The Causal Structure of Neutrino Observations

Brigitte Falkenburg

1. Causation in Physics

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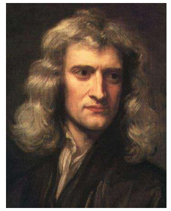
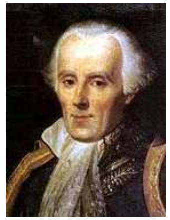




17th Century: Rationalism

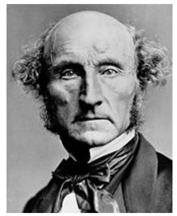
Causal Relations = Necessary & Deterministic

- Leibniz: Principle of Sufficient Reason
- Newton: Laws of Mechanics
- Laplace‘s Demon: Determinism

18th Century: Epistemic Turn

Causal Relations = Subjective, Not Objective

- Hume: Mere psychological habit
- Kant: Causality = Constitutive Principle of Experience



19th Century: Empiricism

Causal Relations = Mere Regularities

- Mill: Cause = Sufficient # of Necessary Conditions
- Causal Analysis, search for causally relevant factors

1. Causation in Physics

Today: What is Causation? Philosophy *vs.* Physics

- Regularity view (Hume, Mills, Mackie) ←?→ Laws of Nature
- Counterfactuals & Possible Worlds (Lewis) ←?→ Real World
- Interventionism/Manipulability (Woodward) ←?→ Causes in Nature
- Probabilistic Causation (Salmon) ←?→ Single Events
- Causal Mechanisms (Salmon, Glennon, …) ←?→ Quantum Theory

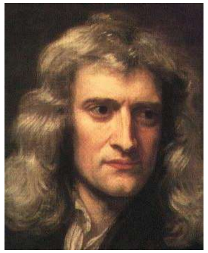
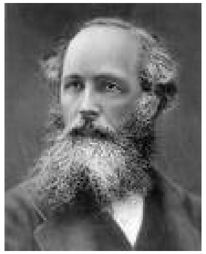
Problem of All Philosophical Accounts:

Physics ←!→ No Unified Account of Causation

1. Causation in Physics

Big debate in Philosophy of Science! (e.g. M. Frisch, 2021: "Causation in Physics", in: Stanford Enc. of Phil.)

BUT we have No Unified Laws of Physics:

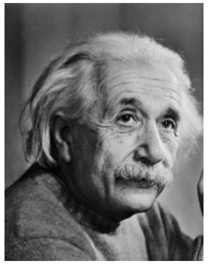



Classical Mechanics & Electrodynamics:

- deterministic system evolution
- reversible, no arrow of time.


Thermodynamics & Quantum Theory:

- probabilistic & indeterministic
- Irreversible, arrow of time



Special Relativity

- Einstein causality
- Signal transmission only within light cone ($v \leq c$)

1. Causation in Physics

Everyday Concept of Causality $\leftrightarrow$ 2 Aspects

- Necessity: Cause gives *necessarily* rise to the effect
- Temporality: Cause *precedes* the effect

Signal Transmission ←!→ Causal Process

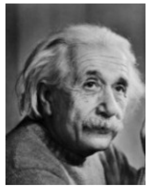



- Propagation: deterministic & reversible
  (electrodynamics & quantum wave functions)
- Detection: irreversible & indeterministic
  (thermodynamics & quantum measurement)

→ Signal transmission *alternately* deterministic & irreversible!

→ Strict law of nature & temporal order are *not realized at once*!

(However, Einstein causality *strictly holds* for *any* signal transmission & detection!)



2. Neutrino Observation

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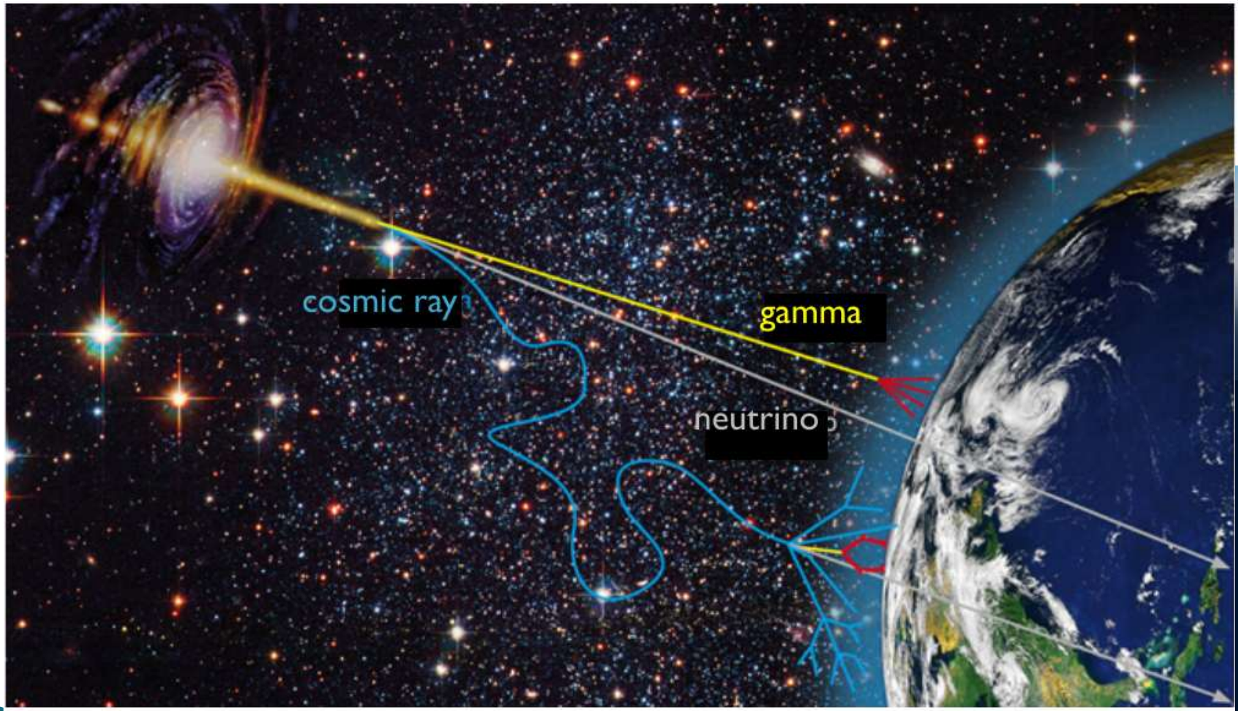
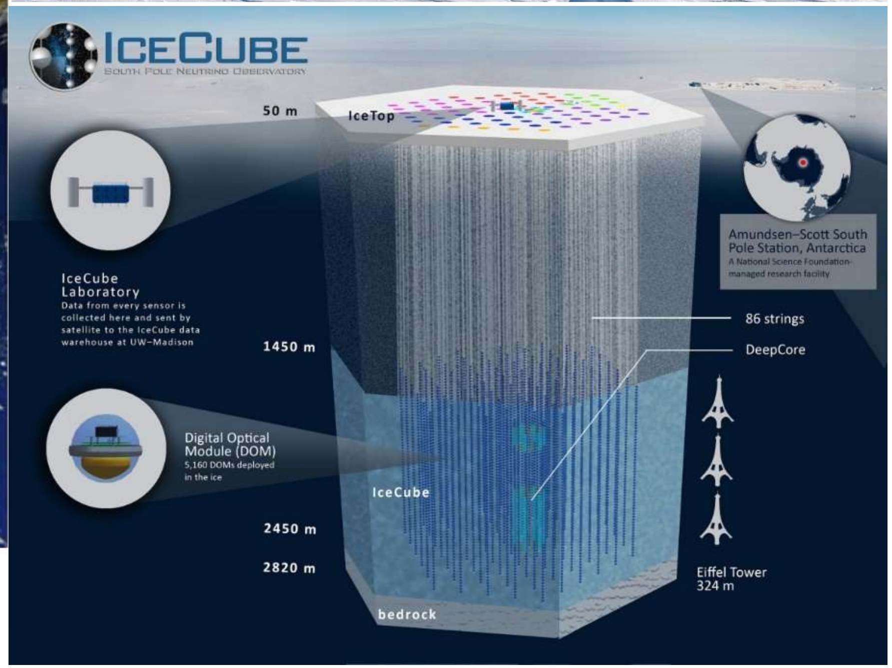
IceCube: Neutrino “Observatory”

1 km^3 telescope for neutrino detection

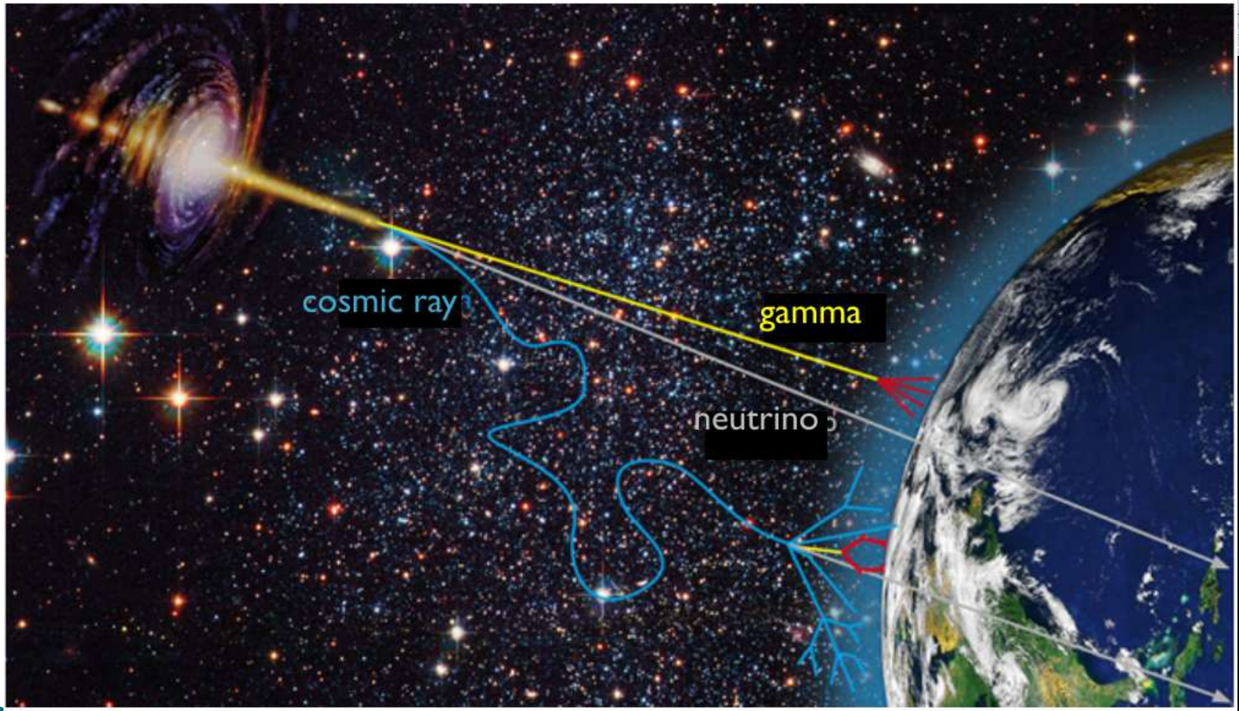


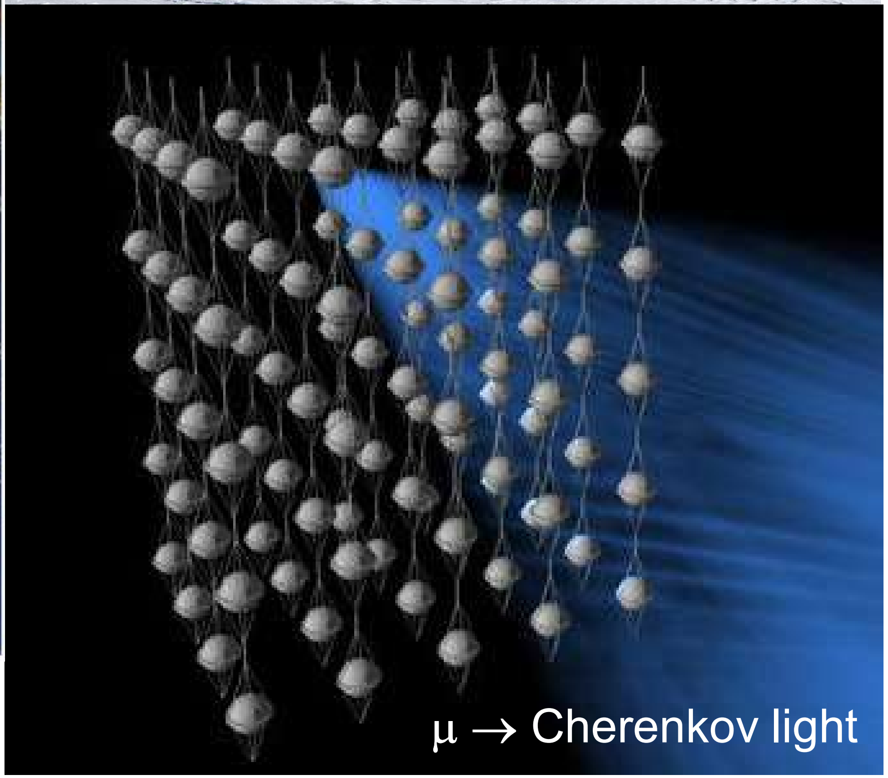


2. Neutrino Observation

Neutrino scattering in ice → muons

$\nu + Z \to \mu + X$ and $\mu \to$ Cherenkov light





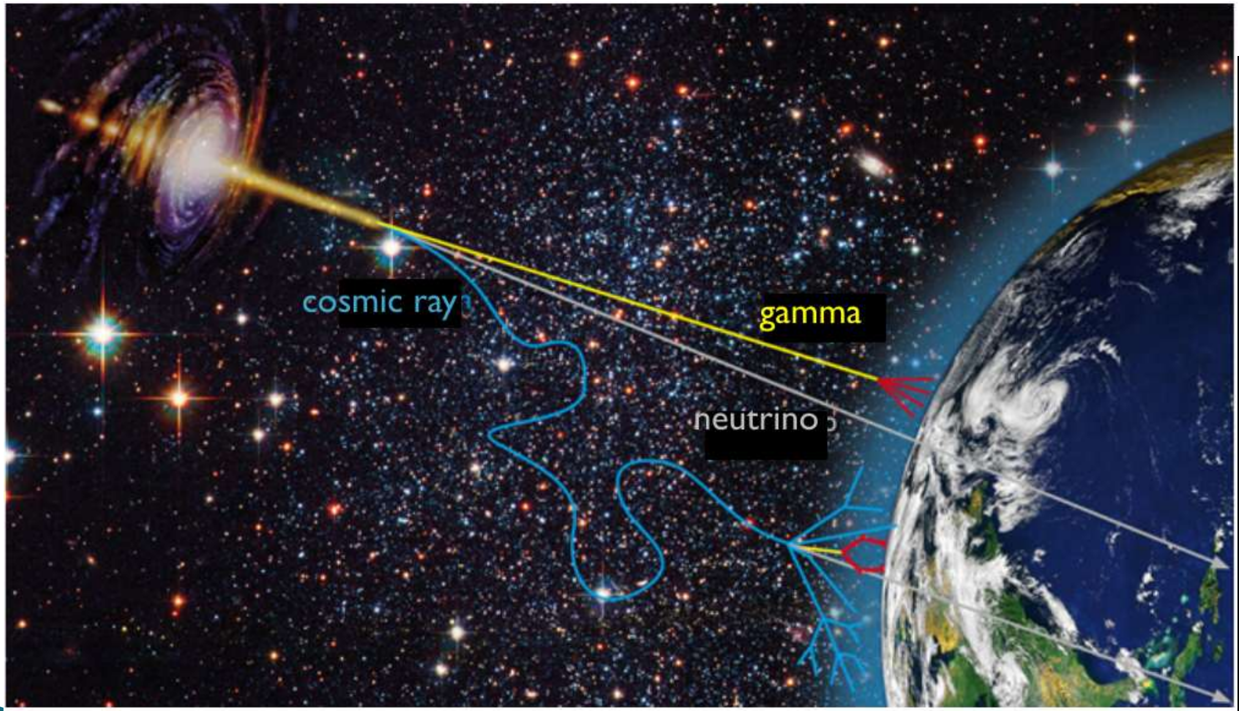
2. Neutrino Observation

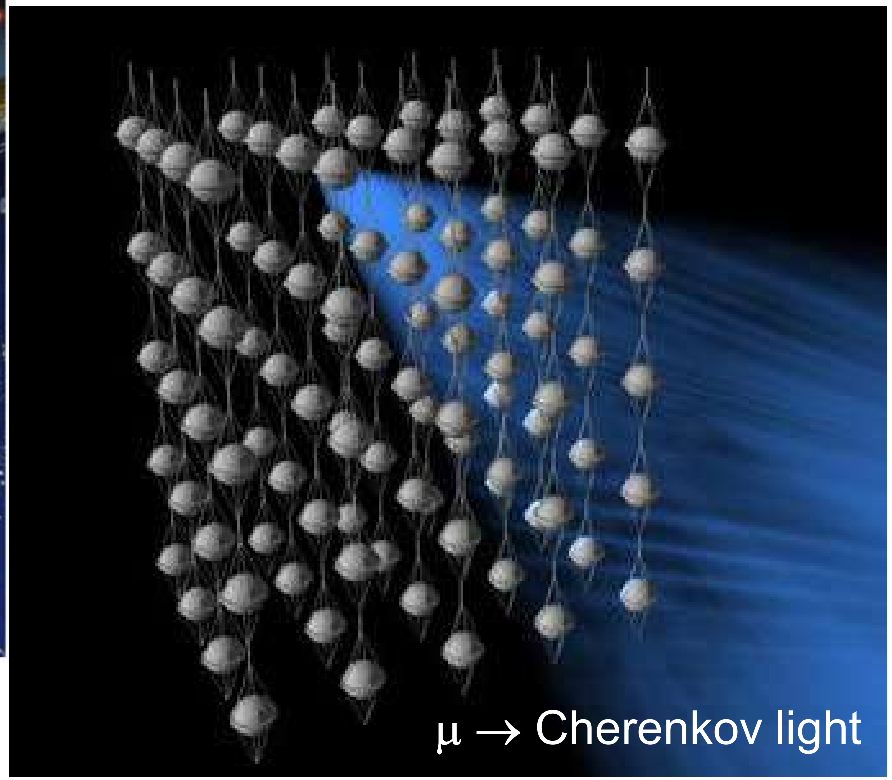
Measured quantities of ν
Direction
Energy
Relative Frequency

Signals: ν from cosmic sources
Background: ν from atmosphere

Physical problem:
Separation
Signals $\leftrightarrow$ Background

Statistical data analysis





2. Neutrino Observation

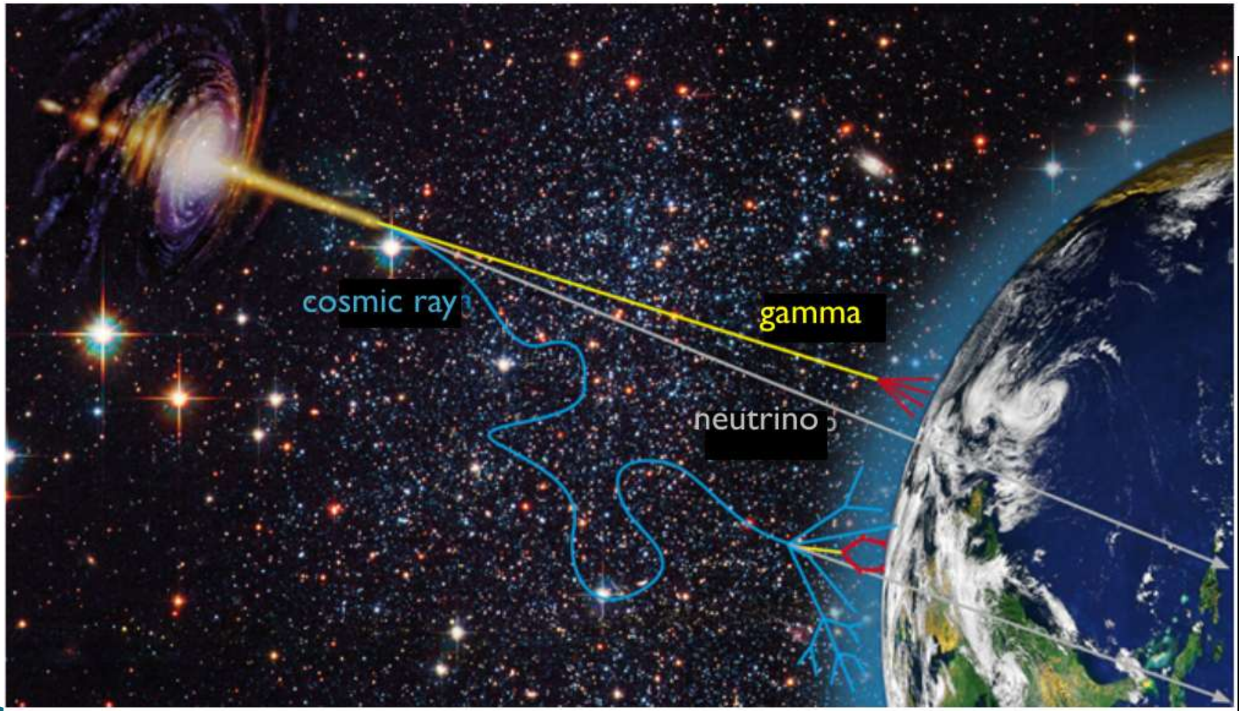
Measured quantities of ν
Direction
Energy
Relative Frequency

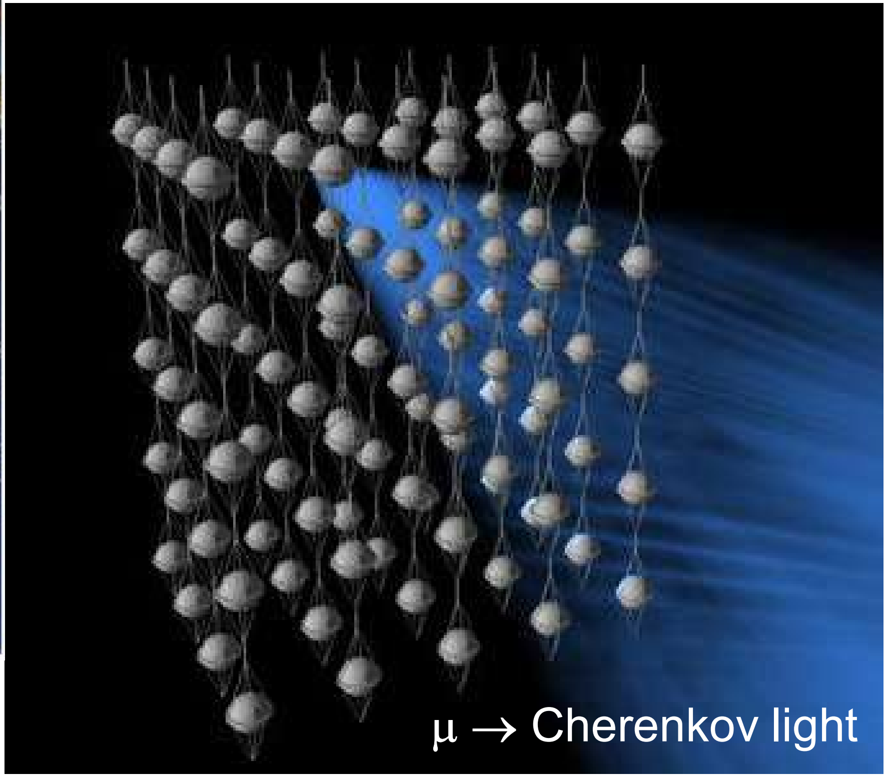
Physical problem:
Separation
Signals $\leftrightarrow$ Background

Statistical data analysis

In which sense is this an “observation”?

Indirect measurement of ν from secondary particle

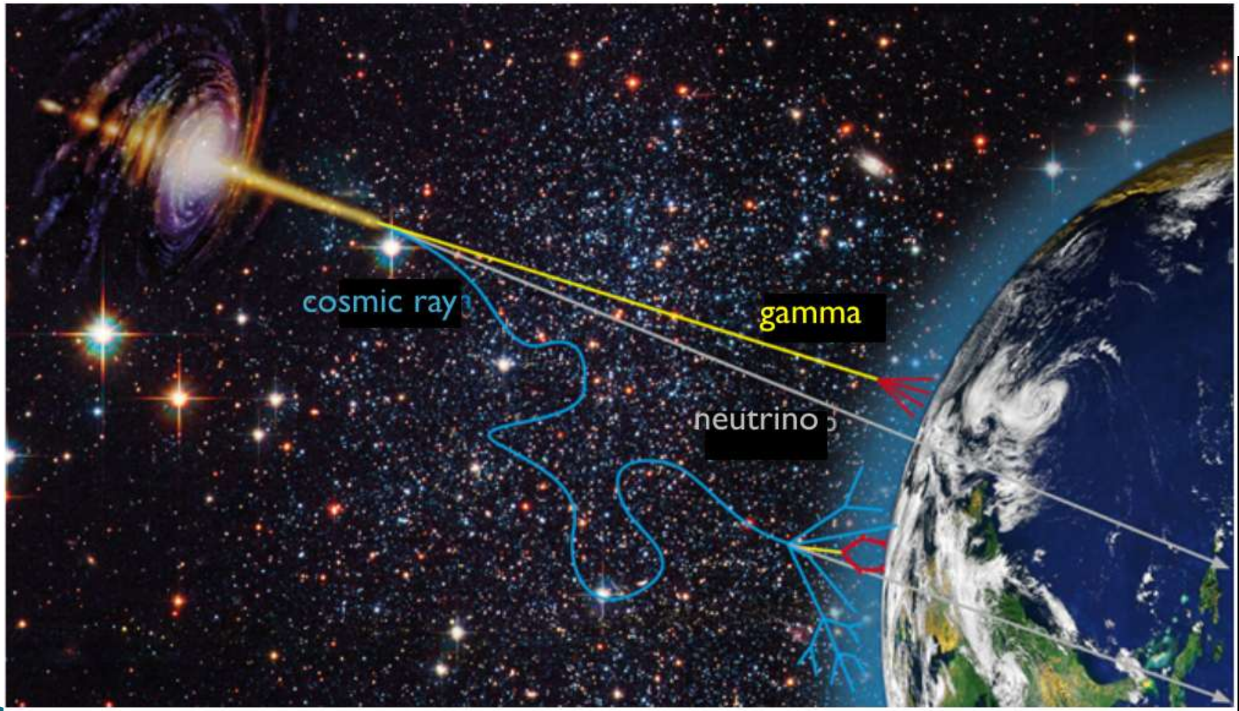


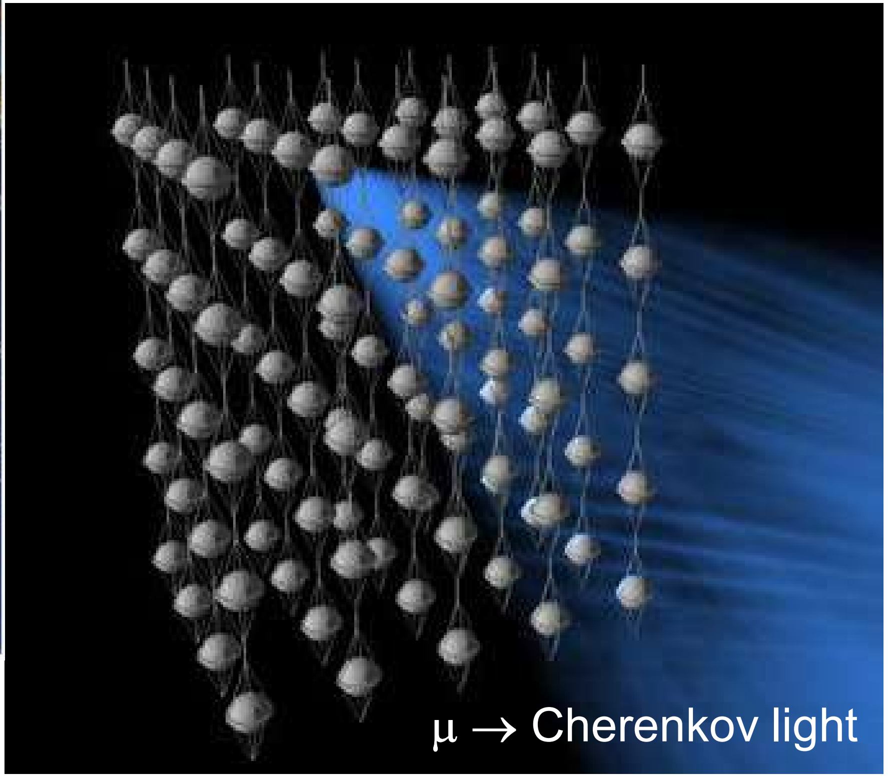


2. Neutrino Observation

Philosophy: Generalized Concept of “Direct Observation” (Shapere 1982)

Astroparticle Physics (APP): Generalized Concept of “Cosmic Messengers”





3. Cosmic Messengers

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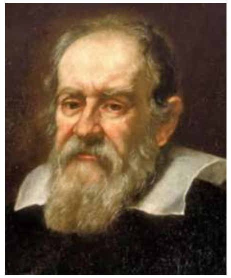


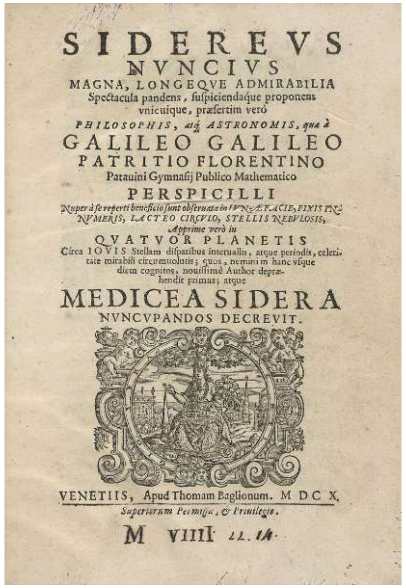
Galileo Galilei
(1504–1642)

Roots: Early Modern Science

Light, the cosmic messenger (astronomy)

Sidereal
Messenger
(1610)

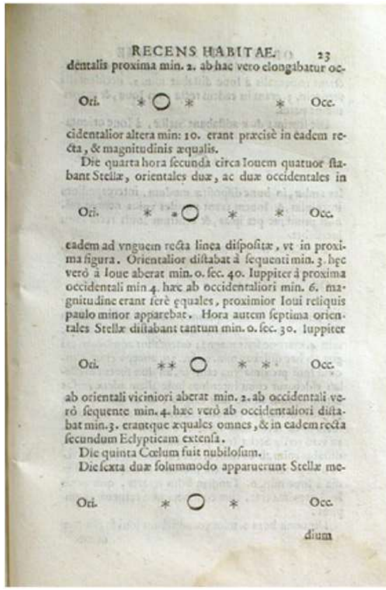
Observations with
the telescope
&
discovery of
Medicean Stars
(Jupiter moons)



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
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

M VIIII 22.14



RECENS HABITAE. 23

dentalis proxima min. 2. ab hac vero elongabatur oc-

Ori. * O * * Occ.

cidentalior altera min: 10. erant præcisè in eadem re-
cta, & magnitudinis æqualis.

Die quarta hora secunda circa Iouem quatuor sta-
bant Stellæ, orientales duæ, ac duæ occidentales in

Ori. * *O * * Occ.

eadem ad vnguem recta linea dispositæ, vt in proxi-
ma figura. Orientalior distabat à sequenti min. 3. hęc
verò à Ioue aberat min. o. sec. 40. Iuppiter à proxima
occidentali min 4. hæc ab occidentaliori min. 6. ma-
gnitudine erant ferè ęquales, proximior Ioui reliquis
paulo minor apparebat. Hora autem septima orien-
tales Stellæ distabant tantum min. o. sec. 30. Iuppiter

Ori. ** O * * Occ.

ab orientali viciniori aberat min. 2. ab occidentali ve-
rò sequente min. 4. hæc verò ab occidentaliori dista-
bat min. 3. erantque æquales omnes, & in eadem recta
secundum Eclypticam extensa.

Die quinta Cœlum fuit nubilosum.

Die sexta duæ solummodo apparuerunt Stellæ me-

Ori. * O * Occ.

dium

PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obseruatum, est ipsius-
met LACTEI Circuli essentia, seu materies, quam Per-
spicilli beneficio adeò ad sensum licet intueri, vt & alter-
cationes omnes, quæ per tot secula Philosophos excrucia
runt ab oculata certitudine dirimantur, nosque à verbosis
disputationibus liberemur. Est enim GALAXYA nihil
aliud, quam innumerarum Stellarum coaceruatim consi-
tarum congeries; in quamcunq; enim regionem illius Per-
spicillum dirigas, statim Stellarum ingens frequentia se se
in conspectum profert, quarum complures satis magnæ, ac
valde conspicuæ videntur, sed exiguarum multitudo pror-
sus inexplorabilis est.

At cum non tantum in GALAXYA lacteus ille candor,
veluti albicantis nubis spectetur, sed complures consimilis
coloris areolæ sparsim per æthera subfulgeant, si in illarum
quamlibet Specillum conuertas Stellarum constipatarum

cętum

3. Cosmic Messengers

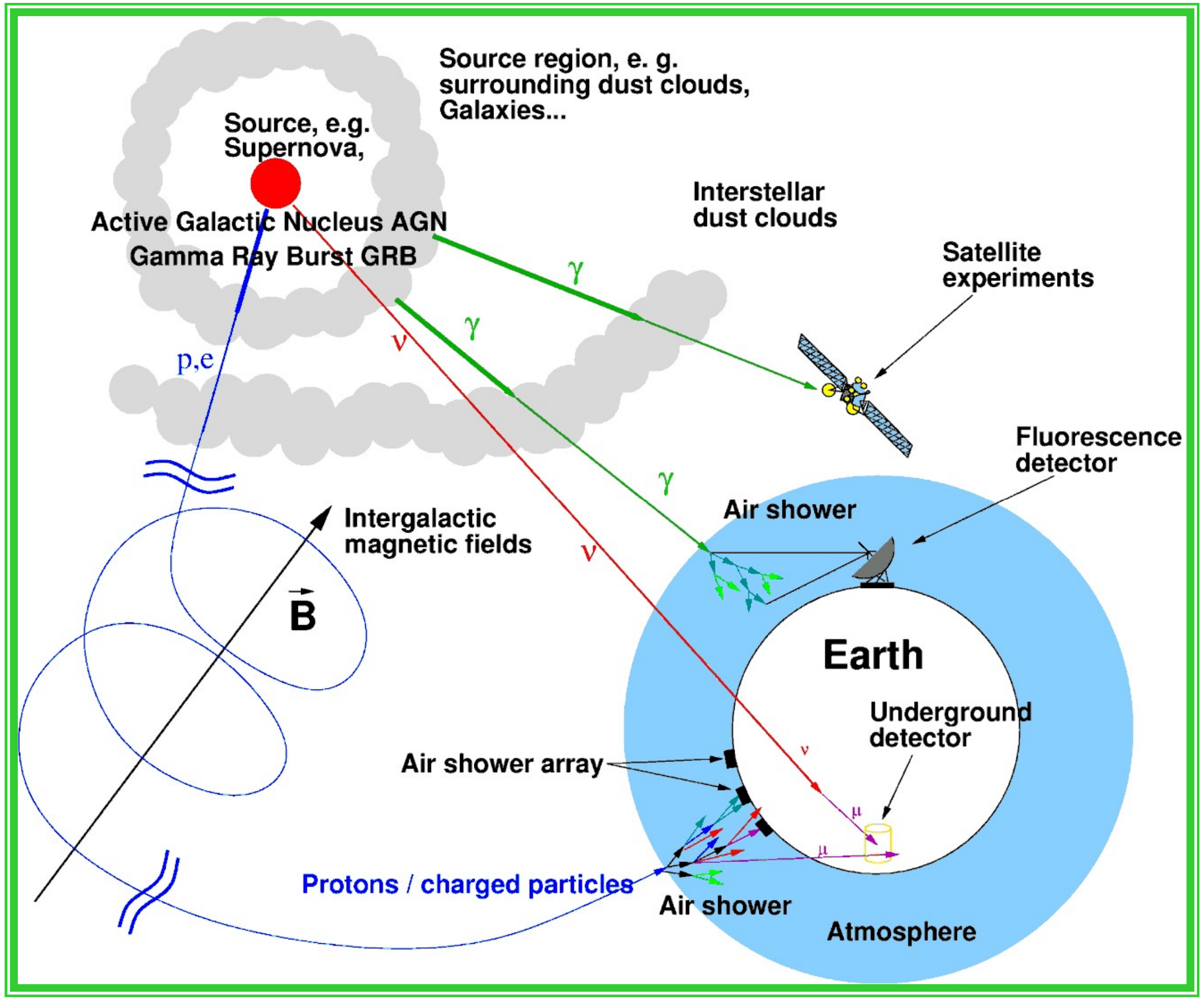
Generalization in APP:
Light → Messenger Particles

Gamma & Neutrino Telescopes *observe* Cosmic Sources

just as Galileo *observed* Jupiter Moons

("direct observation" generalized: D. Shapere 1982)

Proton detection in most cases does not!



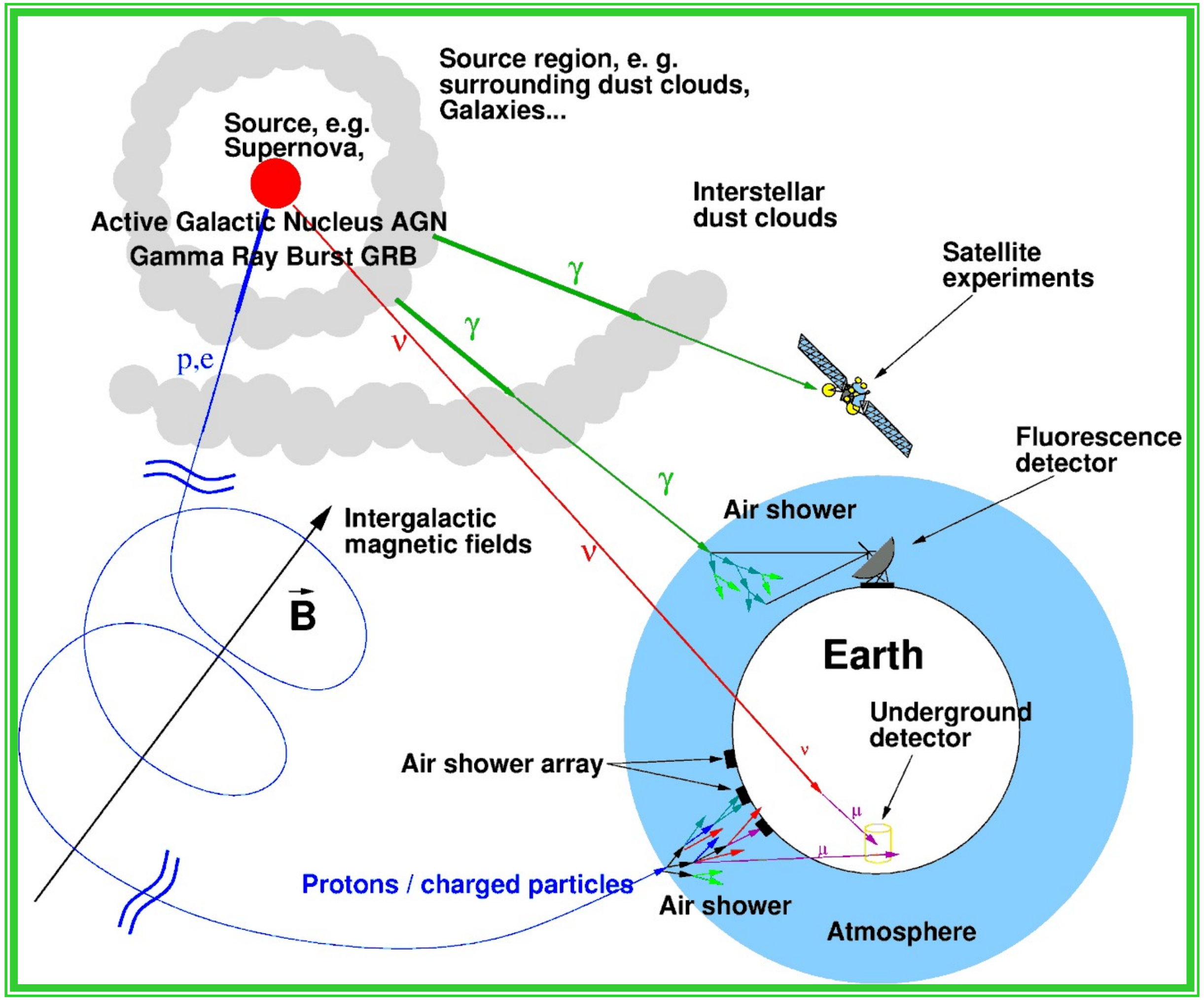
3. Cosmic Messengers

Generalization in APP:
Information transfer by γ and ν

Cosmic Rays
carry information
from
Cosmic Sources

Information
= signal transmission
from emitter
to receiver

= particle propagation
from source
to detector



3. Cosmic Messengers

Result:
Causal-Mechanical Model
of Messenger Particles

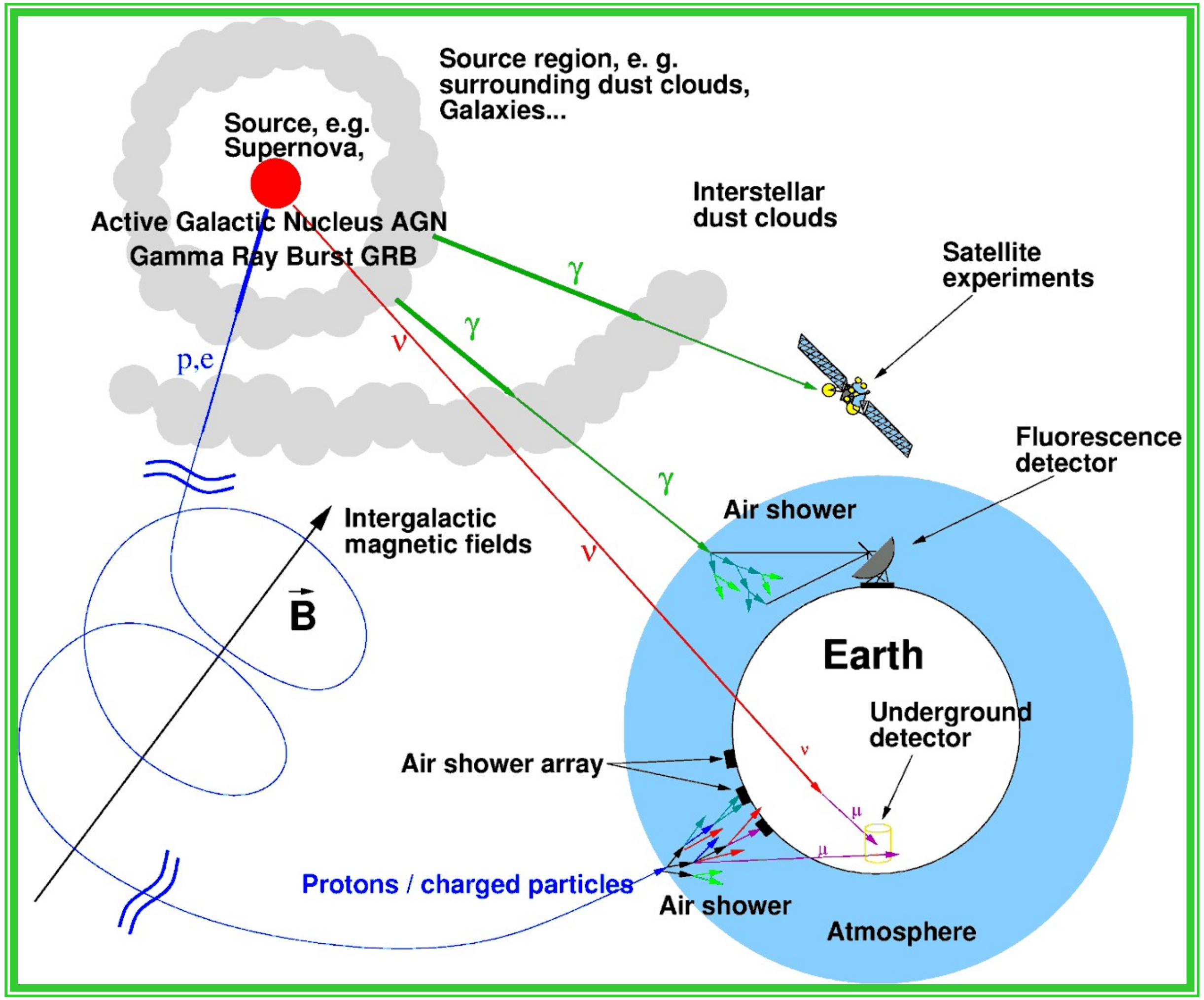
Causal-mechanical explanation:

→ transmission of a conserved quantity (W. Salmon 1984)

→ signal transmission = process of information transfer

Causal explanation in physics:

→ signal transmission (Einstein causality!)



Result:
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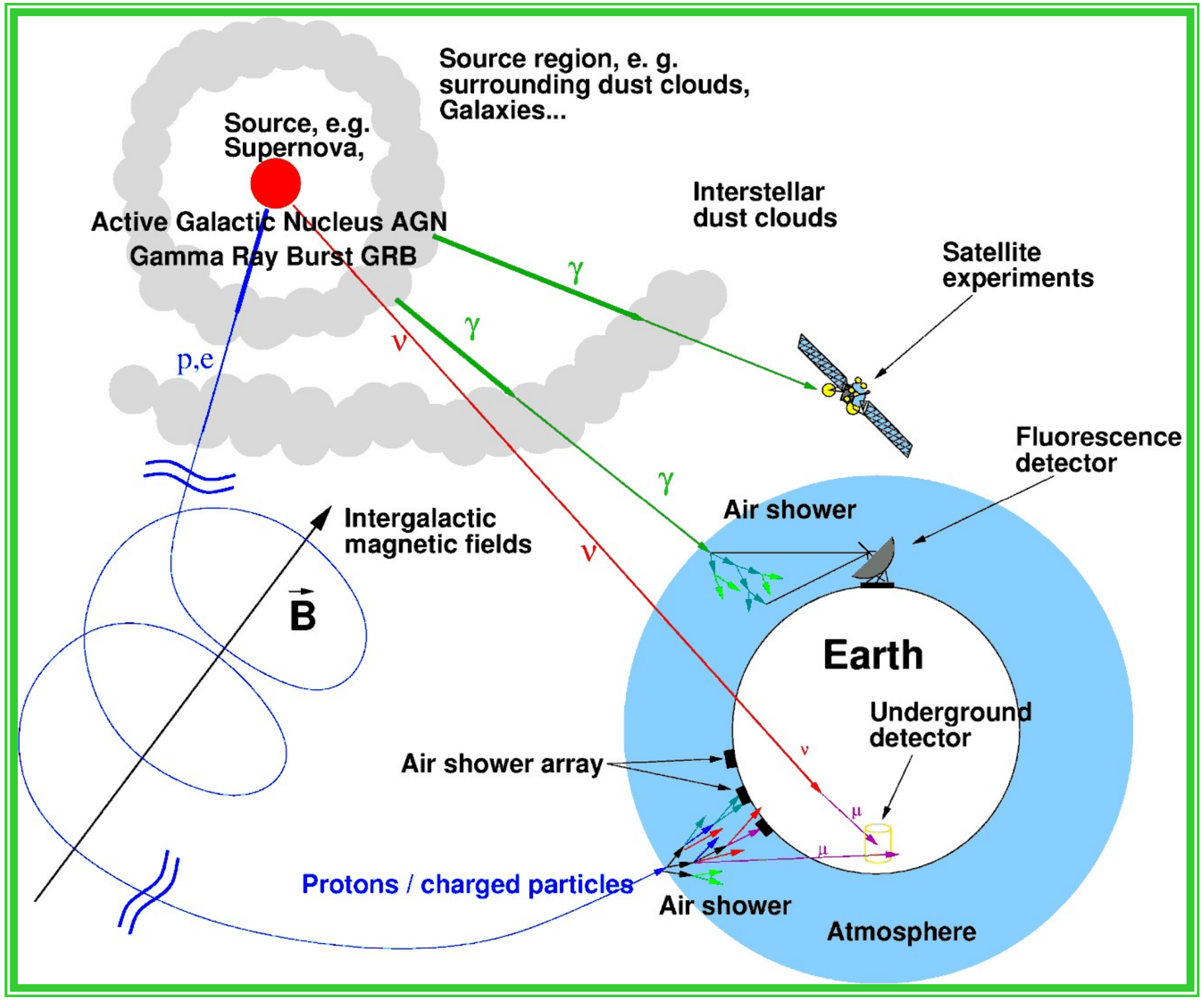
3. Cosmic Messengers

Cosmic Rays
transmit signals from
Cosmic Sources to Earth

Problem:
Disparate Foundations!

Cosmic sources &
Interstellar space
↔ Relativistic Cosmology

Particle propagation
& particle detection
↔ Quantum Field Theory



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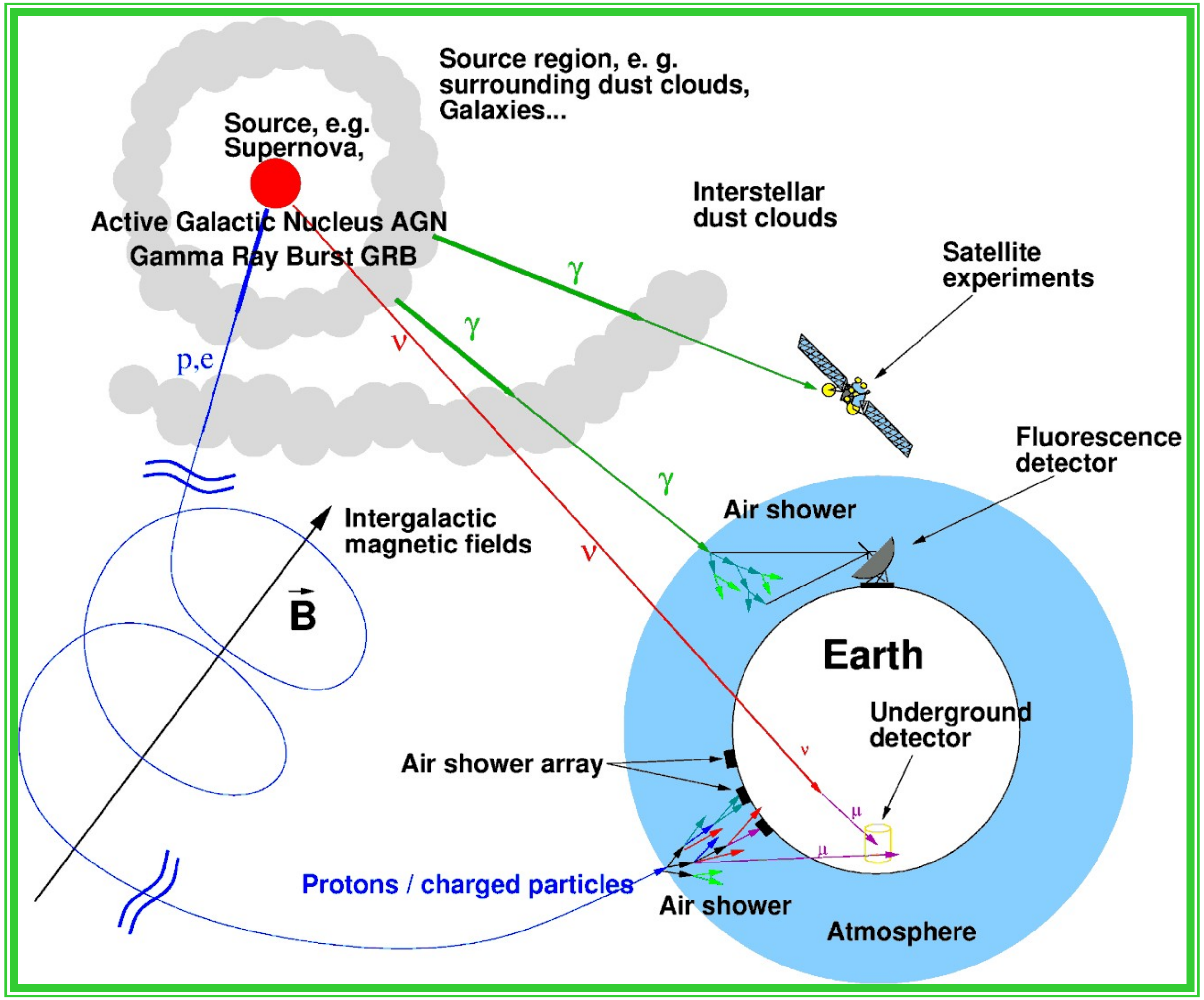
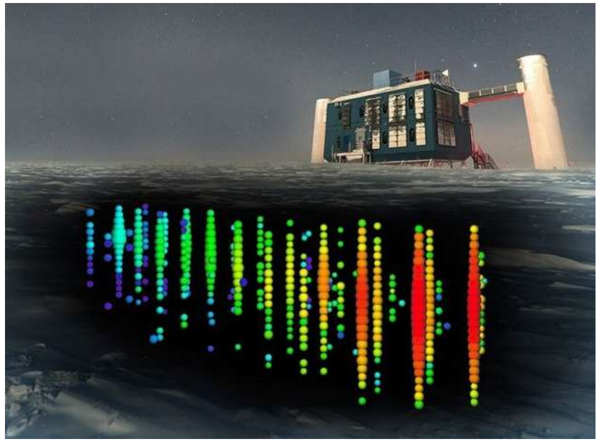


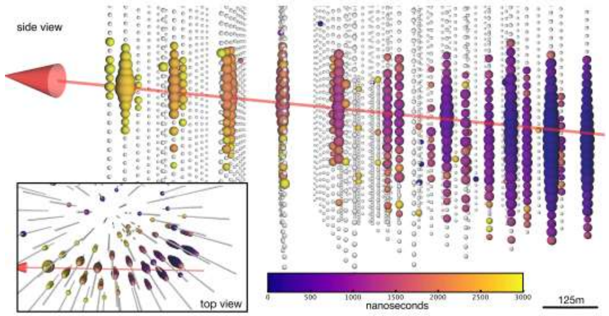
3. Cosmic Messengers

IceCube: ν Signal →
automatic alert to
other ν and γ telescopes

IceCube ν Signal of 2017: Coincidence

with signal from γ-ray blazar TXS 0506+056





- Signal of 2017: ν from below

  Known: direction & energy
  Unknown: cause (= kind of cosmic source)

- Embedded in multi-messenger astronomy

  Automatic alert to *other* telescopes:
  Coincidences help to *identify source*
  → γ rays from blazar TXS 0506+056

- Standard-search for additional evidence!

  Coincidences → Common Cause Argument
  ν signal + γ rays **=** “smoking gun”

- „Sherlock Holmes Method“

  ...probabilistic identification of cause!

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3. Cosmic Messengers

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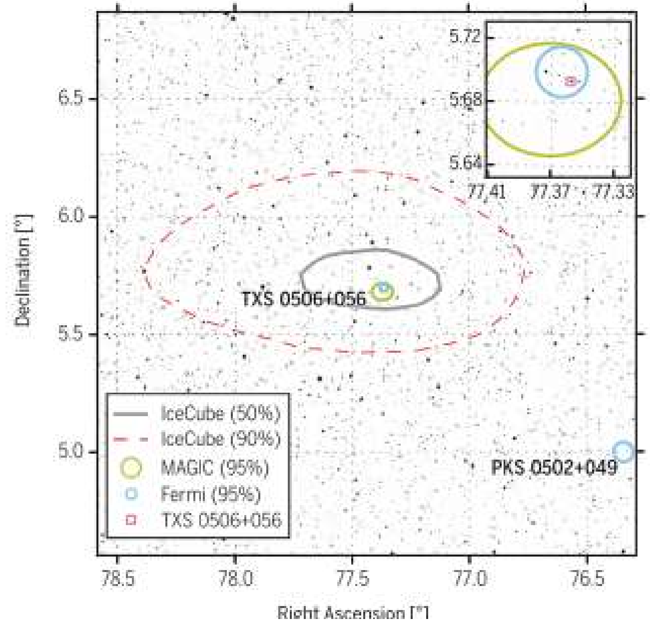

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  ...probabilistic identification of cause!

The IceCube Collaboration *et al.*, *Science* **361**, eaat1378 (2018)

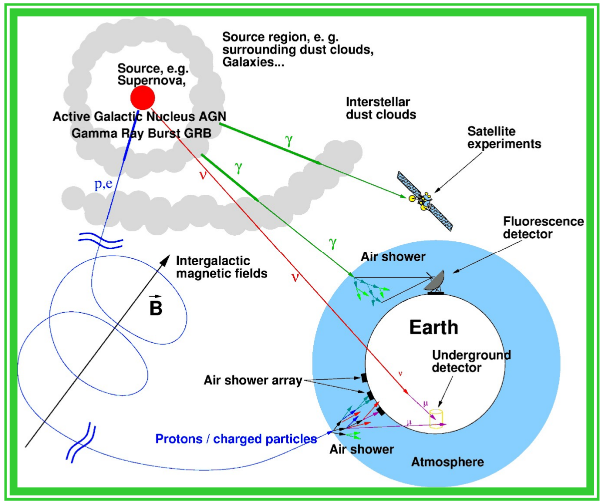
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

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*†

Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electron volts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray–emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

4. Quantum Properties

4. Quantum Properties



Goal of APP: Explain origin of CRs

Model of cosmic messenger particles

↔ Causal-mechanistic model (Salmon 1984), in *probabilistic* terms!

Epistemological remarks:

(1) Cosmic messenger "particles" are field quanta of quantum fields!

» Production & propagation ↔ quantum processes, described by QFT

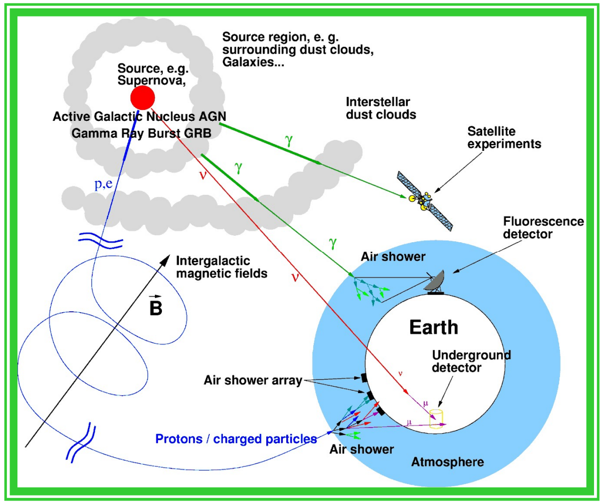
» Neutrino oscillations ↔ quantum superposition $|\nu_e\rangle + |\nu_\mu\rangle + |\nu_\tau\rangle$

» Signature of IceCube signal ↔ measurement of ν_e *or* ν_μ *or* ν_τ

» Loose talk of "particles" ↔ misleading for non-physicists!

Ironically, Shapere (1982) demonstrated his generalized concept of observation in a case study about observing the interior of the sun by the solar neutrino flux, not knowing about neutrino oscillations.

4. Quantum Properties



Goal of APP: Explain origin of CRs

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Epistemological remarks:

(2) Causality ↔ *Signal transfer* from source to detection

» Transmission of a conserved quantity (=energy)

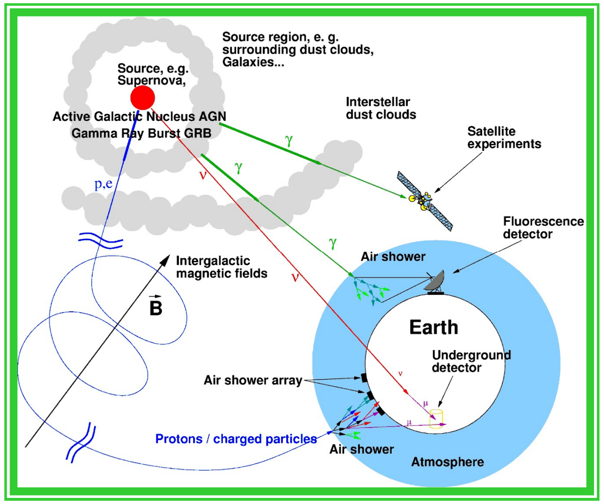
» Einstein causality holds for any signal / single event

» Energy transfer can be calculated

» Reconstruction of a *probable* causal story

» Specific source of a ν signal ↔ additional evidence required
↔ search for coincidence with other signals
↔ multi-messenger astronomy

4. Quantum Properties



Goal of APP: Explain origin of CRs

Model of cosmic messenger particles

↔ Causal-mechanistic model (Salmon 1984), in *probabilistic* terms!

Epistemological remarks:

(3) We deal with *epistemic* probability, here!

» Production & propagation ↔ quantum processes, described by QFT

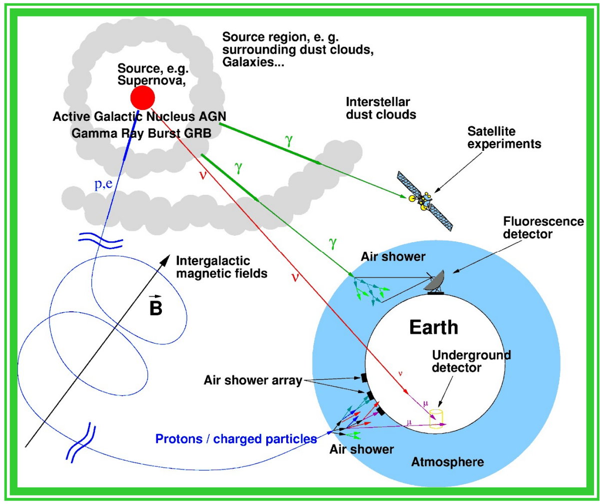
» Detection of a CR signal ↔ *measurement* that “objectifies” the process

» Signature of ν signal ↔ specific kind of neutrino that was measured

» Data analysis of CR signals ↔ *post-factual* reconstruction of origin of CRs
↔ *retrodiction* of a quantum process

» Astronomic sources of CRs ↔ Macroscopic objects

4. Quantum Properties



Goal of APP: Explain origin of CRs

Model of cosmic messenger particles

$\leftrightarrow$ Causal-mechanistic model (Salmon 1984), in *probabilistic* terms!

Epistemological remarks:

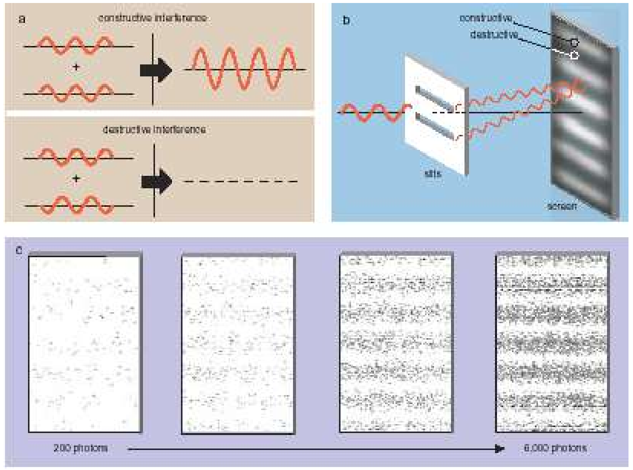
(4) Only the neutrino oscillations result in *ontic* probabilities, here!

» Detection of a ν signal $\leftrightarrow$ *measurement* that “objectifies” the kind of ν

» Neutrino oscillations $\leftrightarrow$ relative frequencies of ν_e *or* ν_μ *or* ν_τ signals

» Analogous case $\leftrightarrow$ Which Way-Experiments of Quantum Optics (double slit experiment with single photons or atoms, Mach-Zehnder interferometer, etc.)

Walborn et al., *Quantum Erasure*, American Scientist 91(2003), 336



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» Detection of a ν signal ↔ *measurement* that "objectifies" the kind of ν

» Neutrino oscillations ↔ relative frequencies of ν_e *or* ν_μ *or* ν_τ signals

(5) Analogous case: Which Way-Experiments of Quantum Optics!

» Double slit experiment ↔ Propagation of quantum superposition (deterministic, reversible)

↔ Detection of single photon or atom (indeterministic, irreversible)

5. Conclusions

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1. Causation in Physics

- Philosophy: Determinism / Regularity View / Causal mechanisms / **…**
- Pre-Theoretical Concept: Causation = Strict & Time-Asymmetric

Physics ←!→ No Unified Account of Causation

- Classical Physics → deterministic & reversible processes
- Thermodynamics → irreversible processes & time arrow
- Quantum Theory → deterministic evolution of wave function & indeterministic measurement results
- Special Relativity → Einstein Causality (universally valid)

Signal transmission as *paradigmatic* causal process:

- Signal propagation: *deterministic & reversible*
- Signal detection: *indeterministic & irreversible*

Best fit with philosophy: Causal-mechanical explanation, BUT given in probabilistic terms

5. Conclusions

2. Neutrino Observation

- IceCube = Neutrino Observatory
- Indirect measurement of ν via Cherenkov light of secondary particle
- In which sense “observation”?

3. Cosmic Messengers

- Generalization: Light → Cosmic Messenger Particles
- Transmission of signals from cosmic sources to Earth
- Causal-mechanical explanation, in probabilistic terms
- Identification of signal origin ←!→ Multi-messenger astronomy

4. Quantum Properties

- Cosmic messengers are subject to QFT → Caution with “particle” talk!
- Causal story of origin → post-factual reconstruction & *epistemic* probability
- Neutrino oscillations → *ontic* probabilities of ν_e *or* ν_μ *or* ν_τ signals
    - Analogy with Which Way Experiments of Quantum Optics!

Thank you for your attention!

- Falkenburg, B., and W. Rhode: Research Project FA 261/19-1 & RH 35/13-1, DFG (German Research Foundation), https://app.physik.tu-dortmund.de/en/research/philosophy-of-astroparticle-physics/
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