Multi-Messenger Astrophysics

(ICHEP2018 Highlights, and More)

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Astrophysical Messengers

- Radio
- IR / Visible / UV
- X-ray
- Gamma ray

Electromagnetic waves / photons

Multi-Messenger Astronomy

- Neutrinos
- Gravitational Waves
- Ultra-high-energy Cosmic Rays

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Connection with Fundamental Forces

We detect these “messengers” through their different interactions with detectors or material (e.g. atmosphere, water, Earth)…

Electromagnetic waves / photons
→ Electromagnetic

Neutrinos
→ Weak

Ultra-high-energy
Cosmic Rays
→ Strong

Gravitational Waves
→ Gravity (?)
A consequence of Einstein’s general theory of relativity (GR)

... which says that gravity is really an effect of “curvature” in the geometry of space-time, caused by the presence of any object with mass

► It’s not actually a force!
► Things naturally move along “straight” paths in the curved spacetime

The Einstein field equations have static solutions describing the regular gravitational field, but also wave solutions which travel at the speed of light.

These waves are perturbations of the spacetime metric — the effective distance between points in space and time, $g_{\mu\nu}$

Looking at a fixed place in space while a gravitational wave travels past, the waves alternately stretch and shrink space and anything in it

➡️ The geometry of space-time is dynamic, not fixed!
A Gravitational Wave in Motion
Can look at individual sources, or populations

**Stellar core collapse**
- gravitational waves? (if non-axisymmetric collapse)
- low-energy neutrinos (from nuclear reactions)
- UV/visible/IR light (from expanding envelope)
- cosmic rays (shock acceleration in SN remnant)

**High-energy cosmic rays** interacting with ambient photons
- high-energy neutrinos (Waxman & Bahcall 1998)

**Relativistic jets** — *generated by accretion around black hole or neutron star*
- high-energy neutrinos (from hadronic interactions and decays)
- EM emissions at a wide range of wavelengths (synchrotron emission from particles in turbulent magnetic fields; inverse Compton scattering)

**Neutron star binary merger**
- gravitational waves
- relativistic jets (see above)
- UV/visible/IR light (from heated ejecta)

And other sources…
We have a large variety of wide-field and pointed instruments

Different observational strengths:
- **Gamma ray**: timing, spectrum, particle acceleration signature
- **X-ray**: timing, good localization, low background
- **Visible/IR**: precise localization, spectroscopy (& redshift), thermal signature
- **Radio**: late-time synchrotron afterglow, precise localization
- **Neutrino**: timing, particle acceleration signature
- **Gravitational waves**: timing, distance, mass parameters

Different views of the event:
- **Core engine**: low-energy neutrinos, gravitational waves
- **Outflows**: high-energy neutrinos, gamma rays, X-rays, visible/IR, radio
- **Environment**: X-ray and radio afterglow

→ **Multi-Messenger Astrophysics**
Comparable detectability?
Will a source be detectable with more than one messenger, given instrument sensitivities?

Coordination — observing a transient source at compatible times
GW and neutrino detectors normally store all useful data, but most EM instruments point
Wide-field EM instruments are more likely to have the source in view, but the most sensitive telescopes tend to be narrow-field and must be pointed in the right direction
Motivates real-time analysis and rapid sharing of information about candidate events (i.e., cross-facility triggering)

Follow-through
Rapid assessment of candidate events
Strategies for additional observations, such as spectroscopy, to fully characterize the event before it fades completely

Interpretation of combined signals
May require sophisticated modeling of astrophysical processes
Supernova 1987A!

Neutrino burst preceded appearance of the supernova light by a few hours.
From Thursday:
I. Shimizu
“Astrophysical Neutrinos at Hyper-Kamiokande”

**Astrophysical Neutrinos**

- **Hyper-K** (187 kton H₂O)
  - §B solar neutrino: 130 events / day
  - Supernova neutrino: ~50,000 events / burst
  - Supernova relic neutrino: ~18 events / year
  - Highest statistics / directional information

- **DUNE** (40 kton Ar)
  - Supernova neutrino: ~3,000 events / burst
  - Complementary with different mode
  - No directional information

- **JUNO** (17 kton LS)
  - Supernova neutrino: ~5,000 events / burst
  - Supernova relic neutrino: ~3 events / year
  - No directional information

- **IceCube** (2,400 kton H₂O)
  - Supernova neutrino: ~300,000 events / burst
  - No energy / directional information
From Friday:
S. Seo
“Physics Potentials of the Hyper-K 2nd Detector in Korea”

Supernova Burst Neutrinos

SN1987A @LMC

11 events @Kamiokande

O(1000) events @Hyper-K/KNO
Can be produced in relativistic jets or by shocks

IceCube has observed a diffuse flux of astrophysical neutrinos [Aartsen et al. 2013, Science 342; 2014, PRL 113]

Above background of atmospheric neutrinos

Have measured flavor ratio [Aartsen et al. 2015, PRL 114]

What are the sources?

Figure from *Multimessenger Astronomy* by I. Bartos and M. Kowalski, a free-to-read eBook at http://iopscience.iop.org/book/978-0-7503-1369-8

*Figure 2.* Scenarios for sources of neutrinos, with varying degrees of jet formation.
From Friday:
A. Creusot
“Latest results of the ANTARES detector and perspectives for KM3NeT/ARCA”

In the Mediterranean Sea

- space/time correlation
- alerts and follow-up

Multi-messenger - ANTARES

- radio: MWA, Parkes
- visible: TAROT, ZADKO, MASTER, SVOM-GWAC
- X-ray: Swift
- γ-ray: Integral
- GeV-ray: Fermi-LAT
- TeV-ray: HESS, HAWC
- GW: Ligo, VIRGO
- neutrino: IceCube
From Friday:
A. Creusot
“Latest results of the ANTARES detector and perspectives for KM3NeT/ARCA”

No neutrino events found coincident in time & space ➔ limits on emission

IceCube, too, has looked for neutrinos coincident with GRBs, with no statistically significant correlation [Aartsen et al., ApJ 824]

- neutrino events in coincidence with observed GRB
- data 200 s after GRB trigger
- GRB 080916C, 110918A, 130427A and 130505A
- internal shock model (up)
- photospheric model (down)

MNRAS 469, 906-915 (2017)
From Friday:
D. Marfatia
“IceCube’s astrophysical neutrino spectrum from CPT violation”

Compare energy spectra for high-energy neutrinos and gamma rays to probe new physics models

- Neutrino spectra softer than shown are inconsistent with Fermi data
- Connection for $p\gamma$ sources weaker because target photons prevent gamma rays from leaving source
An AGN contains a supermassive black hole with an accretion disk which produces a relativistic jet

By the Blandford-Znajek process (extracts energy from black hole spin via magnetic fields)
Or possibly by the Penrose mechanism (extracts energy from frame dragging)

There are many classes of AGN depending on viewing angle, etc.

A blazar is an AGN oriented so that the jet points toward Earth

Can see emissions over the whole EM spectrum, up to gamma rays
Emissions may exhibit variability due to variations in accretion rate or other disk/jet changes

[Figure from Bartos & Kowalski]
In September, IceCube detected an “extremely high energy” muon track pointing back near a known blazar.

The blazar’s gamma-ray emission increased significantly around the same time!

Awaiting paper with final analysis results…

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**Alerts: IC-170922A**

**GCN #21916**  
Sep 22nd, 2017 @20:54:30.43 UTC  
IceCube detects a high-energy muon track with a high probability of being of astrophysical origin (EHE)  
RA: 77.43 deg (-0.80 deg/+1.30 deg, 90% PSF)  
Dec: 5.72 deg (-0.40 deg/+0.70 deg, 90% PSF)  
14 arcm in away from blazar TXS 0506+056!

**ATel #10791**  
Sep 27th, 2017  
Fermi/LAT detection of an increased gamma-ray activity of TXS 0506+056

**ATel #10817**  
Oct 4th, 2017  
MAGIC: 12h of observations Sep 28th-Oct 3rd  
Detection > 5 sigma > 100 GeV  
First time detection of TXS 0506+056 in VHE gamma-rays
The Expanding Network of Advanced GW Detectors

- LIGO Hanford
  - 2015
  - 4 km

- LIGO Livingston
  - 2015
  - 4 km

- GEO-HF
  - 2011
  - 600 m

- Virgo
  - 2017

- KAGRA
  - 2020
  - 3 km

- LIGO India
  - ~2024
  - 4 km

3 separate collaborations working together
LIGO/Virgo have done many *externally triggered* GW searches (deep analysis of GW data around the time and/or sky position of reported EM event) and have collaborated on *joint* searches (compare sets of candidate events).

Many types of objects:

- GRBs
- Known pulsars (CW signal)
- SGR/magnetar flares
- Pulsar glitch (Vela)
- High-energy neutrinos
- Radio transients
- Supernovae

Also initiated an *EM follow-up program*, distributing GW event candidate alerts to observers to enable them to search for counterparts.
Search data from the gravitational-wave detectors for signals expected from compact binary coalescence, as well as generic GW transient signals.
GW170817: first binary neutron star merger

- Strong signal in both LIGO detectors (consistent with masses of known neutron stars)
- No signal in Virgo
  - Worse sensitivity
  - Source location close to a blind spot → Antenna pattern effect
→ Accurate sky localization (30 square deg.)
  - Latency of about 5 hours
  - Consistent with Fermi and Fermi-Integral localizations

Normally the sky localization would be available within minutes, but had to work around a glitch in the LIGO-Livingston data.
GW170817 sky localizations

Adapted from slide by N. Arnaud

- Green: LIGO and LIGO + Virgo
- Blue: information from gamma ray burst satellites

\[ \Delta t = 1.74 \pm 0.05 \, \text{s} \]

⇒ Speed of GWs is just about equal to speed of light

\[ -3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq +7 \times 10^{-16} \]

Astronomers found the optical counterpart!

Independently found by 6 teams within a span of 45 minutes, in the galaxy NGC 4993

GRB 170817A
GW170817
SSS17a
DLT17ck
MASTER J130948.10-232253.3
⇒ AT 2017gfo

From Thursday:
N. Arnaud
“In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors”
No Neutrino Counterpart to GW170817

Tidal Disruption of Neutron Stars

Price/Rosswog/Press
Saw the GW170817 counterpart fade – and change color

Initially visible in ultraviolet and blue – but those faded quickly
Infrared peaked after 2-3 days, then remained visible for weeks

[Drouet et al. 2017, Science 10.1126/science.aaq0049]
... as it cooled

[Drouet et al. 2017, Science 10.1126/science.aaq0049]
Optical emission matches “kilonova” model

**r-process nucleosynthesis** takes place in ejected material

Then radioactive decays drive thermal emission

Evidence for two components: “blue” (lanthanide-poor) and “red” (lanthanide-rich)

Different r-process elements produced ➔ different opacities

Hypermassive neutron star may irradiate central ejecta with neutrinos, converting some neutrons to protons

e.g., Cowperthwaite et al. estimate $0.01 \, M_\odot$ of “blue” ejecta moving at $\sim 0.3 \, c$ plus $0.04 \, M_\odot$ of “red” ejecta moving at $\sim 0.1 \, c$

Also late-time X-ray and radio afterglows

[Metzger, arXiv:1710.05931]
Implication for heavy elements

Strengthens the picture that neutron star mergers produce most of the heaviest elements

[Figure from Wikipedia “r-process” article]
Constraints on tidal deformability

GW data waveform matching rules out some “stiff” equations of state (EOS) which correspond to particularly un-compact neutron stars

Improved measurements of neutron star EOS can test nuclear physics at extreme densities, where exotic particles or fields could play a role

Using binary mergers to probe cosmology

GR relates absolute GW signal amplitude to luminosity distance
... assuming that other source parameters are known: masses, orbit inclination angle, etc.
→ A binary merger is a “standard siren”, measuring distance
  (but with uncertainty if other source parameter aren’t known precisely)

For GW170817, combined GW distance estimate with measured redshift of its host (NGC 4993)
→ $H_0 = 70^{+12}_{-8}$ km s$^{-1}$ Mpc$^{-1}$


There are also a couple of tricks to enable measuring $H_0$ from GW events without EM counterparts
VLBI imaging of the remnant of GW170817 / GRB 170817A sees the expanding jet! [Mooley et al., arXiv:1806.09693]

Knowing the inclination angle better improves the distance determination from the GW signal amplitude

\[ \theta_{\text{obs}} = 20 \pm 5 \text{ deg} \]

New Hubble constant measurement: \[ H_0 = 68.9^{+4.7}_{-4.6} \text{ km/s/Mpc} \] [Hotokezaka et al., arXiv:1806.10596]
A weak signal was detected by the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite about 0.4 second after the time of LIGO’s first event, GW150914

[Connaughton et al., ApJL 826, L13]

Post-trials false alarm prob ~ 0.0022

Would be surprising – a possible window for new physics or new astrophysics

No similar signal seen for the 5 other binary black hole events so far

→ This remains an intriguing hint to be checked with additional events
O3: GW alerts and telescope follow-up


- LIGO-Virgo alerts during O3 will all be public
  - False alarm rate ↔ Purity
  - Compact binary coalescence candidates / bursts

- Information provided through GCN(*) notices and circulars
  - Lowest possible latency – O(10 minutes), maybe less!?
  - Automated checks (detector status, data quality, environment) followed by human vetting
    → Possible retraction notices after a few hours at most

- Data public after 18 months
  - Work in progress to define the LIGO-Virgo core science program
  - 1 hour of data already public around the event when discovery published

→ Communication expected both ways: LIGO-Virgo ↔ Astronomers

(*) GCN: gamma-ray burst coordinates network
We are entering a new era for Multi-Messenger Astronomy and Astrophysics

Neutrino and gravitational-wave observatories are fulfilling their promises — e.g. GW170817
Time-domain astronomy community has highly capable instruments and techniques

Complementary observations enable tests of astrophysical models and fundamental physics

Including theories of gravity, nucleosynthesis, and properties of matter at extreme densities (in neutron stars), which could be influenced by exotic particles and fields

Need to maintain and improve our suite of facilities and instruments

Some major upgrades on the horizon, including LSST (Large Synoptic Survey Telescope) and bigger neutrino detectors
Also need to keep excellent gamma-ray and X-ray instruments in orbit
Low-frequency GW detection with LISA space mission will open new frontiers
r-process nucleosynthesis in action

Credit: J. Lippuner, author of SkyNet simulation software
Understanding outflows: X-ray data

Understanding outflows: radio data

Consistent with X-ray flux, with constant spectral index

Wide-angle, mildly relativistic outflow models

[Mooley et al. 2018, Nature 554]
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O3: Expected rates