Multi-messenger Astrophysics: Probing Compact Objects with Cosmic Particles

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Stanford University
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Compact Objects

Why are compact objects interesting?
• The brightest objects in the Universe
• Extremely strong gravity
• Many unknowns including how they are formed, how they interact with their environment, how they radiate

Multi-messenger provide a new way to study compact objects
Multi-messengers: what are they?

How do we use them?
Multi-messengers: what are they?
Multi-messengers:
Different types of particles and waves sent by our Universe

Cosmic particles:
High-energy photons, cosmic rays, and neutrinos produced by extreme activities of the Universe.
Cosmic Electromagnetic Radiation Background

Temperature [K]

10^3  10^6  10^9  10^{12}

CMB

Infrared

Optical

UV

X-Ray

γ-ray

Radio

Lacasa (2014)

Big bang

Galaxies & stars

Active Galactic Nuclei, starburst galaxies

eV  keV  MeV  GeV  TeV

6
Cosmic Electromagnetic Radiation Background

Fermi IACTs

Attenuated by extragalactic background lights

Auger

HAWC

Fermi

E\ [\text{GeV}]

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$

$\Phi \ [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$10^{-1}$ $10^{1}$ $10^{3}$ $10^{5}$ $10^{7}$ $10^{9}$ $10^{11}$

HAWC 100 TeV Sources

PRELIMINARY

Radio

Optical

UV

X-Ray

Y-ray

CMB

3 x 10$^3$ $10^6$ $10^9$ $10^{12}$

Frequency [Hz]

$10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$

$\Phi \ [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$10^{-1}$ $10^{1}$ $10^{3}$ $10^{5}$ $10^{7}$ $10^{9}$ $10^{11}$

Radio

Optical

UV

X-Ray

Y-ray

CMB

3 x 10$^3$ $10^6$ $10^9$ $10^{12}$

Frequency [Hz]
Cosmic Rays

Man-made accelerators

Victor Hess 1912
Cosmic Rays

Sources Unknown!
Compact objects provide promising sites for extreme-energy particle acceleration.
Cosmic Neutrino Background

- 3 sigma source identified: TXS 0506+056
- The origin of the bulk of astrophysical neutrinos is unknown
Gravitational Waves

From compact objects

Moustakas (2017)
http://gwplotter.com
Multi-messengers: what are they?
Different types of particles and waves.

How do we use them?
How do we use them?

1. Numerical Study of Source Physics
2. Joint Data Analysis
1. Numerical Study of Source Physics
When putting Gamma-rays, Neutrinos, Cosmic rays together..

Despite ten orders of magnitudes difference in energy, UHECRs, IceCube neutrinos, Fermi non-blazar EGB share similar energy injection rate.

Murase, Ahlers & Lacki, PRD (2013)
Waxman 1312.0558
Murase & Waxman PRD (2016)
Wang & Loeb PRD (2017) ...
Multi-messengers Produced by Supermassive Black Hole Jets
Particle Acceleration and Interaction in Black Hole Jets

Electromagnetic extraction of energy from spinning holes: Blandford & Znajek 1977

**Nuclei:** nuclei-photon (Photo-disintegration, photopion, photo-fragmentation), nuclei-proton

**Electrons:** Synchrotron, Inverse-Compton, Bremsstrahlung

**Gamma-rays:** Pair, Bethe-Heitler, Compton

Background image: DESY
Cartoon: shanegarison.org
What happens at each interaction

Test-particle Monte Carlo
- Transport in magnetic field
- Particle interaction
- Tracking of secondary particles

Our numerical approach is crucial to linking models with observation
The Intracluster Medium Environment for Interactions

ICM gas
\[ n_{\text{ICM}}(r) = n_{\text{ICM},0} \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-3\beta/2} \]

Radiation backgrounds: Infrared background from galaxies, CMB, Extragalactic background lights

Magnetic field following Kolmogorov turbulence
\[ B(M, r) \propto n(M, r)^{2/3} \]

Strength of magnetic field in the core of a galaxy cluster

KF & Olinto (2017)
Particle Trajectory in the Intracluster Medium - 10 EeV

Particle Larmor Radius
\[ r_L = 10 E_{19} B_{-6}^{-1} Z^{-1} \text{kpc} \]

Field Correlation Length
\[ l_0 \sim 20 \text{kpc} \]

\[ B_c = 10 \mu G, M = 10^{15} M_\odot \]

\[ D_{\text{total}} = 46 \text{Mpc} \]

Particle Trajectory in the Intracluster Medium - 0.1 EeV

Particle Larmor Radius
\[ r_L = 0.1 \, E_{17} \, B_{-6} \, Z^{-1} \, \text{kpc} \]

Field Correlation Length
\[ l_0 \sim 20 \, \text{kpc} \]

\[ B_c = 10 \, \mu \text{G}, \, M = 10^{15} \, M_\odot \]

\[ D_{\text{total}} \sim t_{\text{cluster}} \]
Cosmic Particles from Black Hole Jets in Galaxy Clusters

Injection Composition = Galactic CR abundance

2. Joint Data Analysis
Challenges:
Limited event rate
Poor angular resolution

Opportunities:
Observatories with wide-field & wide-energy coverage, fast-responses
Natural connections between messengers

Needed:
Efficient source search algorithms
Joint analysis of multi-wavelengths/messengers
2. Joint Data Analysis

The Microquasar SS 433

- “Mini active galactic nucleus”
- Extended X-ray jets piercing supernova remnant detected in 1990s

How is the emission produced?

Where do particles get accelerated in black hole jets?
2. Joint Data Analysis

The Microquasar SS 433

- Point-like TeV gamma-rays in both lobes detected by HAWC
- Particle acceleration happen at intermediate distances from the hole

ROSAT 0.2 keV
HAWC ~20 TeV

HAWC Collaboration, Nature (2018) KF as a main author
• Electrons above 20 TeV were accelerated

• Particle acceleration sites ~30 pc away from hole
Who emitted the photons?


KF as a main author
A Missing Piece in the Broadband Spectrum

What do the lobes look like between 100 MeV and 100 GeV?
Fermi-only Analysis of SS 433

Hint of emission in the eastern lobe is found in 11-year Fermi-LAT data but suffers from **confusion with nearby sources.**

Joint Analysis Disentangles Source from Background

Statistical significance of region-of-interest w. two separate sources is higher (by 4.5 sigma) than w. one common source, suggesting that J1913 is not a TeV emission site

Joint Analysis of Fermi-LAT and HAWC Data

GeV-to-TeV Gamma-ray emission can be explained by inverse Compton emission relativistic electrons that cool efficiently. **Joint analysis framework can be extended to** include other wavelengths and messengers.

Multi-messengers: **what** are they?  
Different types of particles and waves.

How do we use them?  
By coordinated modeling and observation.
Different types of particles and waves.

By coordinated modeling and observation.

The Future of Multi-messenger Astrophysics
An Incomplete List of Future Missions and Concepts

Radio: SKA
IR: JWST, WFIRST
Optical: LSST
UV: LUVOIR
X-ray: IXPE, LYNX, Athena
MeV: AMEGO
GeV: HERD
TeV: CTA
10 TeV: SWGO

γ pe GW

>\text{EeV}: \text{TAx4, AugerPrime, POEMMA, GRAND, EUSO}
\text{PeV-EeV}: \text{GRAND3k}
\text{TeV-PeV}: \text{HERD}

\text{Ground-based}: \text{Einstein Telescope, Cosmic Explorer}
\text{Space-based}: \text{LISA}
\text{Pulsar Timing Arrays}

\text{Astro2020 white paper, Buson, KF+ 1903.04447}
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Southern Wide-field Gamma-ray Observatory (SWGO)

Ground-based: Einstein Telescope, Cosmic Explorer
Space-based: LISA
Pulsar Timing Arrays

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> EeV: TAx4, AugerPrime, POEMMA, GRAND, EUSO
PeV-EeV: GRAND3k
TeV-PeV: HERD

> EeV: ARA, ARIANNA, POEMMA, GRAND
TeV-PeV: IceCube-Gen2, KM3Net
MeV-GeV: DUNE, Hyper-Kamiokande, JUNO

Ground-based: Einstein Telescope, Cosmic Explorer
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Pulsar Timing Arrays

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## Vast Discovery Space

<table>
<thead>
<tr>
<th>(Nearly) Solved questions</th>
<th>Unsolved questions</th>
<th>Unexpected questions</th>
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</thead>
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<td>Existence of TeV-PeV neutrinos</td>
<td>Neutrino sources</td>
<td>TeV halos around pulsars</td>
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<td>Spectrum, composition, arrival directions of Cosmic rays</td>
<td>Mechanism of cosmic accelerators</td>
<td>Wide-angle emission &amp; violation of maximum synchrotron frequency in GRB jets</td>
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<td>Gravitational waves from compact binaries, kilonova ...</td>
<td>Nature of merger remnants</td>
<td>Particle physics at extreme energy (e.g. Muon excess)</td>
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<td>Nature of dark matter ...</td>
<td>Positron excess ...</td>
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Conclusions

- The key to developing Multi-messenger Astrophysics is to understand the connection between messengers.

- Numerical study of high-energy particle interaction and propagation is crucial to linking source physics and observation.

- Efficient algorithms and analysis frameworks are needed to fully exploit the data and to enable collaboration across wavelengths and messengers.