Multi-messenger astronomy
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Astronomical signals from kHz to ZeV

- Gravitational waves
- Gamma-rays
- Neutrinos
- Cosmic rays
- Blazars
- Radio galaxies
- Gamma-rays
- Neutrinos
- Cosmic rays
- Neutron stars / stellar mass black holes / Gamma-ray bursts
- Milky Way and local interstellar medium

Energy / frequency:
- 1 kHz
- 1 GHz
- 10^{15} Hz
- 1 MeV
- 1 TeV
- 1 EeV
- 1 ZeV
Universe from kHz to ZeV

photons: Multi-wavelength astronomy

radio

very-high-energy gamma-ray
Universe from kHz to ZeV

photons: Multi-wavelength astronomy

gravitational waves

Multi-messenger astronomy

"astrophysical" ν (?)

ν (Sun, SN1987A)

UHECR (?)
Multi-messenger signal from gravitational wave bursts

- GW150914 (LIGO)
- GRB 090510 (short GRB, Fermi-GBM, Fermi-LAT)
- γ from the Sun
- γ from SN 1987A
- Visible stars

Energy / frequency:
- 1 kHz
- 1 GHz
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- 1 EeV
- 1 ZeV

log (Flux) [erg/(cm$^2$ s)]
Combined LIGO + INTEGRAL data confirm generic expectation that black hole mergers are not generically expected to produce electromagnetic / neutrino / cosmic ray emission.

GW150904
INTEGRAL / SPI-ACS

Savchenko et al. (2016)
Reference model of high-energy emission from GRBs is based on particle acceleration in relativistic outflow from a black hole formed in the collapse of a massive star or in a merger of neutron stars.
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Nature of electromagnetic emission components of GRBs is not established.

Particle content of relativistic outflows is not well constrained.

Interactions of high-energy protons in GRB outflow could lead to production of neutrinos and initiate electromagnetic cascade.

Multi-messenger signal from GRBs

GRB 090510
γ, Fermi-GBM, Fermi-LAT

“Band” component

High-energy component
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GRB 090510
\(\gamma, \text{Fermi-GBM, Fermi-LAT}\)

\(p + \gamma \rightarrow (p, n) + \pi^0,\pi^\pm\)

\(\gamma + \gamma \rightarrow e^+ + e^-\)

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GRB outflows could potentially accelerate protons to UHECR energies.

IceCube upper limit on GRB flux rules out the possibility that GRBs are responsible for the observed UHECR flux.

IceCube Collab (2012, 2016)
Astrophysical neutrino signal

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GRBs are also not the dominant source of astrophysical neutrino flux.

IceCube Collab (2013-2016)
The flux of astrophysical neutrino signal detected by IceCube in “throughgoing muon neutrino” channel could be produced by same sources that generate UHECR flux.
The flux of astrophysical neutrino signal detected by IceCube in “throughgoing muon neutrino” channel could be produced by same sources that generate UHECR flux.

Estimate of neutrino flux from UHECR sources is, however, inconsistent with the IceCube signal detected in the “high-energy starting events” (HESE) channel.
Pierre Auger Observatory and Telescope array have accumulated a sample of >300 UHECR events (E>5x10^{19} eV). No significant excesses corresponding to individual UHECR sources are detected.

Brightest UHECR sources are bound to have fluxes below ~10^{-12} erg/(cm^2 s).

The most significant anisotropy feature observed is a 3.4 sigma (post-trial) 20-degree-wide “hot spot” reported by Telescope array.

This is the first possibly first astronomical UHECR source. Large angular width of the hotspot has to be explained:
- Galactic/intergalactic magnetic field?
- UHECR particle electric charge?
Multi-messenger signal from blazars

Telescope Array sky map smoothed with 20 degrees
Fermi/LAT gamma-ray map above 100 GeV

Brightest extragalactic source of very-high-energy gamma-rays: Mrk 421 (a “blazar”)
Multi-messenger signal from blazars

Brightest extragalactic source of very-high-energy gamma-rays: Mrk 421 (a “blazar”)

UHECR are ejected into a directed beam by supermassive black holes in blazars?
Reference model of high-energy emission from blazars is based on particle acceleration in relativistic jet ejected by a supermassive black hole.

Similarly to the GRB case, it is not clear if the jet carries also high-energy protons.
IceCube sensitivity has reached the level sufficient for ruling out hadronic models of blazars based on $pp$ interactions.
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... and for constraining hadronic models of blazars based on $p\gamma$ interactions (lower bound on the energy threshold of $p\gamma$ reaction).
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... IceCube rules out hadronic models of based on \( p\gamma \) with UV radiation from the accretion disk around black hole.

Cumulative gamma-ray flux from Fermi blazars

IceCube upper bound on flux from stacked Fermi blazars sample

IceCube Collab. (2016), AN et al. (2016)
IceCube data rule out the possibility that gamma-ray detected blazars provide dominant contribution to the astrophysical neutrino flux.
Even if blazars are not powered by interactions of high-energy protons and they are not the source of IceCube astrophysical neutrino signal, they could carry protons with energies up to UHECR range and produce neutrinos.

IceCube has sufficient sensitivity to test the hypothesis of association of the UHECR hot spot with the nearest blazar Mrk 421.
Multi-messenger signal from radio galaxies

- $\log$ (Flux) [erg/(cm$^2$ s)]
- Energy / frequency

- Radio galaxy M87
- $e^-$, $e^+$, $\gamma$
- VLA, ALMA, VLT, Chandra, Fermi, HESS

- $1$ kHz $1$ GHz $10^{15}$ Hz $1$ MeV $1$ TeV $1$ EeV $1$ ZeV

- Mul$-$messenger signal from radio galaxies
Multi-messenger signal from radio galaxies

\[ \log (\text{Flux}) \quad \text{erg/(cm}^2\text{s)} \]

-12
-11
-10
-9

Energy / frequency

1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV

-13

\((p, n) + \gamma, p \rightarrow (p, n) + \pi^0, \pm\)

\(\gamma + \gamma \rightarrow e^+ + e^-?\)
IceCube sensitivity has reached the level sufficient for constraining hadronic models of radio galaxies based on both $pp$ and $p\gamma$ interactions.

Auger and TA sensitivity is largely enough to detect UHECR signal from nearest radio galaxies, if their isotropic cosmic ray flux extends to UHECR range.

Radio galaxies could be still be responsible for the astrophysical neutrino signal in “throughgoing muon” channel.

However, they would not explain the signal detected in Hight-Energy Starting Events (HESE).
Multi-messenger signal from Milky Way (?)

Spectral properties of the HESE signal (above 30 TeV) match those of the gamma-ray signal below 3 TeV, which is dominated by the flux from cosmic ray interactions in the Milky Way.

3σ evidence for anisotropy of HESE neutrino signal in the direction of Galactic Plane is observed.

AN, Semikoz (2014-2016)
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HESE astrophysical neutrino flux dominated by the Southern Hemisphere and provides a measurement of the spectrum of cosmic rays in the inner Milky Way disk.

Slope of γ-ray spectrum of inner Galactic disk

“Characteristic” slope of the cosmic ray spectrum in the Milky Way is 2.5, rather than 2.7.

Properties of the local cosmic ray spectrum are affected by local star formation history and by the last nearby supernova.

Multi-messenger signal from local cosmic ray source

Kachelriess et al. '15
Wallner et al. '15

Rate of $^{56}$Fe deposits at Earth

Erlykin & Wolfendale (1997)
Cosmic rays from the last supernova are contained in an expanding “cocoon”. Interactions in the interstellar medium lead to deposition of positrons and antiprotons in the cocoon, with the spectrum which repeats that of the supernova cosmic rays.
Summary

Gravitational waves

Gamma-rays

Neutrinos

Cosmic rays

Blazars

Radio galaxies

Gamma-rays

Neutrinos

Cosmic rays

Positrons antiprotons

Neutron stars / stellar mass black holes / gamma-ray bursts

GW 150914
GRB 090510

Gamma-rays

Neutrinos

Cosmic rays

Mrk 421

M 87

Milky Way and local interstellar medium

2 Myr old local supernova

What is the mechanism of formation and particle content of black hole jets?

What extragalactic sources produce UHECR?

What Galactic source(s) produces GeV-PeV cosmic rays?

What sources produce astrophysical TeV-PeV neutrinos?

Is there unexplained multi-messenger signal which could be attributed to DM?