The Dawn of Multimessenger Astronomy

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Multimessenger Astrophysics

- Definition
- Motivations
- Candidate astrophysical sources
- The status quo
  - Messengers & Detectors
  - Discoveries
  - What’s still hidden
- Discovery accelerants
  - New/Upgraded detectors
  - Virtual observatories: AMON and ASTERICS
What is Multimessenger Astrophysics?

**Defn:** The observation of a single source producing distinct signals associated with two or more of the four fundamental forces:

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<tr>
<th>Force</th>
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<th>Source ID’d?</th>
<th>Multi-messenger?</th>
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<tr>
<td>EM</td>
<td>γ</td>
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<td>Loads</td>
<td>Sun, SN1987A</td>
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<tr>
<td>Weak</td>
<td>ν</td>
<td>✓</td>
<td>Twice</td>
<td></td>
</tr>
<tr>
<td>Strong</td>
<td>p, nuclei</td>
<td>✓</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
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<td>Grav. Waves</td>
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In this talk we focus on high energies
Motivations
Motivations

What makes these?

$10^{19}$ eV cosmic ray detected by Auger
Motivations

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10^{19} \text{ eV} \text{ cosmic ray detected by Auger}

Auger superimposed on Sudbury
Motivations

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And these?

10^{15} \text{ eV neutrino detected by IceCube}
Motivations

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And these?

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IceCube event visiting Paris

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TAUP 2017: Multimessenger Astrophysics
What makes these?

10^{19} eV cosmic ray detected by Auger

And these?

10^{15} eV neutrino detected by IceCube

Very difficult to answer when we get only one particle from any given source.
More Motivations

• Consider bonanza from low-energy multimessenger sources:
  – Sun: Used solar EM output to estimate ν production.
    • Measurements fell short → “solar ν problem”
    • Solved right here in Sudbury, deepening understanding of ν’s (and confirming stars’ fusion power source)
  – SN1987A: Coincident ν detection gave
    • Unprecedented insight into SN explosion mechanism
    • Enabled new measurements of fundamental ν properties
    • Generated hundreds of papers
More Motivations

• If we could detect high-energy multimessenger source(s):
  – We’d focus modern EM-based observatories on them, and similarly dramatic advances could ensue:
    • Acceleration mechanism revealed?
    • Source(s) of UHECRs unveiled?
    • Localization (and redshift) of GW emitters determined?
    • Additional fundamental particle properties discovered?
Candidate Astrophysical Sources

- Gamma Ray Bursts
  - Top candidate (but IceCube rules out some models)
- Active Galactic Nuclei; Blazars
  - Continuous sources (but not the most energetic)
- Supernovae
  - Have to play the waiting game for one in Milky Way
- NS-NS mergers, NS-BH mergers
  - BH-BH mergers may “only” produce GWs
- “Top-down”: WIMPs, supermassive GUT relic particles, evaporating primordial BHs,...
  - Very important area of research, but not covered here
High-Energy Astrophysical Messengers

Relative advantages and disadvantages:

**Gamma rays**
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

**Neutrinos**
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

**Cosmic rays**
They are charged particles and are deflected by magnetic fields.
## High-Energy Astrophysical Messengers

### Relative advantages and disadvantages:

<table>
<thead>
<tr>
<th>Messenger</th>
<th>Sample size</th>
<th>Straight trajectory</th>
<th>Pointing resolution</th>
<th>Penetrating</th>
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<tbody>
<tr>
<td>$\gamma$</td>
<td></td>
<td></td>
<td>$\ll 1^\circ$</td>
<td>$E_\gamma &lt; 50$ TeV ($\gamma + \gamma_{IR} \rightarrow e^+ e^-$)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$\sigma_{\nu,\text{matter}} \ll 1$</td>
<td>$\sim 1^\circ$</td>
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<td></td>
</tr>
<tr>
<td>$p$, nuclei</td>
<td>$B$ fields</td>
<td>$\sim 1^\circ$</td>
<td></td>
<td>$E_p &lt; 30$ EeV (GZK cutoff)</td>
</tr>
<tr>
<td>Grav. waves</td>
<td></td>
<td></td>
<td>$\sim 1000 (^\circ)^2$ (only 2 detectors)</td>
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What Has the High-E Universe Given Us So Far?

- GeV-TeV $\gamma$ rays
  - satellites
  - IACTs
  - air shower arrays
- EeV-scale protons, nuclei
  - air shower arrays
- PeV-scale neutrinos
  - IceCube
- Grav. Waves
  - a-LIGO
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TAUP 2017: Multimessenger Astrophysics
Exciting Times for Particle Astrophysics!

- Thunderous gravitational waves
  - Discovered and studied, but no counterparts seen
- Elusive cosmic neutrinos unveiled
  - Discovered but no sources identified yet
- Persistently inscrutable cosmic rays
  - Discovered decades ago, provenance still unknown
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At high energies, why have we only been able to associate γ-rays with astrophysical sources?
Why Only $\gamma$-ray Sources So Far?

- In their first data runs, ($\nu$, p, GW) detectors aimed first for standalone source discoveries
  - Successfully detecting rare events (~1/month) but no astrophysical sources identified
- Next step: send out strong individual detections for (mostly EM) follow-up
  - $O(100)$ follow-ups have been performed: nothing found yet
- Standalone and follow-up searches have been ongoing for nearly a decade
  - Clearly must keep looking, but perhaps new strategies are needed
New Strategy: Medium→Long-Term

- Augment sensitivity of existing detectors, or add new detectors
  - Approved:
    - GW: aLIGO upgrades, VIRGO, GEO600, KAGRA, LIGO-India
    - $p$, nuclei: Telescope Array
  - Proposed:
    - $p$, nuclei: AugerPrime
    - $\nu$: IceCube-Gen2/Phase 1

- Build larger, more sensitive detectors
  - Under construction:
    - $\gamma$-rays: CTA
    - $\nu$: KM3NeT (partial)
  - Proposed:
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Waiting time: years
New Strategy: Short-Term

- Overcome rareness by lowering thresholds; exploit otherwise “unusable” data
  - Examples:
    - IceCube single muon neutrinos at lower energies
    - Single-interferometer LIGO data
  - Can we get S/N large enough to be useful?

- Emphasize transient sources: lower EM background
  - In any smallish region of space, there’s always a few known sources
  - Can we gather (ν, p, GW) signals in real-time and trigger EM follow-up at sufficient low latency?

![Graph of Count Rate vs. Time since Swift BAT trigger]
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- Yes and yes.

![Graphs showing time vs. count rate for different types of GRBs](image-url)
New Strategy: Short-Term

- Can do so by building a *multimessenger, real-time virtual observatory*
  - Pull together signals from disparate “triggering” detectors
    - E.g., IceCube(ν) + HAWC(γ)
  - Find coincidences in time and direction in real-time (& archivally)
  - Issue alerts for fast EM follow-up: catch fading transients & study them

- Benefits:
  - Powerful combination of
    - Wide field-of-view (FoV), 24/7 coverage of triggering observatories
    - High resolution of EM follow-up observatories
  - Can use “sub-threshold” data from triggering observatories
    - Otherwise low-significance data can rise in significance *if in coincidence with other data*
    - Note: This idea generalizes previous efforts, e.g. SNEWS for SNe ν
  - Supports higher than just pair-wise coincidence searches
Two efforts are now underway:

- AMON  
  - Astrophysical Multimessenger Observatory Network (started ~6 years ago)
    - See Astroparticle Physics Vol. 45, 56-70 (2013)

- ASTERICS  
  - Astronomy ESFRI* and Research Infrastructure Cluster (started ~2 years ago)

Similar ideas and goals
- Focus here on AMON

*European Strategy Forum on Research Infrastructures
AMON

- Allows multiple particle astrophysics experiments to work in concert & share data to increase sensitivity to multimessenger transients
  - Provides low-latency, real-time system to
    - gather data
    - search for coincident multimessenger signals
    - issue alerts for rapid follow-up
  - Enables use of sub-threshold data
    - in real-time and archivally

- Simplifies interfaces
  - Straightforward connection to GCN (γ-ray Coord. Network)
  - Standardized event transmission
  - Cleaner interconnect topology
  - Single MoU

Predicted sensitivity gain in sub-threshold GW-ν searches with AMON:
Important Questions for AMON et al.

- Is someone else going to analyze my collaboration’s data?
  - Each observatory retains full rights over use of its data (see AMON MoU)
  - All coincidence analyses require explicit permission of each participating collaboration

- Is the trigger latency small enough?
  - IceCube → Swift: $\mathcal{O}(\text{mins})$

- Is the aggregate data rate manageable?
  - Individual datum: direction, time, quality parameters
  - Adjustable rates, aim for few/hr/observatory
    - Cf.: ~1/month for high significance events
  - Anticipate ~1 TB/yr of data

- Is the system on 24/7?
  - AMON uses two robust servers in separate physical locations, a clustered database,…
  - Achieved downtime of < 1 hr/yr

- Is there adequate sky coverage?
  - 94% of $4\pi \text{ sr-yr}$ in FoV of 3 or more obs.
  - 2+ obs. view any given part of sky at same time
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Multiple *triggering* observatories have joined AMON:
- ANTARES, Auger, FACT, Fermi, HAWC, IceCube, Swift BAT, LIGO/VIRGO
- Are now, or will be, sharing sub-threshold data in real time
- Many are wide–FoV, 24/7 instruments

Multiple *follow-up* observatories have also joined:
- FACT, MASTER, Swift XRT & UVOT, VERITAS
- Have already started performing follow-up observations of AMON-brokered alerts
Results

- Initially enabling archival analyses (“walk before we run”):
  - Fermi LAT + IC40/59 (C. F. Turley et al., in preparation)
  - Primordial black hole search (G. Tešić, PoS(ICRC2015)328 (2015))

- Now starting to enable real-time analyses:
  - Swift XRT/UVOT + IceCube HESE (A. Keivani et al., in preparation)
  - Swift BAT + IceCube sub-threshold ν’s (analysis starting)
  - HAWC sub-threshold + IceCube sub-threshold ν’s (starting)
  - Auger + IceCube sub-threshold ν’s (starting)
  - IceCube Triplet ν follow-up (IceCube Collab., submitted to A&A)

- For these efforts, AMON provides/provided (since April 2016)
  - a software framework for real-time coincidence analyses & alert emission
  - a database populated with private and public data from numerous observatories
  - a “pass-through” service for sending out alerts via GCN
    - E.g., IceCube’s High-Energy Starting Event (“HESE”) data
Event clustering: $\Delta \theta < 5^\circ$ and $\Delta t = t_0 \pm 50$ s

IC40–LAT: $\sim$15M $\gamma$'s, $\sim$13k $\nu$'s

IC59–LAT: $\sim$18M $\gamma$'s, $\sim$108k $\nu$'s

Fermi-LAT exposure corrected map

IC40–LAT:
Data: 2138 $\gamma+\nu$ pairs
BG: 2207±40 $\gamma+\nu$ pairs
p-value: 15%

IC59–LAT:
Data: 9025 $\gamma+\nu$ pairs
BG: 9077±153 $\gamma+\nu$ pairs
p-value: 9%

C. F. Turley et al., in preparation (w/pass 8)
Example AMON-Enabled Real-Time Analysis

- IceCube track-like HESE alerts
  - Sent to AMON (~12/yr) in real time
    - Broadcast via GCN to ~50 subscribers
    - See GCN AMON page for details
  - AMON-based code down-selects ~4/yr
    - Swift time is valuable!
- Swift performs follow-up, auto-tiling sky around reported $\nu_\mu$ direction
  - Total observing request ~90ks
Example AMON-Enabled Real-Time Analysis

- Swift images are then automatically analyzed for new or fading UV or x-ray sources
  - Swift then performs follow-up of ~2 possible sources
- IceCube-160731A:
  - Swift slewed within ~1 hr
  - Covered ~2.1 deg²
  - Saw 6 x-ray sources:
    • all known
  - Saw no transients
# Summary of AMON-Brokered Public IceCube Real-time HESE/EHE in 2016

<table>
<thead>
<tr>
<th>Alert name/type</th>
<th>161103/HESE</th>
<th>160814A/HESE</th>
<th>160806A/EHE</th>
<th>160731A/HESE</th>
<th>160731A/EHE</th>
<th>160427A/HESE</th>
</tr>
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<tbody>
<tr>
<td>RA/DEC (rev1)</td>
<td>[40.87°, 12.62°]</td>
<td>[199.31°, -32.02°]</td>
<td>[122.80°, -0.73°]</td>
<td>[215.11°, -0.46°]</td>
<td>[215.09°, -0.42°]</td>
<td>[239.66°, +6.85°]</td>
</tr>
<tr>
<td>RA/DEC (rev2)</td>
<td>[40.83°, 12.56°]</td>
<td>[200.25°, -32.35°]</td>
<td>[122.81°, -0.81°]</td>
<td>[214.54°, -0.33°]</td>
<td>[214.54°, -0.33°]</td>
<td>[240.57°, +9.34°]</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.42° (50%), 1.23°(90%)</td>
<td>0.48° (50%), 1.49(90%)</td>
<td>0.11° (50%)</td>
<td>0.42° (50%), 1.23°(90%)</td>
<td>0.17° (50%), 0.8°(90%)</td>
<td>1.6° (50%), 8.9° (90%)</td>
</tr>
<tr>
<td></td>
<td>0.65° (50%), 1.1°(90%)</td>
<td>0.35° (50%), 0.75°(90%)</td>
<td>0.35(50%), 0.75(90%)</td>
<td>0.35(50%), 0.75(90%)</td>
<td>0.6° (90%)</td>
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</tr>
<tr>
<td>ST or Signalness</td>
<td>0.30</td>
<td>0.12</td>
<td>0.28</td>
<td>0.91</td>
<td>0.85</td>
<td>0.92</td>
</tr>
<tr>
<td>Latency: Event t0 to GCN alert sending</td>
<td>40 s</td>
<td>42 s</td>
<td>37 s</td>
<td>41 s</td>
<td>54 s</td>
<td>81 s</td>
</tr>
<tr>
<td>Followups</td>
<td><img src="image.png" alt="followups" /></td>
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Legend:
- AGILE
- Fermi LAT
- IPN
- Konus-Wind
- MAXIN
- MAXI/GSC
- Swift
- VERITAS
- FACT
- H.E.S.S
- LCOGT
- Pan-STARSS
- PTF
- Fermi GBM
- INTEGRAL
- MAGIC
- CALET
Conclusions

- Fantastic new particle astrophysics detectors have put high-energy multimessenger astronomy at our fingertips
  - All we need are some source detections!
- No luck so far under current paradigms (standalone, or bilateral & unidirectional)
- AMON (and ASTERICS) expand multimessenger discovery space
  - Establish bidirectional, multilateral connections in real-time (and archivally)
  - Unleash sub-threshold data
    - HAWC+IceCube ($\gamma+\nu$) real-time sub-threshold coincidence analysis ready
  - Simplify multimessenger effort via common xfer protocol, data format, event database and MoU
  - The world’s particle astrophysics detectors are an aggregate investment of $\sim10^9$, so even a small increase in sensitivity is a worth it
  - New partners welcome
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  – The world’s particle astrophysics detectors are an aggregate investment of ~$10^9, so even a small increase in sensitivity is a worth it
  – New partners welcome
• Every time we look at the heavens in a new way, discoveries usually ensue!