Data analysis challenges for multi-messenger astrophysics

BoF 6

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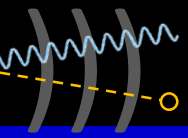
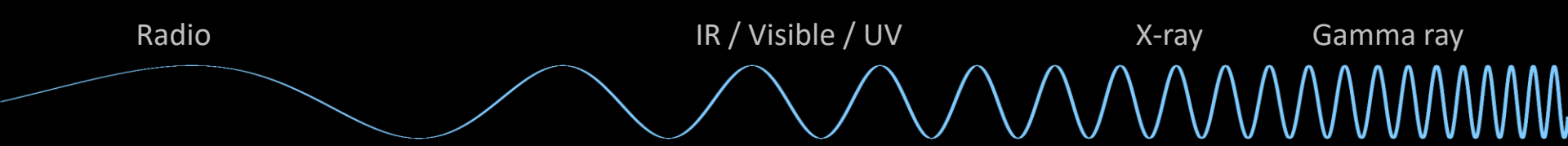
OAC-1841625
PHY-1710286

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler,
D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Astrophysical Messengers



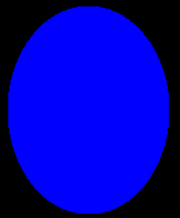


Electromagnetic waves / photons

Multi-Messenger Astronomy

Neutrinos

Gravitational Waves



Ultra-high-energy
Cosmic Rays

Different Emissions from the Same Sources

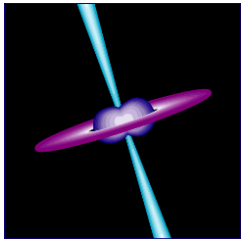
Can look at individual sources, or populations

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

Bill Saxton, NRAO/AUI/NSF

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)
[AGN, GRB] → EM emissions at a wide range of wavelengths
(synchrotron emission from particles in turbulent magnetic fields; inverse Compton scattering)



P.J.T. Leonard, NASA/GSFC

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

And other sources…

Different Messengers Give Complementary Information

We have a large variety of wide-field and pointed instruments

Different observational strengths:

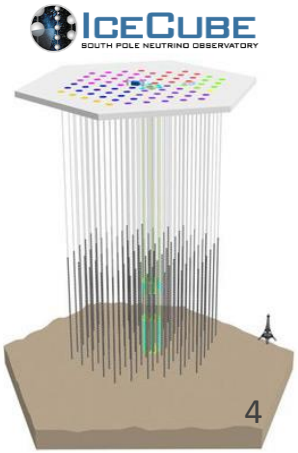
- **Gamma ray**: timing, spectrum, particle acceleration signature
- **X-ray**: timing, good localization, low background
- **Visible/IR**: precise localization, spectroscopy (& redshift), thermal signature
- **Radio**: late-time synchrotron afterglow, precise localization
- **Neutrino**: timing, particle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

Stéphane Courteau/Queen's U

Image courtesy of NRAO/AUI

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***

Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics

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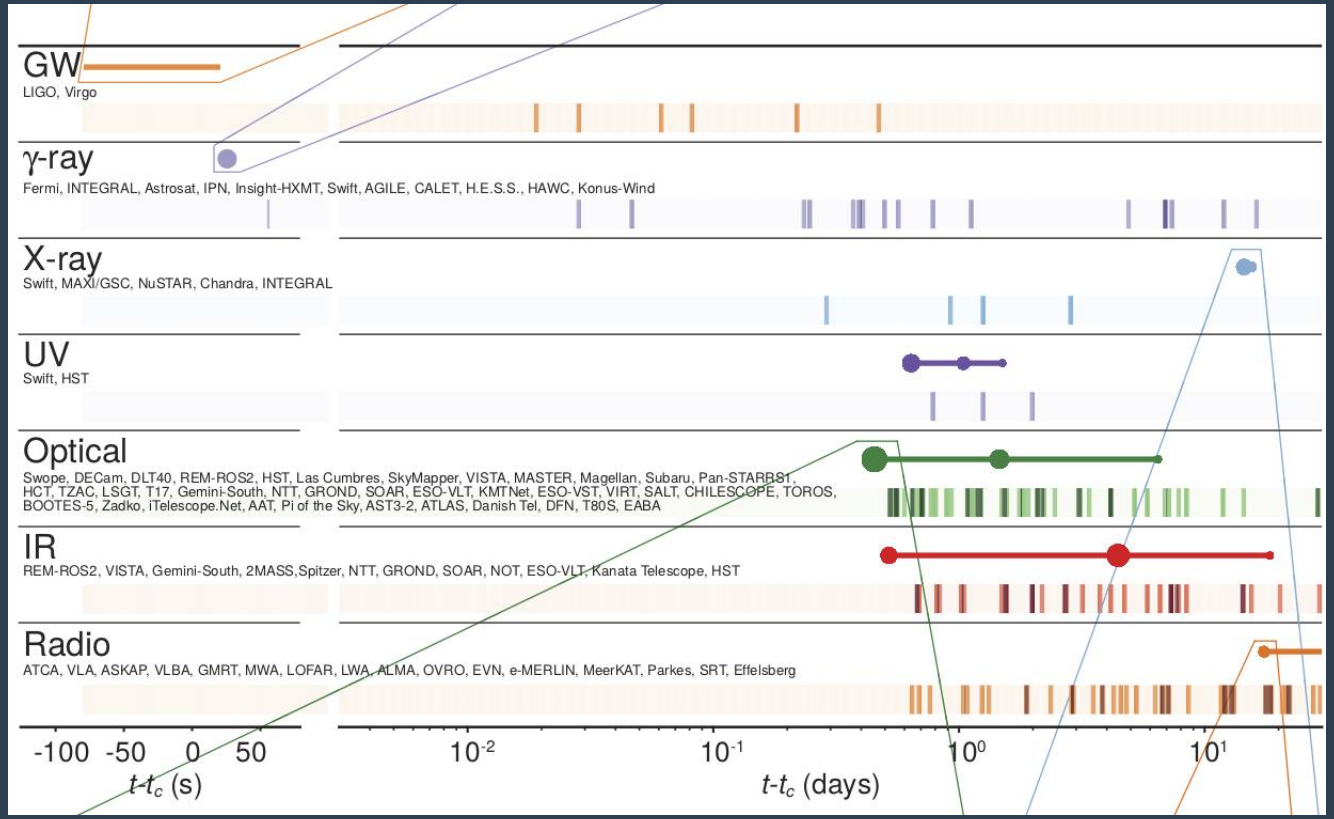
Community Strategic Planning

MMA: sample science drivers

- Early-warning of nearby compact binary mergers via gravitational waves allowing the earliest phase of the EM counterpart to be identified and measured.
- High-energy neutrinos detected and localized to a galaxy cluster trigger EM follow-up and the observation of tidal disruption event.
- Supermassive black-hole binaries detected by pulsar timing arrays would allow studies of galaxy properties and accretion disk physics.
- A Galactic or Local Group supernova observed in all the messengers!

Case study - GW170817 / GRB 170817A / AT 2017gfo / ...



Abbott et al, Ap. J. Letters, Volume 848, Number 2

Anchor facilities …



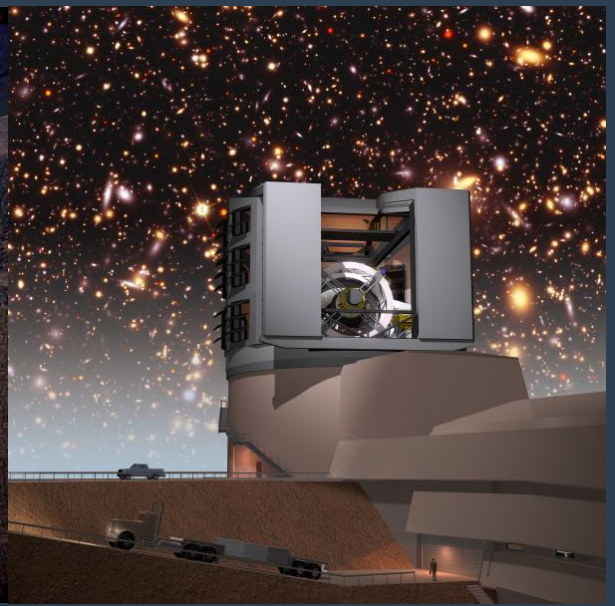
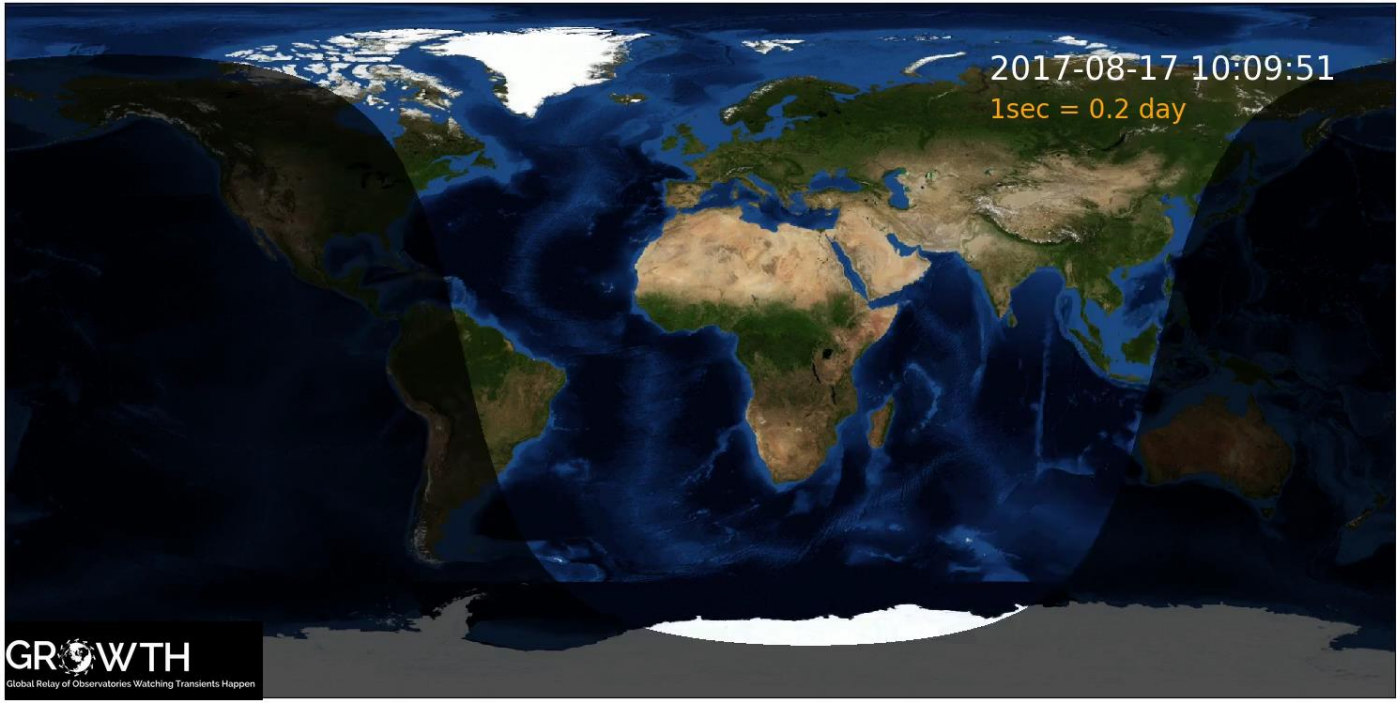


Image credits: IceCube, LIGO, LSST

Follow-up ...



Credit: P. Hebbar, V. Bhalerao (IIT Bombay) & the GROWTH collaboration

Analysis and interpretation ...

- Efficient, robust searches for signals in GW data
  - Candidate signal identification algorithms
  - Detector characterization and data quality assurance
  - Signal modeling and multi-dimensional parameter estimation
- Image processing and photometric analysis
- Detailed source modeling and inference to extract astrophysics from the combined observational data

How to do all that effectively

- Cyberinfrastructure: the distributed data-handling, computing, analysis, and collaboration services/systems to enable discovery, education, and innovation.
- Existing cyberinfrastructure:
    - Transient sky: SNEWS, AMON, GCN, TNS, SNEx, ATEL, ANTARES, VOEvent … IceCube, LIGO, LSST.
    - Static sky: NASA/NED, Vizier/SIMBAD …..

SCiMMA Project

- Goal: Identify the key questions and cyberinfrastructure projects required by the community to take full advantage of current facilities and imminent next-generation projects for Multi-messenger Astrophysics
- Deliverables:
  - **Community white paper** documenting needs & opportunities (April 2019)
  - **Strategic plan** for an institute to address these needs (June 2019)
- Process: open engagement of multiple communities

MMA Challenges

- Highly heterogeneous facilities, data, and people
  - High-volume, high-velocity transient streams
- Rapidly developing, dynamic collaborations
- Heterogeneous data sharing policies
- Competition for follow-up resources
- Rapid modeling to inform intelligent scheduling
- Tension between human/machine communications
  - Human intervention is slow, but this is currently central to follow-up

Examples of desired capabilities

- A framework to facilitate joint analysis, to enable teams to work together, while respecting scientific cultures
- Real-time decision making in event observation & follow-up
- Coordination of observing resources through exchanges, marshalls, or telescope observing managers
- Capability based access controls …
- Sustainable, long-term archival storage …

Examples of desired capabilities (continued)

- Standardization of data sets ...
- Data escrow, pre-registration of analyses, …
- Machine-readable standards & protocols with software ...
- Communication software … machines, human …
- Scalable computing systems …

Opportunities for computer/data science

- Machine learning, deep learning …
- Purpose built hardware for real-time inference …
- Inference/compute on data with differential privacy …
- Uncertainty quantification & predictive modeling …
- Tools of missing data, imbalanced data …
- … and much more!

SCiMMA Project - Join the conversation!

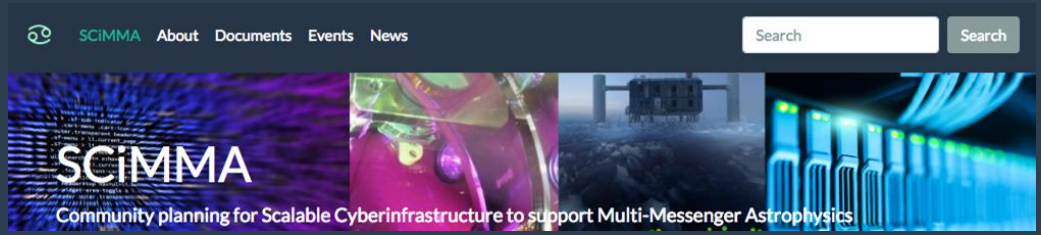
- Get involved at scimma.org
  - https://groups.google.com/forum/#!forum/scimma
  - Attend workshops (dates/topics TBD) & sessions like this one
  - Contribute to activity areas (watch forum for information)
- **Systems**
  - Integrating applications & middleware
- **Data Management**
  - Collaborating on heterogeneous, high-velocity, high-volume data sets.

SCiMMA activity areas (continued)

- **Inference and Machine Learning**
  - Interpreting data & planning observations
- **Modeling and theory**
  - Responding to and informing ongoing observing campaigns, multi-physics
- **Education and workforce development**
  - Building capacity, increasing diversity, and communicating with public
- **Policies and Management**
  - Coordinating an inherently distributed effort through an Institute

SCiMMA Project - Join the conversation!

- Details at scimma.org



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