

High Energy Sources and Multi-Messenger High Energy Astrophysics

Part 1.

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Amaldi Research Center

Roma, March 4th, 2021

We are living in a “*Golden Epoch*” in Astrophysics
with the development of “*Multi-Messenger Astronomy*”

Our knowledge of the Universe has been until now
(nearly) entirely obtained with *observations*
with *Light* [Photons]

The history of astronomy is the marked by improvements
in telescopes and the widening of the wavelength band

Optical, Infrared, ..., Radio, X-rays,, Gamma-Rays

witnessing today:

Opening of Observations with New Messengers:

Cosmic Rays, Neutrinos, Gamma-Rays
Gravitational Waves

*Different way
to look at the sky*

S I D E R E V S
N U N C I V S
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI

1610 Galileo Galilei
“*Nuncius Sidereus*”
“Star Messenger”
[Light, Telescope]

Expanding from
Light
to other
Messengers/
Particles



New “classes” of Sources

“Violent”

SuperNova explosions

“Dynamic”

Gravitational Collapses

Transient

Merging of Compact Objects

“Non-thermal”

Gamma Ray Bursts.

High energy emissions

.....

The Ensemble of these sources:

“The High Energy Universe”

“High Energy Universe”

The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy particles in the Milky Way and in the entire universe.

This field is one of the most significant and fascinating *“Frontiers”* in Science today.

1. Understanding the *“COSMOS”* where we live
2. The sources of the High Energy radiation can be the “laboratories” where we test *(in conditions that are not achievable in “Earth based laboratories”)* our Fundamental Laws of Physics.

Plan of the seminar:

1st Lecture

Historical Introduction

Fundamental ideas

2nd Lecture

Recent Developments

Open Problems

The “First glimpse” of the High Energy Universe:

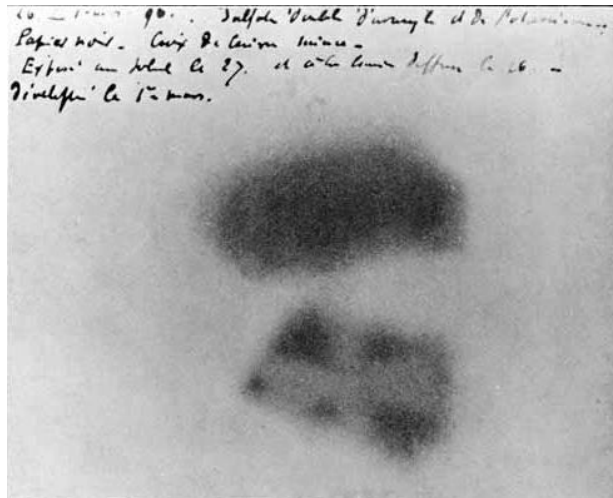
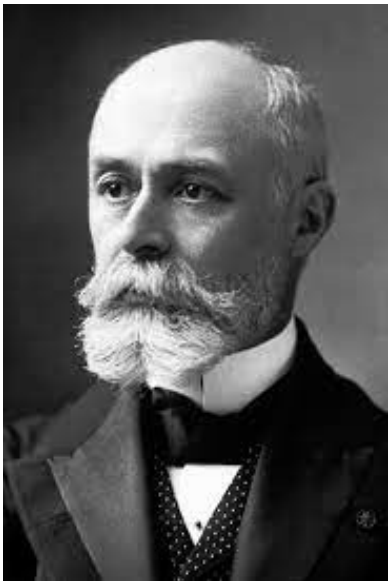
The discovery of Cosmic Rays

[Victor Hess (1912), Nobel (1936)]

but discovery is (most of the time)
a *process* with several persons involved]

“Pre-history”

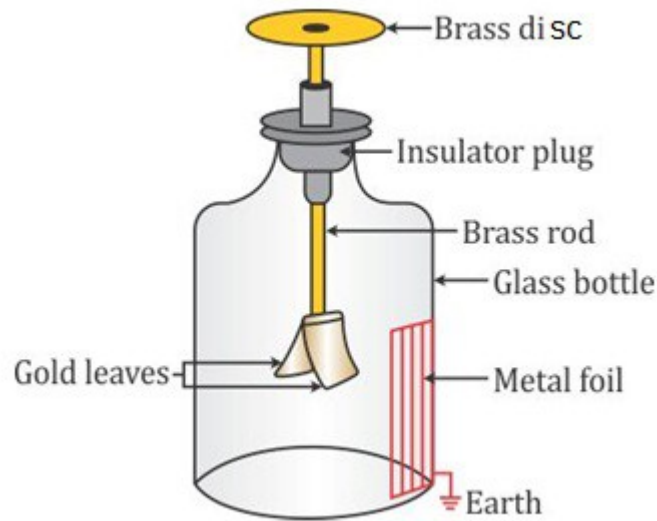
1896 Henri Becquerel discovers **Radioactivity**



penetrating radiation
can darken
photographic emulsion

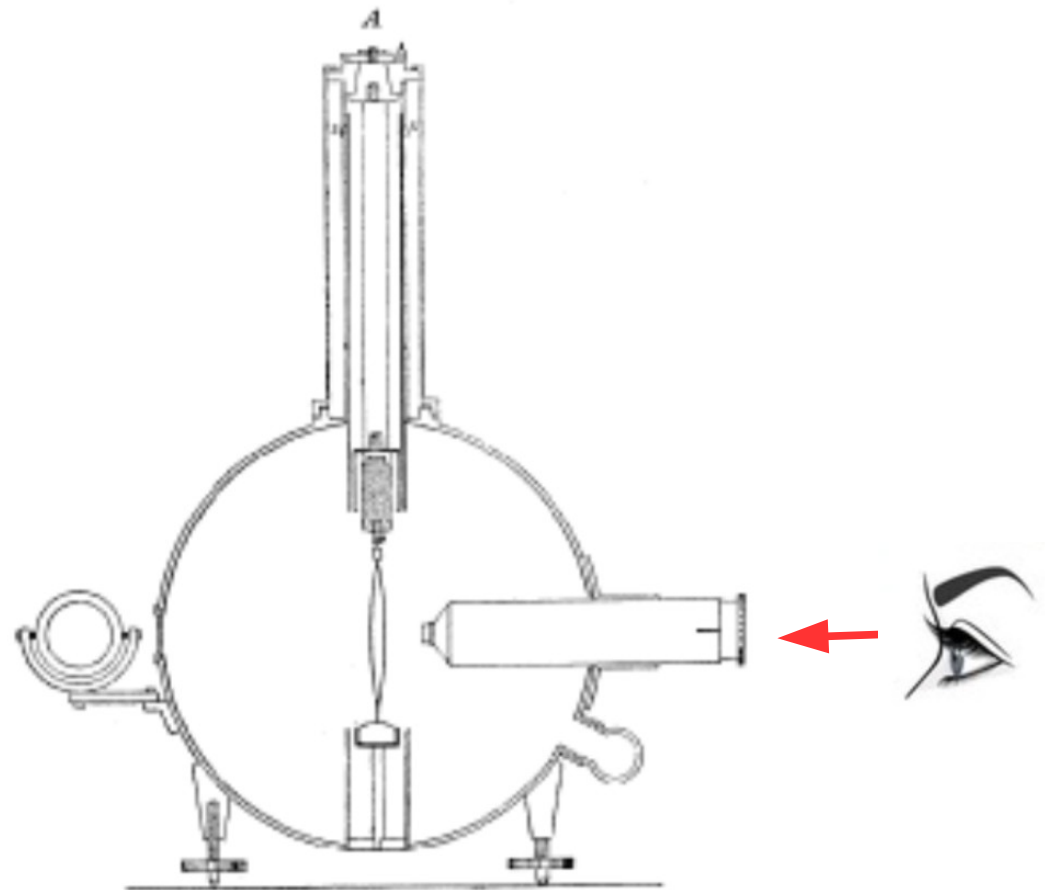
Radioactivity is a “ionizing radiation”

In a gas, the ions created by the radiation induce the *Spontaneous discharge of electroscopes*



Rate of electroscope
discharge

Rate of creation
of ions $(\text{cm}^3 \text{ s})^{-1}$



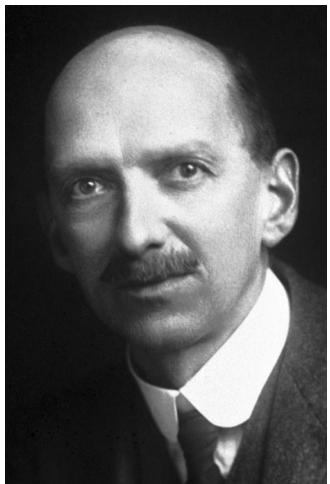
(Theodore) Wulf electroscope



Julius Elster
Hans Geitel

(1900) Ionizing radiation
is “everywhere” also far
from known sources.

*Is this the effect of
radioactive substances
in all Earth's materials ?*



C.T.R. (Charles Thomson Rees) Wilson

Nobel prize 1927
for the “Cloud” (Wilson) chamber.
“for his method of making the paths
of electrically charged particles
visible by condensation of vapour”

(1901) Can this
ionizing radiation
be extraterrestrial ?

One decade to prove this

Manned balloon flights

Walter Kolhörster
[1913]



Victor Hess
[1912]

Establishing the
extraterrestrial nature
of the source of ionization



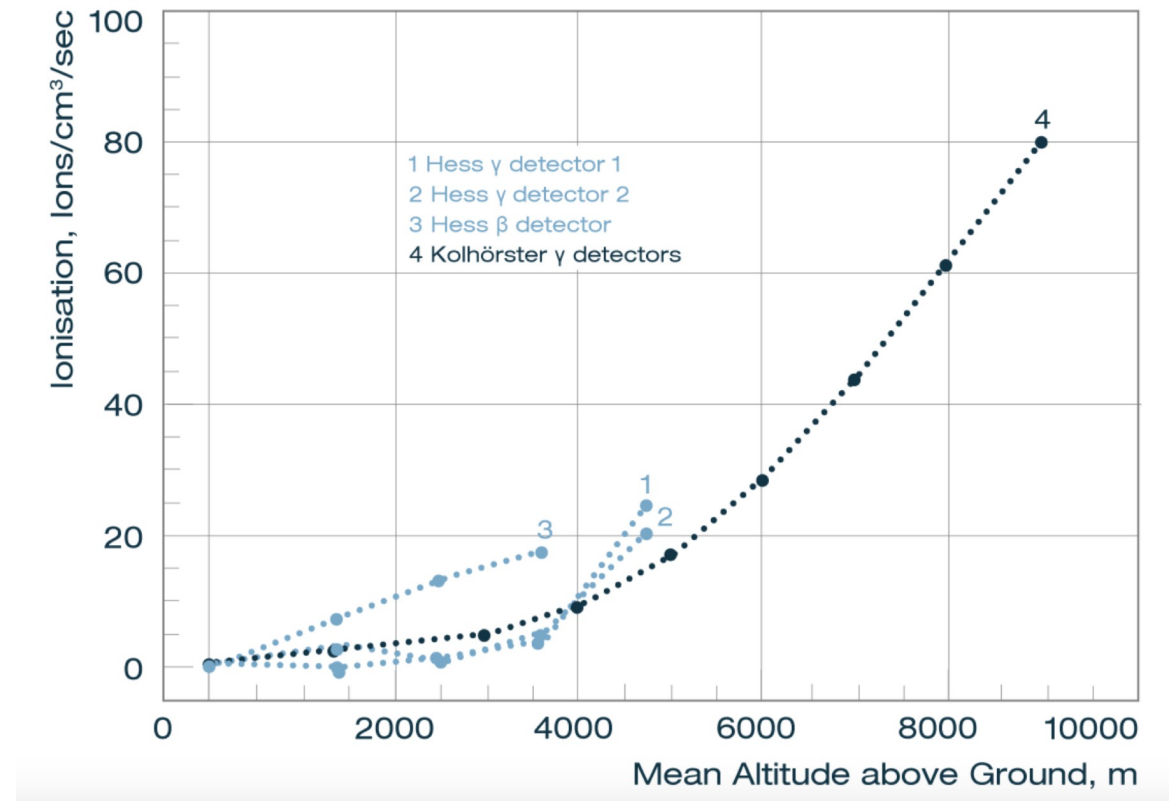
Discovery of COSMIC RAYS and the “*High Energy Universe*”

Study of the rate of ionization in air
with discharge electrosopes:
existence of Extraterrestrial source of Radiation

Ionization unit:
(ions created)/(cm³ s)

Victor Hess
[1912]

Walter Kolhörster
[1913]



Altitude (km)



Victor Hess posing looking into old electroscope (1960)

Role of Domenico Pacini



Nuovo Cimento 8, 93-100 (1912)

LA RADIAZIONE PENETRANTE ALLA SUPERFICIE ED IN SENO ALLE ACQUE.

NOTA DI D. PACINI.

last paragraph:....

quanto appare confermino le esperienze di cui è oggetto questa nota: cioè che *esista nell'atmosfera una sensibile causa ionizzante, con radiazioni penetranti, indipendente dall'azione diretta delle sostanze radioattive del terreno.*

It appears from the results described in this note:
*that a sizable cause of ionization exists in the atmosphere,
originating from penetrating radiation, independent
from the direct action of radioactive substances in the soil.*

Observe decreases of the rate of ionization with depth
for electroscopes immersed in water:
Ionization generated by "cause" the atmosphere

Understanding the nature of Cosmic Rays:
*[Relativistic charged particles
(mostly protons and ionized nuclei)]*

For nearly 20 years the commonly
accepted theory was that cosmic rays
were gamma-rays (the most penetrating known particle)

[Creating relativistic electrons
by (e-gamma or Compton scattering)]



Robert Millikan

[Measurement of the
electron charge (1910)
Nobel prize 1923]

“The birth cries of infant atoms”

Compton- Millikan “Controversy” (1930-1933)

gamma rays or
beta rays ?
(charged particles)

Nobel Prizewinners In Historic
Debate Over Cosmic-Ray Origins



MEET IN FRIENDLY RIVALRY
Robert A. Millikan, Pasadena (Left), and Arthur H. Compton, Chicago, Who Today Discussed Physical Research Findings

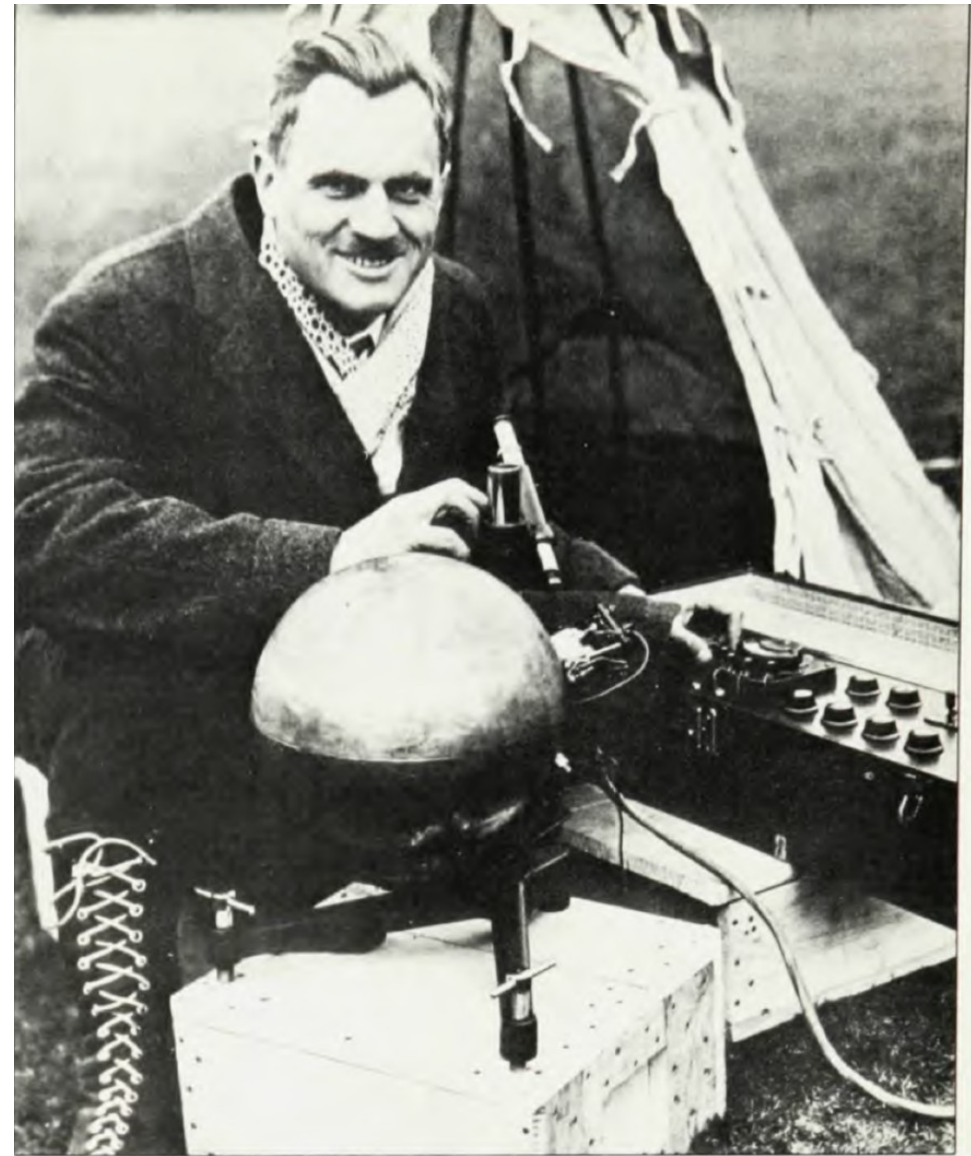
**COSMIC RADIATION
FOES BATTLE OVER
THEORIES OF ORIGIN**

P.S.-N. Dec. 30 '33

Dr. Robert A. Millikan, Dr. Arthur H. Compton
Present Opposing Ideas on Whether Cosmos
Being Recreated or Disintegrated

What most of the 2000 or more physical scientists gathered at Atlantic City for the winter meet-

...iders them the original rays. Dr. Millikan advanced evidences that they are secondary radiation pro-



The *Latitude Effect*

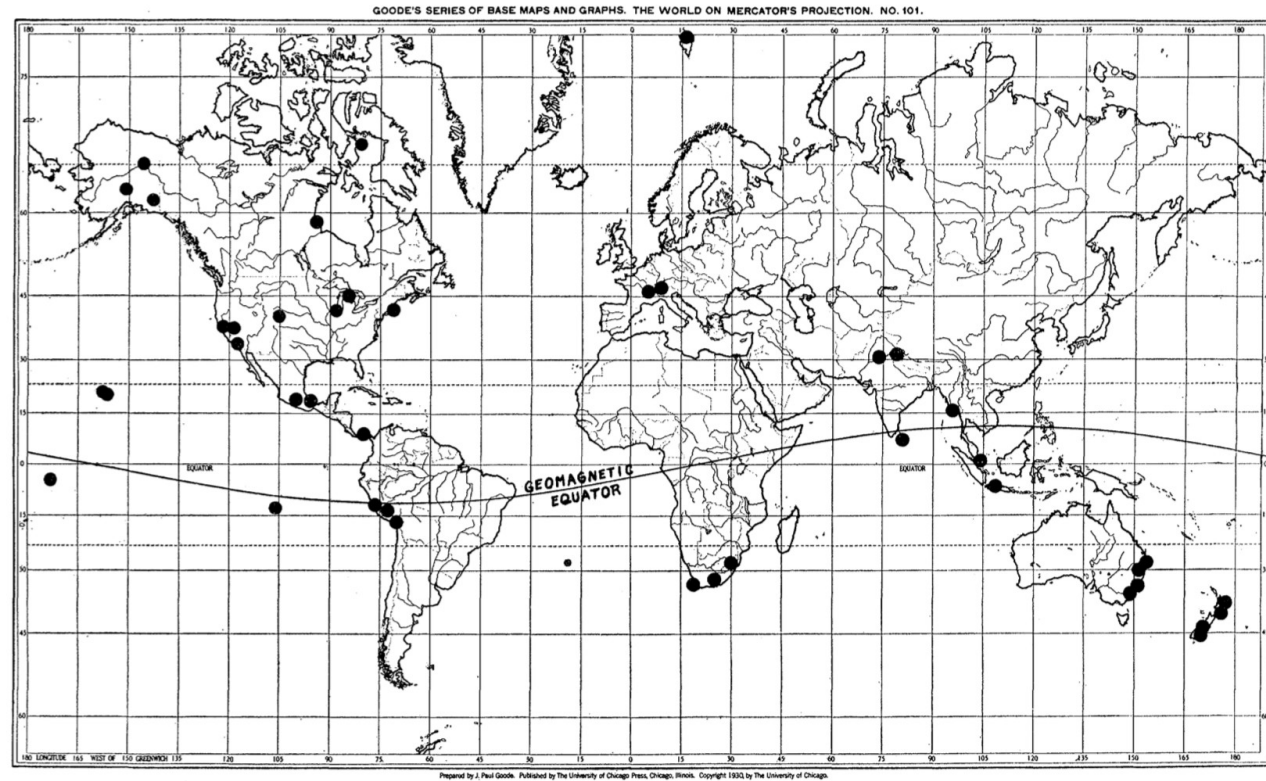
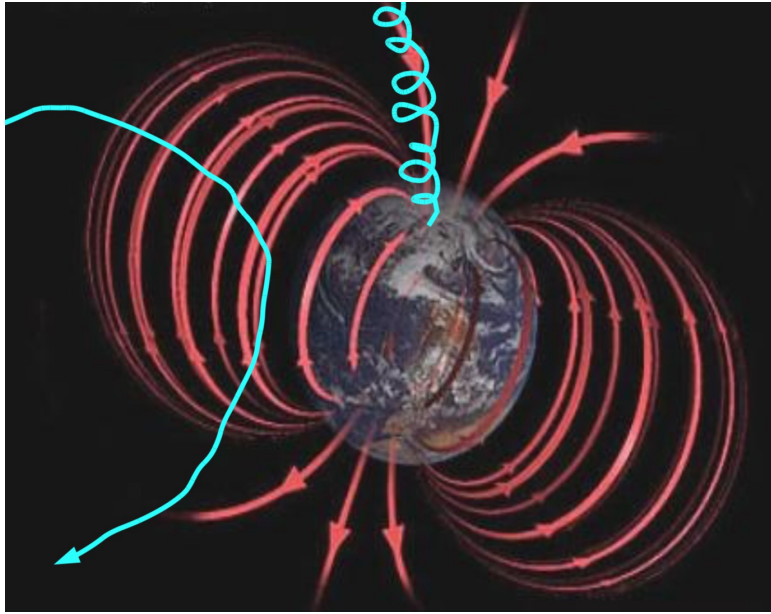


FIG. 1. Map showing location of our major stations for observing cosmic rays.

Arthur Compton

Phys. Rev. 15th march 1933

Cosmic Rays are
electrically charged particles.

Alvarez, Compton (april 1933)

East-West Effect

(most) Cosmic rays have
positive charge

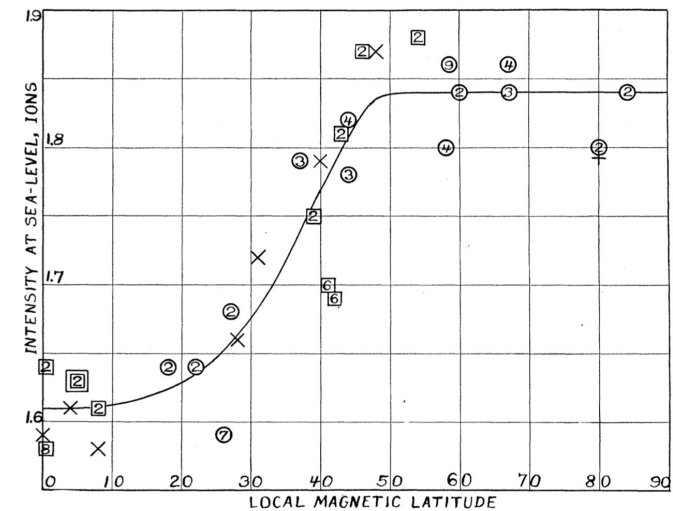


FIG. 9. Intensity vs. local magnetic latitude.

East-West effect

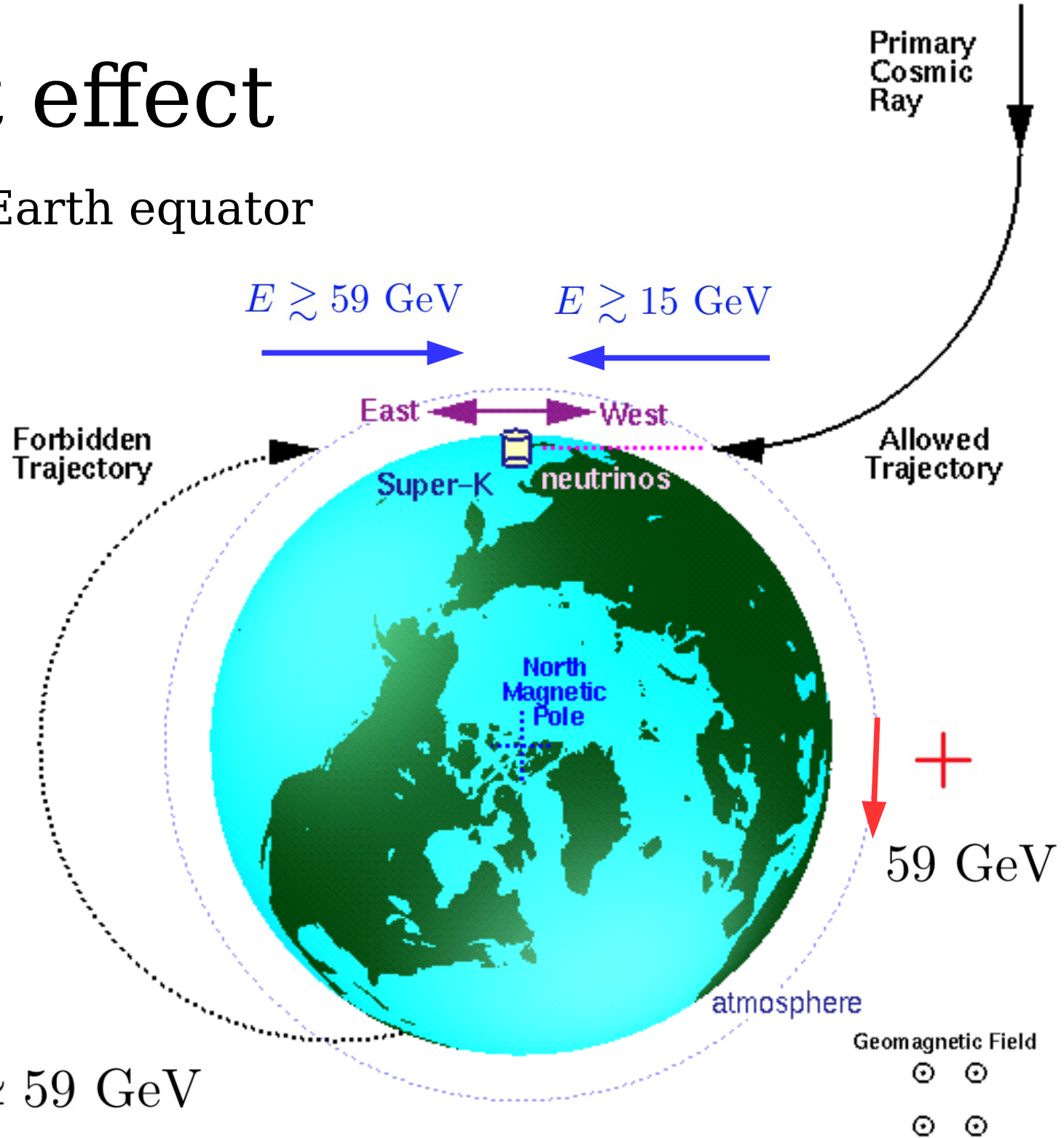
Magnetic field at Earth equator

$$B_{\text{eq}} \simeq 0.31 \text{ Gauss}$$

circular orbit
constant
magnetic field

$$R = \frac{p_{\perp} c}{q B}$$

$$E^* = |q_e| B_{\text{eq}} R_{\oplus} \simeq 59 \text{ GeV}$$



Latitude effect

[Compton 1933].

(Most) Cosmic Rays are charged particles

East-West effect

[Alvarez , Compton 1933
Bruno Rossi (1934)]

Most Cosmic Rays have positive electric charge.
[(Not electrons) [protons?]]

Very High Energy :
particles

$E_{\text{radioactivity}} \approx \text{few MeV}$

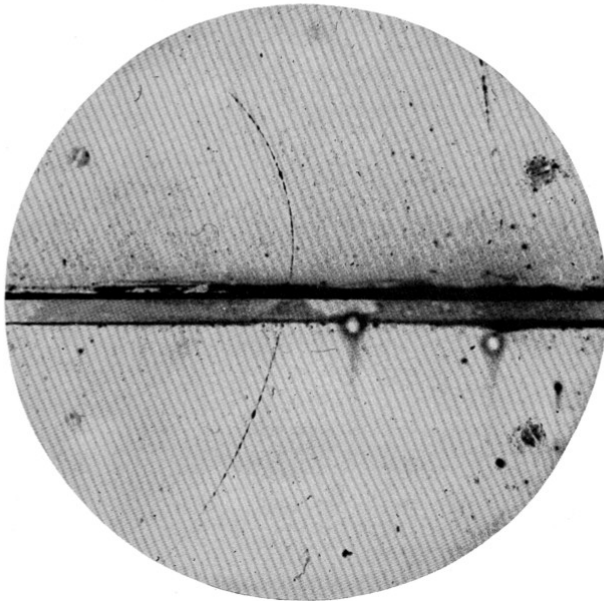
$E_{\text{cosmic rays}} \gtrsim 100 \text{ GeV}$

Understanding the propagation of Cosmic Rays in the atmosphere [Birth of *Particle Physics*]

Same issue of Physical Review [15th march 1933]
of Compton “Geographic Study of Cosmic Rays”

article of Carl Anderson
“The positive electron”

“Wilson chamber” in
a magnetic field.



Chapter 1:

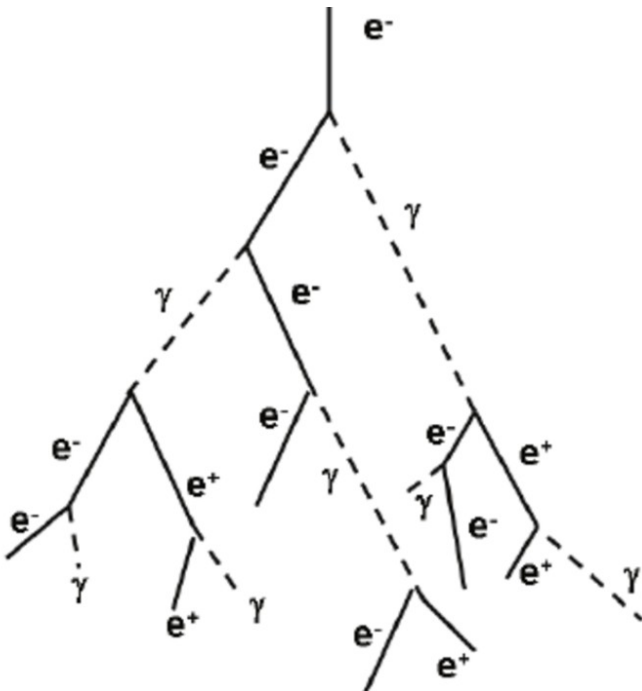
Theory of Electromagnetic Shower

$$\gamma Z \rightarrow e^+ e^- Z$$

Bethe - Heitler
(pair production)

$$e^\pm Z \rightarrow e^\pm \gamma Z$$

Bremsstrahlung



Chapter 2:

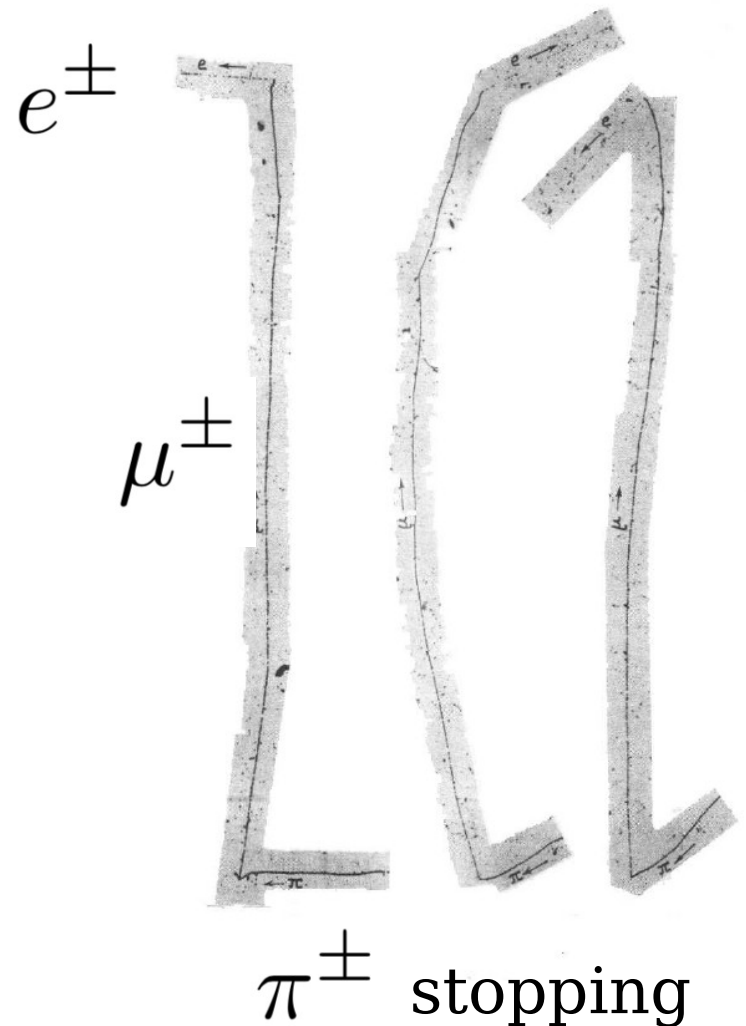
The Penetrating Component [Muons and charged pions]

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

+ charged conjugate modes

nuclear emulsions



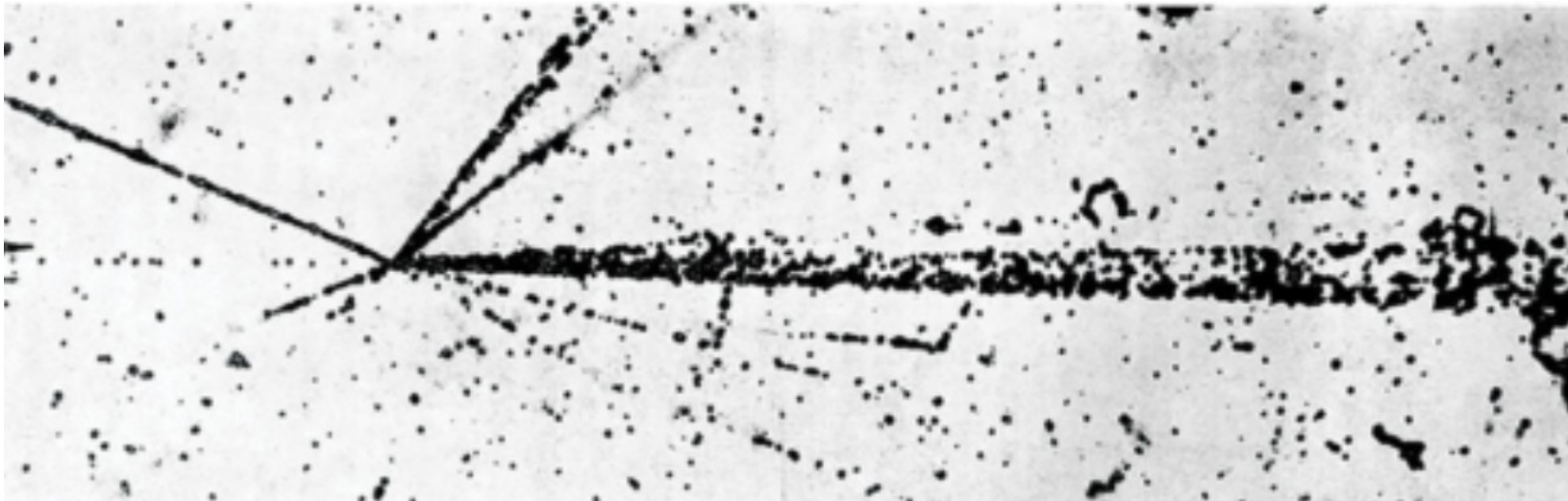
Chapter 3:

Nuclear interactions

[*Prediction* for neutral pion]

[Discovery of strange particles]

$$\pi^{\pm} \quad \pi^0$$
$$\pi^0 \rightarrow \gamma \gamma$$



$p + \text{Air nucleus} \rightarrow \text{many particles}$

[Problem that remains open
(or not calculable from first principles)]

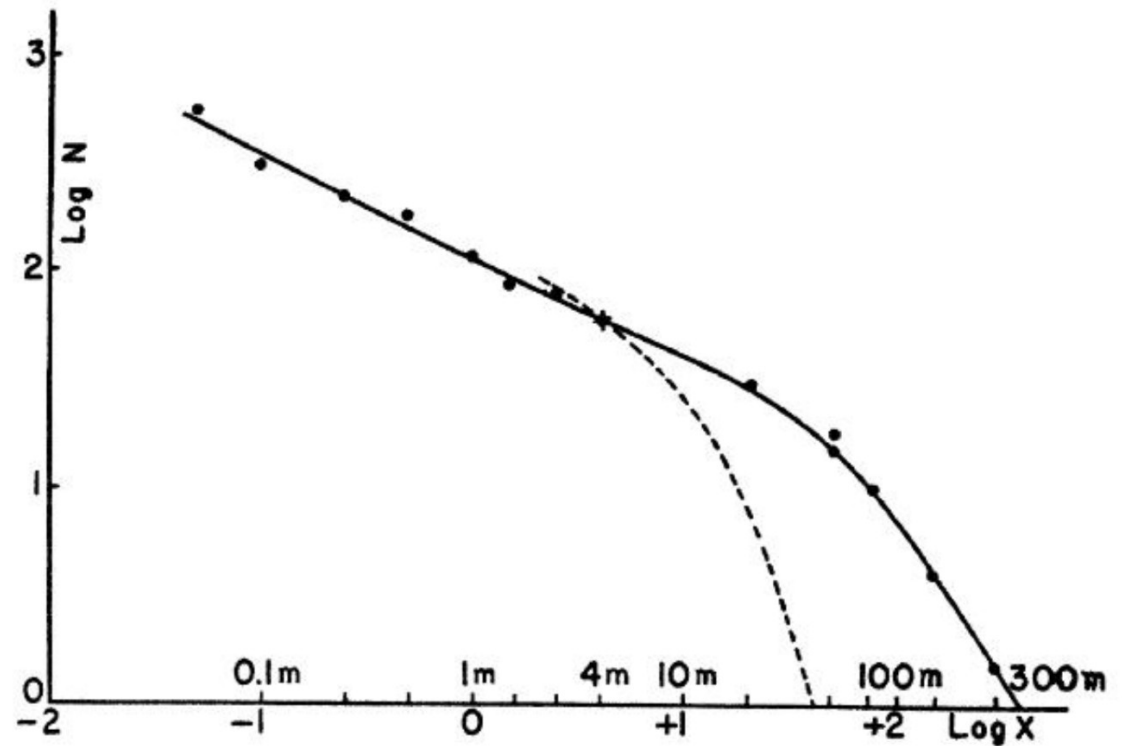
Measuring the energy spectrum [and mass composition of the cosmic rays]

- *Power Law* spectrum
- that extends to *very high energy*

Study of “Extensive Air Showers” [coincidences of detectors at increasing large distances]

Pierre Auger (et al.)

Physical Review (1939)



Shower at the ground extending for < 300 meters

Estimated energies $E \sim 10^{15} \text{ eV} \sim 10^{16} \text{ eV}$

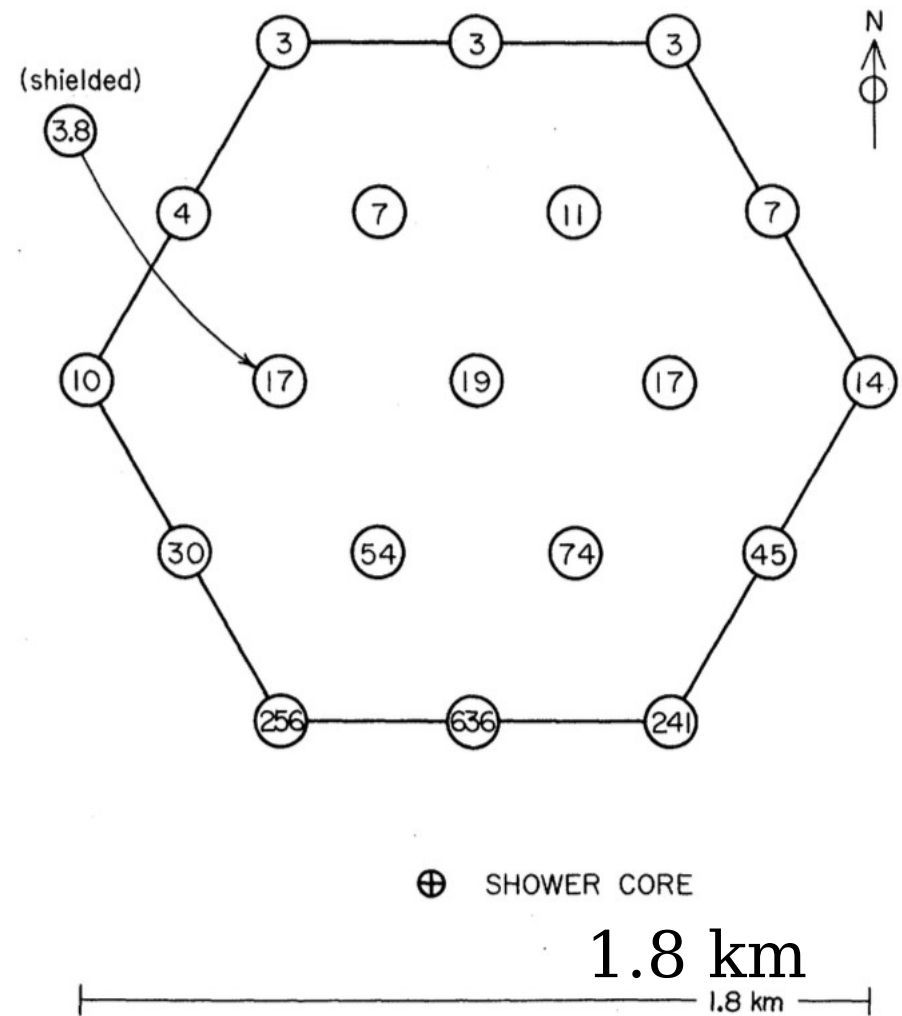
EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,[†] and Bruno Rossi

Phys. Rev. Lett. 6
485, (1961).

$$E \sim 10^{20} \text{ eV}$$

*Looking for anisotropies
in angular distribution
but observed a flux consistent
with isotropy*



MIT Volcano Ranch detector
(New Mexico)

- Where are these very high energy particles coming from ?
- How do they obtain their energy ?

[No imaging of the sources because of
Galactic and extragalactic magnetic fields]

*Only now we are starting to get
answers to these questions.*

A “prophetic” [?] speculation (1934)

COSMIC RAYS FROM SUPER-NOVAE

By W. BAADE AND F. ZWICKY

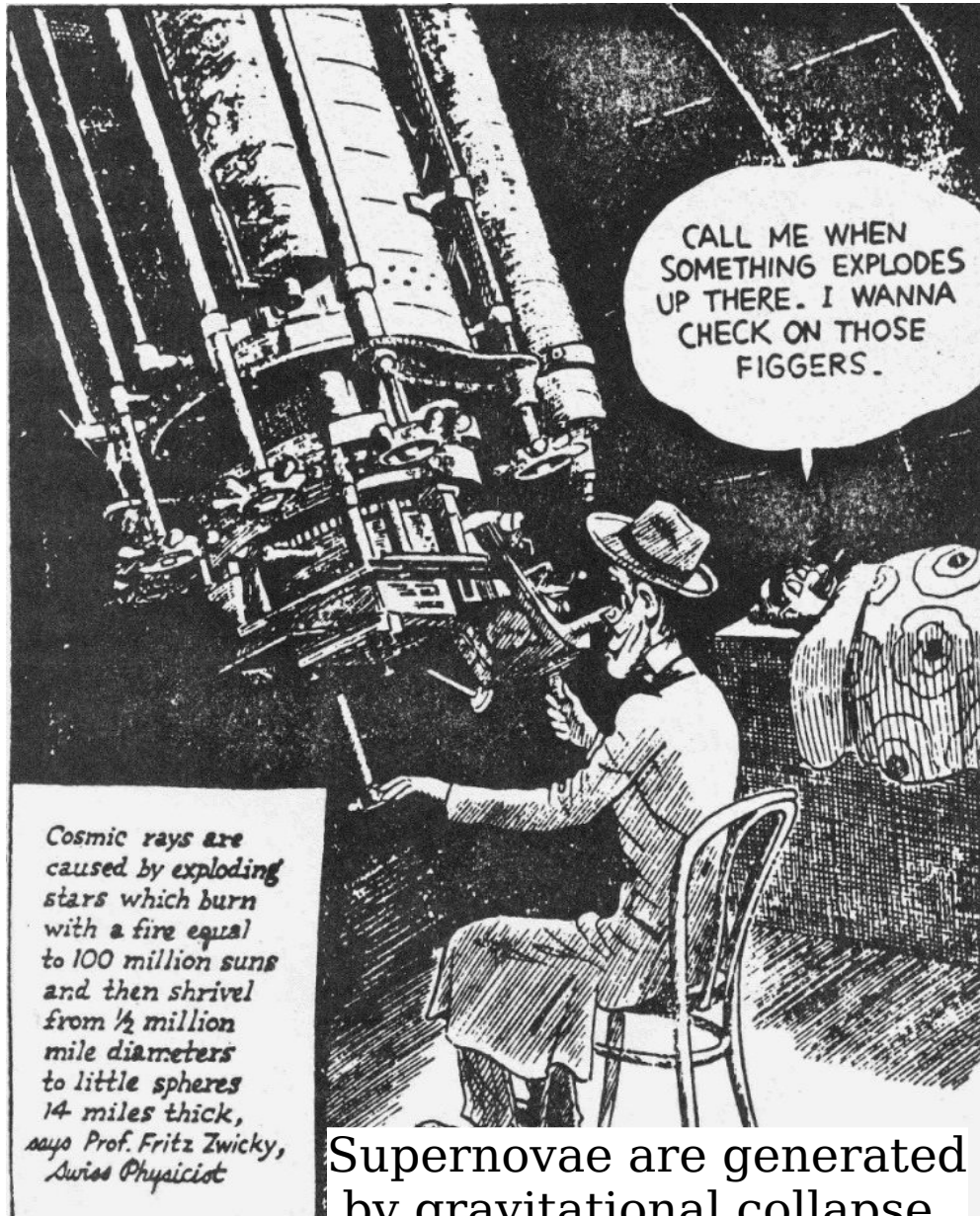
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALI-
FORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934



Comic Strip

Los Angeles Times [Jan. 1934]



Supernovae are generated by gravitational collapse to a neutron star

Baade-Zwicky ideas:

Cosmic Rays are *extragalactic* fill the universe uniformly

Are a mixture of electrons and positrons.

Super-Novae are created by core-collapse of stars to neutron stars

All binding energy of a neutron star is emitted as cosmic rays.

[Mechanism of production is not discussed.]

Electro-Magnetic Fields

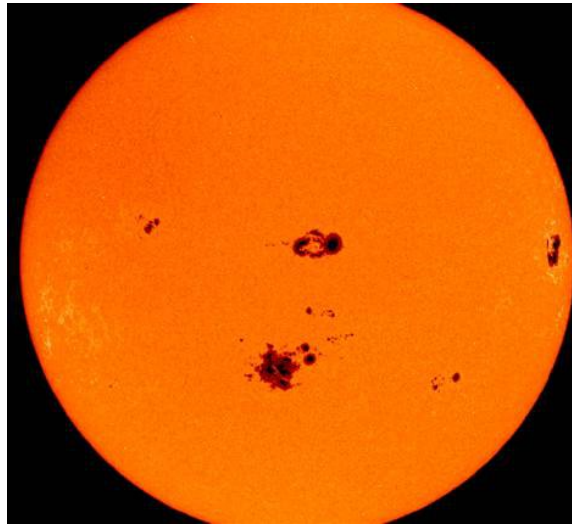


Aurora Borealis

Hannes Alfvén



Nobel prize 1970
“For fundamental work
on magneto-hydrodynamics”



1937-1938
[working
Sunspots, Auroras]
magneto-
hydrodynamic
waves

A. J. Dessler. Science 1970
commenting Nobel prize to Alfvén

“Swedish Iconoclast Recognized after
Many Years of Rejection and Obscurity”

He argued that there could be a weak magnetic field pervading the entire galaxy if there was a very small amount of ionized gas spread throughout the galaxy. This ionized gas could carry the electrical currents that could then create the galactic magnetic field. Alfvén's work was again dismissed, this time on the grounds that it was well known that interstellar space was a vacuum and certainly could not support the electrical currents he was proposing.

Alfvén memory:

“Memoirs of a Dissident Scientist”. *American Scientist* (1988).

Seminar in Chicago in 1948

....Fermi listened to what I said about them [magnetohydrodynamic waves] for five or ten minutes, and then he said:

«Of course such waves could exist.»

Fermi has such an authority that if he said

«of course» today, every physicist said «of course» tomorrow.”

Enrico Fermi immediately applied Alfvén's ideas about the probable existence of extended magnetic fields in our galactic system in a seminal 1949 paper on the mechanisms accelerating cosmic ray particles in space

Hannes Alfven, Robert Richtmyer, Edward Teller
“On the Origin of the Cosmic Rays”
Phys. Rev. **75**, 892-893 (1949)

Cosmic Rays are “local”
generated in the Sun
and the heliosphere

Two papers
on the origin
of Cosmic Rays
in 1949.

Enrico Fermi,
“On the Origin of the Cosmic Radiation”
Phys. Rev. **75**, 1169-1174 (1949)

Cosmic Rays are Galactic

*“[accelerated due] to the interaction
of cosmic particles
with wandering magnetic fields
which, according to Alfvén,
occupy the interstellar space.”*



E. Teller & E. Fermi

The controversy between
Local
Galactic and
Extragalactic models
is now solved.

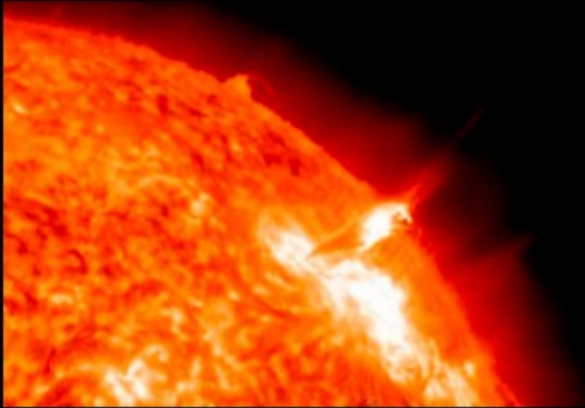
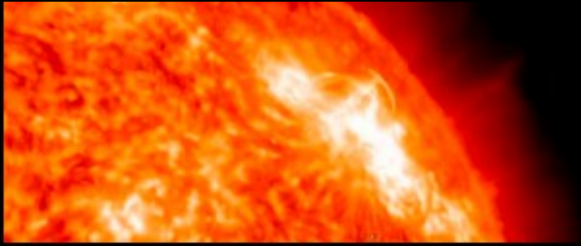
We know that *most* of the cosmic rays are of *Galactic Origin*, and fill a “bubble” around the disk of the Milky Way.

but:

There are solar cosmic rays (accelerated by the Sun) with a spectrum extends to the GeV energy range.

Extragalactic cosmic rays are expected to dominate the flux at the highest energies

The SUN:
small scale laboratory:
Solar Flare



7th march 2011. 20:02 UT

Aurora detected in Canada same night

This aurora image was taken on March 10,
2011 by Zoltan Kenwell near Edmonton,
Alberta, Canada.



©2011 Zoltan Kenwell

Enrico Fermi (1949) theory on the acceleration of Cosmic Rays:

PHYSICAL REVIEW
VOLUME 75, NUMBER 8
APRIL 15, 1949

Cosmic Ray are Galactic
(fill a "bubble" around the Galaxy)

On the Origin of the Cosmic Radiation

ENRICO FERMI

Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

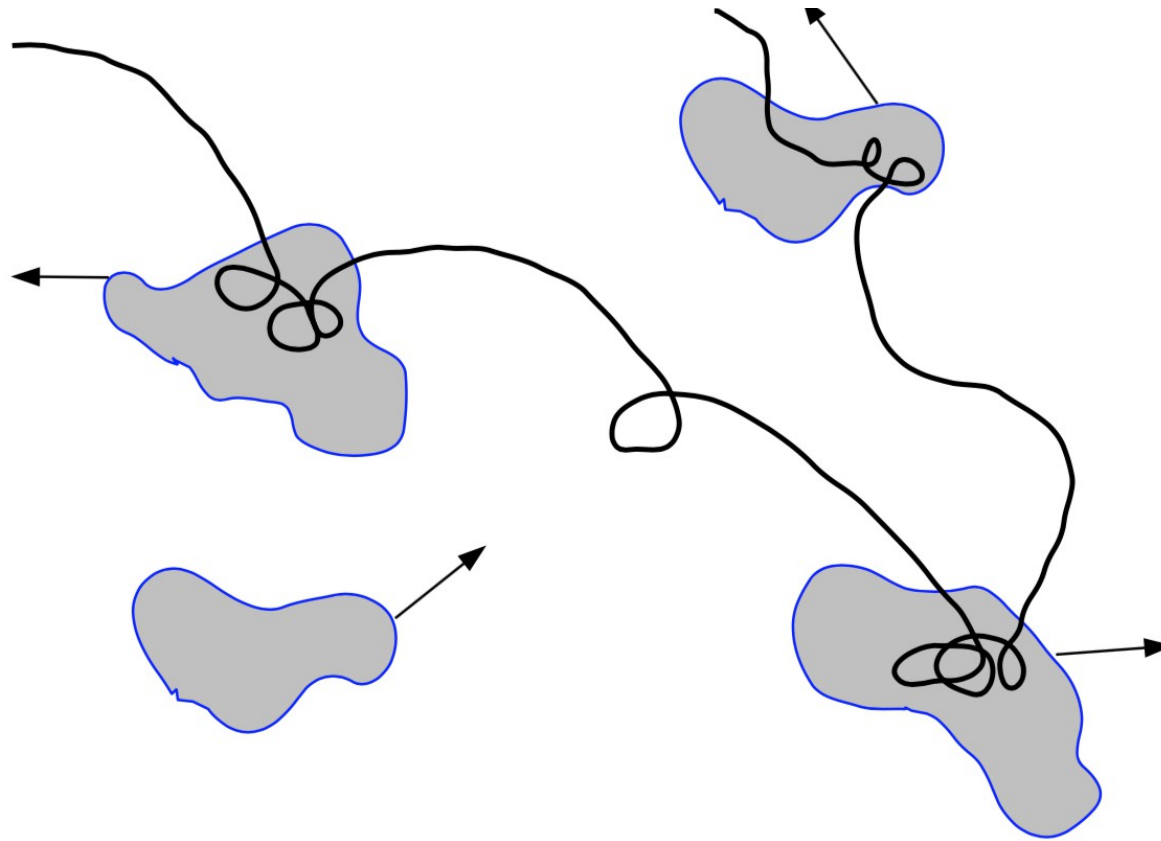
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

“Collisions against moving magnetic fields...
...yield naturally an inverse power law”

Enrico Fermi
original idea:

“Collisions against moving magnetic fields...
...yield naturally an inverse power law”



Encounter with a cloud
of velocity β

$$E_{\text{out}} = E_{\text{in}} (1 + \xi)$$

$$\langle \xi \rangle = \frac{4}{3} \beta^2$$

How many thing and concepts are named after Enrico Fermi ?

Fermi constant G_F

Fermi-Dirac distribution

Fermi (unit)

Fermi gas

Fermi-Walker transport

Fermi golden rule

.....

FERMI ACCELERATION

[Fermi Gamma Ray Telescope]

GLAST renamed



FERMI gamma-ray Space Telescope

Launch
June 11th 2008

crucial instrument
to study the
“High energy Universe”
name in honor of
Enrico Fermi and his
seminal idea



Very important modification / development
of Fermi original idea:

Acceleration due to interaction with a moving
magnetized plasma.

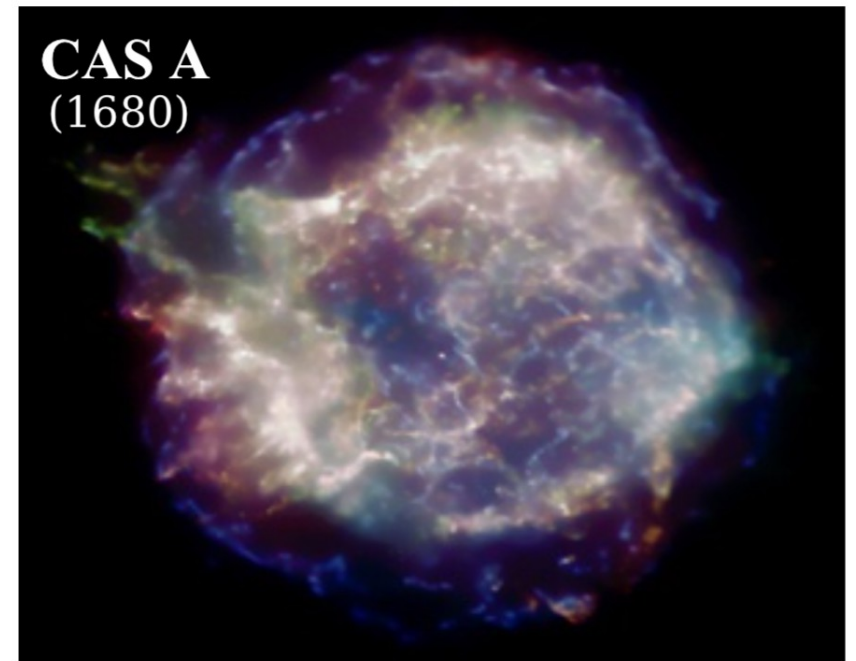
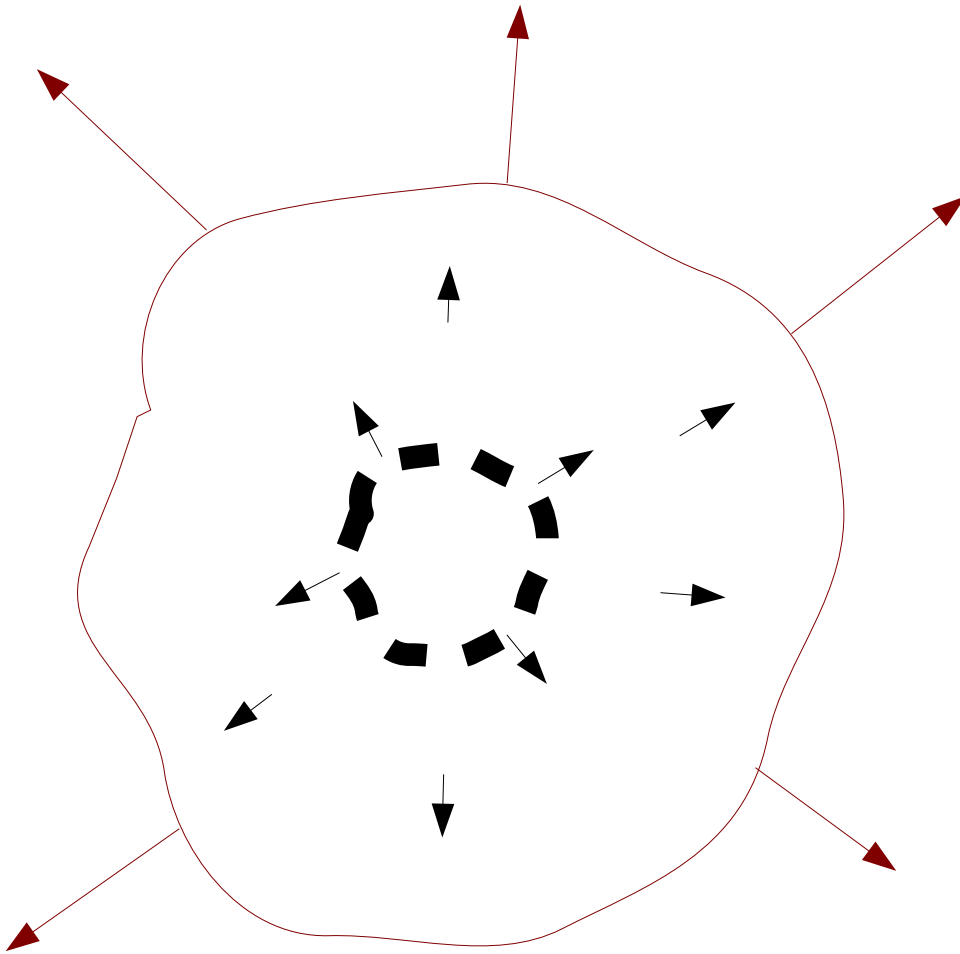
*But the moving plasma is inside a source
freshly accelerated, and forming shocks.*

Fermi Diffusive Shock Acceleration

idea is present in works of
a few authors [Parker (1958), Hoyle (1960),]

Idea (mature and “in the air”)
expressed in the “modern form”
by several authors more or less at the same time
Krymsky(1977), Axford(1977),
Bell (1978), Blandford+Ostriker (1978)

Blast Wave of a SuperNova explosion



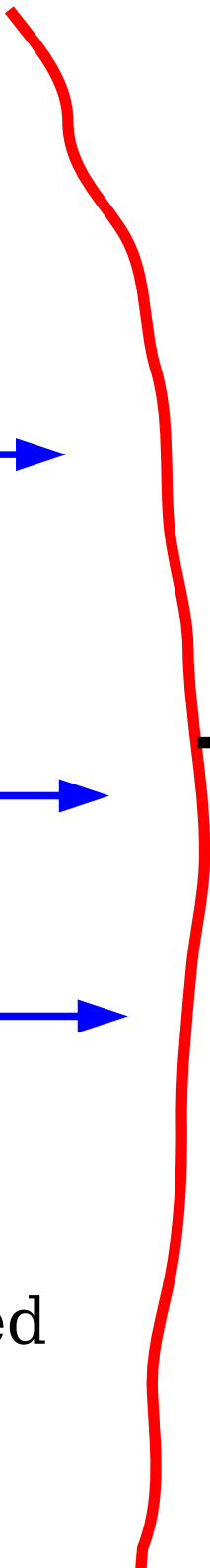
Shocked Gas

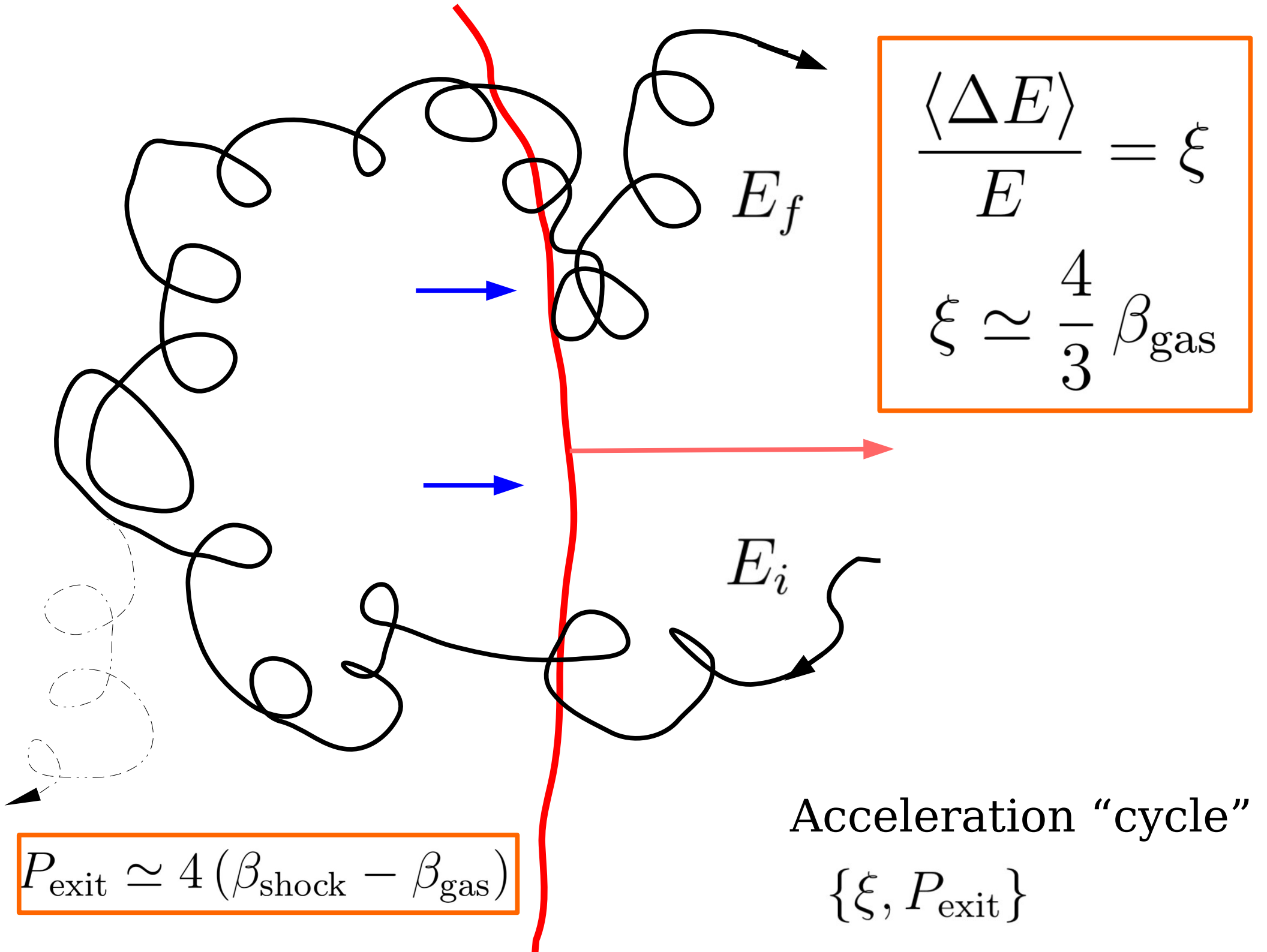
Gas at rest

β_{gas}

β_{shock}

After the passage
of the shock wave
the gas is compressed
and accelerated





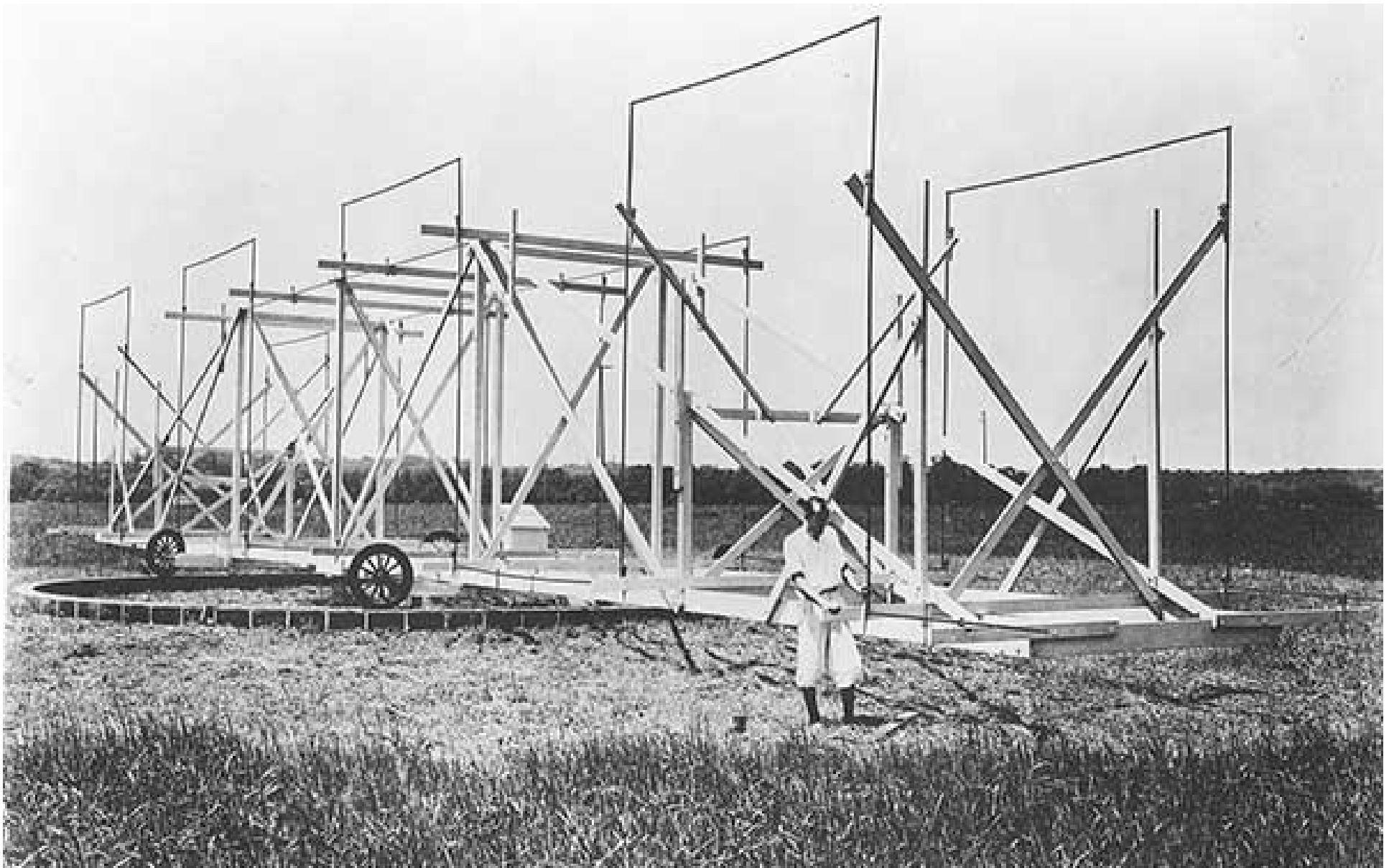
Motivation for the construction of theories for the acceleration of relativistic particles came also from new Astronomical Observations

new wavelengths:

Radio

X-ray

that revealed the existence of new classes of sources



Karl Jansky [1905-1950]

first radio telescope (1931-1932) "Jansky merry go-round"

Astrophysical Observations in new Wavelengths: (1933)

Electrical Phenomena that apparently are of Interstellar Origin

By KARL G. JANSKY*

Electromagnetic waves of an unknown origin were detected during a series of experiments on atmospherics of short wave-lengths. Directional records have been taken of these waves for a period of nearly two years. The data obtained from these records show that the azimuth of the direction of arrival changes from hour to hour and from day to day in a manner that is exactly similar to the way in which the azimuth of a star changes. This fact leads to the conclusion that the direction of arrival of these waves is fixed in space; that is to say, that the source of these waves is located in some region that is stationary with respect to the stars.

Source in Sagittarius [Galactic Center]

Radio Antenna (1937) Grote Reber



2nd radio antenna
1st parabolic reflecting
antenna

[only radio antenna
for a decade]



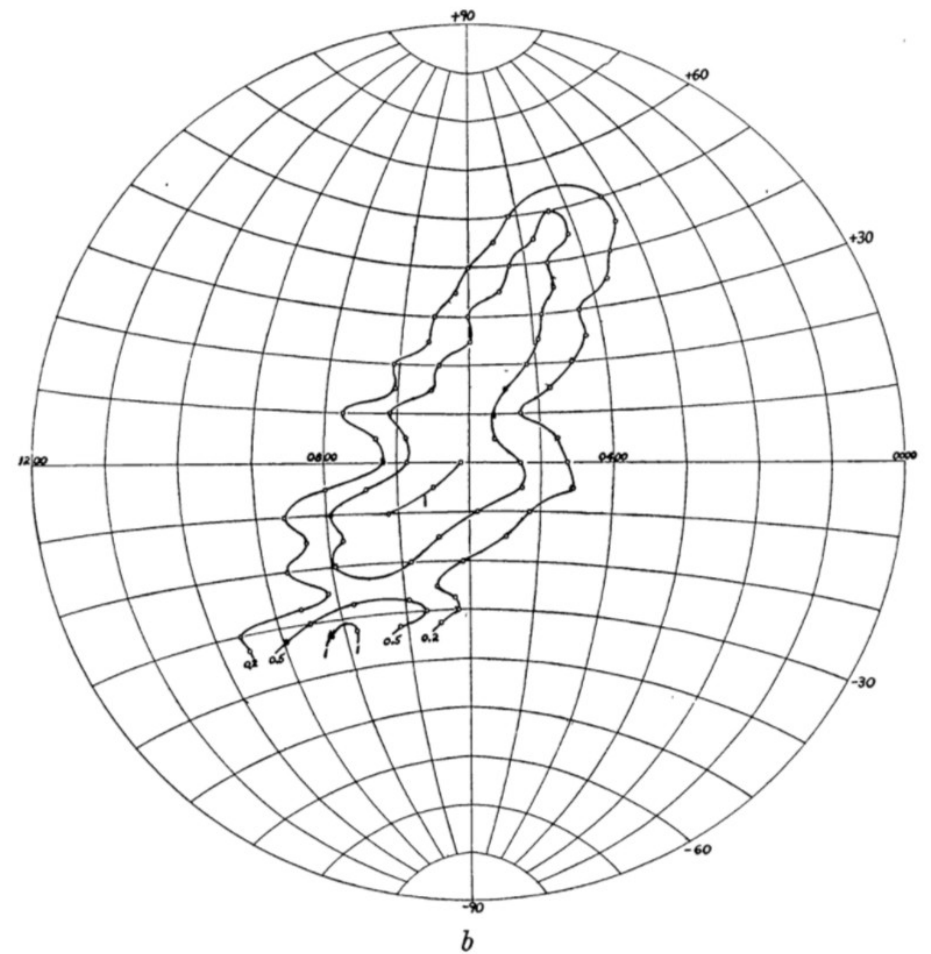
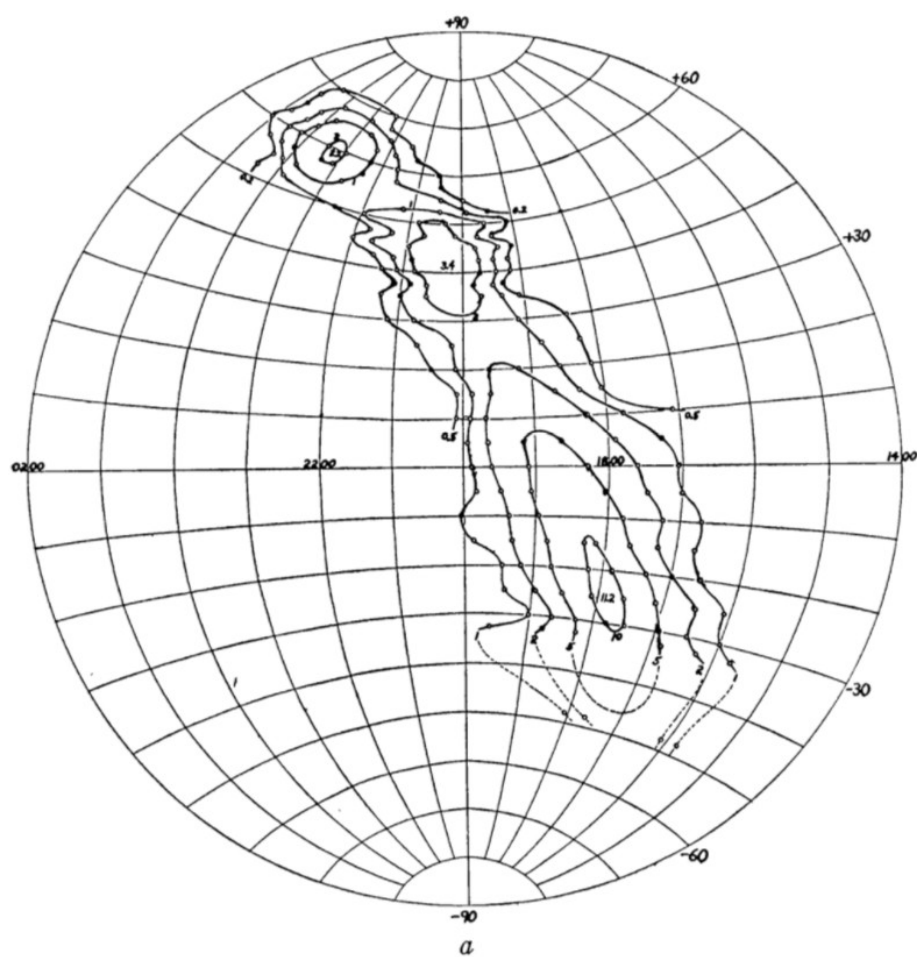
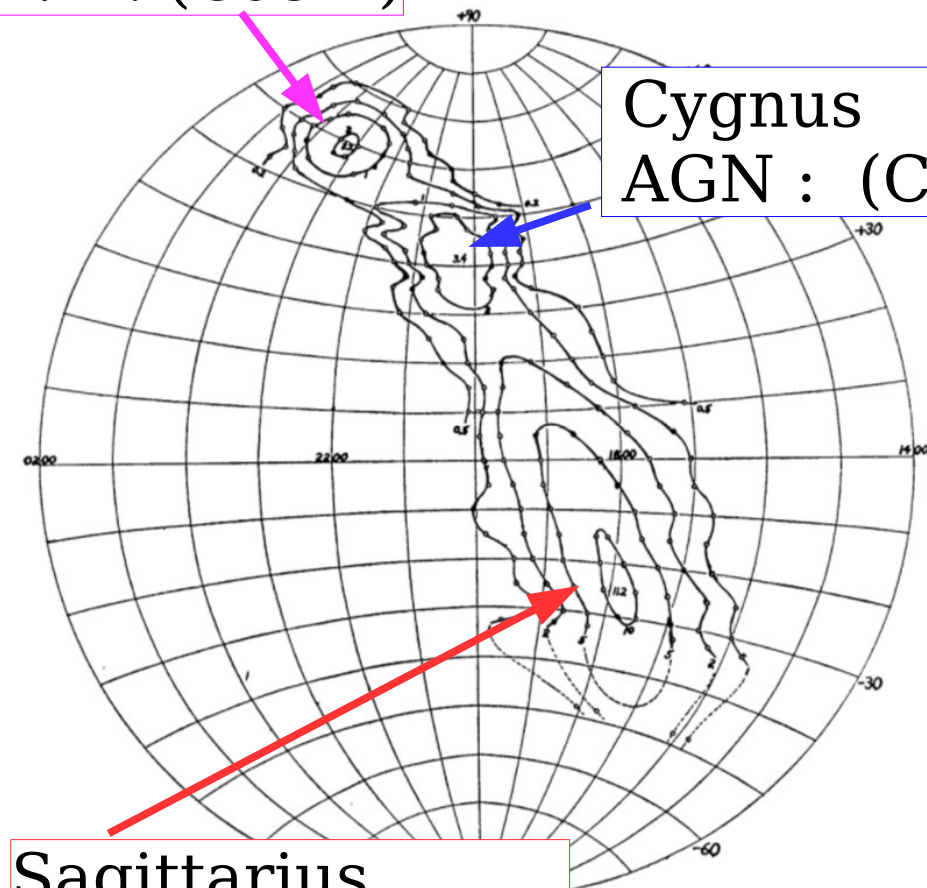


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

First sky survey, and first radio Sky Map:
Astrophysical Journal, 100, p.279 (1944)

Cassiopea
SNR : (Cas A)

Cygnus
AGN : (Cygnus A)



Sagittarius
(Galactic Center)

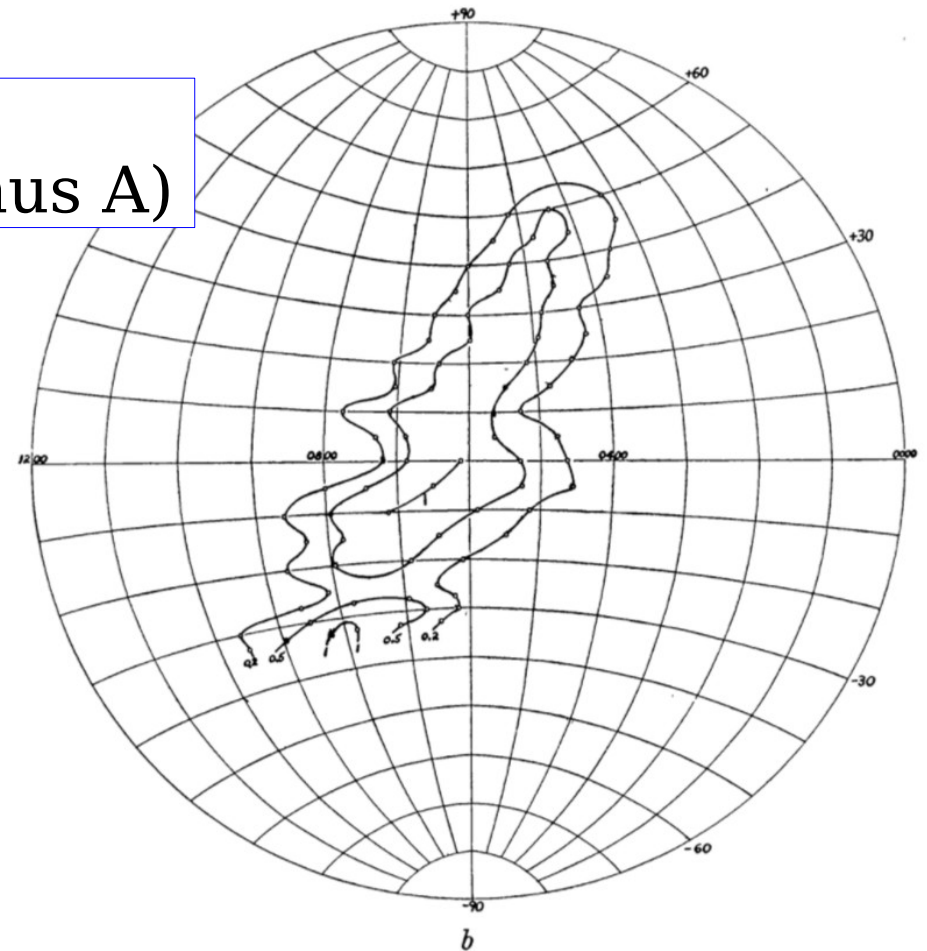
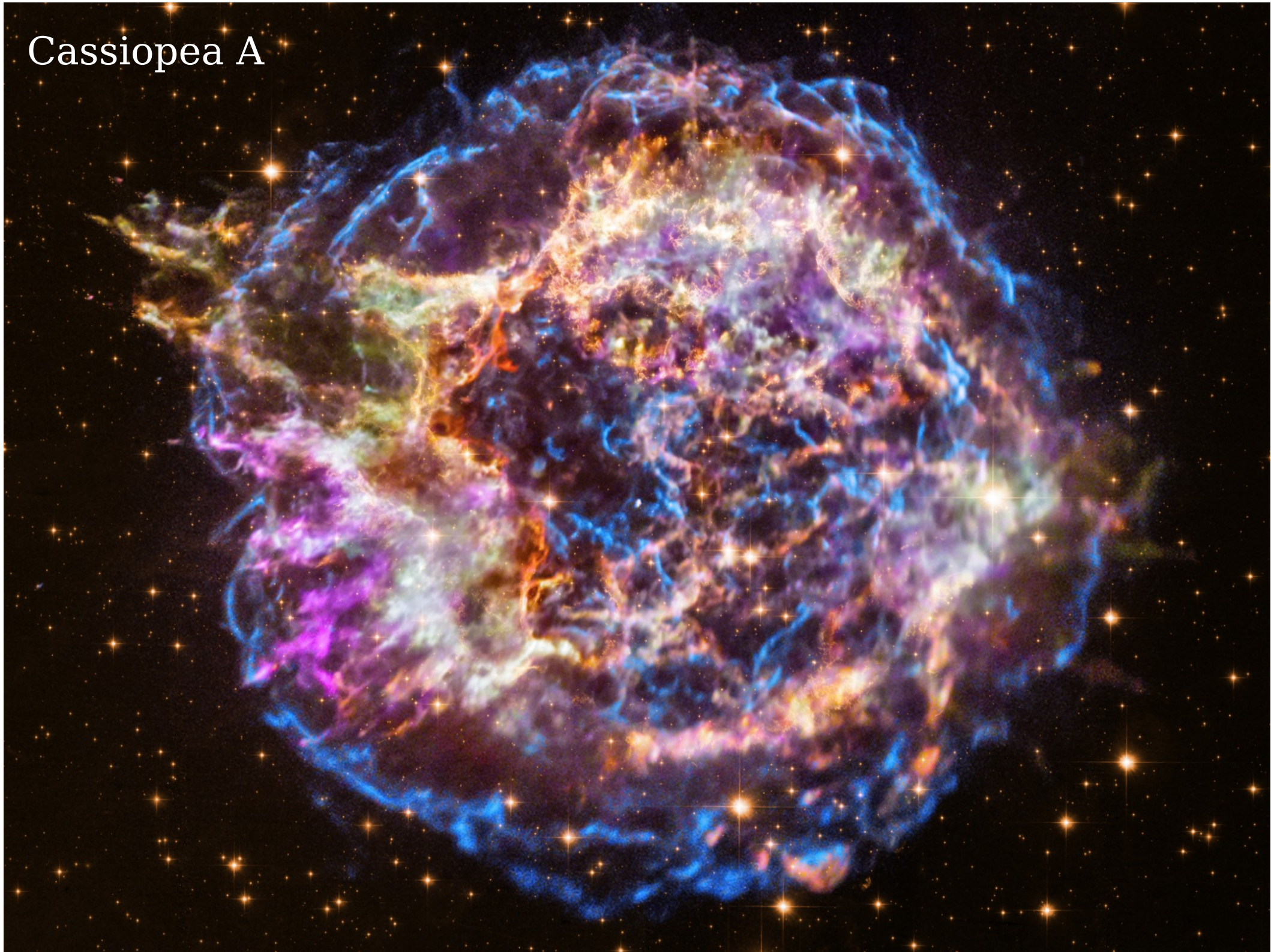


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

Sky Map:
Astrophysical Journal,
100, p.279 (1944)

Synchrotron emission
from relativistic

Cassiopea A



Compact object at the center of the Remnant

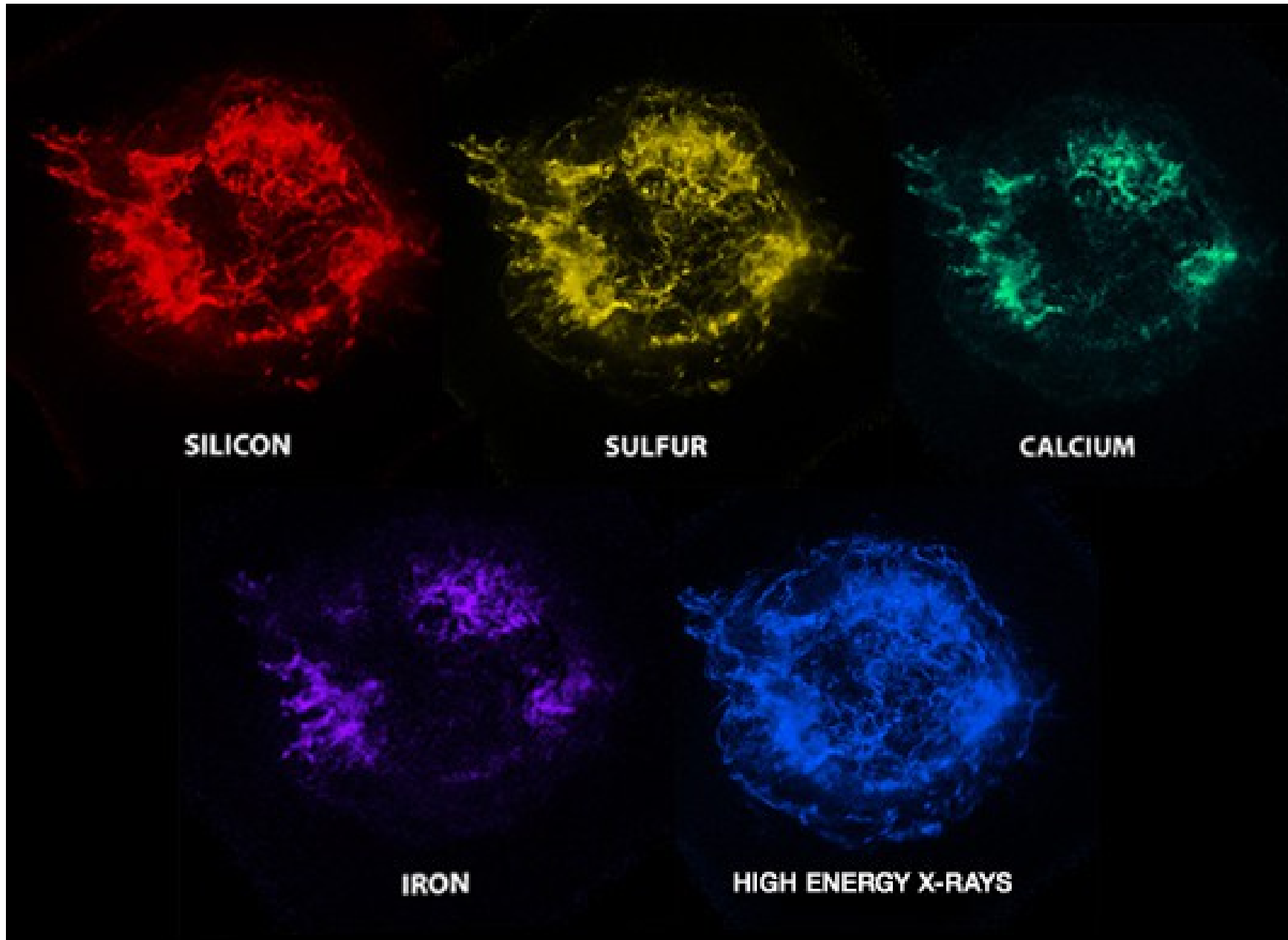
$$t \simeq 340 \text{ yr}$$

$$\langle v \rangle \approx 4300 \text{ km/s}$$

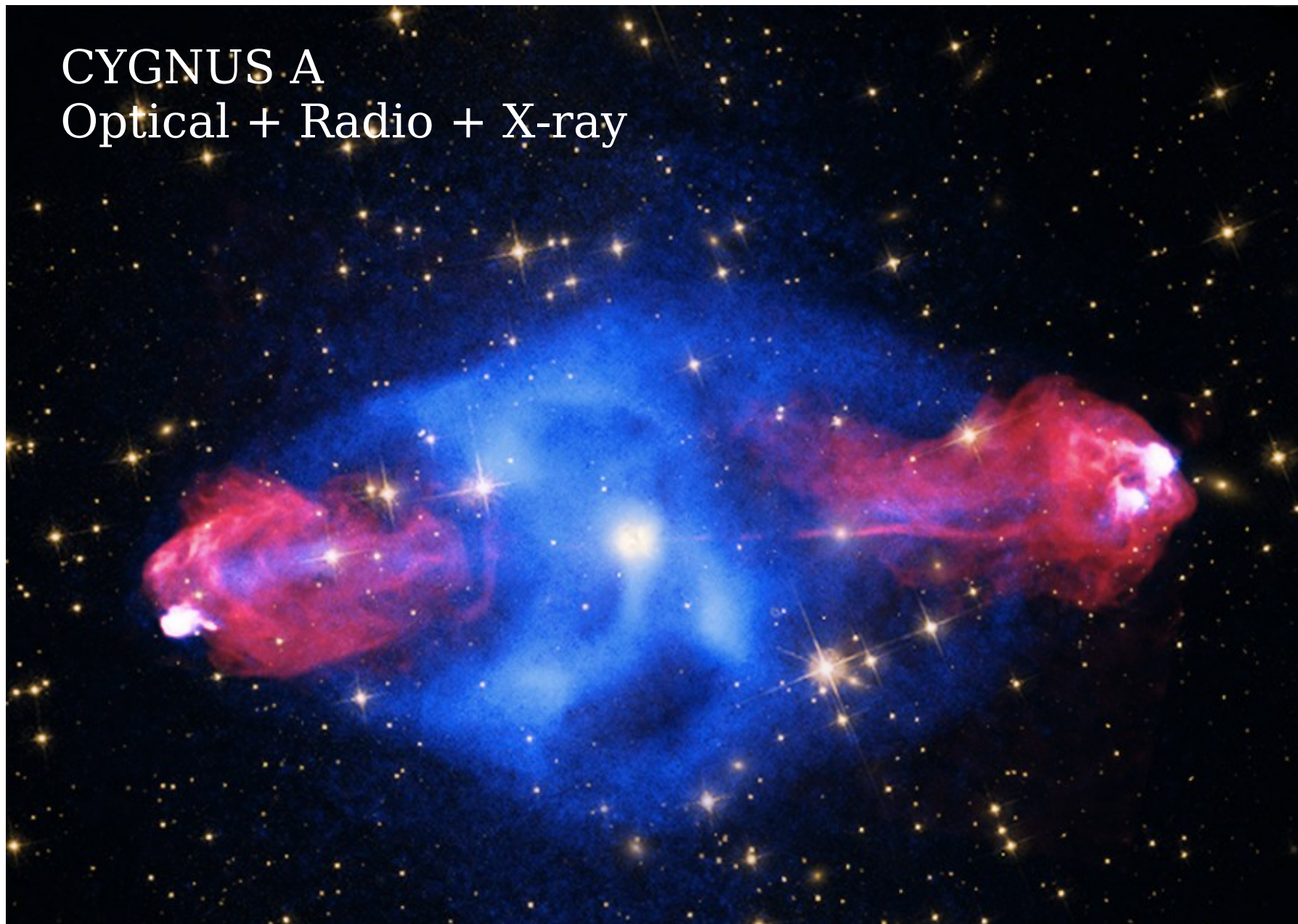
diameter = 3 pc
distance = 3.4 kpc
SN : 16 august 1680 [Astronomer Royal John Flamsteed]



False color image in X-rays of Cassiopeia A [from CHANDRA X-ray Observatory]

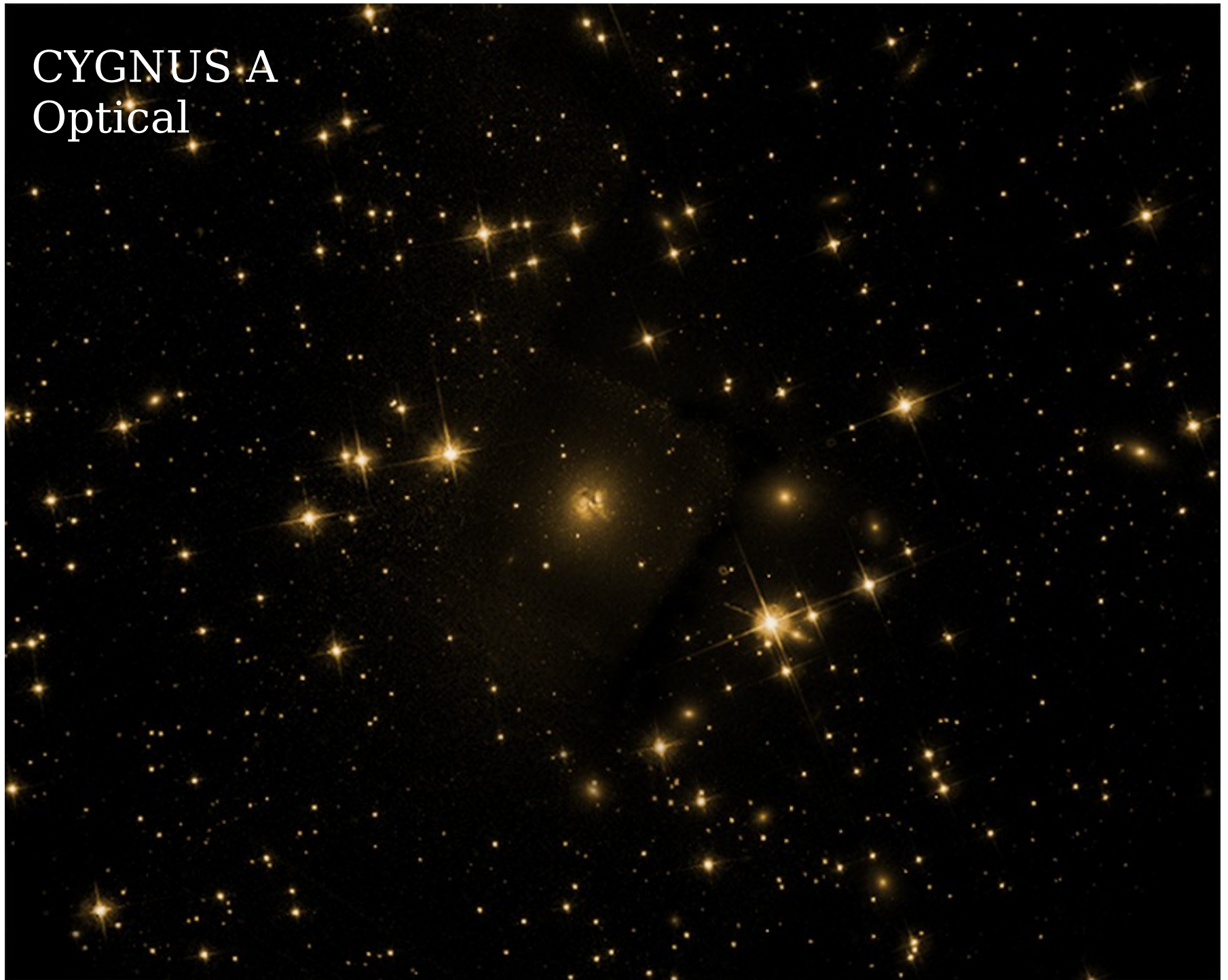


CYGNUS A
Optical + Radio + X-ray



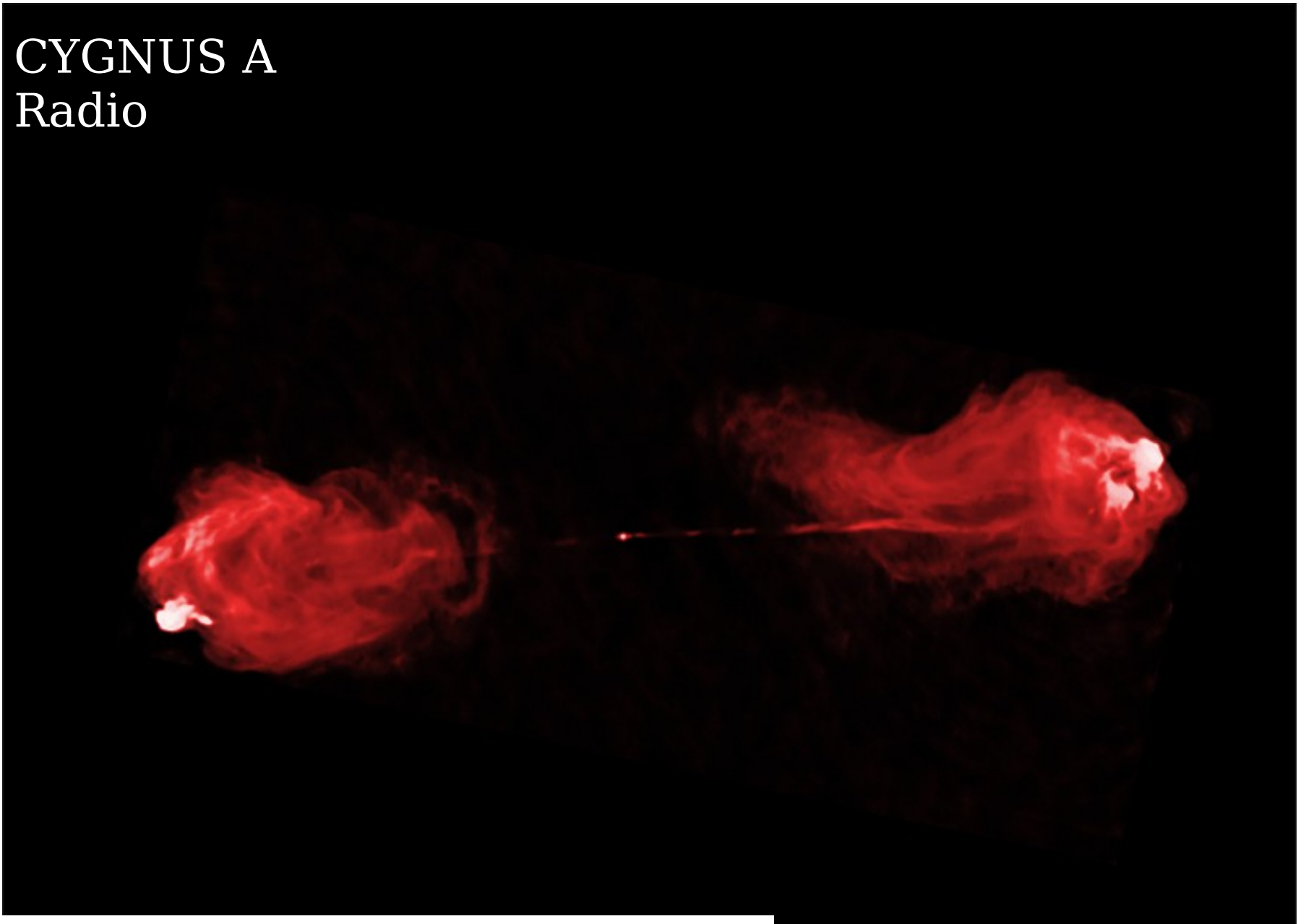
$$M_{\bullet} = (2.5 \pm 0.7) \times 10^9 M_{\odot}$$

CYGNUS A
Optical



CYGNUS A

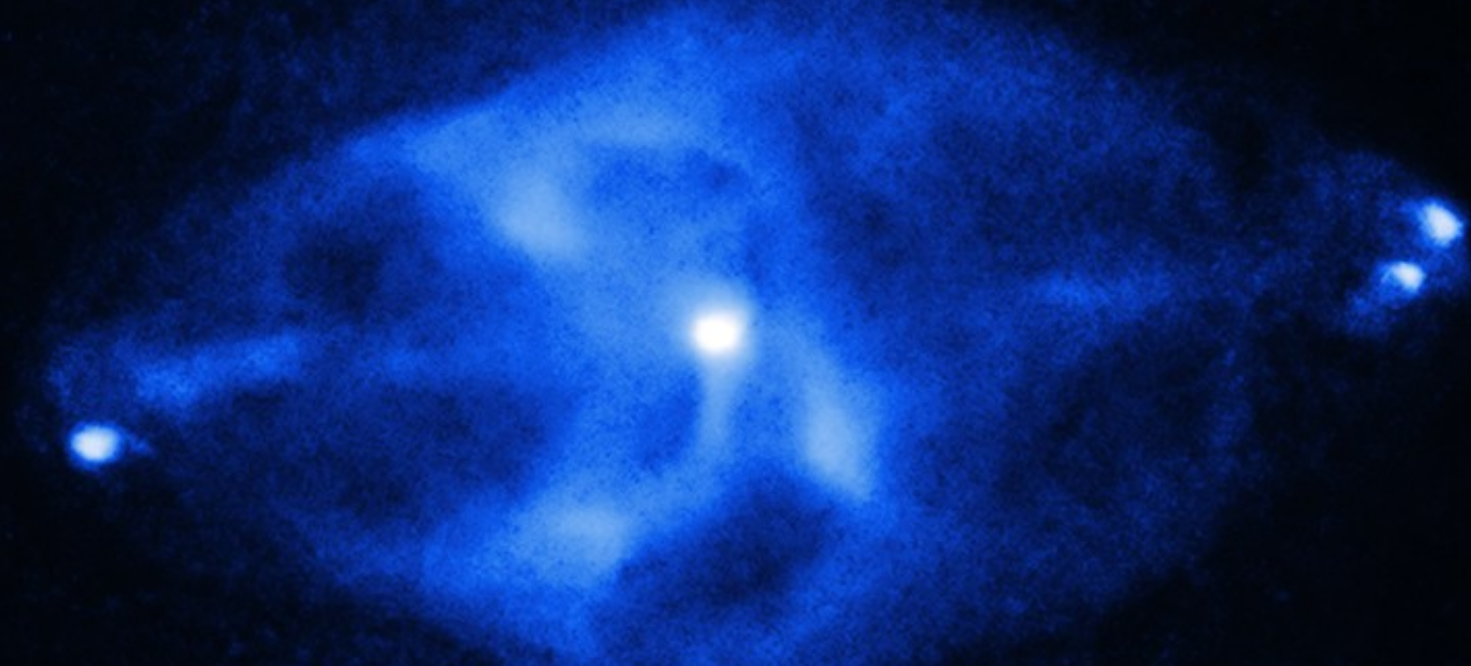
Radio

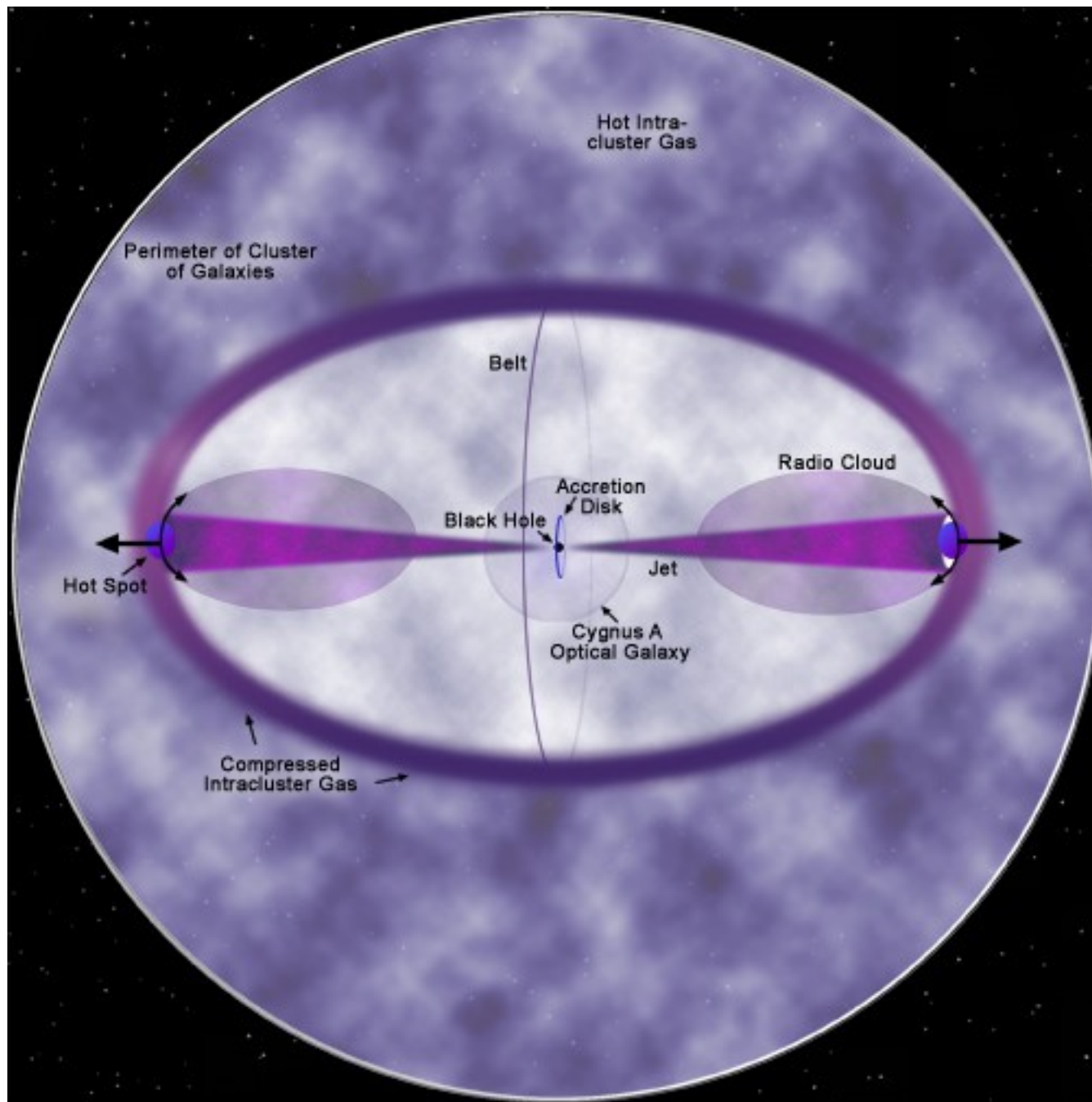


$$M_{\bullet} = (2.5 \pm 0.7) \times 10^9 M_{\odot}$$

$$d \approx 232 \text{ Mpc}$$

CYGNUS A
X-ray





NATURE

March 16, 1963

By DR. M. SCHMIDT

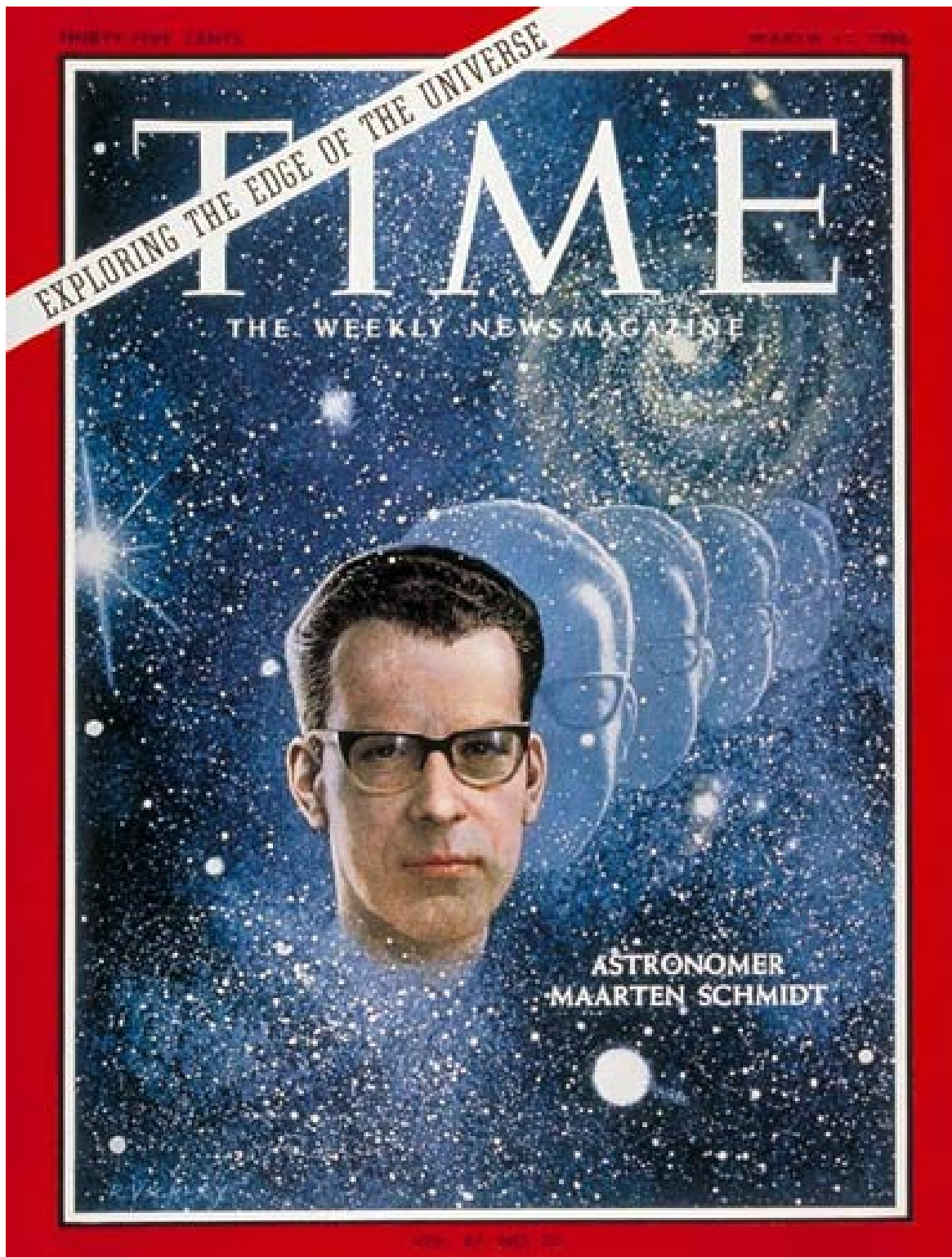
3C 273 : A STAR-LIKE OBJECT

$z = 0.158$

WITH LARGE RED-SHIFT

THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1"-2" and extends away from the star in position angle 43°. It is not visible within 11" from the star and ends abruptly at 20" from the star. The position of the

Discovery of "QUASARS"



Time magazine
March 11th 1966

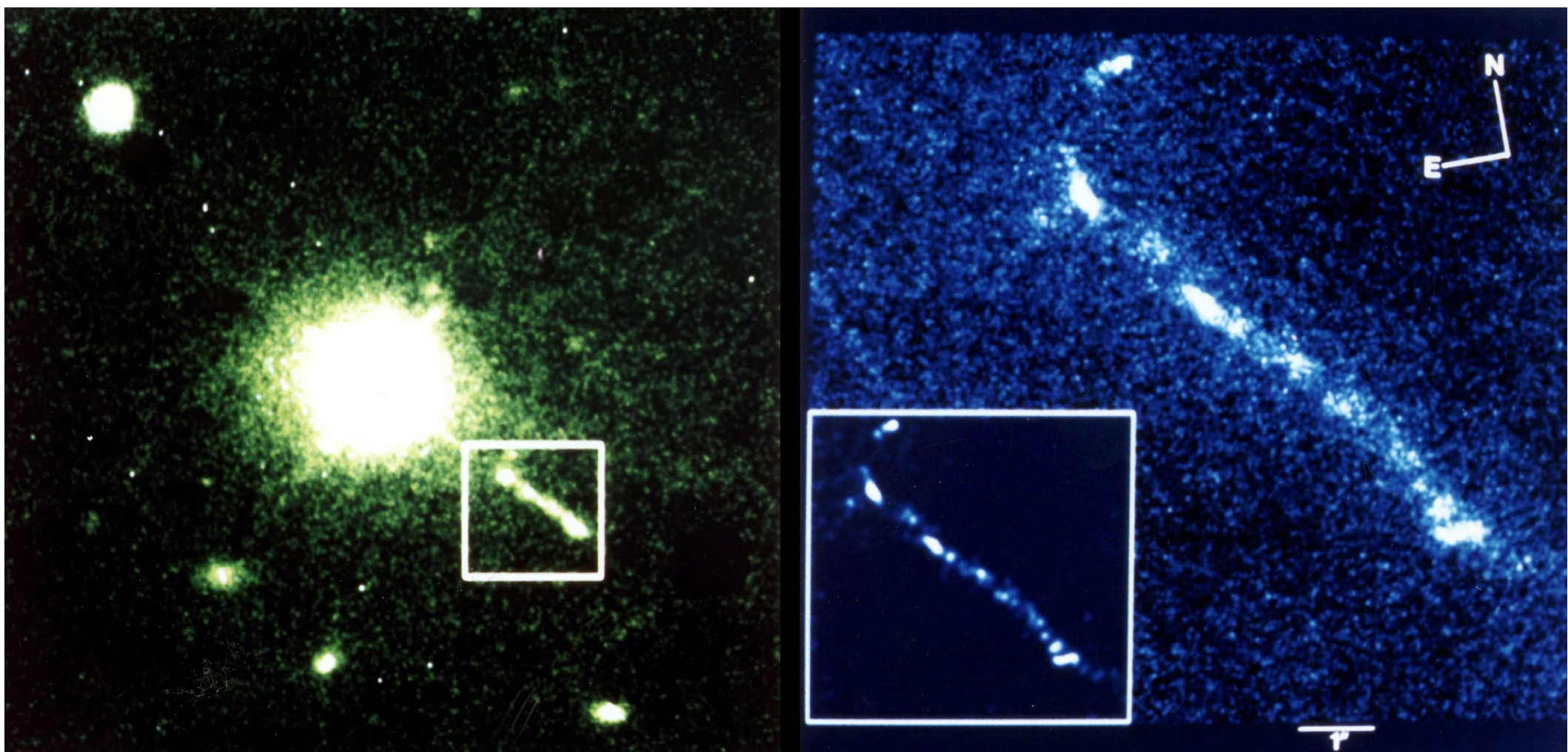
$$d \approx 749 \text{ Mpc}$$

$$\text{Magnitude} \simeq 12.9$$

$$L_{\text{iso}} \simeq 2 \times 10^{12} L_{\odot}$$

“incredible” power
from a tiny (unresolved)
volume

Hubble telescope image of 3C 273



Maarten Schmidt [1963]

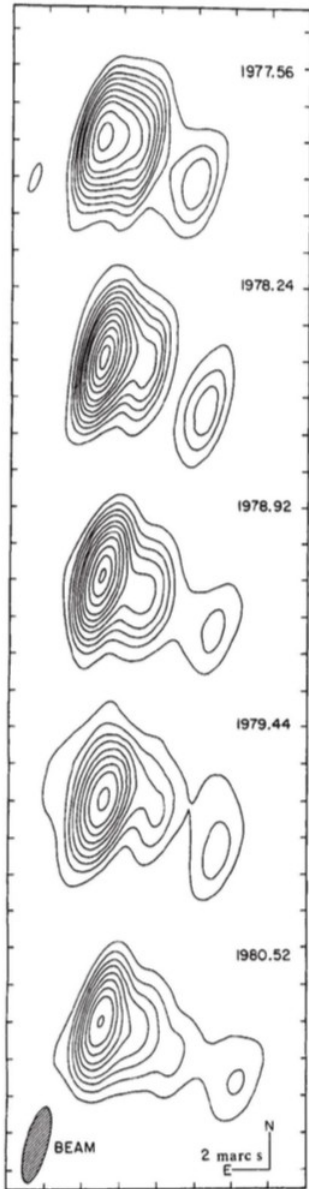
... a thirteenth magnitude star, and a faint wisp or jet...

...

Superluminal expansion of quasar 3C273

VLBI (Very Long Baseline Interferometry) Observations

Pearson et al.
Nature 290, 365, (1981).



Maps of the radio structure of 3C273 show directly that it expanded with an apparent velocity of 10 times the speed of light from mid-1977 to at least mid-1980

$$d \approx 749 \text{ Mpc}$$

$$M_{\bullet} = (0.886 \pm 0.197) \times 10^9 M_{\odot}$$

At the moment:

Supernovae explosions
are considered the main sources of
Galactic Cosmic Rays

Active Galactic Nuclei (such as 3C273)
are considered the main sources of
extragalactic Cosmic Rays

...(but we are not sure yet)

How can we *test* these ideas ?

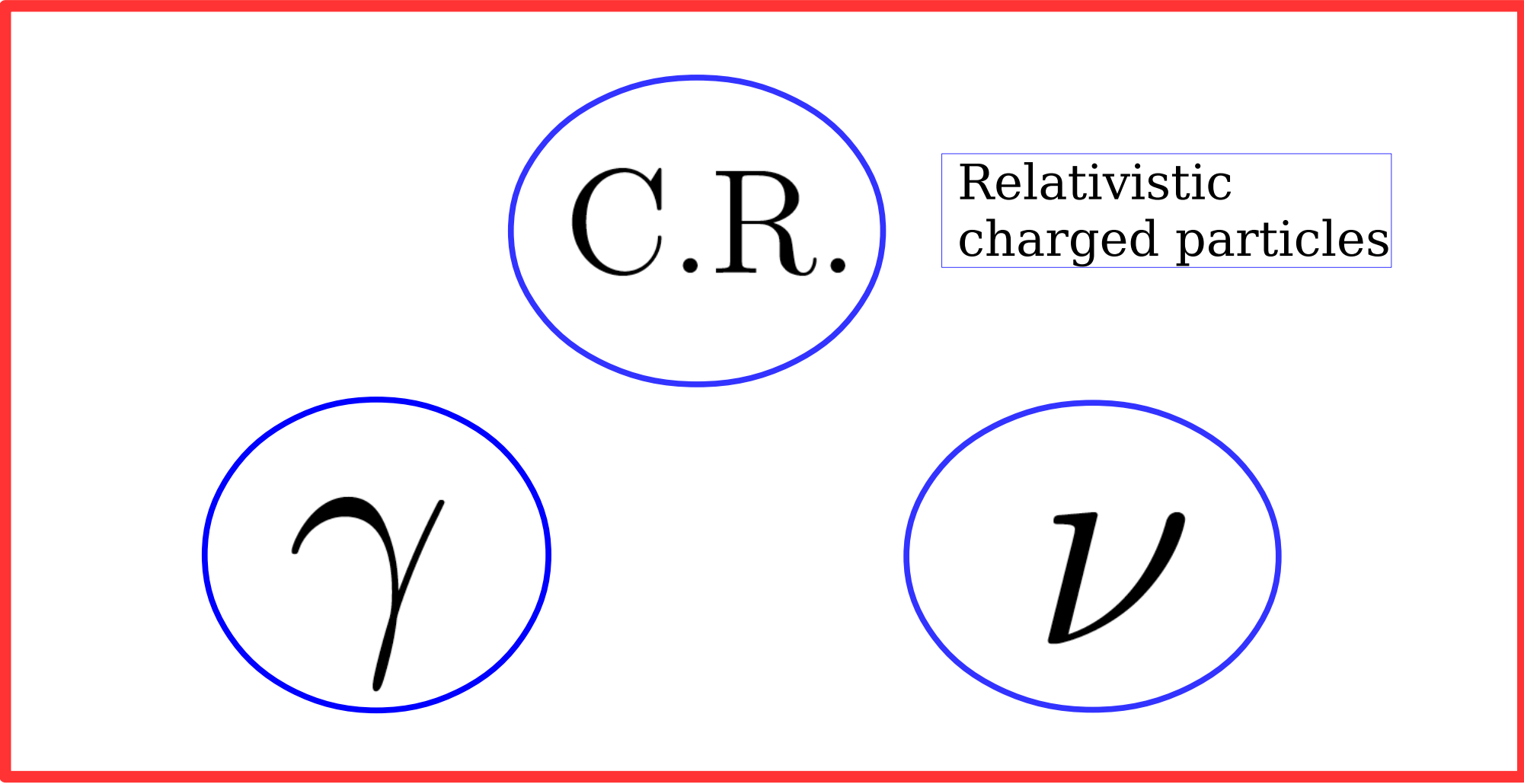
Multi-messenger Astrophysics

Cosmic Rays,
Photons, Neutrinos
Gravitational Waves

4 Messengers
for the study of the
“High Energy Universe”

Three messengers are “inextricably” tied together

[Cosmic Rays, Gamma Rays, High Energy Neutrinos
can really be considered as three probes that study the
same underlying physical phenomena]



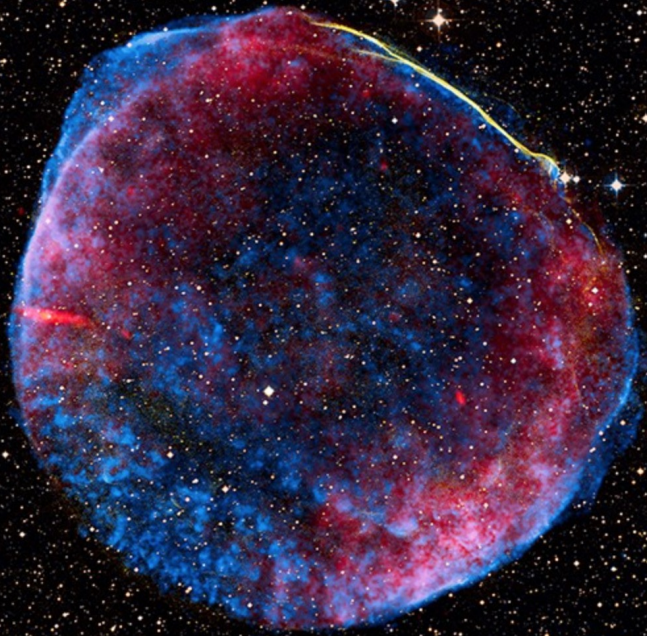
C.R.

Relativistic
charged particles

γ

ν

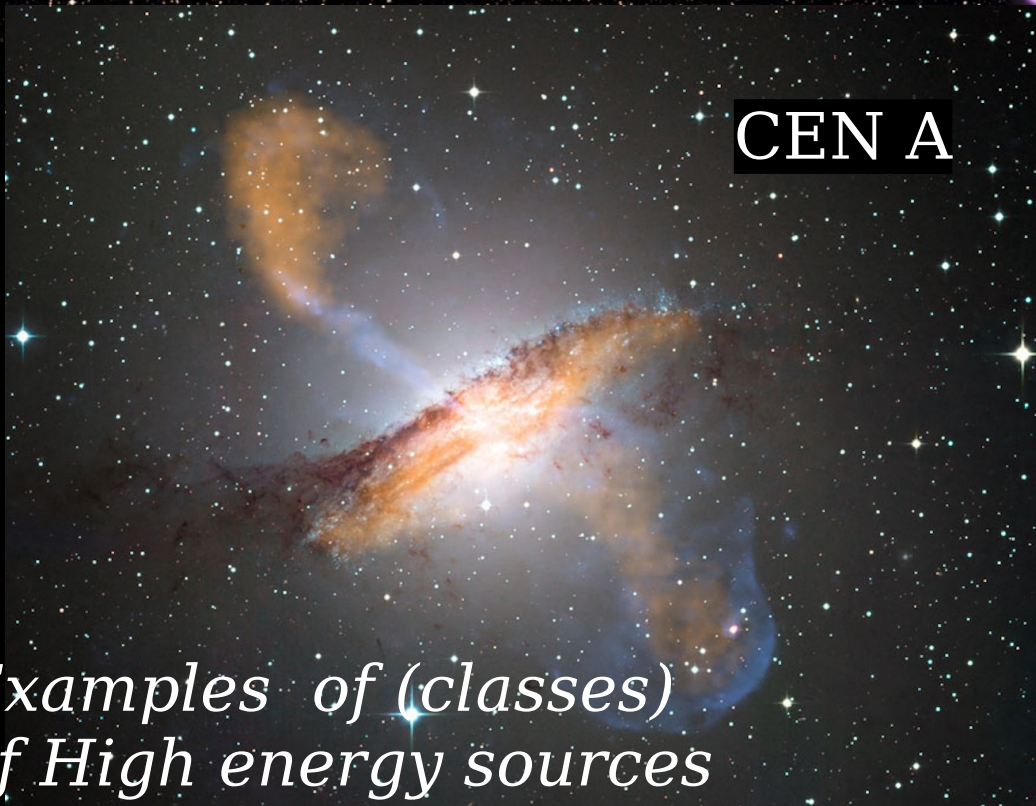
SN 1006



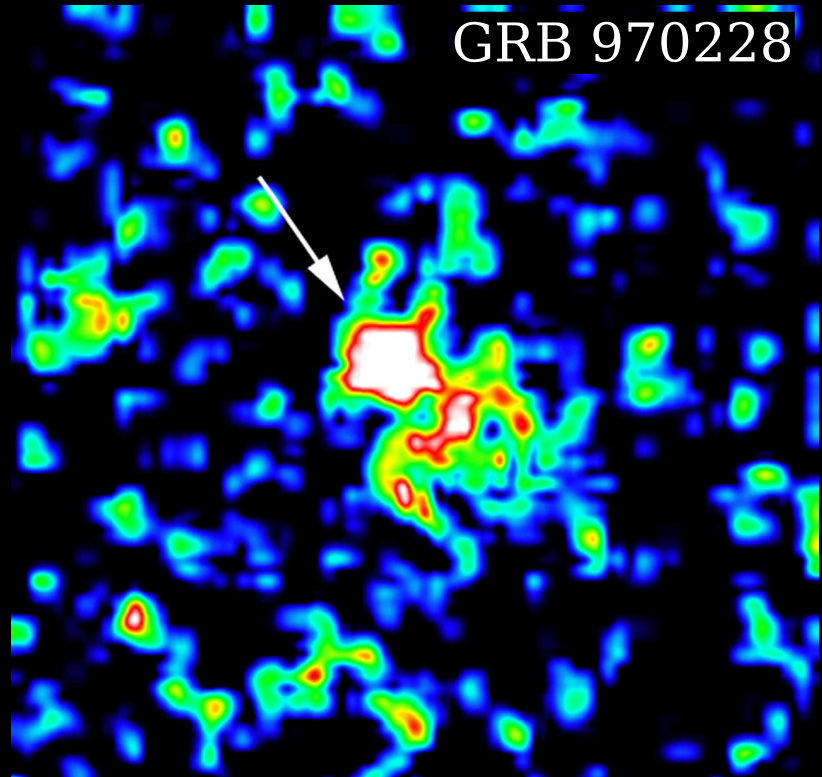
Crab Nebula



CEN A

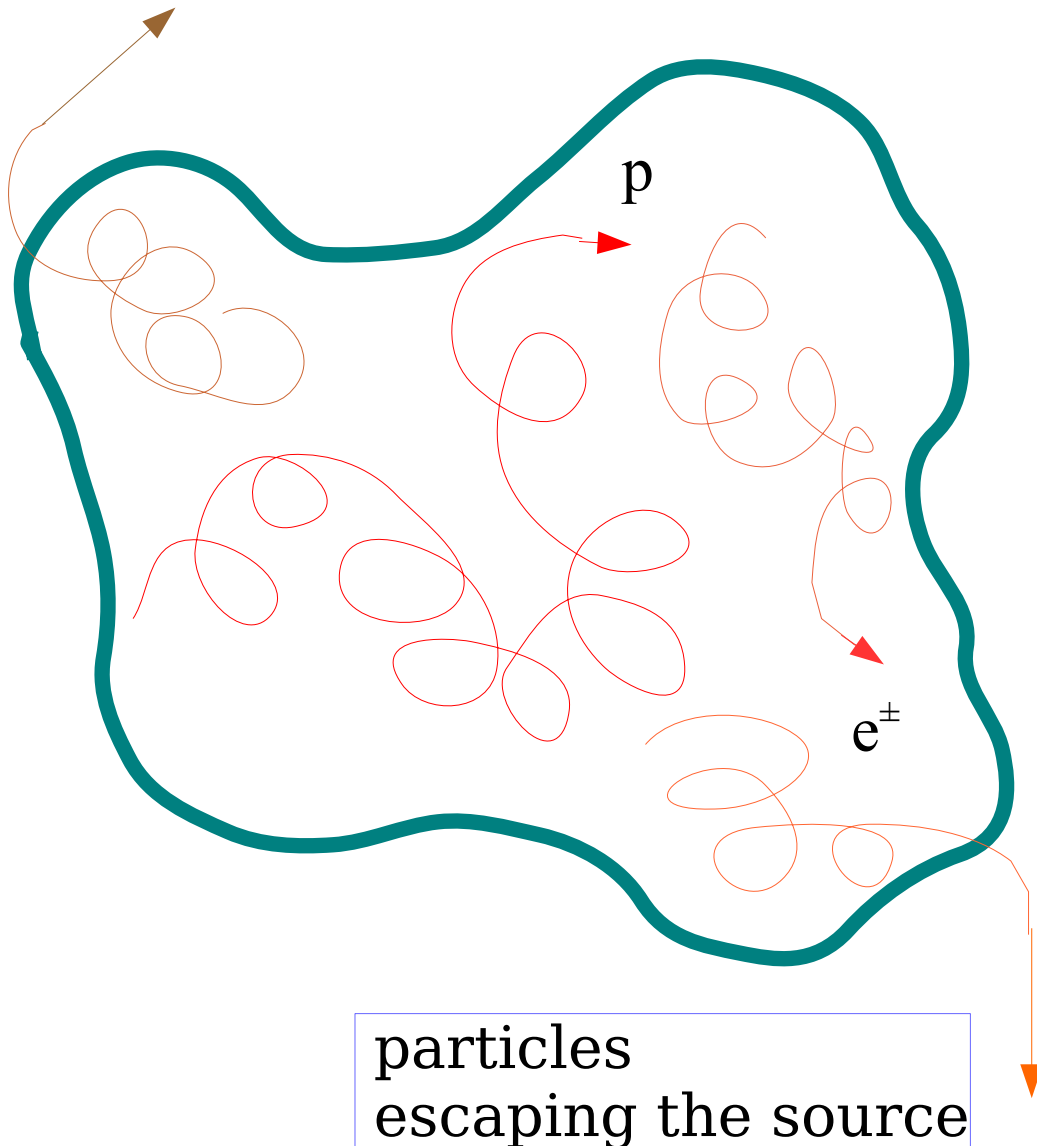


GRB 970228



*Examples of (classes)
of High energy sources*

Cosmic Ray Accelerator



Astrophysical object/transient
accelerating particles to
relativistic energies

Contains populations of
relativistic protons, nuclei
electrons/positrons

Emission of
COSMIC RAYS
PHOTONS
NEUTRINOS

Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy (“non thermal processes”) in astrophysical objects (or better “events”).

Creation of Gamma Rays and Neutrinos via the interactions of these relativistic charged particles.

“Hadronic ”

$$p + X \rightarrow \pi^+ \pi^- \pi^0 \dots$$

$$\pi^0 \rightarrow \gamma \gamma$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\downarrow$$
$$e^+ \nu_e \bar{\nu}_\mu$$

“Leptonic ”

$$e^\pm \gamma_{\text{soft}} \rightarrow e^\pm \gamma$$

$$e^\pm Z \rightarrow e^\pm \gamma Z$$

$$e^\pm \vec{B} \rightarrow e^\pm \gamma_{\text{syn}}$$

Sources are transients

[with a variety of time scales
from a small fraction of a second to thousands of years]

Associated to Compact Objects

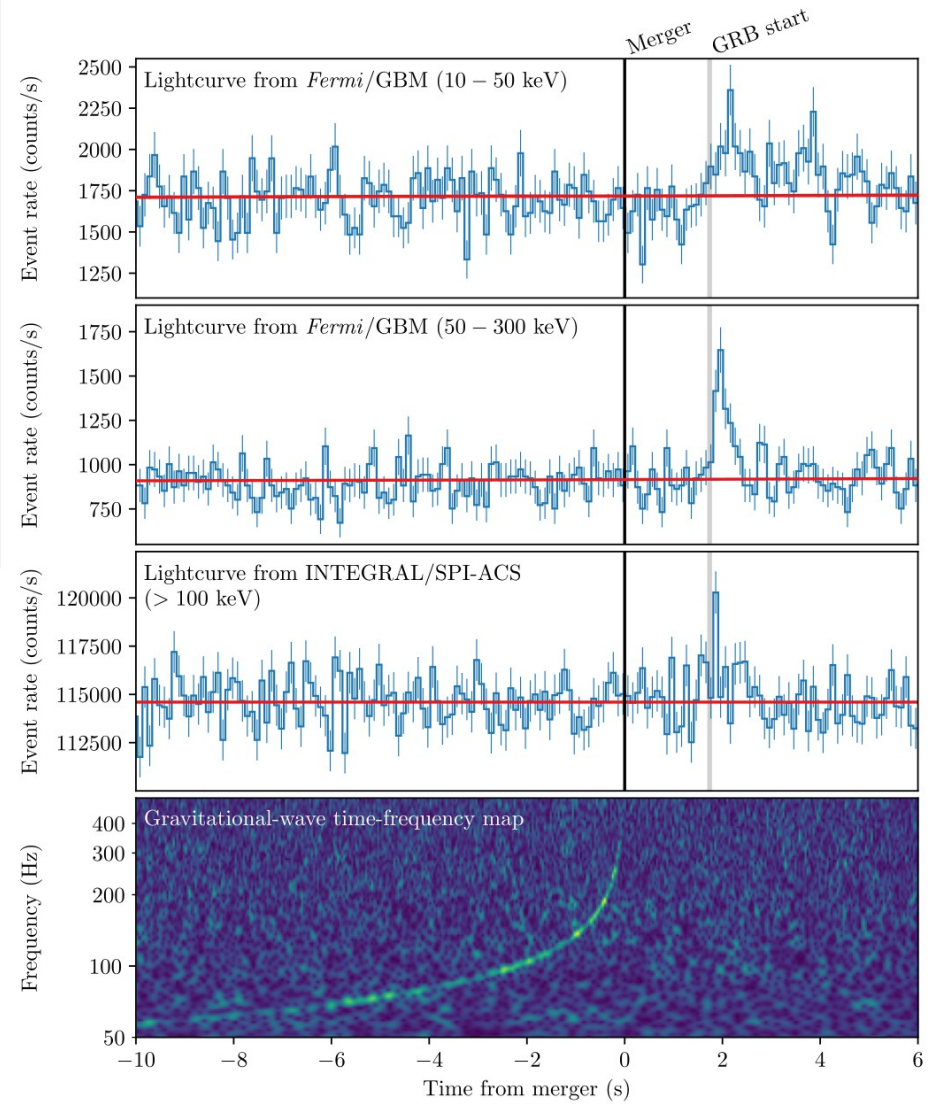
Neutron stars,
Black Holes (stellar and Supermassive)

FORMATION of Compact Objects
(very large acceleration of very large masses)

Natural connection to Gravitational Waves

neutron-star neutron-star merging

GRB 170817A



GW 170817

Gamma Rays

$$E > 100 \text{ MeV}$$

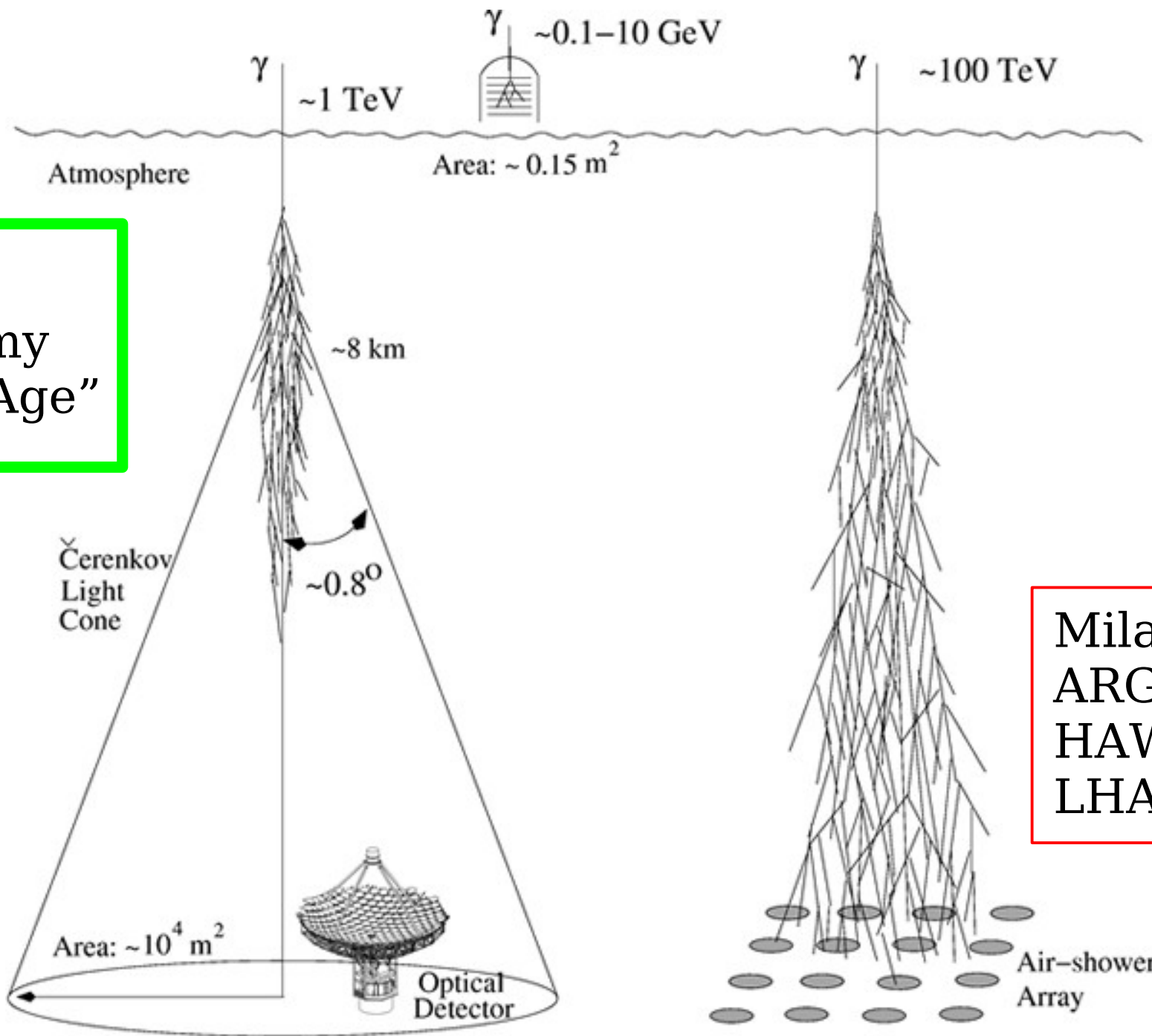
More in general
photons in a very broad range
of energy (wavelength)
[21 orders of magnitudes]
from Radio to 100 TeV
(and above in the future)

Egret
Agile
Fermi

Gamma
Astronomy
“Golden Age”

Hess
Magic
Veritas

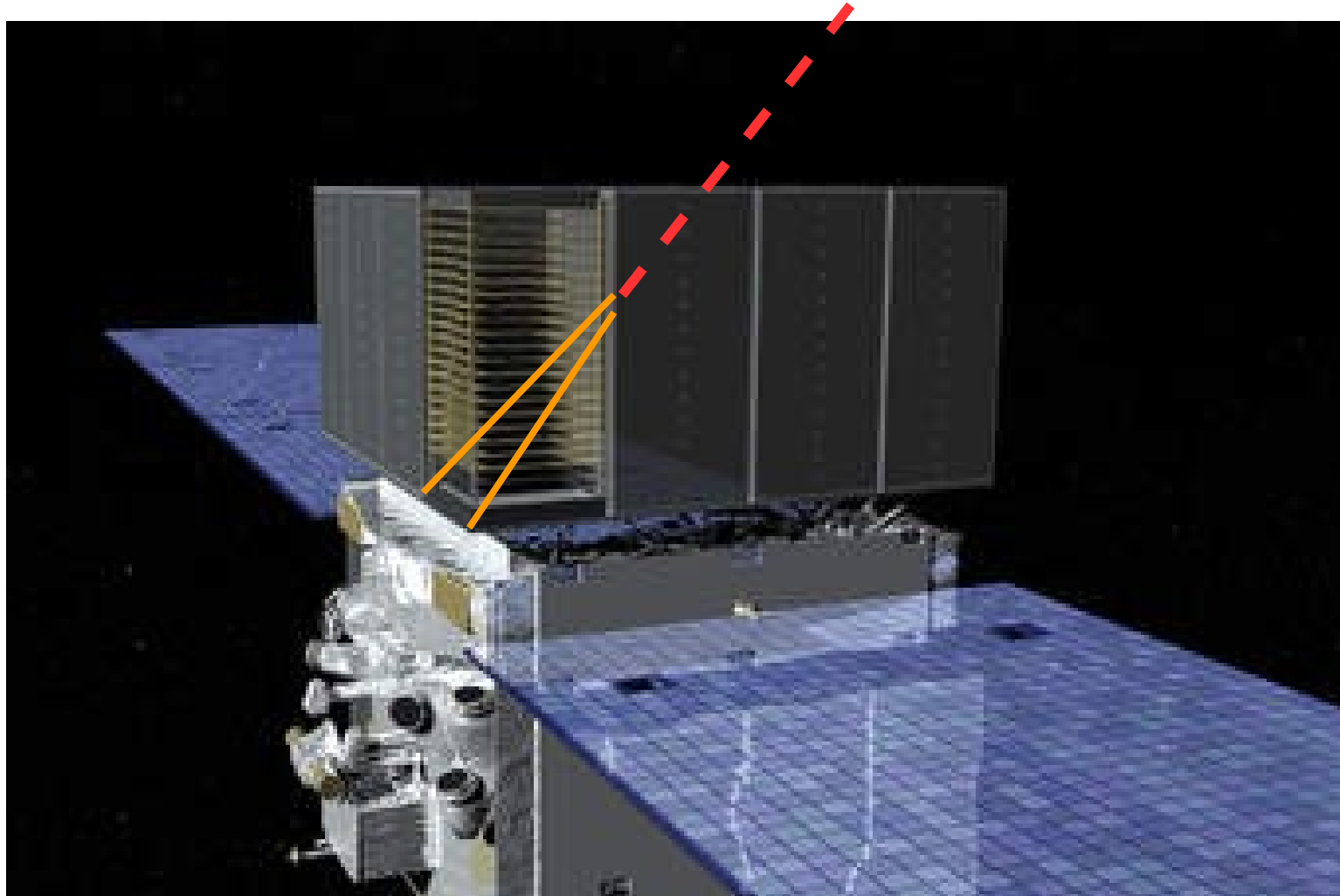
CTA



Milagro
ARGO
HAWC
LHAASO

FERMI Telescope ($E > 30 \text{ MeV}$)

[acceptance allows observations up $E \lesssim 1 \text{ TeV}$



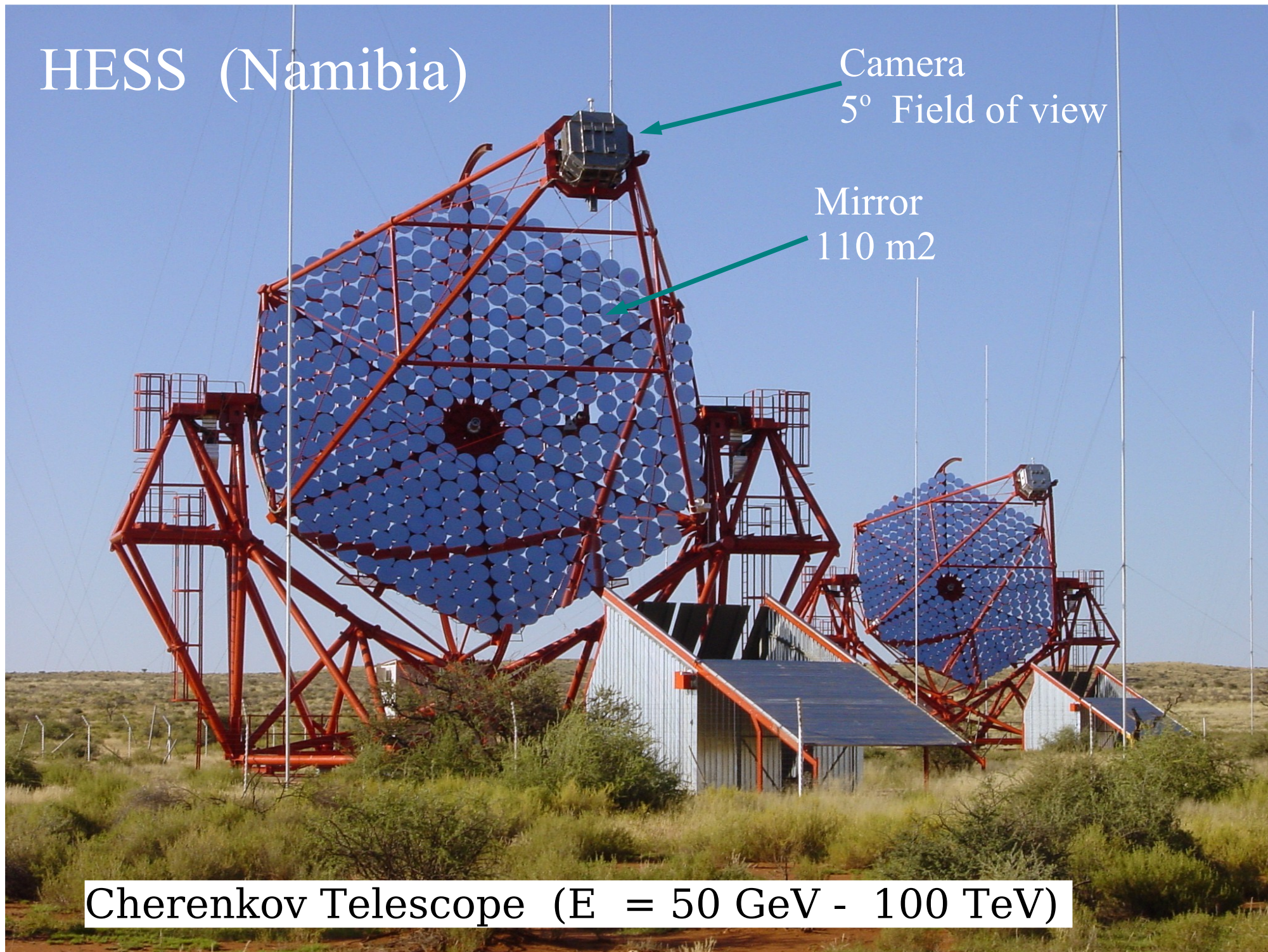
Gamma Ray Burst Monitor [GBM] ($E = 10 \text{ KeV} - 10 \text{ MeV}$)

HESS (Namibia)

Camera
5° Field of view

Mirror
110 m²

Cherenkov Telescope ($E = 50 \text{ GeV} - 100 \text{ TeV}$)



Gamma-ray

Particle shower

Detection of high-energy gamma rays

using Cherenkov telescopes

~ 10 km

Gamma-ray

Particle shower

Detection of high-energy gamma rays

using Cherenkov telescopes

~ 10 km

Cherenkov light

~ 1°

~ 120 m

Gamma-ray

Particle shower

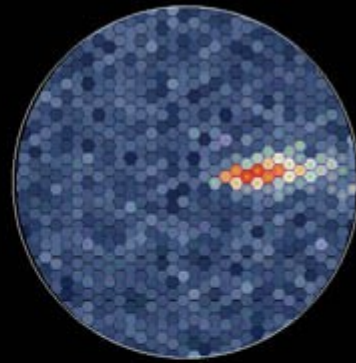
Detection of high-energy gamma rays

using Cherenkov telescopes

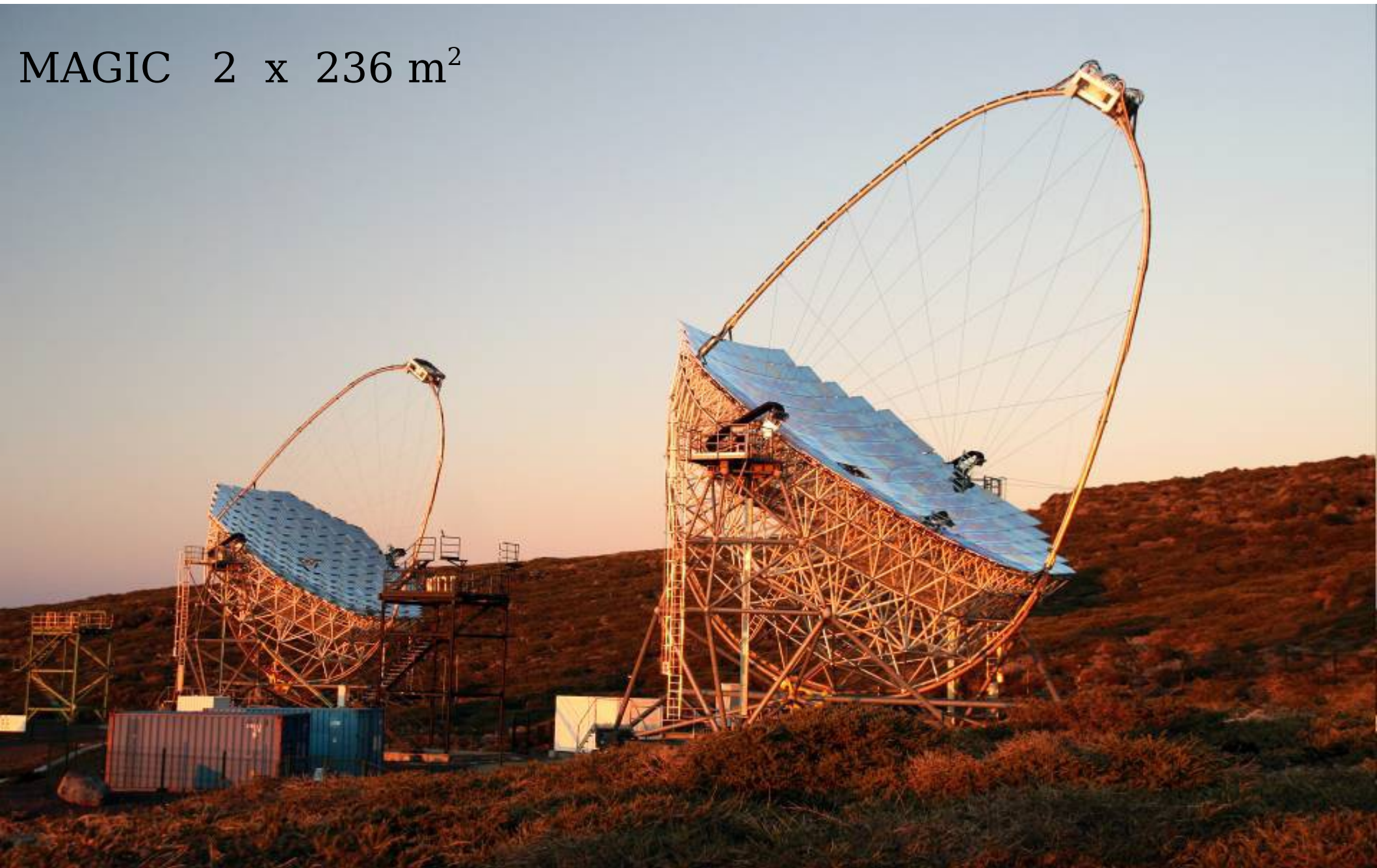
~ 10 km

Cherenkov light

~ 1°

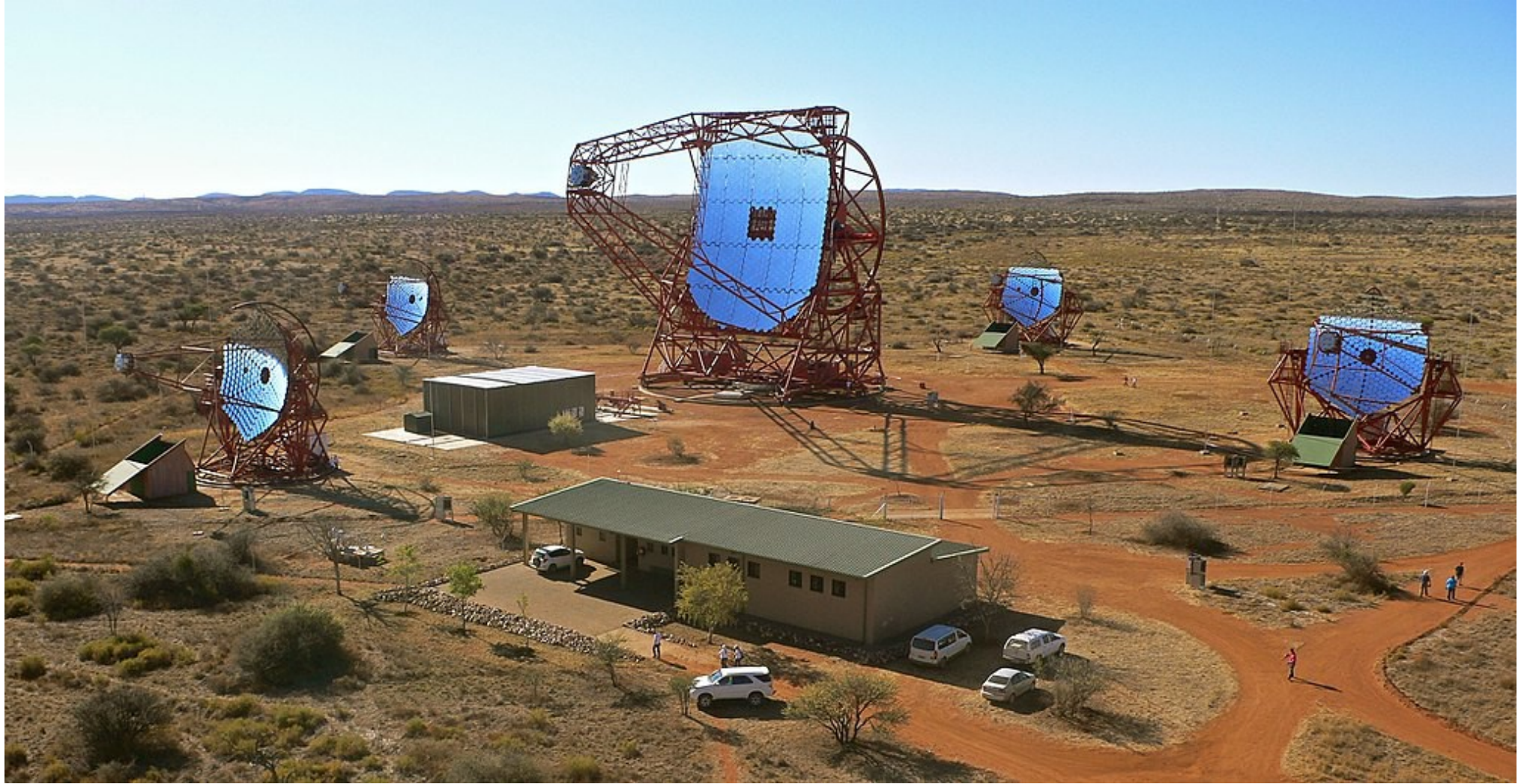


MAGIC 2 x 236 m²



HESS Telescope (Namibia)

4 12 m diameter telescopes
1 28 m “ “



HAWC gamma ray telescope (Mexico)



LHAASO detector in China

Western view

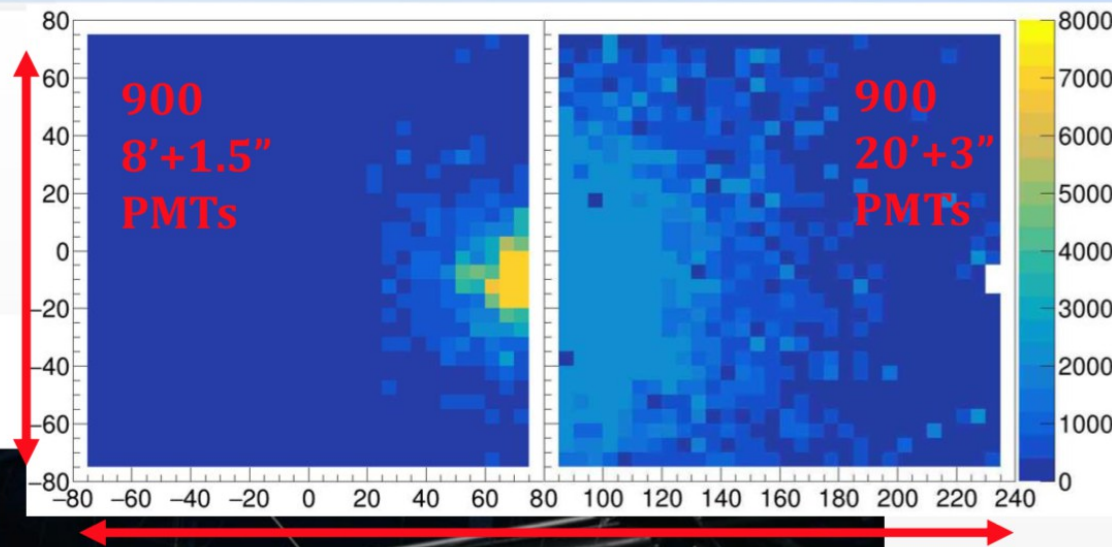
Eastern view

◆ LHAASO bird
view in Oct. 2019



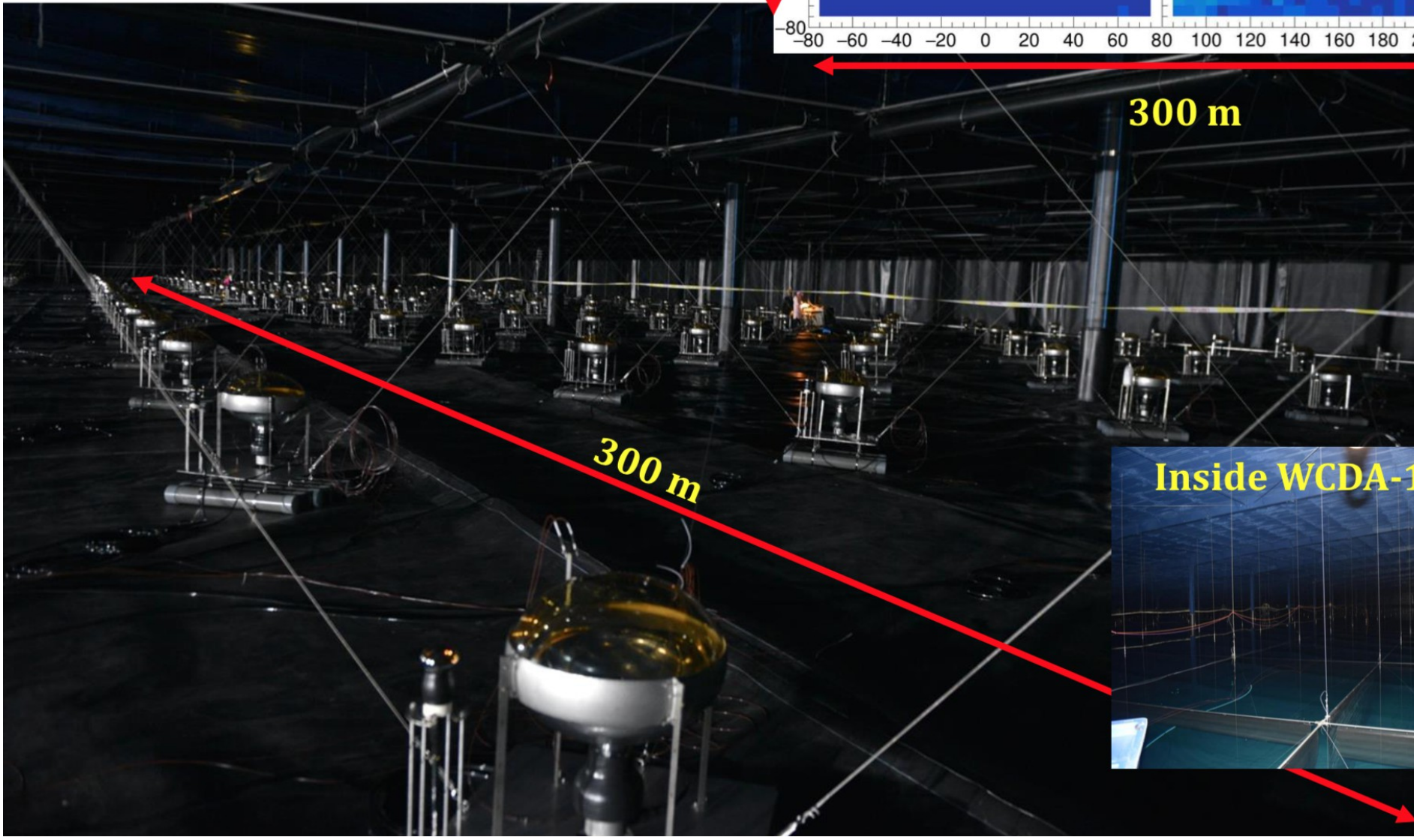
Inside WCDA-3

150 m

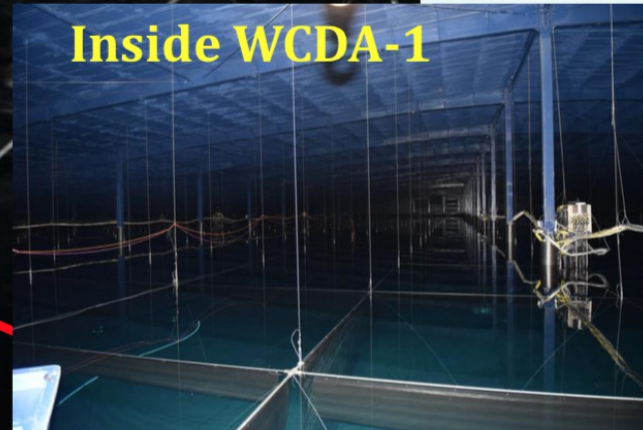


WCDA-1 started operating April 2019

WCDA-1 started operating January 2020



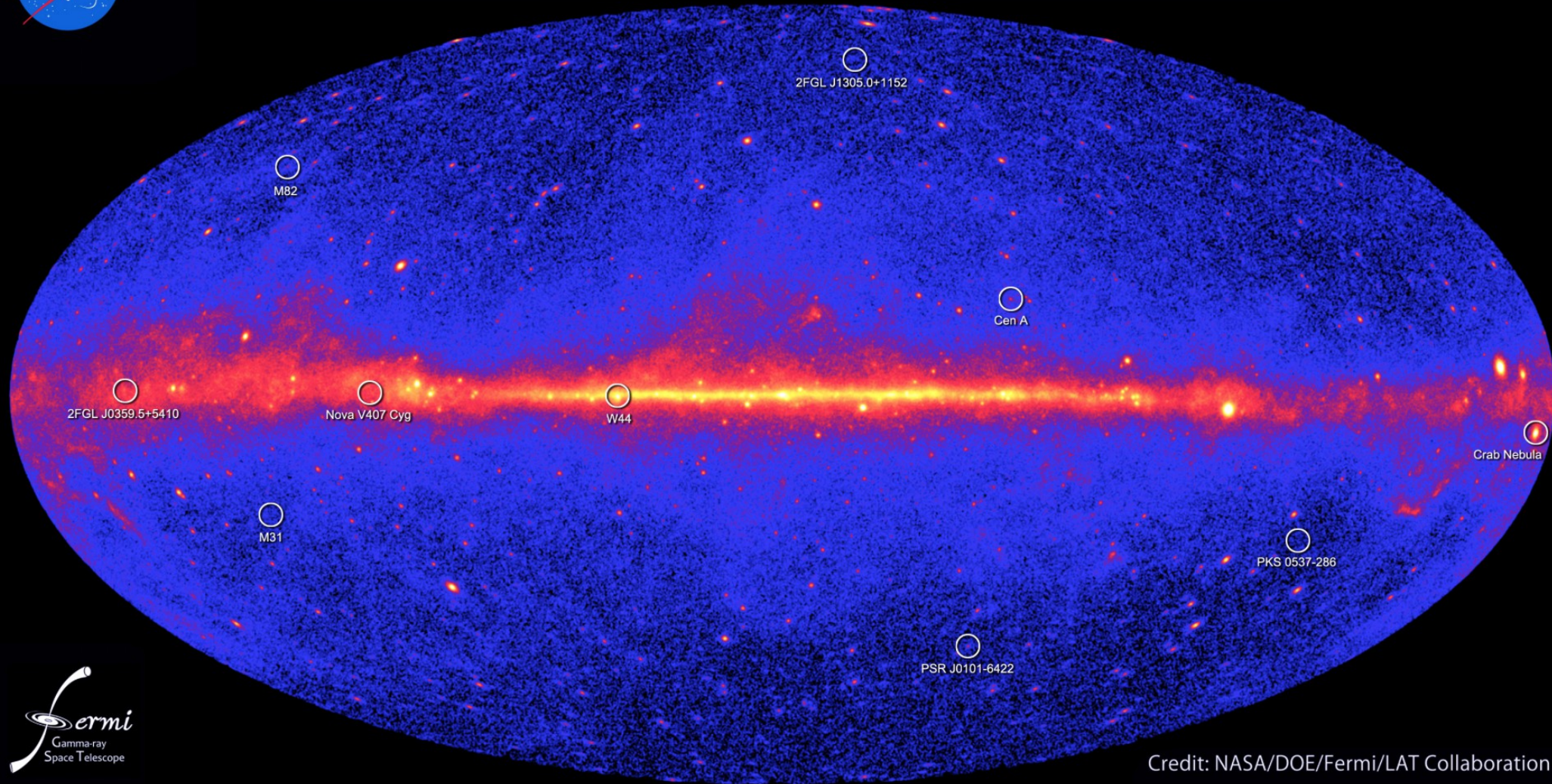
300 m



$$E_{\gamma} \geq 100 \text{ MeV}$$

Gamma Ray Sky

Fermi two-year all-sky map

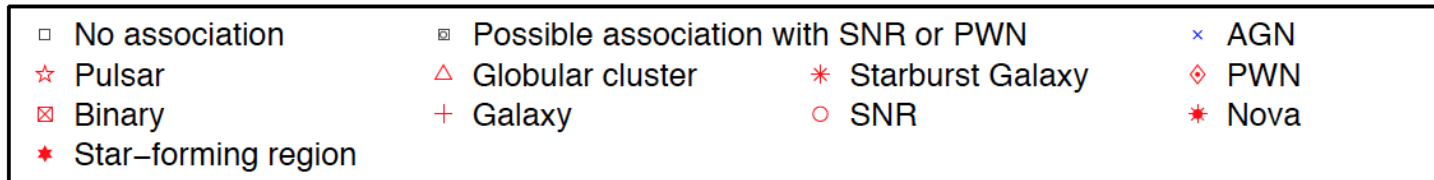
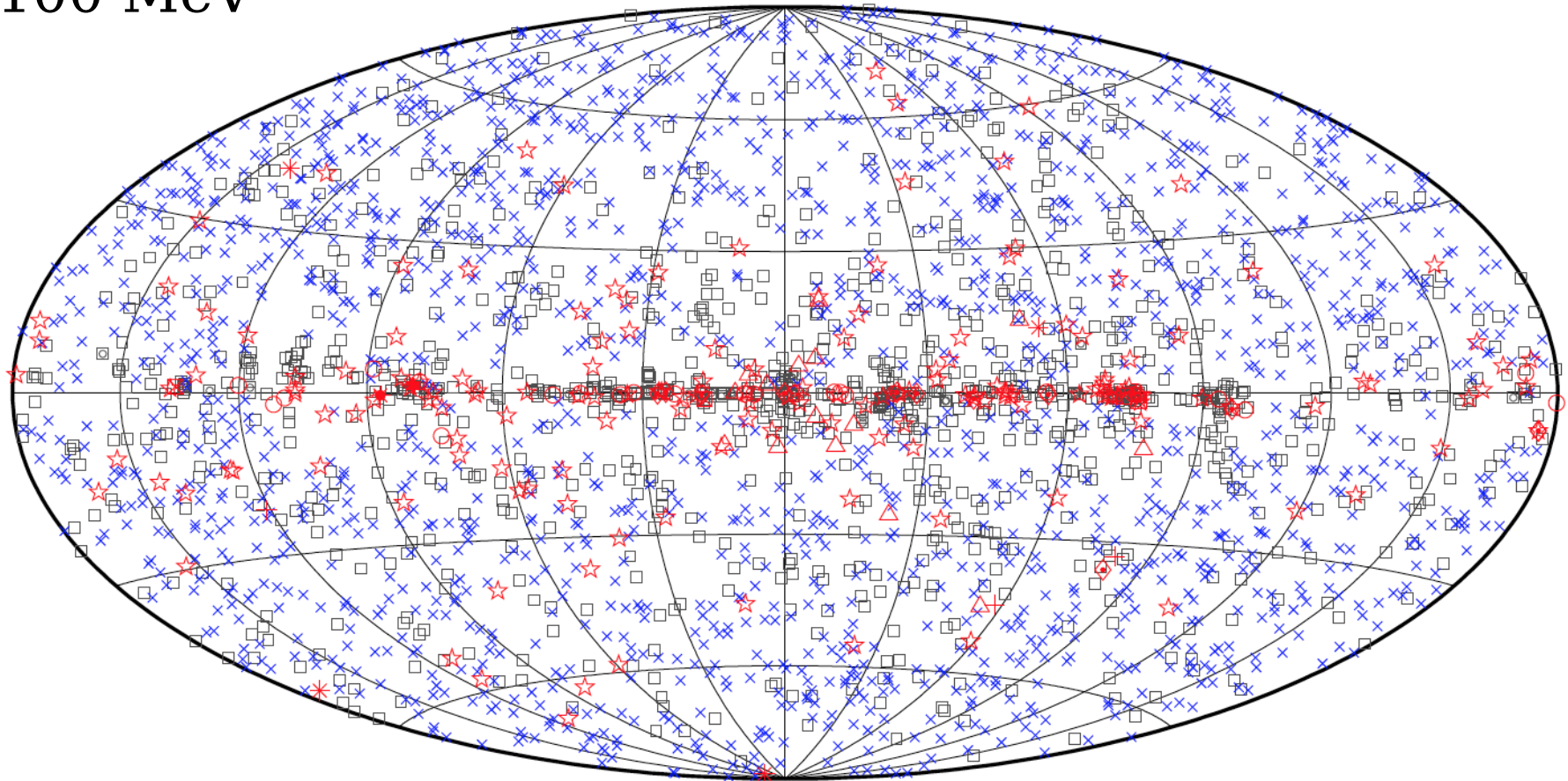


Credit: NASA/DOE/Fermi/LAT Collaboration

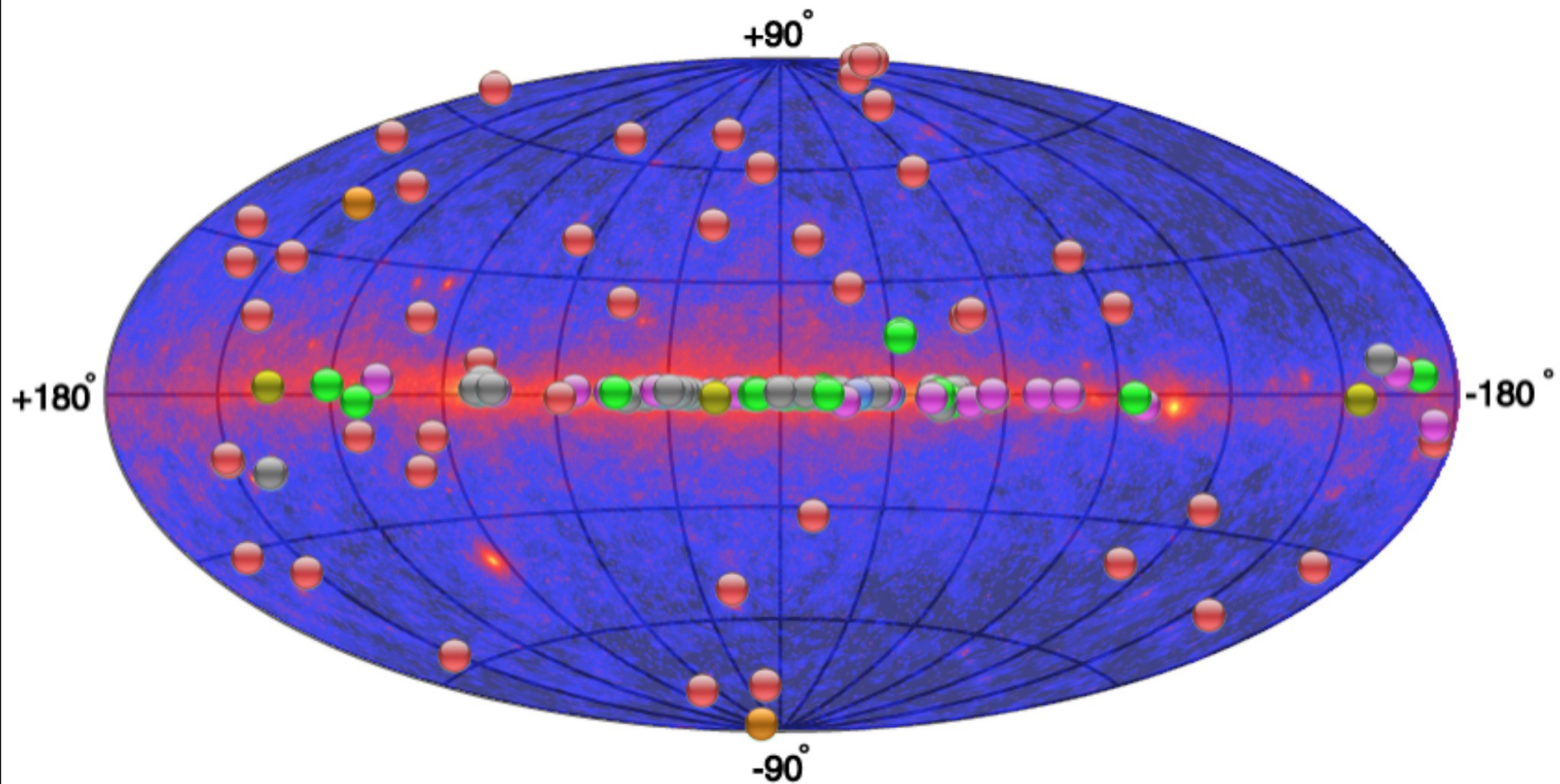
3rd FERMI Catalog

3034 sources

$E > 100$ MeV



TeV Sky 170 $\rightarrow$ 200 Sources



blue-to-red colors $\rightarrow$ 0.1 GeV – Fermi gamma-ray sky

The sky in gamma rays:

1. A diffuse flux generated by the radiation of cosmic rays that fill the Galaxy interacting with gas and radiation fields.
2. An ensemble of Galactic (quasi)-point sources
3. An ensemble of extragalactic point sources