High Energy Neutrinos from Centaurus A

Ricard Tomàs

II. Institut für Theoretische Physik

Universität Hamburg

based on arXiv:0805.2608

in collaboration with M. Kachelrieß and S. Ostapchenko

Neutrino Oscillation Workshop 2008

Conca Specchiulla, Otranto, Italy, 11th September 2008

Outline

Outline

Outline

Astronomy with UHECRs

Starting Point

Observation of Ultra High Energy Cosmic Rays (UHECRs) Talk by V. Berezinsky

Question: where do they come from?

Astronomy with UHECRs

Starting Point

Observation of Ultra High Energy Cosmic Rays (UHECRs) Talk by V. Berezinsky

Question: where do they come from? $\Rightarrow$ approaches

- **top-down**: decay of superheavy particles

Astronomy with UHECRs

Starting Point

Observation of Ultra High Energy Cosmic Rays (UHECRs)   Talk by V. Berezinsky

Question: where do they come from? ⇒ approaches

- **top-down**: decay of superheavy particles → disfavored
- **bottom-up**: accelerated in astrophysical sources → candidates?

Astronomy with UHECRs

Starting Point

Observation of Ultra High Energy Cosmic Rays (UHECRs) Talk by V. Berezinsky

Question: where do they come from? ⇒ approaches

- **top-down**: decay of superheavy particles → disfavored
- **bottom-up**: accelerated in astrophysical sources → candidates?

→ *Hillas argument*: $E_{\max} = \Gamma Z e B R_s$

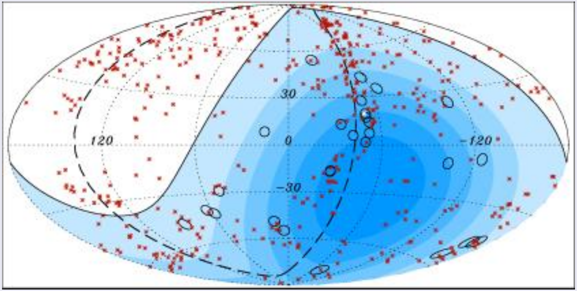
- Pulsars
- Active Galactic Nuclei (AGNs)
- Gamma Ray Bursts (GRBs)
- Supernova Remnants (SNRs), ...

→ *observation ...*

Astronomy with UHECRs

Pierre Auger Observatory (PAO)

correlation: arrival UHECRs directions ↔ positions of nearby AGNs

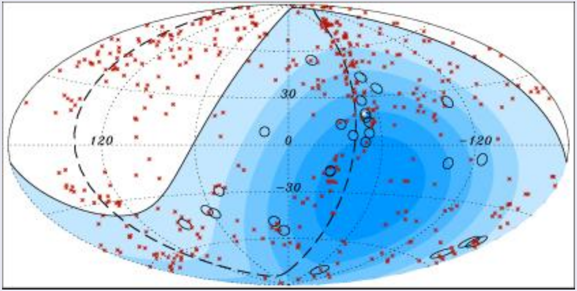


[Abraham *et al.*, 2007], Talks by L. Nellen and N. Busca

Astronomy with UHECRs

Pierre Auger Observatory (PAO)

correlation: arrival UHECRs directions ↔ positions of nearby AGNs



[Abraham *et al.*, 2007], Talks by L. Nellen and N. Busca

However

- results not confirmed by other experiments [Abbasi *et al.*, 2008]
- UHECRs affected by not well-known magnetic fields

Astronomy with Gamma rays

Advantages

- gamma-rays are expected together with UHECRs
  - e.g. $p + \gamma \longrightarrow p + \pi^0 \longrightarrow$ UHECRs + γ-rays
- neutral particles ⇒ not affected by B ⇒ point back to the source
- current γ-rays detectors successful

Talks by N. Giglietto and E. Carmona

Astronomy with Gamma rays

Advantages

- gamma-rays are expected together with UHECRs
  - e.g. $p + \gamma \longrightarrow p + \pi^0 \longrightarrow$ UHECRs + γ-rays
- neutral particles $\Rightarrow$ not affected by B $\Rightarrow$ point back to the source
- current γ-rays detectors successful

Talks by N. Giglietto and E. Carmona

but ...

- high energy photons strongly absorbed: e.g. $\gamma + \gamma_{\rm bkgnd} \rightarrow e^+ + e^-$
  - in the source: optically thick sources
  - during propagation over extragal. distances: universe is opaque to photons for E larger than hundreds of TeV
- difficult to disentangle the origin:
  - Hadronic: $p + \gamma \longrightarrow p + \pi^0 \longrightarrow$ UHECRs + γ-rays
  - Leptonic: synchrotron radiation of e^-, inverse Compton scattering, ...

Astronomy with Neutrinos

Advantages

- HE neutrinos expected together with UHECRs
  - e.g. $p + \gamma \longrightarrow n + \pi^+ \longrightarrow$ UHECRs + ν's
- neutral $\Longrightarrow$ not affected by magnetic fields $\Longrightarrow$ point back to the source
- weakly interacting with matter $\Rightarrow$ carry information from
  - edge of the Universe
  - inner layers of astrophysical objects $\rightarrow$ internal dynamics
- always hadronic origin
- *non-standard* properties: flavor mixing $\Rightarrow$ sensitive to the composition in the source [Learned and Pakvasa, 1995, Beacom, Bell, Hooper, Pakvasa and Weiler, 2003, Anchordoqui, Goldberg, Halzen and Weiler, 2005, Kashti and Waxman, 2005, Serpico and Kachelrieß, 2005, Kachelrieß and R. T, 2006, Kachelrieß, Ostapchenko and R. T., 2007, Farzan and Smirnov, 2008]

Astronomy with Neutrinos

Advantages

- HE neutrinos expected together with UHECRs
  - e.g. $p + \gamma \longrightarrow n + \pi^+ \longrightarrow$ UHECRs + ν's
- neutral $\Longrightarrow$ not affected by magnetic fields $\Longrightarrow$ point back to the source
- weakly interacting with matter $\Rightarrow$ carry information from
  - edge of the Universe
  - inner layers of astrophysical objects $\rightarrow$ internal dynamics
- always hadronic origin
- *non-standard* properties: flavor mixing $\Rightarrow$ sensitive to the composition in the source [Learned and Pakvasa, 1995, Beacom, Bell, Hooper, Pakvasa and Weiler, 2003, Anchordoqui, Goldberg, Halzen and Weiler, 2005, Kashti and Waxman, 2005, Serpico and Kachelrieß, 2005, Kachelrieß and R. T, 2006, Kachelrieß, Ostapchenko and R. T., 2007, Farzan and Smirnov, 2008]

Problem

- very hard to detect $\Rightarrow$ currently only upper bounds Talks by T. Montaruli and U. Katz

Multi-messenger Astronomy

no ideal particle ⇒ multi-messenger astronomy required

Example

- At low energies
  - Sun
  - SN1987A
- At high energies
  - candidate?

Multi-messenger Astronomy

no ideal particle $\Rightarrow$ multi-messenger astronomy required

Example

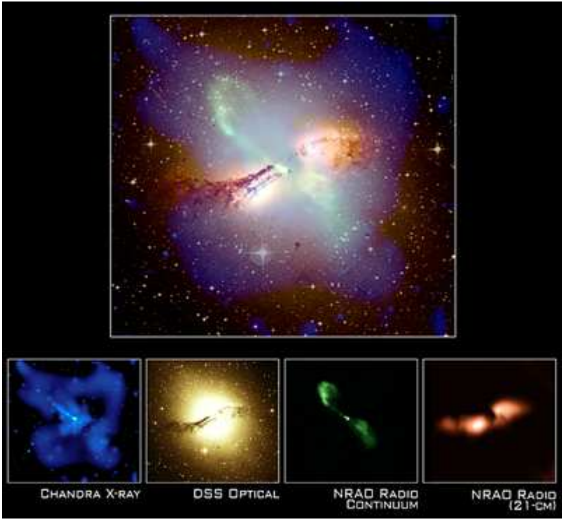
- At low energies
  - Sun
  - SN1987A
- At high energies
  - candidate? $\longrightarrow$ Centaurus A

[Anchordoqui *et al.*, 2004, Cuoco and Hannestad, 2007, Halzen and O'Murchadha, 2008]

Outline

1. Introduction
   - Multi-messenger approach
2. Centaurus A: an example of multi-messenger astronomy?
   - Setup
   - Results
3. Summary

Centaurus A


CHANDRA X-RAY
DSS OPTICAL
NRAO RADIO CONTINUUM
NRAO RADIO (21-CM)

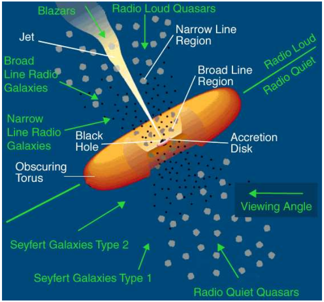
Centaurus A

What?

Active Galactic Nucleus

⟶ Fanaroff-Riley I radio galaxy [Israel, 1998, `http://www.mpe.mpg.de/Cen-A/`]

⟶ in the Centaurus constellation (southern hemisphere)



Centaurus A

What?

Active Galactic Nucleus

⟶ Fanaroff-Riley I radio galaxy [Israel, 1998, http://www.mpe.mpg.de/Cen-A/]

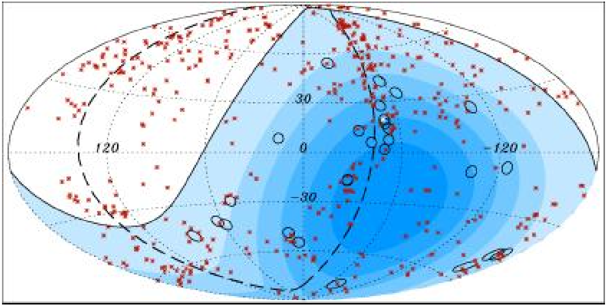
⟶ in the Centaurus constellation (southern hemisphere)

Why is it interesting?

- Nearest AGN: at a distance $d \sim 3.8$ Mpc [Rejkuba, 2004]
- two UHECR events observed by PAO are thought to come from Cen A

  [Abraham *et al.*, 2007]

Centaurus A



Outline

Procedure

- Normalize the UHECR flux to the observed by PAO
- establish the crucial connection

UHECRs $\leftrightarrow$ gamma-rays $\leftrightarrow$ neutrinos

Procedure

- Normalize the UHECR flux to the observed by PAO
- establish the crucial connection

UHECRs ↔ gamma-rays ↔ neutrinos

How? Astronomical observations + Theoretical models

Procedure

- Normalize the UHECR flux to the observed by PAO
- establish the crucial connection

UHECRs ↔ gamma-rays ↔ neutrinos

How? Astronomical observations + Theoretical models

⇓

Scenarios

- *I) acceleration in regular fields close to the core*

  [Blandford, 1976, Lovelace, 1976, Blandford and Znajek, 1977, MacDonald and Thorne, 1982]

- *II) shock acceleration along the radio jet*

  [Rachen and Biermann, 1993, Rachen, Stanev and Biermann, 1993, Romero, Combi, Anchordoqui and Perez Bergliaffa, 1995]

Assumption: acceleration region ≠ target region

Monte Carlo simulation

source

- injected protons $dN/dE \propto E^{-\alpha} \longrightarrow$ a) $\alpha = 2$, b) $\alpha = 2.7$ for $E > E_b$
- target
  - I) photons $\leftarrow$ UV bump + X-ray [Shakura and Syunyaev, 1973, Chakrabati, 1996, Evans *et al.*, 2004]
  - II) protons $\leftarrow$ gas column density [Worrall *et al.*, 2007]

Monte Carlo simulation

source

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha} \longrightarrow$ a) $\alpha = 2$, b) $\alpha = 2.7$ for $E > E_\mathrm{b}$
- target
  - I) photons $\leftarrow$ UV bump + X-ray [Shakura and Syunyaev, 1973, Chakrabati, 1996, Evans *et al.*, 2004]
  - II) protons $\leftarrow$ gas column density [Worrall *et al.*, 2007]

processes

- Hadronic
  - $p + \gamma/p \rightarrow$ secondary mesons (π, K, charm)
    - decay $\longrightarrow$ HE γ's
      $\longrightarrow$ HE ν's

Monte Carlo simulation

source

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha} \longrightarrow$ a) $\alpha = 2$, b) $\alpha = 2.7$ for $E > E_\mathrm{b}$
- target
  - I) photons $\leftarrow$ UV bump + X-ray [Shakura and Syunyaev, 1973, Chakrabati, 1996, Evans *et al.*, 2004]
  - II) protons $\leftarrow$ gas column density [Worrall *et al.*, 2007]

processes

- Hadronic
  - $p + \gamma/p \rightarrow$ secondary mesons (π, K, charm)
    - decay $\longrightarrow$ HE γ's $\rightarrow$ undergo electromagnetic cascade
      $\longrightarrow$ HE ν's $\rightarrow$ escape $\rightarrow$ oscillate $\rightarrow$ Earth

Monte Carlo simulation

source

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha} \longrightarrow$ a) $\alpha = 2$, b) $\alpha = 2.7$ for $E > E_\mathrm{b}$
- target
  - I) photons $\leftarrow$ UV bump + X-ray [Shakura and Syunyaev, 1973, Chakrabati, 1996, Evans *et al.*, 2004]
  - II) protons $\leftarrow$ gas column density [Worrall *et al.*, 2007]

processes

- Hadronic
  - $p + \gamma/p \rightarrow$ secondary mesons (π, K, charm)
    - decay $\longrightarrow$ HE γ's $\rightarrow$ undergo electromagnetic cascade
      $\longrightarrow$ HE ν's $\rightarrow$ escape $\rightarrow$ oscillate $\rightarrow$ Earth
    - scatter: meson$+\gamma/p \longrightarrow \nu$ flux suppression

Monte Carlo simulation

source

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha} \longrightarrow$ a) $\alpha = 2$, b) $\alpha = 2.7$ for $E > E_\mathrm{b}$
- target
  - I) photons $\leftarrow$ UV bump + X-ray [Shakura and Syunyaev, 1973, Chakrabati, 1996, Evans *et al.*, 2004]
  - II) protons $\leftarrow$ gas column density [Worrall *et al.*, 2007]

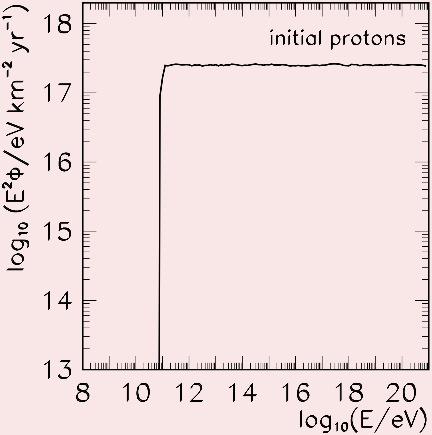
processes

- Hadronic
  - $p + \gamma/p \rightarrow$ secondary mesons (π, K, charm)
    - decay $\longrightarrow$ HE γ's $\rightarrow$ undergo electromagnetic cascade
      $\longrightarrow$ HE ν's $\rightarrow$ escape $\rightarrow$ oscillate $\rightarrow$ Earth
    - scatter: meson$+\gamma/p \longrightarrow \nu$ flux suppression
- Leptonic
  - inverse Compton scattering, e^+e^- pair production, ...

Outline

High energy radiation

Scenario Ia)

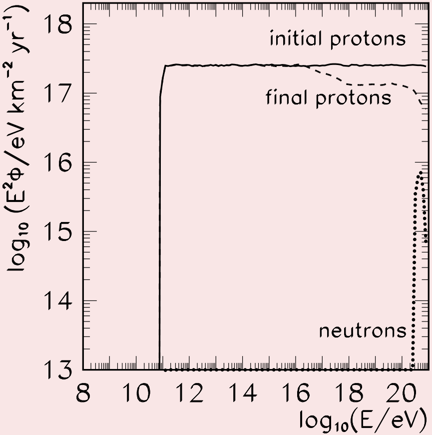


[Kachelrieß, Ostapchenko and R. T., 2008]

- injected spectrum

High energy radiation

Scenario Ia)

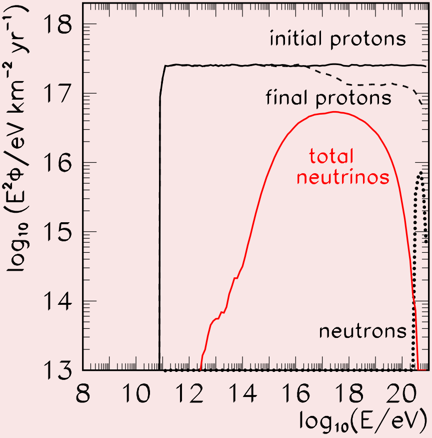


[Kachelrieß, Ostapchenko and R. T., 2008]

- injected spectrum
- energy loss processes
  → final UHECR flux
  → normalized to PAO

High energy radiation

Scenario Ia)



[Kachelrieß, Ostapchenko and R. T., 2008]

- injected spectrum
- energy loss processes
  → final UHECR flux
  → normalized to PAO
- neutrinos emitted
  → events per year?

Neutrinos expected per year

- scenario I)

	α	E_b/eV	
	2.0	10^{18}	10^{17}
Icecube	4×10^{-3}	0.1	0.5
KM3NeT	0.03	0.5	1

- scenario II)

	α	E_b/eV	
	2.0	10^{18}	10^{17}
Icecube	0.02	0.6	3
KM3NeT	0.03	0.8	4

[Kachelrieß, Ostapchenko and R. T., 2008]

Neutrinos expected per year

- scenario I)

	α	E_b/eV	
	2.0	10^{18}	10^{17}
Icecube	4×10^{-3}	0.1	0.5
KM3NeT	0.03	0.5	1

- scenario II)

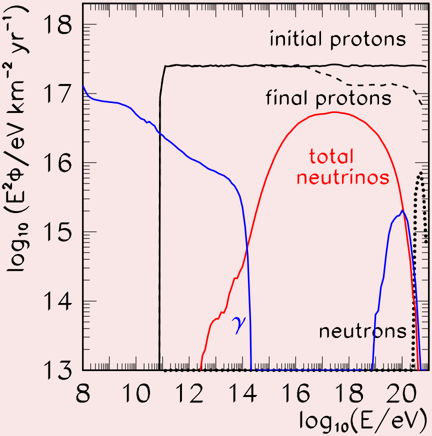
	α	E_b/eV	
	2.0	10^{18}	10^{17}
Icecube	0.02	0.6	3
KM3NeT	0.03	0.8	4

[Kachelrieß, Ostapchenko and R. T., 2008]

up to a few events in models with broken power law fluxes

Gamma-rays

Scenario Ia)

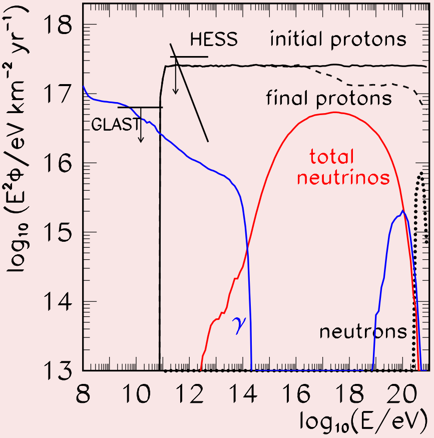


[Kachelrieß, Ostapchenko and R. T., 2008]

- injected spectrum
- energy loss processes
  $\rightarrow$ final UHECR flux
  $\rightarrow$ normalized to PAO
- neutrinos emitted
  $\rightarrow$ few events per year
- gamma-rays after cascading

Gamma-rays

Scenario Ia)

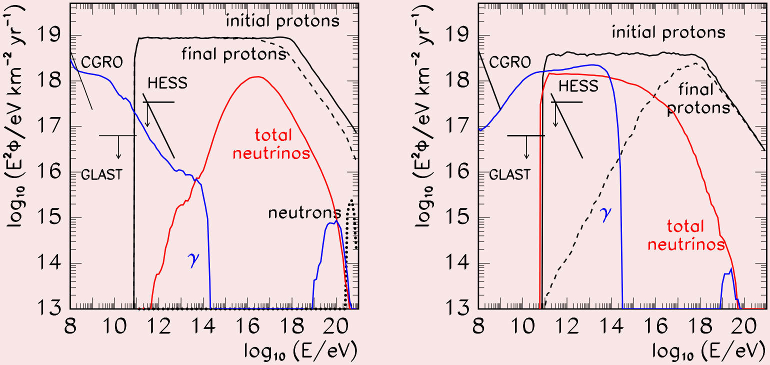


[Kachelrieß, Ostapchenko and R. T., 2008]

- injected spectrum
- energy loss processes
  $\rightarrow$ final UHECR flux
  $\rightarrow$ normalized to PAO
- neutrinos emitted
  $\rightarrow$ few events per year
- gamma-rays after cascading
  $\rightarrow$ not far from exp.

Gamma-rays

broken power law → I) and II)



[Kachelrieß, Ostapchenko and R. T., 2008]

Predicted γ-ray flux in the range of HESS or GLAST

Outline

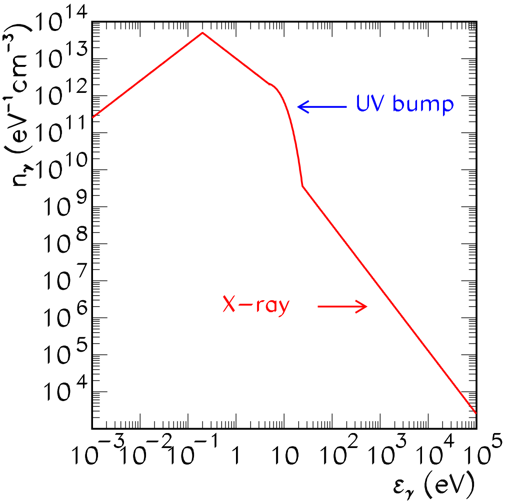
Summary

High Energy Radiation from Centaurus A

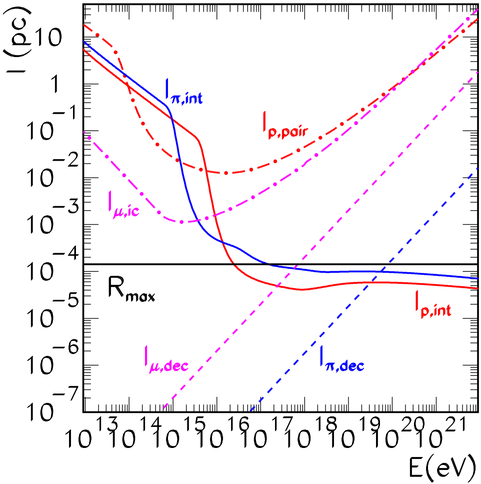
- understanding of the origin of UHECRs requires the use of all tools available: UHECRs, γ-rays, HE neutrinos
- Predictions for the nearest AGN: Centaurus A
  - UHECRs flux normalized to PAO
  - neutrinos: up to a few events per year in km^3 ν telescopes
  - gamma-rays: predicted fluxes in the range of HESS, GLAST, ...

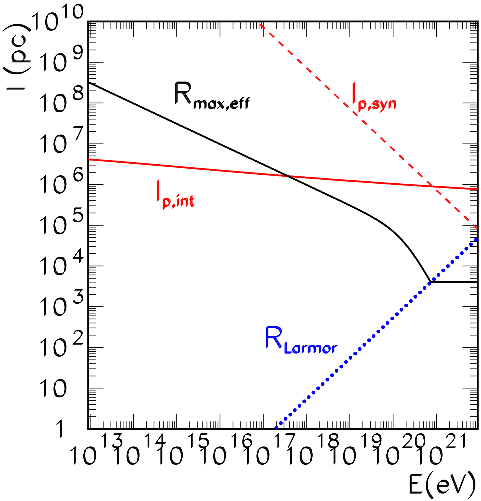
but ...

- normalization to only two events!
- uncertainties: protons or heavy nuclei? deflections in (extra-)galactic magnetic fields, ...
- limitations of the models: omission of the acceleration process, ...



n_γ (eV^{-1}cm^{-3})
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
UV bump
X−ray
10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5}
ε_γ (eV)


l (pc)
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21
E(eV)
l_π,int
l_p,pair
l_μ,ic
R_max
l_p,int
l_μ,dec
l_π,dec


l (pc)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
$R_{max,eff}$
$l_{p,syn}$
$l_{p,int}$
R_{Larmor}
10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
E(eV)

- J. Abraham *et al.*, 2007
- Abbasi *et al.*, 2008
- J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler,
  Phys. Rev. D **68** (2003) 093005
  [Erratum-ibid. D **72** (2005) 019901].
- L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler,
  Phys. Lett. B **621** (2005) 18 .
- T. Kashti and E. Waxman,
  Phys. Rev. Lett. **95** (2005) 181101.
- P. D. Serpico and M. Kachelrieß
  Phys. Rev. Lett. **94** (2005) 211102.
- M. Kachelrieß and R. Tomàs,
  Phys. Rev. D **74** (2006) 063009 [arXiv:astro-ph/0606406].
- M. Kachelrieß, S. Ostapchenko and R. Tomàs,
  Phys. Rev. D **77** (2008) 023007 [arXiv:0708.3047 [astro-ph]].
- J. G. Learned and S. Pakvasa,

Astropart. Phys. **3**, 267 (1995) [hep-ph/9405296].

Farzan and Smirnov, 2008.

Anchordoqui *et al.*, 2004.

A. Cuoco and S. Hannestad,
arXiv:0712.1830 [astro-ph].

F. Halzen and A. O'Murchadha,
arXiv:0802.0887 [astro-ph].

M. Kachelrieß, S. Ostapchenko and R. Tomàs,
arXiv:0805.2608 [astro-ph].

F. P. Israel,
Astron. Astrophys. Rev. **8**, 237 (1998)
see also
http://www.gamma.mpe-garching.mpg.de/~hcs/Cen-A/ for an extensive list of references for Cen A.

M. Rejkuba,
Astron. Astrophys. **413**, 903 (2004)

R. D. Blandford,

Mon. Not. Roy. Astron. Soc. **176**, 465 (1976).

R. V. E. Lovelace,
Nature, **262**, 649 (1976).

R. D. Blandford and R. L. Znajek,
Mon. Not. Roy. Astron. Soc. **179**, 433 (1977).

D. MacDonald and K. S. Thorne,
Mon. Not. Roy. Astron. Soc. **198**, 345 (1982).

J. P. Rachen and P. L. Biermann, Astron. Astrophys. **272**, 161 (1993) [astro-ph/9301010]. J. P. Rachen, T. Stanev and P. L. Biermann, Astron. Astrophys. **273**, 377 (1993) [astro-ph/9302005].

G. E. Romero, J. A. Combi, L. A. Anchordoqui and S. E. Perez Bergliaffa, Astropart. Phys. **5**, 279 (1996) [gr-qc/9511031].

N. I. Shakura and R. A. Syunyaev, Astron. Astrophys. **24**, 337 (1973); S. K. Chakrabarti, Phys. Rep. **266**, 229 (1996).

D. A. Evans *et al.*, Astrophys. J. **612**, 786 (2004) [astro-ph/0405539].

D. M. Worrall *et al.*, arXiv:0712.3579 [astro-ph].