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The surprising effectiveness of cosmic ray acceleration

Tony Bell

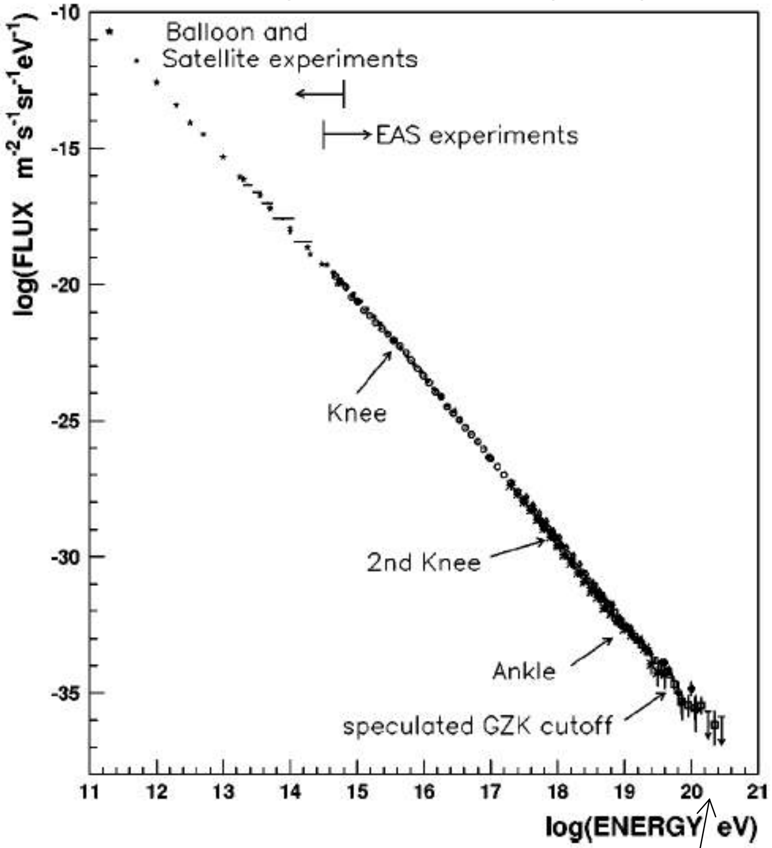
STFC Rutherford Appleton Laboratory
and
University of Oxford

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

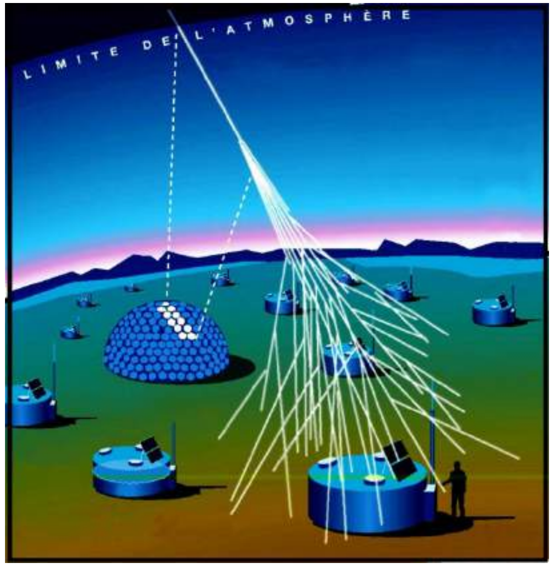
http://hubblesite.org/newscenter/archive/releases/2006/30/image/a/format/xlarge_web/

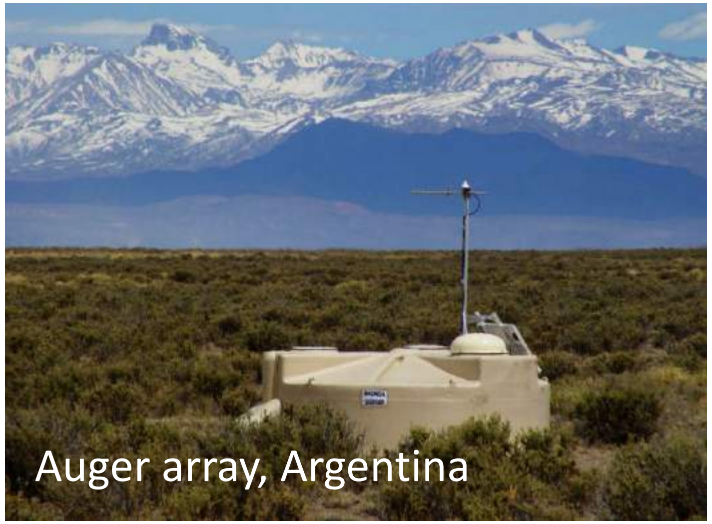
Cosmic rays: high energy charged particles arriving at Earth

Nagano & Watson (2000)



One per square kilometre per century



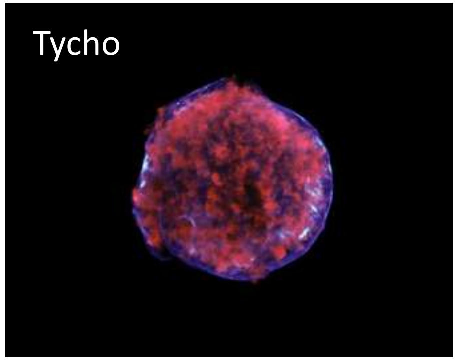


Auger array, Argentina

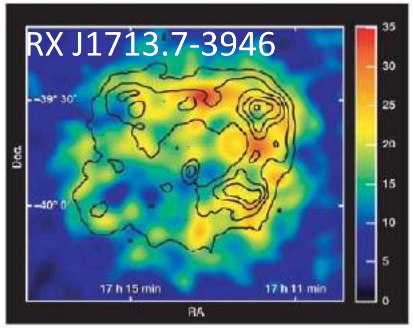
High energy charged particles in supernova remnants

Radio:
GeV electrons

X-ray:
TeV electrons



Gamma-ray:
Up to 100 TeV



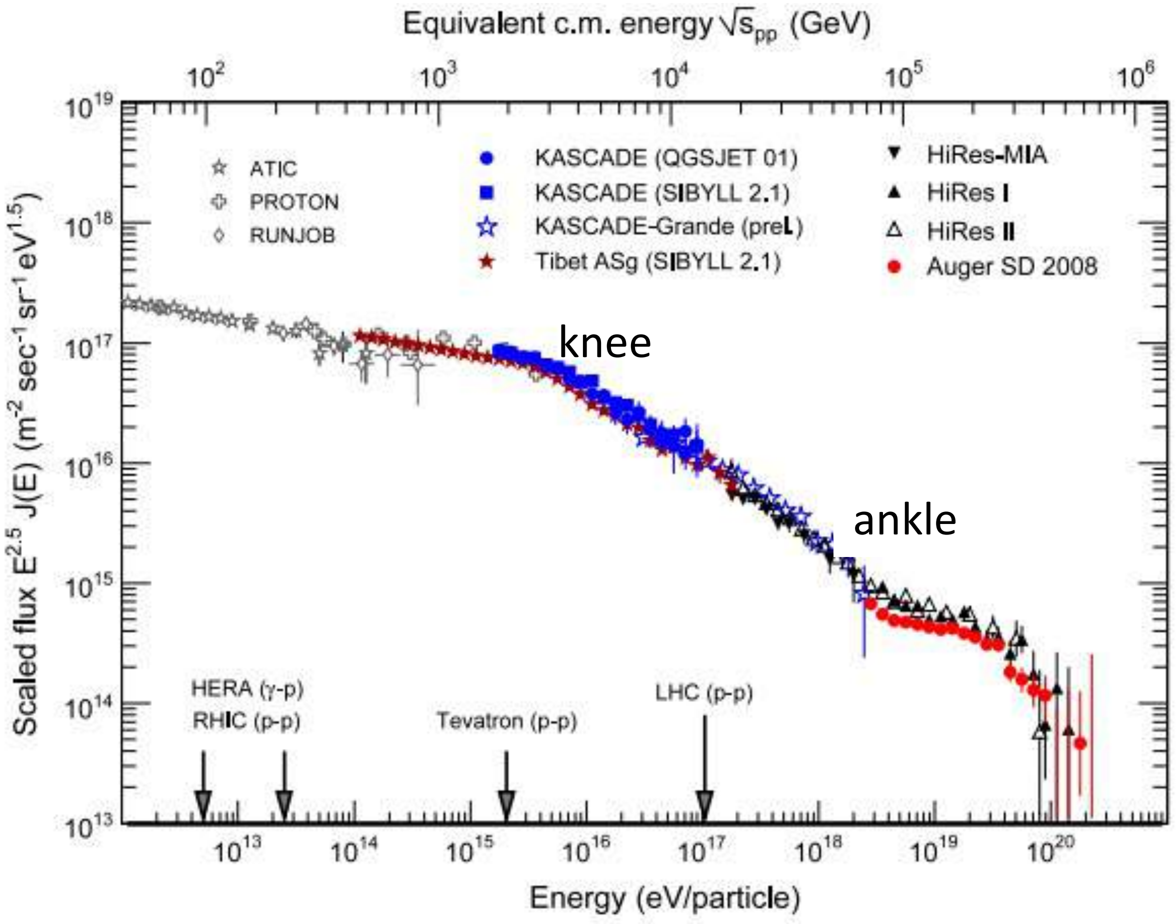
Observations place stringent requirements on CR acceleration

Requires 10-30% of energy output from Galactic supernovae

Efficient acceleration to 3PeV (the 'knee')

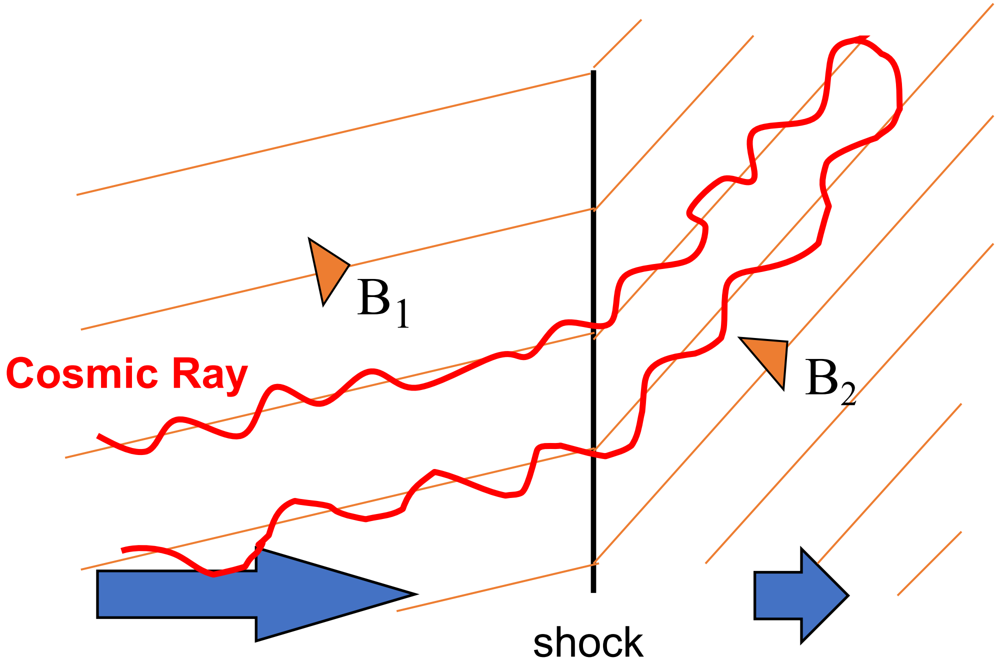
Continuity implies Galactic acceleration to 1000 PeV (the 'ankle')

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

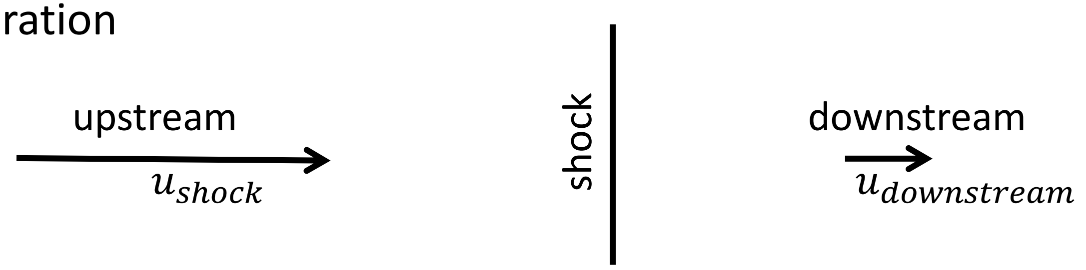
Fractional energy gain $\frac{\Delta\varepsilon}{\varepsilon} = \frac{u_s}{c}$

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

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

Maximum (Hillas) energy

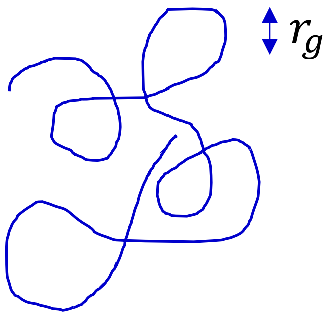
Diffusive shock acceleration



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

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

=1 for maximum energy

For young energetic supernova remnants

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

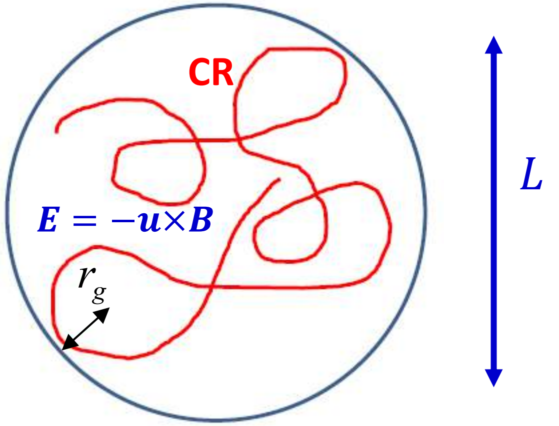
$L\sim 3\times 10^{17}\mathrm{m}$

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 $\boldsymbol{B}$

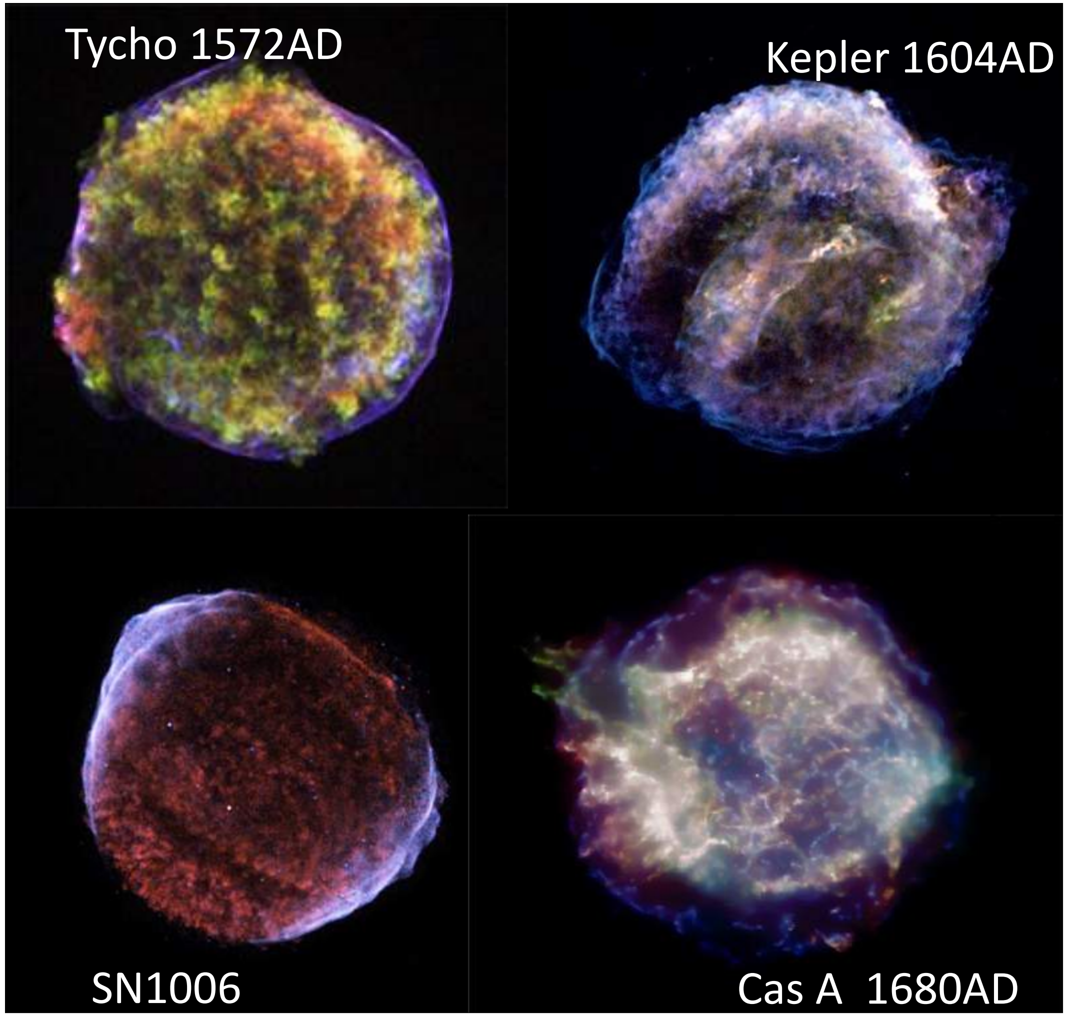
Bohm diffusion is as good as it gets

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

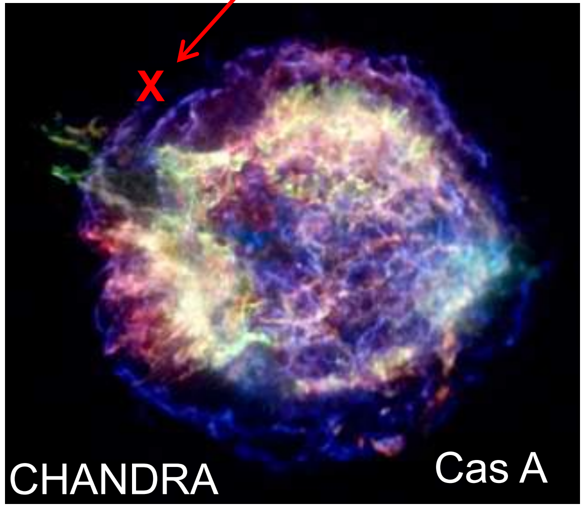


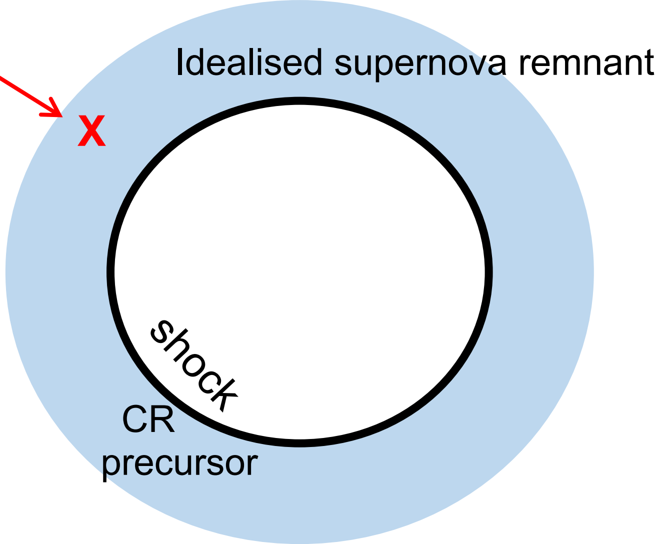
Chandra observations (x-ray)

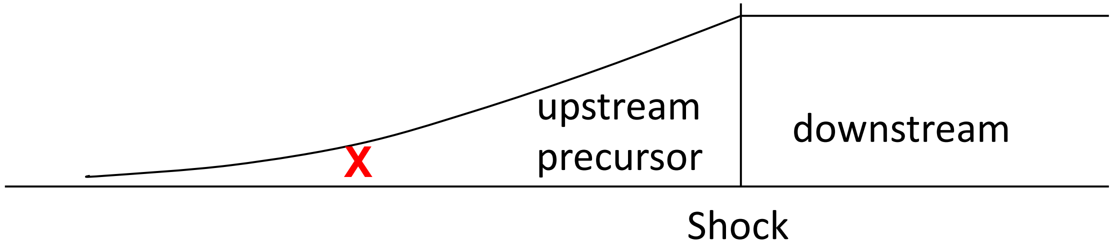
NASA/CXC/Rutgers/ J.Hughes et al.   NASA/CXC/Rutgers/ J.Warren & J.Hughes et al.   NASA/CXC/NCSU/ S.Reynolds et al.   NASA/CXC/MIT/UMass Amherst/ M.D.Stage et al.

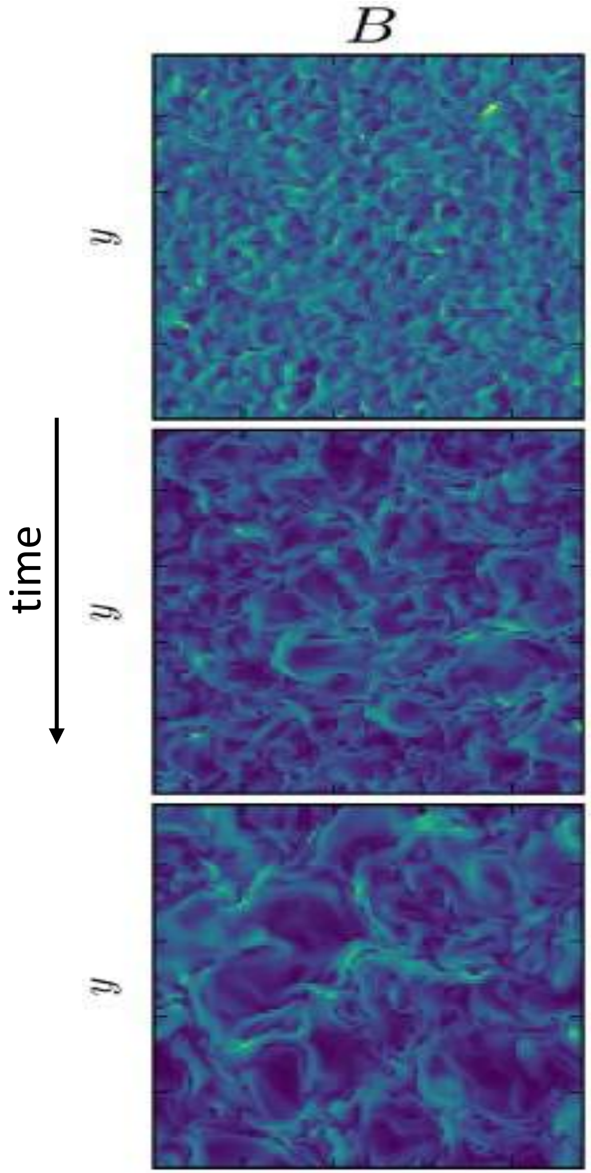
Escaping cosmic rays generate their own magnetic field

Magnetic grows ahead of shock









Matthews et al 2017

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

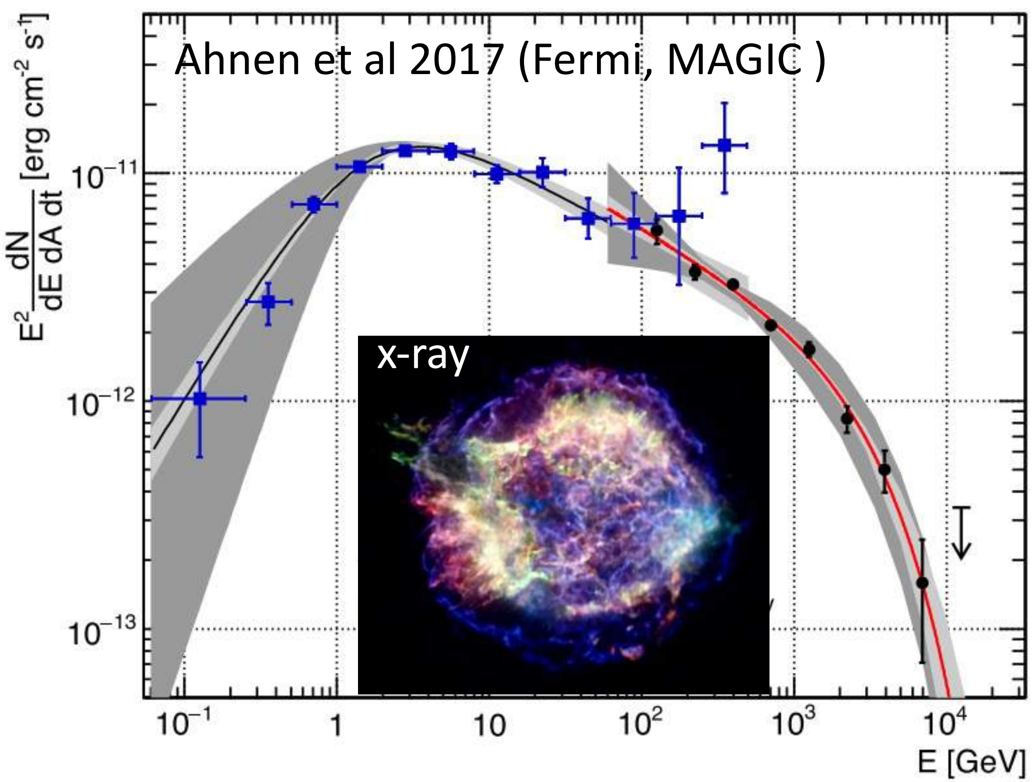
Coupled cosmic transport/magnetic field growth

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

Confirmed by γ-ray observations

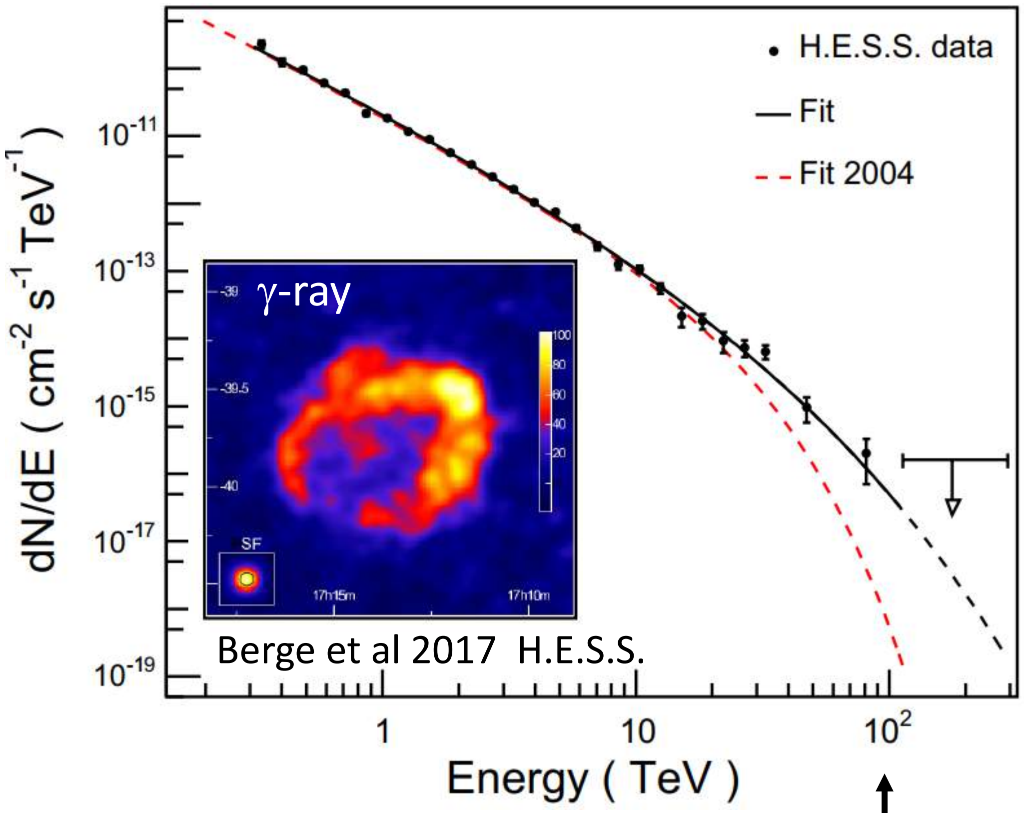
Problem: no known Galactic supernova remnant reaching 1PeV (theory and observation)

Cas A γ-ray spectrum



10TeV

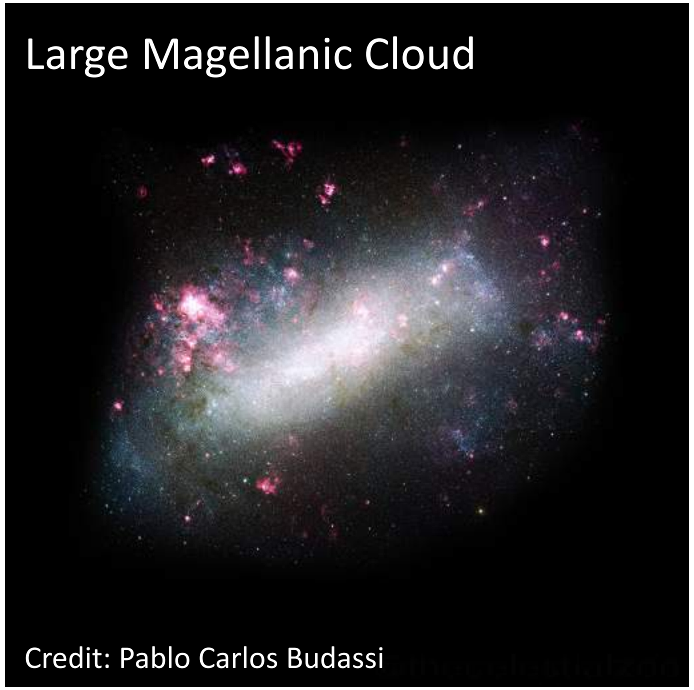
RX J1713.7–3946 γ-ray spectrum



100TeV

Very young supernova remnants (<30 years)

For example SN1987a in nearby Large Magellanic Cloud



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

- Winds from massive stars
- Multiple interacting supernovae
- Galactic wind termination shock
- Galactic Centre
- High velocity outflows from the Galaxy
- Pulsar wind nebulae

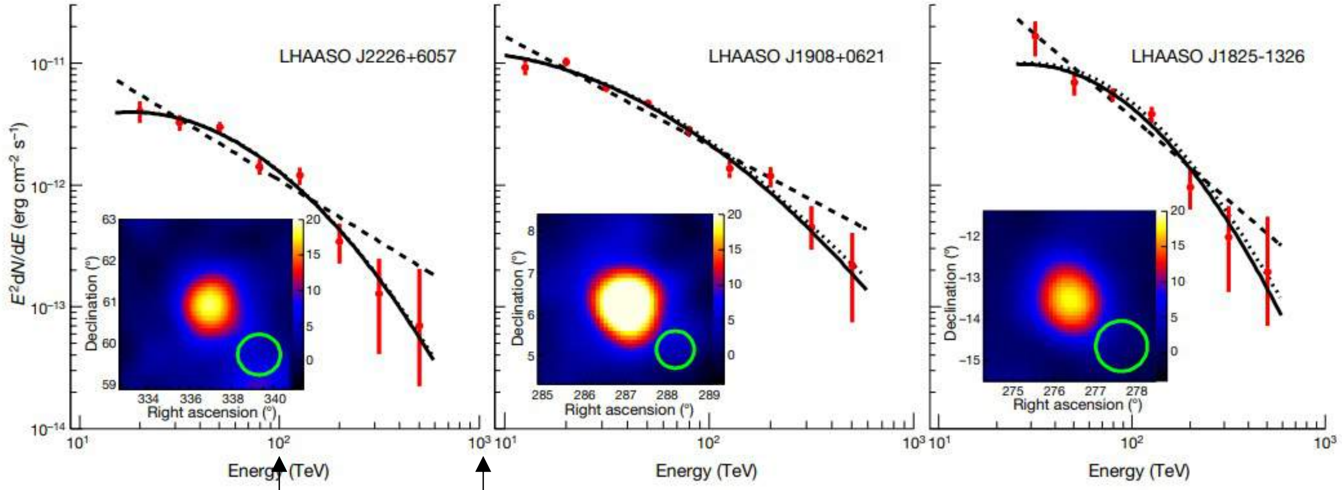
Other processes are available

- Reconnection
- Friction in shear layers
- Cross-field drift in relativistic winds

BREAKING NEWS (12 months ago)

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

1.4PeV photon from J2032.4102 (unidentified)



Cosmic ray energy: ~7x γ-ray energy

100TeV

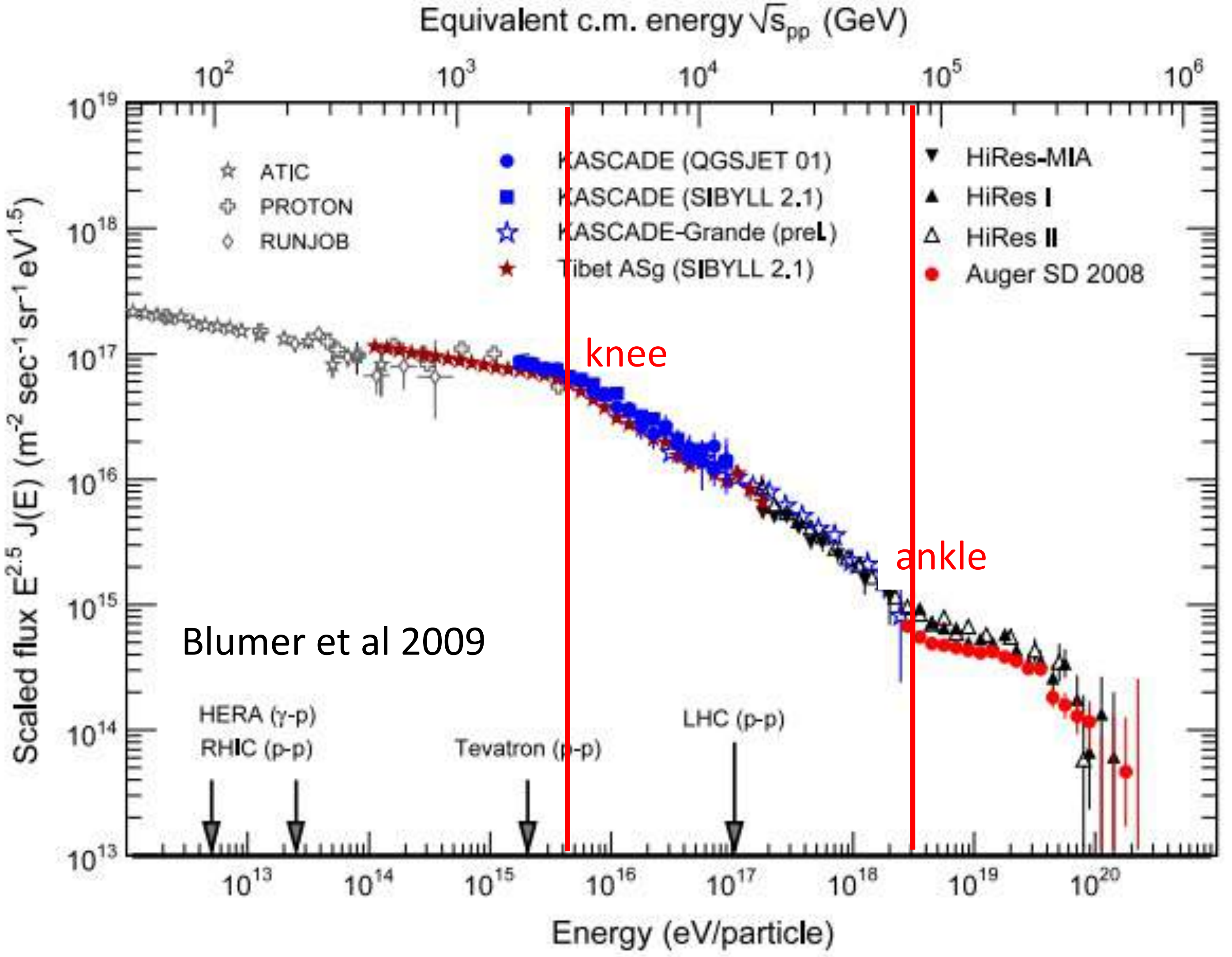
1PeV

Could be electron/positrons in pulsar magnetospheres

Where we stand on cosmic rays in our Galaxy:

Struggle to get to the knee

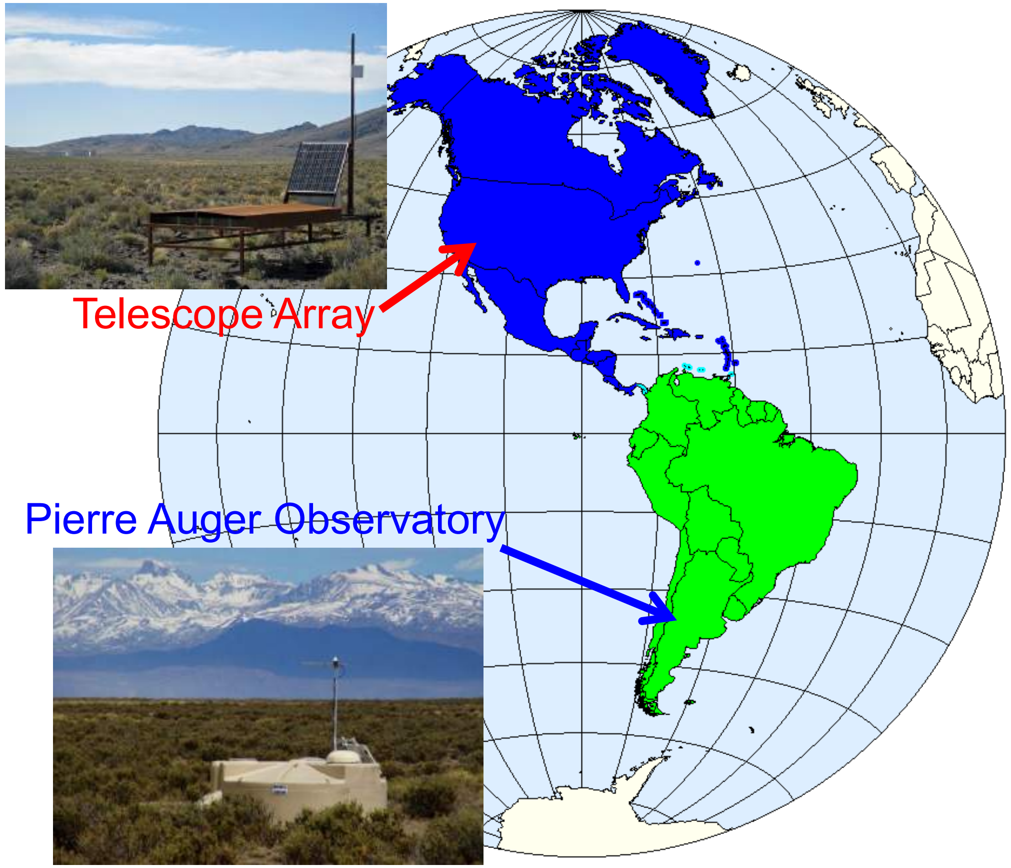
The ankle is more problematic

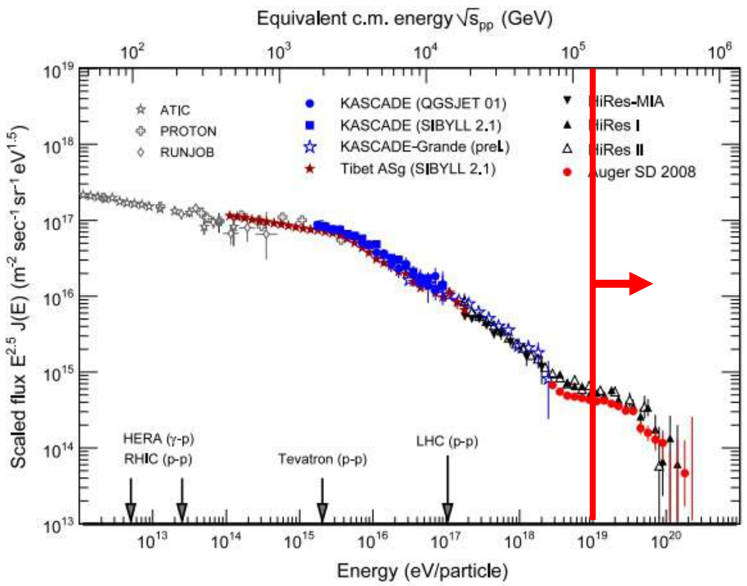


Highest energy cosmic rays must come from outside Galaxy because

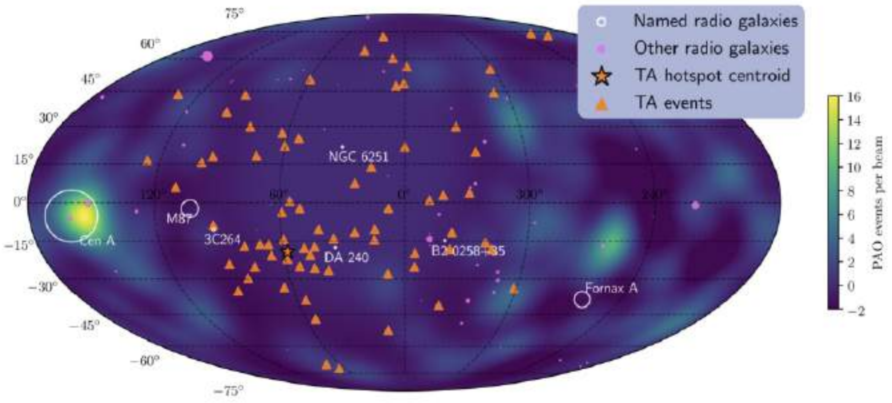
Larmor radius larger than the Galaxy

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





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:

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

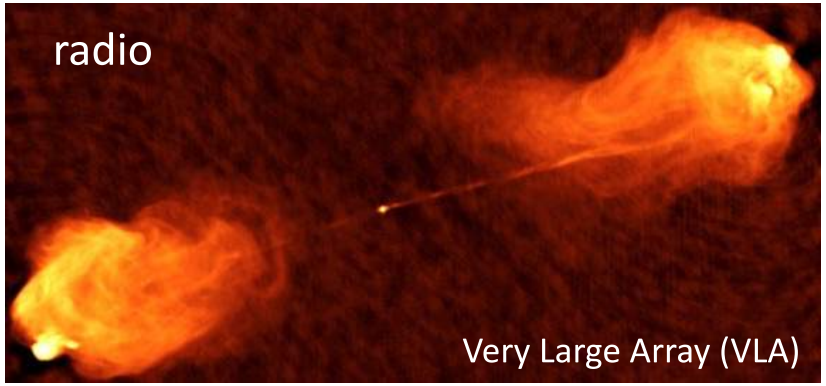
To reach 100EeV

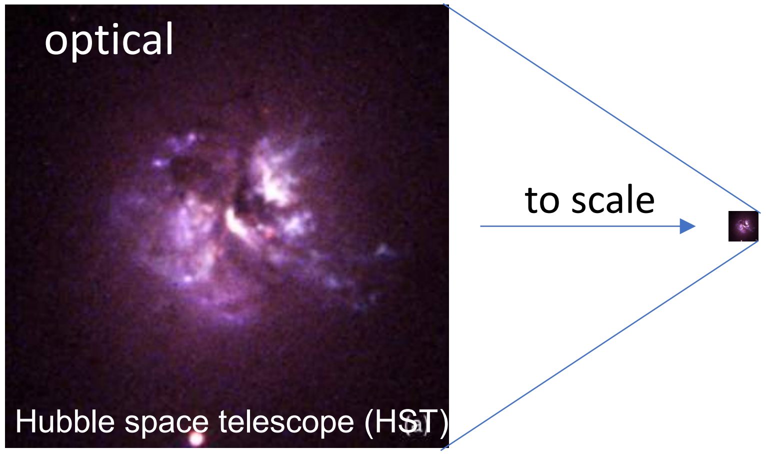
$$P_{mag} > \left(\frac{u}{c}\right)^{-1} 1.2 \times 10^{33}\ \text{W}$$

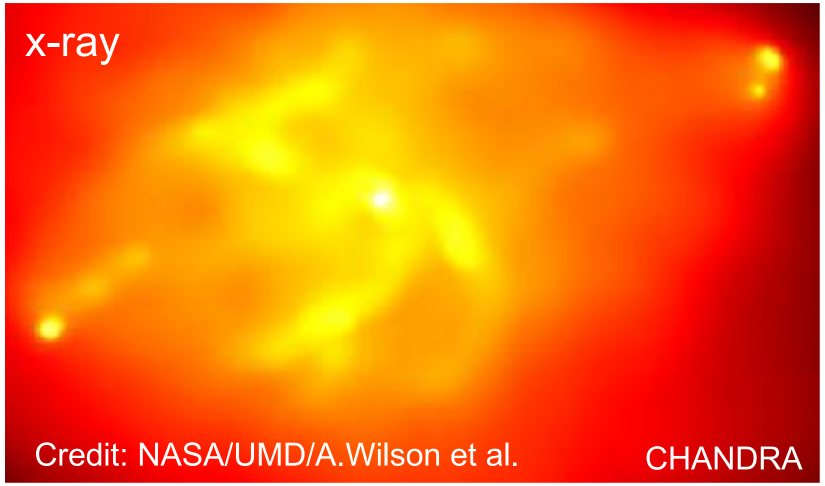
BUT

- 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

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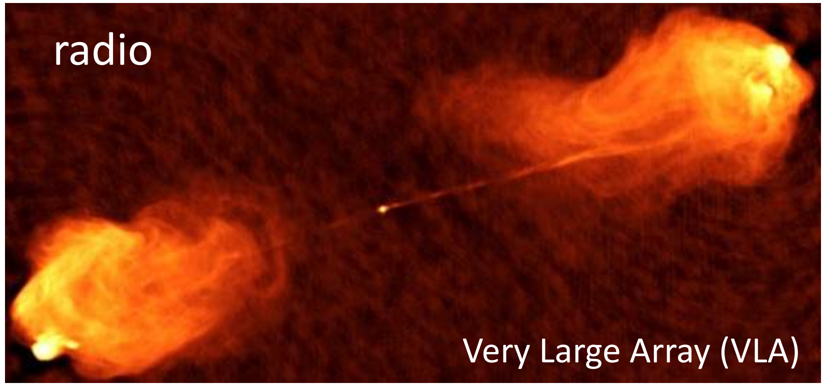
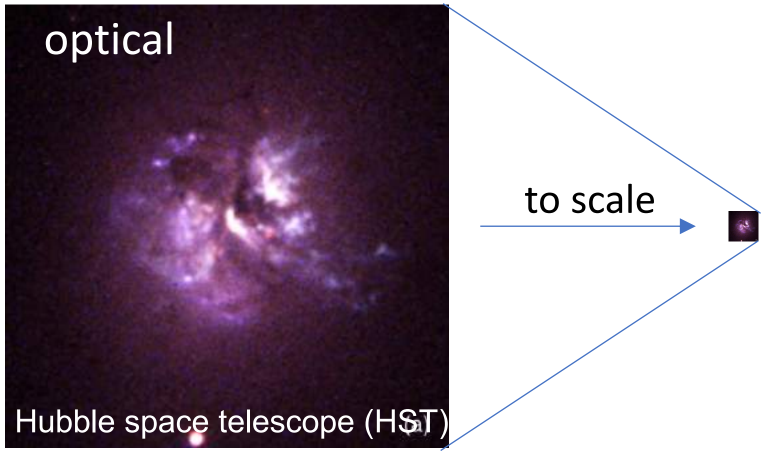
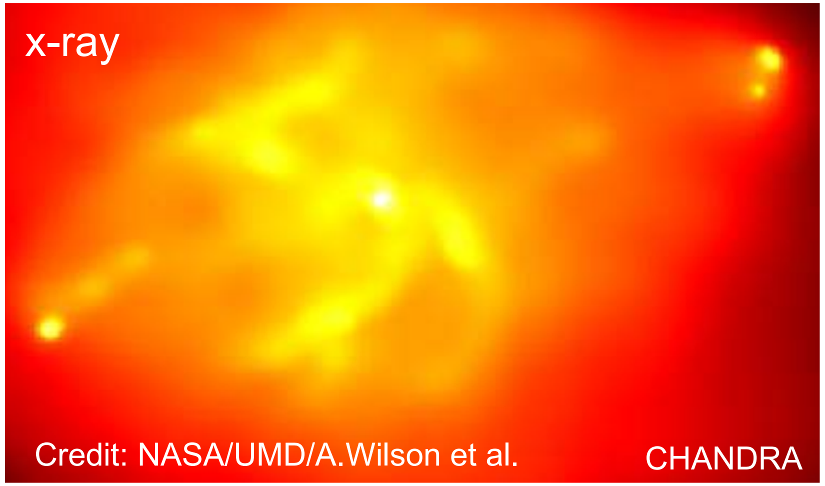
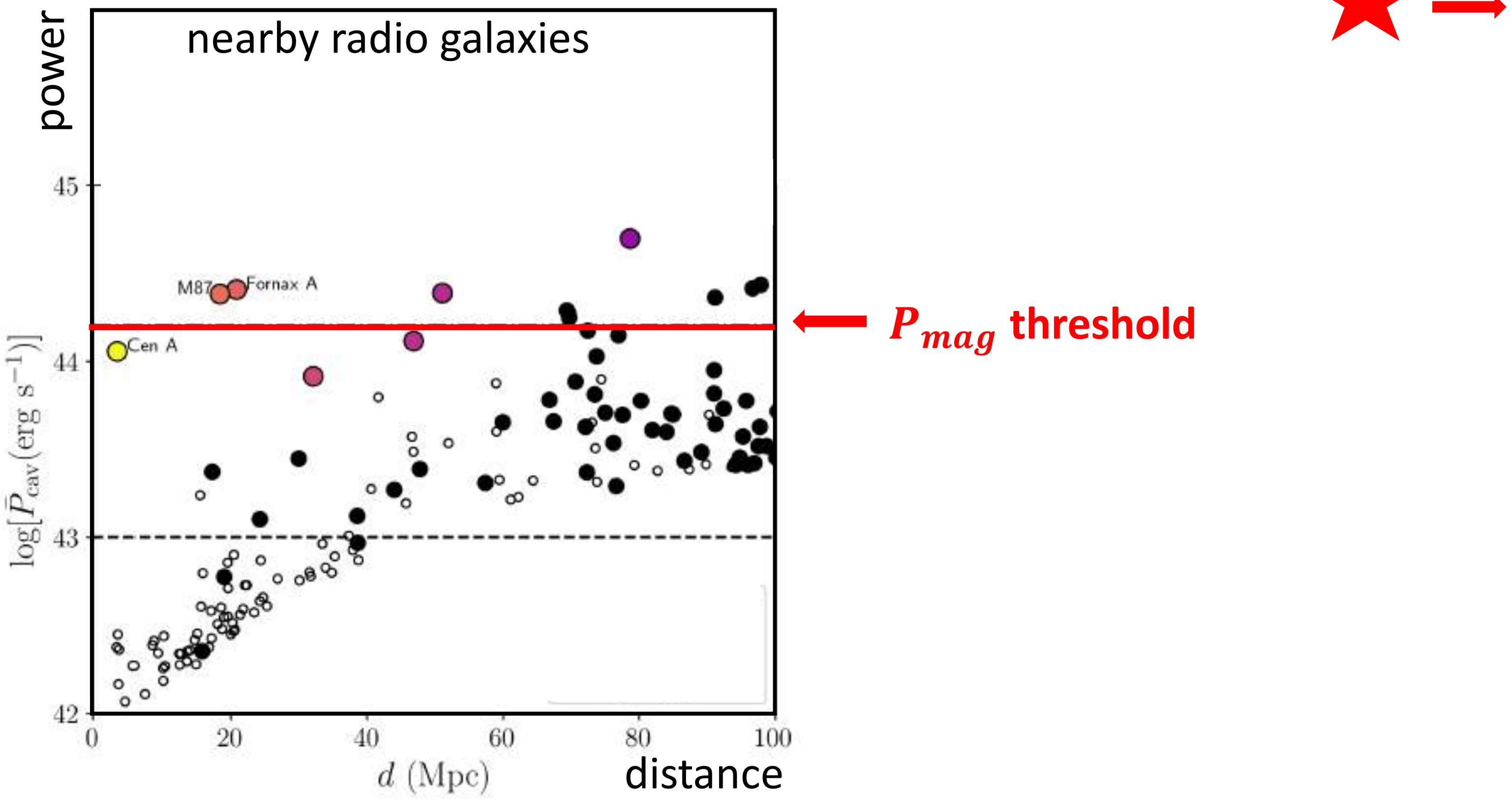
Power ~ 10^{46} erg s^{-1}
Relativistic jet

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



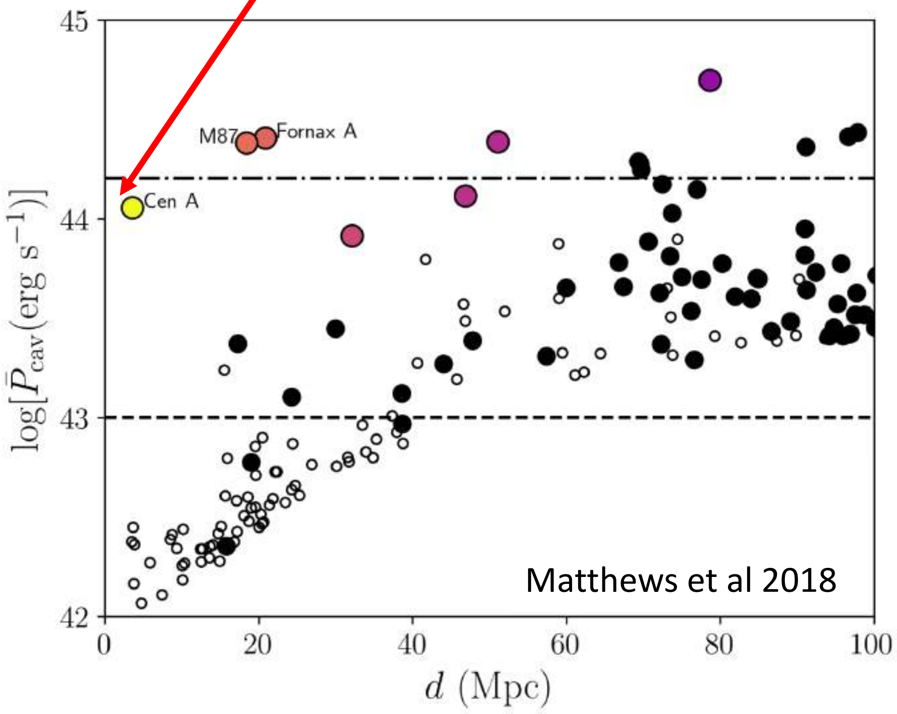


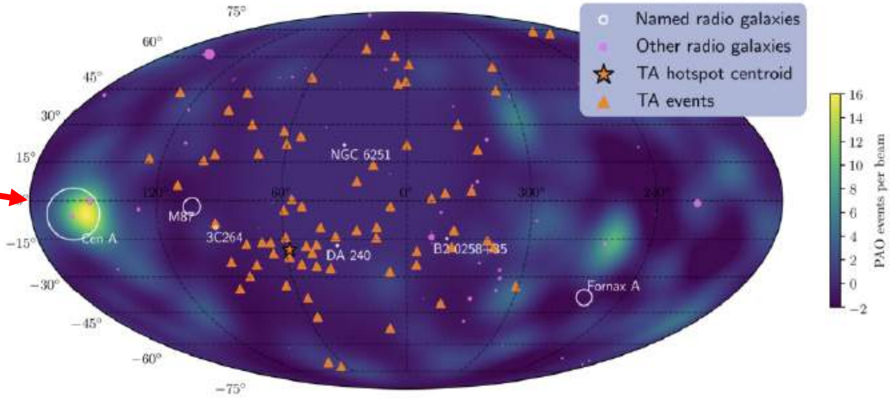




Nearby radio galaxies

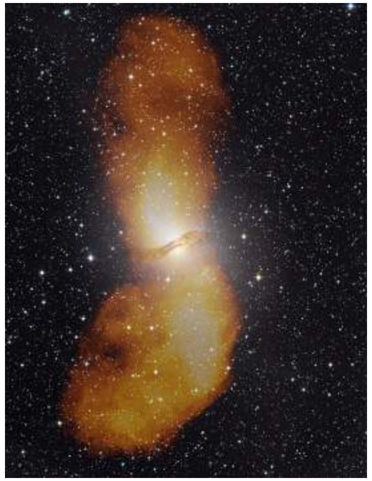
Centaurus A
3σ association





Cosmic ray arrival directions

Centaurus A



Weak jets now, history of stronger activity

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

Similar, weaker case for Fornax A

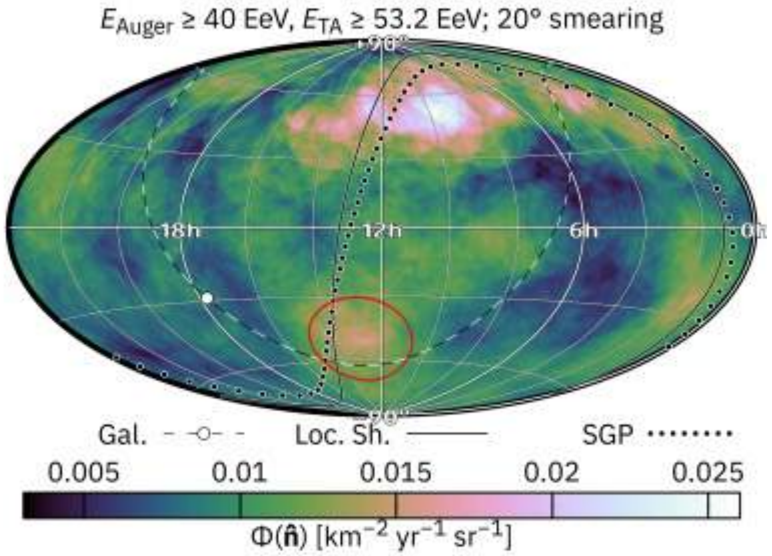
Possible solution

Centaurus A active 20Myr ago (galaxy merger)

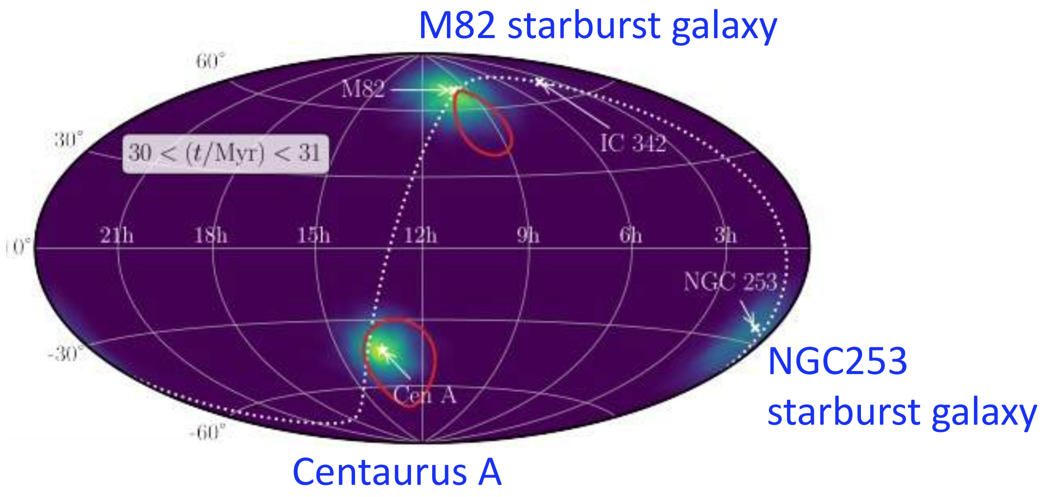
Retained cosmic rays still leaking out of lobes

Seeing echoes from nearby starburst galaxies

The data: di Matteo, ICRC 2019



Synthetic map from model: Bell & Matthews 2022



Model works but not unique

Too many free parameters

SUMMARY: The surprising effectiveness of cosmic ray acceleration

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

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Not what we expect of plasma devices