The surprising effectiveness of cosmic ray acceleration

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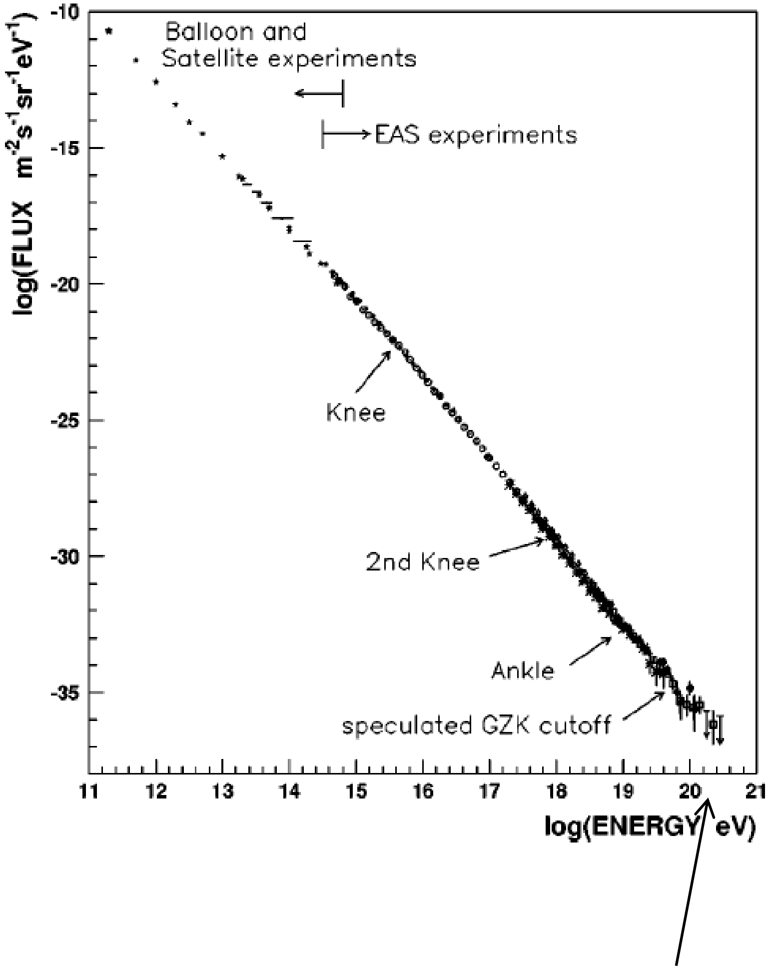
Cassiopeia A, the brightest (extra-solar) radio source in the sky

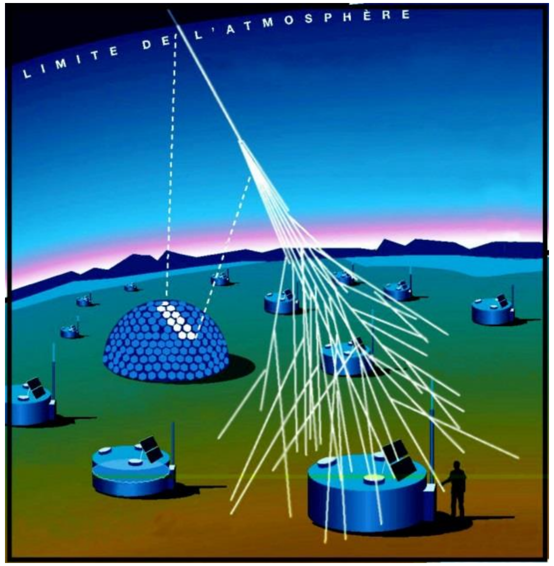
http://hubblesite.org/newscenter/archive/releases/2006/30/image/a/format/xlarge_web/

Cosmic rays: high energy charged particles arriving at Earth

Nagano & Watson (2000)



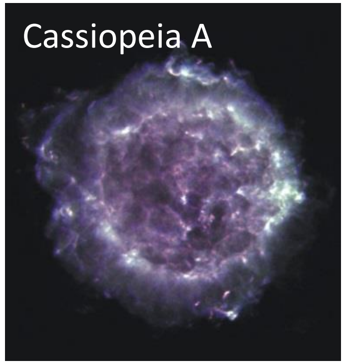
One per square kilometre per century



Auger array, Argentina

High energy charged particles in supernova remnants

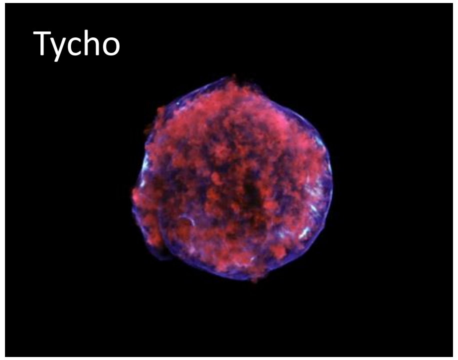
Radio:
GeV electrons



Cassiopeia A

VLA radio telescope

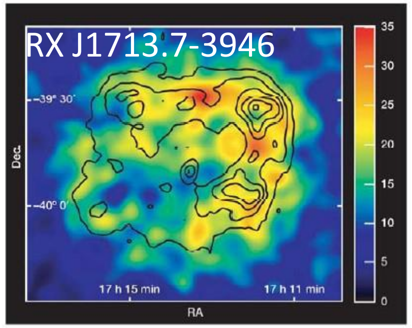
X-ray:
TeV electrons



Tycho

CHANDRA

Gamma-ray:
Up to 100 TeV



RX J1713.7-3946

HESS Cerenkov telescope

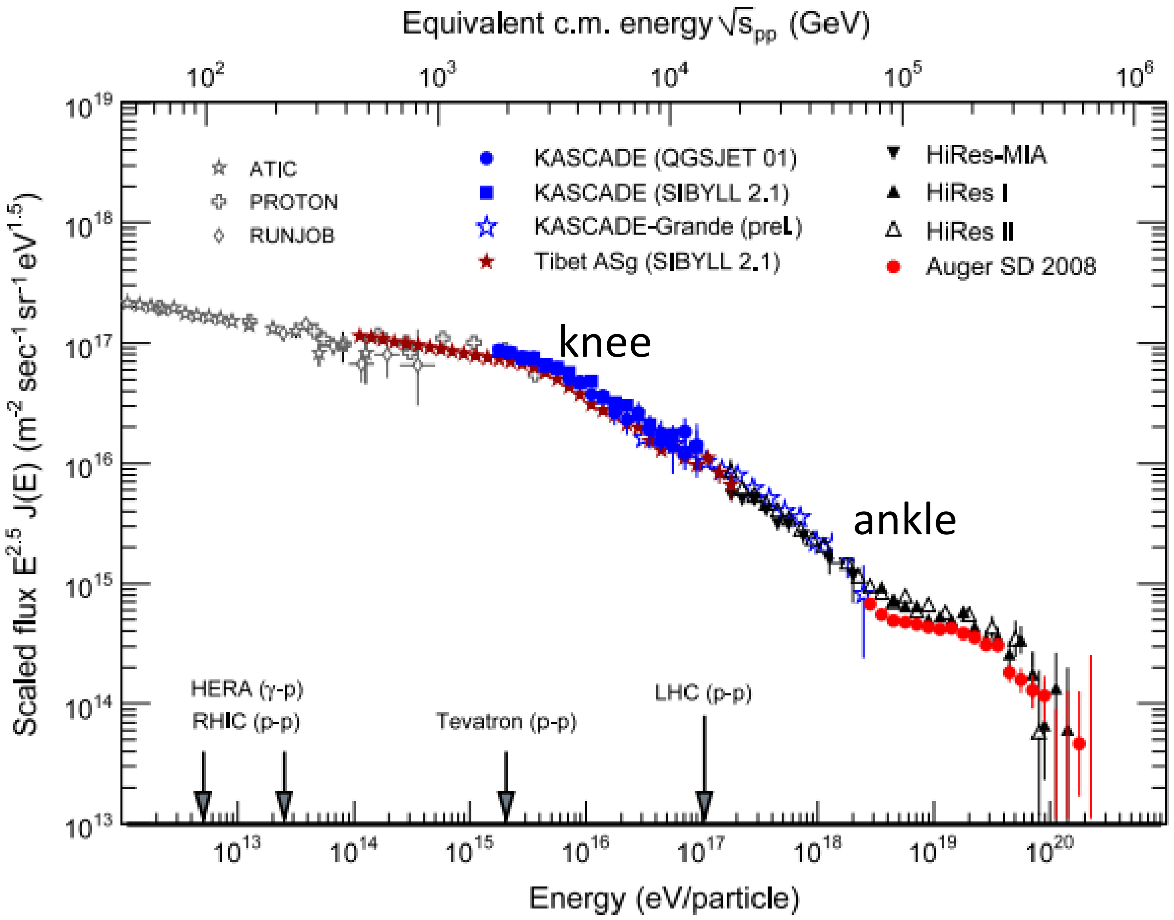
Observations place stringent requirements on CR acceleration

Requires 10-30% of energy output from Galactic supernovae

Efficient acceleration to 3PeV (the 'knee')

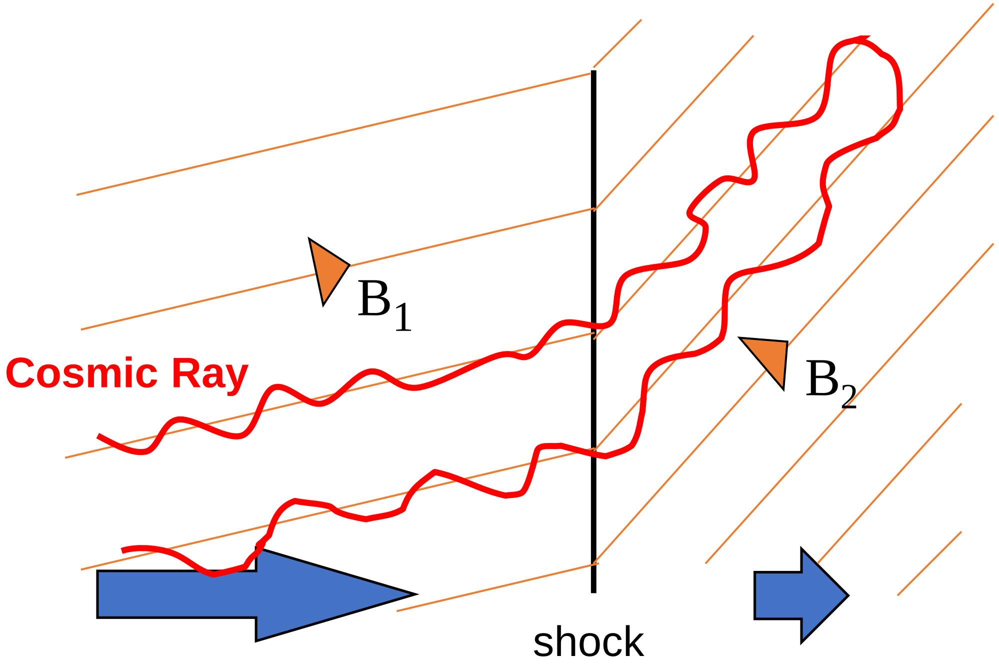
Continuity implies Galactic acceleration to 1000 PeV (the 'ankle')

Extragalactic beyond the ankle



from Blumer et al 2009

The standard model: Diffusive shock acceleration (DSA)



Shock velocity: u_s

CR density at shock: n

At each shock crossing

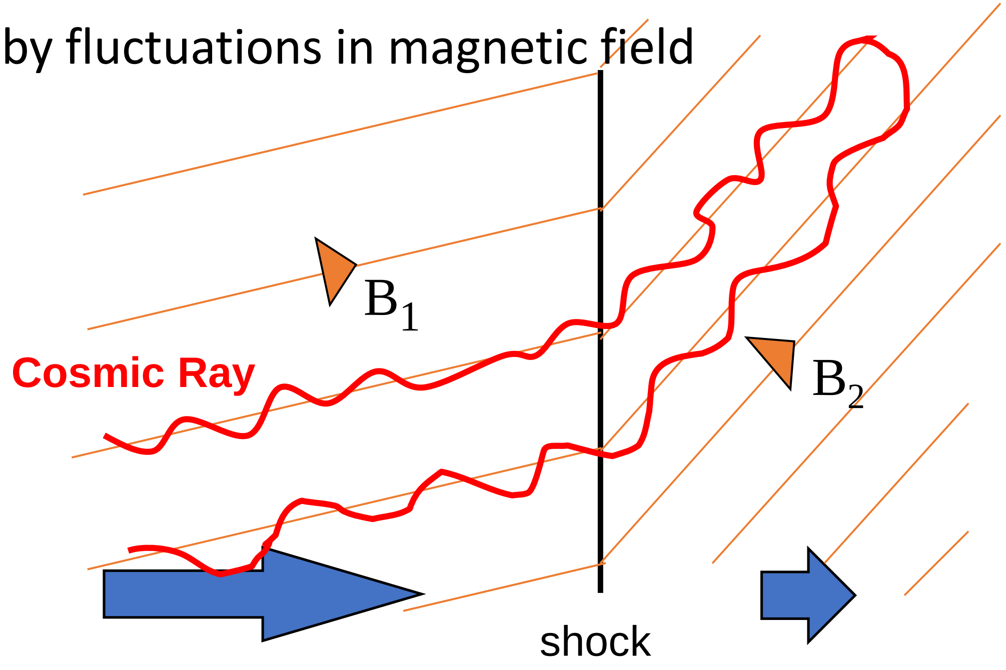
Fractional energy gain $\frac{\Delta\varepsilon}{\varepsilon} = \frac{u_s}{c}$

Fraction of CR lost $\frac{\Delta n}{n} = -\frac{u_s}{c}$

Differential energy spectrum $N(\varepsilon) \propto \varepsilon^{-2}$

Acceleration needs magnetic field which needs energy

CR scattered by fluctuations in magnetic field



Shock velocity: u_{shock}

Cosmic ray density at shock: N

Now add in energy loss to
Magnetic field amplification

At each shock crossing

Fractional energy gain $\frac{\Delta\varepsilon}{\varepsilon} = \frac{u_{shock}}{c}\left(1 - \frac{U_{turbulence}}{U_{CR}}\right)$

Fraction of cosmic rays lost $\frac{\Delta N}{N} = -\frac{u_{shock}}{c}$

$$\boxed{n \propto \varepsilon^{-2-(U_{turbulence}/U_{CR})/(1-U_{turbulence}/U_{CR})}}$$

Bell et al 2019

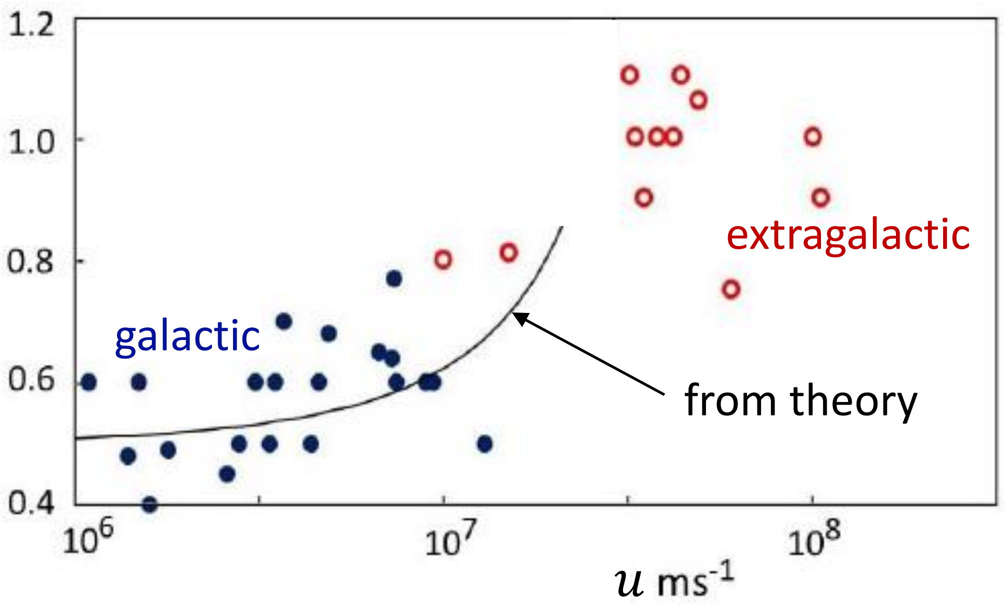
Diffusive shock acceleration: turbulence steepens the CR spectrum

$$n \propto \varepsilon^{-s} \quad \text{where} \quad s = 2 + \frac{U_{turbulence}}{U_{CR} - U_{turbulence}}$$

Non-resonant instability (consistent with observation): $U_{turbulence} \propto \frac{u_{shock}}{c} U_{CR}$

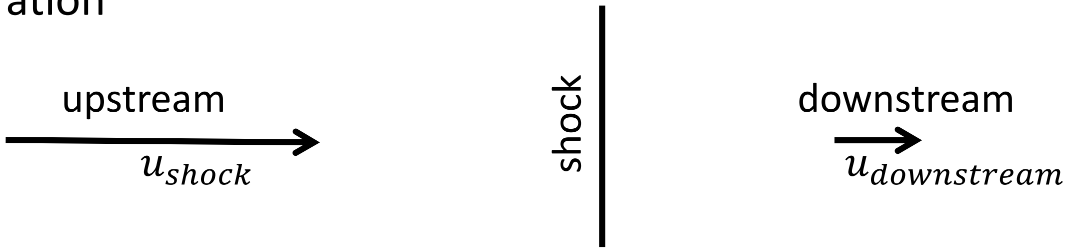
SNR radio spectral index α against expansion velocity

$$\alpha = \frac{s-1}{2}$$



Maximum (Hillas) energy

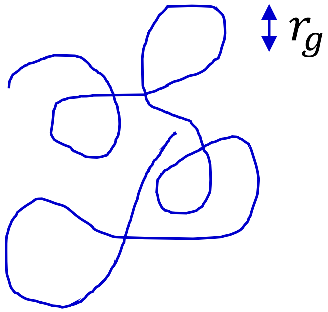
Diffusive shock acceleration



$$\text{Maximum energy (eV)} = \frac{1}{4}\left(\frac{\lambda}{r_g}\right)^{-`1} u_{shock}BL$$

Requires $\lambda \sim r_g$

‘Bohm’ diffusion (so-called by astrophysicists)



Needs magnetic field to be turbulent on scale of gyroradius

Consequences of the 'Hillas' energy

Maximum energy (eV) $= \frac{1}{4}\left(\frac{\boldsymbol{\lambda}}{\boldsymbol{r_g}}\right)^{-`\mathbf{1}} u_{shock}BL$

=1 for maximum energy

For young energetic supernova remnants

$$u_{shock} \sim 5{,}000\ \mathrm{km\ s^{-1}}$$

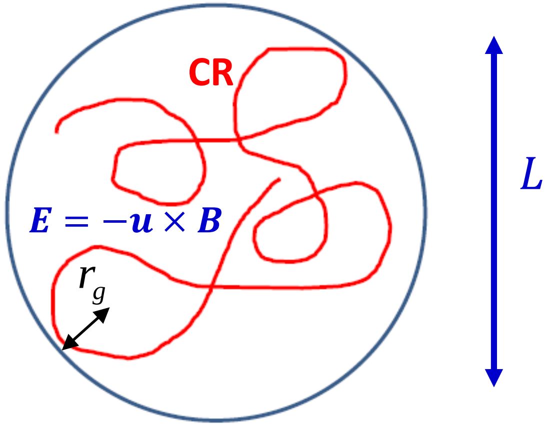
$$L \sim 3 \times 10^{17}\,\mathrm{m}$$

Interstellar magnetic field $B \sim 5 \times 10^{-10}\,\mathrm{Tesla}\ \ (5\mu\mathrm{G})$

Maximum energy $\sim 0.2\ \mathrm{PeV}$

Too small by factor of 10
even to get to the 'knee'

Generality of Hillas energy



1) Spatial confinement

Larmor radius less than size of accelerating plasma

$$r_g = \frac{\epsilon_{max}}{cB}$$

CR energy in eV

$$\boldsymbol{\epsilon_{max} < cBL}$$

2) All acceleration comes from electric field $\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B}$

velocity of thermal (MHD) plasma

Maximum energy gain: $L \times$ maximum electric field $\boldsymbol{\epsilon_{max} < uBL}$

In turbulent magnetic field $\epsilon = \int \boldsymbol{v}.\boldsymbol{E}\,\mathrm{d}\ell = \int \boldsymbol{u}.(\boldsymbol{v} \times \boldsymbol{B})\,\mathrm{d}\ell$

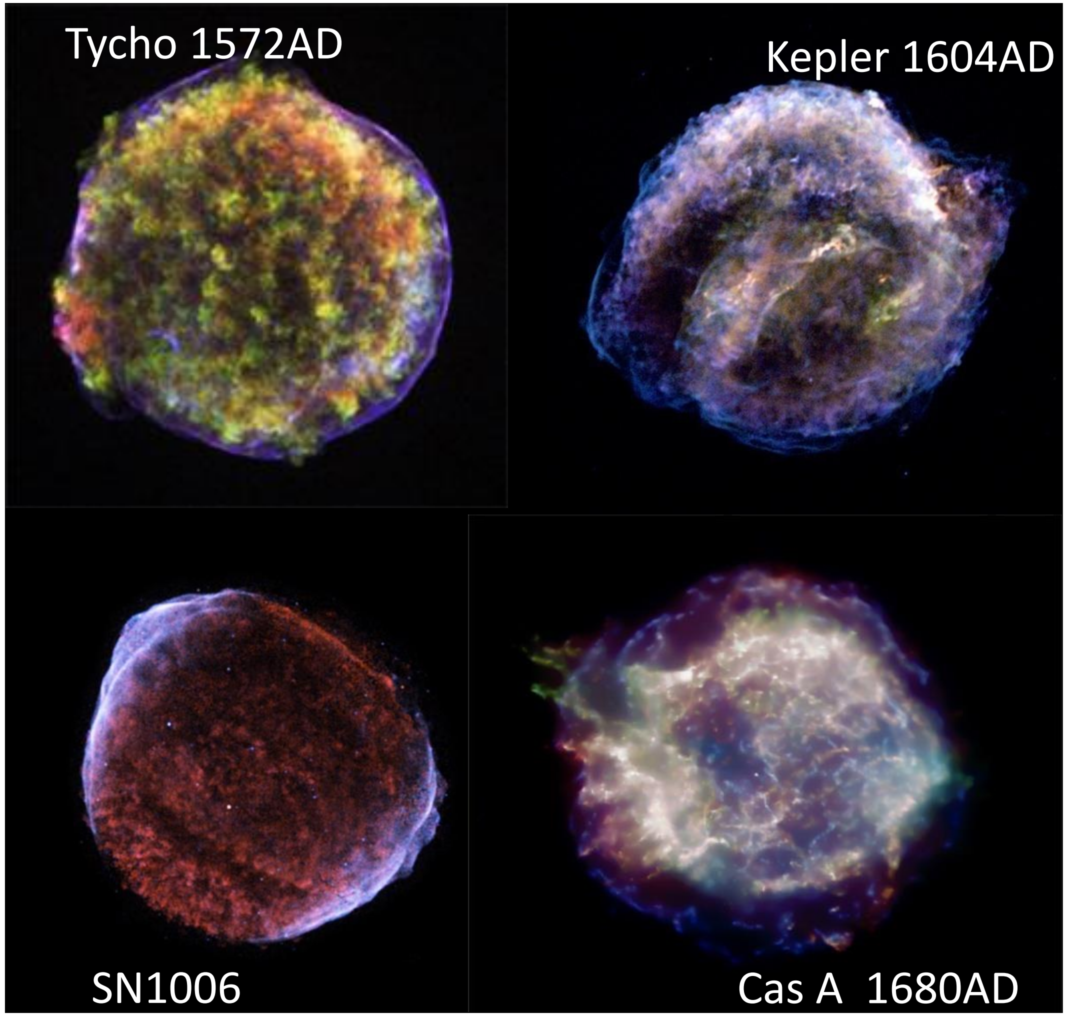
Depends on correlation between $\boldsymbol{v}$ and $\boldsymbol{B}$
Bohm diffusion is as good as it gets

Applies not just to shock acceleration

Historical shell supernova remnants: CR generate their own magnetic field

(Vink & Laming, 2003; Völk, Berezhko, Ksenofontov, 2005)

TeV electrons in 100μG field



Chandra observations (x-ray)

NASA/CXC/Rutgers/
J.Hughes et al.

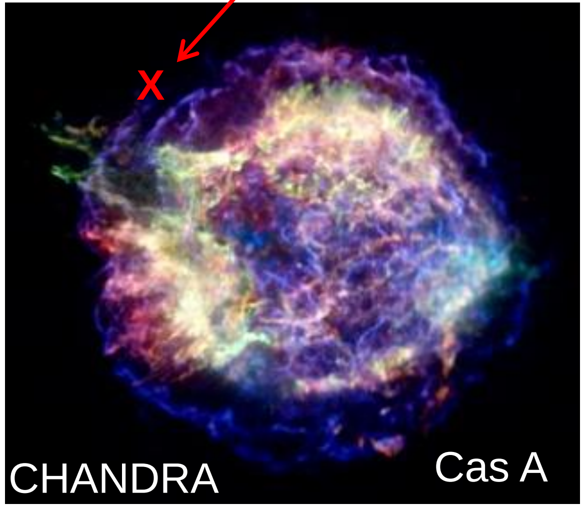
NASA/CXC/Rutgers/
J.Warren & J.Hughes et al.

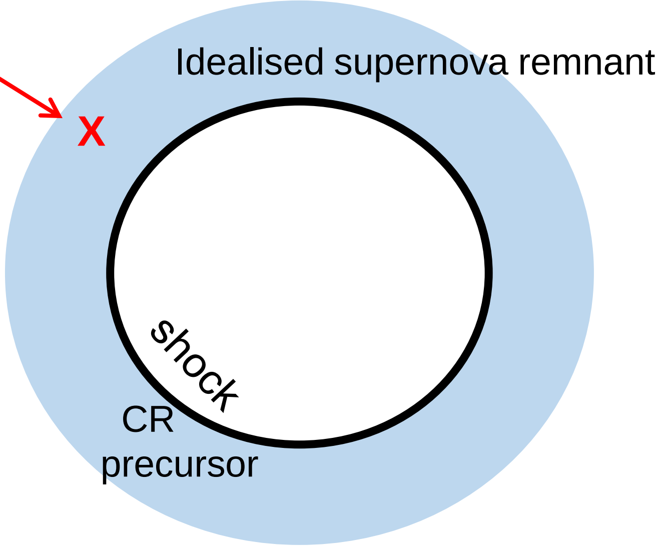
NASA/CXC/NCSU/
S.Reynolds et al.

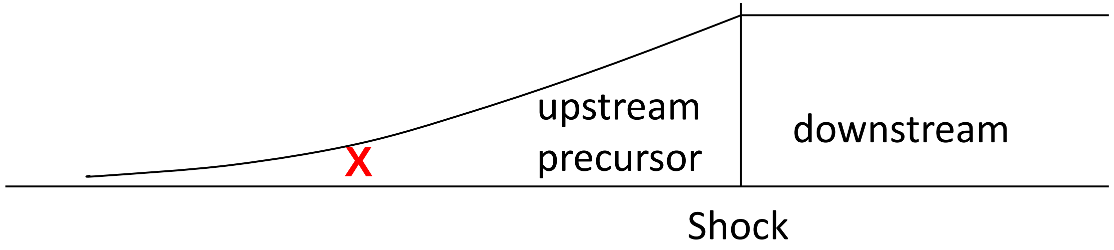
NASA/CXC/MIT/UMass Amherst/
M.D.Stage et al.

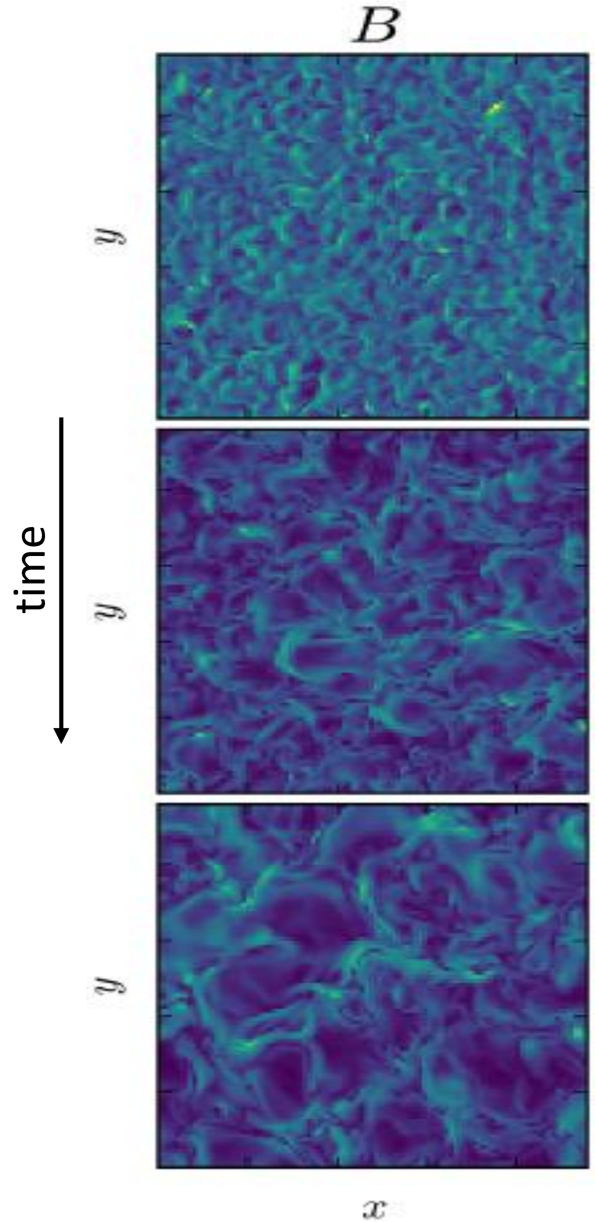
Escaping cosmic rays generate their own magnetic field

Magnetic grows ahead of shock





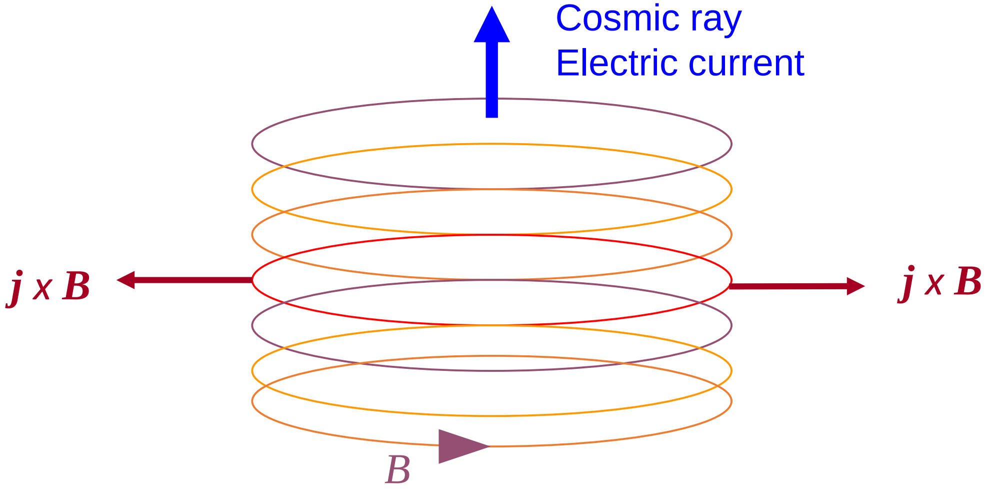




Matthews et al 2017

Magnetic field amplification: how it works in a simple form

Expanding loops of magnetic field



Instability grows until CR get tied to field lines: Loop size = r_g

Automatically saturates with $\lambda \sim r_g$

Unstable magnetic field amplification solves Hillas problem

Boosts field from a few μG to 100s μG

Saturates with wavelength ~ Larmor radius

Hillas limit replaced by new limit

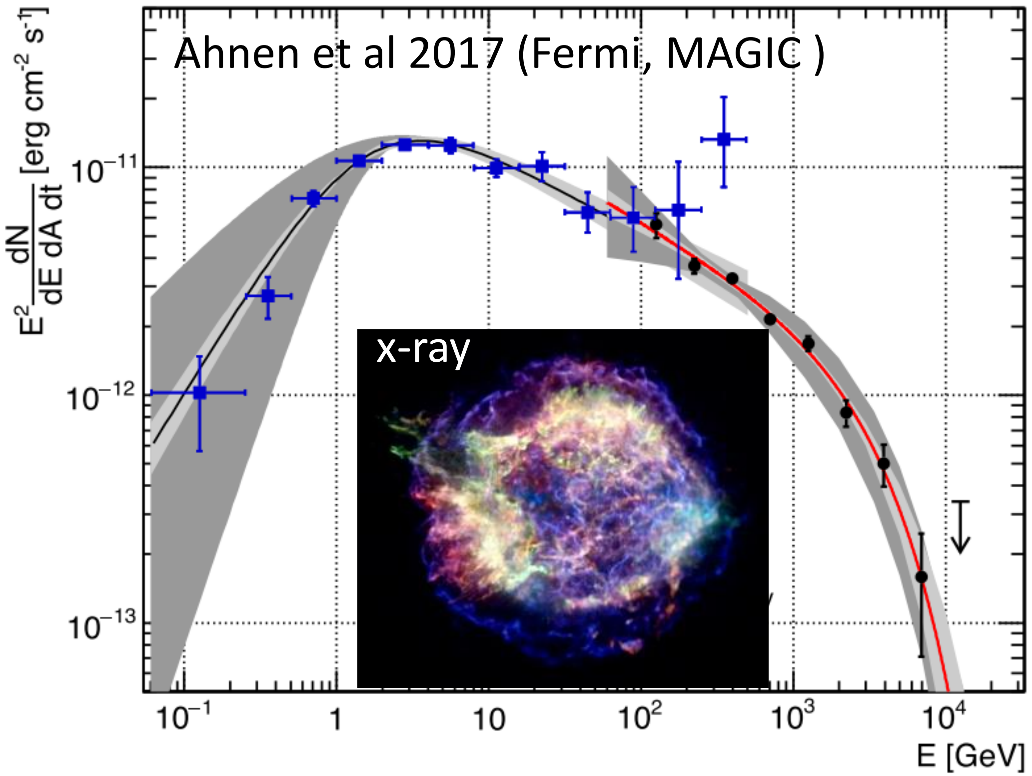
Coupled cosmic transport/magnetic field growth

$$\text{Theory:}\quad \text{Maximum energy} = 230\ \left(\frac{n_e}{cm^{-3}}\right)^{1/2}\left(\frac{\text{velocity}}{10{,}000\ km\ s^{-1}}\right)\left(\frac{\text{radius}}{\text{parsec}}\right)\ \text{TeV}$$

Confirmed by γ-ray observations

Problem: no known Galactic supernova remnant reaching 1PeV (theory and observation)

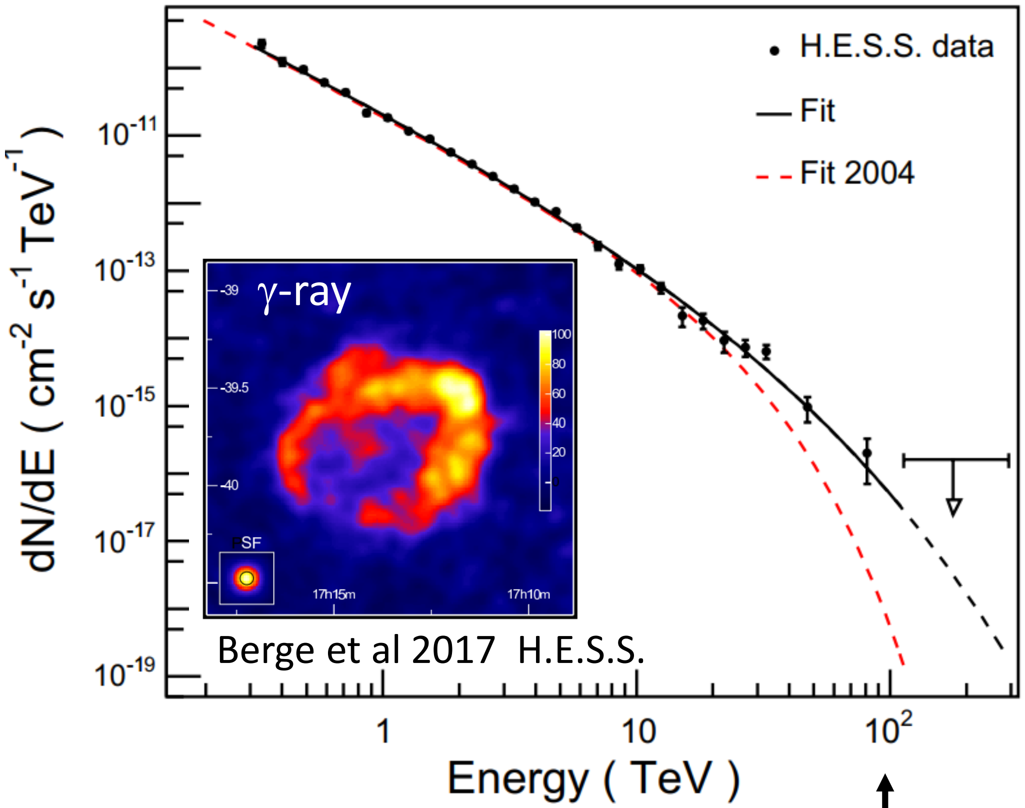
Cas A γ-ray spectrum



Ahnen et al 2017 (Fermi, MAGIC)

↑ 10TeV

RX J1713.7–3946 γ-ray spectrum

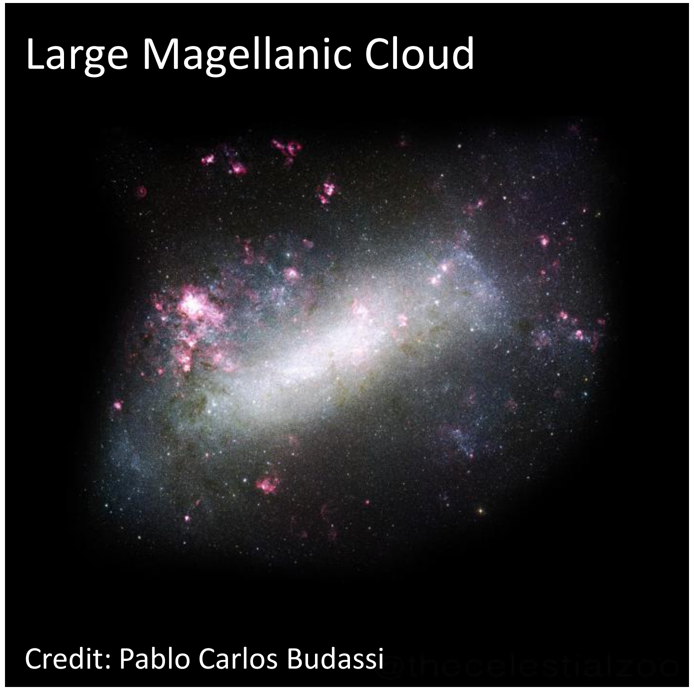


Berge et al 2017 H.E.S.S.

↑ 100TeV

Very young supernova remnants (<30 years)

For example SN1987a in nearby Large Magellanic Cloud



Credit: Pablo Carlos Budassi

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Rapid expansion: 30,000 km s^{-1}

Blast wave runs into dense shell: $10^4 cm^{-3}$

Theory: acceleration to 10PeV

Cosmic rays are available at other outlets

Star clusters/winds from massive stars/multiple interacting supernovae

Galactic Centre

Galactic wind termination shock

High velocity outflows from the Galaxy

Pulsar wind nebulae

Other processes are available

Reconnection

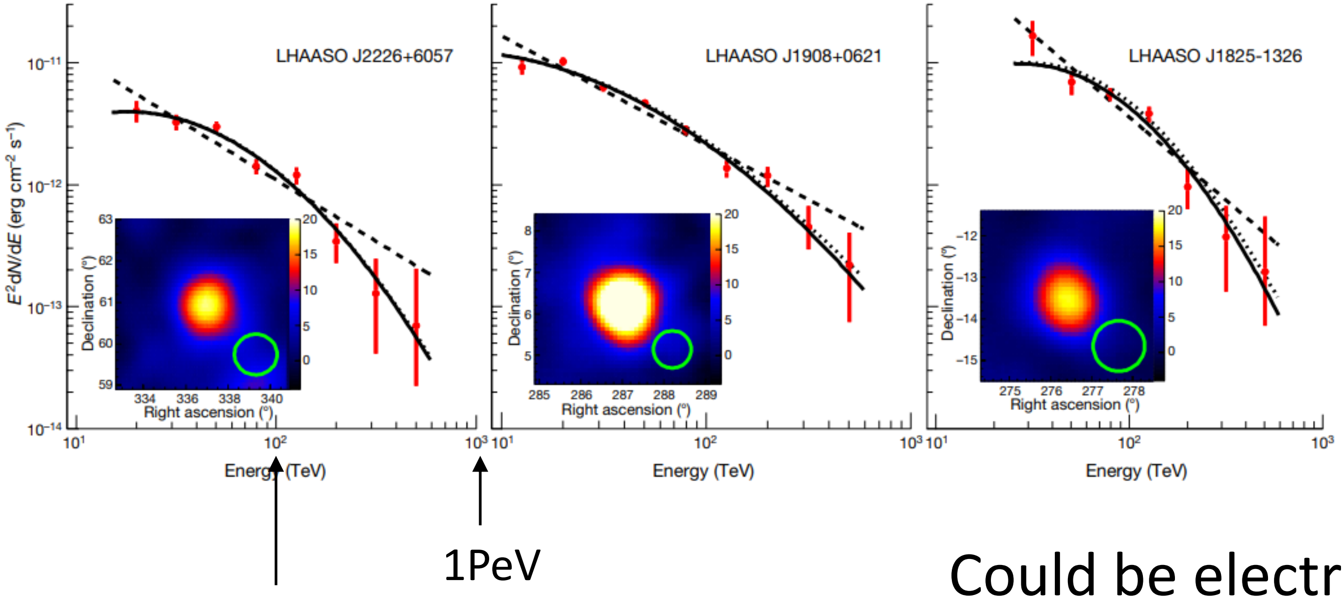
Friction in shear layers

Second order Fermi

Cross-field drift in relativistic winds

LHAASO (Tibet): PeV γ-ray photons from our Galaxy

1.4PeV photon from J2032.4102



100TeV

1PeV

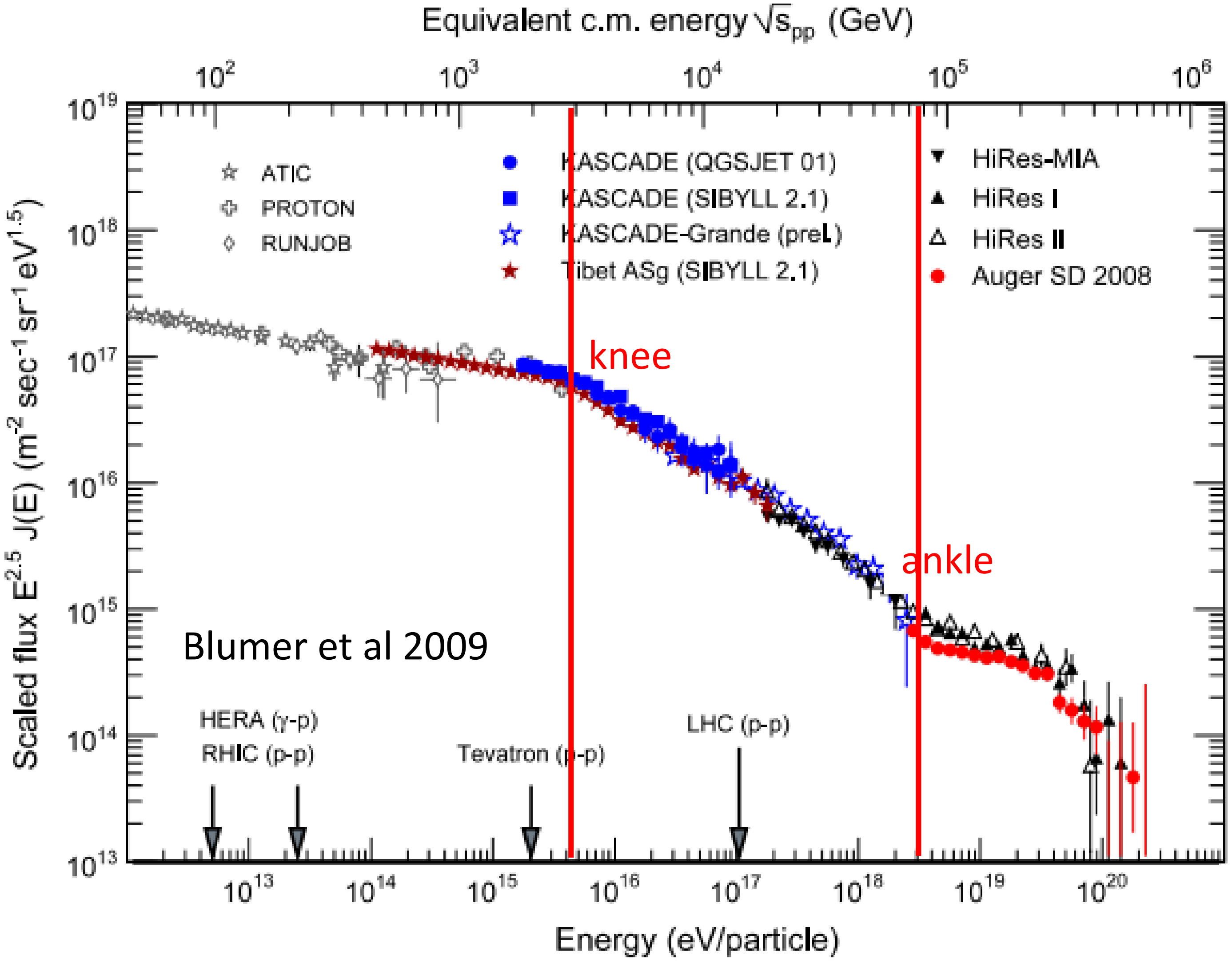
Cosmic ray energy: ~7x γ-ray energy

Could be electron/positrons in pulsar magnetospheres
Or from hadrons stored in dense cloud

Where we stand on cosmic rays in our Galaxy:

Struggle to get to the knee

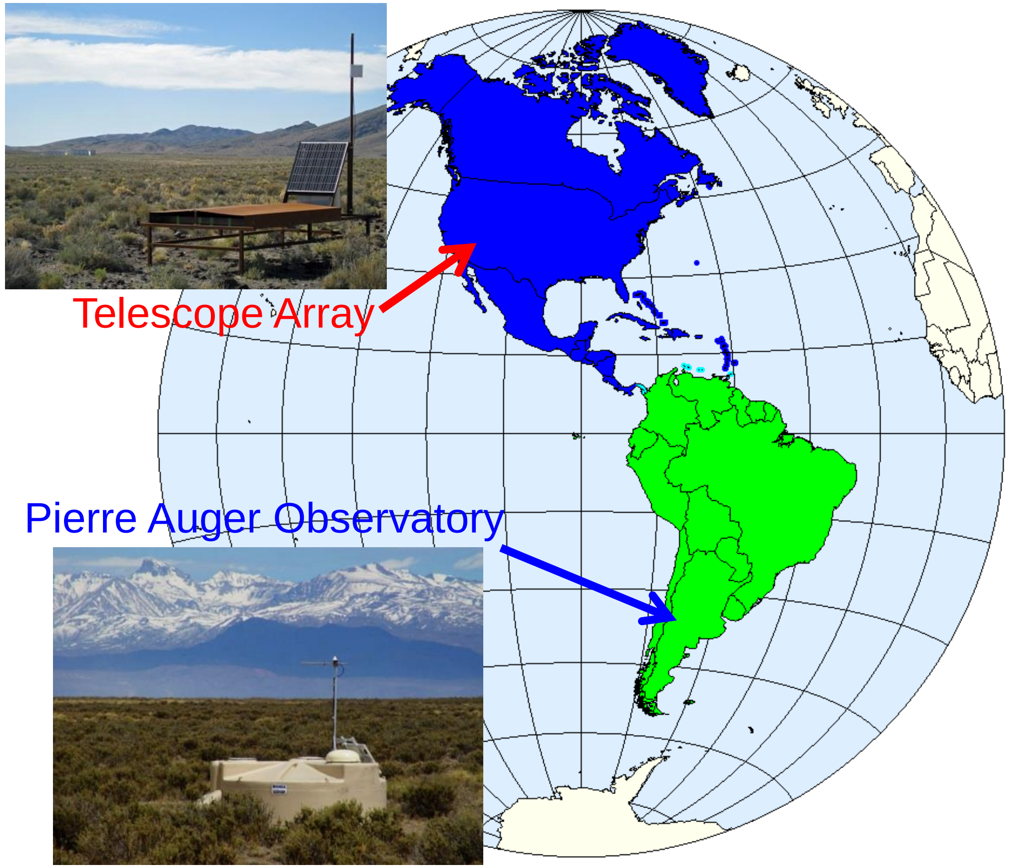
The ankle is more problematic



Highest energy cosmic rays must come from outside Galaxy because

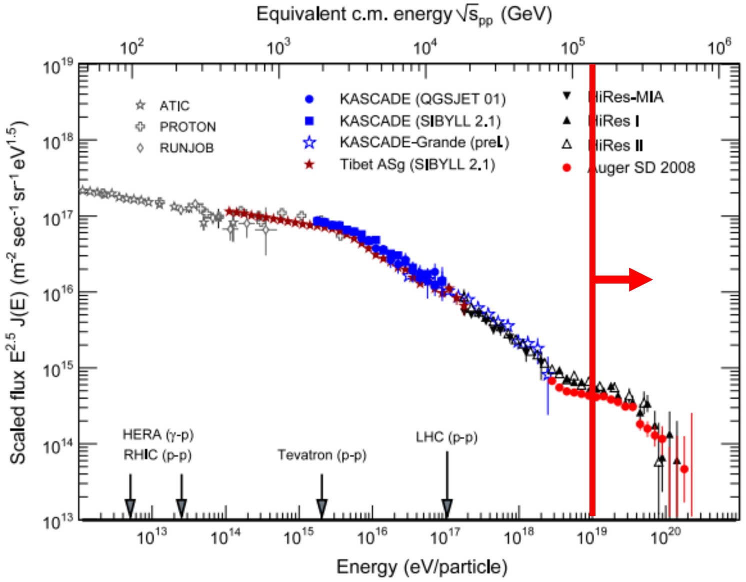
Larmor radius larger than the Galaxy

Ultra-high energy cosmic rays (UHECR, beyond the ankle)

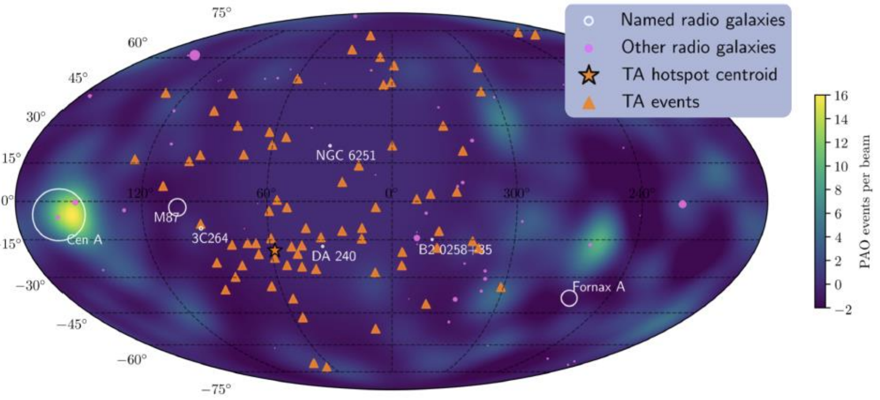


Telescope Array

Pierre Auger Observatory



How AUGER & TA fit together (in supergalactic coords)



Positive correlation (not yet 5σ) with

1) AGN (active galaxies, quasars, jets…)
2) Starburst galaxies

Constraints

- Must come from outside our Galaxy – large gyro-radius
- Must originate within 10s Mpc – GZK/photo-disintegration losses
- Synchrotron losses – rules out compact sources with large magnetic field
- Relativistic shocks (mostly) can’t reach 100EeV – cosmic rays swept away downstream
- Lower limit on source power
- Must be enough sources to supply the numbers

Possible contenders:

- Powerful radio galaxies
- Starburst galaxies – suggested by observation but too low power
- Gamma-ray bursts – losses a problem, not enough of them, expect more neutrinos
- Cluster accretion shocks – large & long-lived but low velocity

Source power must exceed a threshold

‘Hillas condition’

$$\epsilon_{max} < uBL$$

plus ‘magnetic power’

$$P_{mag} = uL^2 \frac{B^2}{2\mu_0}$$

gives:

$$P_{mag} = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}} \left(\frac{u}{c}\right)^{-1} \epsilon_{max}^2$$

To reach 100EeV

$$P_{mag} > \left(\frac{u}{c}\right)^{-1} 1.2 \times 10^{44} \text{ erg s}^{-1}$$

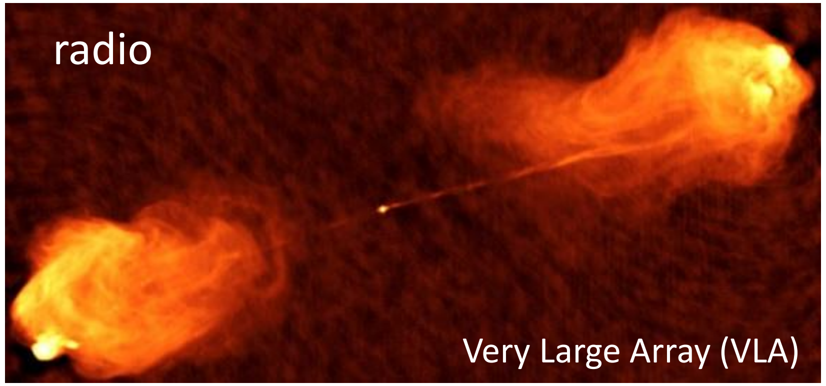
BUT

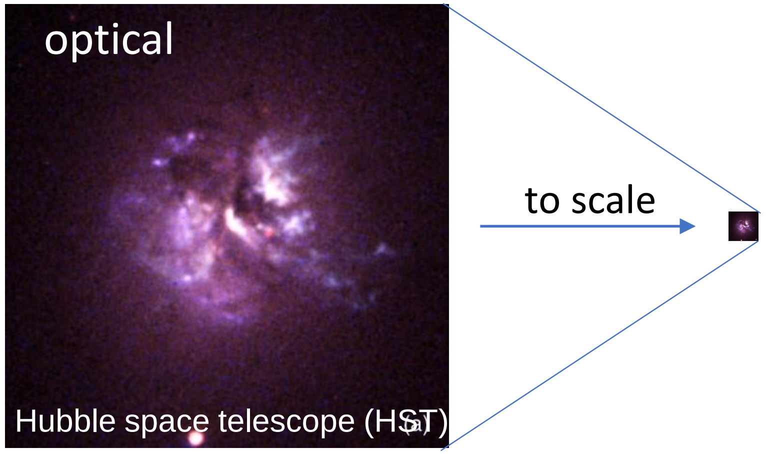
- Total power > P_{mag}
- $u \leq c$
- Relies on ideal geometry

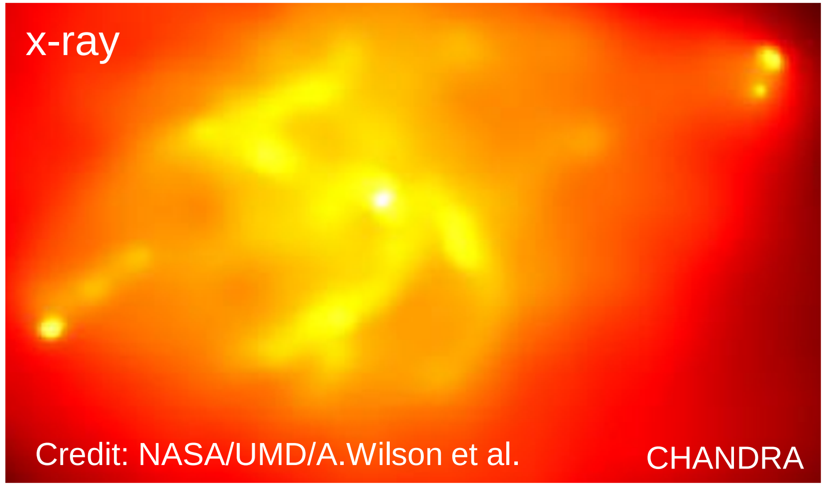
In conjunction with other constraints, points heavily to powerful radio galaxies

Cygnus A

Power ~ 10^{46} erg s $^{-1}$
Relativistic jet





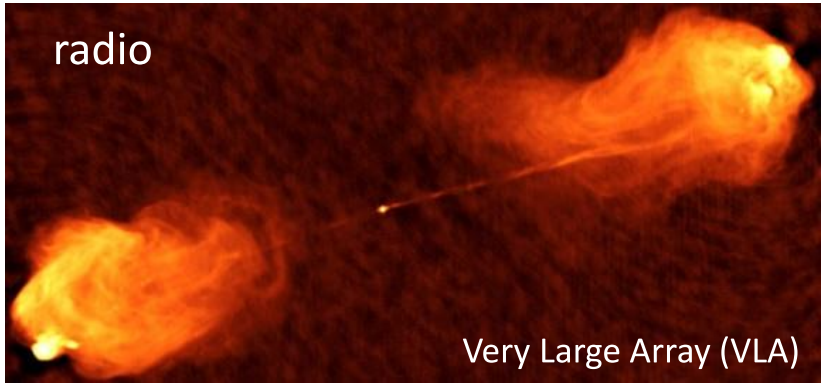


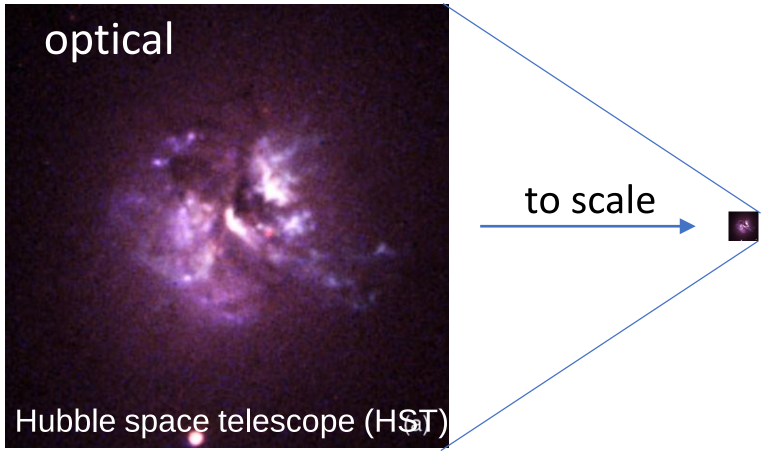
Credit: NASA/UMD/A.Wilson et al.

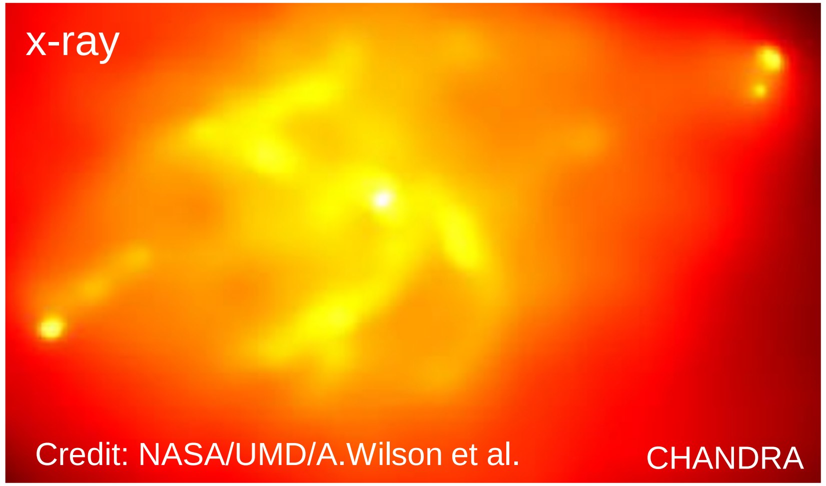
Cygnus A

Power ~ 10^{46} erg s $^{-1}$
Relativistic jet

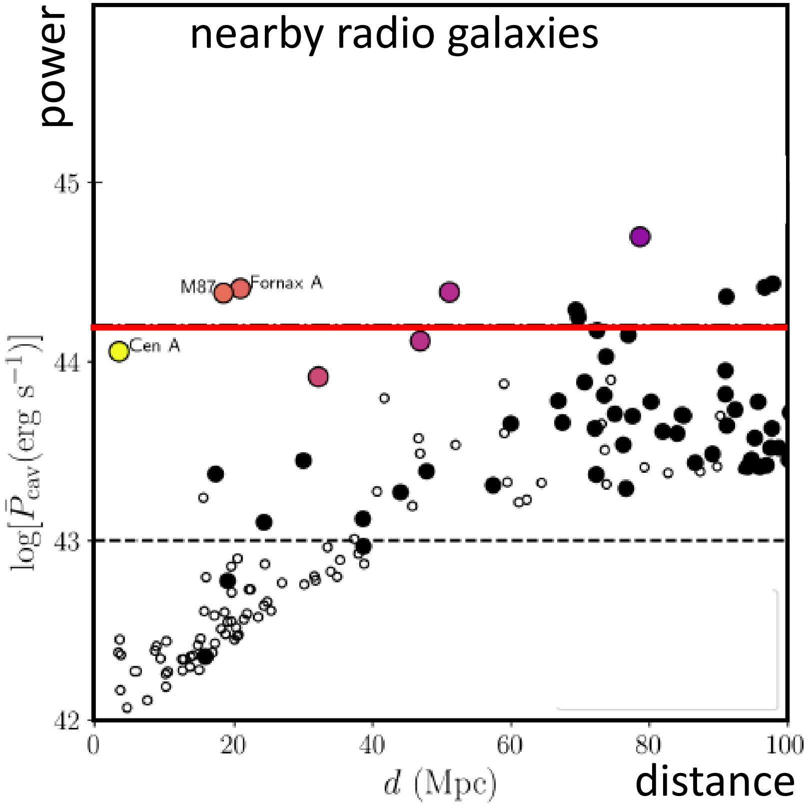
Problem:
Cygnus A too far away
No nearby powerful radio source







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

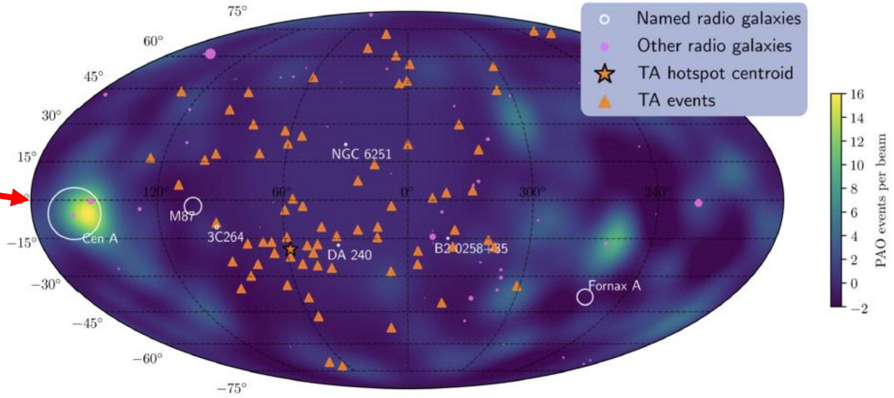


P_{mag} threshold (100EeV rigidity)

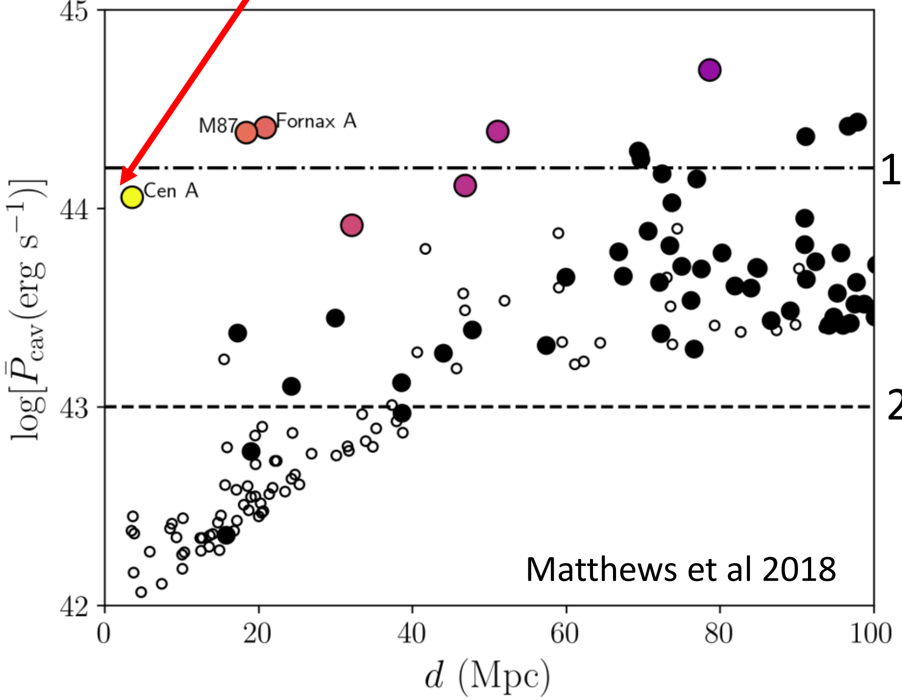
P_{mag} threshold (25EeV rigidity)

Nearby radio galaxies

Centaurus A
3σ association



Cosmic ray arrival directions

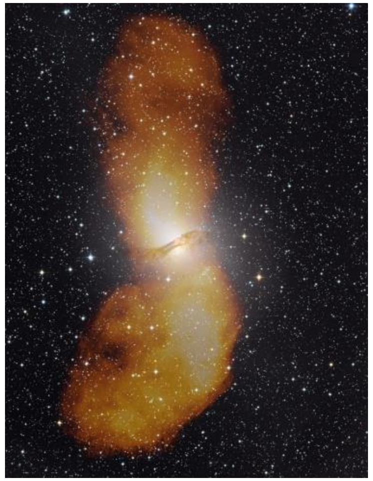


Matthews et al 2018

100EeV rigidity

25EeV rigidity

Centaurus A



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

Weak jets now, history of stronger activity

Similar, weaker case for Fornax A

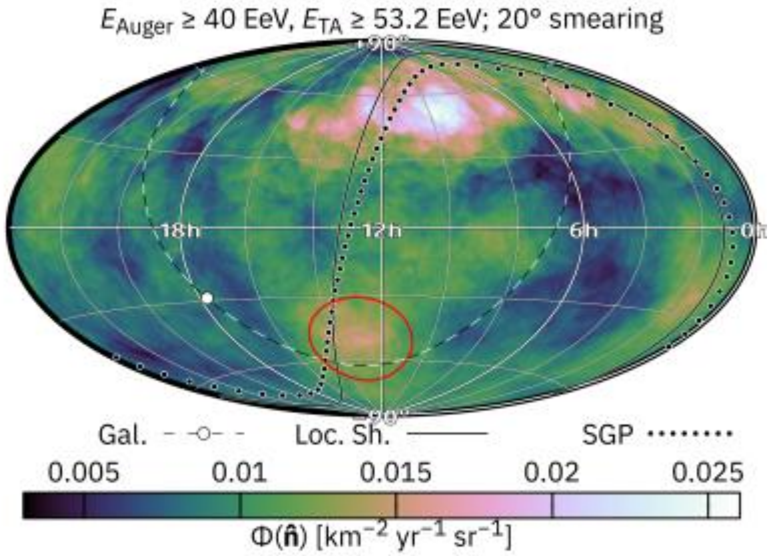
Possible solution

Centaurus A active 20Myr ago (galaxy merger)

Retained cosmic rays still leaking out of lobes

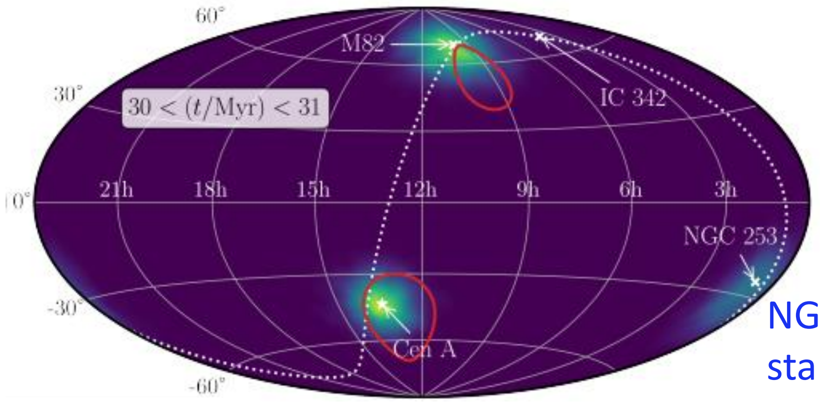
Seeing echoes from nearby starburst galaxies

The data: di Matteo, ICRC 2019



Synthetic map from model: Bell & Matthews 2022

M82 starburst galaxy



NGC253
starburst galaxy

Centaurus A

Model works but not unique

Too many free parameters

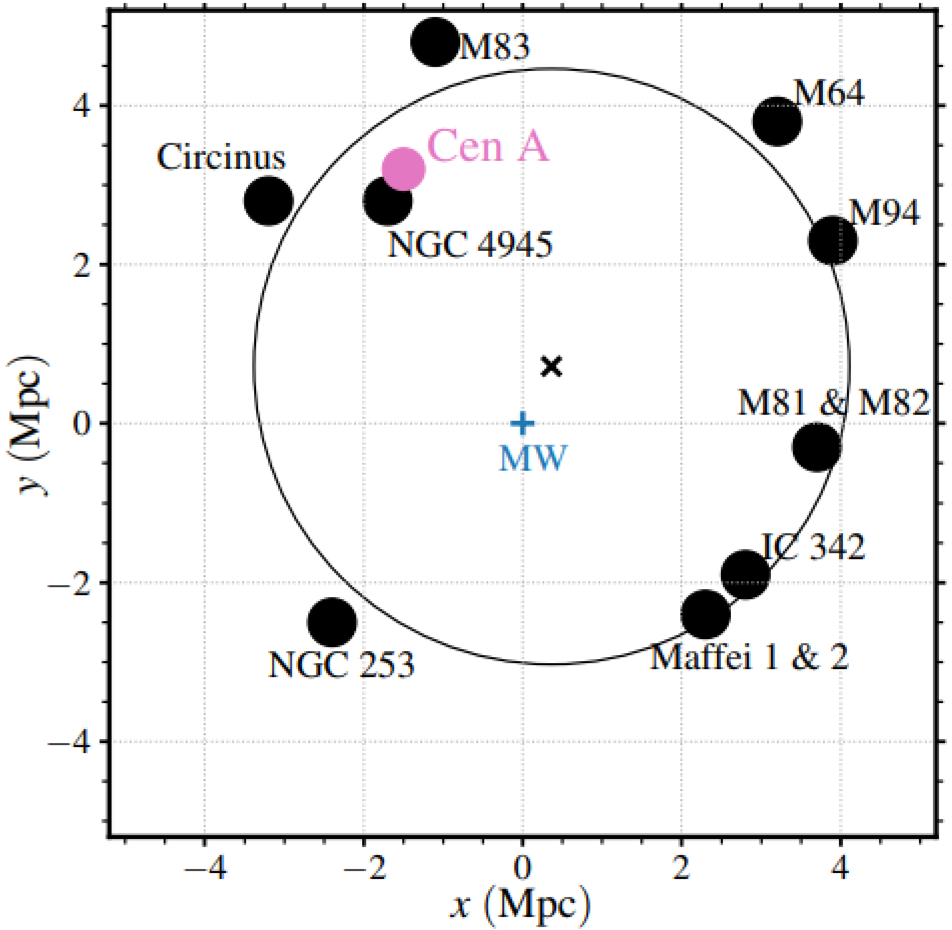
Echoes from ‘Council of Giants’

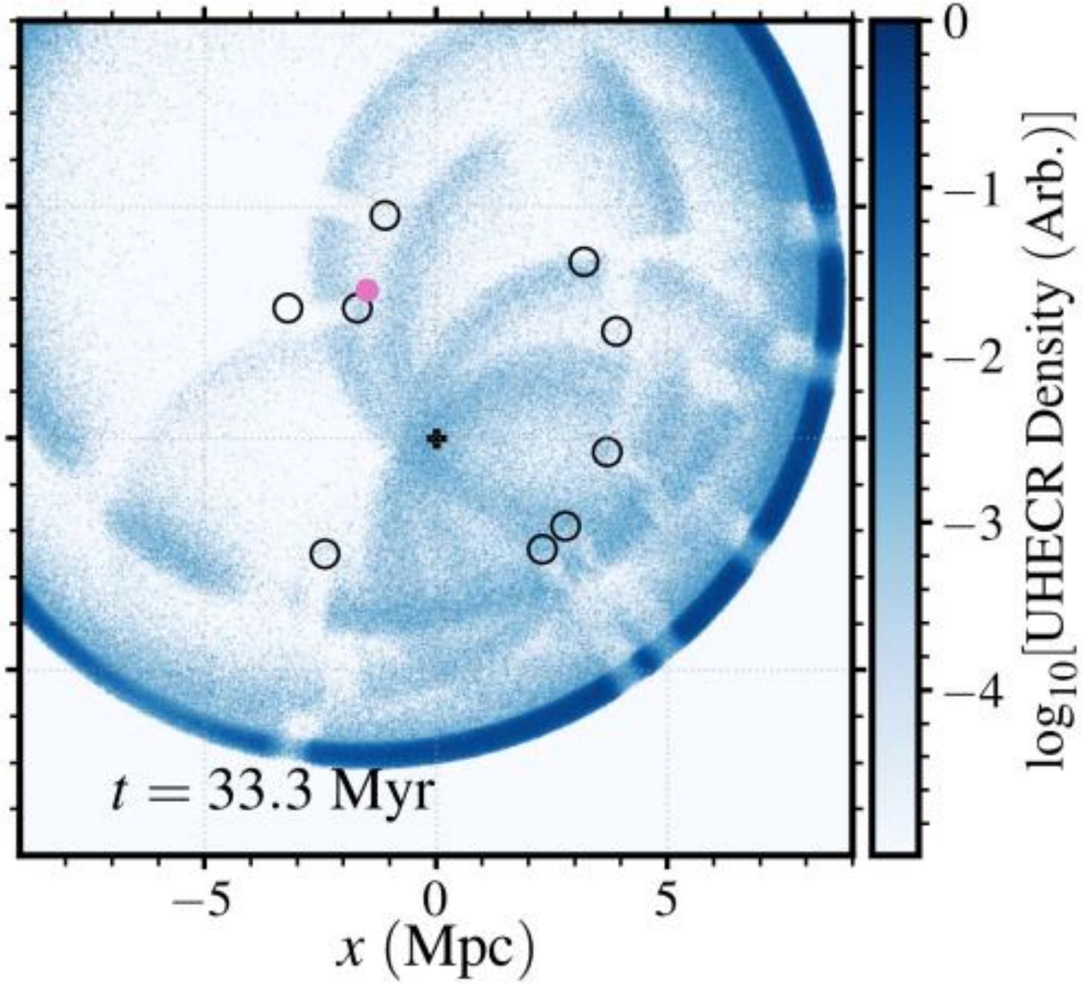
(with Andrew Taylor)

Ring of bright galaxies

Radius 3.75Mpc

Taylor, Matthews, Bell 2023

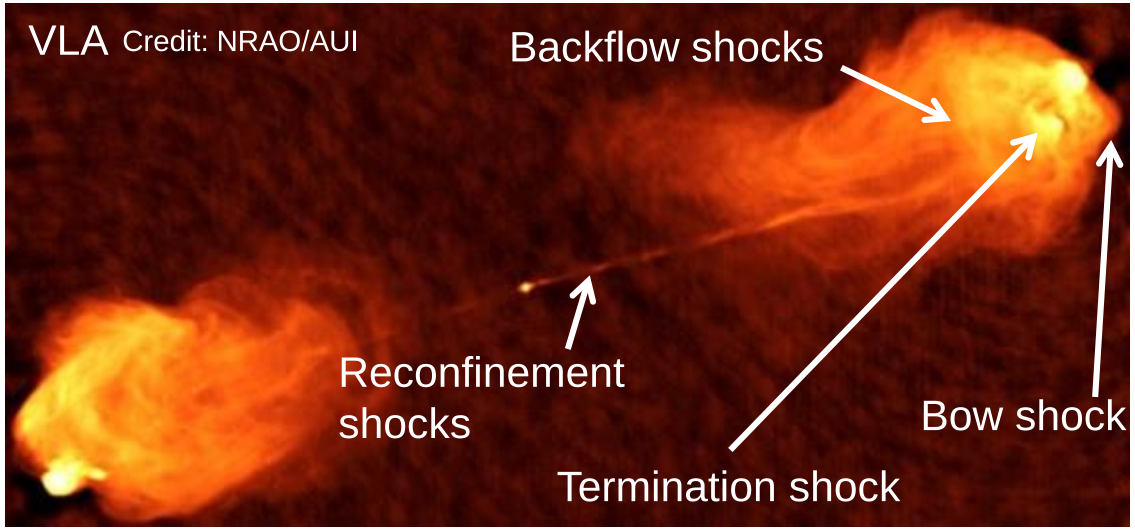




Possible CR-accelerating shocks in radio galaxies

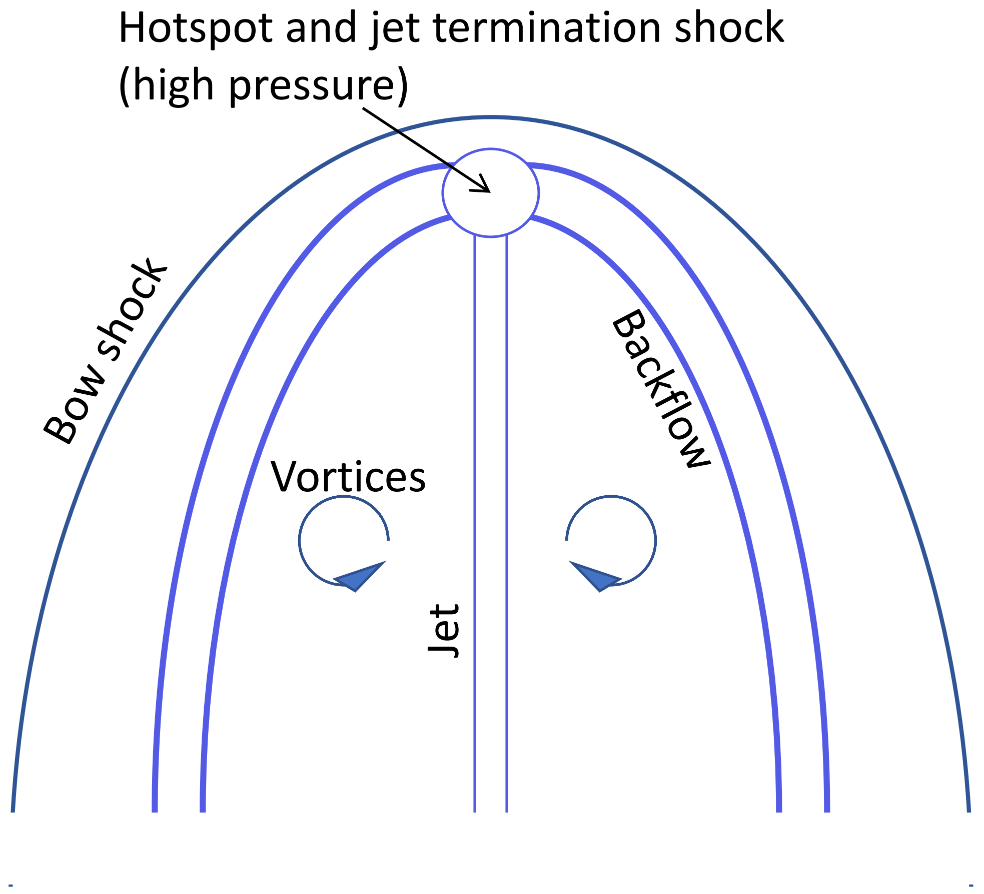
Cygnus A too far away
Maybe Cen A looked more like this 20Myr ago (but less powerful)

Cygnus A radio



Need shocks that are:
- High velocity but not relativistic
- Large & long-lived

Schematic diagram: flux tube



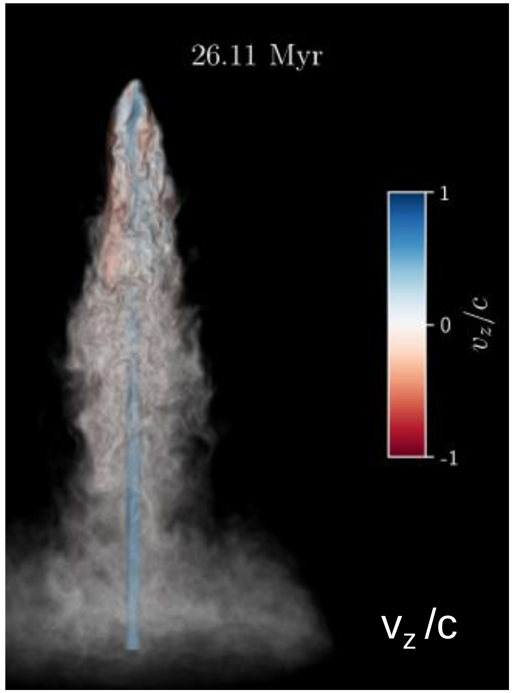
Backflow as Bernoulli flux tube

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

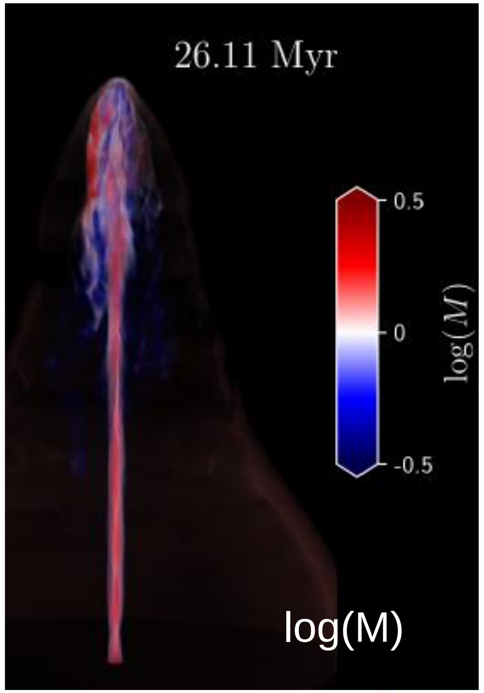
Hydro simulations: A jet at 26.11 Myr

James Matthews

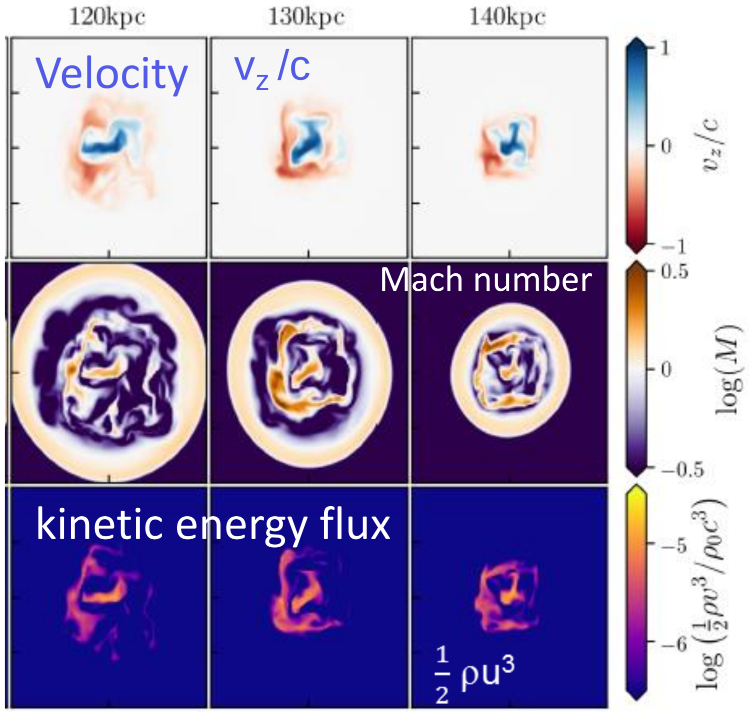
Vertical velocity



Log(Mach number)



Slices across jet



SUMMARY: The surprising effectiveness of cosmic ray acceleration

The Leverhulme Trust

Observations:

Efficient acceleration beyond few PeV in our Galaxy

Extragalactic acceleration to >100EeV

Galactic to extragalactic transition at 0.1 to 1EeV

Probable sources:

Young supernova remnants in our Galaxy

Powerful radio galaxies out to 100Mpc

Observation stretches theory to limits

Cosmic accelerators are well-oiled machines working to optimal effectiveness

Not what we expect of plasma devices