ULTRA HIGH ENERGY COSMIC RAYS AND NEUTRINOS

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1 Abstract

The origin of ultra high energy cosmic ray particles has been a major riddle in high energy physics for many decades now; these particles clearly come from outside our own Galaxy, and quite likely from some nearby radio galaxies. There are apparent contradictions in the results from different air-shower experiments, both as regards arrival direction statistics and chemical element composition. There is now one proposal to unify these seemingly contradictory results into one scheme: The proposal (Gopal-Krishna et al. 2010) states a) that the nearby radio galaxy Centaurus A is the main source of all ultra high energy events, b) that the particles are a mixture of heavy and light nuclei (Stanev et al. 1993), and c) that the lower Z nuclei are scattered less into isotropy in the magnetic wind of our Galaxy (Everett et al. 2008).

Neutrinos are a very good bet to resolve the issues: In such a proposal those radio galaxies with a starburst accompanying the black hole activity provide heavy nuclei at PeV energies as seed particles, and radio galaxies without any strong star formation should mostly provide protons and Helium nuclei as seeds. For neutrino detection those radio galaxies pointing at Earth will be best, recognized as flat spectrum radio sources. As a consequence any correlations between neutrinos and high energy photons will be different between these two sub-classes of flat spectrum radio galaxies, with and without a starburst; we will discuss the few candidates in the most sensitive band in the sky of IceCube, and will also discuss what we expect to detect from Cen A, a radio galaxy not pointing at us.

Neutrinos signature of hadronic interaction, so UHECR sources

- Particles at very high energy $> 10^{20}$ eV,

- Observed at a very low rate - one particle per century per km^2 - Detectors have $> 3000\,\mathrm{km}^2$

- Far beyond LHC at CERN, even in the center of mass frame

- **Insight from stars and their supernova remnants!**

- **Insight from radio galaxies! Injection from WR star explosions or GRB in starburst?**

A massive star, its wind and its magnetic field

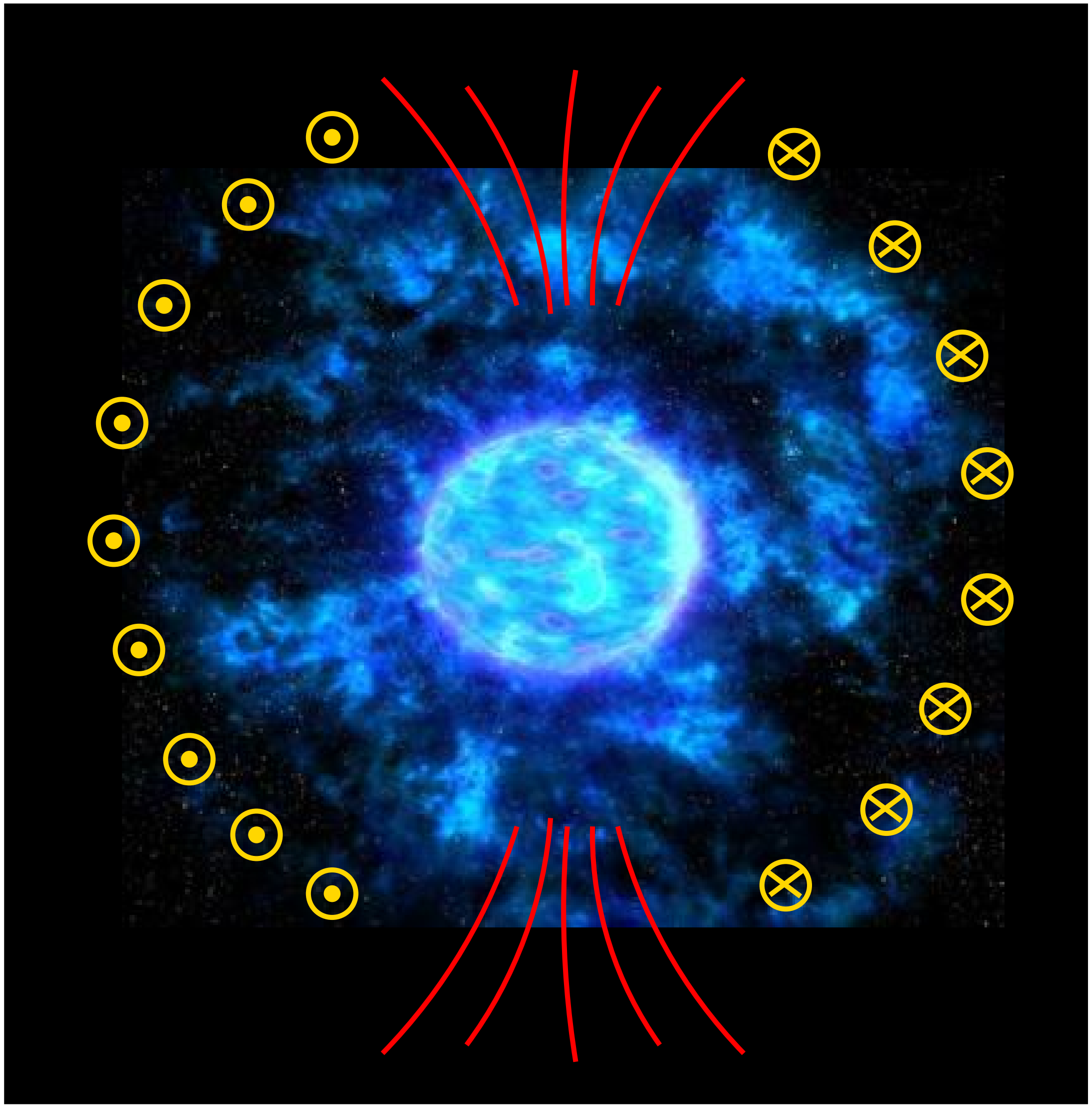


Figure 1 Magnetic field topology around a massive star in its wind: Graph following Parker 1958; central graph NASA, Wolf Rayet star WR124

Cosmic ray knee: paper CR-IV, 1993

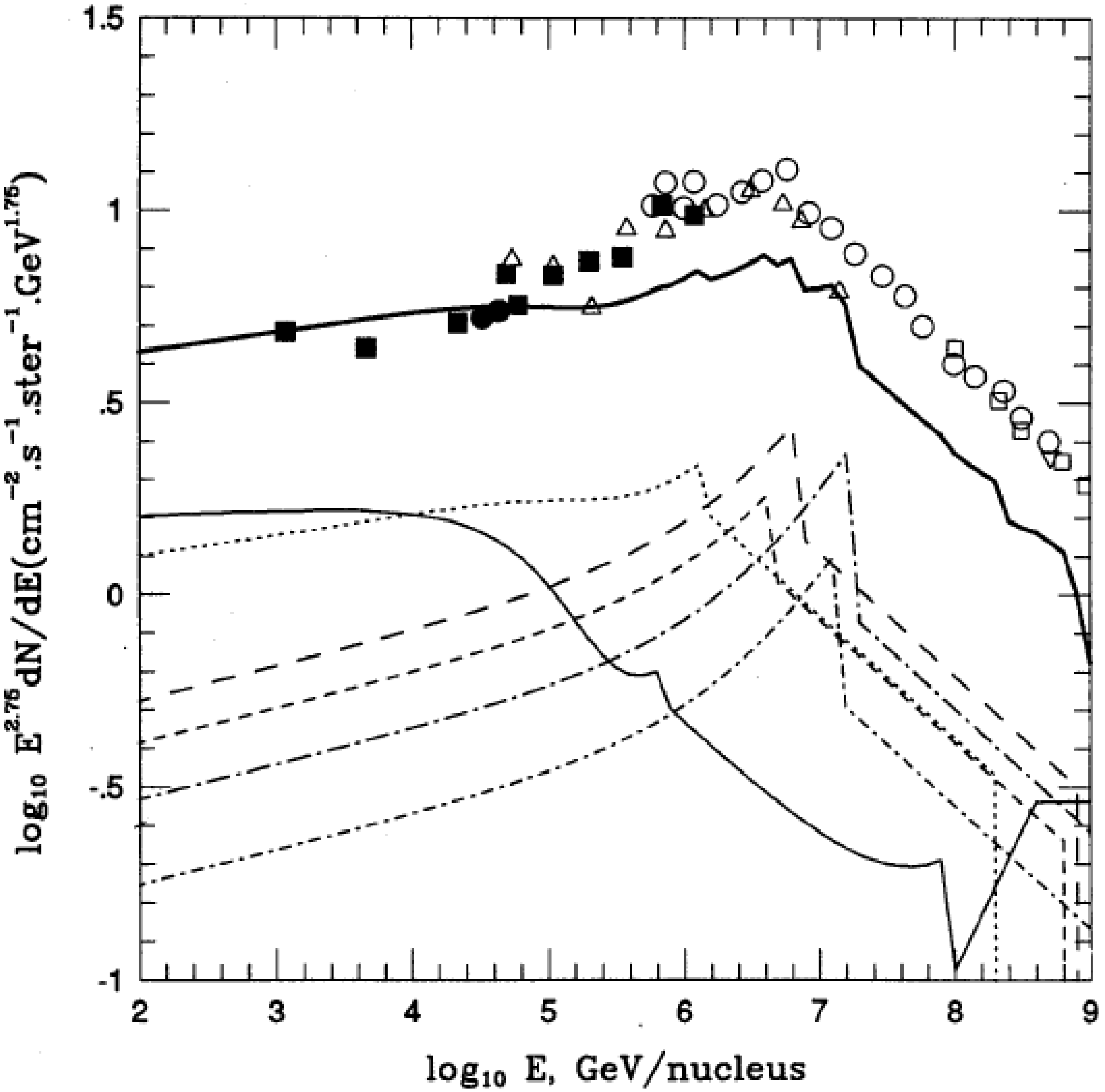
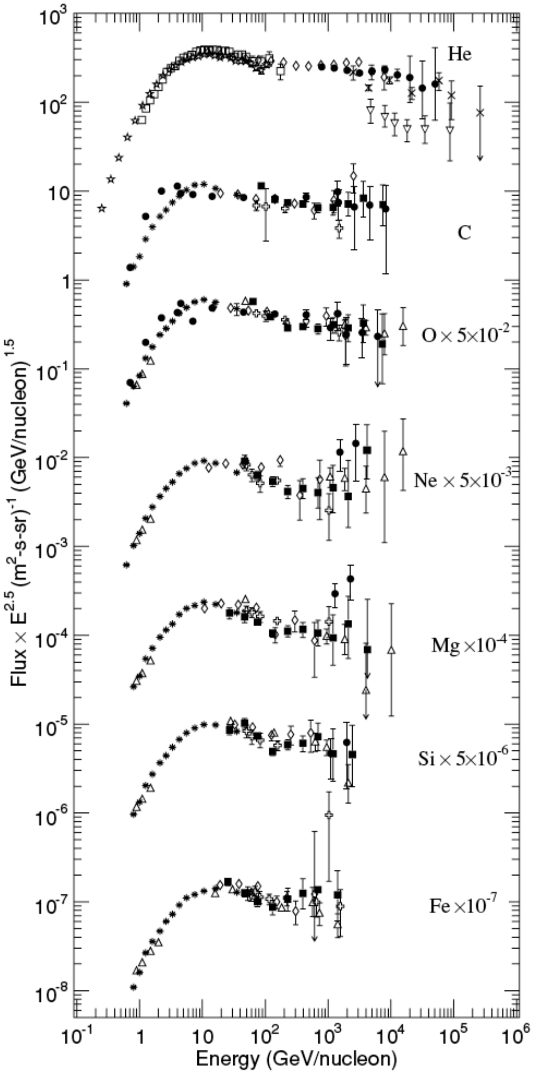


Figure 2 Spectral and chemical structure at the knee, *CR-e^- and CR-e^+ components?*, to be *shifted to high energy* following Gallant & Achterberg (1999) by the head-shock of a relativistic jet? Element groups are H, He, CNO, Ne-S, Cl-Mn, and Fe. All due to structure of magnetic wind of massive stars, obeying Maxwell's laws (Parker 1958). Source: Stanev et al., paper CR-IV 1993

CREAM: CR spectral upturn



'igure 4. Compilation of helium and heavier nuclei data. The CREA

Figure 3 CREAM data showing upturn (Ahn et al. 2010)

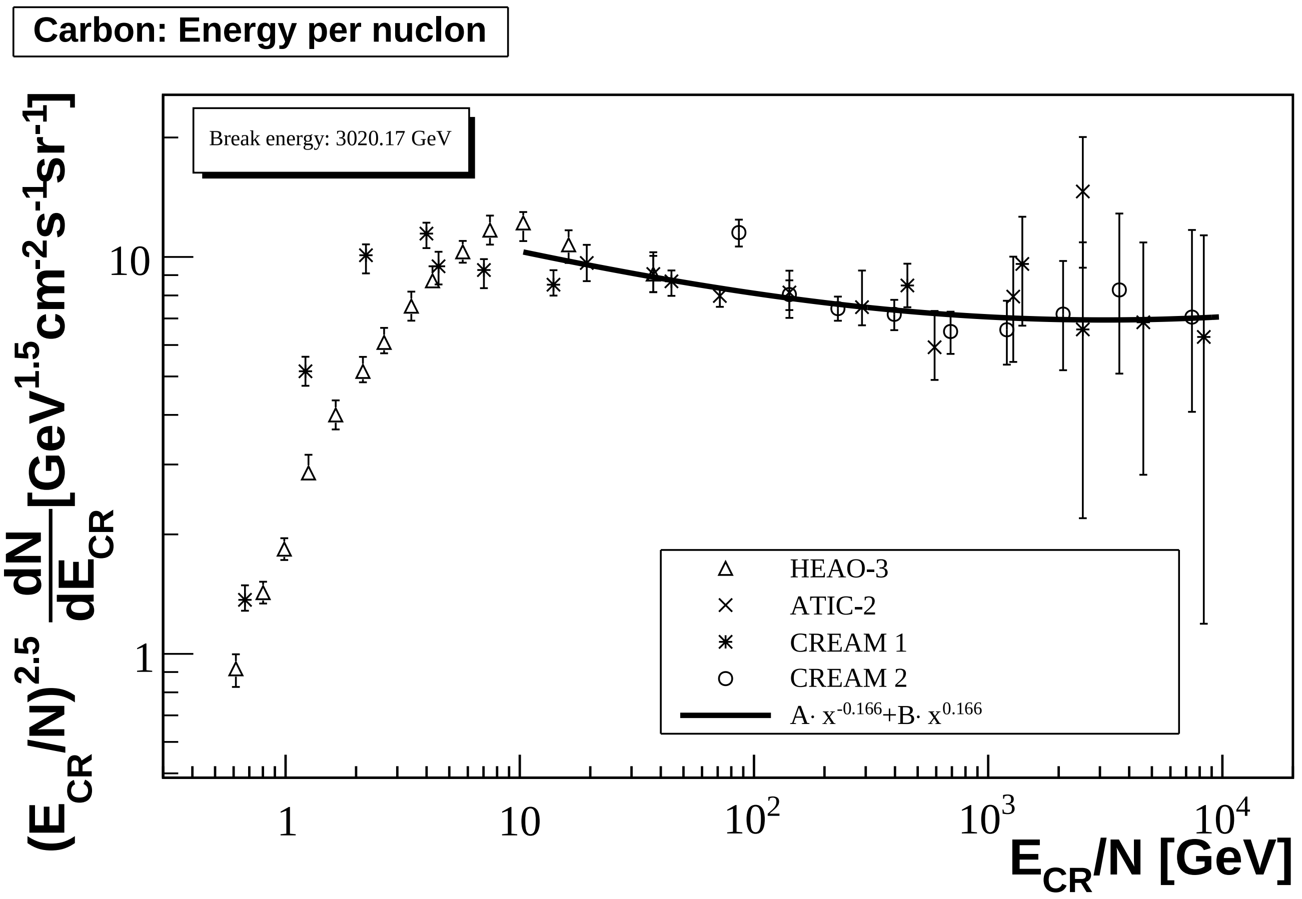


Figure 4 Fit to Carbon data with spectral shape given 1993

Cosmic ray spectra and interactions

No need for DM particle decay: stellar physics!

- Upturn in positron fraction in cosmic rays (Pamela)
- Upturn in electron spectrum in cosmic rays (Fermi, ATIC, H.E.S.S.)
- WMAP haze: Galactic Center region
- Fermi haze: Galactic Center region
- 511 keV emission line: Galactic Center region
- General upturn in all nuclei from Helium (CREAM)
- **All six independent observations quantitatively explained by massive star explosions, all consistent with the model of 1993!**

1993 + 2009/2010 Confirmation!

Cosmic Ray Electrons and Positrons from Supernova Explosions of Massive Stars, Biermann, P. L., Becker, J. K., Meli, A., Rhode, W., Seo, E.-S., & Stanev, T., *Phys. Rev. Letters* **103**, 061101 (2009); arXiv:0903.4048

The WMAP haze from the Galactic Center region due to massive star explosions and a reduced cosmic ray scale height, Biermann, P.L., Becker, J.K., Caceres, G., Meli, A. , Seo, E.-S., & Stanev, T., *Astrophys. J. Letters* **710**, L53 - L57 (2010); arXiv:0910.1197

The origin of cosmic rays: Explosions of massive stars with magnetic winds and their supernova mechanism, Biermann, P.L., Becker, J.K., Dreyer, J., Meli, A., Seo, E.-S., & Stanev, T., *Astrophys. J.* (accepted) 2010

Discovery and Prediction: The GZK-turn-off ?

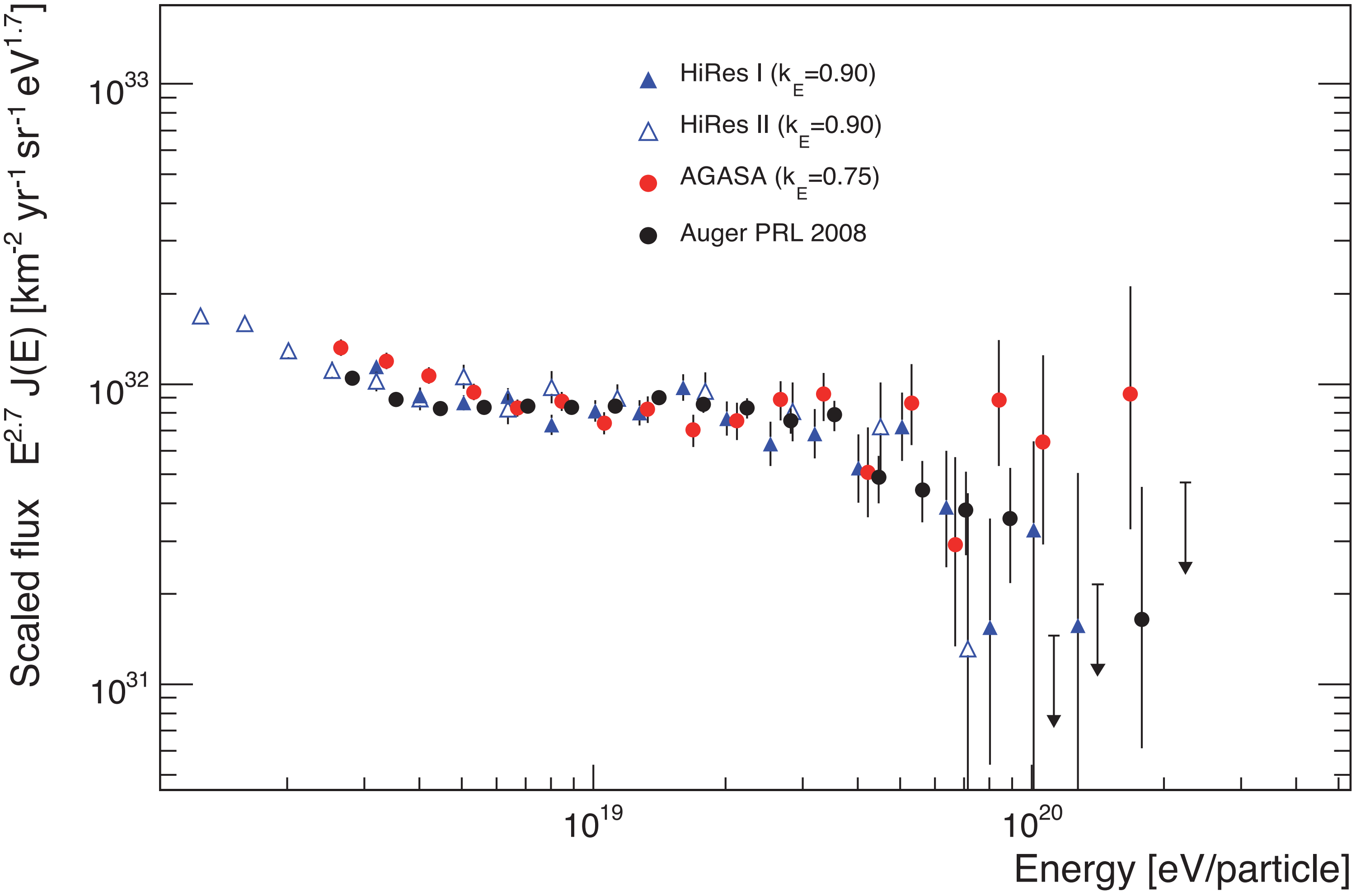


Figure 5 All-particle cosmic ray spectrum from many earlier experiments. Filled circles at the highest energies are recent results from Auger (PRL 2008), clearly showing a cutoff, which may be the Greisen-Zatsepin-Kuzmin cutoff due to the interaction with the cosmic microwave background, if the particles are protons. This is the spectrum to explain, and the strongest radio galaxies can provide an explanation, and source properties give the turn-off. Sources HiRes and Auger Coll. papers 2007 - 2009. Graph produced by M.Roth 2008

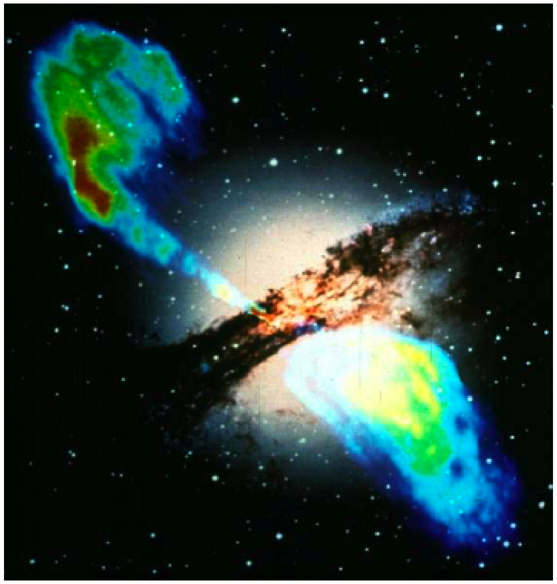
Particle physics to 10^{21} eV

Observe particles at these energies directly! At 10^{12} GeV, $>>$ LHC energies at CERN.

- Linsley (1963): **Detection of first event** $\gtrsim 10^{20}$ eV $= 100$ EeV - uncontainable in magnetic field of Galaxy
- Nearby candidates (Ginzburg & Syrovatskii 1963 *Astron. Zh.*; before discovery of UHECRs): **Radio galaxies** Cen A (= NGC 5128), Vir A (= M87 = NGC 4486), For A (= NGC 1316)
- Prediction (1966) of **GZK-turnoff** near 50 EeV due to proton interaction with the cosmic microwave background (Greisen; Zatsepin & Kuzmin; a.k.a. GZK-cutoff): turn-off established, but physical reason?
- Now many events near and beyond 50 EeV – **anisotropy subtle** (Stanev et al. *Phys. Rev. Letters* 1995)

Radio galaxies: a nearby example

Cen A



Cen A radio galaxy at about 2.5 Mpc.
Combined HST image of the galaxy with
the dust lanes and the VLA (6cm) image
of the jet with radio lobes.

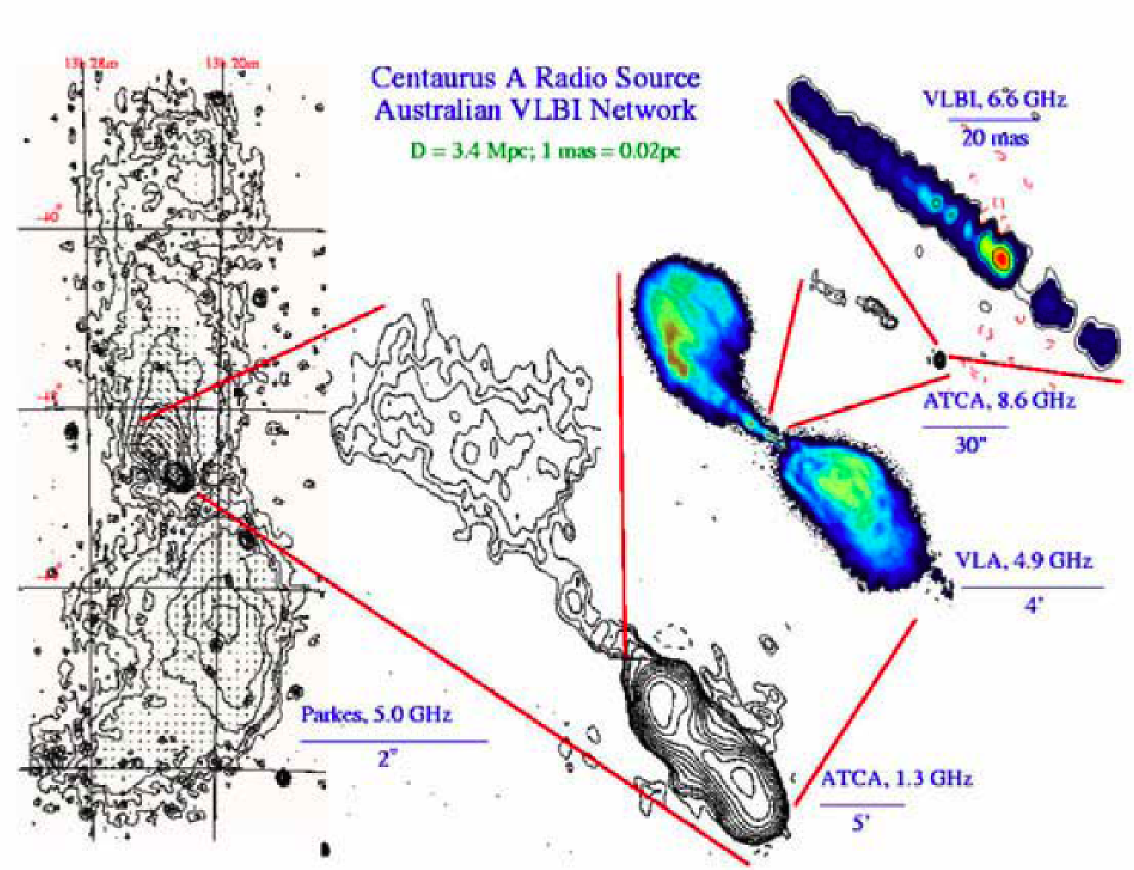


Figure 6 Radio galaxy Cen A - now known to be at 3.8 Mpc - at different scales in radio and optical wavelengths; source lecture S. Britzen

Many potential sources of UHECRs

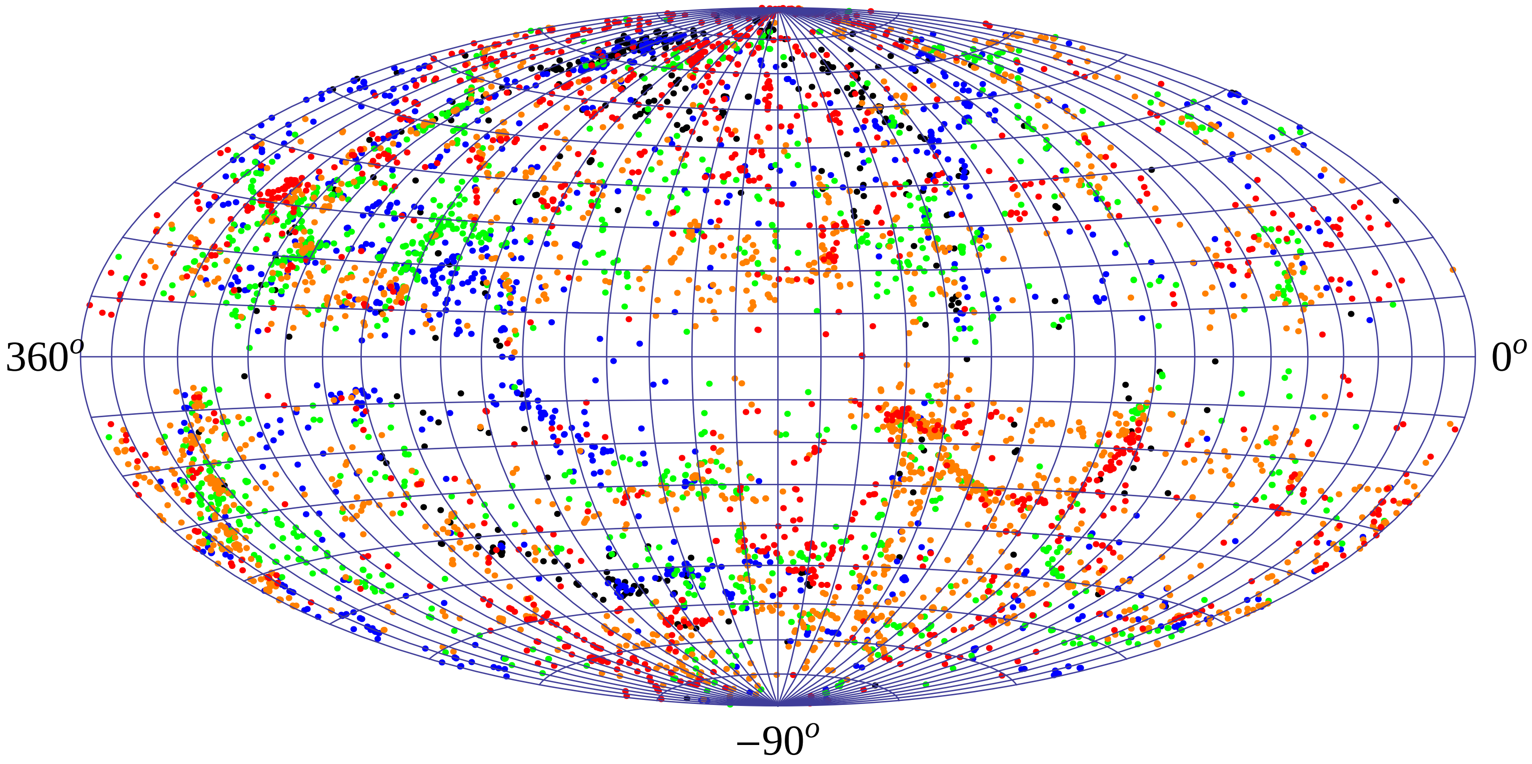


Figure 7 **The sky in black holes**, $\gtrsim 10^7\ M_\odot$: Aitoff projection in galactic coordinates of 5,978 candidate sources in the case of a complete sub sample (the Galactic plane remains obscured). The choice was made from a complete sample of 10,284 candidate brighter than 0.03 Jy at 2 micron, and selected at $z < 0.025$; this uses the 2 micron all sky survey, limited a band in the Galactic plane. Normal and starburst galaxies were counter-selected using color and FIR/radio ratio (Biermann & Fricke 1977, Kronberg et al. 1985, Chini et al. 1989, and other work). These candidate sources are probably all black holes, with masses near to or above 10^7 solar masses; the black hole mass was determined with the black hole versus mass spheroidal stellar population correlation, and tested. The curved feature near NGC315 (Enßlin et al. 2001) - almost a half-circle, with very tight redshift distribution - may be explainable in some models of WDM (Gao & Theuns 2007). The sample is complete to full distance only above $10^8\ M_\odot$. The color code is Black, Blue, Green, Orange, Red corresponding to redshifts betwen 0, 0.005, 0.01, 0.015, 0.02, 0.025: Caramete et al. 2009

The differential black hole mass function: Above $10^8\,M_\odot$ a M_{BH}^{-3} powerlaw

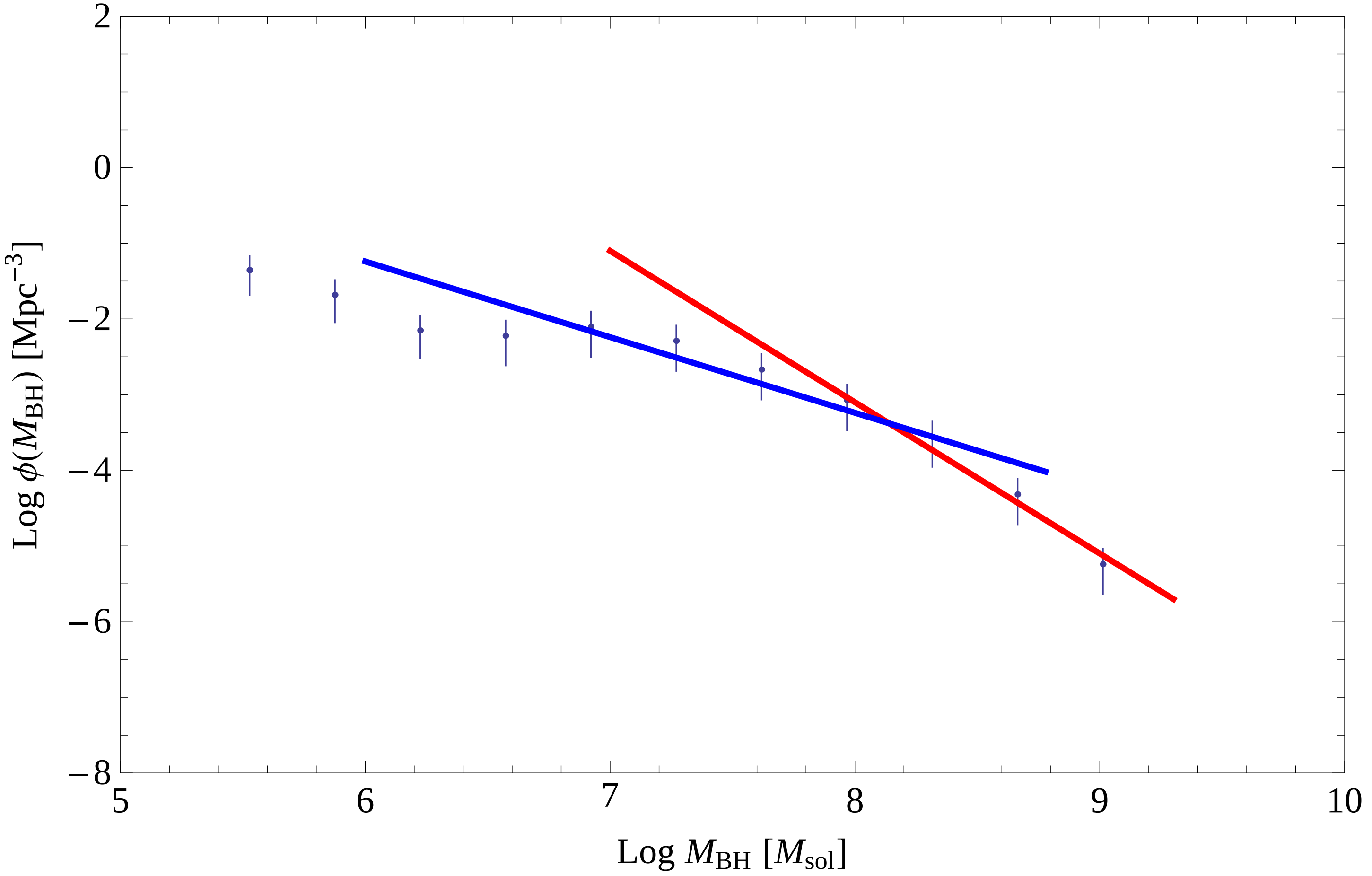


Figure 8 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red −2.0 fitting > $10^8\,M_\odot$, and blue −1.0 fitting between $10^7\,M_\odot$ and $10^8\,M_\odot$. Integrates black hole entropy independent of details; source Caramete & Biermann 2009. This mass function suggests that black holes start near 3 $10^6\,M_\odot$ at very high redshift, of order 50, and grow by merging (see Biermann & Kusenko 2006)

Prediction: Particles in radio galaxies

The Poynting flux limit

- The Poynting flux (Lovelace 1976), lower limit to energy flow, and helical path limit
- If UHECR then UH luminosity in jet $> 10^{47}$ erg/s
- M87 $< 10^{45}$ erg/s, and Cen A $< 10^{43}$ erg/s (Whysong & Antonucci 2003): **Problem** for $Z = 1$.
- Way out: shock in upstream flow γ_{sh} (Gallant & Achterberg 1999)
- $Z >> 1$, $\gamma_{sh} > 1$, and $f_{flar} < 1$ perhaps all required.

Particle energy and particle flux predictions

Complete samples (Caramete et al., 2008).

Spin-down powered jets (Blandford & Znajek 1977, Ensslin et al. 1997):

$$E_{max} \sim D_L \, S_{2.7,tot}^{1/2} \tag{1}$$

$$F_{CR} \sim S_{2.7,tot} \tag{2}$$

Accretion powered jets (Falcke et al. 1995, Taşcău 2003, Taşcău et al. 2008):

$$E_{max}^{\dagger} \sim S_{rad}^{1/3} \, D_L^{2/3} \, M_{BH} \tag{3}$$

$$F_{CR}{}^{\dagger} \sim S_{rad}^{2/3} \, D_L^{-2/3} \tag{4}$$

For distances < 50 Mpc usually NGC5128, possibly NGC1316 and a group around M87 dominate in predicted UHECR flux (Syrovatskii & Ginzburg 1963).

UHECR predictions:

- Using core flux-density at 5 GHz for the complete sample of 29 steep spectrum sources.
- Core flux density estimated from the total flux density by using $\log(P_{core}) = 11.01 + 0.47 \log(P_{tot})$, cf. Giovannini 1988;
- Relative values of the particles maximum energy and UHECR flux by using spin-down (equations above).
- Relative values of the particles maximum energy and UHECR flux by using accretion (O. Taşcău).
- No losses, just spatial limit, flux reduction with distance squared. Energies with an asterisk starburst.

Table 1 Properties of the **complete sample** in passband 6cm (5 GHz), redshift $z \leq 0.025$ flux density brighter than 0.5 Jy, steep spectrum and no dominant starburst, sample of 29 candidate sources

Name	Morphological type	Distance Mpc	M_{BH} $10^8 M_\odot$	S_{core} mJy	B-V mag	FIR/Radio ratio
NGC 5128	S0 pec Sy2	3.4	0.55	8600	0.88	0.313
NGC 4651	SA(rs)c LINER	18.3	0.4	-	0.51	8.229
MESSIER 084	E1;LERG;LINER Sy2	16	15	168.7	0.94	0.174
MESSIER 087	E+0-1 pec;NLRG Sy	16	31	3097.1	0.93	0.005
NGC 1399	cD;E1 pec	15.9	5.1	-	0.95	0.044
NGC 1316	R')SAB(s)0 LINER	22.6	5.1	-	-	0.063
NGC 2663	E	32.5	8.23	-	-	0.084
NGC 4261	E2-3;LINER Sy3	16.5	5.2	-	0.97	0.019
NGC 4696	BCG;E+1 pec LINER	44.4	11.1	-	-	0.076
NGC 3801	S0/a	50	1.95	-	0.9	0.298
IC 5063	SA(s)0+: Sy2	44.9	2.32	-	0.93	11.075
NGC 5090	E2	50.4	8.95	-	11.97	0.099
NGC 5793	Sb: sp Sy2	50.8	0.303	-	0.79	12.756
IC 4296	BCG;E;Radio Galaxy	54.9	2.53	-	0.95	0.079
NGC 0193	SAB(s)0-:	55.5	2	-	0.98	0.76
VV 201	Double galaxy	66.2	1	-	-	0.052
UGC 11294	E0?;HSB	63.6	2.9	-	-	0.326
NGC 1167	SA0-;LINER Sy2	65.2	5.42	5.9	-	0.133
CGCG 114-025	SA0-	67.4	2.19	-	-	0.014
NGC 0383	BCG;SA0-: LERG	65.8	6.67	-	-	0.207
ARP 308	Double galaxy WLRG	69.7	1	89.7	-	0.088
ESO 137- G 006	E1;cD	76.2	15.1	130	10.24	0.021
NGC 7075	E+?	72.7	2.5	-	0.97	0.196
UGC 02783	E?	82.6	4.2	-	0.99	0.924
WEIN 045	E	84.6	4.59	-	-	0.92
UGC 01841	E LERG	84.4	1	-	-	0.035
NGC 3862	E LERG	93.7	6.74	171	0.94	0.106
NGC 1128	E0:	92.2	2	-	1.02	0.056
NGC 5532	FRI	104.8	10.8	-	-	0.022

Table 2 UHECR predictions: $*$ for probable presence of starburst, so feeding from heavy nuclei possible, allowing higher energies per particle by an order of magnitude: Ranking Cen A (= NGC5128), Vir A (= M87 = NGC4486), and For A (= NGC1316): this triplet set was predicted by Ginzburg & Syrovatski 1963

Name (1)	$S_{5GHz}^{extended}$ mJy (2)	$E_{max}^{\Downarrow}/E_{max}^{M87}$ spin down (3)($\alpha = 1$)	$E_{max}^{\Downarrow *}/E_{max}^{M87}$ spin down (4)($\alpha = 0.7$)	E_{max}/E_{max}^{M87} acc. dom. (5)	$F_{max}^{\Downarrow}/F_{max}^{M87}$ spin down (6)($\alpha = 1$)	F_{max}/F_{max}^{M87} acc. dom. (7)
NGC 5128	681000	0.638	0.730	0.013	8.917	12.029
NGC 4651	700	0.110*	0.213	0.003	0.009	0.040
MESSIER 084	2880	0.194	0.318	0.162	0.038	0.112
MESSIER 087	76370	1.000	1.000	1.000	1.000	1.000
NGC 1399	720	0.101	0.201	0.036	0.009	0.043
NGC 1316	49000	0.806	0.860	0.142	0.642	0.741
NGC 2663	950	0.227	0.354	0.099	0.012	0.033
NGC 4261	8320	0.606	0.705	0.120	0.109	0.152
NGC 4696	1320	0.320	0.450	0.167	0.017	0.037
NGC 3801	570	0.270*	0.400	0.026	0.007	0.018
IC 5063	530	0.234*	0.362	0.028	0.007	0.018
NGC 5090	1710	0.397	0.523	0.156	0.022	0.041
NGC 5793	508	0.259*	0.388	0.004	0.007	0.016
IC 4296	1780	0.524	0.636	0.053	0.023	0.036
NGC 0193	650	0.320	0.450	0.030	0.009	0.018
VV 201	2880	0.803	0.858	0.028	0.038	0.044
UGC 11294	690	0.378*	0.506	0.049	0.009	0.017
NGC 1167	901	0.443	0.565	0.102	0.012	0.020
CGCG 114-025	2580	0.774	0.836	0.060	0.034	0.040
NGC 0383	2100	0.682	0.765	0.167	0.027	0.035
ARP 308	1870	0.682	0.765	0.025	0.024	0.032
ESO 137- G 006	7250	1.467	1.308	0.629	0.095	0.074
NGC 7075	510	0.371	0.500	0.042	0.007	0.013
UGC 02783	541	0.435*	0.558	0.078	0.007	0.012
WEIN 045	2160	0.889*	0.921	0.137	0.028	0.031
UGC 01841	3720	1.164	1.112	0.036	0.049	0.044
NGC 3862	1990	0.945	0.961	0.209	0.026	0.027
NGC 1128	2340	1.009	1.006	0.065	0.031	0.030
NGC 5532	1698	0.977	0.984	0.343	0.022	0.023

Gamma ray bursts? Starburst galaxies, selected at 60 μ

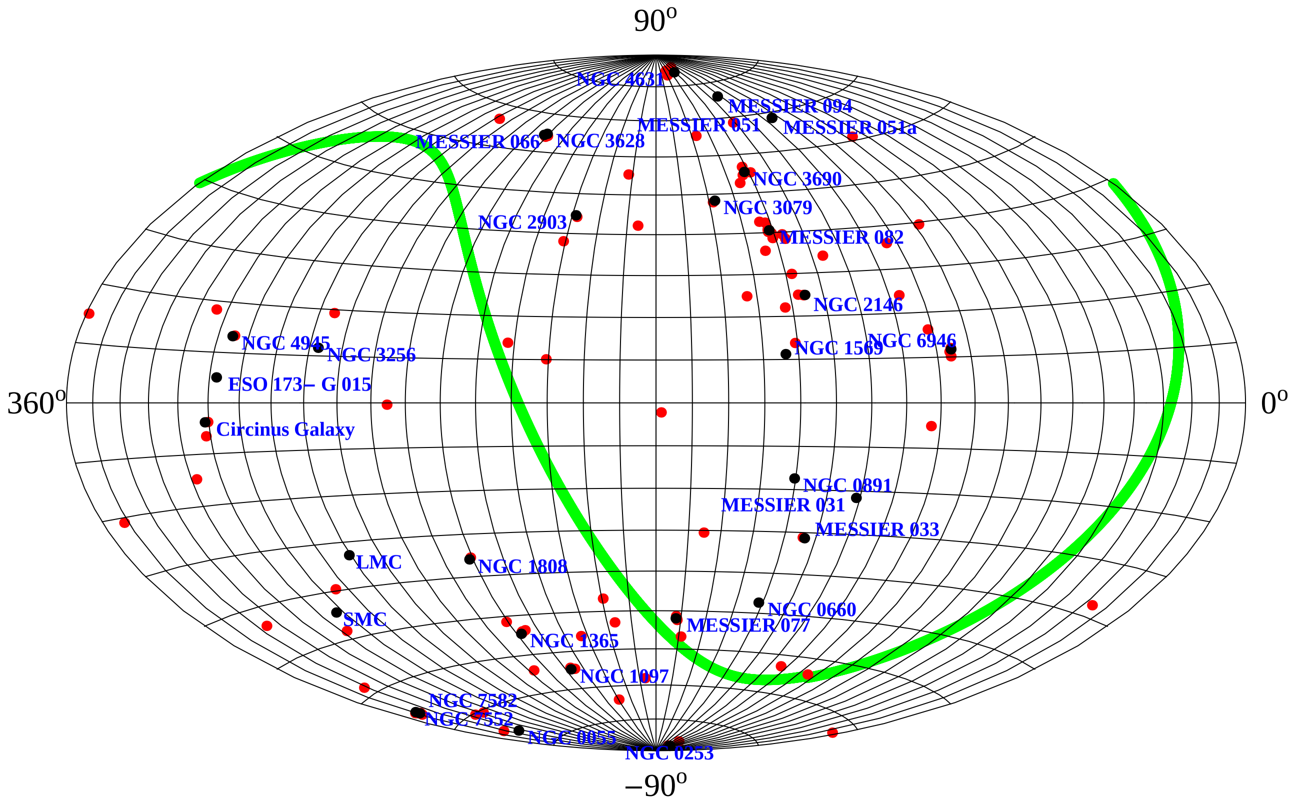


Figure 9 Alternative: Aitoff projection in galactic coordinates of the selection from NED in 60μm, redshift $z \leq 0.0125$, flux density brighter than 50 Jy, starburst selected, sample of 32 candidate sources and 100 virtual events from this sources and weighted contribution. Double Monte-Carlo to simulate the intermittent nature of gamma ray bursts. Source Caramete et al. 2009

UHECR abundances?

- Episode: Merger, starburst, spinflip, bare AGN, decay
- Acceleration to high energy: from sea of galactic CRs, **injection from PeV** (Gallant & Achterberg 1999, Meli & Quenby 2003, Meli et al. 2008)?
- Energies jump in one step by Γ_{sh}^2, and so the spectral pattern at the knee will be repeated at high energy. **Sequence in edges He, CNO,** suggest $\Gamma_{sh} \simeq 50$.
- **Polar cap (confirmed!)** sharpens the edges ?
- If injection from **gamma ray bursts** (Rachen & Mészáros 1998), then maximal energy in neutrons (No Helium), so pure protons predicted! Heavy nuclei ?
- Later in life injection from **intergalactic medium**, diluted cosmic abundances. Abundances and spectra different for M87 (North) and Cen A (South)!

Massive star explosions injection for UHECR spectra!

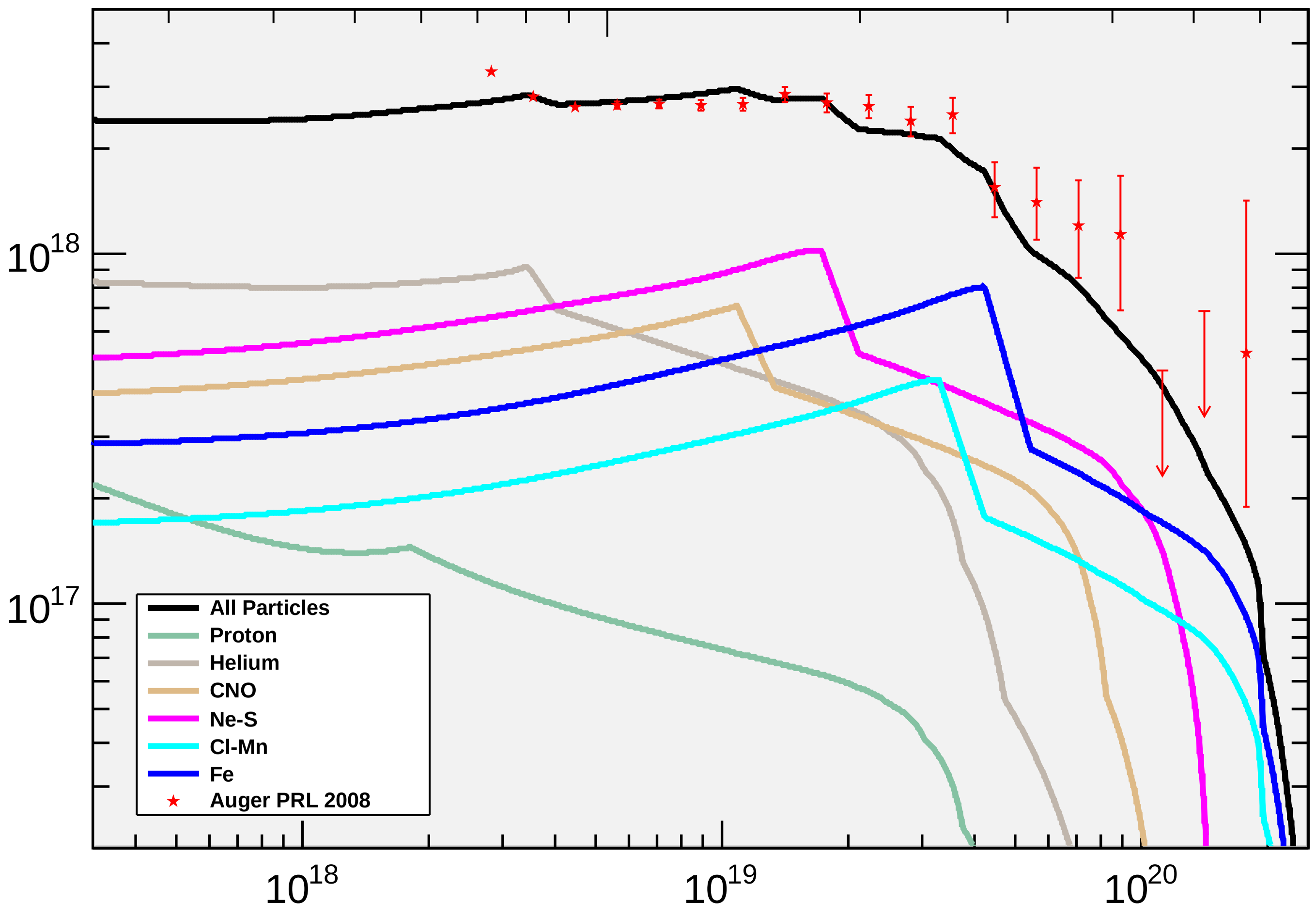


Figure 10 Testing the shift of the spectrum in paper CR-IV matching the propagation calculations of Allard et al. 2008: Note, that the turn-off here near 40 EeV for Fe is due to the MHD structure of massive star winds, *pushed to EeV energies* by a highly relativistic shock; the turnoff seen at high energy near 150 EeV for Fe is due interactions on the way from Cen A to us; the final scattering and isotropization is in the magnetic wind of our Galaxy (Everett et al. 2008; Gopal-Krishna et al. 2010). One may wonder whether GRBs could have the same effect (Calvez, Kusenko & Nagataki 2010; Biermann et al. 2004)

Cen A

- All known can be explained with Cen A, one radio galaxy with a starburst
- Spectral energy distribution for the various elements from CR knee of starburst
- Kicked up by a relativistic shock in one step
- Straight line path: Requires IGM with very inhomogeneous magnetic field distribution (Das et al. 2008, Ryu et al. 2008)
- Requires full sky scattering in Galactic wind (Everett et al. 2008)
- Scattering limited for very light elements
- Shift of central event cloud in sky
- May resolve the conflict between HiRes and Auger: Both may be right

Neutrinos

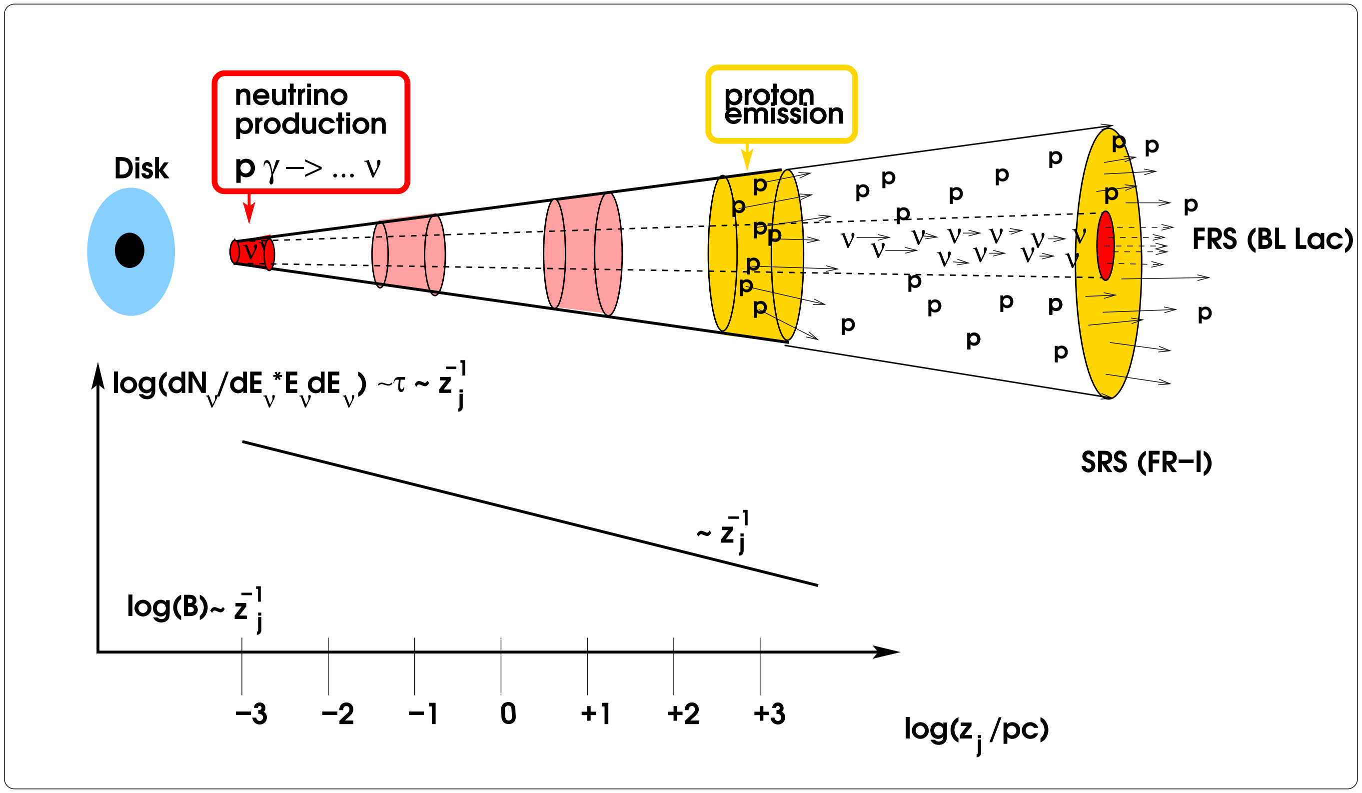


Figure 11 How we picture the basic structure of a relativistic jet, with a first and a last strong shock: Becker & Biermann 2009

Blazar emission I

- Assume: all blazars in spin-down limit (Blandford & Znajek 1977)
- Assume: shocks highly oblique, concept of first and last strong shock (Markoff et al.)
- Assume: flow perpendicular to shock slow enough to attain Kolmogorov spectrum of scattering (Kolmogorov 1941, Matthaeus et al.)
- Hadronic and lepton synchrotron emission (e.g. Biermann & Strittmatter 1987), pion decay, IC and secondary lepton emission,

Blazar emission II

- Calculate synchrotron emission from first strong shock:
- $\nu_{p,max} \sim \nu_{e,max} \sim M_{BH}^{-1/2}$
- $L_{p,syn} \sim L_{e,syn} \sim M_{BH}$
- $\nu_{p,max} = (m_p/m_e)^3 \, \nu_{e,max}$
- $\tau_{p,max} = (m_p/m_e) \, \tau_{e,max}$: this implies that the electron emission is in the loss limit, so steeper by unity (Kardashev 1962)
- νS_ν then $\sim \nu^{+1/2}$ for protons, and $\sim \nu^0$ for electrons and positrons, both secondary and primary (within Thomson limit).

Blazar emission III

- In KN limit νS_ν then $\sim \nu^{-2}$ implying that this component is nearly invisible in competition.
- It follows that any visible emission up to 10 TeV with νS_ν with $\sim \ \nu^0$ requires the Thomson limit,
- so that $\gamma_e \ \ >> \ \ 10^7$, so larger than possible for the primary electrons in this model: hence electrons producing IC emission $\gtrsim$ 10 TeV must be secondary
- $L_{p,syn}/L_{e,syn} \gtrsim 1$, explaining orphan flaring
- The other emission components all scale differently, some have the same scaling with BH mass.

Blazar emission IV

- This may contribute to explain the blazar sequence (Ghisellini et al. 1998 to 2010, Cavaliere et al. 2002).
- The observed TeV spectra range in νS_{ν} (equivalent to $E^2 N(E)$) range between 0. and +0.5 in deduced spectral index. For emission to 10 TeV and beyond in source both spectra suggest protons.
- Since blazars are low power radio galaxies, just pointed at us, supporting the view that radio galaxies in general are sources of UHECRs.
- Neutrinos should then scale with the proton synchrotron emission as well as the secondary π^0 decay photon emission, and with the $\pi^{\pm}$ decay lepton emission.

Blazar emission V

- Injection from WR star explosions or GRBs possible at the first strong shock, a small distance from the BH? Seems dubious. First shock protons and neutrinos.
- Injection from WR star explosions or GRBs quite plausible far from the BH, in last strong shock. Last shock observed UHECRs.
- The majority of radio galaxies have no starburst, as Cen A does have. M87 therefore can inject only from its ISM, so mostly protons and some Helium.
- Cen A itself has a jet pointing far away from the line of sight to us, and so from there we only see the neutrinos from UHE protons or nuclei, that have been scattered around to point at us in interaction (giant radio lobes?).

Table 3 Properties of the top 25 flat and inverted radio spectrum sources of a **complete sample** highest in flux density at 2.7 GHz. Sources above - 10 degrees of the celestial equator are marked; if we furthermore select by flaring and strength, and location in sensitive part of sky, 3C279 and 3C54.3 look like excellent candidates to be one of the first seen in UHE neutrinos.

Name	Redshift	Flux density Jy	Type	l Deg	b Deg
3C 273 = 1226+02	0.158	38.9 *	blazar; Sy1 LPQ	289.79	64.01
ESO 362- G 021= 0521-36	0.061042	12.5	N galaxy;HPQ BLLAC	240.01	-32.65
3C 279 = 1253-05	0.5362	11.2 *	blazar;HPQ BLLAC	304.86	57.59
3C 454.3 = 2251+15	0.859	10 *	blazar HPQ	85.36	-38.85
NGC 1275 = 0316+41	5264	9.64 *	cD;pec;NLRG	150.68	-13.59
2134+004	1.932	7.6 *	Opt.var. LPQ	54.98	-35.83
2MFGC 06756 = 0831+55	0.24117	7.54 *	Radio galaxy Sy3	163.15	36.60
1127-145	1.184	6.5	blazar LPQ	274.77	44.07
0438-436	2.863	6.2	HPQ	247.54	-41.69
3C 345 = 1641+39	0.5928	6.08 *	Opt.var. HPQ	62.26	40.94
BL Lac = 2200+42	0.0686	5.21 *	Opt.var. BLLAC	92.47	-10.40
2203-188	0.6185	5.2	blazar LPQ	37.85	-50.77
0923+392	0.69528	4.6 *	Opt.var.;Sy1 LPQ	184.08	45.98
0637-752	0.653	4.51	FSRQ Sy1	286.11	-27.16
3C 446 = 2223-05	1.404	4.4 *	Opt.var.;HPQ BLLAC	59.17	-48.68
0834-201	2.752	4.15	blazar LPQ	243.42	12.22
2345-167	0.6	4.08	Opt.var.;BLLAC HPQ	67.27	-71.30
PKS 1549-79	0.1501	4.02	Sy2	311.22	-19.39
ABELL S0463 = 0428-53	0.0394	3.84	I-II [BM];R: [A]	261.18	-42.52
0537-441	0.894	3.84	blazar;HPQ BLLAC	249.94	-31.13
4C +12.50 = 1345+12	0.12174	3.8 *	S0;Double nuc. Sy2	346.18	69.77
PKS 0742+10	2.624	3.74 *		210.00	16.28
0440-003	0.844	3.73 *	Opt.var.;HPQ blazar	196.81	-28.28
0208-512	0.999	3.56	blazar;HPQ BLLAC	276.00	-62.07
OJ +287 = 0851+20	0.306	3.42 *	Opt.var. BLLAC	207.07	35.51

Are TeV blazars UHECR sources?

Model: spin-down, first and last shock, use first

Prediction 1: Leptons in loss limit

Prediction 2: $L_{p,syn}/L_{e,syn} \gtrsim 1$

Prediction 3: $L_{p,syn} \sim L_{e,syn} \sim M_{BH}$

Prediction 4: $\nu_{p,syn} \sim \nu_{e,syn} \sim M_{BH}^{-1/2}$

Prediction 5: $\nu_{p,syn}/\nu_{e,syn} = (m_p/m_e)^3$

Prediction 6: For $>$ *10 TeV Thomson limit,* $\nu\, S_\nu$ *spectrum* $\gtrsim 0$*, secondary leptons*

Prediction 7: Neutrinos correlate with proton synchrotron emission, with secondary π^0 *decay photon emission, with the* $\pi^\pm$ *decay lepton emission*

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