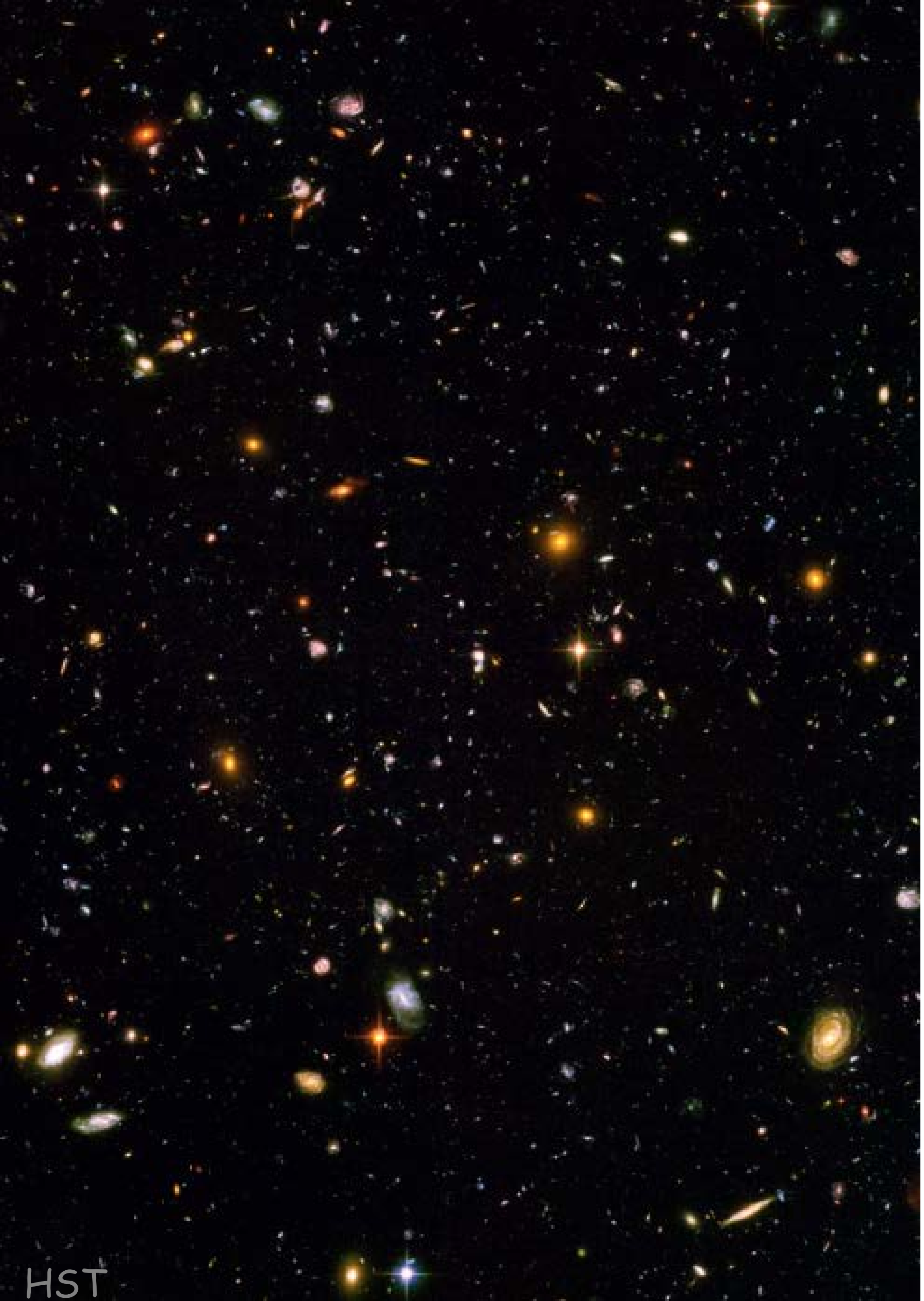


Astroparticle Physisc Introduction – Cosmic Rays

Damien Dornic
(CPPM)

Cosmic rays

- Cosmic rays (CRs) are highly energetic particles that mostly originate outside of our solar system.

- Cosmic rays are in rough energy equipartition with our galaxy's magnetic field, the cosmic microwave background, and starlight.

- The most fundamental questions of cosmic ray research are:
  - What are the source regions of cosmic rays?
  - How are cosmic rays accelerated?
  - How do cosmic rays propagate in the galaxy?

$\Longrightarrow$ Particle astrophysicists have made progress on all of these questions but much work remains

Discovered ~1 century ago

Experiments by Coulomb in 1785 showed that a charged metallic sphere left alone in air gradually loses its charge. Research question in early 1900s: what is the source of atmospheric ionization ?

➢Cosmic rays were first discovered by Victor Hess in balloon in 1912

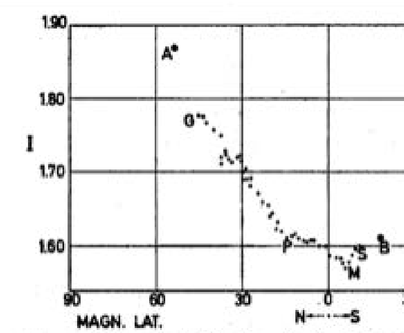
- The amount of atmospheric ionization increased with height
- Origin of atmospheric ionization is extraterrestrial !

➢Sea voyages by Clay (1927) and Millikan (1932) showed a dependence of CR flux on latitude

- Modulation by Earth's magnetic field
- Effect more pronounced for lower energy cosmic ra
- Cosmic rays are (mostly) charged particles !

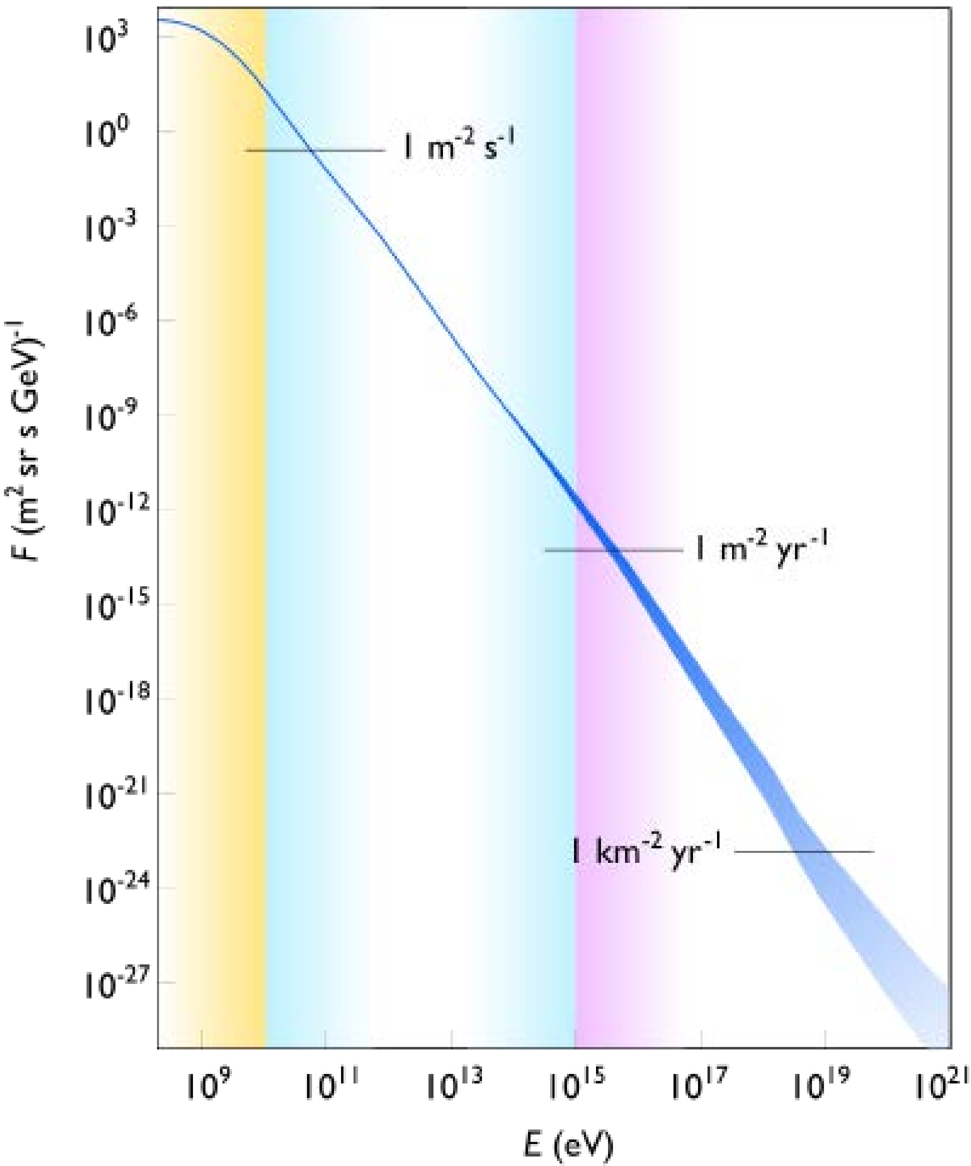
➢ More CRs came from the west than the east (late 1920s · 1930s)

Most CRs are positively charged !



1. Variation of the intensity of the ultra-radiation with the Earth magnet
latitude.

Energy spectrum of cosmic rays



⟹ Universal phenomena without any known equivalent in the Universe, coherent over 32 orders of magnitude, non equilibrium in constant renew !

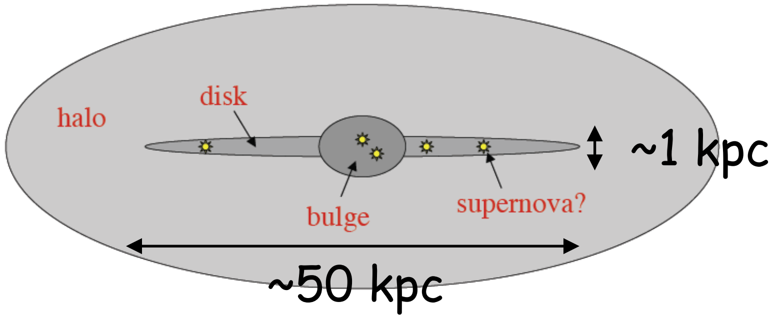
⟹ Their origins are still largely unknown

Units and magnitudes

<u>Units</u>:

Distance: parsec (pc) → 3.086 10^{16} m - 3.26 al

Size of the galaxy:



Distance to the nearest star: 1.3 pc (4.22 al)

Magnetic field: gauss (G) → 10^{-4} T

Earth~0.3 G

Interstellar ~ 10 μ - 10 nG

Neutron star: ~10^{13}-10^{15} G

MRI ~10^{5} G

Units and magnitudes

Units:

Energy: electron-volt (eV) → 1.6 10^{-19} J

(1 PeV = 10^{15} eV; 1EeV = 10^{18} eV)

7 TeV: proton energy at LHC

200 MeV: freed energy from the ^{235}U fission

Mass: Sun mass (M_0) → 2. 10^{30} kg

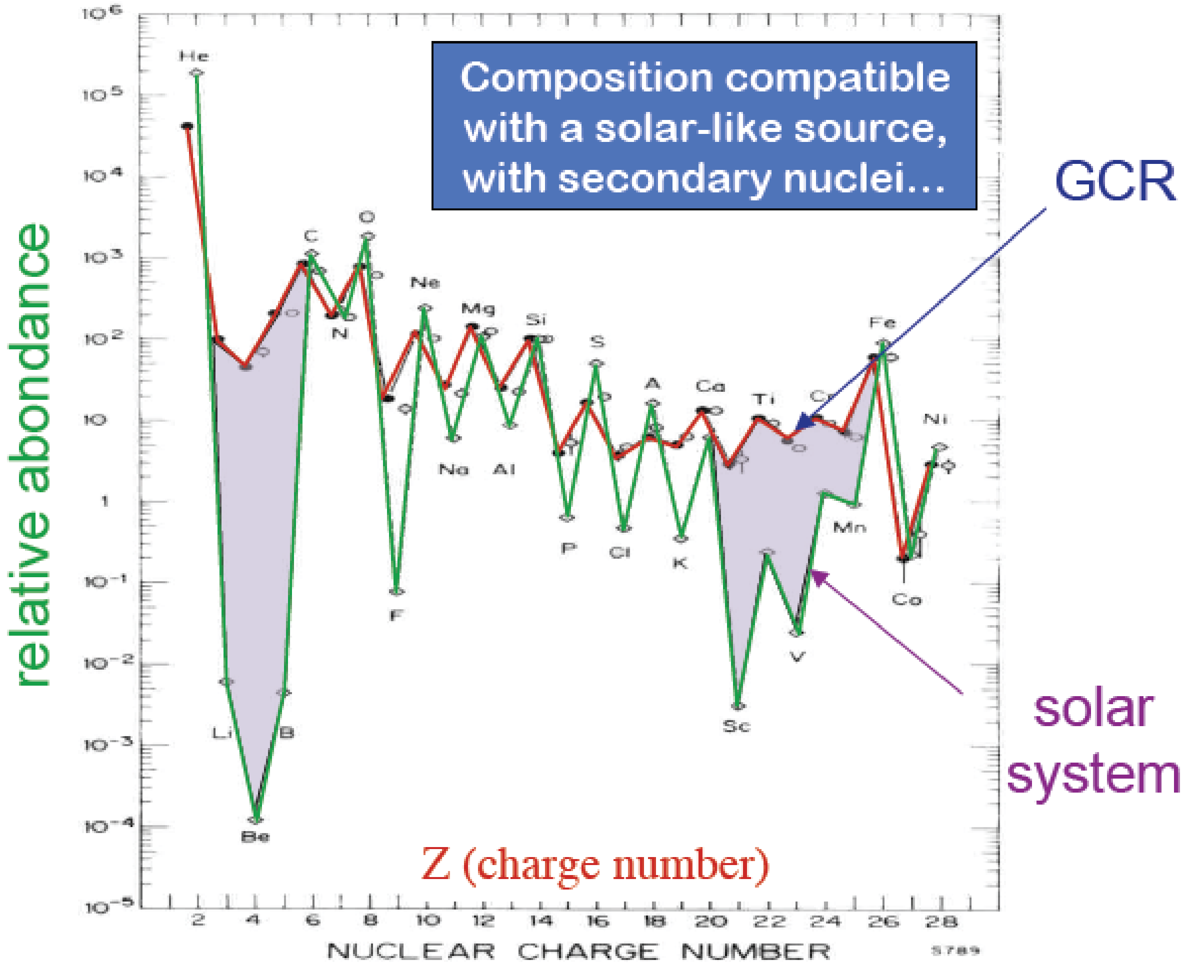
x 3 10^5 M_{Terre}

Black Hole mass: ~ 10^8-10^{10} M_0

Speed: of light (c) → 3. 10^8 m/s

Nature of the CR

Flux: ~ 4 CR/cm²/s → 1 kg/y (~40000 tonnes/y of meteorites)



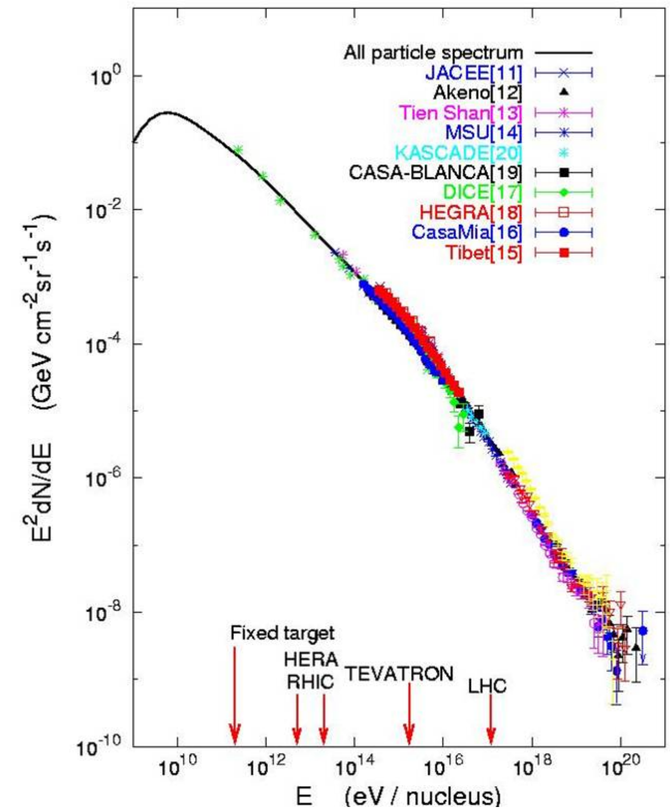
History of the CR

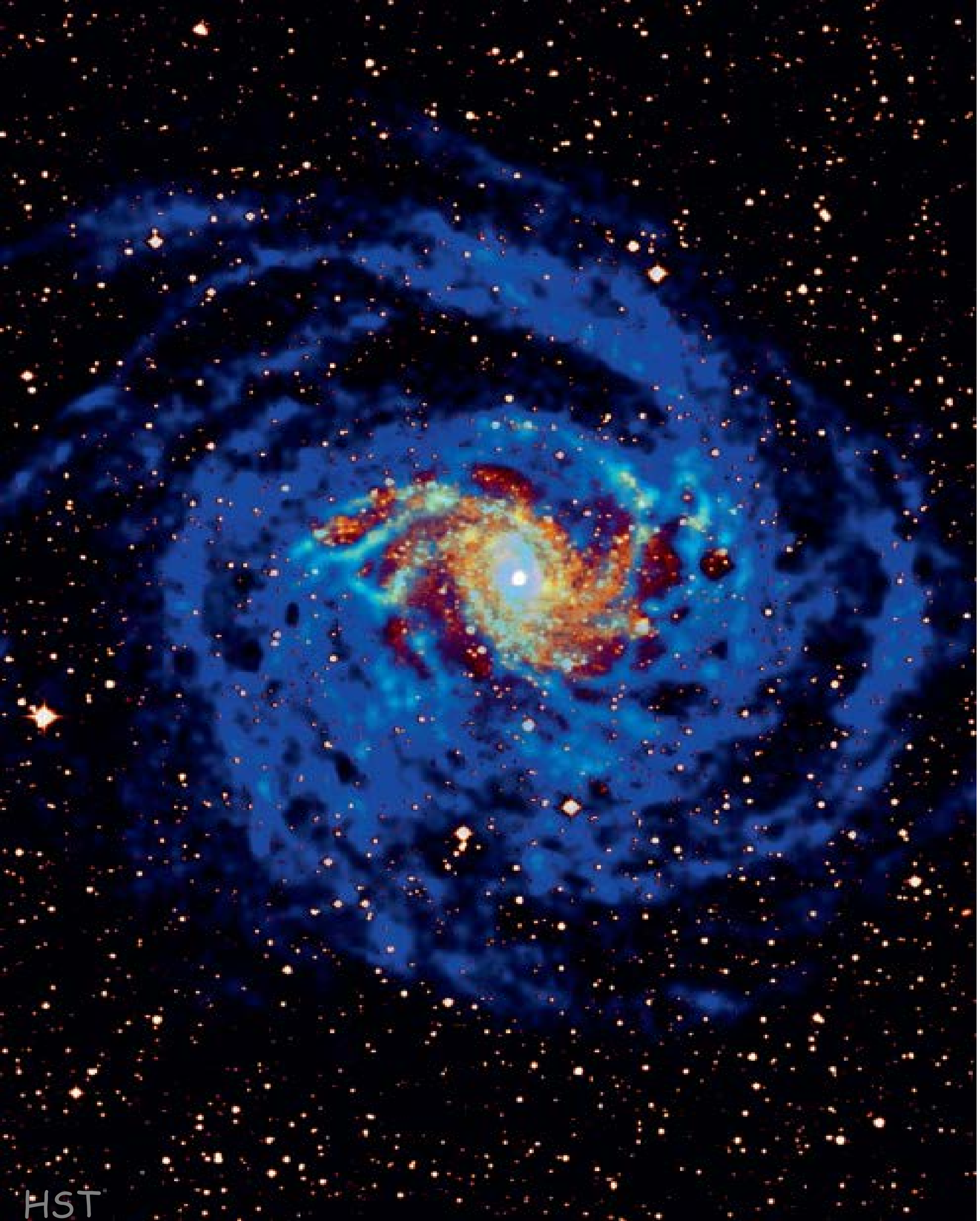
Sources

Observables

Acceleration in the sources

Transport in the turbulent magnetic fields





Acceleration of the Cosmic Rays

To accelerate…
… energy reservoir

Through mechanical collisions (kinetic energy)

- ✦ Translation (shock, moving clouds)
- ✦ Rotation (pulsars, black holes, neutron stars)

Through gravitation

- ✦ Accretion…

Through electro-magnetic interaction (EM)

- ✦ turbulence, compression, magnets rotation…

In the interstellar medium the matter density is too faint to tranfer the energy with a simple shock.

➔ Interaction is produced thanks to EM fields

We will speak about shock waves, but they are non-collisional shocks.

Energy transfer

The particles gain energy mostly thanks to the EM fields.

$$\vec{F}^{em} = q\left(\vec{E} + \vec{v} \otimes \vec{B}\right)$$

(Lorentz force)

➔**Acceleration of charged particles only!**

Photons, neutrons and neutrinos from CRs are, then, secondaries and they are produced during the interaction of the protons or ions with the surrounding medium.

E and B fields in the Universe

1- Electric field E

In the interstellar medium <E> ~0 (ISM is neutral and conductive)

+ transient fields (magnetic reconnection during solar activity)

2- Magnetic fields B

Hyper important

$$\varepsilon_B \approx \varepsilon_{RC} \approx \varepsilon_{CMB} \approx \varepsilon_{opt} \approx 1eV/cm^3$$

Omnipresent: interstellar medium, stars, accrection disks, jets etc…

Sources: large scale mouvements of the ionized medium

→ magnetic fields generation, magnetized clouds…

ISM turbulence

→ magnetic turbulence, B inhomogeneties, plasma waves…

E and B fields in the Universe

$$\varepsilon_B \approx \varepsilon_{RC} \approx \varepsilon_{CMB} \approx \varepsilon_{opt} \approx 1eV/cm^3$$

$\Rightarrow$ Energy exchange between individual particles and macroscopic structures can be very efficient

$\Rightarrow$ Some particles can gain very high energies

➔ Original idea proposed by Fermi en 1949

Magnetic field and acceleration

How it is possible?
B fields never work!

$$\vec{F} \perp \vec{B}$$

Variable B fields

Maxwell-Faraday law

$$\nabla \otimes E = -\frac{\partial B}{\partial t}$$

$\Rightarrow$ transient E field generation
$\Rightarrow$ energy transfer to the particles

Thanks to relativity

Reference frame change:

$$\vec{E}' = \gamma.\vec{v} \otimes \vec{B}$$

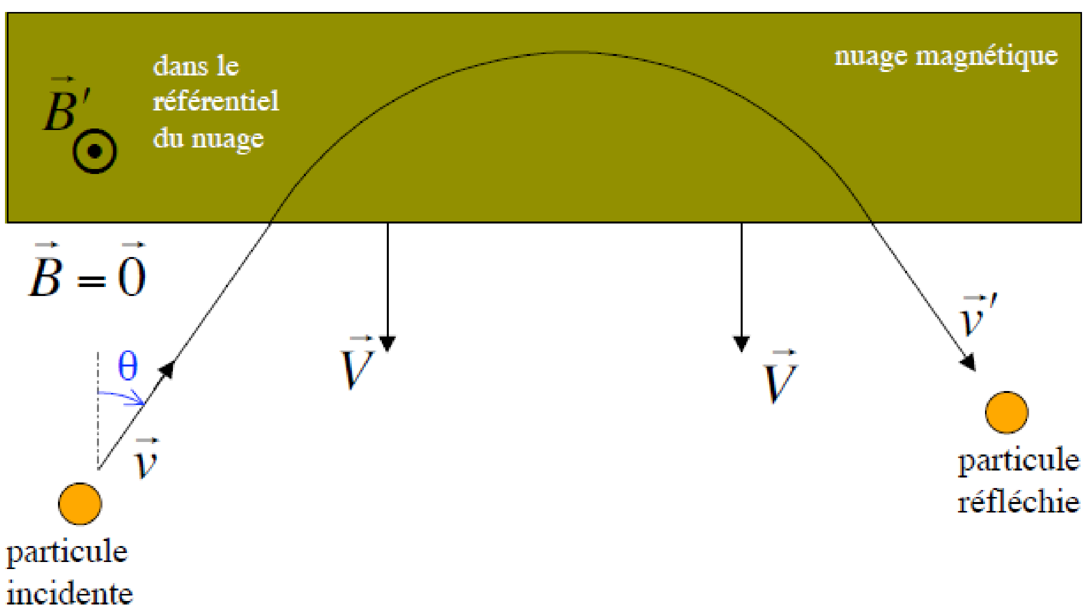
$\Rightarrow$ pure B mixed with E in an other frame!

Fermi acceleration illustration

Charged particles trajectories:

- Withoud B → straight line
- With B → curved

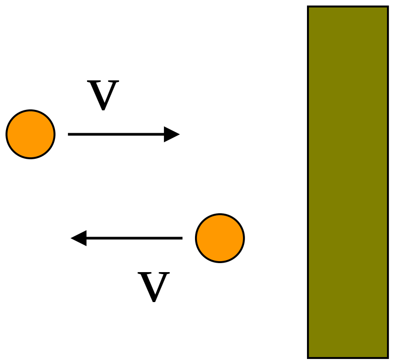
Magnetic mirror example:



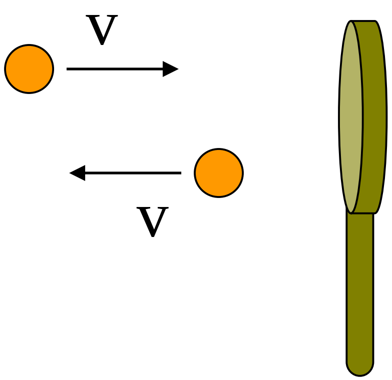
Simple analogy

<u>Tennis ball bouncing against the wall</u>

No energy loss, no gain



Bounce = no speed change

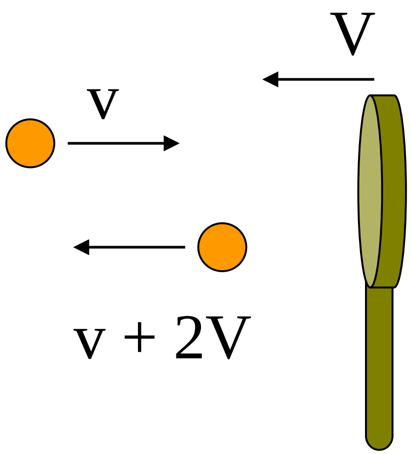


The same for the fixed tennis racket.

How to accelerate the ball and play tennis?

Moving Racket

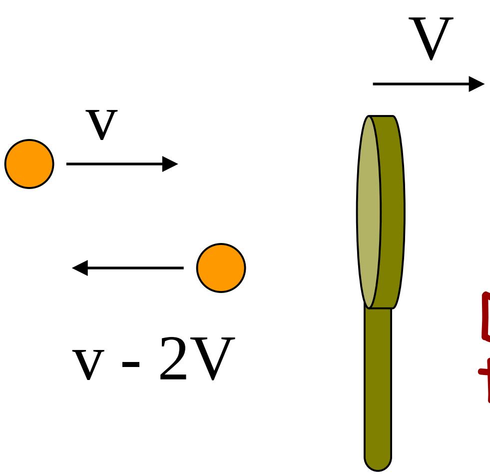
No loss or gain… in the racket frame!



No speed change respect to the racket

→ acceleration due to double reference frame change

Amortization



Deacceleration of the particles…

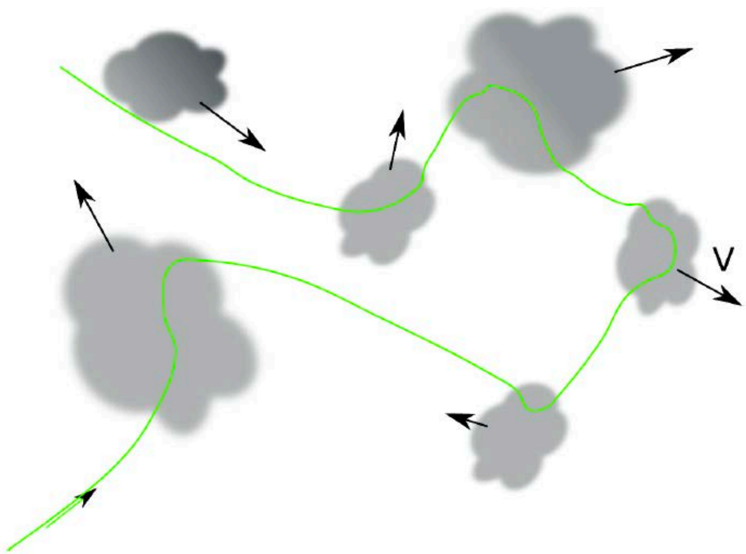
Stochastic Fermi acceleration

Charged particles **interacting with magnitized clouds** (in chaotic movement in ISM) which can reflect them,

When a particle is reflected by the approaching magnetic mirror **(head-on collision)** it gains the energy

When a particle is reflected by the escaping mirror (head-tail collisions) it looses the energy

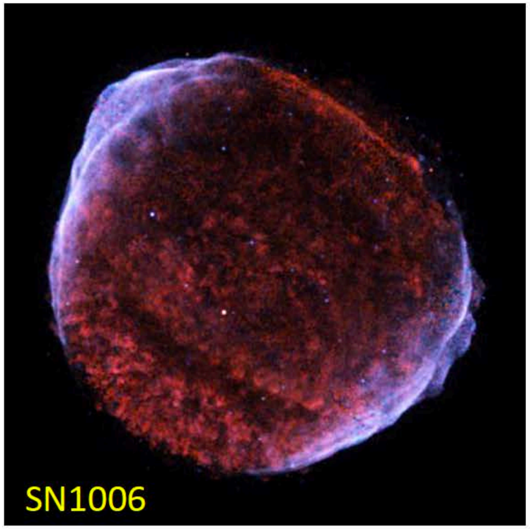
The head-on collisions are more frequent than the head-tail collisions

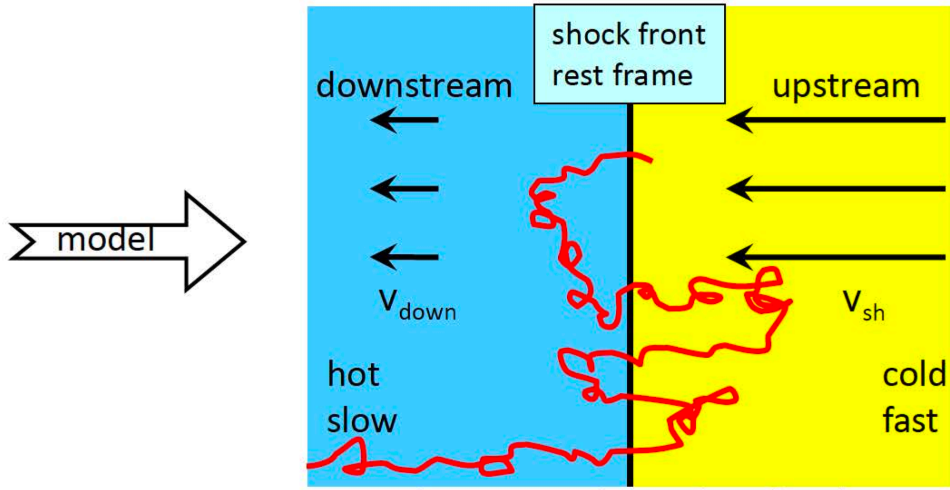


⇒ Energy gain in average $\propto V^2$ (stochastic process)

⇒ Distribution $\propto E^{-2}$

Particule acceleration in SNR shock waves





Diffusive shock acceleration particles are accelerated as they bounce back and forth in the upstream and downstream regions and always approach plasma moving toward them

1st order Fermi acceleration in the front of SNR:
- Universal acceleration mechanism: depends only on few parameters (magnetisation, shock velocity, composition)
- Very efficient in the energy transfert: typically ~10% of the shock energy is transferred to the RC
- Provide a quasi universal power law distribution with the same energy content per energy decade (in log)

Accelerator types

By the field structure:

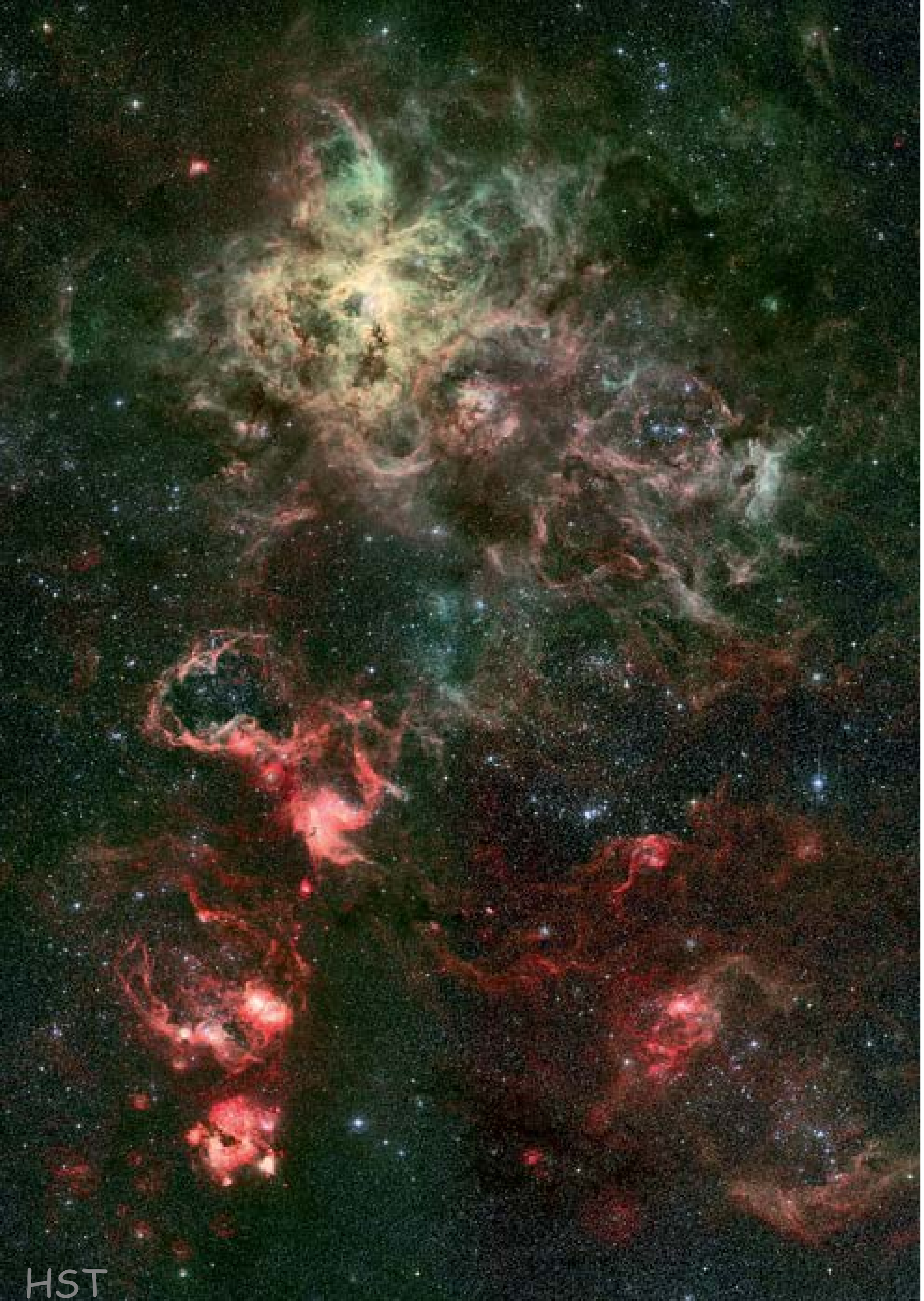
- **Stochastic** (chock waves, turbulent plasma).
- **Unipolar** (Strong magnetic fields: neutron stars -> pulsars, magnetars…). Similar to linear accelerators?!

By the accelerated particles:

- **Leptonic** (accelerate mostly electrons):
- **Hadronic** (accelerate protons and nuclei)

Acceleration + trapping time + energy losses + abundance of particles to accelerate.

Depends on the magnetic field strength and configuration as well as matter density. Mixed acceleratos?



Cosmic Rays transport from a source to the Earth

An unexpected journey: across the Earth atmosphere

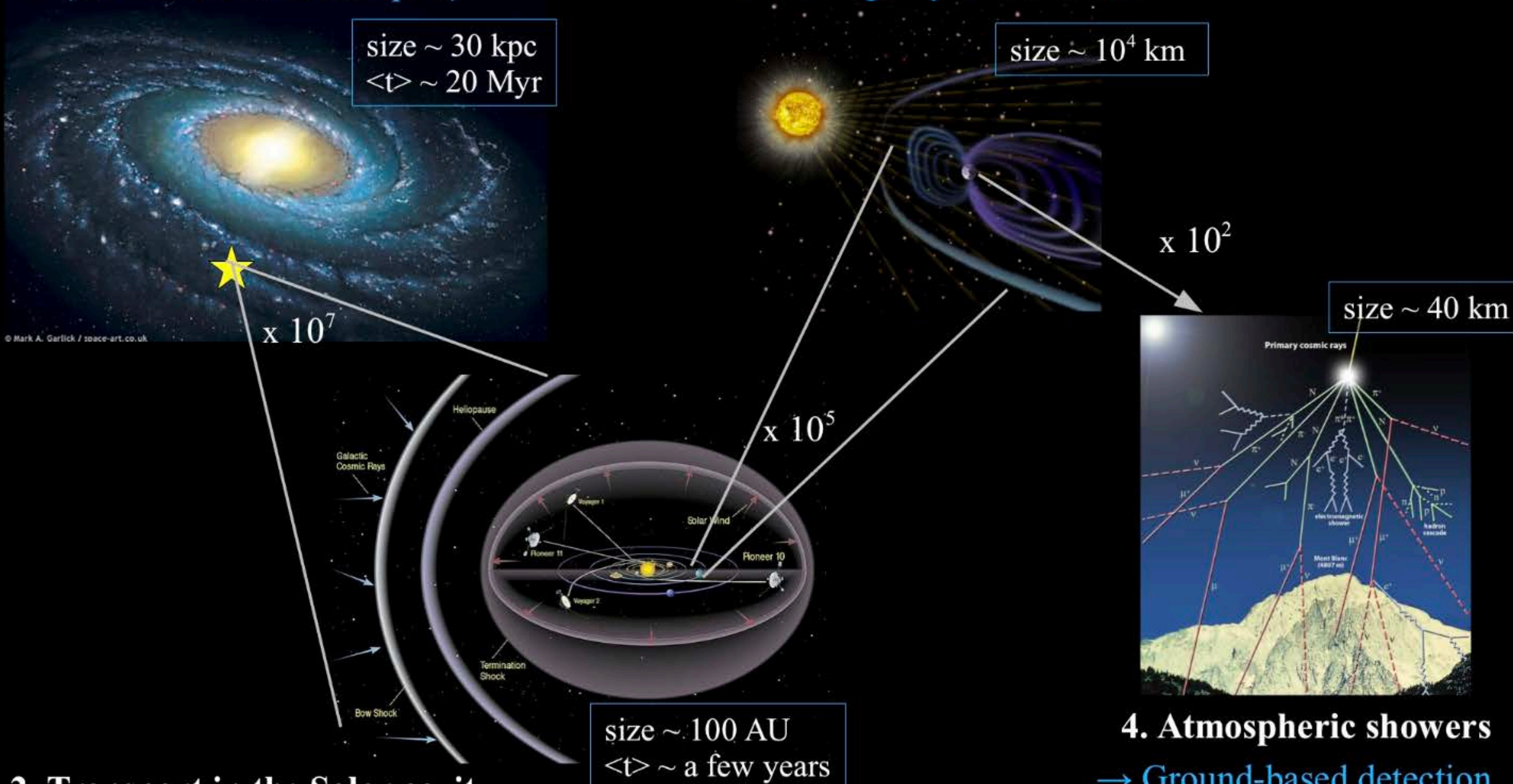
From David Maurin

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

3. Earth magnetic shield

→ Cut-off rigidity for detectors



2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n

→ time dependence

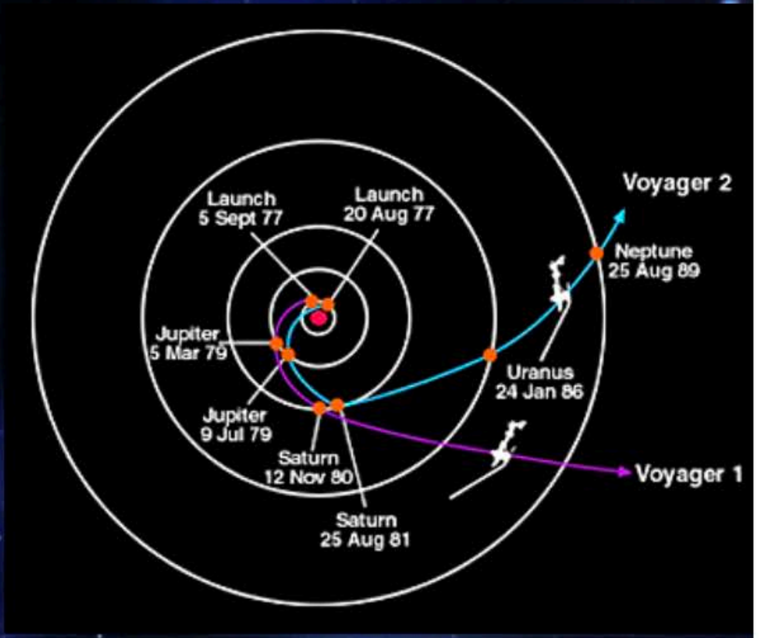
4. Atmospheric showers

→ Ground-based detection

→ Solar activity monitoring

[N.B.: Čerenkov flash ~ 10^{-8} s]

Voyager



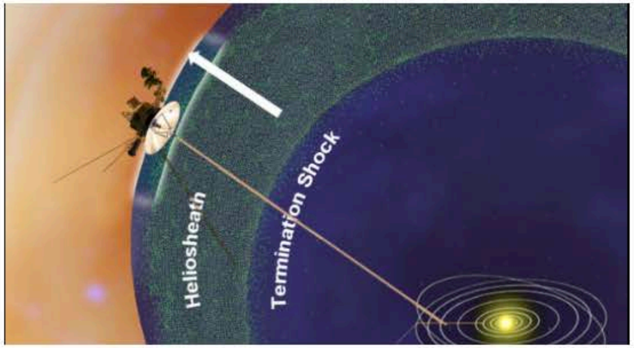
- Voyager 1&2 launched in 1977
- **Used the gravity slingshot method to catapult itself to the furthest planets and eventually beyond the Heliosphere.**
- Payloads still active…**cosmic ray telescopes (CRS) measure the Low energy CR intensity for almost 40 years.**

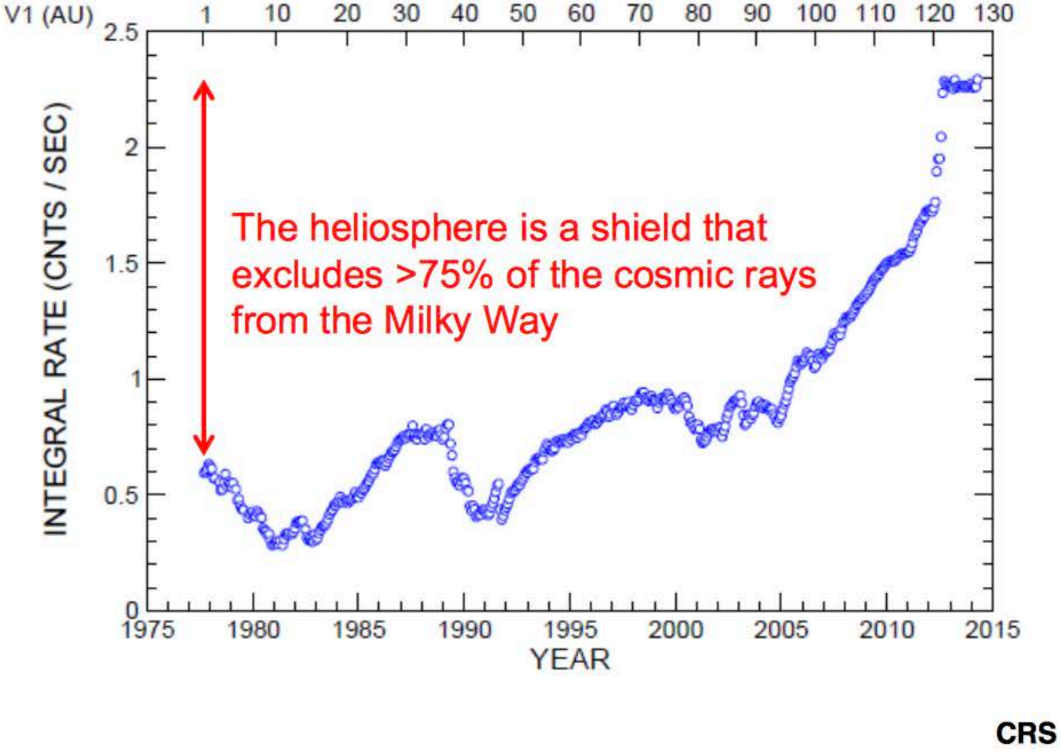
Voyager 1

Measures CR intensity as it travels to the interstellar space:

Variation due to:

- 11-years cycles due to solar activity
- Global rise as Voyager go out from the sun.

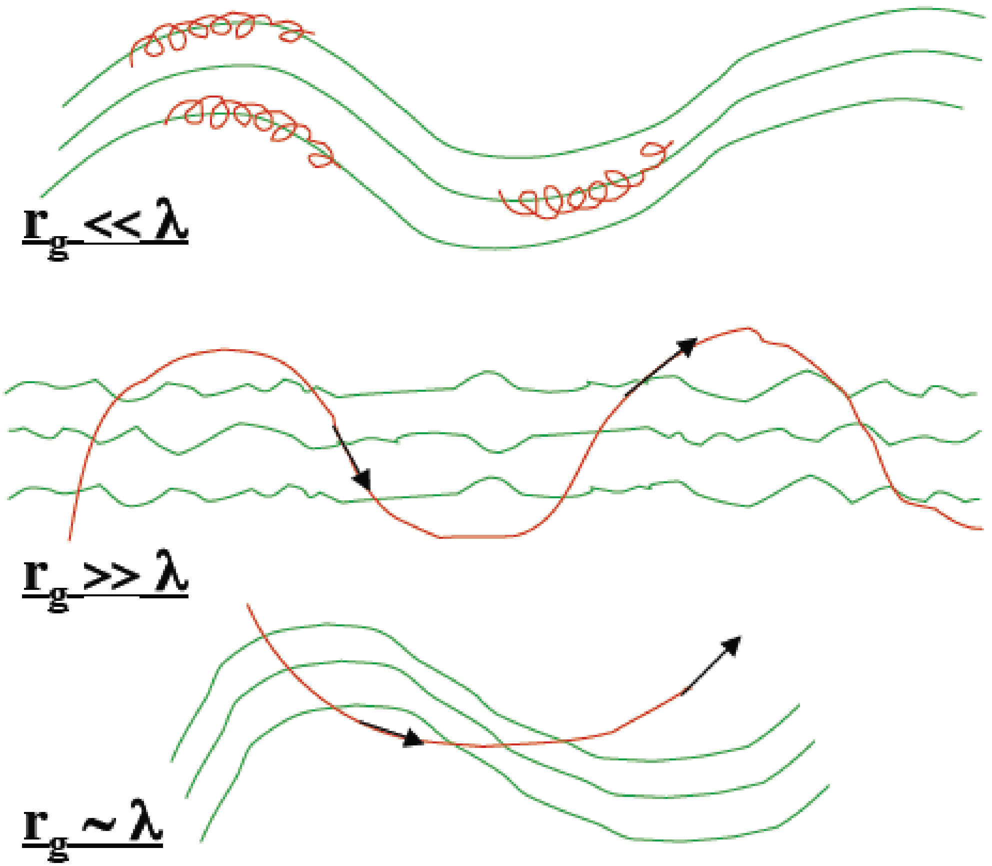




On August 2012, Voyager 1 reached interstellar space at 121 AU.

Cosmic rays transport

Magnetic fields



B field irregularities permit CR acceleration and transport

However, they also limit CR propagation (energy losses)

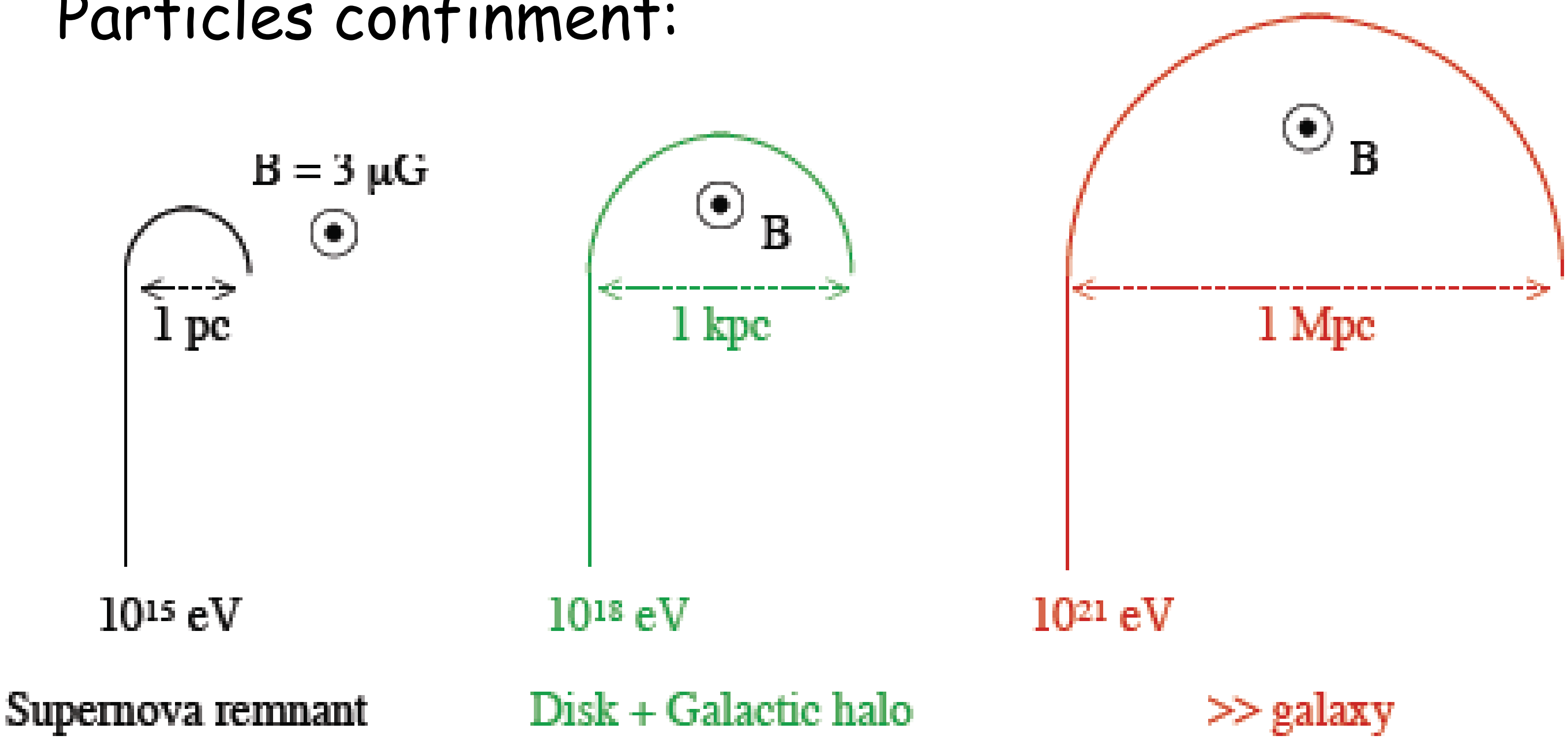
Non straight-line propagation!

With B ⇒ trajectory is curved with gyroradius defined by:

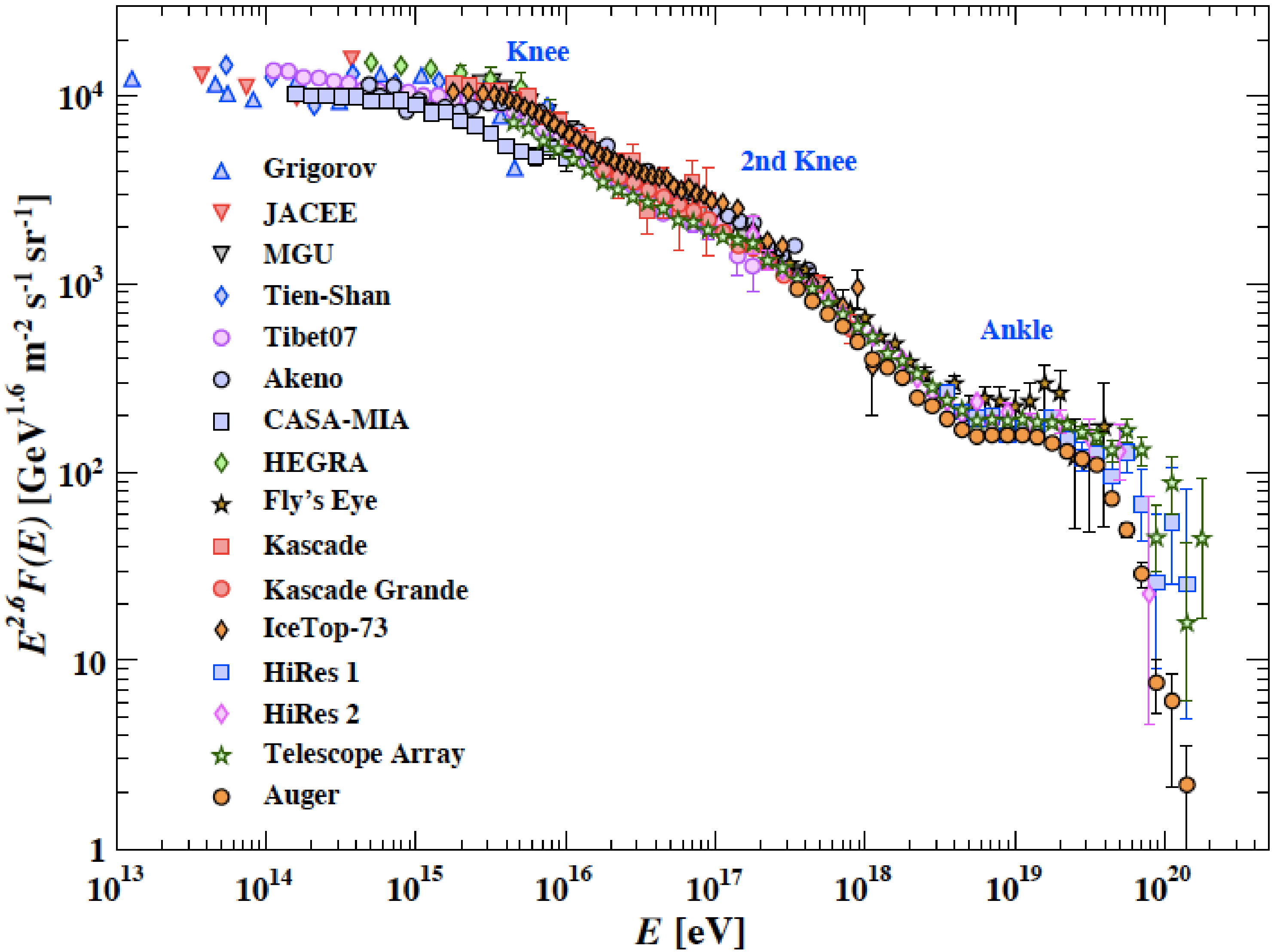
$$r_L(E) = \frac{P}{ZeB}$$

$$\left(r_L[pc] = \frac{E_{15}[10^{15}\,eV]}{B[\mu G]Z} \right)$$

Particles confinment:



Hints on the CR origin



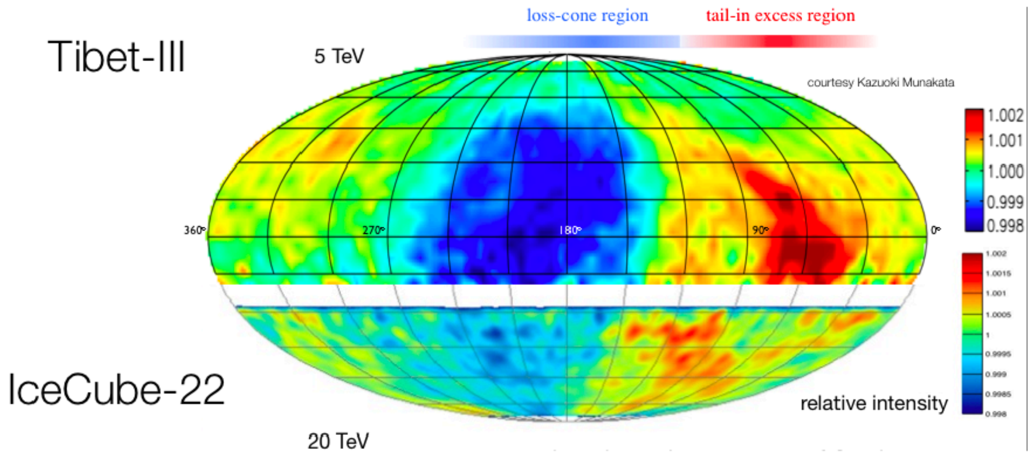
Hints on the CR origin

Changes in the spectral index may indicate a transition in the acceleration or connement mechanism and/or composition.

- The knee is postulated to be an upper limit associated with the acceleration mechanism for galactic cosmic rays
  - Can diffusive shock acceleration in supernova remnants reach this energy?
  - Does the knee have anything to do with particle transport or escape?
- Cosmic rays above the ankle are extragalactic in origin
  - Gyroradius is comparable to size of galaxy

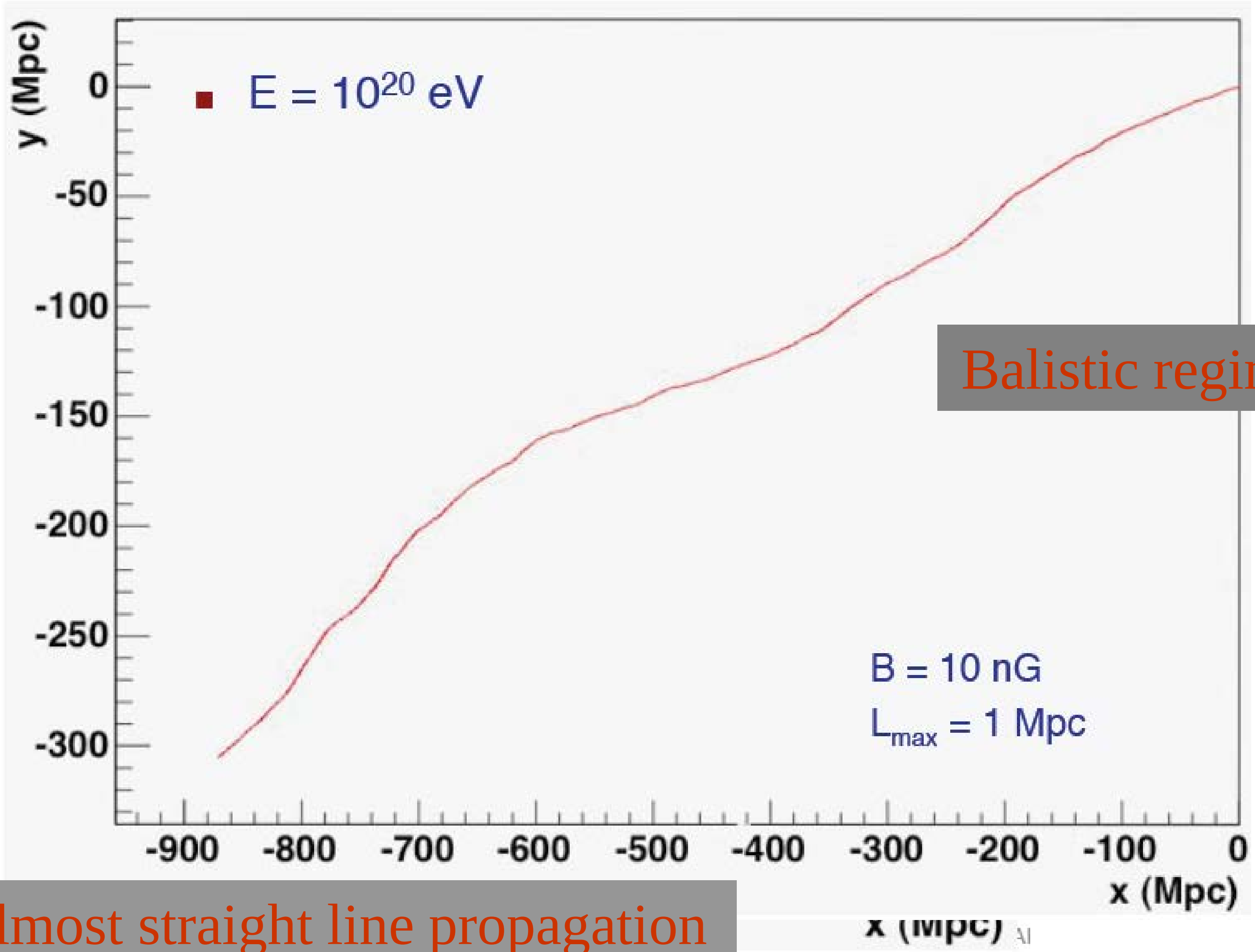
- Neither the knee nor the ankle is well-understood

CR Isotropy below the knee



- Below $\sim 10^{14}$ eV, cosmic rays are highly isotropic
- Cosmic rays propagate along field lines in galaxy
- Propagation and confinement make it difficult to determine source regions
- Scattering and diffusion play an important role
- Weak anisotropy (above) is not well understood

CR trajectories



Balistic regime

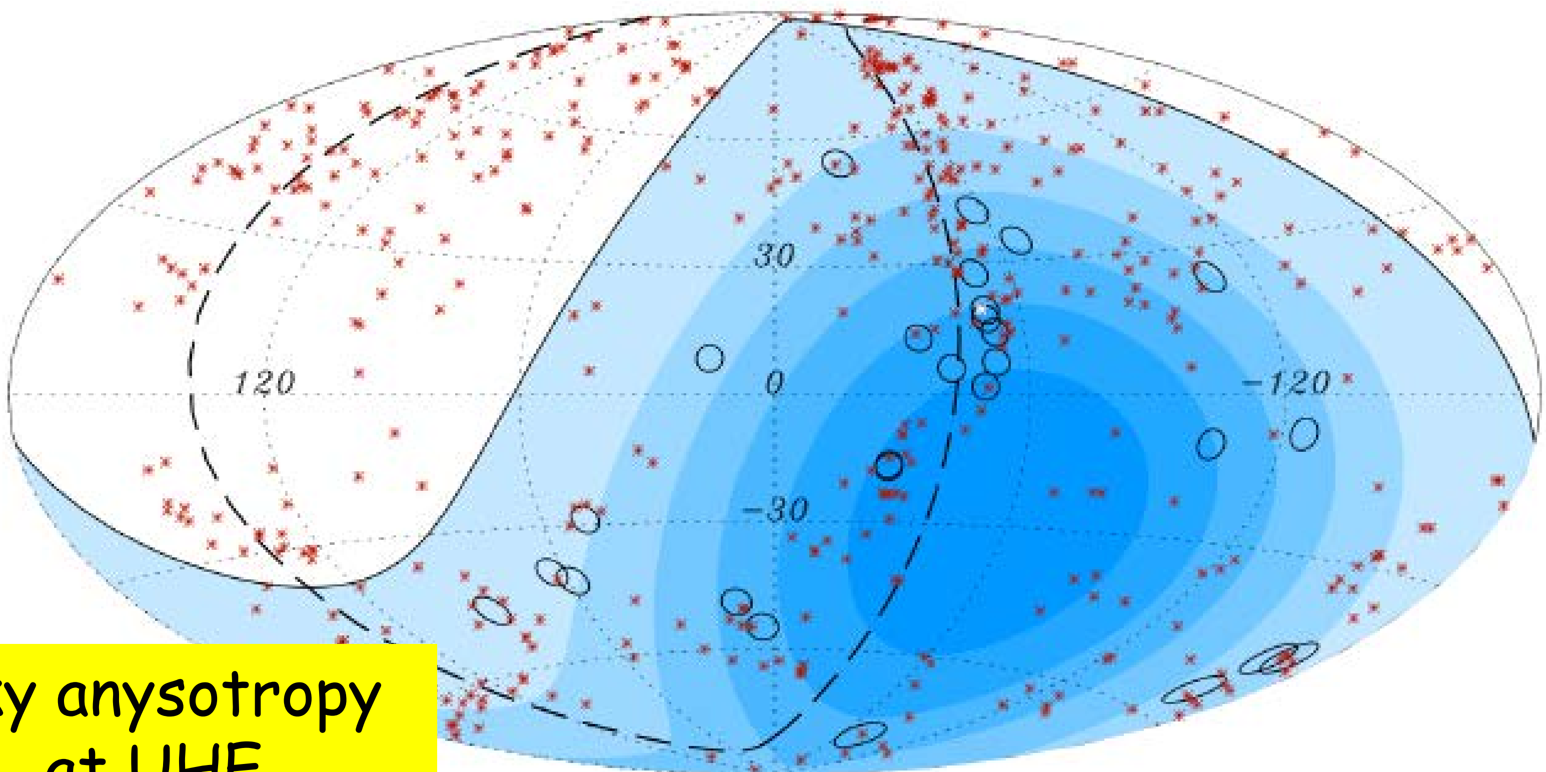
se

ne

Almost straight line propagation

First steps to the astronomy without photons

Detector: Observatoire Pierre Auger (Argentine)
(surface ~3000 km²)



Sky anysotropy
at UHE

Cosmic ray sources

CR are accelerated inside the astronomical sources and the propagated to us

⇒ The sources are mostly Galactic at 10-100 PeV (confinement)

At higher energies they should be extragalactic

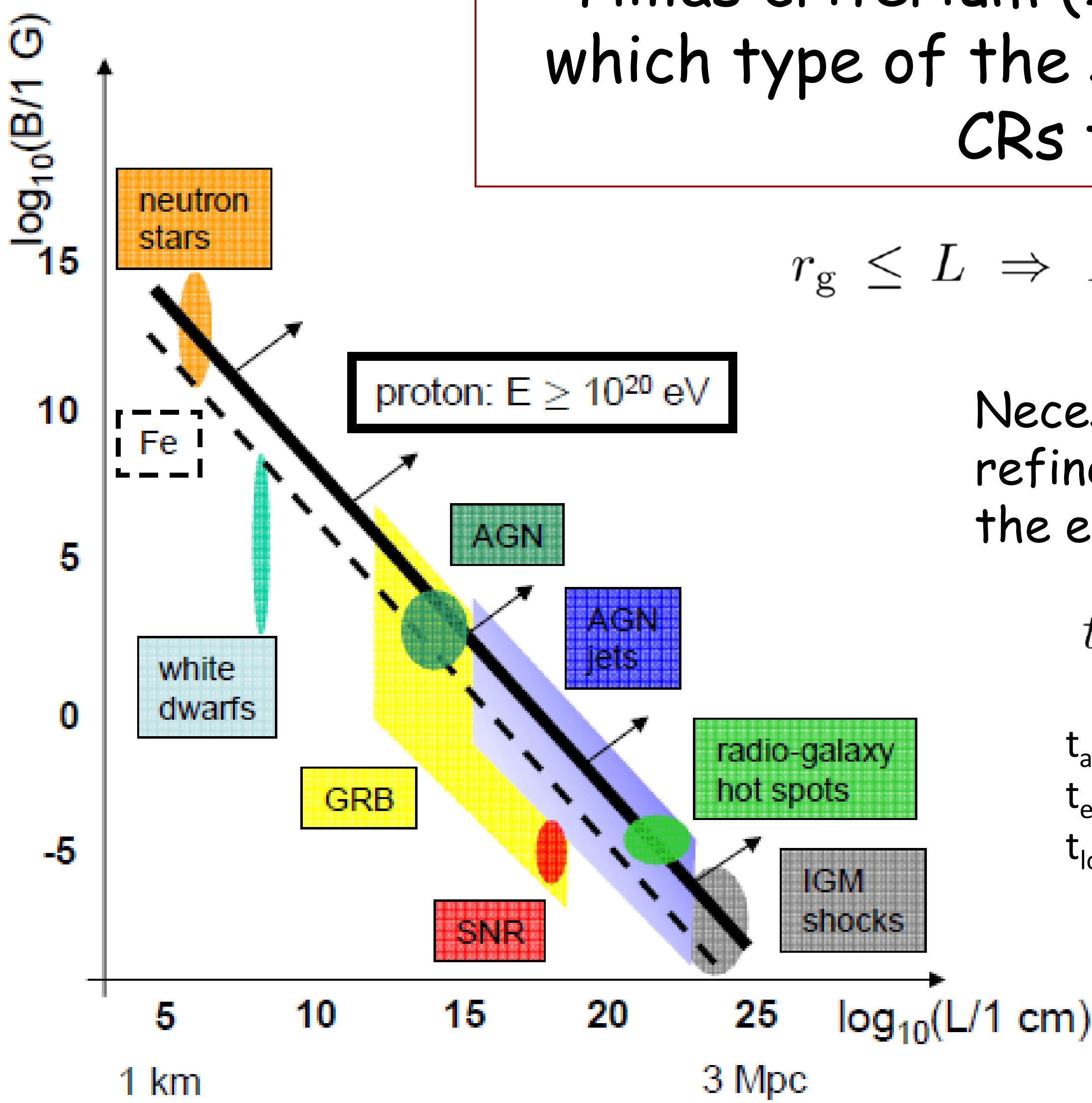
⇒ CR are accelerated in the source until they are confined.

⇒ UHE CR source: extremely magnetized.

⇒ Maximum energy: compromise between acceleration, escape probability and energy lossses.

Sources possibles

Hillas criterium (1984) allows identify which type of the sorces can accelerate CRs till UHE



$$r_g \leq L \Rightarrow E \leq 10^{20}\,\mathrm{eV}\, Z\, B_{\mu G}\, L_{100\,\mathrm{kpc}}$$

Necessary but not sufficient, to refine, need to take into account the energy losses

$$t_{acc} \leq t_{loss},\quad t_{esc}$$

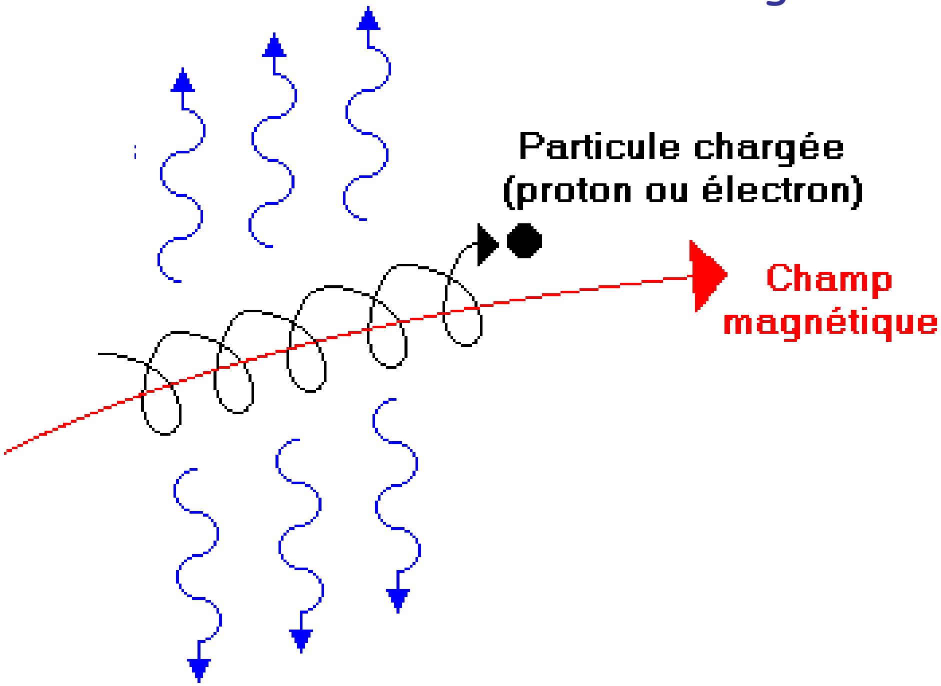
t_{acc} depends on acceleration mechanism...
t_{esc} depends on magnetic field...
t_{loss} depends on environment...

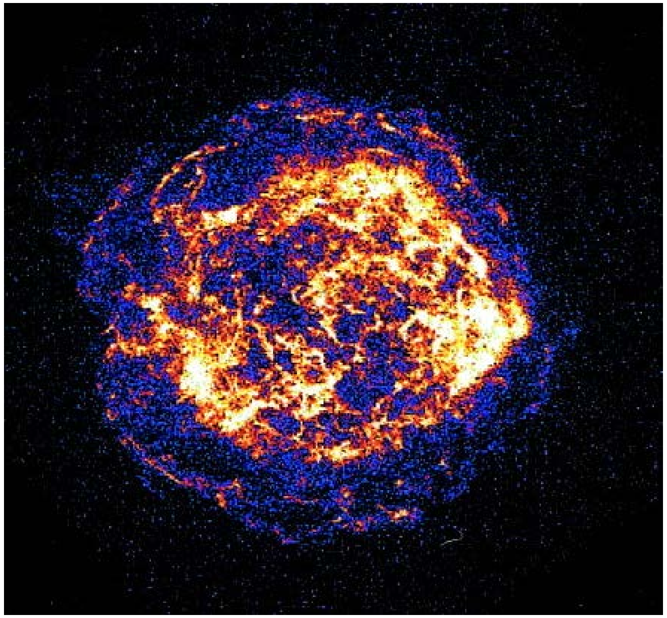
Energy losses

1) Charged particles + Magnetic field

→ synchrotron radiation

Photons emission in all wavelengths: radio, optique et X



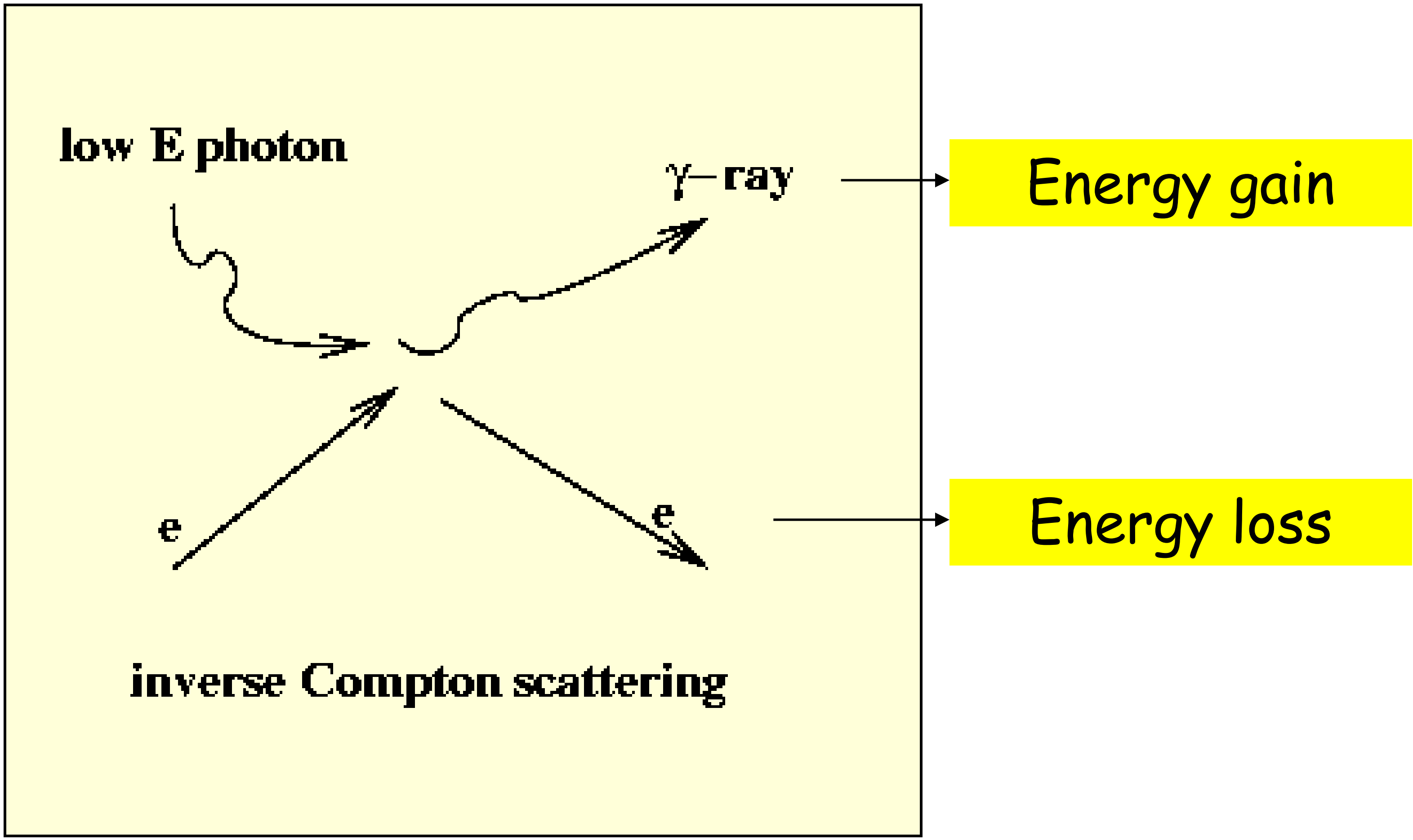


Cassiope A (chandra)

Very efficient to cool low energy electrons.

Energy losses

2) Interaction electron-photon (Inverse Compton process IC)



Energy losses

3) Interactions with matter (thick sources):

$$p + p \rightarrow p + p(n) + a\pi^0 + b(\pi^+ + \pi^-)$$

⇒ Production of the secondary particles (γ, ν, n, e+…)

Interactions with photons:

$p + \gamma \rightarrow p + e^+ + e^-$ pair production

$p + \gamma \rightarrow p(n) + \pi$ pion production

$A + \gamma \rightarrow (A\text{-}1) + p(n)$ nuclei photodisentegration

$$\Rightarrow \begin{cases} \pi^0 \rightarrow 2\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu, \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} \end{cases}$$

Secondary particles detection:

- photon γ HE → Fermi (LAT) satellites, HESS, CTA (Tuesday)
- neutrino HE → neutrino telescopes, ANTARES, KM3NeT (Tuesday)

Hadronic/leptonic gamma emission model

Leptonic accelerator can produce gammas in following processes:

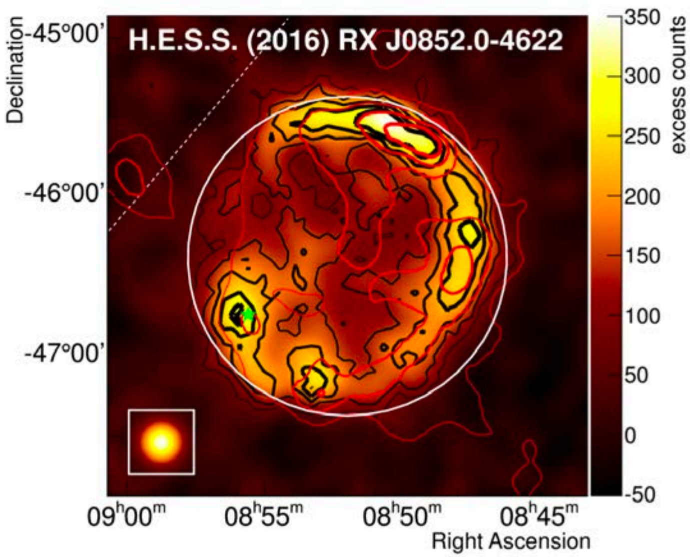
- Syncrotron radiation
- Inverse Compton

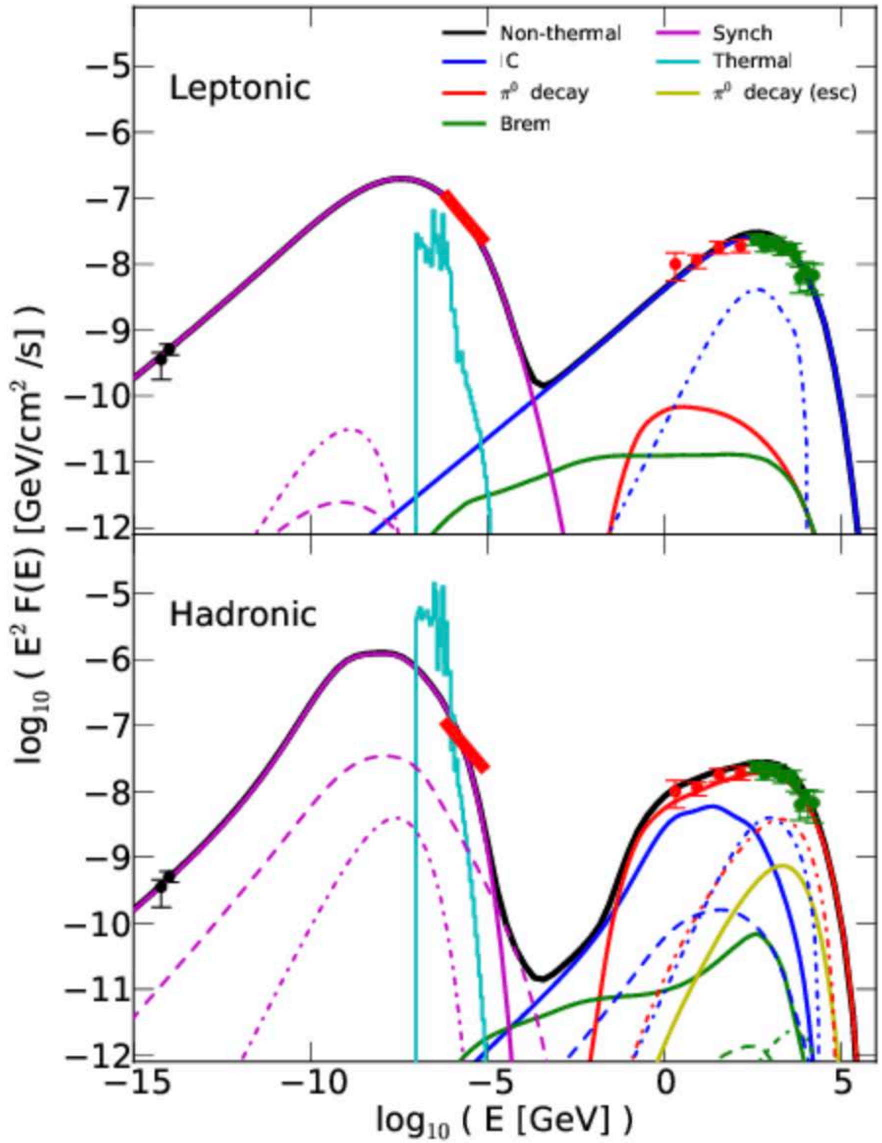
Hadronic accelerator can produce gammas in following processes:

- Interaction with matter
- Interaction with photons

Neutrinos can be produced only be Hadronic accelerator + target!

Hints of CR production in γ-ray flux





D. Dornic, Summer School 2019

Maximum CR energy

We don't know yet till which energies CRs can be accelerated…

HIRES measured one CR with 3 10^{20} eV

300 000 000 000 000 000 000 eV

… several joules – macroscopic energy

… tennis ball energy at 100 km/h

This is incredible!

Worse, this is impossible!!!

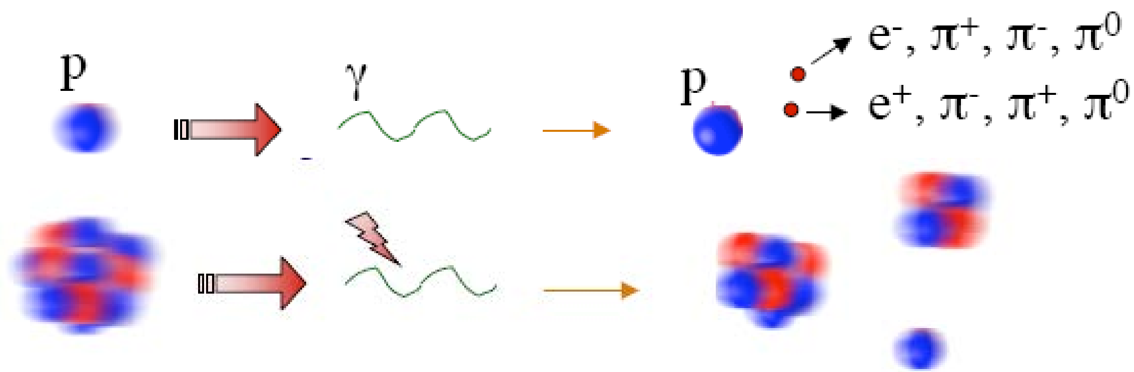
due to microwave background…

GZK effect

1965, Penzias and Wilson: Cosmic Microwave Background discovery (backround at 2.7 K)

The Universe is full of photons, very cold and numerous: 400 par cm^3.

These photons are inoffensive, since their energy is very faint… untill we crash on them with the full speed!



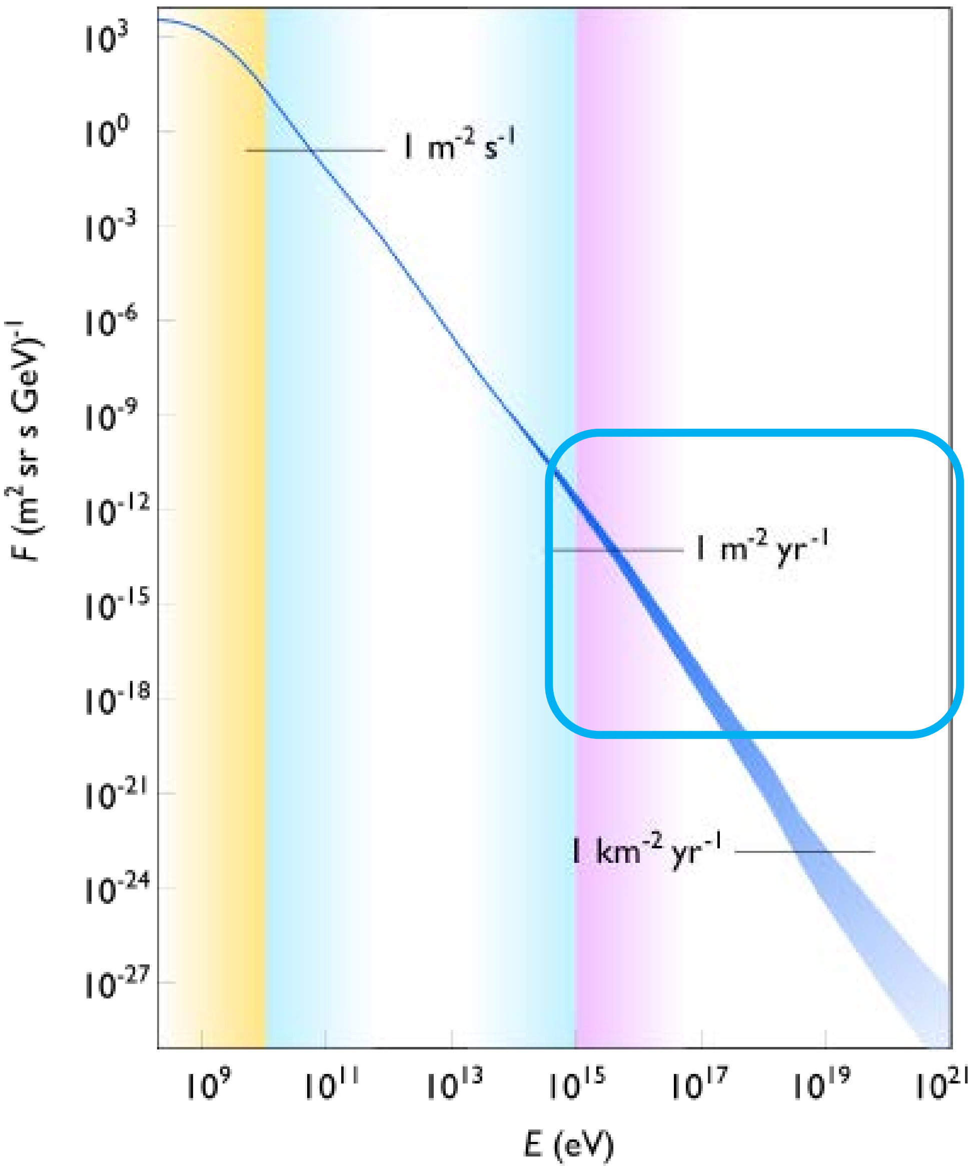
Greisen, Zatsepin and Kuzmin (GZK) understood that protons with energies above 10^{20} eV cannot arrive from too far

10^{20} eV : distance less than 100 Mpc (300 millions al)

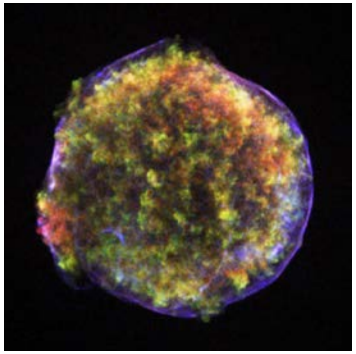
3 10^{20} eV : less than 15 Mpc (50 millions al)

Possible sources of cosmic rays

Possible sources



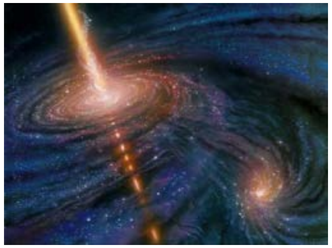
→ Low and high energies



Galactic sources???
(Supernovae, microquasars...)

Transitional area.
Few powerfull galactic sources??

→ Ultra high energies?



Extragalactic sources (AGN??)

To an energy of 1-100 PeV:

→ Galactic sources: main suspect: supernova renmant:

Everything matches: energy, spectrum, composition, spatial distribution, non-thermic source observations , in-situ observation of acceleration…

Kinetic power of SNe : ~ 10^{42} erg/s
To renew RCs in the galaxy, we need : ~ 10^{41} erg/s
⟹ ~10% acceleration efficiency: ~OK

But, looking more in details, there are still some major problems

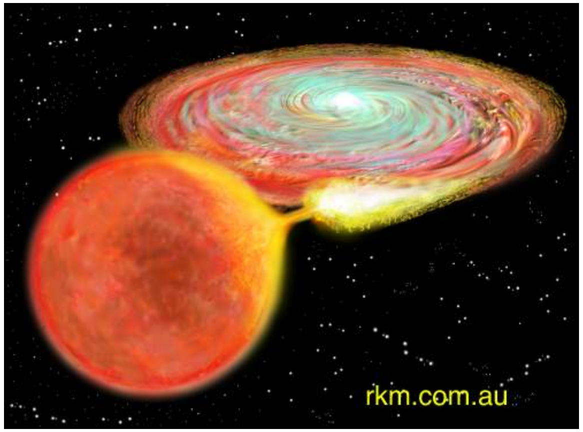
- Li, Be, B : don't work !
- Composition : neither !
- Anisotropy : bof !
- Isolated SN (observed in non-thermic) very few
- Observation of SNRs : E_{max} < 10–100 TeV

⟹ Possible young SNR, but… not a « smoking gun » !
Other possible sources: young pulsars?, Magnetic reconexion? Galactic Center ? Others?

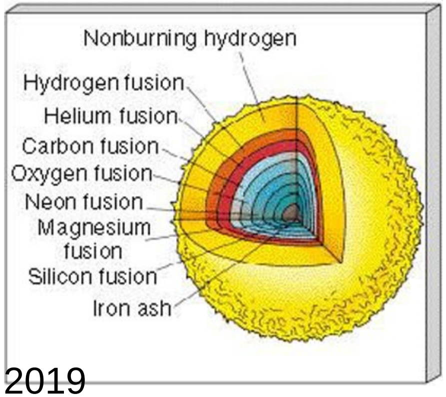
Supernova and its remnant

SN explosion: 2 ways:

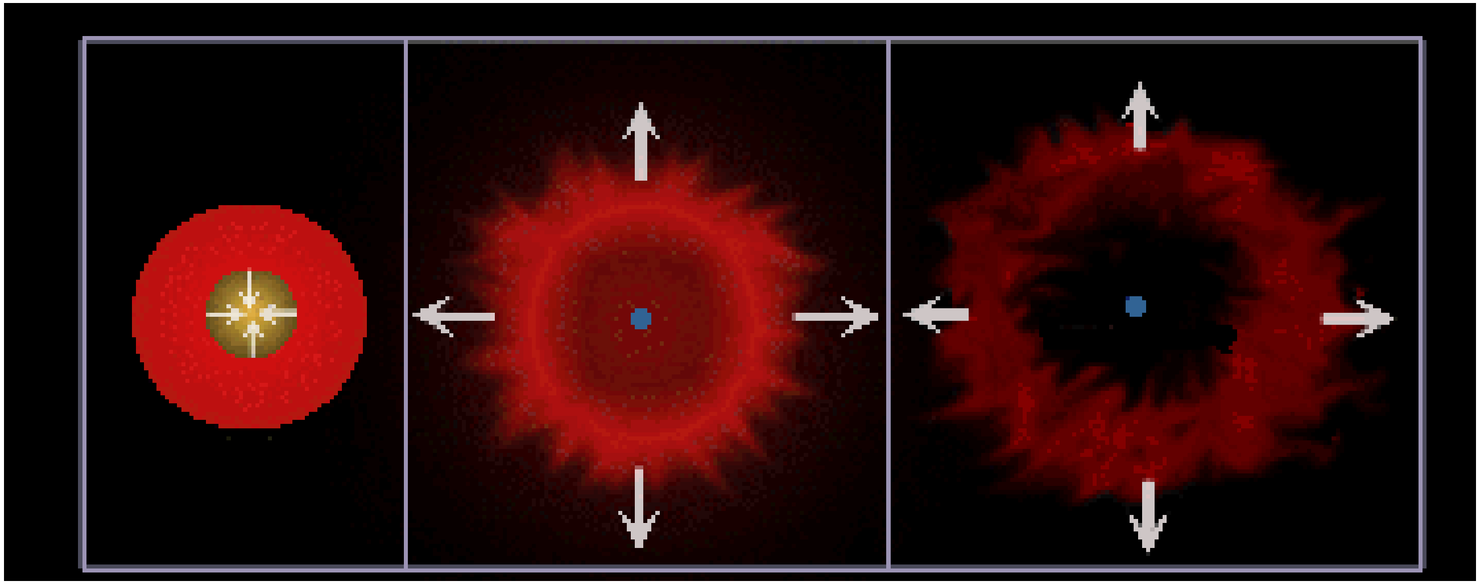
1) Explosion of a white dwarf after accumulating the matter from the companion star in the binary system (thermonuclear SN)



2) Gravitational collapse of the massive star ($>8M_0$)



Supernova and its remnant



Implosion Supernova Residual

Strongly non-spherical process!

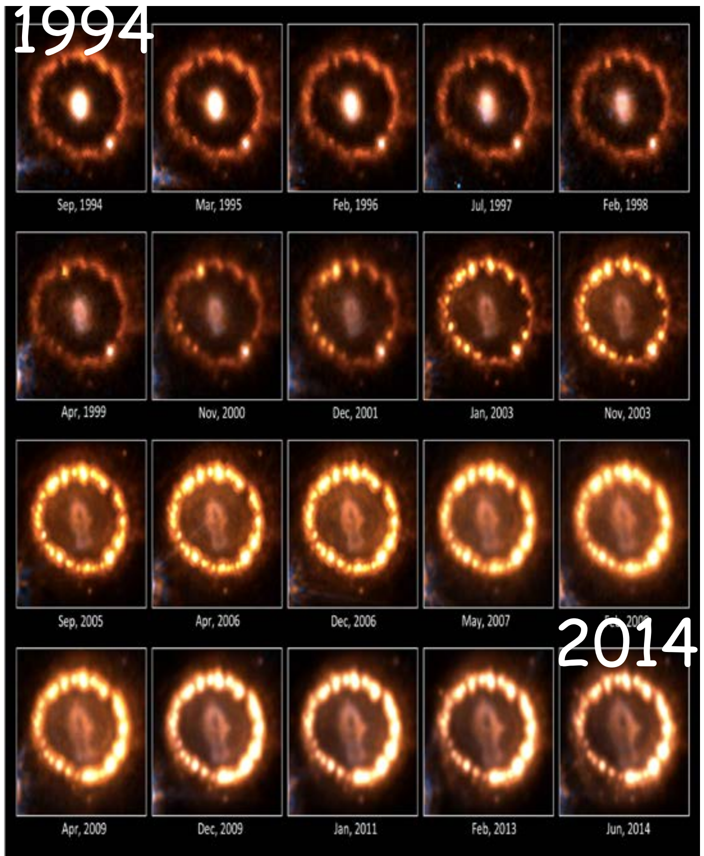
Neutrinos are very important:

- Carry out 99% of the energy
- The core is opaque to neutrinos for several seconds.
- Neutrino driven explosion mechanism?

Supernova and its remnant

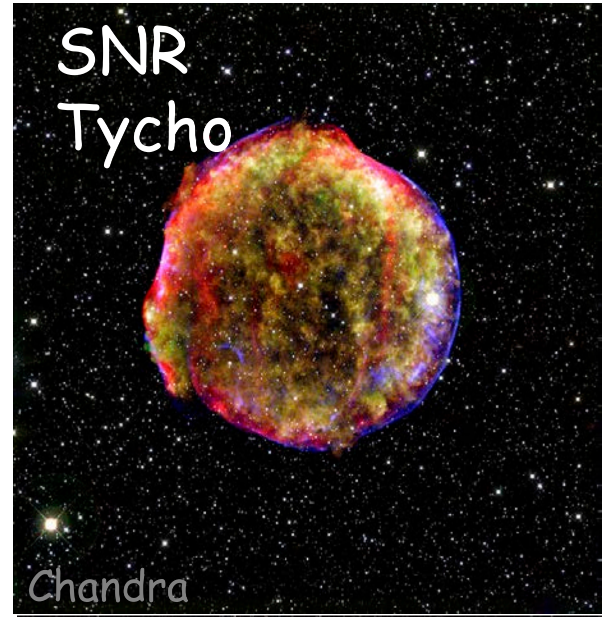
SN1987A transforming towards SNR
Expanding shock hits the matter and hits it to the plasma state.

UV/soft X-.-ray Flash and recombination



Ejecta hits ISM/circum-stellar medium

Molecular clouds around SN – **target**.

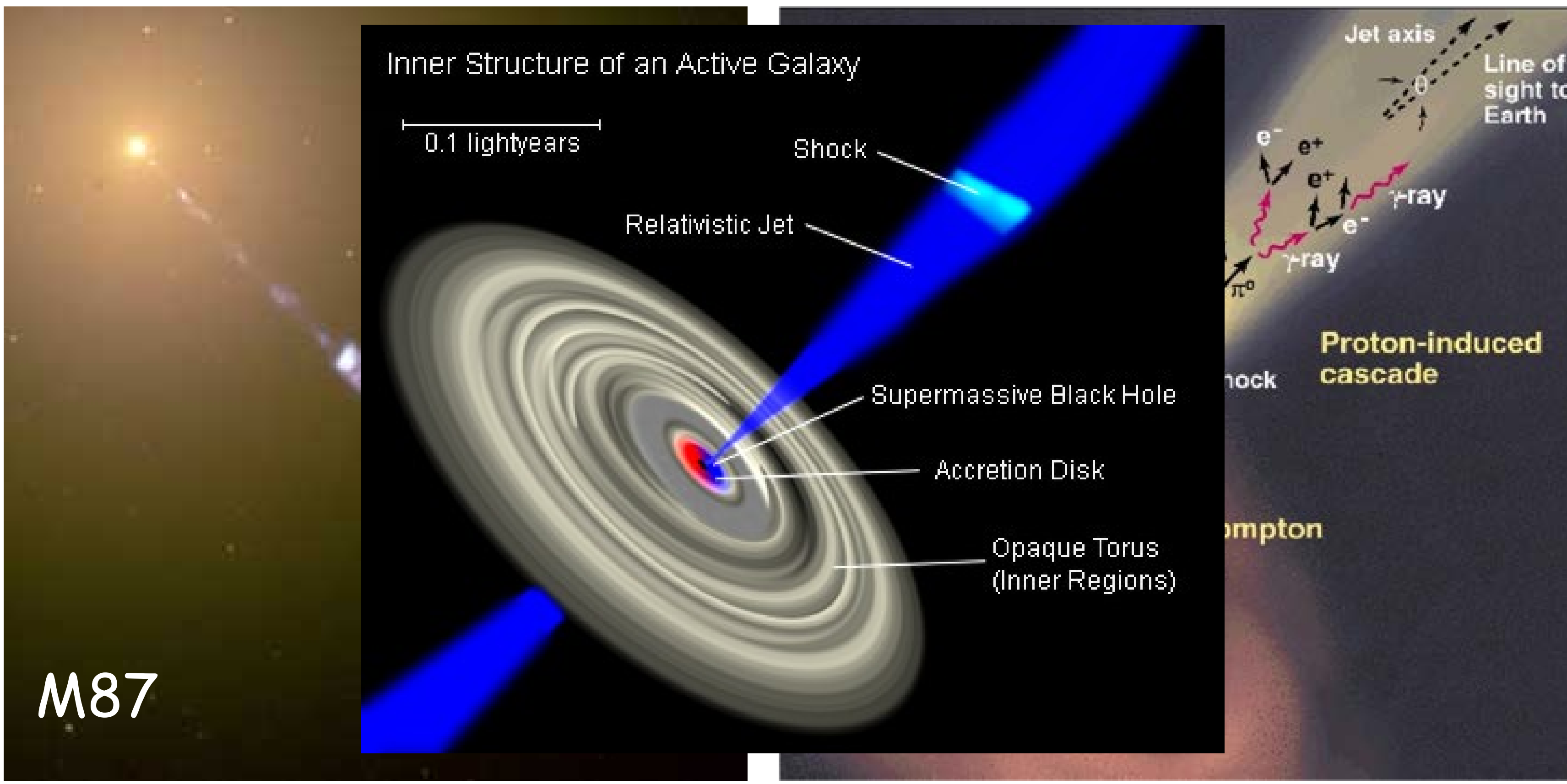


Active Galactic Nuclei

Some percents of the system of the galaxies

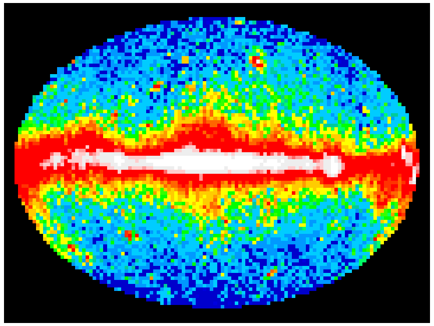
→ Accretion disk + jets

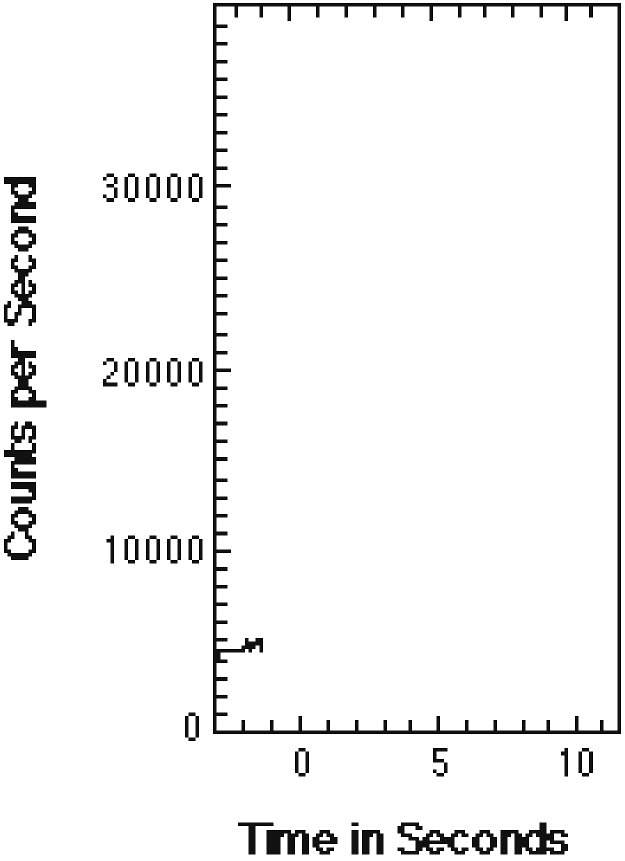
→ Cosmic accelerators: Blazars *(jet tow)*



Gamma ray bursts

Extreme and short photon flux increase in some particular direction.





CRs have a major role in the Universe

- Vertical support of ISM in galaxies

- Ionization and heating of ISM through collisions
  - Allows weak ionization in molecular clouds, protoplanetary disks, and the cold neutral medium
  - Impacts chemistry in the ISM and molecular clouds.
  - Low energy CRs (10 MeV) are most responsible for this

- Probable driver of galactic winds

- Responsible of the amplification of magnetic fields
  - Upstream and downstream of shocks
  - Cosmic ray driven dynamo

- Modification of astrophysical plasma processes
  Shocks, dynamos, jets, reconnection

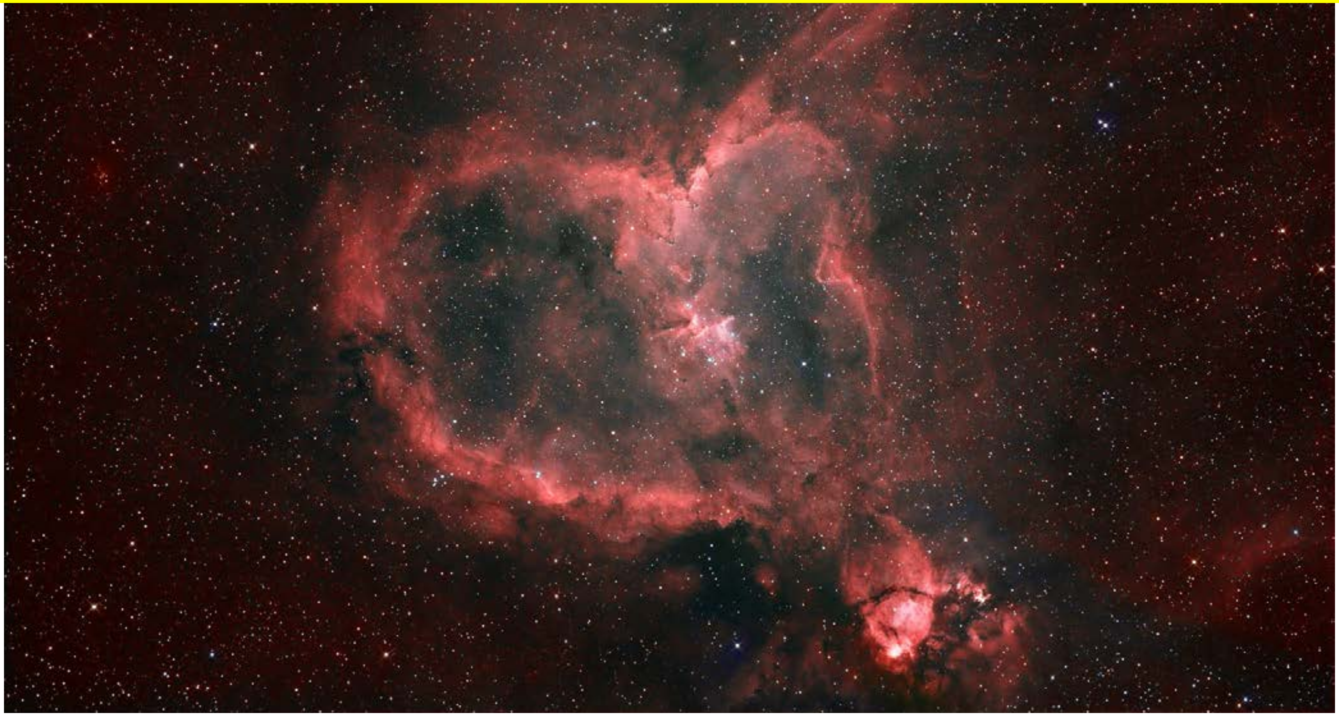
- Astro-chemistry: cosmic evolution (Li, Be & B)

Future

Ongoing observations: Auger, HAWC, HESS, MAGIC, VERITAS, Fermi, AMS, ANTARES, IceCube, LIGO…

Future CR Observations: CTA, KM3NeT, LHAASO…

Towards solving the puzzle of the origin of the CRs till ultra high energies.



CR effects on Earth

- Contribution to atmospheric chemistry
  - Production of 14C in the atmosphere through the neutron capture reaction: n + 14N → 14C + p (~70t in the atmosphere)
  - Historical spikes of 14C production (e.g., 774–775 CE) possibly due to cosmic ray events

- Source of background radiation

This is the cause of the airline pilots flight limitation

- CRs and SEPs are a health hazard for interplanetary space travel (in particular, outside of Earth's magnetosphere)

- Effects on electronics
  - Cosmic rays cause bit flips in the integrated cicuits (transistor/CPU)
  - Increases with altitude in atmosphere
  - Error correction schemes can mitigate these effects

- Role in lightning: runaway breakdown mechanism by CR secondaries