Particles and Waves as Cosmic Messengers

Brigitte Falkenburg

in collaboration with Wolfgang Rhode

1. Cosmic Messengers
2. Astroparticle Physics
3. Observation of Jets
4. Gravitational Waves

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Particles and Waves as Cosmic Messengers

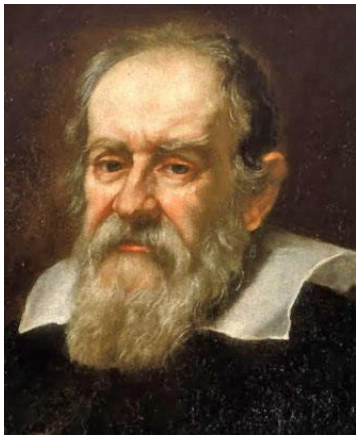
1. Cosmic Messengers

2. Astroparticle Physics

3. Observation of Jets

4. Gravitational Waves

Galileo Galilei
(1504-1642)



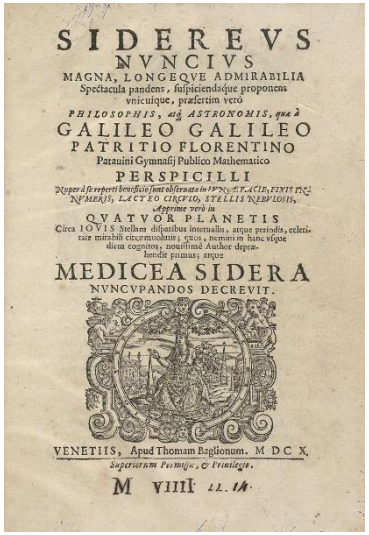
1. Cosmic Messengers

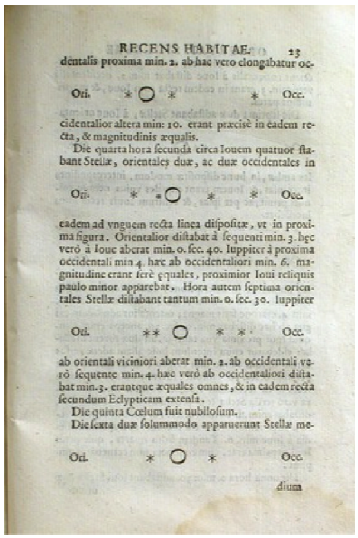
Historical Background:

Light, the cosmic messenger (astronomy)

Sidereal Messenger
(1610)

Observations with
the telescope
&
discovery of
Medicean Stars
(Jupiter moons)


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.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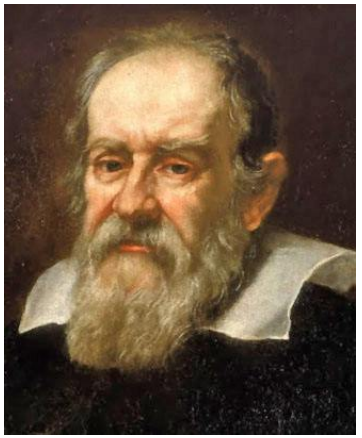
Galileo Galilei
(1504-1642)



1. Cosmic Messengers

Scientific Realism

Goal of physics: to **explain** the **phenomena**

Science & truth: *very* different views!

» science aims at truth (Galileo)
defence of Copernicus‘ system

» observations/empiricism (Aristotle)

» just save the phenomena (Ptolemy)

in terms of: **mathematical models**

» do they describe the *real world*?

1. Cosmic Messengers

Scientific Realism

Goal of physics: to **explain** the **phenomena**

Explanation: *very* different views!

- » „true causes“ (Newton)
- » unification (Einstein, Planck)
- » classification by analogies (Bohr)
- » economy of thought (Mach)

in terms of: mathematical models

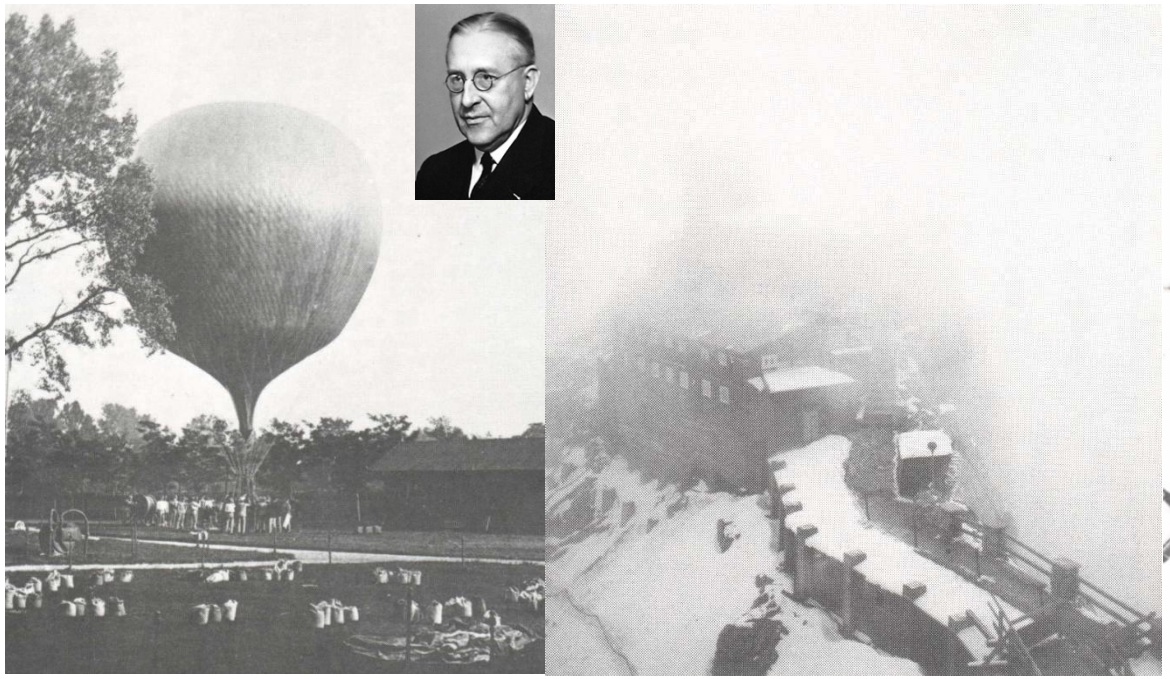
- » do they describe *physical reality*?

1. Cosmic Messengers

The phenomena:

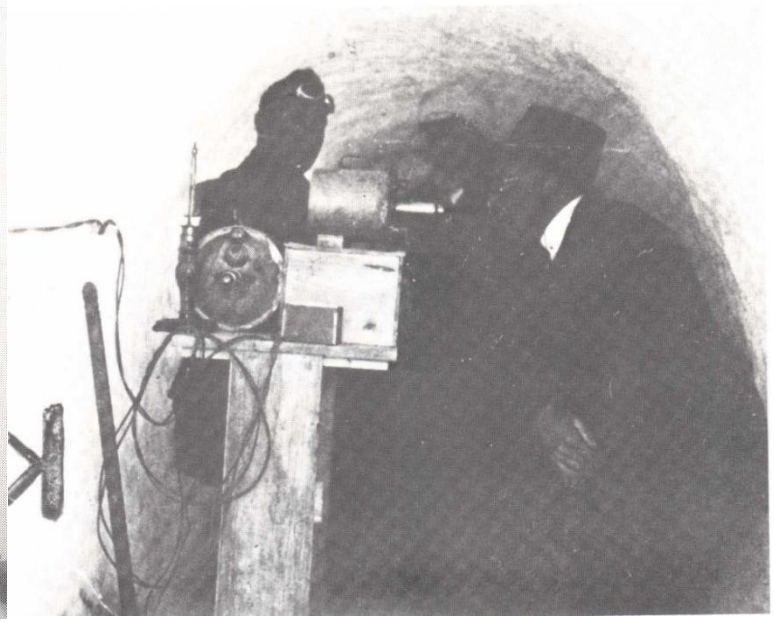
Cosmic rays (CRs)

increasing height
→ increasing # of electrons



Victor Hess (1911/12)
electrometer in baloon

„Höhenstrahlungs-Labor“
on top of Zugspitze



Werner Kolhörster
Eiger glacial (1923)

1. Cosmic Messengers

The phenomena:

Identification of CRs:

Robert Millikan (1920s):
extra-terrestric origin

C. Powell (1940s-50s)

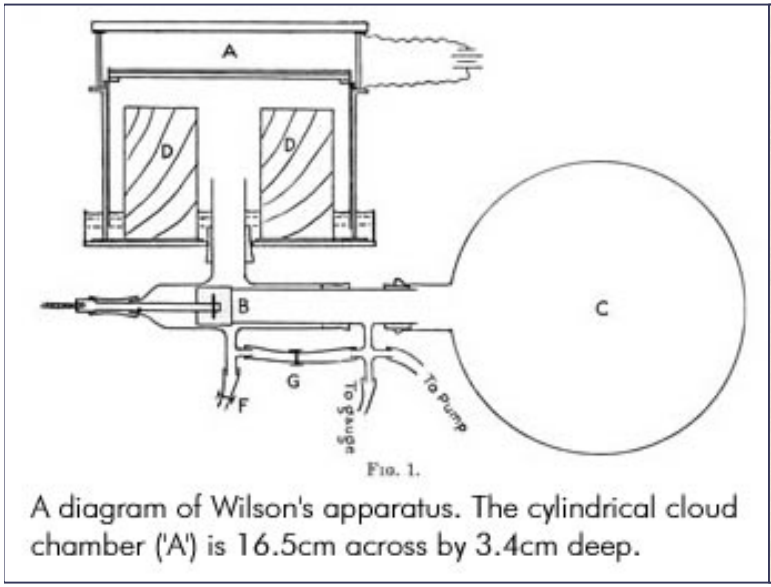
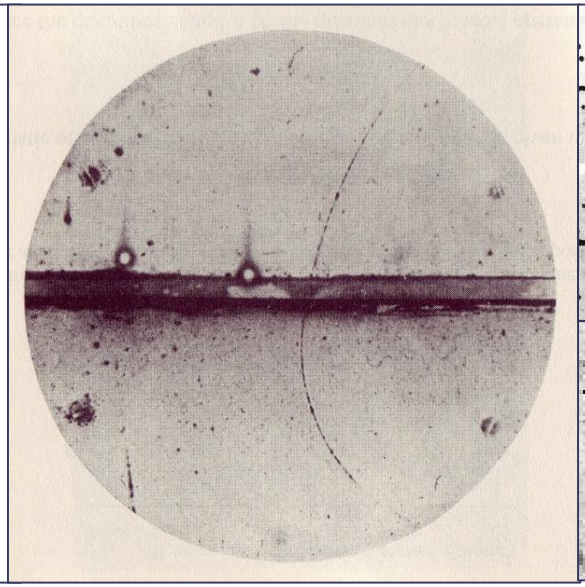


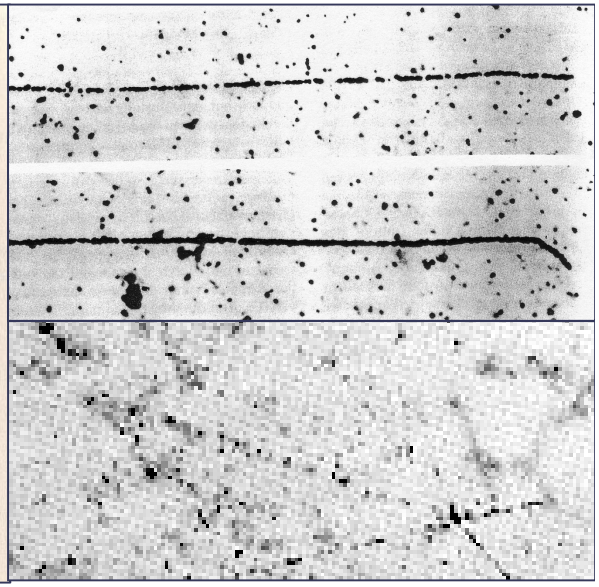
FIG. 1.

A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

C.T.R.Wilson (1911)
cloud chamber



C.D.Anderson (1932)
track of positron



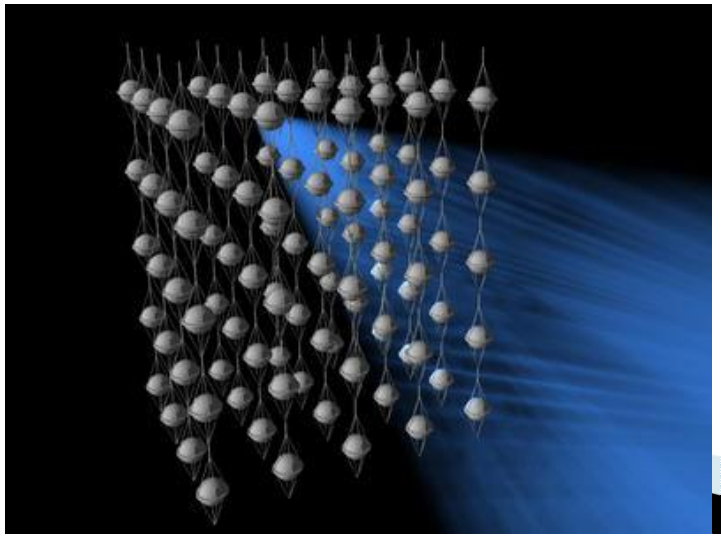
M. Blau & H. Wambacher
(1937) nuclear emulsions

Particle Detectors

The phenomena:
CRs = particles & IR-waves

1. Cosmic Messengers

> 1911	Wilson chamber	*(particle tracks)*
> 1928	Geiger counter	*(coincidence measurements)*
> 1937	nuclear emulsions	*(particle tracks)*
> 1964	antenna	*(3K Cosmic Microwave Background)*
> 1980	Astroparticle physics:	all kinds of particle detectors, arranged as telescopes



MAGIC

Cherenkov neutrino / gamma ray telescopes

ICECUBE

Heuristic model:
Messenger particles
Causal Realism

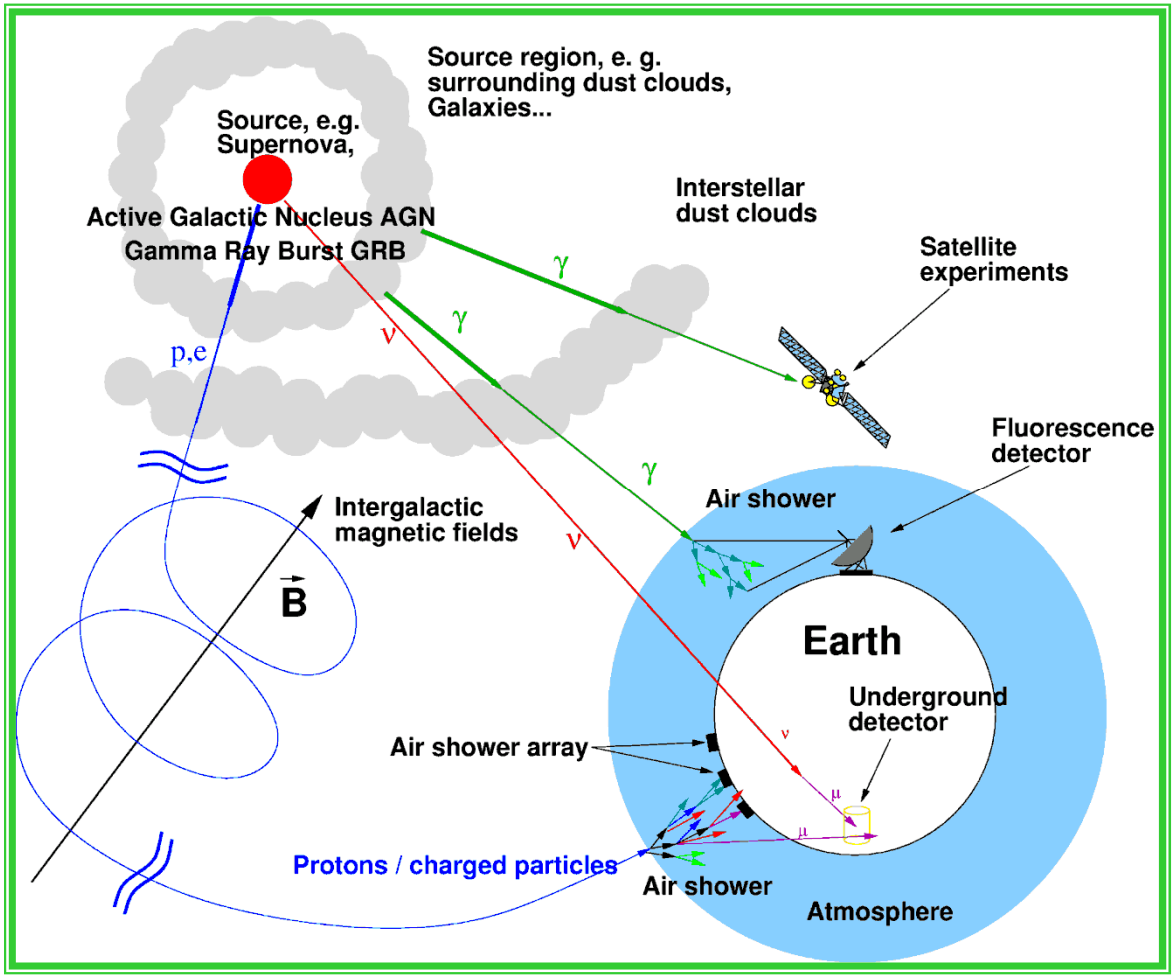
1. Cosmic Messengers

CRs

carry

Information from Cosmic Sources

(in objective sense!)



Heuristic model:
Messenger particles
Causal Realism

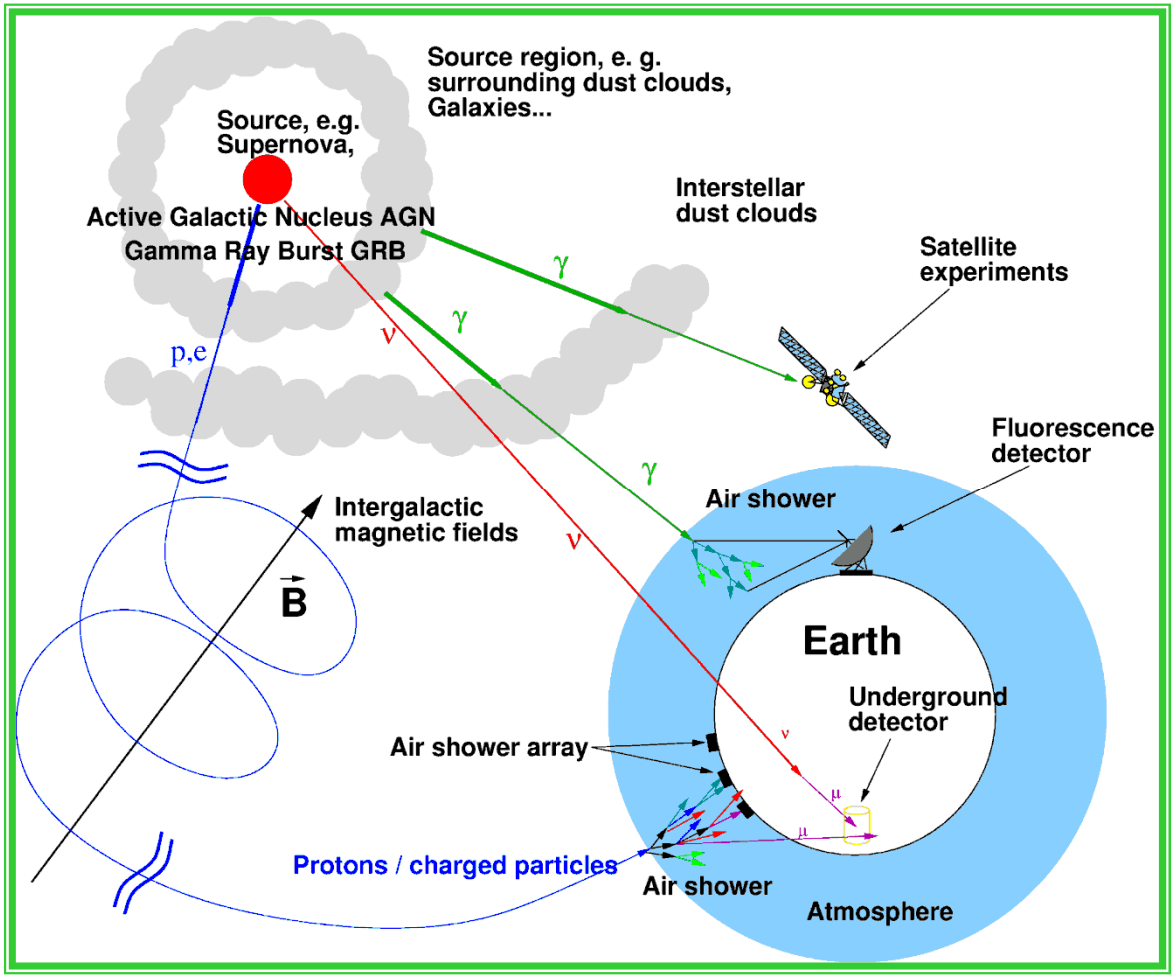
1. Cosmic Messengers

Information

= signal transmisson
from emitter
to receiver

to read it out, you
must know 2 of:

- cosmic source
- nature of signal
- interactions
during transfer



Heuristic model:
Messenger particles
Causal Realism

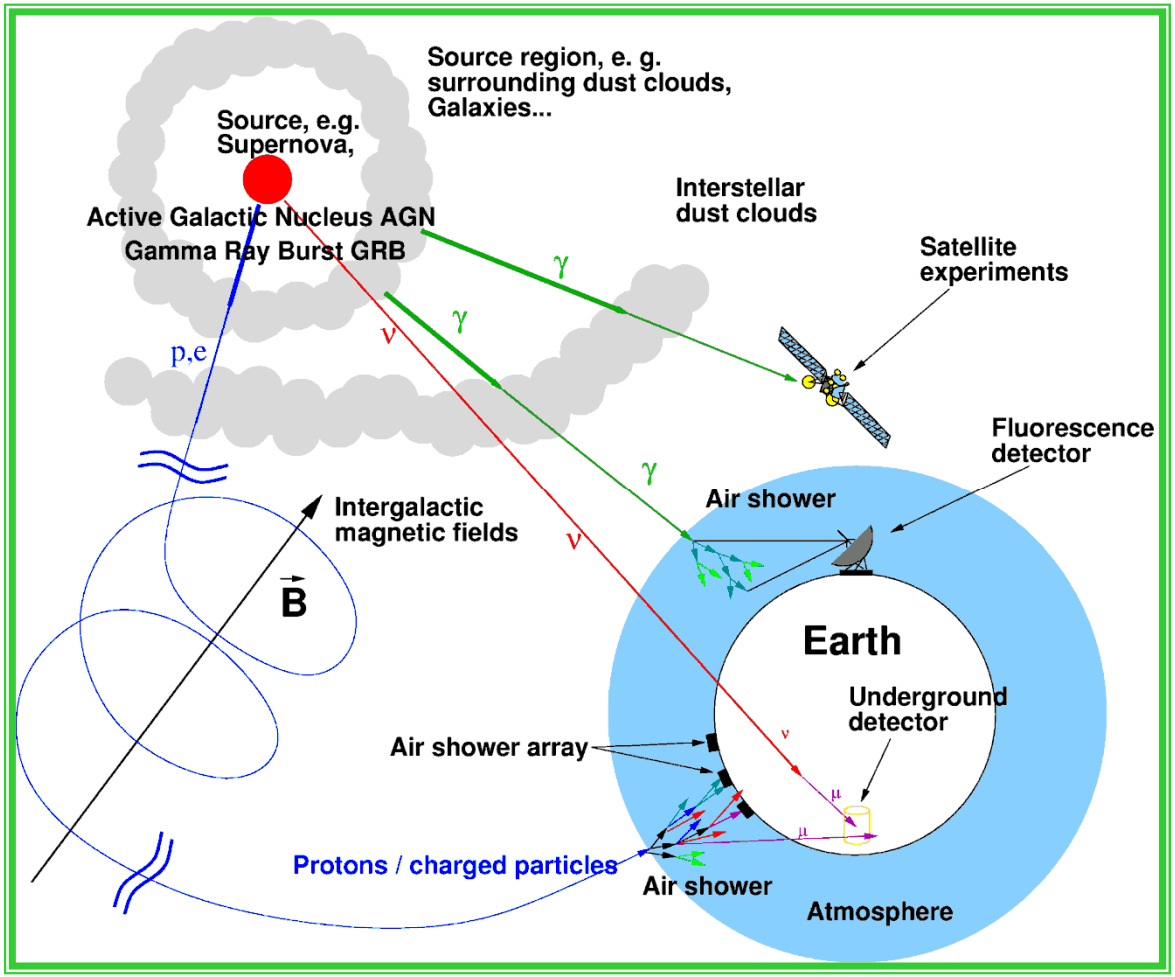
1. Cosmic Messengers

Information

= particle propagation
from source
to detector

reading it out, you will
learn about 1 of:

- cosmic source
- messenger particles
- interactions
during propagation



Heuristic model:
Messenger particles
Causal Realism

1. Cosmic Messengers

Photon & neutrino telescopes

observe

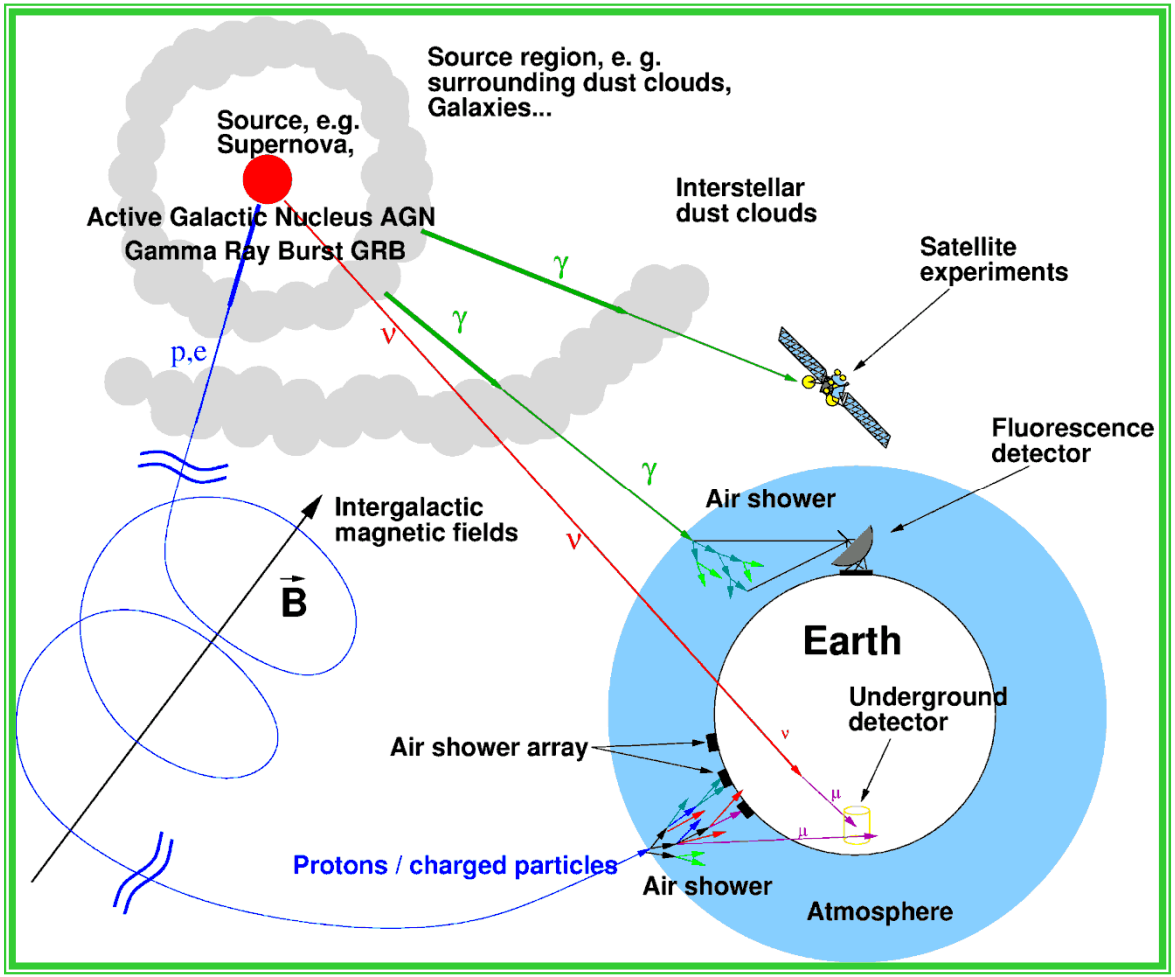
extragalactic sources,

like

Galileo observed Jupiter moons

Proton detection does not!

(except at extremely high energies)



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2. **Astroparticle Physics**
3. Observation of Jets
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2. Astroparticle physics

CRs = *many phenomena!*

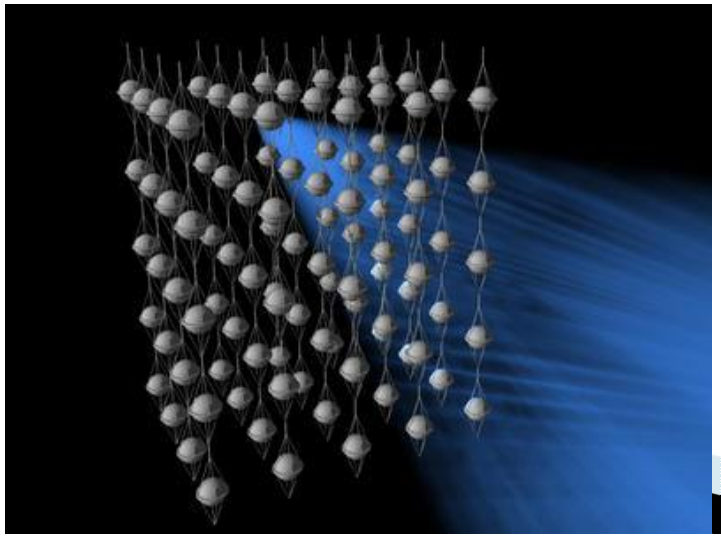
(high & low energy rays)

Scientific Realism

Phenomena = Measured Facts in Nature (Bogen & Woodward)

- effects (Photo, Zeemann, Bohm-Aharanov, Quantum Hall, …)
- *explananda* of theories & *predictions* from theories

Astroparticle physics: *Where do CRs come from?*
Measure & *Explain* the *Spectrum !*



MAGIC

Cherenkov
neutrino&gamma ray
telescopes

ICECUBE

2. Astroparticle physics

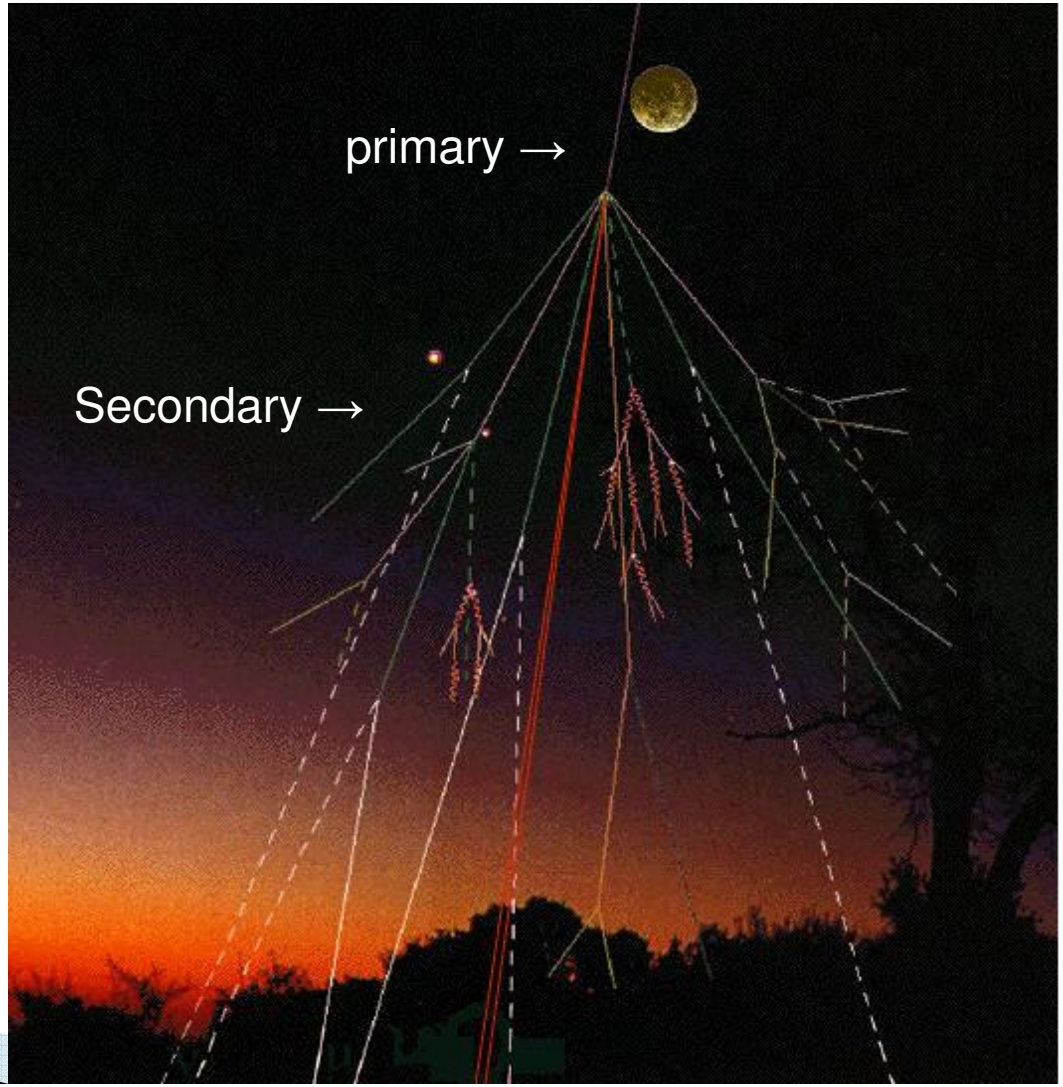
2.1 The Phenomena:

> 1912 ionizing rays in upper atmosphere (V.Hess)

> 1927 particle content investigated (baloons & earthbound experiments

> 1932 discovery of e^+, μ, π (problems of unravelling the particle content)

> 1937 „primary“ & „secondary“ CRs (scattering in atmosphere)



2. Astroparticle physics

2.1 The Phenomena:

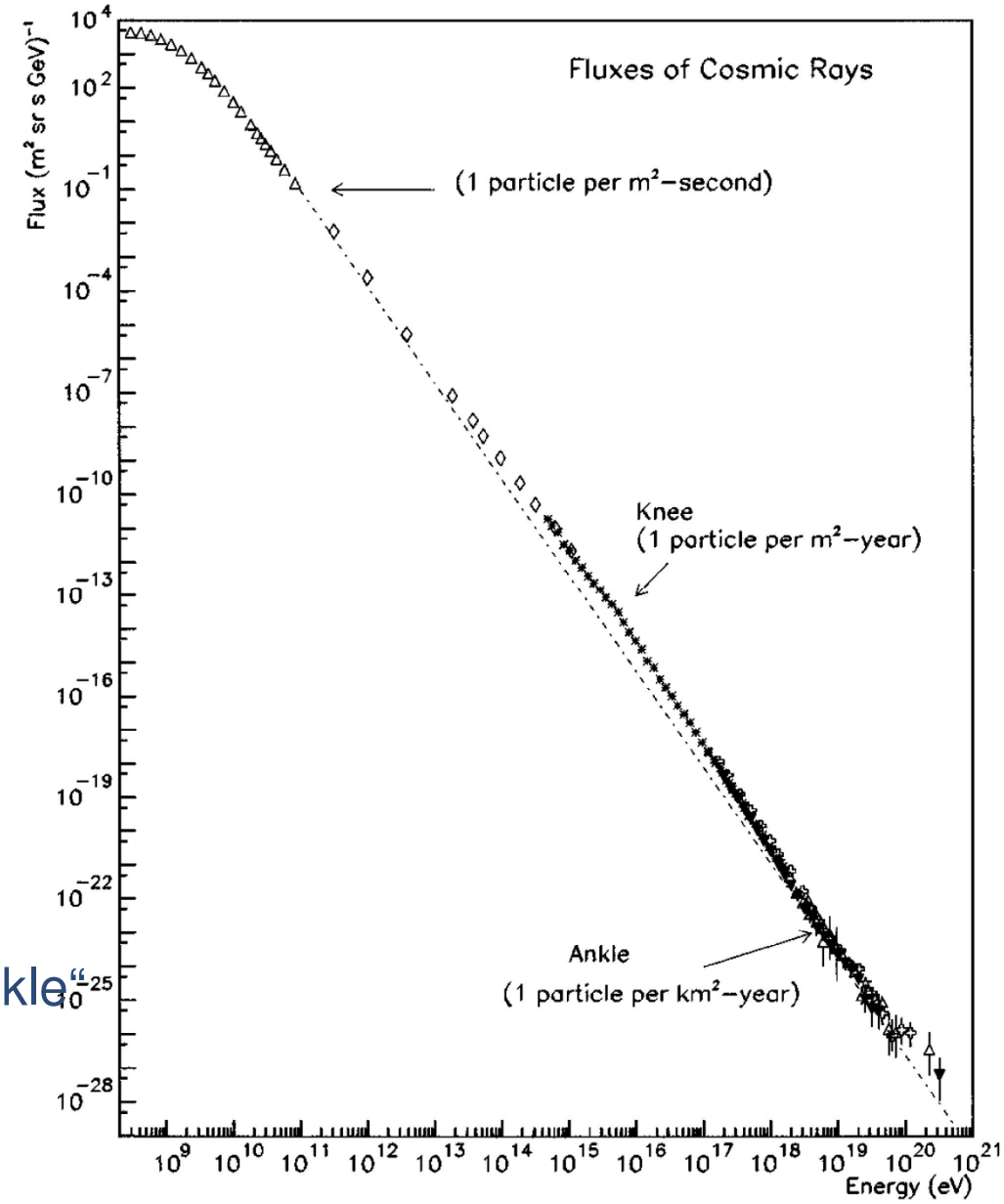
> 1954 energy measurements of of charged CR particles (B.Rossi, MIT)

> 1964 discovery of 3K CMB (A.Penzias, R.Wilson)

> 1967 gamma ray emission from our galaxy (satellites) gamma ray bursts (GBRs) (military defense satellites)

> 1987 energy flux of charged & uncharged CR particles

- Power law decrease
- two „kinks“: „knee“ & „ankle“



2. Astroparticle physics

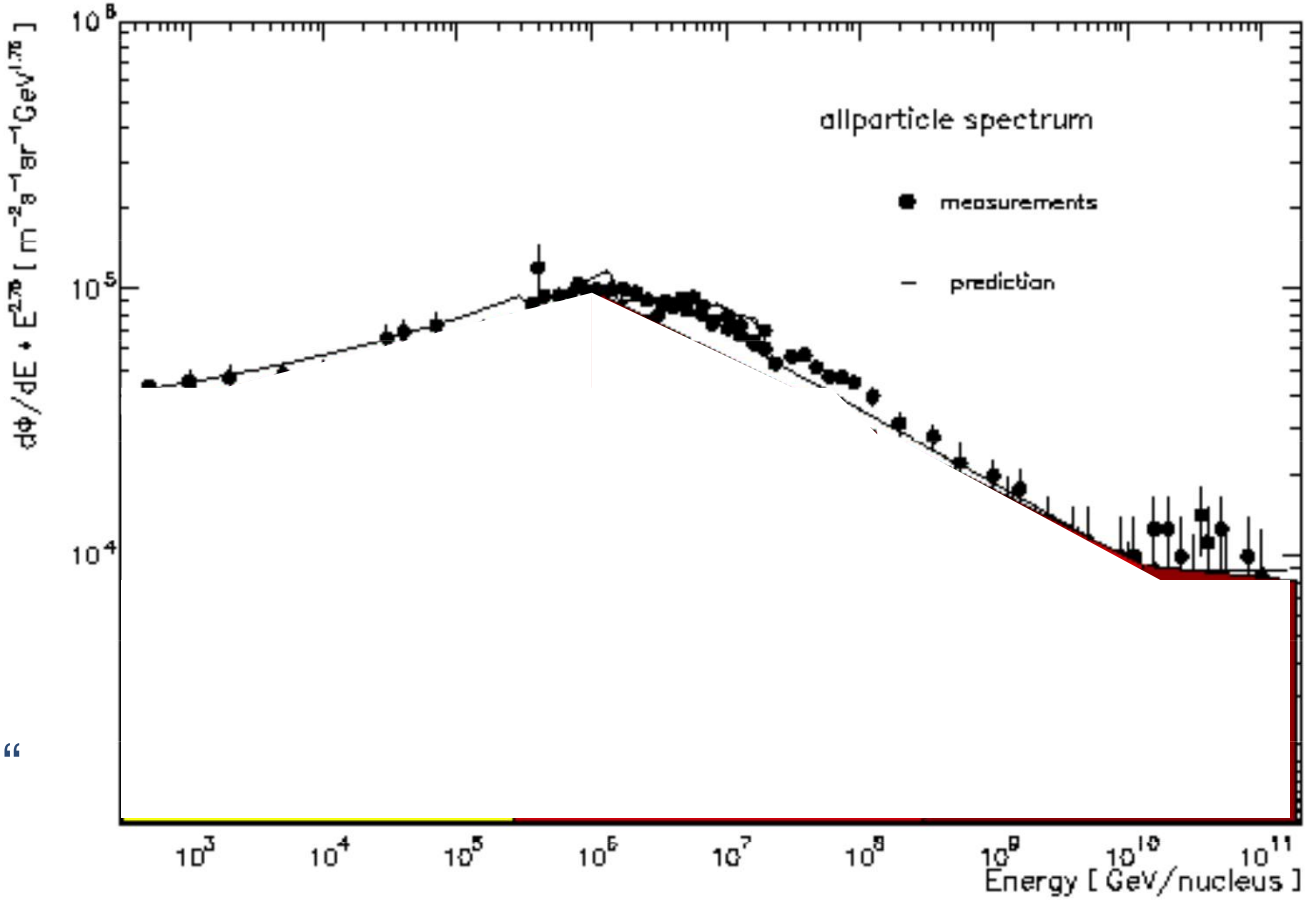
2.1 The Phenomena: All Particle Spectrum of CRs

- Power law decrease

  $d\Phi/dE \cdot E^{2.70}$

- two „kinks“:

  „knee“ & „ankle“



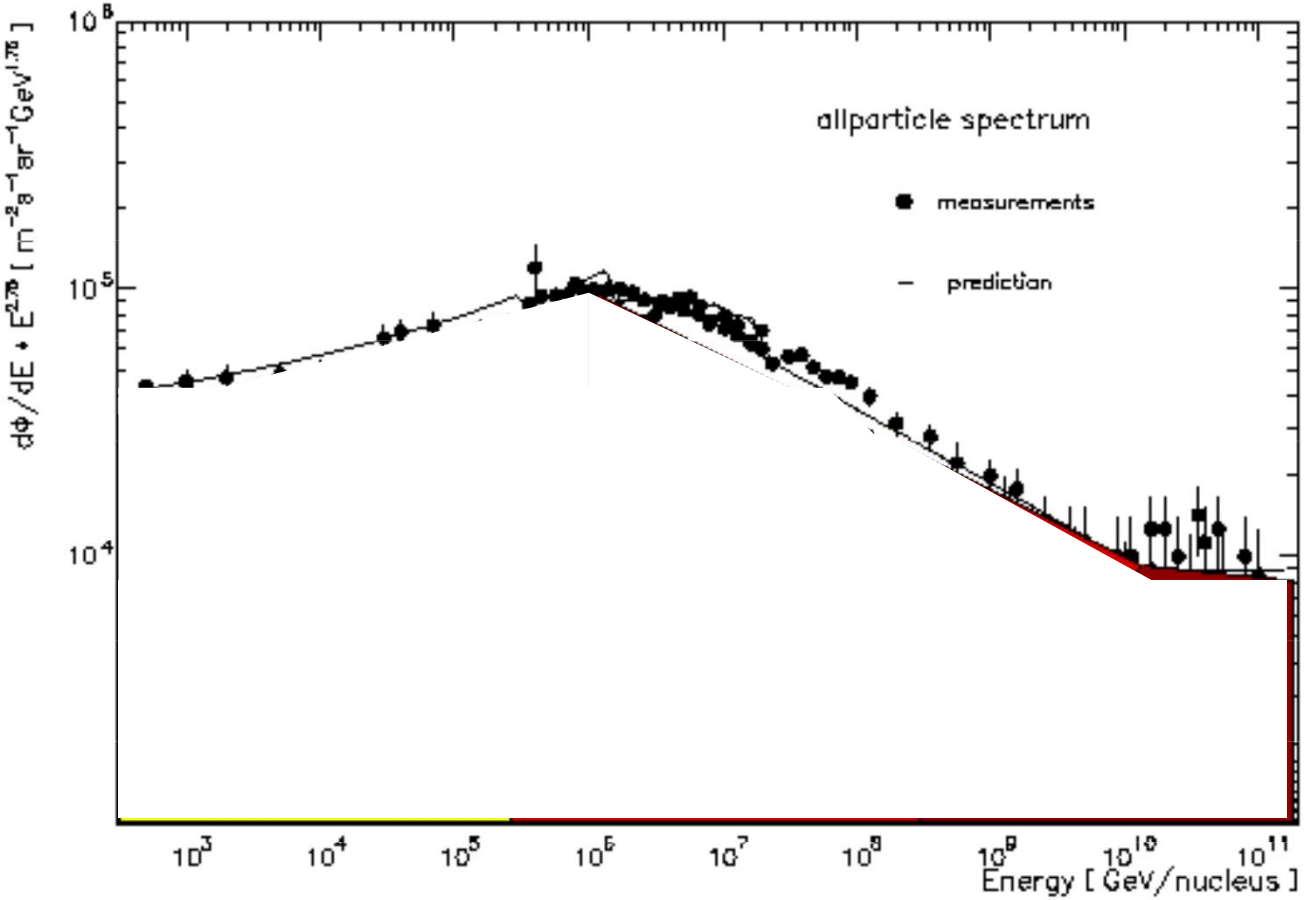
2. Astroparticle physics

2.1 The Phenomena: All Particle Spectrum of CRs

particle content of primary CRs:

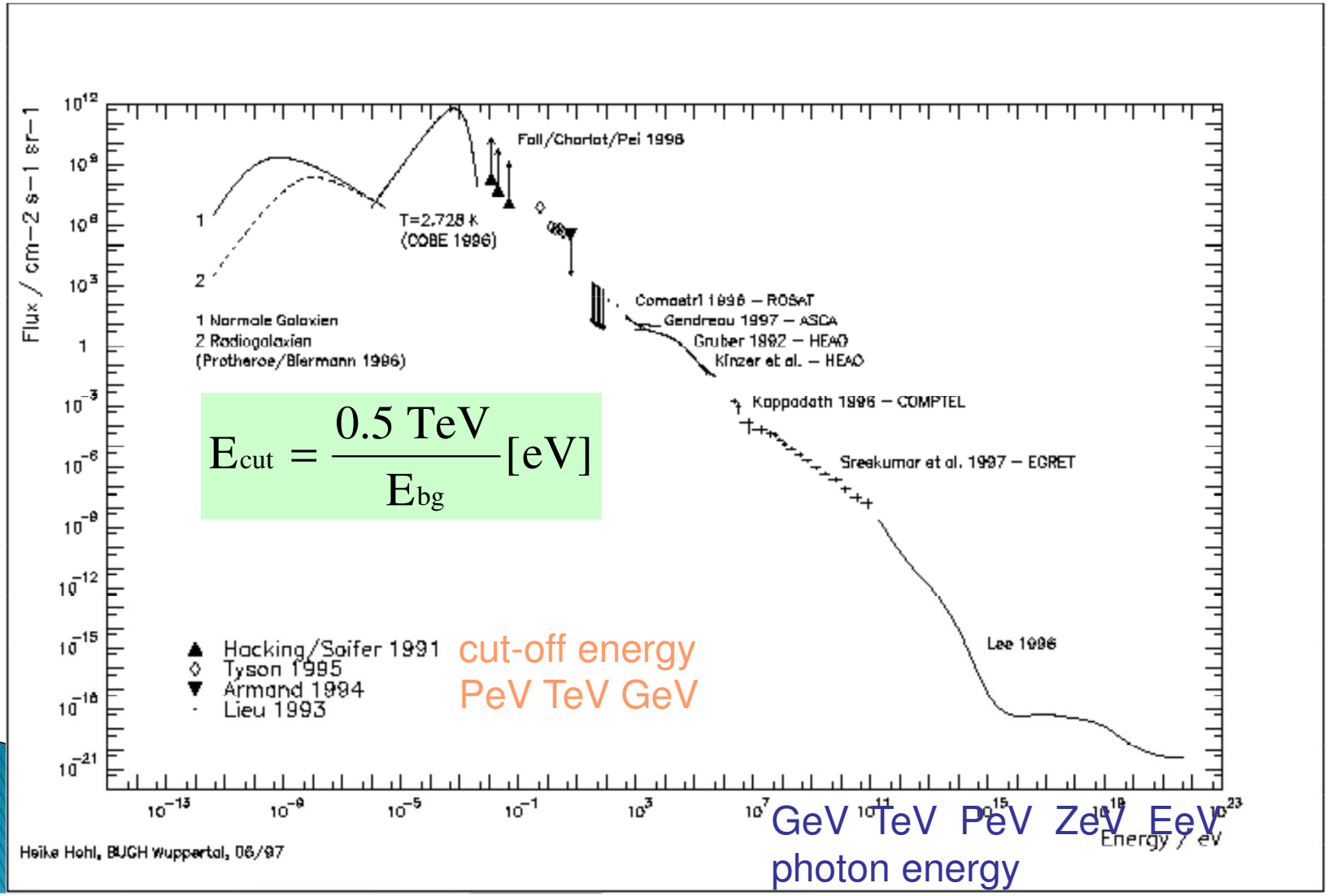
charged particles:
90 % protons
9 % α-particles
1 % electrons

(uncharged particles:
photons & neutrinos)



2. Astroparticle physics

2.1 The Phenomena: Grand Unified Photon Spectrum



$$E_{cut} = \frac{0.5\ \text{TeV}}{E_{bg}}\,[\text{eV}]$$

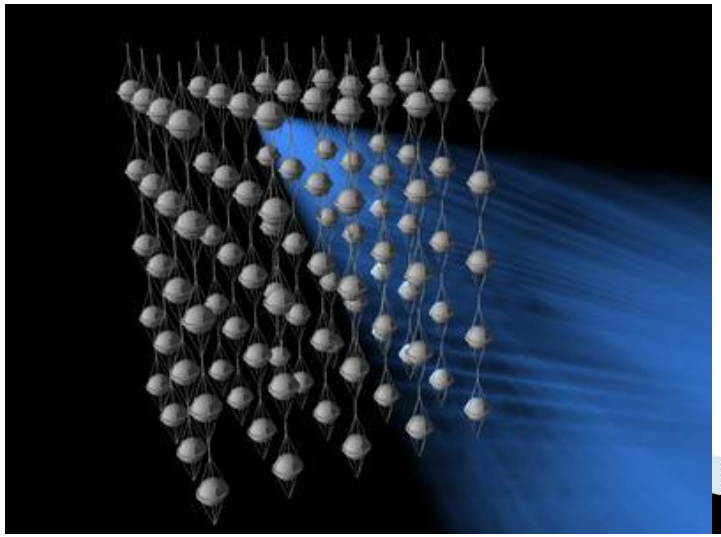
2. Astroparticle physics

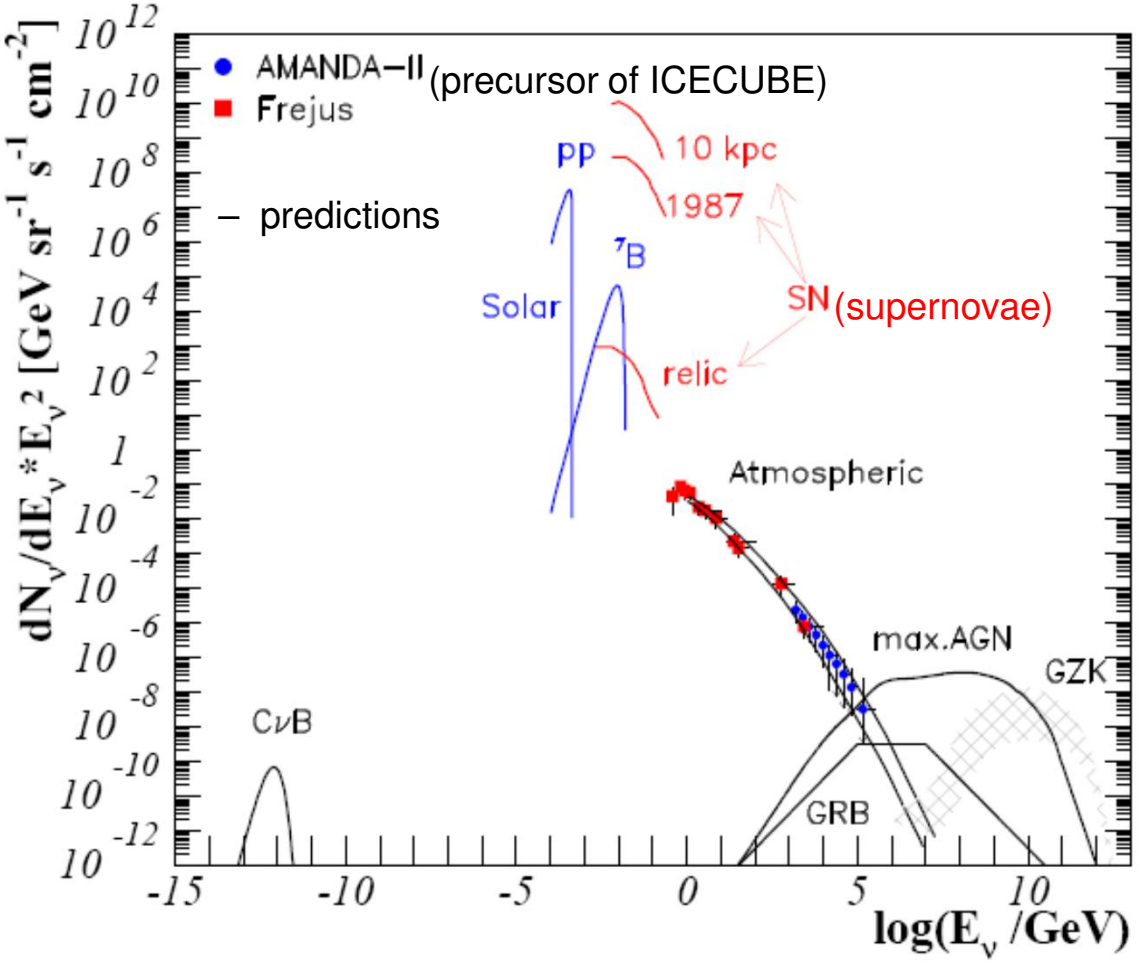
2.1 The Phenomena: Astrophysical Neutrinos

Hard to catch!

very low reaction rate

» look for *bottom-up* neutrino events, in mountains, ice, water





2. Astroparticle physics

2.2 The Problem:

Where do 10^{20} eV CRs come from?

How to explain CRs?

Extragalactic Sources & their activities

astrophysical data:

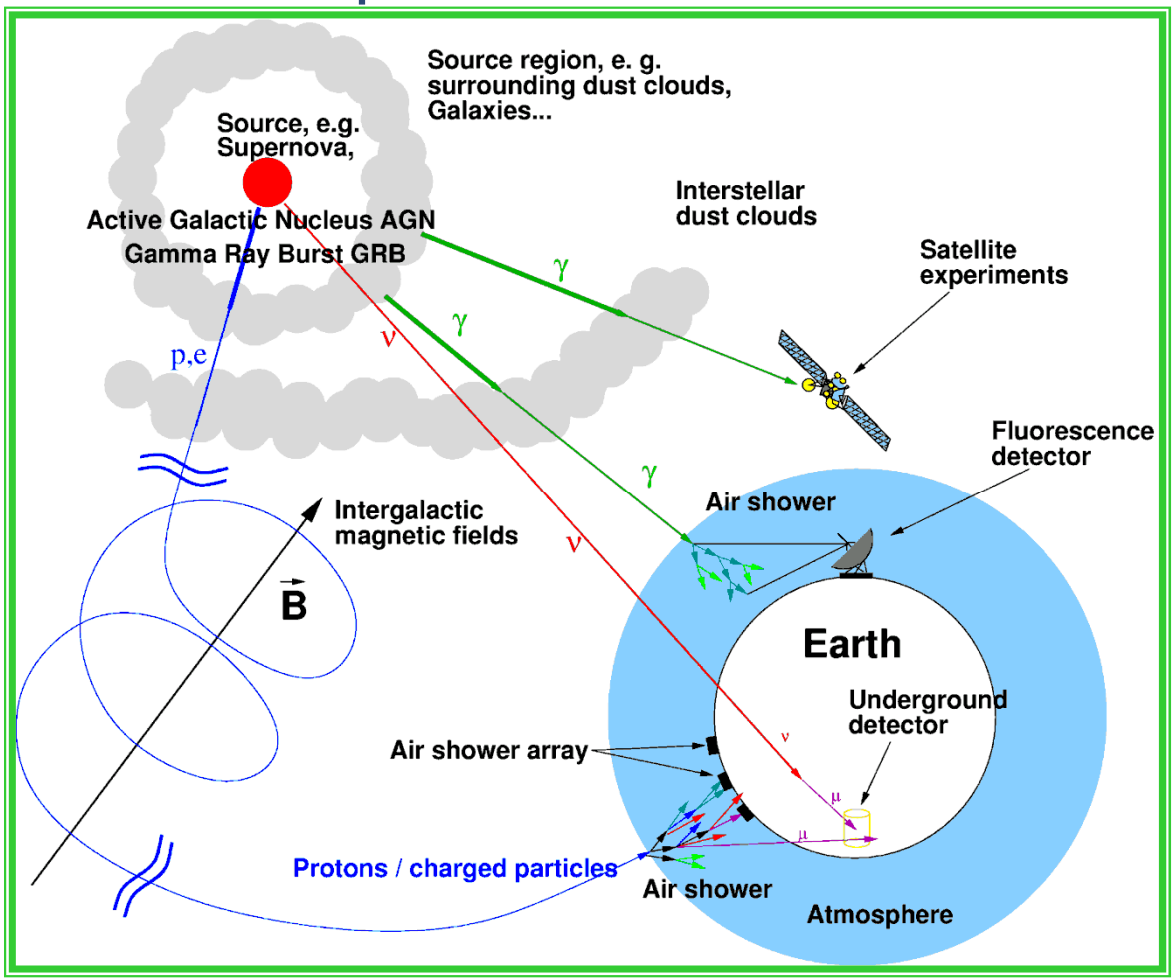
luminosity & spectra & temporal evolution

of

AGNs,

GRBs,

SNRs



2. Astroparticle physics

2.2 The Problem:

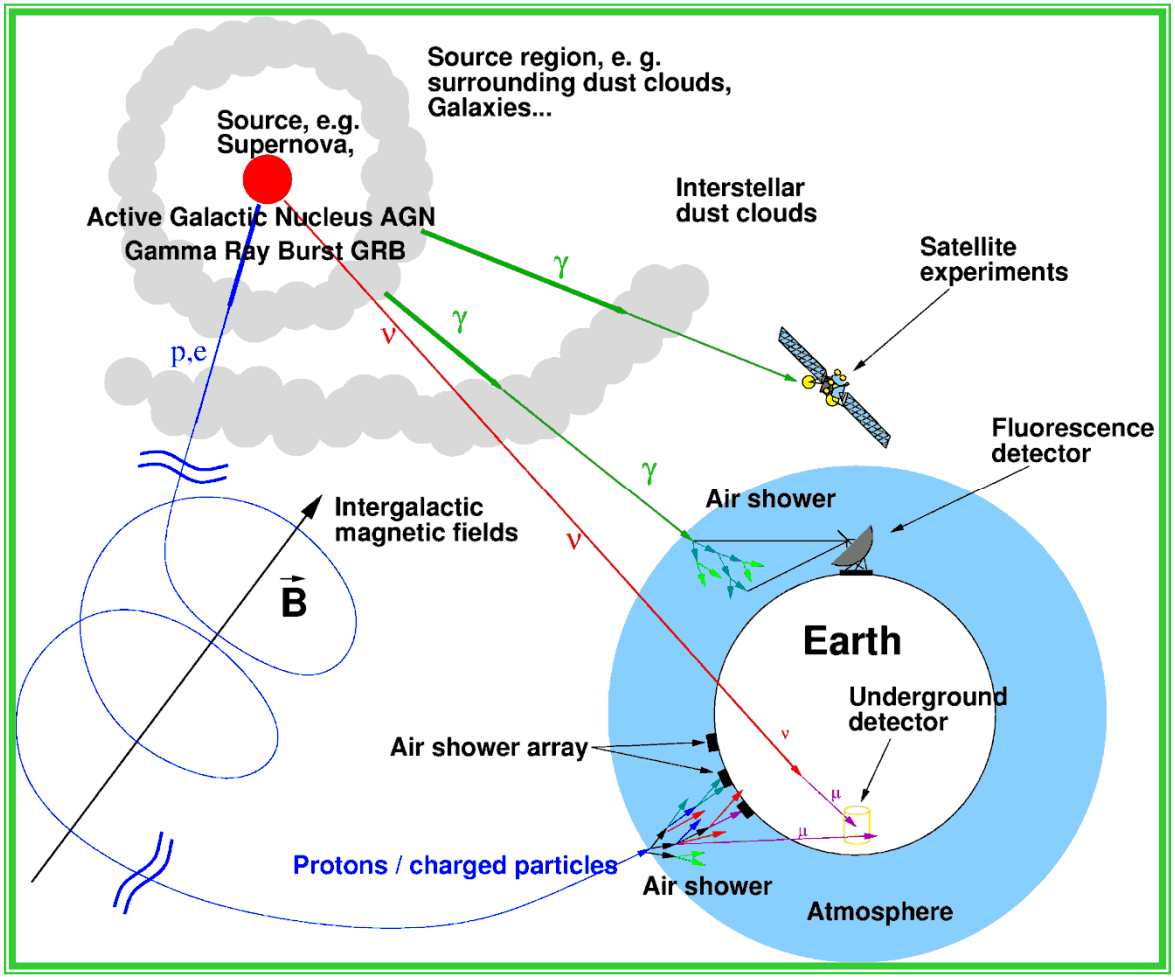
Data analysis not easy!

Use of particle telescopes in APP:

tedious work, *very* complex data analysis

Many parts of physics needed as background knowledge!

(*New method*: machine learning)



2. Astroparticle physics

2.3 The Problem:

Models ↔ Few data

Sources & their activities

astrophysical models

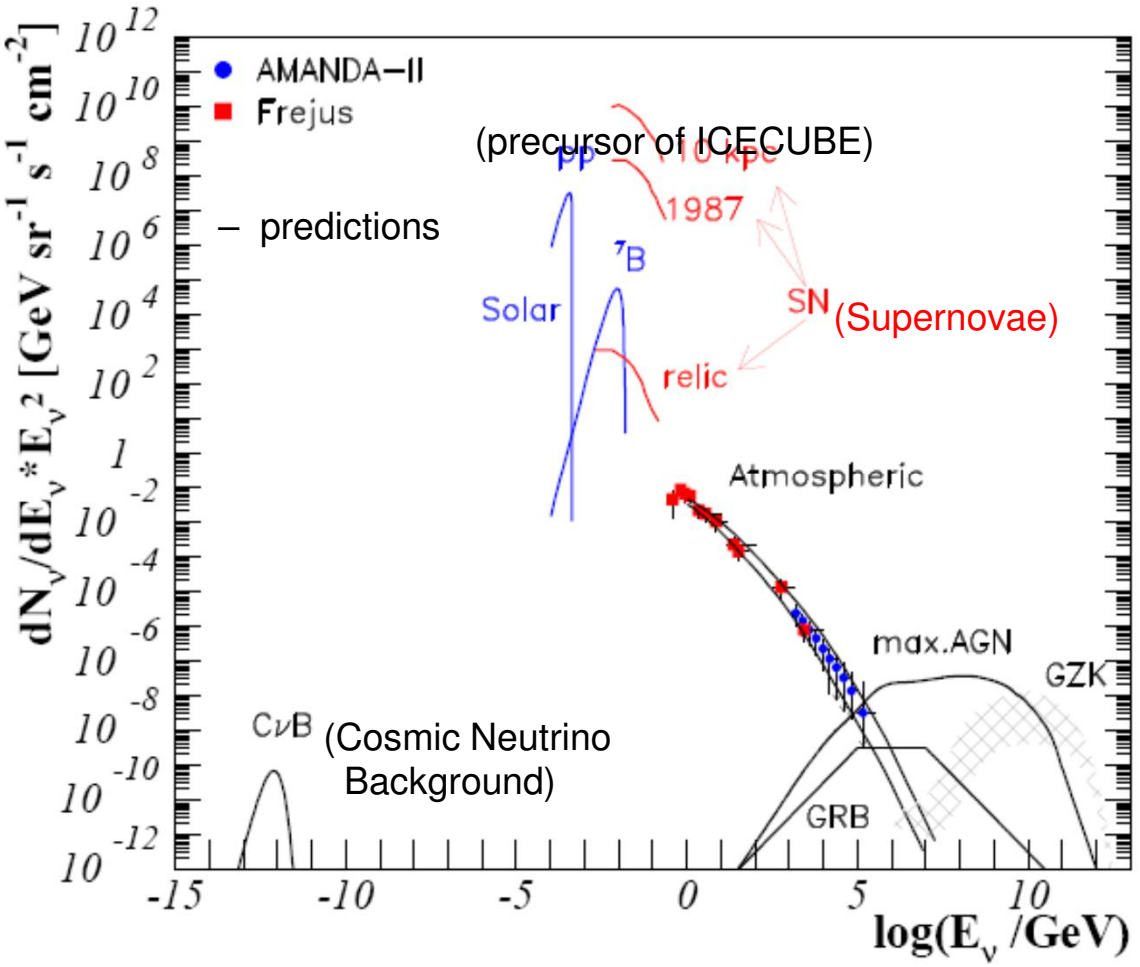
of

AGNs,

GRBs,

SNRs

tested by gamma ray & neutrino telescopes!

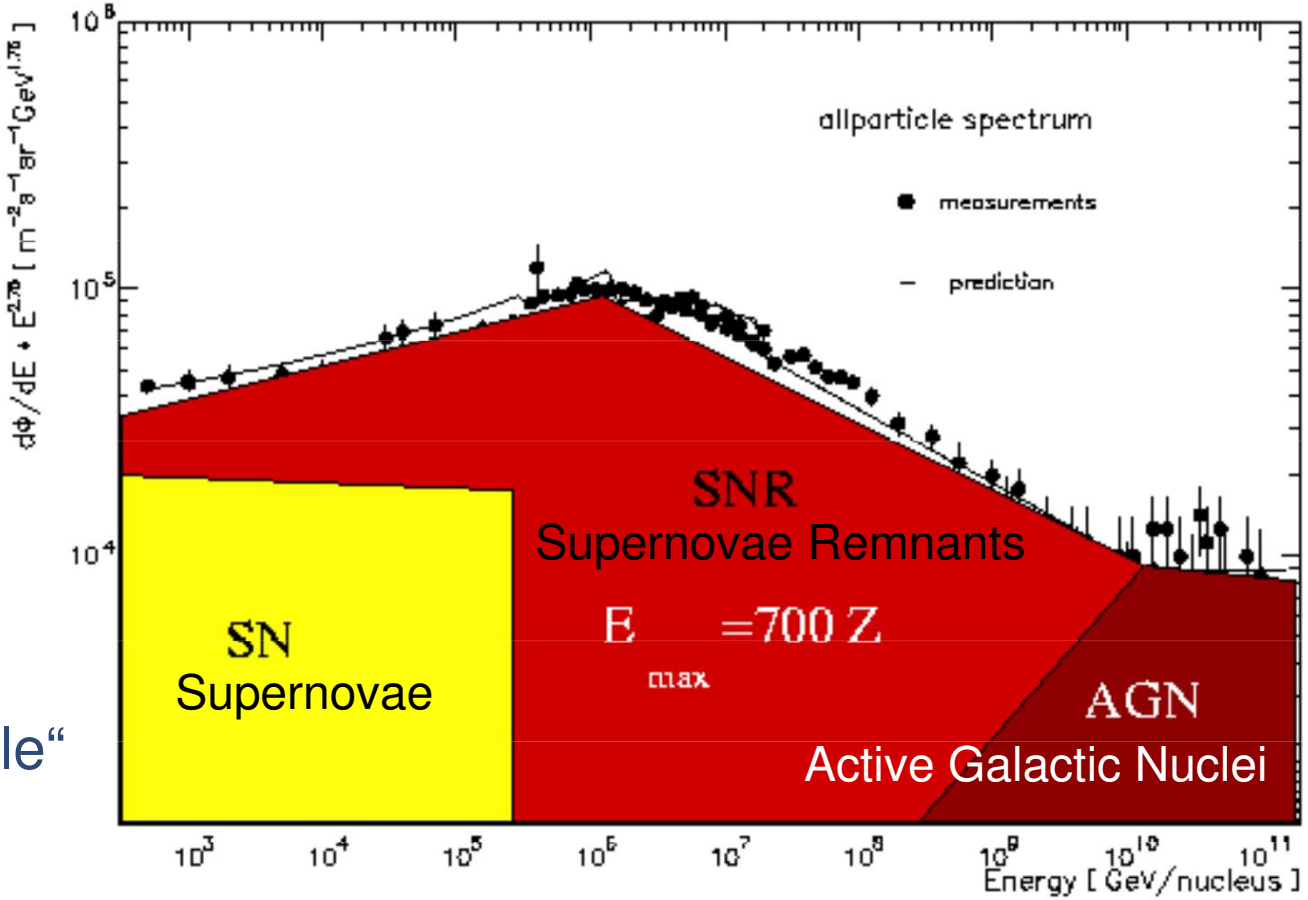


2. Astroparticle physics

2.3 The Models: Astrophysical Explanation of All Particle Spectrum of CRs

Power law decrease
$d\Phi/dE \cdot E^{2.70}$

- two „kinks“:
  „knee“ & „ankle“



2. Astroparticle physics

2.4 The Methods: Astro Particle Physics (APP) – a *peculiar* discipline!

Phenomena: **cosmic rays (CRs)**

light & radio waves, gamma rays, all kinds of subatomic particles

Discipline*s*: particle physics & astrophysics

Methods: *mixed*

- Models: nuclear & particle physics & astrophysics
- Detectors: particle detectors *arranged as* telescopes
- **Theory:** **no theory on its own**

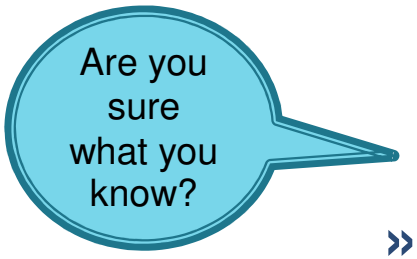
2 standard models & 2 incompatible theories

2. Astroparticle physics

2.4 The Methods: How to explain CRs? Pragmatic unification!

Goal of physics: to explain the phenomena
Astroparticle physics: to explain origin & spectra of cosmic rays

in terms of: concepts & models



- CRs = **messenger particles**
- carry **information** from **extragalactic sources**
- information may be **disturbed**

» do they describe ***physical reality***?

Problem of APP: no *unified* foundations

» „***true causes***“ or ***economy of thought***?

2. Astroparticle physics

2.4 The Methods:

How does
Astro Particle Physics
work?

Pragmatic strategies:

1. Methodological unification:

combine measurement methods
from particle physics & astrophysics:
arrange particle detectors as telescopes,
add data from space telescopes, …

Cherenkov telescopes (Neutrinos, Gamma rays) Hybrid detector (CR showers) CMB

2. Astroparticle physics

2.4 The Methods:

How does Astro Particle Physics work?

Pragmatic strategies:

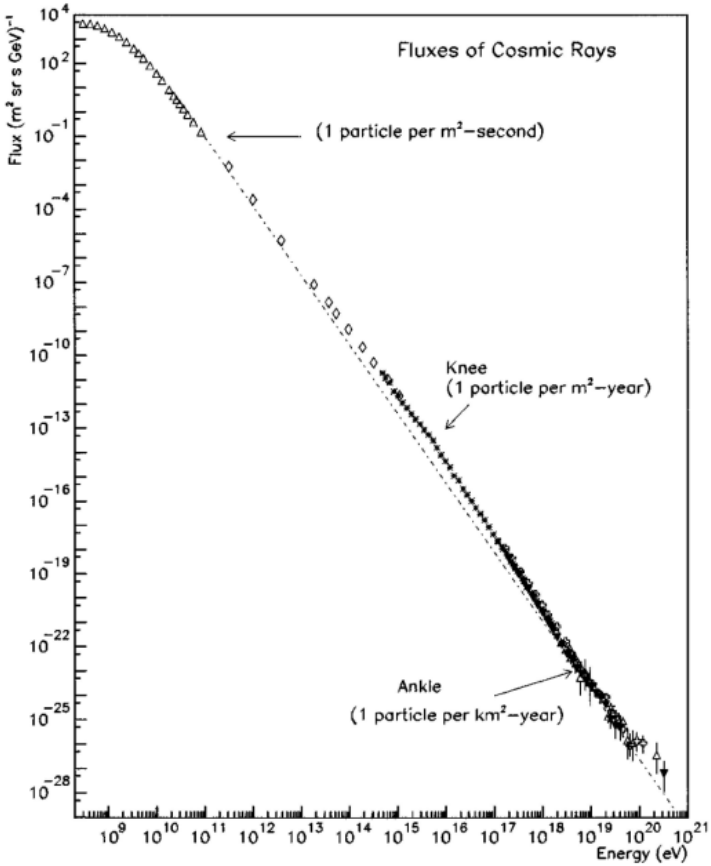
2. Phenomenological unificatior

combine cosmic rays

at low & high energy,

put all kinds together

in „All particles spectrun



2. Astroparticle physics

2.4 The Methods: How does Astro Particle Physics work?

Pragmatic strategies:

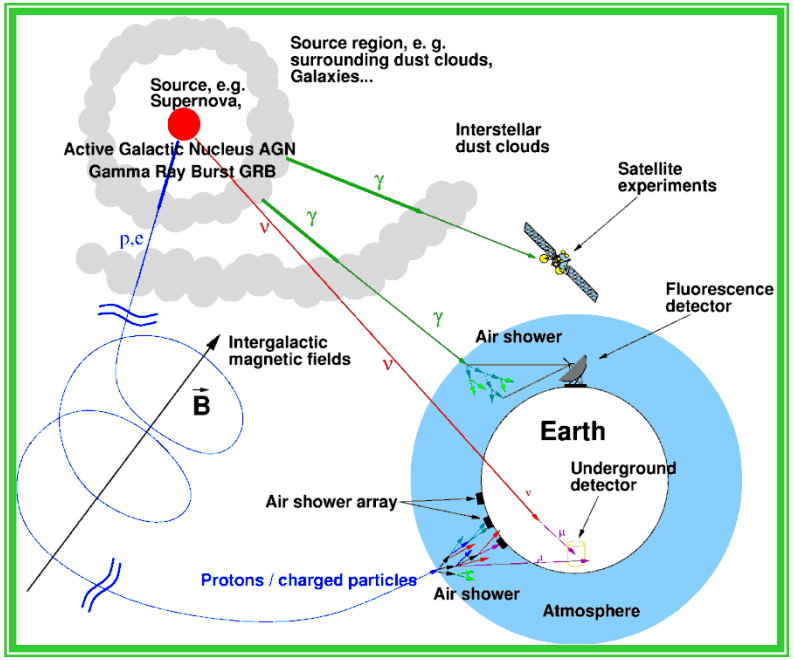
3. Conceptual unification:

tell *causal story* about

messenger particles

carrying information

from cosmic sources



2. Astroparticle physics

2.4 The Methods:

How does Astro Particle Physics work?

Pragmatic strategies:

4. Explanatory unification:

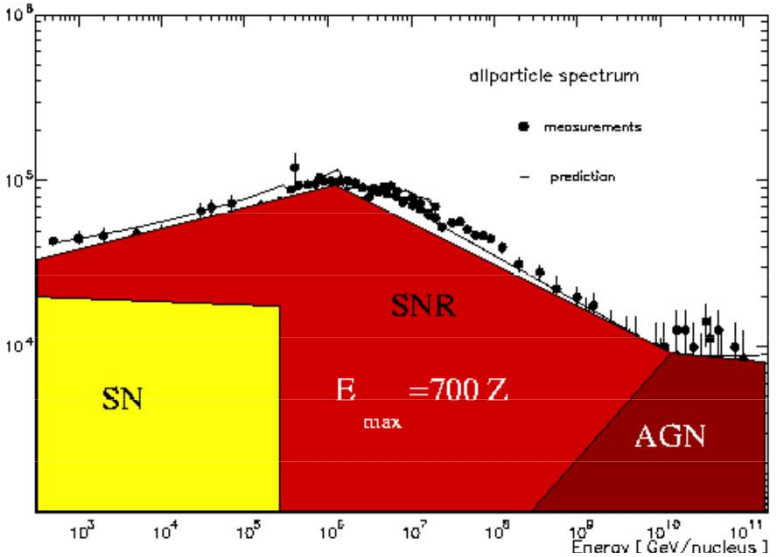
construct *models* of

astrophysical sources &

mechanisms of particle acceleration

in order to explain the

„All particle spectrum“



2. Astroparticle physics

2.4 The Methods:

How does Astro Particle Physics work?

Goal of APP: to **explain** the **CR phenomena**

Explanation: *very* different views!

- » „true causes“ (Newton)
- » unfication (Einstein, Planck)
- » classification by analogies (Bohr)
- » economy of thought (Mach)

In APP: **stronger** & **weaker** views coexist

„messenger particles“ ↔ causal realism

specific models (sources of CR, particle acceleration) ↔ cautious instrumentalism

background knowledge ↔ belief in well-known laws

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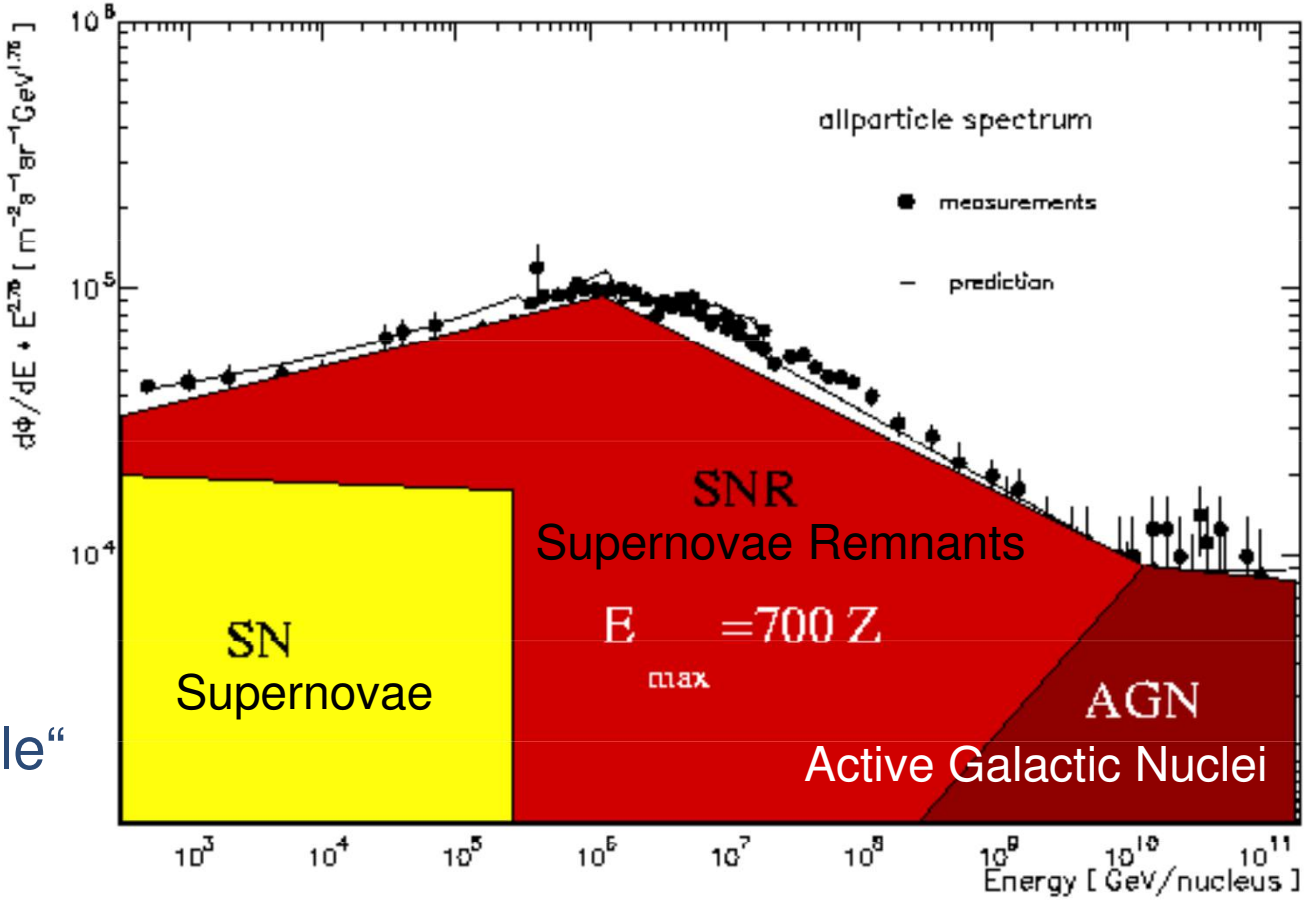
1. Cosmic Messengers
2. Astroparticle Physics
3. **Observation of Jets**
4. Gravitational Waves

3. Observation of Jets

Assumption:
CRs of
highest energy
due to
AGN (Active
Galactic Nuclei)

Astrophysical Explanation
of All Particle Spectrum of CRs



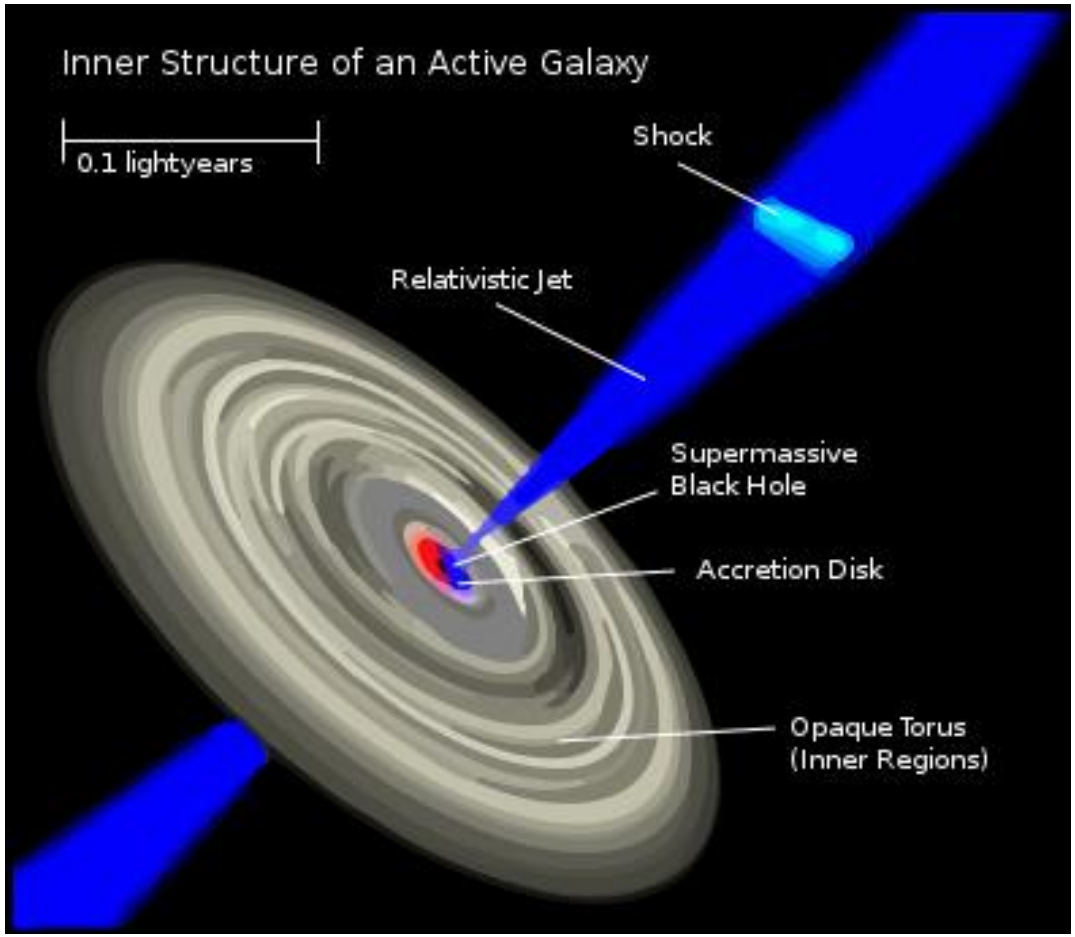
Power law decrease
$d\Phi/dE \cdot E^{2.70}$

- two „kinks“:
  „knee“ & „ankle“

3. Observation of Jets

Assumption:
CRs of
highest energy
due to
AGN (Active
Galactic Nuclei)

Supermassive
Spinning
Black Hole
with
Accretion disk
Emitting 2Jets



https://upload.wikimedia.org/wikipedia/commons/thumb/f/f8/Galaxies-AGN-Inner-Structure.svg/210px-Galaxies-AGN-Inner-Structure.svg.png

3. Observation of Jets

Assumption:
CRs of
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Supermassive
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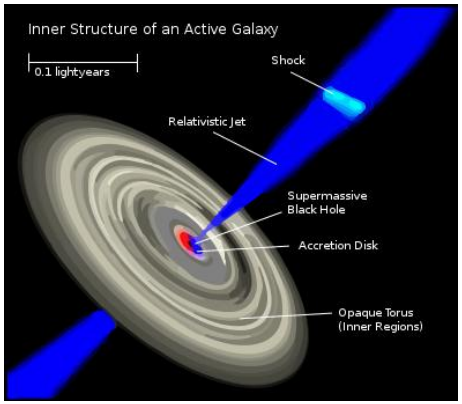
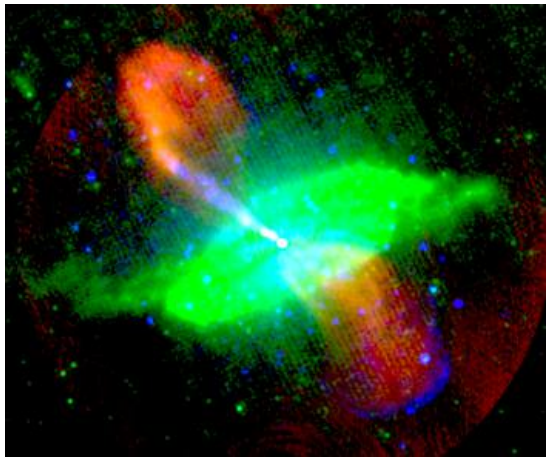


By NASA and The Hubble Heritage Team (STScI/AURA) - HubbleSite: gallery, release., Public Domain, https://commons.wikimedia.org/w/index.php?curid=102873

Jet of 5000 ly length ejected by M87



Radio galaxy Centaurus A

By Martin Hardcastle http://en.wikipedia.org/wiki/Image:Cena-spc.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2186714

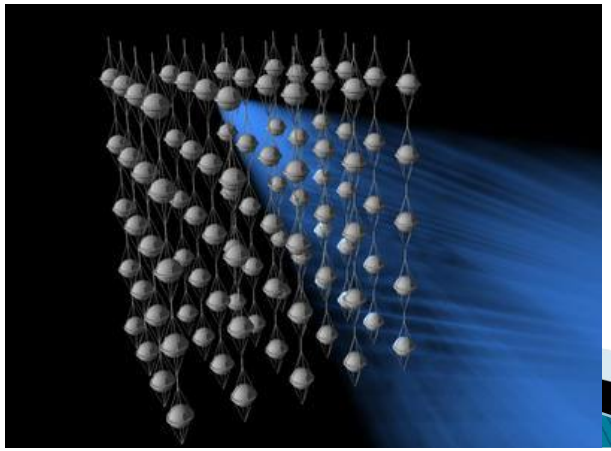
3. Observation of Jets

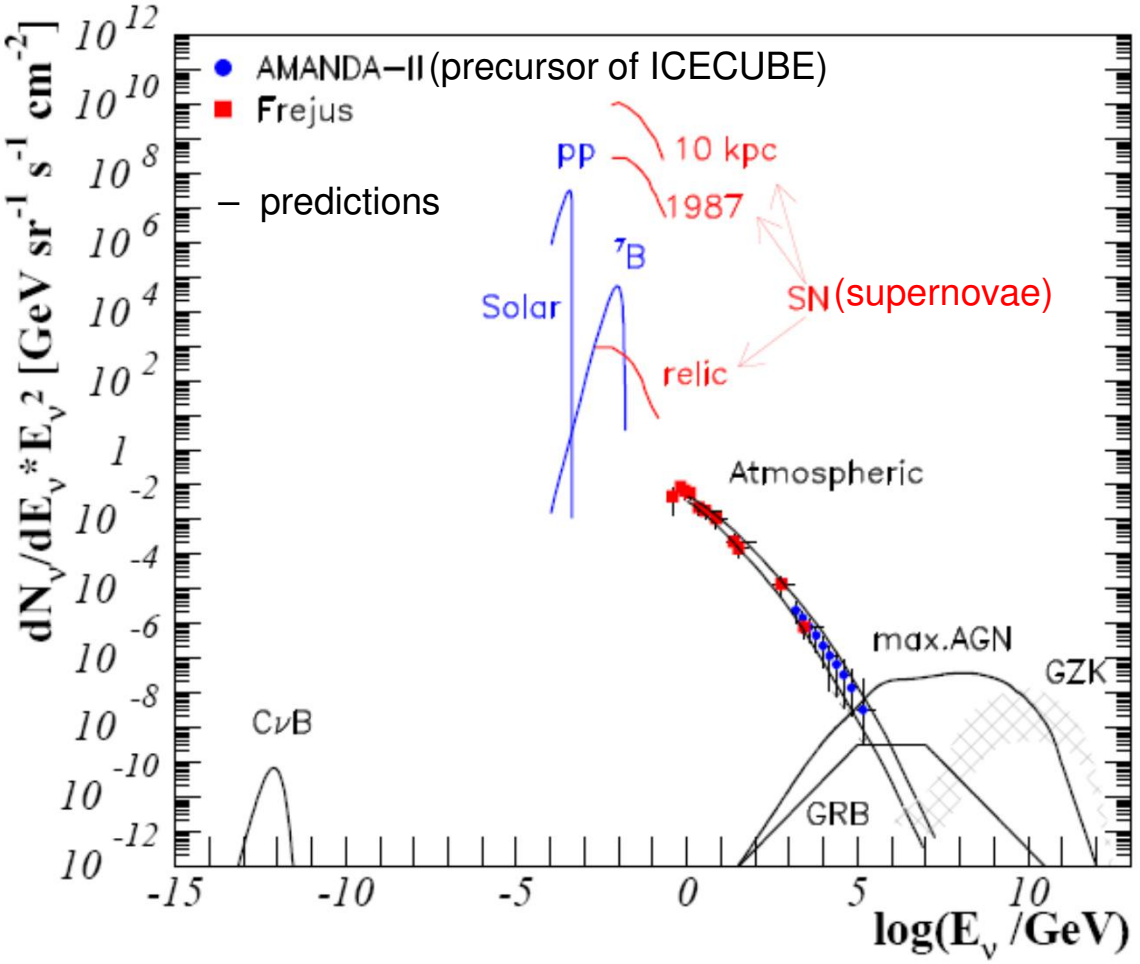
2.1 The Phenomena: Astrophysical Neutrinos

Hard to catch!

very low reaction rate

» look for *bottom-up* neutrino events, in mountains, ice, water





3. Observation of Jets

Assumption:
CRs of
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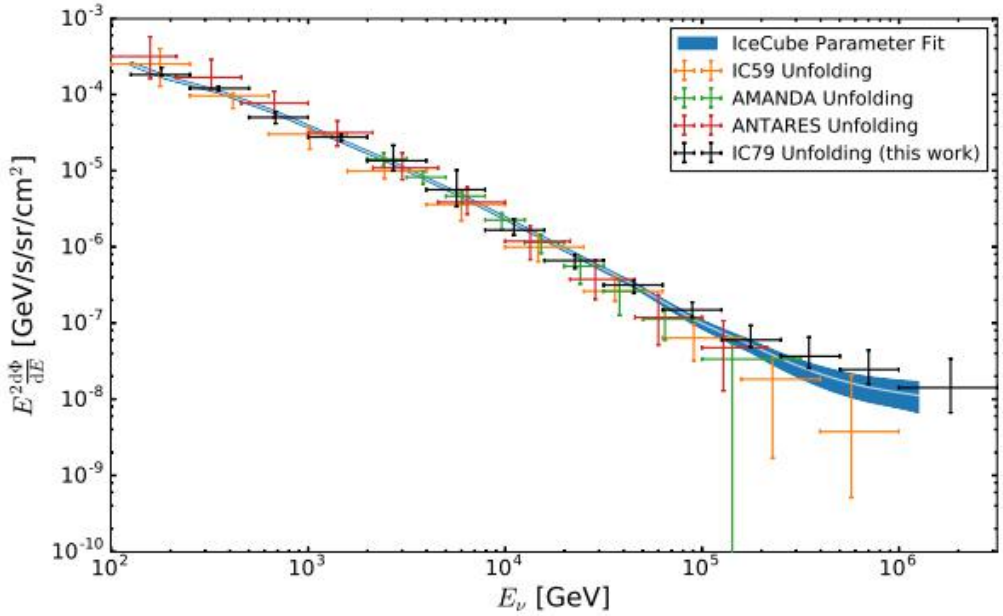
Galactic Nuclei)

Ice Cube Collaboration: Measurement of the ν μ energy spectrum with IceCube-79
(preliminary)



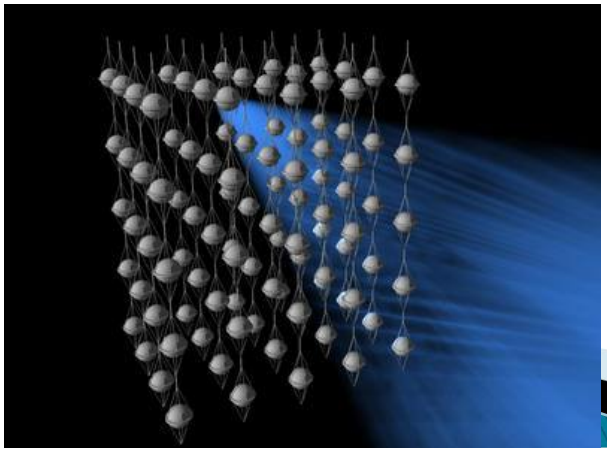


Fig. 7: The obtained ν_μ spectrum of this analysis compared to the unfolding analyses of AMANDA, ANTARES and IceCube-59.

Comparison of the unfolding methods

3. Observation of Jets

Assumption:
CRs of
highest energy
due to
AGN (Active
Galactic Nuclei)

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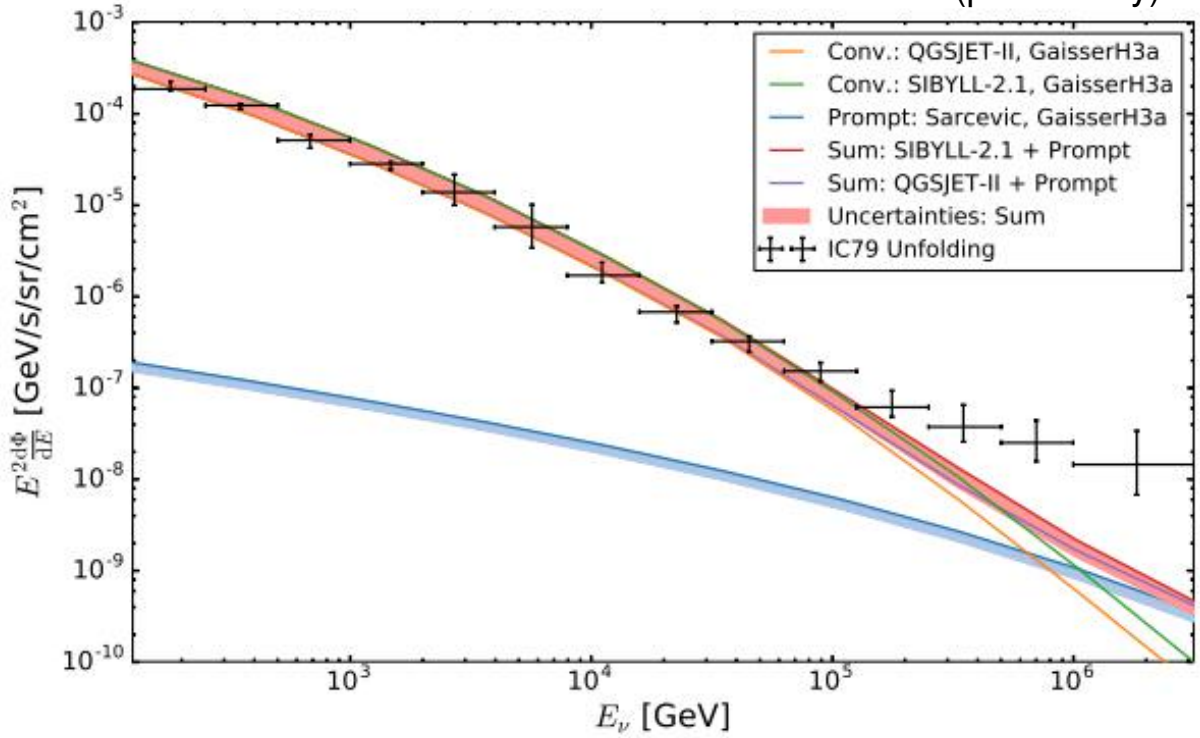
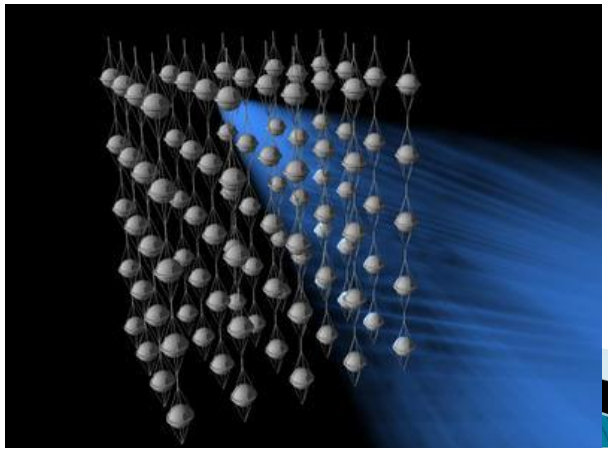


Fig. 8: Unfolded ν_μ energy spectrum compared to theoretical calculations.

Models of atmospheric neutrinos *vs.* data



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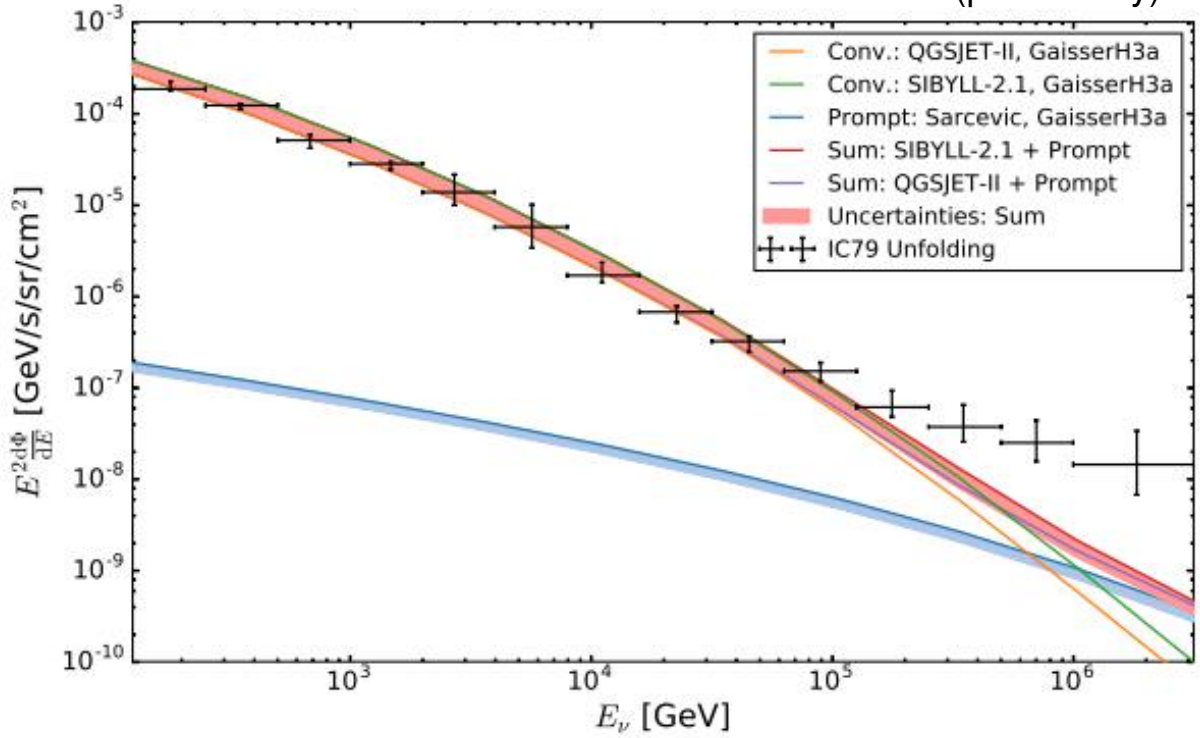

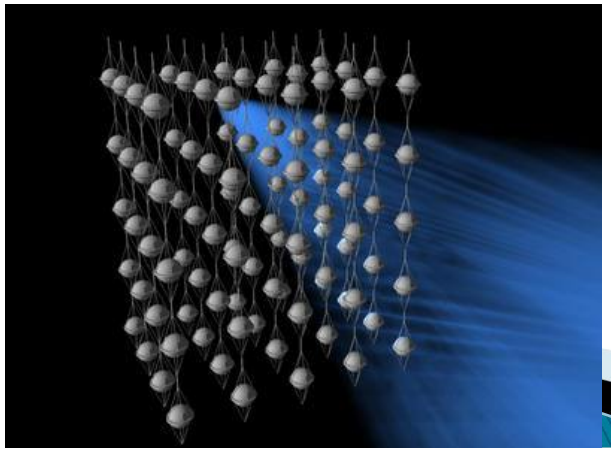

"We therefore conclude that the flattening of the muon neutrino energy spectrum at energies above ≈ 60 TeV is consistent with an astrophysical flux of neutrinos. […] For higher energies the spectrum exceeds an atmospheric only prediction."

3. Observation of Jets

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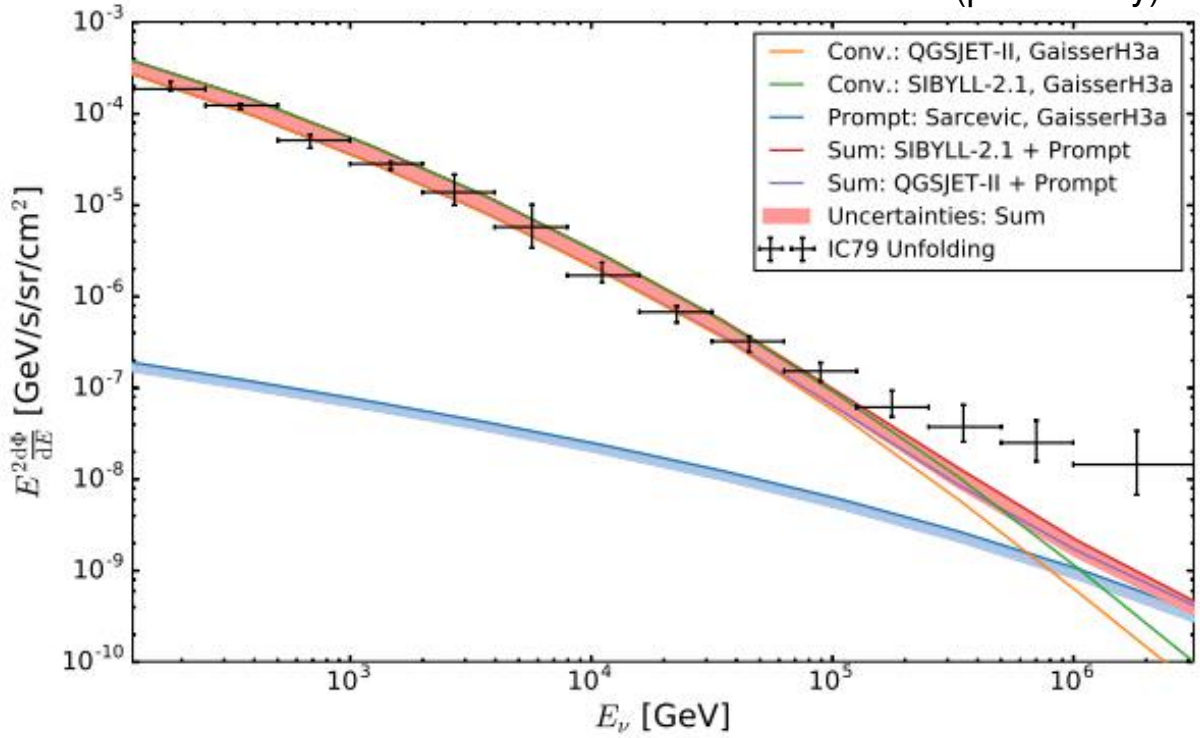
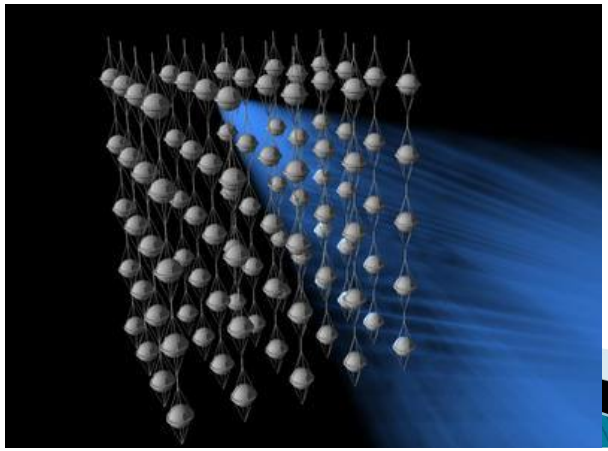


"This excess is compatible with recent measurements of an astrophysical neutrino flux. […] Therefore, it can be most likely attributed to such an additional component. […]



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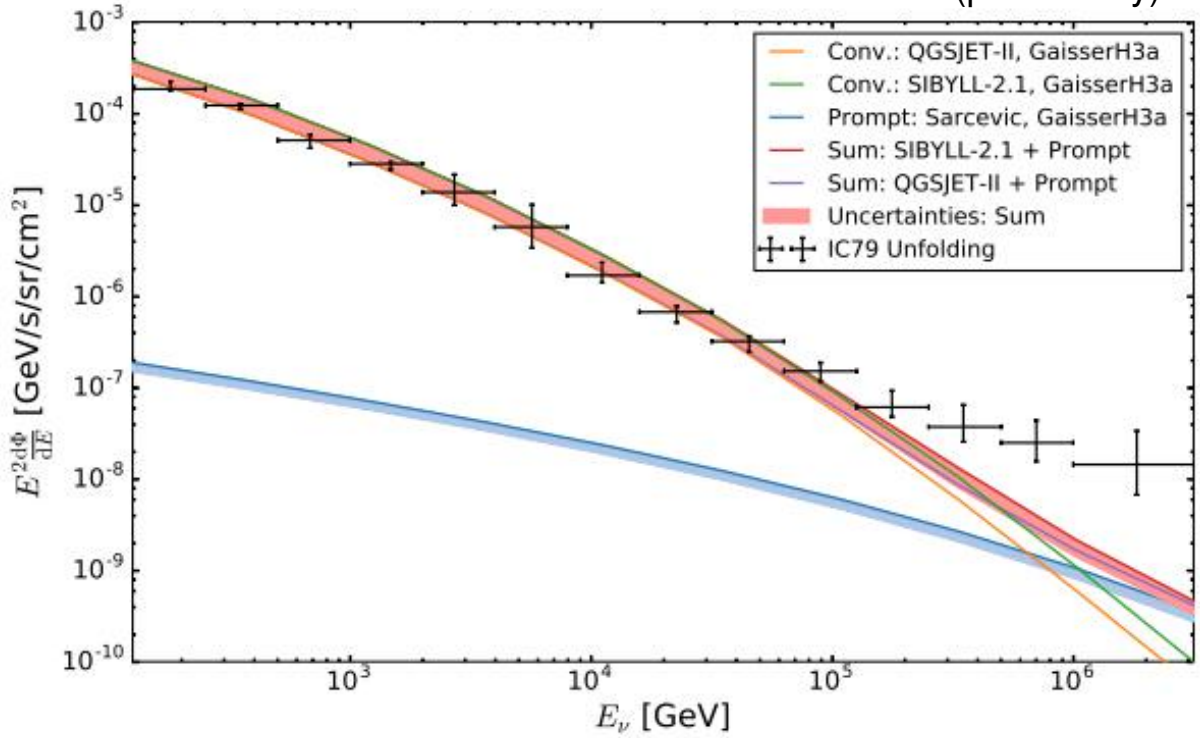
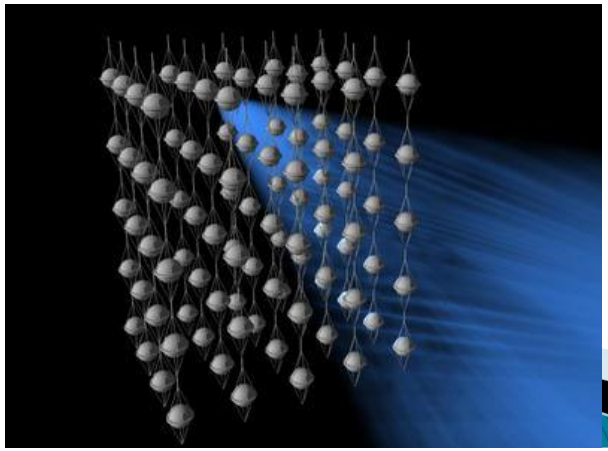


"This analysis presents the first observation of an astrophysical muon neutrino flux in a model independent spectral measurement."



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Particles and Waves as Cosmic Messengers

1. Cosmic Messengers
2. Astroparticle Physics
3. Observation of Jets
4. Gravitational Waves

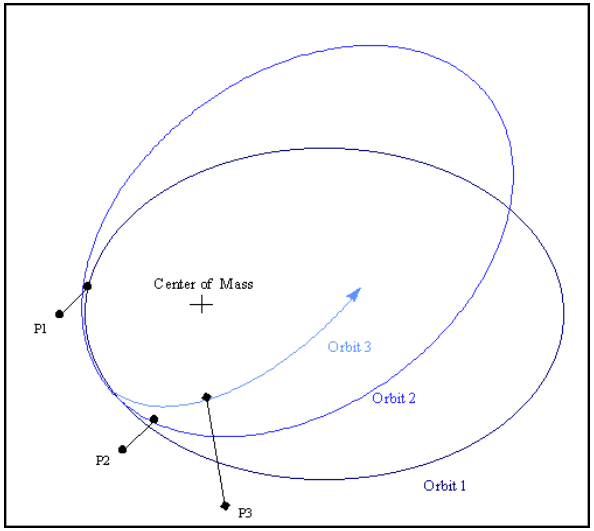
4. Gravitational Waves

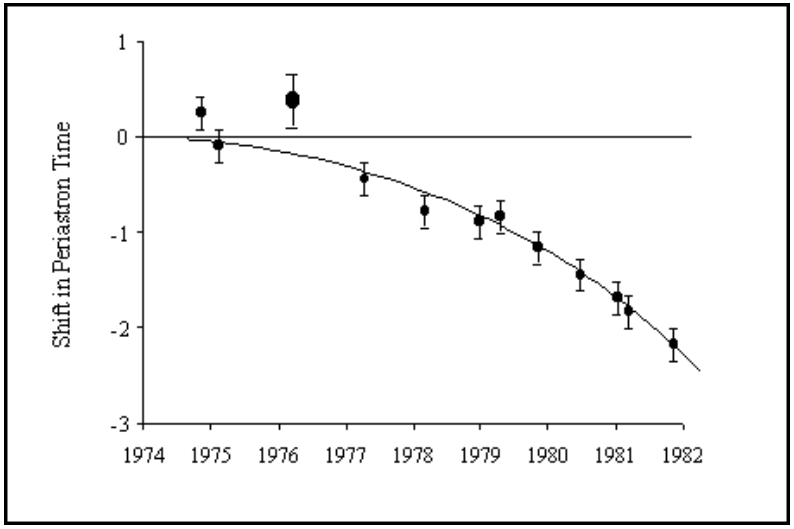
4.1 Indirect Measurement

1974	discovery of pulsar PSR 1913+16 (R. A. Hulse and J. Taylor)
1983	report of decrease in the orbital period
1993	Nobel prize “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation”

Figures from: "Gravitational Waves from an Orbiting Pulsar", Weisberg, J.M., Taylor, J.H. and Fowler, L.A., 1981, *Scientific American* **Oct**, 74

Energy loss by emission of Gravitational Waves





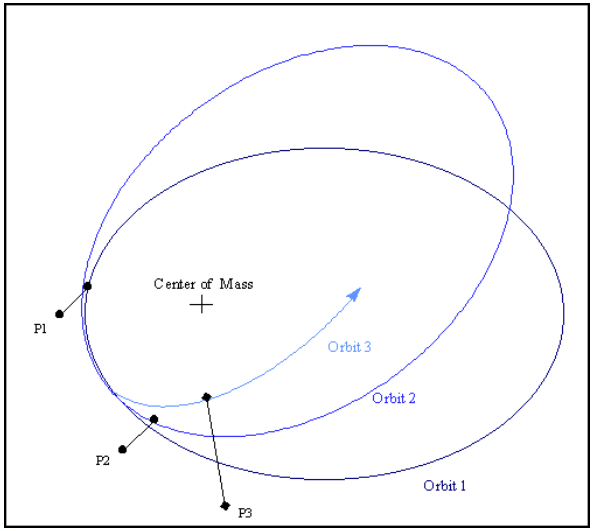
4. Gravitational Waves

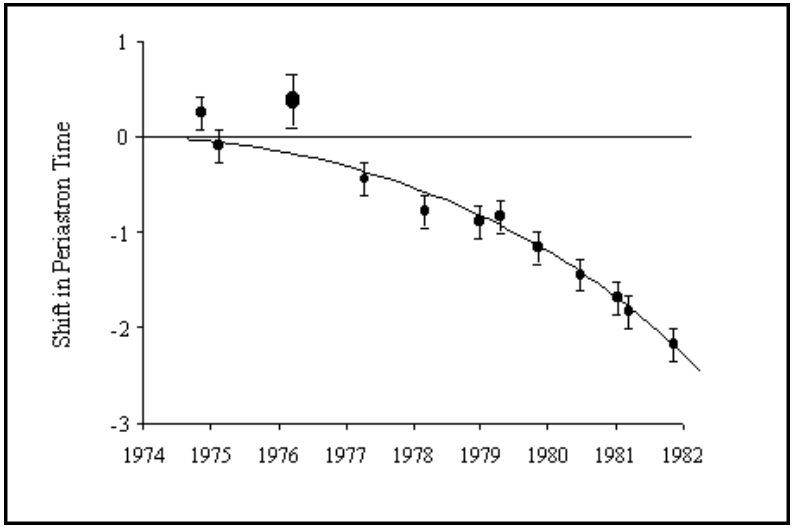
4.1 Indirect Measurement

"Here a new, revolutionary "space laboratory" has been obtained for testing Einstein's general theory of relativity and alternative theories of gravity. […] Of particular interest has been the possibility of verifying with great precision the theory's prediction that the system should lose energy by emitting gravitational waves in about the same way that a system of moving electrical charges emits electromagnetic waves." *(Nobel Prize Press Release)*

Figures from: "Gravitational Waves from an Orbiting Pulsar", Weisberg, J.M., Taylor, J.H. and Fowler, L.A., 1981, *Scientific American* **Oct**, 74

Energy loss by emission of Gravitational Waves





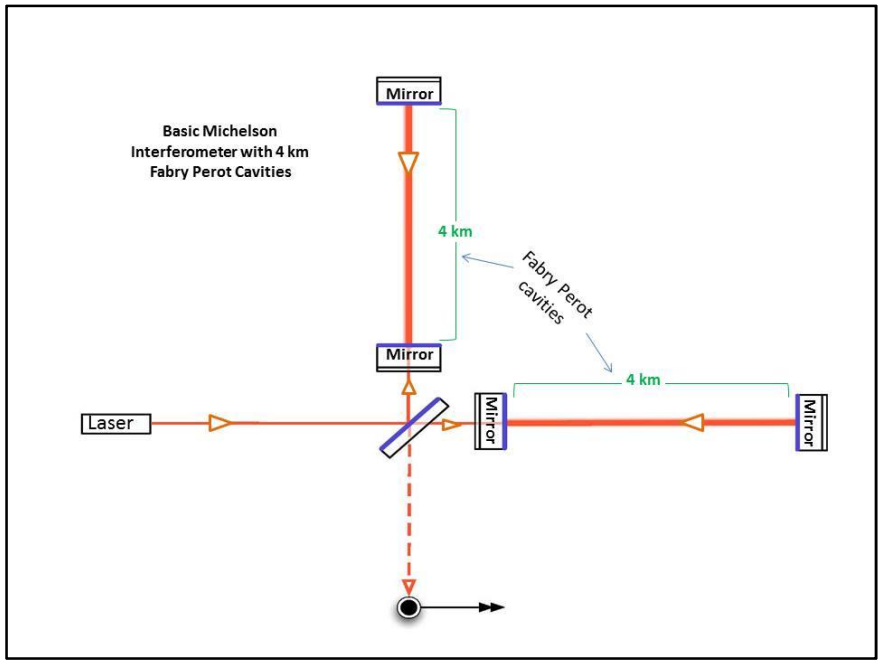
4. Gravitational Waves

4.2 Direct Measurement

2 Twin Interferometers:
LIGO Livingston & LIGO Hanford

https://www.ligo.caltech.edu/page/ligo-detectors

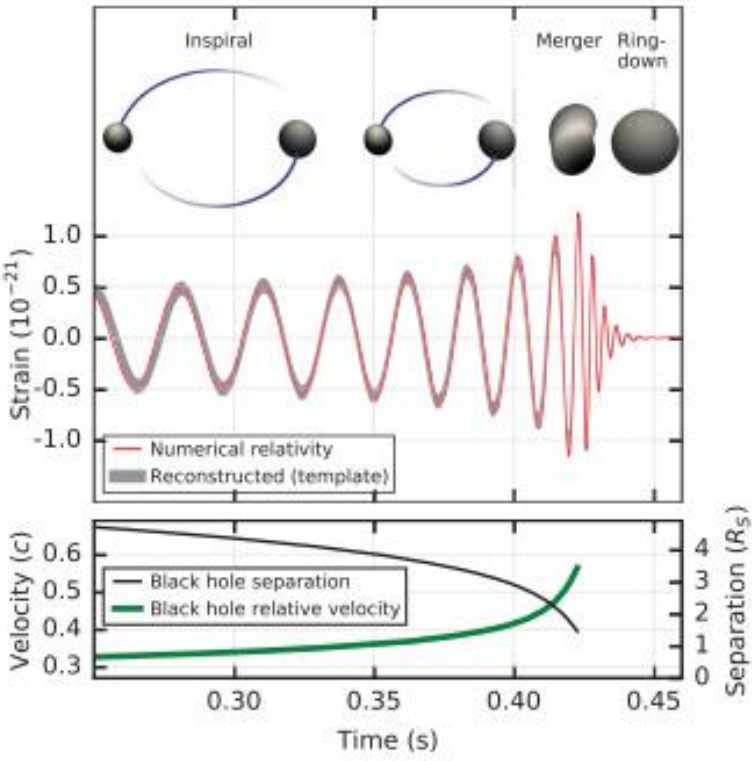
The LIGO Interferometer:

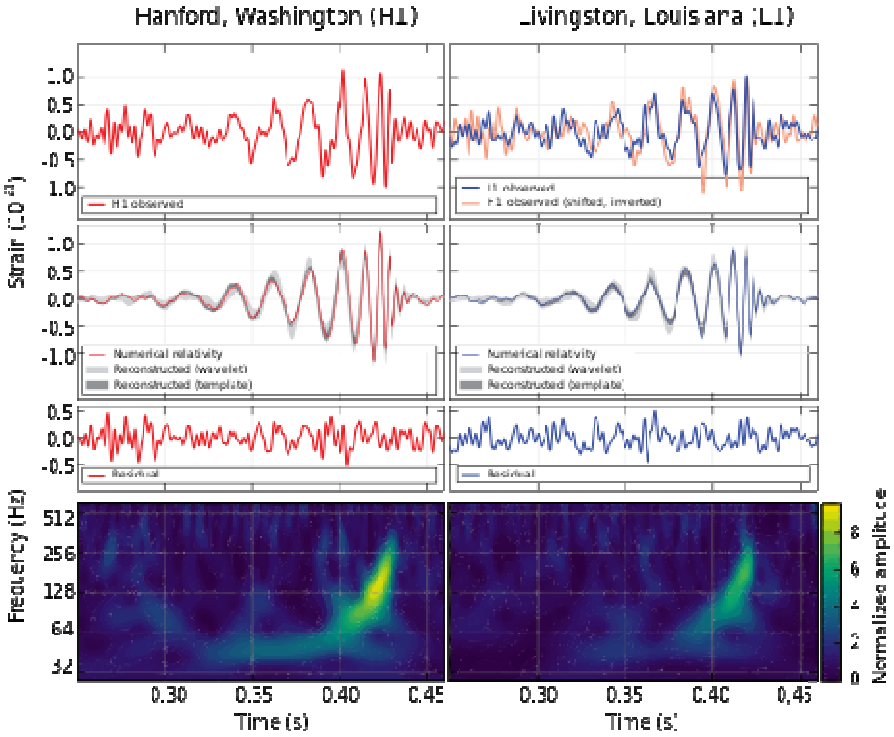


4. Gravitational Waves

4.2 Direct Measurement

September 14, 2015:
1st detection of
gravitational waves





By B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.116.061102,
CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=46987868

Compact Binary Inspiral Gravitational Waves

4. Gravitational Waves

4.3 The Future: Multi-Messenger Astrophysics

- Gravitational waves: The new cosmic messengers
- Investigate correlations of gravitational waves $\leftrightarrow$ CRs
- Merging black holes correlated with GBRs (Gamma Ray Bursts) may point to origin of rotating black holes

  A. Loeb: Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO, arXiv:1602.04735 [astro-ph.HE]
- Use arrays of detectors & spatially separated experiments to locate the origin of CRs $\leftarrow ? \rightarrow$ AGN

  Pierre Auger Collaboration: Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects. Science 09 (2007), pp. 938-943.

  - A targeted search for point sources of EeV photons with the Pierre Auger Observatory, arXiv:1612.04155 [astro-ph.HE]
- Fusion of Astroparticle Physics & Study of Gravitation

Marica Branchesi: Multi-messenger astronomy: gravitational waves, neutrinos, photons, and cosmic rays. XIV International Conference on Topics in Astroparticle and Underground Physics. http://iopscience.iop.org/article/10.1088/1742-6596/718/2/022004/pdf

4. Gravitational Waves

4.3 The Future: Multi-Messenger Astrophysics

A philosophical conclusion:

- Change of relation theory ↔ data
- **Mutual holism**:

  Body of **theoretical knowledge**
  ↔ Body of **independent empirical data**

- **Goal: A most complete body of empirical evidence** from **all** earthbound and satellite experiments

"This 'world detector' would, as required by Bacon, observe 'everything' at the same time. […] This however also means, that more information is barely possible." (Wolfgang Rhode, 2012)

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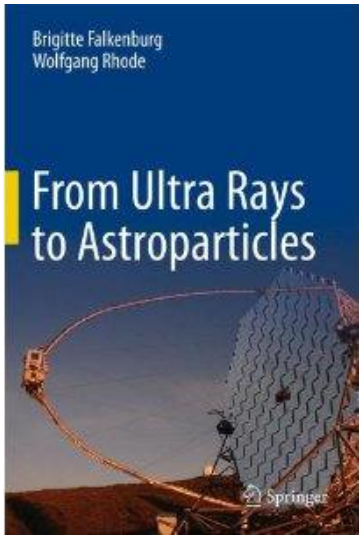
Thank you for your attention!



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4. W. Rhode, Introduction. In: B. Falkenburg and W. Rhode (eds.), *From Ultrarays to Astroparticles. A Historical Introduction to Astroparticle Physics*. Dordrecht: Springer 2012, 1–16.