High Energy Density Physics: An Astrophysicist's Perspective …

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To begin with - the status of HEDP in astrophysics

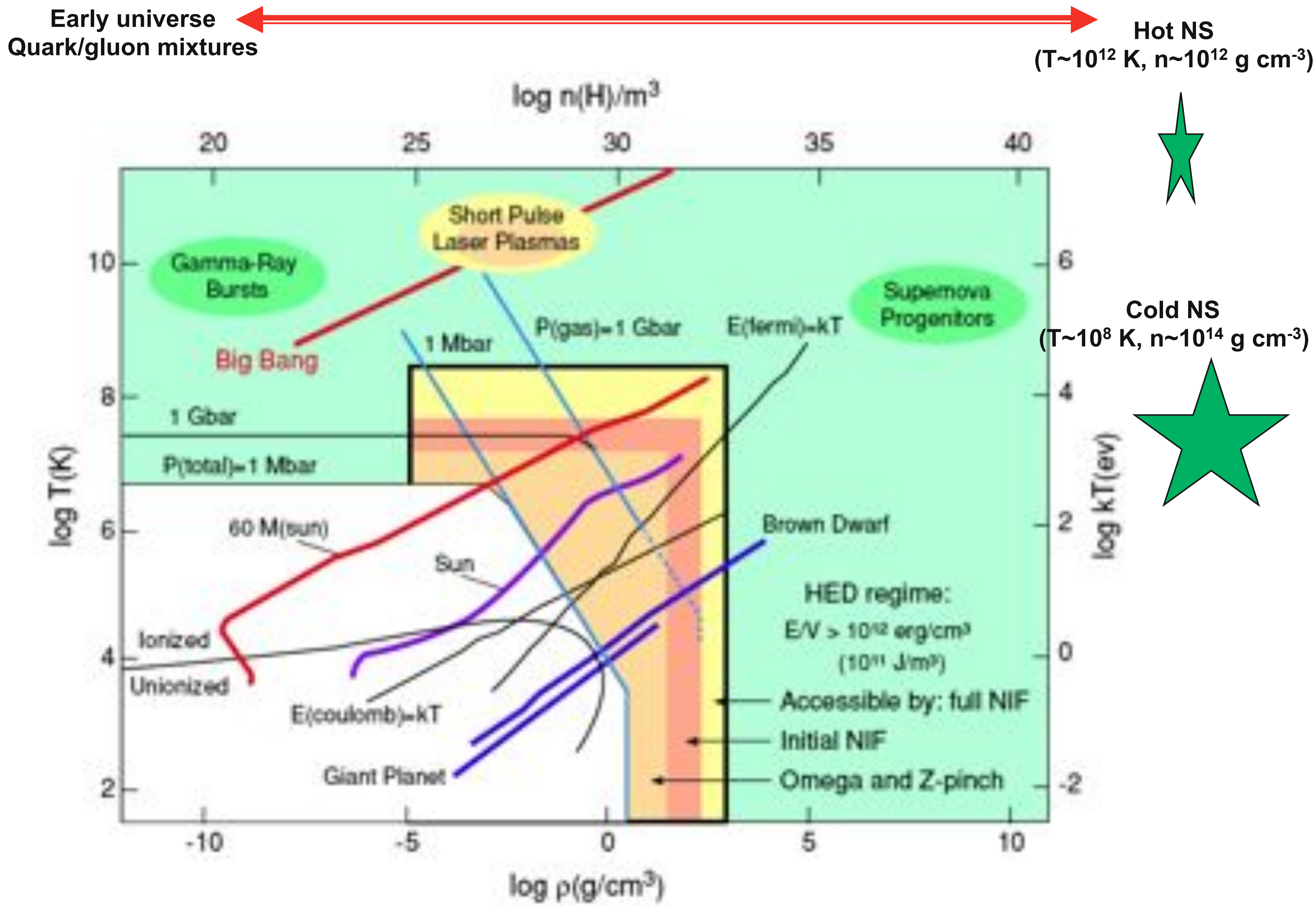
- HEDP is a well-recognized discipline in astrophysics
  - HEDP has in large part emerged from astrophysics
    - *S. Chandrasekhar's work on the EOS of white dwarfs … ApJ, 74, 81-82 (1930)*

- The connections to the laboratory are both
  - "traditional": Nevada test site …
  - "recent":
    - *Nova/LLNL, OMEGA/OMEGA-E/Rochester, Z-Pinch/Sandia, Nike/NRL, …, NIF/LLNL*
    - *University-based experiments …*

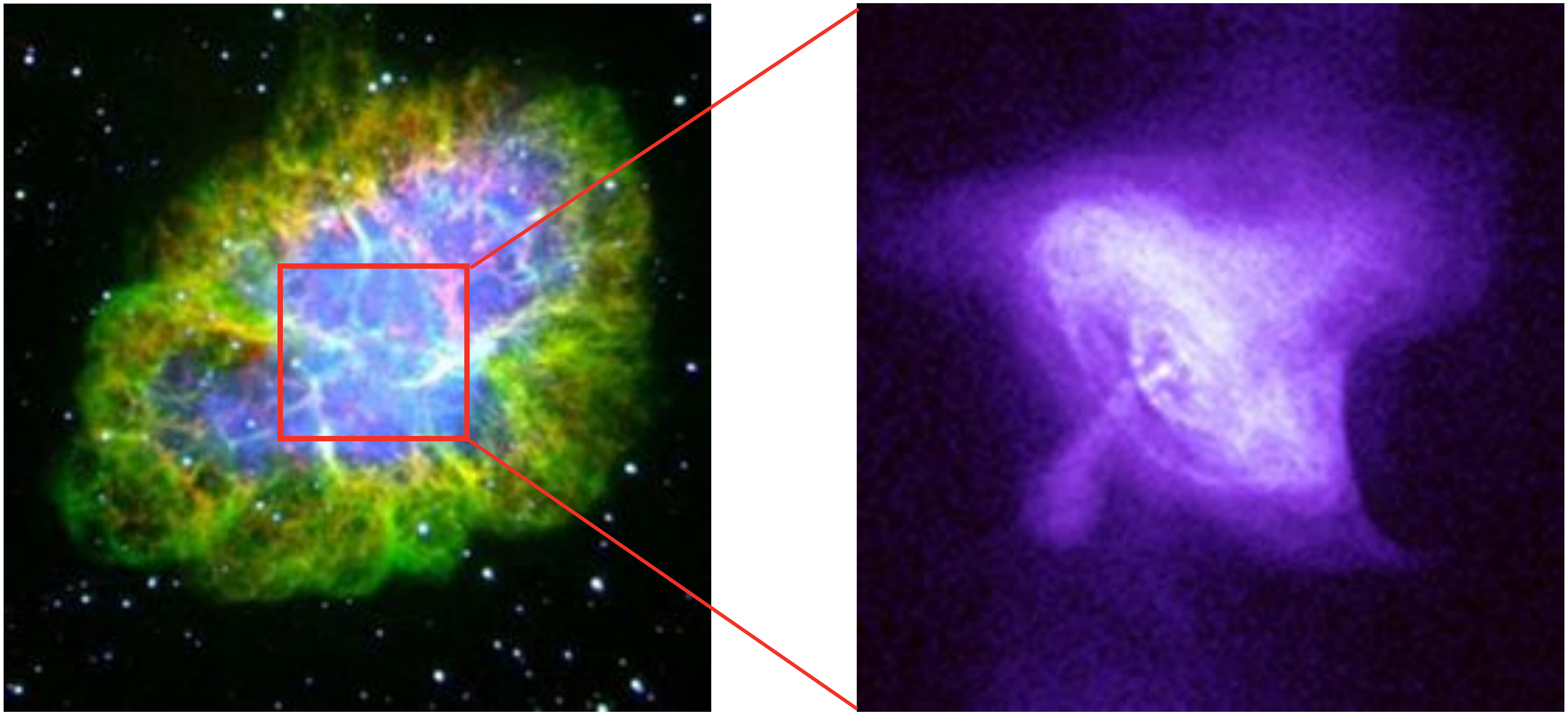
- The level of enthusiasm is great …

- … but there are some obstacles
  - Funding …
  - Structural …

Where does HEDP enter in astrophysics?



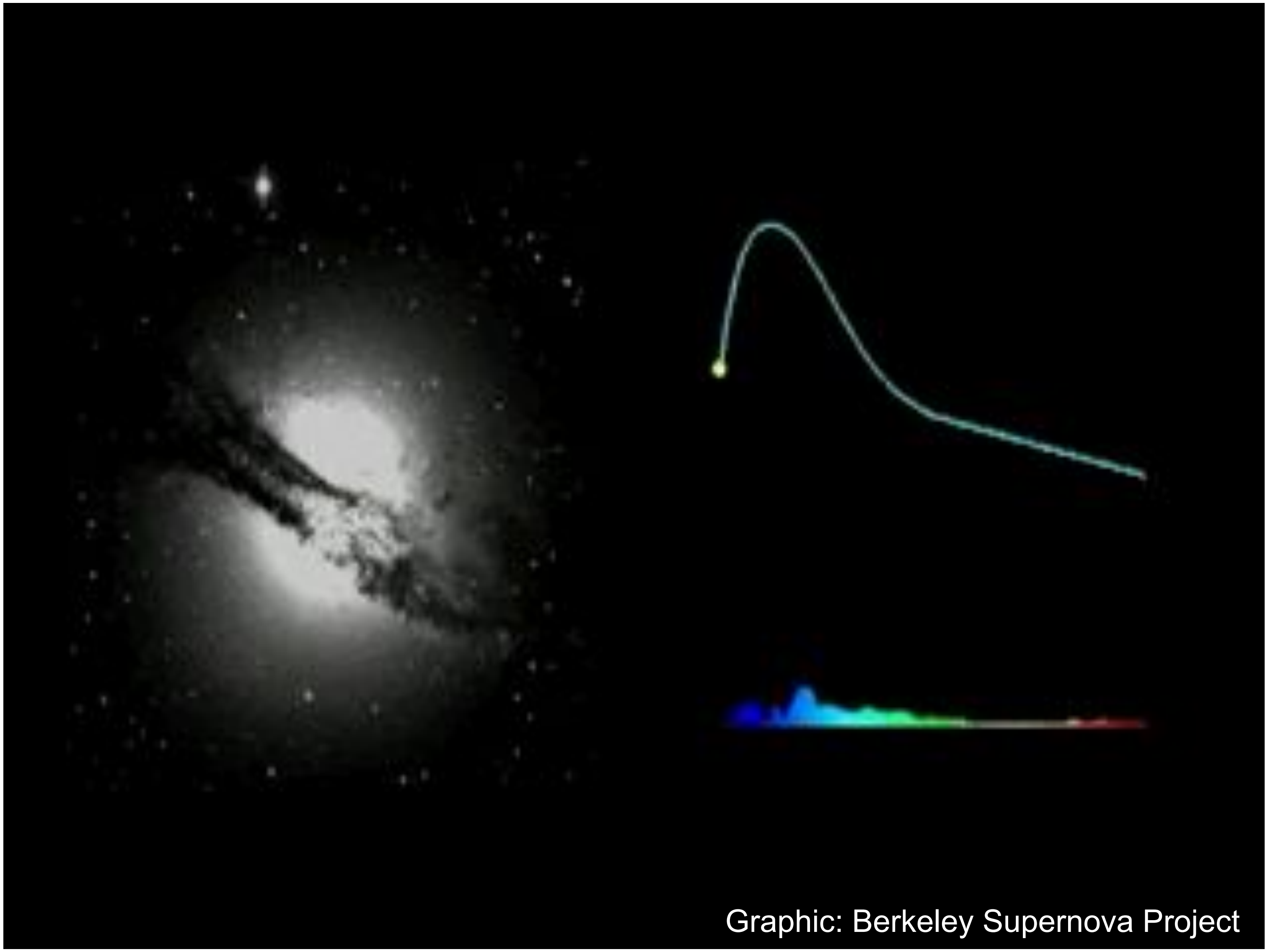
A by-now classic example … a Type II (core collapse) SN …



The Crab Nebula: a view in the optical (left; HST/NASA) and in X-rays (right; Chandra/NASA)

<u>Combining relativistic tenuous plasmas in the nebula with degenerate relativistic matter in the pulsar …</u>

… and the nuclear counterpart, a Type Ia supernova



The Center for Astrophysical Thermonuclear Flashes

Simulation of the Deflagration and Detonation Phases of a Type Ia Supernovae

Ignition occurs 40 km from the center of the star.
Hot material is shown in color and stellar surface in green.

This work was supported in part at the University of Chicago by the DOE NNSA ASC ASAP and by the NSF. This work also used computational resources at LBNL NERSC awarded under the INCITE program, which is supported by the DOE Office of Science.

An Advanced Simulation and Computation (ASC) Academic Strategic Alliances Program (ASAP) Center at The University of Chicago

The "overarching question" for HED astrophysics

- *How does matter behave under conditions of extreme temperature, pressure and density*, and how does it interact with photons and neutrinos under such extreme conditions?
  - Material properties
    - *EOS, opacities, conductivity, diffusivity, viscosity, … , of stellar matter*
  - Basic physics of processes of degenerate matter
    - *convection, Urca, …*
    - *nuclear ignition, deflagration-to-detonation (DDT), …*
  - Phenomenology:
    - *Origin and evolution of giant planets and brown dwarfs, and the death of stars - Type Ia, II supernovae, neutron star & white dwarf cooling, …*
    - *Gamma ray bursters, formation of neutron stars and black holes*
    - *The very early universe: strongly coupled plasmas, and quark-gluon plasmas*
    - *UHECR: origins? composition? propagation?*
    - *Accreting black holes/neutron stars: disks, jets, …*
    - *…*

To no surprise, HED astrophysics is at the core of HEDP …

- **The ReNeW process identified five core questions that define the field of high energy density physics …**
  - ***How does the exotic behavior of dense collections of electrons, ions and photons arise?***
  - ***How does self-organization arise within high energy density matter?***
  - ***Can intense transient flows of energy and particles, unconstrained by conventional material limits, be manipulated and controlled?***
  - ***Can the interactions of matter under extreme conditions be controlled to enable practical inertial fusion energy?***
  - ***What can we learn about the cosmos by creating cosmic conditions in the laboratory?***

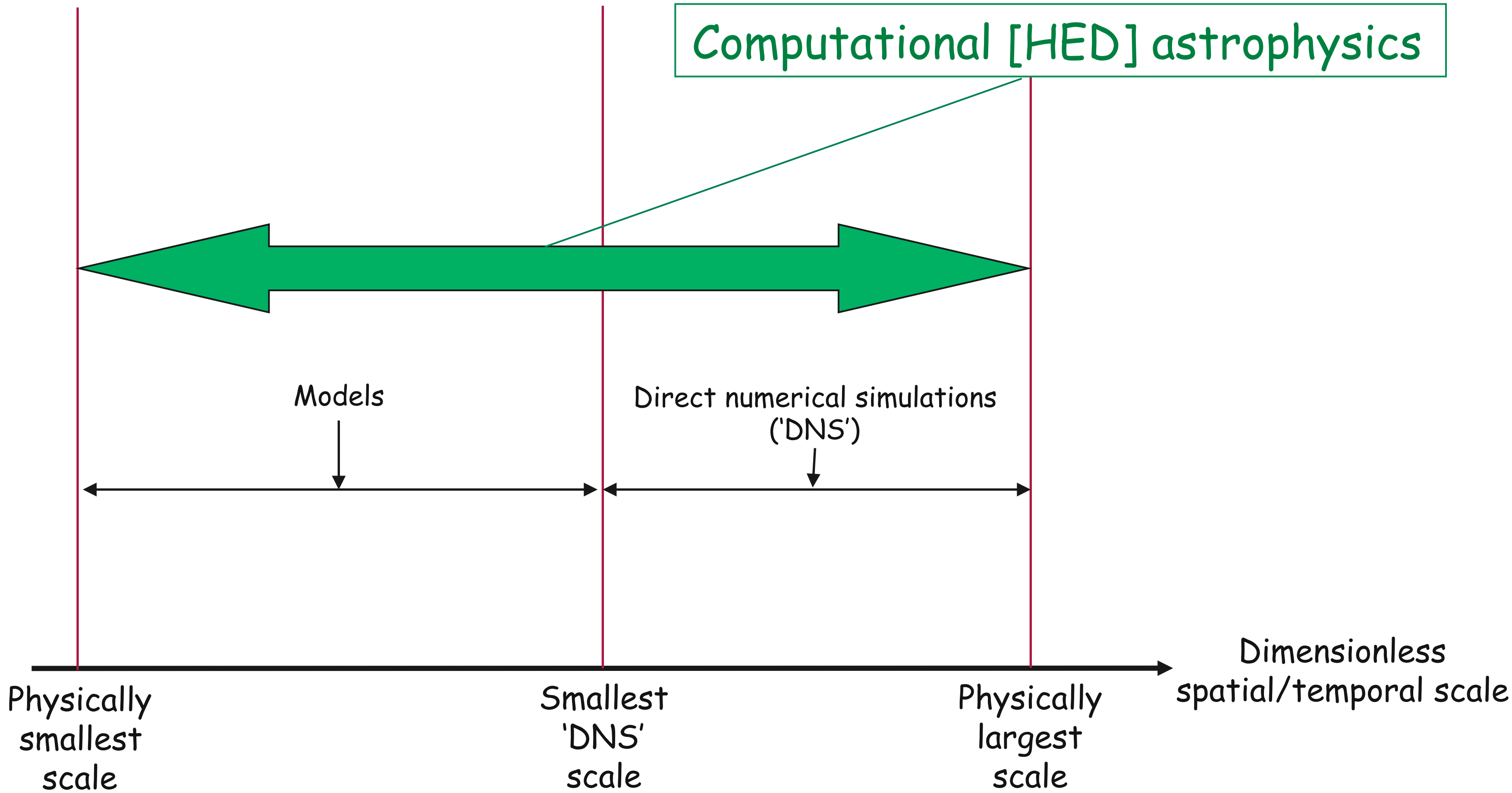
Is HED astrophysics just a conglomeration of topics?

- The scope of possible "thrust areas" by "venue" is overwhelmingly large in astrophysics
  - Conclusion: astrophysical "thrust areas" are best defined by the way one does research, as opposed to the topic of research

- What differentiates HED astrophysics from laboratory-oriented HED physics is the way the science is carried out
  - Virtually all astronomical data is obtained via remote sensing
  - "Experiments" in the traditional physics mode are not possible
  - Enormous disparities in astrophysical temporal and spatial scales make it impossible to construct *complete* 'first-principles' models/theories
    - *Great resemblance to science-based engineering*

- But HED astrophysics is deeply connected to laboratory-oriented HED
  - HEDLP provides the venue by which physics ideas from HED astro can be (and are) tested and explored …

Computational astrophysics unavoidably depends on models for the unresolved scales …



- Astrophysical theory, modeling, and simulations are inherently 'voracious' …
- 'Sub-grid' models require experimental validation …

Organizing by "thrust areas" …

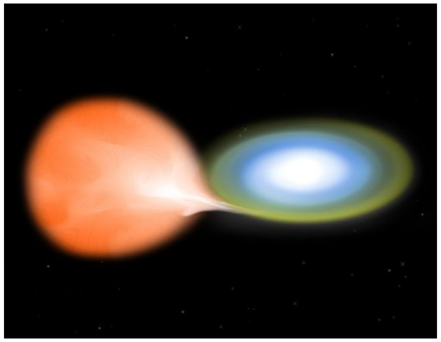
- Astrophysical phenomena: <u>Modeling</u>
  - The use of existing physics theory (or extrapolations of existing theory) to build models describing particular phenomena: "astroengineering"
- Astrophysical basic theory: <u>Fundamental physics</u>
  - Studies of the fundamental physical processes governing matter and radiation under HED conditions
- Astrophysical laboratory studies: <u>HEDLA</u>
  - Measurement of fundamental material properties
  - Exploration of astrophysical phenomenology under controlled lab conditions, to build intuition
  - Direct connections to astrophysical phenomena via scaling
  - Validation of instruments, diagnostics, simulations …

Astrophysical phenomena: Modeling

- Motivating question:
  - What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

- Some examples of science objectives
  - What are gamma ray bursts, where do they occur, and how do they work?
  - How do cosmic accelerators work, where do they occur, and what are they accelerating?
  - How do accretion disks and jets work, and how are they connected to each other?

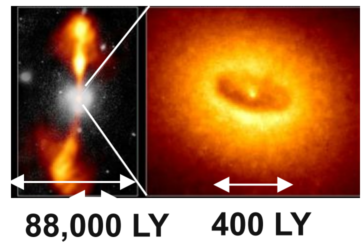
A model/artist's conception of the binary system Nova Aquila (Courtesy Chandra X-ray Observatory)



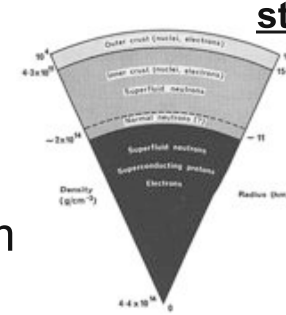
Fundamental physics of high energy density astrophysical phenomena

- Motivating question:
  – What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

Imaging of a black hole candidate system (Piner et al. 2001; Ferrarese et al. 1996)



Example of a model for the internal structure of a neutron star

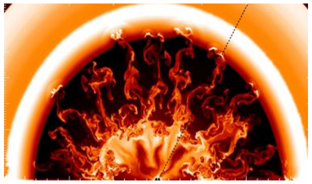


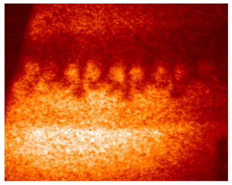
- Some examples of science objectives
  – Why are astrophysical plasmas commonly far from equilibrium conditions?
  – What determines the fundamental properties of matter under extraordinary conditions of density, temperature, and pressure?
  – What is the origin of cosmic magnetic fields? how do cosmic magnetic fields evolve, and eventually dissipate?
  – How do baryonic matter and radiation interact under degenerate and partially degenerate conditions?

Laboratory astrophysics

- Motivating question:
  - What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory; and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems as yet inaccessible to either theory or simulations?
- The four key science objectives
  - Measuring material properties at high energy densities: equations of state, opacities, …
  - Building intuition for highly nonlinear astronomical phenomena, but under controlled lab conditions (with very different dimensionless parameters): radiation hydro, magnetohydrodynamics, particle acceleration, …
  - Connecting laboratory phenomena/physics directly to astrophysical phenomena/physics (viz., in asymptotic regimes for Re, Rm, …): late-time development of Type Ia and II supernovae, …
  - Validating instrumentation, diagnostics, simulation codes, … , aimed at astronomical observations/phenomena

Type II SN shock simulation (Kifonidis et al. 2000)





Type II SN shock experiment (Robey et al. 2001)

Resource needs: What does it take to carry out this science?

- Forefront observational tools from ground and space
  - Instrumentation development
  - Paced implementation strategy that maintains the strength of US research workforce at national labs and universities

- Advances in theory/simulation and instrumentation capabilities
  - Building new generations of codes and new (diagnostic) instrumentation
    - *Funding …*
    - *Relaxed 'classification': export control and beyond …*
  - Open access to forefront facilities
    - *Simulation: smaller-scale development platforms/clusters and massively-parallels "leadership-class" platforms*
    - *Experiments: Laser facilities (OMEGA, NIF, …), Z-pinch, accelerators, …*

- Developing and maintaining the necessary human 'capital'
  - Training experimentalists for developing and building both astronomical and laboratory tools
  - Training theorists for developing the analysis & simulation tools to understand fundamental astrophysical processes/astrophysical modeling/

Resource needs: '… are we there yet?'

- Resource needs cut across at least 3 agencies
  - NASA, NSF, DOE/SC and NNSA
  - Existing coordination is weak … but there is hope (see below!)

- It can be done!
  - Successes of DOE/NNSA ASC/Academic Alliance Program (ASAP) and Predictive Science Academic Alliance Program (PSAAP) allows scaling of likely level of critical-mass efforts in this area:
    - *New generation large simulation codes will require both Center-level funding and large-scale access to forefront computing hardware*
  - Successes of NSF Physics Frontier Centers, and in particular the success of the NSF and DOE/SC/OFES collaborations in astro/laboratory plasma physics
  - The joint DOE/SC/OFES and DOE/NNSA ReNeW(orkshop) on HEDLP generated some (unexpected!) excitement …
    - *Evidence of interest on the parts of both SC (and OFES) and NNSA*
    - *FY2011/2012 budgets for a joint program will show the way …*

And that brings us to …

Questions and Discussion