Astronomy, Astrophysics, and Cosmology

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Lesson XII
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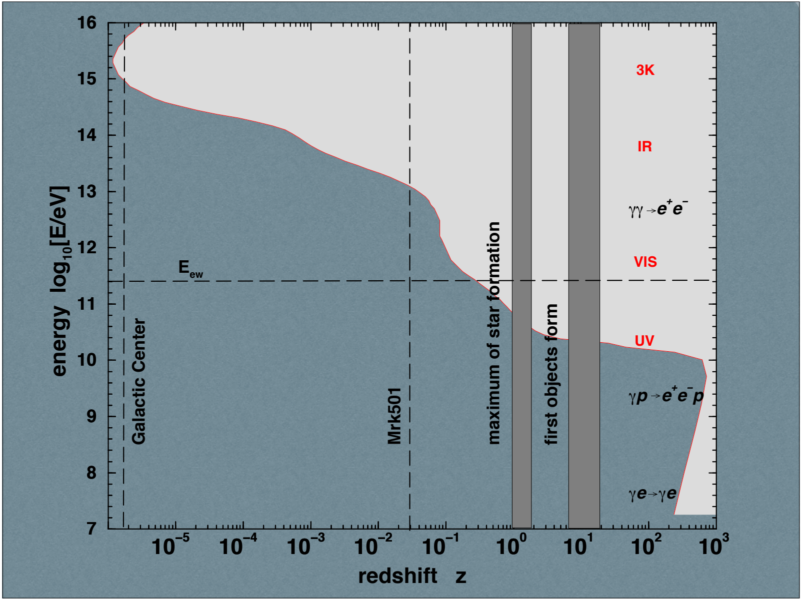
arXiv:0706.1988

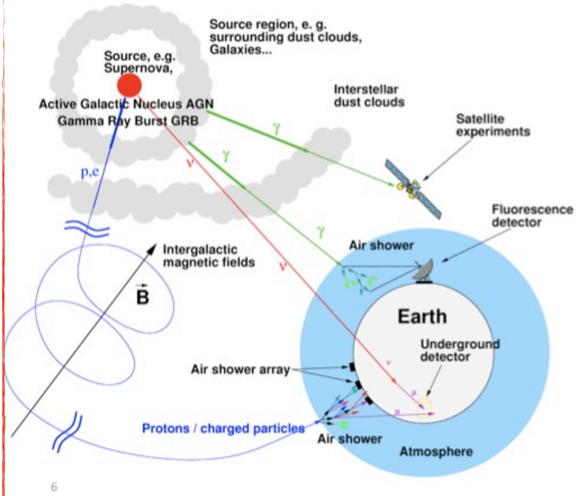
Table of Contents

- For biological reasons
  our perception of Universe ☞ based on observation of photons
  most trivially by staring at night-sky with our bare eyes
- Conventional astronomy
  covers many orders of magnitude in photon wavelengths
  from 10^4 cm radio-waves to 10^{-14} cm gamma rays of GeV energy
- This 60 octave span in photon frequency
  allows for dramatic expansion of our observational capacity
  beyond approximately one octave perceivable by human eye
- Above a few 100 GeV ☞ universe becomes opaque to γ rays
  because of e^+e^- production on radiation background fields
- Pairs synchrotron radiate on extragalactic B-field B4 annihilation
- Photon flux is significantly depleted/modified *en route* to Earth

Mean interaction length for photons on UV, vis, IR, and 3K backgrounds



Roadmap for Multimessenger Astronomy

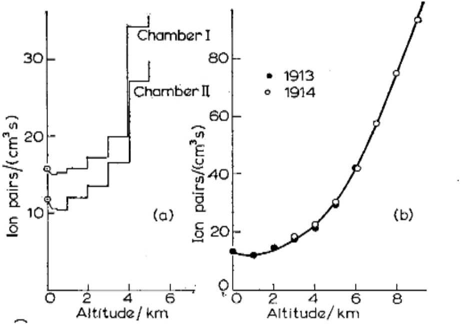


p *Protons:* deflected by magnetic fields.

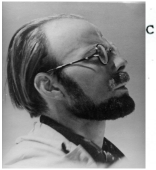
γ *Photons:* easily absorbed by CMB backgrounds.

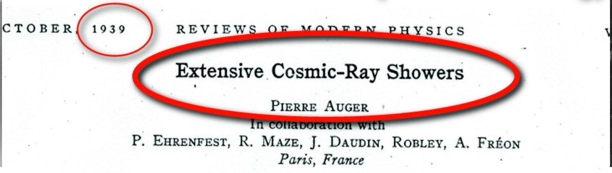
ν *Neutrinos:* not deflected by magnetic fields. Low interaction cross-section.

Cosmic ray discovery (Victor Hess 1912)



- Ionization begins to increase > 1km
- Earth is not the only source of ionization
- Also not (just) the sun. (try it at night)





CTOBER, 1939 REVIEWS OF MODERN PHYSICS

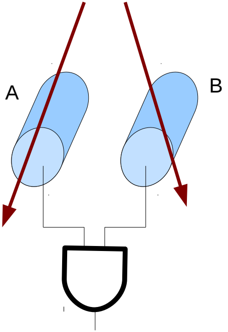
Extensive Cosmic-Ray Showers

PIERRE AUGER

In collaboration with

P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON

Paris, France



Chance Rate :

$$R_{\rm AB} = 2 R_{\rm A} R_{\rm B} \tau$$

- Coincidences higher than chance expectation (even ~ 300m separation)
- CR-induced Extensive Air Showers
- Primary energy estimated $\gtrsim 10^{15}$ eV

The first enormous event

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

~ 20 J

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

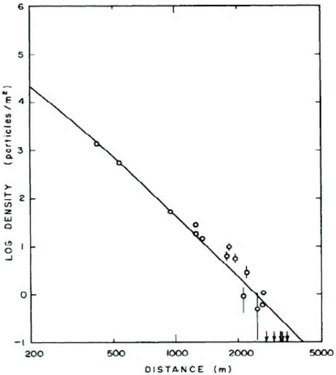
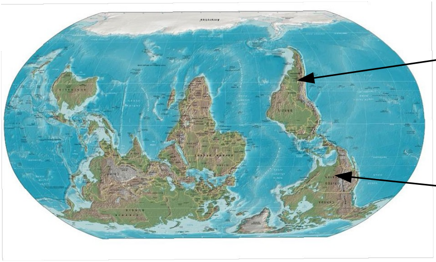


FIG. 2. Observed shower densities as a function of distance from the shower axis. The curve is the Greisen approximation of the Nishimura-Kamata lateral distribution for $s = 1.0$, $N = 5 \times 10^{10}$.

Volcano Ranch (1952-1972)
~10 km² scintillator array

The Pierre Auger Observatory

- Large exposure to capture rare events near end of the spectrum
- Complementary (hybrid) detection techniques - good systematics control



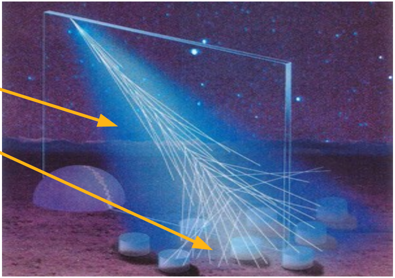
Mendoza Province, Argentina
Completed 2008, (3000 km^2)

Northern Auger site
was proposed, but not funded
TA, Utah, USA (680 km^2)
TAx4 in proposal stages

Hybrid detection

N_2 fluorescence

Particles sampled at ground



Fluorescence

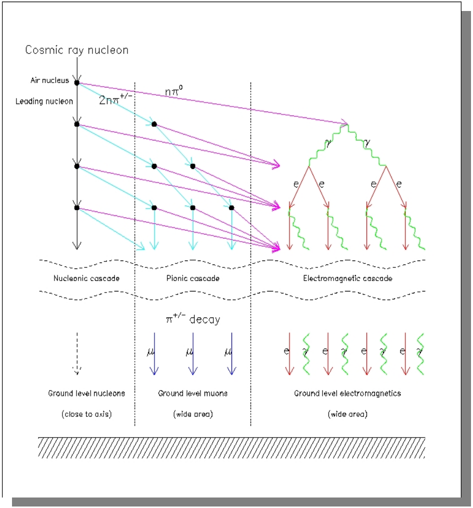
- quasi-calirometric
- direct view of shower evolution
- 13% duty cycle
- Exposure depends on energy, and atmospheric conditions

Surface

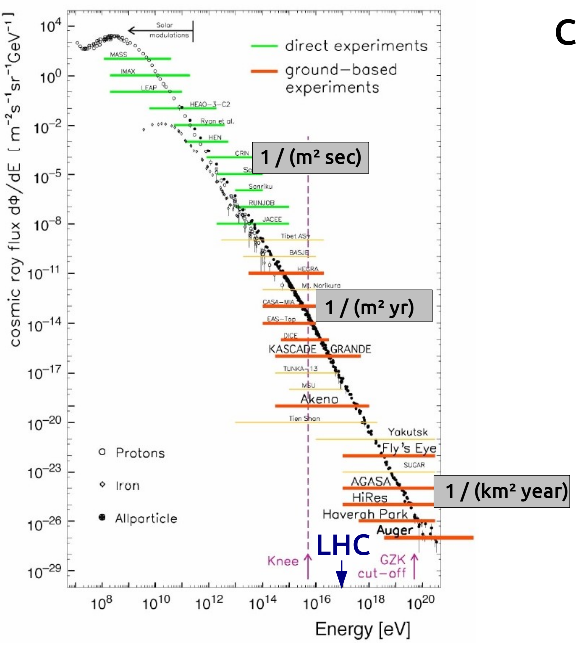
- 100% duty cycle
- Simple geometrical exposure
- Extracting primary energy and mass is model dependent

1 TeV proton

Cloud chamber + lead plates at 3000 m altitude.



Cosmic Ray (CR) spectrum

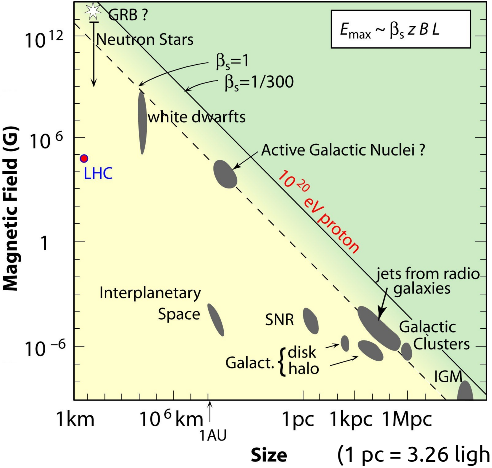


super-dooper collider !

Evatron & Zevatron Candidates ?

(1 EeV = 10^{18} eV)

Hillas Plot



(1 pc = 3.26 light years)

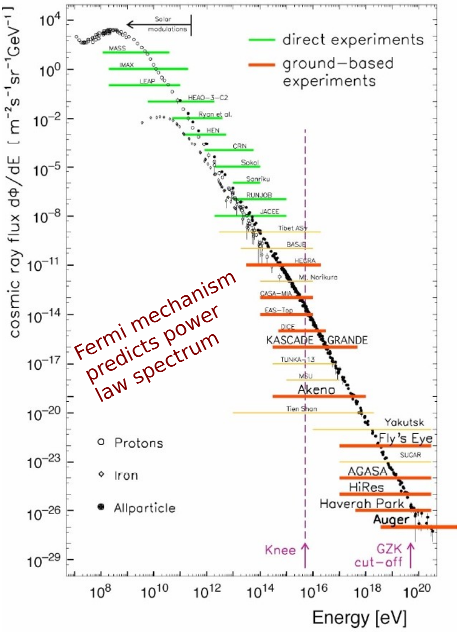
Acceleration sites must be able to contain particle as it accelerates to ~ 10^{20} eV

Bottom up acceleration?

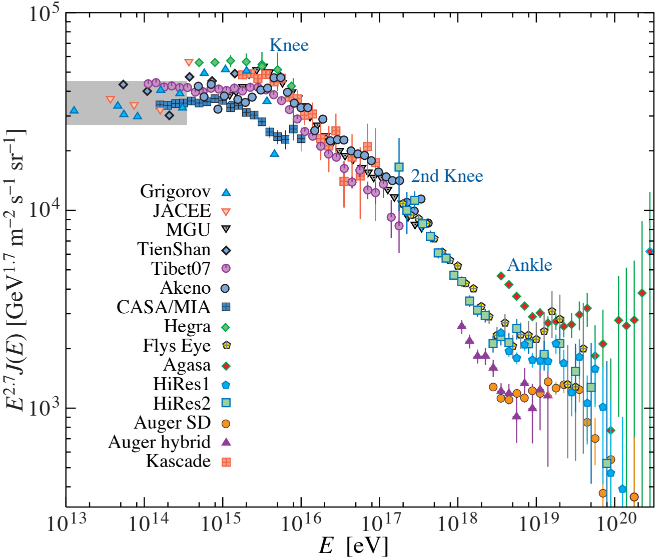
- Fermi mechanism Acceleration in a shock (eg AGN, SNR jet, ..)

Top down production ?

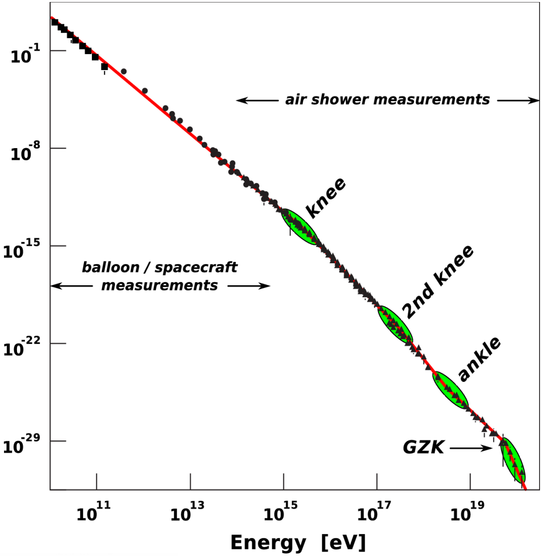
- Decays of supermassive relics


cosmic ray flux dΦ/dE [m^-2 s^-1 sr^-1 GeV^-1]
Energy [eV]
Solar modulations
direct experiments
ground−based experiments
MASS
IMAX
LEAP
HEAO−3−C2
Ryan et al.
HEN
CRN
Sokol
Sanriku
RUNJOB
JACEE
Tibet ASγ
BASJE
HEGRA
Mt. Norikura
CASA−MIA
EAS−Top
DICE
KASCADE
GRANDE
TUNKA−13
MSU
Akeno
Tien Shan
Yakutsk
Fly's Eye
SUGAR
AGASA
HiRes
Haverah Park
Auger
Knee
GZK cut−off
Protons
Iron
Allparticle
Fermi mechanism predicts power law spectrum

Cosmic Leg


Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
$E^{2.7}J(E)$ [GeV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
10^5
10^4
10^3
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
E [eV]

Structure in the spectrum ☞ what is the statistical significance?



Propagation from sources to Earth : a striking feature

1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

Also Zatsepin & Kuzmin

(Received 1 April 1966)

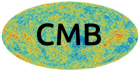
The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}–10^{22} eV.

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

... of the catastrophic cutoff ... intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

GZK suppression : Interaction with CMB degrades CR energies

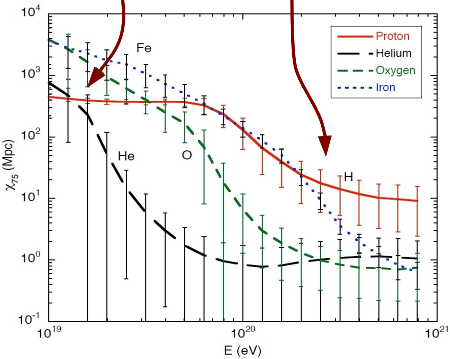
Cosmic ray propagation in the



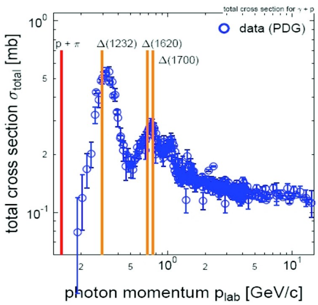
$$\mathrm{p}\ \gamma_{2.7\mathrm{K}} \to \mathrm{p}\ \mathrm{e}^+\mathrm{e}^-$$

$$\mathrm{p}\ \gamma_{2.7\mathrm{K}} \to \Delta^+ \to \mathrm{p}\ \pi^0, \mathrm{n}\ \pi^+$$

- photopion production (protons)
- photodisintegration (complex nuclei)

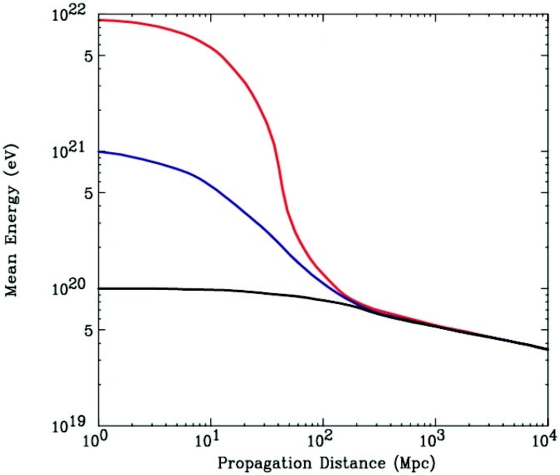


total cross section for $\gamma + \mathrm{p}$ collisions:



energy loss ≈ 20%/interaction

GZK "horizon"



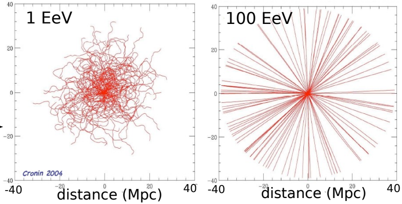
CR's with energies ~10^{20} eV should be "nearby" (~100 Mpc)

→ Anisotropy in the CR arrival directions at highest energies?

Magnetic fields and propagation

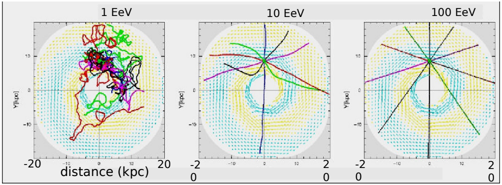
$$\rho(\mathrm{Mpc}) = \frac{1.08\times 10^{2}\,(E/10^{20}\mathrm{eV})}{B(\mathrm{nG})\,Z}$$

proton, 1 nG, 1 Mpc cells

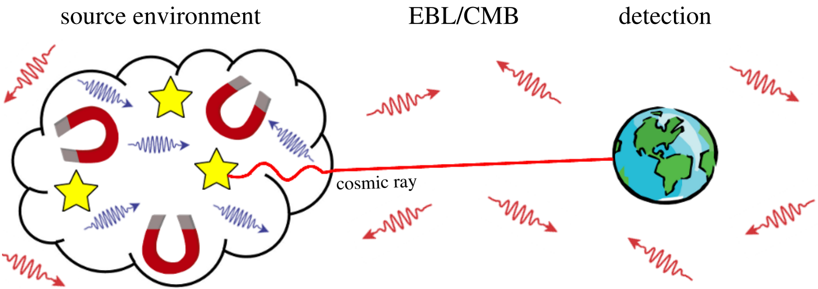


At high energies, charged particle astronomy becomes feasible

proton, GMF ~ μG



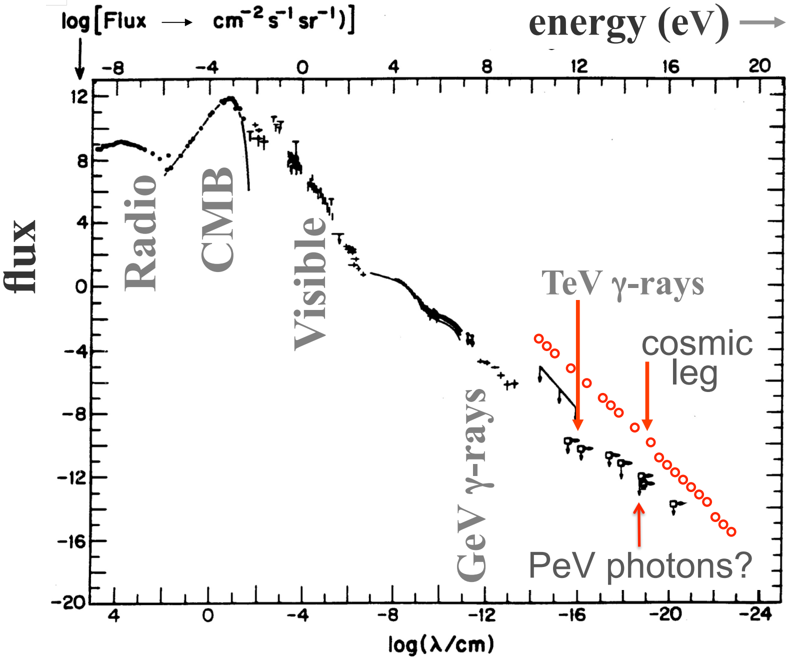
Photodisintegration in source environment ☞ could be key ingredient

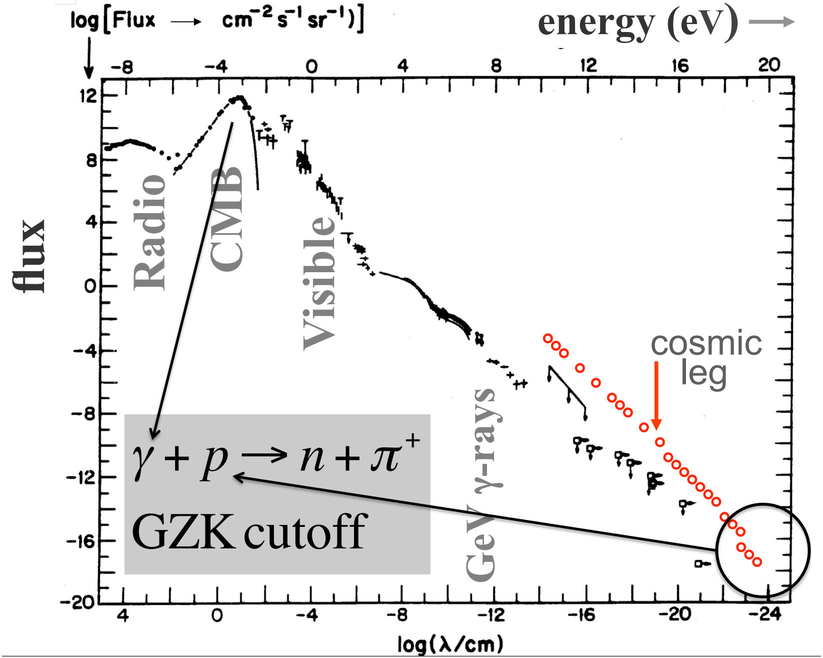


Open questions

- Does the spectrum terminate as predicted? Is it GZK?
- What is the physical significance of other spectral features?
- Does anisotropy emerge and can we pinpoint sources?
- What is the composition? ☞ protons, nuclei, photons, exotica ?
- What acceleration mechanisms are plausible ?
  - bottom-up (e.g. Fermi mechanism) all the way to the top?
  - top-down ☞ decays of massive particles
- Can we learn about HEP at c.m. energies beyond LHC reach?

Cosmic rays discovered ~ 100 years ago.. still many open questions

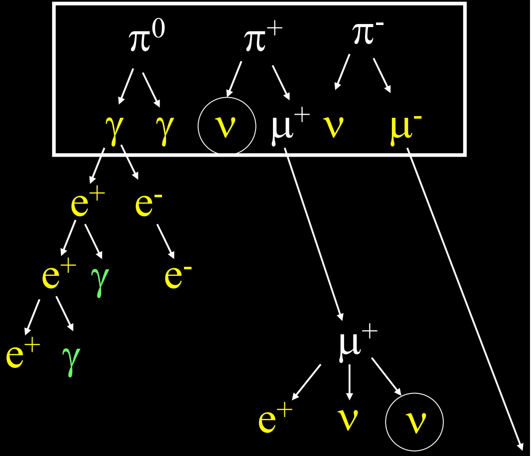

log[Flux → cm^{-2} s^{-1} sr^{-1})]
energy (eV) →
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
TeV γ-rays
cosmic
leg
PeV photons?
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

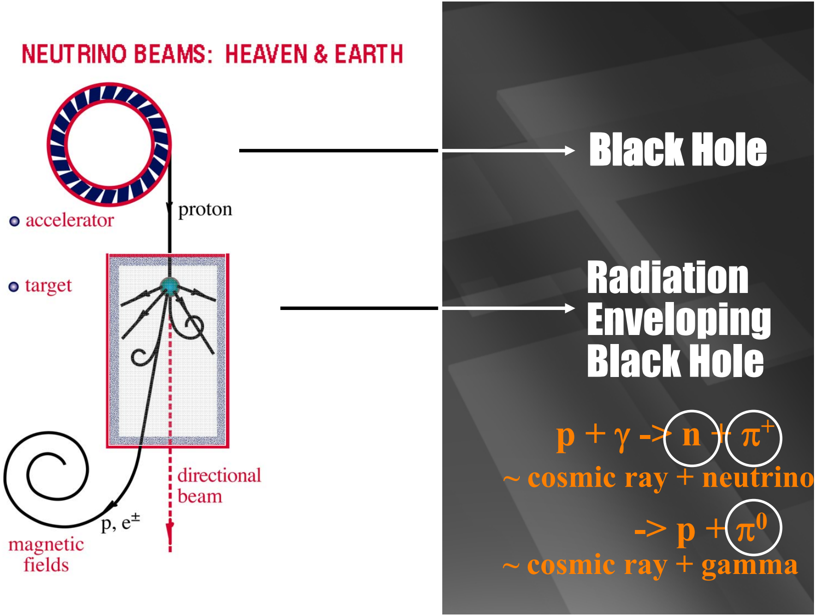

log[Flux → cm^{-2} s^{-1} sr^{-1})]
energy (eV) →
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
flux
Radio
CMB
Visible
GeV γ-rays
cosmic leg
$\gamma + p \rightarrow n + \pi^+$
GZK cutoff
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

neutral pions
are observed as
gamma rays

charged pions
are observed as
neutrinos

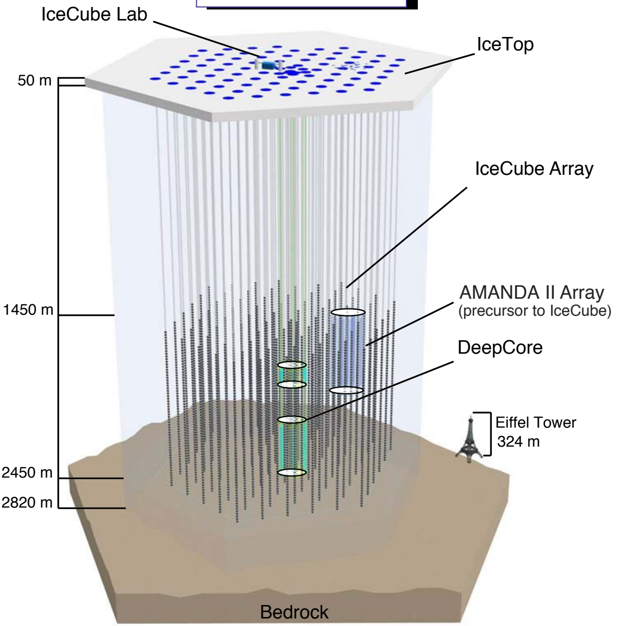
$$\nu_\mu \sim \gamma / 2$$

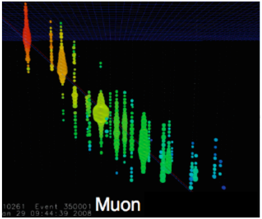


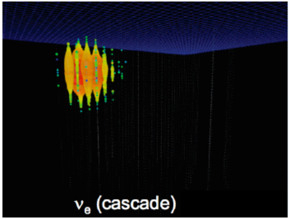

NEUTRINO BEAMS: HEAVEN & EARTH
accelerator
proton
target
directional beam
p, e±
magnetic fields
Black Hole
Radiation Enveloping Black Hole
p + γ -> n + π+
~ cosmic ray + neutrino
-> p + π0
~ cosmic ray + gamma

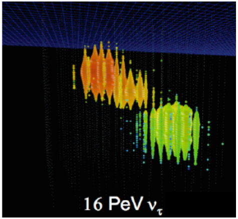
IceCube

IceCube layout





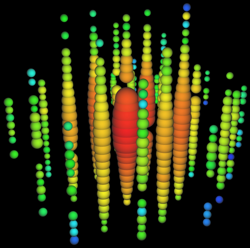




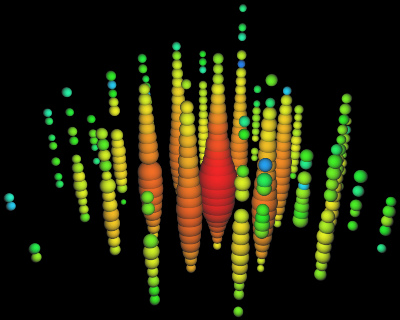
Event topologies

1. ν_e CC interaction produces EM shower which ranges out quickly
   - shower produces symmetric signal $\Rightarrow$ poor angular resolution
   - fully contained shower event $\Rightarrow$ precise energy measurement
   - same for all NC interactions + ν_τ CC interactions $\Leftrightarrow E_{\nu_\tau} \lesssim 3$ PeV
2. ν_μ CC interaction generates tracks
   - tracks point in direction of original $\nu_\mu \Rightarrow$ good angular resolution
   - $E_{\rm EM}$ deposited represents only lower bound of true E_{ν_μ}
3. $10^{6.5} \lesssim \frac{E_{\nu_\tau}}{\rm GeV} \lesssim 10^{7.5} \Rightarrow$ sweet spot for τ double-bang detection

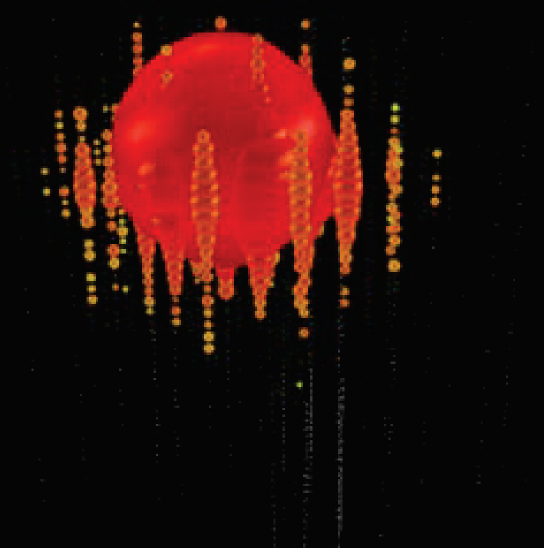
Bert



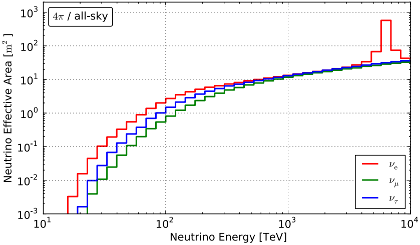
Ernie



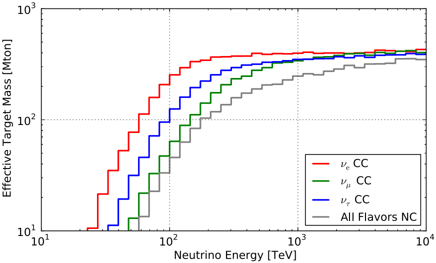
Big Bird



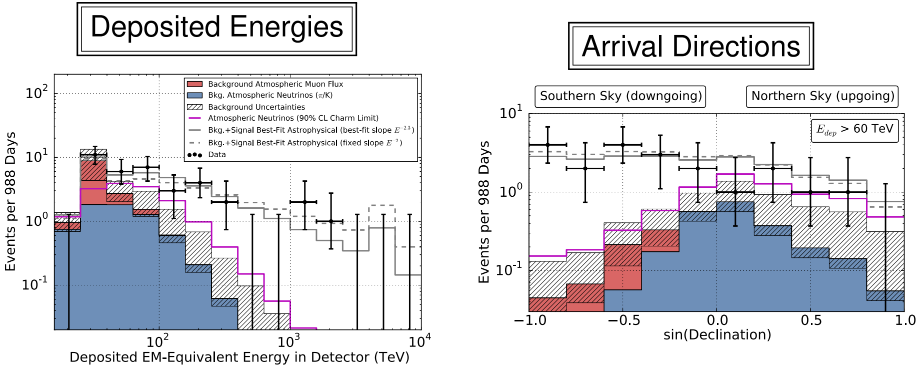
Effective Area



Effective Volume

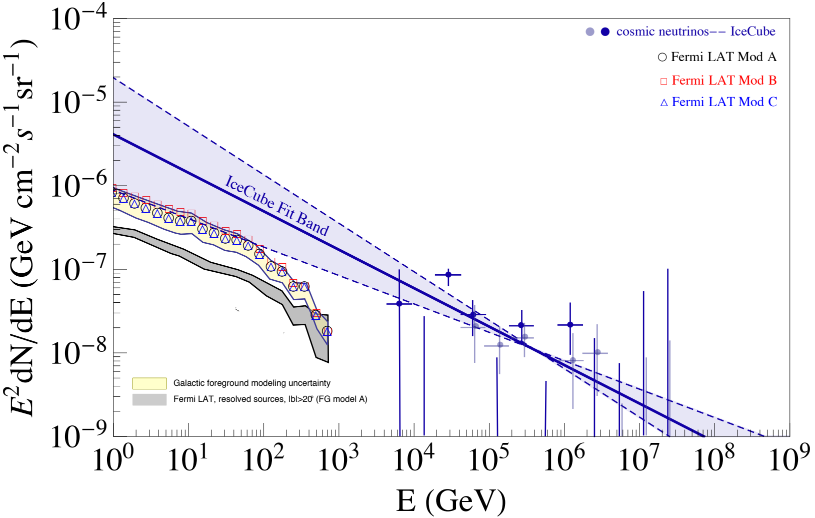


IceCube Collaboration 2013

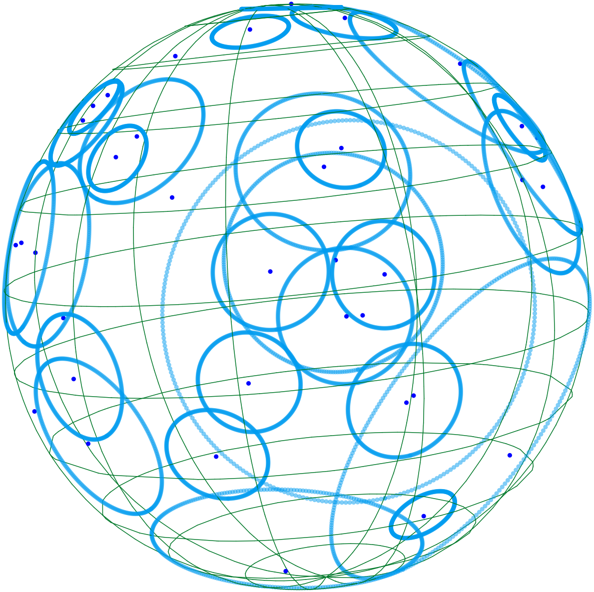


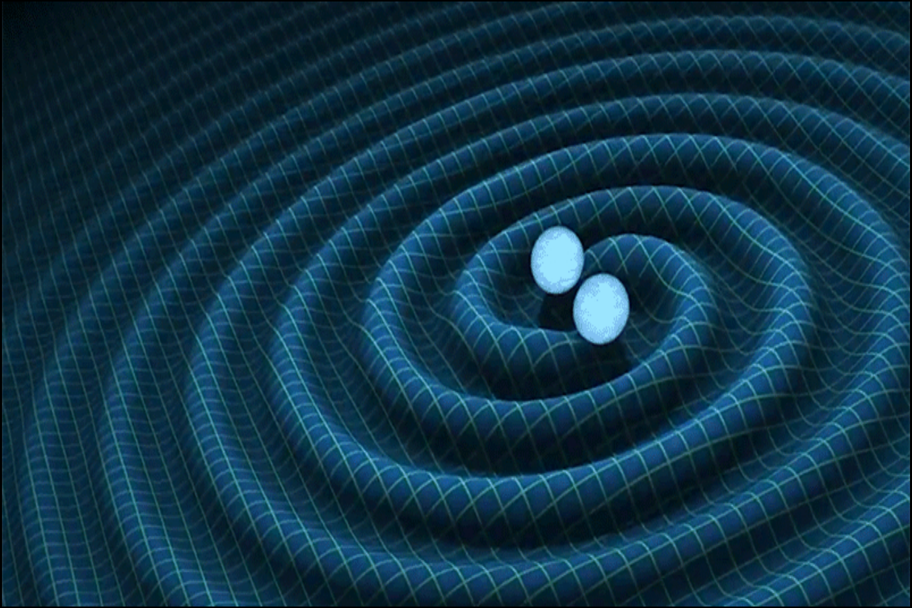
IceCube Collaboration 2014

γ's accompanying ν's saturate Fermi-LAT data



Distribution of arrival directions





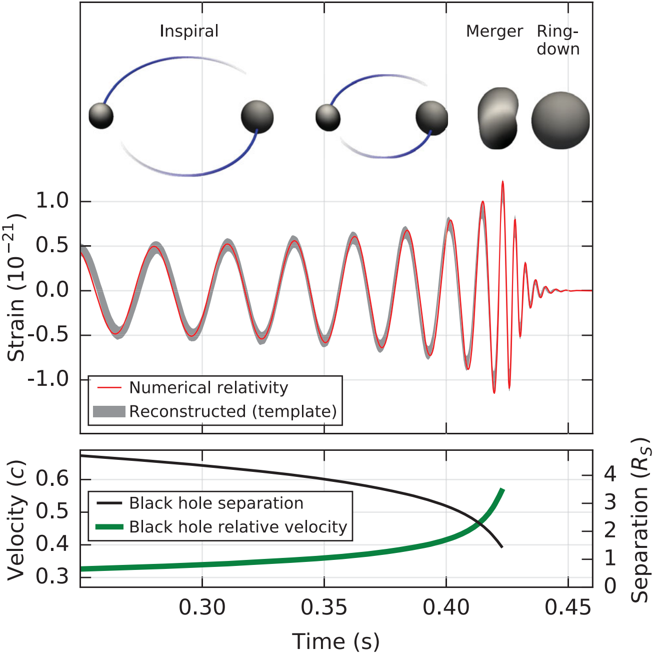
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

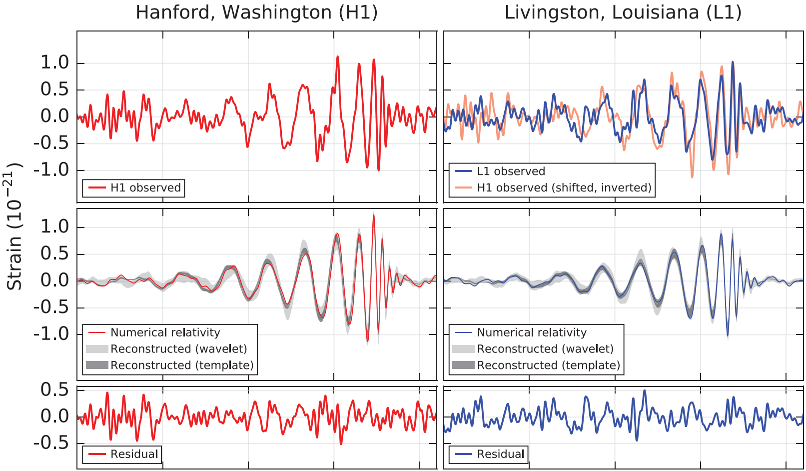
Observation of Gravitational Waves from a Binary Black Hole Merger

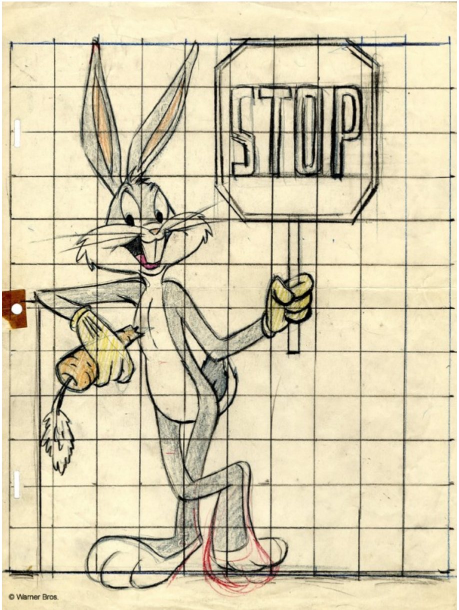
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

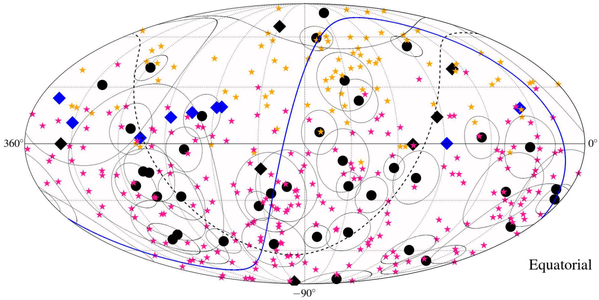
DOI: 10.1103/PhysRevLett.116.061102

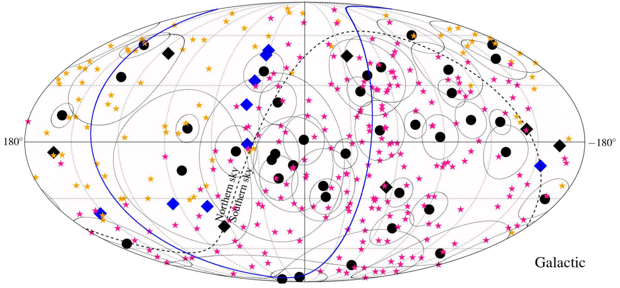

Inspiral
Merger
Ring-
down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual

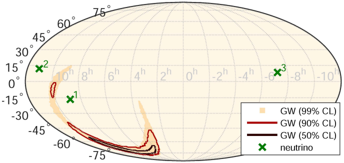

STOP
© Warner Bros.

ν's and UHECRs





ν's and gravitational waves



#	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\rm rec}$ [°]	$E_\mu^{\rm rec}$ [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%


More data is coming!!!


That's all Folks!