{\mathrm{brk}} \simeq 4 \times 10^6$ in NGC 1068 and Circinus, compared to 10^6 for Fermi bubbles from Kataoka et al. (2013)
- Therefore less constrained than Fermi bubbles, possibly detectable by further VHE observations
- Hadronic bubble emission can also contribute, which would further constrain electron energy break

Temporal characteristics of NGC 4945

- VHE flux variability can be caused by SNe or AGN jets
- Wojaczyński & Niedźwiecki (2017) reported evidence for
  - Anti-correlation between daily hard X-ray fluxes from Swift and γ-ray flux from Fermi-LAT
  - Correlation between hard X-ray flux and γ-ray spectral hardness ($\Delta\Gamma = 0.36 \pm 0.11$)
  - Indication of AGN contribution to the HE γ-ray emission
  - Extrapolation of subdominant hard component to TeV energies would be substantial
- $\sim$ 80% of H.E.S.S. exposure during strong hard X-ray flux state $\rightarrow F(> 1\,\text{TeV}) = (4.3 \pm 0.8) \times 10^{-13}\text{cm}^{-2}\text{s}^{-1}$
- Suggestive of cutoff during strong hard X-ray state

Spectral characteristics of NGC 4945

- Two-state behavior can lead to spectral hardening of HE γ-ray spectrum under assumption of broken power-law spectrum
- Low-energy part dominated by soft γ-ray component produced during weak hard X-ray state, high-energy part dominated by hard γ-ray component produced during strong hard X-ray state.
- Broken power law can also result from two different spectral components e.g. Centaurus A
- Xiang et al. (2021): spectral hardening in Fermi-LAT 11 year spectrum
- With two hadronic components, high-E component has very hard proton power law spectral index of $\alpha = 1.12^{+0.13}_{-0.19}$, harder than NLDSA $\alpha = 1.5$
- H.E.S.S. differential flux UL at 0.84 TeV is $E^2 dN/dE < 4.7 \times 10^{-13}$ ergcm^{-2}s^{-1} which is less than the Xiang et al. two-zone model $E^2 dN/dE = 7.4^{+1.0}_{-3.4} \times 10^{-13}$ergcm^{-2}s^{-1}
- Sufficient to constrain, but to fully test, flux UL must be lowered by a factor of two.

Multi-messenger channels: Astrophysical neutrinos

- *pp* or $p\gamma$ interactions produce both charged pions which decay into muons and neutrinos and neutral pions which decay into γ rays.
- The neutrino channel can be used to constrain the VHE γ ray production and absorption

$$\frac{\mathrm{d}N_i}{\mathrm{d}E_i} = k_i \left(\frac{E_i}{\mathrm{TeV}}\right)^{-\Gamma}, \quad i = \{\nu_\mu + \tilde{\nu}_\mu, \gamma\}$$

where $k_{\nu_\mu+\tilde{\nu}_\mu} \approx (0.71 - 0.16\Gamma)k_\gamma$ for *pp* interactions and $k_{\nu_\mu+\tilde{\nu}_\mu} \approx 2^{-\Gamma}k_\gamma$ for $p\gamma$ interactions

- Neutrinos interact extremely weakly and travel to Earth without attenuation, while γ rays can be heavily absorbed by photon fields within the source.

IceCube neutrino excess and NGC 1068

- Refined analysis of IceCube data from 2008/4/6 to 2018/7/10 showed an excess of 79^{+22}_{-20} neutrinos associated with NGC 1068 at a significance of 4.2σ
- Reported averaged best-fit at $E_\nu = 1$ TeV is $\Phi^{1\mathrm{TeV}}_{\nu_\mu+\tilde{\nu}_\mu} = (5.0 \pm 1.5_{\mathrm{stat}} \pm 0.6_{\mathrm{sys}}) \times 10^{-11}$ cm^{-2} s^{-1} TeV^{-1} with power law index $\Gamma = 3.2^{+0.2}_{-0.2}$
- Too high to be explained by starburst scenarios
- Given H.E.S.S. integral flux UL above 0.33 TeV of $I_\gamma = 3 \times 10^{-13}$ cm^{-2}s^{-1}, the optical depth for internal $\gamma\gamma$ absorption is $\gtrsim 4000$ for pp neutrino sources and $\gtrsim 8000$ for $p\gamma$ neutrino sources

Multi-messenger channels: UHECR channel

- Observed correlation between starburst galaxies and UHECR arrival directions as seen by Pierre Auger Observatory (PAO), suggesting CRs accelerated to $> 3.9 \times 10^{19}$ eV
- Favored model with 9.7% of UHECR flux above 3.9×10^{19} eV from nearby starburst galaxies (remaining 90.3% isotropic)
- UHECR hotspot in Centaurus A/M83 group which contains NGC 4945
- UHECR excess close to south Galactic pole -> contributions from NGC 253 and NGC 1068
- Assuming CR power-law with spectral index s harder than 2.7 below $> 3.9 \times 10^{19}$ eV, CR luminosities above proton energy 10 GeV compared with those by SNRs - strongly depends on spectral index

Auger excesses and NGC 4945 + NGC 253

- For NGC 4945 and NGC 253, corresponding to 39% and 36% of possible UHECR flux from SBGs, CR power comparable with CR power produced by SNRs if $s = 2.2$ and $> 10\times$ the CR power produced by SNRs if s is 2.4 or softer.
- Therefore, calorimetry limits from H.E.S.S. and Fermi-LAT observations of NGC 4945 and NGC 253 are violated if CR-UHECR sources have soft spectra $s \gtrsim 2.2$
- Potential CR-UHECR sources in Seyfert/starbursts include starburst superwinds, hypernova remnants, and kpc-scale jets.

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Conclusion

Summary

- Composite Seyfert/starburst galaxies NGC 1068, Circinus, and NGC4945 were observed in VHE γ rays by H.E.S.S.
- Only flux upper limits obtained, constraining
  - fraction of SN explosion KE converted into CR energy in NGC 1068 and NGC 4945
  - electron populations inside the kpc-scale bubbles in NGC 1068 and Circinus
  - temporal and spectral properties of NGC 4945 previously suggested from Fermi-LAT observations
  - propagation of VHE γ rays produced via hadronic interactions and expected to accompany neutrinos seen with IceCube, for a SMBH surrounded by gas or photons in NGC 1068, and
  - spectral hardness of hypothetical CR-UHECR sources in NGC 4945 producing both CRs interacting with gas in NGC 4945 and UHECRs observed on Earth.

Summary

- These ULs are among the most stringent constraints to date.
- In conclusion, VHE γ-ray observations of composite Seyfert/starburst galaxies probe a broad range of phenomena
- CTA will be able to reach comparable sensitivities in one tenth the exposure time, with the possibility of detecting differential fluxes at 1 TeV greater than 1×10^{-13} ergcm^{-2}s^{-2}.

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Thanks for your attention!

Backup

IceCube neutrino excess and NGC 1068

Optical depth for a γ ray of energy E in a source of luminosity $L_{\epsilon\mathrm{b}}$, at energy $\epsilon_{\mathrm{b}} = 1\ (E/1\mathrm{TeV})$ eV and size, R, can be written in the form

$$\tau(E) \sim 10^8 \left(\frac{L_{\epsilon\mathrm{b}}}{L_{\mathrm{Edd}}}\right) \left(\frac{R_{\mathrm{S}}}{R}\right) \left(\frac{E}{1\mathrm{TeV}}\right),$$

where R_{S} is the Schwarzschild radius and L_{Edd} is the Eddington luminosity.

- Based on the above optical depth constraint, the upper limit of the source size, $R < 1700\ R_{\mathrm{S}}$ (or $R < 2 \times 10^{-3}$ pc) for *pp* neutrino sources and $R < 850\ R_{\mathrm{S}}$ (or $R < 10^{-3}$ pc) for $p\gamma$ neutrino sources, is obtained from this equation for a black hole mass of $10^7 M_{\odot}$ and infrared luminosity of the NGC 1068 AGN core of 8.6×10^{43} erg s^{-1}.
- Conservative constraint (IR luminosity could be attributed to larger region)
- However, if the ν spectrum has a low-E cutoff due to threshold photomeson production in $p\gamma$ interactions, the UL on the source size could be about 25x less constraining (see Model B)

Transition to heavier nuclei

- Transition to heavier compositions at $E > 10^{19}$eV due to Peters cycle
- If UHECRs at these energies mostly carbon nuclei, *Cp* rather than *pp* should be used, extrapolated to lower energies
- For $s = 2.2$, resulting γ-ray luminosity smaller by a factor of $\simeq 2$, and γ-ray fluxes remain below H.E.S.S. ULs
- Thus, the spectral index of CR-UHECR proton sources must be harder than 2.2 or the CR-UHECR sources must be dominated by heavier nuclei, for example, CNO nuclei.