Astroparticle Physics 2021/22

Tuesday 13:30 - 15:15 HG 03.082
Thursday 8:30 - 10:15 HG 00.065

- lectures
- student presentations
- oral exam, ca. 45 min

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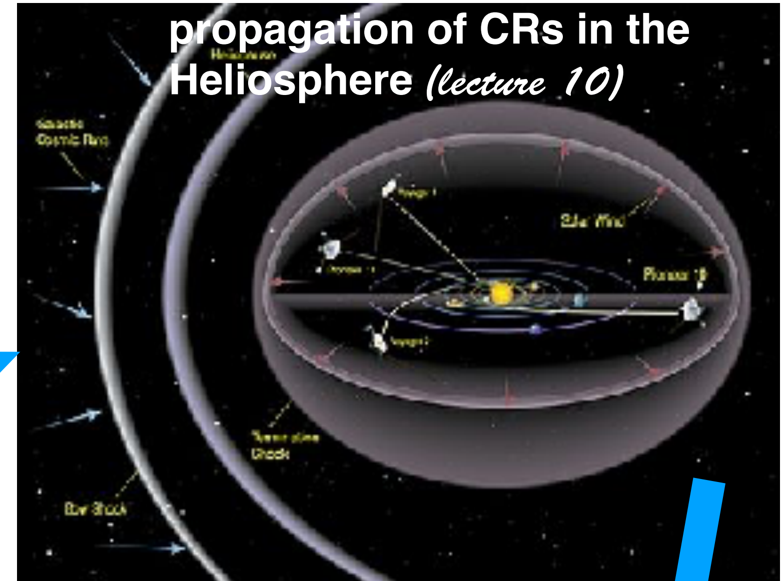
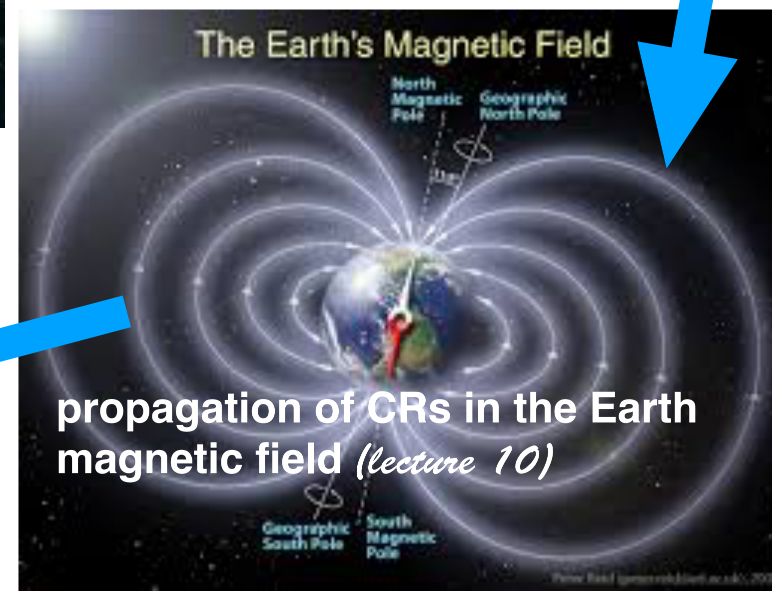
http://particle.astro.ru.nl/goto.html?astropart2122

birth of cosmic rays
CRs: supernova remnants
neutrinos: e.g. Sun *(lecture 9)*

propagation of CRs in the Galaxy
interactions with ISM *(lecture 9)*

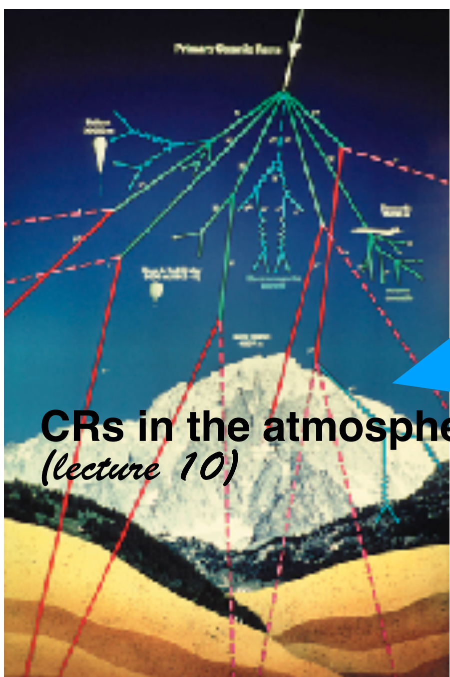


propagation of CRs in the Heliosphere *(lecture 10)*



propagation of CRs in the Earth magnetic field *(lecture 10)*

CRs at the top of the atmosphere *(lecture 11)*



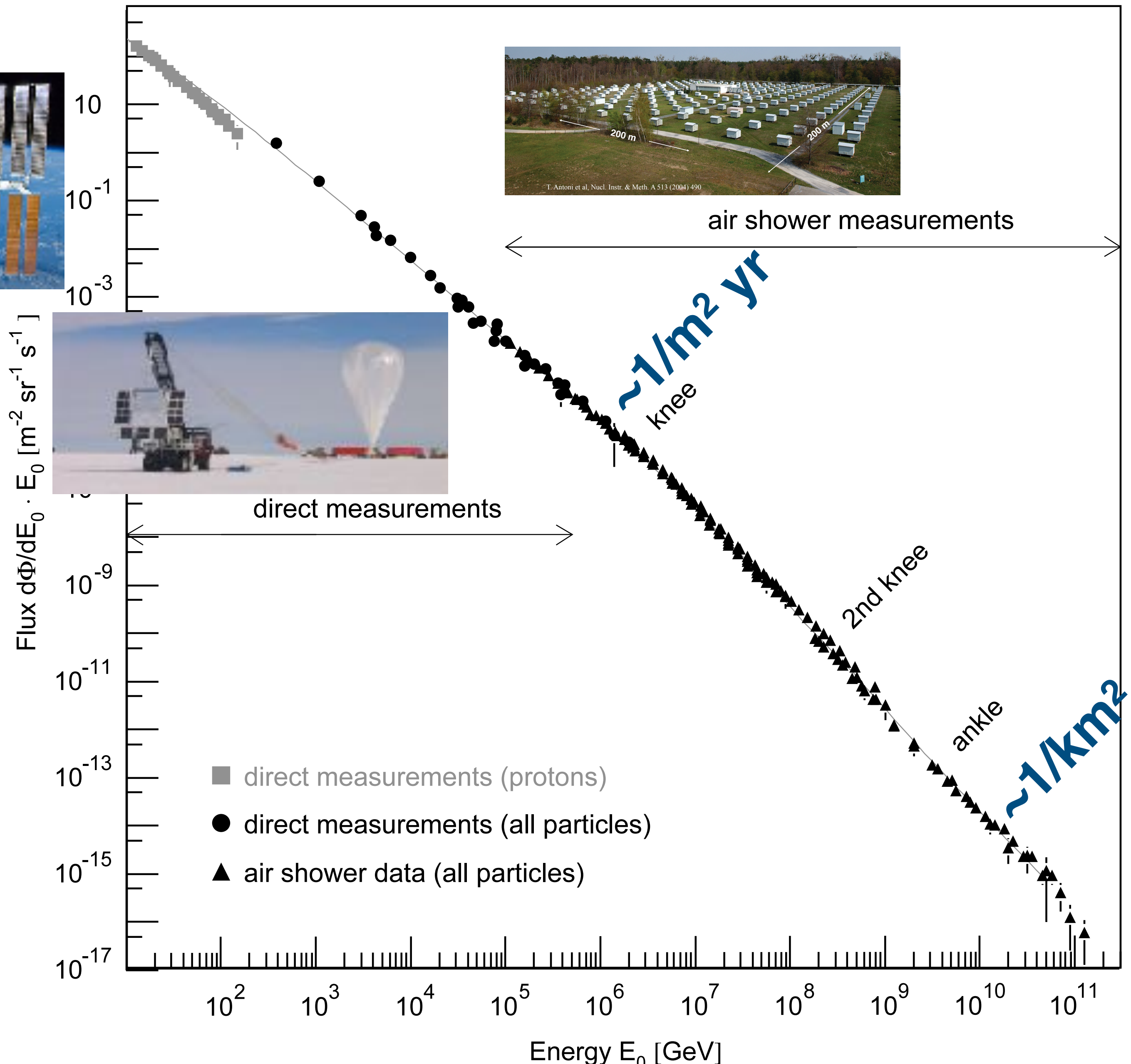
CRs in the atmosphere *(lecture 10)*

CRs underground *(lecture 12)*
neutrino oscillations *(lecture 12+13)*

Particles and the Cosmos

J. Blümer et al. / Progress in Particle and Nuclear Physics 63 (2009) 293–338

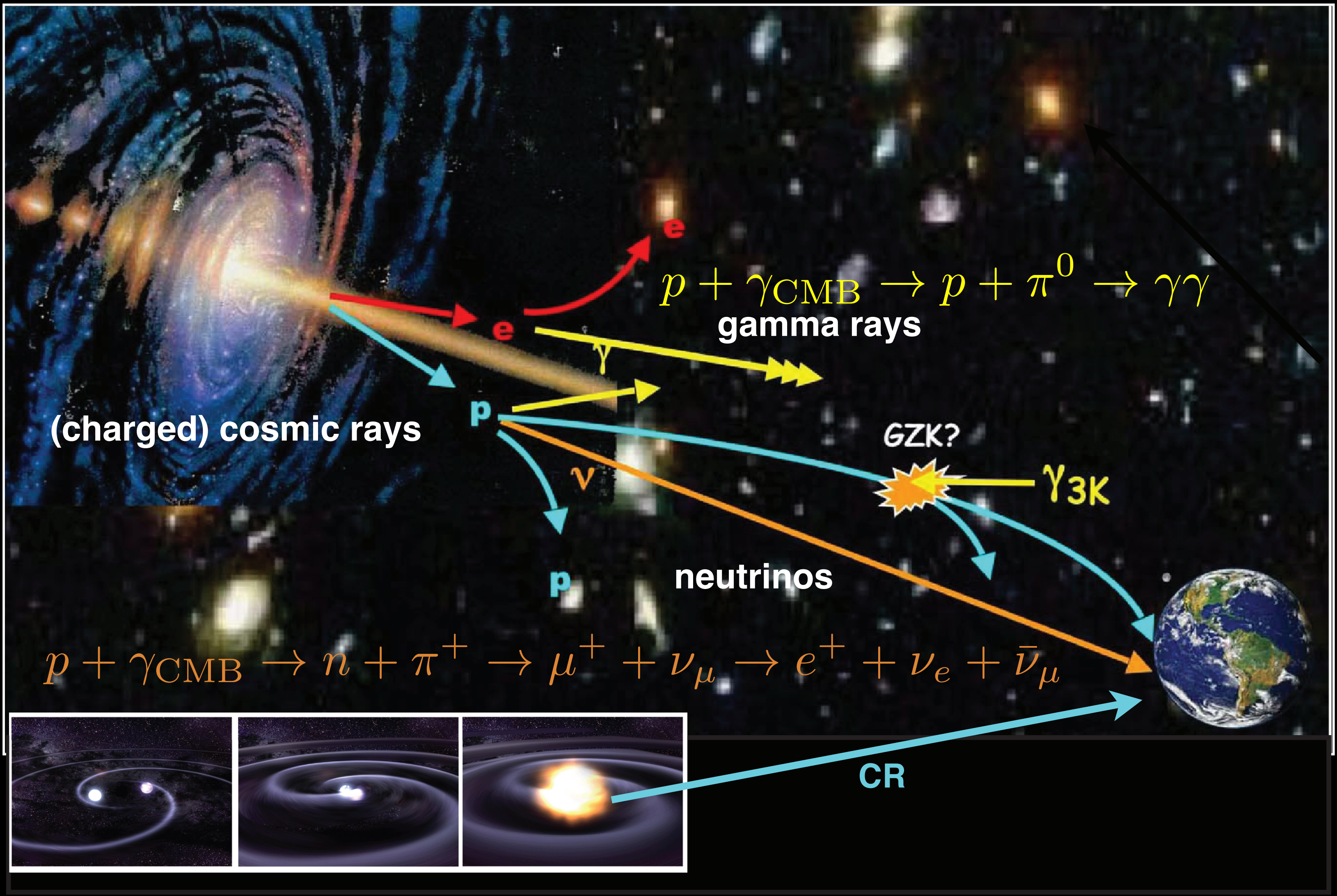
~1000/m² s



energy spectrum of cosmic rays extends to extremely high energies:

10^{20} eV ~16 J

Origin of cosmic rays
multi messenger technique



RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

INTRODUCTION: Neutrinos are tracers of cosmic-ray acceleration: electrically neutral and traveling at nearly the speed of light, they can escape the densest environments and may be traced back to their source of origin. High-energy neutrinos are expected to be produced in blazars: intense extragalactic radio, optical, x-ray, and, in some cases, γ-ray sources characterized by relativistic jets of plasma pointing close to our line of sight. Blazars are among the most powerful objects in the Universe and are widely speculated to be sources of high-energy cosmic rays. These cosmic rays generate high-energy neutrinos and γ-rays, which are produced when the cosmic rays accelerated in the jet interact with nearby gas or photons. On 22 September 2017, the cubic-kilometer IceCube Neutrino Observatory detected a ~290-TeV neutrino from a direction consistent with the flaring γ-ray blazar TXS 0506+056. We report the details of this observation and the results of a multiwavelength follow-up campaign.

RATIONALE: Multimessenger astronomy aims for globally coordinated observations of cosmic rays, neutrinos, gravitational waves, and electromagnetic radiation across a broad range of wavelengths. The combination is expected to yield crucial

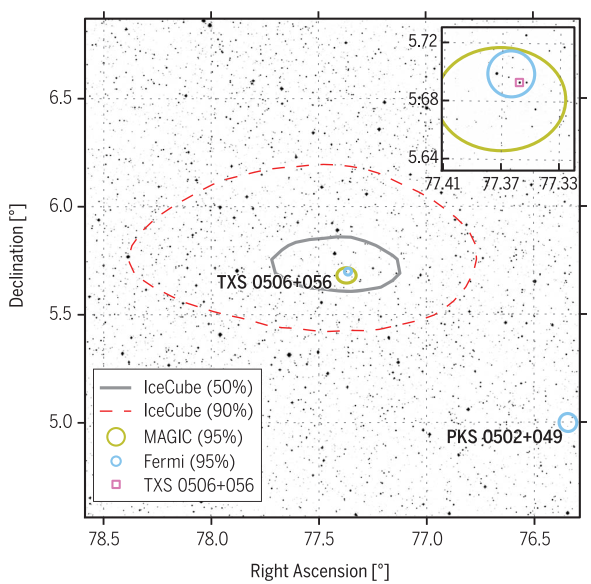
mic rays. The discovery of an extraterrestrial diffuse flux of high-energy neutrinos, announced by IceCube in 2013, has characteristic properties that hint at contributions from extragalactic sources, although the individual sources remain as yet unidentified. Continuously monitoring the entire sky for astrophysical neutrinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the direction of the neutrino was coincident with a cataloged γ-ray source, 0.1° from the neutrino direction. The source, a blazar known as TXS 0506+056 at a measured redshift of 0.34, was in a flaring state at the time with enhanced γ-ray activity in the GeV range. Follow-up observations by imaging atmospheric Cherenkov telescopes, notably the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, revealed periods where the detected γ-ray flux from the blazar reached energies up to 400 GeV. Measurements of the source have also been completed at x-ray, optical, and radio wavelengths. We have investigated models associating neutrino and γ-ray production and find that correlation of the neutrino with the flare of TXS 0506+056 is statistically significant at the level of 3 standard deviations (sigma). On the basis of the redshift of TXS 0506+056, we derive constraints for the muon-neutrino luminosity for this source and find them to be similar to the luminosity observed in γ-rays.

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aat1378

CONCLUSION: The energies of the γ-rays and the neutrino indicate that blazar jets may accelerate cosmic rays to at least several PeV. The observed association of a high-energy neutrino with a blazar during a period of enhanced γ-ray emission suggests that blazars may indeed be one of the long-



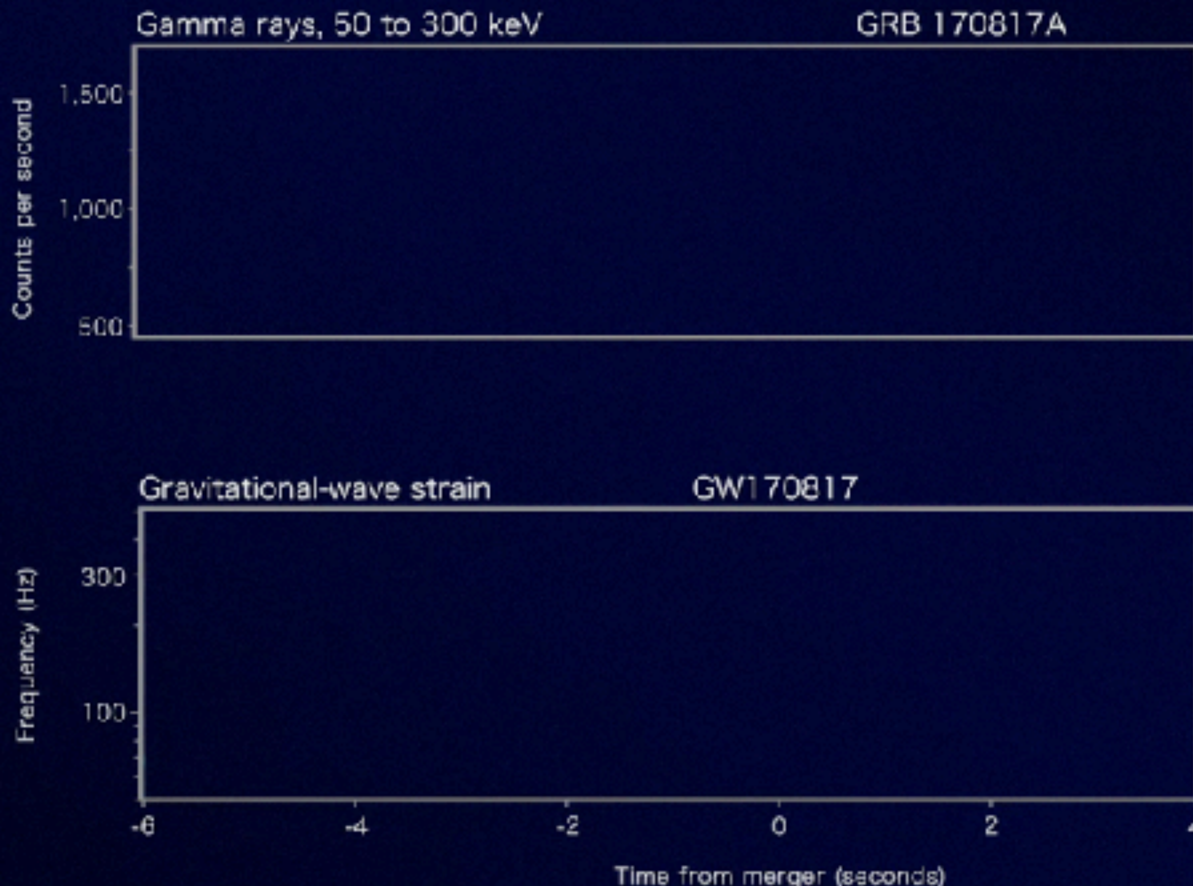
Multimessenger observations of blazar TXS 0506+056. The

NATA FOR THE R-BAND IN MAGNIFIED VIEW

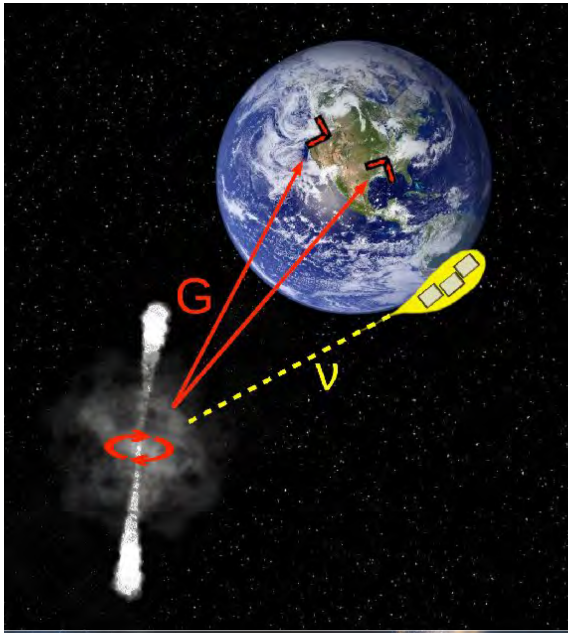
Follow-up of GW170817 with PAO (neutrinos)

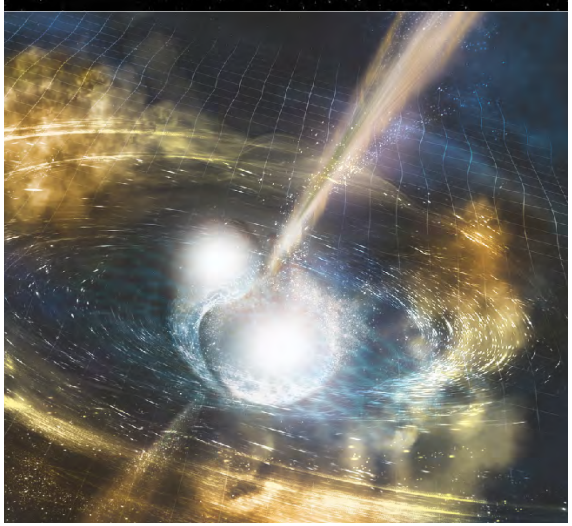
Fermi

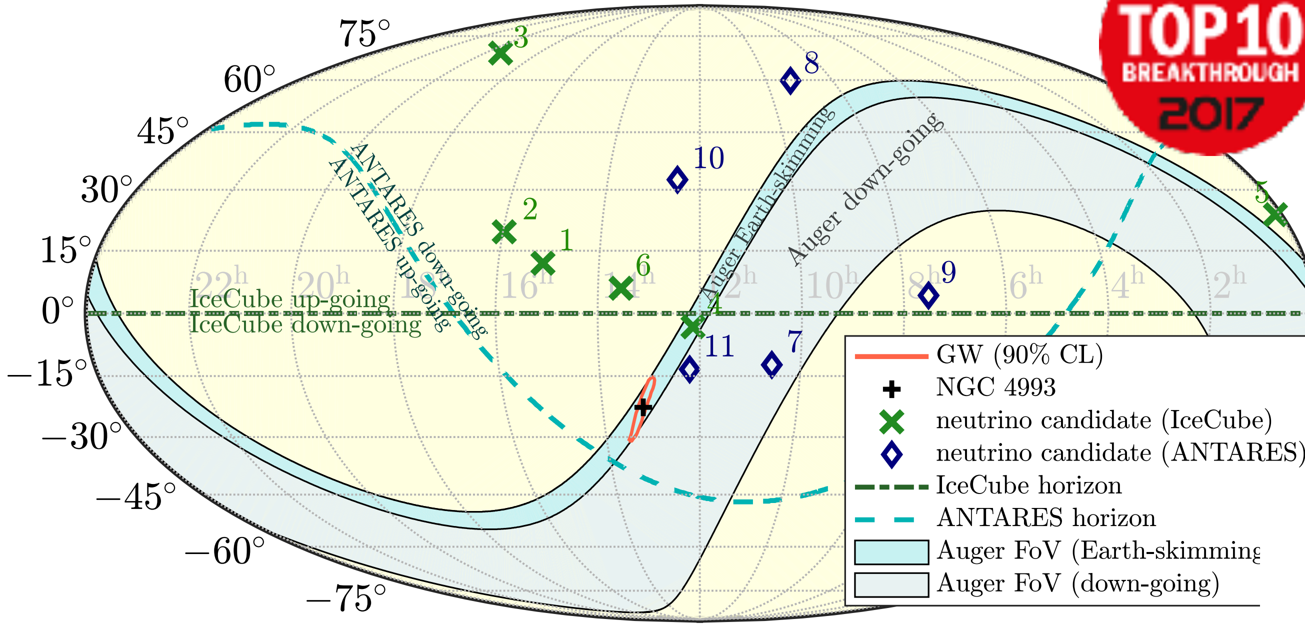
LIGO



Follow-up of GW170817 with PAO (neutrinos)







physicsworld TOP 10 BREAKTHROUGH 2017

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

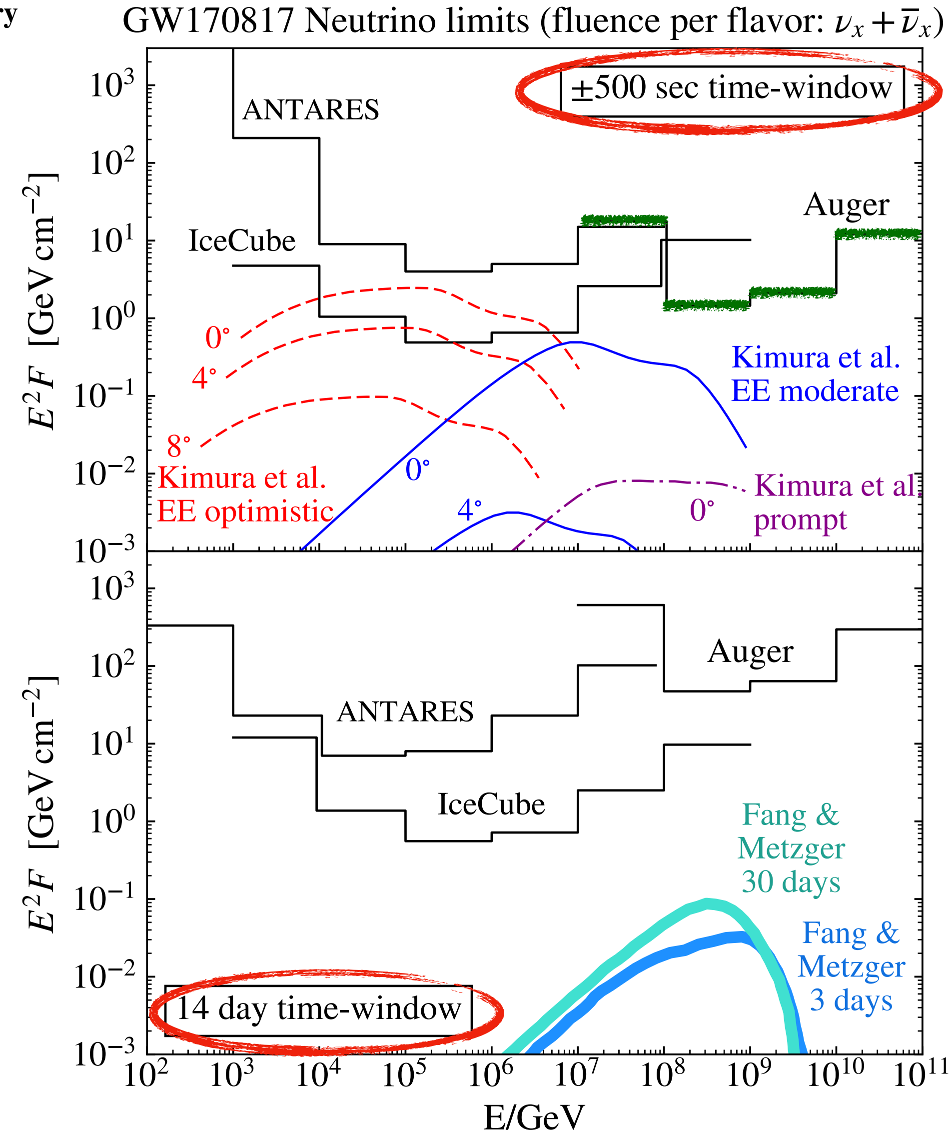
Malargüe N

Follow-up of GW170817 with PAO (neutrinos)

THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1
https://doi.org/10.3847/2041-8213/aa9aed

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration



PAO in pre-defined +/- 500 s window as sensitive as IceCube

A&A 619, A71 (2018)
https://doi.org/10.1051/0004-6361/201832640

Astronomy & Astrophysics

The γ-ray spectrum of the core of Centaurus A as observed with H.E.S.S. and *Fermi*-LAT

ABSTRACT

Centaurus A (Cen A) is the nearest radio galaxy discovered as a very-high-energy (VHE; 100 GeV–100 TeV) γ-ray source by the High Energy Stereoscopic System (H.E.S.S.). It is a faint VHE γ-ray emitter, though its VHE flux exceeds both the extrapolation from early *Fermi*-LAT observations as well as expectations from a (misaligned) single-zone synchrotron-self Compton (SSC) description. The latter satisfactorily reproduces the emission from Cen A at lower energies up to a few GeV. New observations with H.E.S.S., comparable in exposure time to those previously reported, were performed and eight years of *Fermi*-LAT data were accumulated to clarify the spectral characteristics of the γ-ray emission from the core of Cen A. The results allow us for the first time to achieve the goal of constructing a representative, contemporaneous γ-ray core spectrum of Cen A over almost five orders of magnitude in energy. Advanced analysis methods, including the template fitting method, allow detection in the VHE range of the core with a statistical significance of 12σ on the basis of 213 hours of total exposure time. The spectrum in the energy range of 250 GeV–6 TeV is compatible with a power-law function with a photon index $\Gamma = 2.52 \pm 0.13_{\rm stat} \pm 0.20_{\rm sys}$. An updated *Fermi*-LAT analysis provides evidence for spectral hardening by $\Delta\Gamma \simeq 0.4 \pm 0.1$ at γ-ray energies above $2.8^{+1.0}_{-0.6}$ GeV at a level of 4.0σ. The fact that the spectrum hardens at GeV energies and extends into the VHE regime disfavour a single-zone SSC interpretation for the overall spectral energy distribution (SED) of the core and is suggestive of a new γ-ray emitting component connecting the high-energy emission above the break energy to the one observed at VHE energies. The absence of significant variability at both GeV and TeV energies does not yet allow disentanglement of the physical nature of this component, though a jet-related origin is possible and a simple two-zone SED model fit is provided to this end.

Key words. gamma rays: galaxies – radiation mechanisms: non-thermal

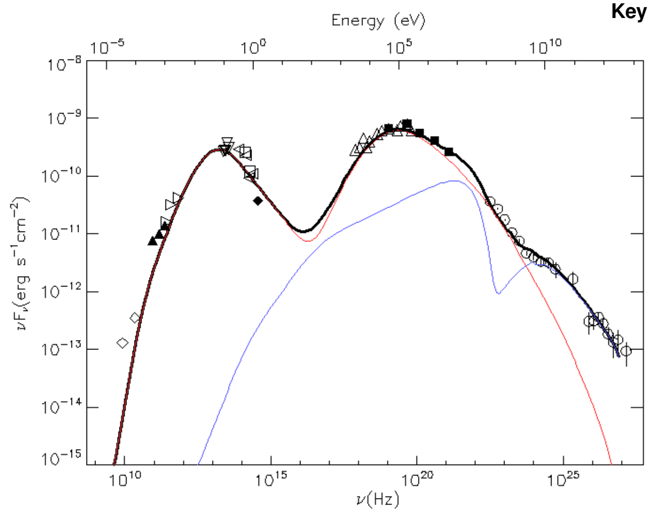
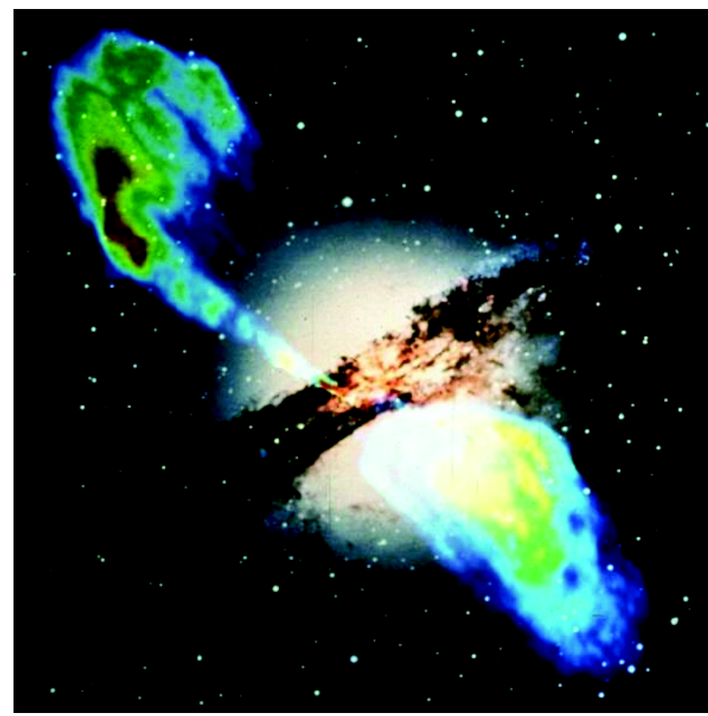


Fig. 3. SED of Cen A core with model fits as described in text. The red curve corresponds to an SSC component designed to fit the radio to sub-GeV data. The blue curve corresponds to a second SSC component added to account for the highest energy data. The black curve corresponds to the sum of the two components. SED points as derived from H.E.S.S. and *Fermi*-LAT data in this paper are shown with open circles. Observations from the radio band to the MeV γ-ray band are from TANAMI (◇), SEST (▲), JCMT (▹), MIDI (▽), NAOS/CONICA (◃), NICMOS (□), WFPC2 (♦), *Suzaku* (△), OSSE/COMPTEL (■). The acronyms are described in Appendix B.



COSMIC RAYS

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

physicsworld TOP 10 BREAKTHROUGH 2017

Anisotropy detected at >5.2 sigma
dipole amplitude 6.5%

$E>8*10^{18}$ eV $\quad$ $3*10^{4}$ CRs

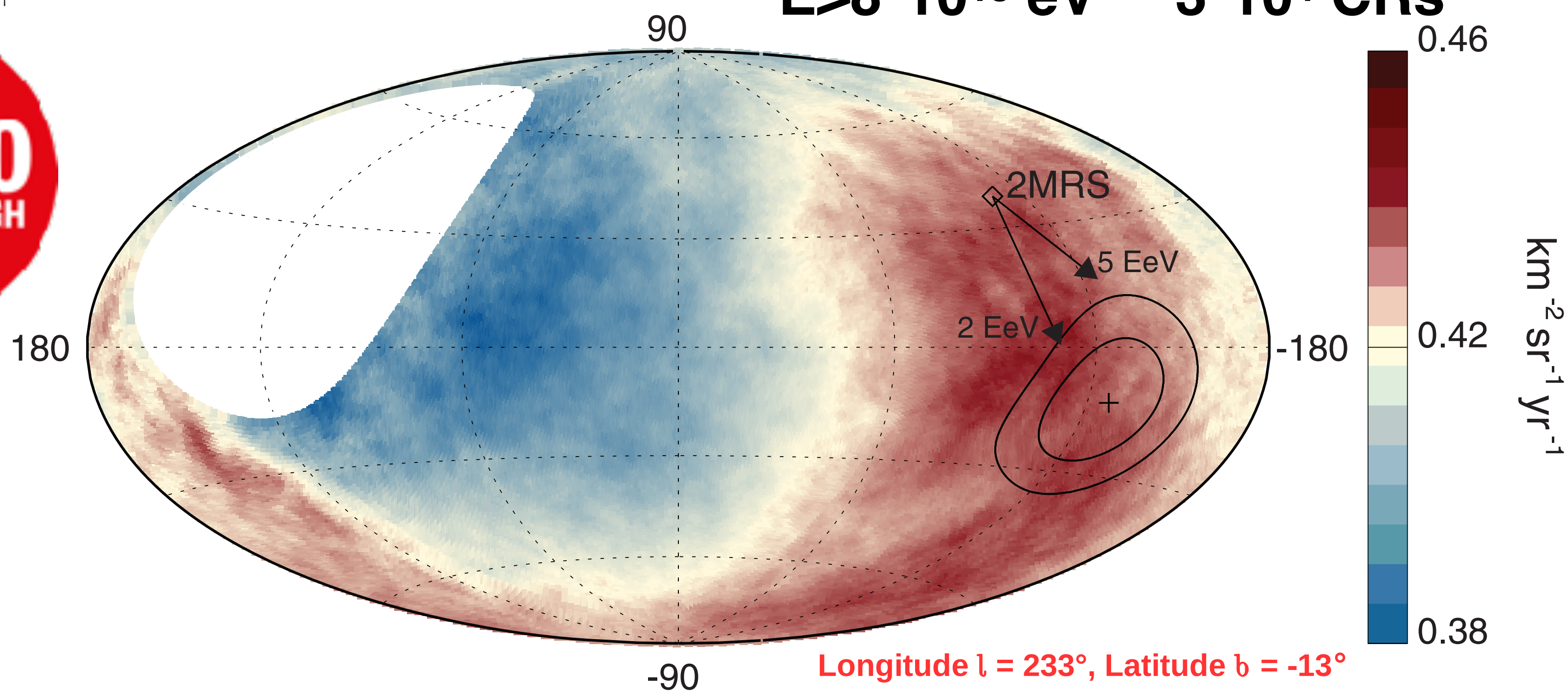
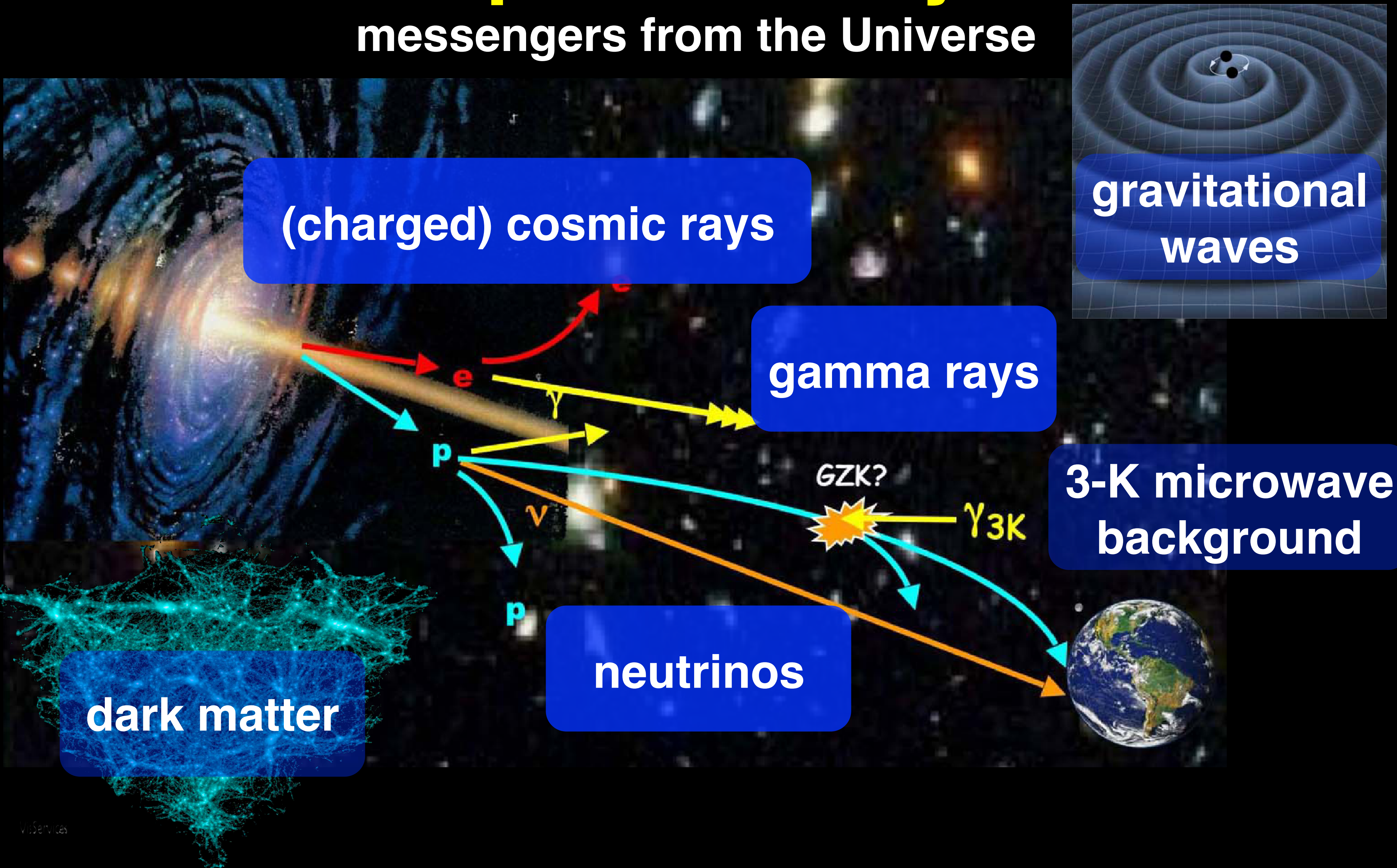


Fig. 3. Map showing the fluxes of particles in galactic coordinates. Sky map in galactic coordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45° top-hat function. The galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for a particular model of the galactic magnetic field (8) on particles with E/Z = 5 or 2 EeV.

A. Aab et al., Science 357 (2017) 1266

Astroparticle Physics

messengers from the Universe

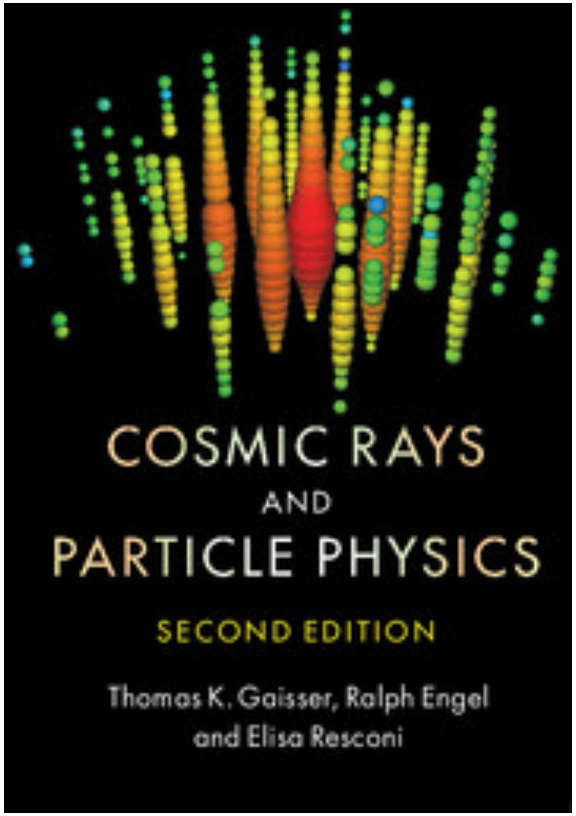


Literature

Particles & Cosmos: Stanev

Astroparticle Physics:
Tom Gaisser, Cosmic rays and particle physics
Cambridge University Press (2016)

+ primary literature (journal articles)



Astroparticle Physics 2021/22

1. Historical introduction - basic properties of cosmic rays
2. Hadronic interactions and accelerator data
3. Cascade equations
4. Electromagnetic cascades
5. Extensive air showers
6. Detectors for extensive air showers
7. High-energy cosmic rays and the knee in the energy spectrum of cosmic rays
8. Radio detection of extensive air showers
9. Acceleration, Astrophysical accelerators and beam dumps
10. Extragalactic propagation of cosmic rays
11. Ultra-high-energy energy cosmic rays
12. Astrophysical gamma rays and neutrinos
13. Neutrino astronomy
14. Gamma-ray astronomy

Student talks

- Students will present selected topics, based on journal publications.
- Learn how to derive information from primary literature.
- Presentation followed by discussion and questions.
- 60 min presentation, 15 min discussion
- You are expected to participate in discussions and ask questions.
- Your presentation + interaction will be part of your grade.

Student talks

- Air showers - Matthews Heitler model
- Radio detection of air showers
- CR anisotropy at TeV energies, IceCube/Top, HAWC
- the knee in the energy spectrum of cosmic rays
- Detectors for UHE CRs, Auger, TA
- Auger proton-air cross section
- GZK effect and the end of the CR spectrum, Auger, TA
- CR mass composition at highest energies, Auger, TA
- CR anisotropy at highest energies, Auger, TA
- IceCube neutrino astronomy
- KM3NeT project ARCA+ORCA
- H.E.S.S. TeV gamma-ray astronomy galactic center emission
- H.E.S.S. TeV gamma-ray astronomy galactic plane survey
- Cherenkov Telescope Array - CTA
- XENON dark matter search
- LIGO + Virgo gravitational waves

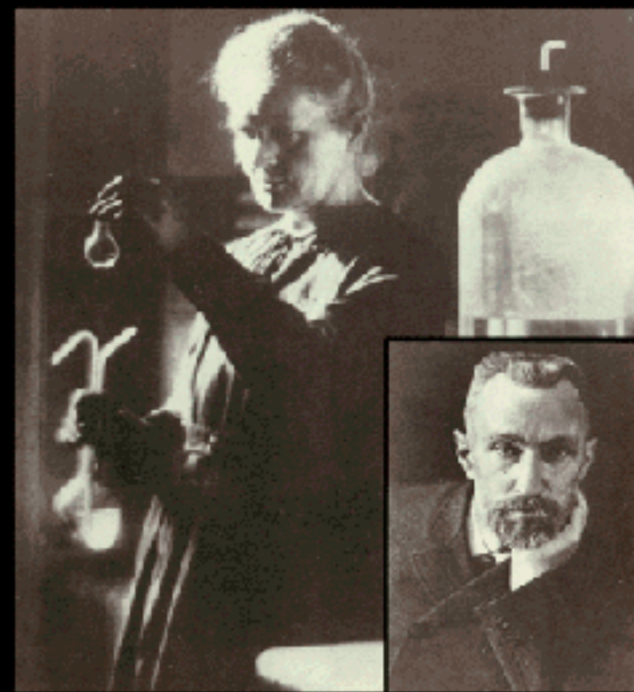
lecture 1

Historical introduction

Basic properties of Cosmic Rays

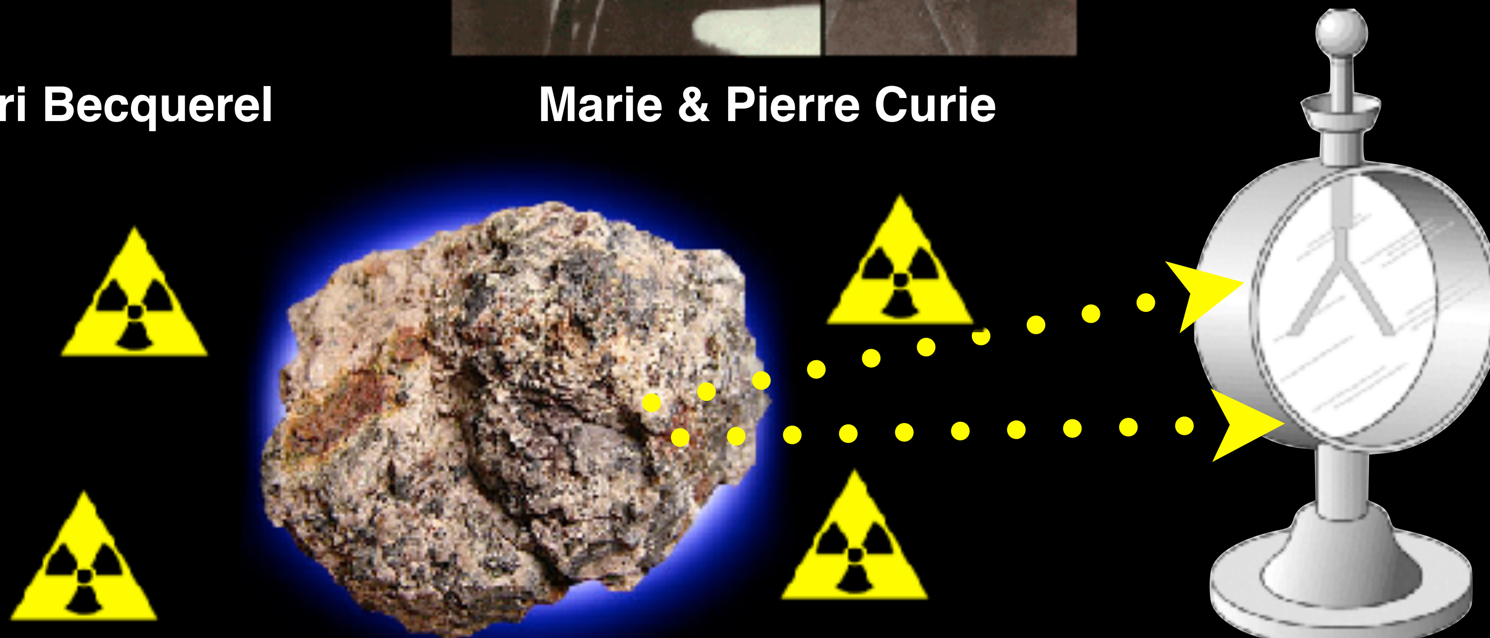
Discovery of Radioactivity

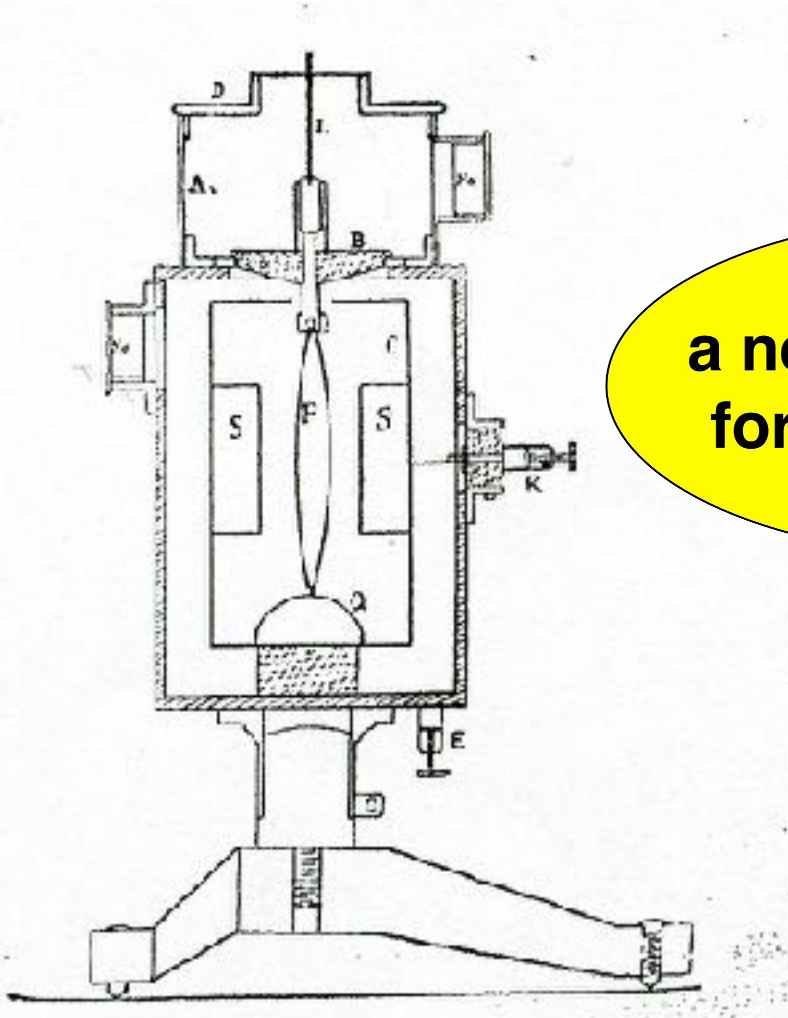
Henri Becquerel



Marie & Pierre Curie

Nobel Prize 1903





Ein neues Elektrometer für statische Ladungen.

Dritte Mitteilung[1]).

Von Th. Wulf.

a new electrometer for static charges

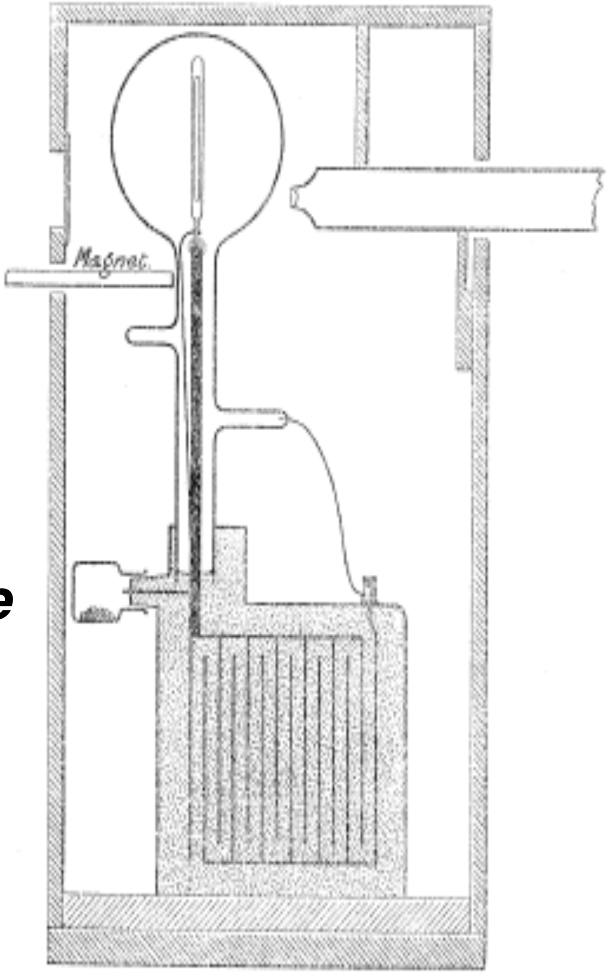
... Mitteilung enthält einige ...her beschriebenen Appa- ...öhung seiner Transport-

Sir J.J.Thomson
Nobel Prize 1906

Conduction of electricity through gases (1928):

It would be one of the romances of science if these obscure and prosaic minute leakages of electricity from well-insulated bodies should be the means by which the most fundamental problems in the evolution of the cosmos came to be investigated.

Detector used by Wilson to investigate ionization of air



"the continuous production of ions in dust-free air could be explained as being due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or cathode rays, but of enormously greater penetrating power"

C T R Wilson, Proc Roy Soc A 68 (1901) 151 on the origin of gamma radiation in the atmosphere

Über den Ursprung der in der Atmosphäre vorhandenen γ-Strahlung.

Von Th. Wulf.

Tabelle I.
Strahlung der Wände von Gebäuden.

Ort	Material	Alter	Strahlung Ionen pro ccm u. Sekunde
Abtei Maria Laach bei Andernach a. Rh. . .	Vulkanisch Tuff	50 Jahre	13,7
Valkenburg, Colleg, Holland-L.	Ziegelsteine	15 „	5,7
Löwen, Colleg, Belgien	Ziegelsteine	—	8,0
Namur, Colleg N. D. de la paix, Belgien . . .	Ziegelsteine	ca. 100	3,7
Wynandsrade Kasteel, Holland	Ziegelsteine	200 Jahre	0,0

Nur in dem alten holländischen Kasteel Wynandsrade, vor fast 200 Jahren aus Ziegelsteinen erbaut, zeigte sich kein Unterschied in der Strahlung im Zimmer und im Freien. — Am stärksten war die Strahlung in Maria Laach in einem

Man kann den Inhalt dieser Arbeit kurz so zusammenfassen. Es wird über Versuche berichtet, welche beweisen, daß an dem Beobachtungsort die durchdringende Strahlung von primär radioaktiven Substanzen verursacht wird, welche in den obersten Erdschichten liegen, bis etwa 1 m unter der Oberfläche.

Wenn ein Teil der Strahlung aus der Atmosphäre stammt, so ist er doch so klein, daß er sich mit den gebrauchten Mitteln nicht nachweisen ließ.

Die zeitlichen S… …ankungen in der γ-Strah-
lun… …eben
d… …de
… …ie

the radiation originates from the soil
maybe a small contribution from the atmosphere

~1910

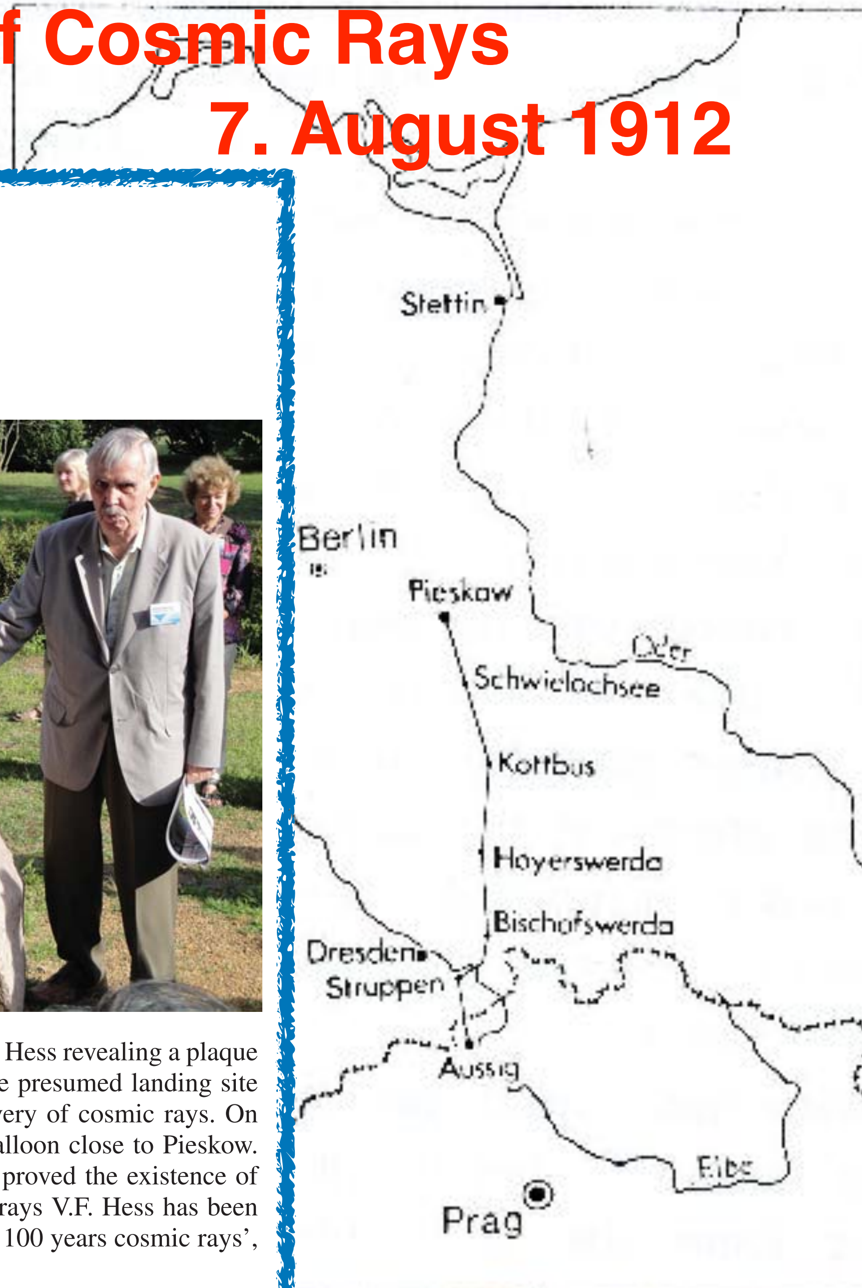
Theodor Wulf

1909: Soddy & Russel: attenuation of gamma rays follows an exponential law

$$I = I_0 e^{-\mu L}$$

Discovery of Cosmic Rays

Viktor Franz Hess 7. August 1912



Early cosmic-ray work published in German

Jörg R. Hörandel

Citation: AIP Conf. Proc. **1516**, 52 (2013); doi: 10.1063/1.4792540

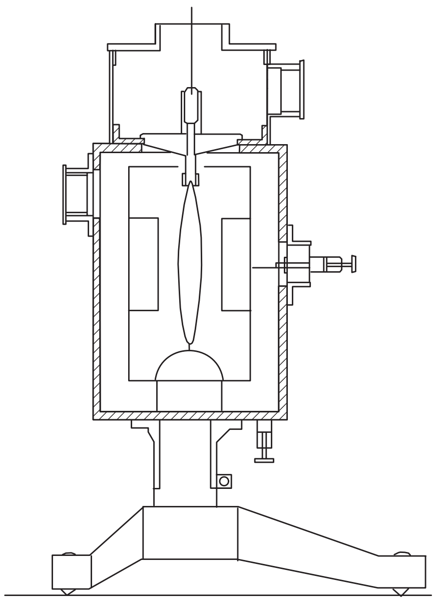


FIGURE 1. *Left*: Electrometer after Th. Wulf [5]. *Right*: Two grandsons of V.F. Hess revealing a plaque to commemorate the discovery of cosmic rays on August 7th, 2012, close to the presumed landing site of V.F. Hess in Pieskow close to Berlin. It reads: "To commemorate the discovery of cosmic rays. On 7 August 1912 landed the Austrian physicist Victor F. Hess with a hydrogen balloon close to Pieskow. On the journey from Lower-Bohemia he reached an altitude of 5300 m and he proved the existence of a penetrating, ionizing radiation from outer space. For the discovery of cosmic rays V.F. Hess has been awarded the Nobel Prize in Physics in 1936. The participants of the symposium '100 years cosmic rays', Bad Saarow-Pieskow, 7 August 2012".

Aeronautisches Gelände im Wiener Prater, vo
seine ersten Freiballon-Forschungsfahrten u
schichtliche Mu

Hess on

Route des Entdeckungsfluges der kosmischen Strahlung.

Aus der Abteilung für Geophysik, Meteorologie und Erdmagnetismus:

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten.

on the observation of the penetrating radiation during 7 balloon campaigns

Im Vorjahre habe ich bereits Gelegenheit gehabt, zwei Ballonfahrten zur Erforschung der durchdringenden Strahlung zu unterneh-

7. Fahrt (7. August 1912).

Ballon: „Böhmen" (1680 cbm Wasserstoff). Führer: Hauptmann W. Hoffory.
Meteorolog. Beobachter: E. Wolf. Luftelektr. Beobachter: V. F. Hess.

hydrogen!

		Mittlere Höhe		Beobachtete Strahlung					
		absolut	relativ m	Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	Apparat 3 reduz. q_3	Temp.	Relat. Feucht. Proz.
1	15h 15—16h 15	156	0	17,3	12,9	—	—	—	—
2	16h 15—17h 15	156	0	15,9	11,0	18,4	18,4	1½ Tag vor dem Auf-	
3	17h 15—18h 15	156	0	15,8	11,2	[illegible]	17,5	stiege (in Wien)	
4	[illegible]	1700	1400	15,8	14,4	[illegible]	[illegible]	+6,4°	60
[illegible]	[illegible]	2750	2500	17,3	[illegible]	[illegible]	[illegible]	+1,4°	41
[illegible]	[illegible]	3850	3600	19,8	[illegible]	[illegible]	[illegible]	—6,8°	64
7	[illegible]	4800 (4400-[illegible])	4700	40,7	[illegible]	[illegible]	—	—9,8°	40
8	10h 45—11h 15	4400	4200	28,1	22,7	—	—	—	—
9	11h 15—11h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11h 45—12h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12h 25—13h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow, Brandenburg)	

altitude

intensity

wurde.

Elektrometers gesetzter Zinkstift von

Aus der Abteilung für Geophysik, Meteorologie und Erdmagnetismus:

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben

V.F. Hess in 1936–37, on the occasion of Nobel prize.

Nobel Prize 1936

erweitertes Beobachtungsmaterial wurde.

der Atmosphäre zurückzuführen.

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt, und auch noch in deren untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft. Die Intensität dieser Strahlung scheint zeitlichen Schwankungen unterworfen zu sein, welche bei einstündigen Ablesungsintervallen noch erkennbar sind. Da ich im Ballon weder bei Nacht noch bei einer Sonnenfinsternis eine Verringerung der Strahlung fand, so kann man wohl kaum die Sonne als Ursache dieser hypothetischen Strahlung ansehen, wenigstens solange man nur an eine direkte γ-Strahlung mit geradliniger Fortpflanzung denkt.

Daß die Zunahme der Strahlung erst jenseits 3000 m so stark merklich wird, ist nicht

Absorption in the atmosphere

Neue Untersuchungen über die durchdringende Hesssche Strahlung.

Von E. Steinke in Königsberg i. Pr.

Intensity as functio[n] for different altitude[s]

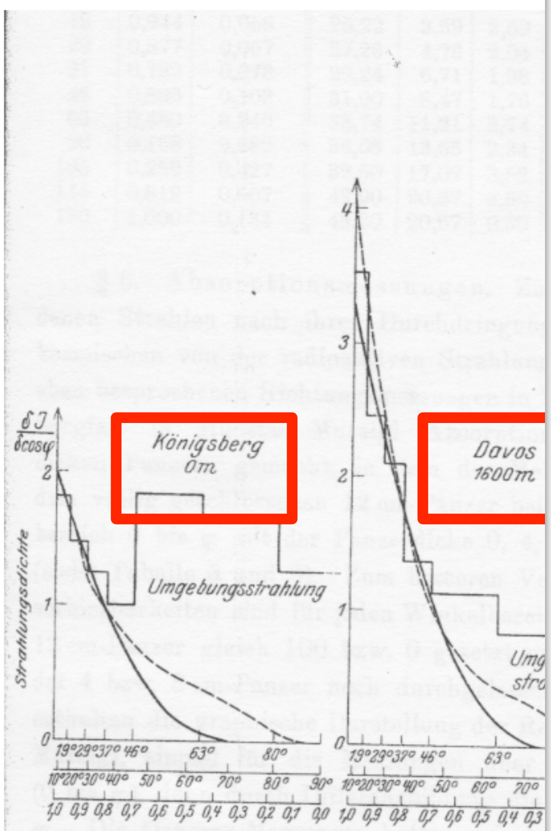


Fig. 9. Richtungsverteilung der durchdringenden Strahlu[ng] ... kurve gibt die beobachteten Werte an. Ferner bedeute[t] ... die berechnete Kurve f[ür] ... und 0,05 cm−1 zusamm[en]

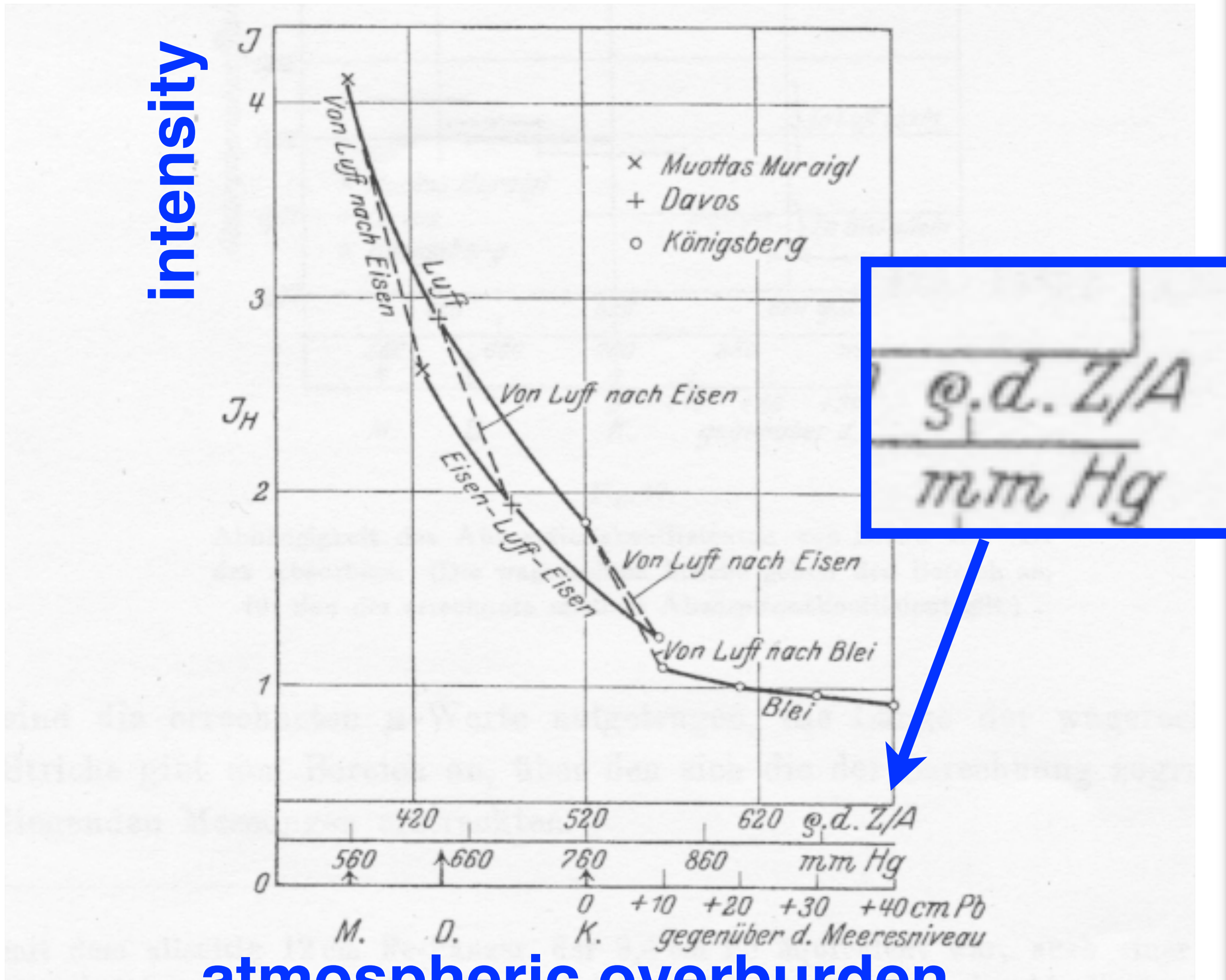


Fig. 15.

Intensität der durchdringenden Strahlung in Abhängigkeit von der Absorptionsschicht.

E. Steinke, Z. f. Physik 48 (1928) 647