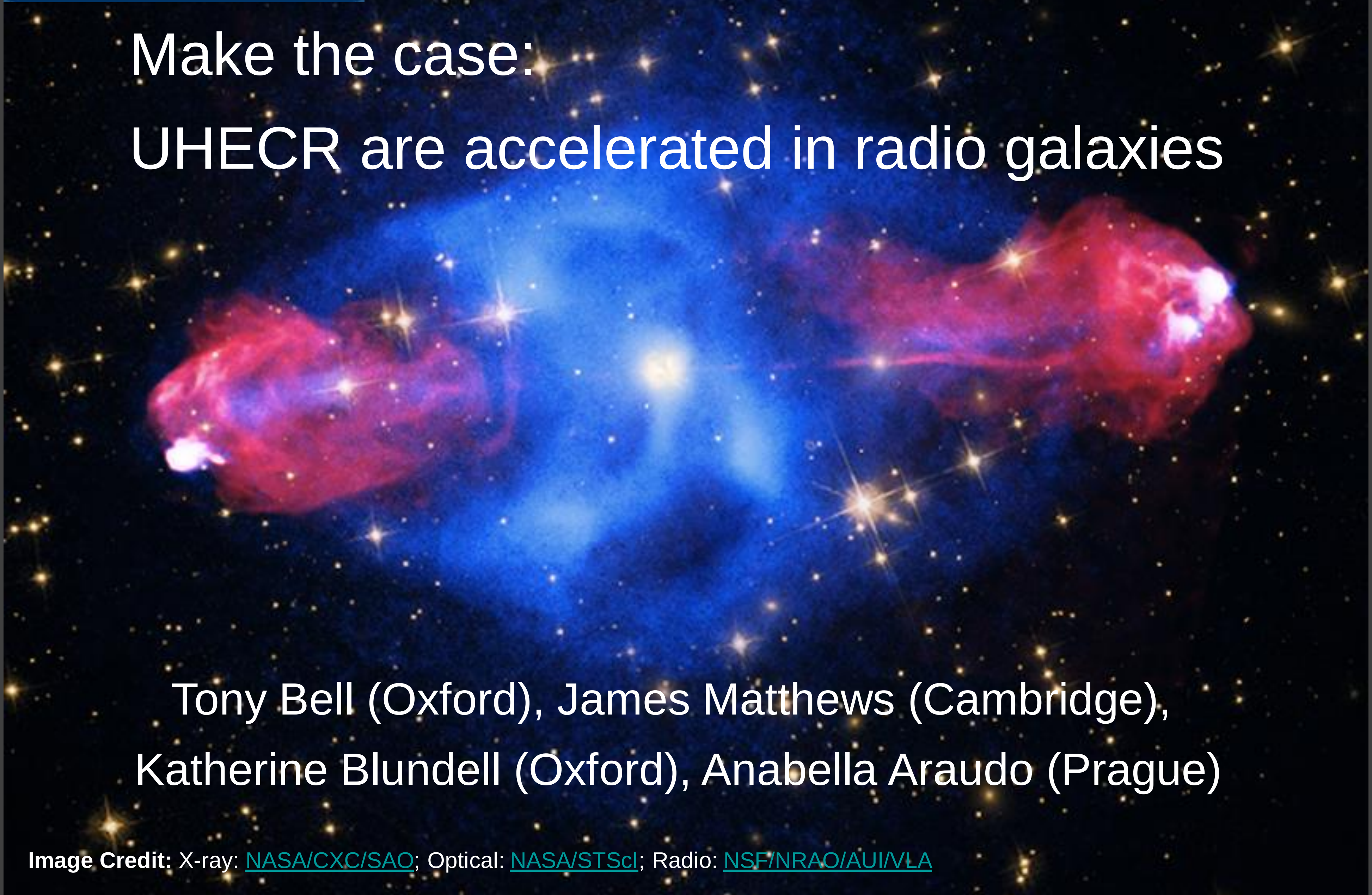
Make the case:

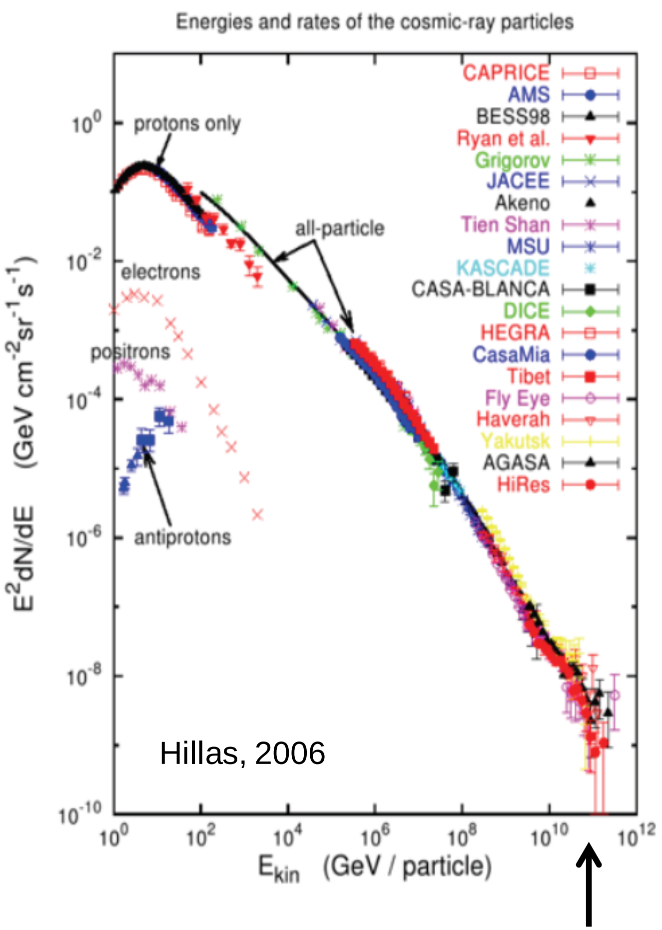
UHECR are accelerated in radio galaxies



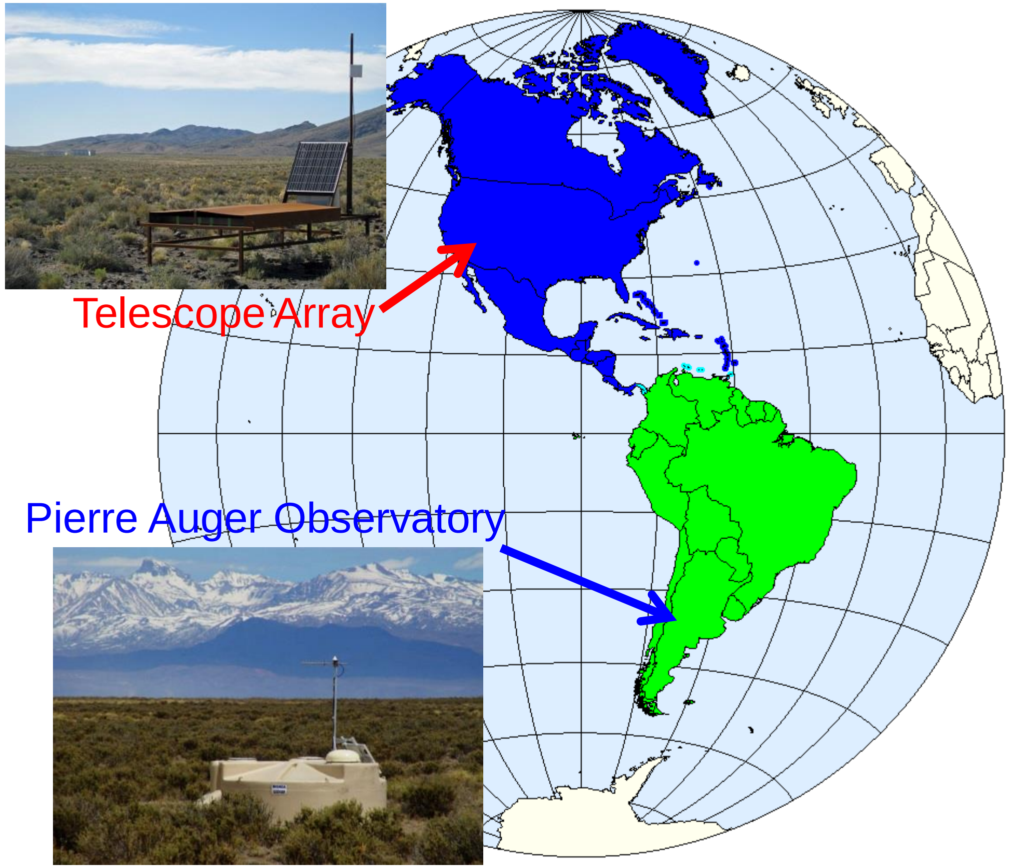
Tony Bell (Oxford), James Matthews (Cambridge),
Katherine Blundell (Oxford), Anabella Araudo (Prague)

Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA

Detections of ultra-high energy cosmic rays (UHECR)



One per square kilometre per century



Starbursts or radio galaxies

Teresa Bister for the Pierre Auger Collaboration 2021 Phys. Scr. 96 074003

Source catalogues

Association with starburst galaxies: 4.5σ

Association with active galaxies: 3.0-3.7σ

Individual sources

Association with Centaurus A: 3.9σ

Note: Starburst NGC4945 very close to Cen A

My aim: Make the case that UHECR are accelerated by radio galaxies

SOURCE POWER (Lovelace/Blandford/Waxman)

Magnetic energy passing through CR source (shock?): $P_{mag} = \left(\frac{B^2}{2\mu_0}\right) uL^2$

Combine with Hillas energy: $E = ZuBL$

Rearrange: power needed to accelerate CR to energy E

$$P_{source} > P_{mag} = \left(\frac{Z}{6}\right)^{-2} \left(\frac{E}{100EeV}\right)^{2} \left(\frac{u}{c}\right)^{-1} 4 \times 10^{42}\ \mathrm{erg\ s}^{-1}$$

Starburst galaxies

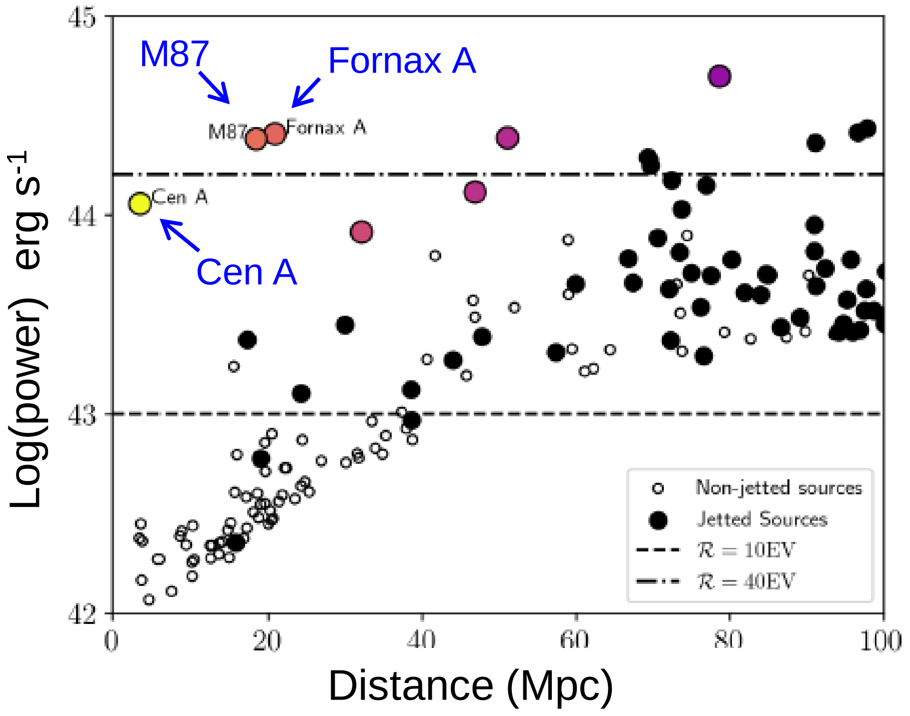
u ~ c/1000 – c/300

Power up to ~ 10^{43} erg s^{-1}

Anchordoqui 2017, Heckman et al 1990, Aab et al (Auger) 2018

Candidate radio galaxies for UHECR

Radio galaxies within 100 Mpc



UHECR from powerful radio jets?

Cygnus A is the archetypal radio galaxy

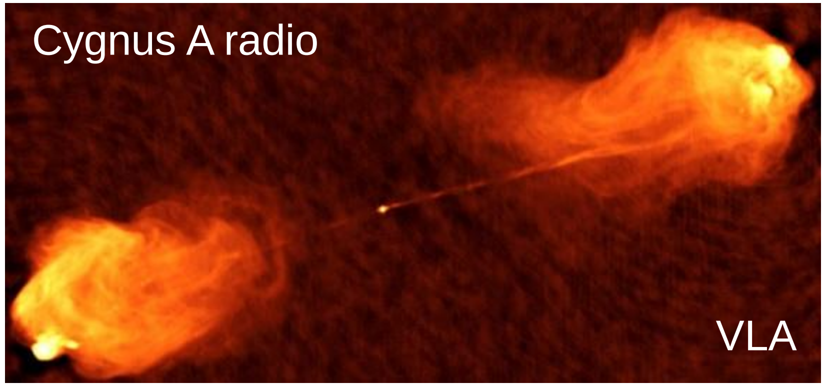
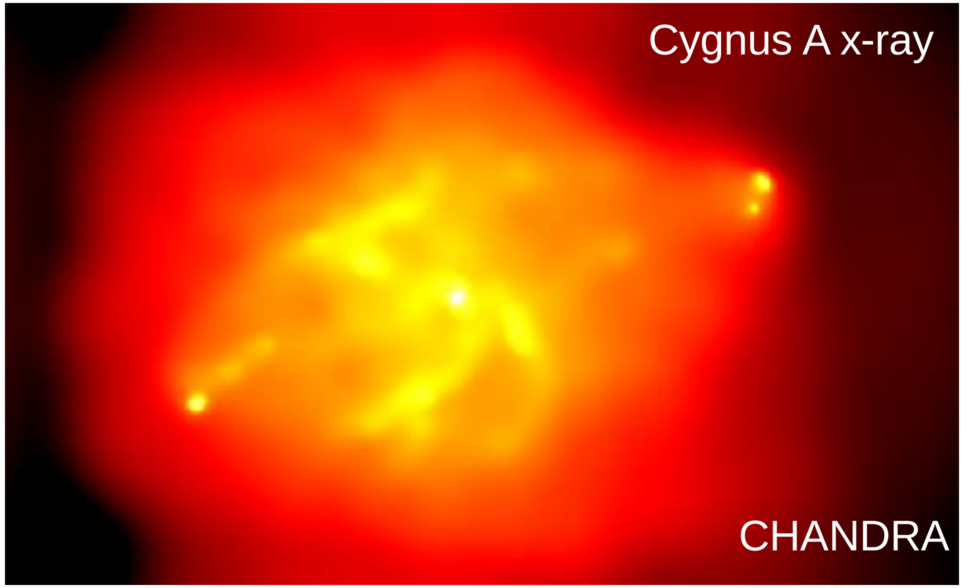


Image courtesy of NRAO/AUI



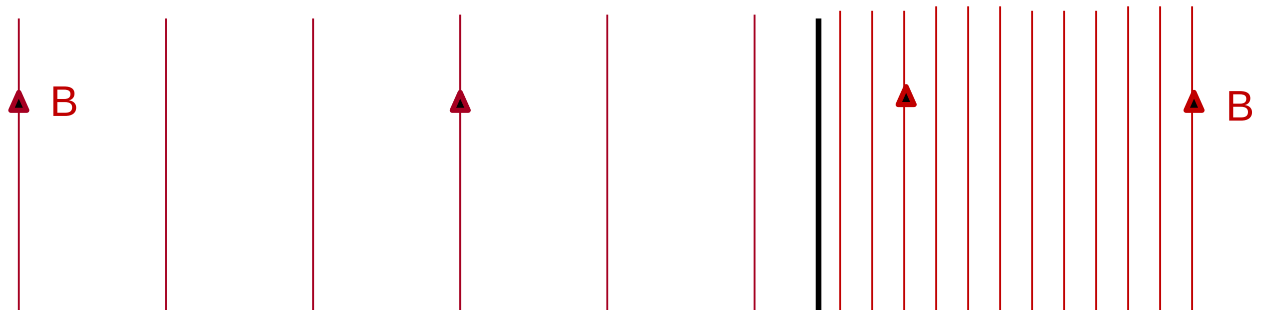
Credit: NASA/UMD/A.Wilson et al.

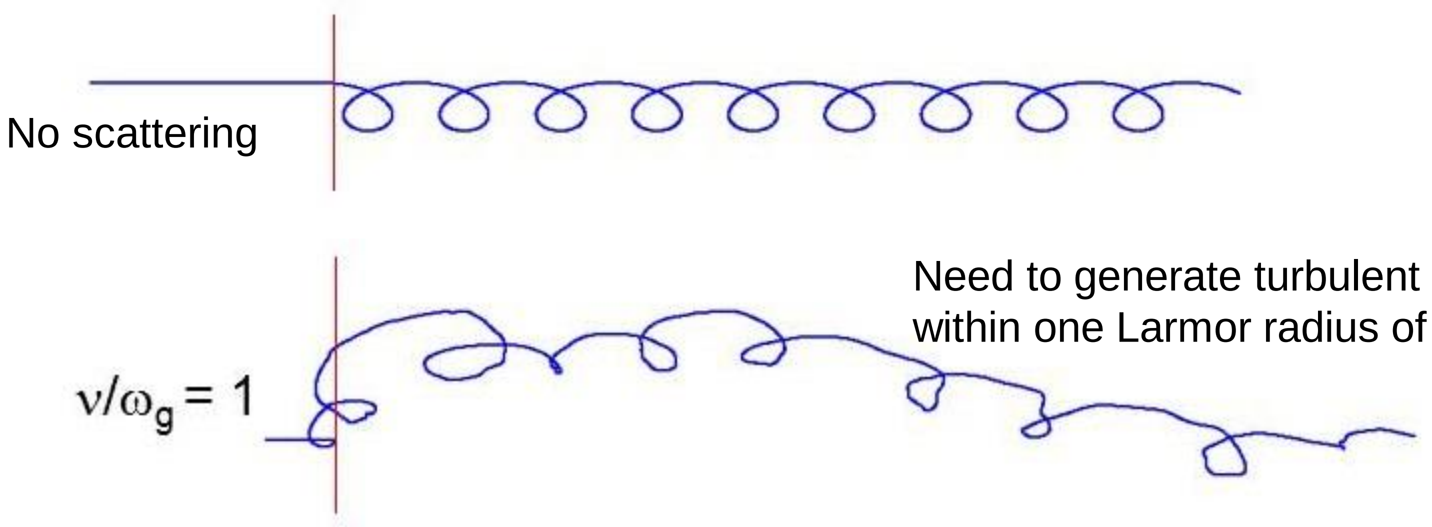
Power ~ 10^{46} erg s^{-1}
Jet velocity ~ c/3 - c

B~300 μG
L ~ 3 kpc
ZuBL ~ 300Z -1000Z EeV

High velocity shocks

Perpendicular relativistic shock – poor UHECR accelerator





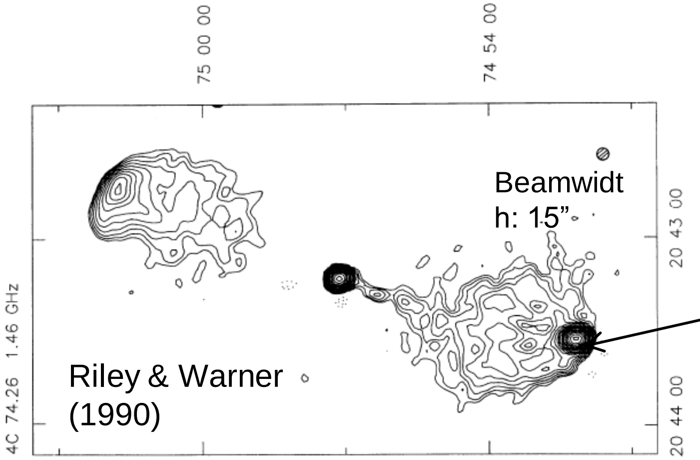
Need to generate turbulent field within one Larmor radius of shock

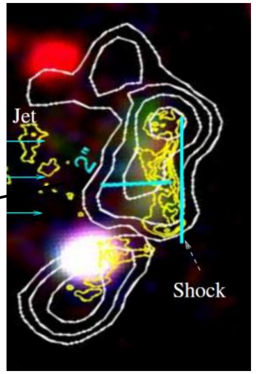
Not enough jxB to push plasma around in short time
See Bell et al (2018) for more detail

Similar effect found in PIC simulations of Weibel-mediated relativistic shocks
shock must be nearly unmagnetised
(Sironi, Spitkovsky & Arons 2013)

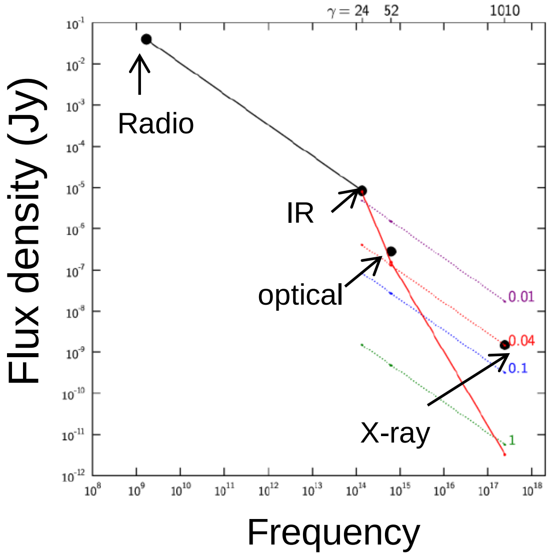
Quasar jet 4C74.26

(Araudo et al 2015)





Erlund et al 2010
Merlin telescope



Turnover in IR/optical: ~TeV electrons

Not due to synchrotron losses

Turnover applies to ions

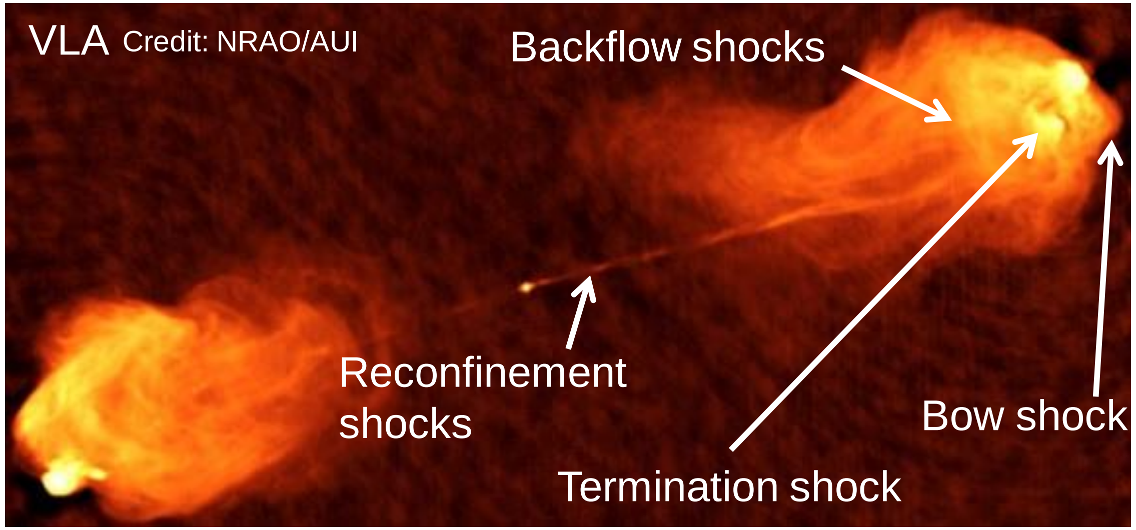
Feature of jet termination hotspots

Shocks in jet lobe backflows

Matthews et al 2018/19

Possible shocks in radio galaxies

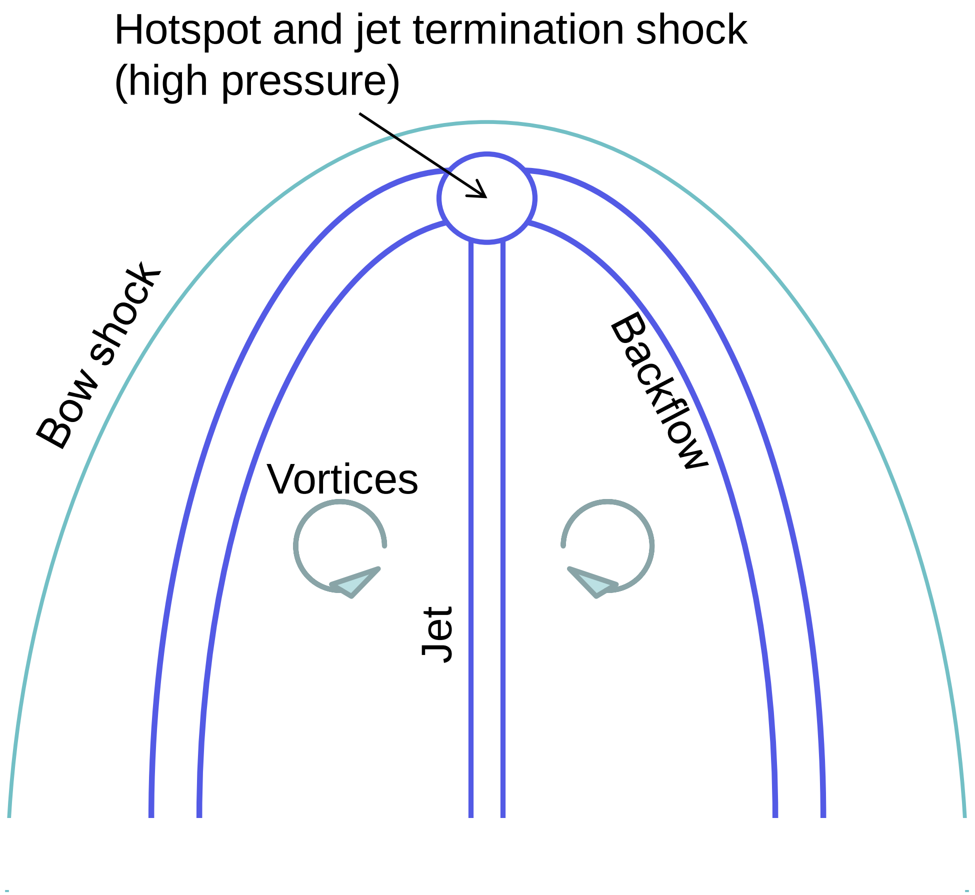
Cygnus A radio



Need shocks that are:

- High velocity but not relativistic
- Large & long-lived

Schematic diagram: flux tube

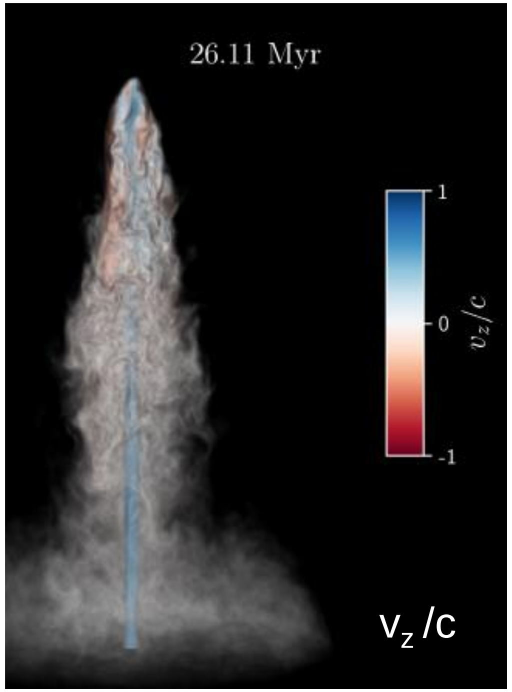


Backflow as Bernoulli flux tube

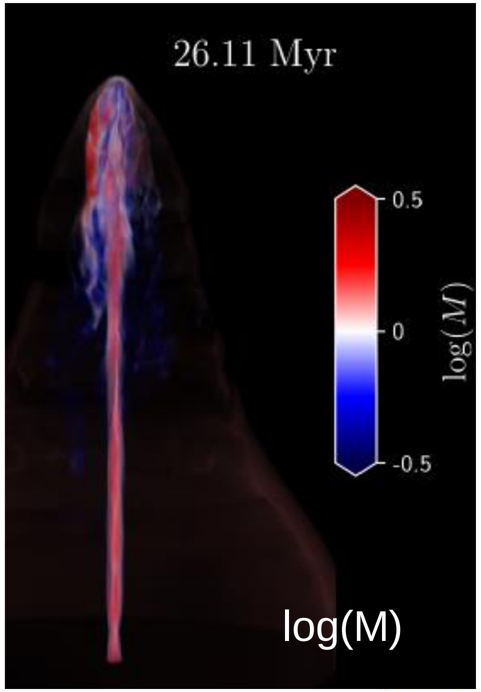
Flow out of hotspot:
pressure drops
sound speed drops
velocity increases
Mach number increases
→ shocks

Hydro simulations: The jet at 26.11 Myr

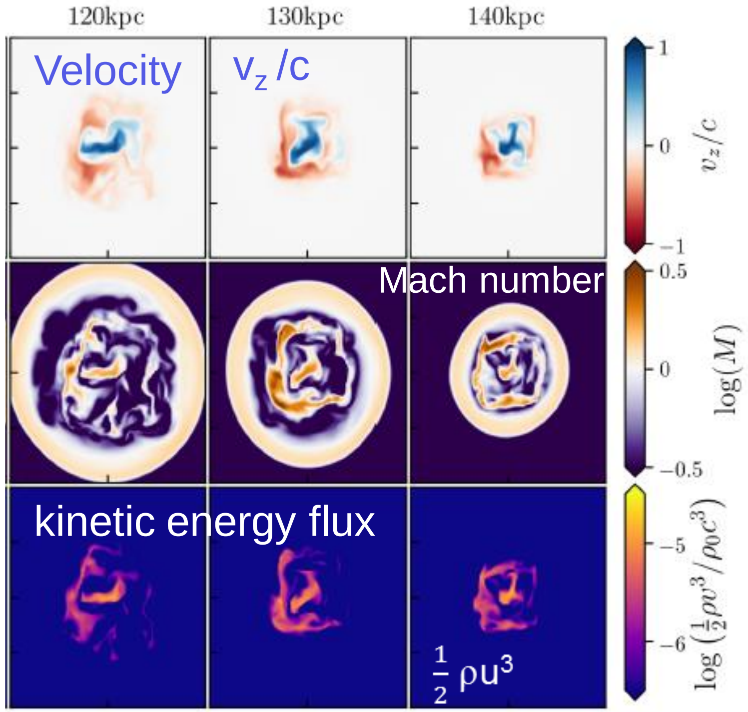
Vertical velocity



Log(Mach number)



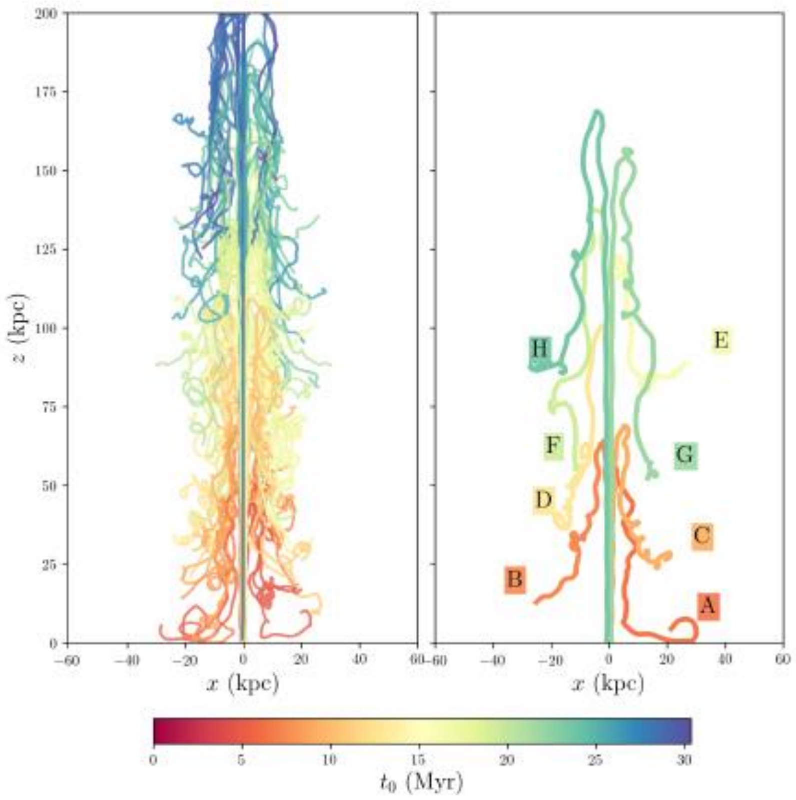
Slices across jet



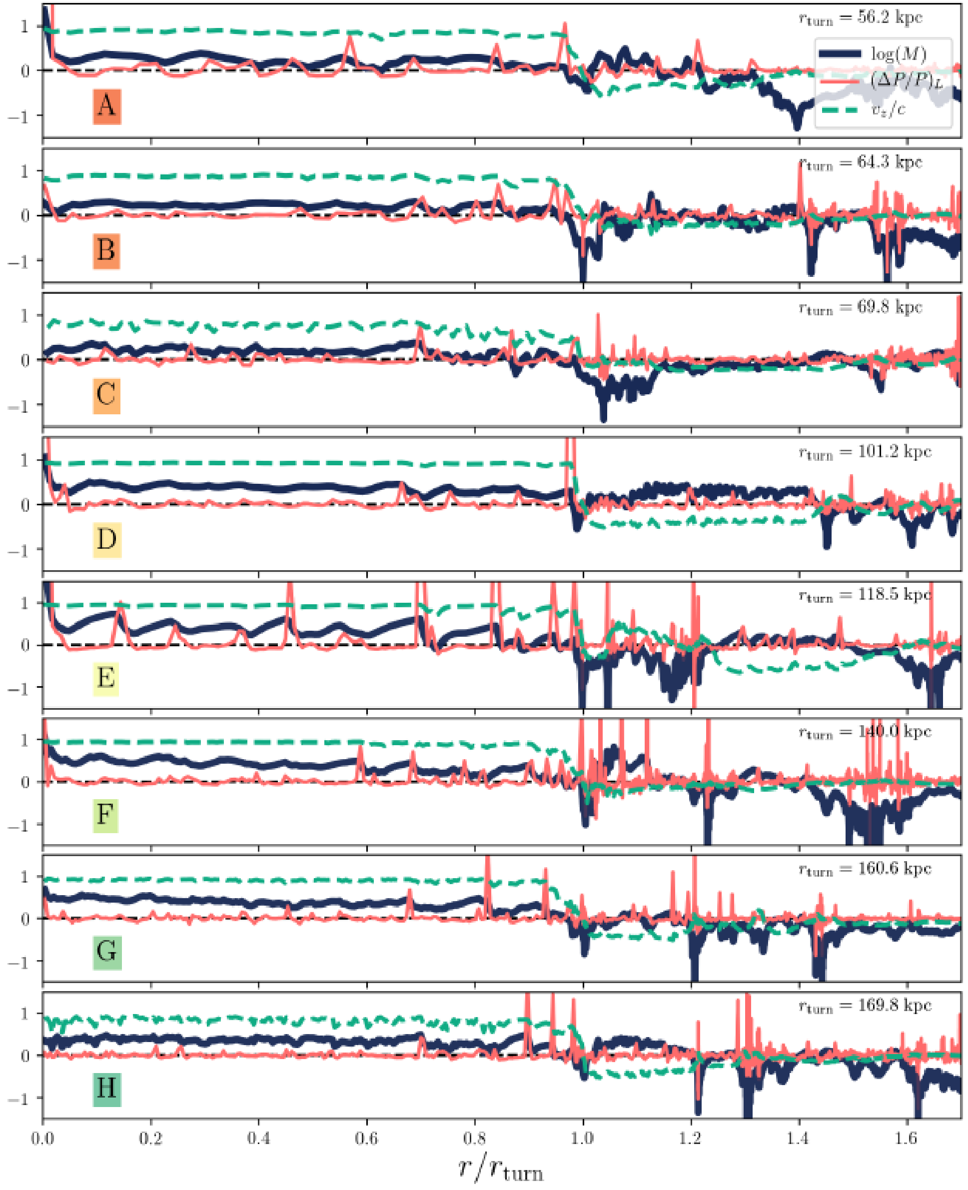
For full story see Matthews et al 2019

Shocks in back-flows

Particle histories

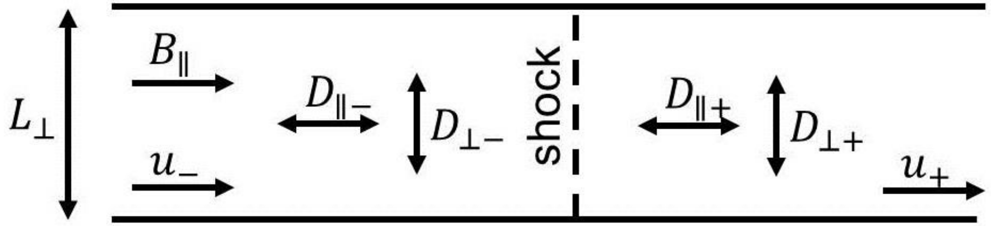


Tracer particle histories: log(M), v_z/c, delta(P)/P



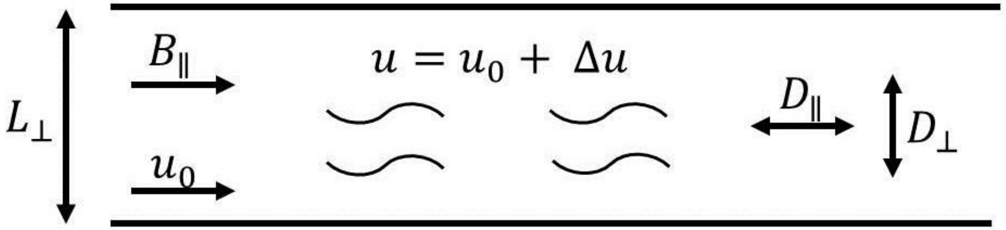
CR acceleration in flux tube

1st order Fermi: diffusive shock acceleration



Max CR energy $E_{max} \simeq Z u_\parallel B_\parallel L_\perp$

2nd order Fermi: flow velocity u varies along flux tube



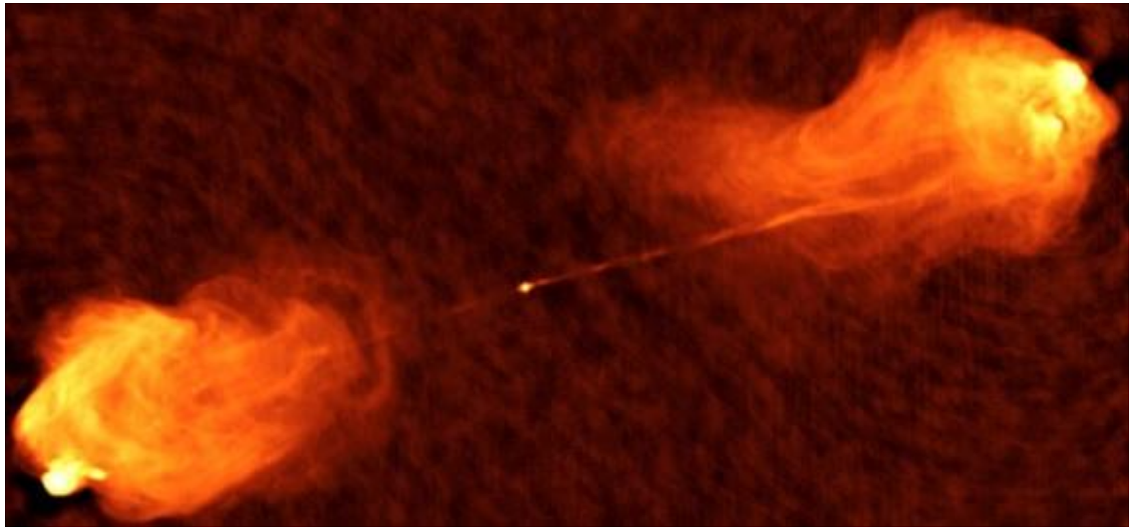
Max CR energy $E_{max} \simeq Z u_0 B_\parallel L_\perp \left(\frac{\Delta u}{u_0}\right)^2$

Flux tube on border between 1st & 2nd order Fermi

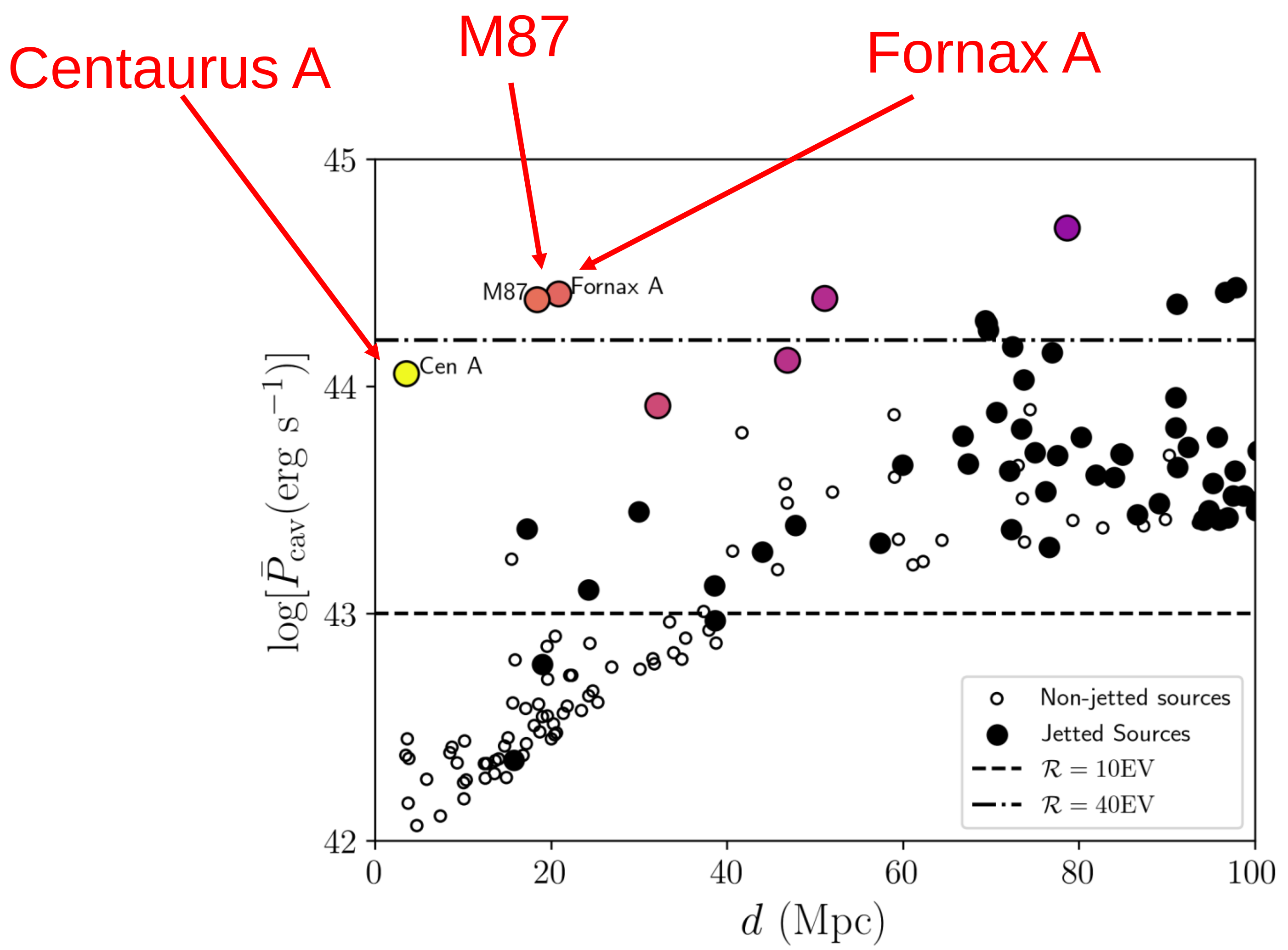
Multiple shocks at low Mach number
Flow velocity varies with $\Delta u / u_0 \sim 1$

$$E_{max} = \left(\frac{Z}{6}\right)\left(\frac{u}{c/3}\right)\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{L}{3\mathrm{kpc}}\right) 60\ \mathrm{EeV}$$

Problem: no nearby strong FRIIs



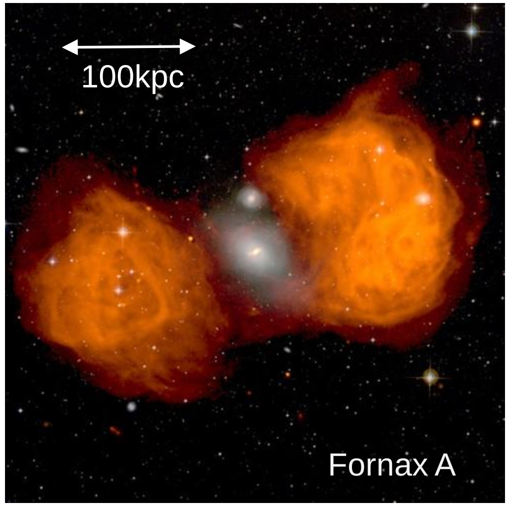
Nearby powerful radio galaxies

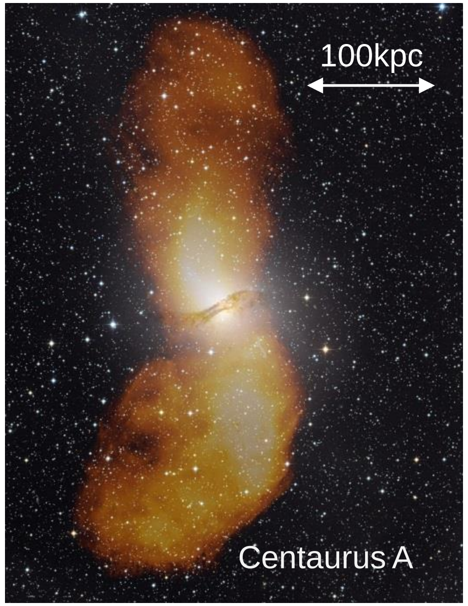


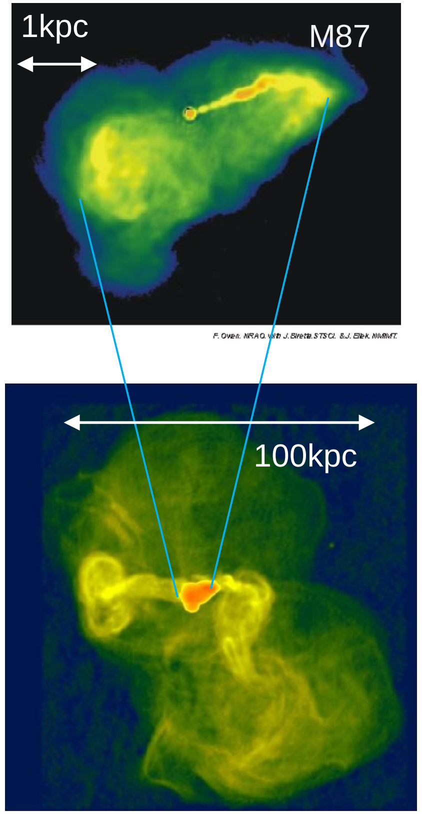
Matthews et al 2018

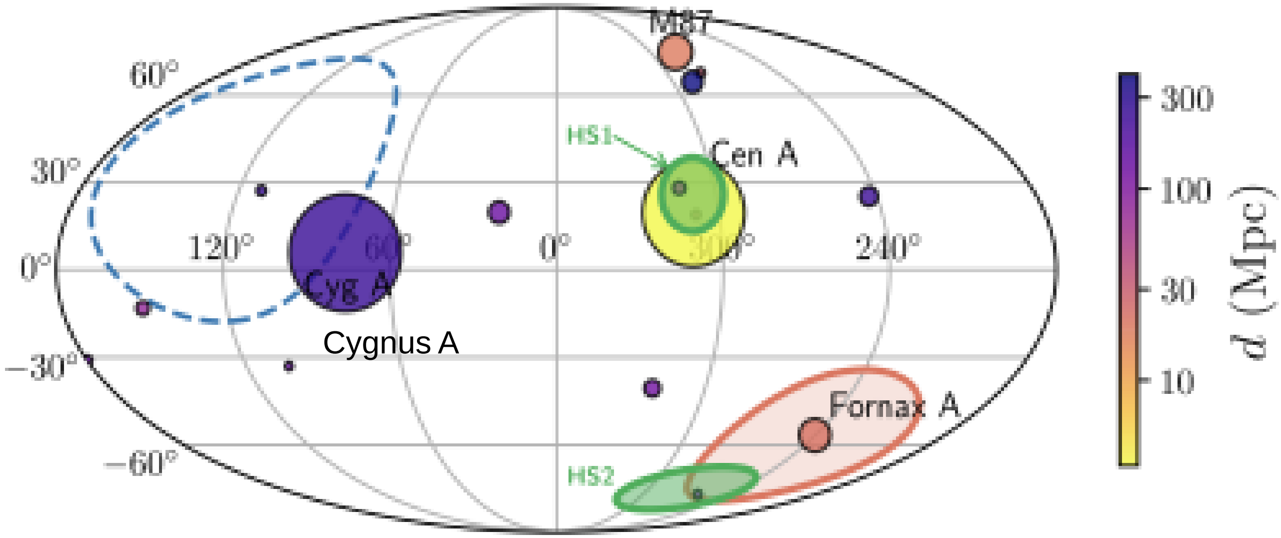
M87 different from Cen A and Fornax A

Credits, captions & references on next slide









Green: AUGER hotspots
Other colours: distance (radio galaxies)
Size: radio flux at 1.1GHz

Centaurus A & Fornax A were more active in past as a result of result of galaxy mergers

Speculate:
Giant lobes a CR reservoir from past FRII-like activity

Credits and figure captions on previous slide

Credit: Capella Observatory (optical), with radio data from Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR). https://svs.gsfc.nasa.gov/10770

Image courtesy of NRAO/AUI and J. M. Uson
Ed Fomalont (NRAO), Ron Ekers (ATNF), Wil van Breugel and Kate Ebneter (UC-Berkeley).
Radio/Optical superposition by J. M. Uson

Image courtesy of NRAO/AUI and F.Owen

Matthews et al 2018 (MN Letters)

Figure 1. The positions of the 16 brightest radio galaxies in Galactic coordinates, with the area of the points proportional to 1.1 GHz radio flux and colour corresponding to distance from the Earth. The radio flux is calculated from table 2 of van Velzen (2012). The orange circle around Fornax A illustrates a deflection angle of 22.5°, while the green shaded regions mark the approximate PAO excesses above 60 EeV (HS1 and HS2) from A18 as described in the text. The blue dashed line marks the area of the sky inaccessible to PAO. The projection is the same as that of fig. 7 of A18, with image coordinates (x, y) mapped to Galactic coordinates in degrees (l, b) by $x = \lambda \cos\theta$, $y = b$ where $\sin\theta = b/90^\circ$ and $\lambda = -l$ (for $l \le 180$), $\lambda = 360^\circ - l$ (for $l \ge 180$)

Starbursts or radio galaxies

Teresa Bister for the Pierre Auger Collaboration 2021 Phys. Scr. 96 074003

Source catalogues

Association with starburst galaxies: 4.5σ

Association with active galaxies: $3.0\text{-}3.7\sigma$

Individual sources

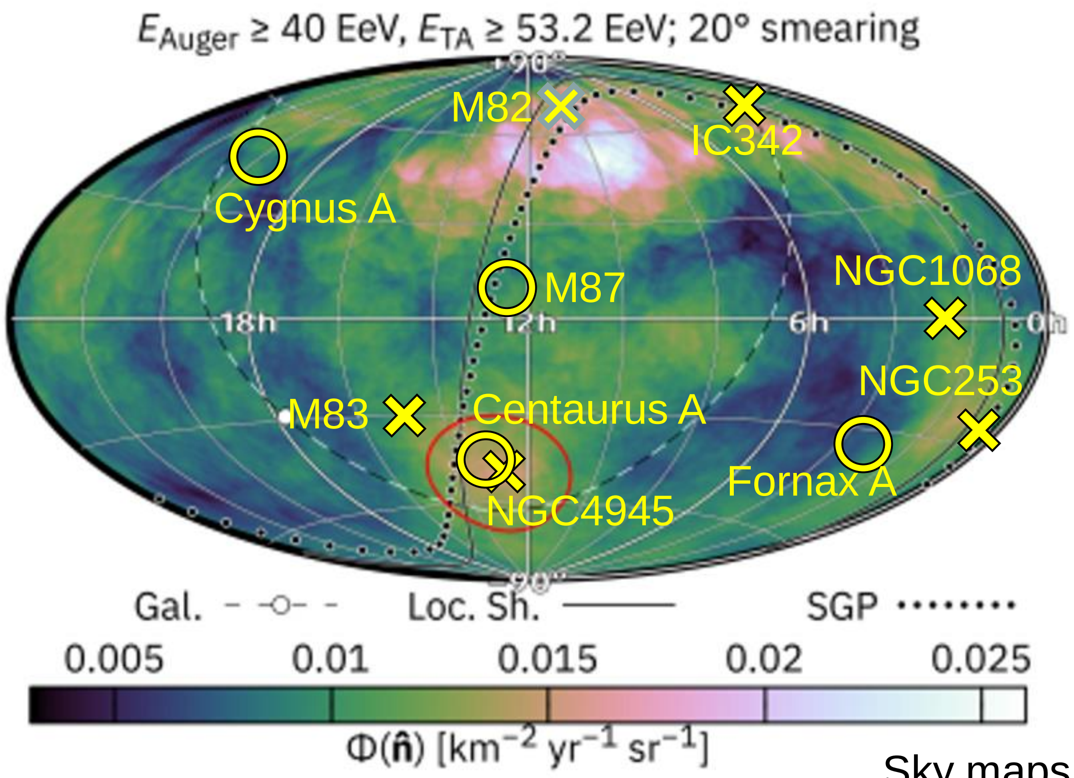
Association with Centaurus A: 3.9σ

Note: Starburst NGC4945 very close to Cen A

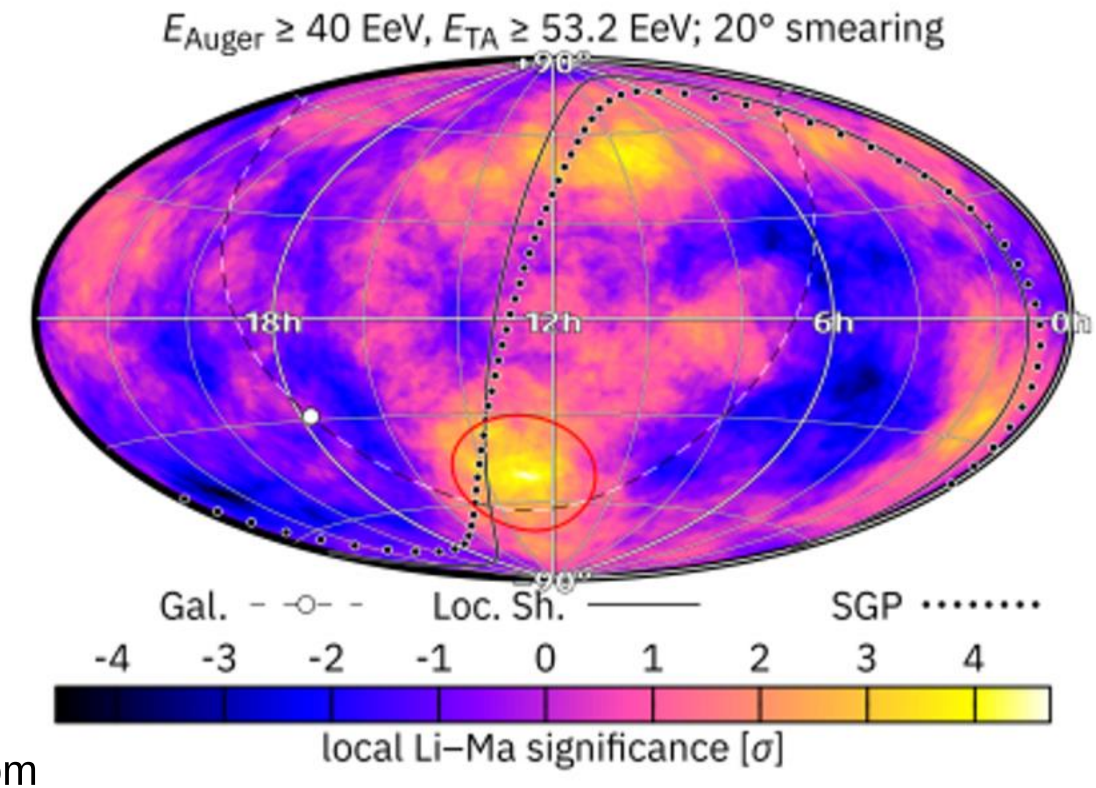
Starbursts and radio galaxies superimposed on di Matteo et al, Proc ICRC2019

Starburst	$L_{1.4GHz}$	Distance Mpc
NGC253	4.2	2.5
M82	10.6	3.4
NGC4945	10.8	3.7
IC342	3.7	3.7
M83	4.3	3.7
NGC1068	167	16.7

Radio Galaxy	cavity power erg/s	Distance Mpc
Centaurus A	10^44	3.7
Fornax A	3x10^44	21
M87	3x10^44	18
Cygnus A	10^46	230



UHECR flux



Local significance

Sky maps from
di Matteo et al IRC2019

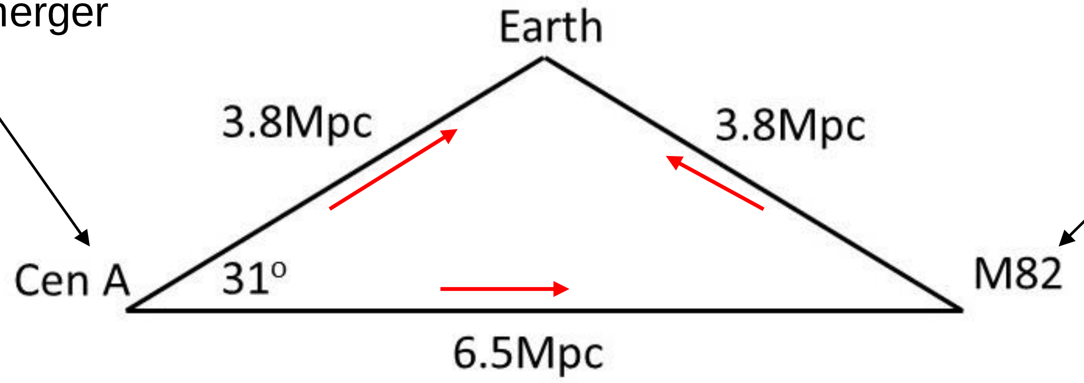
How to reconcile the association with both radio galaxies and starburst galaxies

MODEL: Cen A radio galaxy as UHECR source, M82 starburst as an echo

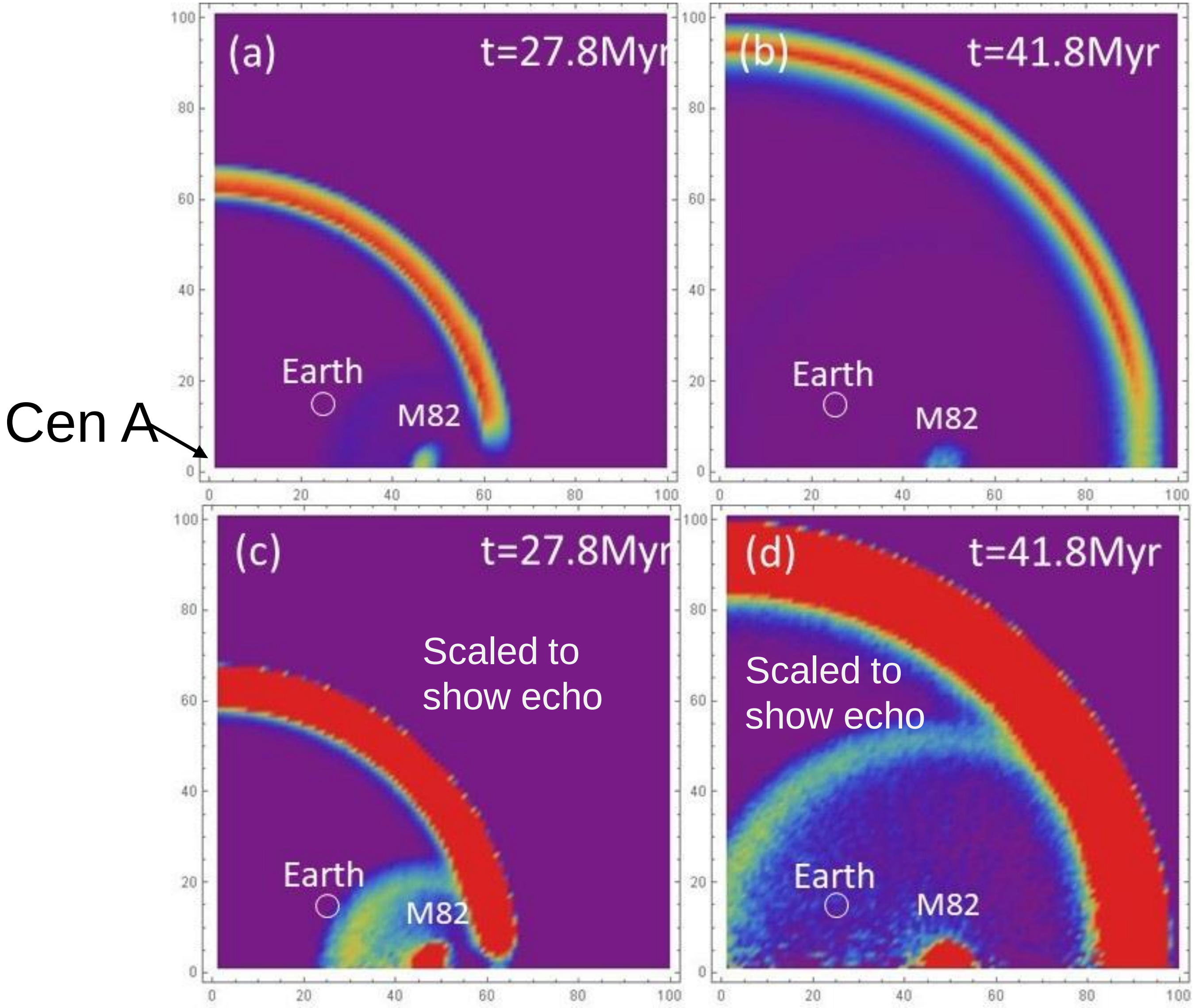
UHECR at Earth
1) Leakage from Cen A reservoir
2) Echo arriving from M82 (delayed by 20Myr)

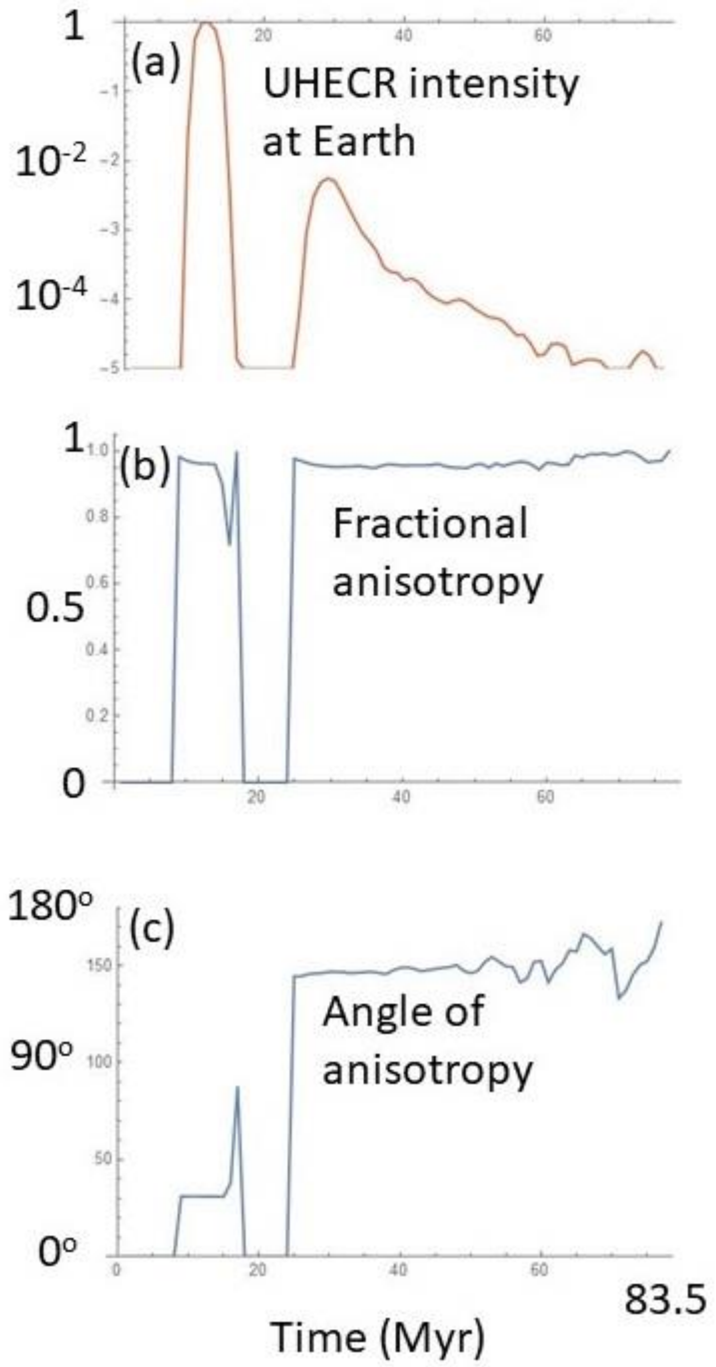
UHECR source
Active 20Myr ago during merger

Enhanced scattering from
M82 starburst halo



Monte Carlo scattering: monoenergetic UHECR released from Centaurus A at t=0





Parameters

IGM: Scattering matched to observed AUGER Cen A hotspot

M82 halo: sphere of enhanced (10x) scattering

Halo radius (800kpc) matches TA hotspot (10-15^{o}, 0.6-1.0 Mpc)

B = 10nG sufficient for Lamor radius < halo radius (Zx10 EeV)

(Starburst fields reach 300 μG in central kpc)

Energetics (provisional)

UHECR (>53EeV) from M82 hotspot: 5×10^{-17} $m^{-2}s^{-1}$

Monte Carlo: Peak direct flux from Cen A was 100x larger at peak

Implied Cen A peak UHECR luminosity: 10^{41} erg s^{-1}

Compare with

Cen A Eddington luminosity: 5×10^{45} erg s^{-1}

Present observed Cen A jet power: $1\text{-}5 \times 10^{43}$ erg s^{-1}

Model consistent with enhanced Cen A activity 20Myr ago

10% of Eddington luminosity given to CR with energies above 1GeV

CR energy spectral index -2.35 from 1GeV to 50EeV

SUMMARY: Radio galaxies as source of UHECR

Radio galaxies have right characteristics

powerful, large, long-lived, numerous

Centaurus A anomalously close (but not FRII)

Evidence of past merger, enhanced activity

UHECR hotspot associated with Cen A

Model:

Centaurus A: strong jets from merger 20Myr in past

UHECR accelerated in mildly relativistic shocks in jet backflow

Lobes are leaking UHECR reservoirs

TA hotspot is echo from M82 starburst halo

Accounts for

UHECR associated with both starbursts and radio galaxies

UHECR from direction of starbursts that have insufficient power

UHECR from Cen A despite present low power

UHECR from radio galaxies despite lack of nearby FRIIs