Astroparticle Physics

Lecture 1

- Introduction
- The data
- Sources of high-energy beams from space

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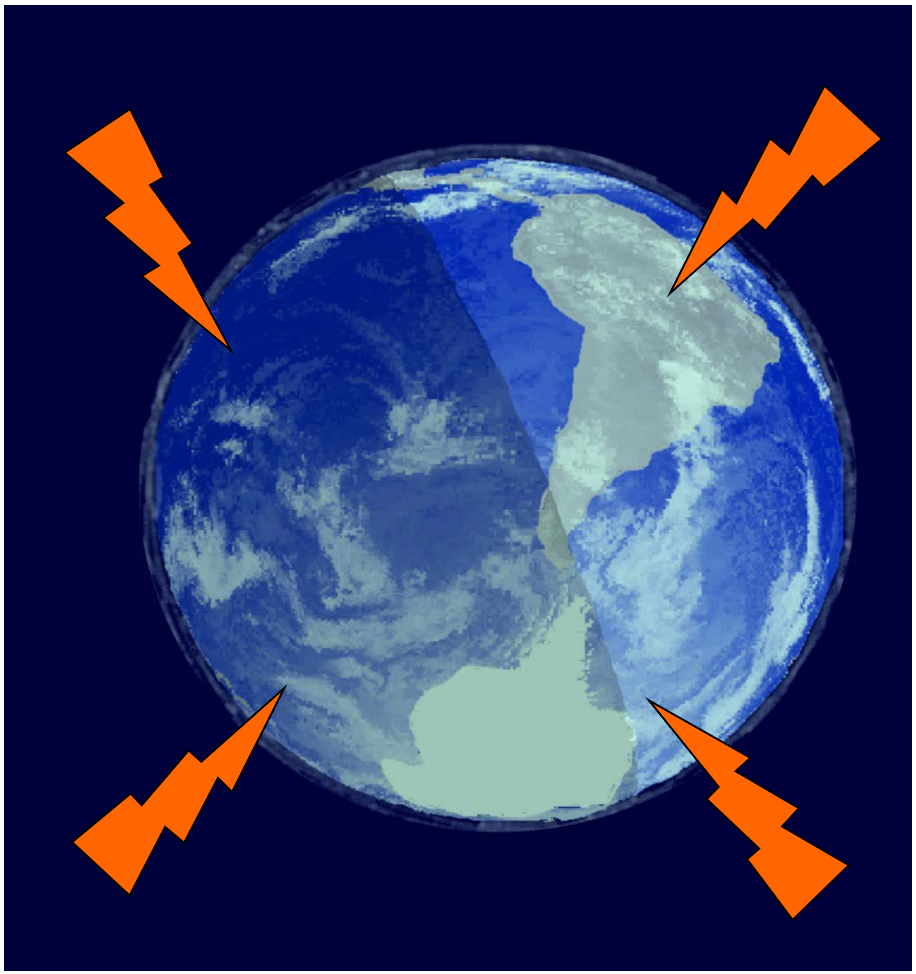
Lund, March 2014

Messengers from the High Energy Universe



Photons

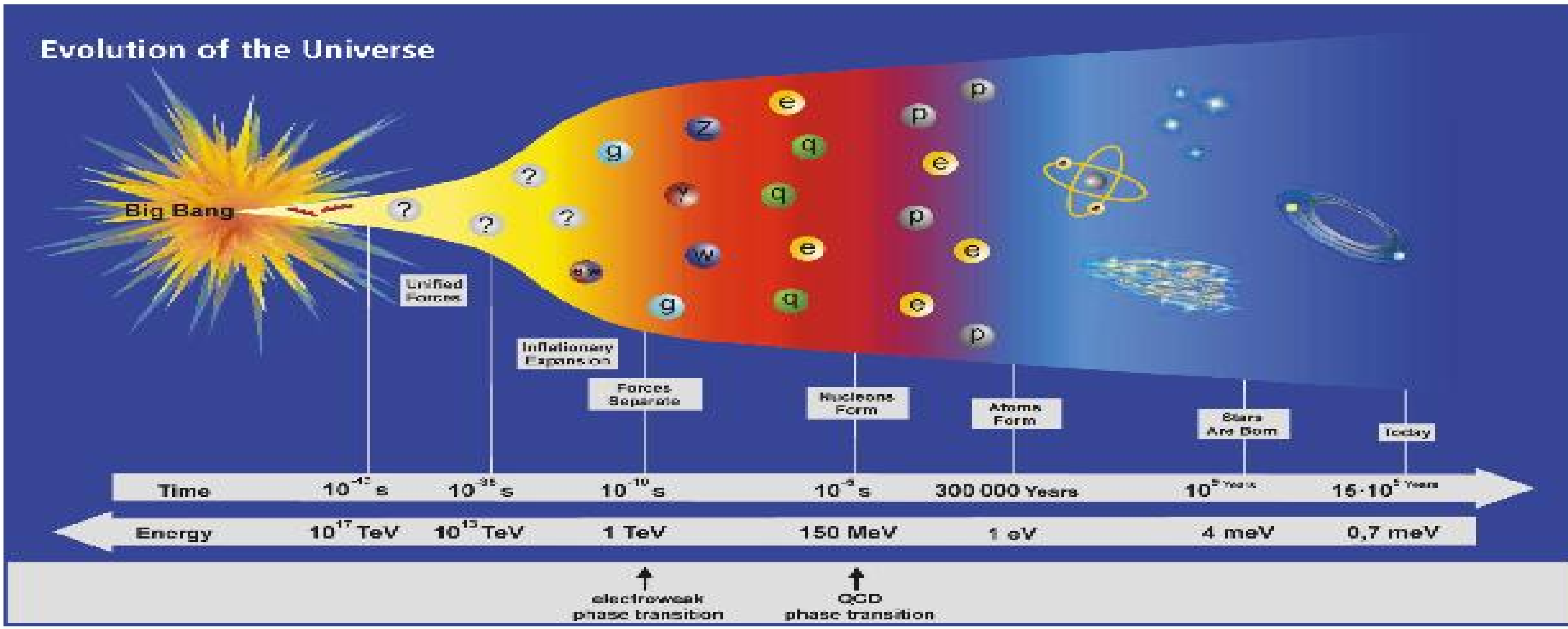
Cosmic rays

Neutrinos

Gravitational Waves

???

The Physics



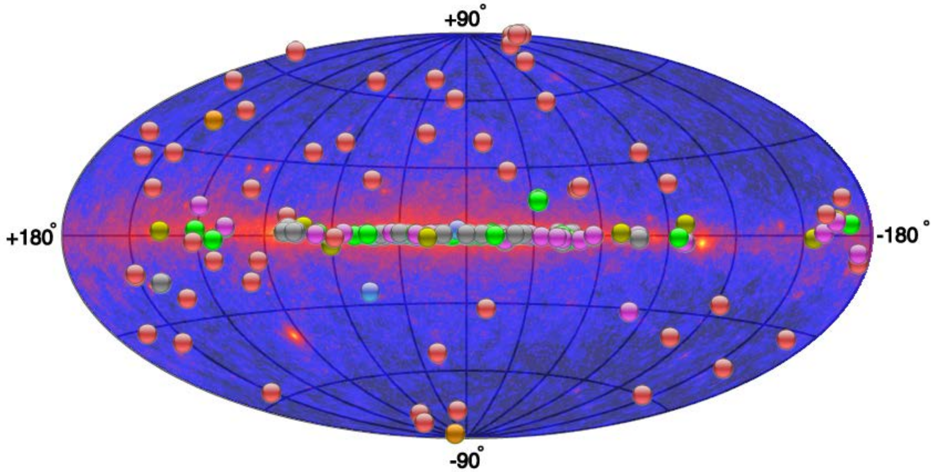
Evolution of the Universe
Big Bang
Unified Forces
Inflationary Expansion
Forces Separate
Nucleons Form
Atoms Form
Stars Are Born
Today
Time
10^{-10} s
300 000 Years
Energy
10^{17} TeV
10^{13} TeV
1 TeV
150 MeV
1 eV
4 meV
0,7 meV
electroweak phase transition
QCD phase transition

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

Astrophysics

Sources:AGNs, Pulsares, GRBs, SNRs…

Aceleration mechanisms, propagation



γ sky > 100 GeV
Mar 2013

Particle Physics

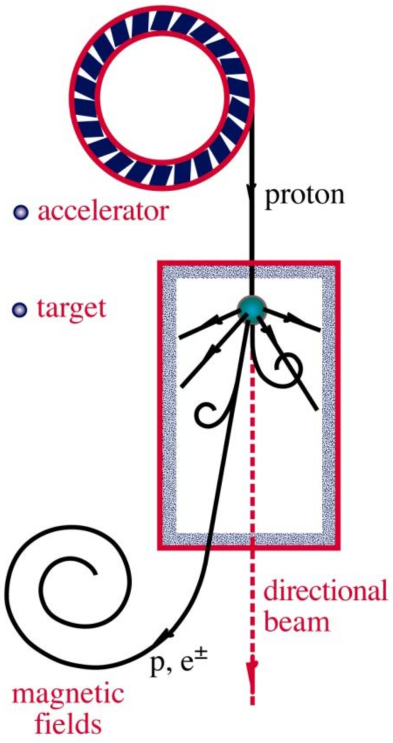
High Energies

$\sqrt{s}$ ~ 100 – 400 TeV

Low fluxes

Limited kinematic region

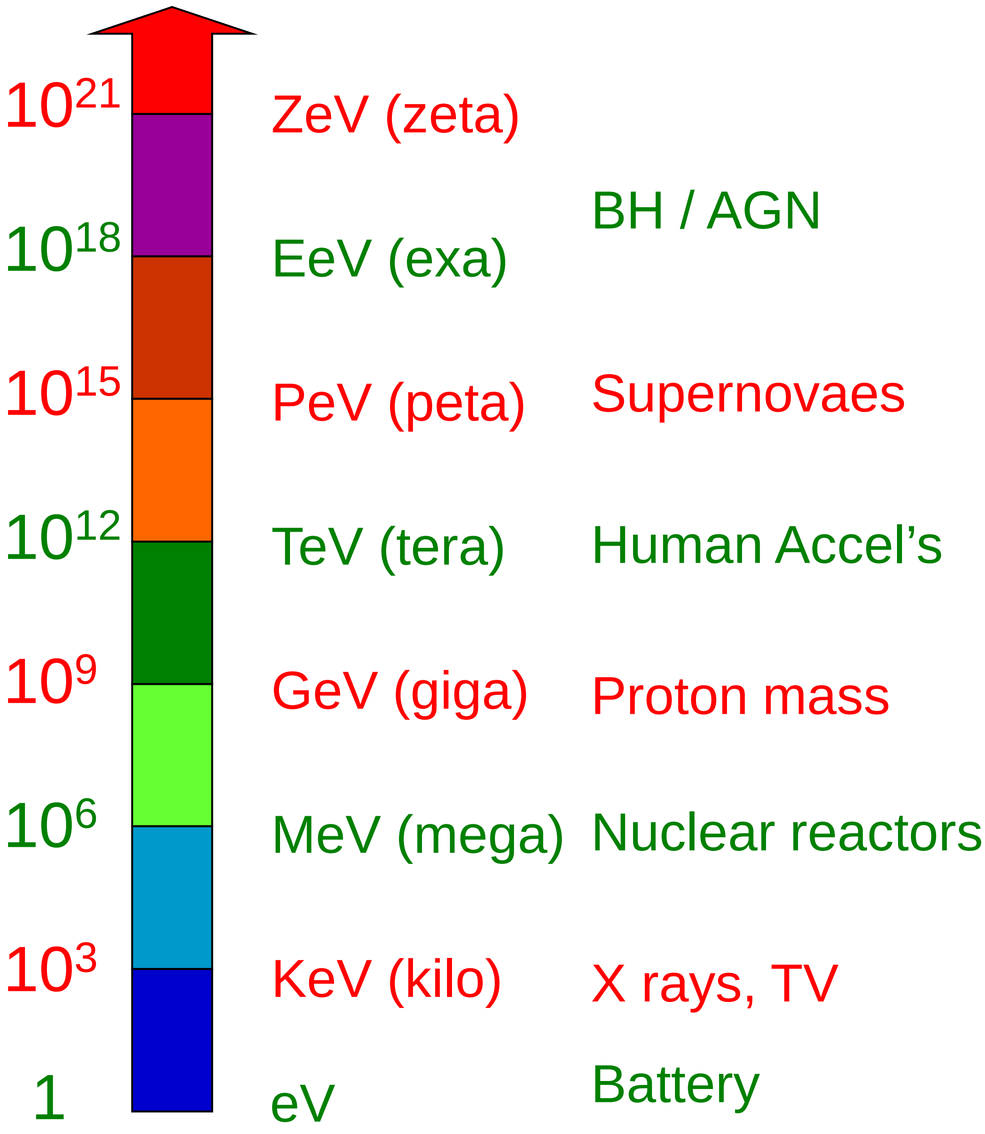
Poor detection capabilities



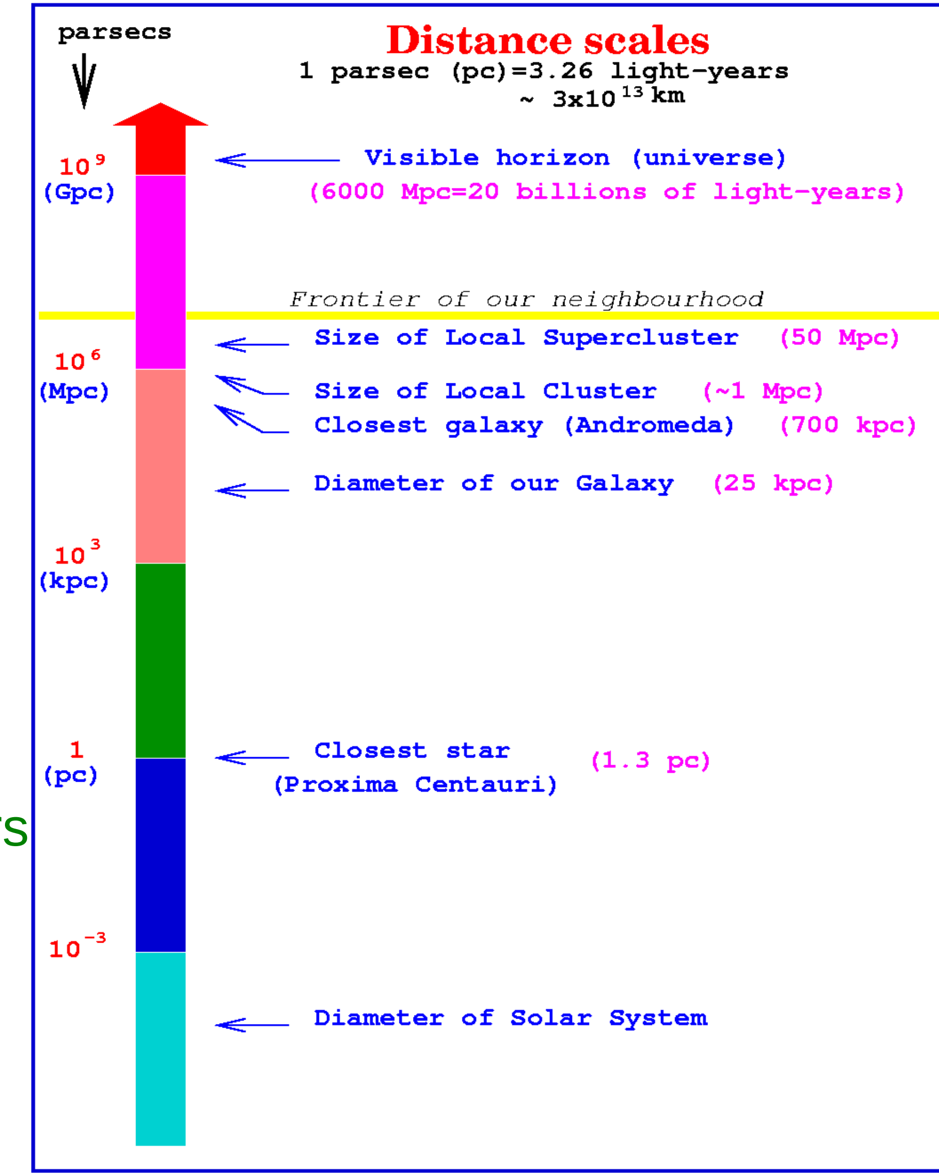
Cosmology/Fundamental Physics

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

Energy scales



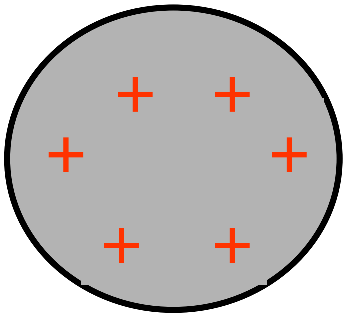
Distance scales



THE BEGINNINGS

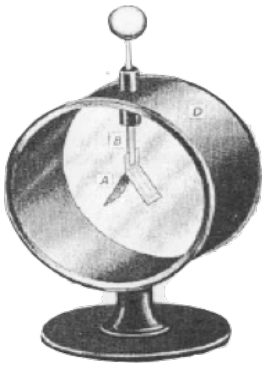
Free electrical charges in the atmosphere

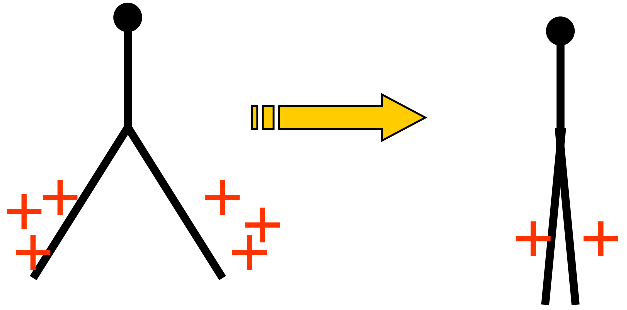
Coulomb, 1785



Spontaneous discharge of
charged conductors ...

End of XIX century

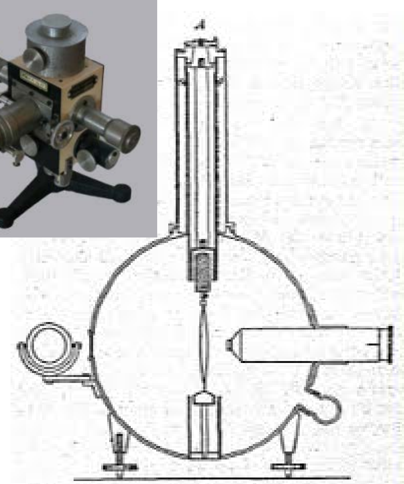




Curie: Radioactivity ?

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

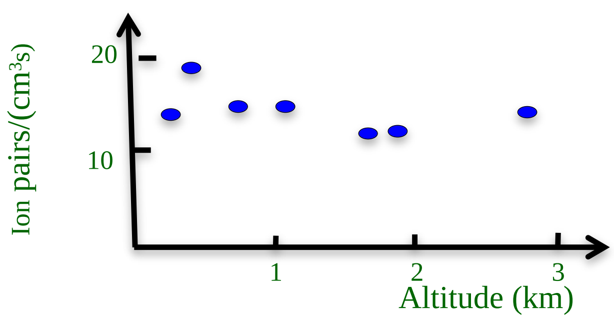
By sea and by sky

Wulf 1909-1910

Gockel 1909

Domenico Pacini1911

Results not conclusive



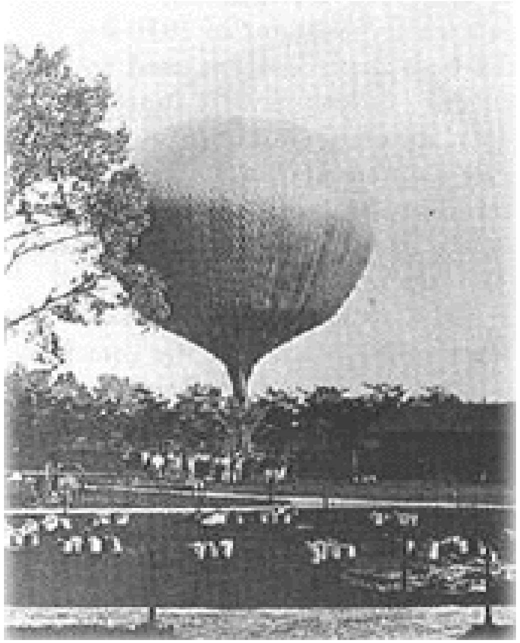
the winning idea: immersing an electroscope 3m deep in the sea Pacini finds a significant (20% at 4.3σ) reduction

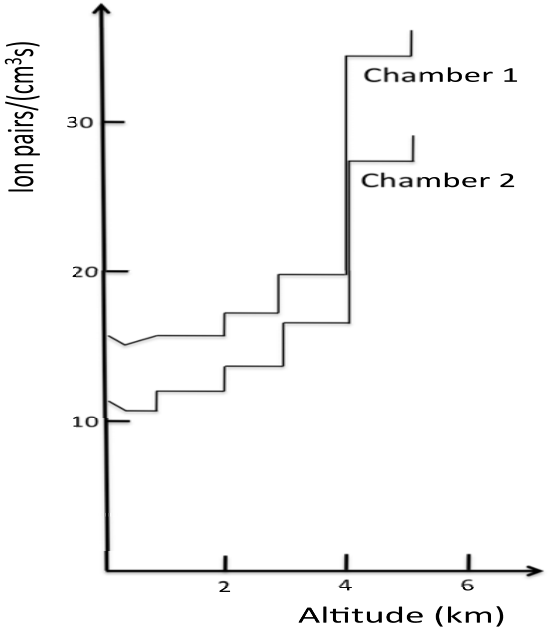
Part of the radiation comes from the sky!!!

Victor Hess, 1912

Several flights up to 6 Km

Day/night, eclipses, ...

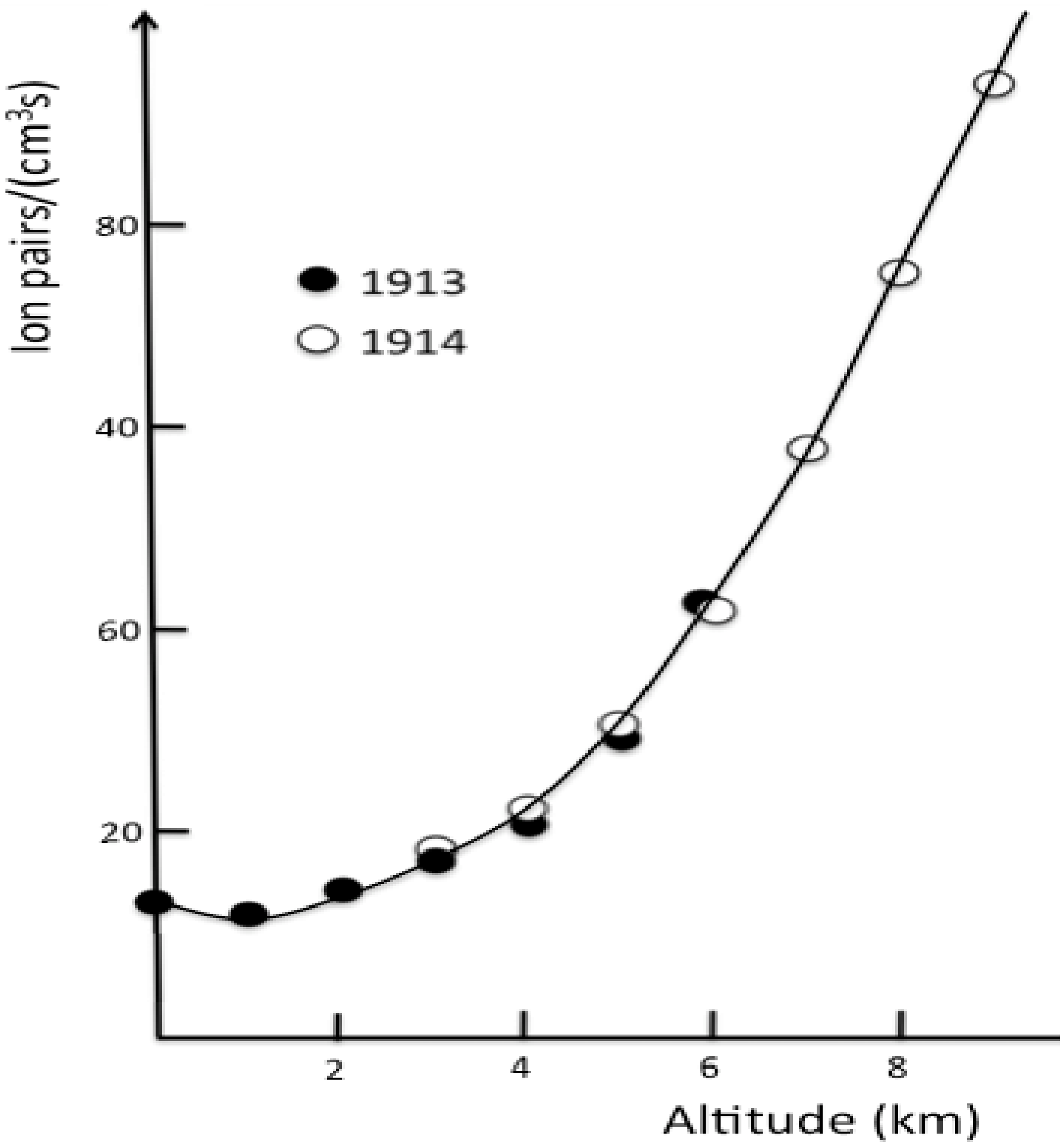




“Cosmic Rays” (Millikan 1926)

The confirmation

Kolhörster



Flights up to 9200 m

Final flight in the day

in which WWI started

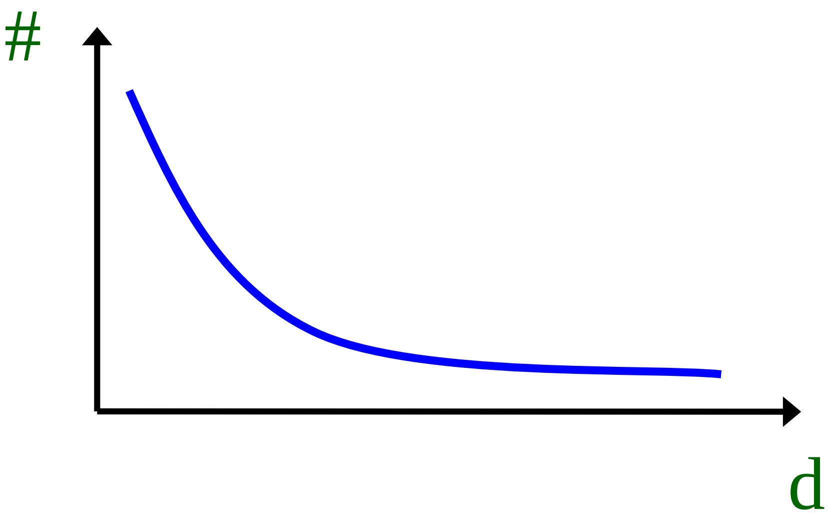
=> New world

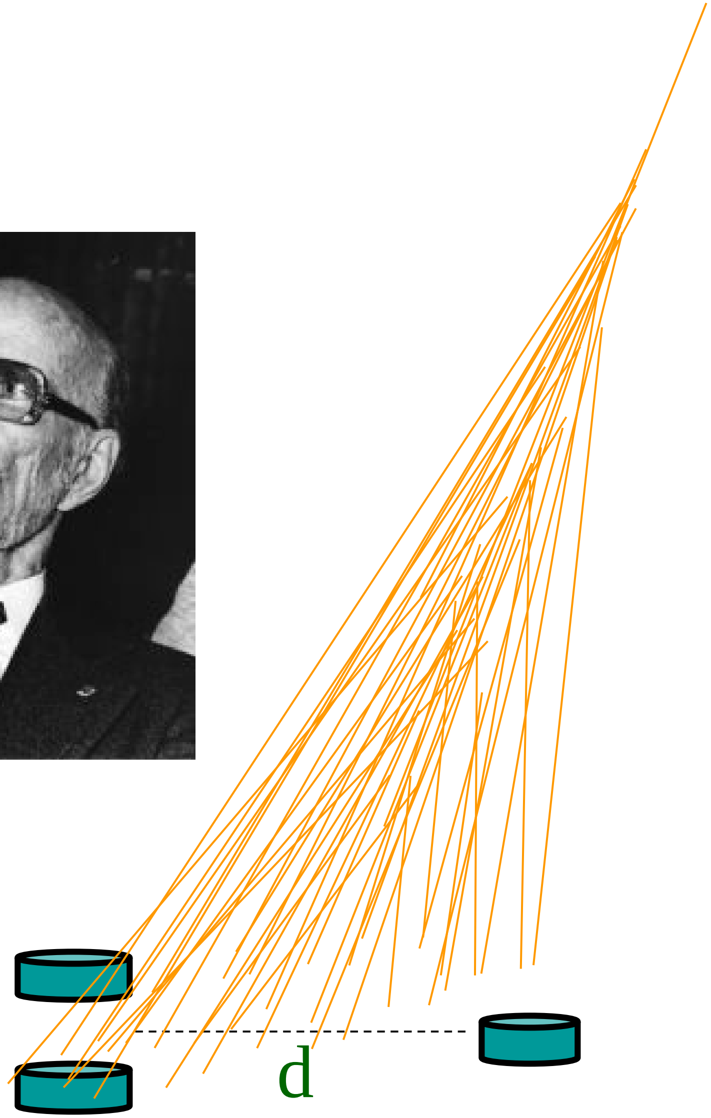
Particle showers

Rossi 1934

Pierre Auger, 1938

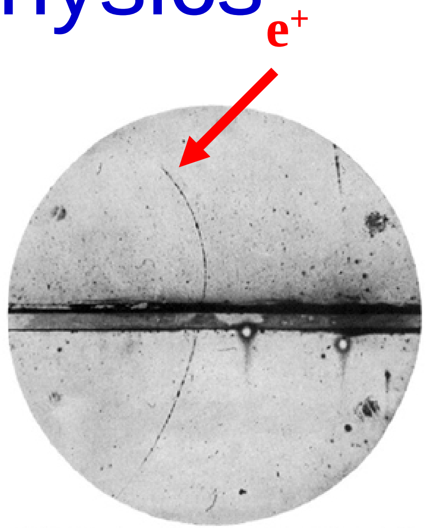
Coincidences





First shower energy estimates

The Birth of Particle Physics



Positron (Anderson 1932)

Antimatter! (Dirac)

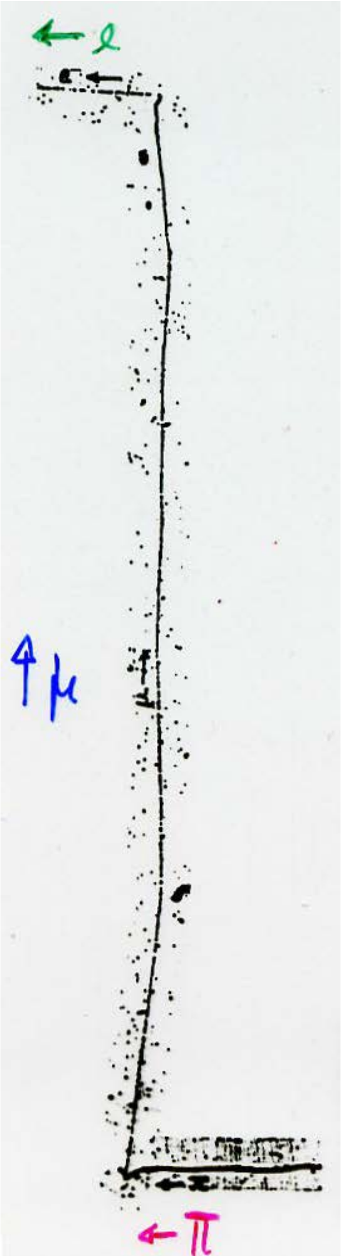
$\gamma \rightarrow e^+e^-$ (Einstein)

μ (Anderson 1937)

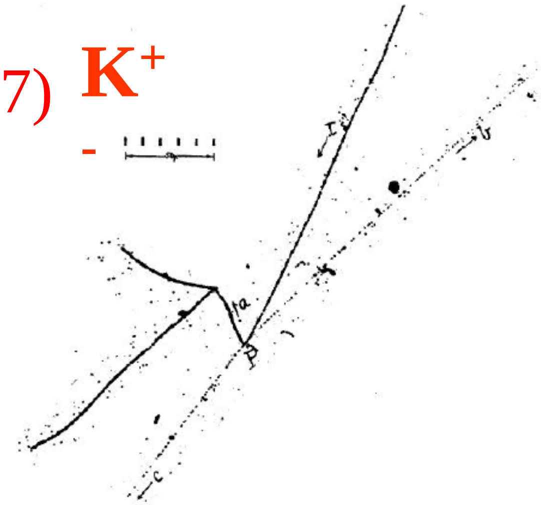
Rossi, 1940:

Muon life time.

Time dilation!



π (Lattes, Occhialini, Powell 1947)



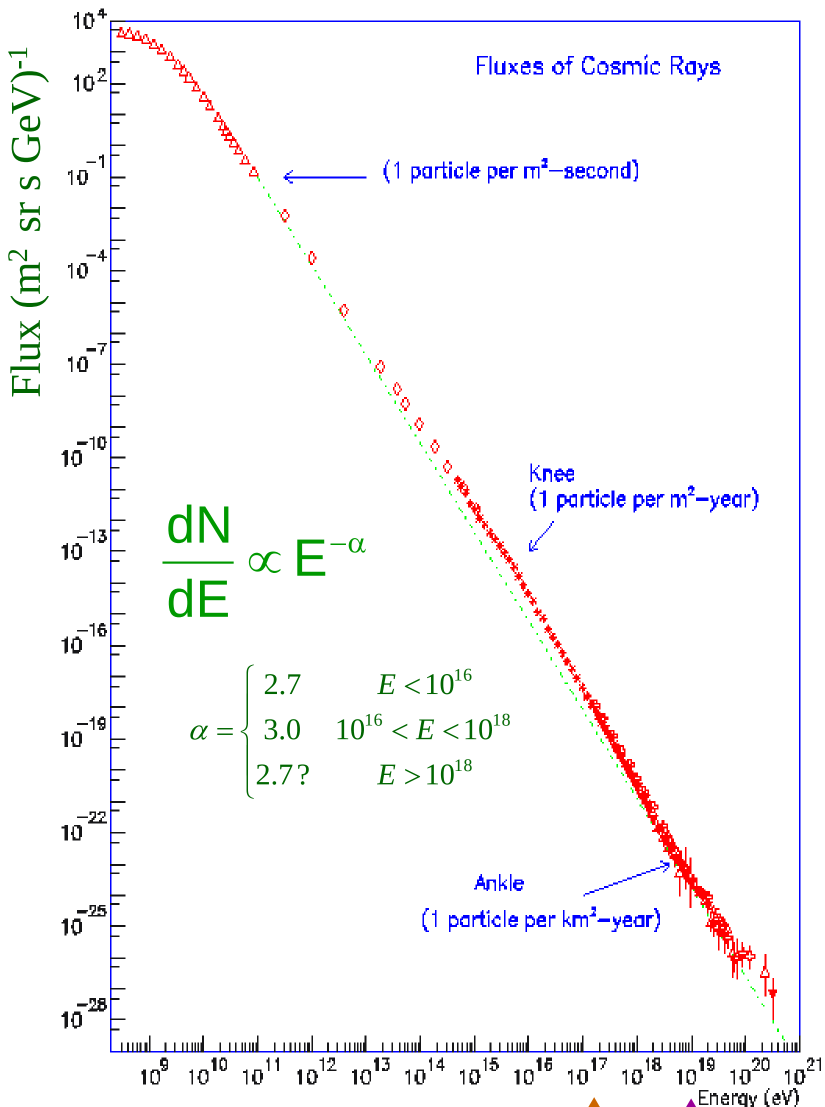
Strong interactions (Yukawa)

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

Strangeness

WHAT THE UNIVERSE TOLD US
(up to now)

Charged cosmic rays (p/nucleus)



Energy (eV)

LHC

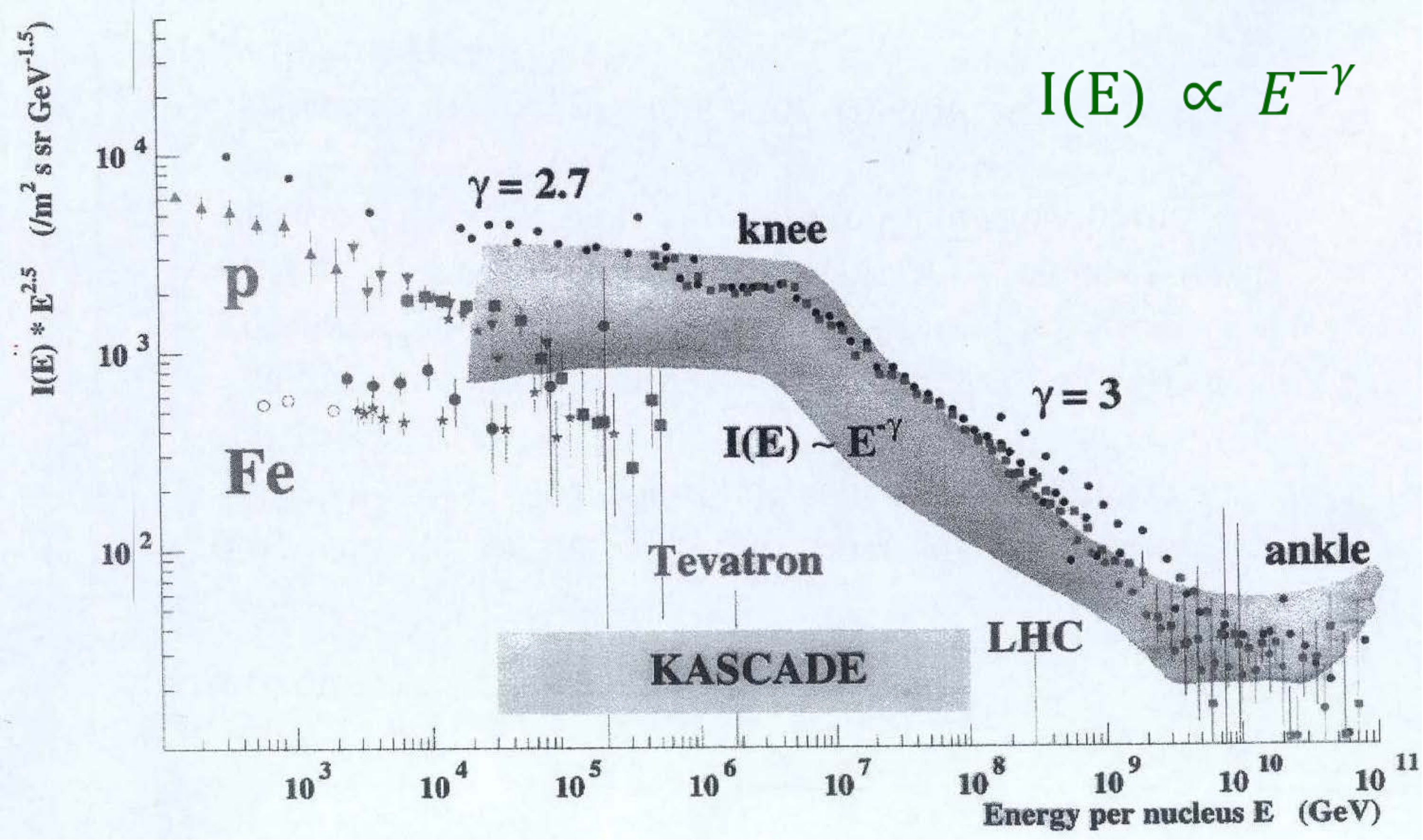
100 TeV

John Linsley, 1962

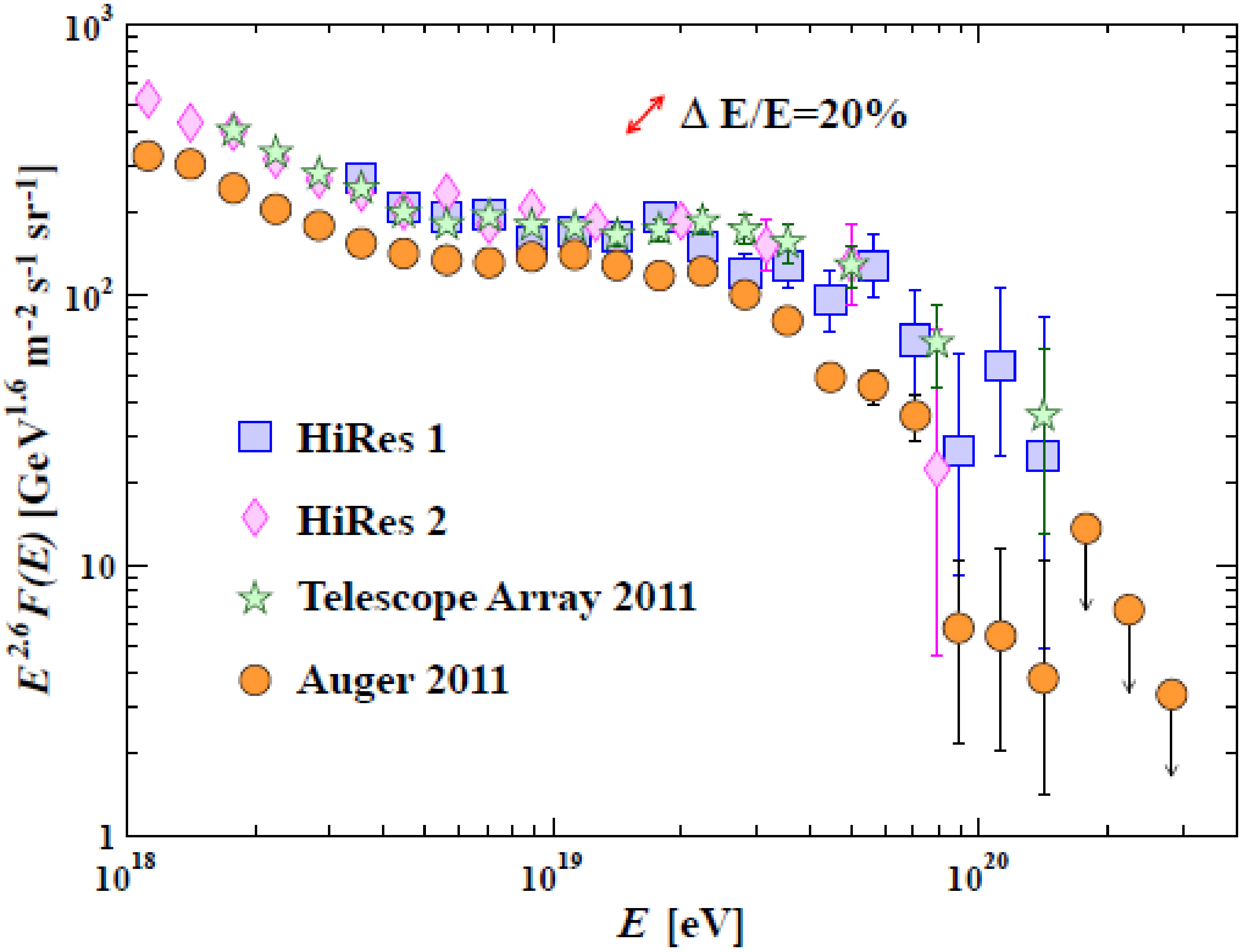
Forward Region
Extreme Energies

Small fluxes
indirect measurements

Anthropomorphic representation

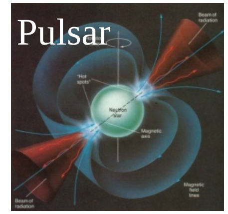


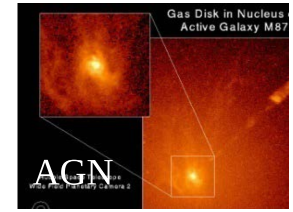
The highest energy region (E >10^{18} eV)



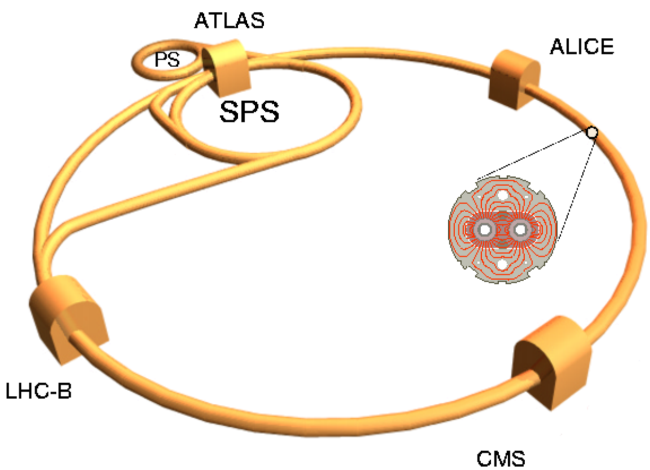
J. Beringer et al (PDG) PR D86 010001 (2012)

Where can be these accelerators in the Universe?





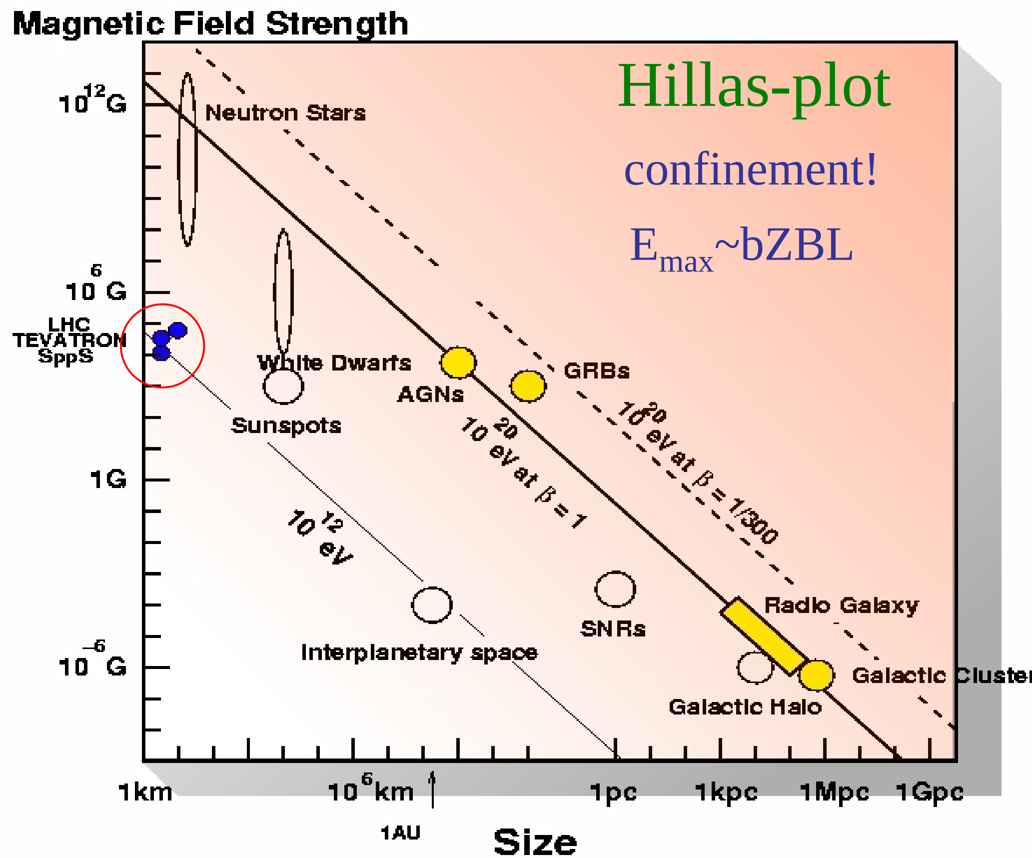
Large Hadron Collider



$E \propto BR$

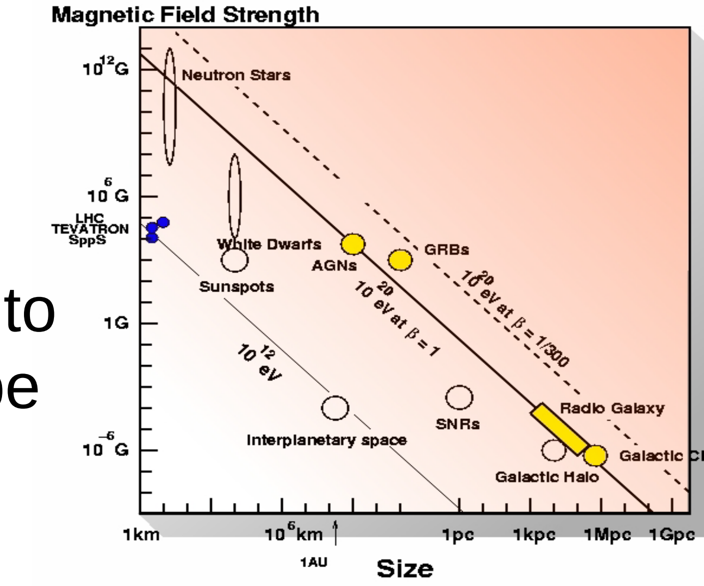
$R \sim 10\,\mathrm{km}$, $B \sim 10\,\mathrm{T}$

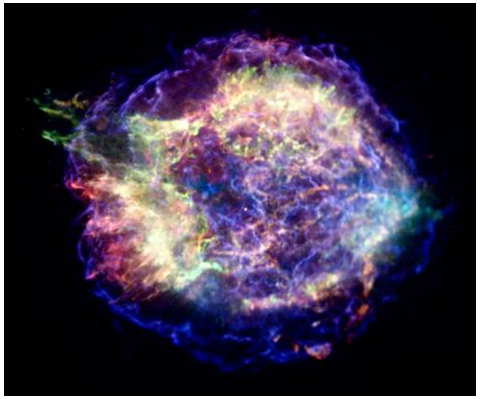
$E \sim 10\,\mathrm{TeV}$



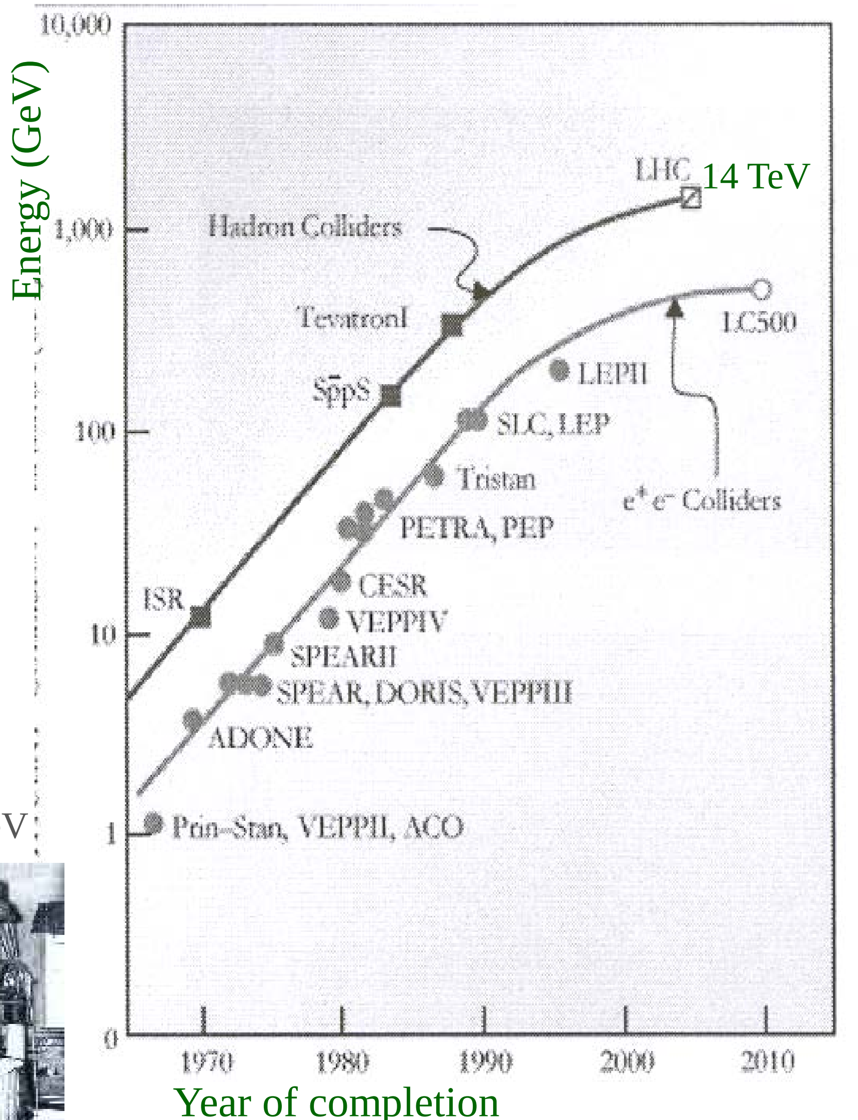
A few new terms

- 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.

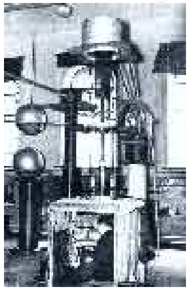




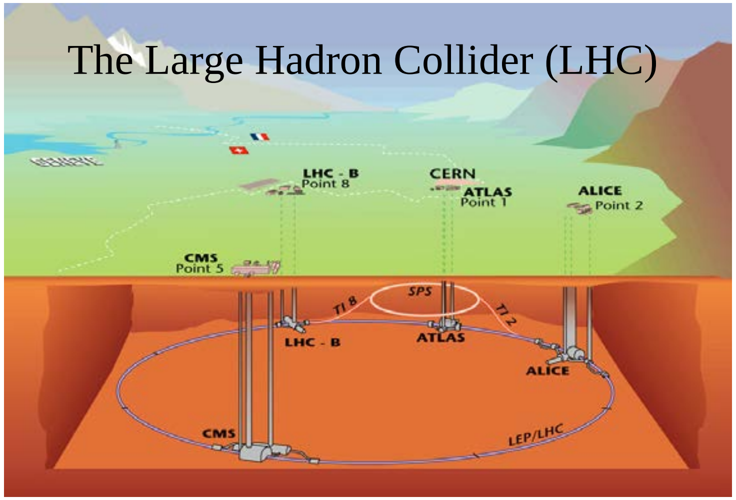
They surpass human-made accelerators



~ 10 MeV



~1930



High Luminosity
Sophisticated detectors

Central region
Energy limited

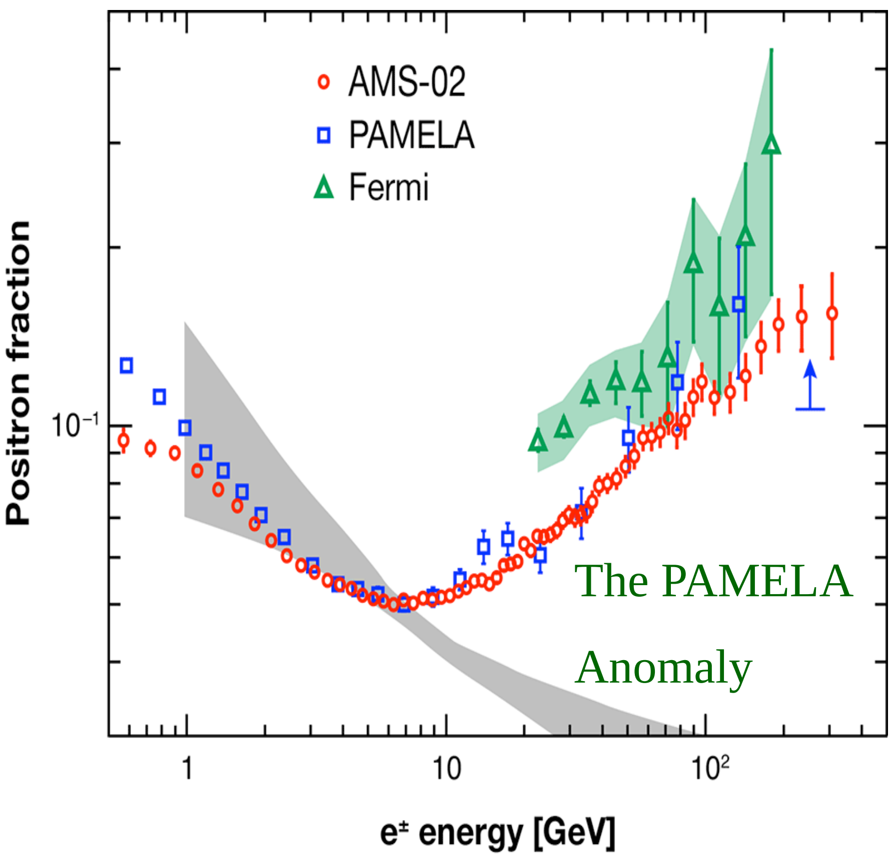
Cosmic-Ray Composition

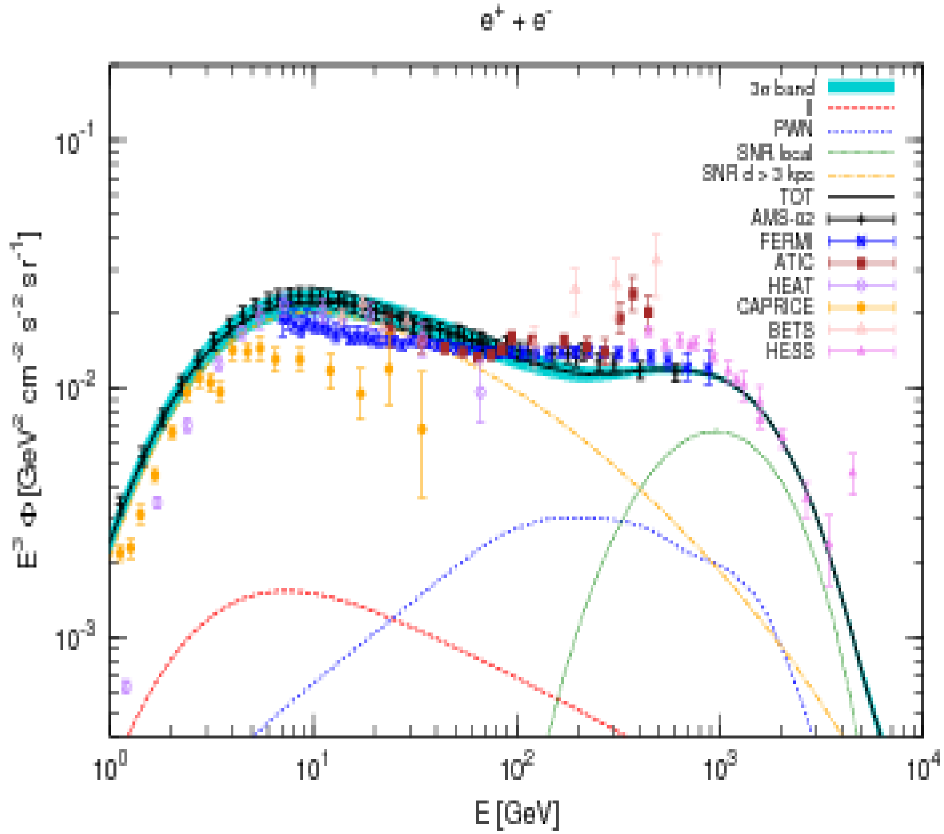
Z	Element	F	Z	Element	F
1	H	540	13–14	Al-Si	0.19
2	He	26	15–16	P-S	0.03
3–5	Li-B	0.40	17–18	Cl-Ar	0.01
6–8	C-O	2.20	19–20	K-Ca	0.02
9–10	F-Ne	0.30	21–25	Sc-Mn	0.05
11–12	Na-Mg	0.22	26–28	Fe-Ni	0.12

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.

J. Beringer et al (PDG) PR D86 010001 (2012)

Antimatter from Space





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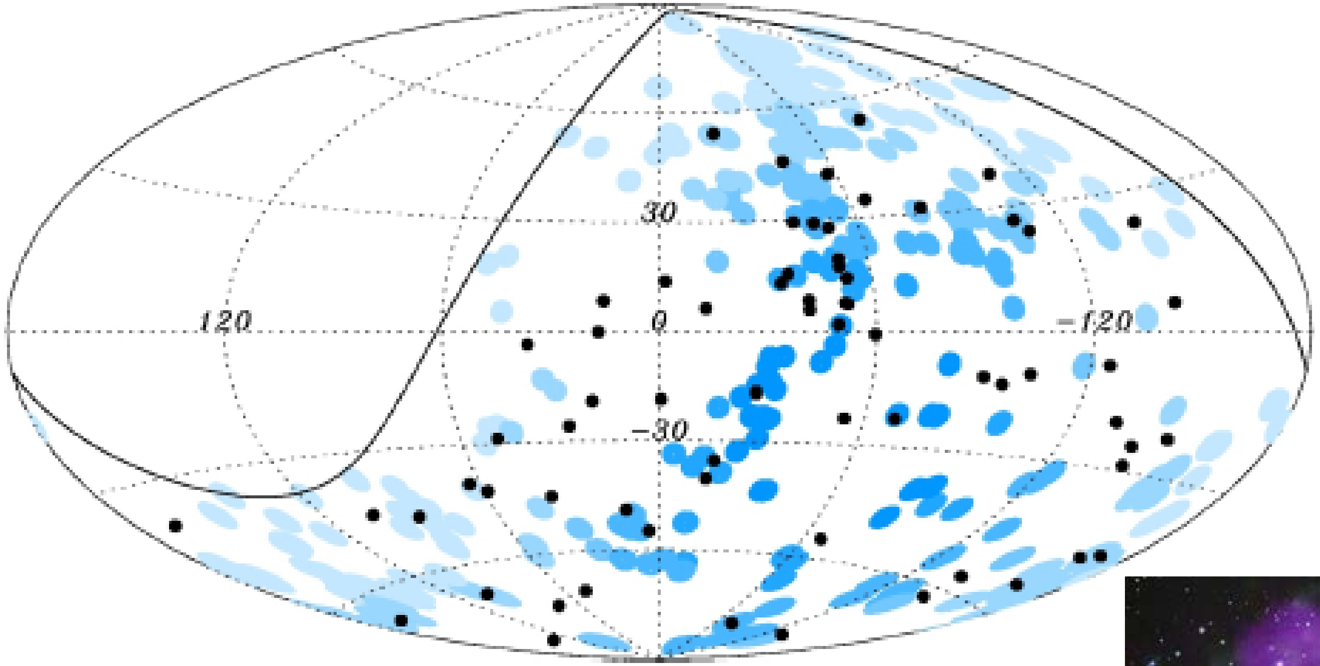
UHECR Correlation with AGNs



28 out of 84 correlate

Vernon-Cetty-Vernon AGN catalog

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

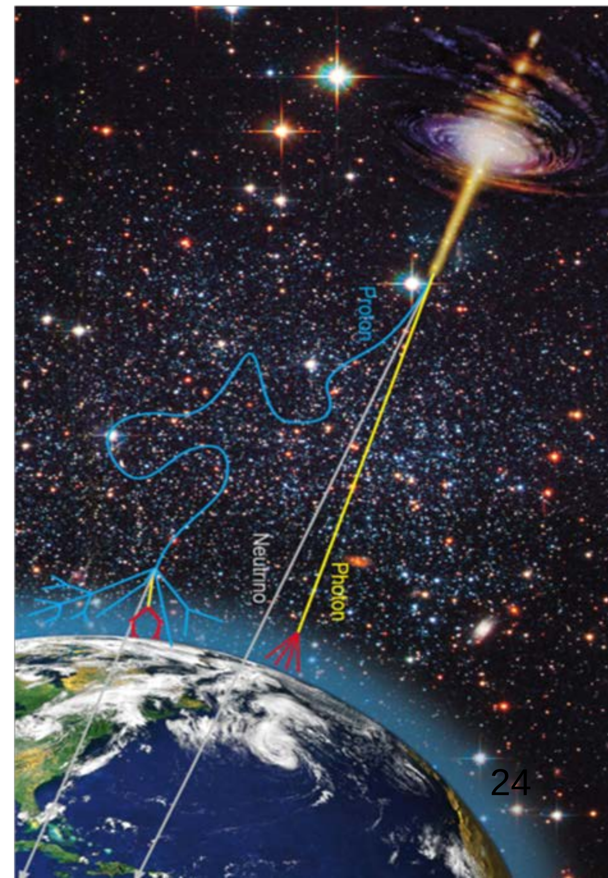
Cen A?

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

$$\frac{r}{1\ \mathrm{pc}} \simeq \frac{\frac{E}{1\ \mathrm{PeV}}}{\frac{B}{1\ \mu G}}$$

- 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

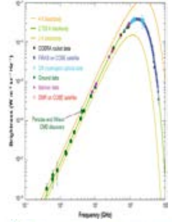
=> Locating the sources of charged CR is ~~impossible~~ AT GROUND

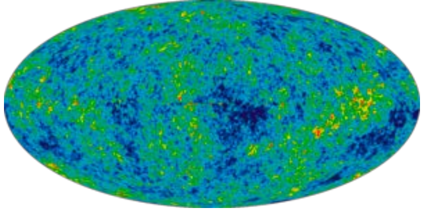
- We need to detect a large statistics of protons with E between 10^{19} eV and 10^{21} eV
- Areas ~ 30 thousand km^2 (1/10 of Italy), ~impossible to find
- Needs satellites
- VHE photons
- Neutrinos
  - Detected only from Sun and SN1987A
- Gravitons
  - Undetected up to now; we shall not discuss them

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

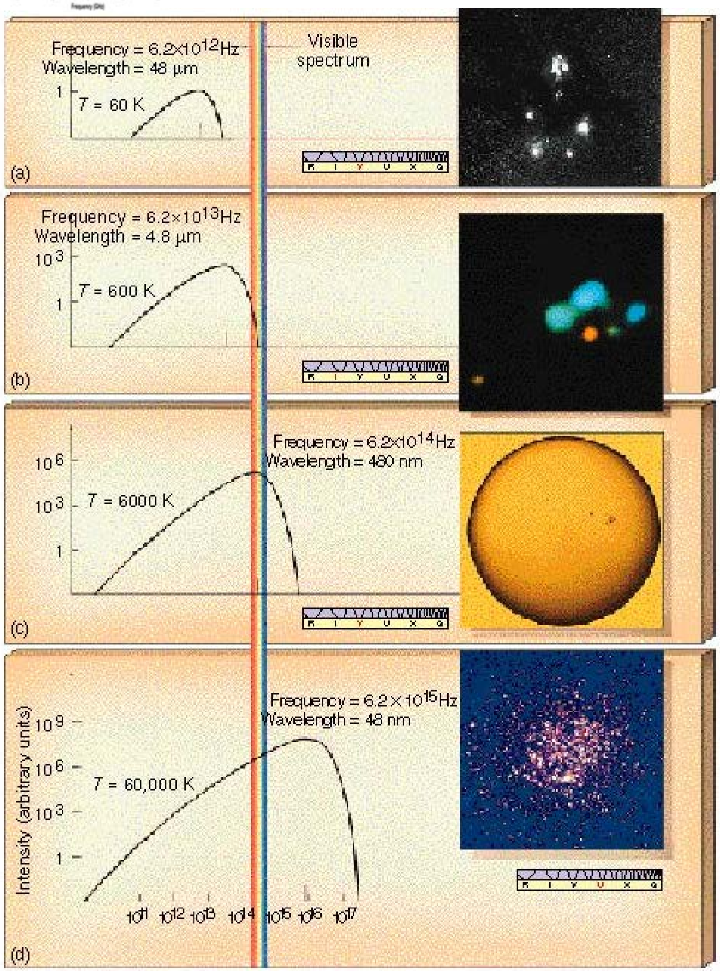
the Sun:

6000 K

Cluster of very bright stars, Omega Centauri,

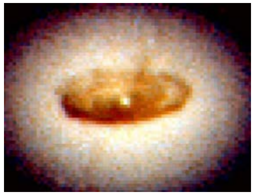
as observed from the space:

60,000 K



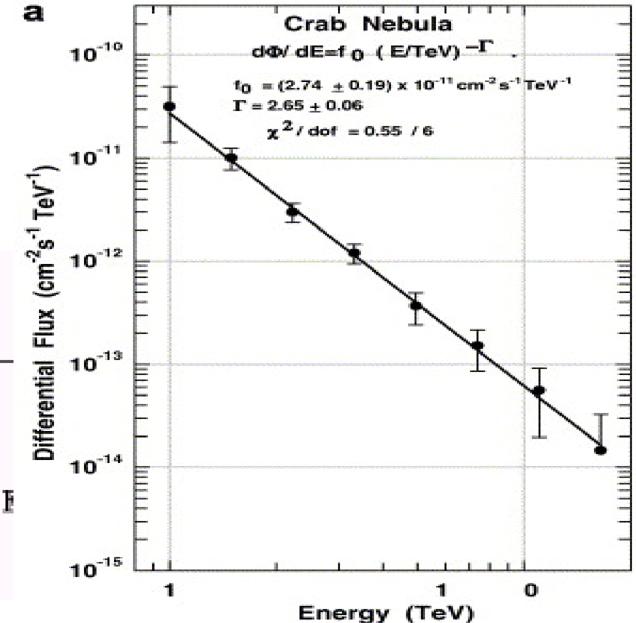
Accretion Disks can reach

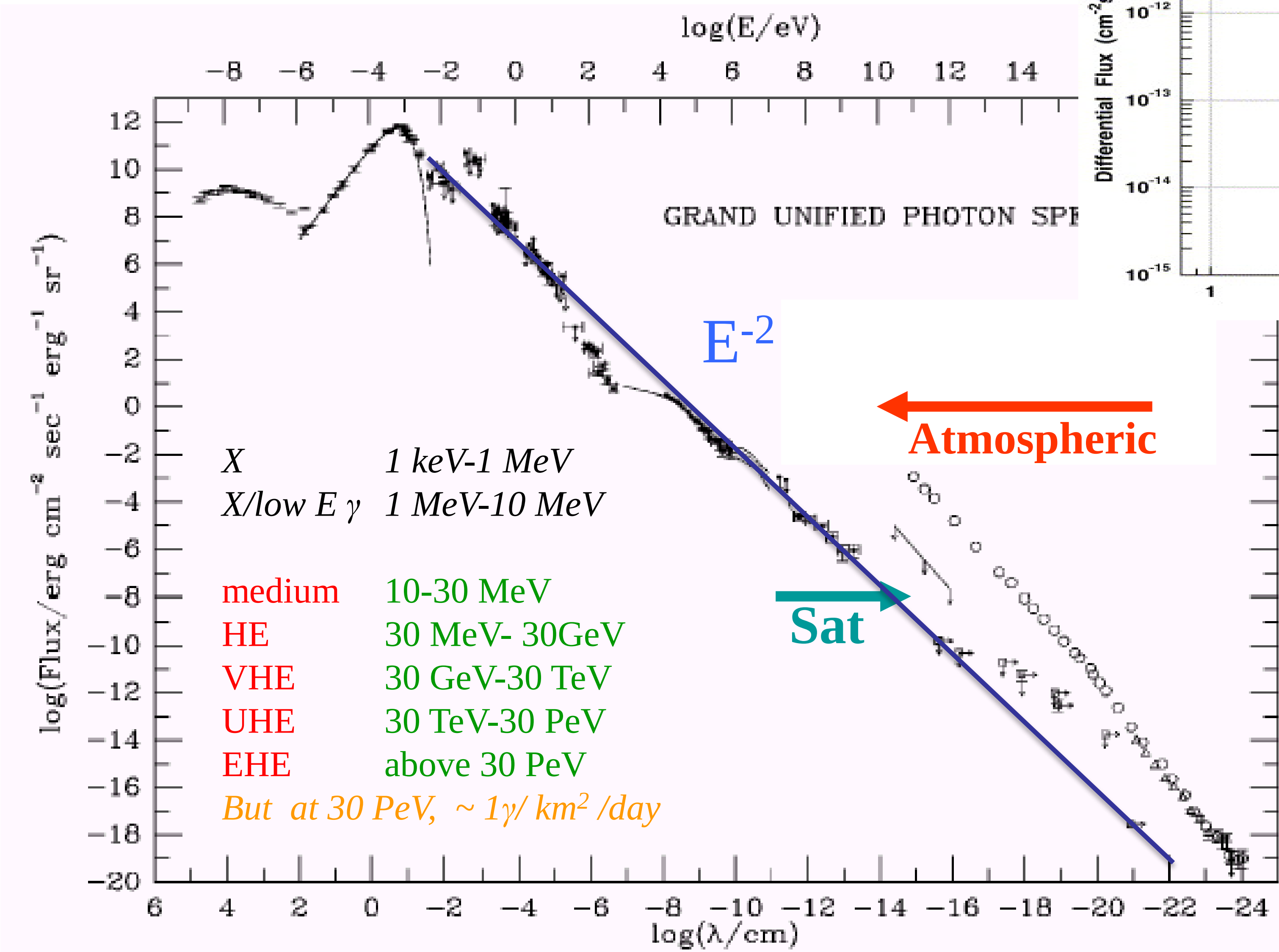
temperatures >> 10^5 K



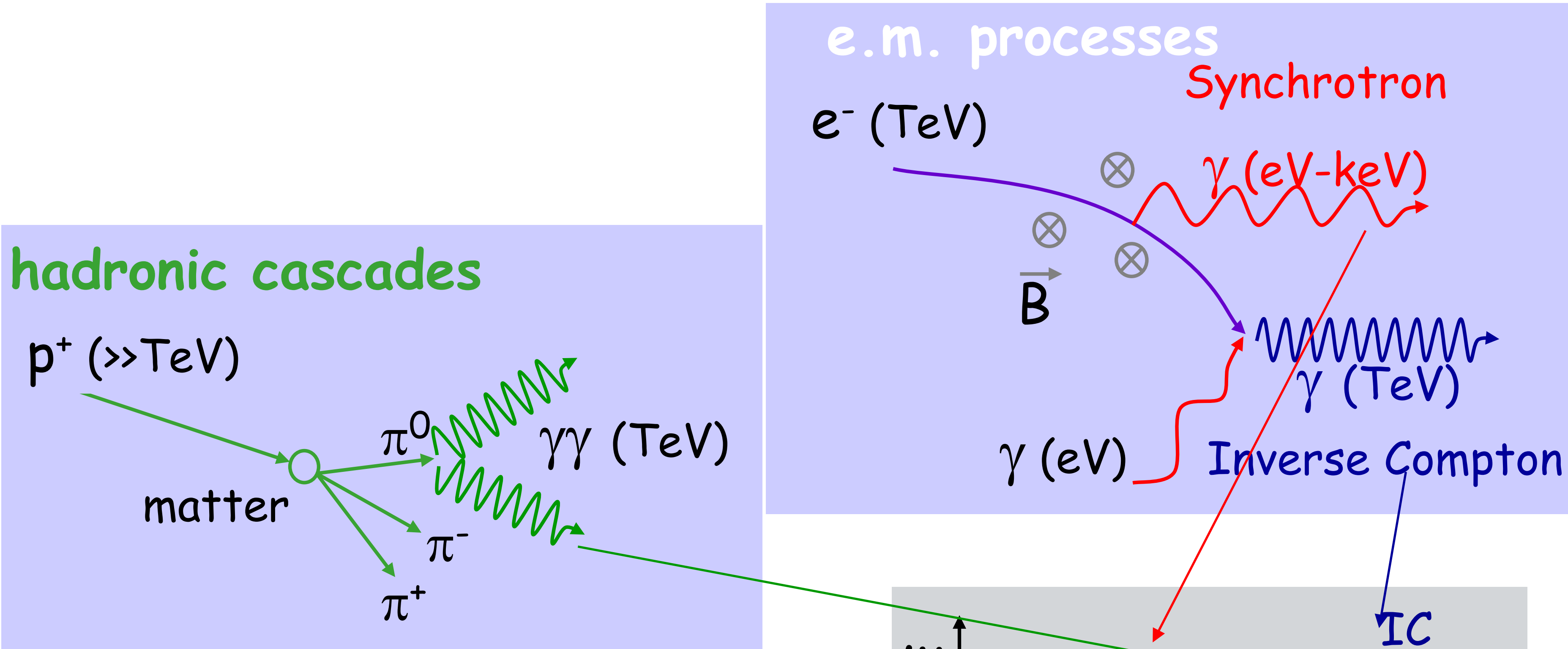
But this is still ~1 keV, in the X-Ray band!

γ energy spectrum



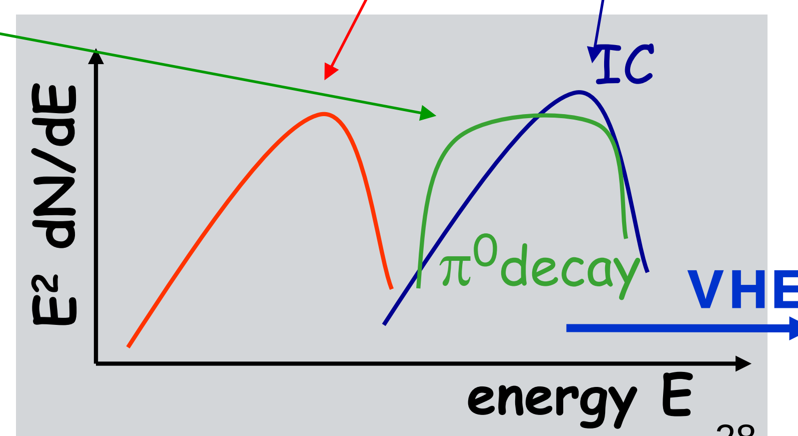


Cosmic γ rays: two different production mechanisms expected to be at work



In the VHE region,

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



To distinguish between had/leptonic origin

study Spectral Energy Distribution (SED):

(differential flux) · E^2

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)

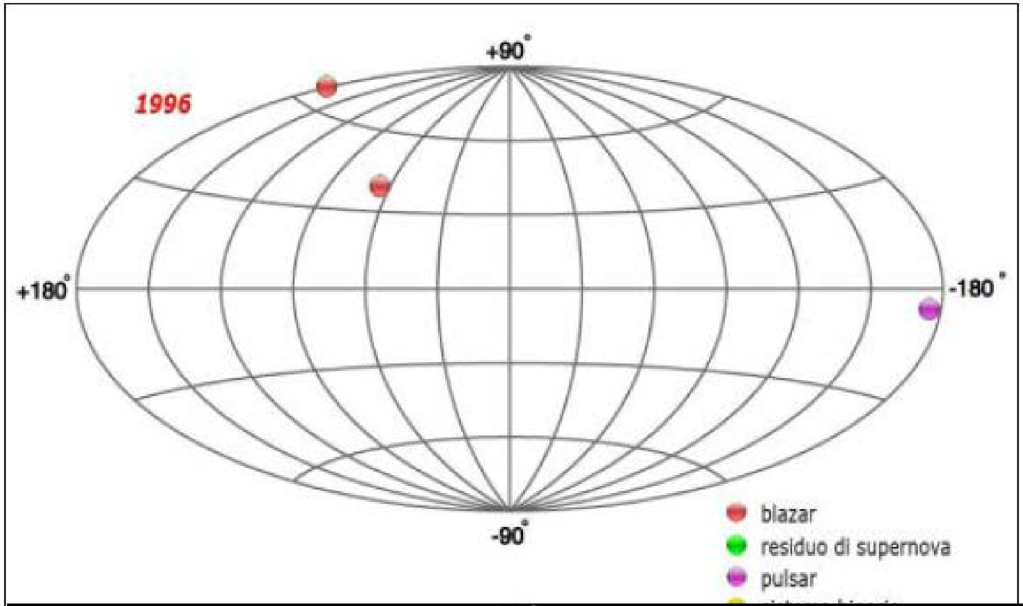
- No deflection from magnetic fields, gammas point ~ to the sources

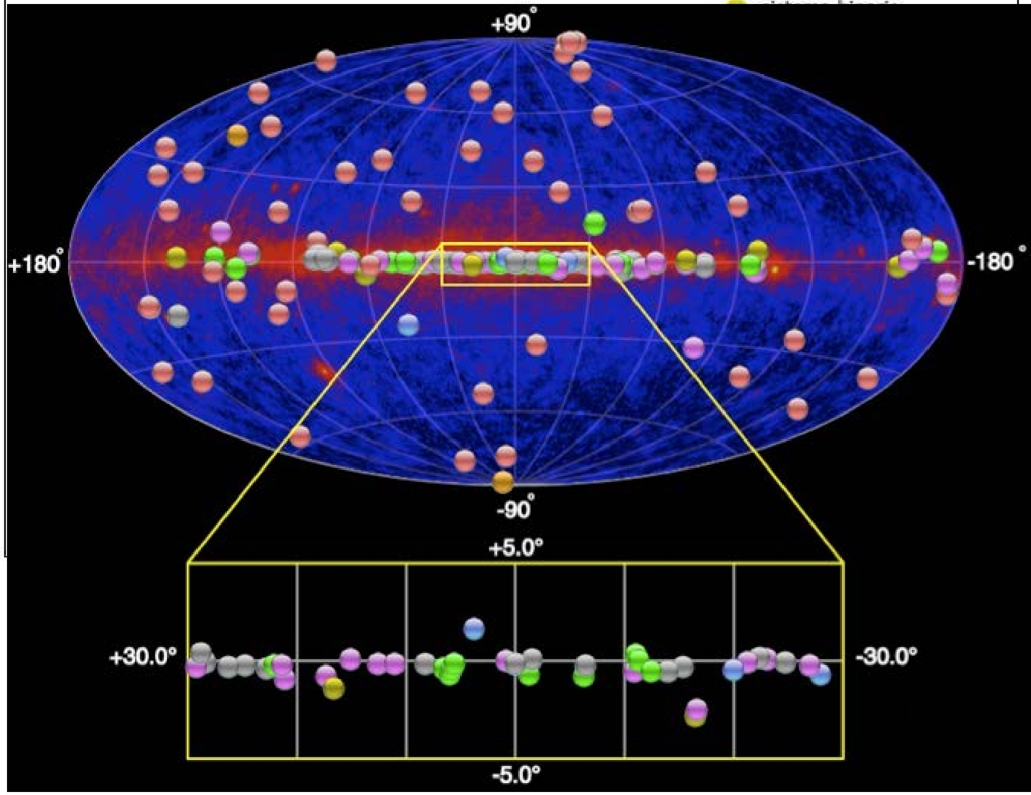
  Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

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: ~ 200 (and >200 papers) in the last 10 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*



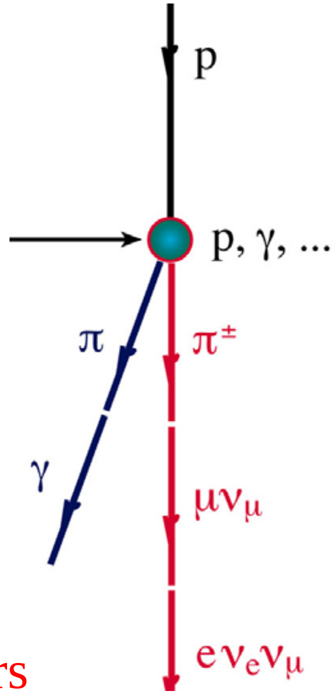


Neutrinos

- 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 ~2×10^{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

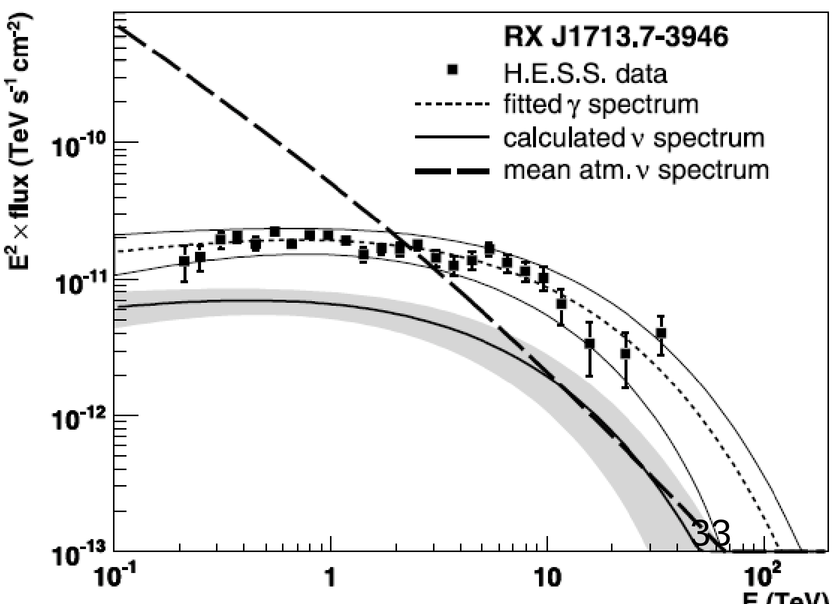
- Smoking gun would be a correlation of VHE CR (difficult: magnetic fields) or a neutrino signal
- Many model uncertainties present in the gamma/p relation disappear when studying gamma/neutrino



$\Rightarrow$Very accurate input for neutrino detectors

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

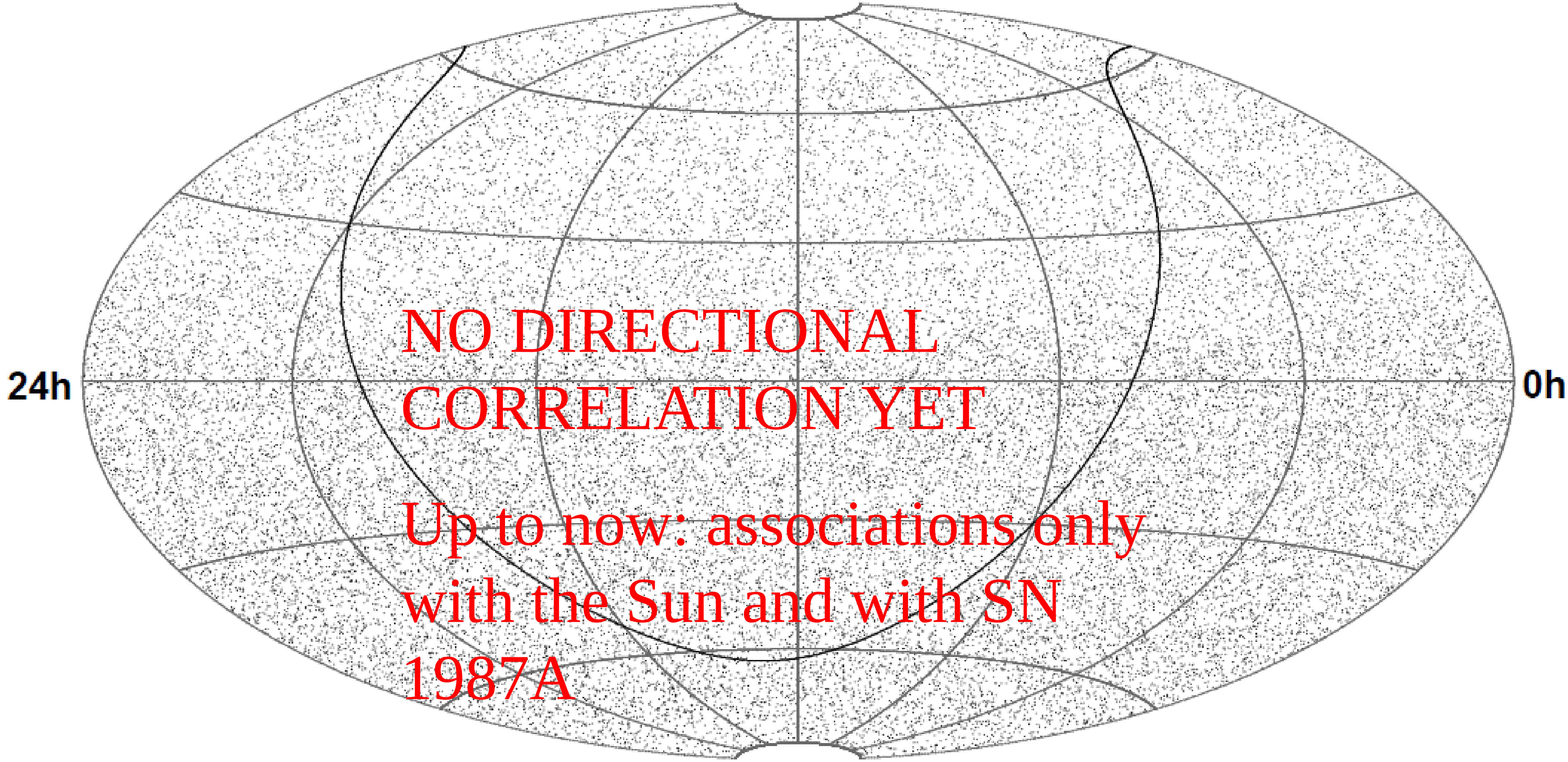
(reflects the fact that pions decay into gamma rays and neutrinos that carry 1/2 and 1/4 of the energy of the parent. This assumes that the four leptons in the charged pion decay equally share the charged pion's energy)



IceCube 40 strings

operated 375.5 days

northern sky: 14139 neutrinos



NO DIRECTIONAL CORRELATION YET

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

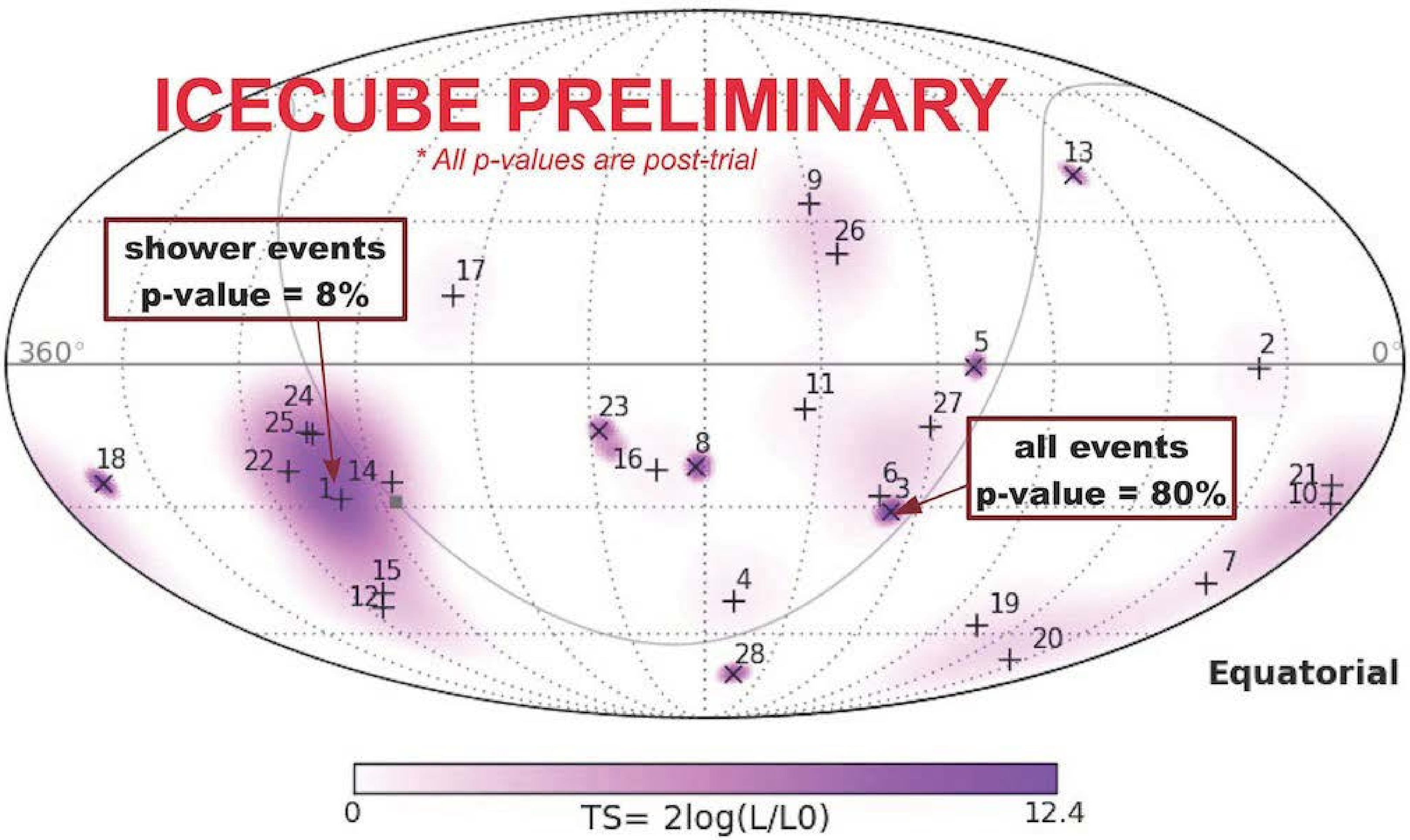
southern sky: 23151 muons

search for

- clustering
- high energy (>> 100 TeV)

2 (3?) neutrino events > PeV

- Must be cosmogenic!
- 28 events above 30 TeV; do they cluster?



THE SOURCES

Where to find the particle accelerators in Space?

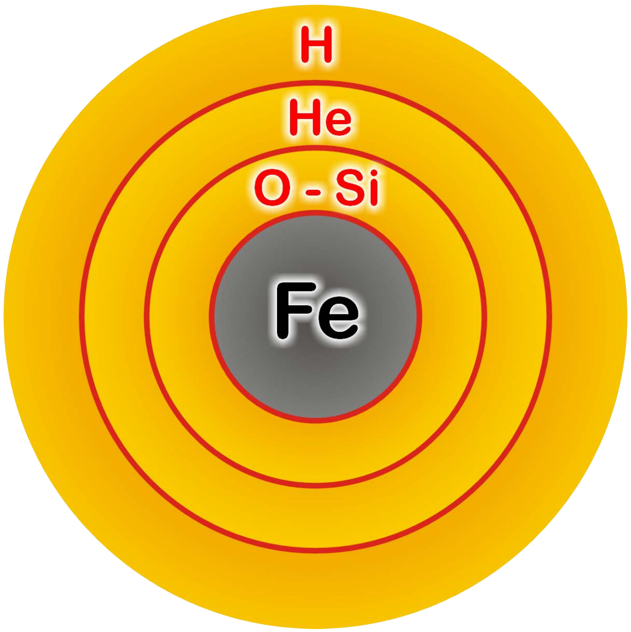
Remember: you need E, B, R

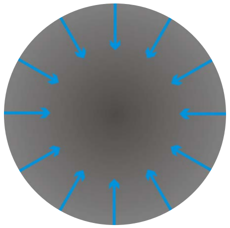
- Stellar endproducts
- AGN

(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 3α -> 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

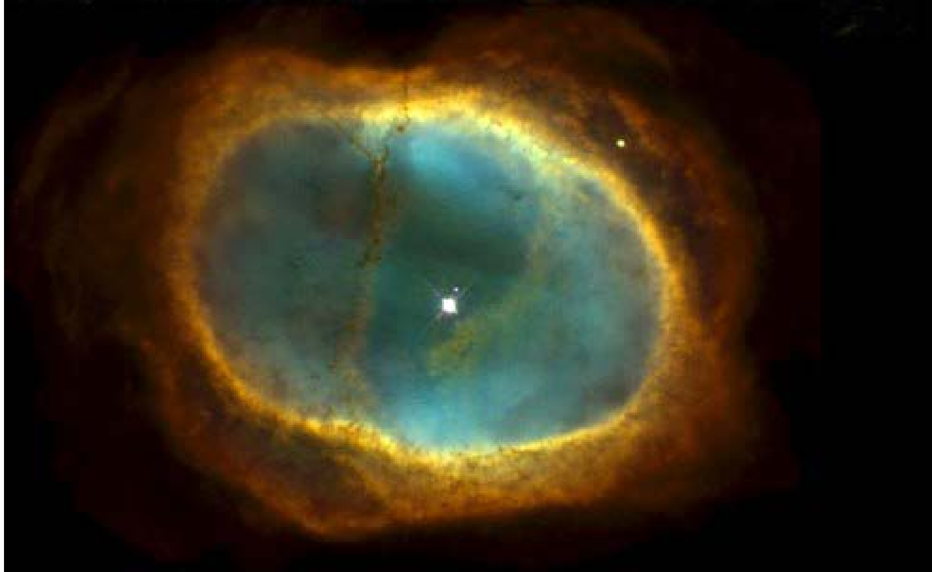
$M < 0.08\ M_{sun}$	Never ignites hydrogen → cools ("hydrogen white dwarf")	Brown dwarf
$0.08 < M \lesssim 0.8\ M_{sun}$	Hydrogen burning not completed in Hubble time	Low-mass main-squence star
$0.8 \lesssim M \lesssim 2\ M_{sun}$	Degenerate helium core after hydrogen exhaustion	• Carbon-oxygen white dwarf • Planetary nebula
$2 \lesssim M \lesssim 5–8\ M_{sun}$	Helium ignition non-degenerate	
$8\ M_{sun} \lesssim M < ???$	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

(Zwicky in 1930)

- 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
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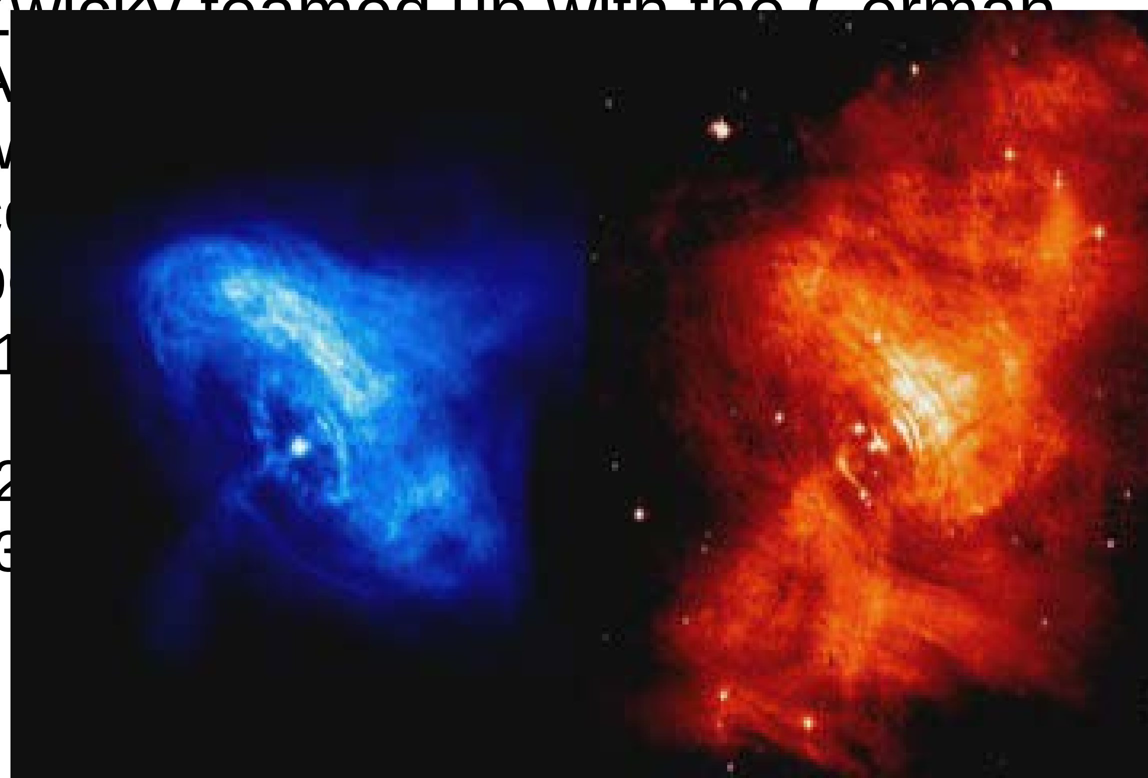
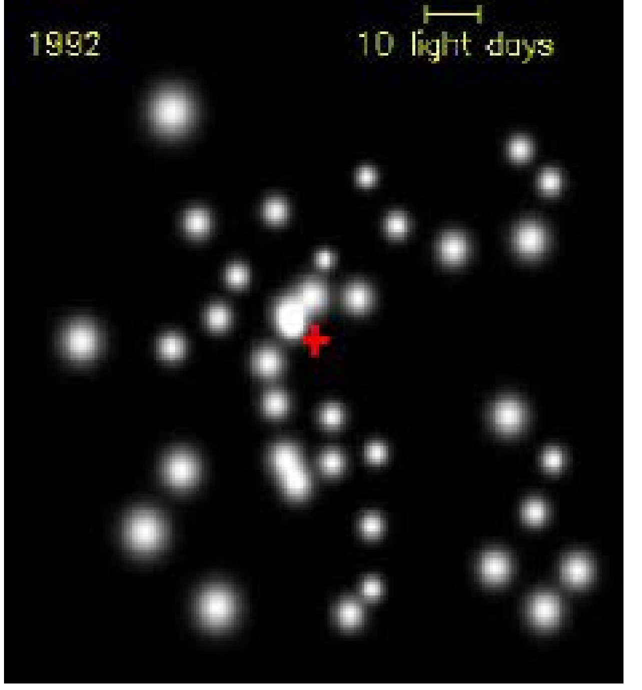
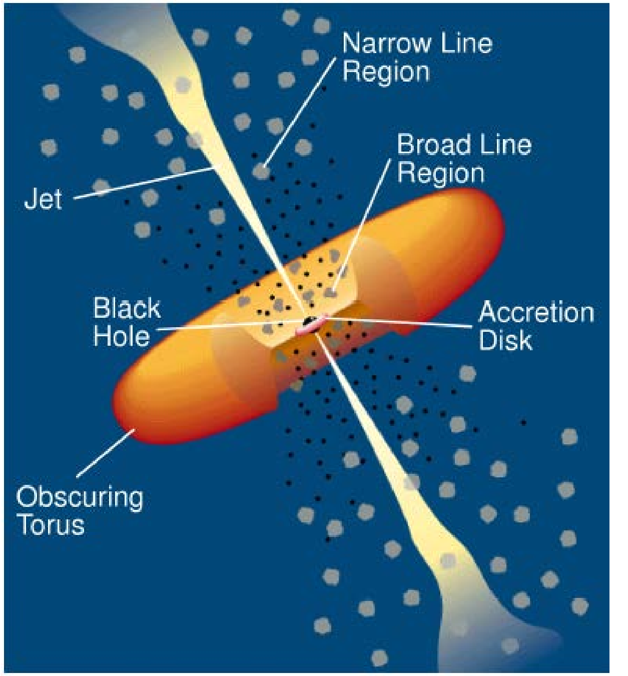


AGN

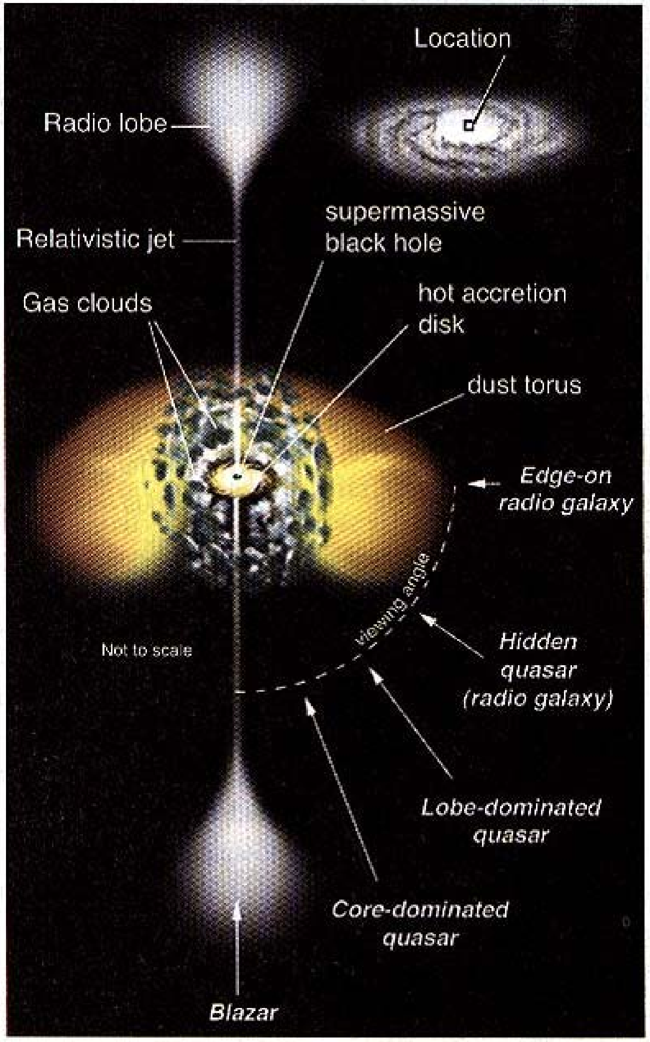
- Supermassive black holes (SMBH) of 1M-10G solar masses reside in the cores of most galaxies (the centre of our Galaxy hosts a BH ~4 million solar masses, its mass having been determined by the orbital motion of nearly stars.
- Their fueling by infalling matter can produce a spectacular activity; when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



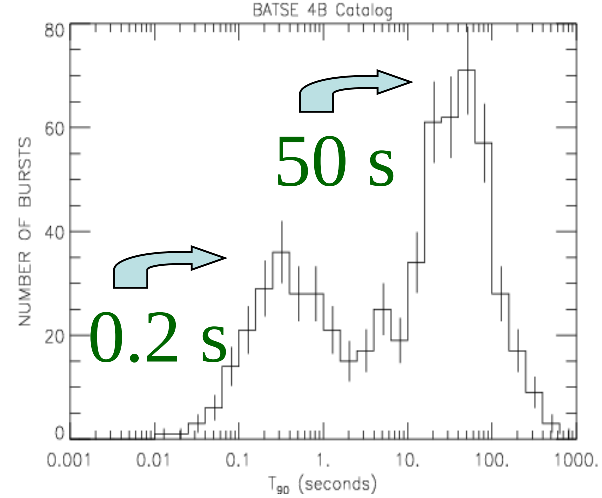
Slanted story. Seemingly diverse astronomical objects may be different views of galactic cores.

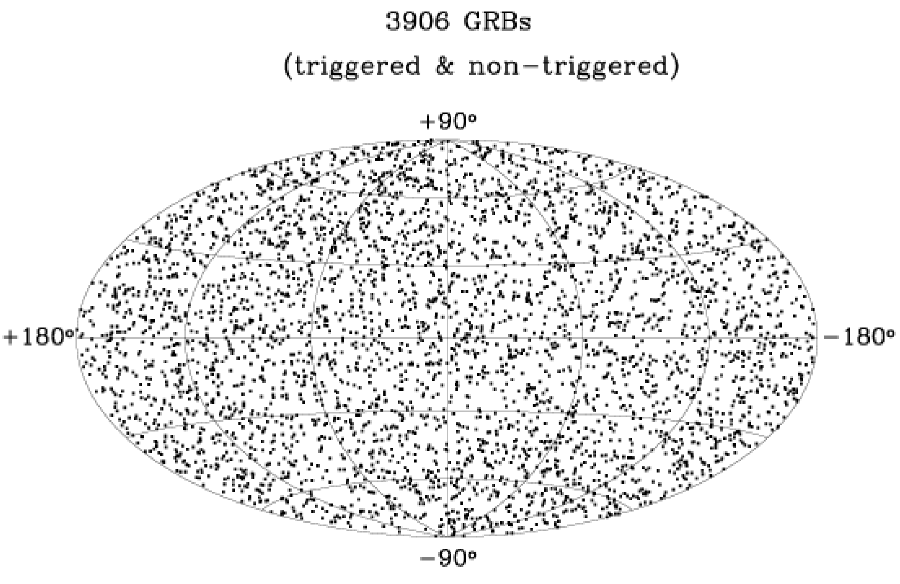
Gamma-Ray Bursts

- 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

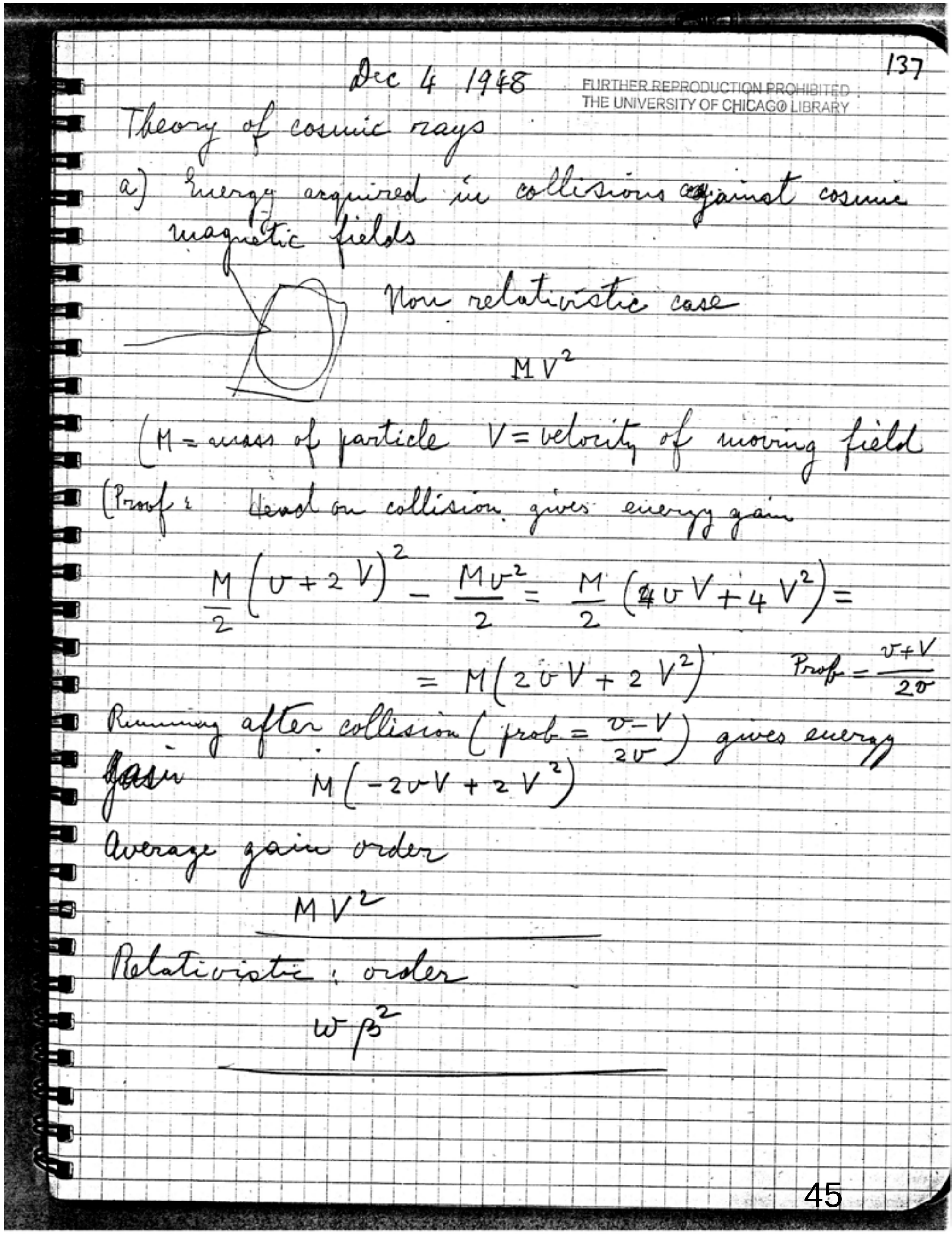
- Long GRBs are thought to come from a hypernova (an old star of large mass), or a core-collapse supernova. There is a prevailing consensus that the basic mechanism of GRB emission is an expanding relativistic fireball, with the beamed radiation due to shock waves. No direct confirmation that they are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





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 $(1+\beta)$


Dec 4 1948

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Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$

$= M(2vV+2V^2)$ Prob $= \frac{v+V}{2v}$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain

$M(-2vV+2V^2)$

Average gain order

MV^2

Relativistic: order

$w\beta^2$

1^{st} order Fermi acceleration

- A simplified model of the Fermi 1^{st} 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 $E = E_0(1 + \langle \beta \rangle)^n$

1^{st} order Fermi acceleration

- $E = E_0(1 + \langle ß \rangle)^n$

- 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

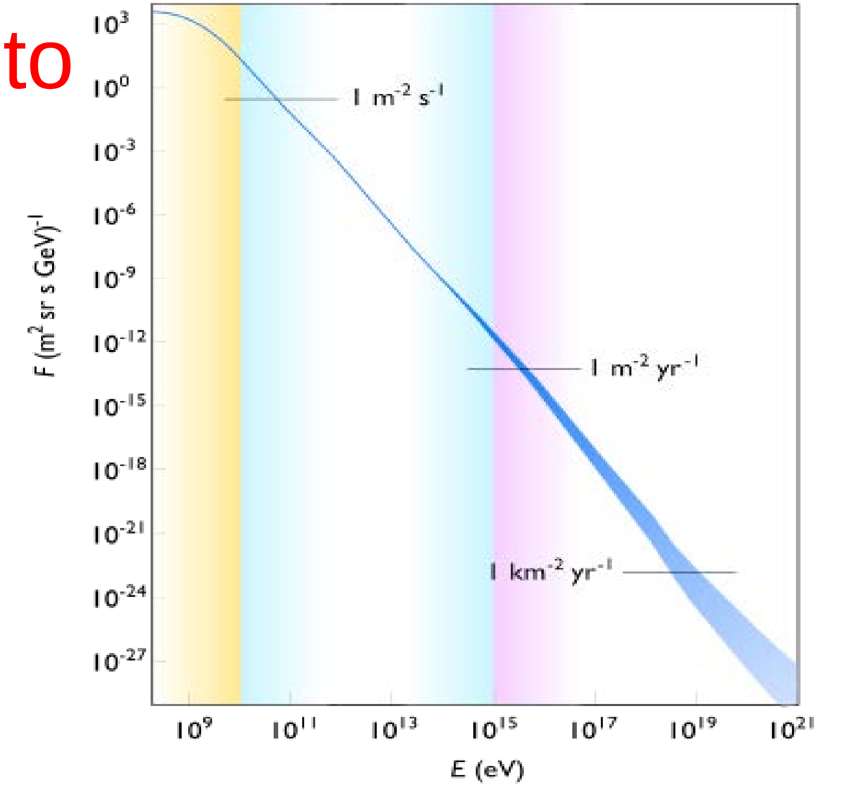
$$\frac{N}{N_0} = P^n \Rightarrow \ln\left(\frac{N}{N_0}\right) = n \ln P = \frac{\ln(E/E_0)\ \ln P}{\ln(1+\langle\beta\rangle)} \equiv -s \ln\left(\frac{E}{E_0}\right) \Rightarrow N(>E) \propto E^{-s}$$

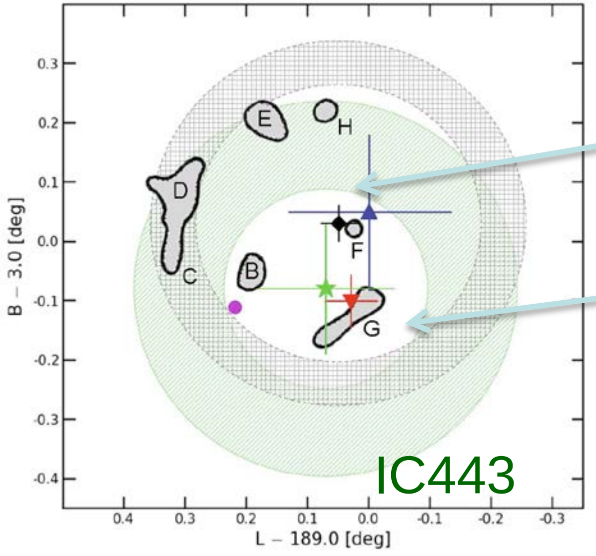
$$\Rightarrow \frac{dN}{dE} \propto E^{-s-1} \equiv E^{-\Gamma}$$

- For <ß> ~1/30, (1-P)~0.05 one has Γ ~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)



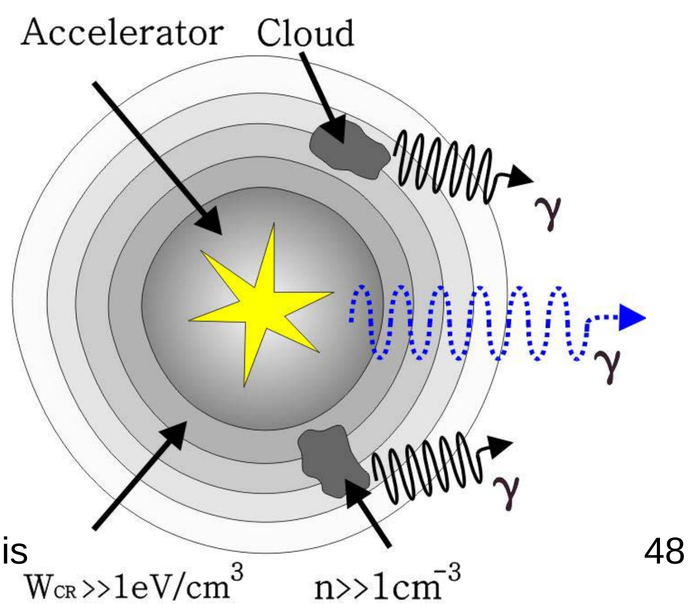


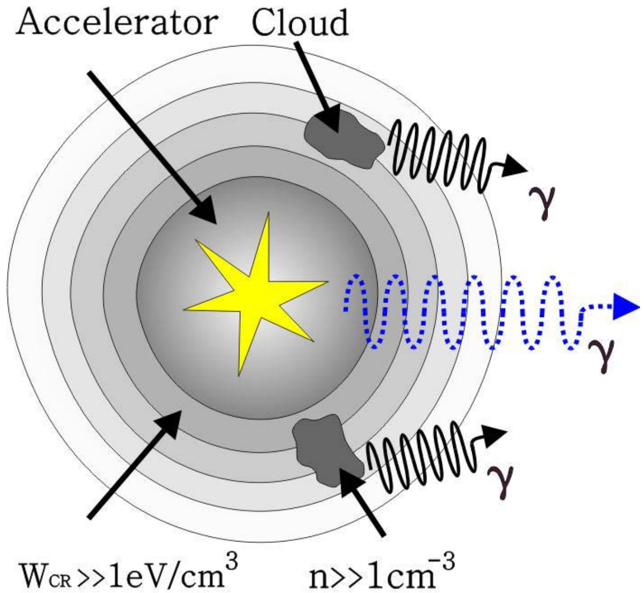
Fermi,

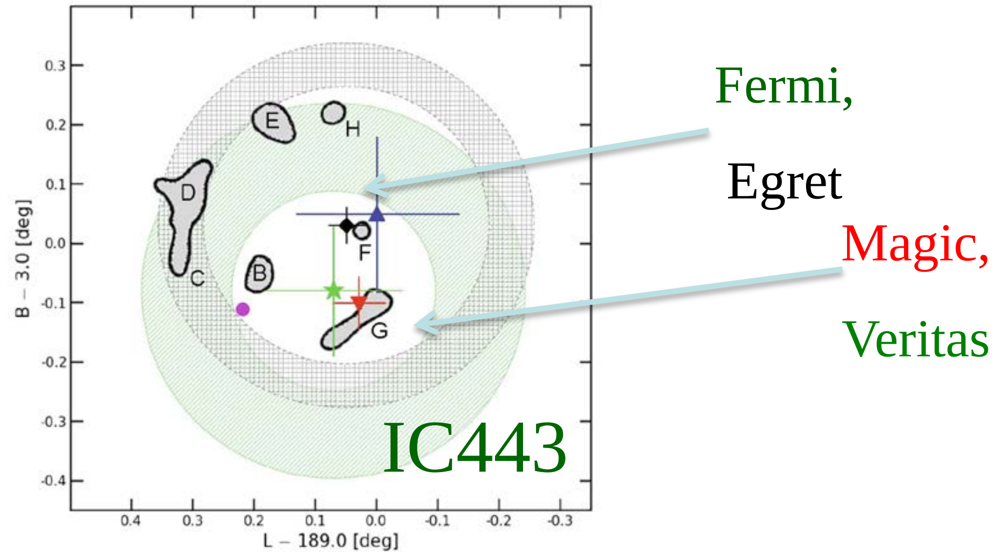
Egret

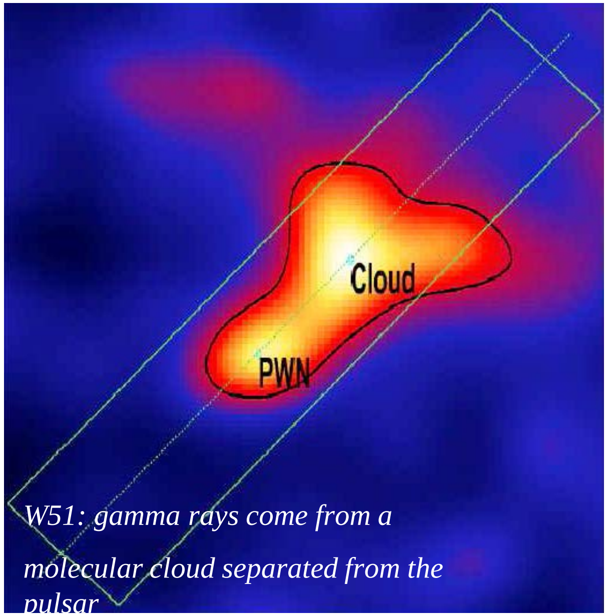
Magic,

Veritas

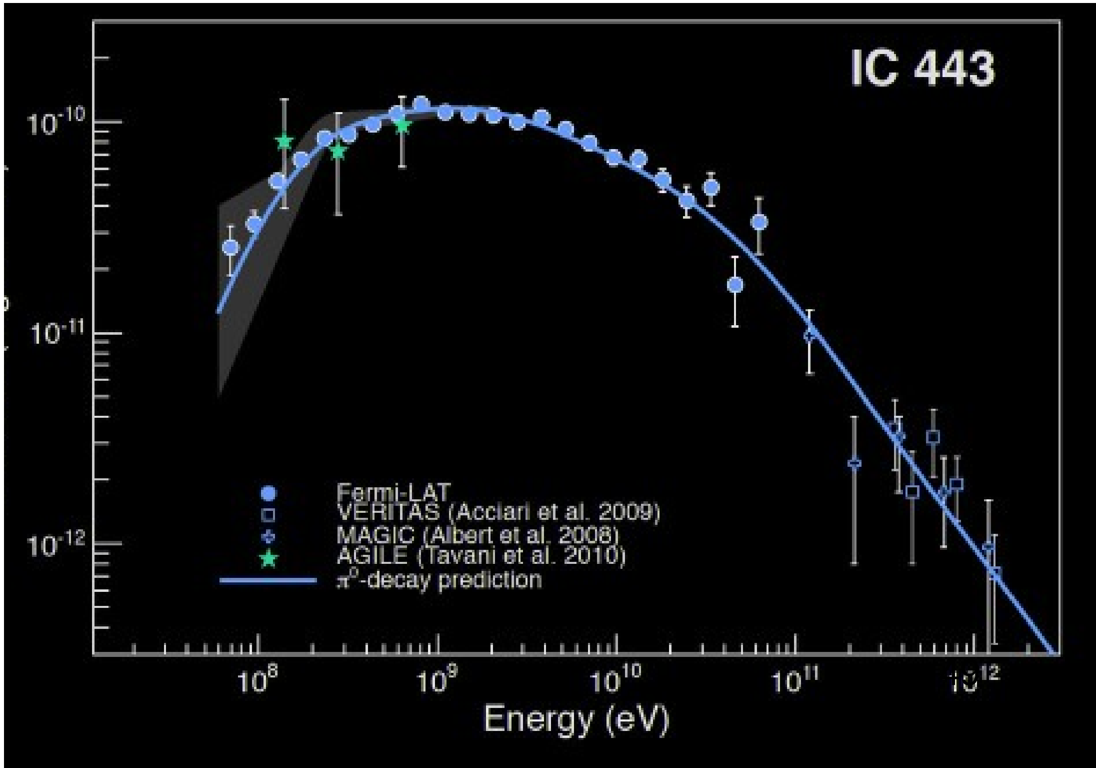






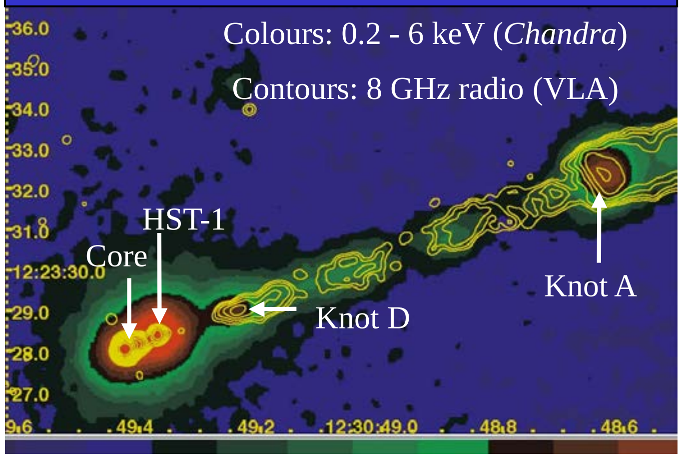


W51: gamma rays come from a molecular cloud separated from the pulsar



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

The M87 radio-galaxy Jet



- 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)