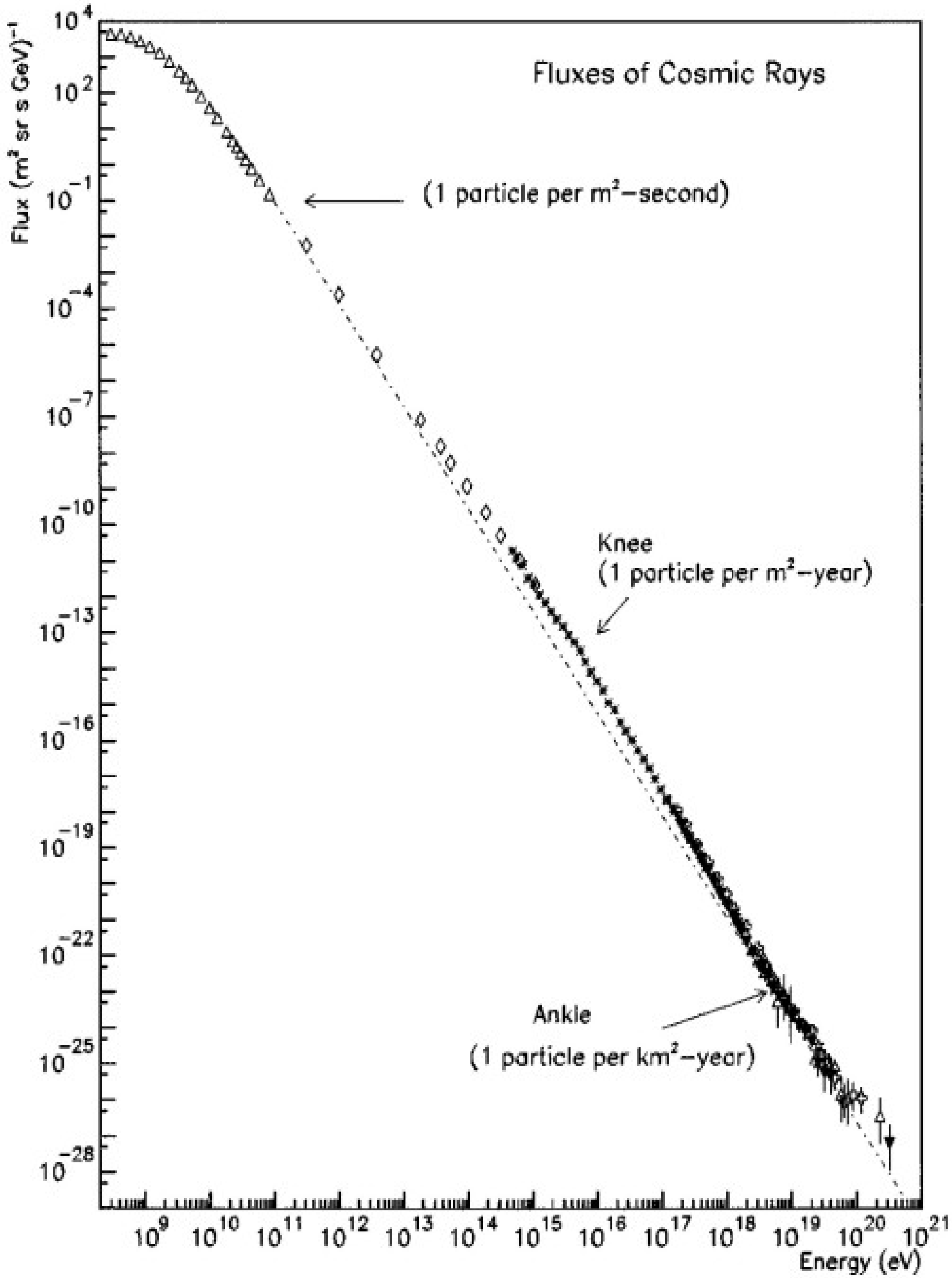
Astroparticle Physics
- an introduction with a focus on galactic cosmic rays

Christian Stegmann
ECAP, Erlangen

Key questions

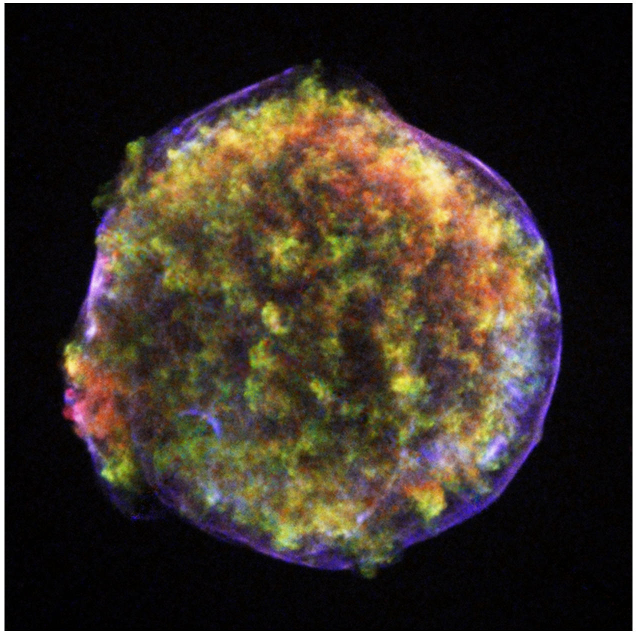
- How are non-thermal spectra produced?
- Why is there a universal index?
- Lifetime of CRs in galaxy is finite → how is the CR flux sustained?
- What are the sources of Cosmic Rays?

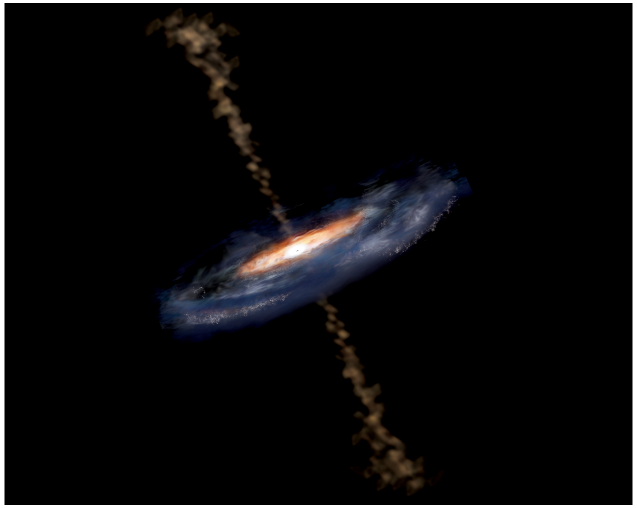


Somewhat agreed scenario

- particles are accelerated in shock fronts
- stochastic Fermi acceleration

- most Galactic CRs accelerated in supernova remnants
- Active Galactic Nuclei one of proposed sources for extragalactic CRs





Acceleration of cosmic rays – Fermi-Acceleration

Want to obtain a scale-free power law in energy

We need

- acceleration ∝ E
- particle escape independent of E

Acceleration: $\frac{dE}{dt} = a\,E$

Escape: $N(t+dt) = N(t) - N(t)\,b\,dt \quad \Rightarrow \quad \frac{dn(E)}{dt} = -b\,n$

$$\frac{dn(E)}{dt} = \frac{dn}{dE}\frac{dE}{dt} = \frac{dn}{dE}\,a\,E$$

$\Rightarrow \quad \frac{dn}{dE} = -\frac{b}{a}\frac{N}{E} \quad \Rightarrow \quad n(E) = n_0\,E^{-b/a}$ scale free power law if b/a independent of energy

Second order Fermi-Acceleration

Energy spectrum from Fermi-acceleration

particle loss time scale τ_{esc}

Spectrum from diffusion loss equation

$$\frac{\partial n}{\partial t} = \vec{\nabla}(D\vec{\nabla} n) + \frac{\partial}{\partial E}\left[b(E)n(E)\right] + Q(E) - \frac{n}{\tau_{esc}}$$

$b(E) = -\frac{dE}{dt}$ is “energy gain” term

consider static solution, no sources, no diffusion, no spallation

$$\frac{\partial}{\partial E}\left[\alpha E n(E)\right] = \frac{n}{\tau_{esc}}$$

$\Rightarrow \quad n(E) = n_0 E^{-x}$ with $x = \left(1 + \frac{1}{\alpha \tau_{esc}}\right)$

Fermi-Acceleration

- succeeded in obtaining power-law

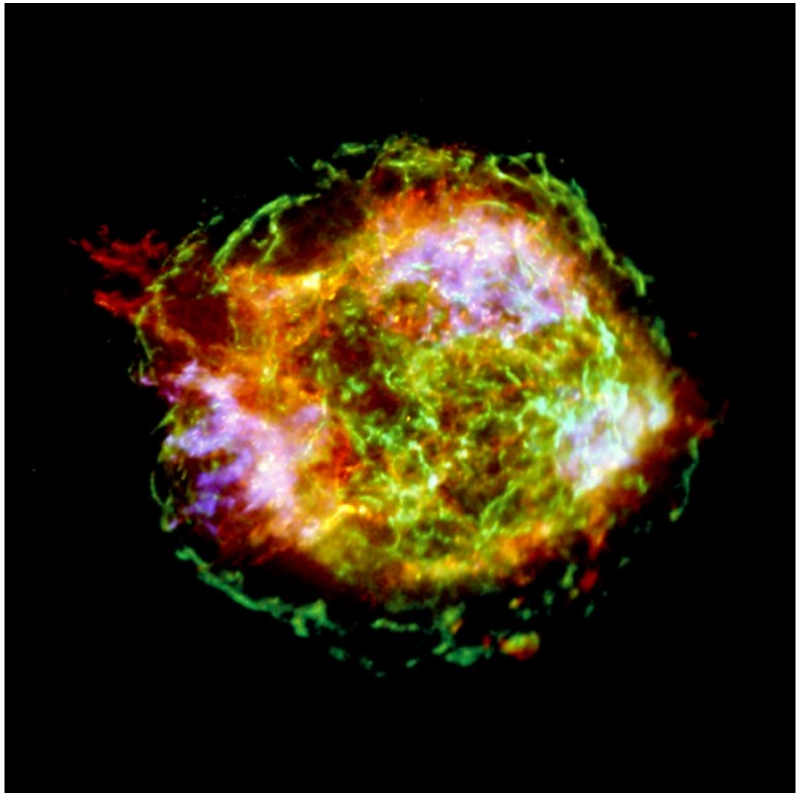
$$n(E) = n_0 E^{-x} \text{ with } x = \left(1 + \frac{1}{\alpha \tau_{esc}}\right)$$

- only ingredients:
  - acceleration ∝ energy
  - escape time independent of energy

But

- index depends on $V, L, \tau_{esc},$ not universal
- velocity of interstellar clouds typically $V \approx 10-4\, c$
  → not much gain per single collision
- typical distance $L \approx 1\, pc$ → collision rate $c/L \approx 0.3/yr$
- quite general problem: acceleration at low energies hampered by ionisation losses → either accelerate efficiently or inject at high energies

Acceleration in strong shocks



- Shock: pressure wave with velocity $u > c_s$
- for strong shocks, $u \gg c_s$
- gas ahead of shock (“upstream”) cannot react

- many astrophysical environments:
  - supernova remnant shocks
  - termination shocks in pulsar wind nebulae
  - bow shock caused by solar wind

- strong shocks provide good environment for particle acceleration
  - large shock speeds
  - turbulent motion on small scales

- application of Fermi acceleration results in
  - energy increase ∝ u/c
  - universal spectral index of 2 in the easiest case

First order Fermi-Acceleration

First order Fermi-Acceleration

Find universal power law

$$\frac{dn}{dE} = n_0 E^{-2}$$

substantial modifications of spectral index possible for

- weak shocks (steeper spectra)
- synchrotron losses (cut-off)
- feedback due to particle pressure (hardening)
- magnetic fields
- relativistic shocks (in general hardening)
- magnetic effects much more complicated