The nature and origin of ultra-high energy cosmic ray particles **Peter L. Biermann**[1,2,3,4]

Special Thank You: 2011 participation fully booked, wedge tornado: impossible to come

May 25, 2016; lecture at Vulcano

[1] MPI for Radioastr., Bonn, Germany; [2] Dept. of Phys., Karlsruhe Inst. for Tech. KIT; [3] Dept. of Ph. & A., U. Alabama, Tuscaloosa, AL, USA; [4] Dept. of Phys. & Astron., U. Bonn; with Biman B. Nath (RRI Bangalore), Laurenţiu I. Caramete (ISS Bucharest, MPIfR Bonn), Laszlo Gergely (U. Szeged), Benjamin C. Harms (U. Alabama), Emma Kun (U. Szeged), Athina Meli (U. Gent), Felix Mirabel (Buenos Aires, Paris), Eun-Suk Seo (U. Maryland), Vitor de Souza (San Carlos), Todor Stanev (Bartol, Delaware), & Julia Becker Tjus (U. Bochum)

Challenges in High Energy Events

- **1 Ultra-high energy CR particles (UHECRs)**
- **2 UHECRs: Composition and directionality**
- **3 UHECRs: p & He vs C, O, ..., background**
- **4 TeV photon variability**
- **5 High energy neutrinos**
- **6 Gravitational waves (GWs)**
- **7 Common concept of origin ?**
- **8 Super-massive binary black hole mergers**

The overall spectrum of cosmic rays

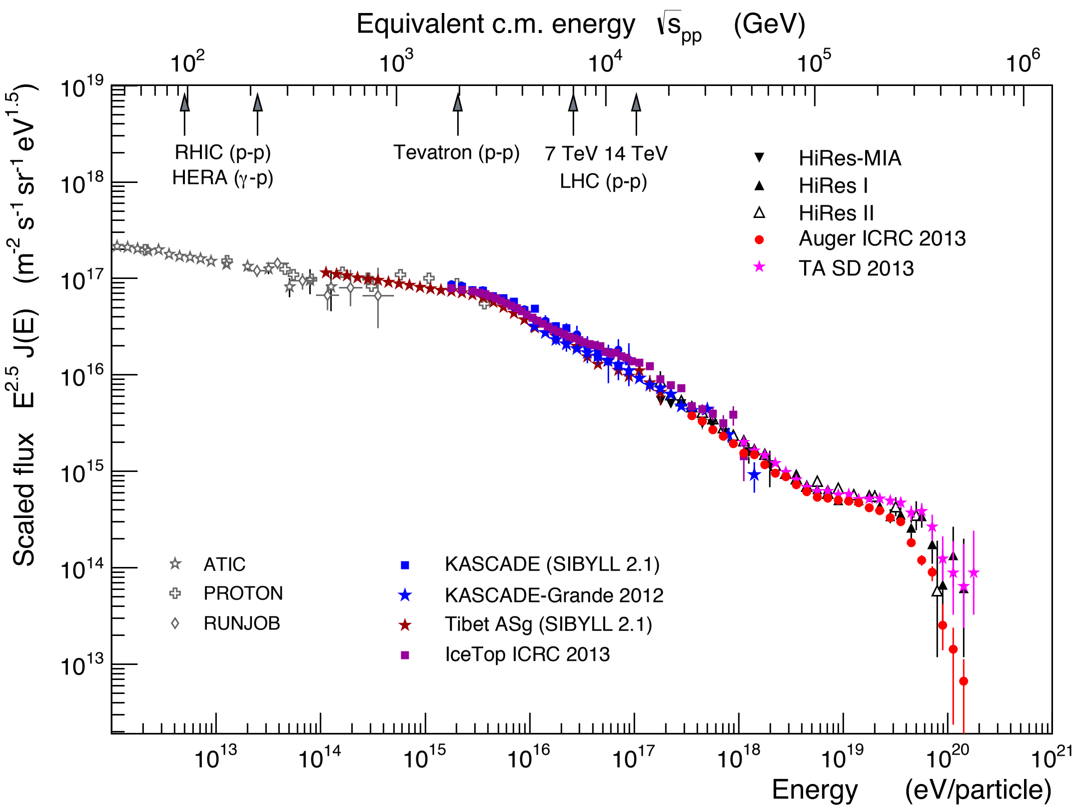


Figure 1 The overall spectrum of cosmic rays. Source Ralph Engel 2016.

The overall spectrum of cosmic rays: model

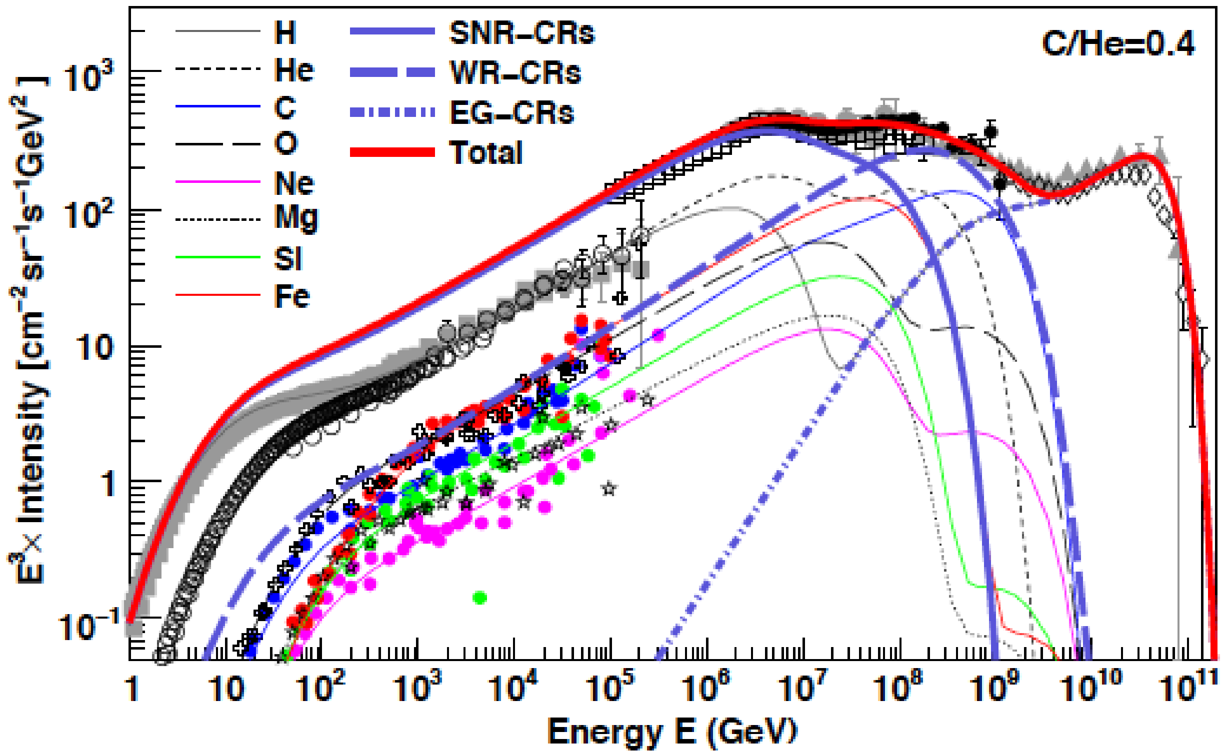


Figure 2 A simple model for overall cosmic rays: **Remember the radio-SN data of SN explosions into winds:** $E_{Bohm} = 10^{15.3\pm0.3}\, Z$ **eV; and** $E_{Jokipii} = 10^{17.3\pm0.2}\, Z$ **eV**. Source Thoudam et al. 1605.03111.

Distribution of arrival directions: all sky

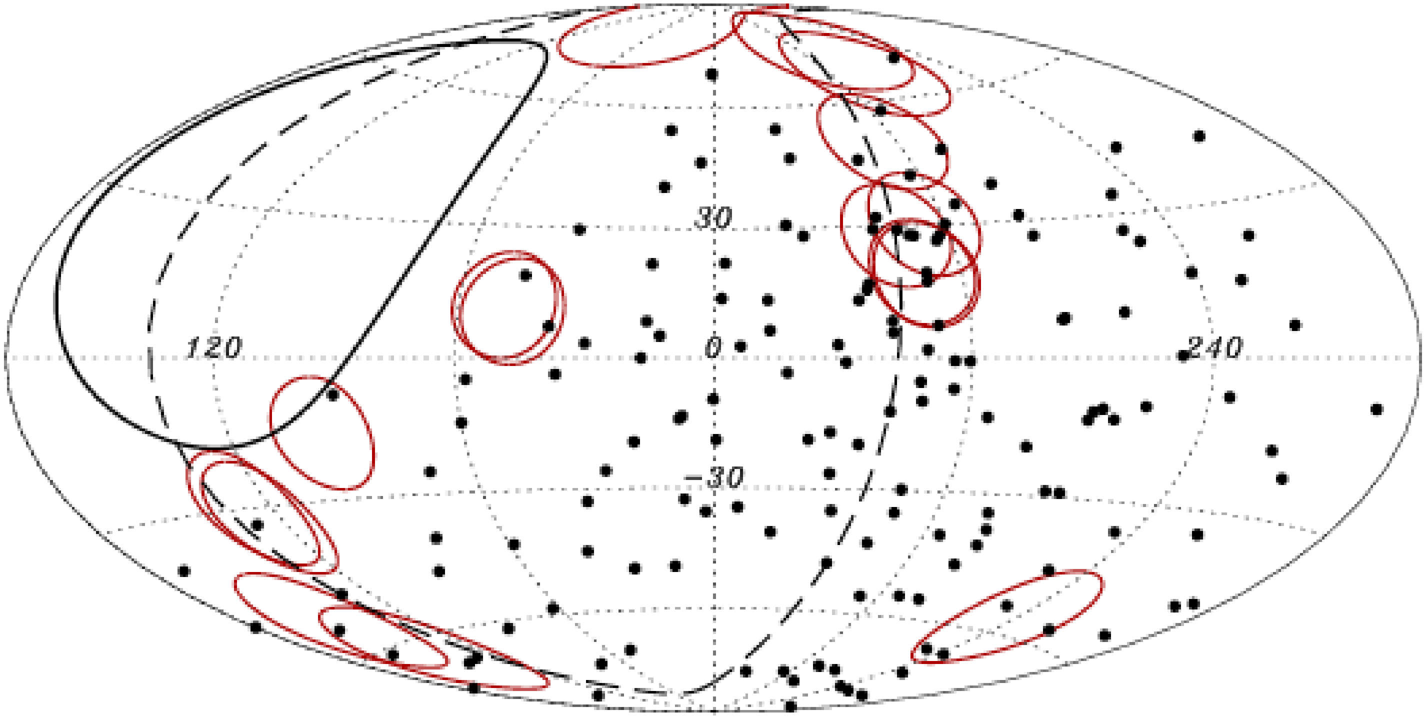


Figure 3 The arrival directions of UHECR events (Auger) with energy above 58 EeV in Galactic coordinates; the super-galactic plane is the dashed line. Nearby bright radio galaxies marked in red circles with radius 12 degrees. Source Auger-Coll. 2015 ApJ 804, 15, Fig. 9.

Distribution of arrival directions: Cen A

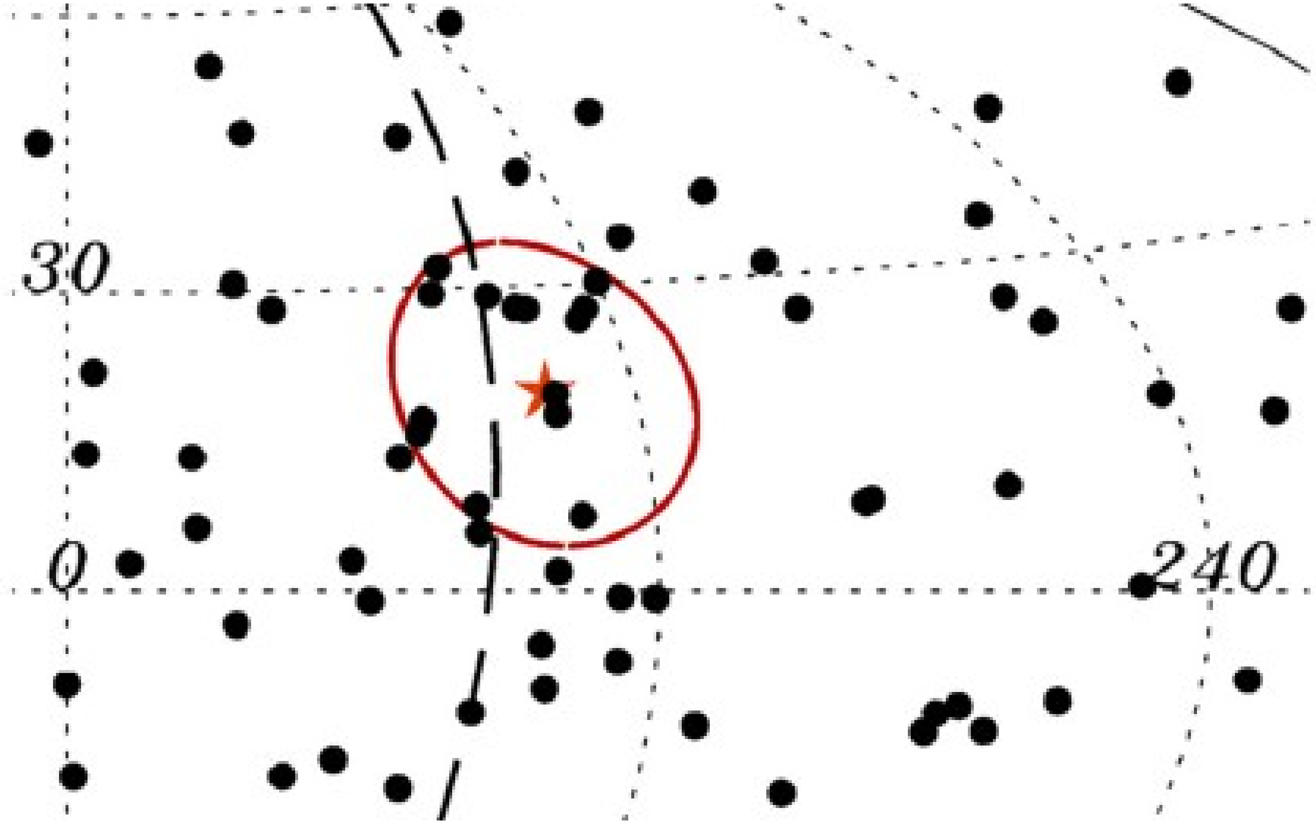


Figure 4 The arrival directions of UHECRs (Auger), only events above 58 EeV, focussed on the radio galaxy Cen A, with circle of 15 degrees radius. Source Auger-Coll. 2015 ApJ 804, 15, Fig. 10.

Cosmic rays 10^{17} eV to $3 \cdot 10^{17}$ eV: LOFAR

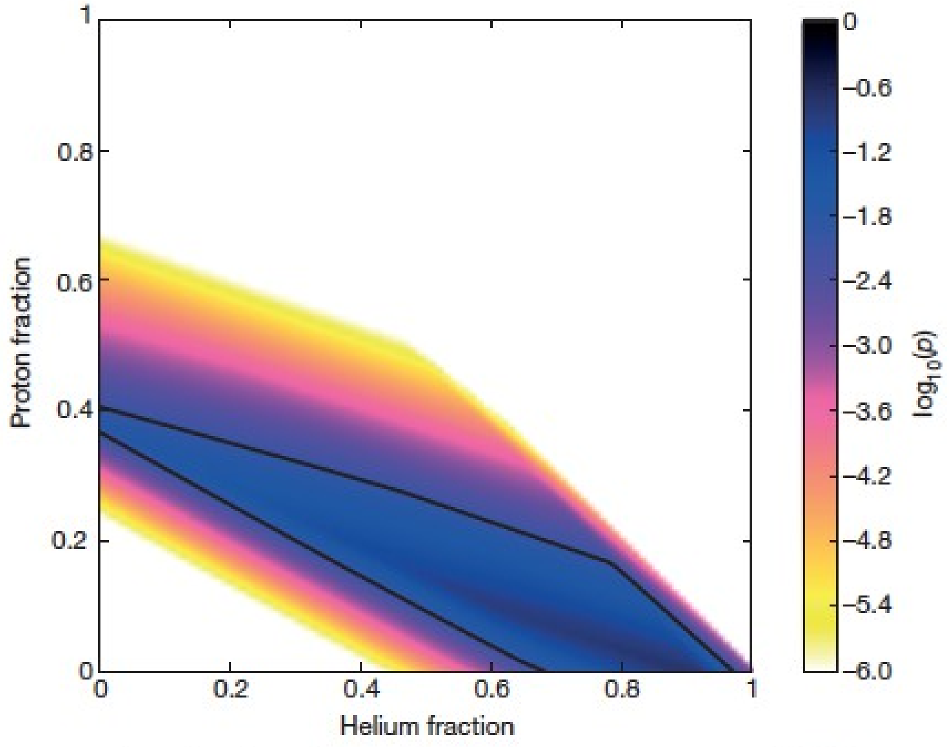


Figure 5 Cosmic rays 10^{17} eV to $3 \cdot 10^{17}$ eV as seen with LOFAR: "The black contour line bounds all regions with $p > 0.01$. At this significance level the **total fraction of H and He combined lies between 0.38 and 0.98**." Source Buitink et al. 2016 Nature 531, 70 (LOFAR).

Kaskade Grande

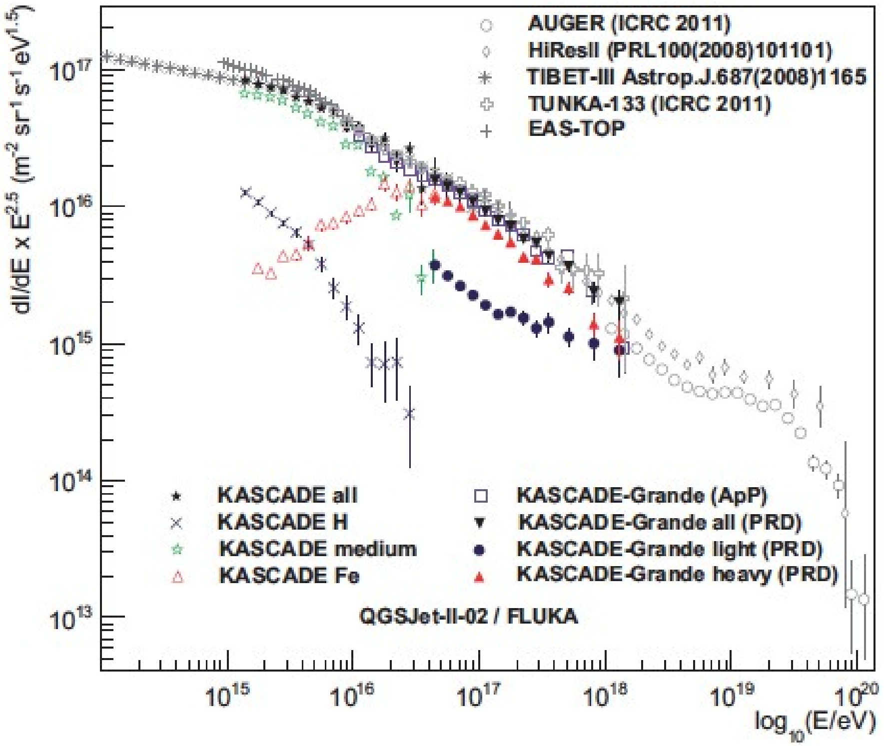
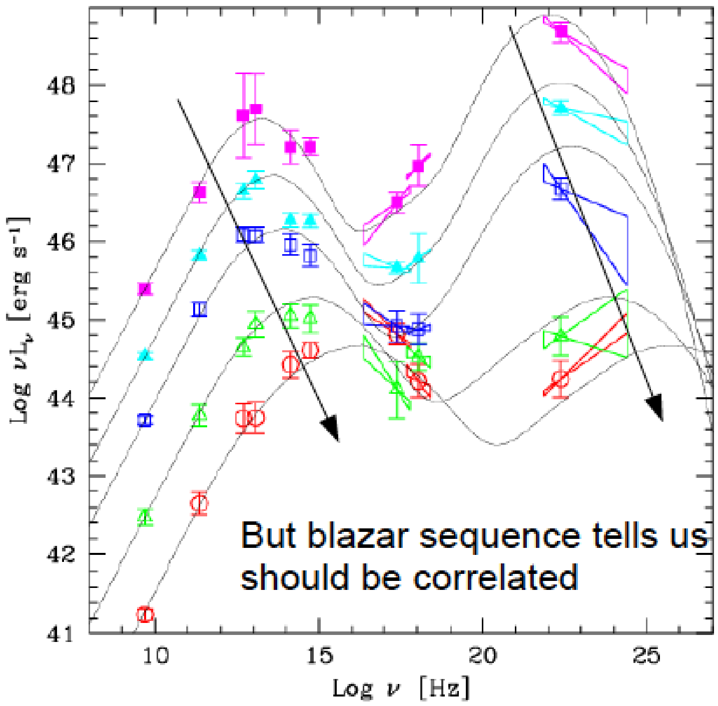


Figure 6 Cosmic ray spectra in different elements: **from how far and from what epoch do these predicted low energy UHECR protons come from?** Source Arteaga-Velázquez et al. 2016 J.Ph.C.S. 651, 012001.

Double-bump spectra of blazars



But blazar sequence tells us should be correlated

Figure 7 The double-bump spectra of blazars. Source Lenain, lecture Heidelberg 2009.

Cut-off spectrum of 3C33 south −> UHECR

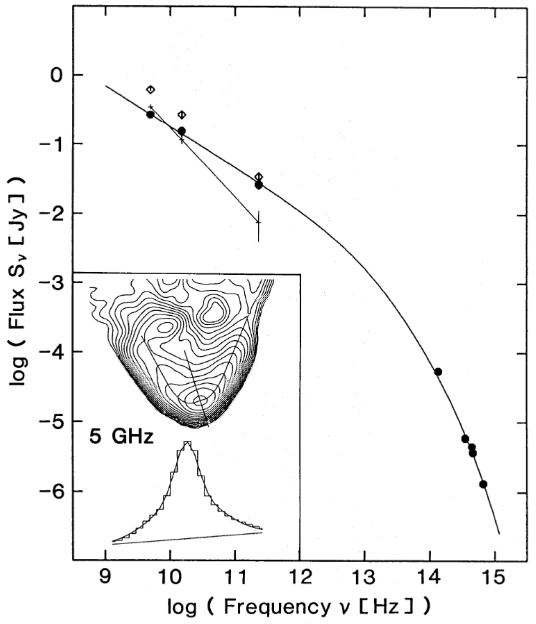
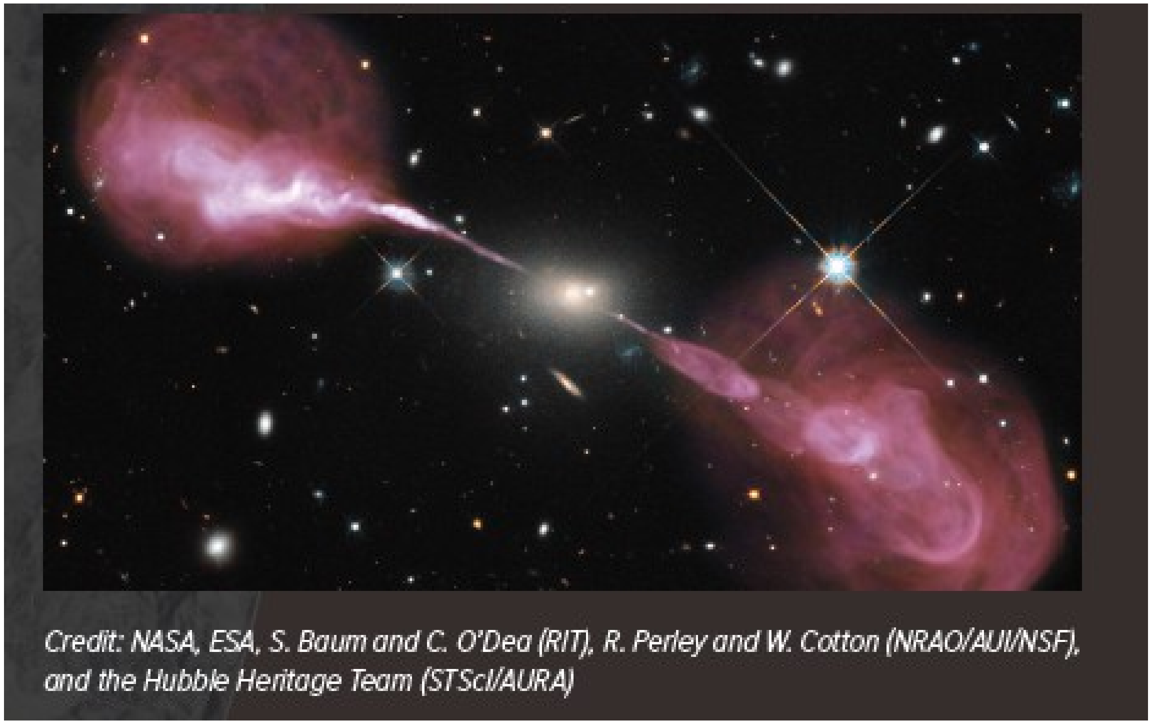


Figure 8 Decomposition of the observed spectrum of 3C 33 south (K. Meisenheimer et al., *Astron. & Astroph.* 1989). This type of cut-off spectrum is ubiquitously observed in **compact nuclei, knots in jets, and hot spots of radio galaxies** (Rieke et al. 1976, 1979, 1982; Rieke & Lebofsky 1980; Bregman et al. 1981; Stocke et al. 1981; Sitko et al. 1983; Brodie et al. 1983; Röser & Meisenheimer 1986; Meisenheimer & Röser 1986; Perez-Fournon et al. 1988).

The bursting radio-galaxy Hercules A



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Figure 9 The bursting radio galaxy Hercules A. Source Baum & O'Dea 2015.

Basics of relativistic jets with oblique shocks

PLB & Strittmatter 1987; Falcke et al.; Markoff et al.; Becker & PLB 2009; Gergely & PLB 2009; PLB et al. 2011 Neutrino (Lecce)-meeting; PLB et al. 2014; +++

- Jet flow suffers dramatically from **adiabatic losses**, and yet keeps going **from $\sim$ 3,000 r_S** to order 10^{24} cm, sometimes to 10^{25} cm or even more
- Jets can be expected to start at a near-relativistic speed of sound, but cool down rapidly.
- Each shock system consumes **only minute fraction** of kinetic energy (remember, **entropy is increased in any shock**).
- Each **shock strong**: Internal sound-speed sub- or only weakly relativistic: **fitting observations**

- All shocks that allow jet-flow to survive **highly oblique**; in fact, the emission topology is **helical**, as seen in a number of relativistic jets, on various scales
- **Protons** get accelerated in shock, go to **loss limit**, initiate wave-field $\boldsymbol{E^{-2} -> k^{-5/3}}$ (Bell 1978):
- Proton loss limit is synchrotron emission in TeV range
- **Electrons** get accelerated in shock, scatter in given wave field, go to **loss limit**, produce cut-off in synchrotron emission spectrum, maximal frequency:

$$\boldsymbol{\nu_e^\star \lesssim 3 \times 10^{14}\,\mathrm{Hz}}$$

independent of any parameter: **Ubiquitously observed in compact sources, knots in jets, and radio galaxy hot spots** (slightly modified for IC losses)

- Translates to loss limit $B \sim 10^{-2}$ to 10^{-4} Gauß:

$$E_{p,max} \simeq 1.4 \times 10^{20}\mathrm{eV} \left(\frac{\nu_e^\star}{3.10^{14}\,\mathrm{Hz}}\right)^{1/2} B^{-1/2}$$

- **Spatial limit** near (Lovelace 1976; Falcke et al. 1995)

$$10^{21}\, L_{46}^{1/2}\ \mathrm{eV} \tag{1}$$

- Therefore in combination (no boosting here)

$$\boldsymbol{E_{p,max} \simeq 1.4 \times 10^{21}\mathrm{eV}}$$

- Very weak dependence on parameters (e.g. Miley 1980 ARAA, Bridle & Perley 1984 ARAA)
- Various **photon-interaction** losses also

- **Double-bump of blazars**:

$$\frac{\nu_{syn,p,max}}{\nu_{syn,e,max}} = \left(\frac{m_p}{m_e}\right)^3$$

- **Integrating downstream (Kardashev 1962) gives**

$$\frac{L_p}{L_e} \sim \frac{n_{p,0} m_p}{n_{e,0} m_e} \frac{\gamma_{p,max}}{\ln(\gamma_{e,max}/\gamma_{e,min})} \left(\frac{m_e}{m_p}\right)^{+3} \sim 1$$

- **Variability: $\tau \simeq r/(2\gamma^2 c)$** (Piran 1999), 1 minute $->$ $10^{16.6}$ cm, $\simeq 3000$ R_S of 10^8 $M_\odot$ SMBH, **where jets start !**: **Source of νs, TeV γs,..**

- Old prediction, new argument: **Radiogalaxies sources at energies $> 10^{20}$ eV**! Lower energy jet-sources: gamma ray bursts, microquasars, jet-supernovae
- Nearby candidates (**Ginzburg & Syrovatskii 1963**; before discovery of UHECRs):

Radio galaxies

Cen A (= NGC 5128), BH merger

Vir A (= M87 = NGC 4486), BH merger

For A (= NGC 1316), BH merger ?

- Auger suggests **Cen A**, matching **composition**

Reorienting the spin of the merged Black Hole

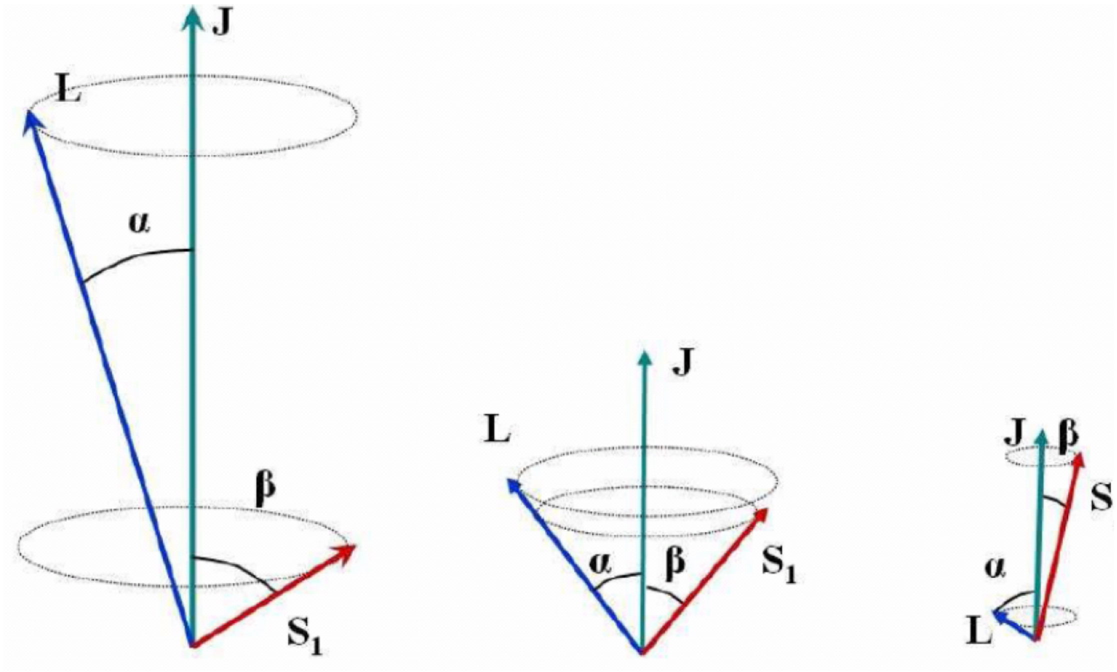


Figure 10 The spin-flip phenomenon in supermassive black hole binary mergers: Individual BH spin is $\boldsymbol{S}$, orbital angular momentum is $\boldsymbol{L}$, and total angular momentum is $\boldsymbol{J}$. These three steps show the envisaged **temporal evolution of the final stages of the merger**. L.A. Gergely & PLB: 2009 ApJ

Integral BH mass fct starts at $\sim 3 \cdot 10^6\, M_\odot$

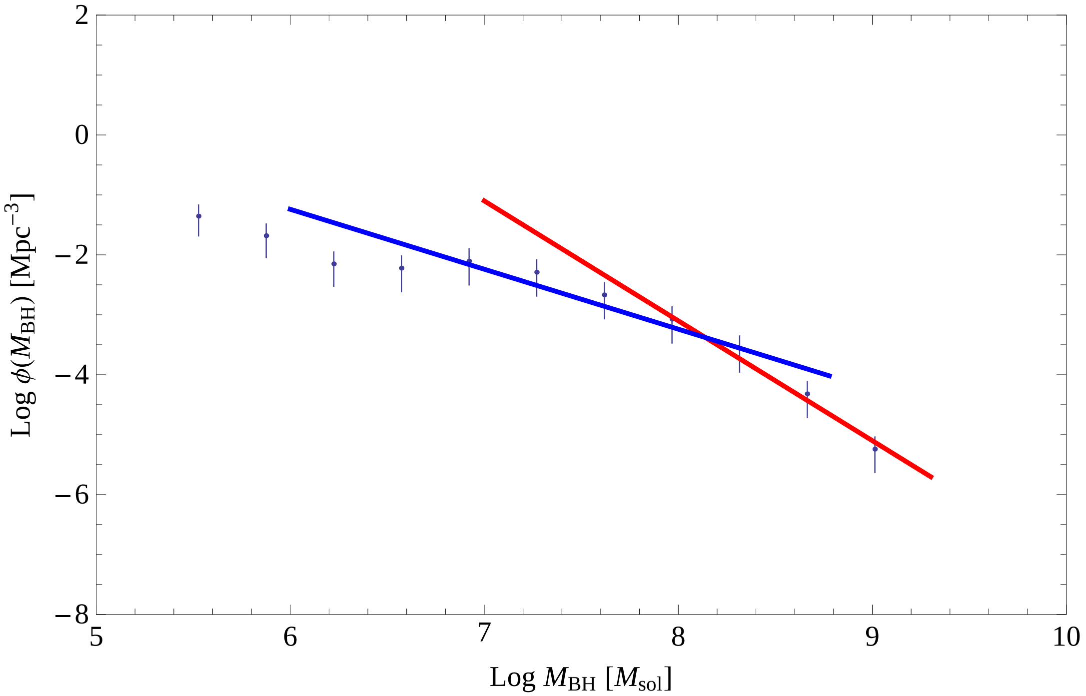


Figure 11 Integral mass function corrected for Hubble type sampling, 2928 objects, the slope of the lines is: red -2.0 fitting $> 10^8\, M_\odot$, and blue -1.0 fitting between $10^7\, M_\odot$ and $10^8\, M_\odot$. See Caramete & PLB, *Astron. & Astroph.* **521**, id.A55 (2010); arXiv:0908.2764. This mass function suggests that black holes start near $3 \cdot 10^6\ M_\odot$, possibly at redshift of order ~ 30 to 80, and grow by merging (see PLB & Kusenko 2006, PRL): Note that redshift 80 corresponds to only 22 million years after Big Bang

Why Black Holes of around $\mathbf{3 \cdot 10^6}\ M_\odot$?

- First massive stars can form in dense groups in gravitational potential of **DM of dwarf galaxy**: stars agglomerate (Spitzer 1969) to form more massive star
- Massive stars also have **winds**, driven by radiation interaction with heavy elements (Lucy & Solomon 1970 and many later papers): So maximum mass several hundred $M_\odot$ at most (Yungelson et al. 2008)
- At **zero heavy element abundance** massive stars can grow to **much higher mass**, close to $\mathbf{10^6}\ M_\odot$
- Massive stars hit an **instability**, combining radiation pressure with subtle effects of General Relativity (Appenzeller & Fricke 1972a, b) just below this mass
- So with infall the mass of about $\mathbf{3 \cdot 10^6}\ M_\odot$ possible

Black holes (BHs) > $3 \cdot 10^7\ M_\odot$: colors are distance: Black, Blue, Green, Orange, Red

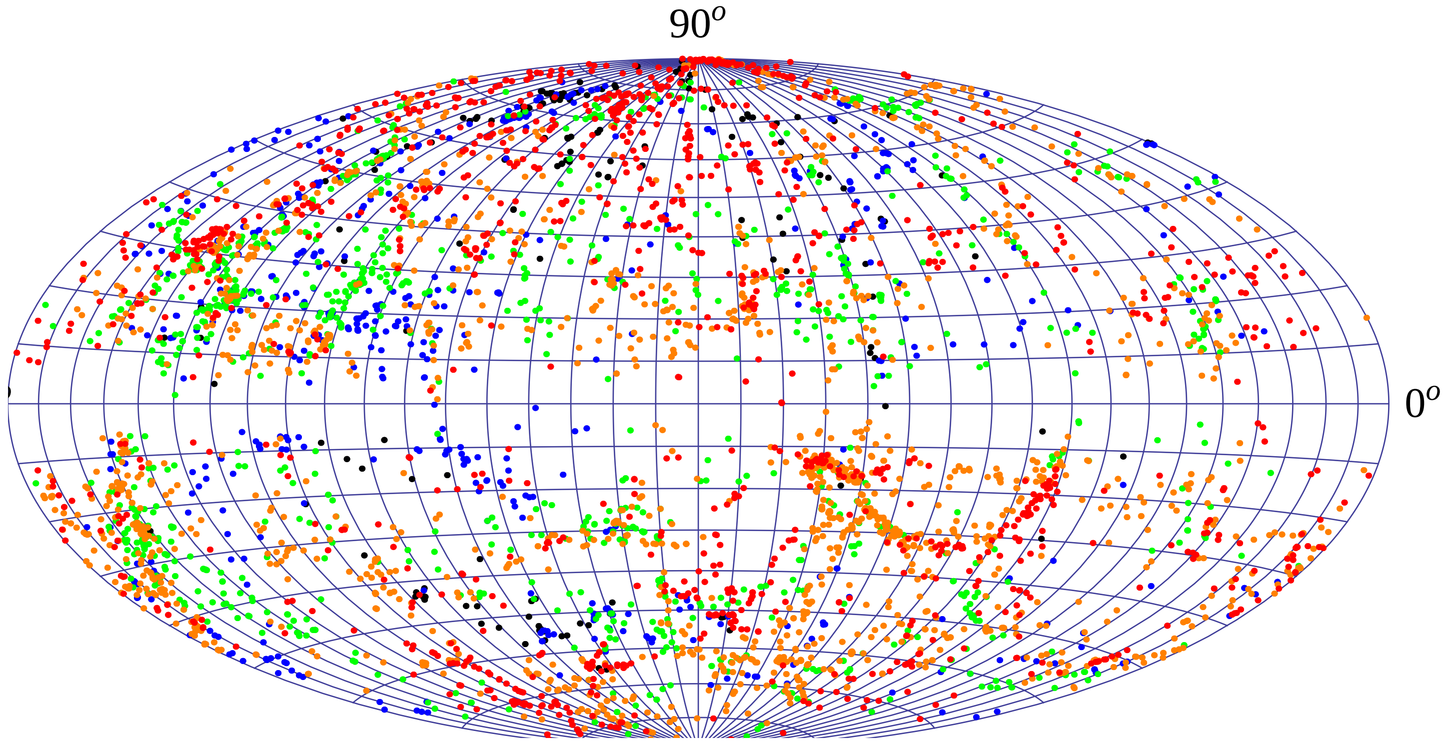


Figure 12 The sky in black holes, $\gtrsim 3 \cdot 10^7\ M_\odot$: The color code corresponds to distance: Black, Blue, Green, Orange, Red for the redshifts intervals 0, 0.005, 0.01, 0.015, 0.02, 0.025, corresponding to distance intervals of 0, 60, 120, 180, 240, and 300 million light-years: (−> Caramete & PLB 2011); coordinate system with Galactic plane across center, and Galactic Center (GC) at the right edge

Concept for HE backgrounds

- **Super-massive BHs** start early, evolve by merging
- Each merger ejects **burst of gravitational waves**
- Each merger **reorients dominant spin**
- So new jet has to bore **fresh channel**
- Maximizing injection, acceleration and **interaction**
- Ubiquitous energetic particles, **electrons, protons and nuclei** (starburst CRs: Gopal-Krishna et al. 2010)
- Interaction: **$->$ TeV γ-rays and HE neutrinos**
- **Prediction: Neutrino emitter is jet pointed at us, so relativistically boosted, but with all the hallmarks in radio emission of**

very recent merger

M87: a recent merger

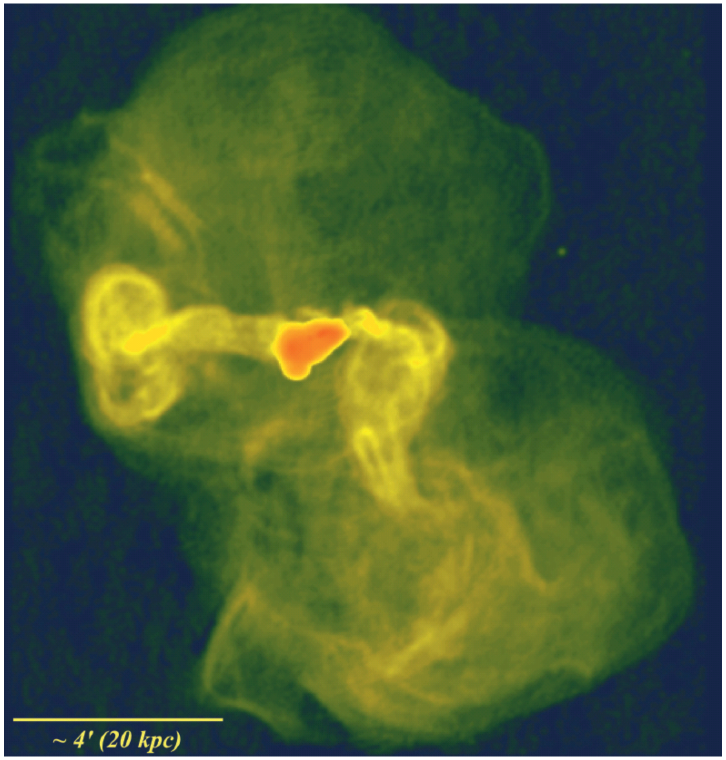


Figure 13 The M87 jet and counter-jet, clearly demonstrating a spin-flip. Source Owen et al. 2000 ApJ

Cen A: a recent merger

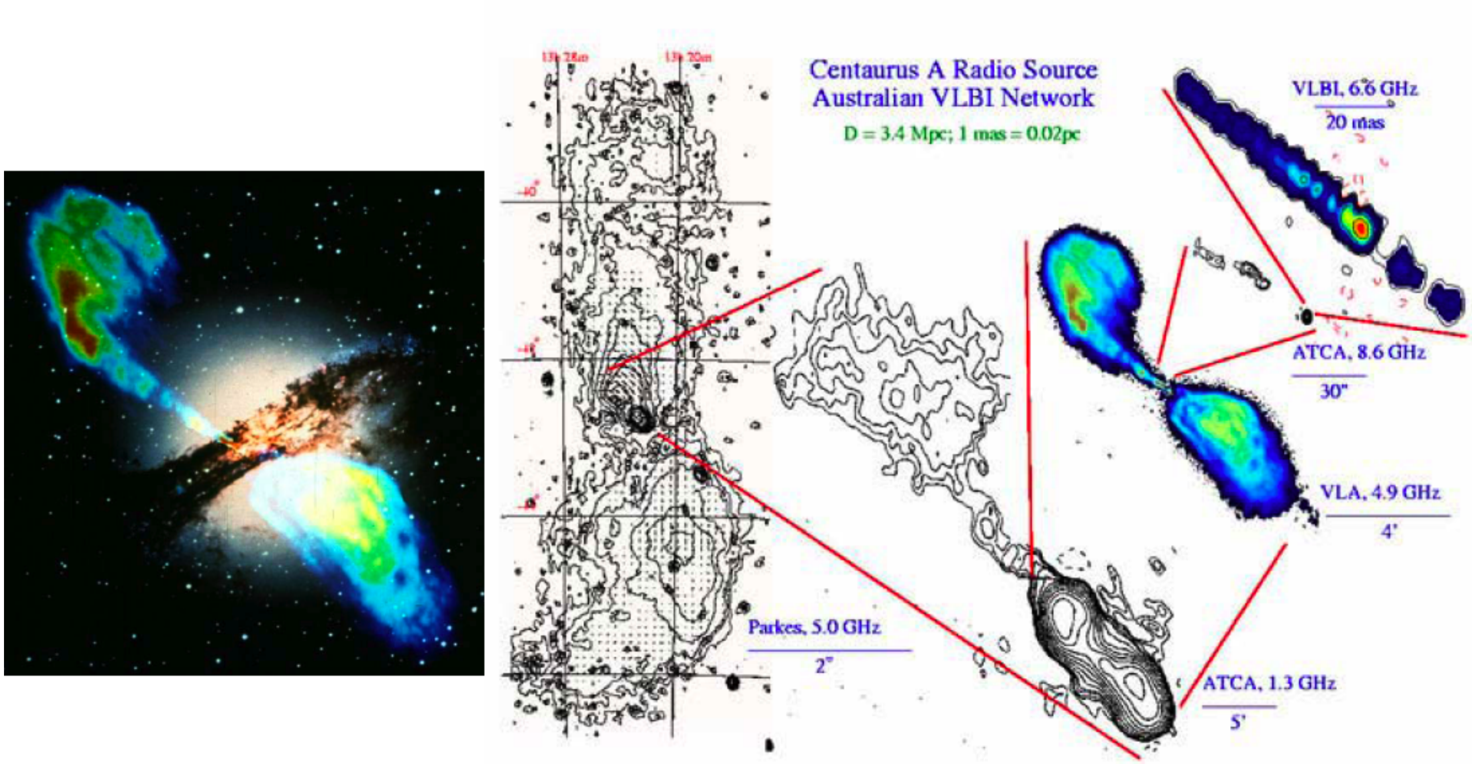


Figure 14 The radio galaxy Cen A with old and new structures, clearly demonstrating a spin-flip. Source S. Britzen lectures

Where are the sources? IceCube 2015

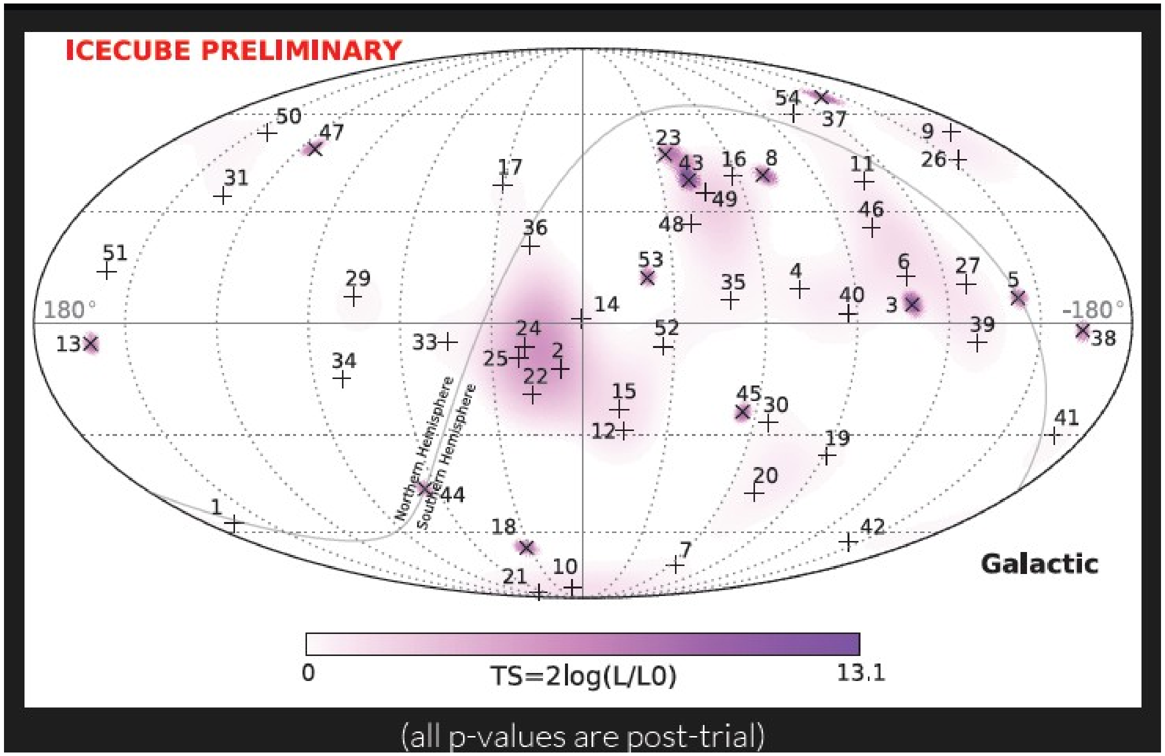
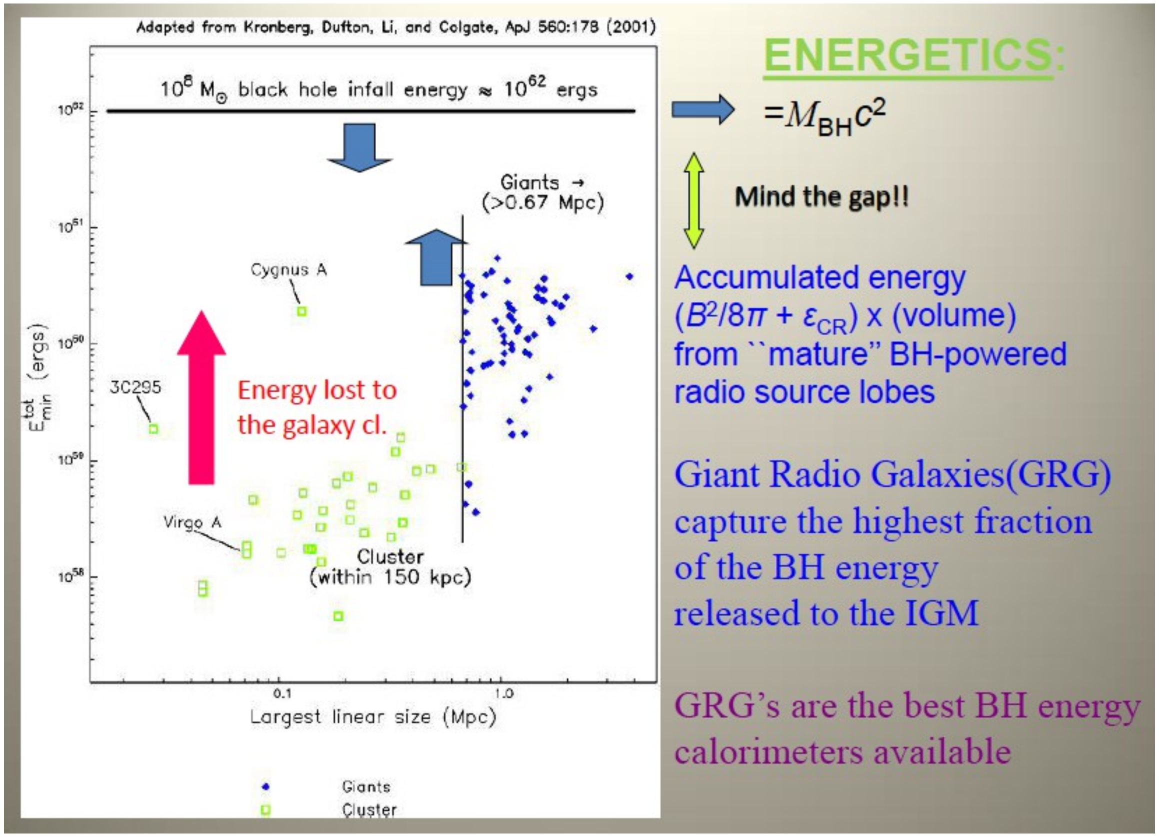


Figure 15 The HE neutrino events 2015; ”x”-symbols are better directions than crosses. GC at center. **Fresh SMBH mergers – the candidates – are flat spectrum radio sources at high redshift**, since merger rate steeply rising fct of redshift. Source ICRC 2015 talk.

Black Hole energetics ~ (1/2) $\Delta M_{BH} c^2$



ENERGETICS:

$=M_{BH}c^2$

Mind the gap!!

Accumulated energy
$(B^2/8\pi + \varepsilon_{CR})$ x (volume)
from ``mature" BH-powered
radio source lobes

Giant Radio Galaxies(GRG)
capture the highest fraction
of the BH energy
released to the IGM

GRG's are the best BH energy
calorimeters available

Figure 16 Radio galaxies and their visible energetics, outside clusters and inside. These authors used $10^8\, M_\odot$, but in a typical merger very much less energy might be available, so the efficiency required is quite high: source lecture **P.P. Kronberg at DRAO Nov 2015**

Black Holes & Dark Energy: + Ben Harms

- Limit (1/2) rest mass energy for BH seen in radio galaxies (above). Budget

  $$\frac{1}{2} N_{BH,0} \, M_{BH} \, c^2 (1 + z_\star)^3 \sim 10^{-8} \, \mathrm{erg/cc}$$

- for $N_{BH,0} = 1 \, Mpc^{-3}$, $M_{BH} = 3 \cdot 10^6 \, M_\odot$, $z_\star = 50$: **Gravitational waves?**
- Combined $\underline{10^4 \text{ uncertainty}}$ in $N_{BH,0}$, $z_\star$, etc.
- Requires very high redshift: possible with DM decay **stimulated H_2 formation, star formation, and SMBH formation** (PLB & Kusenko 2006 PRL)
- If GWs then near **10 μHz the GW background** due to SMBH binary mergers might become **detectable**

GWs at various redshifts, <u>detected</u> and limits

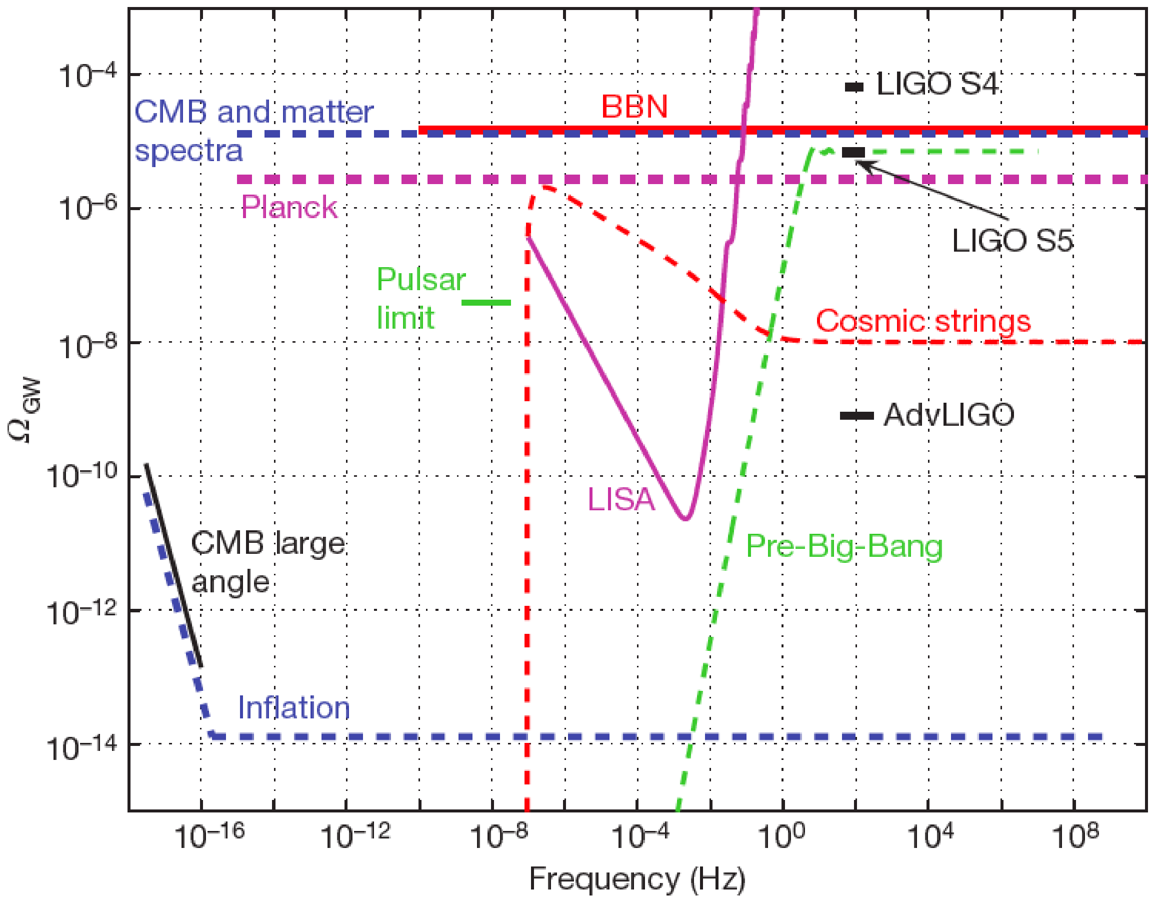


Figure 17 Limits on gravitational waves. Source: Virgo and Ligo Coll. Nature 2009. Feb 2016 (1602.03847 AdvLIGO) we predict $\boldsymbol{\Omega_{GW}(25Hz) = 1.1^{+2.7}_{-0.9}\,10^{-9}}$ **with 90% confidence** after GW detection

Physics laboratories: UHECRs (ZeV), HE νs (PeV), γ-photons (TeV) and GWs (10μ-Hz) ?

- Very early star and BH formation, $z \lesssim 100$?
  - SMBH mergers $->$ reoriented jet: maximal interaction
- $->$ GWs, γ-photons, neutrinos, UHECRs
- Test I: Identify the HE ν-sources !
- Test II: Detect μHz GW background
- Test III: Detect first SMBH activity !

Thank you!