Multi-messenger astronomy with Centaurus A

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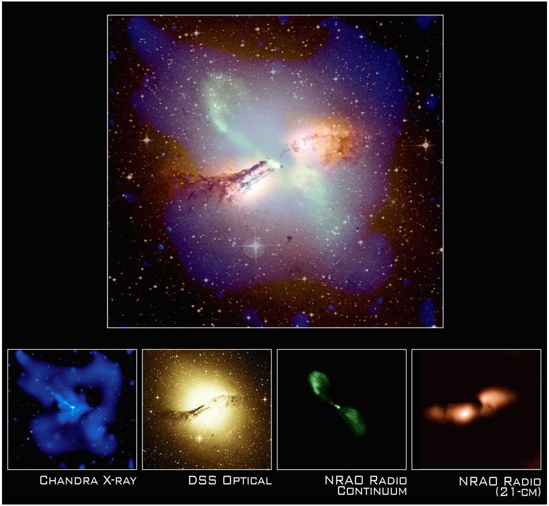
based on arXiv:0805.2608 (to appear in N.J. of Phys.)

in collaboration with M. Kachelrieß and S. Ostapchenko

Searching for the Origins of Cosmic Rays

Department of Physics, NTNU Trondheim, Norway 18 June 2009

Centaurus A

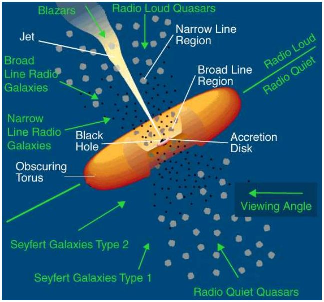


From multi-wavelength ⟶ multi-messenger astronomy

What? Active Galactic Nucleus

- Fanaroff-Riley I
  - low-luminosity radio galaxy ($L_{\rm bol} \approx 10^{43}$ erg/s)
  - *misaligned* BL Lac $\rightsquigarrow 70^0$

[Israel, 1998, http://www.mpe.mpg.de/Cen-A/]



- in the Centaurus constellation (southern hemisphere)
  - declination= -43^0, right ascension= $13^{\rm h}25^{\rm m}27^{\rm s}$

Talks by F. Rieger and M. Hardcastle

Interest

Nearest radio-loud AGN: at a distance $d \sim 3.8$ Mpc [Rejkuba, 2004]

Name	Distance (Mpc)	Object
Cen A	3.8	FRI
NGC 1068	14	SyII
M87	17	FRI
NGC 3783	40	SyI
NGC 7469	61	SyI
Mkn 421	120	BL
3C 120	130	FRI
Mkn 501	140	BL
Pictor A	150	FRII

- observed at many frequencies: from radio (VLA, ...) to X-ray (XMM-Newton, Chandra, Suzaku, ...)

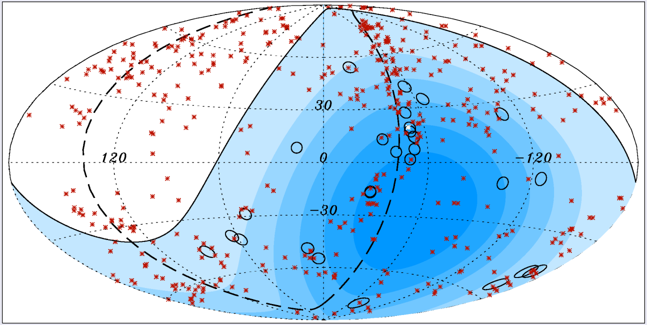
but can we do multi-messenger astronomy?

Interest

Nearest AGN: multifrequency $\surd$ $\longrightarrow$ multi-messenger?

- UHECRs? $\rightarrow$ PAO: Clustering of UHECR events around Cen A

  [Abraham *et al.*, 2007]



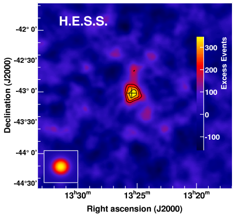
- Cen A source of UHECRs? not agreement (Talk by G. Ghisellini [Lemoine, 2008])
  $\longrightarrow$ but possible $\surd$ [Gorbunov *et al.*, 2008, Moskalenko *et al.*, 2009]

Interest

Nearest AGN: multifrequency $\surd$ $\longrightarrow$ multi-messenger?

- UHECRs $\rightarrow$ PAO $\surd$ [Abraham *et al.*, 2007]

- gamma-rays $\surd$
  - 70's: emission above 300 GeV: $I = (4.4 \pm 1.0) \times 10^{-11}$ cm^{-2}s^{-1} [Grindlay *et al.*, 1975]
  - 90's: EGRET detected emission above 100 MeV [Sreekumar *et al.*, 1999]
  - Feb. 2009: Fermi-LAT $\rightarrow$ spectral index $\Gamma = 2.91$, $F(E > 100\ \mathrm{MeV}) = 21.5 \times 10^{-8}$ s^{-1}cm^{-2} (Talk by L. Baldini, [Abdo *et al.*, 2009])
  - March 2009: H.E.S.S. $\rightarrow 2.45 \times 10^{-13}$ cm^{-2}s^{-1}TeV^{-1} $(E/1\ \mathrm{TeV})^{-2.73}$ (Talk by F. Rieger, [Aharonian *et al*, 2009])



Interest

Nearest AGN: multifrequency $\surd$ $\longrightarrow$ multi-messenger?

- UHECRs $\rightarrow$ PAO $\surd$ [Abraham *et al.*, 2007]
- gamma-rays $\surd$
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- neutrinos $\rightarrow$ no observation ... yet Talk by E. Resconi

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Nearest AGN: multifrequency $\surd$ $\longrightarrow$ multi-messenger?

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  - 70's: Narrabri [Grindlay *et al.*, 1975]
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  - March 2009: H.E.S.S. [Aharonian *et al*, 2009]
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Goal: collect all this information

- test the PAO correlation hypothesis + H.E.S.S. observation
- predictions for UHEν's

[Anchordoqui *et al.*, 2004, Cuoco and Hannestad, 2007, Halzen and O'Murchadha, 2008, Gupta, 2008, Rachen, 2008, Hardcastle *et al.*, 2008, Aharonian and Rieger, 2009]

Procedure

- First step : establish connection of fluxes

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

$\downarrow$

Astronomical observations + Theoretical (hadronic) models

+

Assumption: acceleration region $\neq$ target region

$\Downarrow$

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]

Talks by F. Rieger, M. Hardcastle, S. Troitsky, ...

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- Second step: PAO: UHECRs normalization $\rightsquigarrow$ γ-ray + neutrino fluxes

Setup: Monte Carlo simulation

source

- injected protons: spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ and $E_{\max} = 10^{20}$ eV
  - a) power law $\alpha = 2$
  - b) broken power law $\alpha = 2.7$ for $E > E_\mathrm{b}$
- target: photons and protons

[Evans *et al.*, 2004, Worrall *et al.*, 2007]

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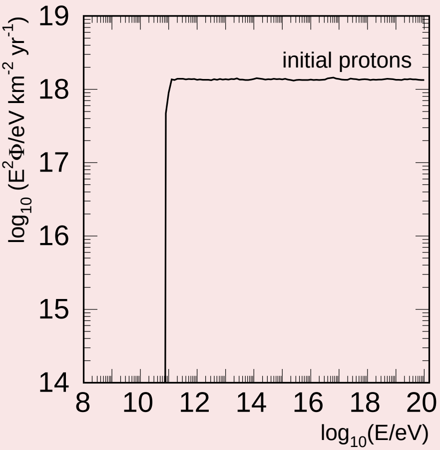
processes

$p + \gamma/p \rightarrow$ secondary mesons (π, K, charm)

- decay $\longrightarrow$ HE γ's $\rightarrow$ electromagnetic cascade
  $\longrightarrow$ HE ν's $\rightarrow$ escape $\rightarrow$ oscillate $\rightarrow$ Earth
- scatter: meson$+\gamma/p \longrightarrow \nu$ flux suppression

Results: *I) acceleration close to the core*

Ia) power law $\alpha = 2$



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

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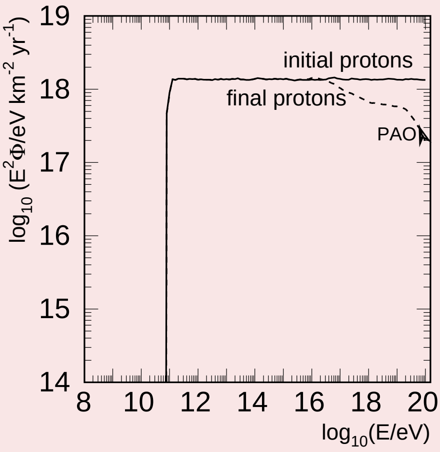

[Kachelrieß, Ostapchenko and R. T., 2008]

fluxes

- injected p spectrum:

$\downarrow$

energy loss: $p + \gamma$

$\Rightarrow E_{\text{th}} \approx 10^{16}$ eV

$\Rightarrow \tau_{p\gamma} \approx$ a few

$\Downarrow$

- final p spectrum
  $\rightarrow$ normalized to PAO

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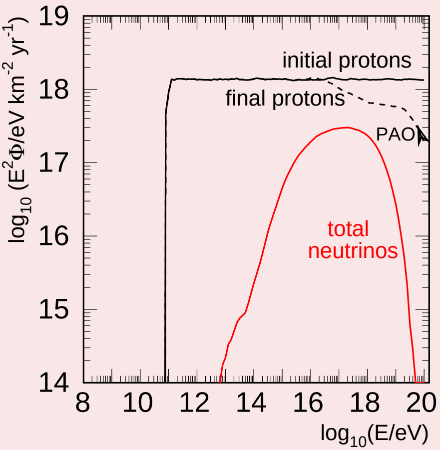

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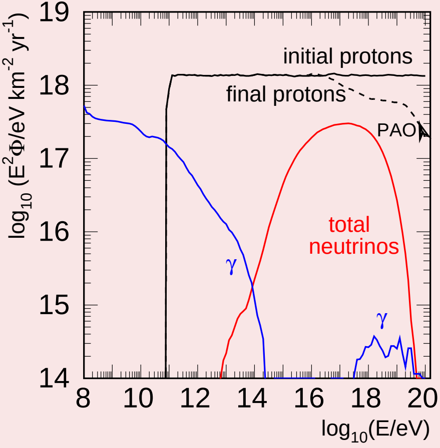

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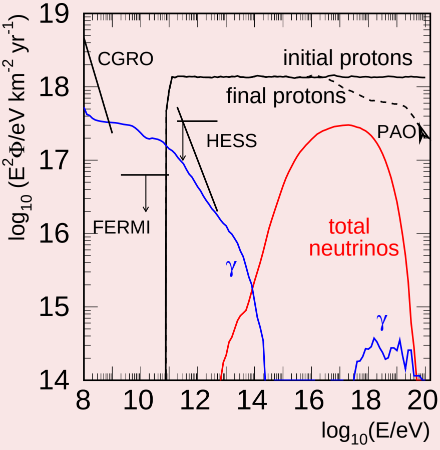
- gamma-ray bump
  $\rightarrow$ cascade down

Ia) power law $\alpha = 2$ (before H.E.S.S.)



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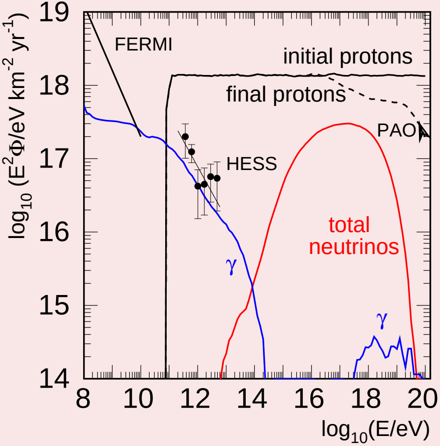

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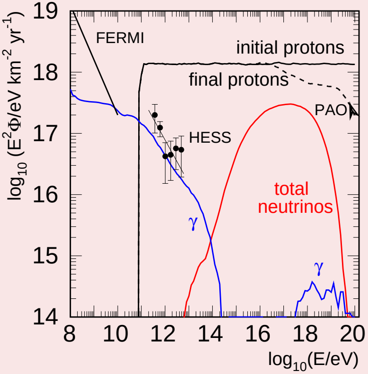
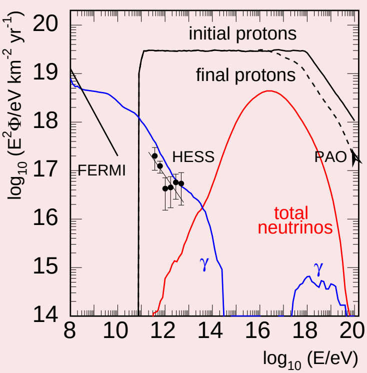


Ib) broken power law

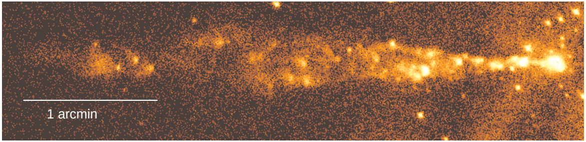


[Kachelrieß, Ostapchenko and R. T., 2008]

PAO correlation and H.E.S.S. observation in agreement

Results: *II) acceleration along the jet*

Chandra observation of X-ray emission [Worrall *et al.*, 2007]



column density $n_{\rm H} \approx 10^{21}$ cm^{-2} and size$\approx$ *kpc* $\Longrightarrow \tau_{pp} \approx 0.01$

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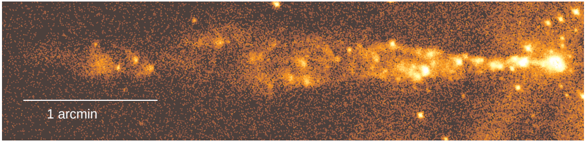

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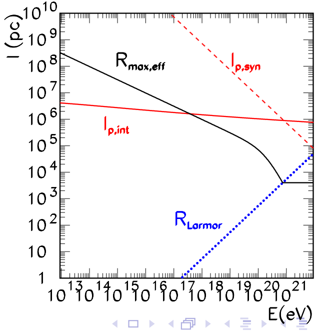
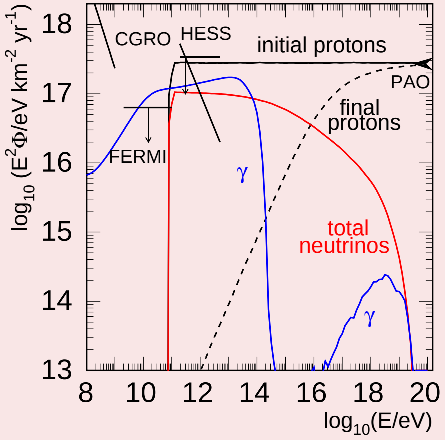
but ...
diffusion at low energies
$\Rightarrow \tau_{pp}^{\rm eff}$ increases



Results: *II) acceleration along the jet*

IIa) power law $\alpha = 2$ (bef. H.E.S.S.)



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

fluxes

- injected *p* spectrum:

$\downarrow$

energy loss: $p + p$

$\rightarrow$ no E_{th} effects

$\rightarrow$ diffusion at low E

$\Downarrow$

- final *p* spectrum
  $\rightarrow$ normalized to PAO
- neutrinos
  $\rightarrow$ escape
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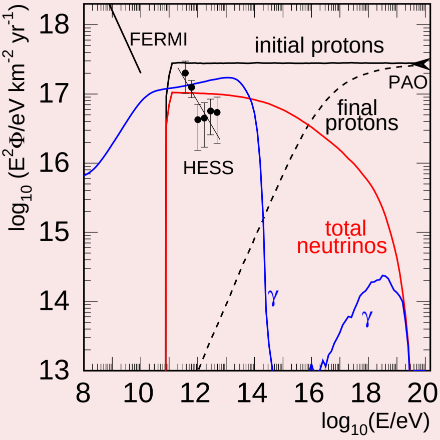

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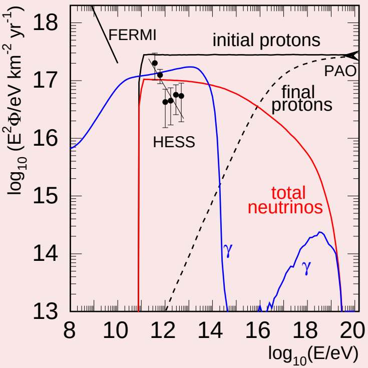

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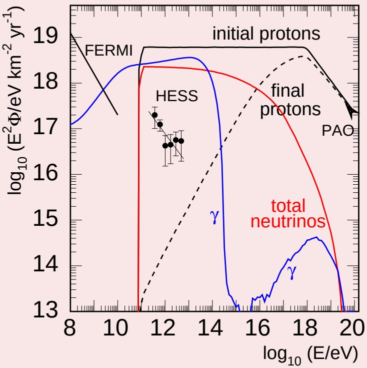

[Kachelrieß, Ostapchenko and R. T., 2008]

H.E.S.S. spectrum disfavours acceleration along the jet

What about neutrinos? Events in km^3 detectors per yr

- *I) acceleration close to the core*

	power law	broken power law	
	$\alpha = 2.0$	$E_b = 10^{18}$ eV	10^{17} eV
cascade	0.01	0.3	0.9
μ track	1×10^{-3}	2×10^{-2}	0.1

- *II) acceleration along the jet*

	power law	broken power law	
	$\alpha = 2.0$	$E_b = 10^{18}$ eV	10^{17} eV
cascade	0.02	0.4	2
μ track	5×10^{-3}	0.1	0.5

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

What about neutrinos? Events in km^3 detectors per yr

- *I) acceleration close to the core*

	power law	broken power law	
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cascade	0.01	0.3	0.9
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	power law	broken power law	
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cascade	0.02	0.4	2
μ track	5×10^{-3}	0.1	0.5

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

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

Summary

High Energy Radiation from Centaurus A

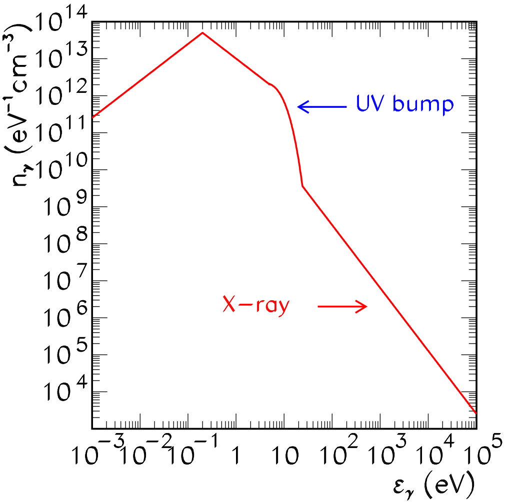
If UHECRs flux normalized to PAO + H.E.S.S. observation

$\Downarrow$

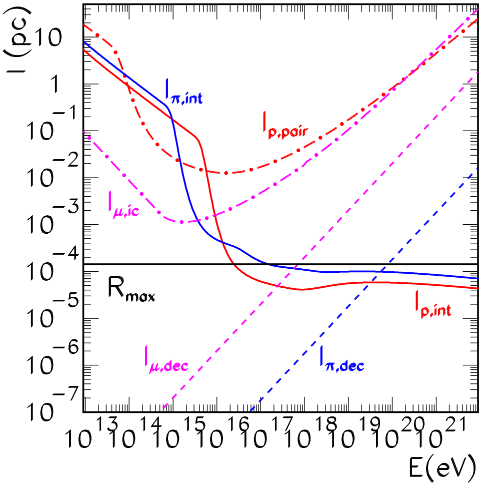
- acceleration close to the core $\rightarrow$ consistent
- slope of H.E.S.S. spectrum $\rightarrow$ disfavours acceleration along the jet
- neutrinos $\rightarrow$ up to $\mathcal{O}(1)$ in northern km^3 ν telescopes

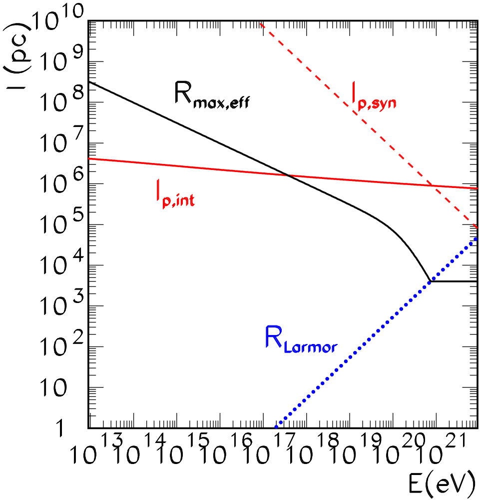
but ...

- 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, ...
- Cen A might not be a UHECRs source



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
l_π,int
l_p,pair
l_μ,ic
R_max
l_p,int
l_μ,dec
l_π,dec
10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21
E(eV)


l (pc)
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21
E(eV)
R_max,eff
l_p,syn
l_p,int
R_Larmor

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see also
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