40 years of observing mergers of spinning black holes State of the art and understanding

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Mergers of spinning black holes (BHs)

- **Starburst galaxies host BH mergers: M82**
- **Magnetic fields of freshly born rotating BHs**
- **Galactic Cosmic Rays (GCRs) and ...**
- **Spin-flip visible**
- **Flat spectrum radio galaxies and quasars merger of Super-Massive spinning Black Holes (SMBHs)**
- **M87 magnetic fields near BH**
- **Ultra High Energy CRs (UHECRs)**
- **Flares in HE gammas and neutrinos**

Spinning BHs and their mergers –> GCRs, UHECRs, HE gammas, HE neutrinos, GWs

M82 Galaxy explodes due to many Super-Novae (SNe)

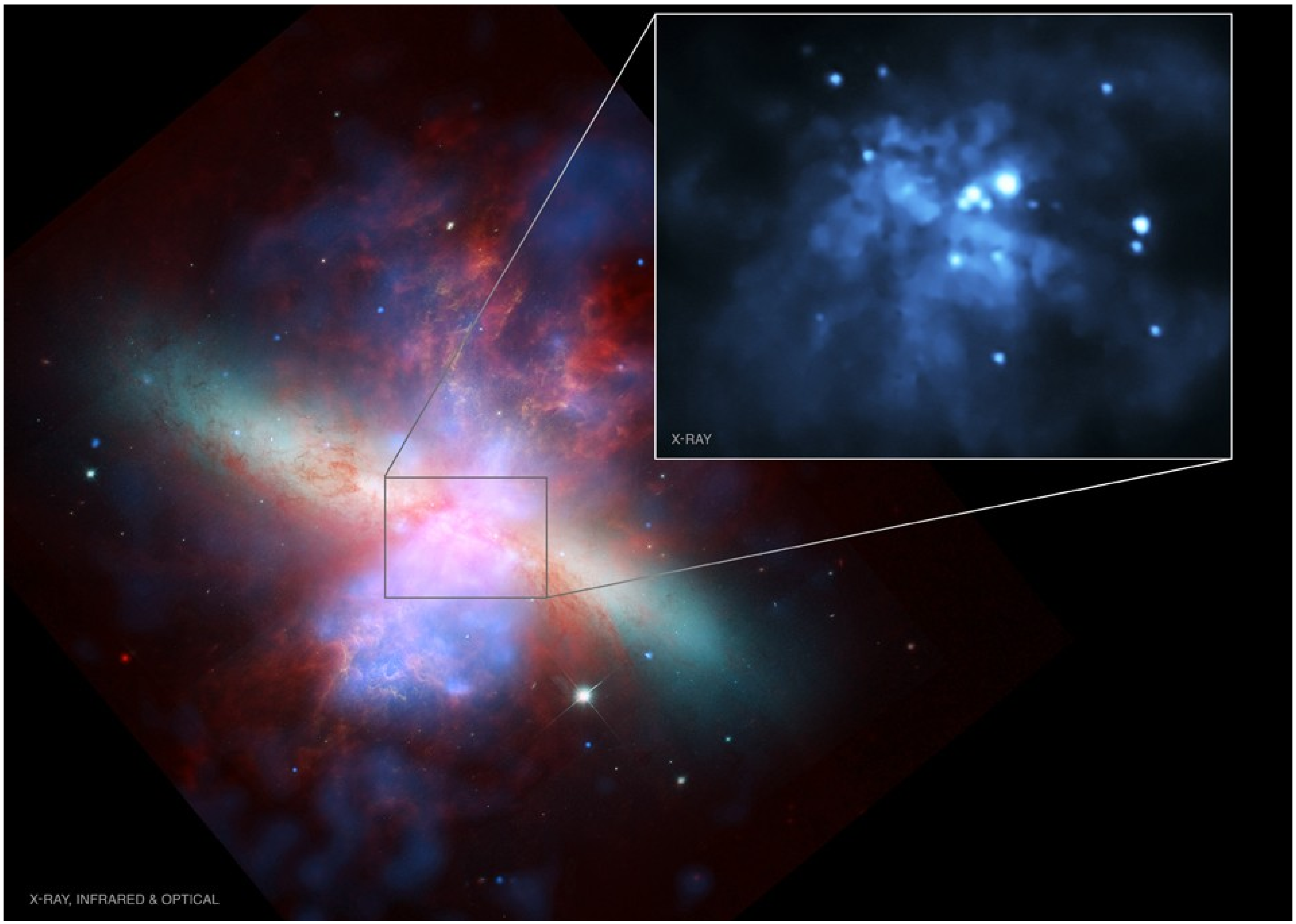

Figure 1 The starburst galaxy M82 with strong burst of star formation; with enlarged view of inner region. Chandra (X-rays), HST (optical), Spitzer (Infrared; extra image) satellite-telescopes; source: NASA

M82 radio map 1981: RSN 41.9+58, youngest

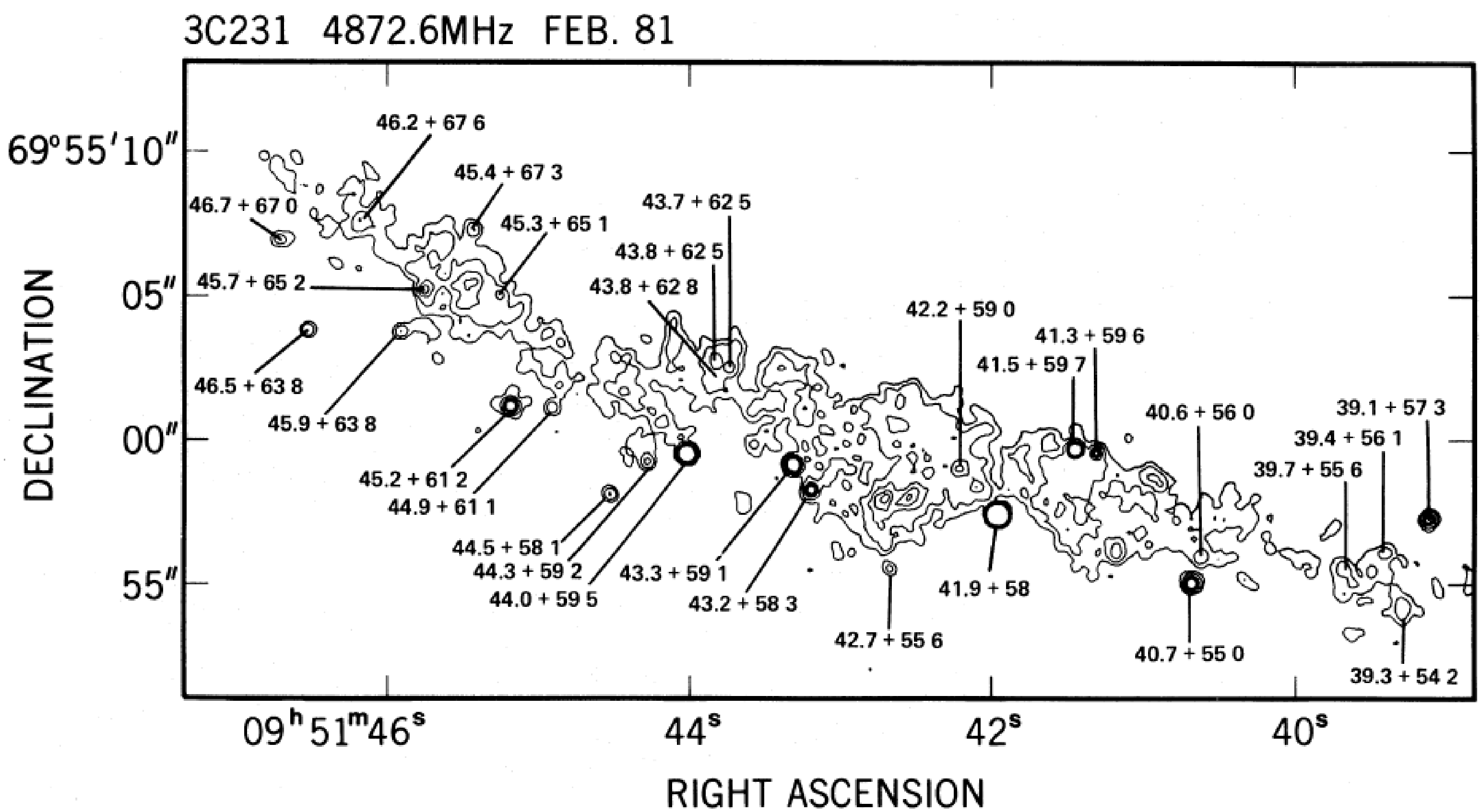

Figure 2 A detailed sub-arcsecond resolution, 5 GHz VLA image of the inner ∼ 600 pc of M82. 1 arc sec corresponds to about 15 pc. It is the first of a series of subsequent images at similar resolution, which span widely different variability rates, spectrum, and radio luminosity. Other related High Energy Physics (HEP) and gravitational physics issues are discussed below (IR, X-ray, gamma ray, and CR observations), and elsewhere. **Almost every compact radio source here can be understood to be due to a blue super giant star explosion into its wind, with 41.9+58 possibly a GRB, and a BH merger with spin-flip and kick.** Source Kronberg, PLB, & Schwab 1985 ApJ 291, 693

Reorienting the spin of the merging Black Holes: Precession cone!

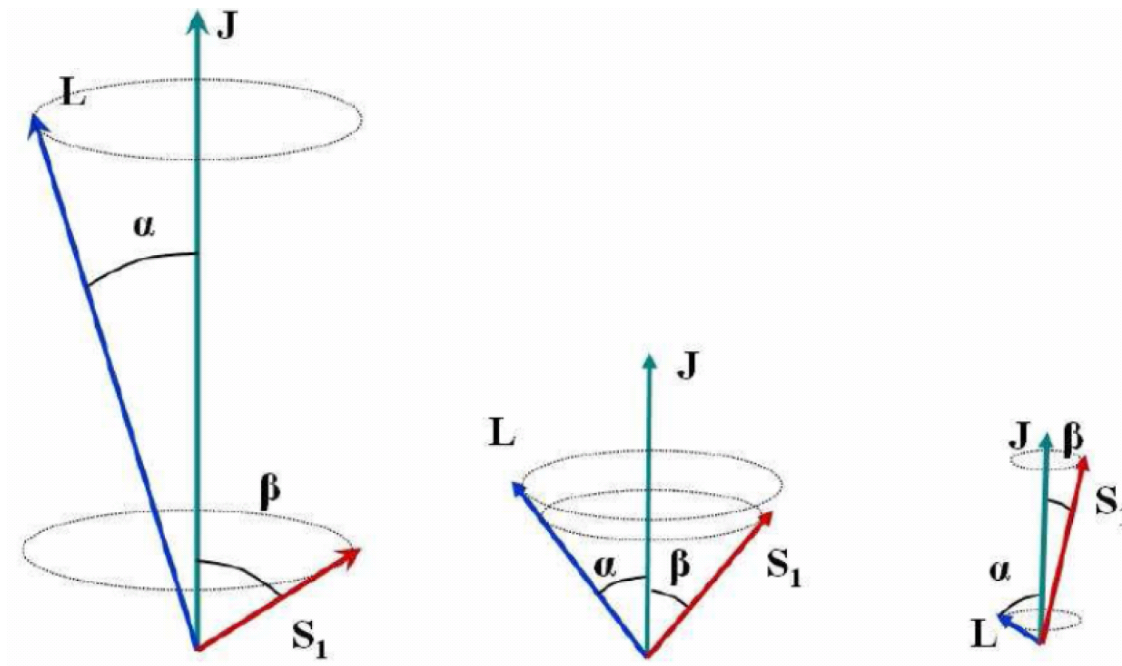

Figure 3 The spin-flip phenomenon in supermassive black hole binary mergers: Individual BH spin is $\boldsymbol{S_1}$ for the dominant BH, orbital angular momentum is $\boldsymbol{L}$, and total angular momentum is $\boldsymbol{J}$. The spin of the second BH is ignored here. These three steps show the envisaged temporal evolution of the final stages of the merger. Source: L.A. Gergely & PLB: 2009 ApJ 697, 1621

Reorienting the spin of the merging Black Holes: Time scales

Order of Magnitude Estimates for the Inspiral Rate $\dot{L}/L$, Angular Precessional Velocity Ω_p, and Tilt Velocity $\dot{\alpha}$ of the Vectors $\mathbf{L}$ and $\mathbf{S}_1$ with Respect to $\mathbf{J}$, Represented for the Three Regimes with $L > S_1$, $L \approx S_1$ and $L < S_1$, Characteristic in the Domain of Mass Ratios $\nu = 0.3$–0.03

Parameter	$L > S_1$	$L \approx S_1$	$L < S_1$
$-\dot{L}/L$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-15})$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-11})$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-7})$
Ω_p	$\frac{2c^3}{Gm}\varepsilon^{5/2}\eta\ (\approx 10^{-11})$	$\frac{2c^3}{Gm}\varepsilon^{5/2}\eta\frac{J}{L}\ (\approx 10^{-8}\frac{J}{L})$	$\frac{2c^3}{Gm}\varepsilon^3\ (\approx 10^{-5})$
$\frac{\dot{\alpha}}{\sin(\alpha+\beta)}$	$\frac{32c^3}{5Gm}\varepsilon^{9/2}\frac{\eta}{\nu}\ (\approx 10^{-16})$	$\frac{32c^3}{5Gm}\varepsilon^{9/2}\frac{\eta}{\nu}\frac{L^2}{J^2}\left(\approx 10^{-11}\frac{L^2}{J^2}\right)$	$\frac{32c^3}{5Gm}\varepsilon^{7/2}\eta\nu\ (\approx 10^{-8})$

Notes. The numbers in brackets represent inverse timescales in s^{-1}, calculated for the typical mass ratio $\nu = 10^{-1}$, post-Newtonian parameter 10^{-3}, 10^{-2}, and 10^{-1}, respectively, and $m = 10^8\ M_\odot$ (then $c^3/Gm = 2 \times 10^{-3}\ s^{-1}$).

Figure 4 **The time scales for the merger: First the rate of change of the orbital spin, second the precession rate, and third the tilt-angle-rate. Here are the rates per second for a SMBH of $10^8\ M_\odot$, for a $10\ M_\odot$ stellar mass black hole these rates would be 10^7 times faster. $\eta = \nu/(1+\nu^2)$, where $\nu = M_{BH,2}/M_{BH,1} < 1$ by definition. ε is the Post-Newtonian (PN) parameter, r_g/r, also ε_{PN}. S_1 refers to the spin of the dominant BH**. Source: L.A. Gergely & PLB: 2009 ApJ ApJ 697, 1621

GWs drive the inspiral and spin-flip from $\varepsilon_{PN} \simeq 10^{-3}$, so $\varepsilon_{PN,-3} := \frac{\varepsilon_{PN}}{10^{-3}} \simeq 1$.

Reorienting the spin of the merging Black Holes: Time evolution

Angular momentum removal by magnetic fields (for maximal BH spin) versus GWs for 10 $M_{\odot}$ BHs, $\varepsilon_{PN} = 10^{-3}$, equal masses ($\eta = 1/4$):

$$\frac{\dot{L}}{L} \simeq -10^{-9.2}\,\varepsilon_{PN,-3}^{-1}\,s^{-1} - 10^{-8.3}\varepsilon_{PN,-3}^{+4} s^{-1} \tag{1}$$

showing, that for slightly smaller ε_{PN}, so a larger system, **magnetic fields drive the BHs together**.

Both time scales scale linearly with BH mass, same effect happens at SMBH scales, just slower. At SMBH scales the gravitational torque interaction with giant molecular clouds could be even faster (e.g. Julian & Toomre 1966 ApJ 146, 810; v. Linden et al. 1993 AA 280, 468).

M82 41.9+58: Merging black holes (BHs): Conical clean-out by jets in spin-flip, kick

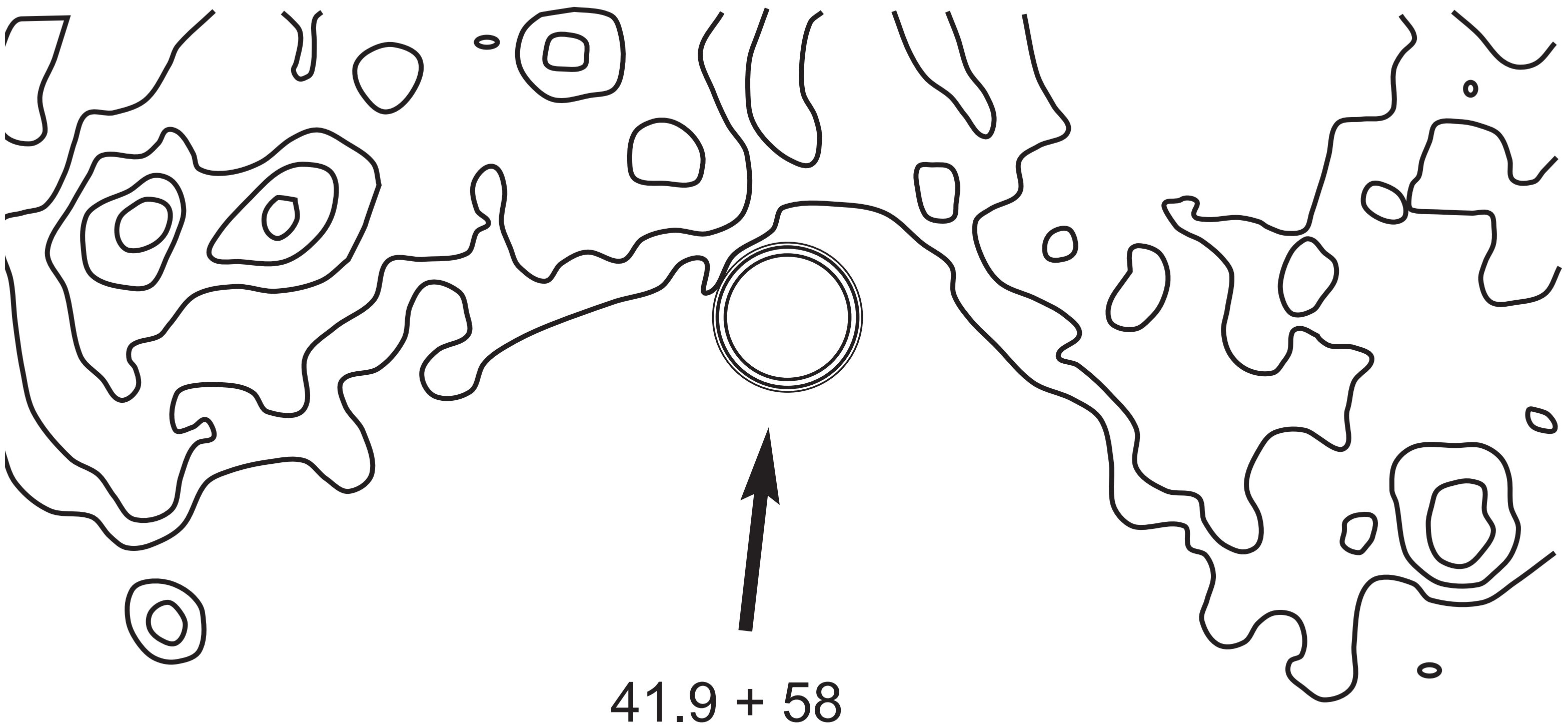

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Figure 5 The circle denoting 41.9+58 not to scale. Source Kronberg, PLB, & Schwab 1985 ApJ 291, 693: excerpt of Fig. 2, produced by P.P. Kronberg 2017. 41.9+58 was observed with very high spatial resolution (VLBI) by N. Bartel et al. 1987 ApJ 323, 505 and shows a major axis size of 25 ± 4 milli-arcsec, corresponding to about 10^{18} cm.

M82 radio map 1981: RSN 44.0+595, second?

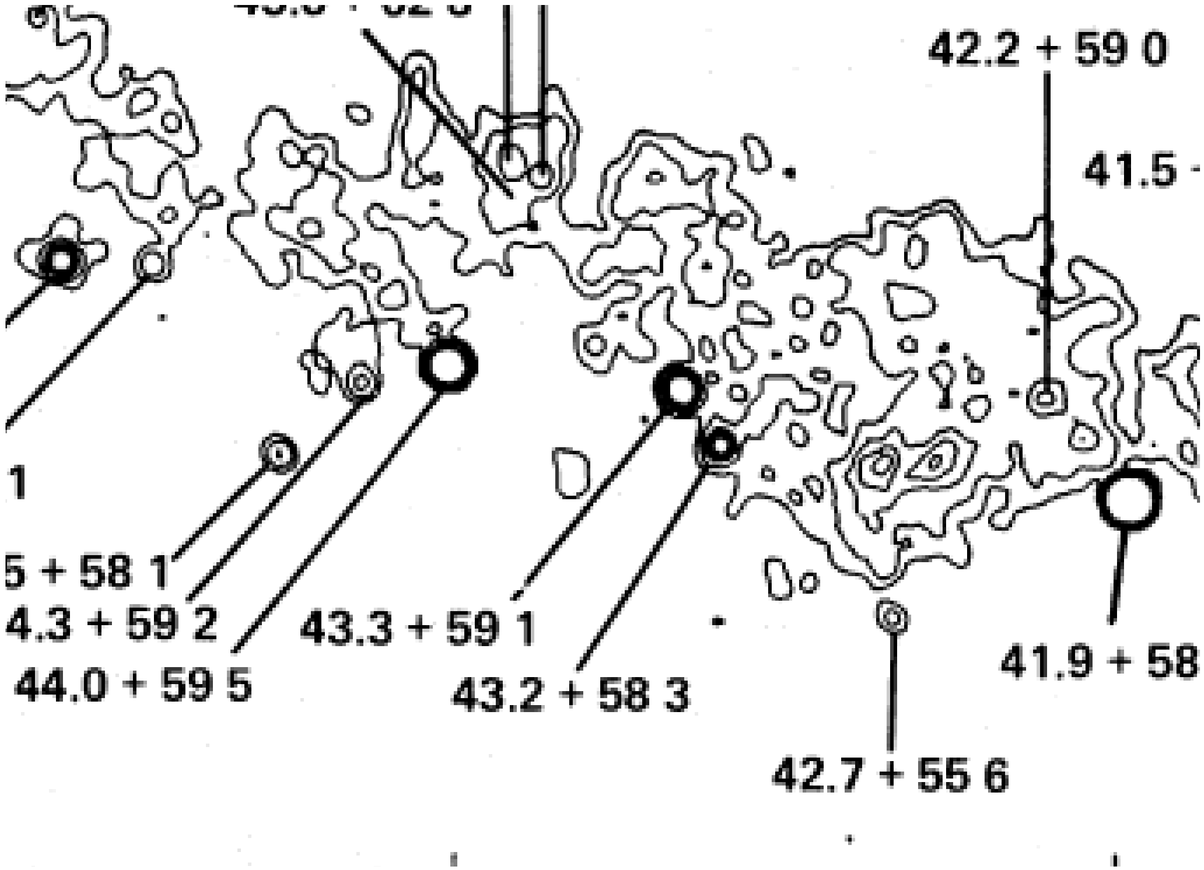


Figure 6 Another enhancement of part of the radio image of M82. Source Kronberg, PLB, & Schwab 1985 ApJ 291, 693. **Caution and questions: Starburst region ring, ending perhaps in bar or spiral: in projection that might also lead to such structures. Actual merger GRB? If so, what is the equivalent for a SMBH merger? What is the inherent time scale? If kick, then what geometry? At right angles to final spin axis as possible in stellar binaries with SN?**

M82 TA UHECR hot spot

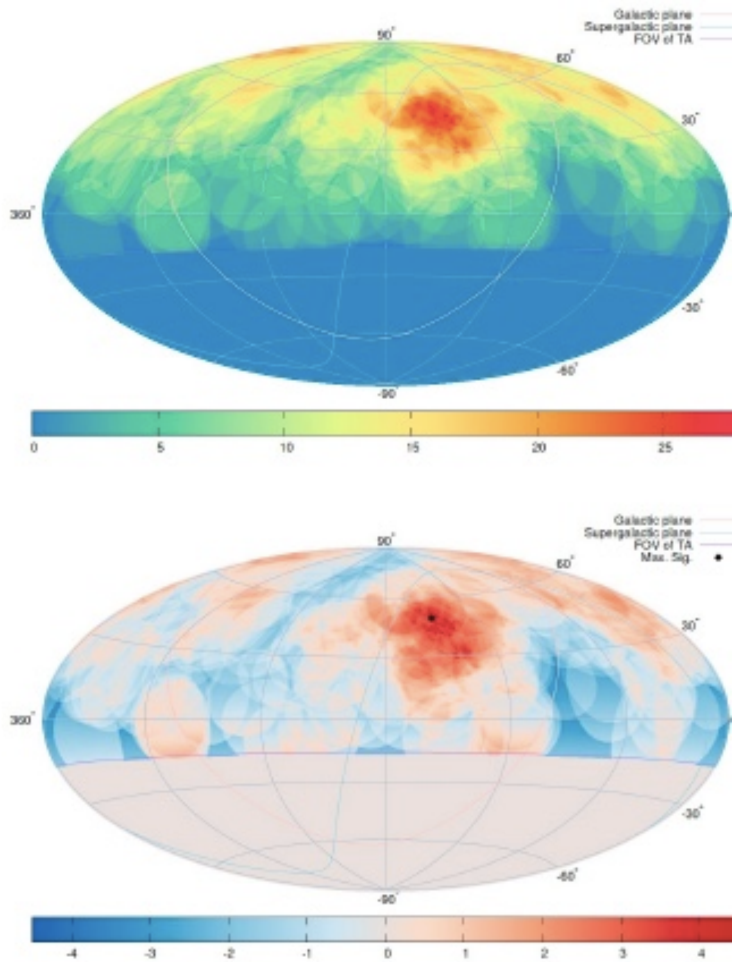


Figure 7 Hot spot close to M82 in TA UHECR data; magnetic deflection and scattering in our Galactic halo wind readily explain shift and scattering scale (PLB et al. 2015). Source P. Sokolsky 2021; 2020 ApJ 899, 86

M82 TA UHECR hot spot - correlation wedge

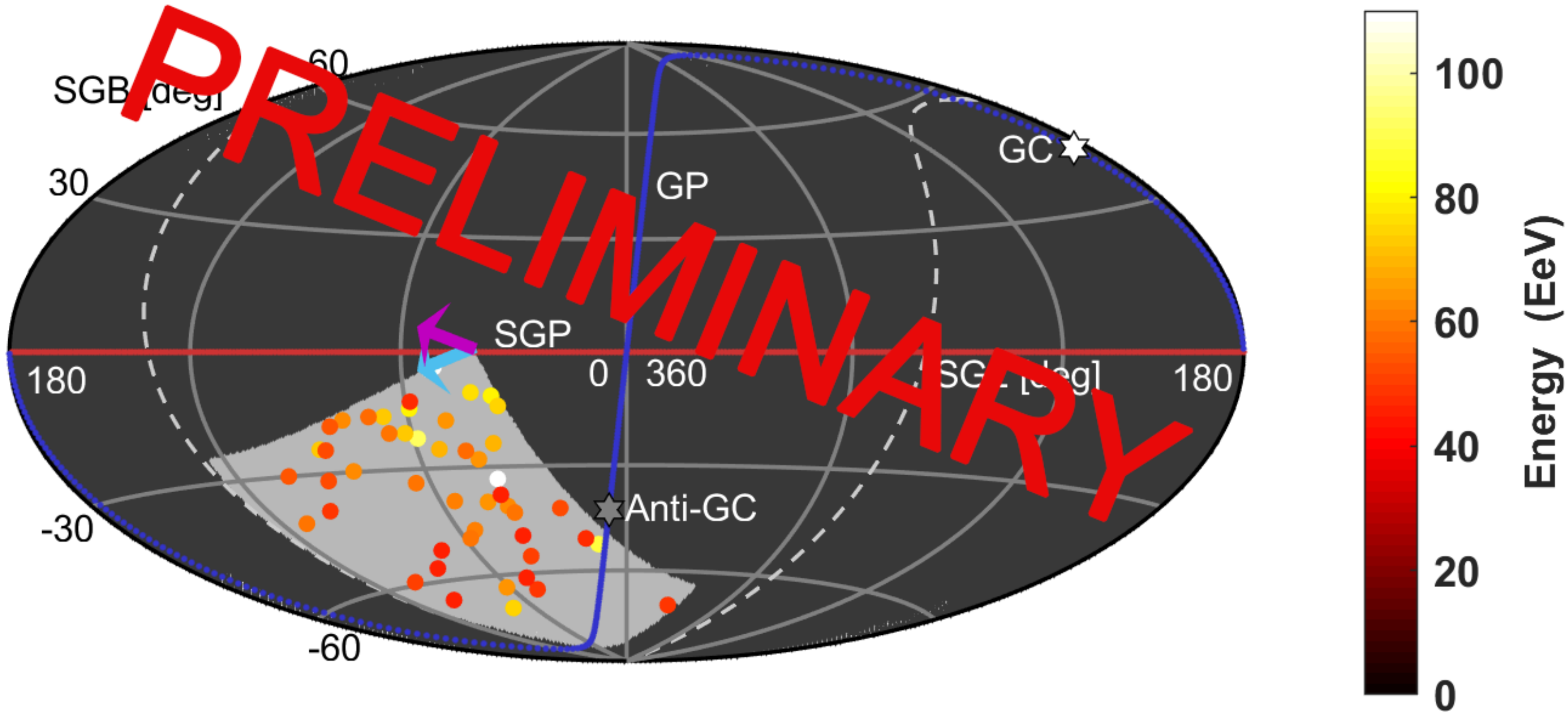


Figure 8 The angular correlation wedge centered on M82 in the SuperGalactic Plane. "The hypothesis here is that M82 is a source and we look for the most significant correlation wedge with an apex a M82. This is what we get. Clearly, if we moved a bit further along the SG plane, we would also get significant correlations, so this does not prove M82 is the source, it just says M82 is consistent with being a source." Source P. Sokolsky 2021; 2020 ApJ 899, 86. In ranking starburst galaxies M82 gets the highest slot by far.

M82 41.9+58: Conical clean-out/kick merging black holes (BHs) −> UHECRs!

- Point-source explosion in stratified atmosphere yields chimney-like structure, never a cone (Kompaneets, 1960 Sov. Phys. Dokl., +). Chimneys in many disk galaxies, also M82.
- Double conical clean-out (Gergely & PLB 2009 ApJ: in spinflip in BH merger) by jets and counter-jets
- predicted BH kick visible! GRB (Muxlow)?
- Requires maximal jet-powers from $P\,dV$ −> near maximal spin of both BHs! Spin-down !
- M82 UHECR source: TA-Coll. 2020 ApJ
- M82 BH merger rate consistent with LIGO/VIRGO.
- BH merger in starburst galaxy MCG+08-11-002 source of Fly's Eye event (320 EeV)?

M82: SN-winds transport angular momentum

Table 1 Supernova remnants (SNRs) in starburst galaxy M82, based on Allen & Kronberg (their Table 5; 1998 ApJ 502, 218), Allen (1999 Ph.D. thesis); see 2019 Galaxies 7, 48. **Three samples to confirm the numbers: $< \log(B \times r) >$ same, range 10^3 in r. $->$ Galactic Cosmic Ray (GCR) knee, ankle, pevatrons**

Coordinate name	size $2\,r$ in pc	flux density in mJy	sp. index	est. magnetic field B in mGauss	$\log(B \times r)$ in Gauss $\times$ cm
40.68 + 550	3.72	17.9	-0.52	1.80	**16.0**
41.31 + 596	2.17	8.59	-0.54	2.32	**15.9**
41.96 + 574	0.33	122.8	-0.72	26.4	**16.1**
42.53 + 619	1.71	30.9	-1.84^*	11.7	**16.5**
42.67 + 556	3.02	4.44	-0.61	1.46	**15.8**
43.19 + 583	1.16	15.3	-0.67	4.79	**15.9**
43.31 + 591	3.02	30.3	-0.64	2.54	**16.1**
44.01 + 595	0.78	62.0	-0.51	9.83	**16.1**
44.52 + 581	3.72	7.2	-0.61	1.40	**15.9**
45.18 + 612	3.49	24.1	-0.68	2.13	**16.1**
45.86 + 640	1.09	4.10	-0.53	3.39	**15.8**
46.52 + 638	3.88	9.71	-0.73	1.53	**16.0**
46.70 + 670	3.41	5.22	-0.57	1.37	**15.9**
Mean and	**stand.dev.**				**16.0 ± 0.12**
Source	42.53 + 619	not used	due	to steep spectrum	

Hillas: $->$ $E_{CR,knee}$, $E_{CR,ankle}$, pevatrons.

with LIGO $->$ angular momentum transport!

Stellar mass black hole (BH) spins usually consistent with zero before merging

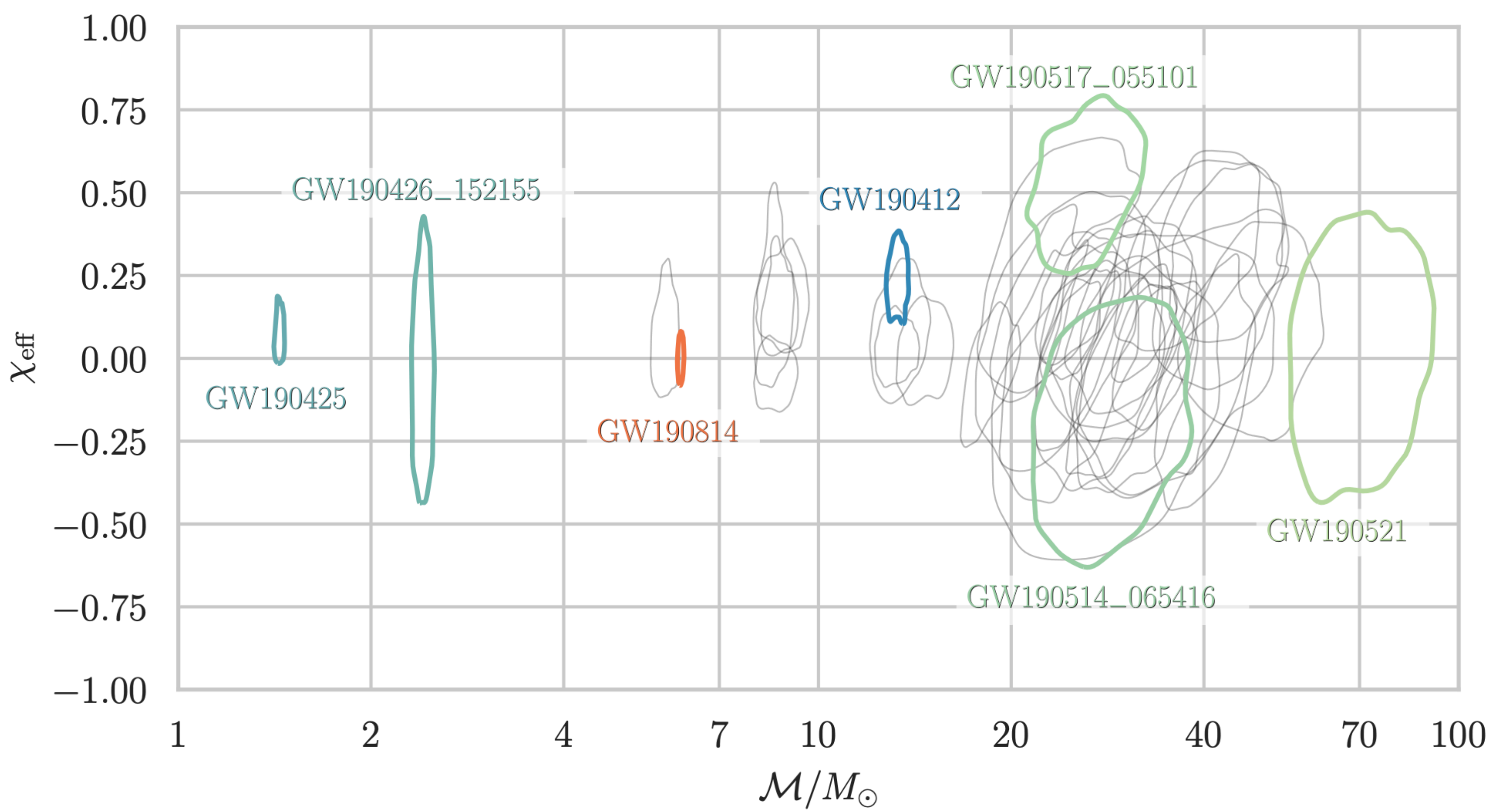


Figure 9 A plot showing the effective spin parameter for many BBH mergers, χ_{eff} is weighted combined individual spin parallel to the orbital spin, dimensionless. Source: LIGO/VIRGO 2020, arXiv:2010.14527 (GWTC2).

YET: Massive star can collapse to final BH with near maximal rotation

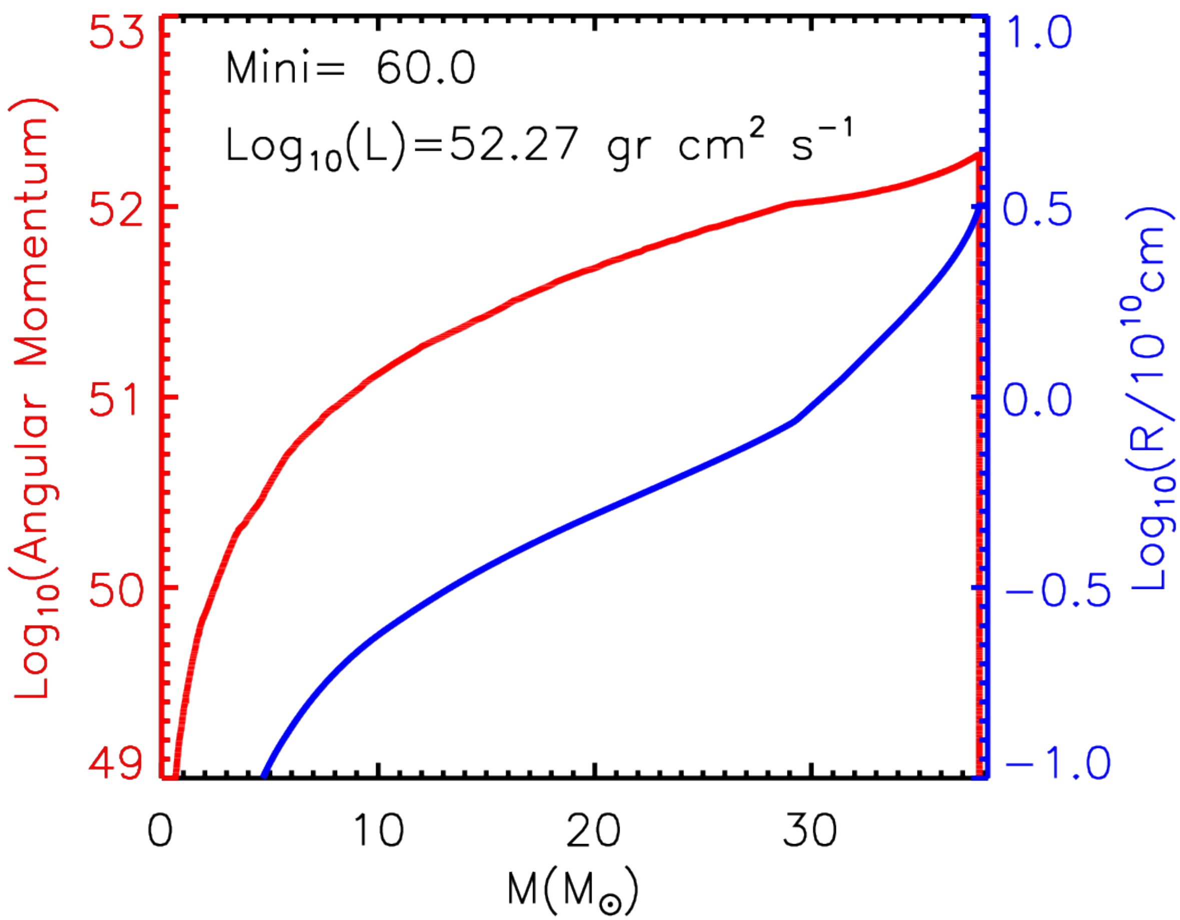


Figure 10 Internal structure of 60 $M_\odot$ star just before making black hole of 38 $M_\odot$. Source: Chieffi 2019 priv.comm., Limongi & Chieffi 2018 ApJS 237, 13. **Spin $10^{52.27}$ erg s factor of $\sim$ $10^{0.21}$ over limit at 38 $M_\odot$. This excess is similar for other masses. Maximal differential rotation.** **Massive stars often in quadruple systems –> two merger sequence! Contrast between observations and LIGO data require spin-down, given by the magnetic wind.**

1 Jy 5 GHz Catalogue 1981:

S5 1803+784 and S5 1928+738 merging black holes

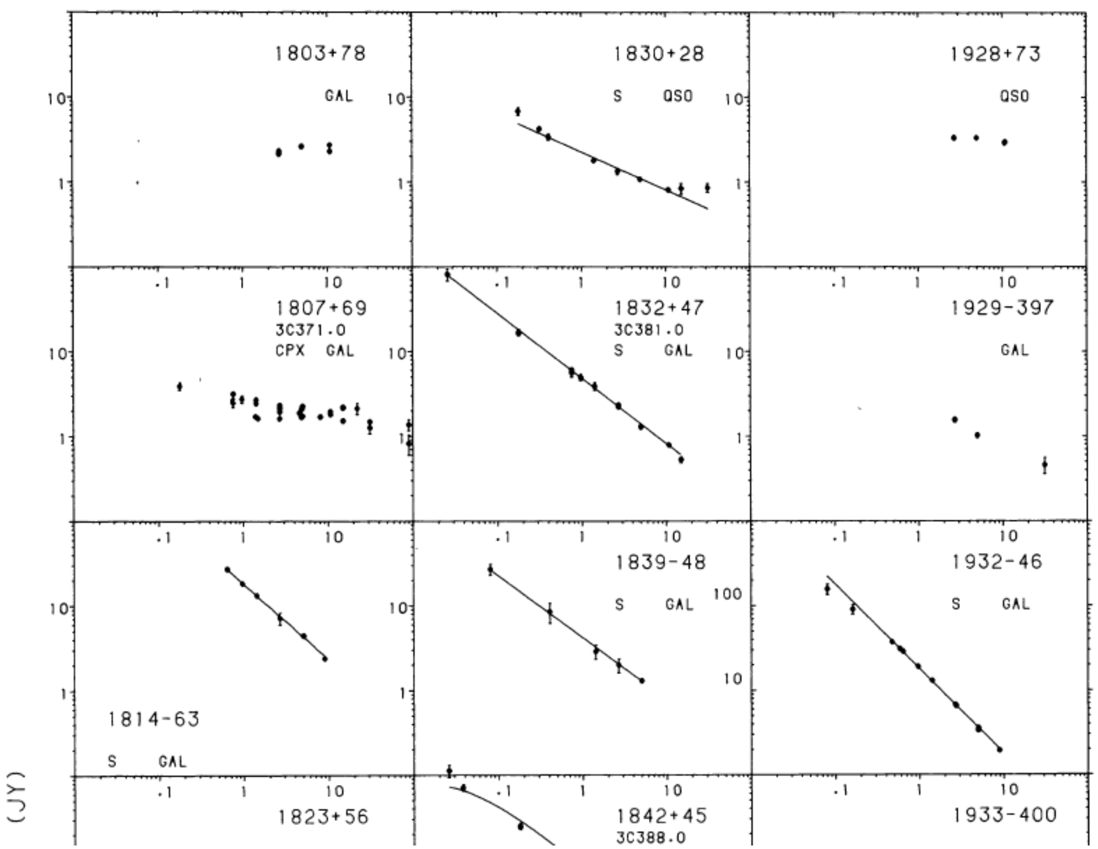


Figure 11 Spectra of the two sources S5 1803+784 and S5 1928+738; Half of all sources in this 5 GHz survey were "flat", and now we suspect all of them are SMBBHs soon to merge. Sources Kühr et al. 1981 AA.Suppl. 45, 367 (1 Jy cat. at 5 GHz) and 1981 AJ 86, 854 (S5 survey at 5 GHz, fifth instalment).

Two spectra of SMBHs soon to merge

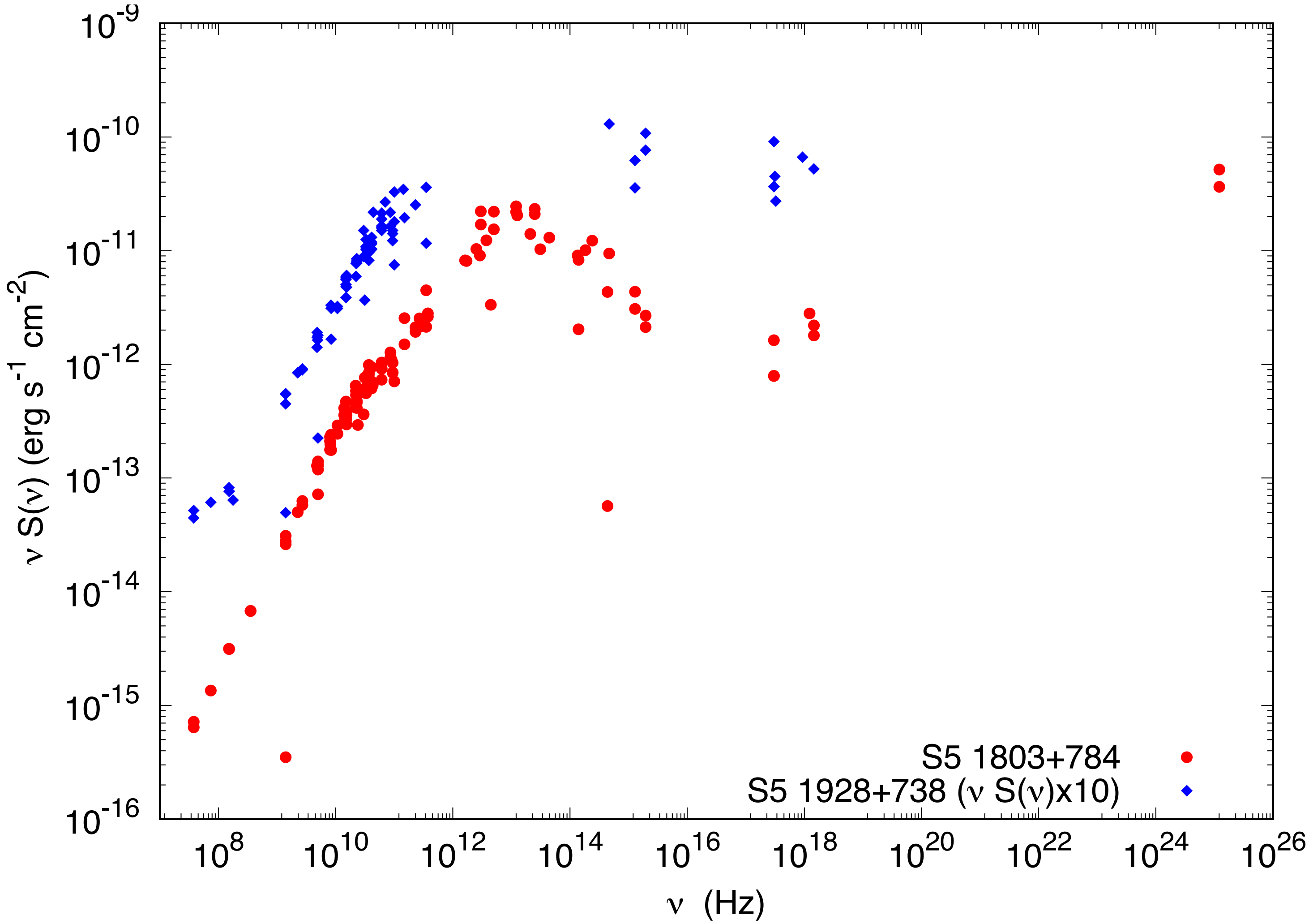


Figure 12 The spectra of the sources S5 1803+784 and S5 1928+738; plotted is νS_ν, i.e. luminosity versus frequency, **shifted wrt each other**. TeV corresponds to about $10^{26.4}$ Hz. Composed by E. Kun. Source NED.

S5 1928+738 VLBI structure: precession

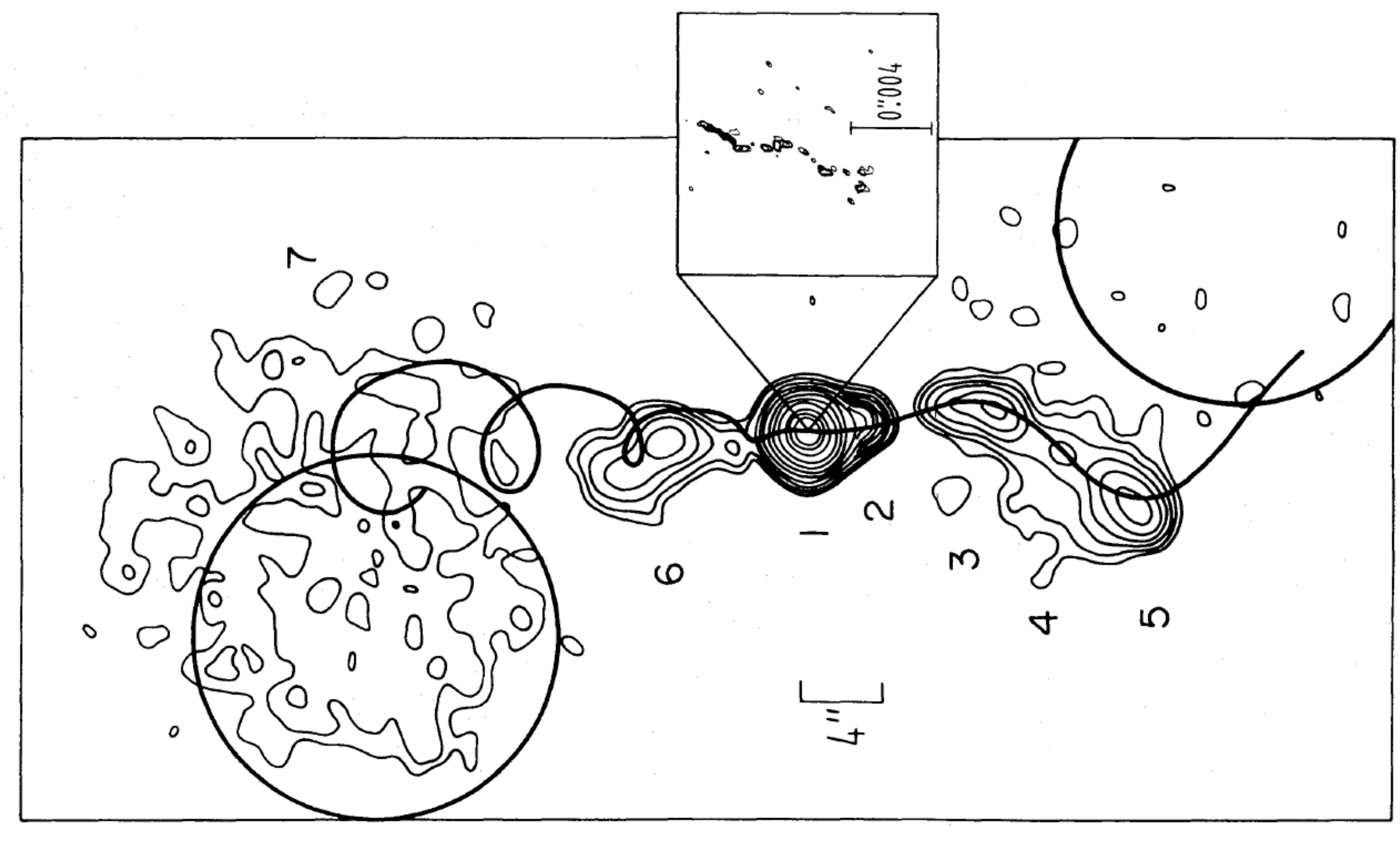


Figure 13 The VLBI spatial structure of S5 1918+738 showing the precession cone. Source Hummel et al. 1992 AA 257, 489

Stars + their winds around SMBBH −> torus

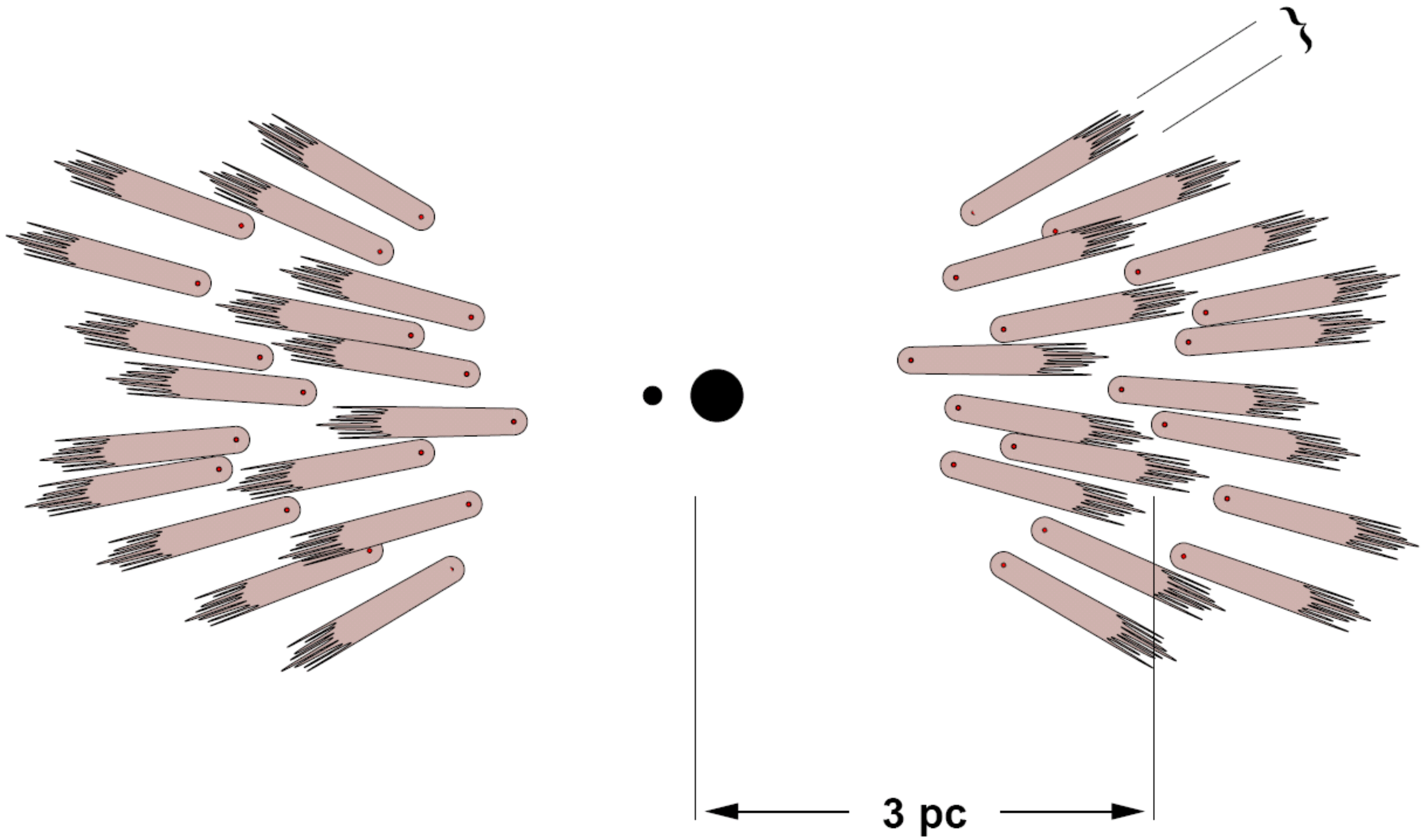


Figure 14 This figure illustrates the spatial structure of the red giant stars with winds torqued by the binary black hole system. This can explain the properties of the torus observed. **Curly bracket: Width of wind 0.004 pc**. Source: Zier & PLB 2001 AA 377, 23; 2002 AA 396, 91

Reminder: Orbital spin wins in a merger

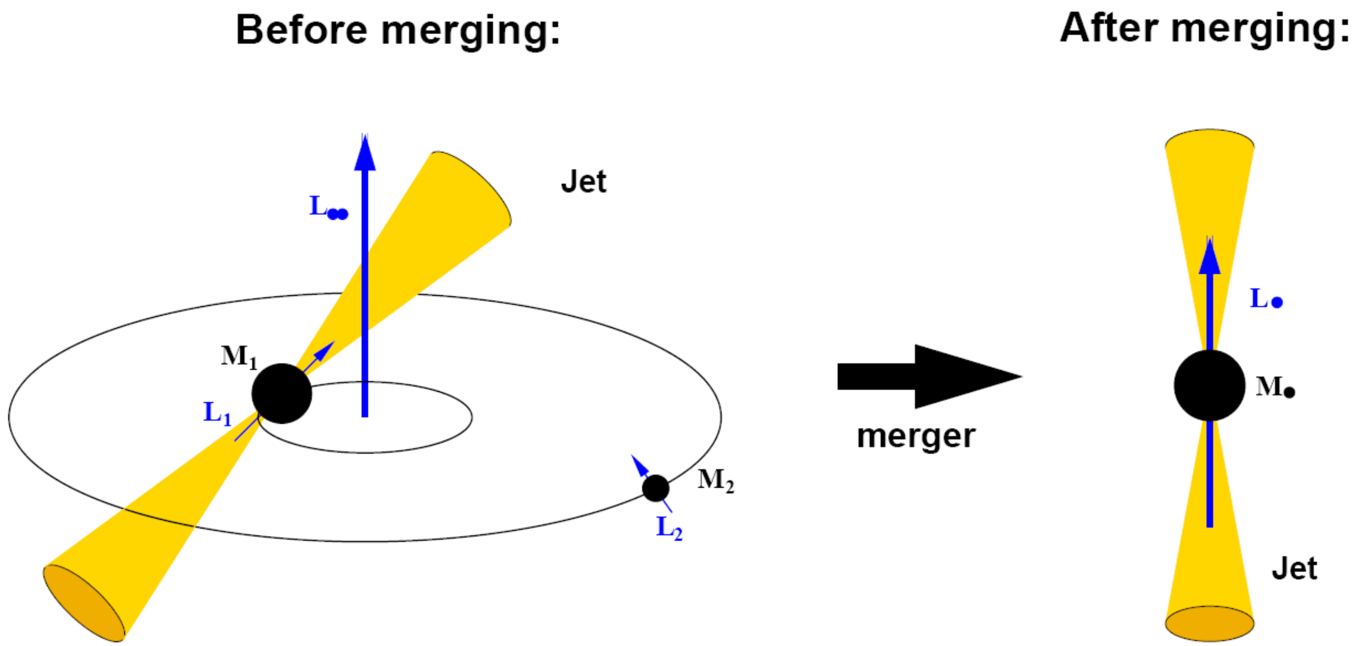


Figure 15 This figure illustrates the change of the direction of the spin of the BH, induced by the merger of 2 massive BHs, and consequently the change of the direction of the jet. Basically the orbital spin wins over the two intrinsic spins as the former is larger. The left panel shows the situation before the merger, when the jet is aligned with the individual spin of the primary black hole of the binary system (Zier + 2001 AA 377, 23; 2002 AA 396, 91).

Cen A: a recent merger with spin-flip

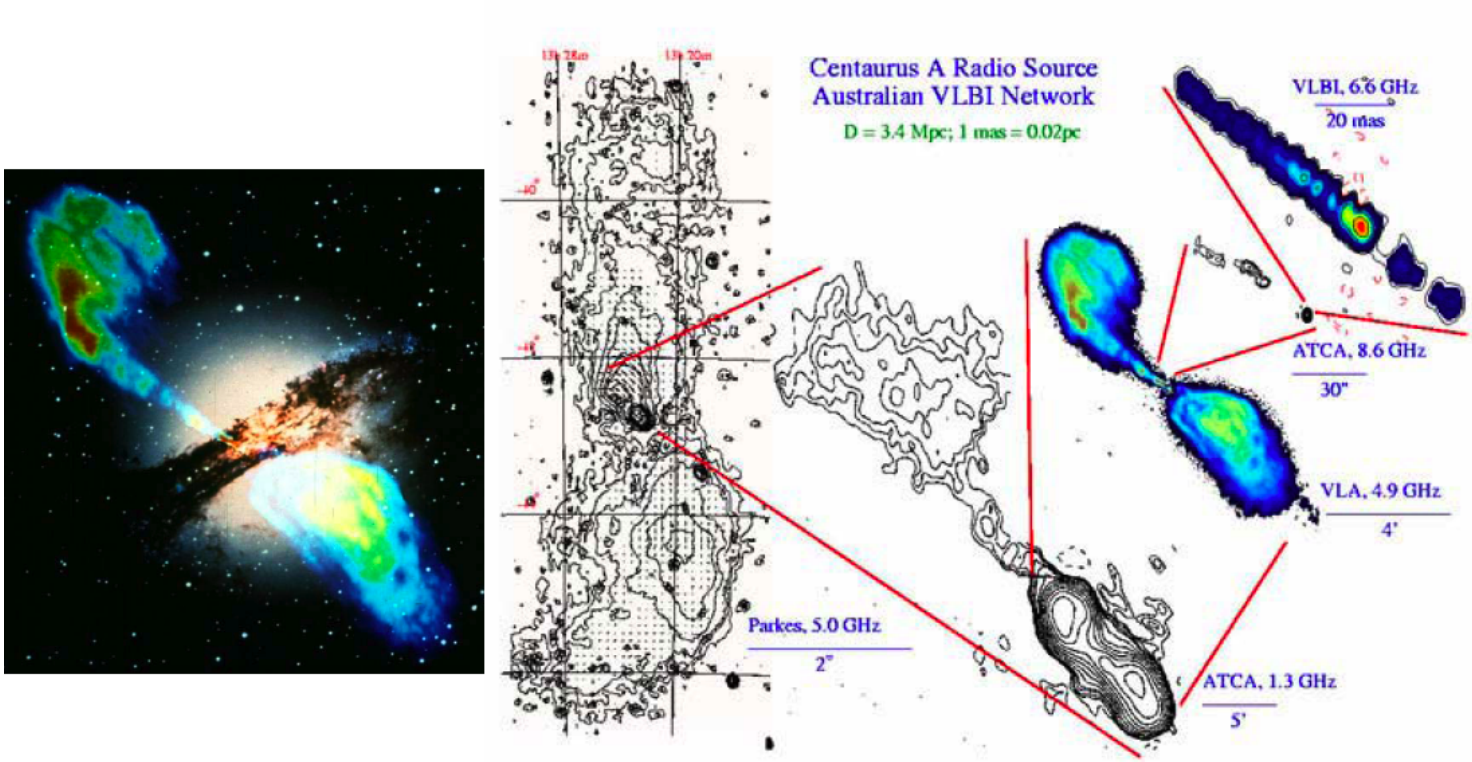


Figure 16 The radio galaxy Cen A with old and new structures, suggesting a spin-flip. **In such a merger do two BHs of spins near 1 merge to yield a new BH spin near 1? Do mergers then always yield near spin 1? Radio galaxy SMBH usually near maximal spin!** Source S. Britzen lectures. Spins can also cancel each other, see Keresztes & Gergely 2021 PRD (in press) for a detailed discussion.

M87: a recent merger with spin-flip

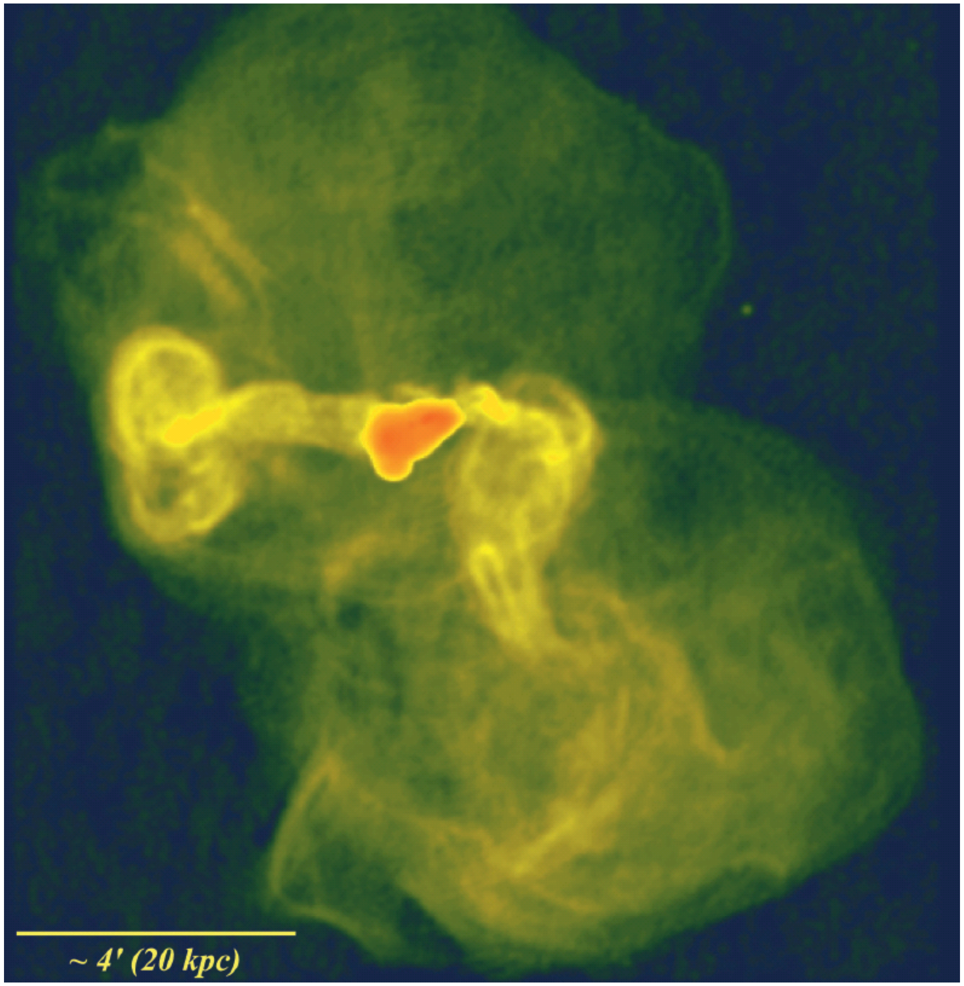


Figure 17 **The M87 jet and counter-jet, suggesting a spin-flip. Central SMBH probably near maximal spin.** Source Owen et al. 2000 ApJ 543, 611

M87: Magnetic fields close to the SMBH

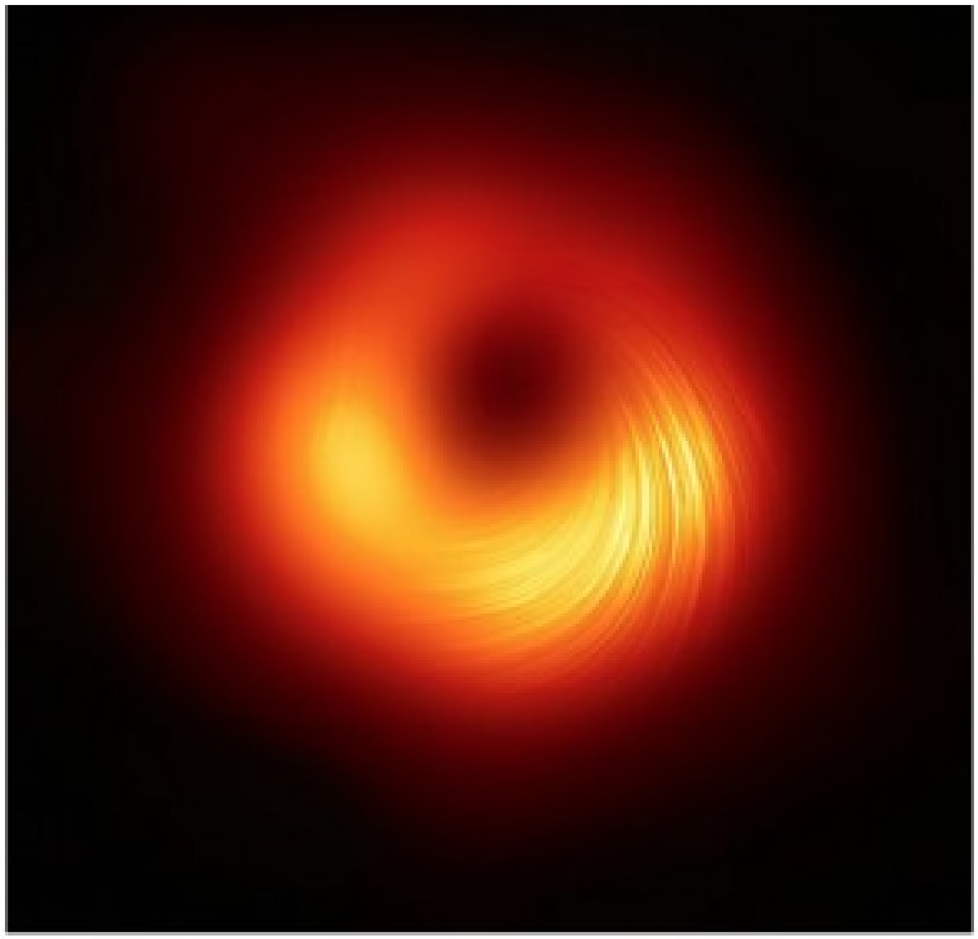
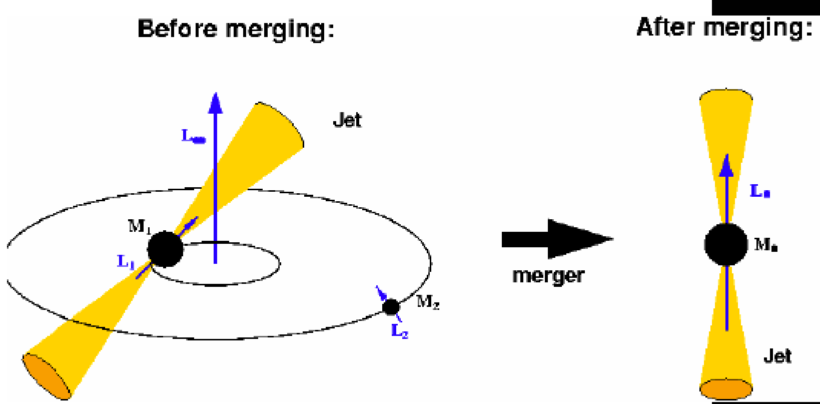


Figure 18 **The magnetic field structure close to the BH (”Field line plot”); it appears to be basically a Parker spiral with about the same strength of the magnetic field in terms of $B * r$ as in RSNe, and with B_ϕ locally to be roughly similar to B_r. By analogy with RSNe $->$ angular momentum transport! Source EHT-Coll. 2021 ApJL 910, L12 + L13, Mar 24, 2021**

Radio galaxy NGC326 merging with spin-flip

- NGC 326
- Merging of Black Holes: Jets change their direction
- Jet-flip due to Spin-flip of the primary Black Hole



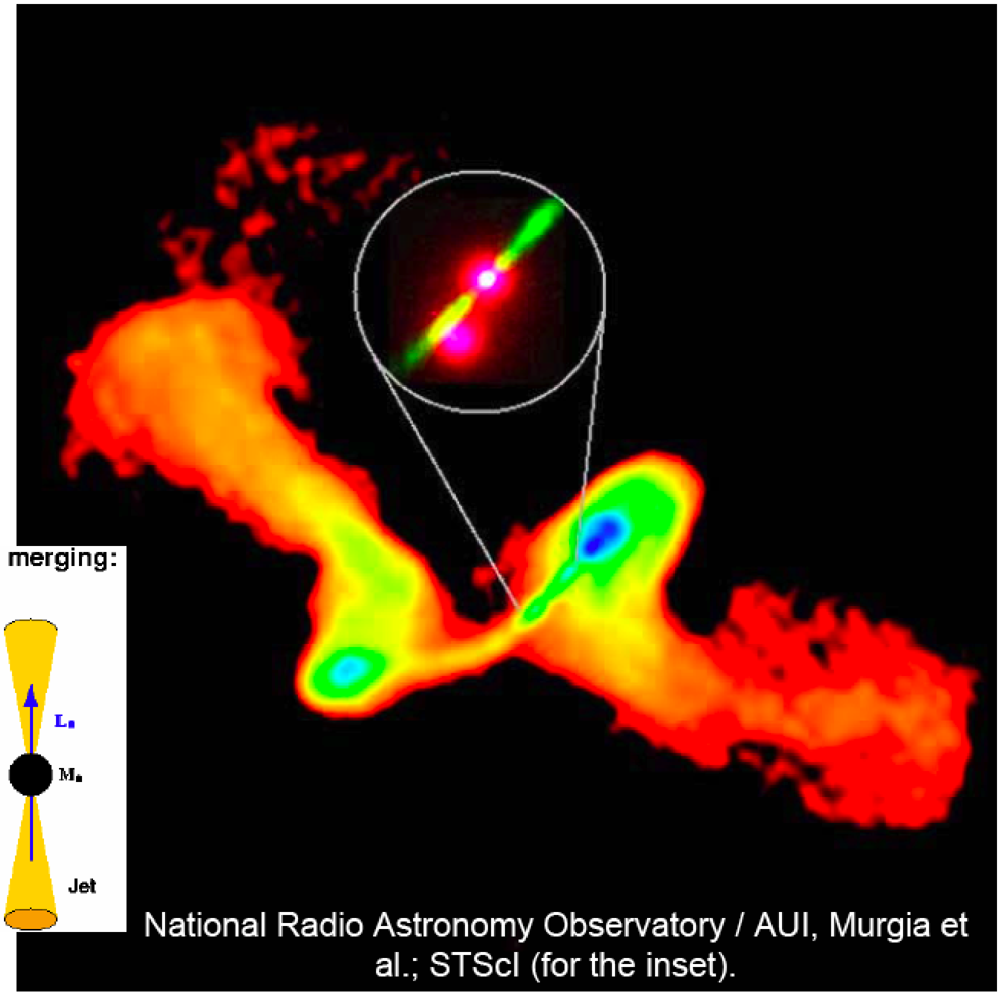


Figure 19 The radio galaxy NGC326 and its merger. Source Lecture S. Britzen. Insert Zier & PLB 2001 AA 377, 23; 2002 AA 396, 91

Auger Sky: starbursts and AGN I

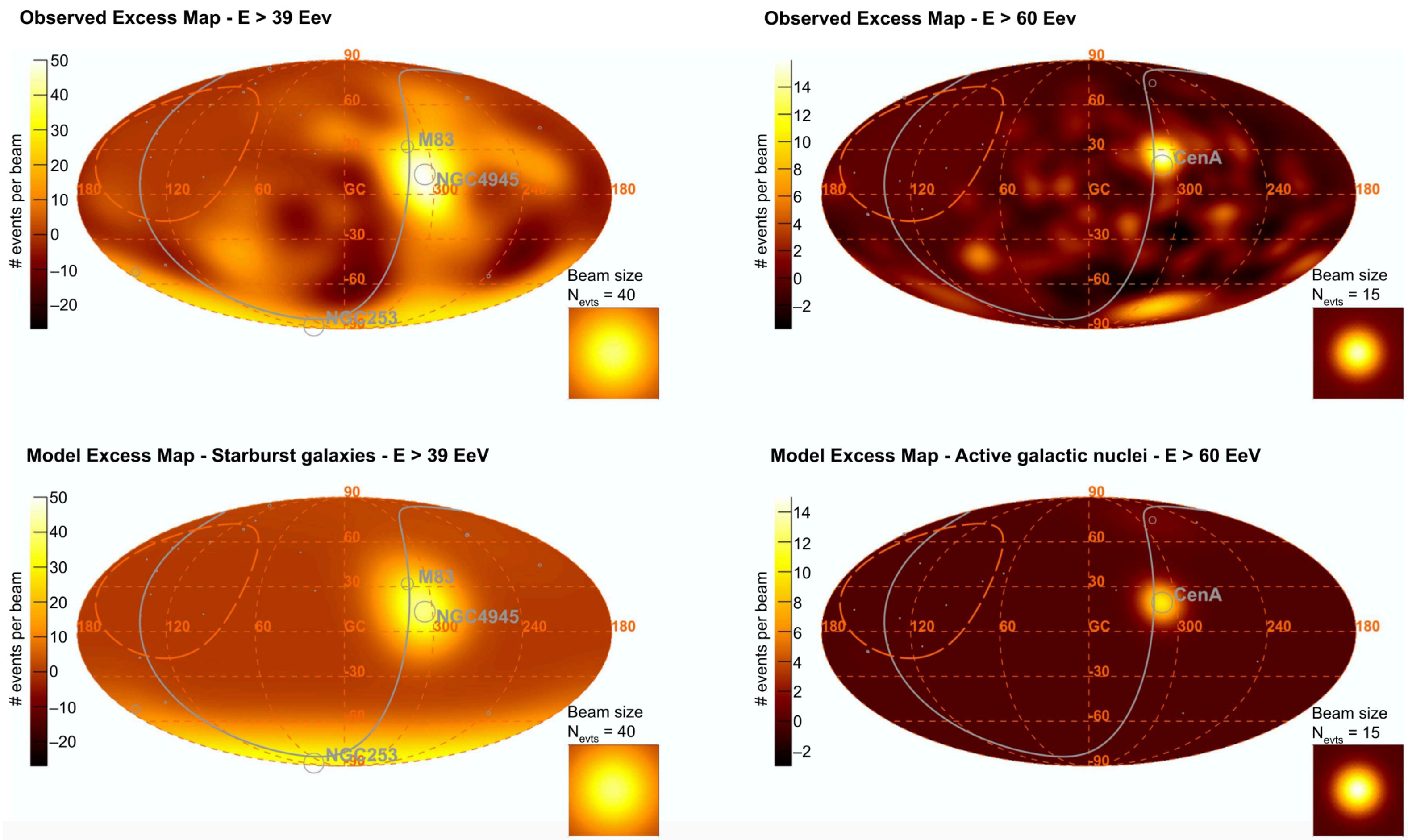


Figure 20 Auger sky in starbursts and AGN. Source Auger-Coll. 2018 ApJL 853, L29. **Top three starbursts M82, N253 and N4945; top three radio galaxies N5128 = Cen A, M87 = Vir A, N1316 = For A (all three already predicted by Ginzburg & Syrovatskij 1963 Astr. Zh. 40, 466); FSRQ only one close enough, N1275 = Per A.** Source Caramete PhD thesis 2016.

Auger Sky: starbursts and AGN II

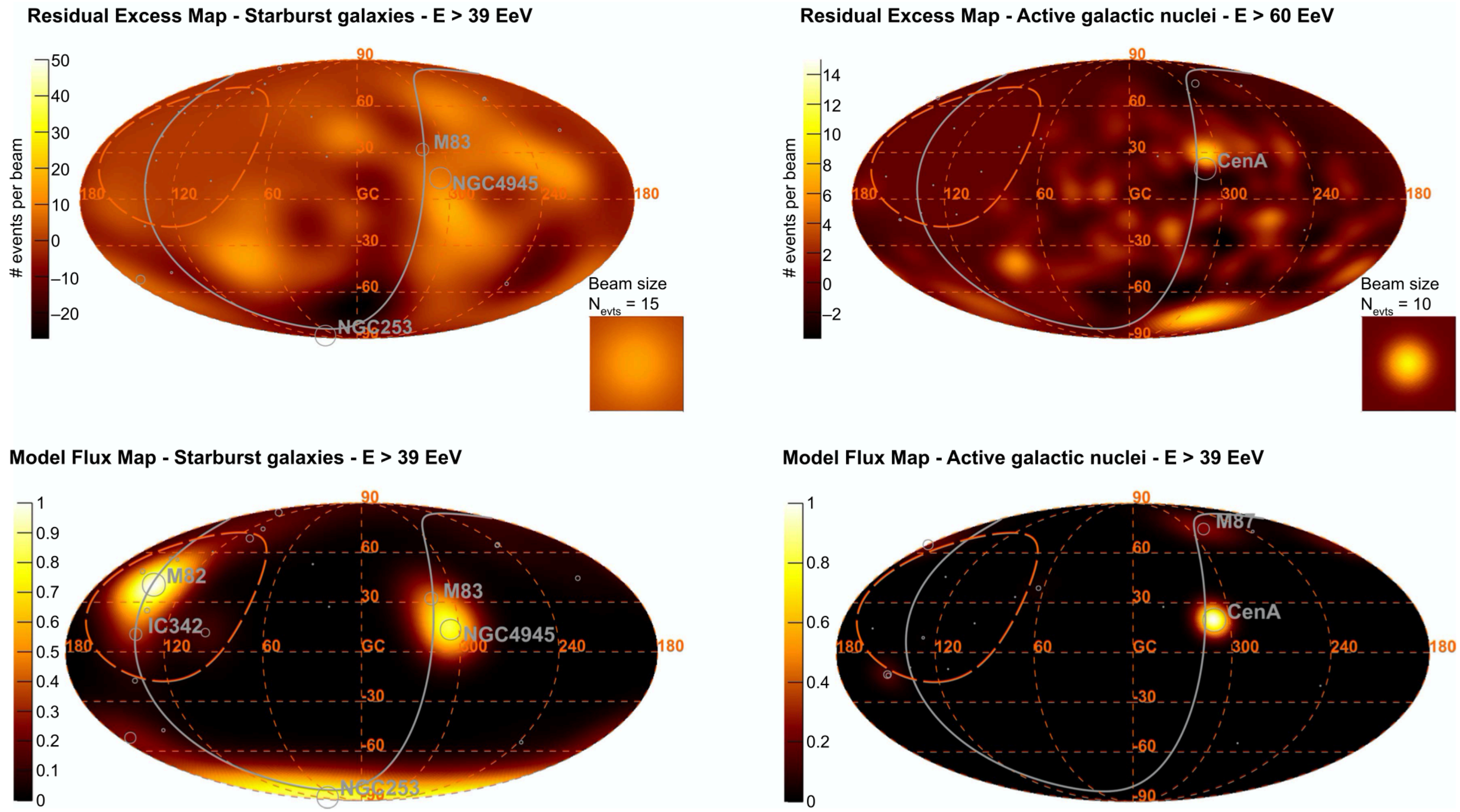


Figure 21 Auger sky in starbursts and AGN. Source Auger-Coll. 2018 ApJL 853, L29. **Top three starbursts M82, N253 and N4945; top three radio galaxies N5128 = Cen A, M87 = Vir A, N1316 = For A (all three already predicted by Ginzburg & Syrovatskij 1963 Astr. Zh. 40, 466); FSRQ only one close enough, N1275 = Per A.** Source Caramete PhD thesis 2016.

Merging BHs with jet interaction: Neutrinos

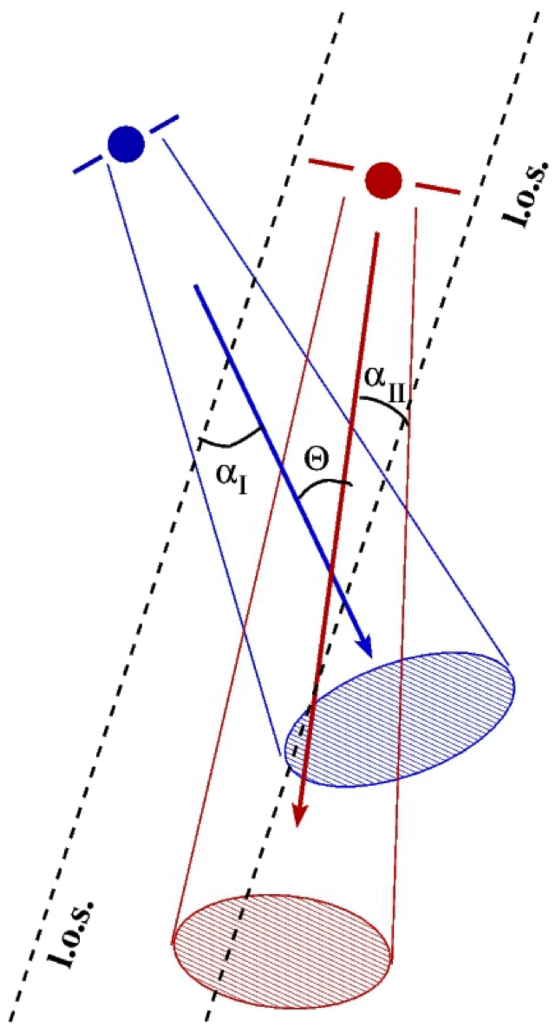


Figure 22 Jet interaction during a merger of SMBHs, TXS0506+056. Source Britzen et al. 2019 AA 630, A103

Precessing jets of merging BHs planting a ring

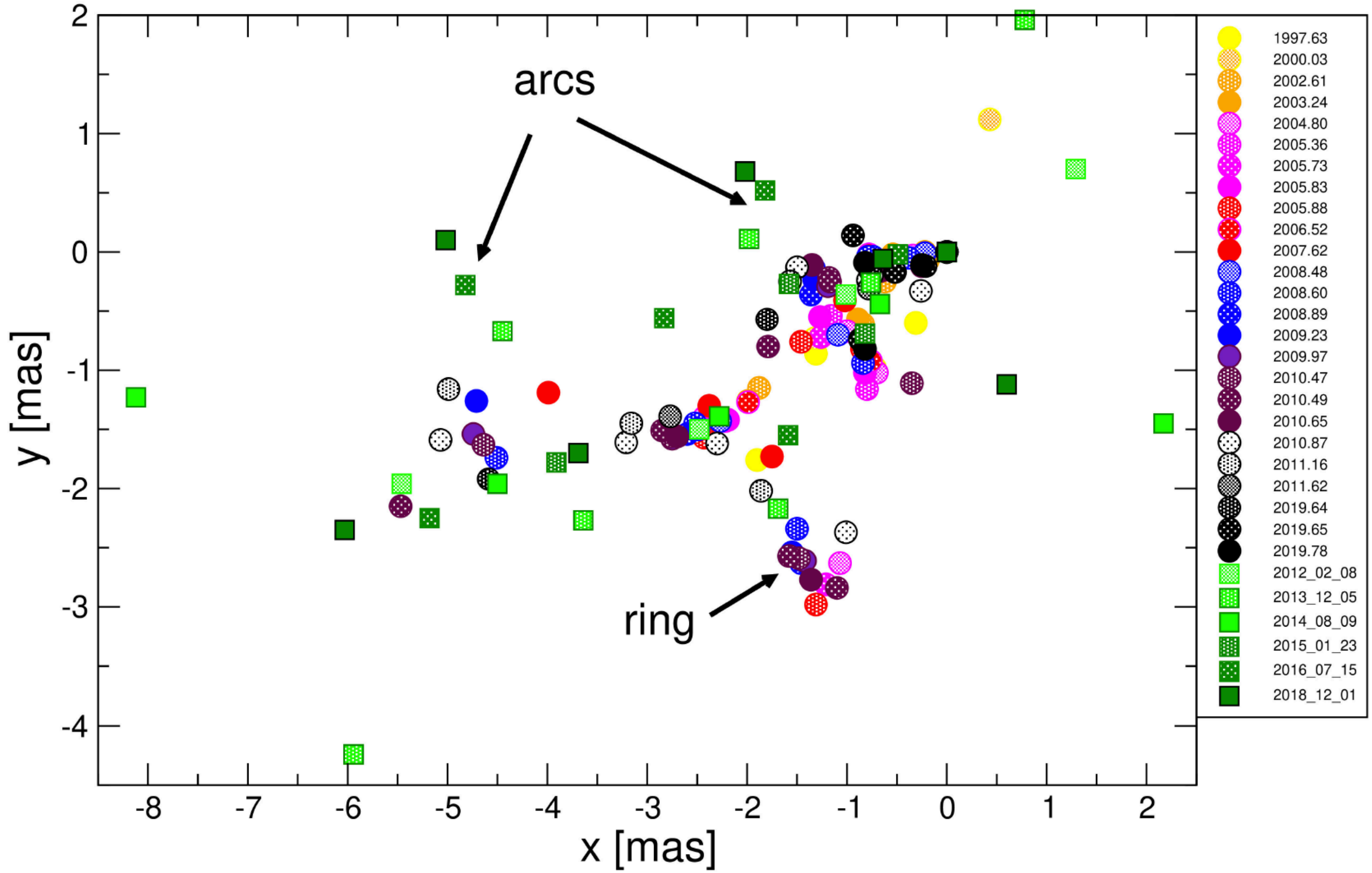


Figure 23 Jet precession plants a ring, PKS1502+106+056. Source Britzen et al. 2021 AA (in press) 2103.00292

Jet precession with quasi-periodic neutrinos

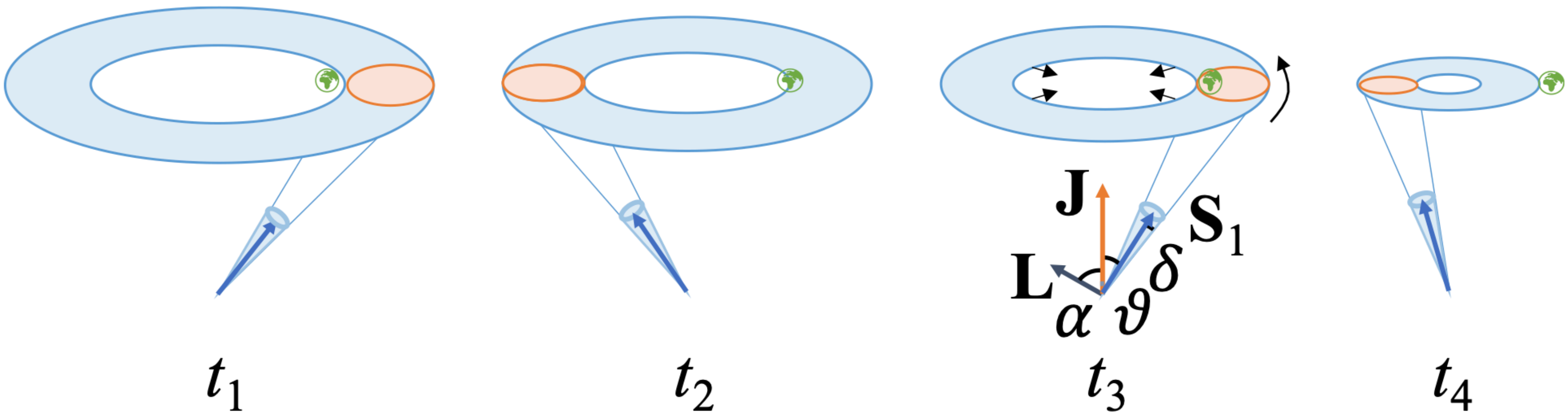


FIG. 2. Representation of the signal-structure an AGN jet that recurrently points at Earth. Four time steps are shown, indicating that the periodicity of the events seen from Earth decrease with time

Figure 24 **Periodic precession with neutrinos. Small green symbol denotes Earth. Allows to predict neutrinos and then merger event.** Source de Brujn et al. 2020 ApJL 905, L13, A103

High density gamma-ray opacity with UHECRs –> neutrino production

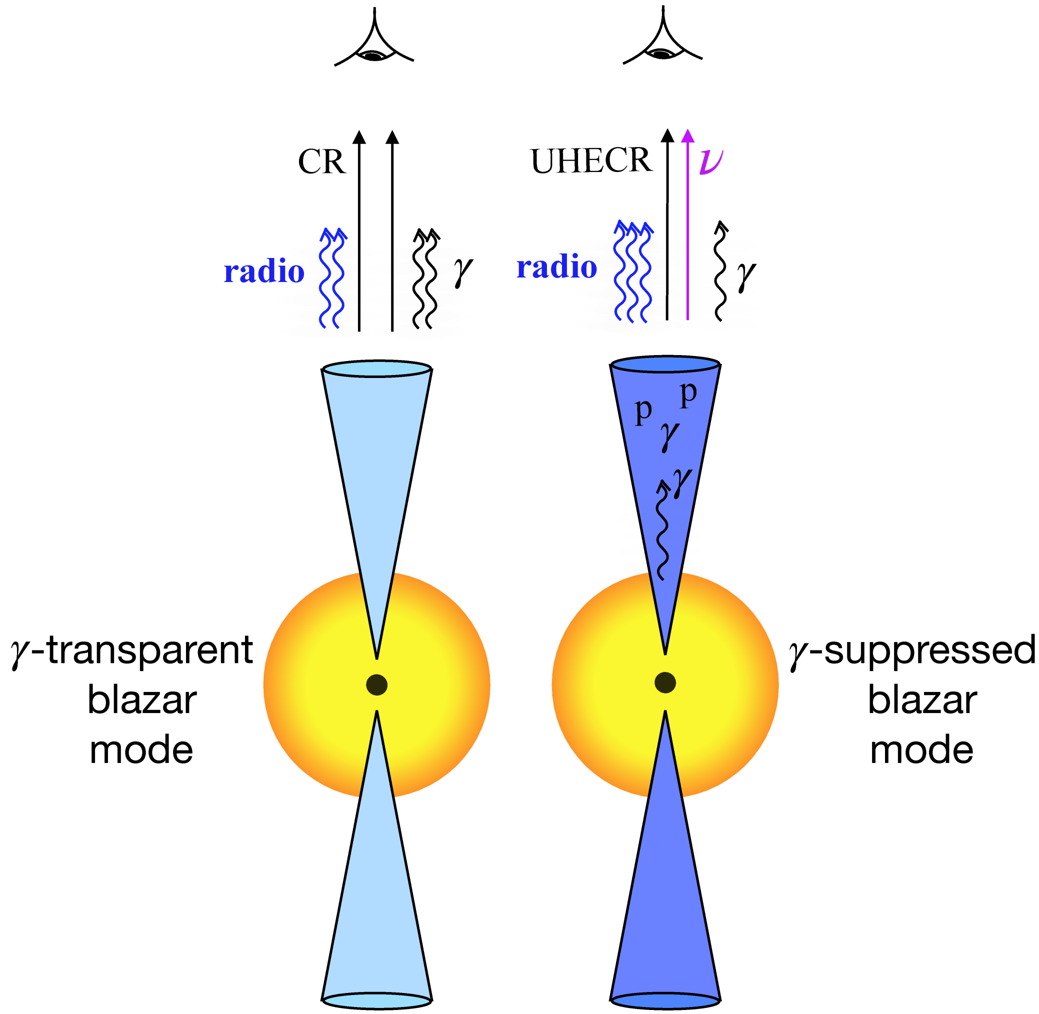


Figure 25 **gamma ray flare –> high gamma opacity –> neutrino production.** Source Kun et al. 2021 ApJL (in press) 2009.09792

High density gamma-ray opacity with neutrino production: Dips

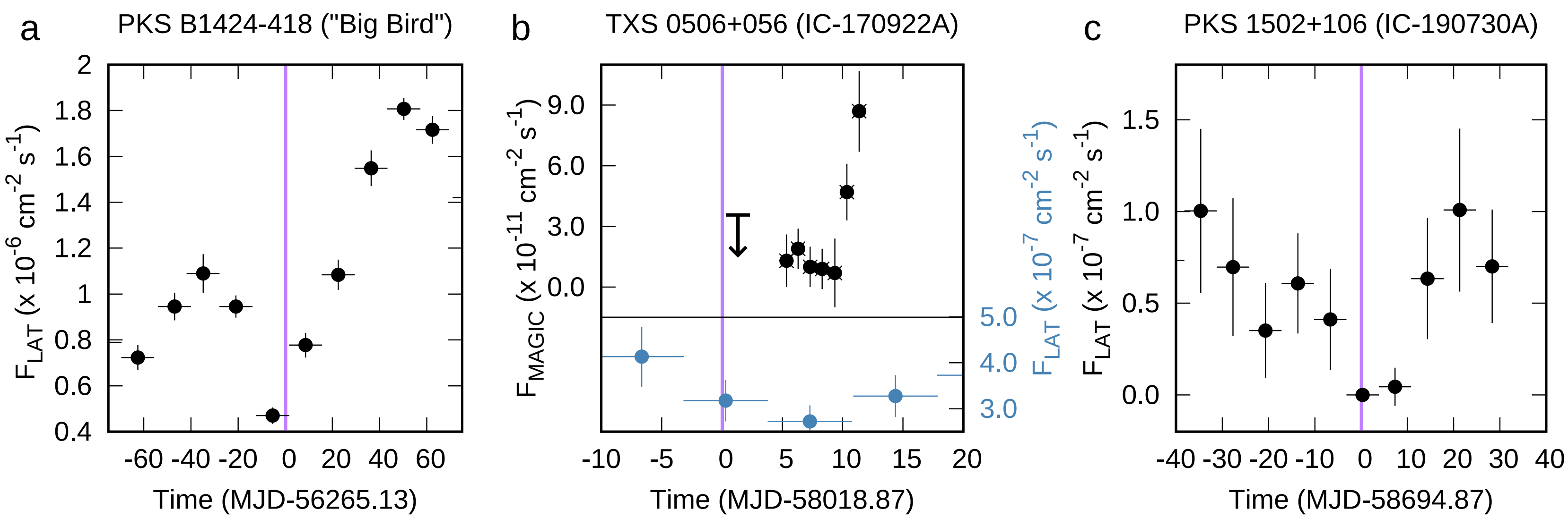


Figure 26 **gamma ray flare −> high gamma opacity −> neutrino production: Dips.** Source Kun et al. 2021 ApJL (in press) 2009.09792

TA Coll. blob in sky in Perseus-Pisces region

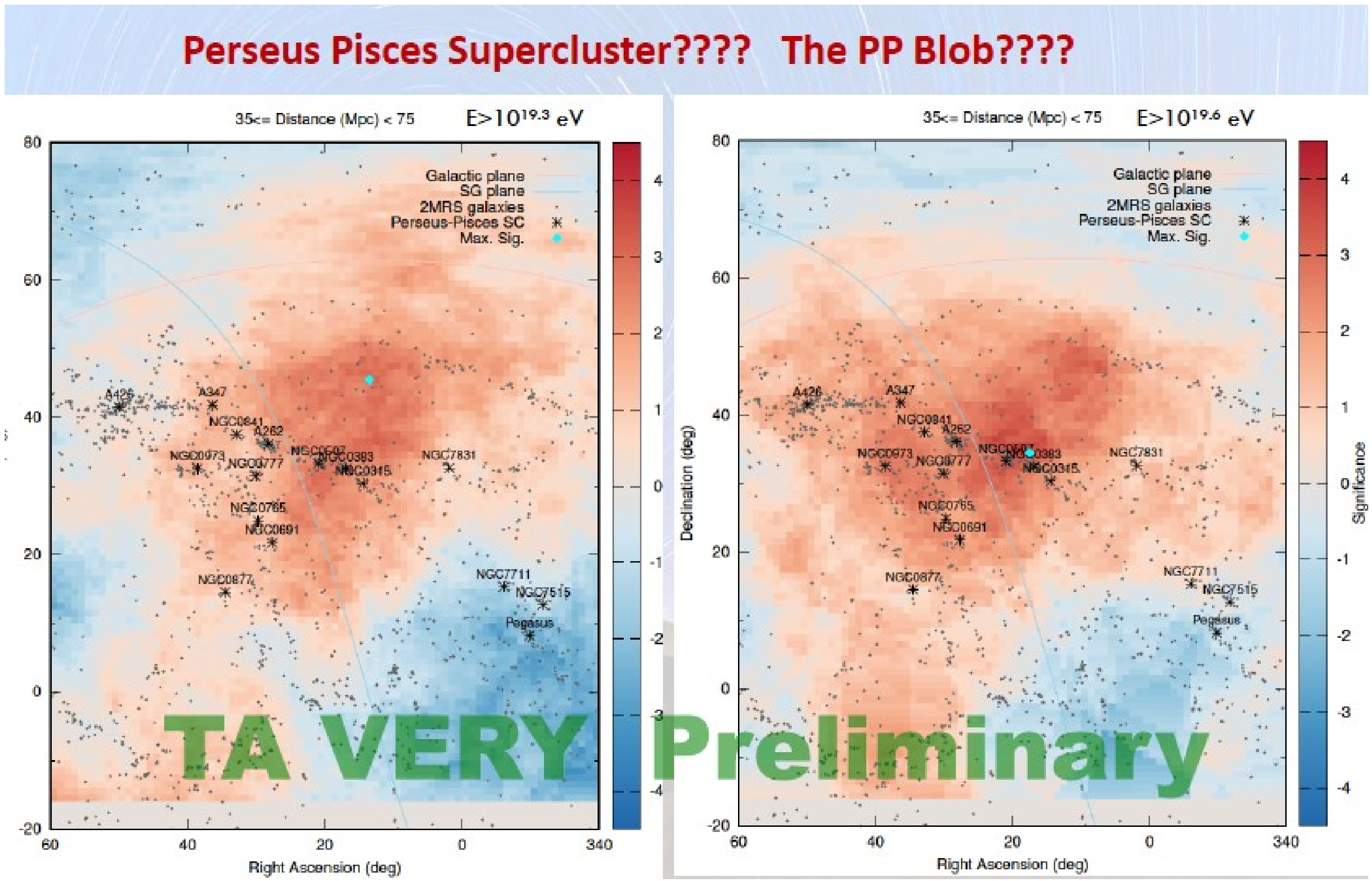


Figure 27 **Blob of possible arrival direction near famous radio galaxies N1275, N383 and N315. N1275 is strongest near flat spectrum radio galaxy. N383 sits in group of galaxies that has structure of spindle, with jets pointing along spindle's axis. N315 extends through accretion shock of LSS filament (Ensslin et al. 2001 ApJL 549, L39).** Source TA-Coll. COSPAR meeting 2020

Cosmic ray spectrum, knee at $\simeq 3 \cdot 10^{15}$ eV and ankle at $\simeq 3 \cdot 10^{18}$ eV, believed to be transition to extragalactic CRs

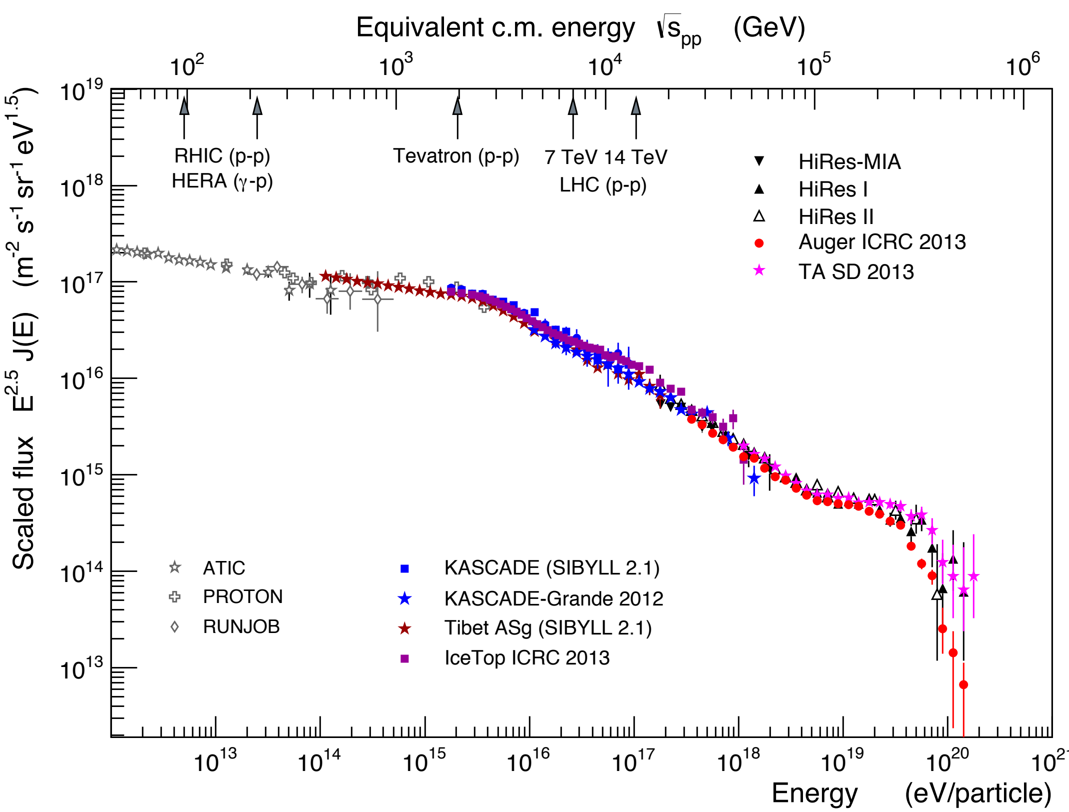


Figure 28 Overall spectrum of cosmic rays, the classical High Energy Particles (HEP). **We suspect that many SN-explosions contribute flux at the features; by Hillas' (1984 ARAA 22, 425) argument their value of $B_{\phi} \times r = const(r)$ must be the same in all contributing SNe. It fits.** Source R. Engel 2016.

Predict for near maximal BH spin in mergers:

- **Allen 1999 RSNe: $B_\phi \times r \simeq 10^{16.0 \pm 0.12}$ Gauss cm: Parker 1958 limit! Blue Super Giant stars.**
- **About the same $B_\phi \times r$ in M87 BH ring.**
- **SN-formed BHs, M87 BH, radio galaxy BHs all consistent with near maximal spin BH**
- **Hillas $->$ GCR knee, ankle, pevatrons +.**
- **Massive star system often quadruples, all making BHs, naturally two merger sequence**
- **$B_\phi \, B_r$ spin down BH pairs (Weber & Davis 1967): plus spin down from GW emission.**
- **BH merger M82 $->$ UHECRs, seen by TA.**
- **BH merger MCG+08-11-002 ? Fly's Eye!**
- **FSRQ all candidates to be SMBH mergers**
- **BHs: GCRs, UHECRs, HE γs, HE νs**

THANK YOU

Title: 40 years of observing mergers of spinning black holes

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The starburst galaxy M82 is showing us (i) the Radio-Super-Novae (RSNe) from exploding stars that make black holes, mostly former Blue Super Giant Stars, and (ii) a merger of such black holes, cleaning out the ISM in a precession cone during the spin-flip leading up to the actual merger. As such stars often come in quadruples, a two merger sequence can follow, helped by the magnetic field orbital angular momentum loss. The merger rate deduced is consistent with the rate determined by LIGO/VIRGO.

We identify the RSNe as the sources of Cosmic Ray (CR) particles across the knee and to the ankle, demonstrating where PeV CRs come from, so what the Pevatrons are. The CR knee and ankle energy may be quantitative testimony to the spin-down of near extremal stellar mass black holes. The BH merger shows where the starburst contribution of UHECRs come from, as detected by Fly's Eye, TA and Auger. Flat Spectrum Radio Sources (now many known as blazars) correspondingly can be understood as the merger of two Super-Massive Black Holes (SMBHs). The spin-down of rapidly rotating black holes by their inherent magnetic fields matches the data from RSNe and radio galaxies, with the same magnetic field in terms of $B * r$, so the angular momentum transport $\sim M_{BH}^{1}$. This allows to understand the lower limit of the jet power of radio galaxies as pure spin-down power ($\sim M_{BH}^{0}$).

The new M87 polarization data are consistent with this concept, with about the same number for $B * r$. The enhanced feeding of particle acceleration during the spin-flip can explain High Energy (HE) gamma-ray, and HE neutrino emission, as detected by the Cherenkov TeV telescopes and IceCube. So blazars and radio galaxies (i.e. blazars not aiming at Earth with their relativistic jet) are one other source of UHECRs. For blazars we may be able to predict the actual BH merger. The directional correlations in the Fly's Eye, TA and Auger data are fully consistent with these two populations of sources (starburst galaxies and radio galaxies/blazars).

Literature: PLB et al. 2018 Adv.Sp.Res., 2019 Galaxies
Blandford & Znajek 1977 MNRAS, and later
Parker 1958 ApJ
Penrose 1971 Nature, and later
Piran 1975 to 2016 PRD
Weber & Davis 1967 ApJ