Astroparticle Physics
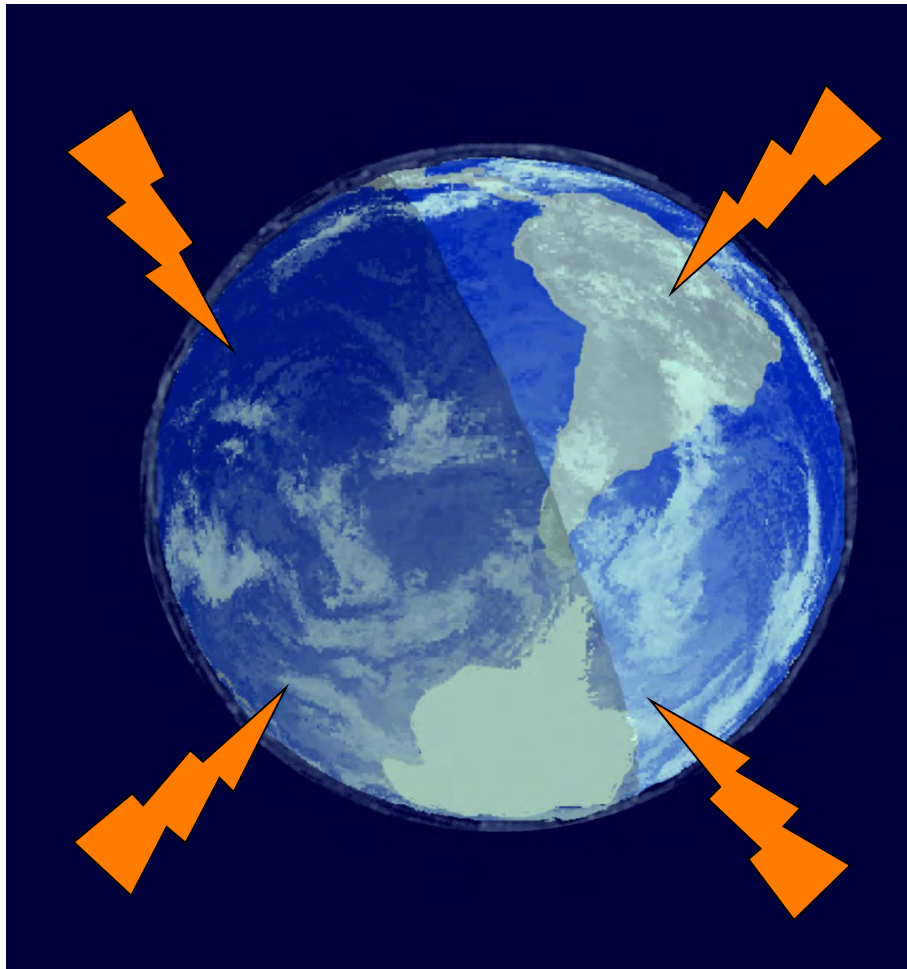
Lecture 1

• Introduction

• The data

• Sources of high-energy beams from space

Alessandro De Angelis
INFN-U.Udine/INAF/LIP-IST Lisboa

Lund, March 2013

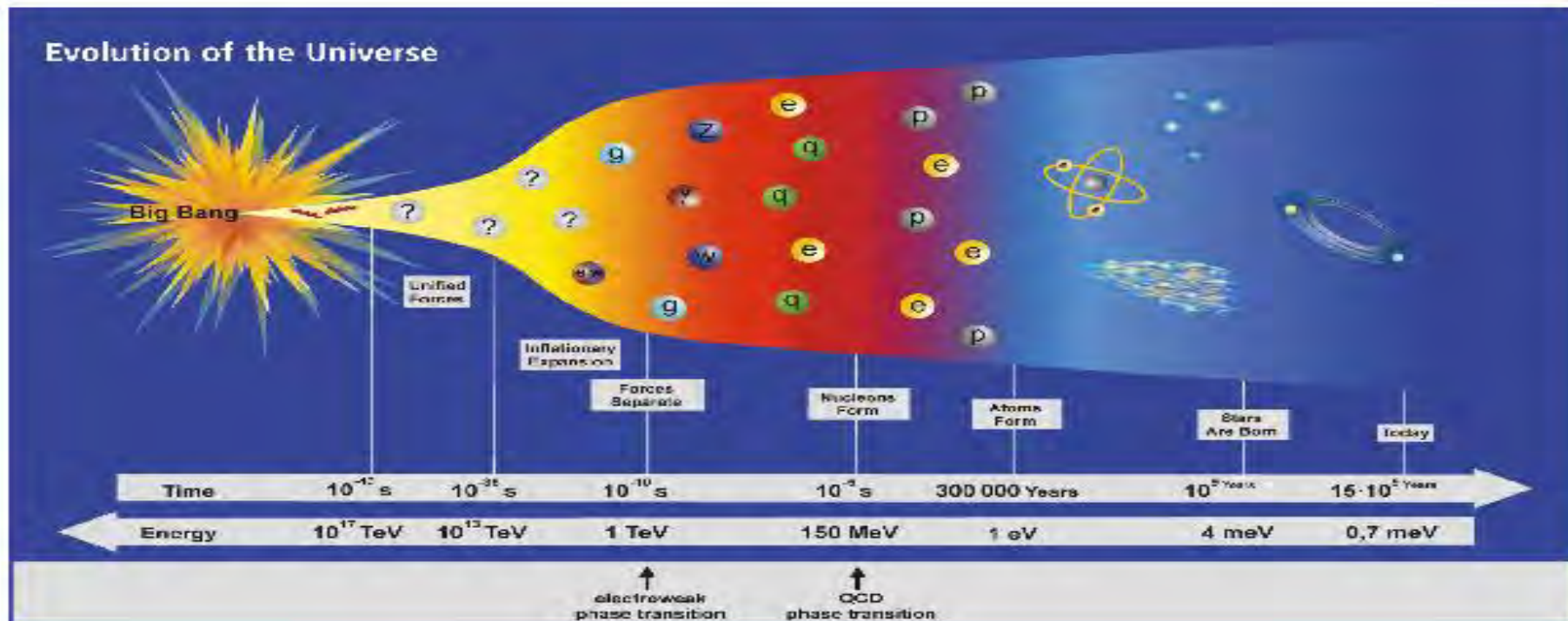# Messengers from the High Energy Universe

Photons

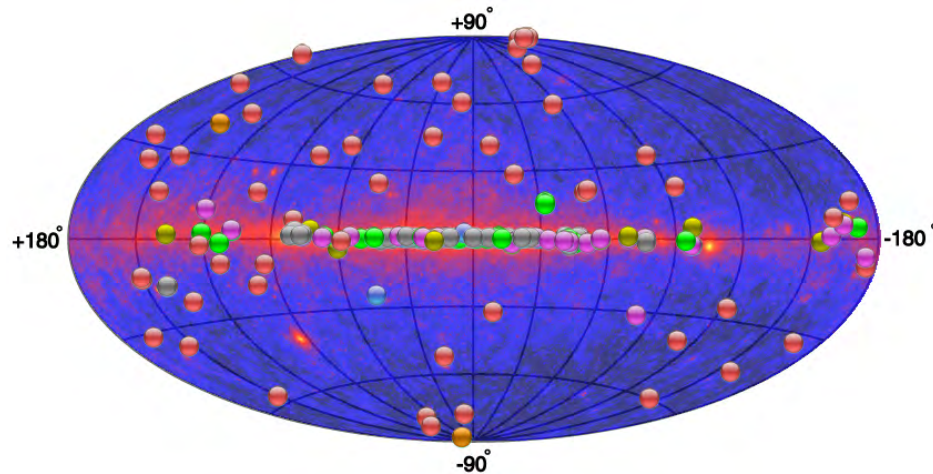Cosmic rays

Neutrinos

Gravitational Waves

???

The Physics

Evolution of the Universe

The Physics (γ, p/nucleus, ν, ? beams)

Astrophysics

Sources: AGNs, Pulsares, GRBs, SNRs…

Aceleration mechanisms, propagation

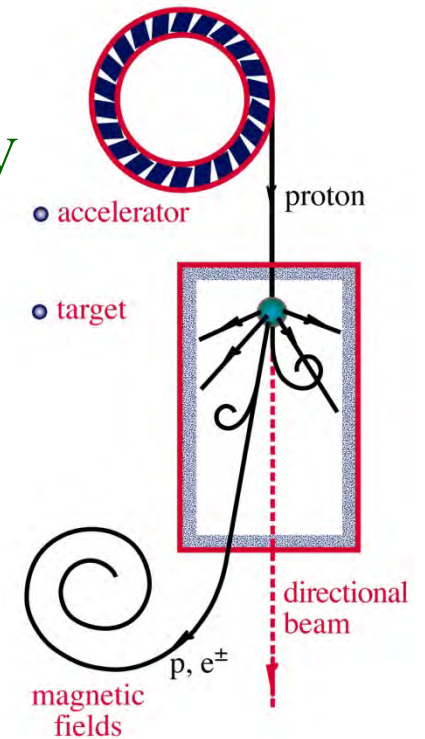γ sky > 100 GeV
Mar 2013

Particle Physics

High Energies

$\sqrt{s} \sim 100 - 400$ TeV
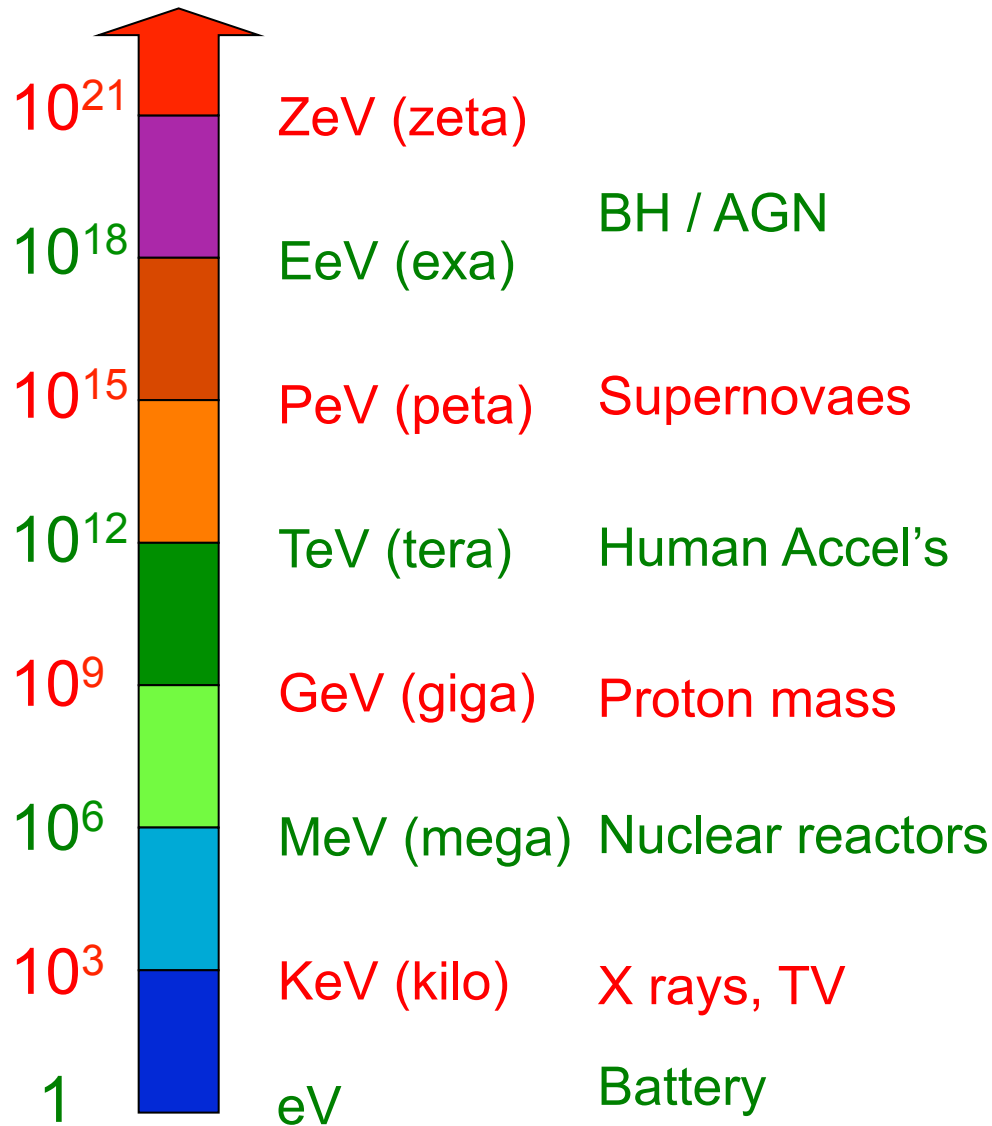
Low fluxes

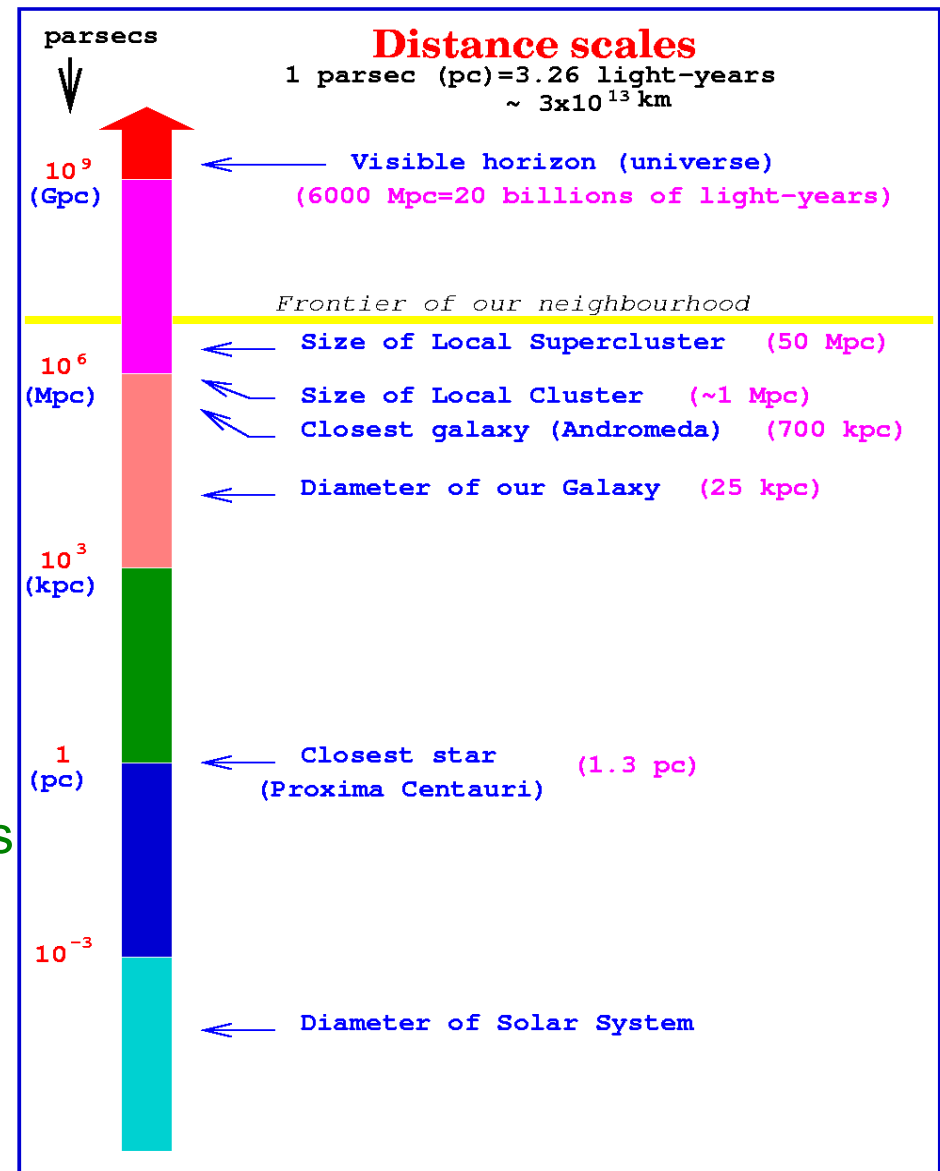Limited kinematic region

Poor detection capabilities

Cosmology/Fundamental Physics

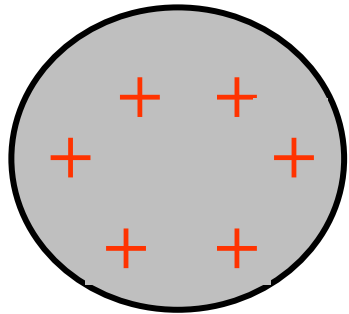Lorentz symmetry violation, extra-dimensions, dark matter, dark energy …

Energy scales

10^{21} — ZeV (zeta)

10^{18} — EeV (exa) — BH / AGN

10^{15} — PeV (peta) — Supernovaes

10^{12} — TeV (tera) — Human Accel's

10^{9} — GeV (giga) — Proton mass

10^{6} — MeV (mega) — Nuclear reactors

10^{3} — KeV (kilo) — X rays, TV

1 — eV — Battery

Distance scales

parsecs

Distance scales
1 parsec (pc) = 3.26 light-years
~ 3×10^{13} km

10^{9} (Gpc) ← Visible horizon (universe)
(6000 Mpc = 20 billions of light-years)

Frontier of our neighbourhood

10^{6} (Mpc) ← Size of Local Supercluster (50 Mpc)
← Size of Local Cluster (~1 Mpc)
← Closest galaxy (Andromeda) (700 kpc)
← Diameter of our Galaxy (25 kpc)

10^{3} (kpc)

1 (pc) ← Closest star (1.3 pc)
(Proxima Centauri)

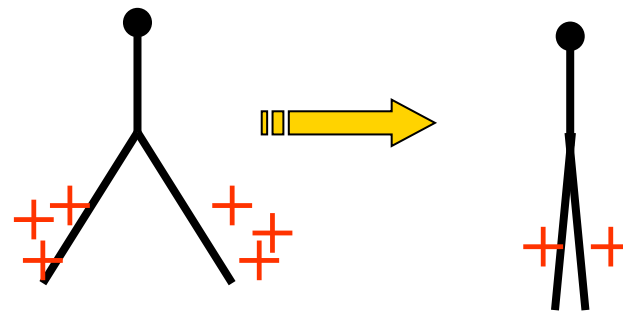10^{-3}

← Diameter of Solar System

THE BEGINNINGS

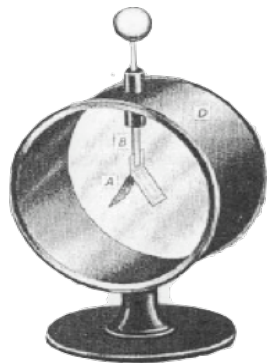# Free electrical charges in the atmosphere

Coulomb, 1785

Spontaneous discharge of charged conductors ...
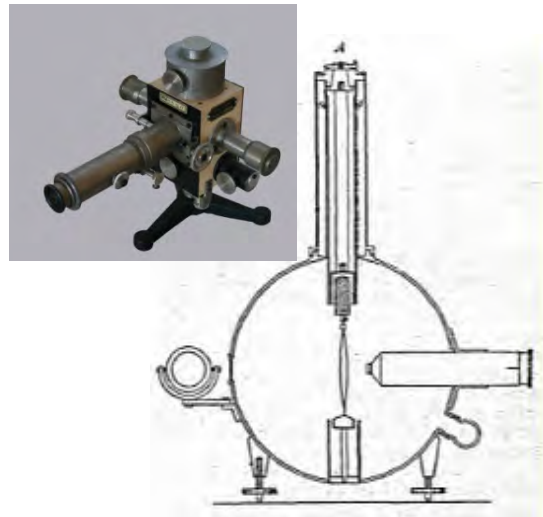
End of XIX century

Curie: Radioactivity ?

Making good electroscopes

The two friends Julius Elster and Hans Geiter, gymnasium teachers in Wolfenbuttel, around 1900

Theodor Wulf, German Jesuit teaching in Holland and in Roma, perfected the electroscope in 1908-09, making it transportable
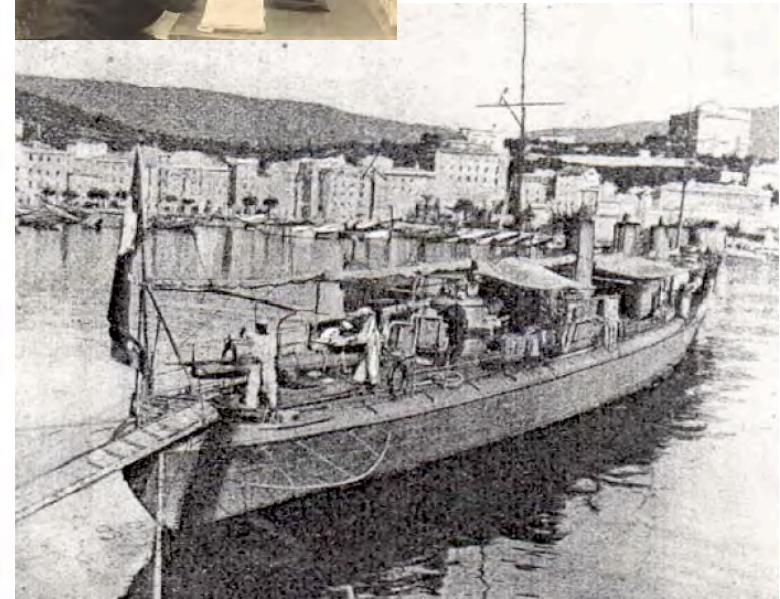
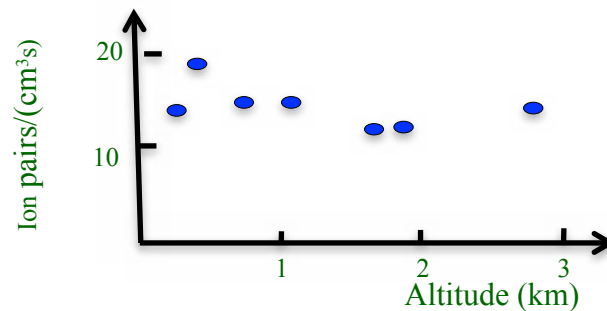# By sea and by sky

Wulf
1909-1910

Gockel 1909

Domenico
Pacini1911

Results
not
conclusive
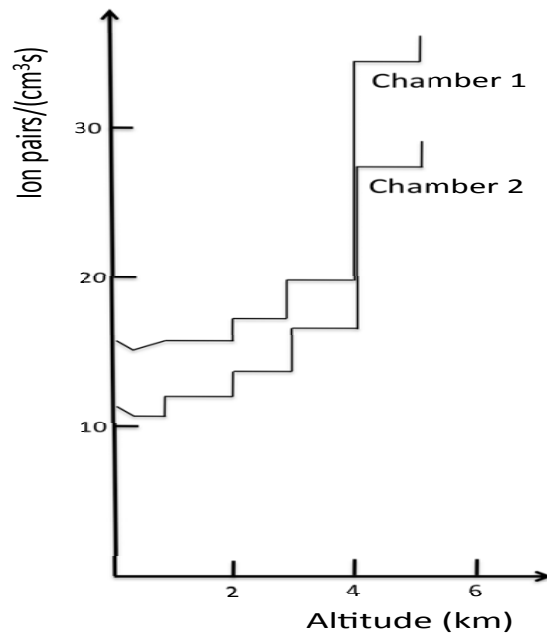

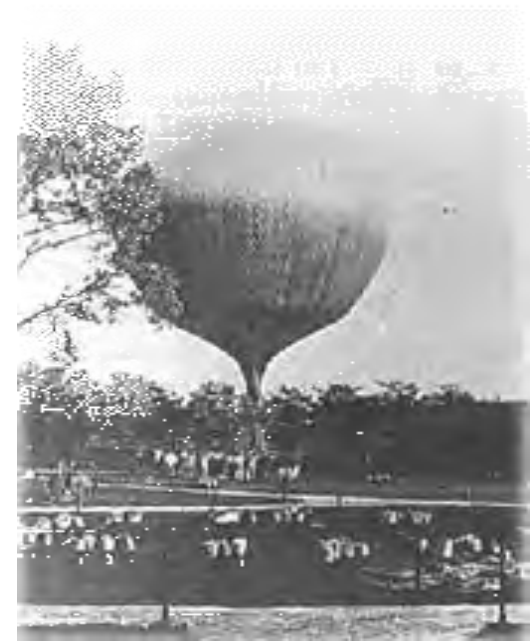Ion pairs/(cm³s) vs Altitude (km)

the winning idea: immersing an electroscope 3m deep in the sea Pacini finds a significant (20% at 4.3σ) reduction

Part of the radiation comes from the sky!!!
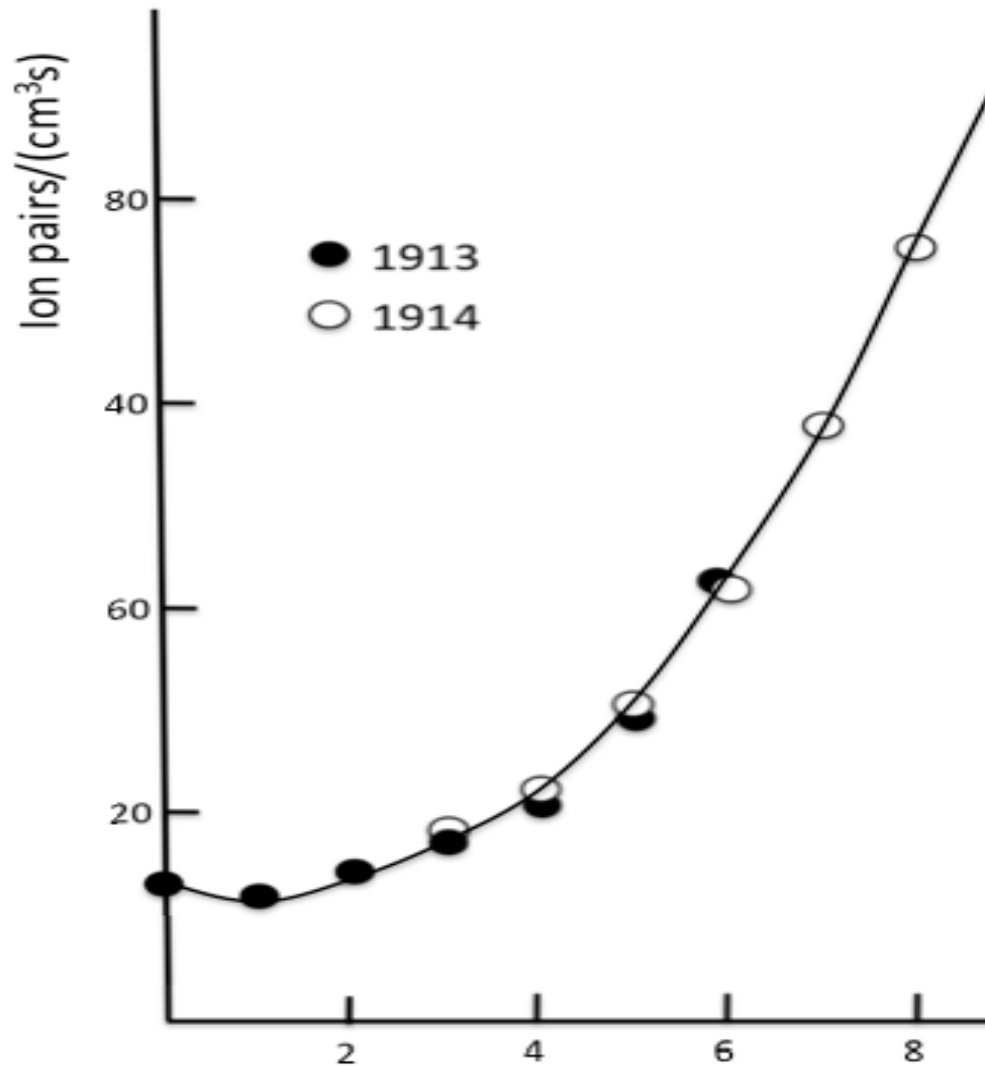

Victor Hess, 1912
Several flights up to 6 Km
Day/night, eclipses, ...

"Cosmic Rays" (Millikan 1926)

The confirmation

Flights up to 9200 m

Final flight in the day

in which WWI started

=> New world

Particle showers

Rossi 1934

Pierre Auger, 1938

Coincidences
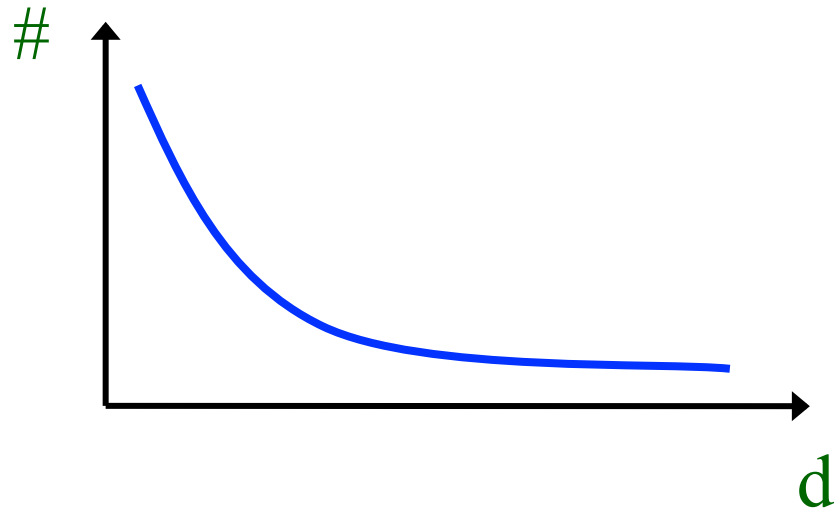
First shower energy estimates

The Birth of Particle Physics

Positron (Anderson 1932)

   Antimatter! (Dirac)

   $\gamma \rightarrow e^+ e^-$ (Einstein)

μ (Anderson 1937)

   Rossi, 1940:

   Muon life time.

   Time dilation!

π (Lattes, Occhialini, Powell 1947)

   Strong interactions (Yukawa)

K, Λ, ... (Leprince Ringuet 1944, Rochester , Butter 1947, …)

   Strangeness
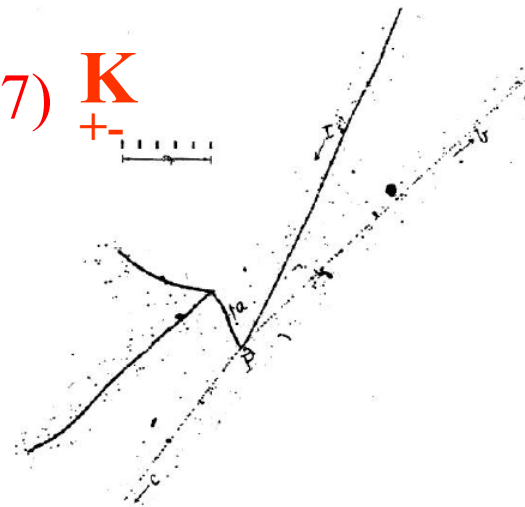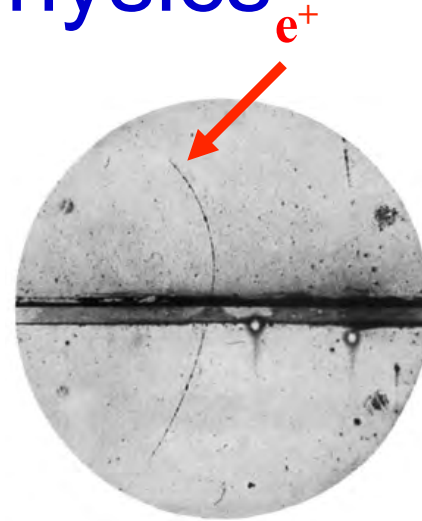
WHAT THE UNIVERSE TOLD US
(up to now)

Charged cosmic rays (p/nucleus)
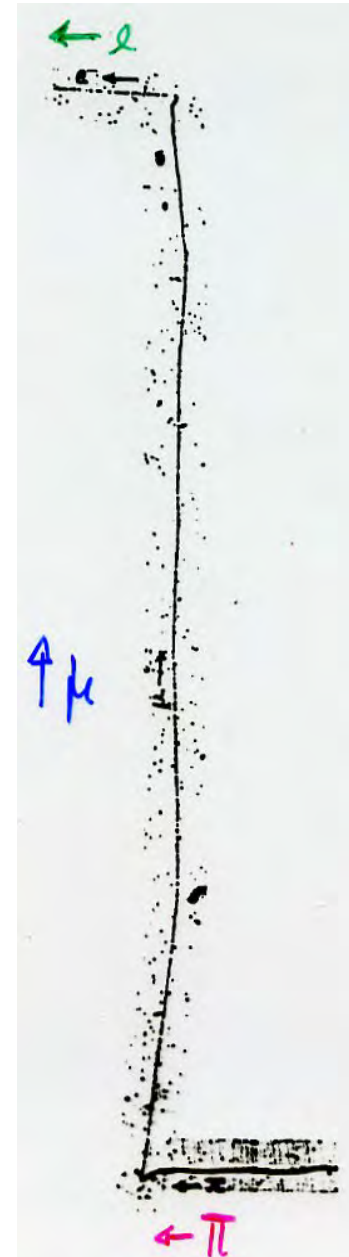

Fluxes of Cosmic Rays

Flux (m² sr s GeV)$^{-1}$

(1 particle per m²−second)

$$\frac{dN}{dE} \propto E^{-\alpha}$$

$$\alpha = \begin{cases} 2.7 & E < 10^{16} \\ 3.0 & 10^{16} < E < 10^{18} \\ 2.7? & E > 10^{18} \end{cases}$$

Knee
(1 particle per m²−year)

Ankle
(1 particle per km²−year)

Energy (eV)

LHC   100 TeV
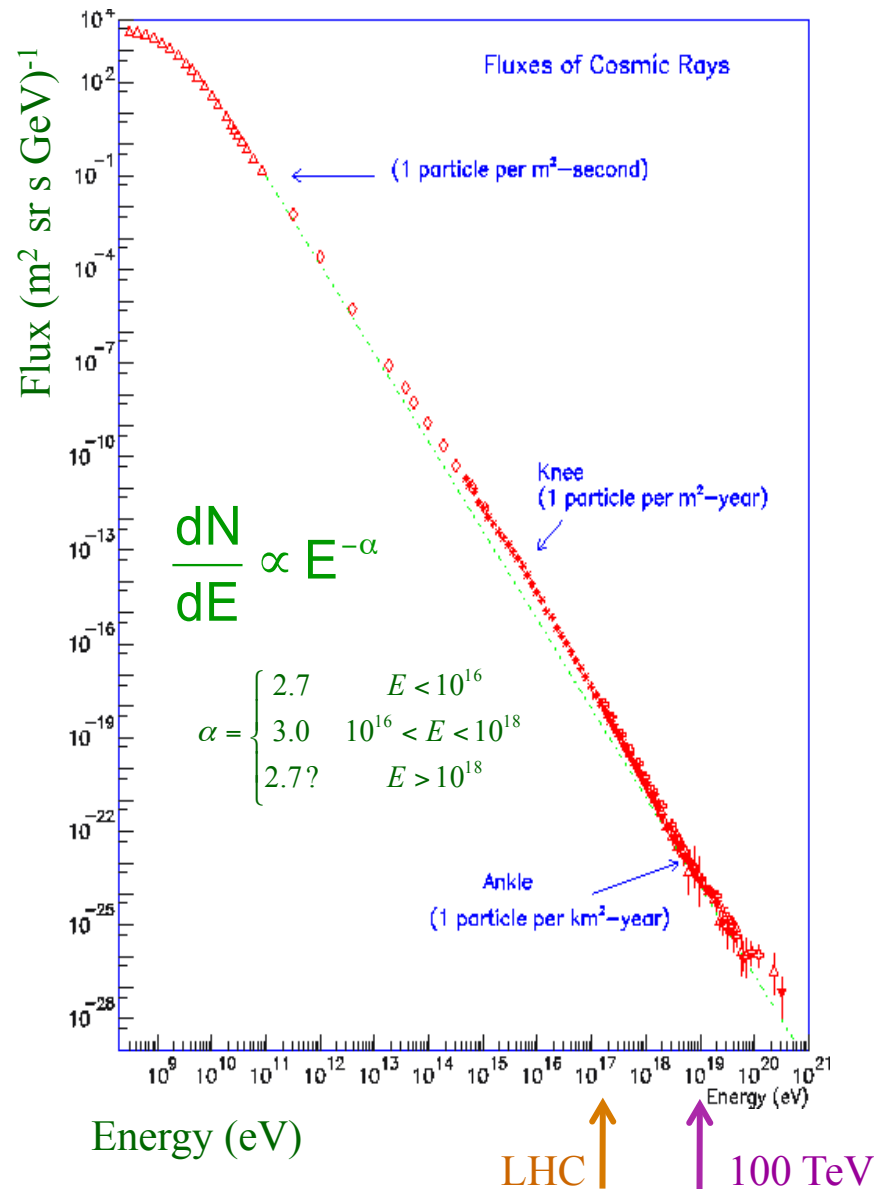
John Linsley, 1962

Forward Region
Extreme Energies

Small fluxes
indirect measurements

Anthropomorphic representation

The highest energy region (E >10^{18} eV)

Where can be these accelerators in the Universe?

Pulsar

SNR

AGN
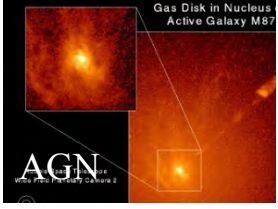
Large Hadron Collider

$$E \propto BR$$

R ~ 10 km, B ~ 10 T
E ~ 10 TeV

Magnetic Field Strength

Hillas-plot

confinement!

$E_{max} \sim bZBL$
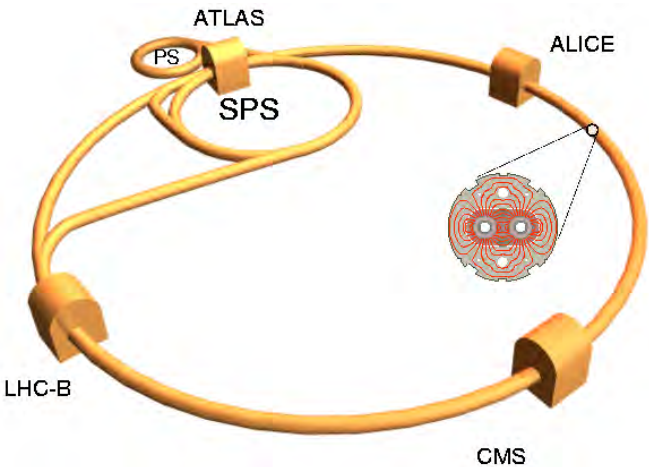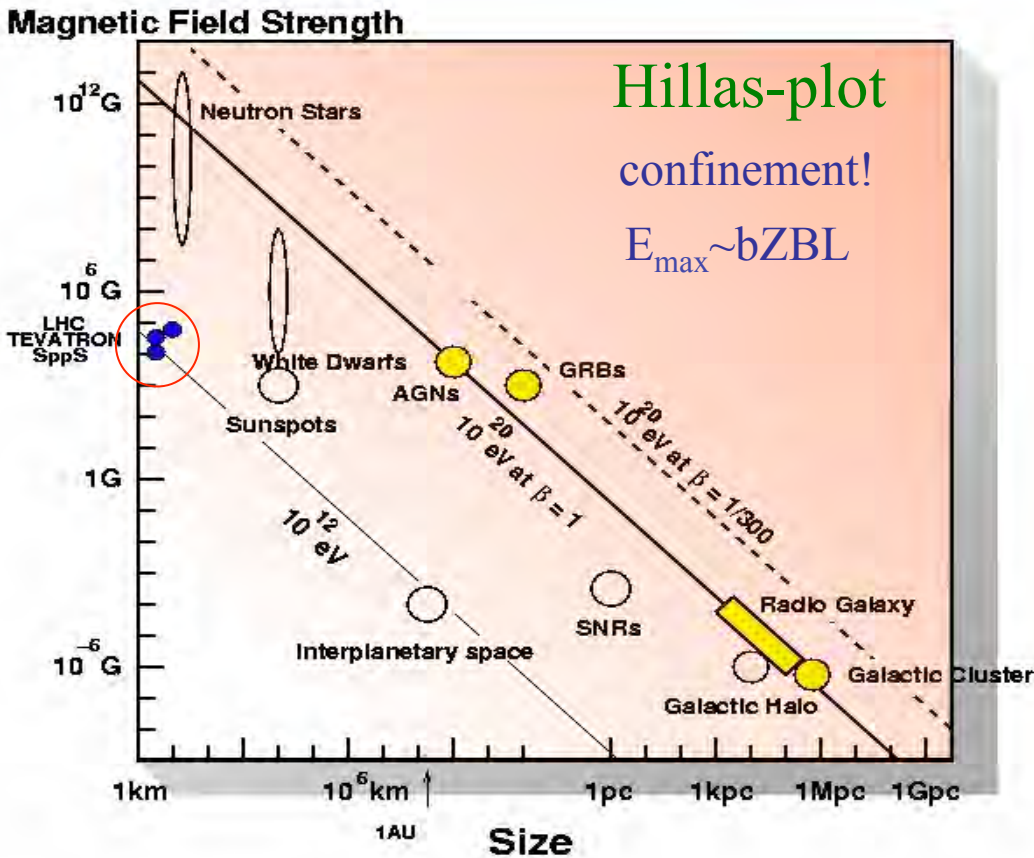
A few new terms

- Stellar endproducts. A star heavier than the Sun collapses at the end of its life into a neutron star (R ~ few km, which can be pulsating – a pulsar) or into a BH, and ejects material in an explosion (SuperNova Remnant).
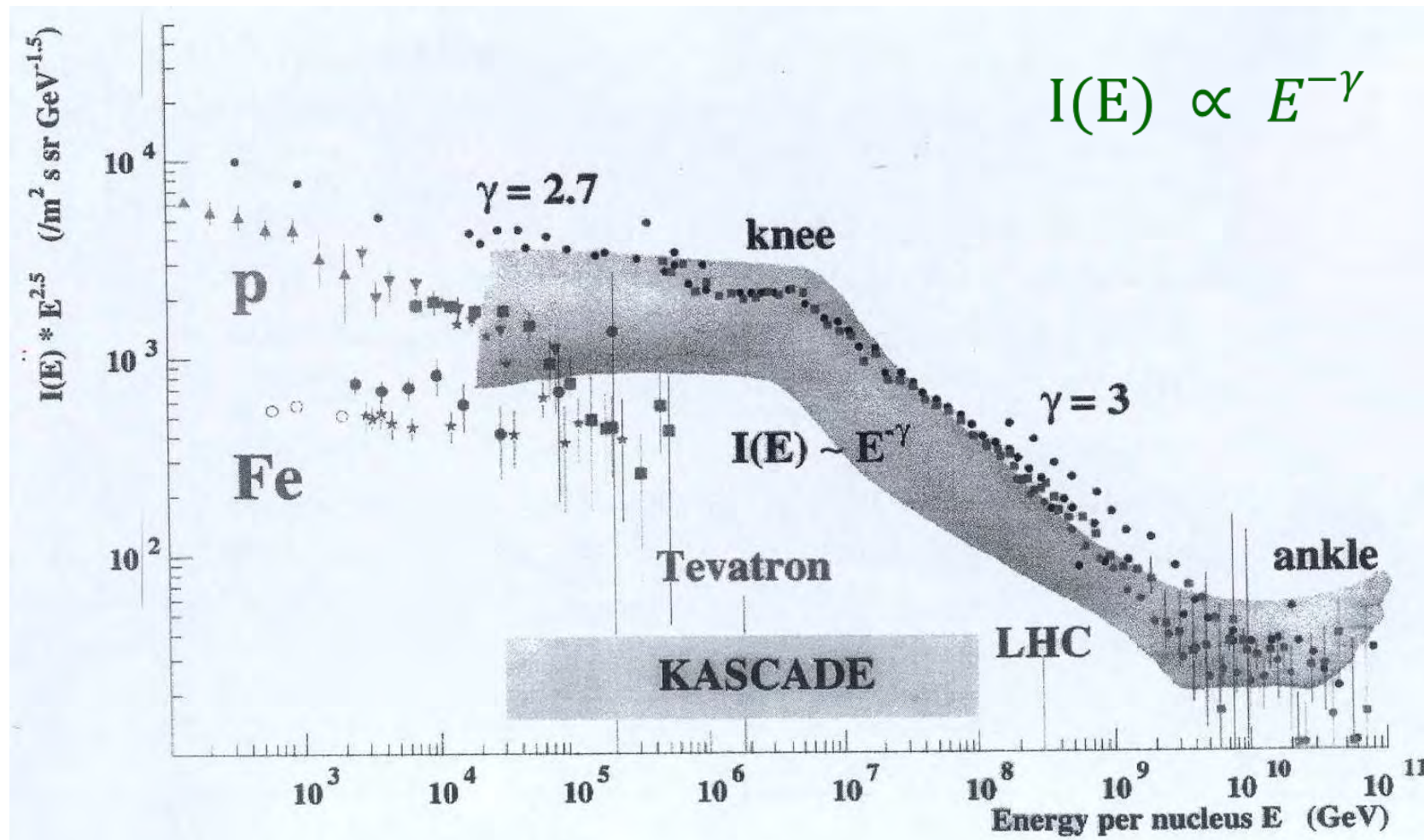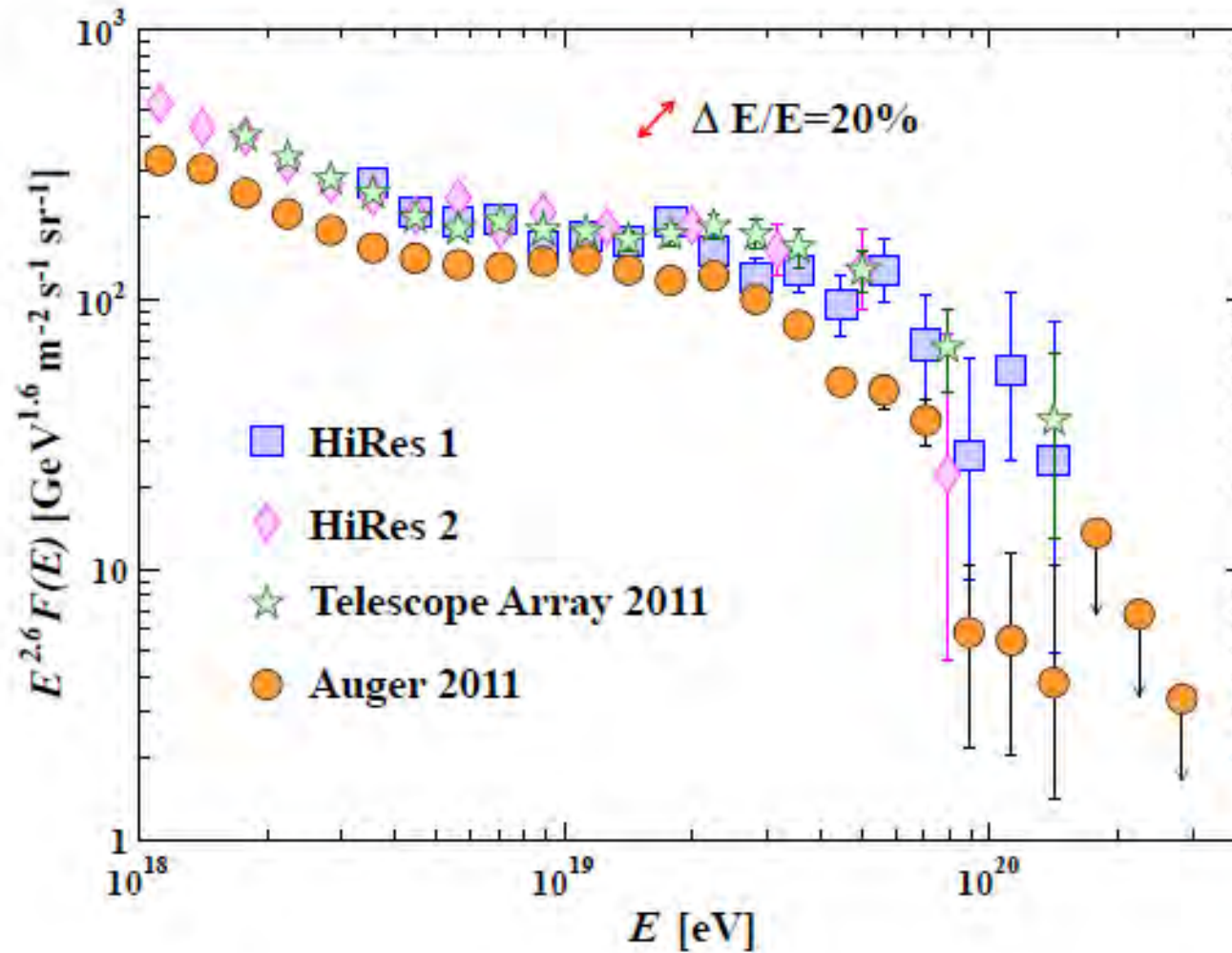 - Very large B fields are in the pulsar; magnetic fields also in the SNR

- The centres of galaxies host black holes, often supermassive (millions or even billion solar masses). They might accrete at the expense of the surrounding matter, and accelerate particles in the process. When they are active, they are called Active Galactic Nuclei.
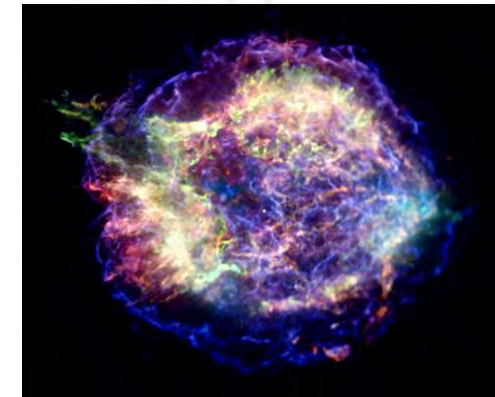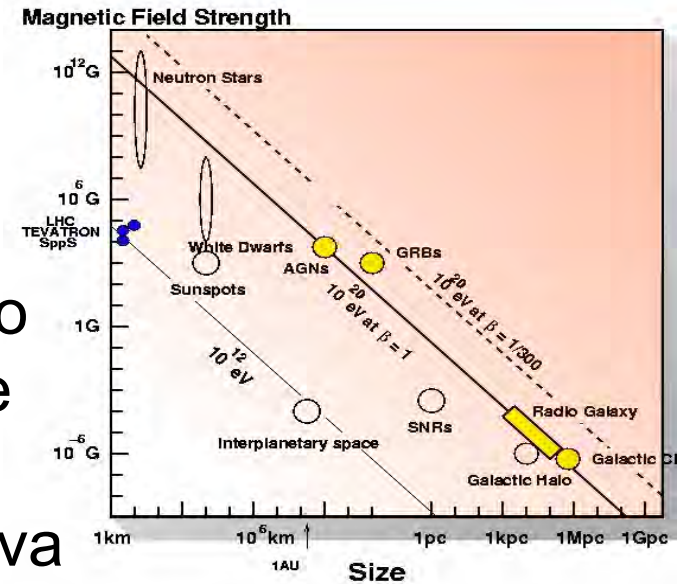
They surpass human-made accelerators

The Large Hadron Collider (LHC)
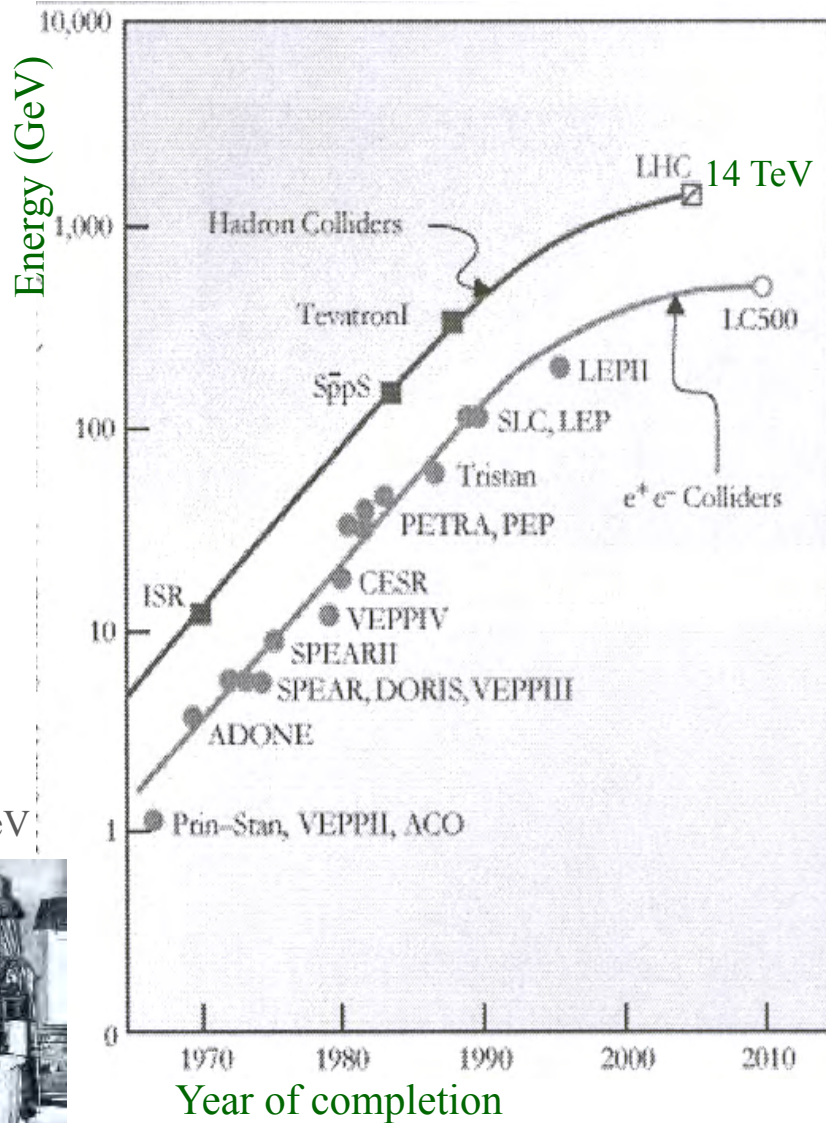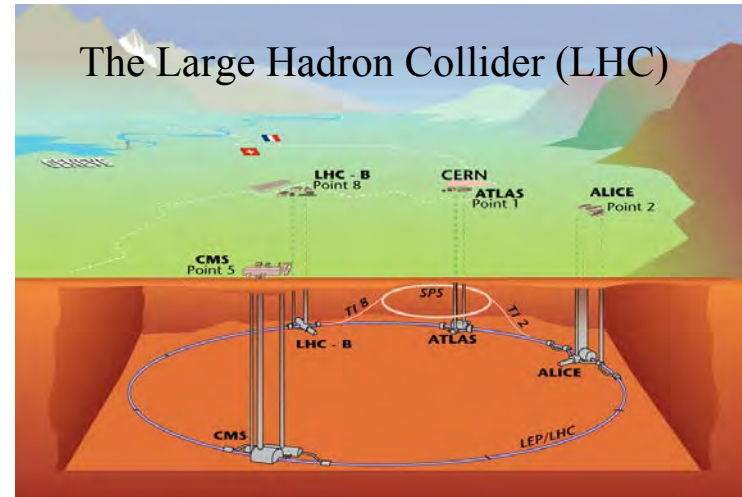
High Luminosity
Sophisticated detectors

Central region
Energy limited

Cosmic-Ray Composition

Z	Element	F	Z	Element	F
1	H	540	13–14	Al-Si	0.19
2	He	26	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

Table 26.1: Relative abundances F of cosmic-ray nuclei at 10.6 GeV/nucleon normalized to oxygen ($\equiv 1$) [6]. The oxygen flux at kinetic energy of 10.6 GeV/nucleon is 3.26×10^{-2} (m^2 s sr GeV/nucleon)$^{-1}$. Abundances of hydrogen and helium are from Refs. [2,3]. Note that one can not use these values to extend the cosmic ray flux to high energy because the power law indicies for each element may differ slightly.

Antimatter from Space
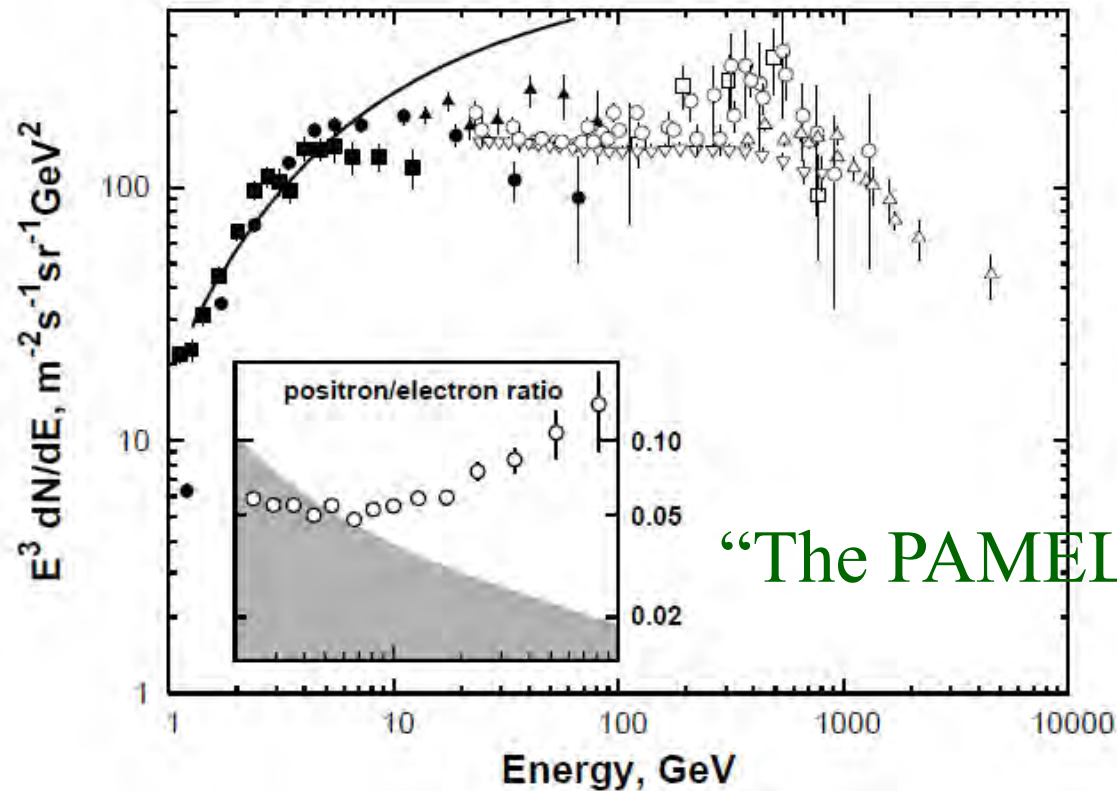
"The PAMELA Anomaly"

Figure 26.2: Differential spectrum of electrons plus positrons multiplied by E^3 (data from [17–23]) . The line shows the proton spectrum multiplied by 0.01. The inset shows the positron to electron ratio measured by PAMELA [24] compared to the expected decrease [25].

UHECR Correlation with AGNs
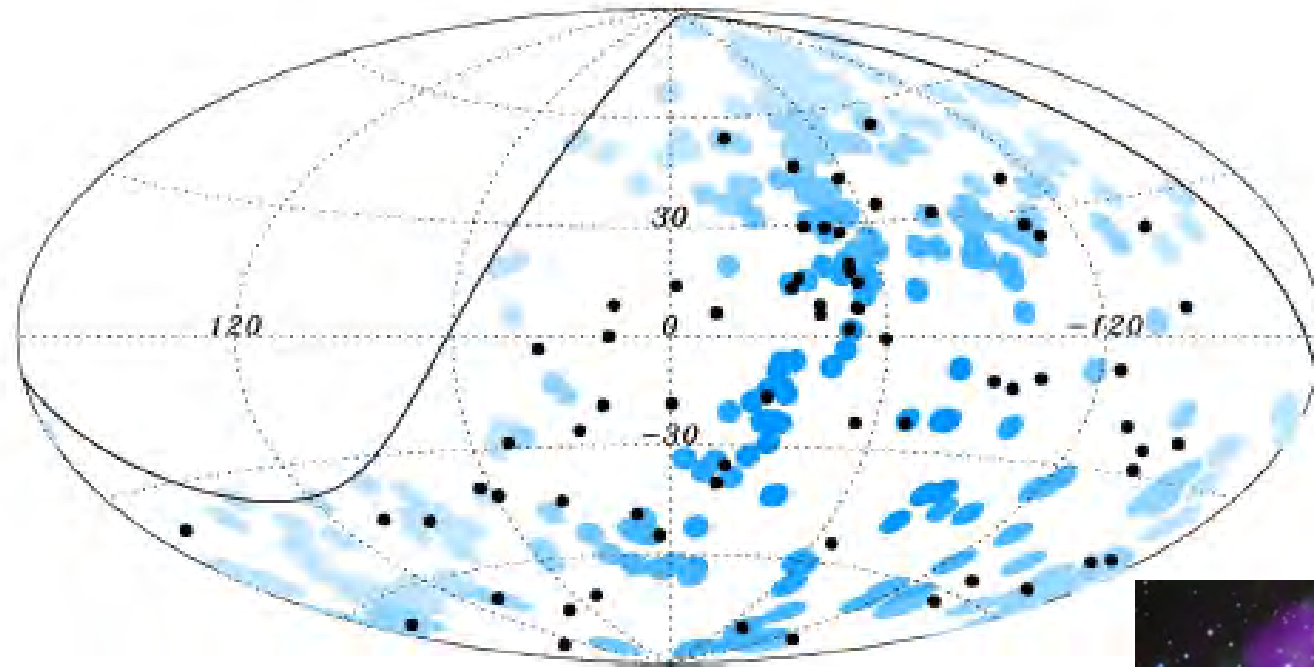
28 out of 84 correlate

Vernon-Cetty-Vernon AGN catalog

E> 57 EeV, z<0.018, distance < 3.1 deg.

Cen A?

Cosmic magnetic fields & CR propagation (CR for astronomy?)

$$\frac{r}{1\ pc} \cong \frac{\dfrac{E}{1\ PeV}}{\dfrac{B}{1\ \mu G}}$$

- Gyroradius for a proton
  - Typical B field in the Galaxy: ~ 1-3 µG
  - Intergalactic B field largely unknown

    1 nG < B < 1 fG

- If you want to look at the GC (d ~ 8 kpc) you need E > 2 10^{19} eV
  - But only 1 particle / km2 / year
  - And: no galactic emitters expected at this energy

- But in principle one could look outside the galaxy, were B is smaller and there are SMBHs…
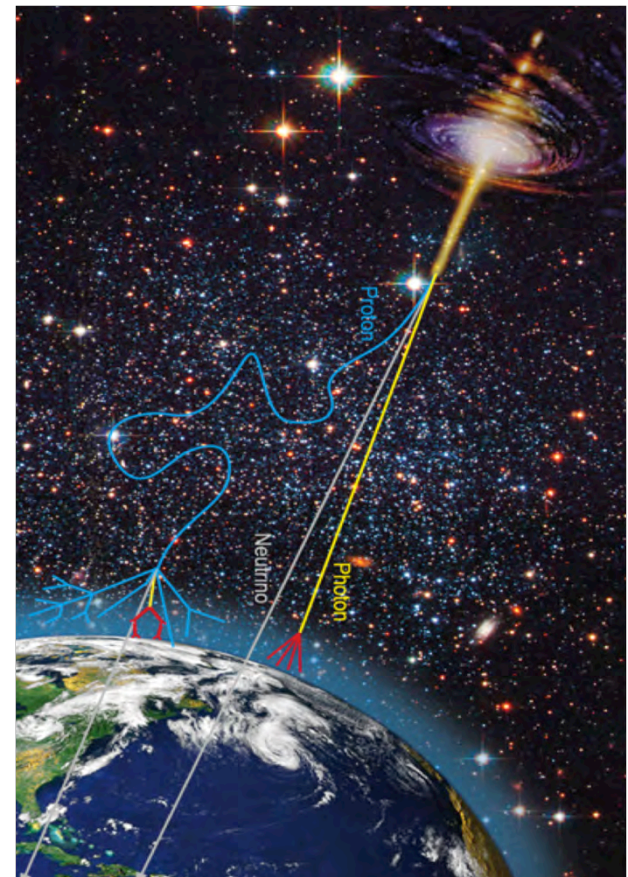
extremely difficult

=> Locating the sources of charged CR is impossible AT GROUND

- We need to detect a large statistics of protons with E between 10^{19} eV and 10^{21} eV
- Areas ~ 30 thousand km^2 (1/10 of Italy), ~impossible to find
- Needs satellites
- VHE photons
- Neutrinos
  - Detected only from Sun and SN1987A
- Gravitons
  - Undetected up to now; we shall not discuss them

Thermal radiation: Black Body Spectrum

Cosmic Microwave Background:

2.7 K
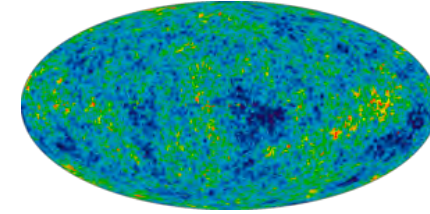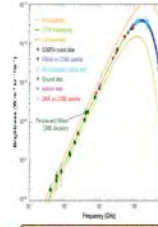
A Galactic gas cloud

called Rho Ophiuchi:

60 K

Dim star near the

center of the Orion Nebula:

600 K

the Sun:

6000 K

Cluster of very bright stars, Omega Centauri,

as observed from the space:

60,000 K
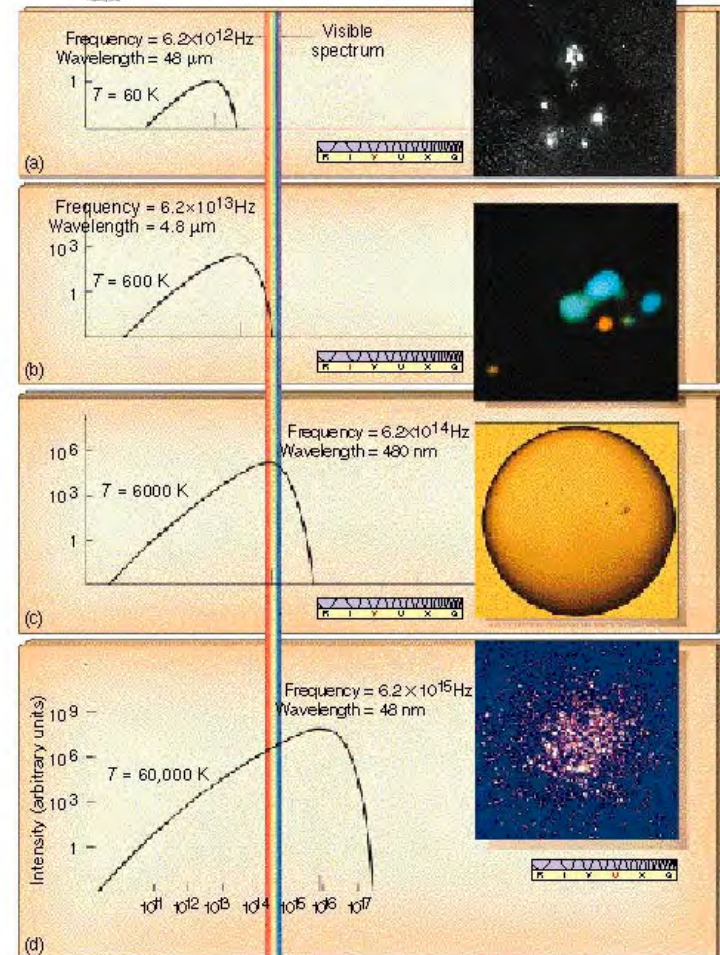
Accretion Disks can reach

temperatures $\gg 10^5$ K

But this is still ~1 keV, in the X-Ray band!

26

γ energy spectrum

GRAND UNIFIED PHOTON SP

E^{-2}

Atmospheric

Sat

X	1 keV-1 MeV
X/low E γ	1 MeV-10 MeV
medium	10-30 MeV
HE	30 MeV- 30GeV
VHE	30 GeV-30 TeV
UHE	30 TeV-30 PeV
EHE	above 30 PeV

But at 30 PeV, ~ 1γ/ km² /day

Crab Nebula

$d\Phi/ dE = f_0 (E/TeV)^{-\Gamma}$

$f_0 = (2.74 \pm 0.19) \times 10^{-11} \, cm^{-2} \, s^{-1} \, TeV^{-1}$

$\Gamma = 2.65 \pm 0.06$

$\chi^2 / dof = 0.55 / 6$
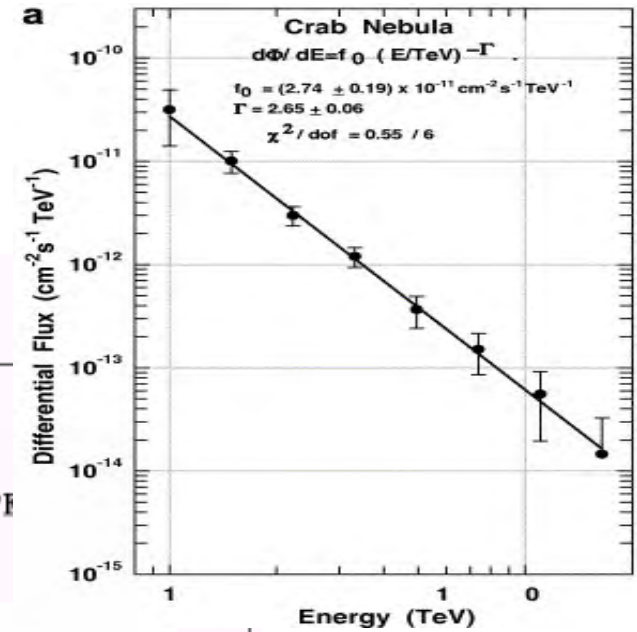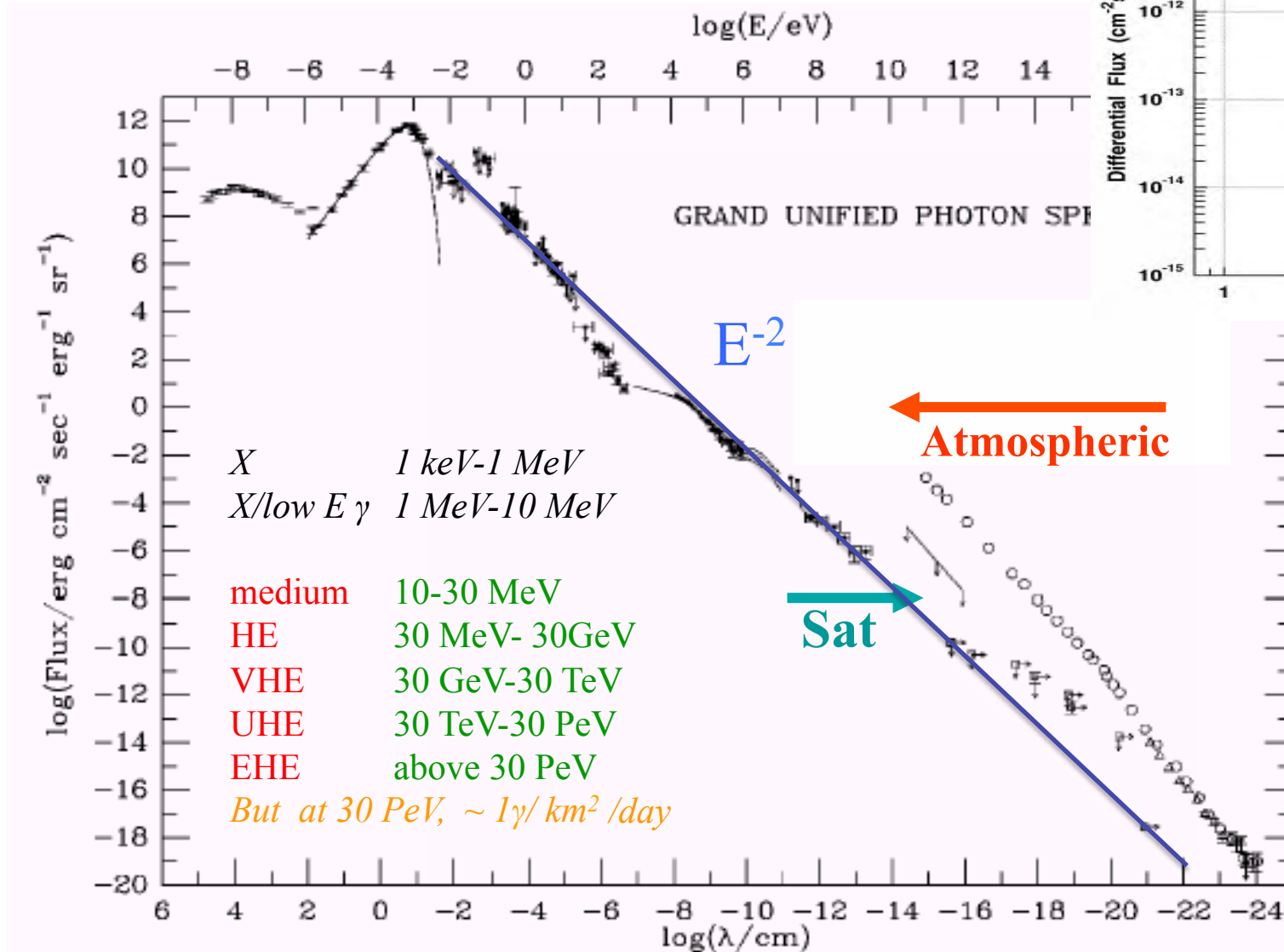
Cosmic γ rays: two different production mechanisms expected to be at work

hadronic cascades

p^+ (>>TeV)

matter

π^0 $\gamma\gamma$ (TeV)

π^-

π^+

e.m. processes

e^- (TeV)

Synchrotron

γ (eV-keV)

$\vec{B}$

γ (TeV)

γ (eV)   Inverse Compton
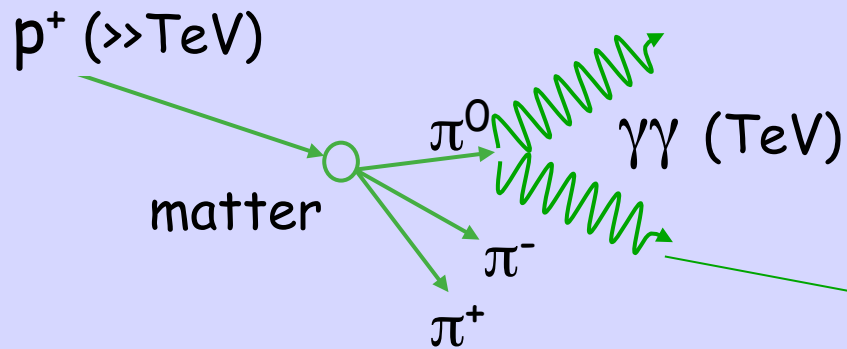
In the VHE region,

dN/dE ~ $E^{-\Gamma}$ (Γ: spectral index)

To distinguish between had/leptonic origin

study Spectral Energy Distribution (SED):

(differential flux) · E^2

E^2 dN/dE

IC

π^0 decay

VHE

energy E

28
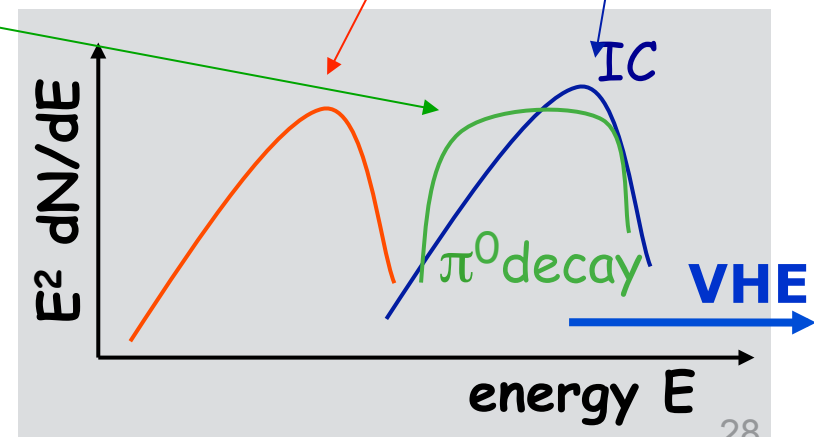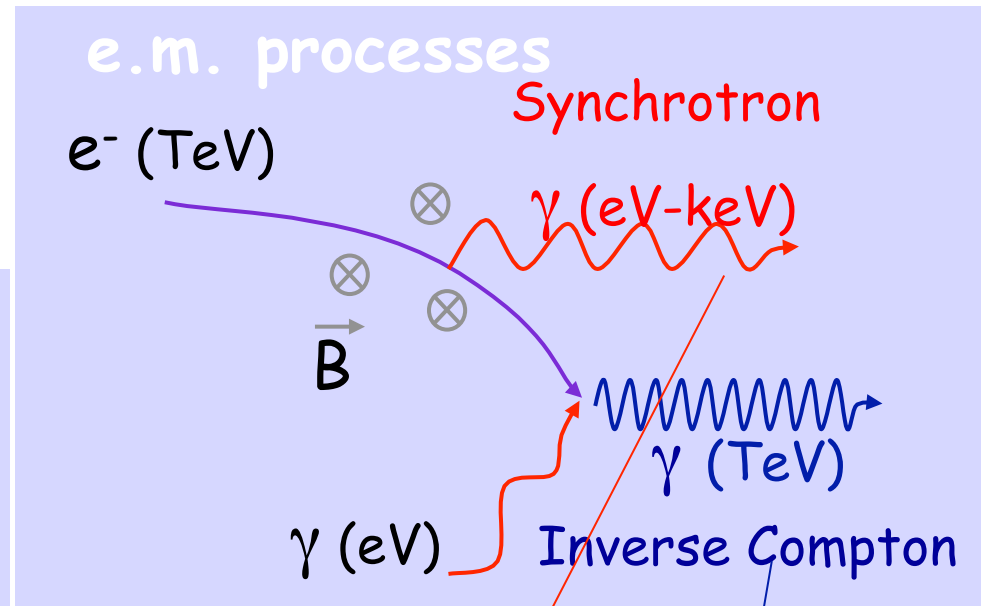
Leptonic vs. Hadronic models for γ emission

- SSC: currently explain most emissions
  - easy to accelerate electrons to TeV energies
  - easy to produce synchrotron and IC gamma-rays

  But:
  - recent results would require more sophisticated leptonic models

- Hadronic Models:
  - protons interacting with ambient hadronic targets -> neutrinos (1)
    - But needs adequate targets: works well for SNR, more difficult for AGN
  - protons interacting with photons (hadronic photoproduction) -> neutrinos (2)
  - proton synchrotron (no neutrinos)
    - very large magnetic fields

High Energy γ rays: non-thermal Universe

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, …;
    Intergalactic Magnetic Fields, …
- Gamma rays traveling to us!
  - HE: 30 MeV to 30 GeV
  - VHE: 30 GeV to 30 TeV

Plus: "new" particles (e.g. Dark Matter)

- No deflection from magnetic fields, gammas point ~ to the sources
  Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

Studying Gamma Rays allows us to see these aspects of the Universe

VHE sources have been located using gammas

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 30 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 150 (and >200 papers) in the last 7 years

    - And also a better knowledge of the diffuse gammas and electrons

- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources

- A new tool for cosmic-ray physics and fundamental physics

- *In the Galaxy, mostly associated to stellar endproducts (PWN in particular). Extragalactic emission associated to AGN*
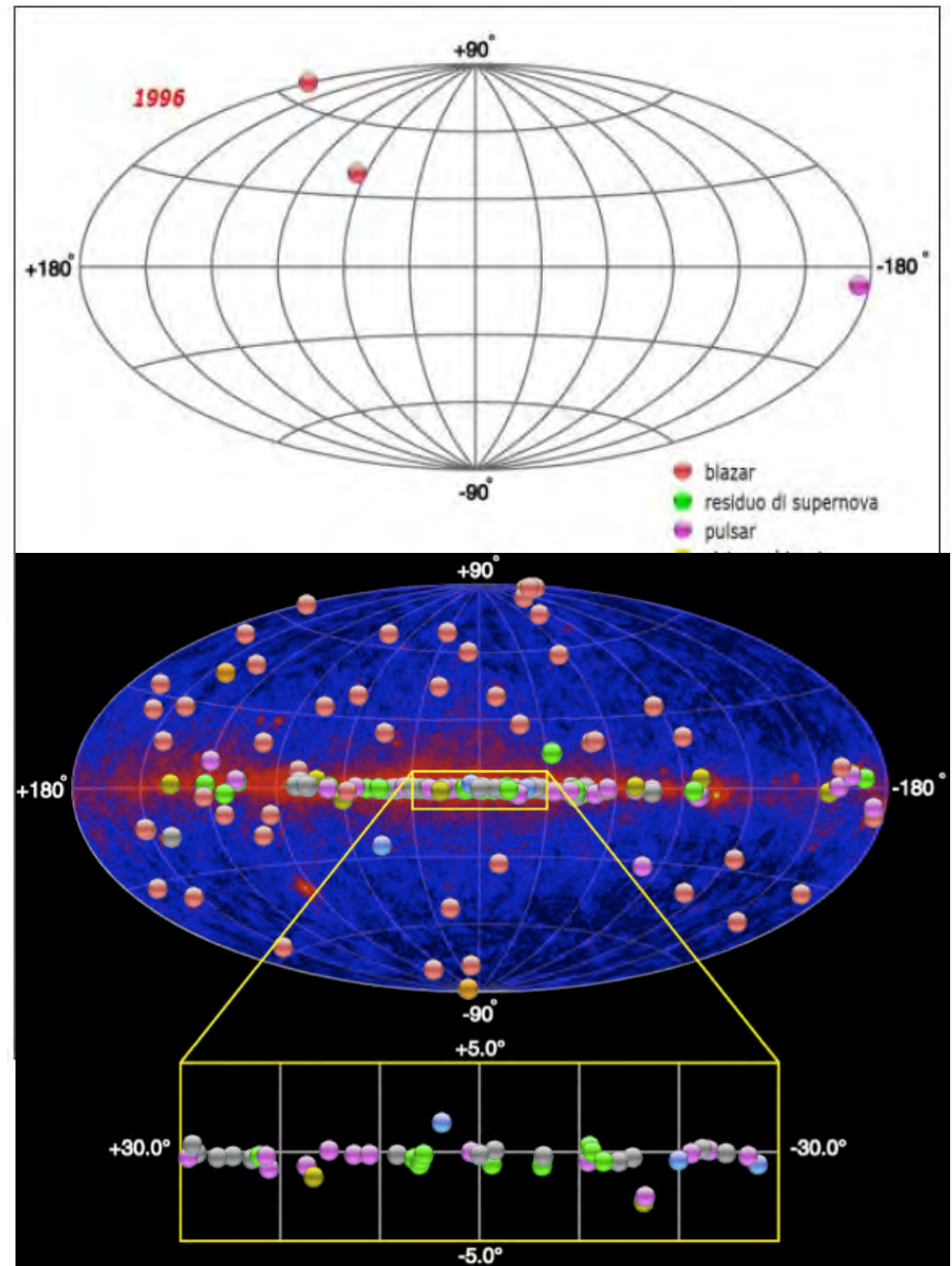
Neutrinos

- Neutrinos play a very special role in particle astrophysics. Their cross section is small, and they can leave production sites without interacting => can carry information about conditions deep in the core of astrophysical objects that produce them

- They are produced in the nuclear reaction chains by which stars generate energy. Each conversion of 4p into He produces two neutrinos - the Sun emits ~$2x10^{38}$ neutrinos per second

- They are also produced in nature's most violent explosions, including the Big Bang

- They are produced as secondary byproducts of cosmic-ray collisions also in the atmosphere. Detection of these neutrinos can help constraining properties of the primary cosmic ray spectrum, more effectively than photons. Neutrinos produced by reactions of ultra-high-energy cosmic rays can provide information on otherwise inaccessible cosmic accelerators

CR: clear synergy gammas-neutrinos

- Smoking gun would be a correlation of VHE CR (difficult: magnetic fields) or a neutrino signal

- Many model uncertainties present in the gamma/p relation disappear when studying gamma/neutrino

$$\frac{dN_\nu}{dE} \approx \frac{1}{2} \frac{dN_\gamma}{dE}$$

(reflects the fact that pions decay into gamma rays and neutrinos that carry 1/2 and 1/4 of the energy of the parent. This assumes that the four leptons in the charged pion decay equally share the charged pion's energy)
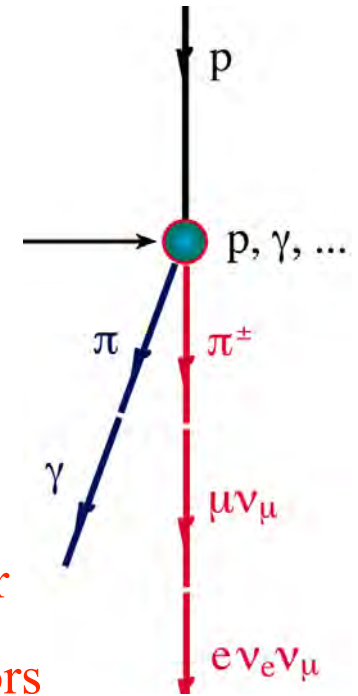
⇒Very accurate input for

neutrino detectors

RX J1713.7-3946
- ■ H.E.S.S. data
- ····· fitted γ spectrum
- —— calculated ν spectrum
- - - - mean atm. ν spectrum
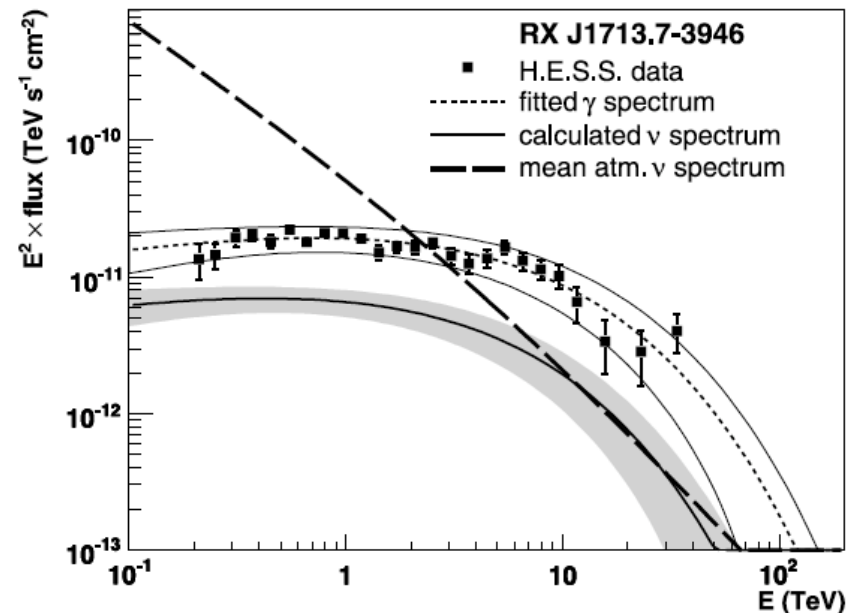
IceCube 40 strings
operated 375.5 days

northern sky: 14139 neutrinos

NO SIGNAL YET

Up to now: associations only
with the Sun and with SN
1987A

24h

0h

southern sky: 23151 muons
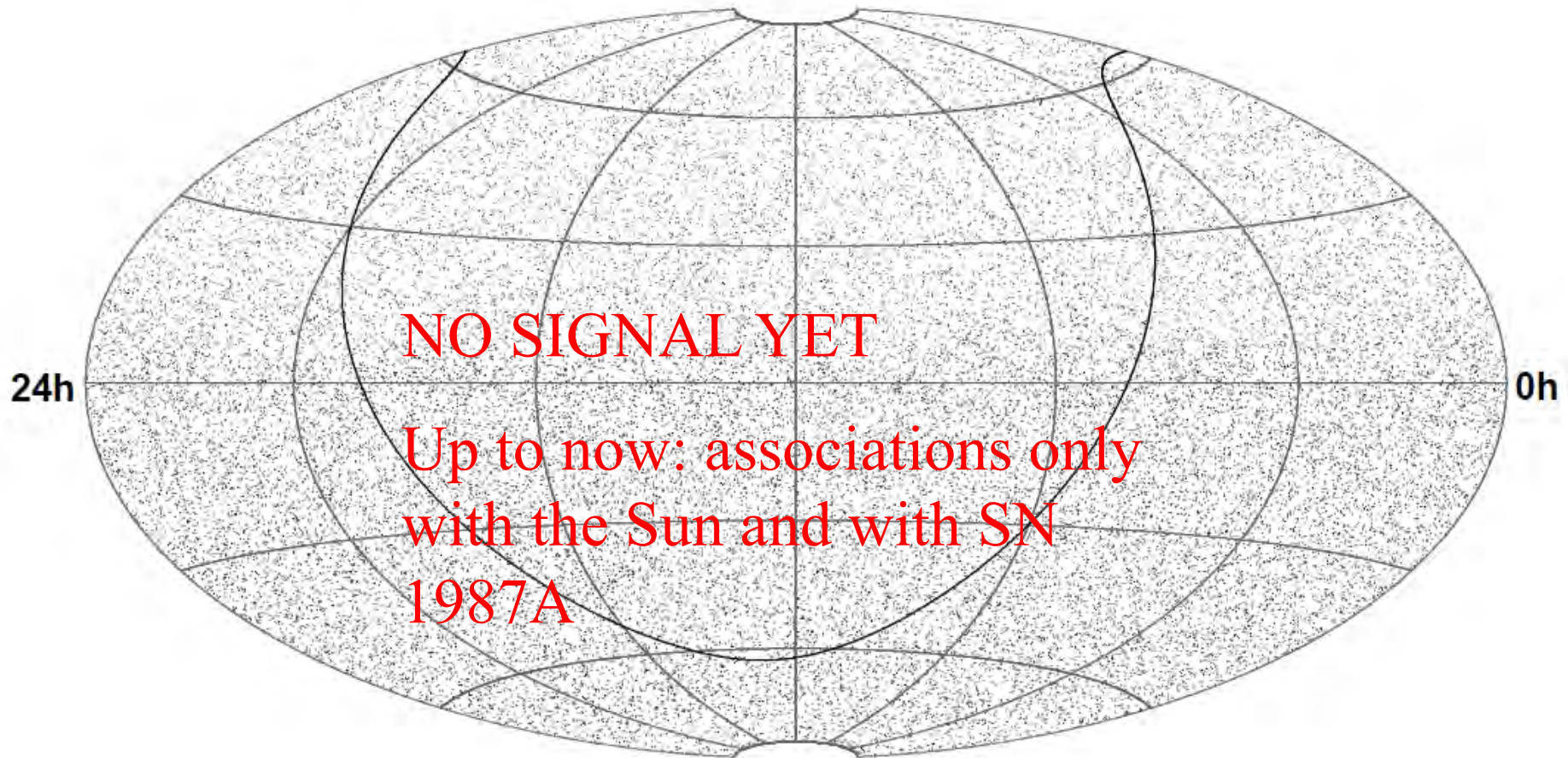
search for

• clustering

• high energy (>> 100 TeV)

THE SOURCES

Where to find the particle accelerators in Space?

Remember: you need E, B, R

- Stellar endproducts

- AGN

(one has energy from the gravitational potential energy, and magnetic fields from plasma motions)

Stellar endproducts (supernova remnants)

A massive star begins its lifetime burning the H in its core under conditions of equilibrium. When the H is exhausted, the core contracts until $3\alpha \rightarrow 12C$ can take place. He is then burned to exhaustion. This pattern (fuel exhaustion, contraction, heating, and ignition of the ashes of the previous cycle) might repeat several times depending on the mass, leading finally to an explosion. A 25-solar-mass star would go through the set of burning cycles ending up in the burning of Si to Fe in about 7 My, with the final explosion taking ~days
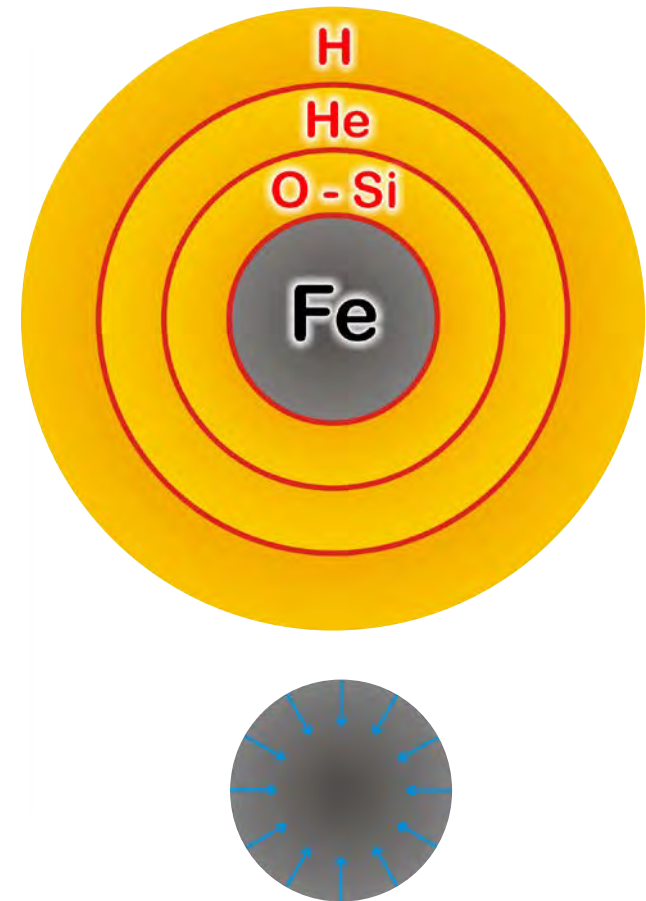
Evolution of Stars depends on mass

$M < 0.08\ M_{sun}$	Never ignites hydrogen → cools ("hydrogen white dwarf")		Brown dwarf
$0.08 < M \lesssim 0.8\ M_{sun}$	Hydrogen burning not completed in Hubble time		Low-mass main-squence star
$0.8 \lesssim M \lesssim 2\ M_{sun}$	Degenerate helium core after hydrogen exhaustion		• Carbon-oxygen white dwarf
$2 \lesssim M \lesssim 5{-}8\ M_{sun}$	Helium ignition non-degenerate		• Planetary nebula
$8\ M_{sun} \lesssim M < ???$	All burning cycles → Onion skin structure with degenerate iron core	Core collapse supernova	• Neutron star (often pulsar) • Sometimes black hole? • Supernova remnant (SNR), e.g. crab nebula

Rate of SN in our galaxy: ~ 1 every 30 years (CR considerations); ~1/century (astrophysical cons.)

Observed: ~1/400 years

SNR (continued)

- If mass is large enough to explode/collapse, the supernova remnant (SNR) is the structure left over after a supernova explosion: a high density n star (or a BH) lies at the center of the exploded star, whereas the ejecta appear as an expanding bubble of hot gas that shocks and sweeps up the interstellar medium.
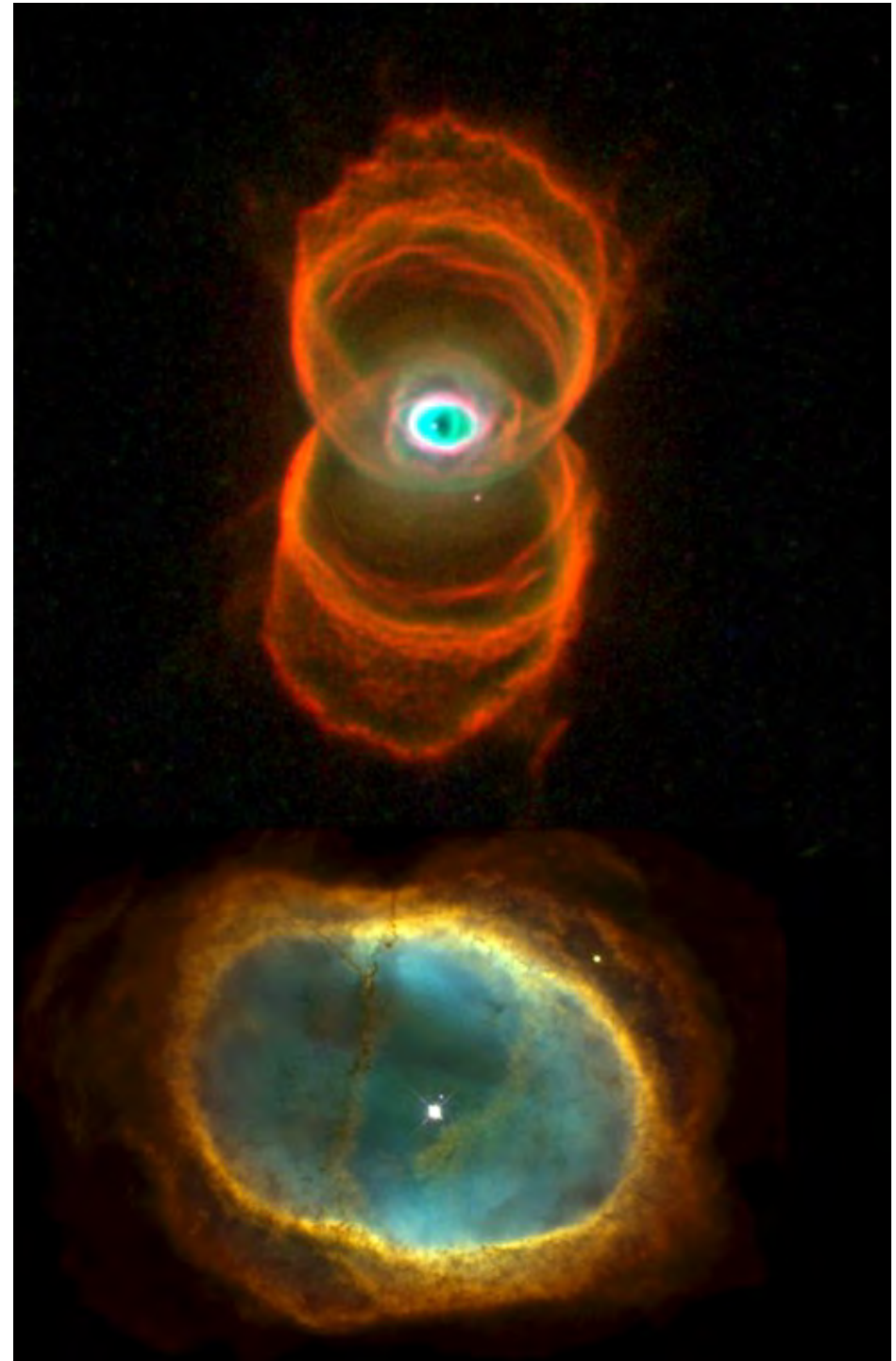
A conjecture on the origin of CR

- In a 1931 lecture course at Caltech, Zwicky introduced the term "super-nova" to distinguish the explosion of an entire star from the less powerful nova, which involved violent and repeated outbursts on the surface of an unstable star

- Zwicky teamed up with the German A
  w   tific
  c   ee
  b
    1   s
    2
    3   of

(Zwicky in 1930)

AGN

- Supermassive black holes (SMBH) of 1M-10G solar masses reside in the cores of most galaxies (the centre of our Galaxy hosts a BH ~4 million solar masses, its mass having been determined by the orbital motion of nearly stars.

- Their fueling by infalling matter can produce a spectacular activity; when they are active, i.e., they are powered by accretion at the expenses of nearby matter, these BH are called Active Galactic Nuclei (AGN).
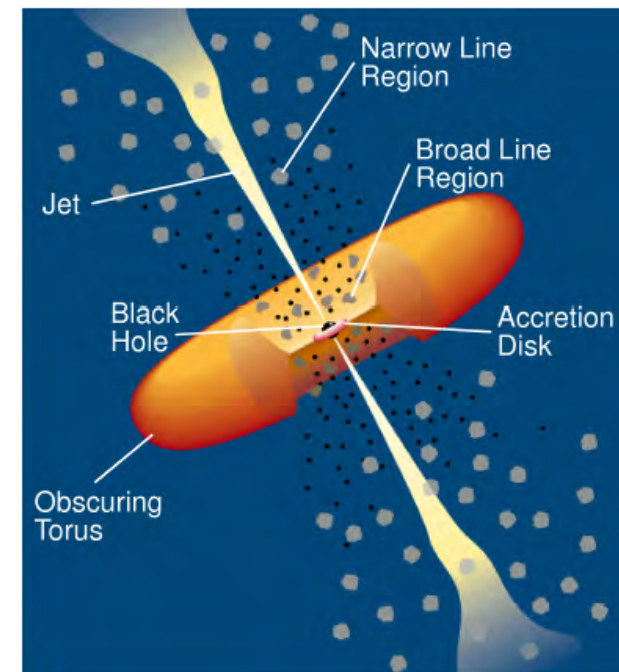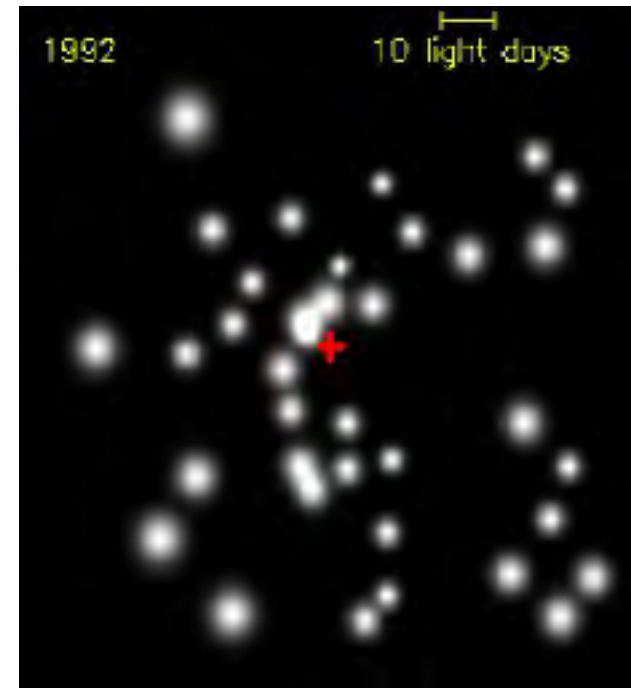
AGN

- It is believed that a "unified model" accounts for all AGN . The SMBH and its inner accretion disk is surrounded by a dusty torus of matter, and the type of active galaxy that is seen depends on the orientation of the torus and jets relative to the observer's line of sight.

- The jet radiates strongly along its axis, also due to the Lorentz boost. The view of an observer, who is looking very close to this axis, will be dominated by the jet emission, and a possibly variable source with no spectral lines will be seen: this is called a BL Lac object, or blazar

- Looking at a modest angle to the jet, an observer will see an unobscured compact source inside the torus; this is in general called a quasar

- From a viewpoint closer to the plane of the torus, the central engine is hidden, and one observes the jets and lobes (extended radio-emitting clouds) of a radio galaxy

- Typical values of B are of the order of 10 G to 10000 G.

- The jet can be traced down to a scale size of order 0.01 pc which is < 100 000 times its total length and <100 times the radius of the BH
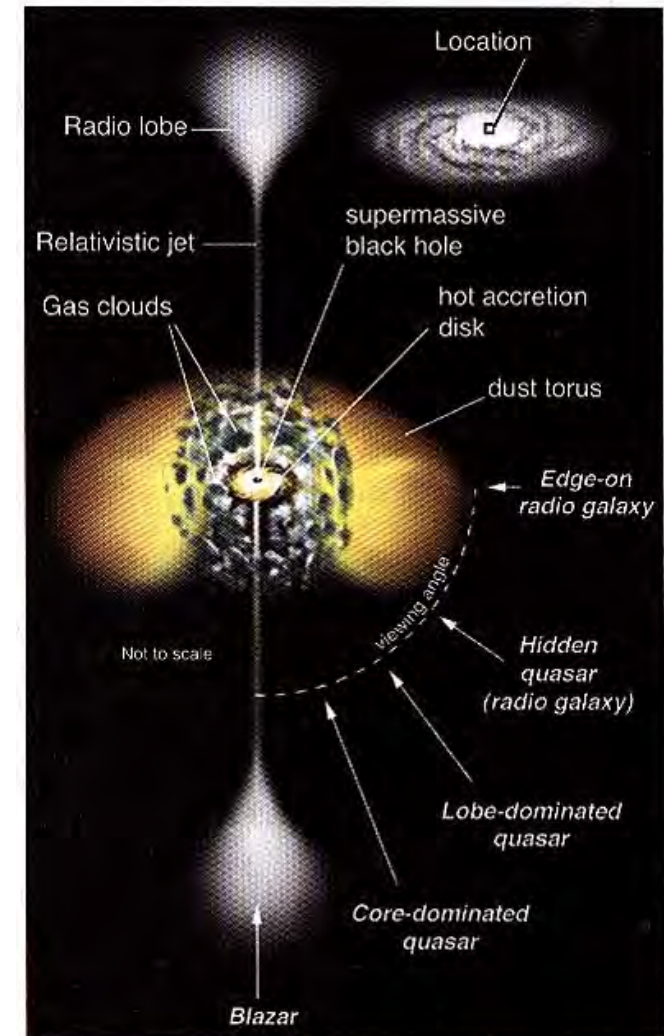
**Slanted story.** Seemingly diverse astronomical objects may be different views of galactic cores.

Gamma-Ray Bursts

- For short period of times, ~ seconds
  - GRB have a bimodal distribution of duration; accordingly, they are classified as "long" or "short"

  a source emits more energy in Gamma ray than the rest of the Universe

- Long GRBs are thought to come from a hypernova (an old star of large mass), or a core-collapse supernova. There is a prevailing consensus that the basic mechanism of GRB emission is an expanding relativistic fireball, with the beamed radiation due to shock waves. No direct confirmation that they are CR emitters

- During the abrupt compression the magnetic field could be squeezed to extremely large values, of the order of 10^{12}G to 10^{14}G, in a radius of some tens of kilometers


BATSE 4B Catalog

50 s

0.2 s
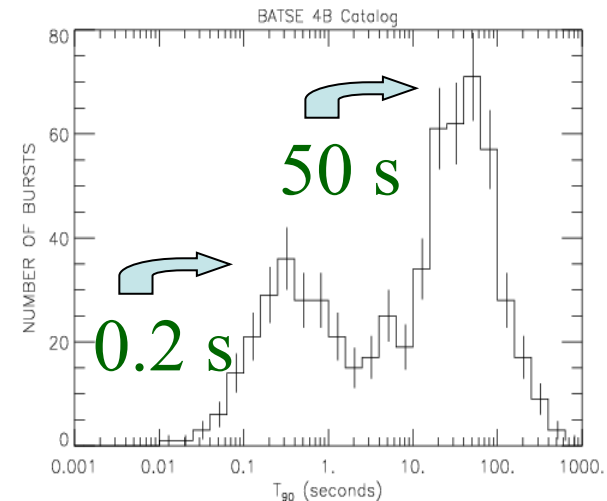
3906 GRBs
(triggered & non-triggered)
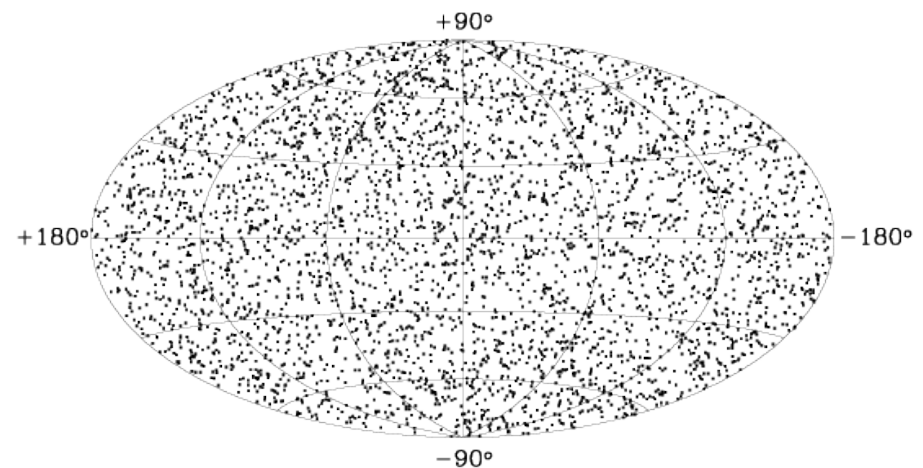
How-to?
Fermi acceleration

- Particles are accelerated by collisions with magnetic clouds

- Fermi's original 2nd-order Fermi acceleration involved randomly moving magnetic clouds that swept up charged particles in the ISM

  - At every collision, energy increases by $(1+\beta^2)$

- If shocks are coherent, 1st order (more effective

  - At every collision, energy increases by $(1+\beta)$
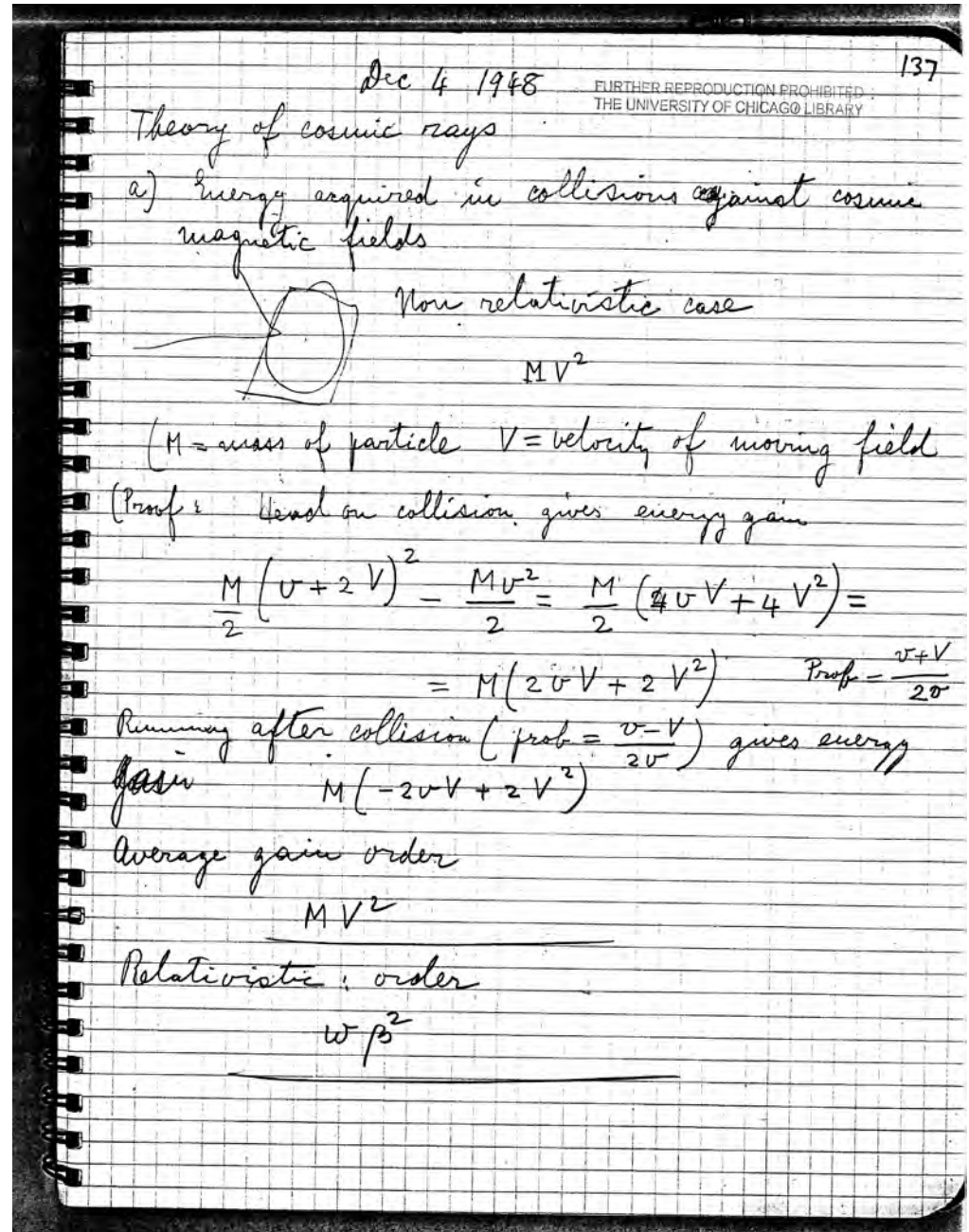
1st order Fermi acceleration

- A simplified model of the Fermi 1st order is

  – Particle moves with energy E, shock is moving opposite with velocity ß

  – The CR particle is reflected back and gains an energy

$$\frac{\Delta E}{E} \simeq \beta$$

- Particle is reflected back, either by magnetic cloud or outer shock shell moving with lower velocity than the inner shell

- At each cycle particle gains fractional energy ß

  => after n cycles the particle will have energy $E = E_0(1 + <ß>)^n$

1st order Fermi acceleration

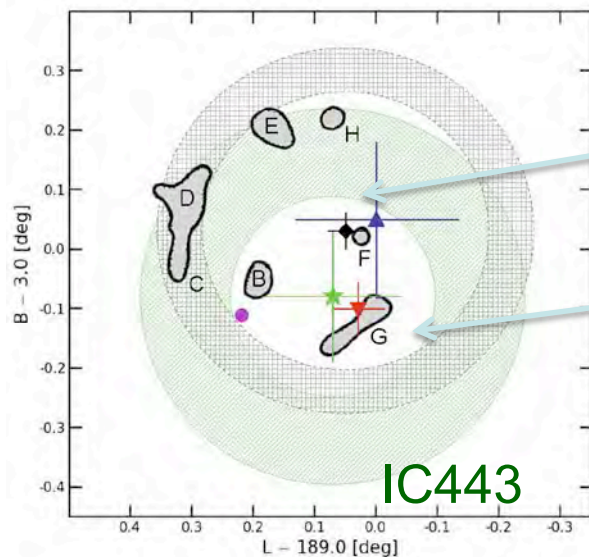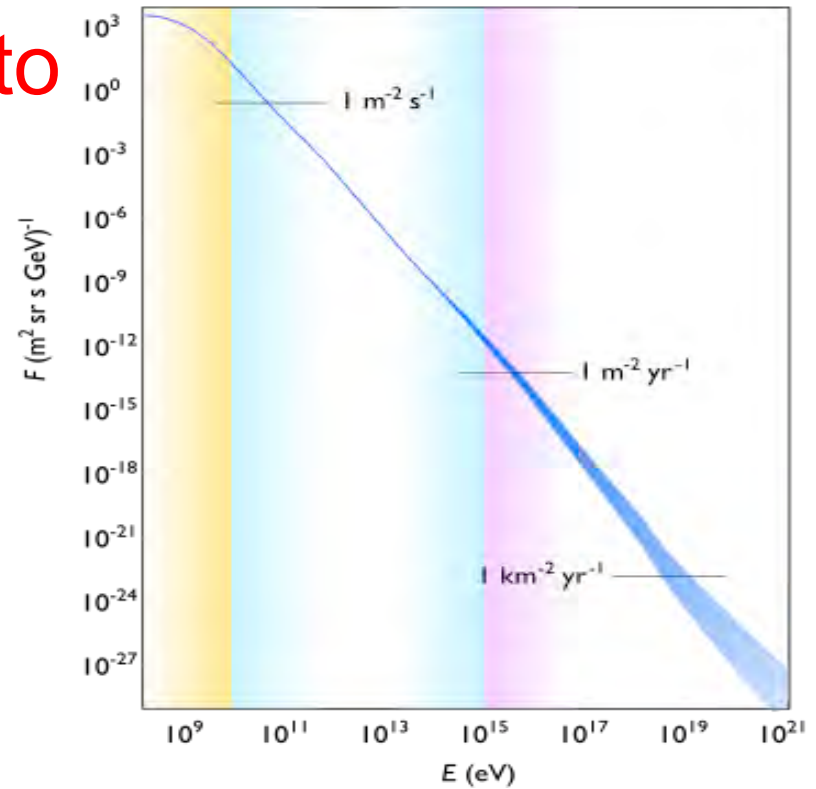- $E = E_0(1 + <\beta>)^n \Rightarrow n = \dfrac{\ln(E/E_0)}{\ln(1 + \langle\beta\rangle)}$

- At each acceleration, a particle has a probability P(E,B) of escaping. Let us neglect the dependence on E, and take an average <P>. One has thus

$$\frac{N}{N_0} = P^n \Rightarrow \ln\left(\frac{N}{N_0}\right) = n \ln P = \frac{\ln(E/E_0) \ln P}{\ln(1 + \langle\beta\rangle)} \equiv -s \ln\left(\frac{E}{E_0}\right) \Rightarrow N(> E) \propto E^{-s}$$

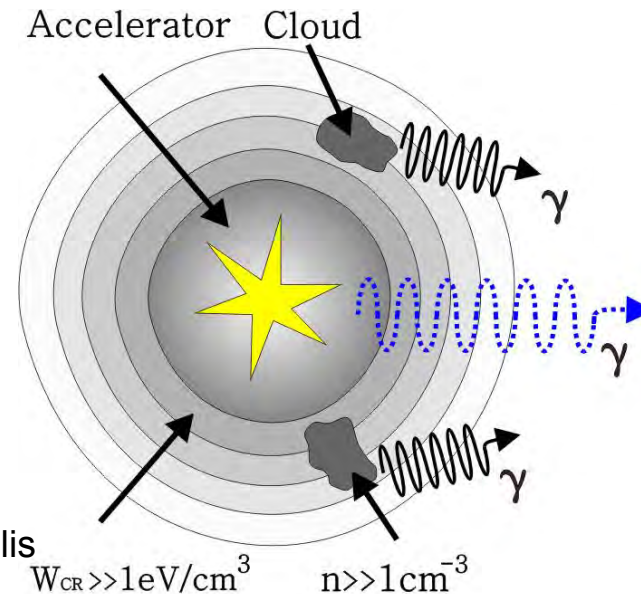$$\Rightarrow \frac{dN}{dE} \propto E^{-s-1} \equiv E^{-\Gamma}$$

- For $<\beta> \sim 1/30$, $(1-P)\sim0.05$ one has $\Gamma \sim 2.7$

Proof of the origin of CR up to almost the knee

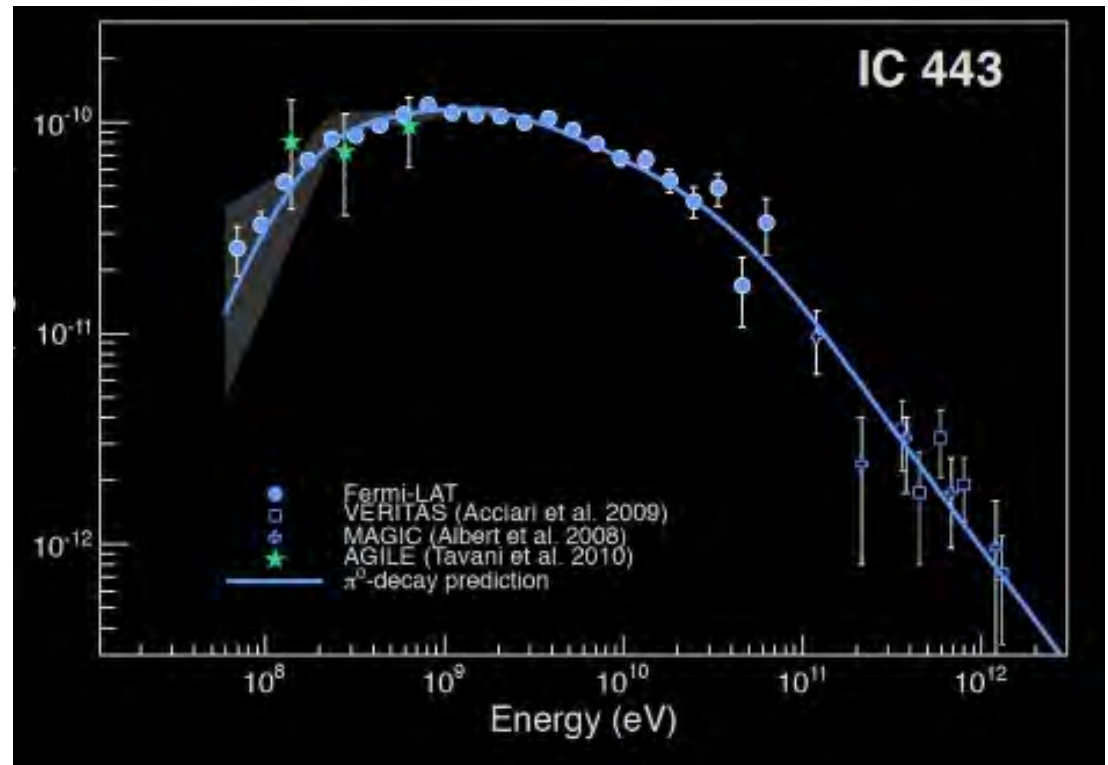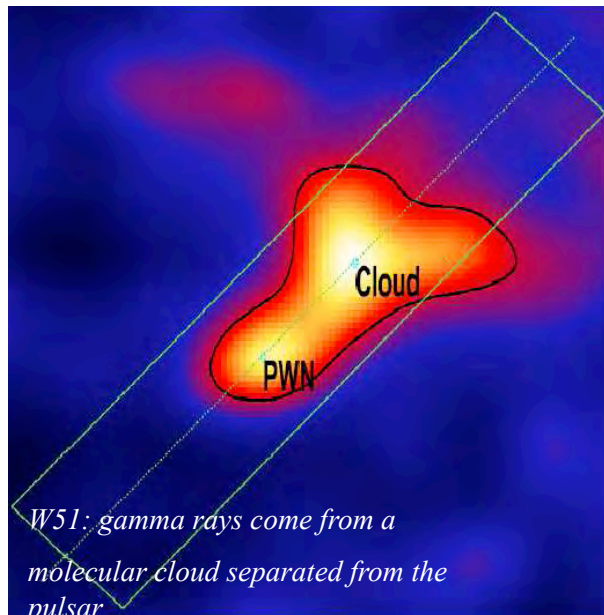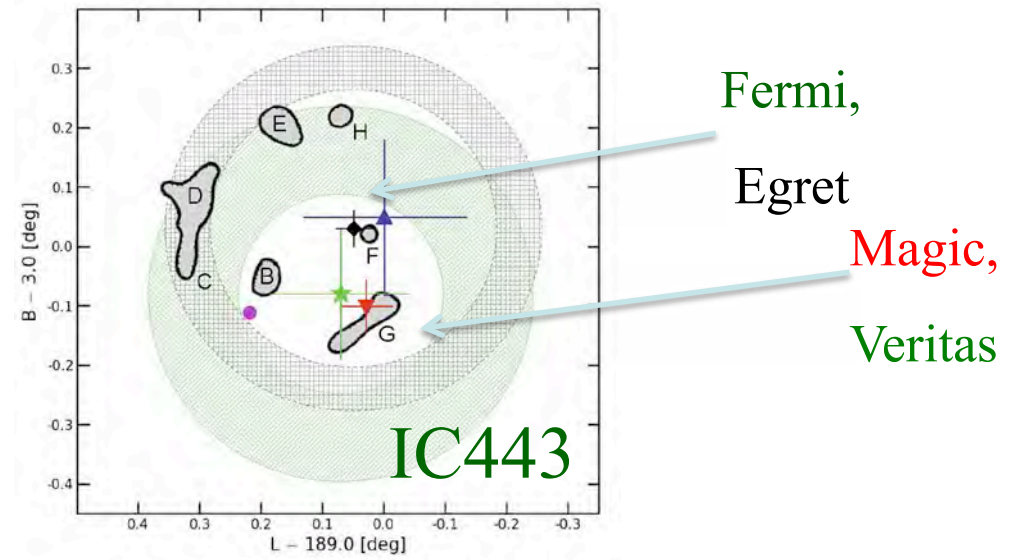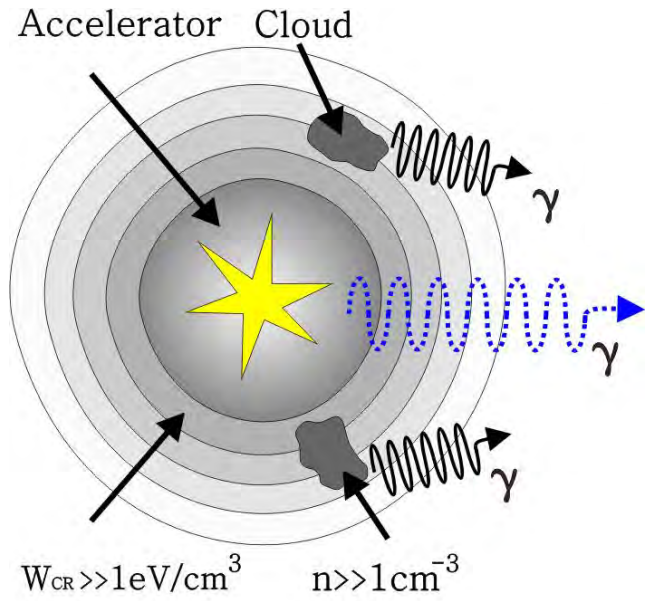- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004) with photons

- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)

Fermi,

Egret

Magic,

Veritas

IC443

Alessandro De Angelis

47

Accelerator   Cloud

$W_{CR} \gg 1eV/cm^3$ $n \gg 1cm^{-3}$

Fermi,

Egret

Magic,

Veritas

IC443

W51: gamma rays come from a molecular cloud separated from the pulsar

Cloud

PWN

IC 443

Fermi-LAT
VERITAS (Acciari et al. 2009)
MAGIC (Albert et al. 2008)
AGILE (Tavani et al. 2010)
π^0-decay prediction

Energy (eV)

Extragalactic sources: situation less clear (Auger?)
Joint HESS-MAGIC-VERITAS campaign on M87 (Science 2009)

The M87 radio-galaxy Jet

Colours: 0.2 - 6 keV (*Chandra*)
Contours: 8 GHz radio (VLA)

HST-1
Core
Knot D
Knot A
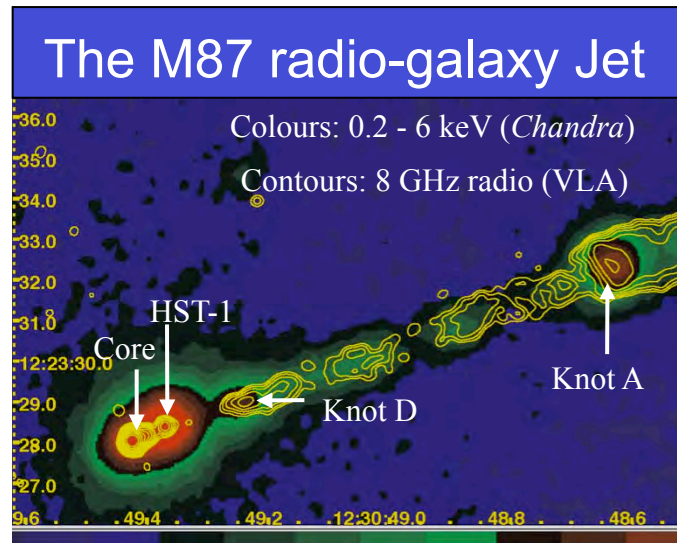
- Al ~60 Mly
- Shared monitoring HESS, MAGIC VERITAS
- Confirmation of day-scale VHE variability
- Correlation with the nucleus in X & Radio.
- Evidence of central origin of the VHE emission (60 Rs to the BH)

VHE

X-ray
nucleus

Radio
nucleus
Peak flux
jet