(Very/Ultra) High Energy Astrophysics
I – Introduction

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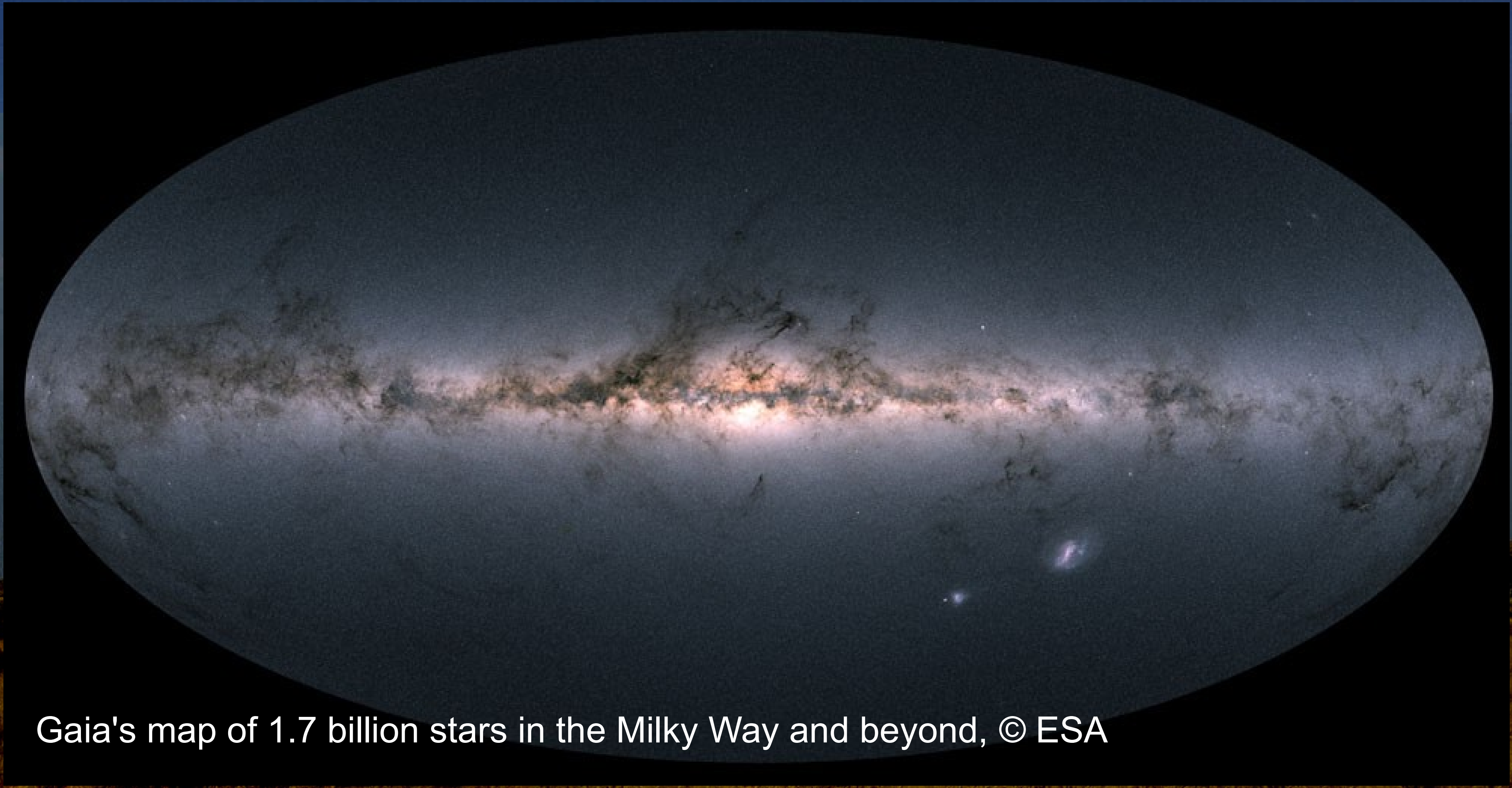
- Revolutions in Astronomy
- What is High Energy Astrophysics ? The main problematic
- Quick panorama of observations techniques

Revolutions in Astronomy

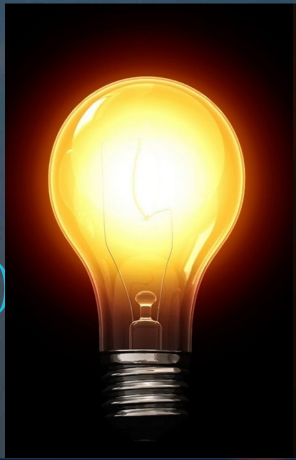
The Sky in Optical



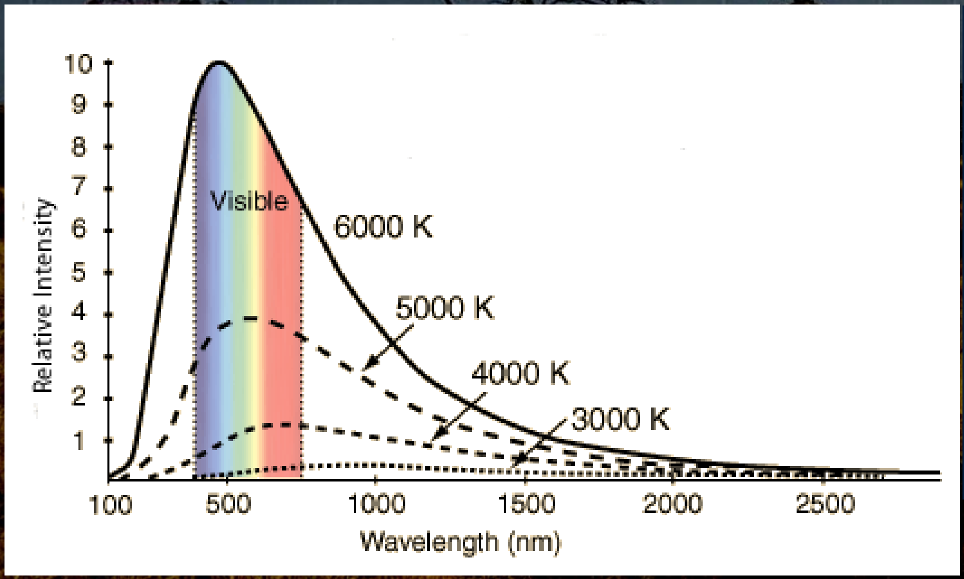
Gaia's map of 1.7 billion stars in the Milky Way and beyond, © ESA

What shines in Visible Light?

- Thermal emission from hot objects
  - Black-body spectrum
  - Direct relation between temperature and colour
  - + Spectroscopic lines (quantum effects – atomic lines)

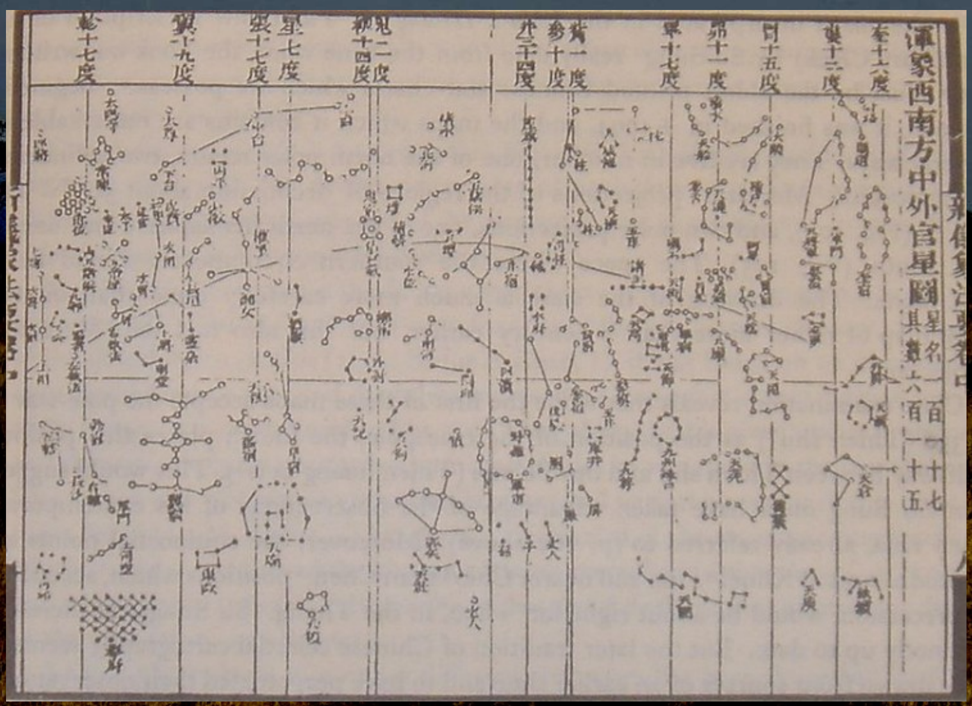



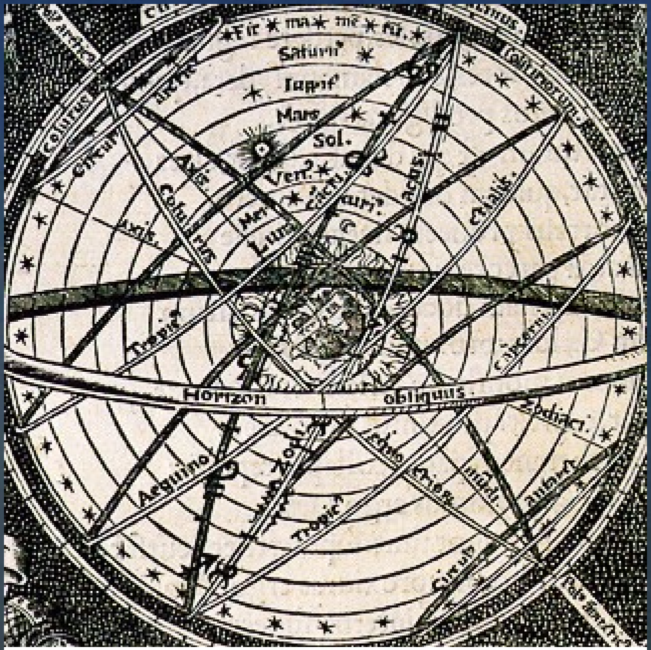




Ancient Astronomy

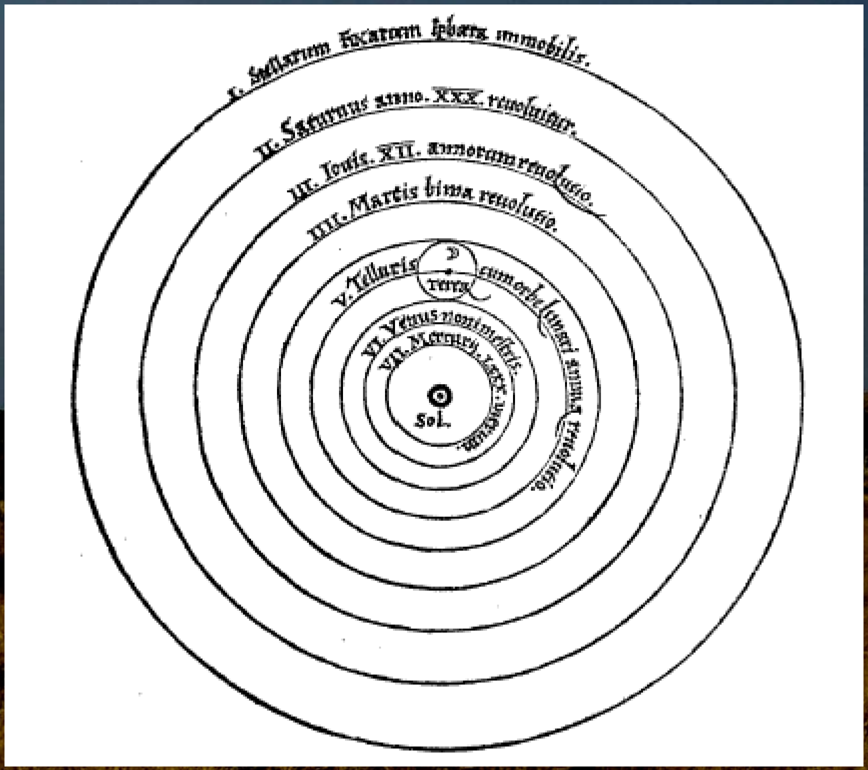
- Movement of planets
- Stars & Constellations
- Cosmology centred on Earth





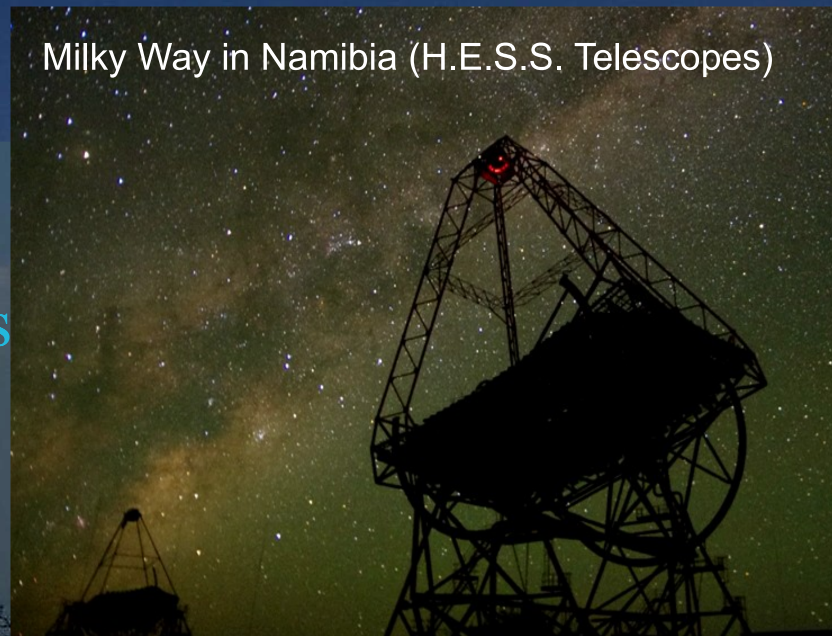
Middle Age

- First instruments (Galileo, 1609)
- Heliocentric system (Copernicus, 1530)



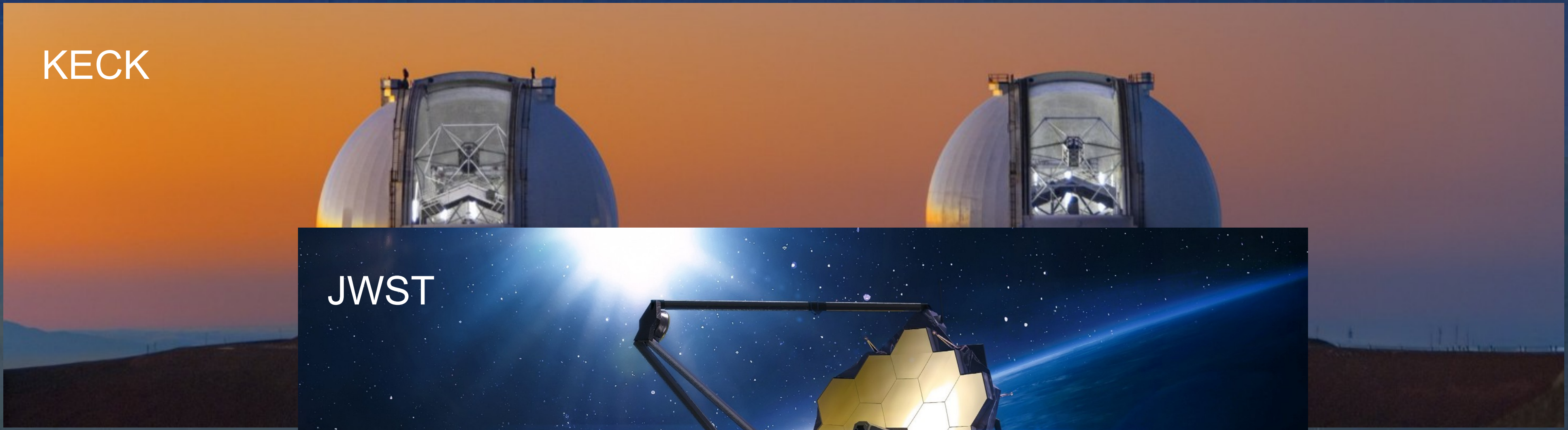
Astronomical Objects in Visible – Ancient Astronomy

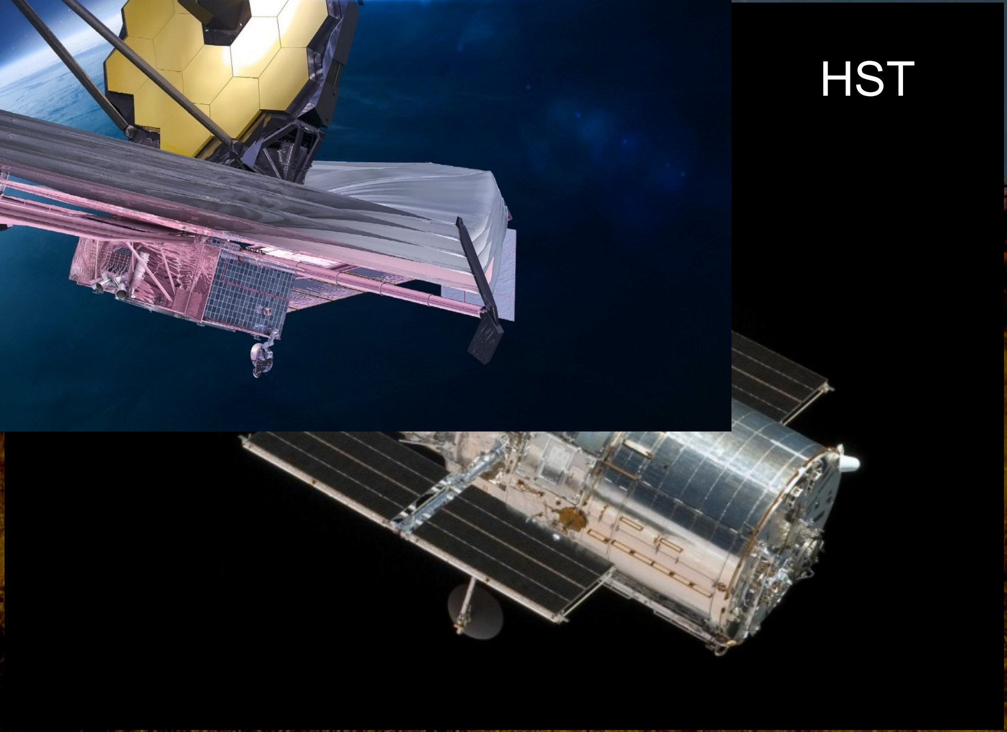
- Hot objects (stars, nebulae, galaxies)
- Illuminated objects (planets)



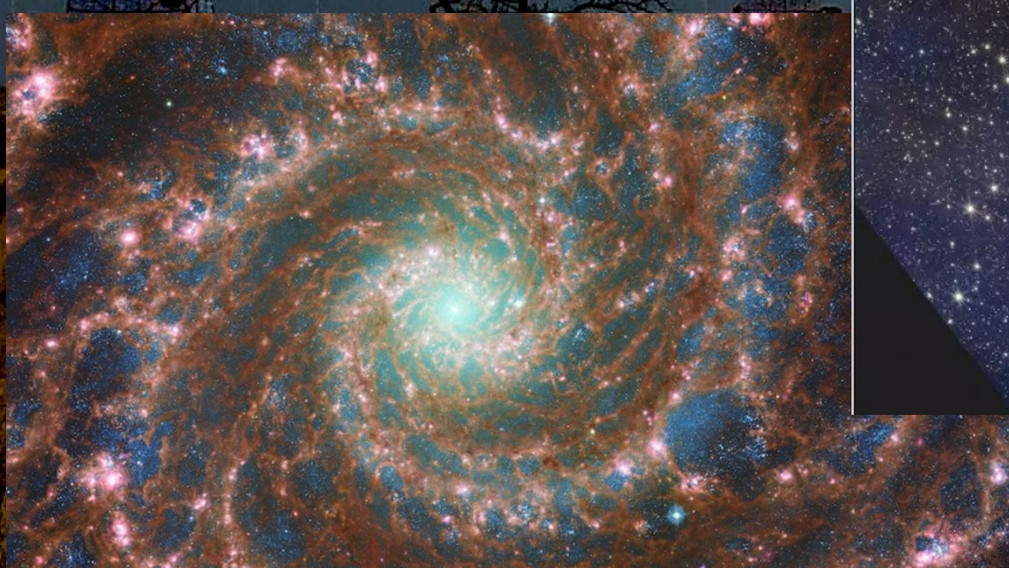
- Physics:
  - Motion (Kepler) → Dark Matter
  - Energy Source → Nuclear fusion
  - Composition, Mass, Evolution of stars,
  - …

Modern Optical Astronomy



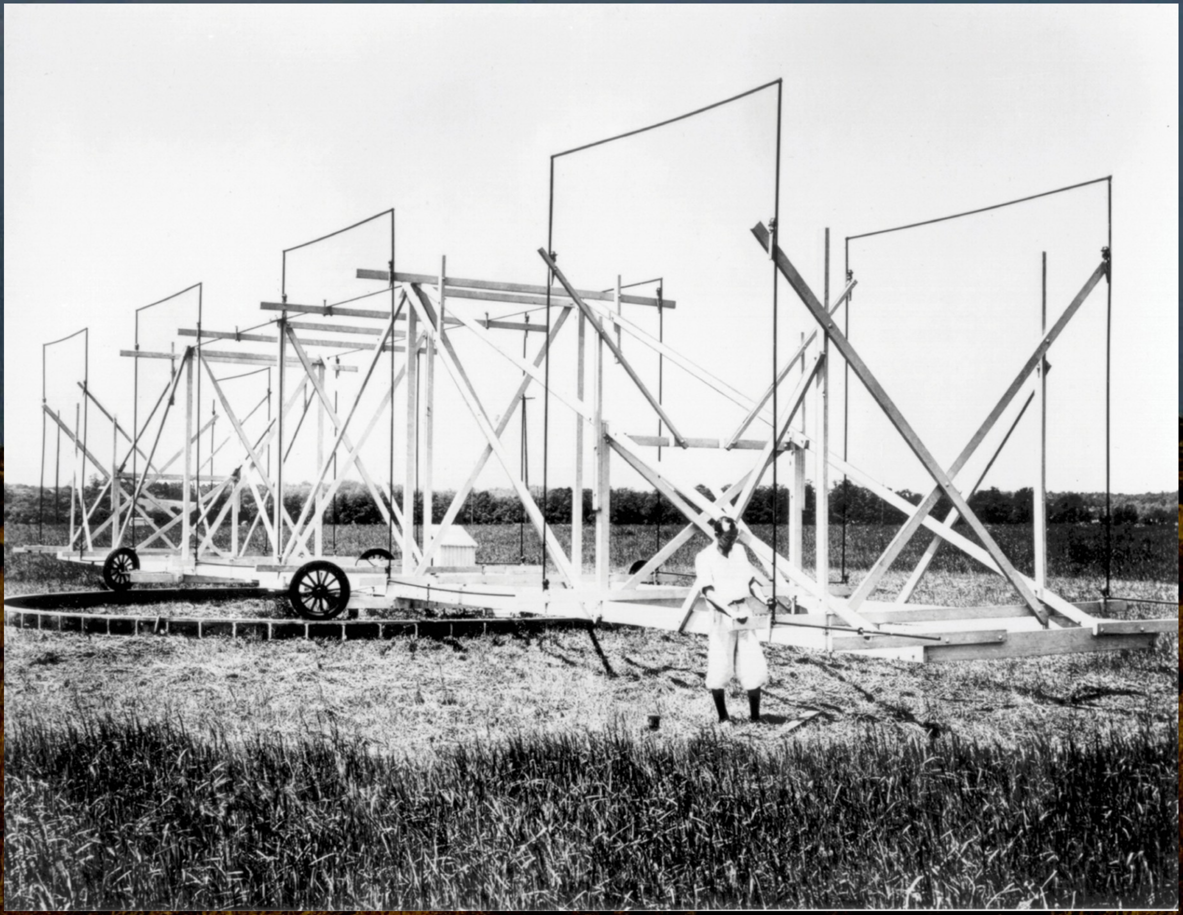


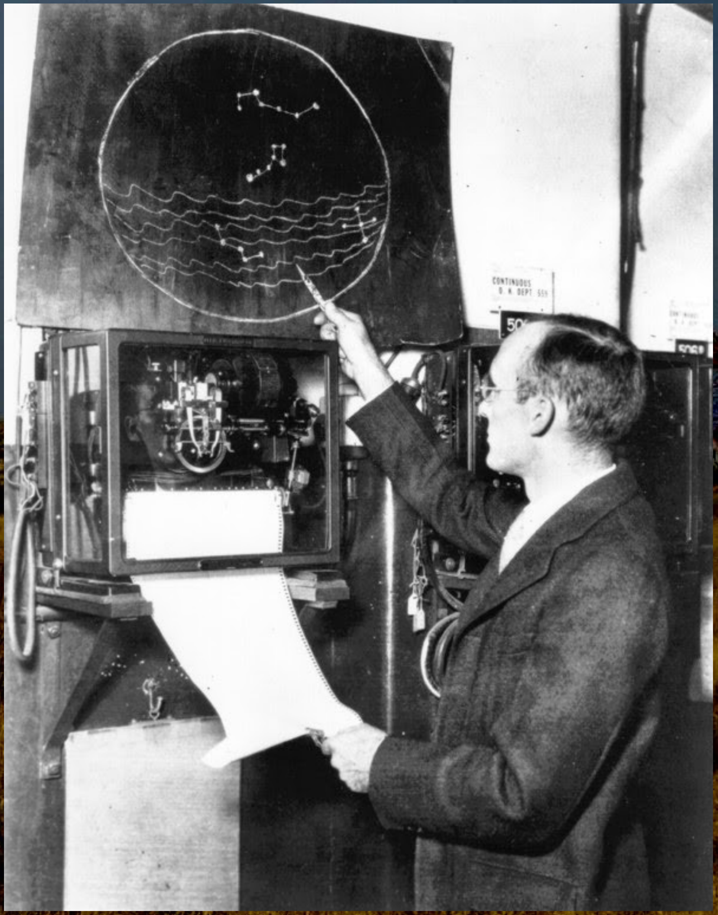
JWST



First Astronomical Revolution - Radio

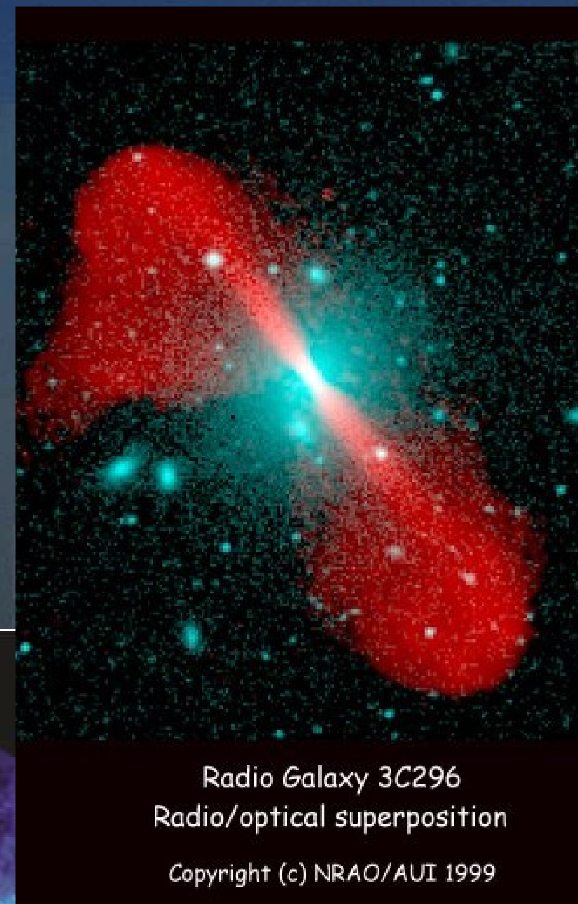
- Accidental detection of radio waves from the Galaxy when searching for the sources of interferences in transatlantic communications (Karl Jansky, 1932)

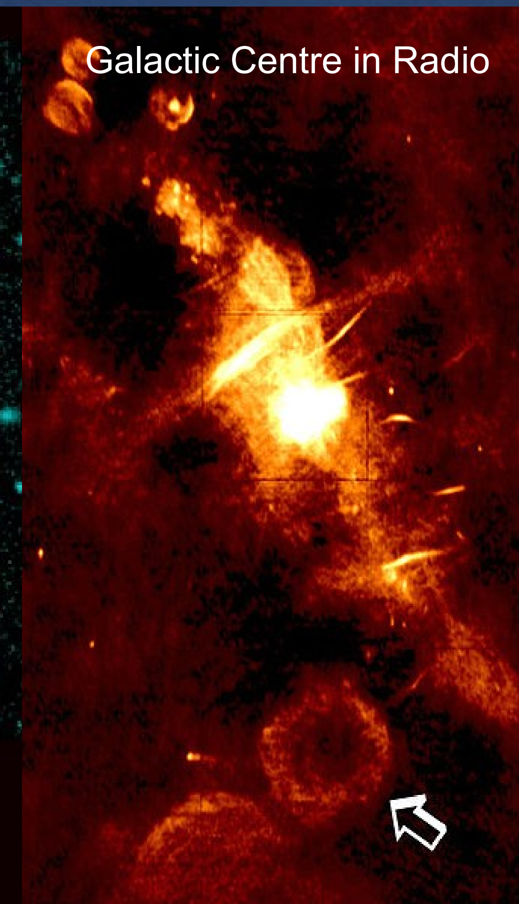


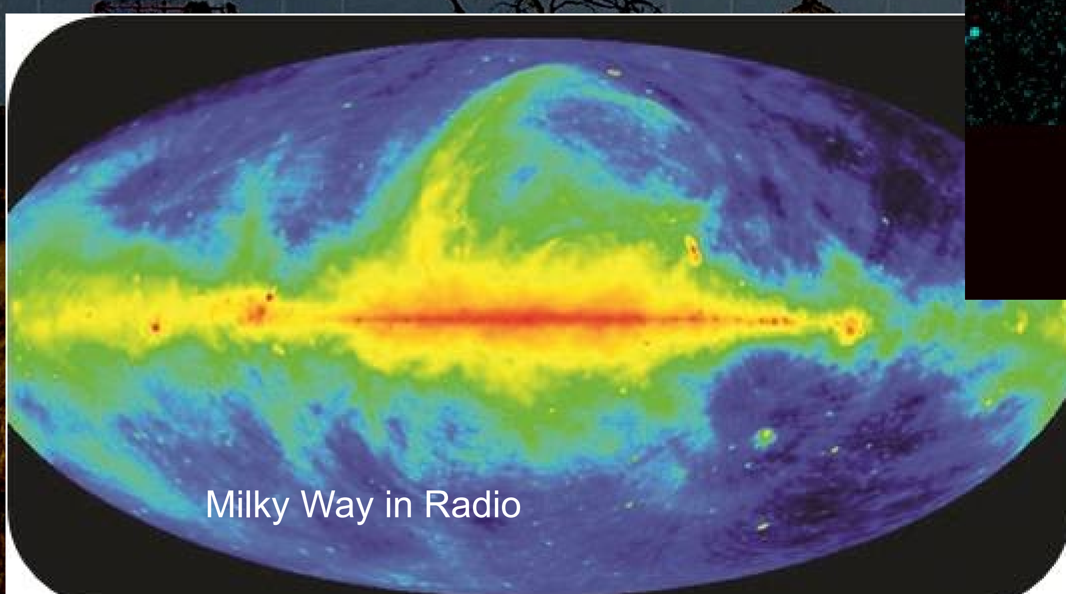


The Sky in Radio

- Radio emission (mostly) from synchrotron emission of accelerated electrons in large magnetic fields.
- New classes of objects: radio-galaxies, quasars, …
- First hint of a Violent Universe – High energy Phenomena

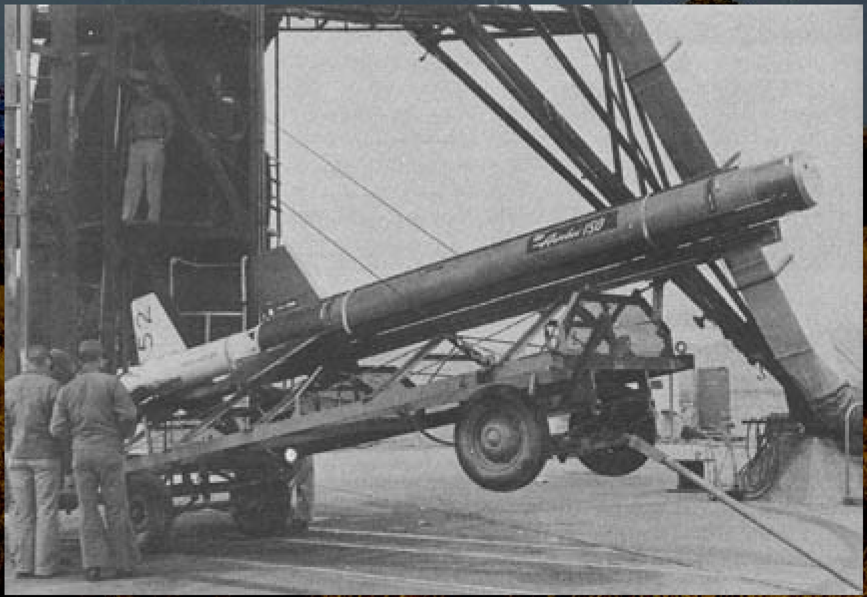


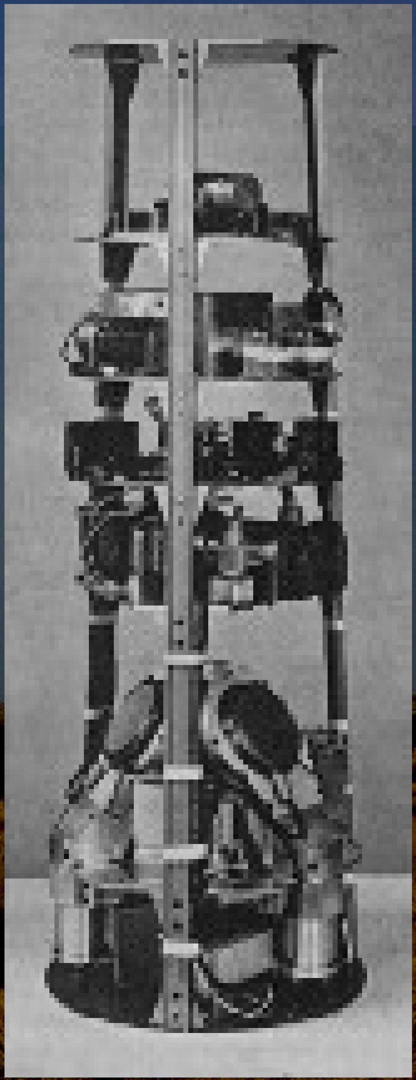




Second Astronomical Revolution – X-Rays

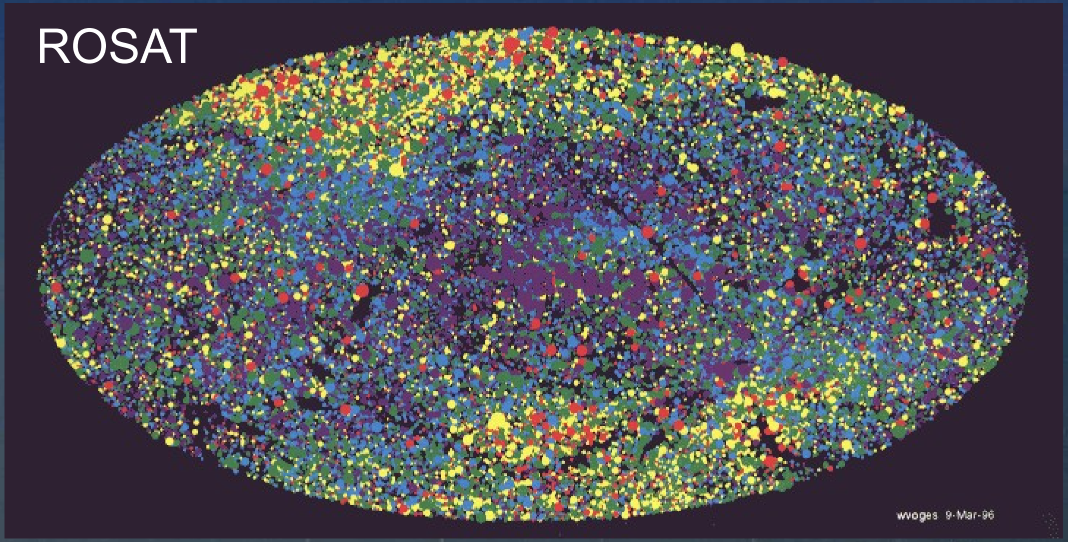
- Originated from the study of the radio waves, reflected by the ionosphere: ionisation attributed by H. Friedman to X-ray emission from the sun
- Observation became possible with rockets (atmosphere opaque to X-rays)
- First detection of a hard X-ray source, Scorpius X-1, 1962
- Many sources quickly detected

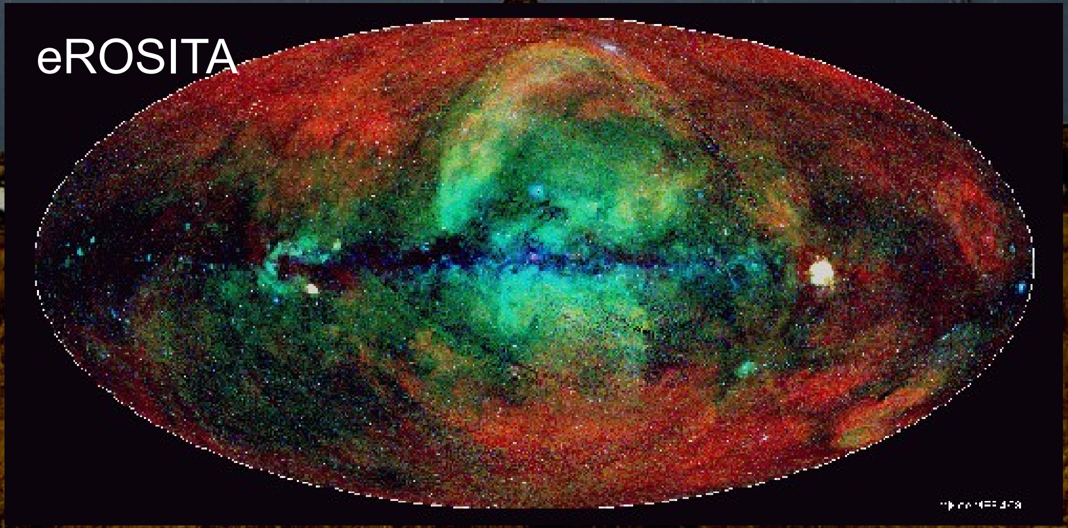




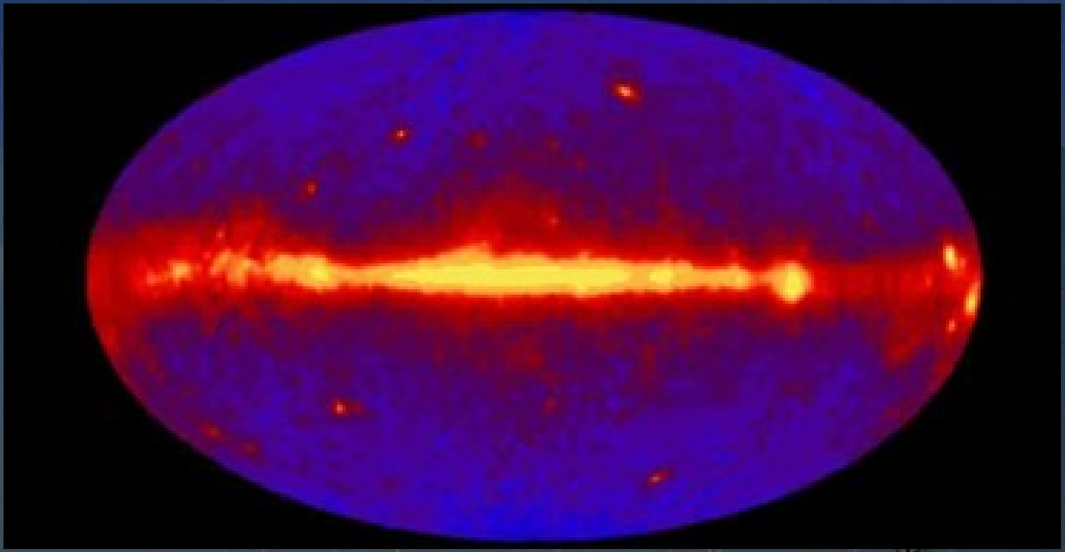
The Sky in X-rays (now)

- Superposition of:
  - Thermal emission from hot, compact sources (~10^6 K): Neutron stars, pulsars, quasars, …
  - "Non-thermal" emission from high energy particles interacting with interstellar medium (Bremsstrahlung) and magnetic field (Synchrotron)
  - Second hint of a Violent Universe – High energy Phenomena

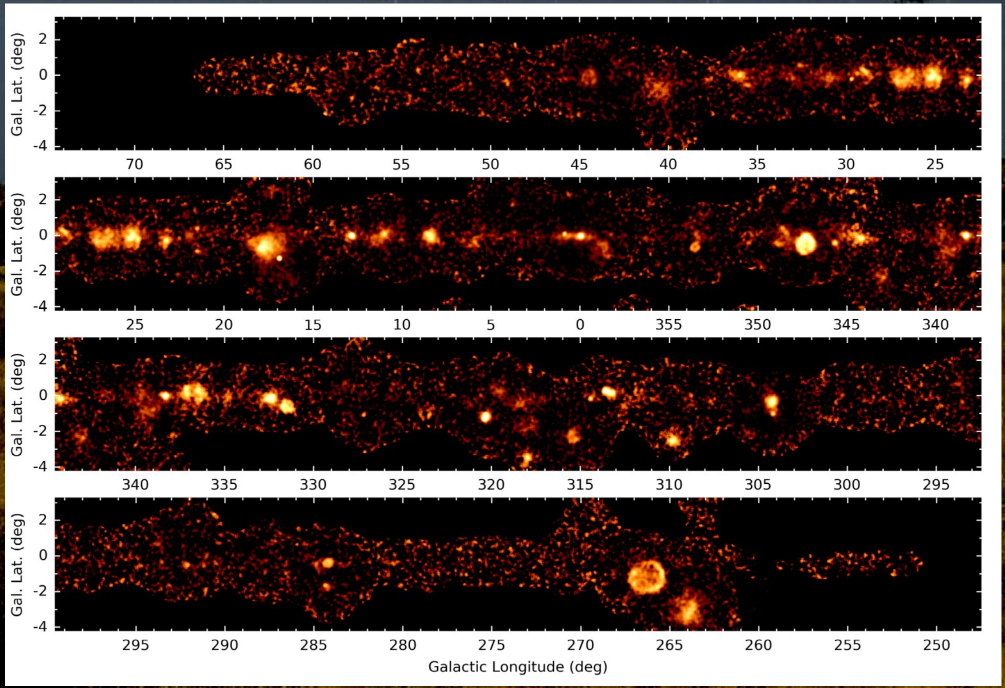




Third Astronomical Revolution – γ-rays



- γ-rays ideal probes to Very High Energy Universe (only produced in most energetic phenomenon)
- First from space (COS-B, EGRET, Fermi)



- Second from ground (Whipple, CAT, HEGRA → MAGIC, VERITAS, H.E.S.S.)
- See next lecture

“Cosmic Rays”

Electroscope Discharge

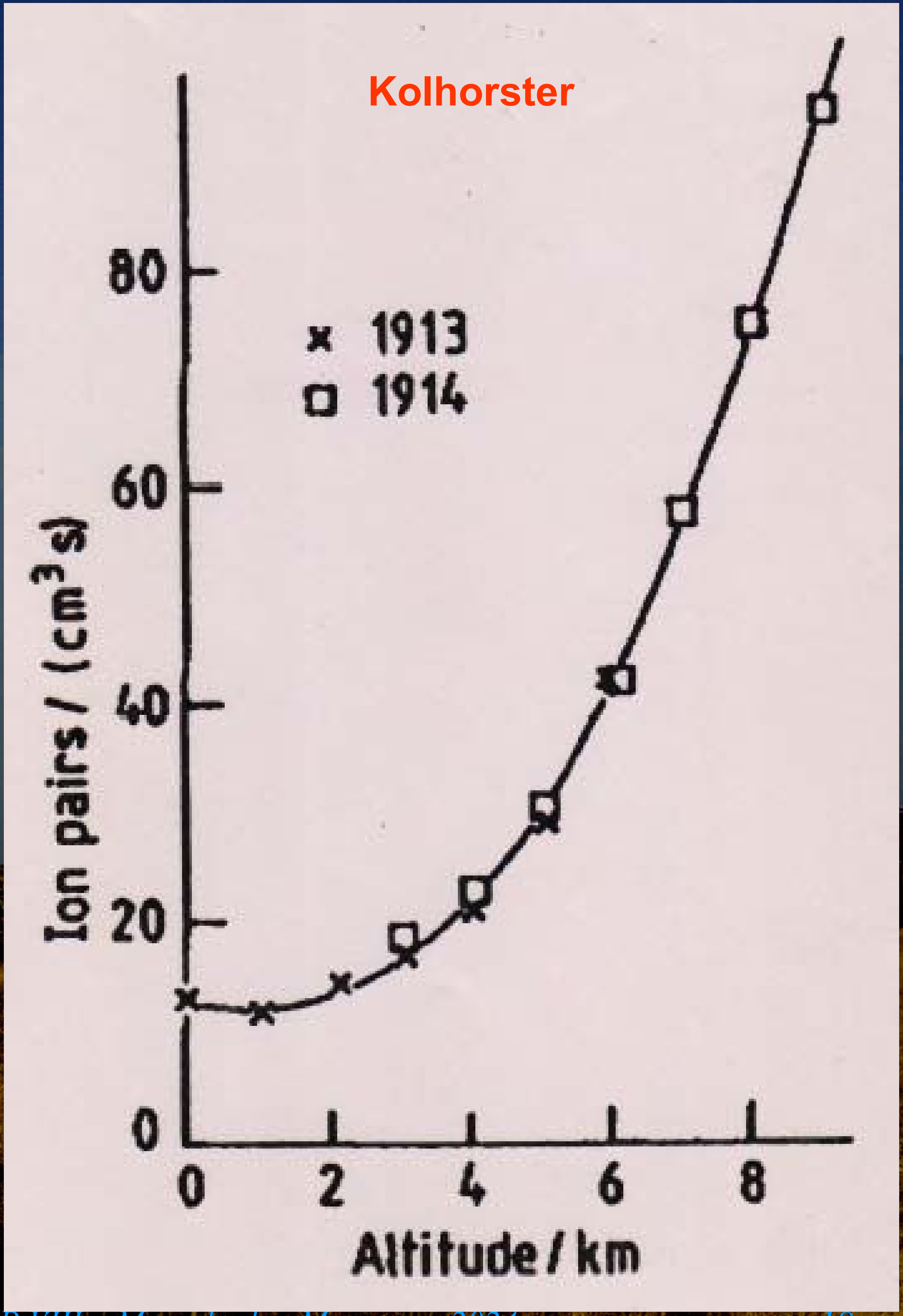
- 1785: Coulomb found that electroscopes spontaneously discharge in air, even insulated
- 1835: Confirmed by Faraday
- 1879: Discharge rate proportional to pressure (Crookes)
  → discharge caused by ionized air

- What continuously ionizes the air? High Energy particles from where?

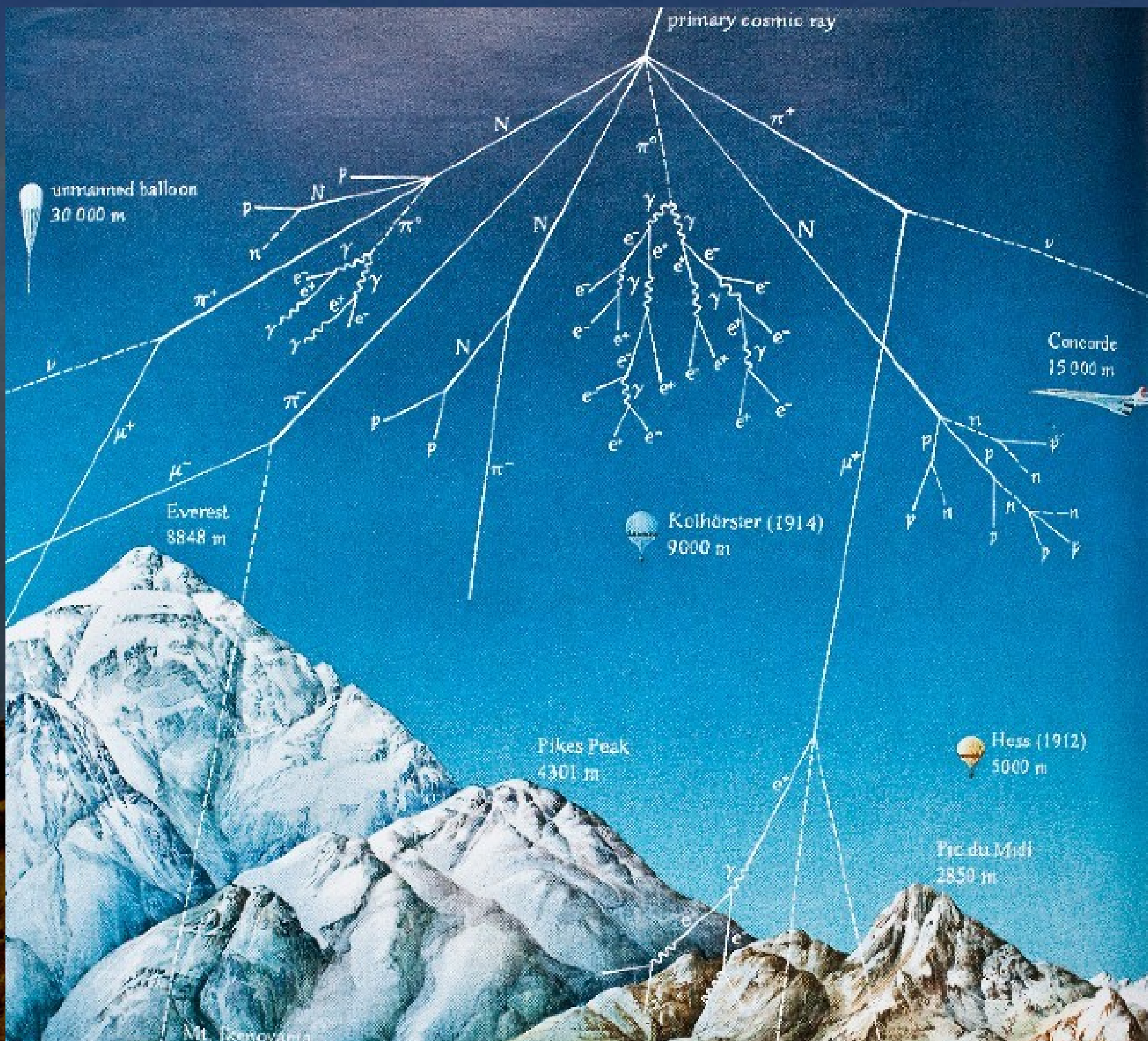
The Cosmic Ray Mystery

1912 : Discovery by Victor HESS (Nobel Prize 1936 with Anderson): flux of ionizing particles increases with altitude

- 1913-1914: Werner Kolhörster repeats and confirms findings of Victor Hess ⇒ 9 km
- 1928-1929: uses Geiger counters: ⇒ Charged cosmic rays are most probably charged (Science, 1930)



Why do we care?



- Earth constantly bombarded by High Energy Particles from the Cosmos ("Cosmic Rays")
- Numerous implications:
  - Evolution acceleration (genetic mutations)
  - Creation of radioactive isotopes (^{14}C)
  - Numerous discoveries in particle physics (e^+, $\mu^\pm$, $K^\pm$, Y, ...)
  - Irradiation of flying crew
  - Probable seed for lightenings
  - Possibly seed for cloud formation

Cosmic Rays

- Cosmic rays generate random error in electronic chips, potentially dramatic
  ~ 1 error/256MB/Month
  - Quantas plane plunged over several 100 m without explanation
- Borealis aurora can be lethal for astronauts and have massive consequences
  - 1972: large black-out in the US (6 Million people)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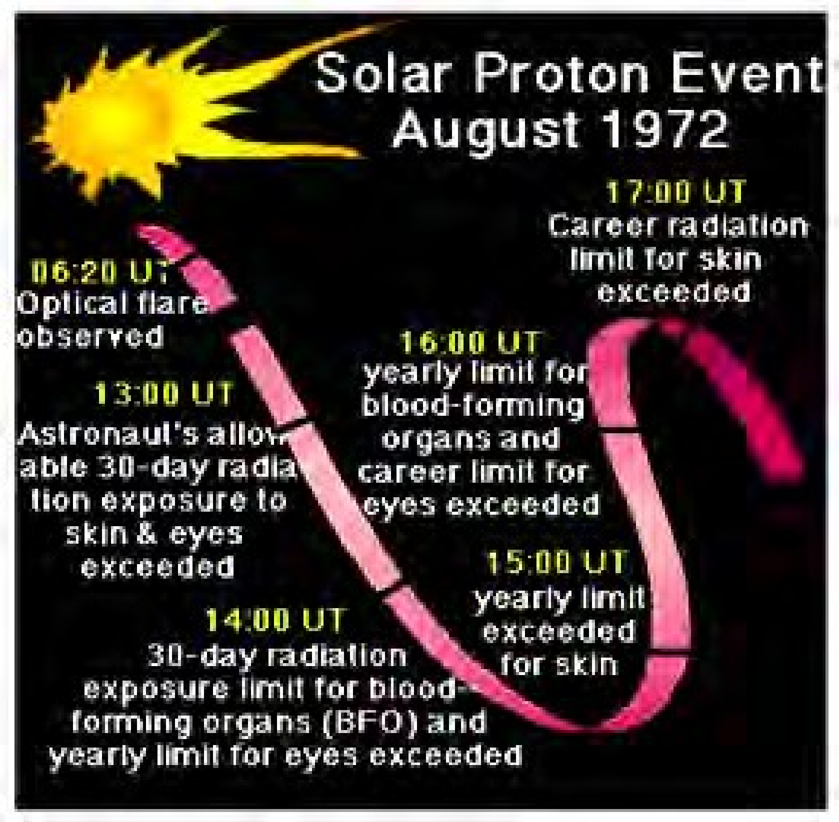
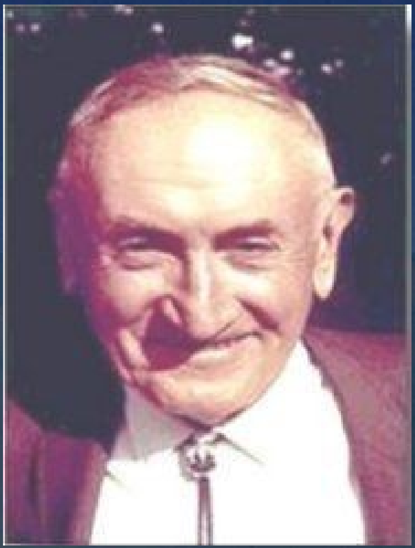
'Cosmic rays' may have hit Qantas plane off Australia's northwest coast

COSMIC rays may have been responsible for a near disaster involving a Qantas jet off Australia's northwest coast. Safety investigators have isolated...



Some major dates

- 1934 : Supernovas proposed as putative sources of CRs. (Baade & Zwicky)
- 1938: Neutron star collapse can be used as cosmological standard candle ⇒ cosmology



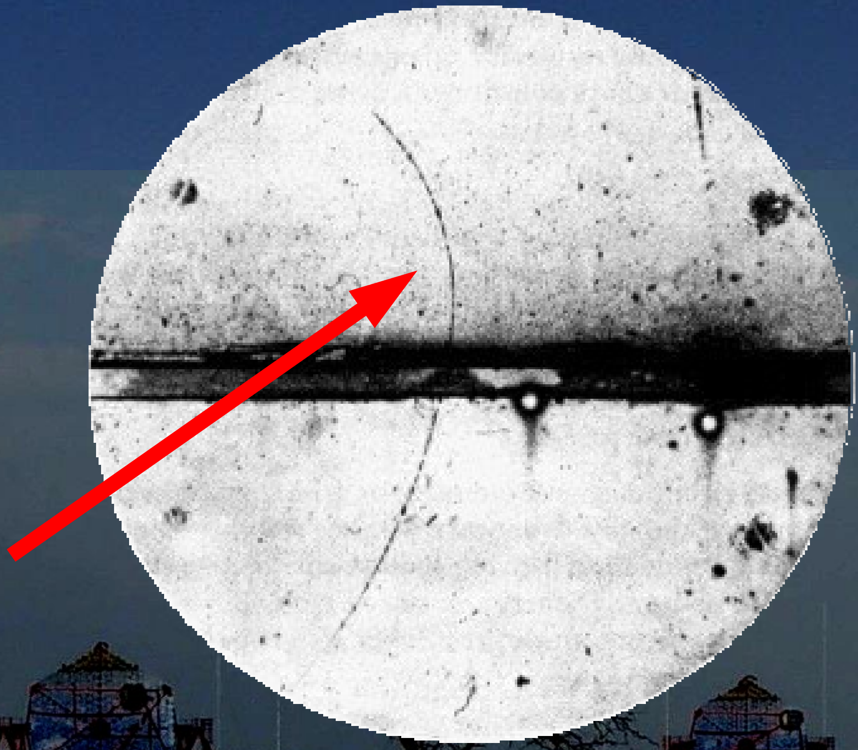
ON SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

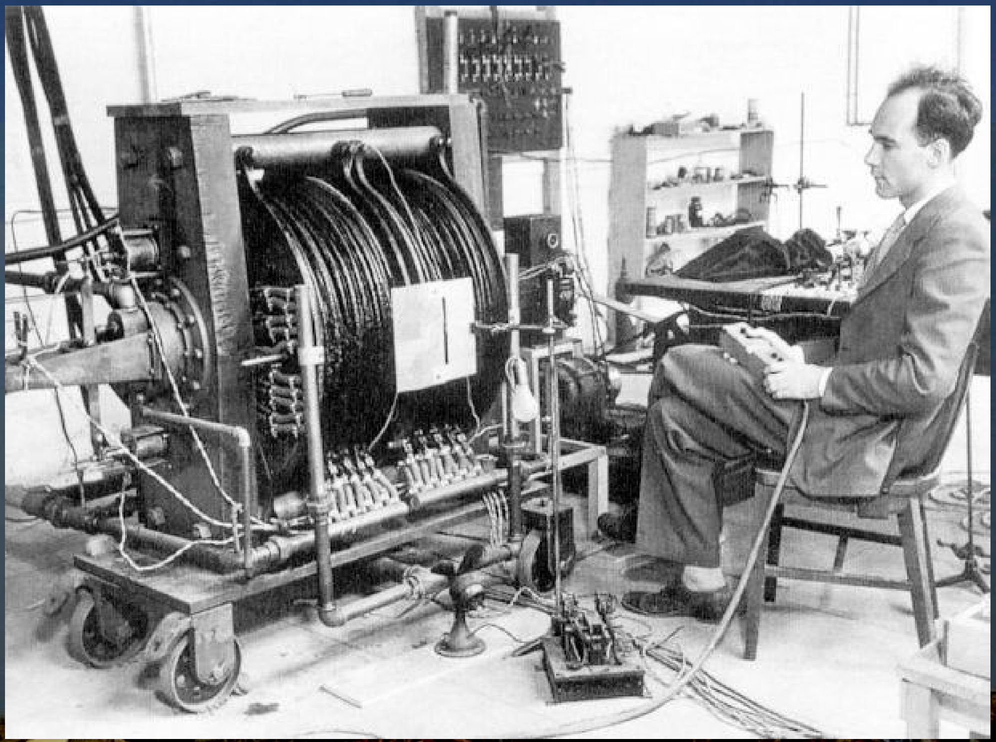
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

Some major dates – con’t



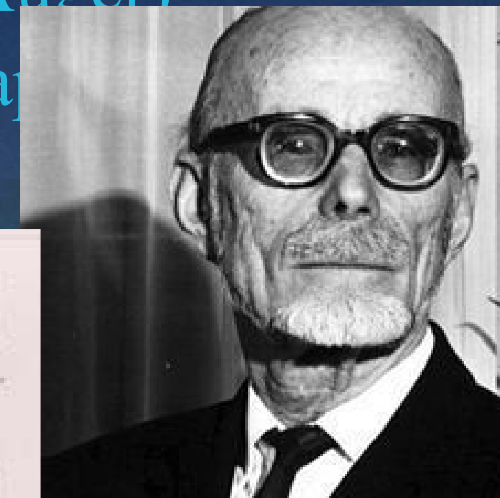
First positron
Anderson, Phys. Rev. (1933)



- 1933: Discovery of positron (e+) in the cosmic rays
- ⇒ Strong relation with particle physics (μ± (1936), π± (1947), Strange particles (1947), ...)

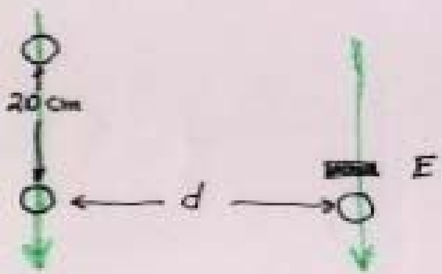
Discovery of giant showers

- 1939 : Discovery of giant showers (Pierre Auger) using coincidence between detectors 50 m a[...]
- Up to 10^{15} eV (at least) !!



PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note (¹) de MM. **Pierre Auger** et **Roland Maze**, présentée par M. Jean Perrin.

1. Nous avons montré (²) l'existence de gerbes de rayons cosmiques produites dans l'atmosphère et dont l[...] plusieurs mètres. Nous avons pu éten[...] de plusieurs dizaines de mètres et [...] corpuscules de très haute énergie da[...]



3 com[...]

d.	E = 0,2.	5.
2ᵐ	1,7	0,86
5ᵐ	1,4	0,7
20ᵐ	0,9	0,4

JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

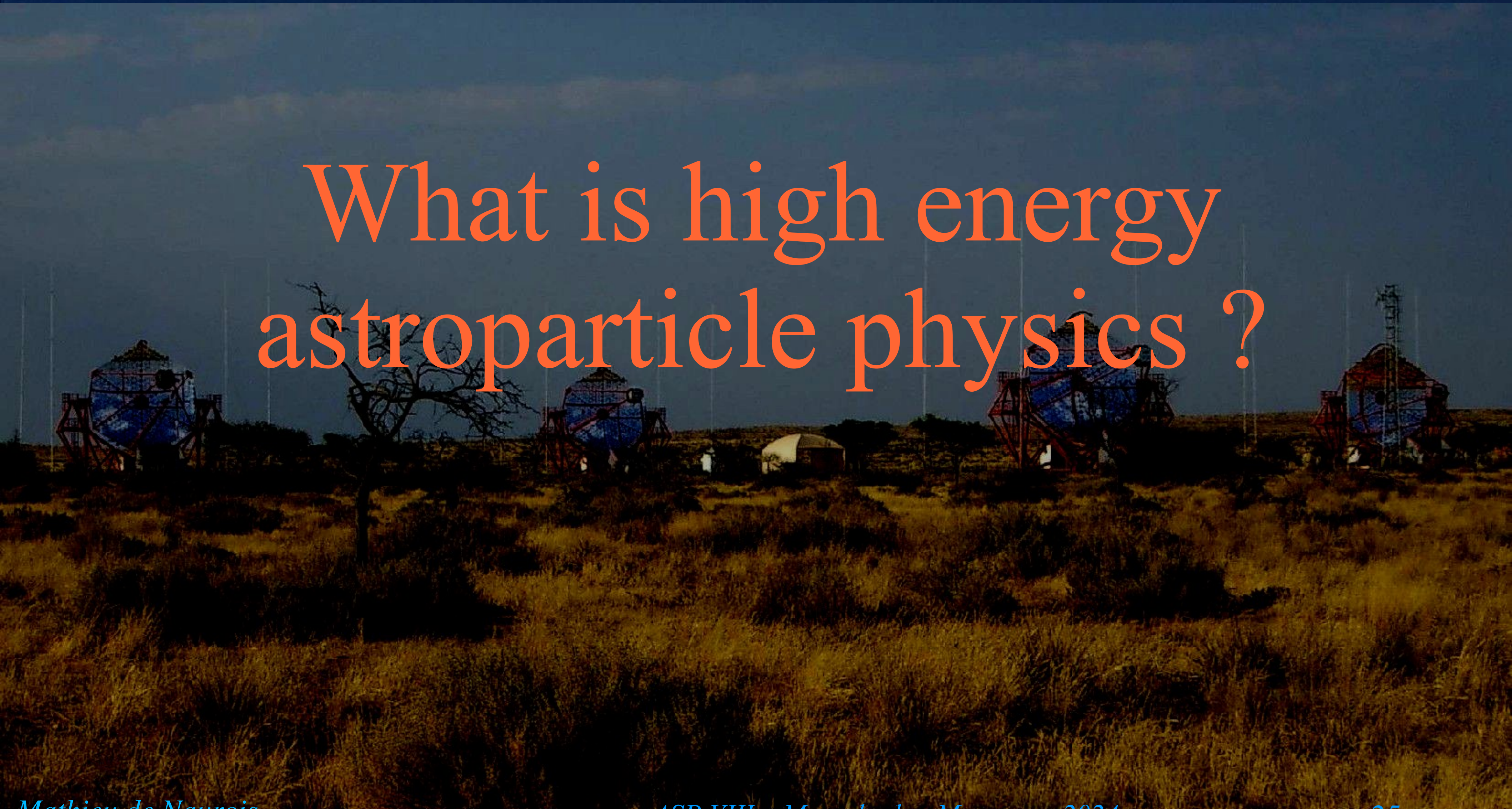
Pierre Auger
In collaboration with
P. Ehrenfest, R. Maze, J. Daudin, Robley, A. Fréon
Paris, France

Conclusion

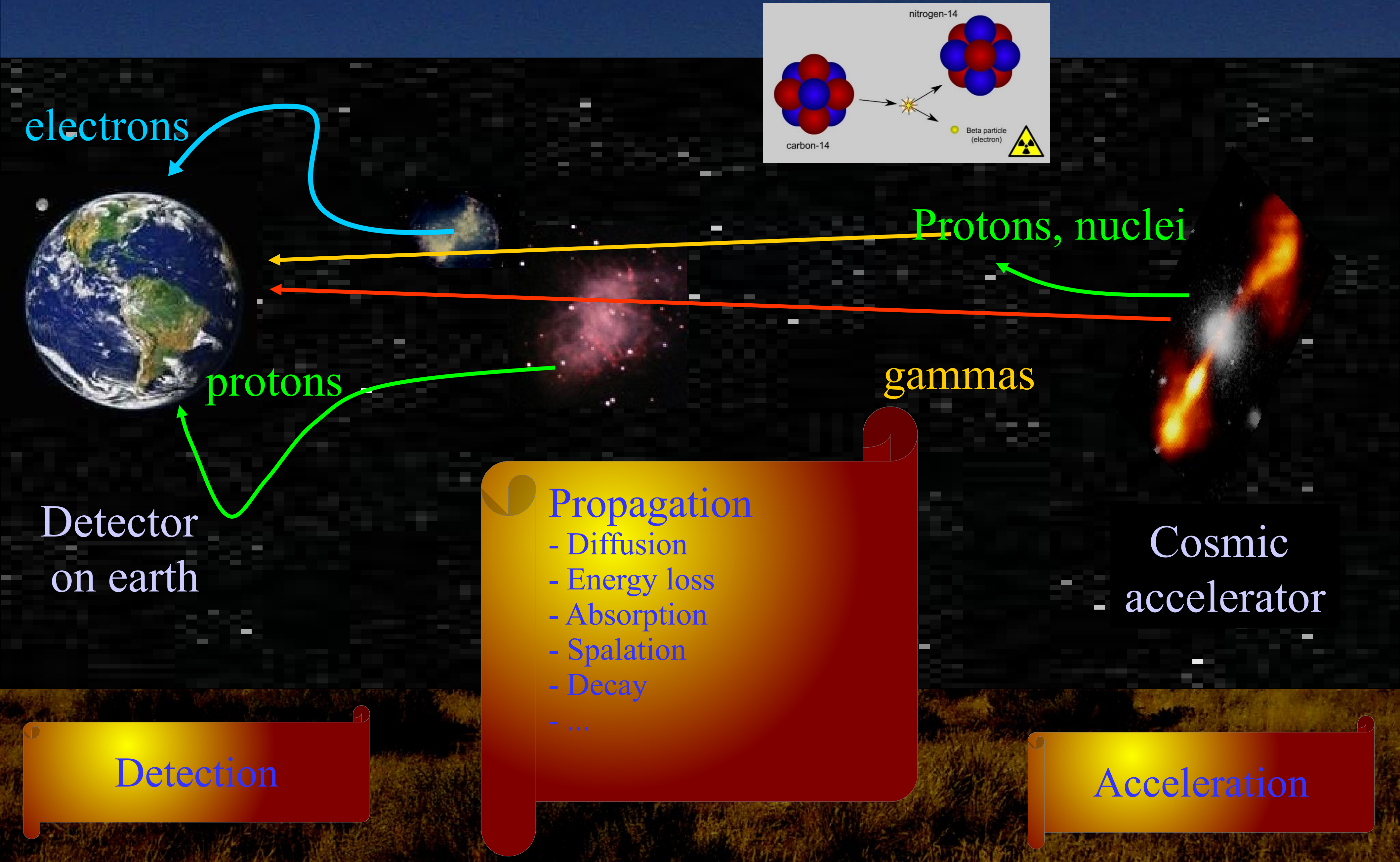
One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

Cosmic Ray Conference University of Chicago July 1939

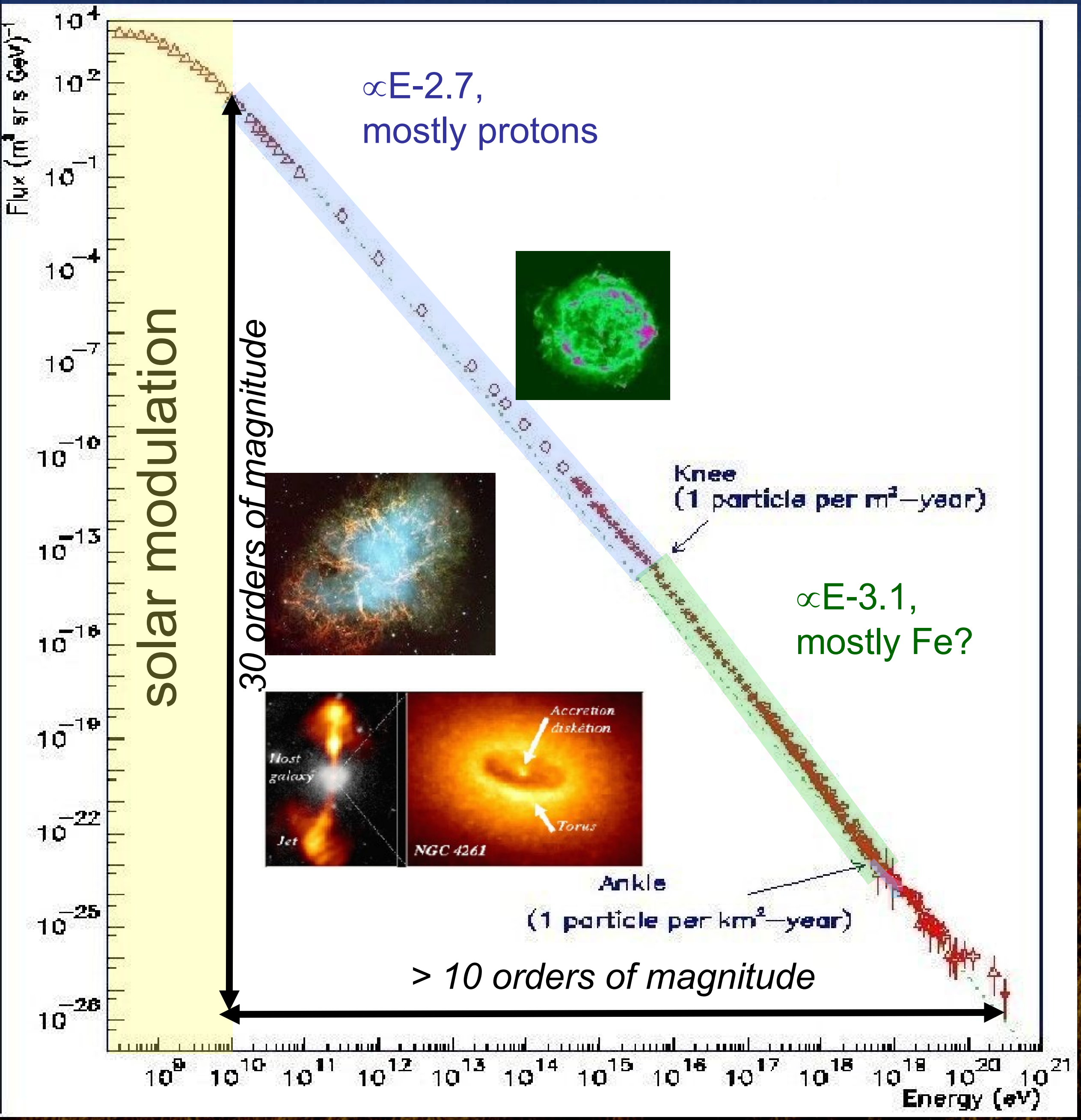
What is high energy astroparticle physics ?



Overall picture



Cosmic Ray Spectrum

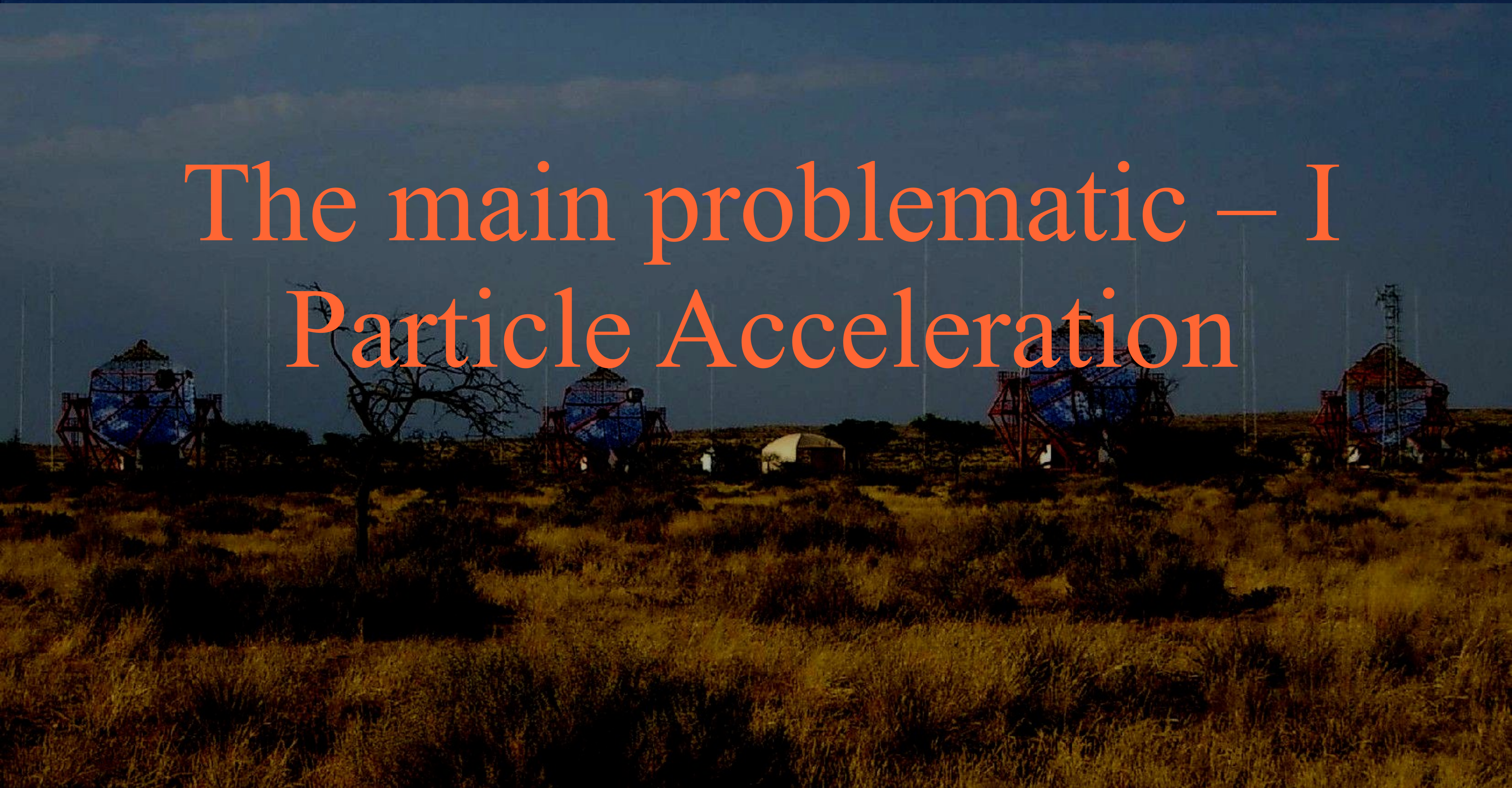


- One wonder of physics
- 12 orders of magnitude in energy, 32 orders in flux → various detection techniques
- Very low spectra at high energy → huge area needed (>1000 km²)
- Sources unknown
- Isotropic (above 10 GeV)

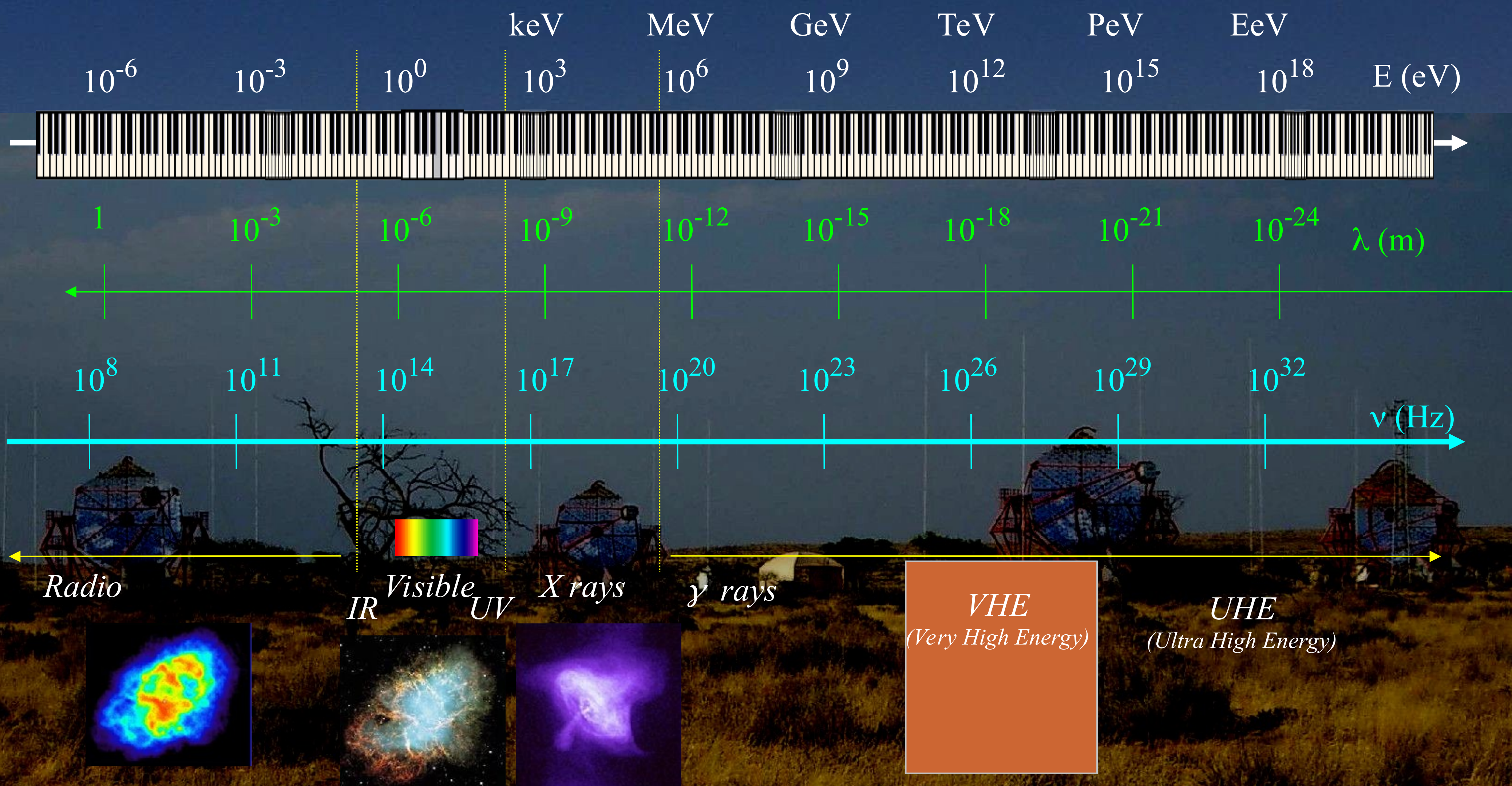
Open questions

- What the sources of cosmic rays?
- What are the acceleration mechanisms, what are the accelerated particles?
- Is there new physics in there? (Dark Matter, ...)
- How do high energy particles propagate in Universe ? What can we learn from the propagation ?
- Link with cosmology: large structure formation, tomography of Universe

The main problematic – I
Particle Acceleration



Electromagnetic spectrum



Cold objects (10K),
Dust,...
Synchrotron emission of accelerated electrons

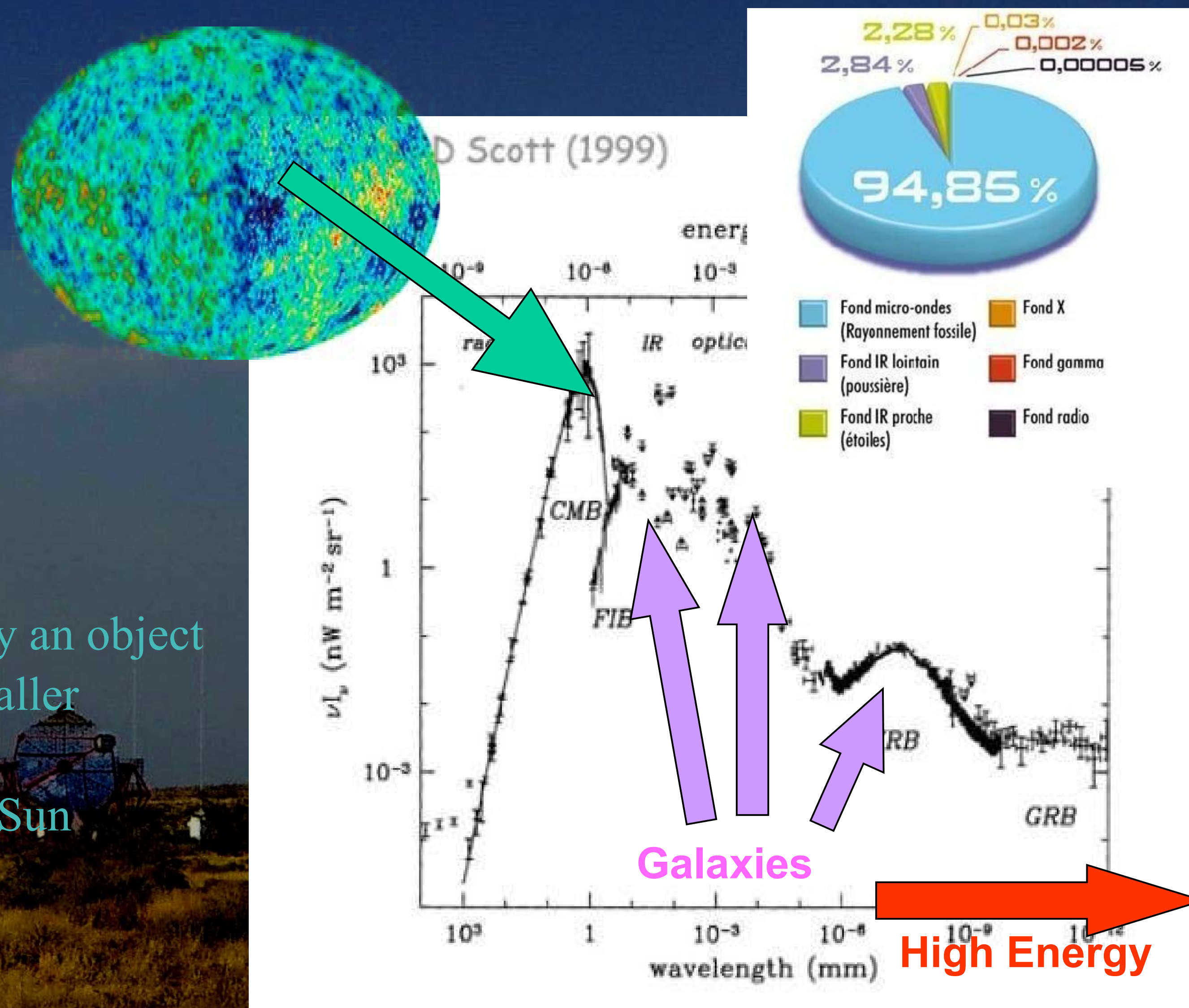
Hot objects
(~2000K),
sun,
nebula

Very hot compact objects
(~10^6K),
pulsars, black holes...
Size ~km

Extreme objects, non-thermal processes
(Particle acceleration in shocks)
Inverse Compton, Bremstrahlung, Annihilation,
Pion disintegration

(Photon) Energy distribution in Universe

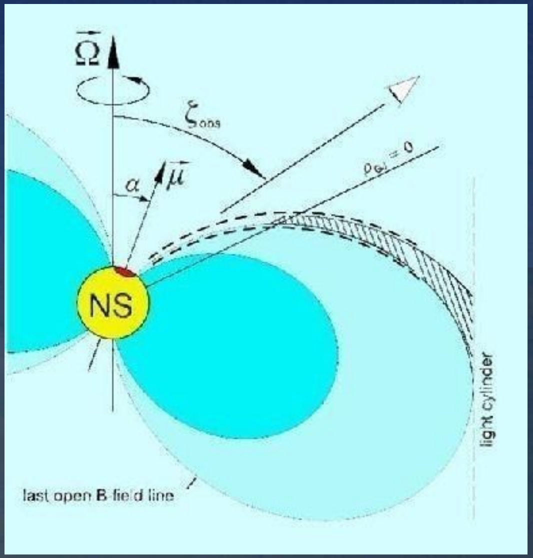
- Photon Energy Distribution
  - CMB 3K
  - Galaxies
    (Star light and dust)
  - Compacts objects (X)
- Emitting Power
  - P = σ × T⁴ × R² (Stefan)
    ⇒ Same power emitted by an object 10 × hotter and 100 × smaller
  - X-Rays (10 keV) :
    ~ 1km (Neutron Star) ⇔ Sun
  - VHE (1 GeV):
    0.2 nm ⇔ Sun



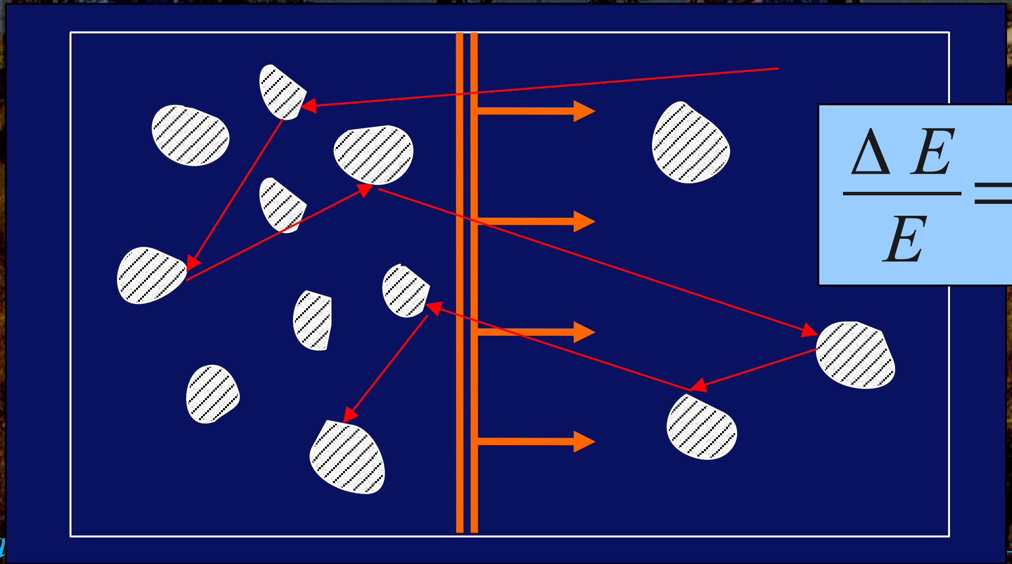
⇒ VHE Universe is Non-Thermal

Astroparticle will mainly concern non-thermal Universe

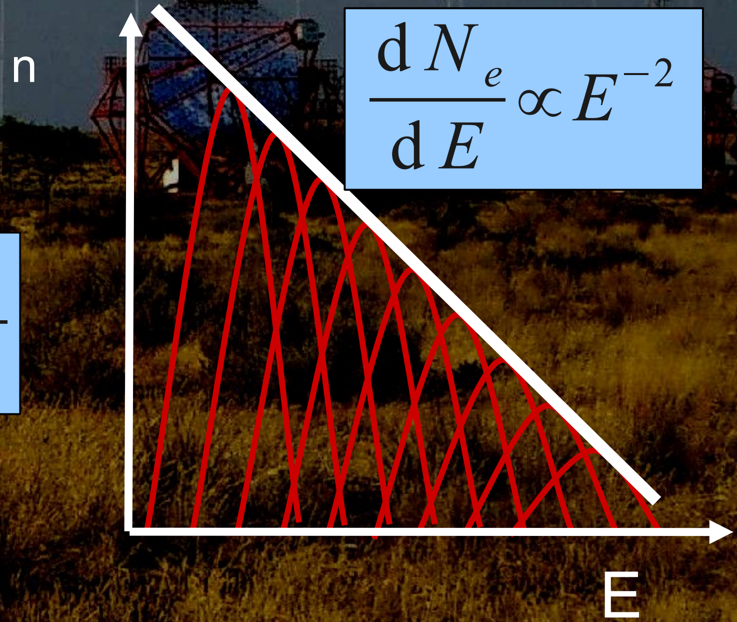
Particle Acceleration



- Intense electromagnetic fields: pulsars (magnetized compact stars in fast rotation)
  ~ dynamo effect, V ~ 10^{12} V
- Astrophysical shocks: « ping-pong » particle accelerated at each shock crossing, retro diffused by B
  (First order Fermi)
- Diffusive acceleration

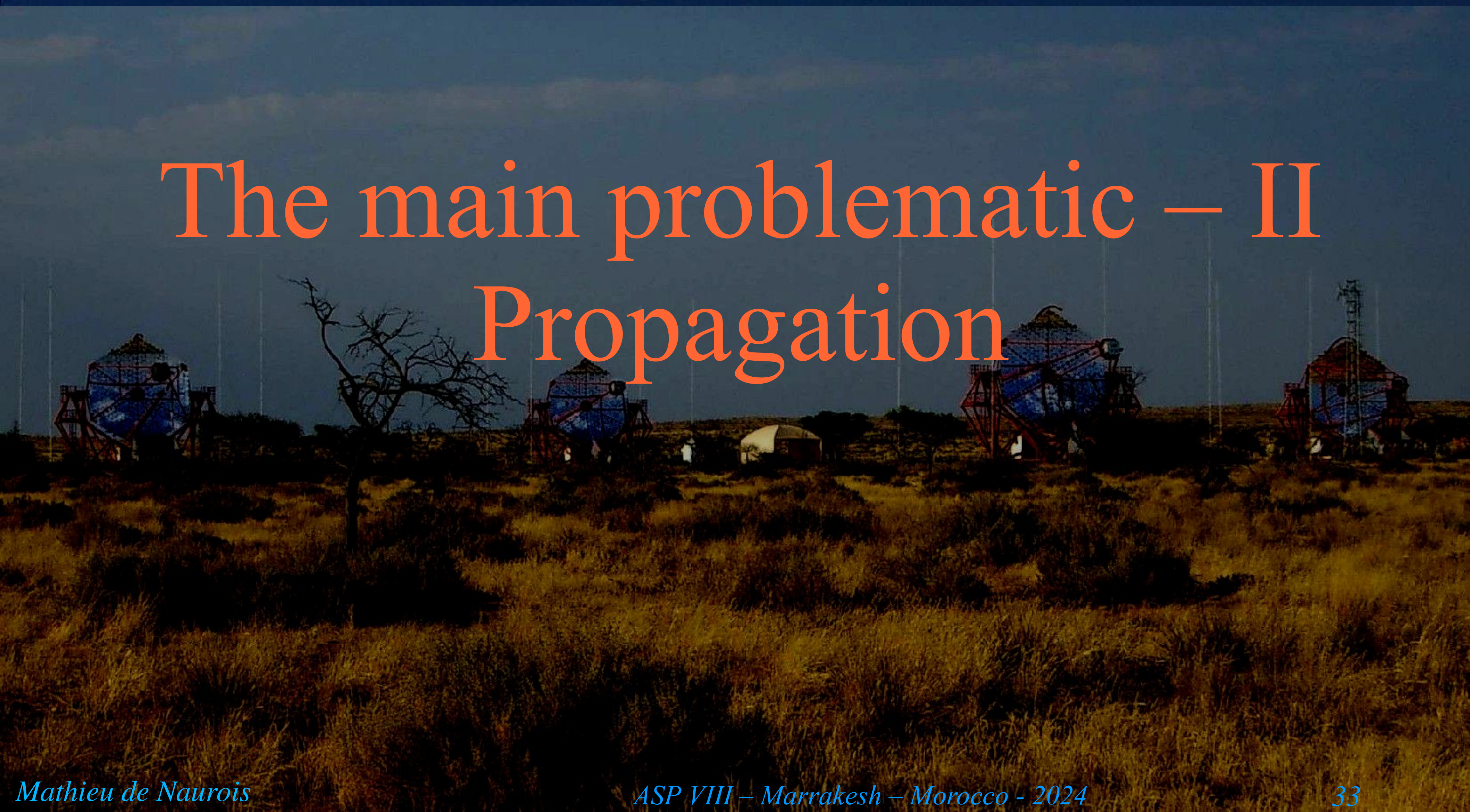


$$\frac{\Delta E}{E} = -2 \frac{\vec{v}\,\vec{V}}{c^2}$$

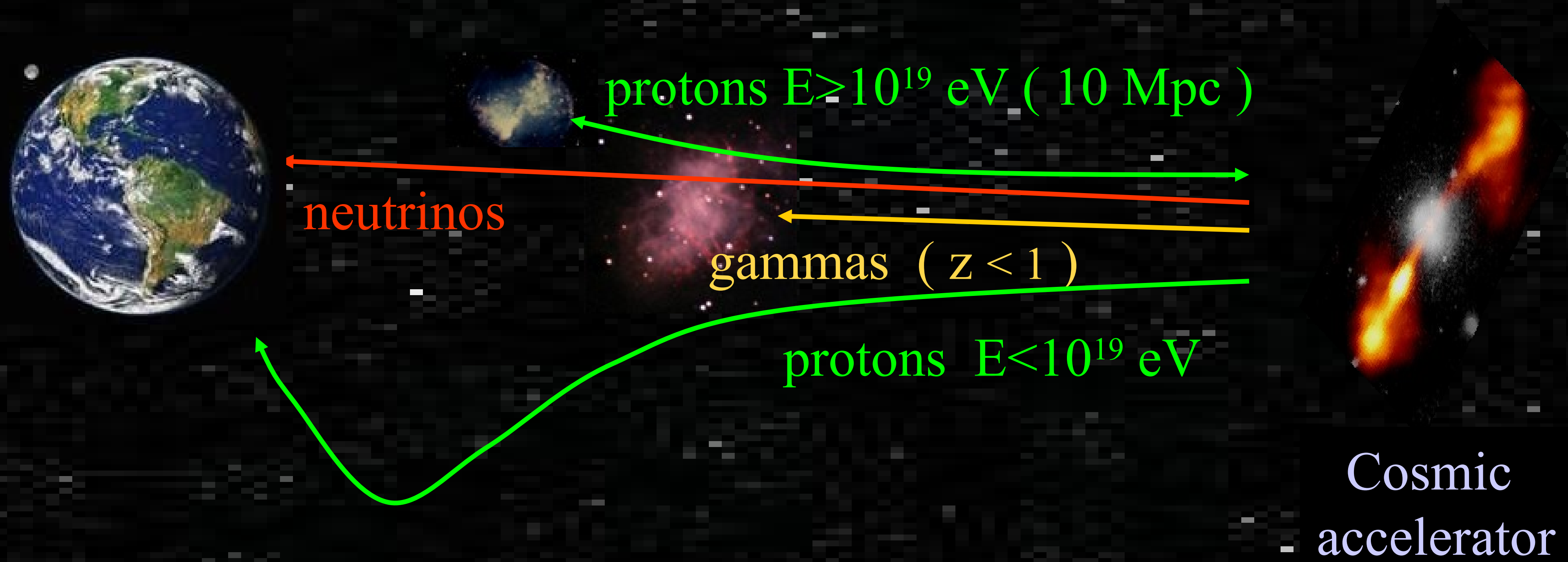


$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \propto E^{-2}$$

The main problematic – II
Propagation



Multi-messenger observations of the Cosmos



photons: Absorbed by dust and radiation (pair creation on CMB)

protons/nuclei: Deviated by B field, absorbed by CMB (GZK effect)

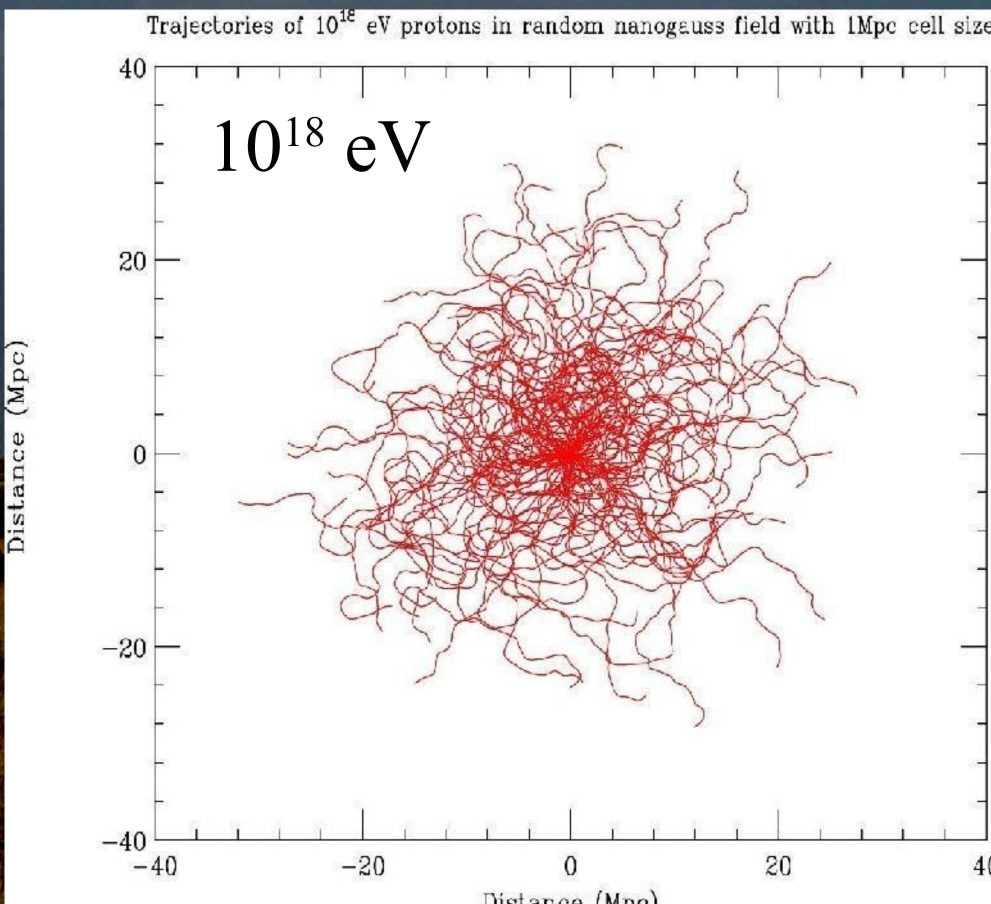
neutrinos: Difficult to detect

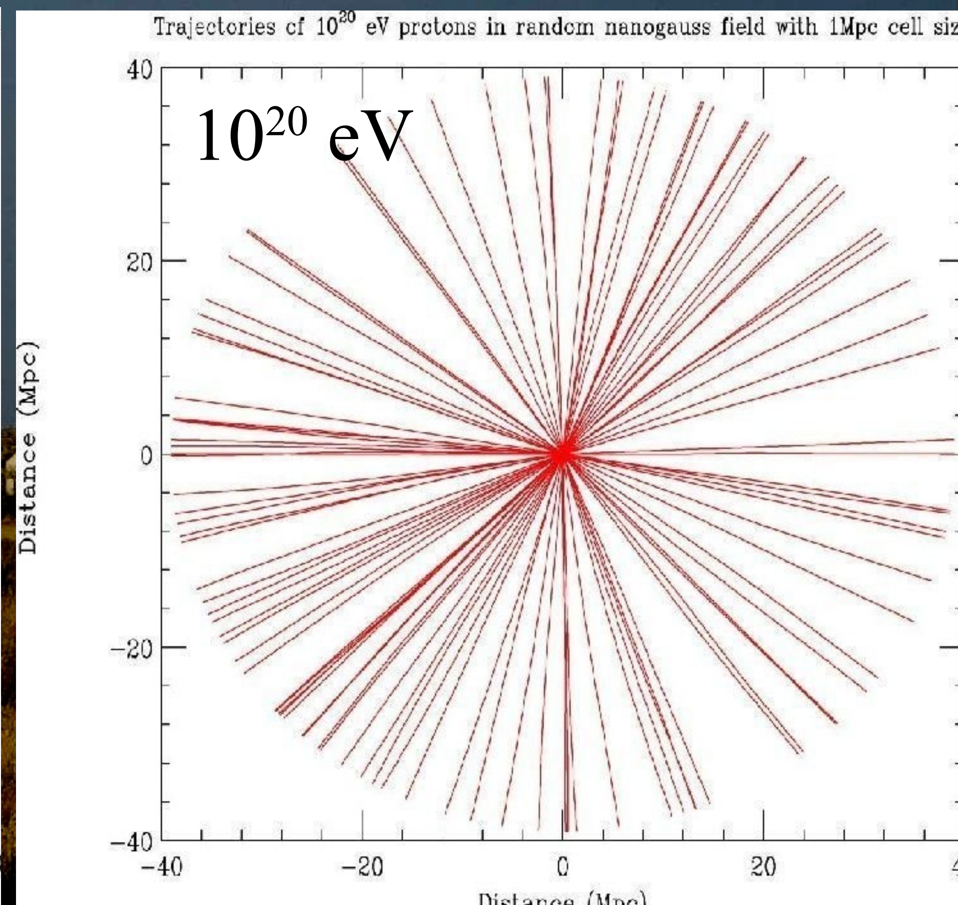
gravitational waves: Emerging

⇒ **Four "astronomies" possible...**

Propagation – Magnetic deflection

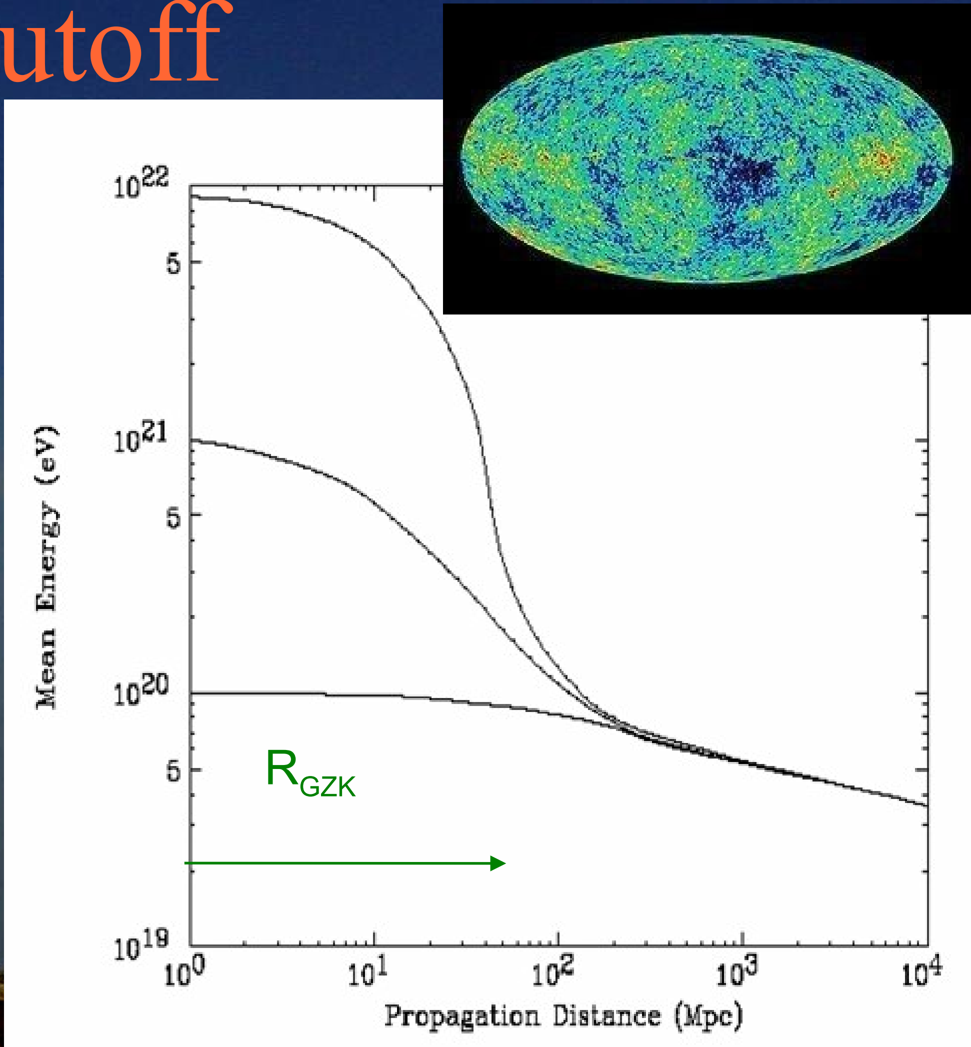
- "low energy" charged cosmic rays are deflected by magnetic field and have an isotropic distribution at earth
- Above 10^{20} eV a proton astronomy becomes possible





GZK cutoff

- 1965: discovery of cosmological background by Penzias & Wilson (CMB)
  T°= 6 10^{-4} eV (2.7 Kelvin) ,
  N = 400 cm^{-3}
- Interaction of nuclei with CMB photons ⇒ effet GZK (Greisen, Zatsepin et Kuzmin) (1965)
  particle degraded to lower energies:
  10^{22} down to 10^{20} after 100 Mpc



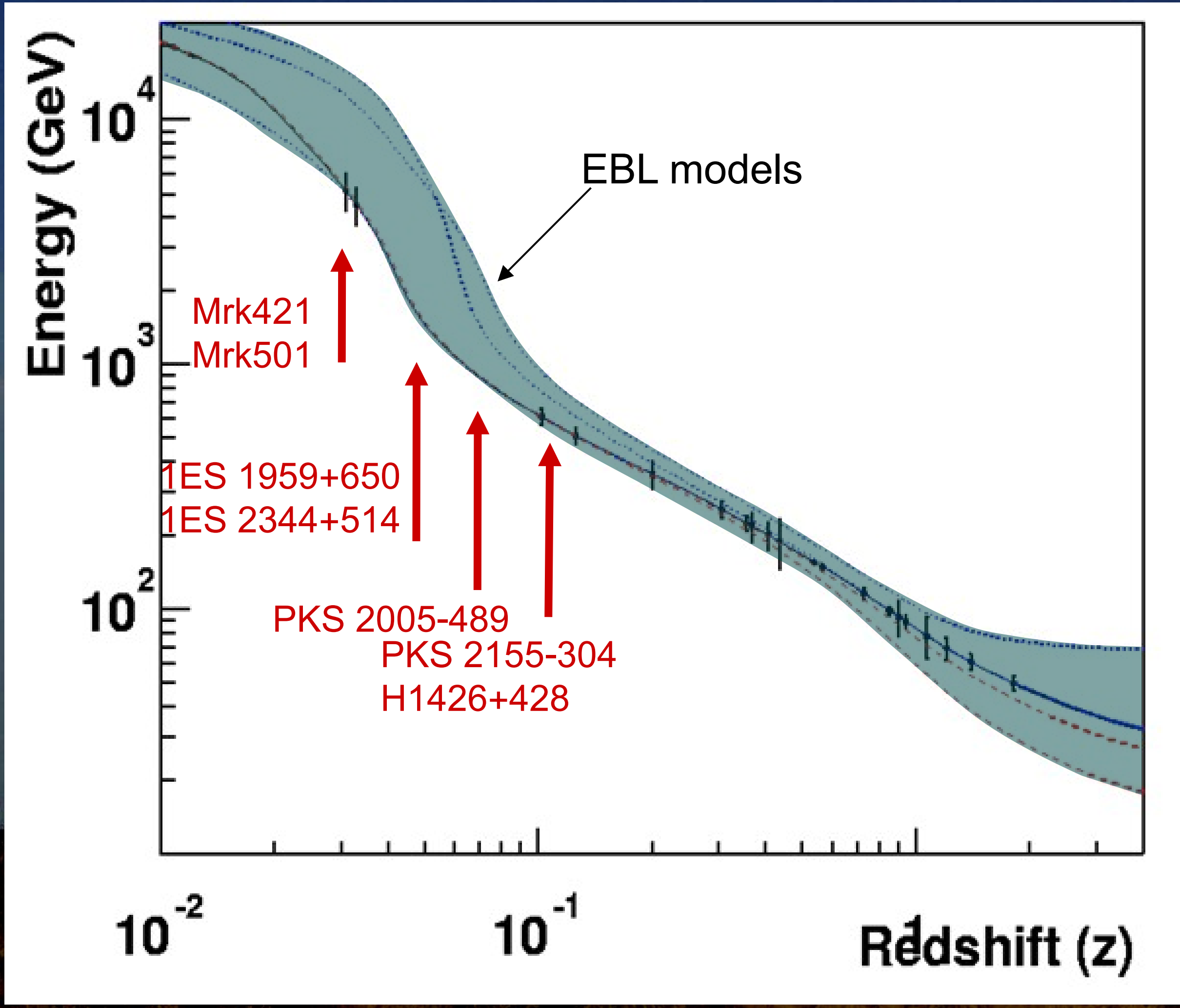
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \begin{cases} \rightarrow p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ \rightarrow n\,\pi^{+} \rightarrow n\,\nu_\mu\,\mu^{+} \rightarrow n\,\nu_\mu\,\bar{\nu}_\mu\,\nu_e\,e^{+} \end{cases}$$

γ - ray Horizon

- γ –rays absorbed by pair creation on infrared background:

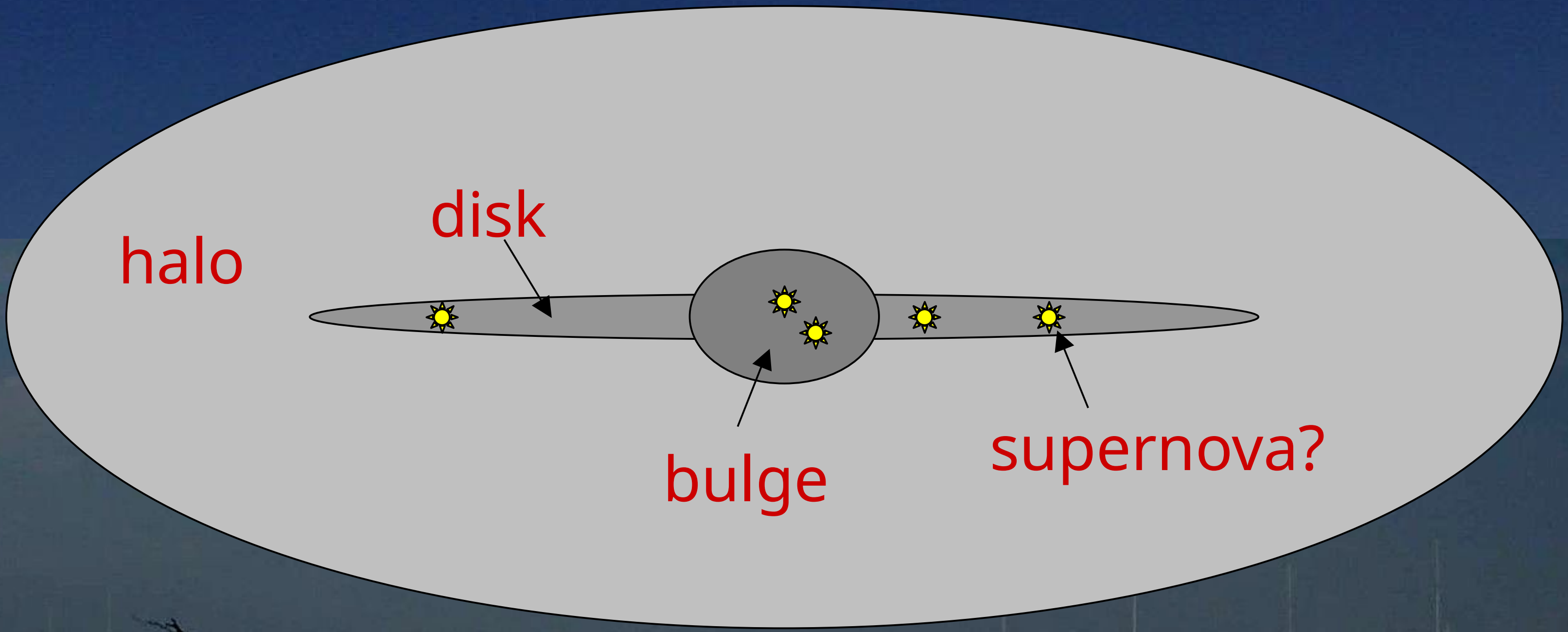
$$\gamma + \gamma_{CMB} \rightarrow e^{+} e^{-}$$

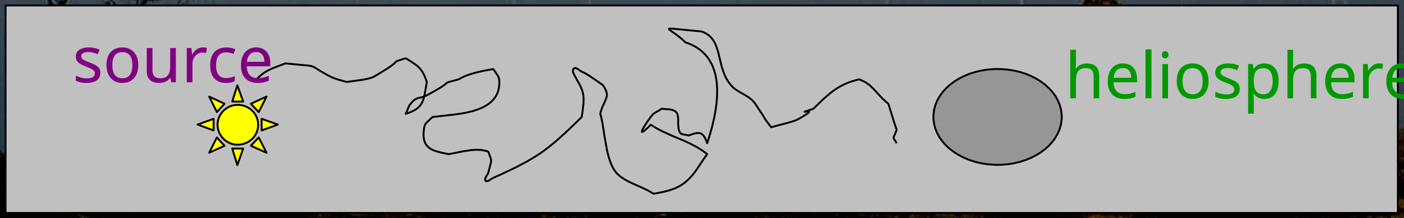
- Limits the size of observable Universe:
  - z < 0.1 @ 500 GeV
  - z < 0.01 @ 2 TeV



- Indirect measurement of dust & star background through tomography (energy spectrum vs distance) ⇒ link with cosmology

Propagation in Galaxy – Diffusion

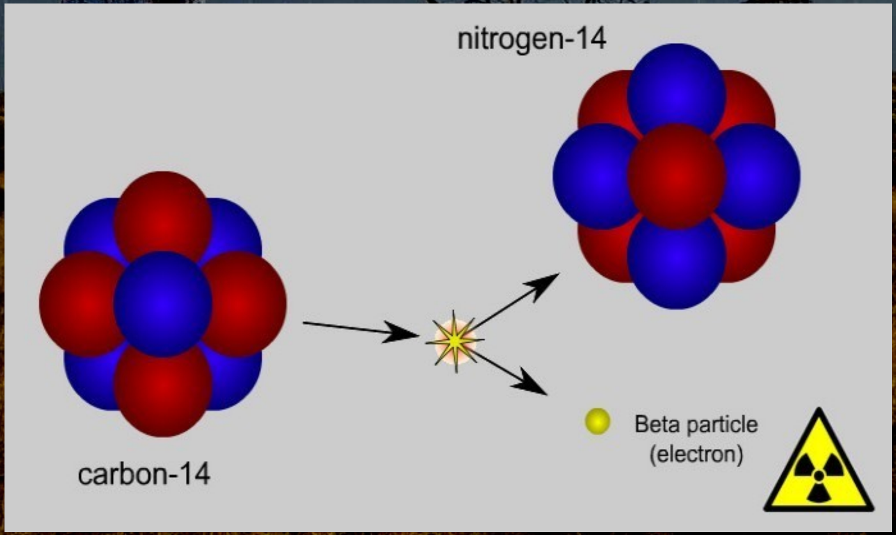


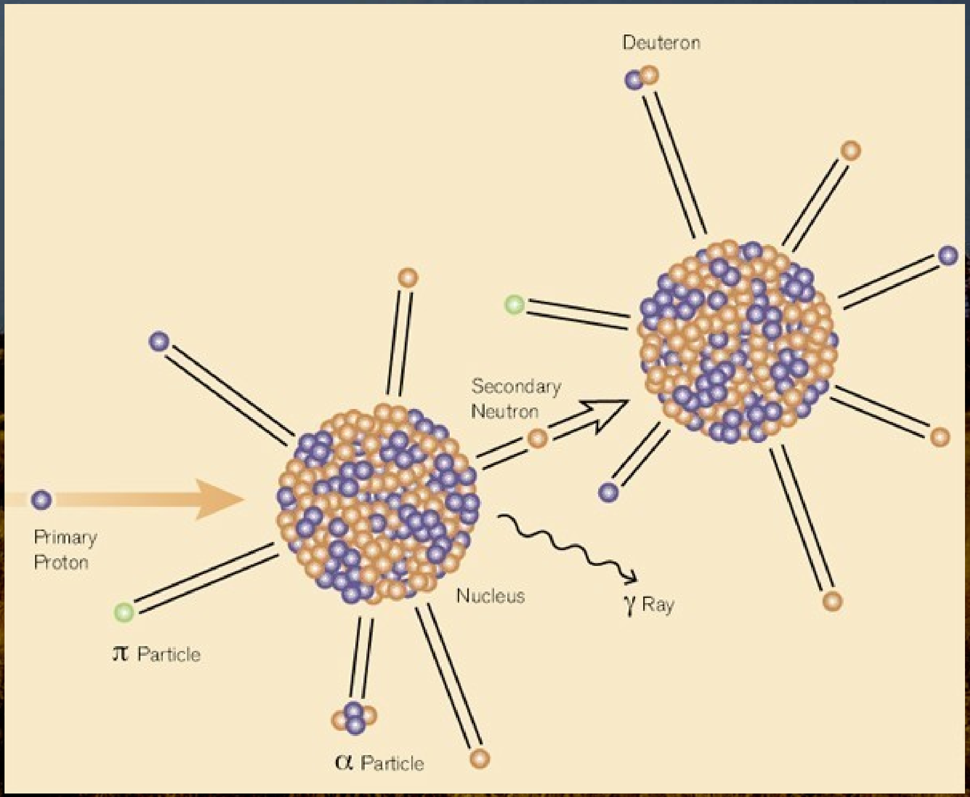


- Diffusion of particles: high energy particle escape first ⇒ Observed spectrum steeper than source spectrum. e.g. $E^{-2.7}$ at earth vs $E^{-2.0}$ at galactic center.
- Composition change: spallation (nuclear reaction)

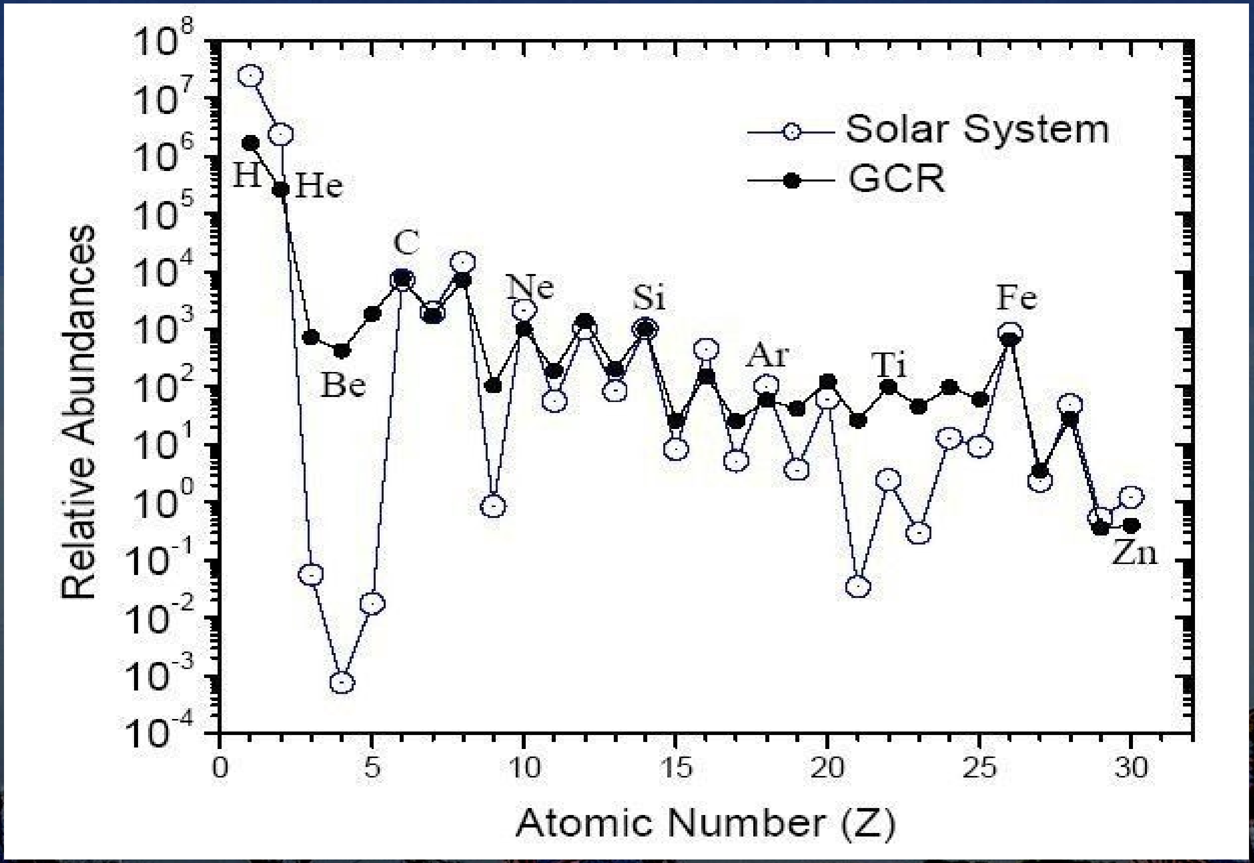
Propagation – Spalation

- Composition of cosmic rays is altered by propagation!
  - Spallation
  - Beta decay
  - Production of γ rays by π^0 decay
  - ….





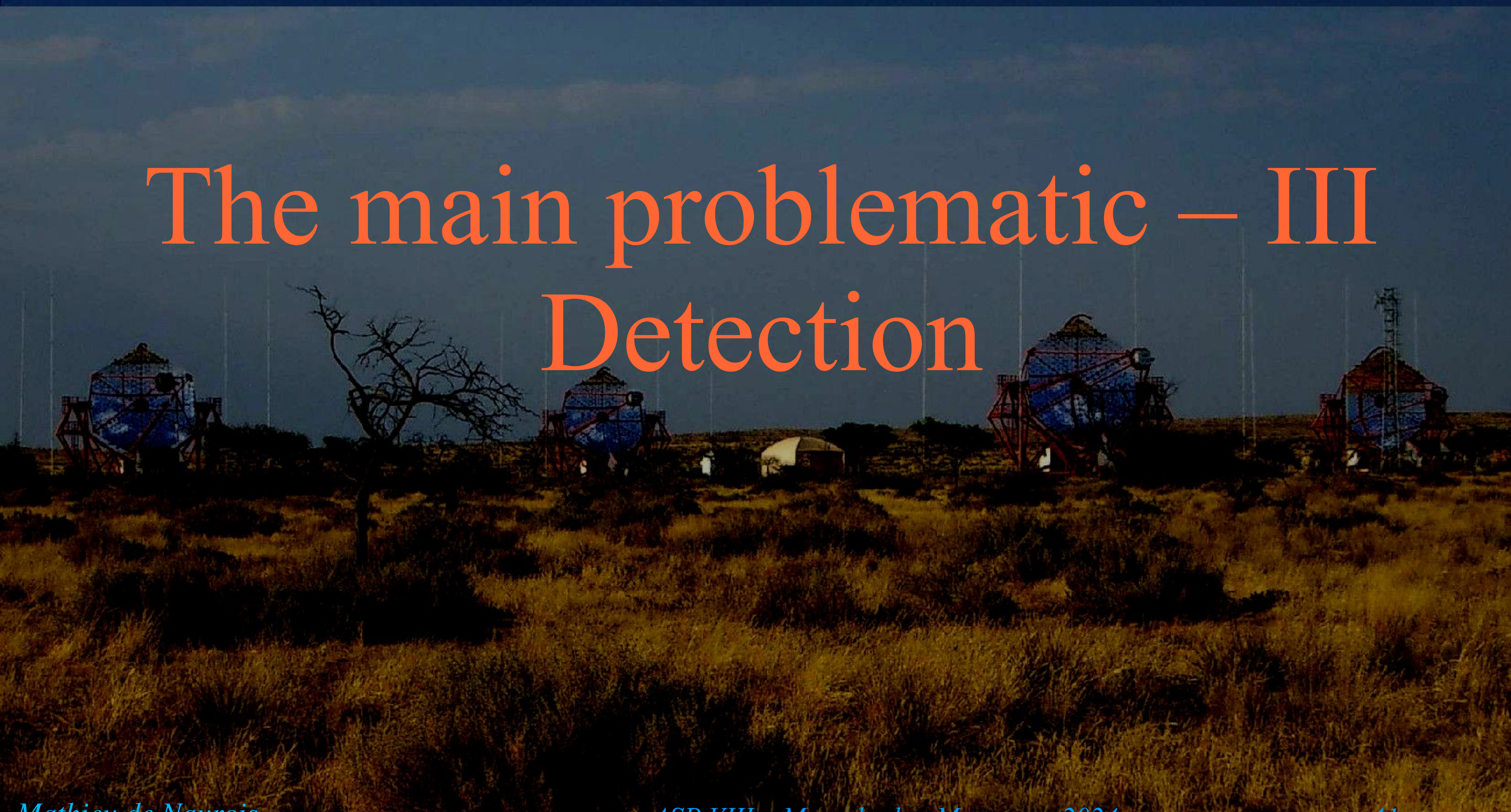
Propagation in Galaxy – Composition



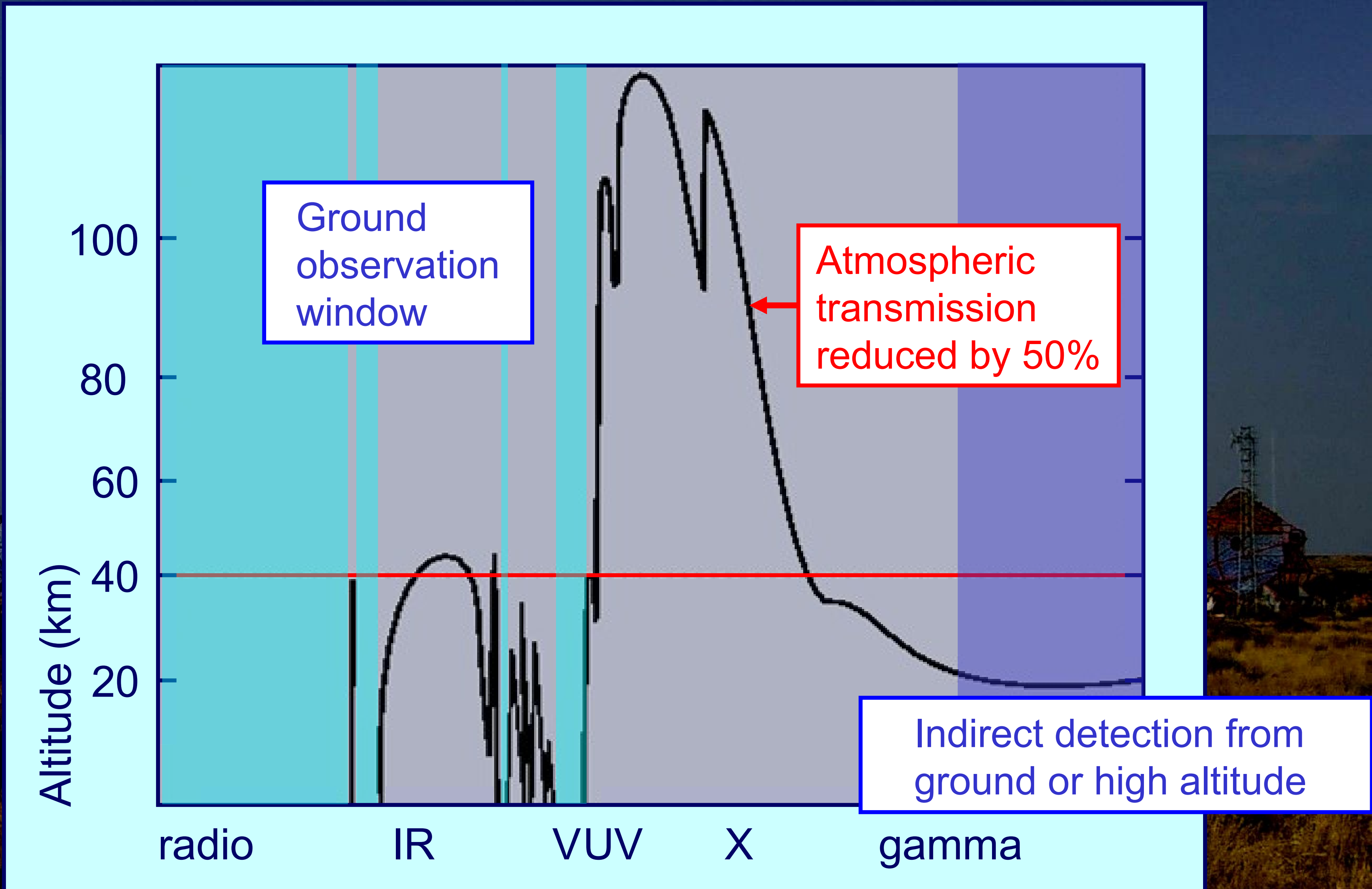
70 to 280 MeV/nucléon, Satellite

- CR abundances differs from local measurement
  - Excess of Li - Be - B et sub Fe
  - Secondary nucleus created by spallation ⇒ constraints on propagation
  - Primary nuclei (CNO, Fe,.) accelerated in sources
  - Other particles are produced in propagation (γ, ν, antiparticles). Excess w/o prediction can be the sign of new physics

The main problematic – III
Detection

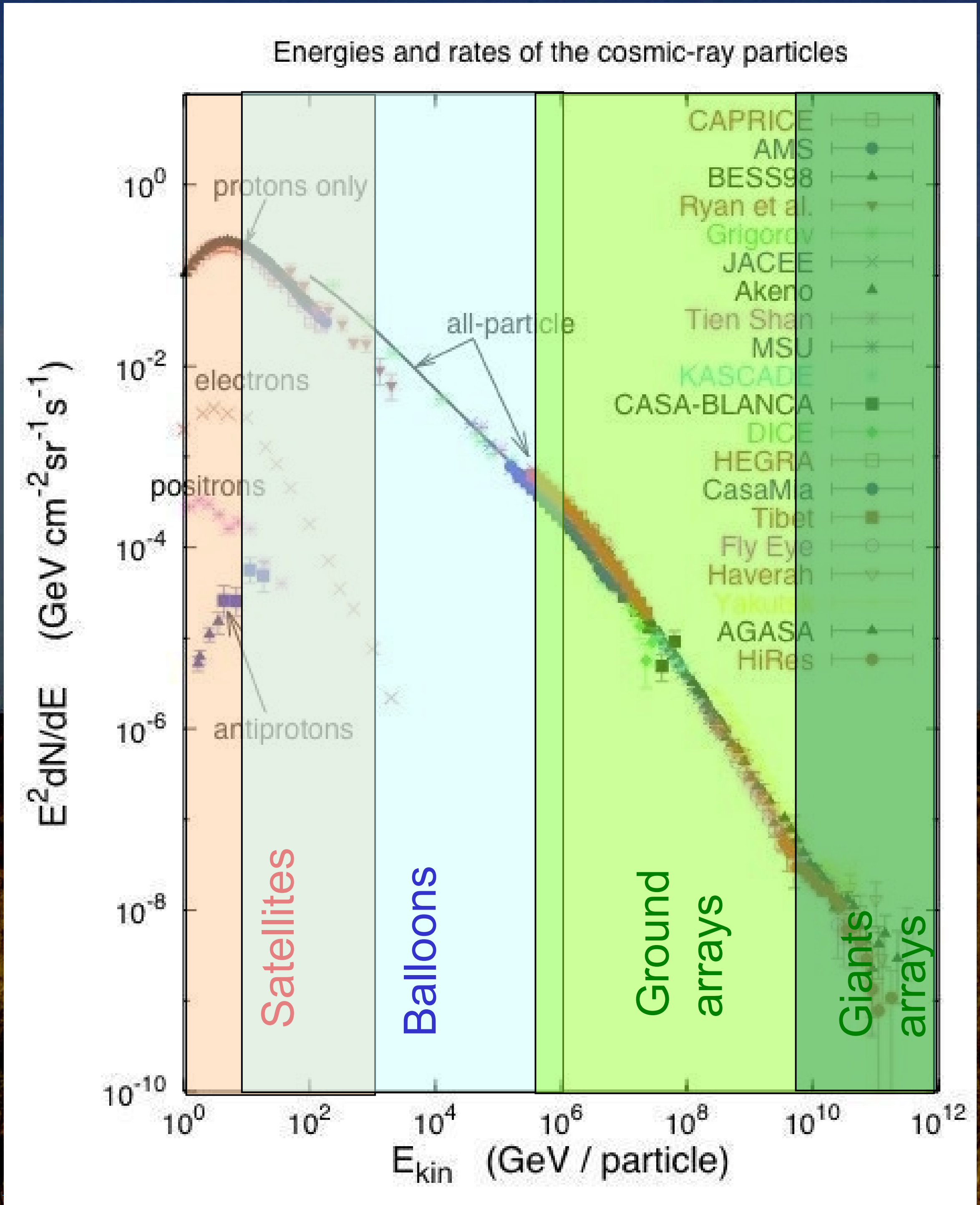


Atmospheric Transparency



Acceptance & fluxes

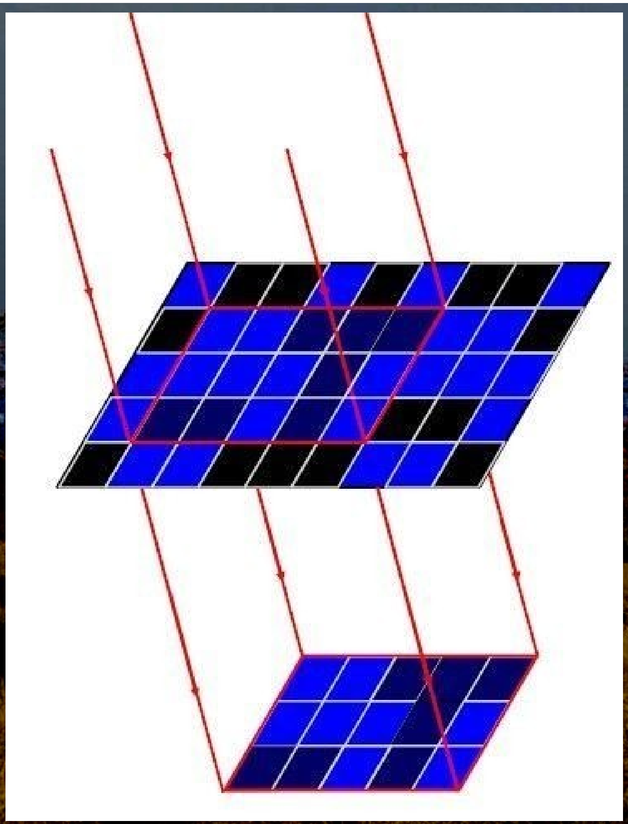
- The higher the energy, the biggest the needed acceptance:
  - 10 GeV : 1 CR/m²/s ⇒1 m² (satellite or balloon)
  - Knee: 1 CR/m²/an ⇒ 1 km² (ground array)
  - Ankle: 1 CR/km²/century ⇒ 1000 km² (giant array)



Photons

1 PeV | 100 TeV | 10 TeV | 1 TeV | 100 GeV | 10 GeV | 1 GeV | 100 MeV | 10 MeV | 1 MeV | 100 keV

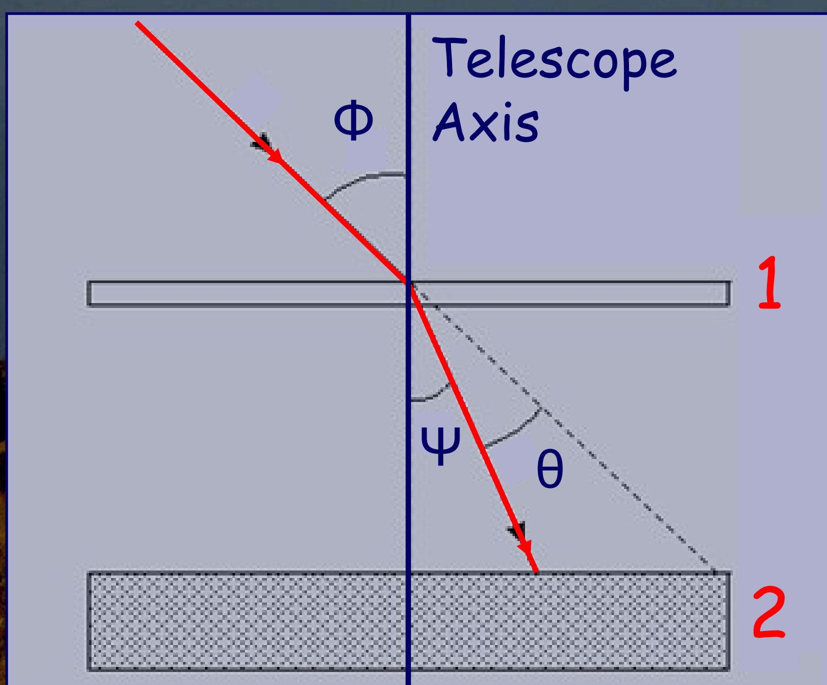
Space



Coded mask telescope

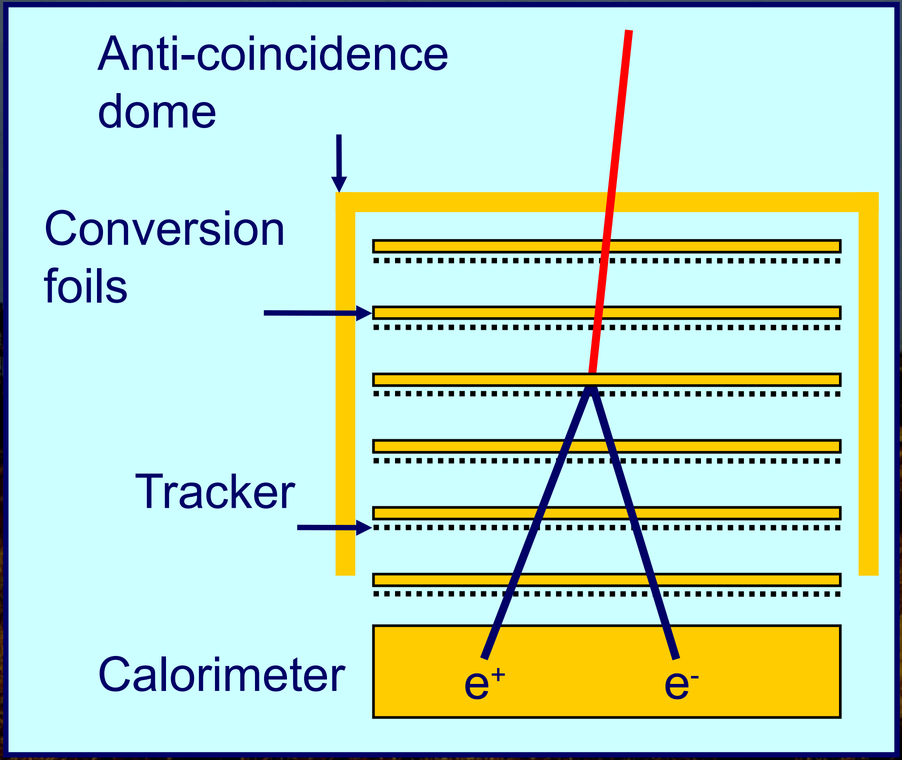
Photons

Space



Compton Telescope

High Energy Photons

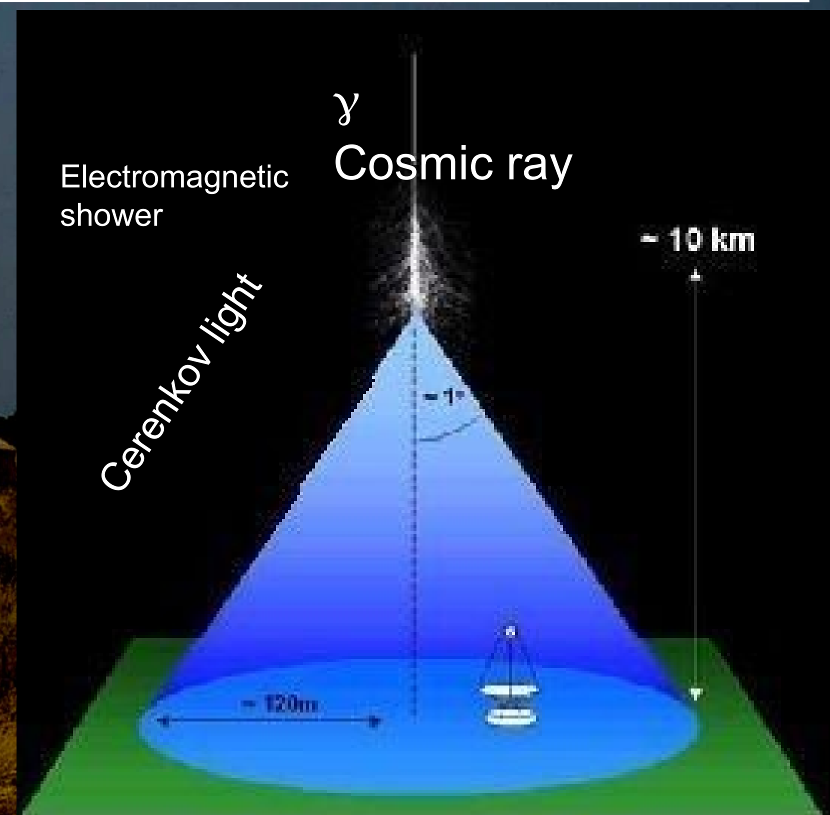


Pair creation telescope

Space

Very High Energy Photons

From ground



Atmospheric Cerenkov Telescopes

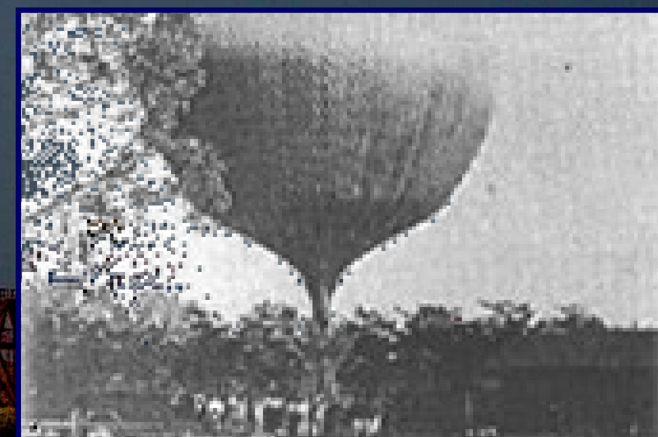
Charged Particles

100 EeV | 10 EeV | 1 EeV | 100 PeV | 10 PeV | 1 PeV | 100 TeV | 10 TeV | 1 TeV | 100 GeV | 10 GeV

Extended air showers – from ground

Direct detection

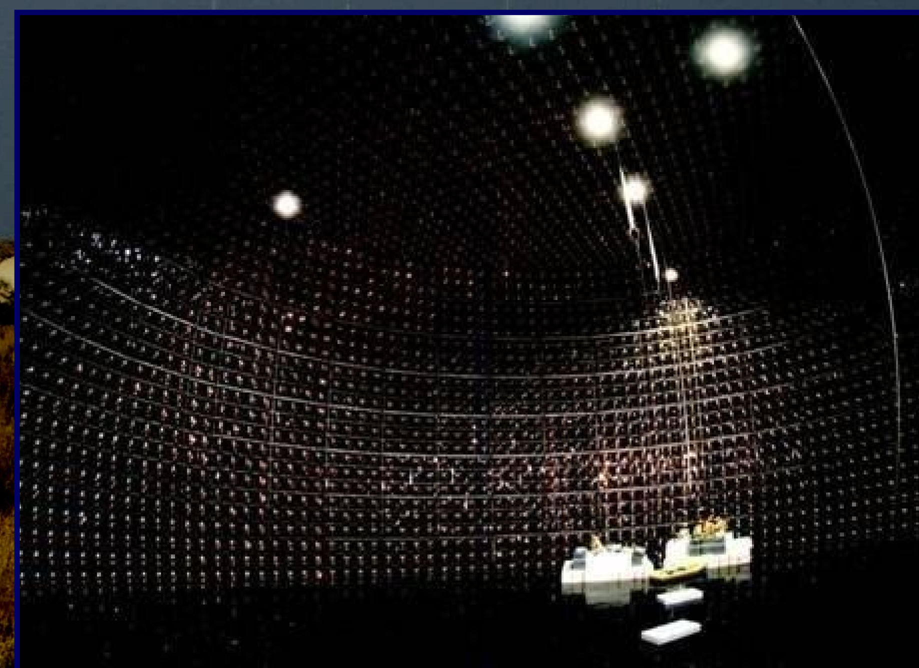
Ballons



Space

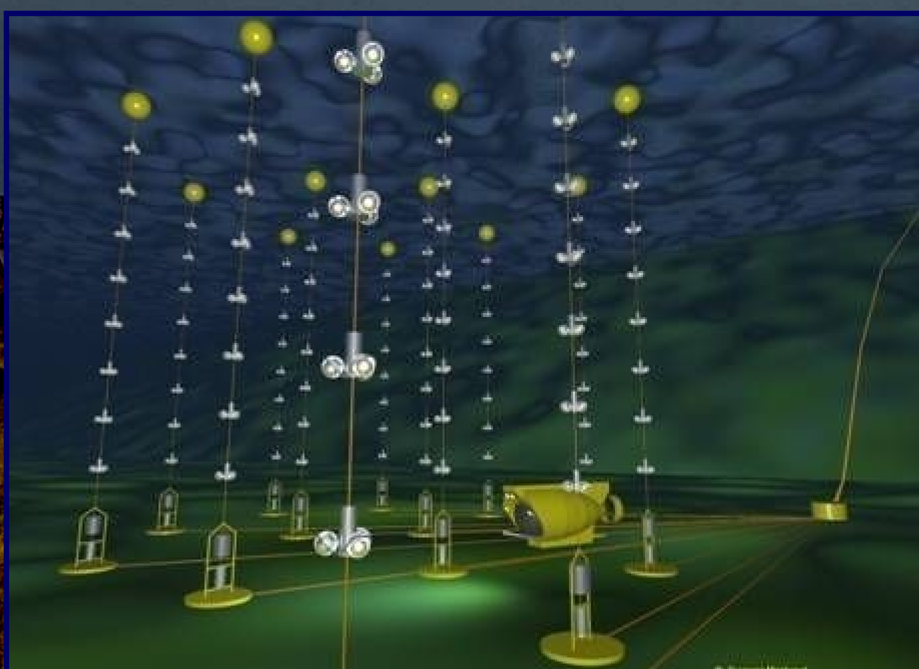
Neutrinos

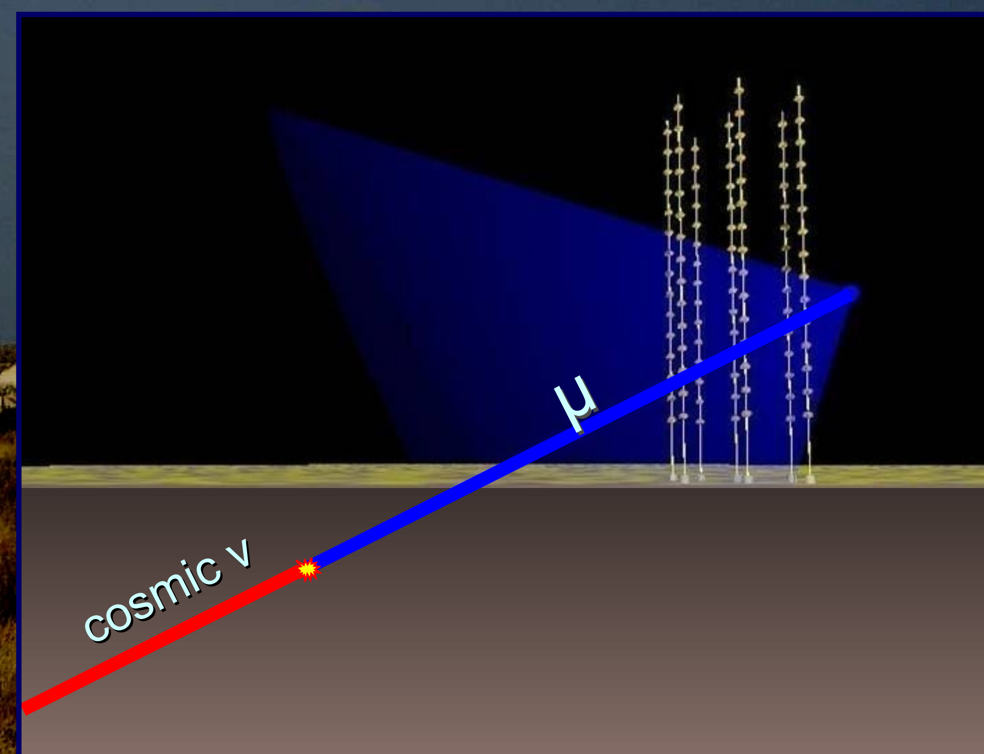
- Neutrino Scattering off one electron
- Cherenkov emission of the electron in water



Neutrinos

Deep water or ice

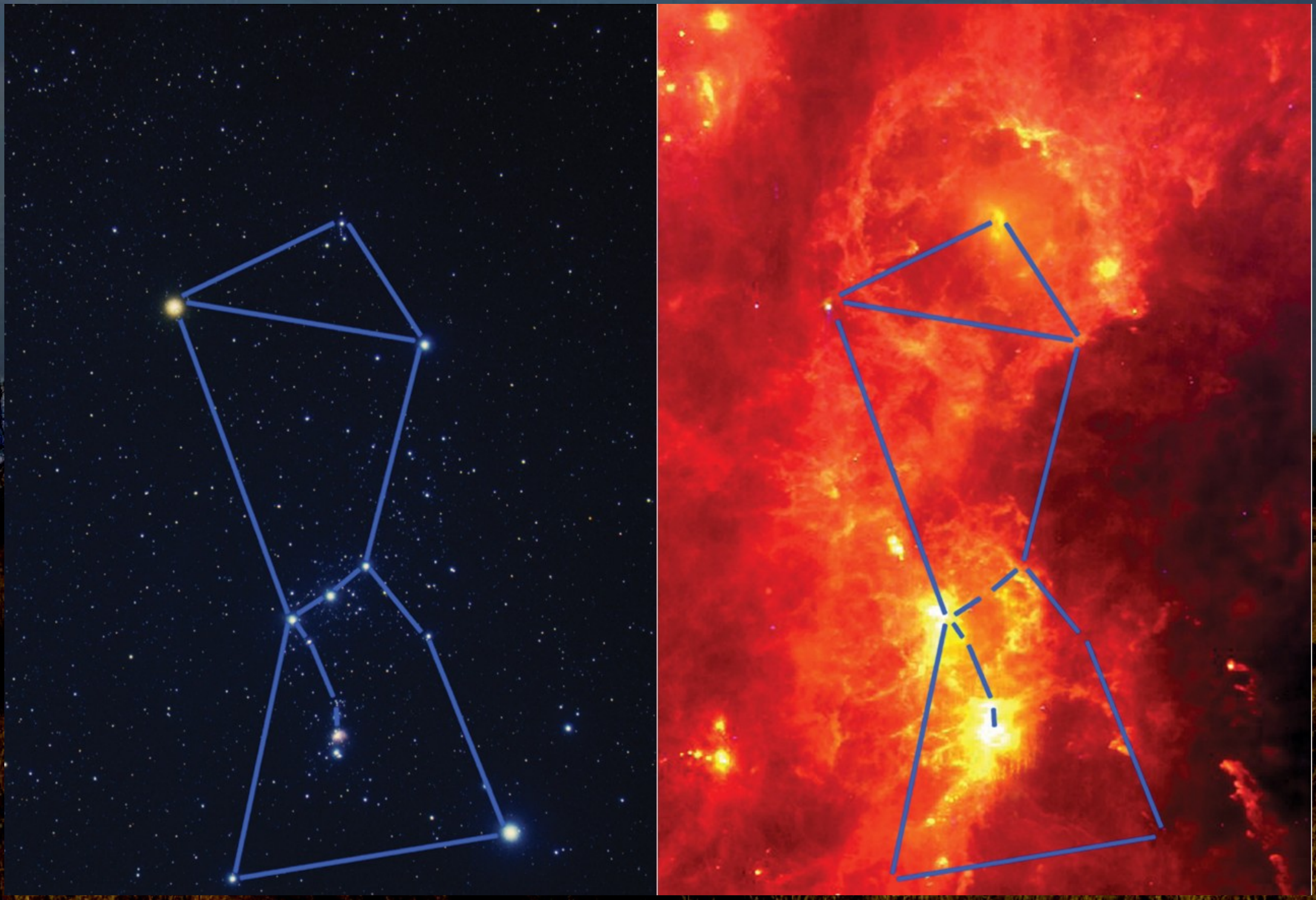




Cherenkov Detector

Different Worlds

- Orion Nebula in Optical (left) and Infrared (right)
- Different wavelengths reveal vastly different Universes!



Cosmic rays...


YOU'VE TURNED INTO MONSTERS... BOTH OF YOU!! IT'S THOSE RAYS! THOSE TERRIBLE COSMIC RAYS!
NOW I KNOW WHY I'VE BEEN FEELING SO WARM! LOOK AT ME!! THEY'VE AFFECTED ME, TOO! WHEN I GET EXCITED I CAN FEEL MY BODY BEGIN TO BLAZE!