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Particle Astrophysics

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High energy particle astrophysics: mechanisms and sources

ACCELERATION MECHANISMS
DIFFUSIVE SHOCK ACCELERATION
SUPERNOVA REMNANTS AS COSMIC RAY ACCELERATORS
EXTRAGALACTIC COSMIC RAYS

Astrophysical accelerators

Terrestrial accelerators use electric fields to accelerate particles and magnetic fields to steer them.

- Magnetic fields do not accelerate particles because the force is perpendicular to the velocity, so no work is done.

However, persistent electric fields are very rare in the cosmos, because much of the interstellar medium is ionised.

- Therefore acceleration must be due to magnetic fields.
- Static magnetic fields cannot do this, but *moving* ones can.
  - The process is exactly analogous to gravitational slingshot manoeuvres used by spacecraft.

Acceleration by a moving magnetic field

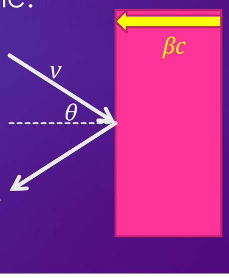
Assume that a particle with energy E scatters elastically off the magnetic field of a gas cloud moving with speed βc in the x direction.

In the rest frame of the cloud, the energy of the particle is $E' = \gamma E + \beta\gamma p\cos\theta$ (in units with $c = 1$), and its momentum in the x direction is $p'_x = \gamma p\cos\theta + \beta\gamma E$.

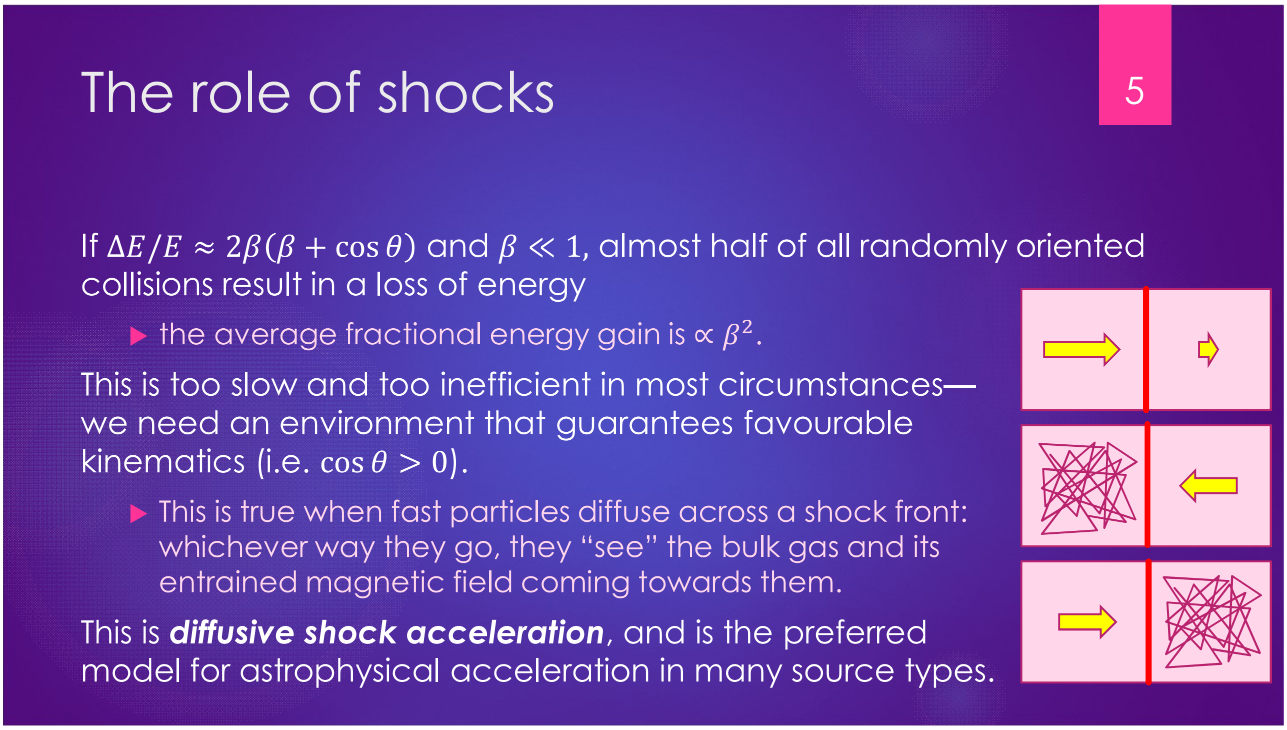
Typical gas clouds have masses $\gg M_\odot$, so we can assume that the particle just bounces off, reversing p_x but not changing the energy in this frame.

Transforming back to the lab frame then gives

$$\begin{aligned} E'' &= \gamma E' + \beta\gamma p'_x \\ &= \gamma^2 E\left(1 + \beta^2 + 2\beta\frac{p}{E}\cos\theta\right). \end{aligned}$$



Therefore, as $\beta \ll 1$, $\gamma^2 \approx 1 + \beta^2$ and $\Delta E/E \approx 2\beta(\beta + \cos\theta)$ for $v \approx c$.



The role of shocks

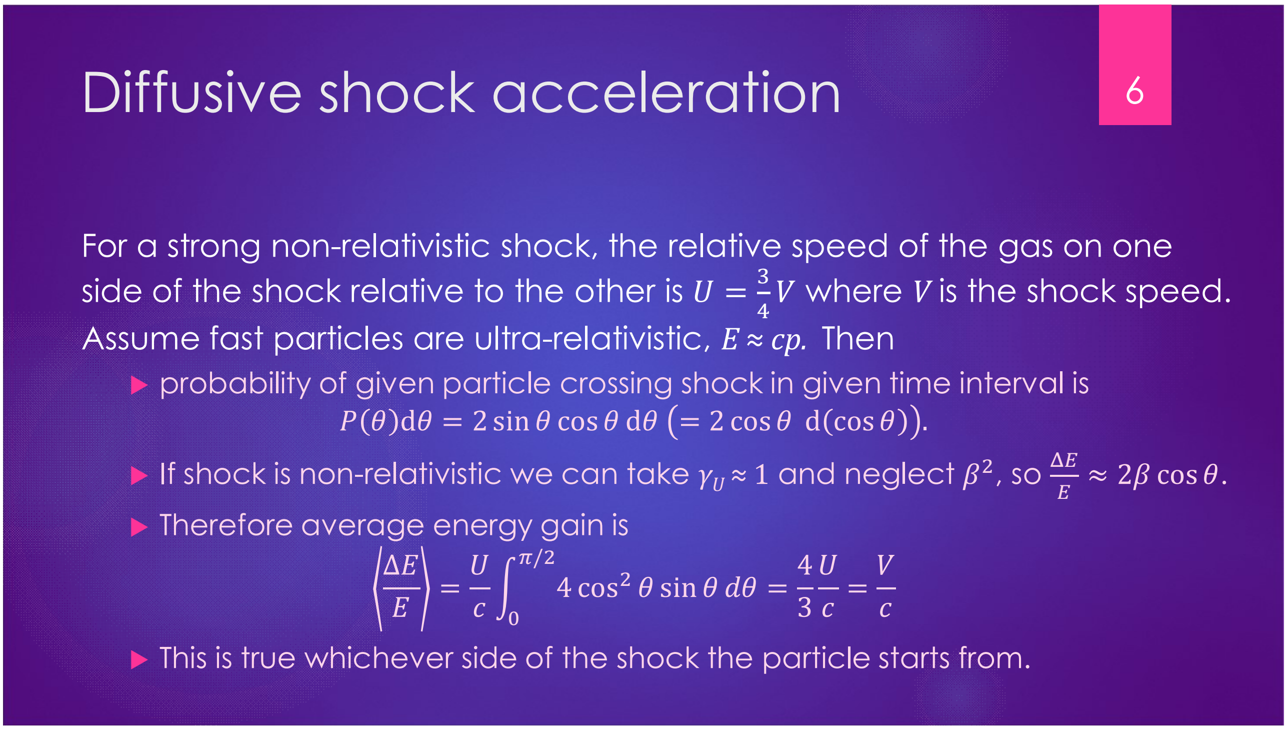
If $\Delta E/E \approx 2\beta(\beta + \cos\theta)$ and $\beta \ll 1$, almost half of all randomly oriented collisions result in a loss of energy

- the average fractional energy gain is $\propto \beta^2$.

This is too slow and too inefficient in most circumstances—we need an environment that guarantees favourable kinematics (i.e. $\cos\theta > 0$).

- This is true when fast particles diffuse across a shock front: whichever way they go, they "see" the bulk gas and its entrained magnetic field coming towards them.

This is ***diffusive shock acceleration***, and is the preferred model for astrophysical acceleration in many source types.



Diffusive shock acceleration

For a strong non-relativistic shock, the relative speed of the gas on one side of the shock relative to the other is $U = \frac{3}{4}V$ where V is the shock speed. Assume fast particles are ultra-relativistic, $E \approx cp.$ Then

- probability of given particle crossing shock in given time interval is
$$P(\theta)\mathrm{d}\theta = 2\sin\theta\cos\theta\,\mathrm{d}\theta\ \big(= 2\cos\theta\ \mathrm{d}(\cos\theta)\big).$$
- If shock is non-relativistic we can take $\gamma_U \approx 1$ and neglect β^2, so $\frac{\Delta E}{E} \approx 2\beta\cos\theta$.
- Therefore average energy gain is
$$\left\langle\frac{\Delta E}{E}\right\rangle = \frac{U}{c}\int_0^{\pi/2} 4\cos^2\theta\sin\theta\, d\theta = \frac{4}{3}\frac{U}{c} = \frac{V}{c}$$
- This is true whichever side of the shock the particle starts from.

Energy spectrum from diffusive shock acceleration

After k shock crossings, the particle has energy $E_k = (1 + \beta_V)^k E_0$.

The probability that the particle is carried downstream and never crosses the shock again also turns out to be V/c, so after k shock crossings the number of particles remaining is $N_k = (1 - \beta_V)^k N_0$.

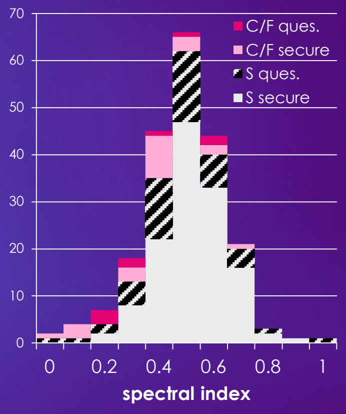
- Taking logs, $\ln E_k = k\beta_V + \ln E_0$ and $\ln N_k = -k\beta_V + \ln N_0$
  since $\ln(1 \pm \beta_V) \approx \pm\beta_V$ for $\beta_V \ll 1$.
- Therefore $\ln N_k = -\ln E_k + \ln(N_0/E_0)$, i.e. $N(E \geq E_k) \propto E_k^{-1}$.
- To get $\mathrm{d}N/\mathrm{d}E$ we differentiate: $N(E)\mathrm{d}E \propto E^{-2}\mathrm{d}E$.

Note that this is independent of the details of the shock.

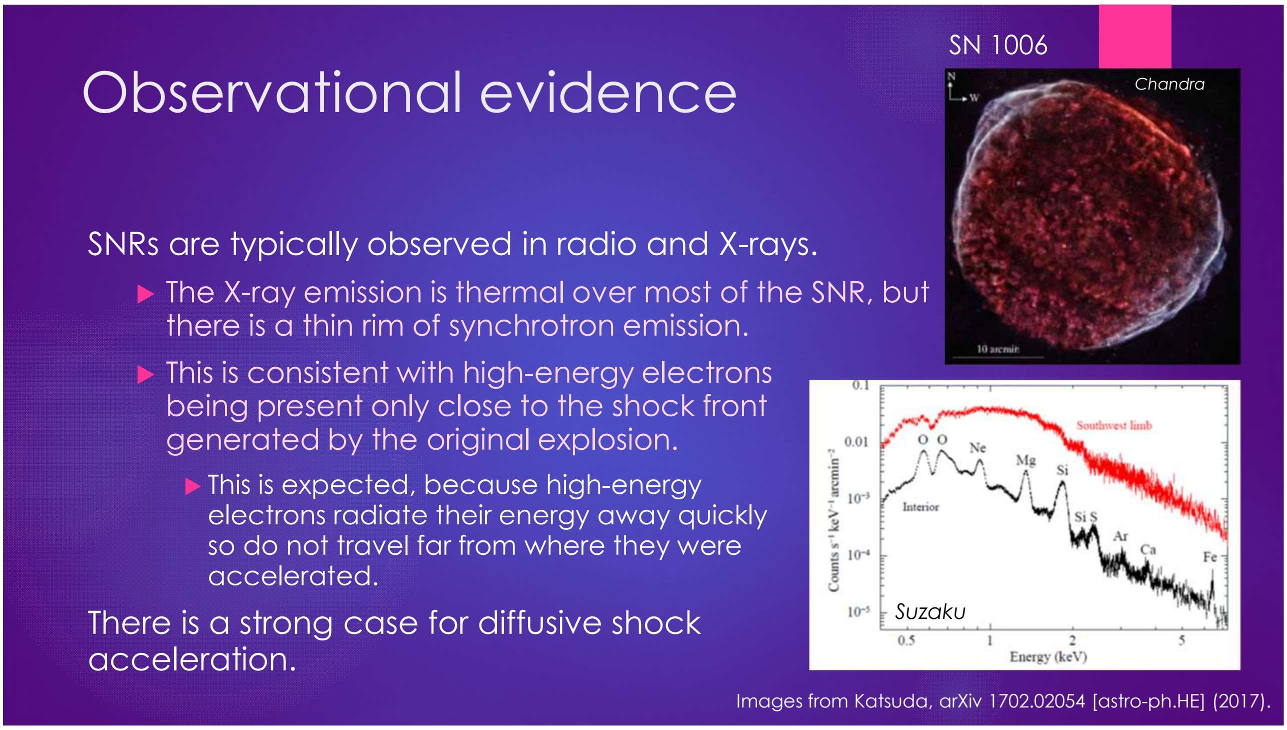
Supernova remnants as cosmic ray sources

Supernova remnants are a probable example of diffusive shock acceleration.

- Assuming a supernova rate of ~2/century and an average energy release (excluding neutrinos) of 10^{44} J, supernova remnants can maintain the energy density in cosmic rays if acceleration in ~10% efficient.
  - This is in line with simulations and with measurements of particle acceleration in solar system shocks.
- If the electron energy spectrum is $\propto E^{-2}$, the synchrotron spectrum should be $\propto \nu^{1/2}$, which is consistent with what we see in SNR radio data.



Data from Green's catalogue of supernova remnants.



Observational evidence

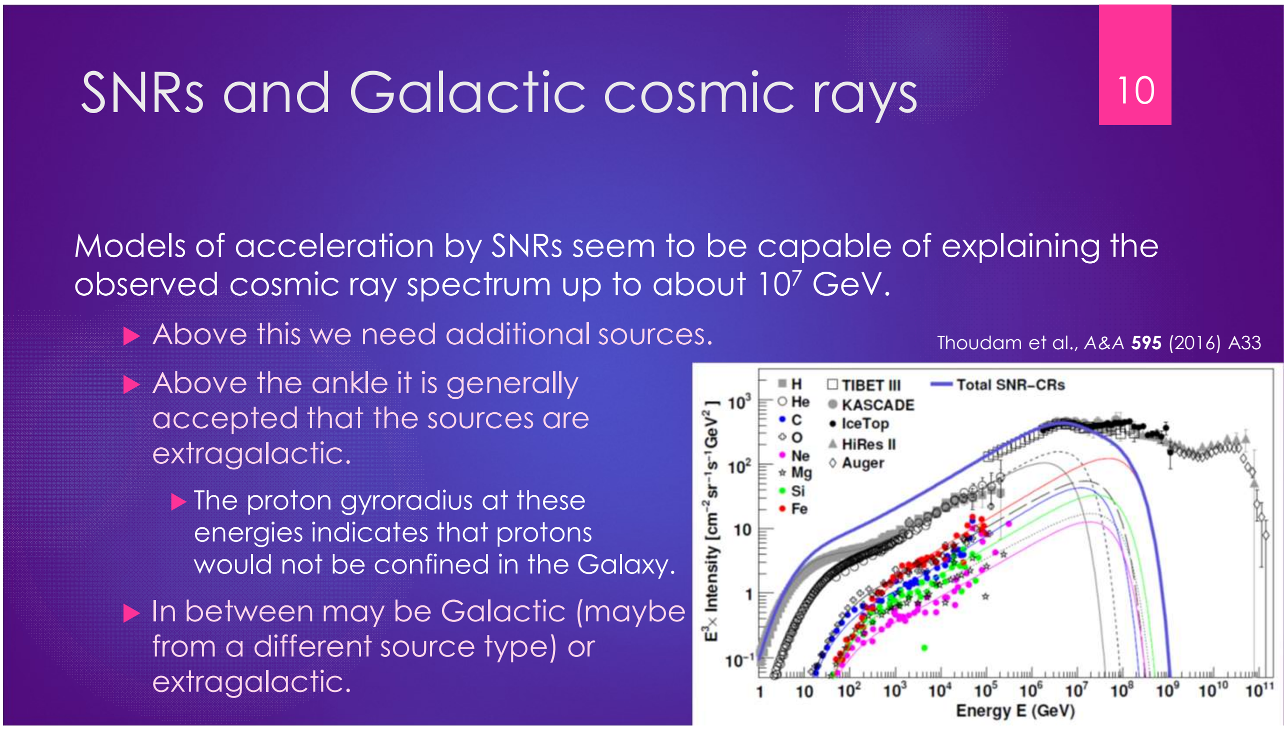
SN 1006

SNRs are typically observed in radio and X-rays.

- The X-ray emission is thermal over most of the SNR, but there is a thin rim of synchrotron emission.
- This is consistent with high-energy electrons being present only close to the shock front generated by the original explosion.
  - This is expected, because high-energy electrons radiate their energy away quickly so do not travel far from where they were accelerated.

There is a strong case for diffusive shock acceleration.

Images from Katsuda, arXiv 1702.02054 [astro-ph.HE] (2017).



SNRs and Galactic cosmic rays

Models of acceleration by SNRs seem to be capable of explaining the observed cosmic ray spectrum up to about 10^7 GeV.

- Above this we need additional sources.
- Above the ankle it is generally accepted that the sources are extragalactic.
  - The proton gyroradius at these energies indicates that protons would not be confined in the Galaxy.
- In between may be Galactic (maybe from a different source type) or extragalactic.

Thoudam et al., *A&A* **595** (2016) A33

Origins of the highest energy cosmic rays

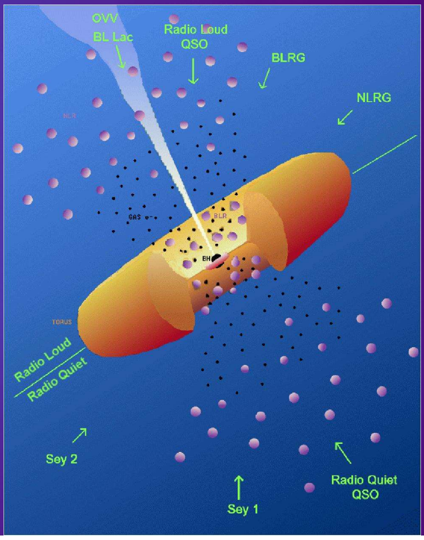
The very highest energy cosmic rays must be extragalactic.

- The relativistic gyroradius is given by $r = \frac{\gamma m v_\perp}{qB}$.
  - For a proton of energy 10^{19} eV and a Galactic magnetic field of order 0.1 to 1 nT, this gives a gyroradius of order 1–10 kpc.
  - Therefore protons of this energy should rapidly escape from the Galaxy.
- This also suggests that the deflection of these cosmic rays should be small enough to retain some correlation between arrival direction and point of origin.

Note that the range of cosmic rays with energies $\gtrsim 10^{19}$ eV is quite limited, because of interactions with the CMB.

The prime suspects: active galactic nuclei (AGN)

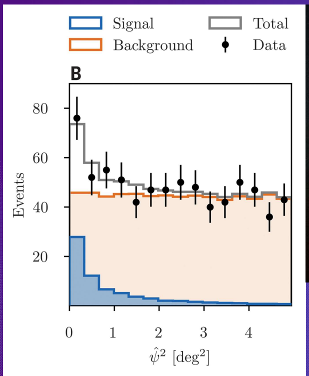
Urry and Padovani



Active galaxies are galaxies whose luminosity comes largely from an actively accreting supermassive black hole.

- Radio-loud AGN launch relativistic jets from near the black hole; radio-quiet AGN (the majority) do not.
  - Blazars—radio-loud AGN where we look almost directly down the jet—are the dominant extragalactic source of GeV and TeV photons.
  - However, IceCube do not find a significant correlation between high-energy neutrinos and radio-loud AGN with $S_{8.6\ \mathrm{GHz}} \geq 150$ mJy.

Smoking guns?



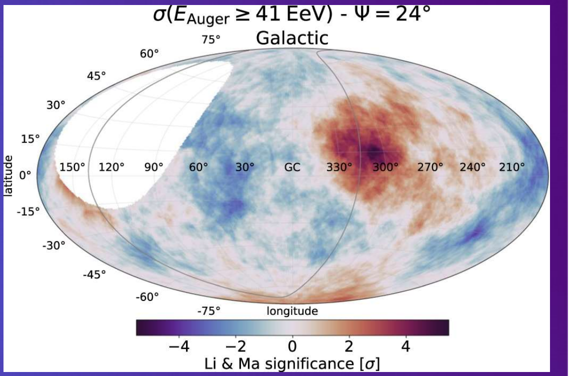
M77: Seyfert galaxy which appears to be a neutrino source.

IceCube, *Science* **378** (2022) 538


NASA, ESA & A. van der Hoeven

No correlation found between IceCube neutrinos and PAO UHECRs.

(Not as surprising as it might seem, because of limited range of UHECRs.)



Clear "hot spot" in arrival directions of UHECRs from Pierre Auger Observatory—but this encompasses a radio galaxy, a Seyfert galaxy *and* a starburst galaxy.

Abreu et al., *ApJ* **935** (2022) 170.

Acceleration mechanisms

AGN are more complicated objects than SNRs, and more acceleration mechanisms are viable.

- *Stochastic acceleration*, with random encounters between particles and moving magnetic fields, doesn't work within our Galaxy because $\langle \Delta E/E \rangle \propto \beta^2$ makes it too slow, but it may be viable in AGN where the speeds involved are much higher.
- Shocks in AGN jets are often *relativistic*—this significantly affects the energy gain per shock crossing and resulting energy spectrum compared to diffusive shock acceleration.
- The ordered velocity structure in an AGN jet may support *shear acceleration*, which exploits the non-random relative velocities similarly to DSA.
- *Magnetic reconnection* is a totally different acceleration mechanism seen in solar flares, and may well be relevant in the complicated fields of AGN jets.

Starbursts vs AGN

PAO say that the distribution of their UHECRs matches starburst galaxies better than AGN.

- Superwinds in starburst galaxies do create appropriate conditions for acceleration.
- The cosmic ray energy density in starburst galaxies is very high—not surprising since the supernova rate is high—so there is a seed population of fast particles which might be reaccelerated to higher energies.
- However, a detailed study of conditions in the nearby starburst galaxy NGC 253 suggests that it would be difficult to achieve energies above 10^{18} eV in this galaxy. (Romero, Müller & Roth A&A **616** (2018) A57)

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Summary

Particles can be accelerated in astrophysical sources by encounters with moving magnetic fields.

- Probably the most prevalent mechanism is diffusive shock acceleration, in which particles are accelerated by repeatedly crossing a supersonic but non-relativistic shock front.
  - This is almost certainly the mechanism operating in supernova remnants, which are believed to be responsible for the bulk of Galactic cosmic rays.

The highest energy cosmic rays are extragalactic, but the source(s) are not certainly identified.

- A few individual sources are known, but may not represent the main source type.
  - These higher-energy accelerators may involve a number of different acceleration mechanisms.