Simulations and Theory for Multi-Messenger Astronomy

Windows on the Universe

With NSF's selection of Windows on the Universe among it's 10 Big Ideas, we are presented with both a tremendous opportunity and a tremendous challenge to address the science of Multi-Messenger Astronomy.

The goal for this workshop is a wide-ranging discussion among the many constituencies in our community, observational, theoretical, and computational, on what we need to meet this challenge and deliver on this opportunity.

These needs could simply be organizational. They could be financial. They may already be met by other programs.

These needs certainly span all of the scientific areas that touch on MMA; astronomy, gravitational, particle & nuclear physics, and computational science.

Observations over Time

To me, one of the most distinctive features of Multi-Messenger Astronomy is the long timeline of observations.

For example, for Supernova 1987a, we have

1) progenitor observations of a blue supergiant
2) the neutrino signal at neutron star formation
3) photospheric and nebular observations of the supernova
4) the beginnings of a supernova remnant.

This crosses 35+ years of time and a tremendous range of physics.

For GW170817, the range of physics is similar, though the timeline is compressed.

Does this range impose additional demands?

Existing Support

There is already considerable support for the theory and simulations side of MMA.

1) Individual Investigator awards from NSF, NASA & DoE.

2) Scientific Discovery through Advanced Computing program (SciDAC) and Exascale Computing Project (ECP)

3) Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

4) Focused Research Hubs in Theoretical Physics (FRHTP)

5) Software Institutes

Are these not enough? What is missing?

How could any gaps be filled?

SciDAC

The Scientific Discovery through Advanced Computing Program is jointly funded by the DoE Office of Advanced Scientific Computing with the other DoE scientific offices to support teams of Application Scientists and supporting Computational Scientists.

The program has run since 2001 with some variations in how the Application teams and Computational Scientists are supported.

Under SciDAC-1, support included the *Supernova Science Center* (PI Woosley) and the *Terascale Supernova Initiative* (PI Mezzacappa).

Under SciDAC-2, support included the *Computational Astrophysics Consortium* (PI Woosley)

For SciDAC-3, proposals *Petascale Investigations of our Nuclear Origins* (PI Mezzacappa) and *Supernovae and Neutron Stars as Laboratories for Fundamental Nuclear Physics* (PI Woosley) were unsuccessful.

Toward Exascale Astrophysics of Mergers & Supernovae

Argonne National Laboratory
- Anshu Dubey

Los Alamos National Laboratory
- Chris Fryer
- Josh Dolence
- Wes Even

Oak Ridge National Laboratory
- Raph Hix
- Bronson Messer

Stony Brook University
- Mike Zingale
- Alan Calder

University of California, Berkeley
- Dan Kasen

University of Notre Dame
- Rebecca Surman

Lawrence Berkeley National Laboratory
- Andy Nonaka
- Ann Almgren

Michigan State University
- Sean Couch
- Luke Roberts

Princeton University
- Adam Burrows
- David Radice

University of Tennessee
- Andrew Steiner
- Tony Mezzacappa

University of California, San Diego
- George Fuller

University of Washington
- Sanjay Reddy

TEAMS Goals

The overall goal of the TEAMS collaboration is to explore as many of the proposed sites of the r-process (and p-process), with much higher physical fidelity using the coming generation of exascale computers.

Iron Core-Collapse Supernovae: FORNAX (Princeton), CHIMERA, FLASH

Oxygen-Neon Core-Collapse: CHIMERA (ORNL), FORNAX, FLASH

MHD-driven Supernovae: FLASH (MSU), FORNAX

Neutron Star Decompression: WhiskyTHC (~~Princeton~~), FLASH/CLASH

Black Hole Accretion Disks (NSM or Collapsar): FLASH/CLASH (UCB), bhlight (LANL)

Epstein, Colgate & Haxton Mechanism (in the supernova shocked He layer of stars): CHIMERA (ORNL), FORNAX

Compute multi-D supernova progenitors: Maestro (Stony Brook/LBNL).

Compute photon signatures using Sedona (UCB), Cassio & SUPERNU (LANL).

TEAMS Goals II

Reaching our goals for improved physical fidelity with near-exascale simulations requires improvements not just in our astrophysics, but also in our nuclear physics.

To this end, TEAMS includes expertise in nuclear physics and nucleosynthesis.

Nuclear Equation of State for Supernovae and Neutron Stars:
Steiner (UTK)

Consistent Neutrino Opacities:
Reddy(UW) and Roberts (MSU)

Nuclear Physics Uncertainty Quantification for the r-process:
Surman (Notre Dame)

Astrophysical Uncertainty Quantification for Nucleosynthesis:
Surman (Notre Dame), Hix (ORNL), and Fryer (LANL).

ExaStar

The Exascale Computing Project, part of the National Strategic Computing Initiative, is a collaboration of DoE-SC and NNSA to deploy exaflop computing hardware and the software to take advantage of it by 2021.

ExaStar is an application development focus area for nuclear astrophysics. The collaboration of LBNL, ORNL, ANL and Stony Brook is working on what we originally called CLASH framework.

CLASH unites exascale adaptive mesh refinement package AMReX, with block level physics from Castro, FLASH and CHIMERA.

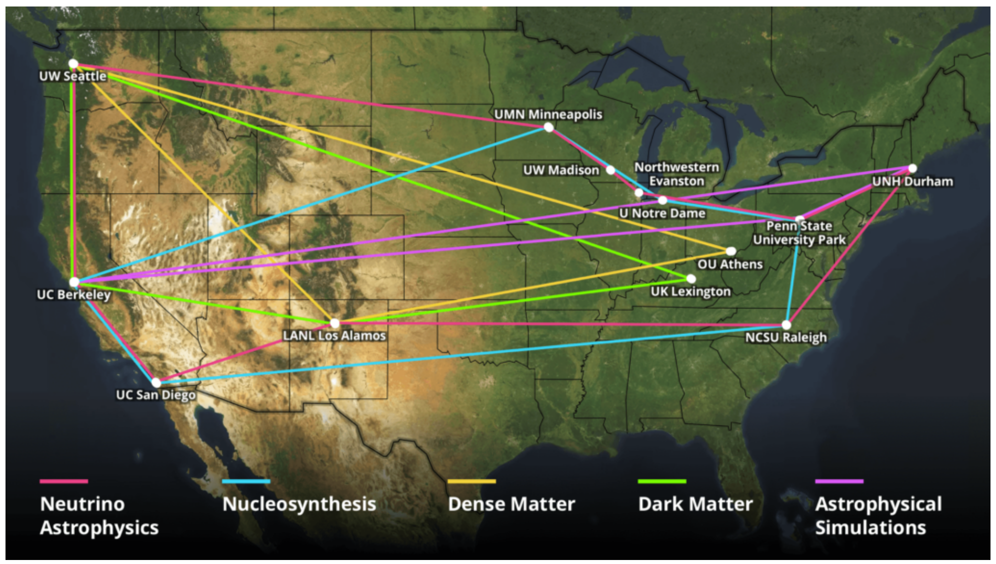
CLASH also includes new radiation transport developments, a implicit/explicit moment method neutrino transport solver (thornado) and improvements to Monte Carlo transport (Sedona).

Exastar will deliver code (e.g. next version of Castro and FLASH), but not science.

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries

PHYSICS FRONTIER CENTER

NSF



Multi-institutional network of senior investigators and postdoctoral fellows.








N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
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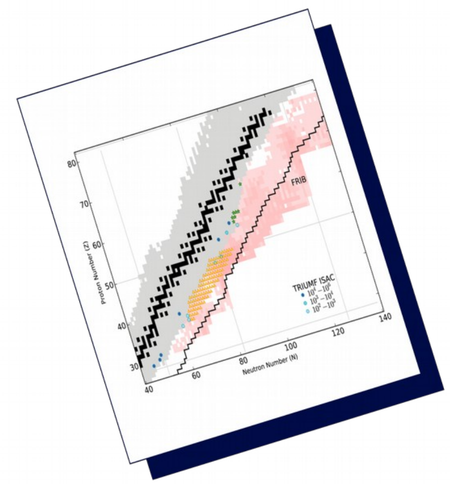
Focus areas

Neutrinos

Credit: Australian Astronomical Observatory

Nucleosynthesis

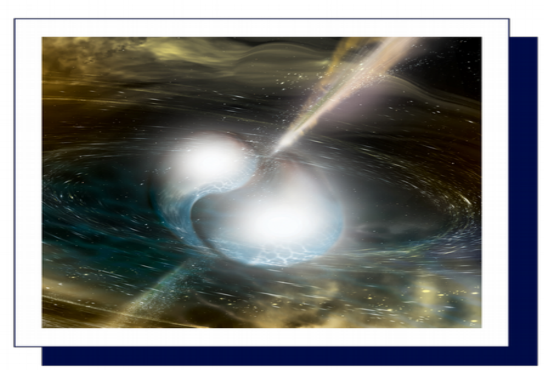


Dense matter and neutron stars

Credit: NASA and STScI

Dark Matter

Astrophysical simulation

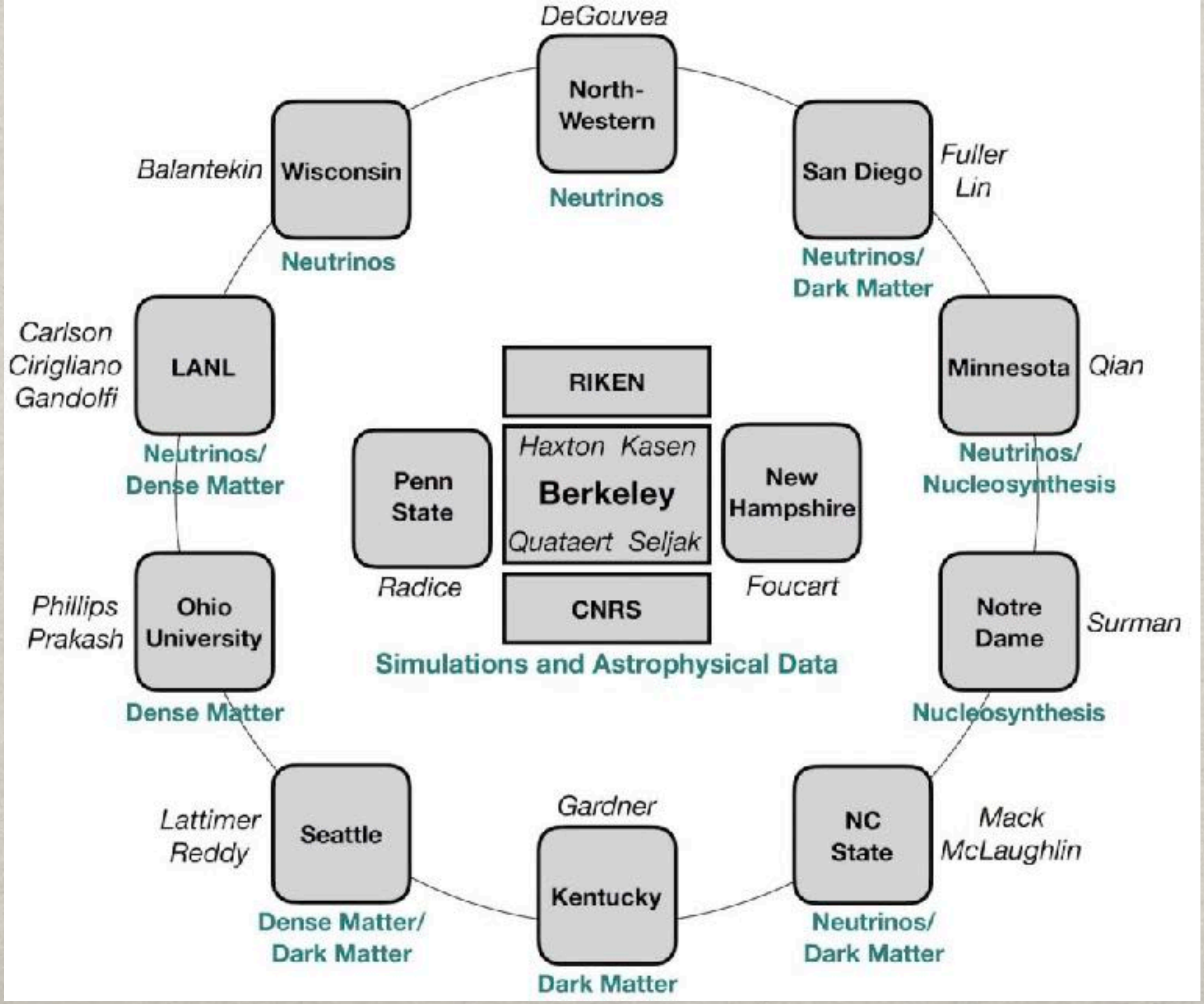


Credit: National Science Foundation/LIGO/
Sonoma State University/A. Simonnet.

Postdoctoral training:

collaborations across the network, seminars, journal clubs, scientific writing, teaching certificates, outreach

N3AS Senior Investigators



Focused Research Hubs in Theoretical Physics

N3AS began life as a FRHTP in 2016, before becoming a PFC in 2020.

In the FY2021 FRHTP call, Theoretical Nuclear Physics solicited a new hub in the area of Models and Simulations for Nuclear Astrophysics. Award will be 5 years, less than $4.3 million.

There are probably several proposal teams at this workshop planning to respond to the call.

NSF Software Institute

Office of Advanced Cyberinfrastructure has a program of Software Institutes, bring together domain application scientists with computational science and applied mathematics experts.

A recent example is the Institute for Research and Innovation in Software for High-Energy Physics (IRIS-HEP), a $25 million, 5 year effort to tackle the unprecedented amount of data that will come from the High-Luminosity Hadron Collider, the world's most powerful particle accelerator.

Our community submitted an unsuccessful proposal to that program in 2019.

Would something like this be a useful vehicle to meet our MMA challenges?

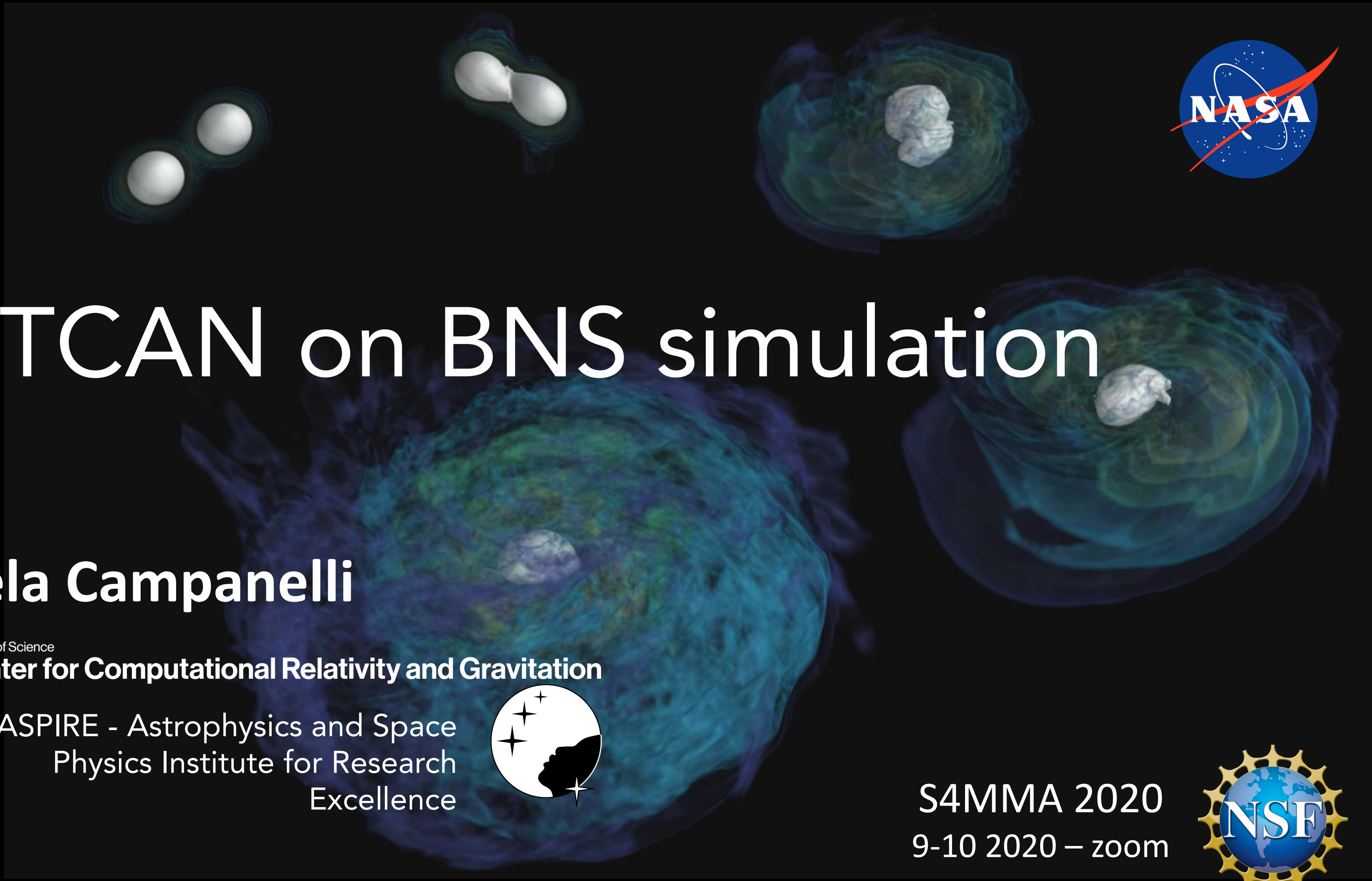
Other efforts?

What have I missed?

TCAN

SciMMA

DoE Topical Collaborations



The TCAN on BNS simulation

Manuela Campanelli

RIT | College of Science
Center for Computational Relativity and Gravitation

ASPIRE - Astrophysics and Space Physics Institute for Research Excellence

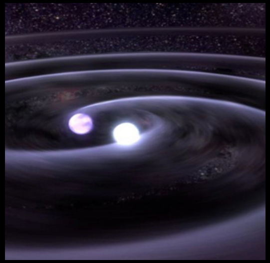
S4MMA 2020
9-10 2020 – zoom

About BNS simulations …

Long, accurate, GRMHD BNS and BH/NS simulations are required in full 3d:

- NR + GRMHD
- Nuclear and Neutrino Physics, EOS
- Neutrino/photon transport
- R-processes/nucleosynthesis

And they are inherently multi-physics, multi-scale!



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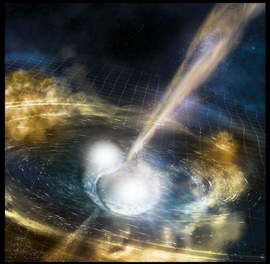
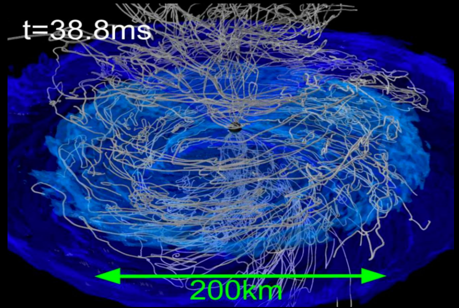


GW170817

GRB 170817A

What is the central engine of a sGRB?
How is the jet launched?
What is the nature of the remnant?

- BH + accretion disk
- Hypermassive long-lived NS + torus – delayed collapse to a BH
- Stable NS



resolution of 17.5 m for 4--5 ms after the onset of the merger

Kenta Kiuchi+ 2015

Need to simulate ~1 sec after the onset of the merger with resolutions of the scale of the MRI!

TCAN: Building an Integrated set of Computational Tools for the entire BNS merger

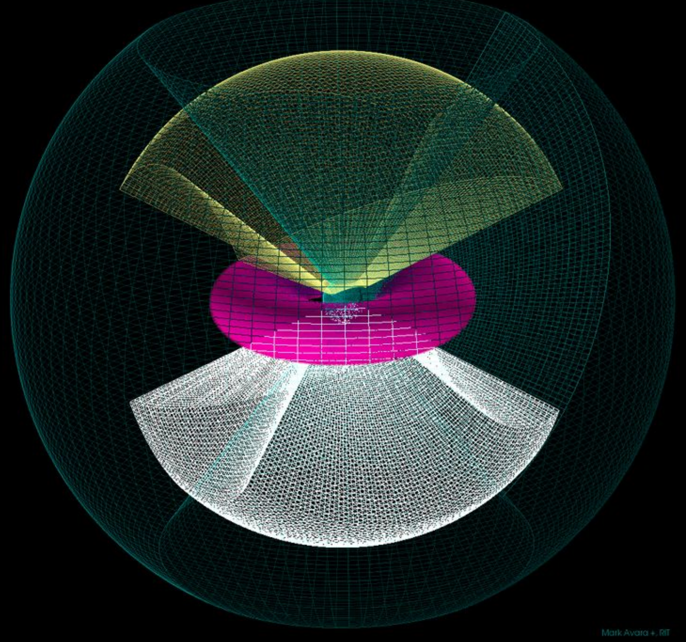
Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds and Jets in Neutron Star Mergers

- initial data for both neutron stars' structures + surrounding spacetime
- merger proper: gravitational wave radiation + MHD
- prompt ejecta dynamics
- orbiting bound matter dynamics and radial profile
- jet-launching and propagation through ejecta
- nuclear evolution in ejecta and disk
- outflows: thermodynamics, nuclear evolution, photon spectrum

TCAN: compact-binaries.org

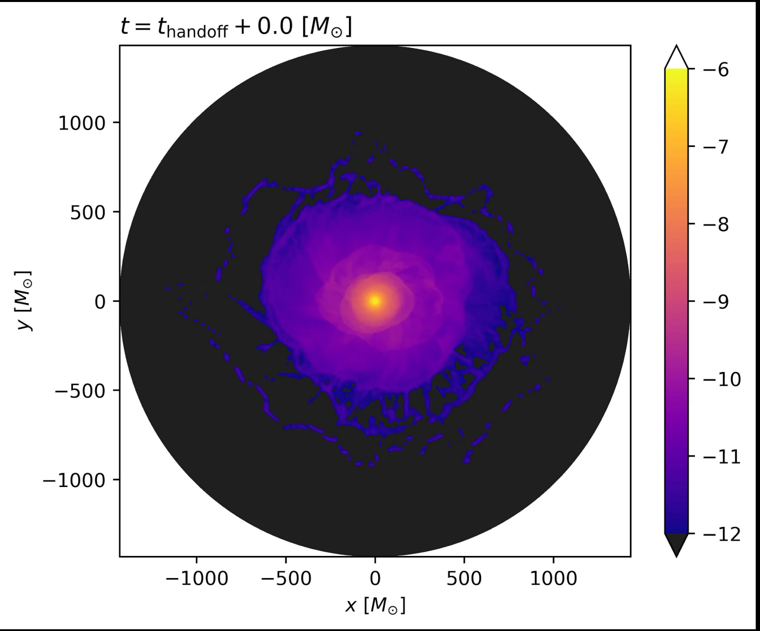
TCAN: Computational Strategy

- Provide pipeline of BNS and BH/NS initial data sets from Lorene.
- General tabulated EOS using neutrino-matter interaction rates from NuLib, Helmholtz EOS compatible with SkyNet for follow-up nucleosynthesis, and neutrino leakage/neutrino transport.
- AMR NR + GRMHD for the merger proper (Cartesian, vector-potential: e.g., IGM and Spritz)
- After collapse to BH or stable NS, handoff data to post-merger code using spherical grids: e.g. HARM3D/PWMHD, SphericalNR (requires good treatment of polar axis for jets)
- Evolve for ~1s: jet formation and kilonovae emission.
- Multiple codes to validate simulations via comparisons with collaborators.
- Make the ecosystem of codes and data sets publicly available.



PatchworkMHD – Avara+ 2020 in prep, Shiokawa+ 2018
New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.

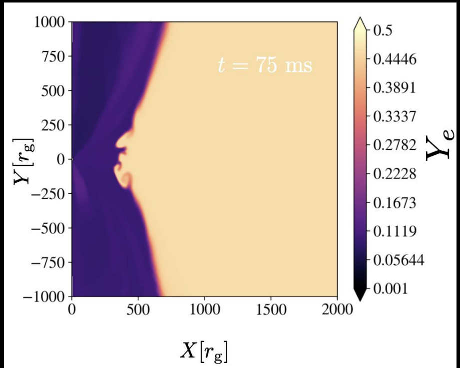
TCAN: Status Update



Handoff of BNS from IGM/Spritz to Harm3D postmerger evolution – Lopez-Armengol+ 2020

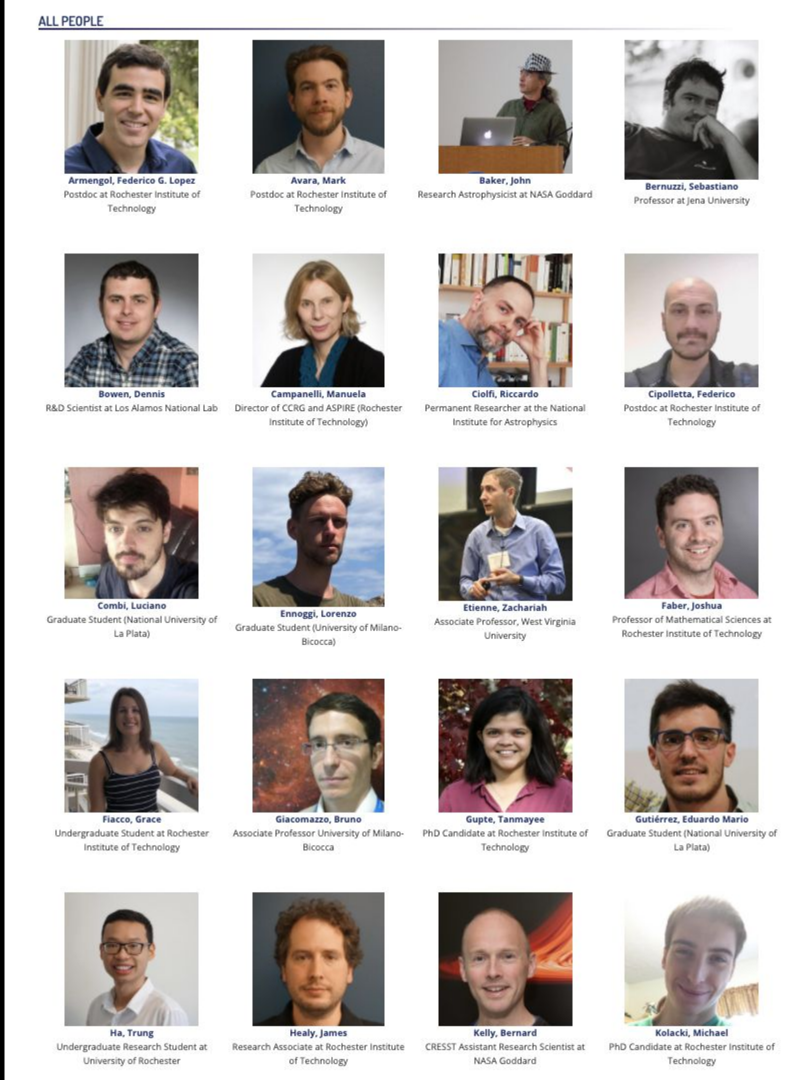
Using tabulated EOS SLy4 and grey neutrino leakage scheme- Murguia-Berthier+ 2020 in prep

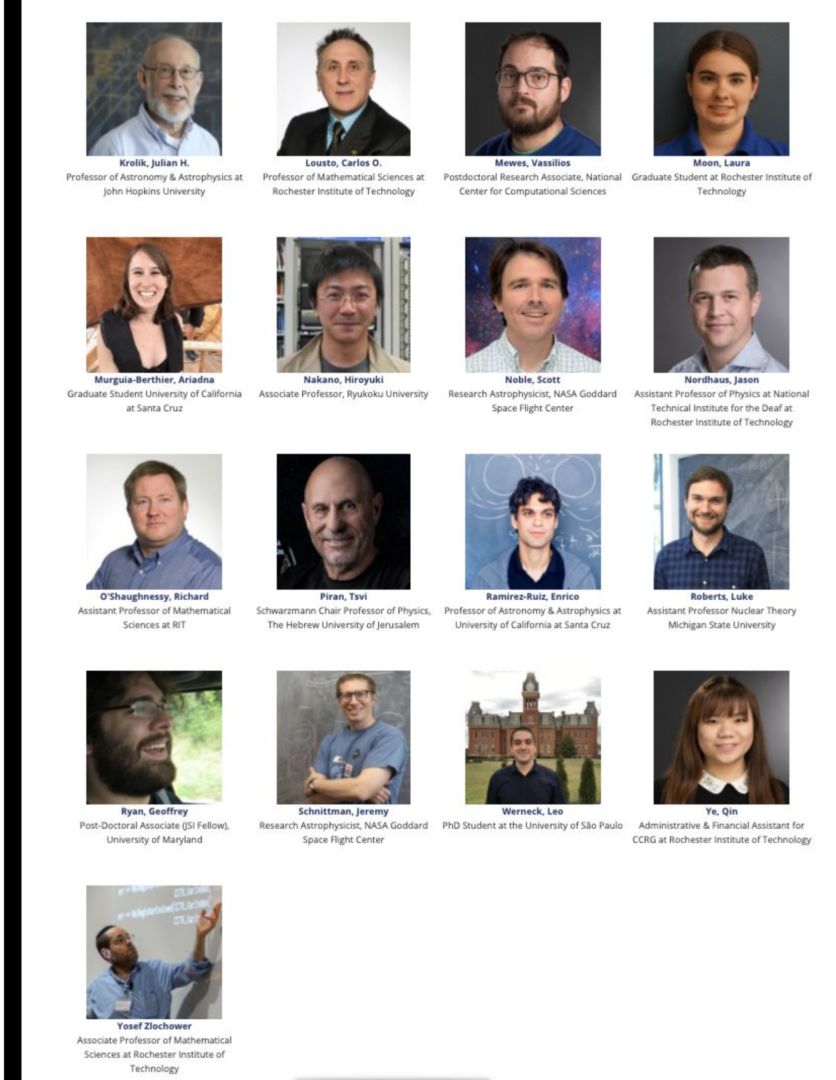
- Pipeline of BNS initial data sets from Lorene, now available in compact-binaries.org
- The Handoff was very challenging due to algorithmic differences e.g. atmosphere treatment, common EOS, neutrino physics, and treatment of MHD.
- But now complete and postmerger simulations are underway on TACC'sFrontera.



TCAN: Pioneering a new approach to complex Simulations

- Divide problem according to physical characteristics; different codes for different regimes
- Large (few dozen member) team structured by working groups
- Physical consistency for stable data hand-off from one code to another
- Coordinated scheduling to avoid development bottlenecks
- Weekly group video conferences to keep everyone informed and on-schedule
- Annual (when possible, in-person) all-team + external workshop
- Recruit new team members for additional expertise, larger workforce


ALL PEOPLE
Armengol, Federico G. Lopez
Postdoc at Rochester Institute of Technology
Avara, Mark
Postdoc at Rochester Institute of Technology
Baker, John
Research Astrophysicist at NASA Goddard
Bernuzzi, Sebastiano
Professor at Jena University
Bowen, Dennis
R&D Scientist at Los Alamos National Lab
Campanelli, Manuela
Director of CCRG and ASPIRE (Rochester Institute of Technology)
Ciolfi, Riccardo
Permanent Researcher at the National Institute for Astrophysics
Cipolletta, Federico
Postdoc at Rochester Institute of Technology
Combi, Luciano
Graduate Student (National University of La Plata)
Ennoggi, Lorenzo
Graduate Student (University of Milano-Bicocca)
Etienne, Zachariah
Associate Professor, West Virginia University
Faber, Joshua
Professor of Mathematical Sciences at Rochester Institute of Technology
Fiacco, Grace
Undergraduate Student at Rochester Institute of Technology
Giacomazzo, Bruno
Associate Professor University of Milano-Bicocca
Gupte, Tanmayee
PhD Candidate at Rochester Institute of Technology
Gutiérrez, Eduardo Mario
Graduate Student (National University of La Plata)
Ha, Trung
Undergraduate Research Student at University of Rochester
Healy, James
Research Associate at Rochester Institute of Technology
Kelly, Bernard
CRESST Assistant Research Scientist at NASA Goddard
Kolacki, Michael
PhD Candidate at Rochester Institute of Technology


Krolik, Julian H.
Professor of Astronomy & Astrophysics at John Hopkins University
Lousto, Carlos O.
Professor of Mathematical Sciences at Rochester Institute of Technology
Mewes, Vassilios
Postdoctoral Research Associate, National Center for Computational Sciences
Moon, Laura
Graduate Student at Rochester Institute of Technology
Murguia-Berthier, Ariadna
Graduate Student University of California at Santa Cruz
Nakano, Hiroyuki
Associate Professor, Ryukoku University
Noble, Scott
Research Astrophysicist, NASA Goddard Space Flight Center
Nordhaus, Jason
Assistant Professor of Physics at National Technical Institute for the Deaf at Rochester Institute of Technology
O'Shaughnessy, Richard
Assistant Professor of Mathematical Sciences at RIT
Piran, Tsvi
Schwarzmann Chair Professor of Physics, The Hebrew University of Jerusalem
Ramirez-Ruiz, Enrico
Professor of Astronomy & Astrophysics at University of California at Santa Cruz
Roberts, Luke
Assistant Professor Nuclear Theory Michigan State University
Ryan, Geoffrey
Post-Doctoral Associate (JSI Fellow), University of Maryland
Schnittman, Jeremy
Research Astrophysicist, NASA Goddard Space Flight Center
Werneck, Leo
PhD Student at the University of São Paulo
Ye, Qin
Administrative & Financial Assistant for CCRG at Rochester Institute of Technology
Yosef Zlochower
Associate Professor of Mathematical Sciences at Rochester Institute of Technology

Discussion:

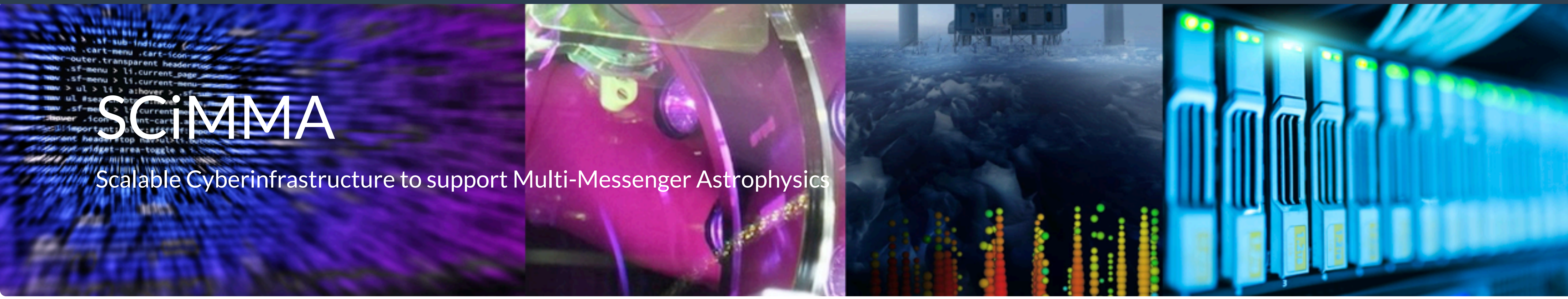
- Theory and simulations are key to the interpretation of observations of binary compact MMA sources.

- The demand for high-fidelity physical models will only increase as more exciting discoveries are made.

- The promise of MMA can be realized only if sufficient, sustained and community cyberinfrastructure is available!
  - Multi-domain expertise of astrophysicists, physicists and software engineers.
  - Sustained ecosystem of collaborative software.
  - Public, coordinated, data and code repositories and common portal /hub to share simulation products with the larger scientific community and observers.
  - Scalable software Infrastructure and access to Peta/Exascale Supercomputers
  - Workforce training and retention

White Papers: Kollmeier+2020, Allen+2020, Chang+2020,
Kavli-IAU white paper by Cenko+2020,
S4MMA coming soon!

Growing Convergence
Research



Multi-Messenger Astrophysics (MMA) is an exciting new field of science that combines traditional astronomy with the brand new ability to measure phenomena such as gravitational waves and high-energy neutrino particles that originate from celestial objects.

The promise of Multi-Messenger Astrophysics can be realized only if sufficient cyberinfrastructure is available to rapidly handle, combine, and analyze the very large-scale distributed data from all the types of astronomical measurements. This project is to carry out community planning for scalable cyberinfrastructure to support MMA. The primary goal is to identify the key questions and cyberinfrastructure projects required by the community to take full advantage of current facilities and imminent next-generation projects for MMA. Two products of the project will be: 1) a community white paper that presents an in-depth analysis of the cyberinfrastructure needs and the opportunities for collaborations among astronomers, computer scientists, and data scientists; and 2) a strategic plan for a scalable cyberinfrastructure institute for multi-messenger astrophysics laying out its proposed mission, identifying the highest priority areas for cyberinfrastructure research and development for the US-based multi-messenger astrophysics community, and presenting a strategy for managing and evolving a set of services that benefits and engages the entire community.

In this context, cyberinfrastructure consists of the distributed data-handling, computing, analysis, and collaboration services/systems to enable discovery, education, and innovation.

Participate

- SCiMMA GitHub
- SCiMMA YouTube Channel
- Join the SCiMMA Google Group by logging into Google or sign up with any email account by sending an email to scimma+subscribe (at) googlegroups.com with the subject "subscribe"

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