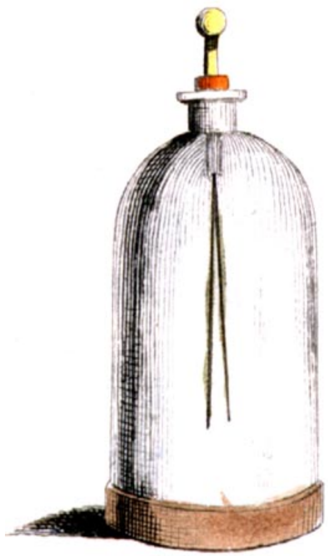
Cosmic Rays

- Discovery of cosmic rays
- Local measurements
- Gamma-ray sky (and radio sky)
- Origin of cosmic rays

Discovery of Cosmic Rays



Problem that electroscopes would always lose their charge.

In 1912 Hess flew electroscopes in balloons (up to 17,500 feet) and showed that the rate of loss increased with altitude, thus showing that the particles causing the loss of charge were produced external to the Earth. He called them cosmic radiation.

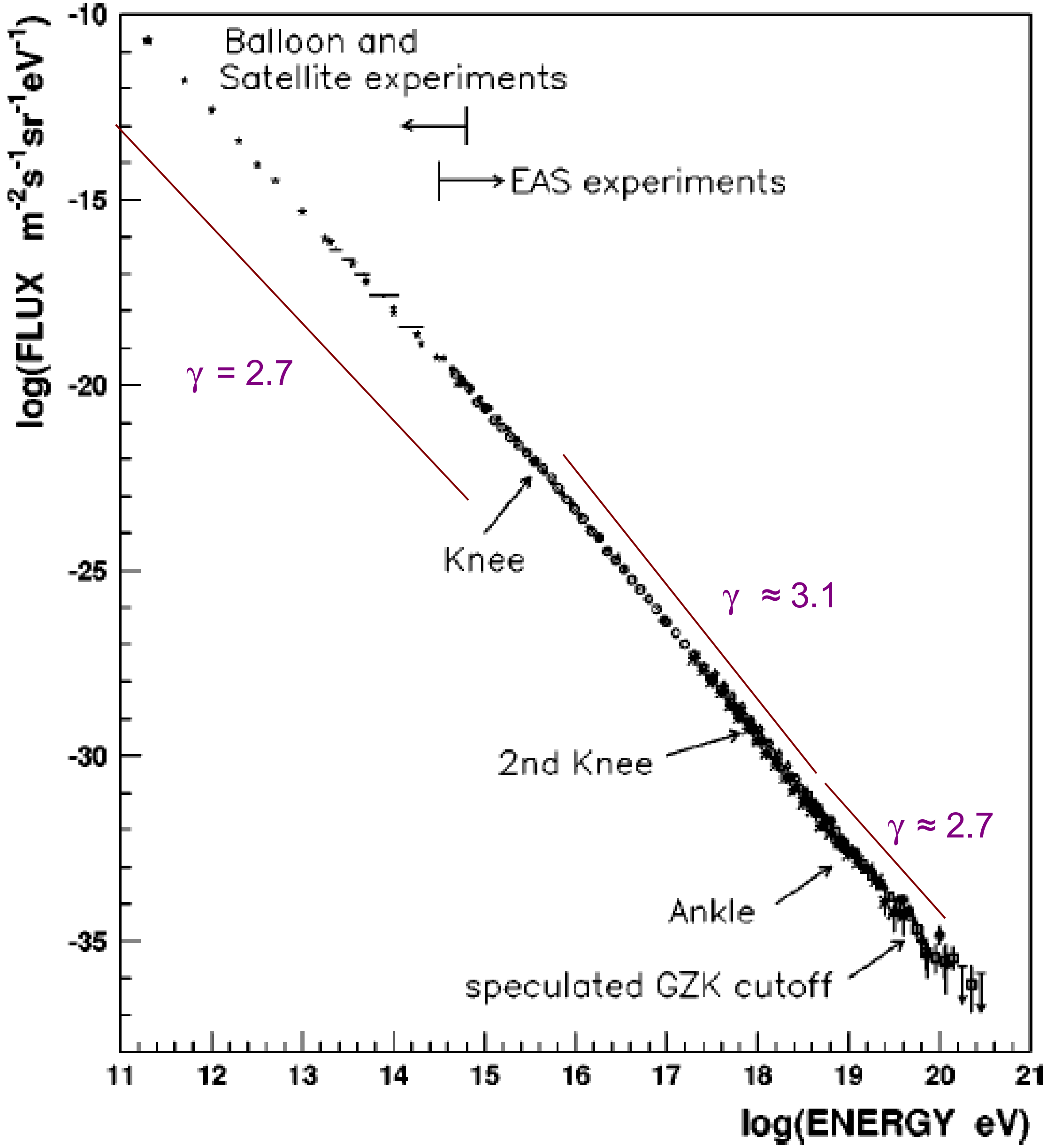
Cosmic rays

Isotropic

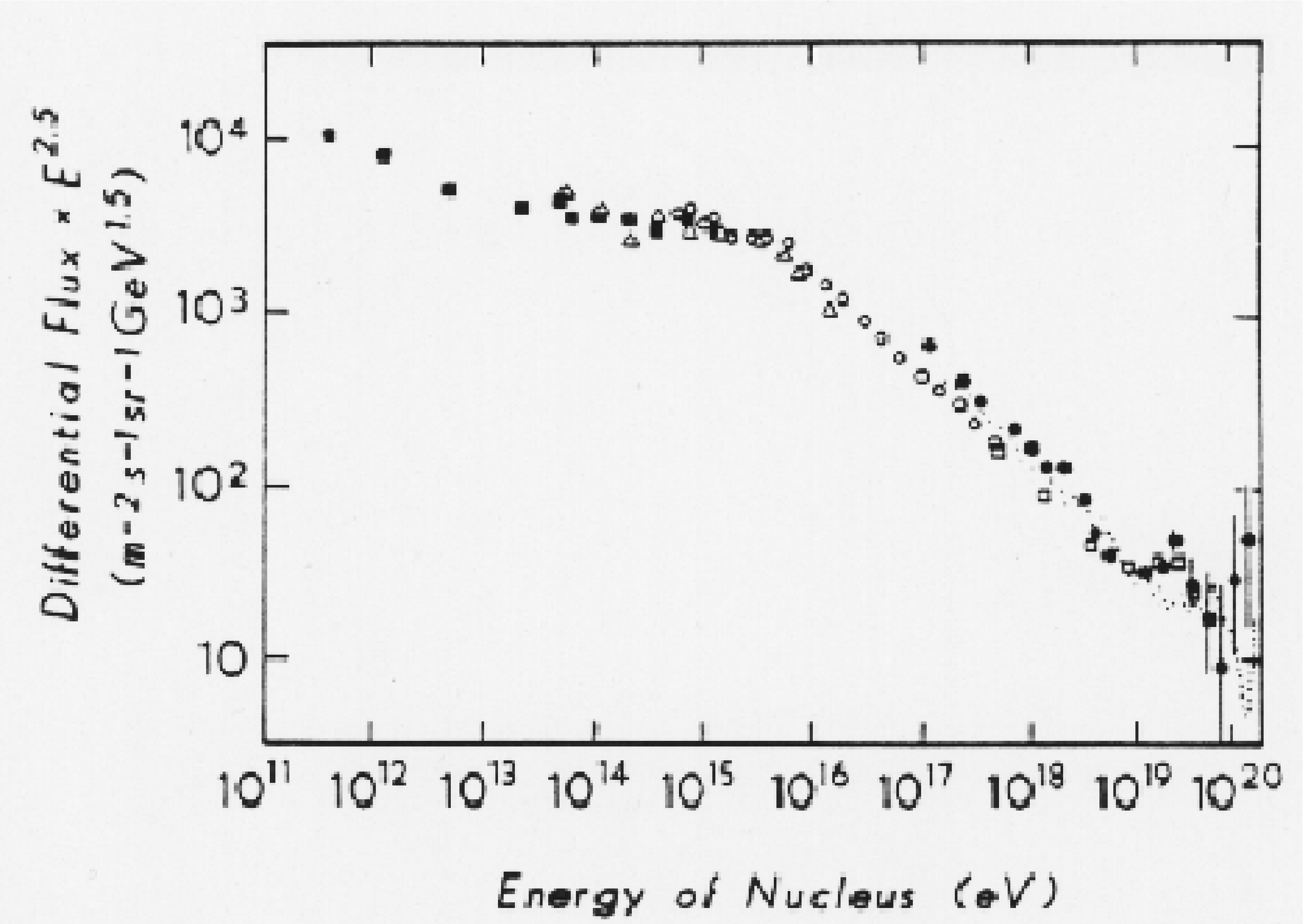
CR: 2% electrons, 98% hadrons. Hadrons: 89% H, 10% He, 1% heavier elements.

Energy density
CR ~ 1 eV/cm^3
Starlight ~ 0.3 eV/cm^3
B-field ~ 0.2 eV/cm^3
CMB ~ 0.3 eV/cm^3

"Knee" at 3×10^{15} eV



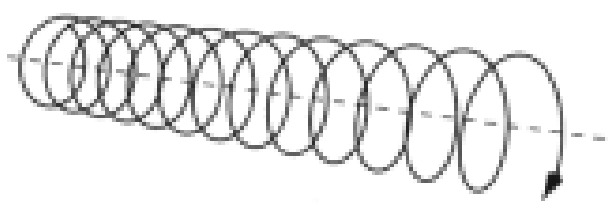
Cosmic ray spectrum



Confinement

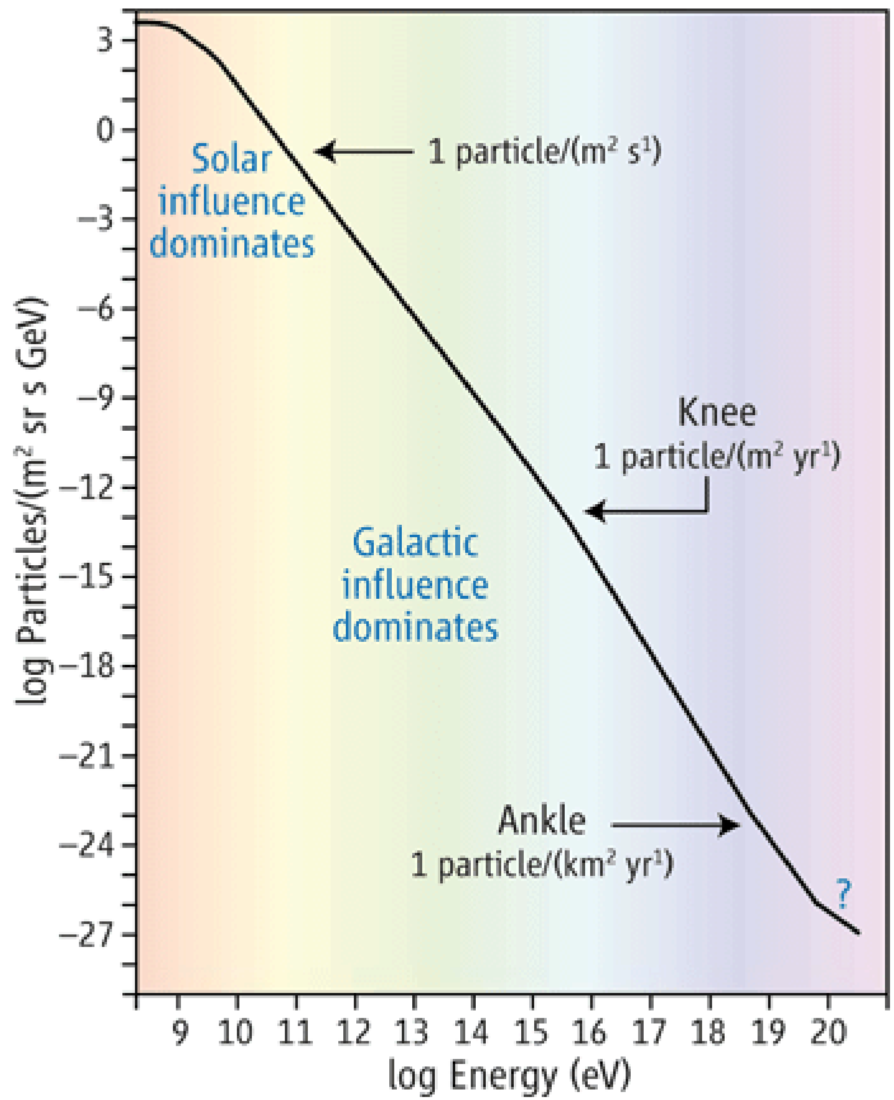
Milky Way B ~ 3 μG.

Lamour radius $r_g = p/qB$, for protons, $r_g = 10^{12}$ cm (E/GeV).



Scale height of Galactic disk is ~5× 10^{20} cm, thus, protons with energies up to about 10^{17} eV can be confined.

At low energies, heliosphere affects trajectories.

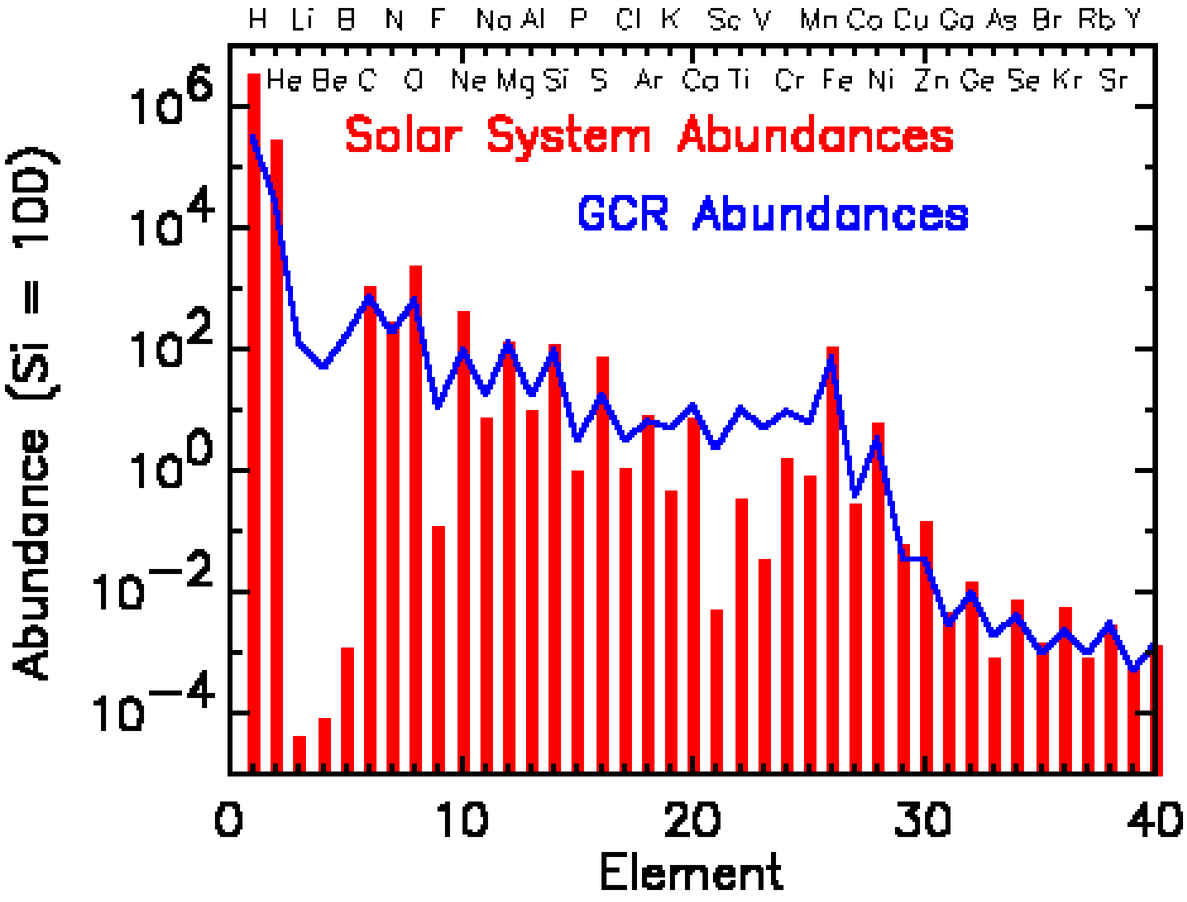


Greisen-Zatsepin-Kuzmin Cutoff

- Cosmic rays will interact with cosmic microwave background: $p+\gamma \rightarrow p+\pi$
- Only occurs when proton has enough energy to produce pion, $E \sim 5\times 10^{19}$ eV

- Detection of particles above this energy requires “local” sources (or new physics).

Cosmic ray abundances



Rare elements and radioactive isotopes are over abundant due to spallation.

Spallation

Cosmic rays collide with nuclei in ISM, changing the composition. For example:

$$p + {}^{16}_{8}O \rightarrow {}^{7}_{3}Li + X$$

Observed CR composition depends on:

- Initial CR composition
- CR path length/life time
- CR energy

Measurement of CR composition, including isotopes, allows one to constrain these quantities.

Find path length traversed by CR by comparing abundant elements to those produced by spallation (i.e. B vs C, Cr vs Fe). Path length ~ 50 kg m^{-2} (with some energy dependence).

Radioactive Clocks

- If there is a cosmic ray nucleus with a radioactive isotope and we can determine the ratios of the different isotopes produced via spallation, then we can figure out the age of cosmic rays.
- ^{10}Be is about 10% of all Be produced by spallation, has a half-life of 1.6×10^6 years.
- The measured fraction of ^{10}Be in Be cosmic rays is about 3%.
- Conclude that cosmic rays are confined in the Galaxy for about 10^7 years before escaping.

Leaky Box

"Leaky box" model – CRs diffuse inside a containment volume (volume of Milky Way disk) and are reflected at boundaries with some probability of escape. Typical path length ~ 50 kg m^{-2} and typical lifetime ~ 10^7 years.

Confinement is assumed to be done by Galactic magnetic field.

Note that highest energy CR are not confined by magnetic fields of Milky Way.

Implies roughly uniform distribution of cosmic rays through out the Galaxy.

Photon production by cosmic rays

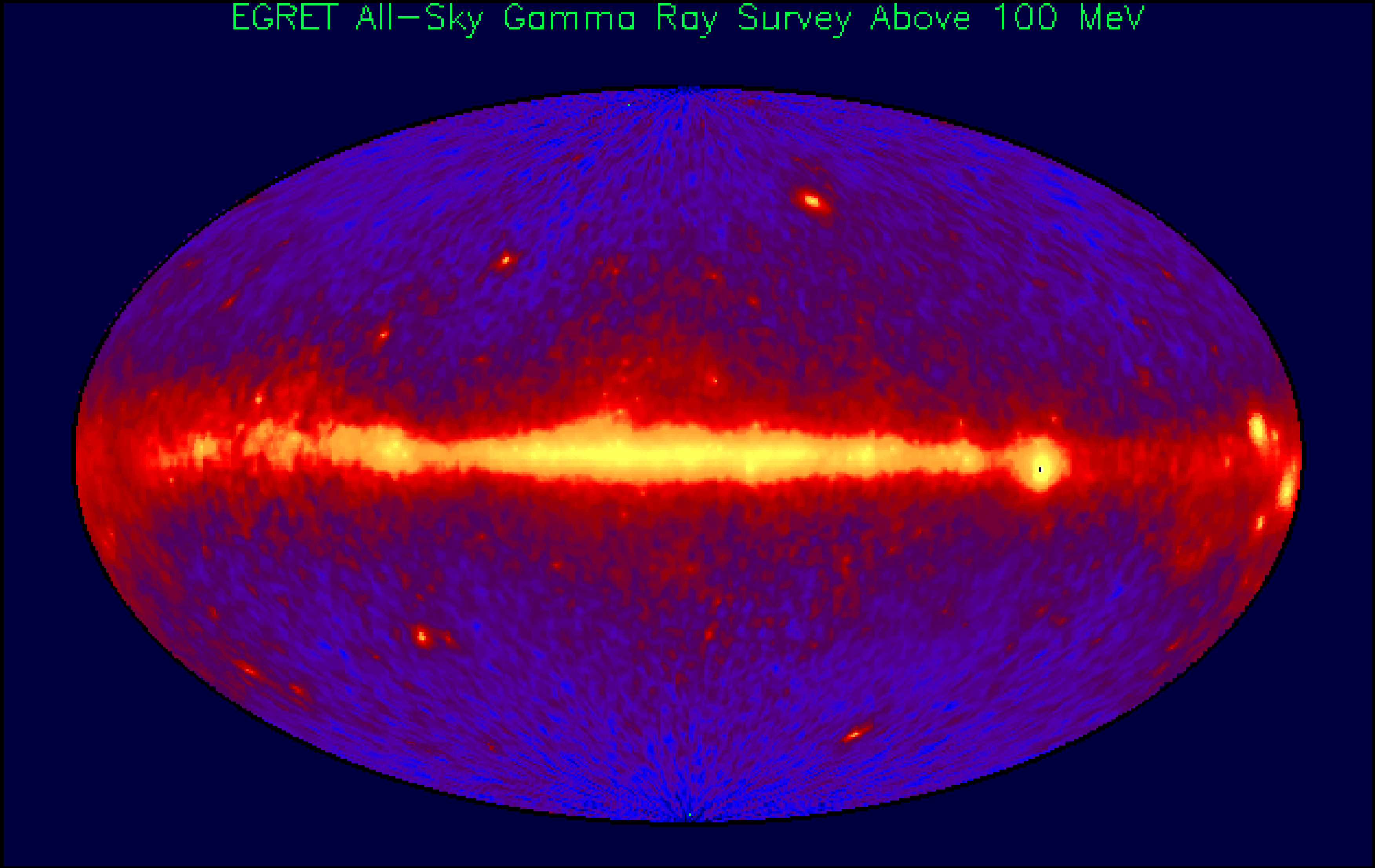
$$\pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$$

- Pion production:
  $p + N \rightarrow \pi^0 + X$
  π^0 has total charge = 0, baryon number = 0
  so π^0 can decay via $\pi^0 \rightarrow \gamma\gamma$

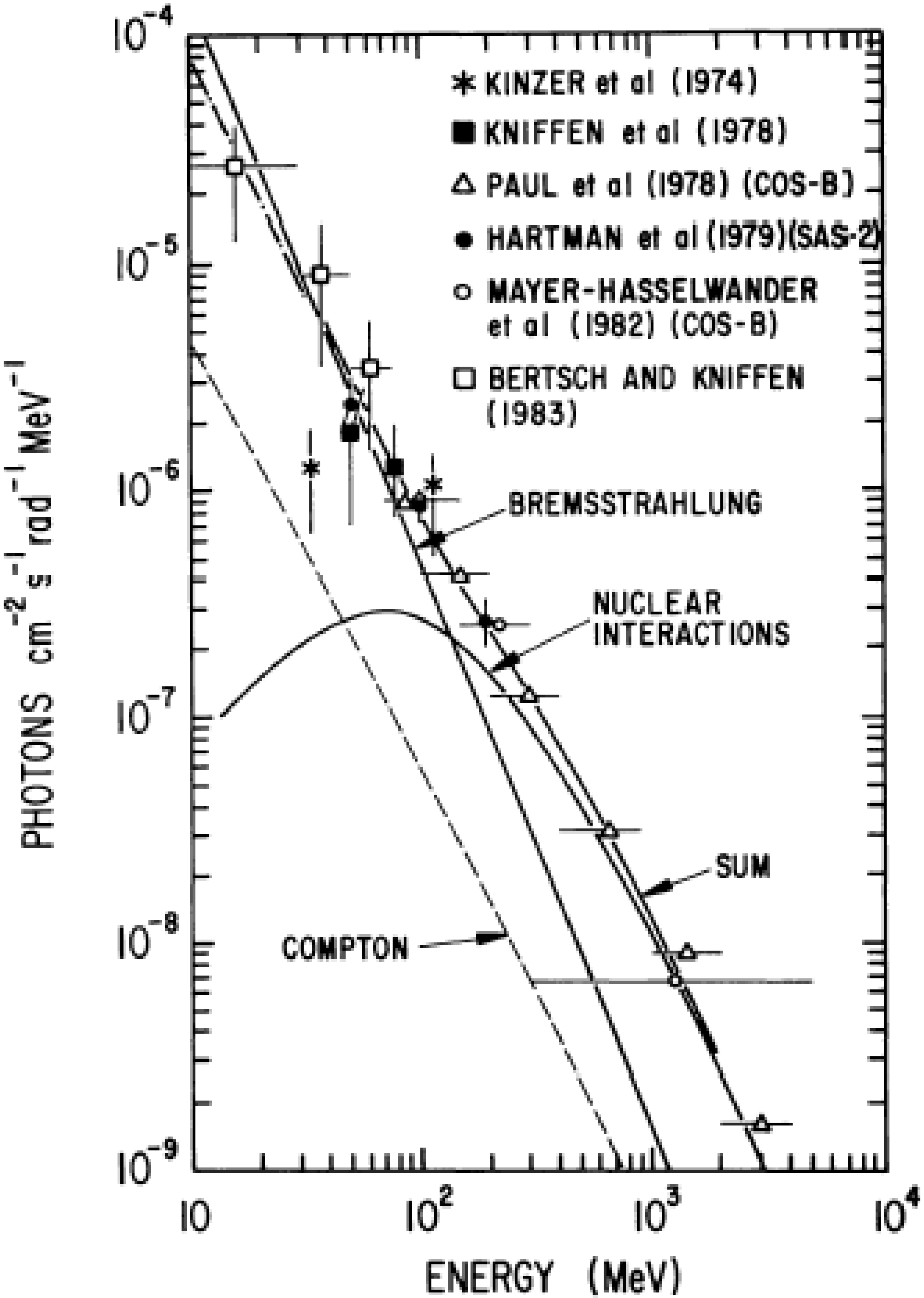
Neutron pion mass = 135 MeV,
Decay produces two photons of ~70 MeV

- Electron bremsstrahlung – cosmic ray electrons on ISM
- Inverse Compton – cosmic ray electrons on star light

Gamma-Ray Sky



Gamma-ray spectrum



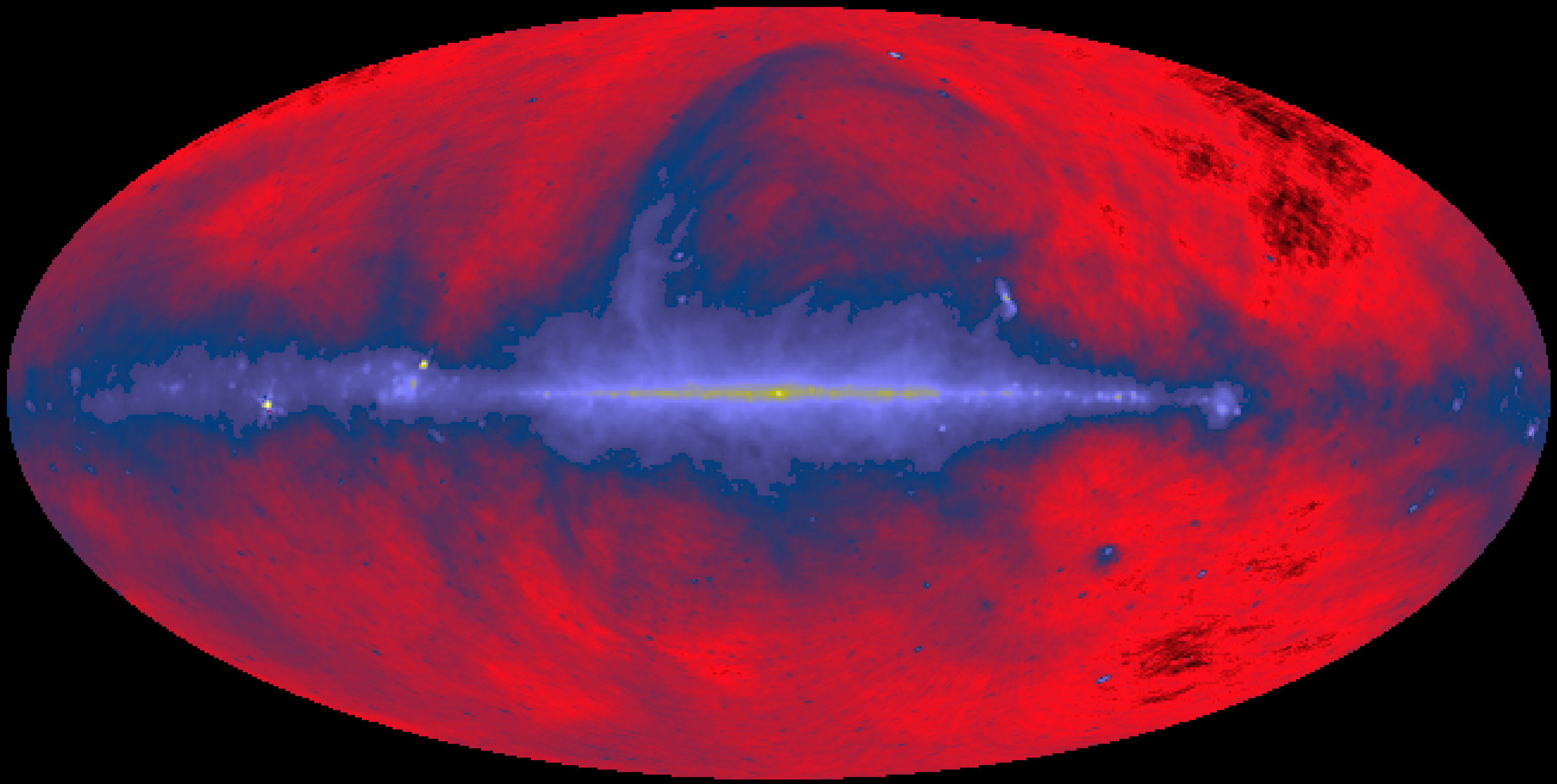
Photon production by cosmic rays

- Electron cosmic rays produce radio emission via synchrotron radiation in the Galactic magnetic field
- Radiated spectrum peaks at a frequency

$$\nu \approx (3.2\,\mathrm{GHz})\left(\frac{E}{10\,\mathrm{GeV}}\right)^2\left(\frac{B}{3\mu G}\right)$$

As for gamma-rays, need to convolve the electron CR spectrum with the Galactic magnetic field distribution along each line of sight.

Milky Way at 408 MHz



Total Power in Cosmic Rays

Volume of Galactic disk $V \sim \pi R^2 d$.

For $R \sim 15$ kpc, $d \sim 200$ pc, find $V \sim 4\times 10^{66}$ cm^3.

Power in cosmic rays $L \sim V\rho/\tau$.

ρ = energy density ~ 1 eV/cm3

τ = lifetime of CR ~ 10^7 years.

Find $L \sim 10^{41}$ erg/s in high energy particles.

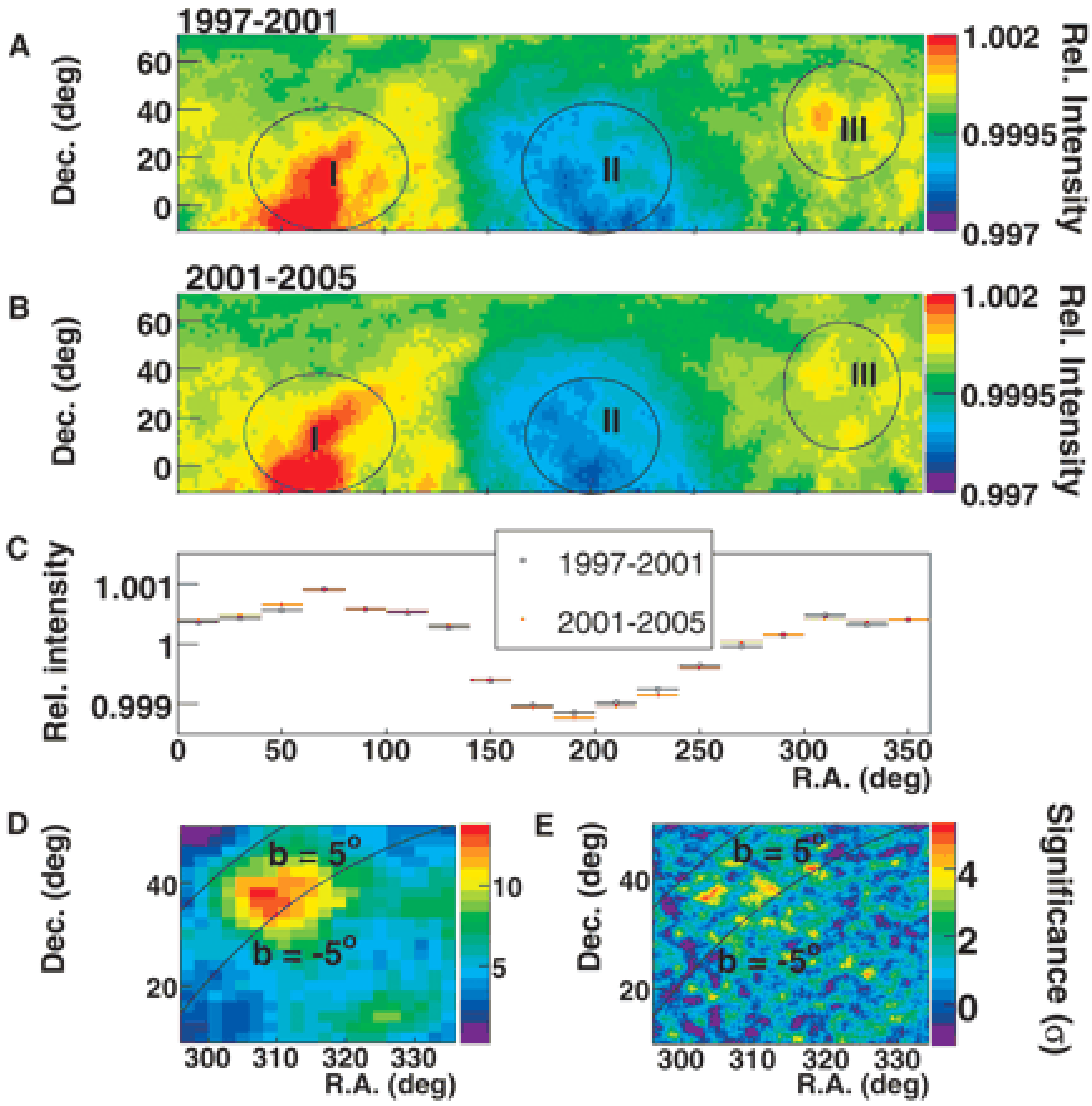
Power Source: Supernovae?

- Supernovae –
  - E = Mechanical energy ~ 10^{51} erg
  - R = rate 1/100 years
  - η = efficiency for conversion of mechanical energy into relativistic particles ~ 10% (?)
- $L_{SN} \sim \eta E R \sim 2\times 10^{41}$ erg/s
- Need mechanism for acceleration, need to know if acceleration is really 10% efficient.

Power Source: Massive Star Winds?

- O and B star winds –
  - Winds have speeds of 2000-4000 km/s
  - Expect multiple stars within OB associations
  - Cyg OB2 has a wind luminosity ~ 10^{39} erg/s, would need 1000 such associations in the Milky Way to power cosmic rays
- OB associations are bright in gamma-rays

Cosmic Ray Map



Power Source: X-Ray Binaries?

- Jets from X-ray binaries known to contain relativistic particles –
  – Only SS 433 is know to accelerate hadrons, and that jet is not ultrarelativistic
  – Integrated output of X-ray binaries appears to be too low to power full CR population, but may contribute a few percent