Particle Acceleration I: Astrophysical Mechanisms

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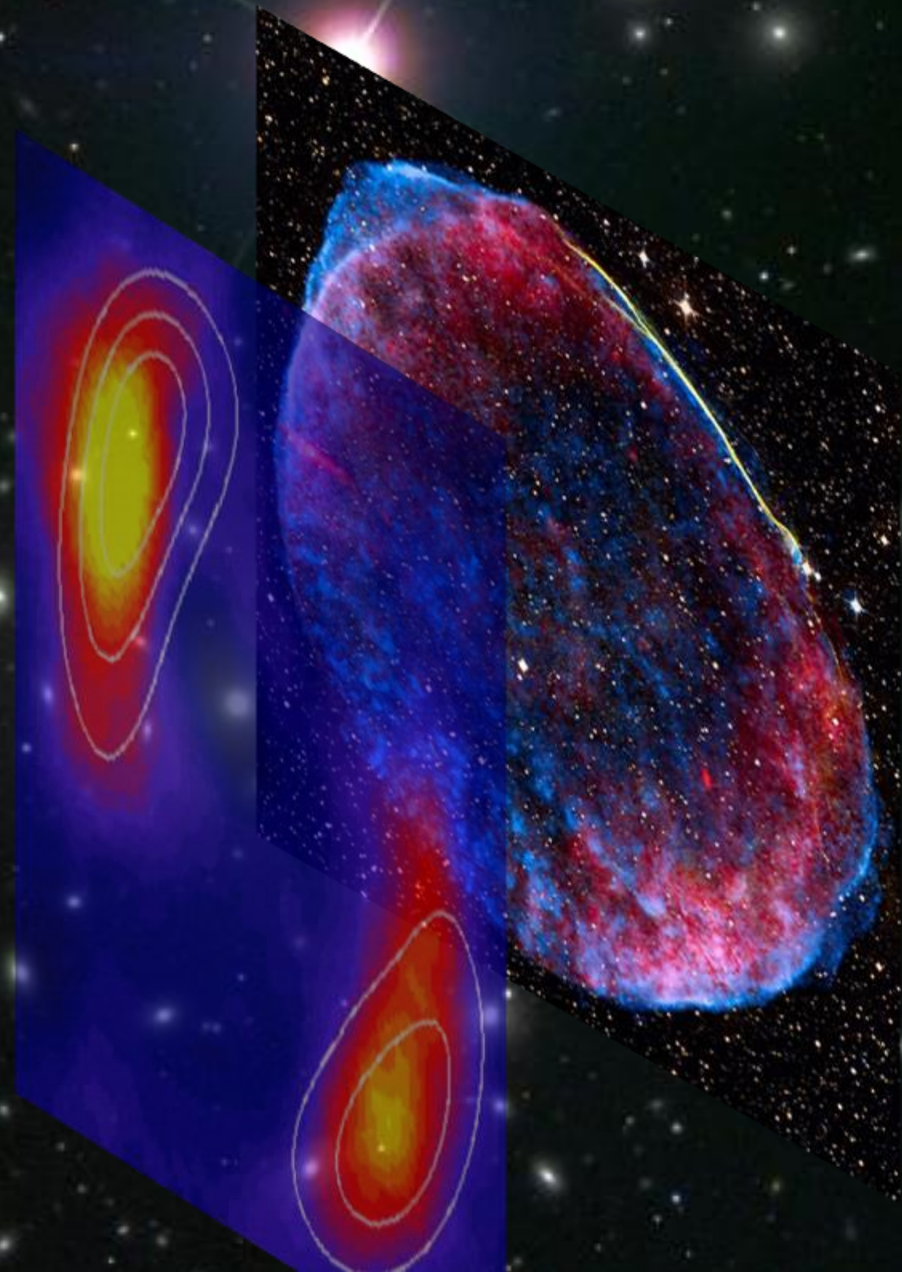

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Accelerated Particles – Cosmic Rays

High energy charged particles reaching the Earth's atmosphere:

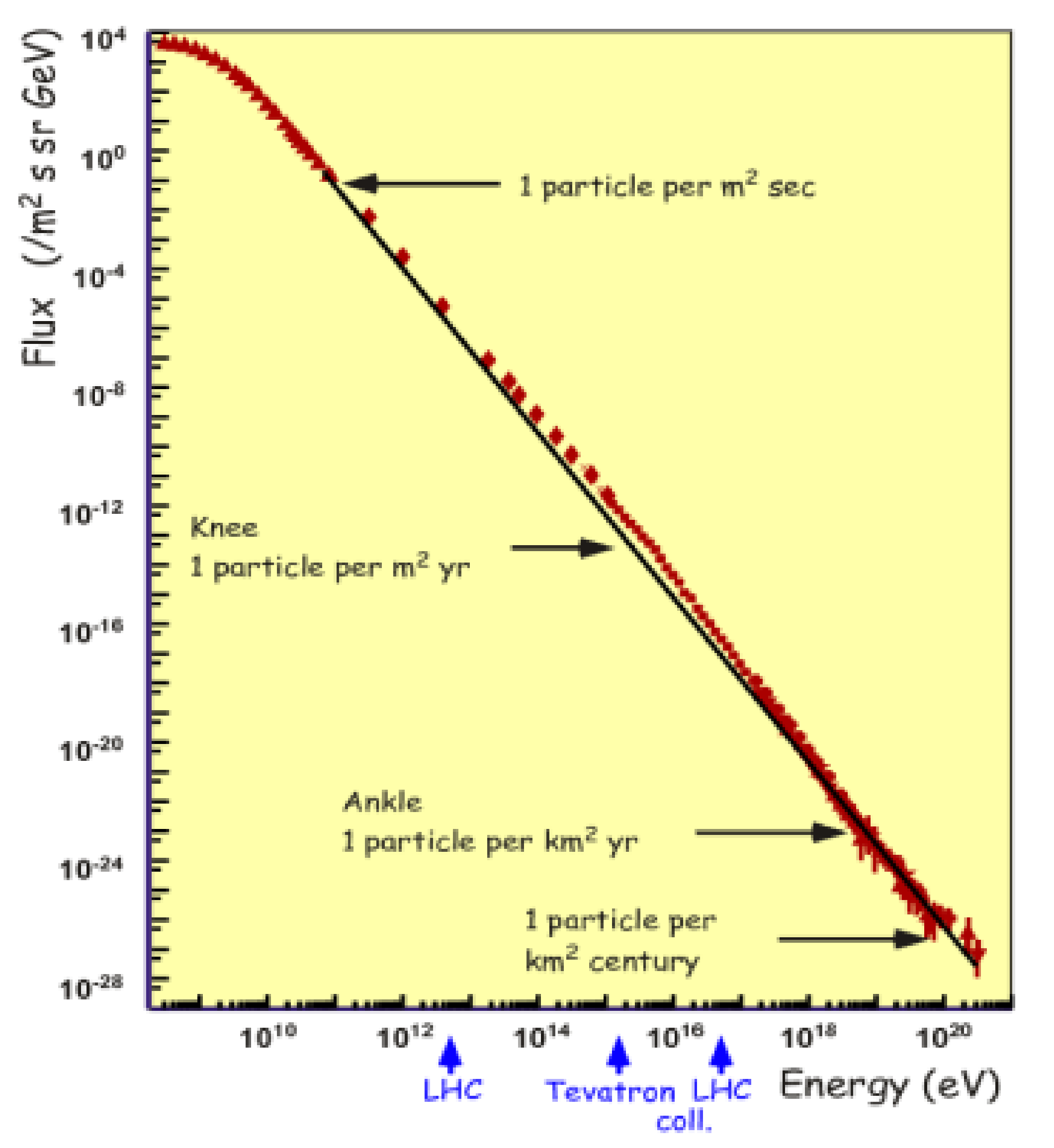
- **electrons** ~ 1%

- **protons** ~ 89%

- **heavier nuclei, mainly helium** ~ 10%

- **very few: antiparticles, muons, pions, kaons** (from interactions of CRs with the interstellar gas)

COSMIC RAY SPECTRUM

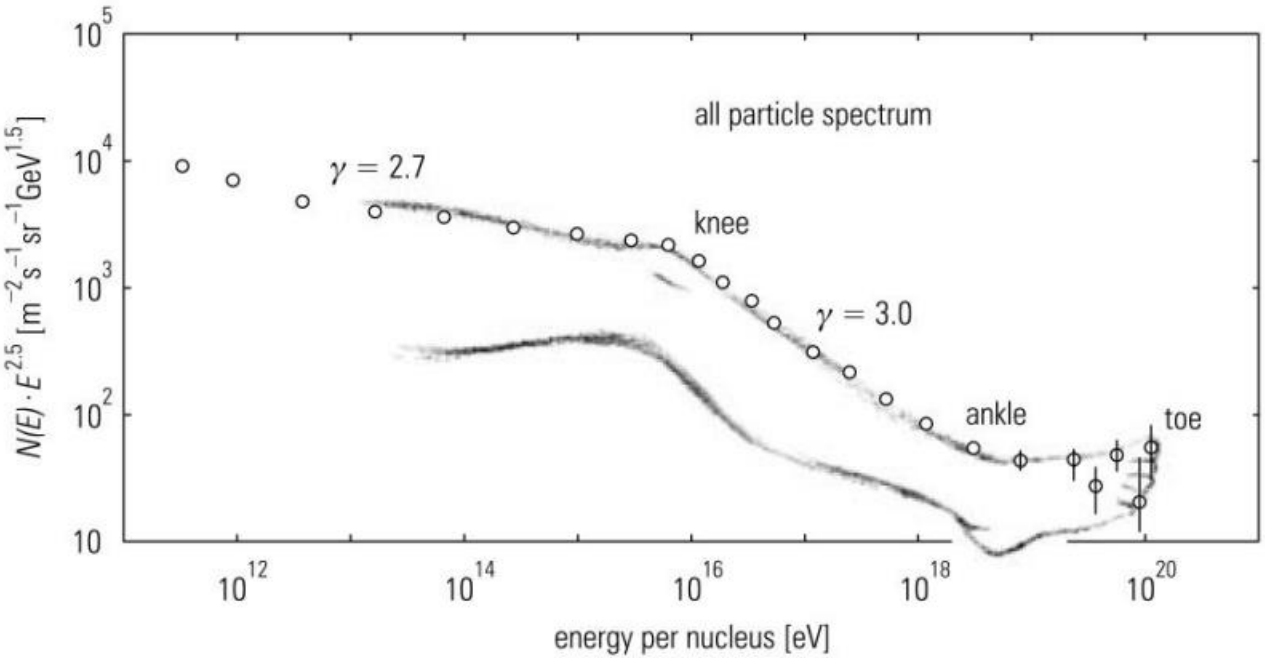


- **power law:**

$$N(E) \propto E^{-\gamma}$$

$$\gamma = 2.7 \quad \text{for} \quad 10^9\text{eV} < E < E_{knee},$$
$$\gamma = 3.0 \quad \text{for} \quad E_{knee} < E < E_{ankle},$$
$$\gamma = 2.7 \quad \text{for} \quad E_{ankle} < E < E_{GZK},$$

COSMIC RAY SPECTRUM



- **knee**:
  particles with $E > 10^{15}$ eV start to leak from the galaxy, maximum from supernova explosions near 10^{15} eV
- **ankle**:
  extragalactic particles
- **GZK-cut off** at
  $\approx 6 \cdot 10^{19}$ GeV

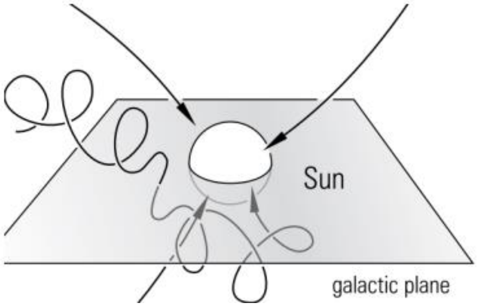
$$\gamma = 2.7 \quad \text{for} \quad 10^9 \text{eV} < E < E_{knee},$$
$$\gamma = 3.0 \quad \text{for} \quad E_{knee} < E < E_{ankle},$$
$$\gamma = 2.7 \quad \text{for} \quad E_{ankle} < E < E_{GZK},$$

CR – Magnetic Fields

Charged particles – circular orbits in Magnetic Field (MF):

gyro-radius:

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v}\times\mathbf{B} \quad \rightarrow \quad r_g = \frac{p}{qB} = \frac{\gamma m_0\, v}{Ze\, B}$$



- **CRs with energies < 10^{15} eV**: sky distribution **ISOTROPIC**

- **Higher energy CRs:**

are not as much deflected: **ANISOTROPIC**

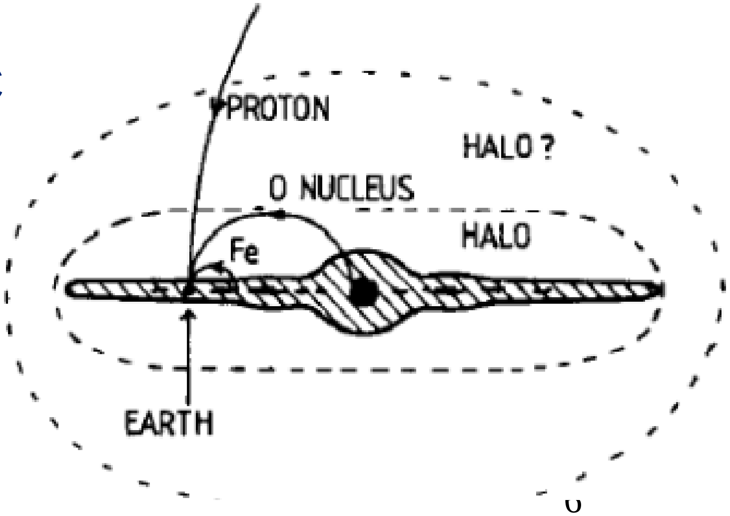
Example:

$E = 10^{19}$ eV

$B = 2$ μG $\rightarrow$ **$r_g = 10$ kpc**

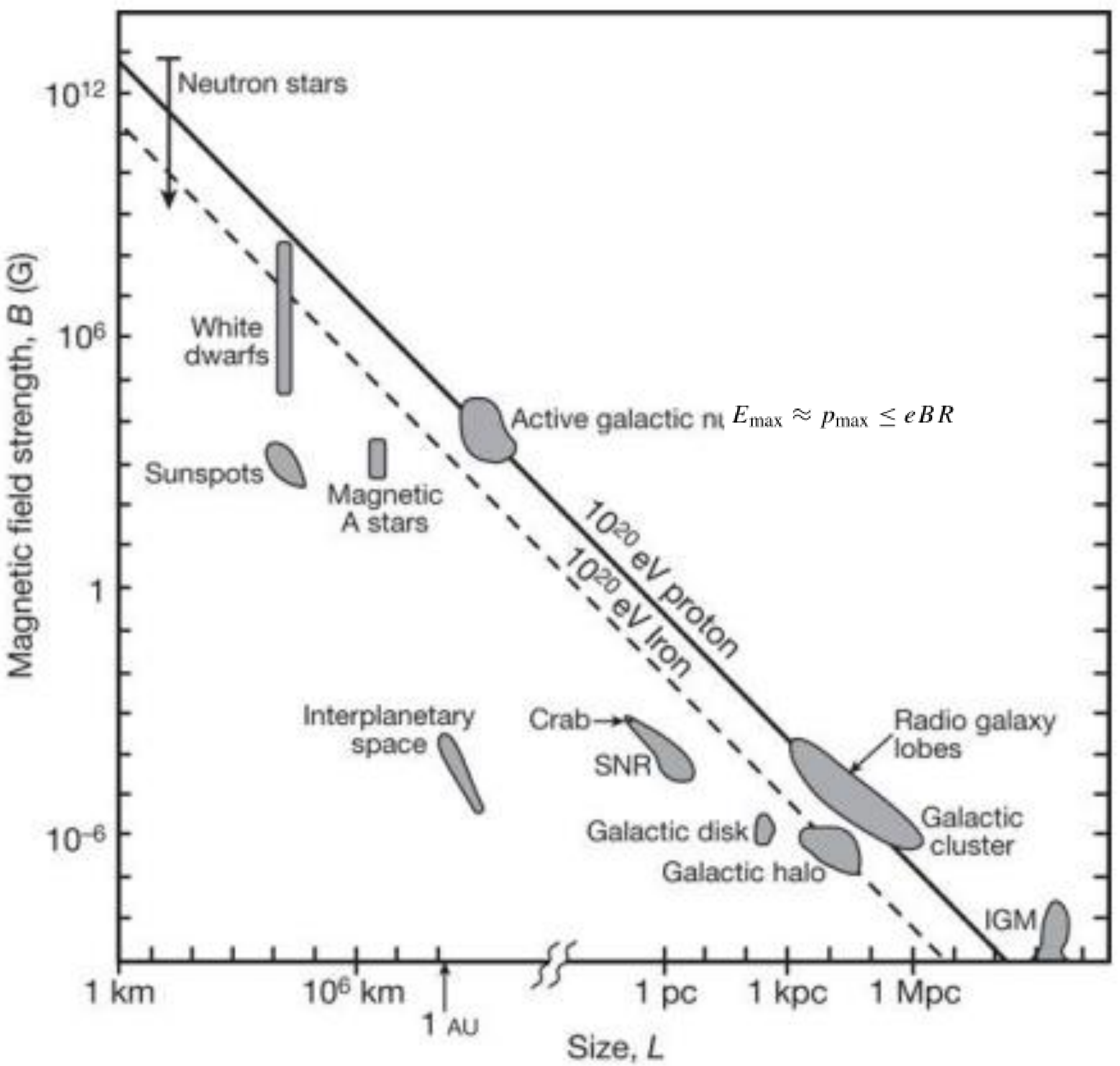
no correlation with galactic plane:

extragalactic origin



COSMIC RAY SOURCES

Hillas diagram.1984



For particle to be confined within accelerating source:

Gyro-radius < source size

$$r_g < L$$

$$E_{max} = B\, L$$

E_{max}:
Maximum energy that can be extracted from the source for acceleration

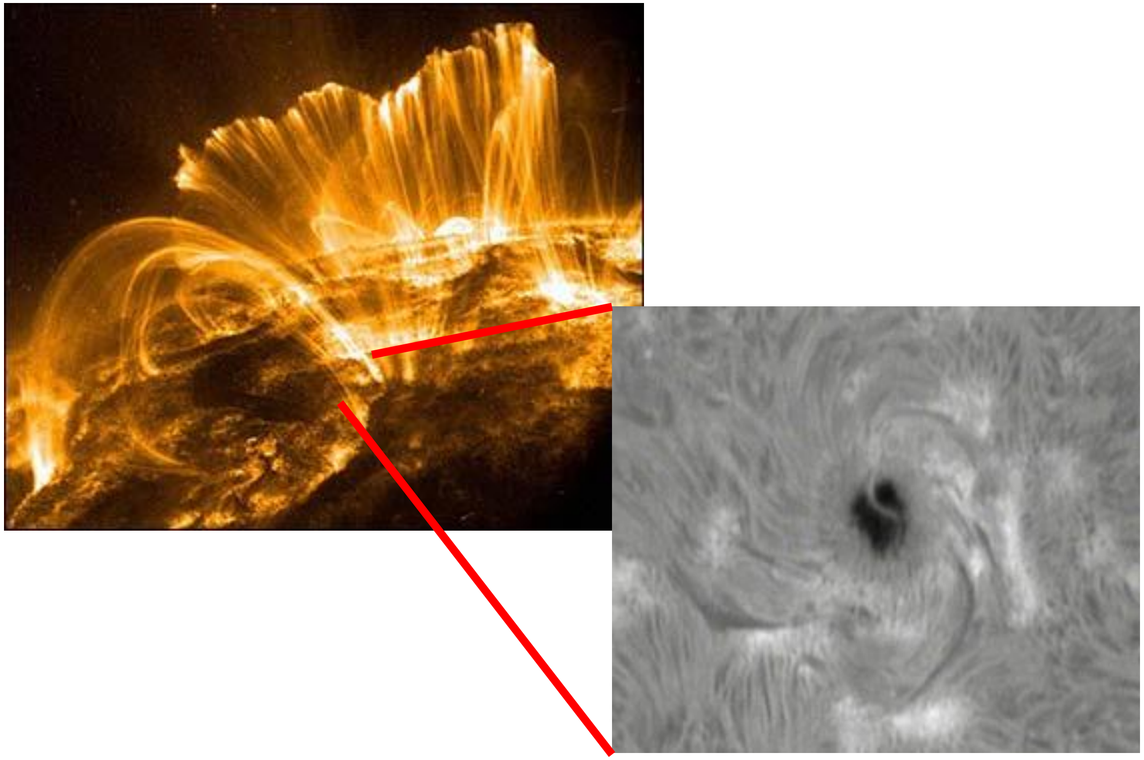
CONTENTS

- Introduction
- **Acceleration mechanisms**
  - Changing Magnetic Fields
  - Mirror Effect
  - 2nd Order Fermi Acceleration (turbulence)
  - Diffusive Shock Acceleration (1st Order Fermi)
  - Acceleration in Reconnection zones
- Astrophysical Sites

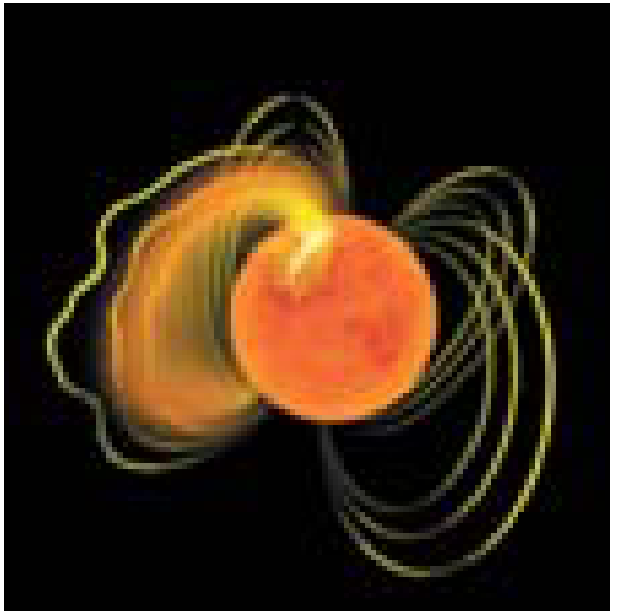
Electromagnetic Acceleration

- **Time dependent MFs:**

  Compact sources with large scale magnetic fields



solar sunspots



pulsars

Electromagnetic Acceleration

Faraday's law

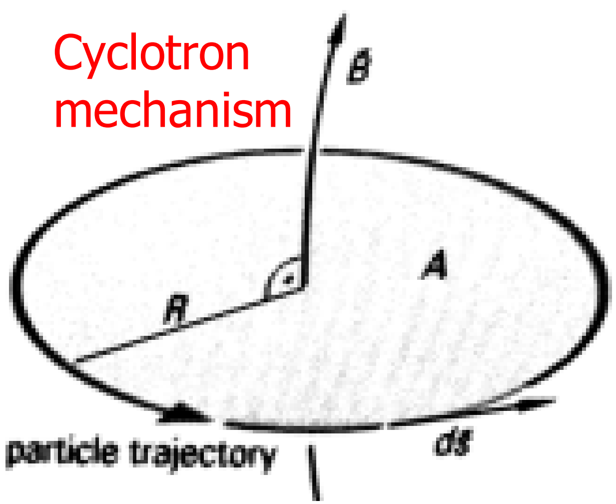
$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}$$

decaying magnetic field $\Rightarrow$ electric field $\Rightarrow$ acceleration

- magnetic flux: $\Phi = B \cdot A = B\pi R^2$
- change of the flux $\Rightarrow$ potential:

$$U = \oint \mathbf{E} \cdot \mathrm{d}\mathbf{s} = -\dot{\Phi} = -\dot{B}\pi R^2$$

Cyclotron mechanism



energy gain

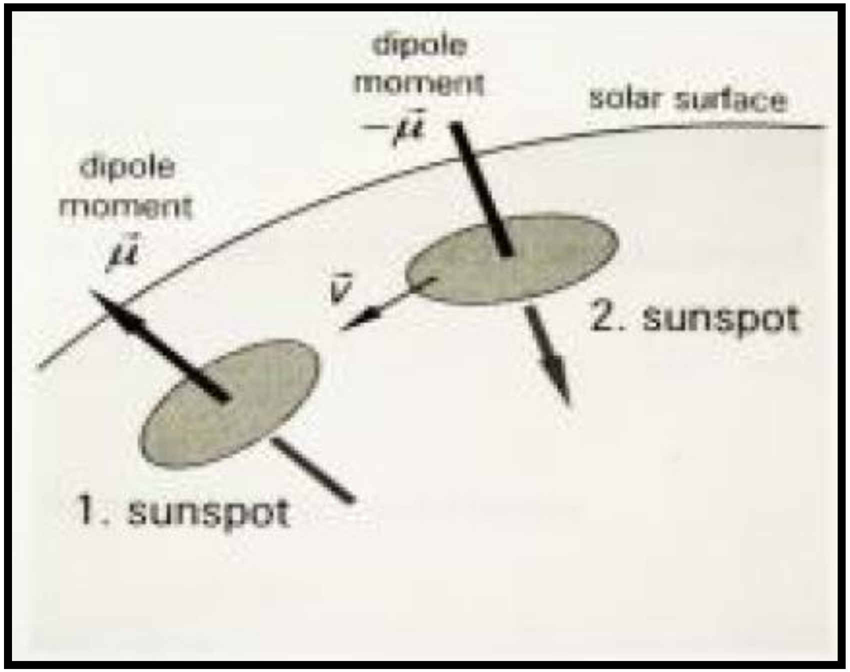
$$\Delta E = eU = e\pi R^2 \dot{B}$$

from one gyration

Kaiser courtesy

Electromagnetic Acceleration

Example : Merging Sunspots

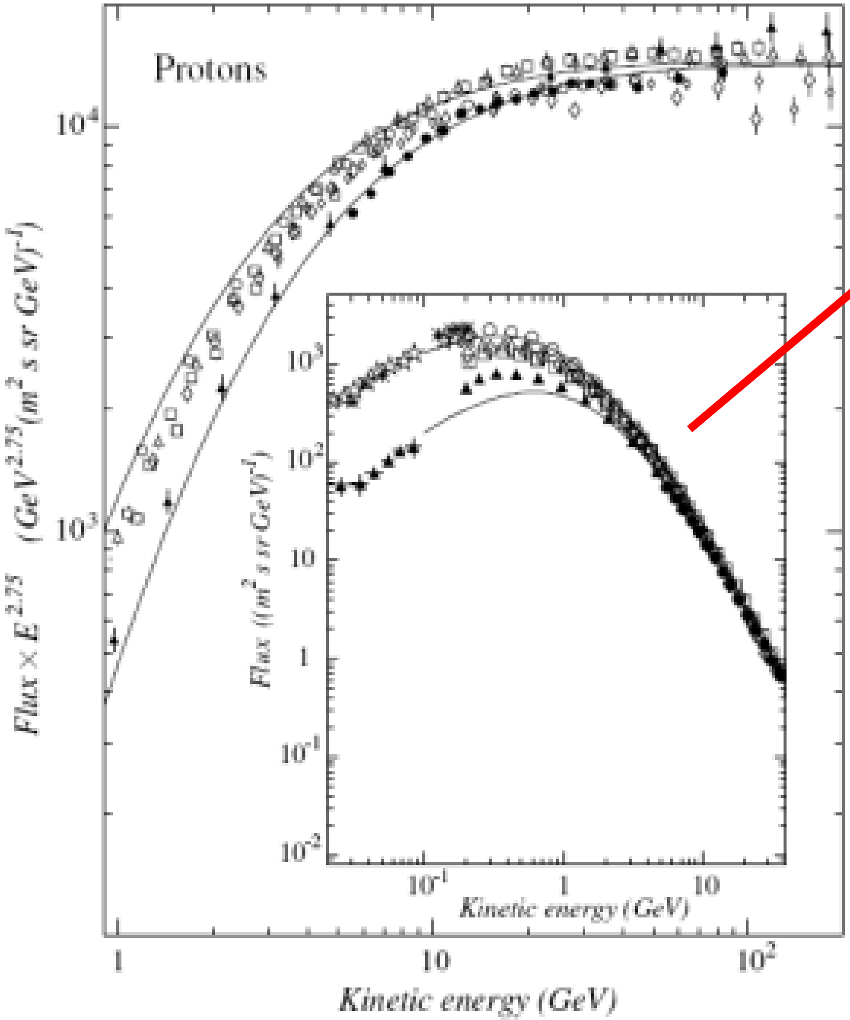


energy estimate:

- flux tube radius $R \approx 10^4$km
- magnetic field $B \approx 2000\,\mathrm{G}$
- merging in 1 day,
  $\dot{B} = 2000\,\mathrm{G/day}$

$\Rightarrow E = 0.73\,\mathrm{GeV}$

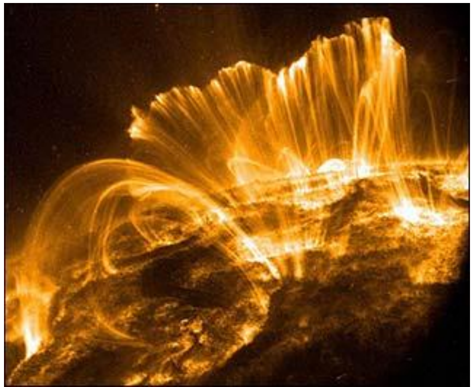
CRs from the Sun



Power law spectrum at high energies

Other mechanisms can be occurring:

- Diffusive shock acceleration
- Magnetic Reconnection

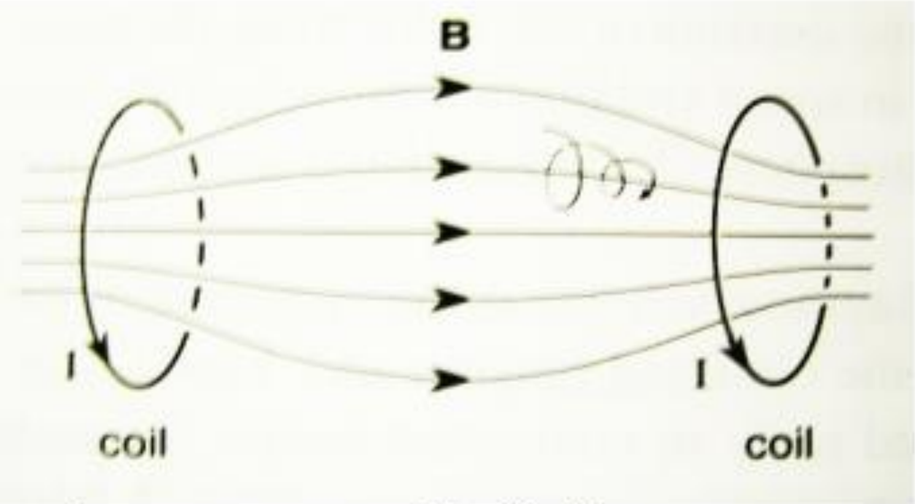


FERMI ACCELERATION – MIRROR EFFECT

particles entering regions of higher magnetic field strength are reflected backwards

- charged particles follow cyclotron orbits

  gyro-radius: $r_g = p_\perp / qB$



Rule

The magnetic flux $\Phi = B \cdot \pi r_g^2 \propto v_\perp^2 / B$ through the particles' cyclotron circle is constant.

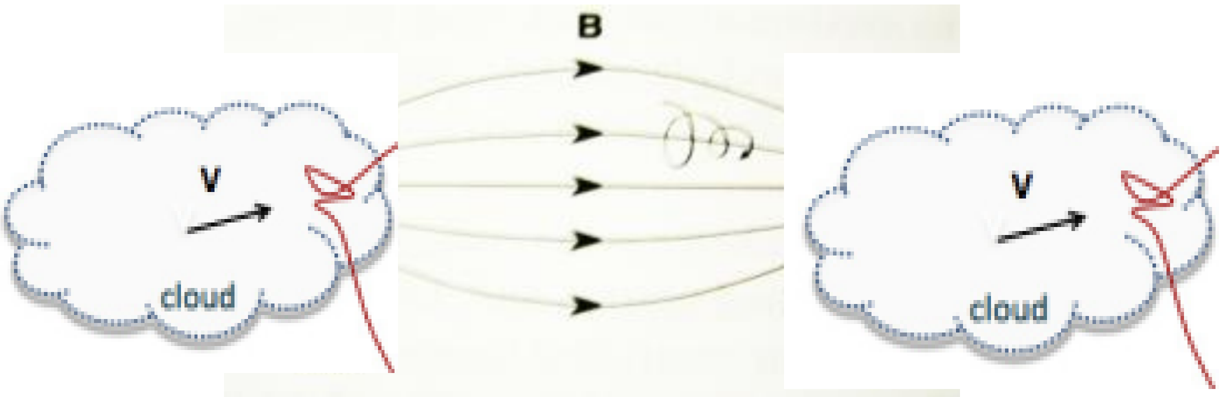
stronger magnetic field

$\Rightarrow$ smaller gyro-radius, increased perpendicular velocity $v_\perp$

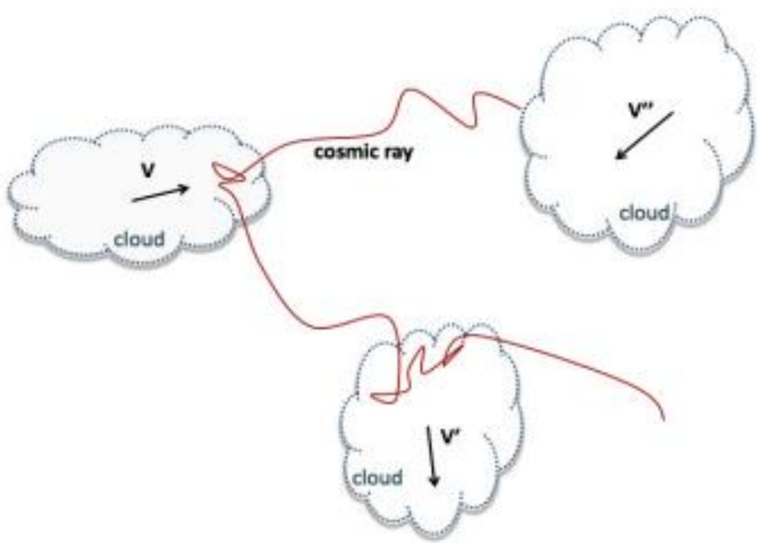
$\Rightarrow$ decrease of parallel velocity $v_\parallel$ (energy conservation)

$\Rightarrow$ $v_\parallel \to 0$, then reflection

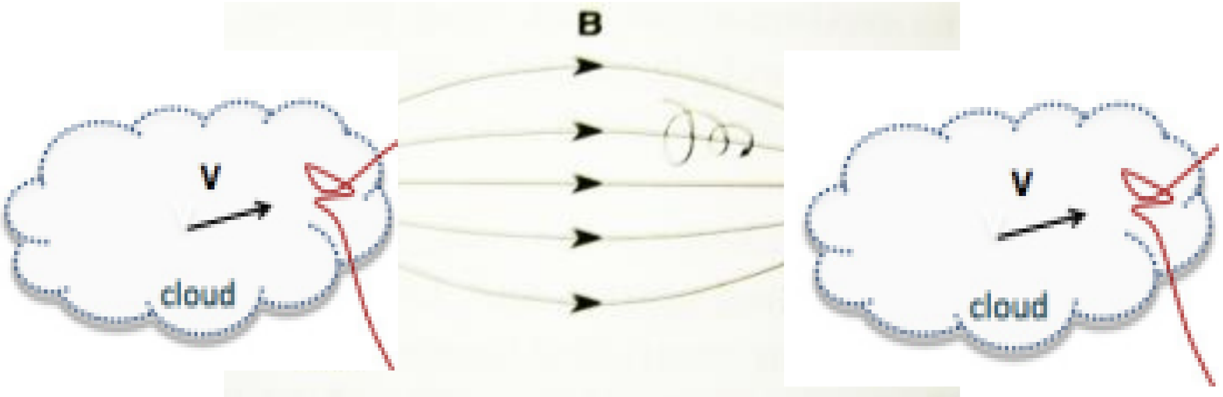
FERMI ACCELERATION



Fermi (1949): could CRs be produced via **random scattering with magnetized interstellar clouds?**



FERMI ACCELERATION

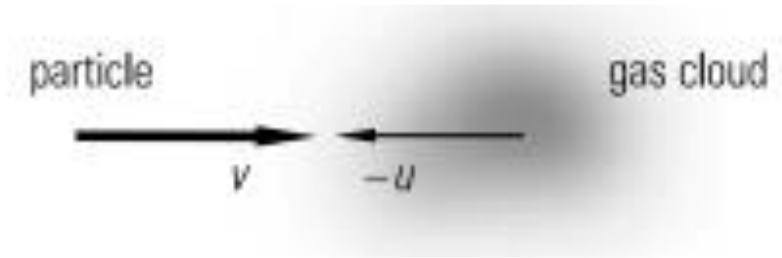


Frequency of head-on collisions > frequency of catch-up collisions

→ **net energy gain by particles**

FERMI ACCELERATION

Head-on collision:



- change in kinetic energy:

$$\Delta E = \tfrac{1}{2}m(v+u)^2 - \tfrac{1}{2}mv^2$$

Catch-up collision:

$$\Delta E_2 = \frac{1}{2}m(v-u)^2 - \frac{1}{2}mv^2$$

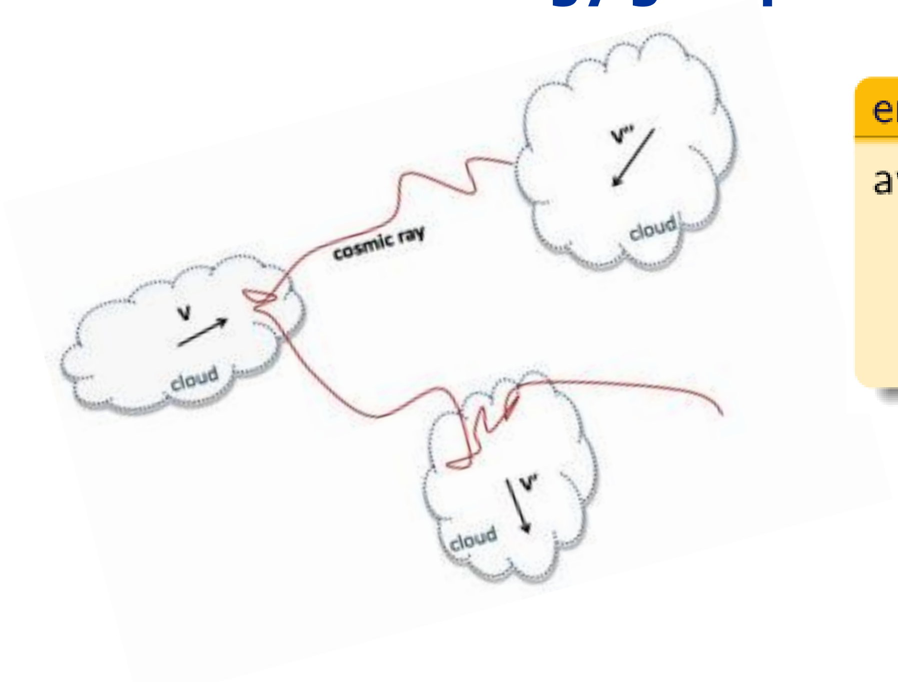
→ **Net energy gain:**

$$\Delta E = \Delta E_1 + \Delta E_2 \;\rightarrow\; \boxed{\frac{\Delta E}{E} = 2\frac{u^2}{v^2}}$$

2^{nd} Order Fermi

2^{nd} ORDER FERMI ACCELERATION

There is net energy gain per collision:



energy gain

average over all angles of incidence ϑ:

$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \frac{u^2}{v^2}$$

u <<v ≈ c: the energy gain per collision is very small

- **Statistical reflection on many different clouds in a galaxy**
- **Stochastic acceleration** in magnetized turbulent medium

2^{nd} ORDER FERMI ACCELERATION

energy gain

average over all angles of incidence ϑ:

$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \left(\frac{V}{v}\right)^2$$

✓ **Energy increases exponentially** with # of reflections ($\Delta E \propto E$):

$$\frac{dE}{dt} = \langle \Delta E \rangle \nu = 4\nu \left(\frac{V}{v}\right)^2 E \equiv \alpha E$$

α = Acceleration rate

➢ **BUT - second order energy gain:**

too slow to obtain high energy particles in the few million years that a cosmic ray stays in the galaxy

2^{nd} ORDER FERMI ACCELERATION

✓ Particles accelerated in this statistical process satisfy diffusion-loss equation:

$$\frac{dN}{dt} \approx -\frac{\partial}{\partial E}[N(E,t)\alpha E] - \frac{N(E,t)}{\tau}$$

α =**Acceleration rate** $\alpha \equiv 4\nu(V/v)^2$

τ = **time a cosmic ray stays in the galaxy**

➢ **Power Law spectrum:**

$$N(E) \approx N_0 E^{-(1+1/\alpha\tau)}$$

γ

2nd ORDER FERMI ACCELERATION

Result: power law

$$f(E) \propto E^{-\gamma}, \qquad \gamma = \left(1 + \frac{1}{\alpha\tau}\right)$$

Nice, BUT:

$$\alpha \sim < V^2 > / Lv = < V^2 > / Lc$$

- L = 100pc = mean separation between clouds (scatterers)
- <V> = 10 km/s = clouds average velocity
- $\tau = 2\times10^{7}$anos = decay time of CRs in the Galaxy

$$\frac{1}{\alpha\tau} = \frac{3\times10^{20}cm \times 3\times10^{10}cm/s}{10^{12}cm^2/s \times 6\times10^{14}s} \simeq 1.5\times10^{4} \quad !!!$$

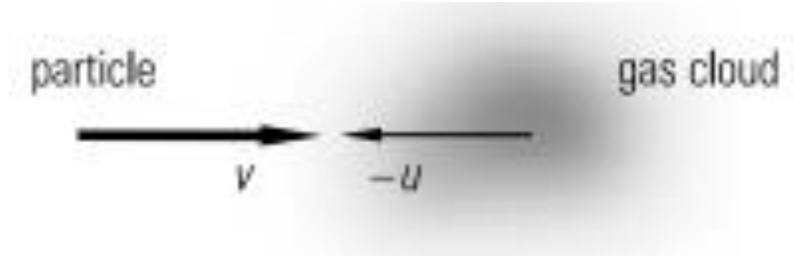
Observed $\gamma \sim 2.7$!!

→ 2nd ORDER FERMI: too slow

1^{st} ORDER FERMI ACCELERATION

REMEMBER:

Head-on collision:



→ Net energy gain:

relativistic calculation →

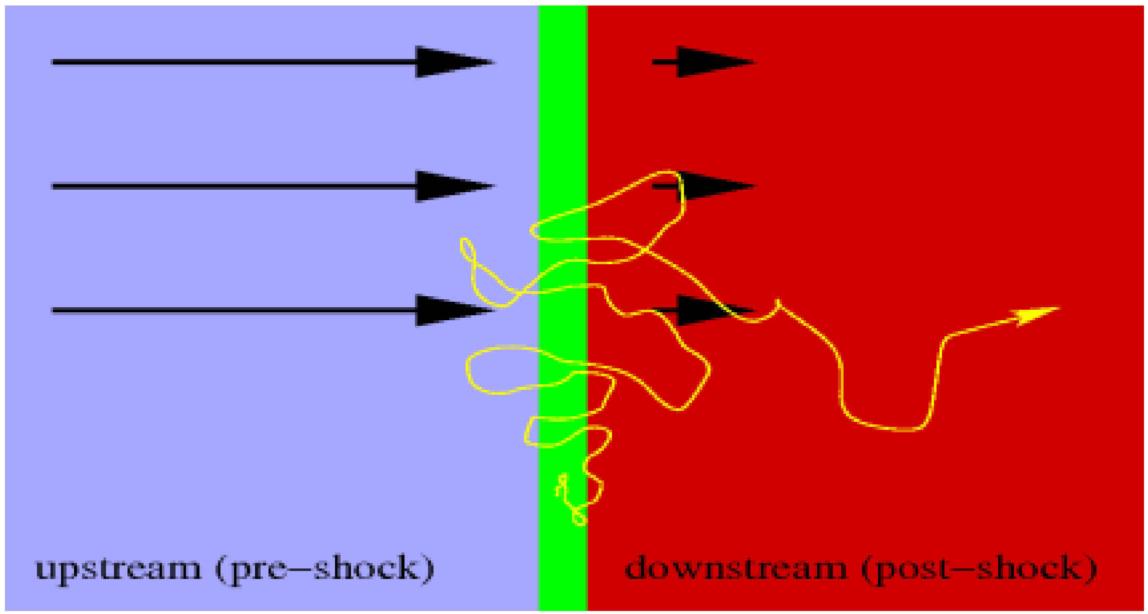
$$\Delta E \propto E, \qquad \frac{\Delta E}{E} = 2\frac{uv}{c^2} + \frac{u^2}{c^2} \overset{v \approx c}{=} \underbrace{2\frac{u}{c}}_{\text{1st order}(\pm)} + \underbrace{\frac{u^2}{c^2}}_{\text{2nd order}}$$

→ **1^{st} Order Fermi**

Thus we need scattering in a CONVERGING FLOW:
→ acceleration in a SHOCK (Bell et al. 78)

DIFFUSIVE SHOCK ACCELERATION

picture in the rest frame of the shock front



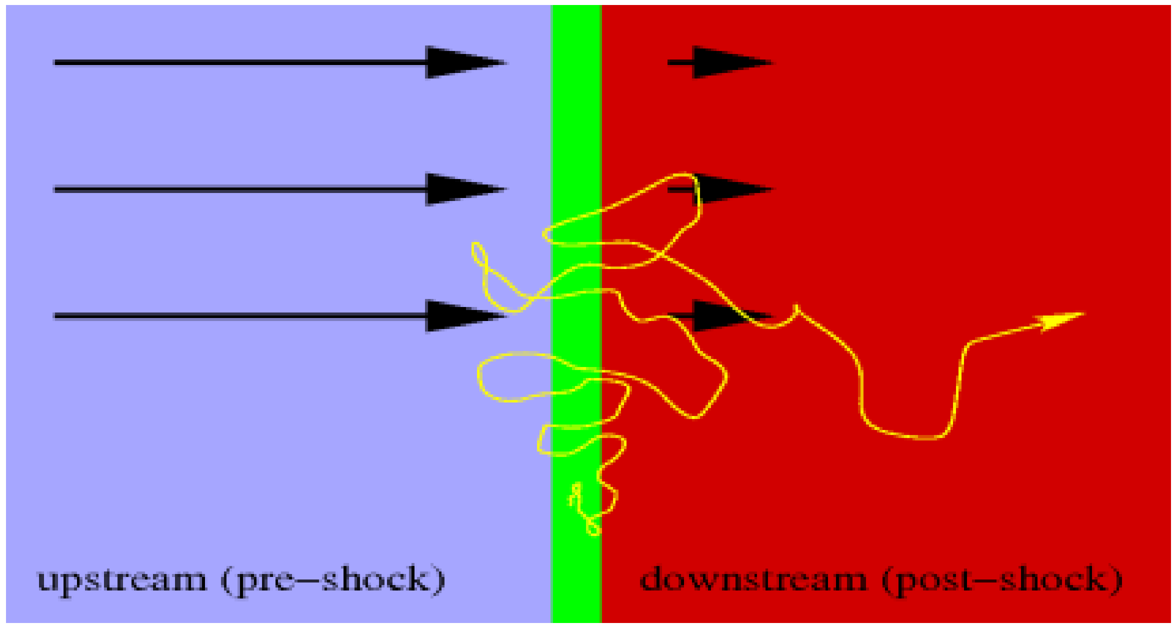
- Particles with higher velocity than the plasma flow may travel against the stream and cross the shock

- Scatter and interact with magnetic field fluctuations (Alfven waves)

- Shock contains **converging** scatterers because particles experience **higher (head-on)** collision velocities **upstream** than **(catch-up)** velocities **downstream**

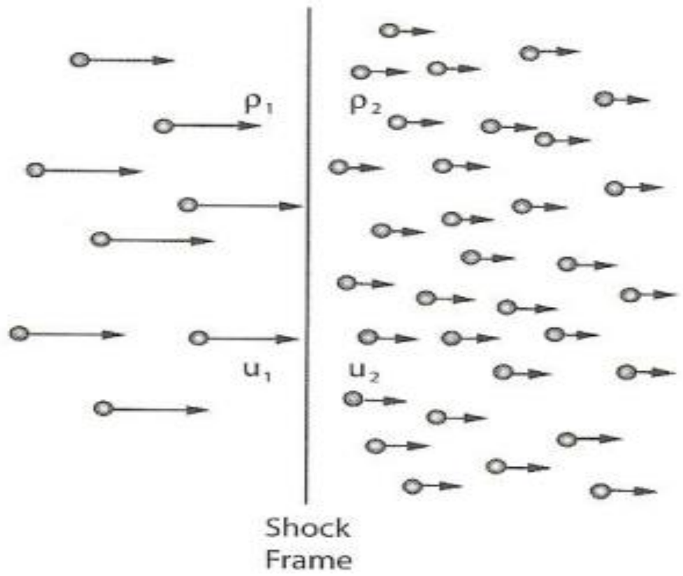
DIFFUSIVE SHOCK ACCELERATION

picture in the rest frame of the shock front



- reflection in upstream $\Rightarrow$ energy gain $\propto v_{\rm up}/c$
- reflection in downstream $\Rightarrow$ smaller energy loss $\propto v_{\rm down}/c$
- repetition until particle is not scattered back upstream

DIFFUSIVE SHOCK ACCELERATION



Every round trip: particle executes one catch-up and one head-on

→ **Average energy gain:**

$$\frac{\langle \Delta E \rangle}{E} \approx \frac{2(u_1 - u_2)}{v} = \frac{2\Delta u}{v}$$

1^{st} order in ~u/c

→ **Fermi I more efficient than Fermi II**

DIFFUSIVE SHOCK ACCELERATION

- **$\Delta E/E \sim u/c$**
- **loss of particles downstream in each cycle: $\Delta N_{loss}/N \propto u/c$**

$\Rightarrow$

- energy increases exponentially with # of cycles
- # of participating particles N decreases exponentially with # of cycles

power law for $E > E_{\text{inj}}$

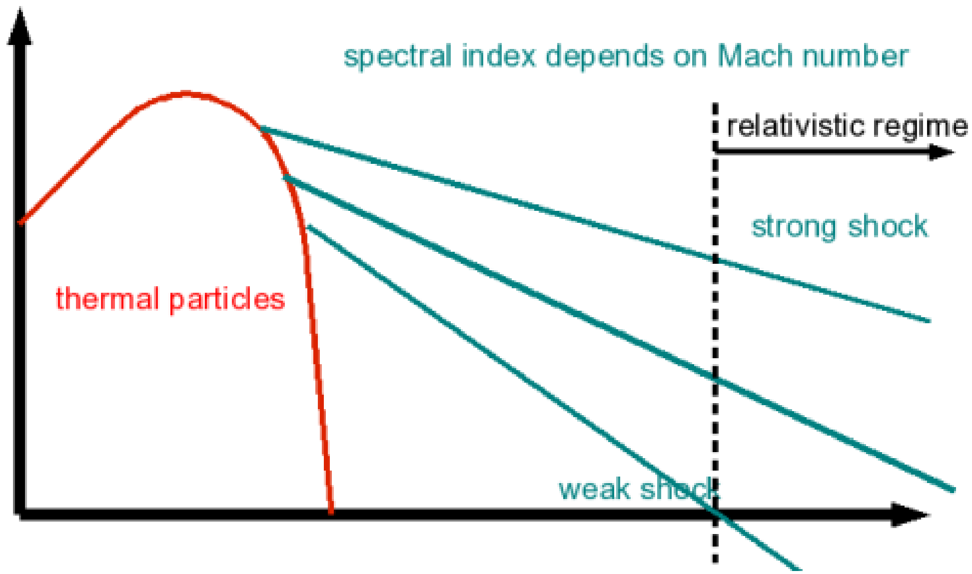
$$f(E) \propto \left(\frac{E}{E_{\text{inj}}}\right)^{-\gamma(M)} \theta(E - E_{\text{inj}})$$

DIFFUSIVE SHOCK ACCELERATION

power law for $E > E_{\rm inj}$

$$f(E) \propto \left(\frac{E}{E_{\rm inj}}\right)^{-\gamma(M)} \theta(E - E_{\rm inj})$$

mach number $M = v_{\rm upstream}/c_{\rm sound}$



DIFFUSIVE SHOCK ACCELERATION

Calculating the spectrum

β= average particle energy change/collision: $\beta = 1 + \frac{2\Delta u}{v}$

P= probability that particle remains in the acceleration regime after one collision

After *k* collisions, the number of particles still scattering *N* :

$$N = N_0 \mathcal{P}^k$$

$$E = E_0 \beta^k$$

Thus, eliminating *k*:

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln \mathcal{P} / \ln \beta} \rightarrow dN = KE^{\ln \mathcal{P} / \ln \beta - 1}\, dE$$

DIFFUSIVE SHOCK ACCELERATION

P= probability that particle remains in the acceleration region after one collision:

- number of particles (w/ ~ c) crossing unit surface area/time: $\frac{1}{4}Nc$

- steady state, the number of particles that cross back upstream: $\frac{1}{4}Nc - u_2 N$

→ $$\mathcal{P} = \frac{\frac{1}{4}Nc - u_2 N}{\frac{1}{4}Nc} = 1 - \frac{4u_2}{c}$$

Thus: $\ln \mathcal{P} = \ln\left(1 - \frac{4u_2}{c}\right) \approx -\frac{4u_2}{c}$ **and** $\ln \beta = \ln\left(1 + \frac{2\Delta u}{c}\right) \approx \frac{2\Delta u}{c}$

for STRONG shock → **M>>1** → $u_1/u_2 = 4$

Observed γ **~ 2**

$$\frac{\ln \mathcal{P}}{\ln \beta} = \frac{-4u_2}{2(u_1 - u_2)} = -\frac{2}{3}$$

➡ $$dN(E) = KE^{-5/3}\, dE$$!!!

LIMITS TO ACCELERATION

- energy gains have to exceed the **losses**:
  - **radiative**: synchrotron radiation, bremsstrahlung, inverse Compton scattering
  - **non-radiative**: coulomb scattering, ionization
  - **catastrophic**: hadronic interactions: $p + p \ldots$
  - **GZK-cut-off**: interaction with CMB photons

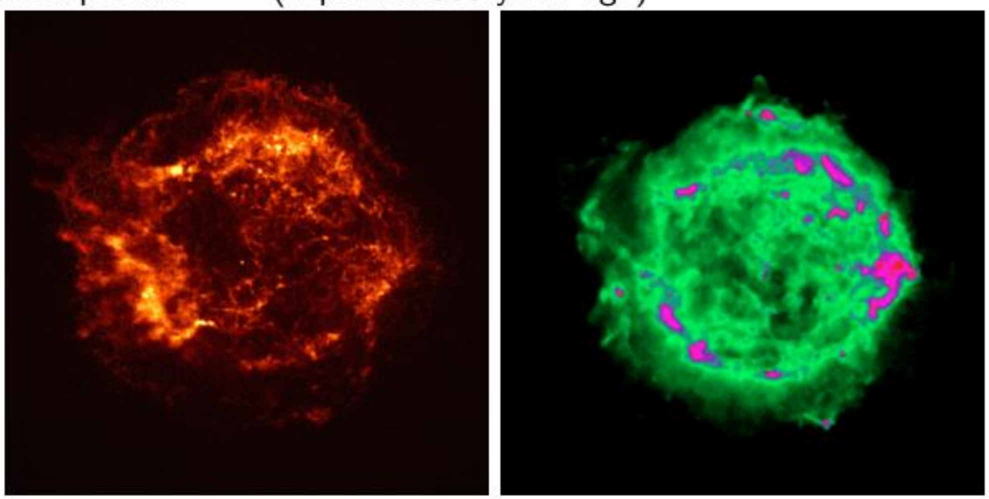
ACCELERATION SITES

- **Varying large scale MFs:**
  - pulsars
  - sunspots
- **Diffusive shock acceleration (1st order Fermi):**
  - structure formation shocks (e.g. in merging galaxy clusters)
  - supernovae remnants
  - shocks in jets and active galactic nuclei (AGNs)
  - compact sources (near black holes or neutron stars)
  - galactic winds
  - solar flares?
- **2nd Order Fermi acceleration:**
  - near shock fronts (smaller contribution $\frac{u^2}{c^2} \ll \frac{u}{c}$)
  - turbulent regions in ISM and IGM (scattering @ B irregularities)
- **Acceleration in Reconnection zones (1st order Fermi ?):**
  - solar/stellar flares
  - accretion disks (around black holes, neutron stars,…)

ACCELERATION SITES

Supernova Remnants (SNRs):

Cassiopeia A (exploded 300 years ago)



x-ray picture - hot gas | radio picture - synchrotron radiation

- **SN II eject shell – shock front**

  $M = 10\ M_{sol}$
  $v = 100$ km/s
  SN rate $= 10^{-2}\ yr^{-1}$

➢ **Power output:**

$$P_{SN} = 5 \times 10^{42}\ J\ yr^{-1}$$

- **Power to accelerate CRs in the Galaxy:**

  galactic radius: R~15 kpc
  thickness: D~0.2 kpc
  CRs energy density: $\rho_E = 1$ eV cm^{-3}

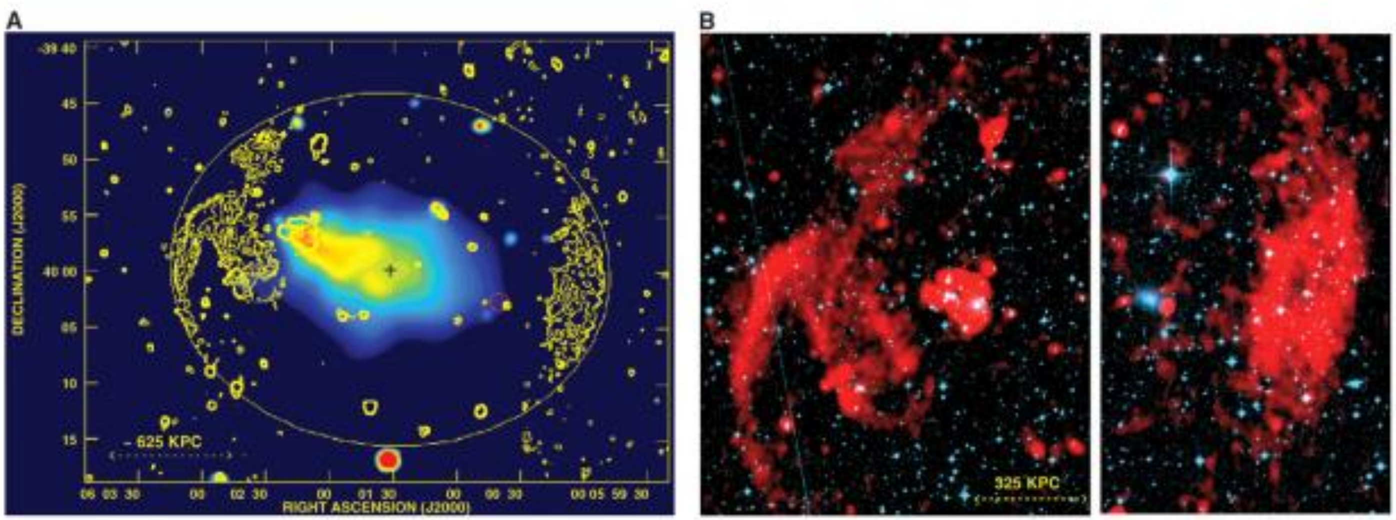
$$P_{CR} = 2 \times 10^{41}\ J\ yr^{-1}$$

SNRs more than sufficient to account for GCRs

ACCELERATION SITES

Merging clusters of galaxies:

Galaxy cluster Abell 3376



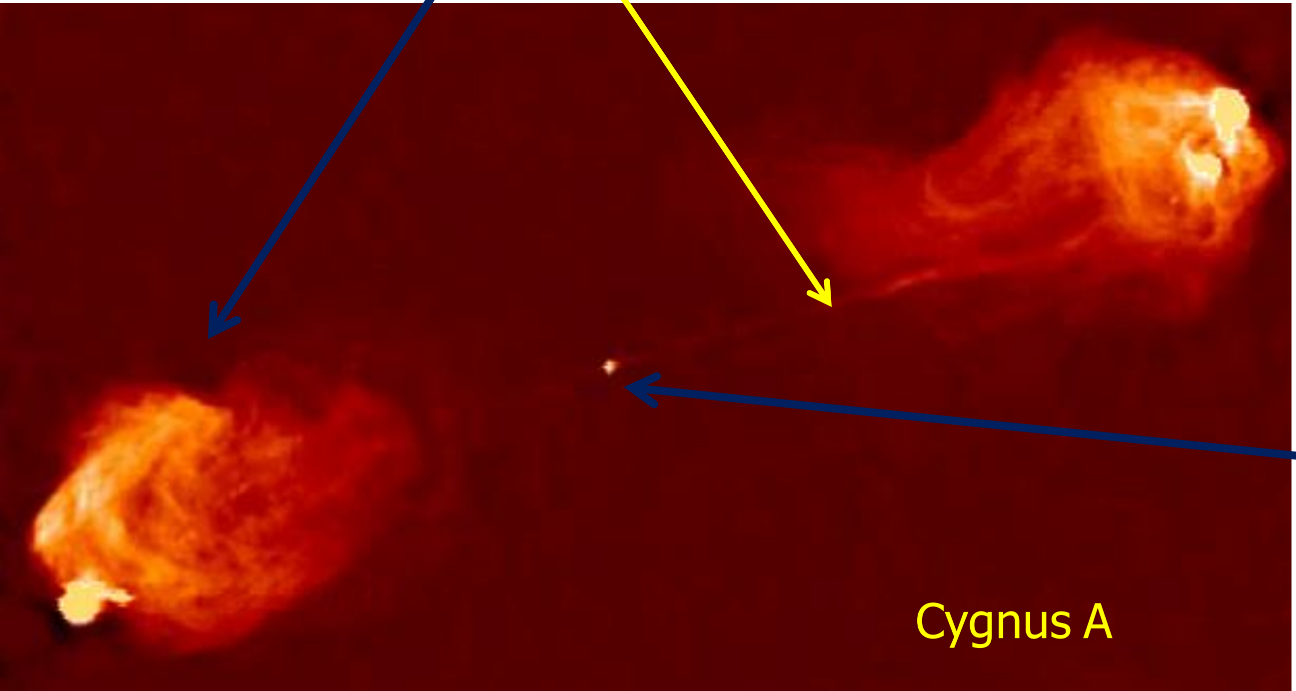
Bagchi et al. 2006

- Mpc-scale supersonic radio-emitting shockwaves
- radio sources (synchrotron radiation..) may be acceleration sites boosting particles up to 10^{19} eV ???
- hints to subcluster merger activities

ACCELERATION SITES

Astrophysical Jets:

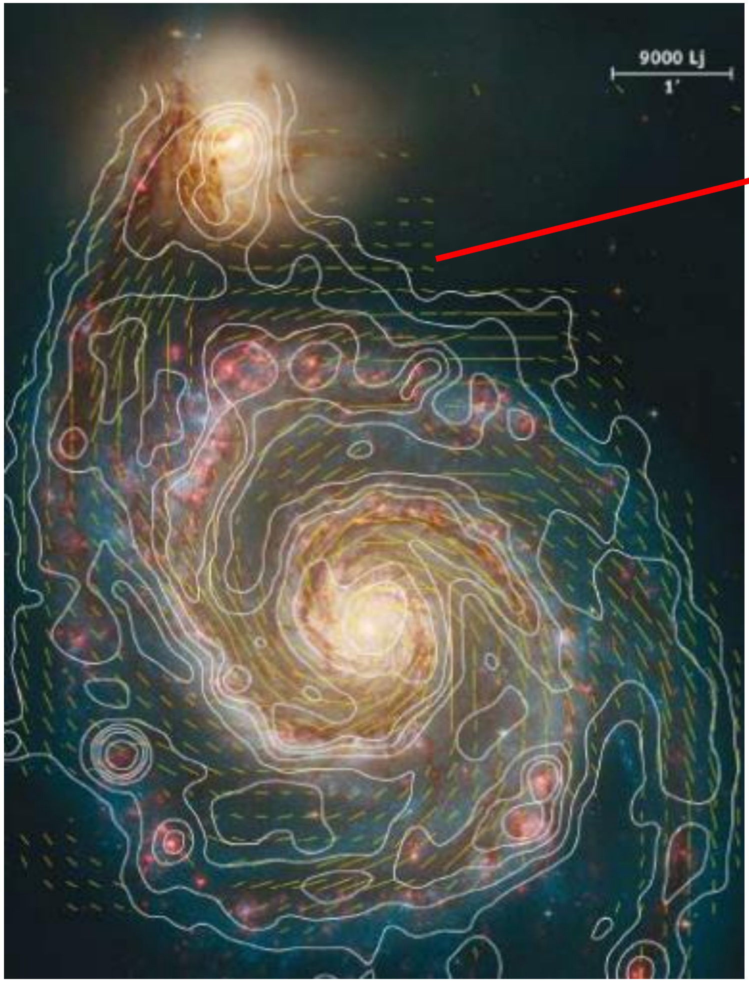
Shock Acceleration:
in internal shocks
and terminal shocks (hot spots)



Acceleration in
Magnetic
Reconnection

ACCELERATION SITES

ISM and Star formation regions in galaxies:



galaxy M51

- **Synchrotron radiation** traces MFs and relativistic electrons – CR sites

- **turbulent MFs in spiral arms** where ISM, star formation regions, and SNRs

  → **diffusive shock acceleration** (1st order)
  behind shocks in stellar jets and SNRs

  → **2nd order Fermi** in turbulent ISM

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