Multi-Messenger Astronomy in the Exascale Era

Edward Seidel + Rob Pennington, NCSA/UIUC team + friends
Director, National Center for Supercomputing Applications
University of Illinois

LSST  LIGO  NCSA’s Blue Waters  GLIF
Observing the Universe through all fundamental forces: Gravity, Weak, E&M, Strong…

MULTI-MESSENGER
ASTRONOMY
A Few Representative Questions
Multimessenger astronomy informs them all…

• Physics:
  • Do gravitational waves exist? Do they travel at speed of light?
  • What happens in a core collapse supernova, before, during and after the core bounce?
  • What is the equation of state of dense matter?
  • What are various classes of gamma-ray burst progenitors?
  • What is the nature of the expanding universe?

• Compute:
  • How can we measure, analyze, compute, serve information to communities about all this, with the “exascale crises” at hand?
  • How can appropriate software tools be built and verified?

• Collaboration:
  • How can grand challenge communities work together?
Observing the Universe

- **Seeing**: Most of what we know from photons
  - Optical/IR, Radio, frequencies > 10Mhz
  - Incoherent superposition, surface processes
  - Interact very strongly with matter: can’t see much!
  - Take years for photons to emerge from stellar core

- **Detecting**: Neutrinos
  - Neutrinos weakly interacting, completely different processes
  - Yet even neutrinos trapped in stellar core collapse!

- **Listening**: Gravitational waves
  - Predicted by Einstein, not yet directly detected
  - Respond to coherent bulk motion of matter
  - Omnidirectional, frequencies below 10Khz

Each field undergoing revolution in next decade…

Imagine combining them all to observe the Universe!

Each results from completely different process, on different time scales…

Camland Project, Japan
Theory and Observation Combine to Create New Field

GRAVITATIONAL WAVES
Gravitational Wave Astrophysics

$G_{\mu\nu} = 8\pi T_{\mu\nu}$

Compact binaries, supernovae collapse, gamma-ray bursts, oscillating NSs, gravitational waves, ...
Sources of Gravitational Waves

- Continuous
  - Spinning NS “with bump”

- Transients
  - BH Ringdown
    - BHs are “Perfect” objects, defined by mass, spin
    - Perturbed: Quasi-normal modes uniquely determine M, S, no E&M counterpart
  - Binary Inspiral
    - BH – BH, BH – NS, NS – NS
    - How many will aLIGO see? 40/year?

- Bursts: Core Collapse

- Fingerprints: Remnants of Big Bang

- Expect the unexpected.. 
  - Because we’ve never seen a GW before!
(1) Theory: It takes a village…peta-exascale computing, shareable software frameworks…

SIMULATING SOURCES OF GRAVITATIONAL WAVES
Community Einstein Toolkit

“Einstein Toolkit: open software for astrophysics to enable new science.

Many groups can do this: field explodes! Major triumph of Computational Science---solve EEs!

Community + software + algorithms + hardware +...
Binary BH Breakthroughs of 2005-6 and beyond

Suddenly, all groups can solve most complex PDEs in Physics; many using same software framework to compete...
Core Collapse: Photons, GWs, Neutrinos

- Axisymmetry
  - Rapidly rotating stellar collapse
  - Can now compute GWs and neutrino signals
- Full 3D on Blue Waters
  - Full 3D GR models for GRB central engine understanding
  - AMR, MHD
- Exascale simulations
  - Track explosion to stellar surface; 10000x more expensive; want GW, ν, γ

Christian Ott, Caltech, computed on Blue Waters
Listen up! We need a worldwide network...

(2) Listening to Einstein’s Revolution

OBSERVING SOURCES OF GRAVITATIONAL WAVES
LIGO and Advanced LIGO (aLIGO)

- **LIGO goals**
  - Direct detection of gravitational waves (GWs), Initiate GW Astro
  - Initial LIGO complete, now constructing Advanced LIGO (aLIGO)
  - Sensitivity of detectors by order of magnitude
  - Searchable volume of space by a factor of ~1000
  - Starts 2016, anticipate discoveries!
    - TBs/day, 10Ks (inspiral) to billions (continuous) of templates for matching → very compute intensive

Collaboration with the Virgo detector in Italy

LIGO – Hanford, WA

LIGO Livingston, LA

Virgo – Cascina, Italy
LIGO India: Extraordinary Opportunity

- Gravitational Wave (GW) detectors have no directional ability; can only identify sky position by measuring the time of arrival of a signal with widespread array of detectors.

- India near optimal location on planet to complement LIGO, Virgo detectors; enables multi-messenger astronomy.

- Multi-messenger astronomy: correlate GWs with telescopes, gamma-ray, cosmic-ray, neutrino detectors.

Full worldwide detector array operating ~ 2020+

Note: LSST FoV 3.5 degrees!

LIGO + Virgo: ~1.5° x 10° (average)
LIGO + Virgo + India: ~1.5° x 2.3° (average)
Multi-Messenger Basics

- GWs carry very different information, at different frequencies and times, from different processes, e.g.:
  - Core collapse (SN II, Long GRBs, etc): GWs promptly from inner core bounce, neutrinos trapped later, photons later (if it explodes!) (See Ott)
  - NS-BH/NS-NS inspiral will generate GWs; some seem likely to be Short GRB
    - Short GRB could be EM counterpart to GW source!
    - GWs would probe inner GRB engine; EOS etc
  - Consider EM transients…
    - EM Trigger: increase confidence of signal of certain type at certain time
    - EM follow-ups: GWs may come first! 1-10min triggers!
      - Trigger allows one catch SN, GRB, kilonova, or ???
    - LIGO team and others already preparing…MOUs

NS-NS coalescence, Luciano Rezzolla, AEI
Revolutions afoot in optical, radio, & neutrino astronomy

OTHER MESSENGERS!
Transformation of Astronomy towards Data Services

Astronomy 1500-2000:
- Look through telescope
- Record KB of data in notebook
- Require reproducibility

Sloan Digital Sky Survey 2000+
- Record data for decade (40TB)
- Serve to entire world

Dark Energy Survey
- 2012 - 2018
- LSST: 8.4m aperture, 3.5 degree field of view
- Movie of Universe!
- 1 SDSS + Millions of transients per night!

NCSA developing data services pipelines for both DES and LSST
Large Synoptic Survey Telescope (LSST)

*It looks like a telescope, but it’s really a data service*

- Probing dark matter; dark energy; mapping Milky Way; Near earth asteroids…
- Transient Optical Sky
  - Changes in the sky over the time-scales of days,
    - Stellar variability, asteroids,
    - Optical counterparts of GW events: SN, GRB, inspirals
  - Image every 16 secs; 10 million alerts per night!!
- Urgent computing: Data come to NCSA; alerts in 60 secs!
  - Realtime data/image processing at NCSA: detect changes in sky
  - 6.4GB image every 16 secs; must be at NCSA 5 secs later!
  - Transient alerts to world within 60 seconds of shutter closing
  - Complex pipeline for processing: two clusters in parallel
  - NCSA Data services available for all US community
LSST: A 6.4 GB image is taken every 15 seconds, every night, for 10 years. Each image requires 1500 HDTVs to display.
LSST Data Management Sites and Centers

**Headquarters Site**
- Headquarters Facility
- Observatory Management
- Science Operations
- Education and Public Outreach

**Base Site**
- Base Facility
- Alert Production
- Long-term storage (copy 1)
- Data Access Center
  - Data Access and User Services

**Archive Site**
- Archive Center
  - Nightly Reprocessing
  - Data Release Production
  - Long-term Storage (copy 2)
  - Data Access Center
  - Data Access and User Services

**Summit Site**
- Summit Facility
  - Telescope and Camera
  - Data Acquisition
  - Crosstalk Correction

(Credit: LSST Project)
Another messenger…

NEUTRINO OBSERVATORIES
Ice Cube Very High Energy Neutrinos

Nov 2013

• Team has 276 people, 12 countries
• High energy (TeV – Pev) cosmic neutrinos discovery announced in November
• 28 events, much higher than anticipated
• Don’t come from atmosphere nor galactic plane; no understanding yet what they come from (e.g., AGN, GRB…)
• Data: 1.1TB/day collected at South Pole; 100GB/day sent via satellite
But how are we going to pull all this together?

SCIENCE PROBLEMS
REVOLUTIONIZED
Going Beyond Single Communities: Transient & Multi-Messenger Astronomy

- **New era:** seeing events as they occur
- **Here now**
  - ALMA, EVLA
  - Ice Cube neutrinos
- **On horizon**
  - 20-30m optical?
  - LSST
  - aLIGO, Indigo
- **SKA = exabytes**
- **Simulations integrate physics**

**Communities need to share data, software, knowledge, in real time**

**NCSA helping to integrate compute/data across disciplines, end-to-end**
COMPUTING CHALLENGES

NCSA/UIUC role in addressing these challenges

Blue Waters

- 22,640 Cray XK6 nodes
  - 362,240 cores
- 3,072 XK7 nodes w/Kepler GPU
  - 49,152 cores
- 12PF, Over 1PF sustained
- CPU memory: 1.510 PB
- 400Gbit optical links soon

National Petascale Computing Facility

COMPUTING CHALLENGES
Many of these scenarios require...

- Rapid/urgent computing
  - Data analysis for triggers to be created, broadcast
  - Advanced algorithms to filter millions of events
  - Complex pipelines for data retrieval/analysis
- Simulations to predict/guide observations
  - Future GW detectors tunable for enhanced sensitivity
- Software engineering at extreme scale…
  - Not your standard “Prof + Grad project”
- Huge, bursty data transfers around specific events
  - Detectors around world, in isolated places: optical nets!
- Computing power continues to grow…but exascale will have special challenges: do not underestimate!
- Critical mass expertise at centers + communities
### One-Page Summary

<table>
<thead>
<tr>
<th>Final Image Collection – All Data Releases</th>
<th>Inclues Virtual Data (475 PB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope</strong></td>
<td></td>
</tr>
<tr>
<td>Dark Energy Survey (DES)</td>
<td></td>
</tr>
<tr>
<td>Large Synoptic Survey Telescope (LSST)</td>
<td></td>
</tr>
<tr>
<td>Square Kilometer Array (SKA) (exaflop compute: not just image processing!)</td>
<td>1-10 TB/sec</td>
</tr>
</tbody>
</table>

#### Number of Alerts Generated
- 28 billion

#### LSST Nodes
- Peak Number of Nodes: 1750

#### Storage
- Final Disk Storage: 375 PB
- Final Tape Storage: 121 PB
- Final Database: 16 PB

#### Telescope
- Dark Energy Survey (DES)
- Large Synoptic Survey Telescope (LSST)
- Square Kilometer Array (SKA) (exaflop compute: not just image processing!)

#### Performance
- Telescope Raw data rate: 0.1 TB/night, 2.5 PB
- Large Synoptic Survey Telescope (LSST): 15 TB/night, 345 PB
- Square Kilometer Array (SKA): 1-10 TB/sec, $O$(EB)/year

#### Data Size
- Final Image Collection – All Data Releases
- Data Release 11 (Year 10)

#### Data Type
- Virtual Data: data that is dynamically recreated on-demand from provenance information

---

**Culture**---there's a tipping point here: can’t serve data to users for local analysis---profound social implications for culture of field…
Multi-messenger-related UIUC/NCSA Activities

- **NCSA (National Center for Supercomputing Applications)**
  - Continues its historic role as leading scientific computing facility
  - Blue Waters: most powerful US university system
  - Leads XSEDE: $120M project for national services
  - Integrated systems lab for experimental hardware applications
  - 200+ staff, faculty, postdocs, students
  - Developing as a data-intensive science center
    - DES, LSST, ...Genomics, Geoinformatics, Information sciences, more
  - Will be expanding its role as research center with deeper integration with faculty groups on campus, nationally

- **UIUC**
  - $100M Grainger gift for Big Data and BioEngineering
    - 35 endowed chairs!
  - Increasing activity in multi-messenger astronomy
    - Fortner chair in astrophysics
  - Plan to help community efforts going forward
  - Workshop planning for data and multi-messenger

Multimesenger in Exascale Age is profoundly different: will take a critical mass of people, expertise...NCSA/UIUC building on strengths; look forward to working with you

Consider serving your community at NSF!
Thanks!

- NCSA/UIUC: Gabrielle Allen, Ryan Foley, Mike Freemon, Charles Gammie, Athol Kemball, Rob Pennington, Don Petravick, Ray Plante
  - Many more of 200+ staff/faculty/students at NCSA involved!
- LSU: Gabriela Gonzales
- Caltech: Stuart Anderson, Christian Ott
- Chicago: Daniel Holz
- Wisconsin: Patrick Brady (Milwaukee), Francis Halzen (Madison)
- AEI: Bernard Schutz, Ian Hinder