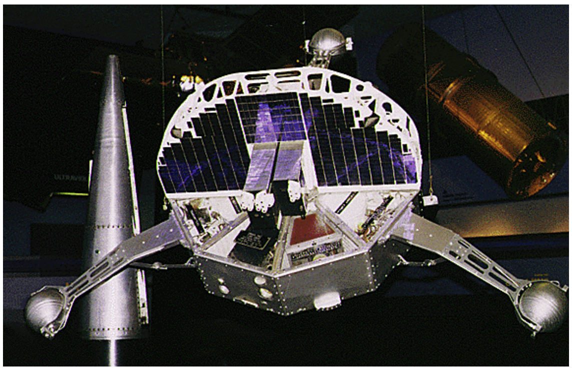
5. Gamma Rays and Cosmic Rays

In HEA1 we defined the gamma ray region of the E-M spectrum as photons with energy $E > 100\ \mathrm{keV}$

Gamma ray emission from the plane of the Milky Way first detected by the orbiting Solar observatory (OSO) 3, in 1967.

Huge leap forward in 1991, with the launch of the **Compton Gamma Ray Observatory**



Model of OSO 3 in the National Air & Space Museum

CGRO in orbit: artist's impression

Compton Gamma-Ray Observatory (CGRO)

The Compton Gamma-Ray Observatory was launched on April 5, 1991. The second of NASA's great observatories, CGRO has four instruments that cover an unprecedented six orders of magnitude in energy, from 30 keV to 30 GeV. Over this energy range CGRO has an improved sensitivity over previous missions of a full order of magnitude. It operated for almost 9 years and the mission ended on June 4 2000. Unlikely most satellites, CGRO was too large to burn up entirely in the atmosphere during re-entry. To ensure safety on the Earth's surface, NASA redirected the spacecraft into Earth's atmosphere with a controlled re-entry.

Mission Characteristics

- Lifetime : 5 April 1991 - 4 June 2000
- Energy Range : 30 keV - 30 GeV
- Special Features : First Great Gamma-Ray observatory
- Payload :
  - The Burst and Transient Source Experiment (BATSE) an all sky monitor 20-1000 keV
  - The Oriented Scintillation Spectrometer Experiment (OSSE) 0.05-10 MeV energy range
  - The Compton Telescope (Comptel) 0.8-30 MeV capable of imaging 1 steradian
  - Energetic Gamma Ray Experiment Telescope (EGRET) 30 MeV-10 GeV

Science Highlights

- The Discovery of an isotropic distribution of the Gamma-ray burst events
- Mapping the Milky Way using the 26 Al Gamma-ray line
- Discovery of Blazar Active Galactic Nuclei as primary source of the highest energy cosmic Gamma-rays
- Discovery of the "Bursting Pulsar"

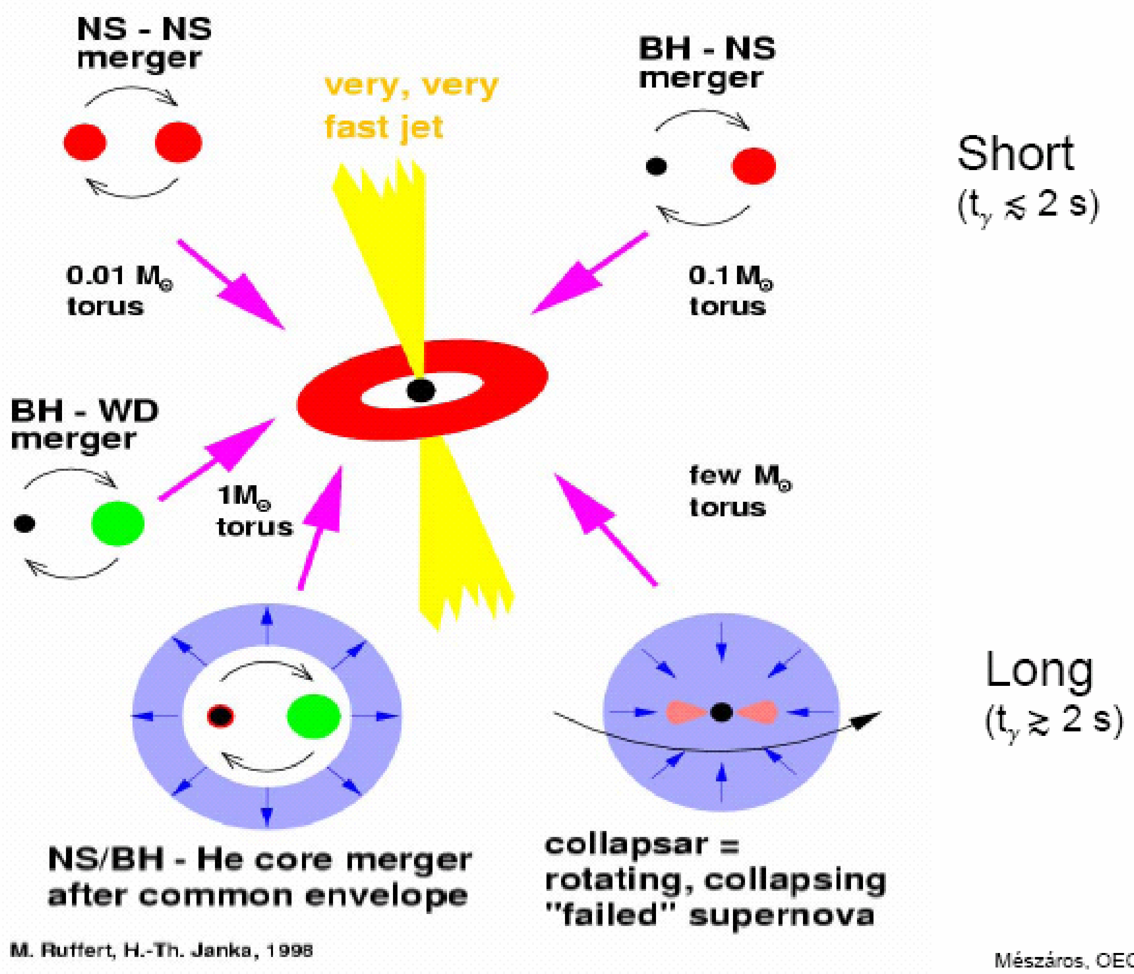
5.1 Gamma Ray Bursts

- The most luminous physical phenomena in the Universe: flashes of gamma rays lasting from seconds to hours – the longer bursts followed by several days of **afterglow**.

- Long duration bursts (> 2 sec): beamed energy from a **hypernova**, collapse of a 40 – 100 solar mass star, or **NS/BH** merger inside common envelope

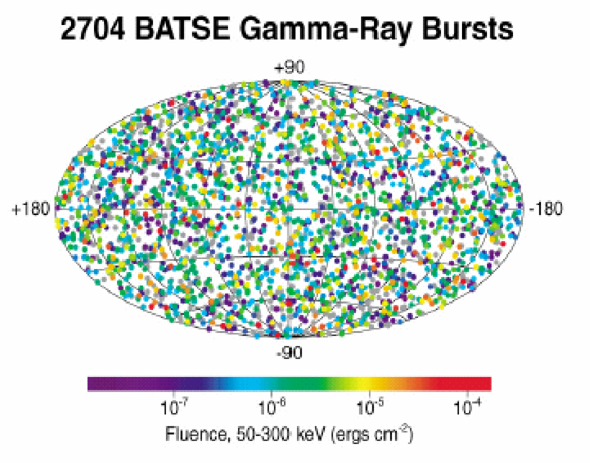
- Short duration bursts (< 2 sec): NS/NS, BH/NS or BH/WD merger

GRB: → Hyperaccreting Black Holes (current paradigm)



Mészáros, OECD03

- Strong evidence for isotropy came from CGRO BATSE by late 1990s
- Supported cosmological origin for GRBs
- Direct evidence of cosmological distance from **afterglows**:
  - From 1997 BEPPO-SAX made simultaneous gamma ray and X-ray observations, pinning down sky position for optical follow-up.



- First example: GRB 970228, too faint to obtain optical redshift, but others followed quickly – confirmed that many GRBs are at great distance ($z > 1$). Current record holder (Sep 2006) $z = 6.29$

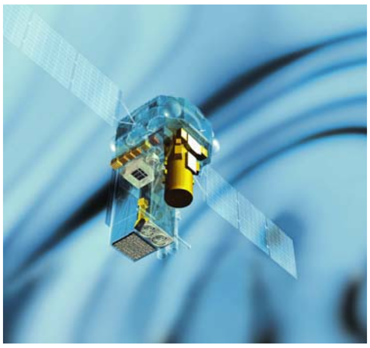
- More recently, launch of SWIFT (Nov 2004) satellite promises up to 200 GRBs per year, localised and followed-up in gamma / X-rays / optical

5.2 Electron – positron annihilation

When electrons and positrons interact, their annihilation can produce photons of energy $E = 511$ keV (equal to the rest mass energy of these particles).

Photons of this energy have been detected in recent years from a variety of astrophysical sources – e.g. the Sun and the Galactic Centre. We 'see' these photons as a **gamma ray emission line**.

In recent years the high (~2 keV) spectral resolution of e.g. CGRO, RHESSI and INTEGRAL has greatly improved our observations of emission from electron-positron annihilation.



INTEGRAL

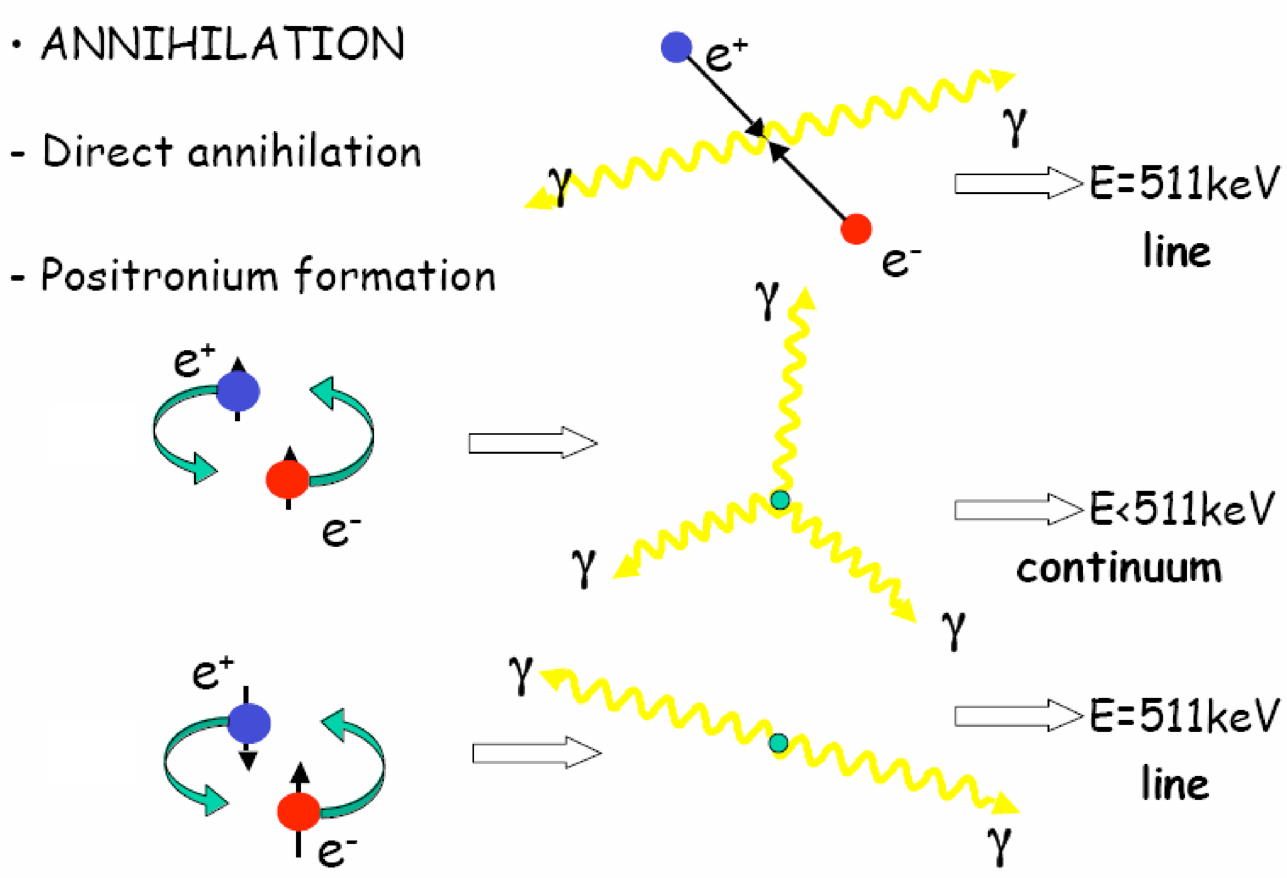
RHESSI

5.2.1 The Solar electron – positron annihilation line

- Flare-accelerated protons, α-particles and heavier ions interact with the solar atmosphere, producing radioactive nuclei which decay, releasing a **positron**
- Positrons slow down via Coulomb interactions (producing bremsstrahlung) and interact with electrons, leading to:

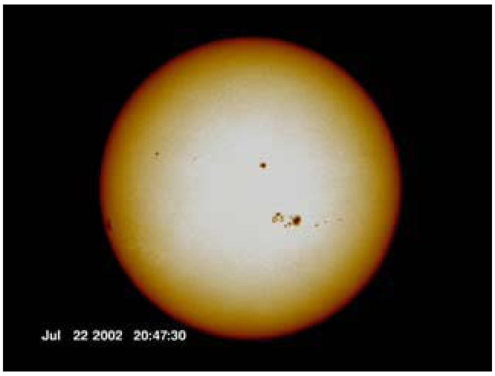
1. Direct annihilation — creates ***two*** 511 keV photons — Line emission
2. Formation of **positronium**, then annihilation:
   - \`singlet' spin state ⇒ creates ***two*** 511 keV photons — Line emission
   - \`triplet' spin state ⇒ creates ***three*** photons of varying energies — Continuum

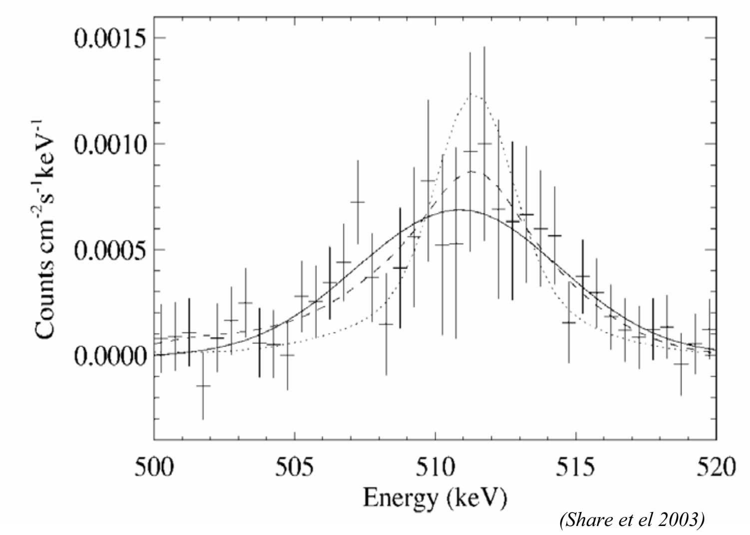
- Ratio of annihilation photons in the continuum and line determined by temperature, density and composition of the plasma in which the positrons slow down – can predict this ratio from theory.



Adapted from Pierre Jean (2003)

- RHESSI has observed annihilation radiation from the 2002 July 23 solar flare.





(Share et el 2003)

- Two very different environments can match observed 511 keV line profile:

1. Hot ionised plasma at $T \sim 5 \times 10^5$ K **Solid line**
2. Neutral / partially ionised 'quiet sun' at $T \sim 6000$ K **Dashed line**

(but e.g. $T = 5000$ K *gives poor fit - dotted line)*

- Case 2 excluded because predicts wrong continuum / line ratio

- What about case 1 ?...

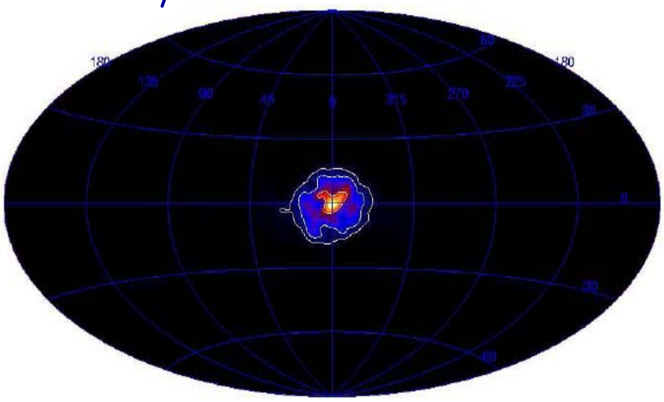
Also puzzling, since $T \sim 5 \times 10^5$ K corresponds to number densities of $n \sim 10^{18}$ H nuclei m^{-3}

However, positrons are produced at densities of $n \sim 10^{20}$ H nuclei m^{-3} in a medium which is sufficiently dense to slow them down.

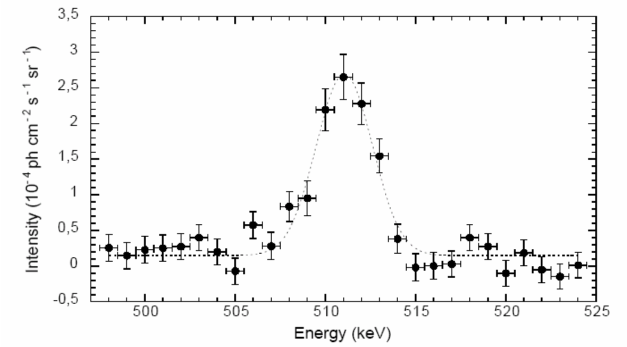
Why don't we see annihilation radiation from lower down in the solar atmosphere, at $n \sim 10^{20}$ H nuclei m^{-3} ?

5.2.2 Electron – positron annihilation from the Galactic Centre

- 511 keV line first detected from the Galactic Centre region in 1973.
- Maps by INTEGRAL have much improved spatial and spectral resolution and sensitivity



From Knodlseder et al (2005).
Contours denote $10^2, 10^1, 10^0$ photons $m^{-2} s^{-1} sr^{-1}$



From Jean et al. (2003)

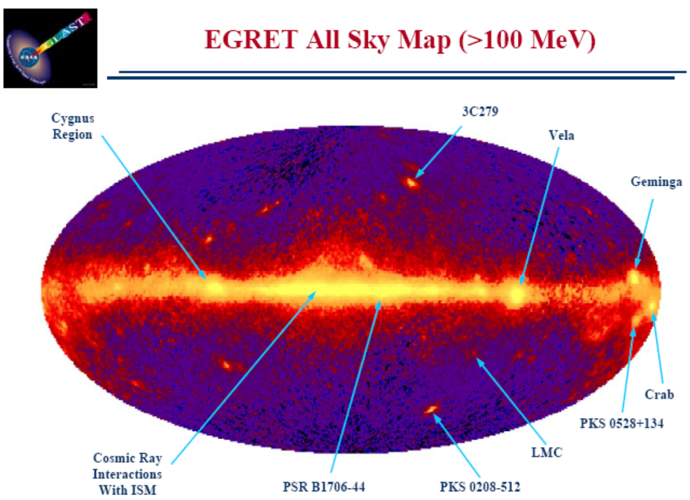
Line emitting source is *diffuse* (not point source)

Observed flux within 5 degrees of GC is (9.9 ± 4) photon m^{-2} s^{-1}

$\Rightarrow$ Luminosity $L_{GC} \sim 7 \times 10^{29}$ W and a positron injection rate of $\sim 10^{43}\, e^{+}\, s^{-1}$

Origin of GC annihilation emission?

1. Massive stars, core collapse SN, hypernovae? ✗ No recent SF in bulge, GC
2. Cosmic ray interactions with interstellar medium? (see 5.3)



(from Gehrels 2000)

Pion decay: $N + p \rightarrow \pi^{+} \rightarrow e^{+}$

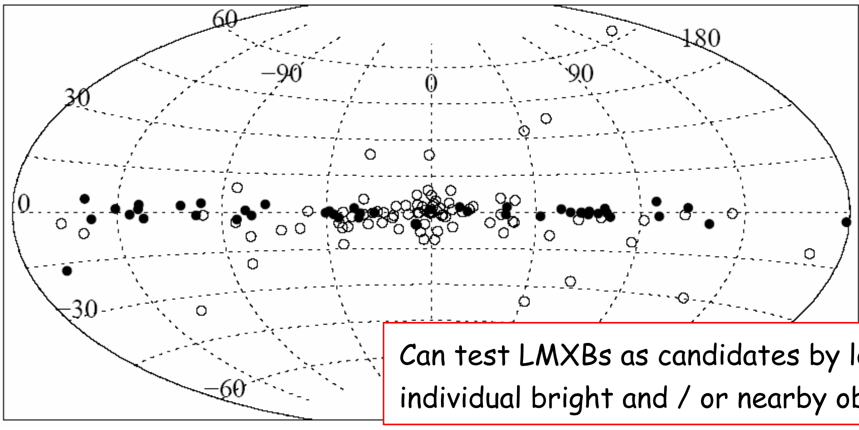
Nucleus   Cosmic ray proton

Spatial distribution of these CR protons revealed by EGRET map of Gamma rays with $E > 100$ MeV.

CR protons trace galactic disk, so why no annihilation emission from disk? ✗

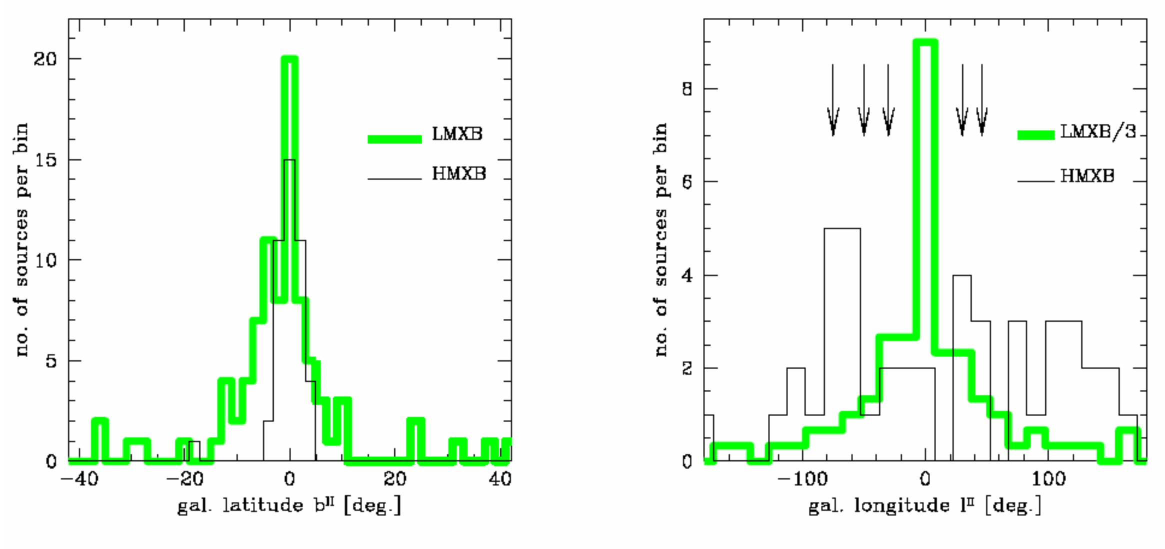
3. XRBs? Recall results of Section 1: HMXBs trace galactic disk ✗

   LMXBs concentrated towards GC ✓



Open circles = low mass XRBs
Filled circles = high mass XRBs

Can test LMXBs as candidates by looking for 511 keV emission from individual bright and / or nearby objects – e.g. Sco X-1, Cen X-4



From Grimm et al. 2003

Origin of GC annihilation emission?

4. Type Ia supernovae?

Strong source of positrons: $\sim 2.5 \times 10^{54}\ \mathrm{e}^+ / \mathrm{SNIa}$

Typical positron escape fraction: $f \sim 0.03$

To match positron injection rate $\sim 10^{43}\ e^+\ \mathrm{s}^{-1}$, we need $\sim 0.5\ \mathrm{SNIa/century}$

Difficult to measure SNIa rate in our own Galactic Bulge, but can interpolate from measured SNIa rate in external galaxies.

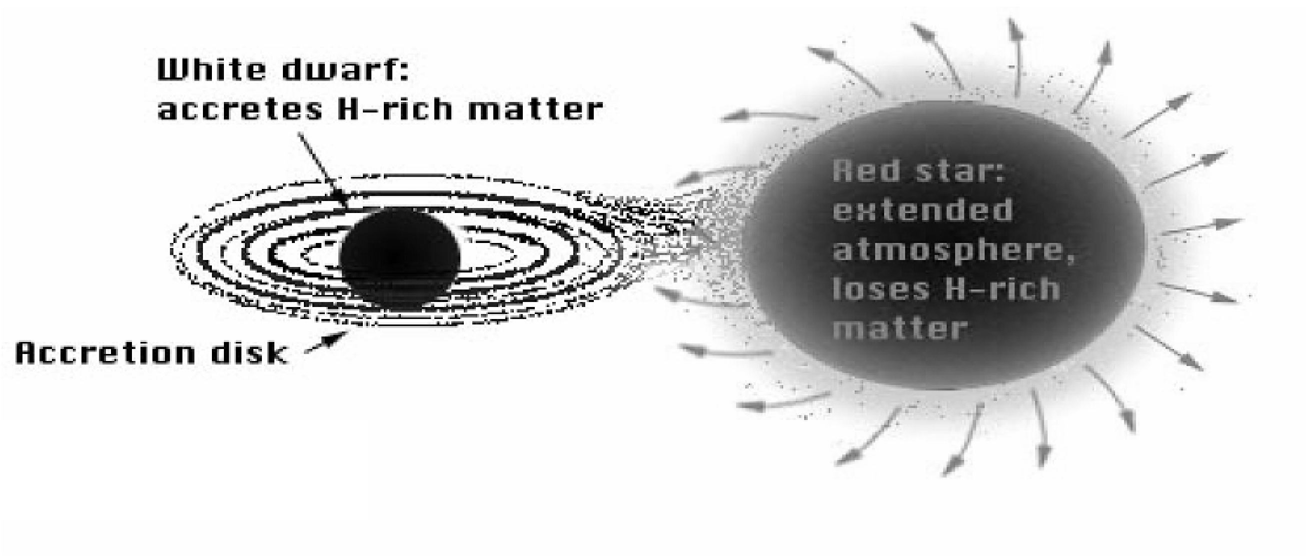
e.g. Mannucci et al. (2005) find $\sim (0.3 - 1.1)\ \mathrm{SNIa/century}$ ✓

Can also search for 511 keV emission from individual SNIa remnants.

5. Dark matter annihilation? Exotic, if exciting candidate. Not enough known about DM distribution in GC to judge if plausible. Future searches in external galaxies?

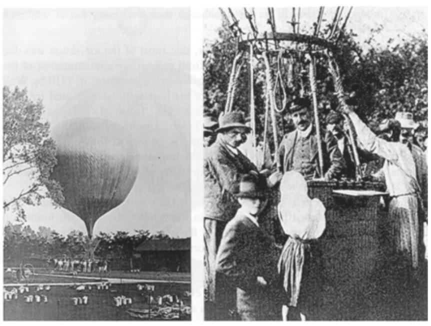
Type Ia Supernova

White dwarf star with a massive binary companion. Accretion pushes white dwarf over the Chandrasekhar limit, causing **thermonuclear disruption**



5.3 Cosmic Rays

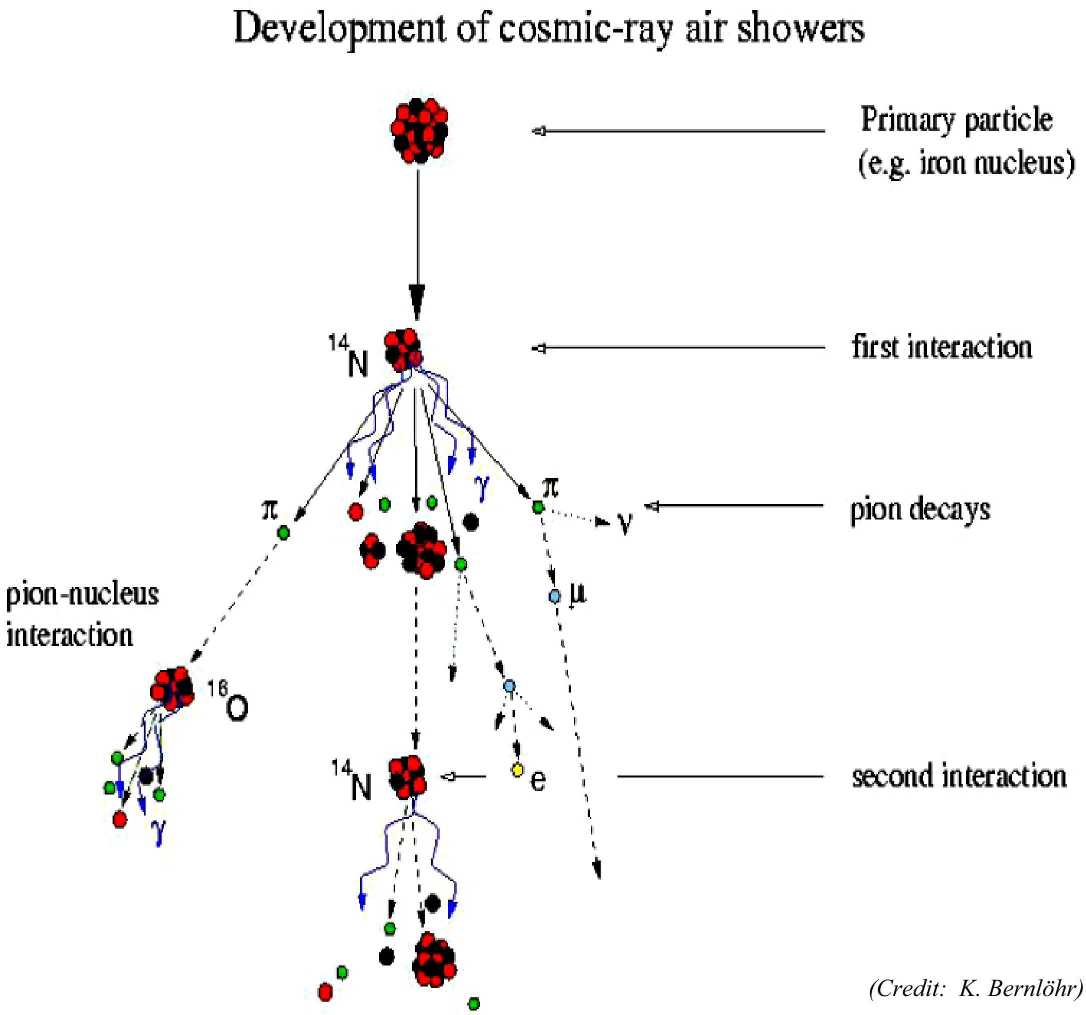
- Generic name for very high energy particles incident on Earth's atmosphere
- Discovered in 1912 by Victor Hess: balloon-borne electroscope discharged more rapidly than one on the ground.



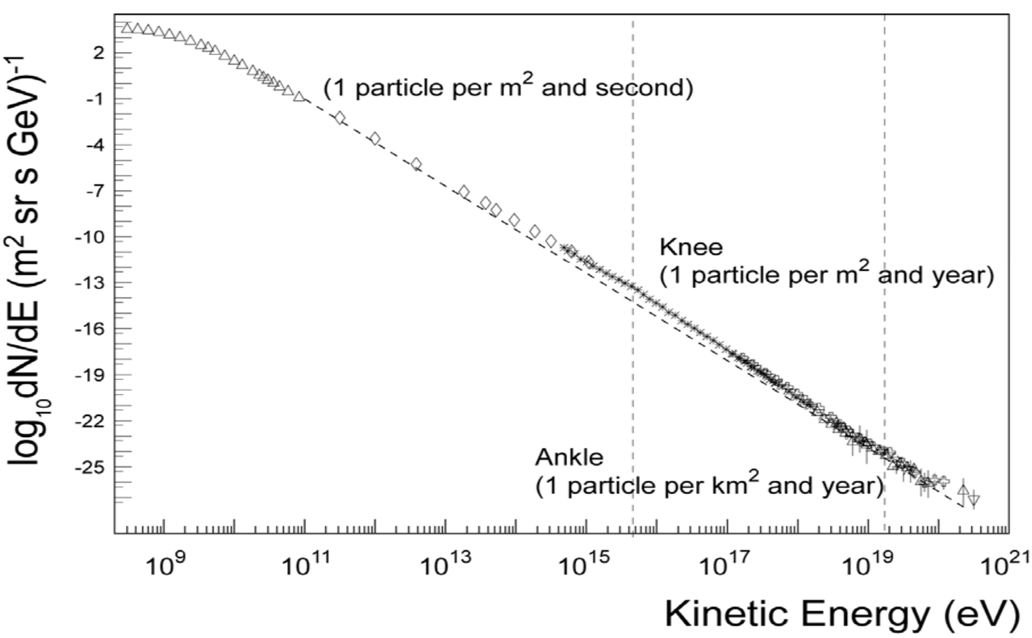
Radiation entering atmosphere from outside?

(Hess won Nobel Prize in 1936)

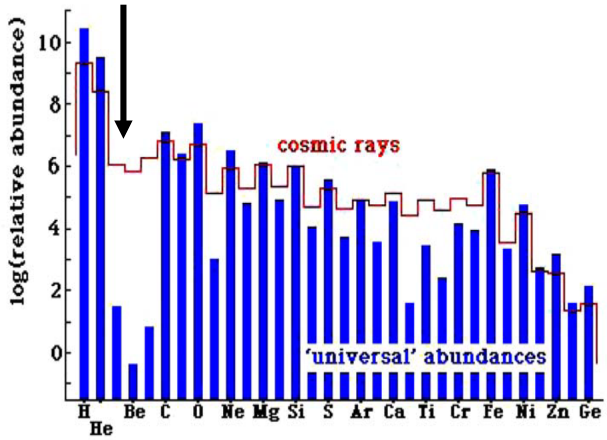
- Inventory: 87% protons (H nuclei)
  12% alpha particles (He nuclei)
  1% electrons and positrons, heavier nuclei
- Incident cosmic rays interact with nuclei high in the Earth's atmosphere, producing a cascade of secondary particles (mainly π-mesons) – air shower



- Energy spectrum well-described by broken power law
- Breaks at 10^{16} eV and 10^{19} eV
- Below the 'knee' at 10^{16} eV CR particles believed to originate from shocks acceleration in SN within the Milky Way



- CR particles which are light nuclei (e.g. Li, Be, B) are over-abundant compared with their universal abundances



- Believed to be due to spallation: break-up of heavier nuclei (e.g. C,O) due to collisions with protons in the interstellar medium

- From the over-abundance of the spallation products, we can estimate the column density of material which they have passed through before reaching us: $\rho_{\text{column}} \sim 50\,\text{kg}\,\text{m}^{-2}$

- We can then, in turn, estimate the *lifetime* of these cosmic ray particles:

  Assuming $\upsilon \sim c$ and taking the mean density of the ISM to be 10^6 H atoms $\text{m}^{-3} = 1.67\times10^{-21}\,\text{kg}\,\text{m}^{-3}$

$$\tau_{\text{lifetime}} \sim \frac{50}{1.67\times10^{-21}\times3\times10^{8}}\ \text{sec} = 3\times10^{6}\ \text{years} \qquad (5.1)$$

- This inferred lifetime is a puzzle. If the CR nuclei propagate at $\upsilon \sim c$, and travel in straight lines through the galaxy, they should escape in about one hundredth of this lifetime.

- Accepted theory is that the CR nuclei are **confined** e.g. by galactic magnetic field. (This will also confine protons, electrons and positrons).

What about higher energy cosmic rays?

- Above the 'knee' ($E > 10^{16}$ eV), the gyro-radius of a proton, assuming typical B-fields (e.g. equipartition value) for a SN remnant, becomes comparable to the size of the remnant itself.

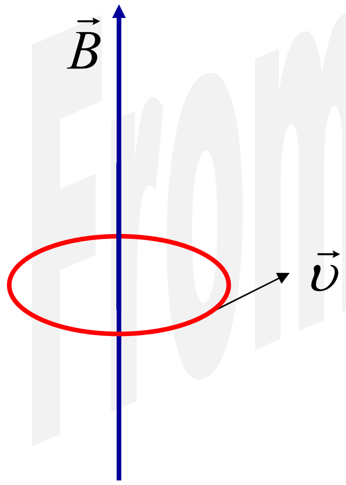
  For $E = \gamma m_P c^2 = 10^{16}\,\text{eV} \;\Rightarrow\; \gamma \sim 10^7$

$$r_{\text{gyro}} = \frac{c\gamma m_P}{eB} \sim \frac{3\times10^{8}\times10^{7}\times1.67\times10^{-27}}{1.6\times10^{-19}\times10^{-8}} \sim 3\times10^{15}\,\text{m} \sim 0.1\,\text{pc} \qquad (5.2)$$

14. Synchrotron Radiation

Cyclotron Radiation

Consider a non-relativistic electron, with $\upsilon << c$, following a circular orbit or radius, r, around a field line of a uniform magnetic field, $\vec{B}$



Lorentz force = 'circular' force

$$e\upsilon B = \frac{m\upsilon^2}{r}$$

Larmor angular frequency

$$\therefore \quad \frac{\upsilon}{r} = \frac{eB}{m} = \omega_L$$

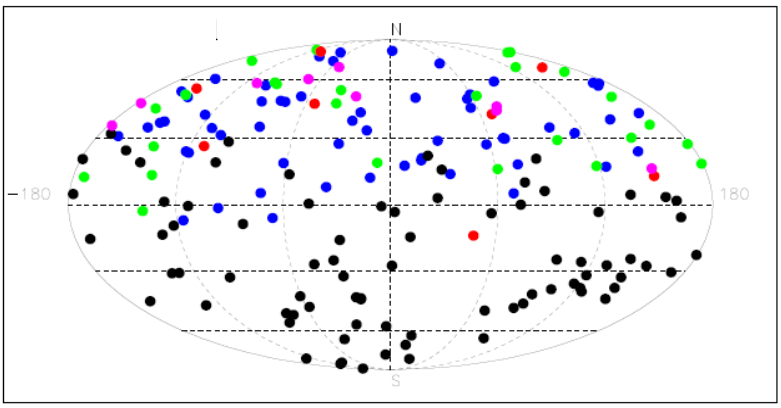
From HEA1 notes

- So at these energies, shock-induced acceleration in SN remnants is no longer an efficient enough mechanism to give the CR particles their energy.

- Likely source is, instead, shock acceleration in AGN.

  (Although B-fields in e.g. AGN jets are smaller, the size of the jet is hugely bigger than a SN remnant. No problem with gyro-radius = physical radius).

- AGN origin also explains why very high energy cosmic rays appear to be isotropically distributed on the sky.



$E > 40$ EeV
Blue ... AGASA (58), Black ... SUGAR (80), Red ... Volcano Ranch (8),
Green ... Haverah Park (26), Magenta ... Yakutsk (9)

What about above the 'ankle'? i.e. $E > 10^{16}\,\mathrm{eV}$

- For these energies it seems that even AGN aren't enough!

Greisen-Zatsepin-Kuzmin limit:

above $E \sim 5\times10^{19}\,\mathrm{eV}$ protons interact with CMBR photons, to produce pions,

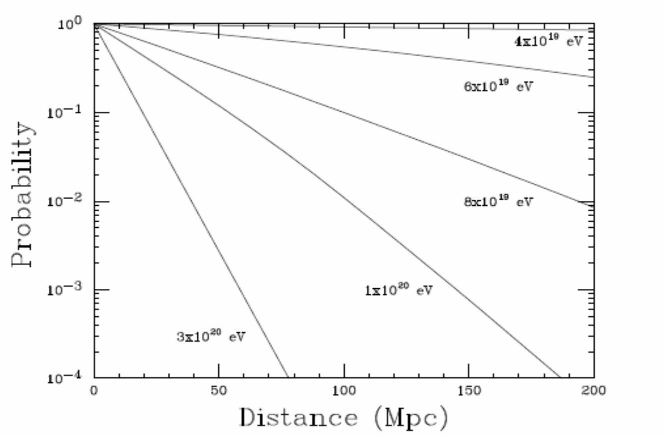
- mfp for this reaction is about 30 Mpc at the GZZ limit.

- so we shouldn't see cosmic rays with energies above the GZZ limit, unless they are of local origin.

- But such CR events *are* seen (dubbed 'Oh My God' particles)

- What could be producing them?
  - hypernovae in nearby galaxies?
  - ultra high-energy exotic particles?
  - cosmic string loops?
  - ??????

} 'top down' (ultra high-energy exotic particles?, cosmic string loops?)



(from Cronin 2004)

Pierre Auger Observatory:

- 3000 km^2 detector arrays in the Southern and Northern hemisphere.
- Detect cosmic rays from air showers
- Southern observatory under construction in Argentina
- May solve the mystery of the origin of ultra high energy cosmic rays.