Burning Plasma Science Workshop

Astrophysics and Laboratory Plasmas

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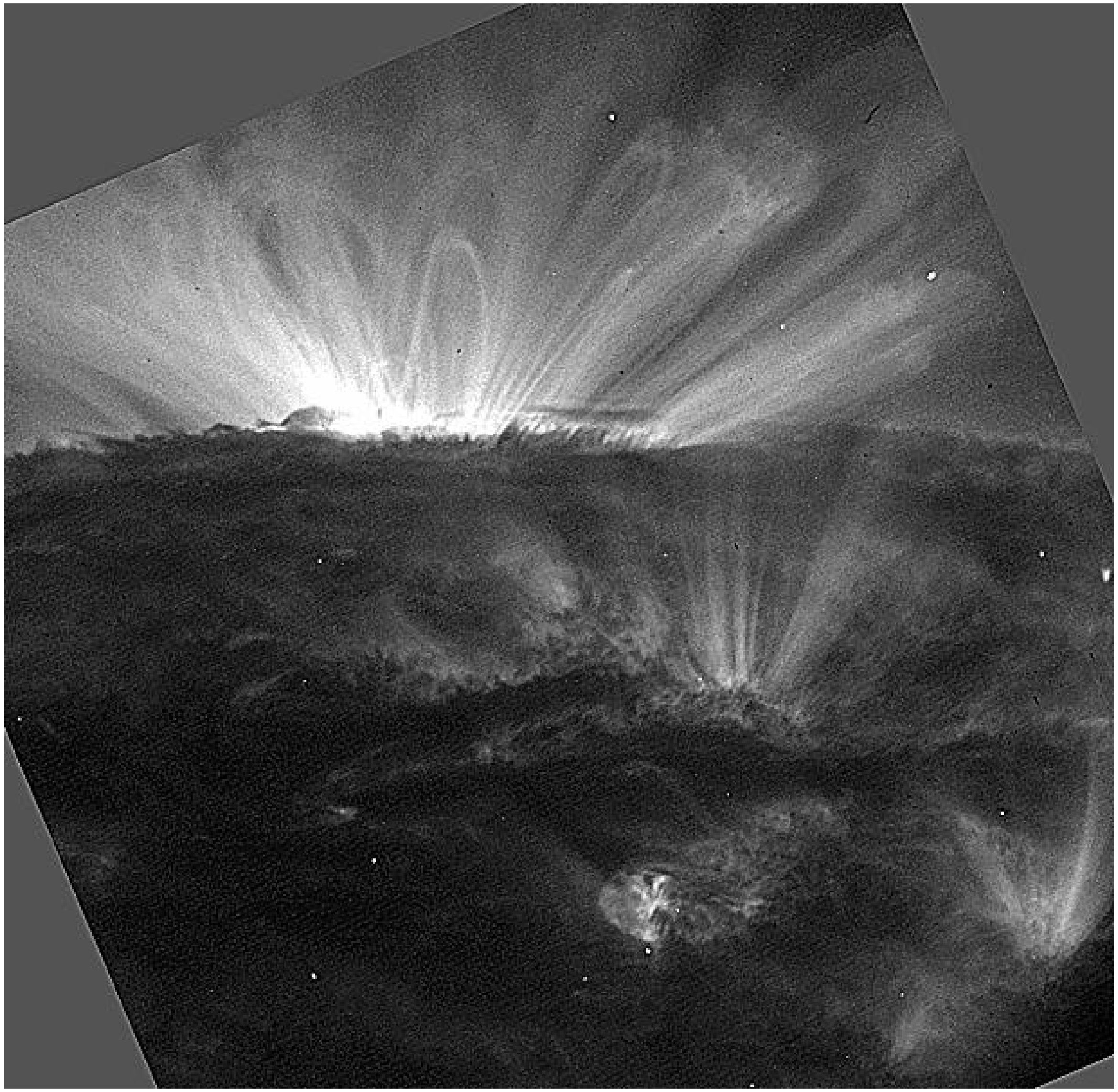
(http://flash.uchicago.edu)

What I will talk about …

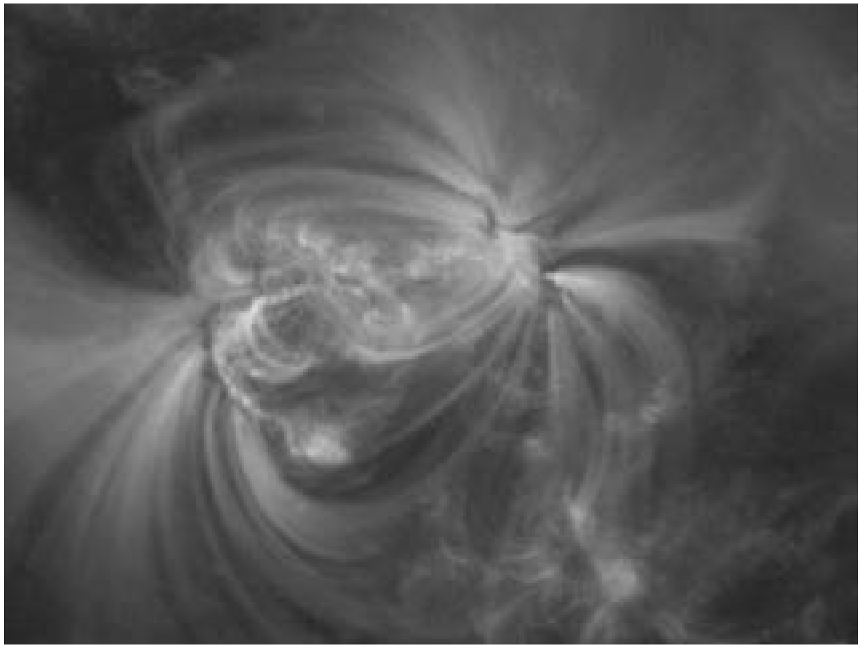
- Illustrations of astrophysical plasmas
- Plasma conditions
- Overview of plasma physics issues for astrophysics
- Specific examples

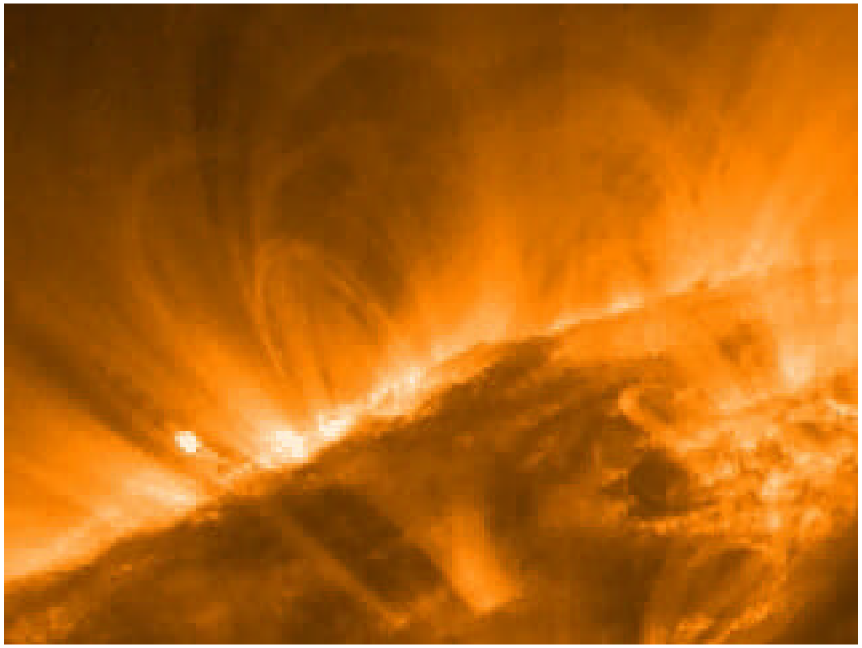
The nearest astrophysical plasma …



Credit: NASA/Trace

The dynamical Sun …

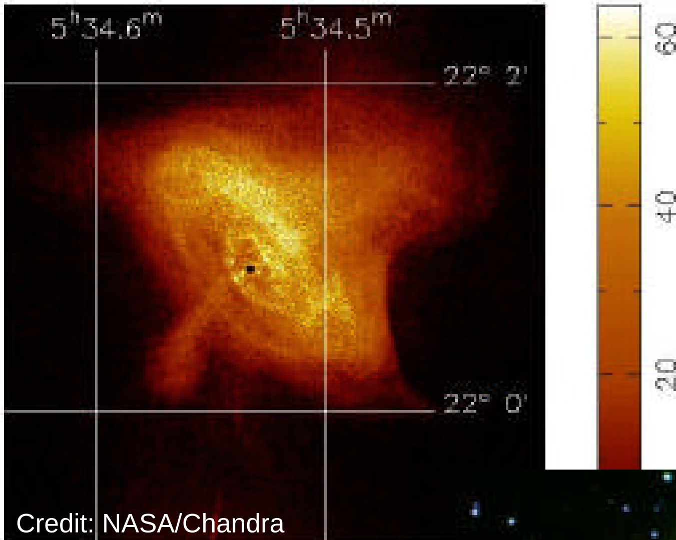




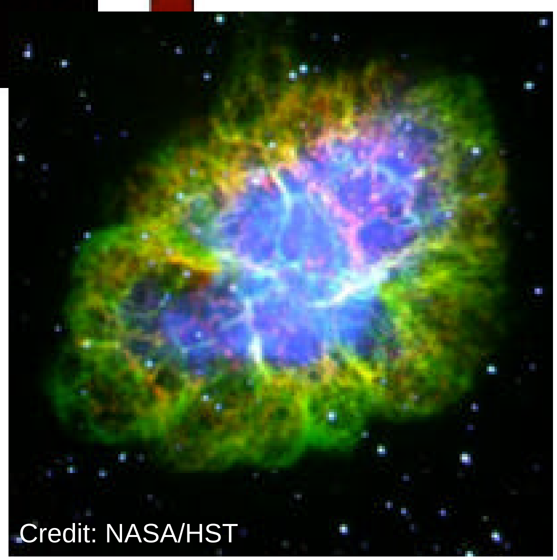
Credit: NASA/Trace

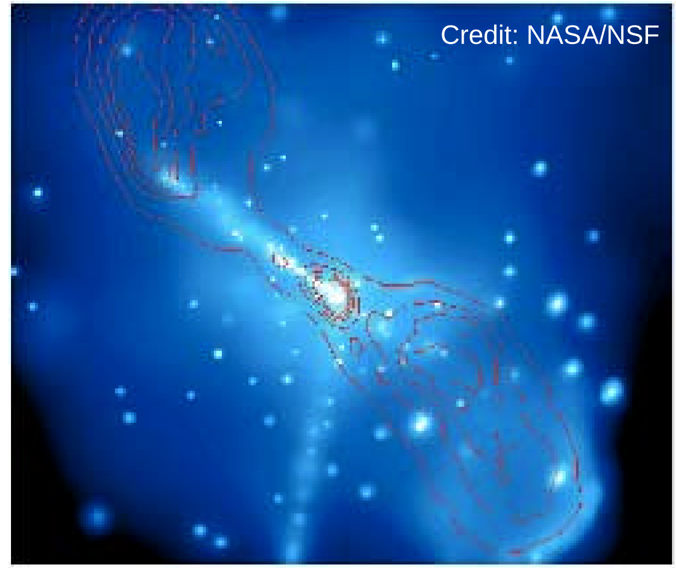
More distant astrophysical plasmas …

The Crab nebula: soft X-ray & optical images



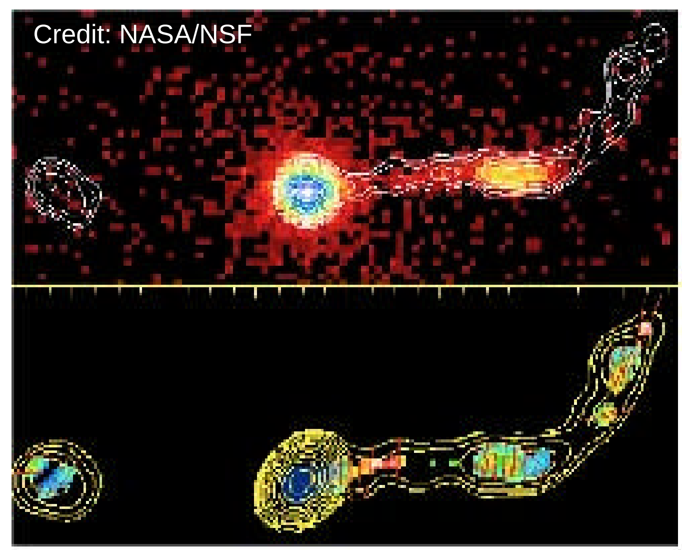
Credit: NASA/Chandra


Credit: NASA/HST

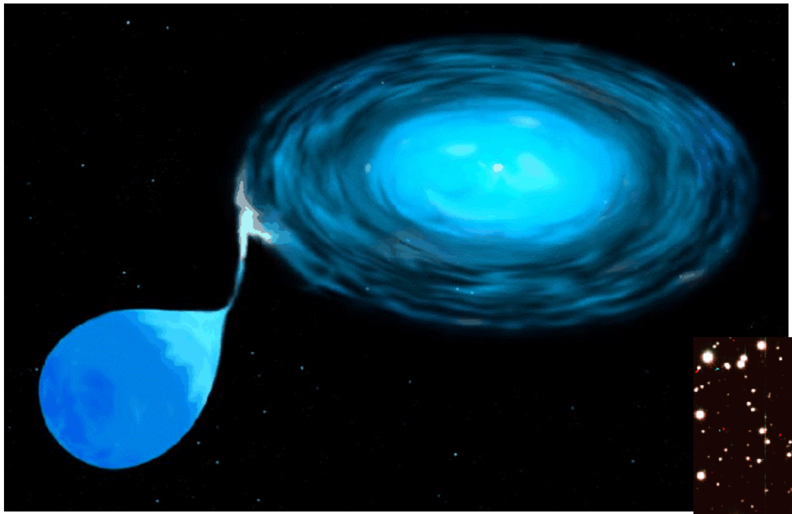

Credit: NASA/NSF

Cen_A: 1-3keV & 13cm images

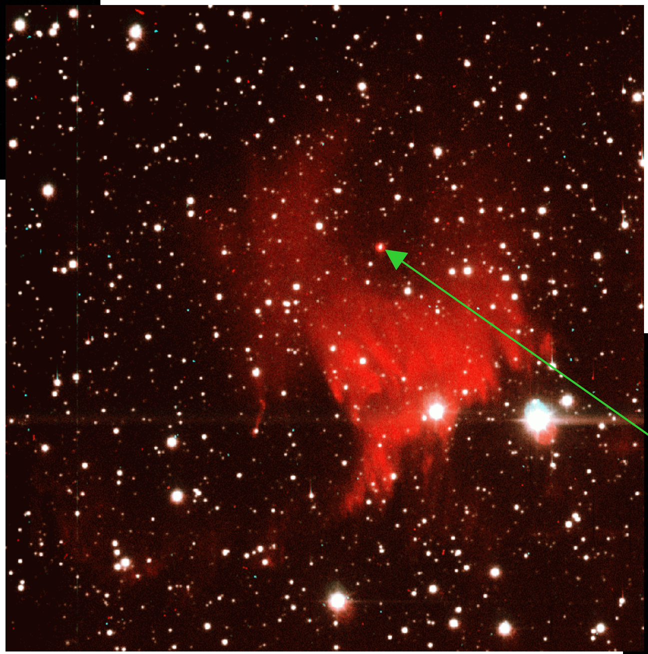
PKS_0637-752: soft X-ray & radio


Credit: NASA/NSF

Dynamical astrophysical plasmas …

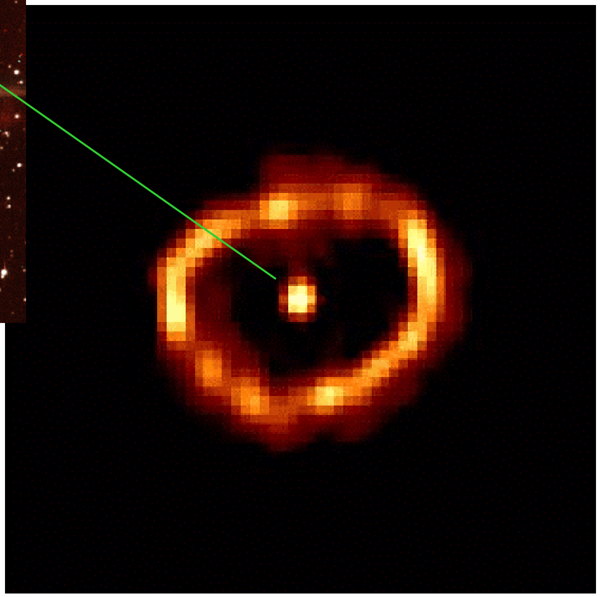


Credit: NASA/HST artist



Nova Cygni 1992

Credits: NASA/STScI



“Typical” Physical Conditions and Approaches

Conditions

- Densities ~ 10^{-5} to 10^{32} cm^{-3}
- Temperatures ~ 10 to 10^{9} K
- Magnetic fields ~ 10^{-12} to 10^{12} G
- Plasma beta ~ 10^{-5} to 10^{20}
- Reynolds #s > 10^{4}

Approaches

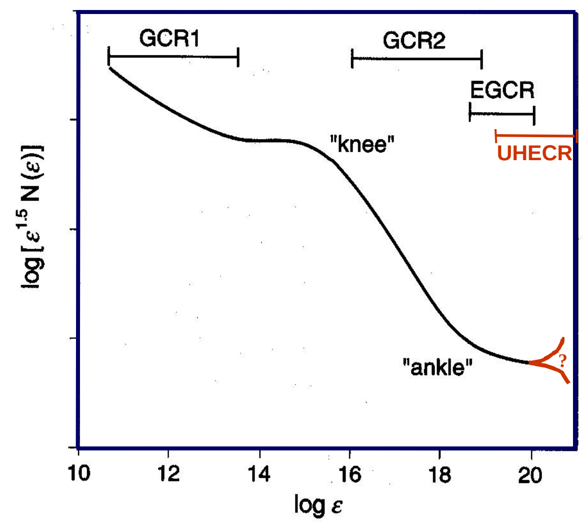
- Most astrophysicists use single-fluid MHD theory
  - Solar/stellar magnetic field evolution
  - Jets/winds
  - Star/disk magnetospheres
- Prominent exceptions:
  - Pulsar atmospheres
  - Particle acceleration and particle emission processes
  - …
- The next steps for plasma astrophysics theory:
  - Hall MHD
  - Gyro-kinetic/gyro-fluid models

What do astrophysicists want to know?

- Transport and diffusion processes
  - Thermal conduction: how is thermal transport modified by turbulent B?
  - Plasma attachment: how does accretion occur?
- Magnetic field evolution and structure
  - Reconnection: does “fast” reconnection exist, and if so, under what conditions?
  - Magnetic dynamos: how are astrophysical magnetic fields generated?
- Plasma heating and acceleration
  - Stellar coronae and winds
    - Resonant coupling to minor species
- Particle acceleration
  - Solar cosmic rays
  - Galactic cosmic rays
  - Ultra-relativistic cosmic rays
- Nuclear processes
  - Synthesis of the light elements during Big-bang nucleosynthesis
  - Nuclear ignition, flame propagation, deflagration-detonation transition
- Radiation hydrodynamics/instabilities
  - Filamentation
  - Plasma acceleration

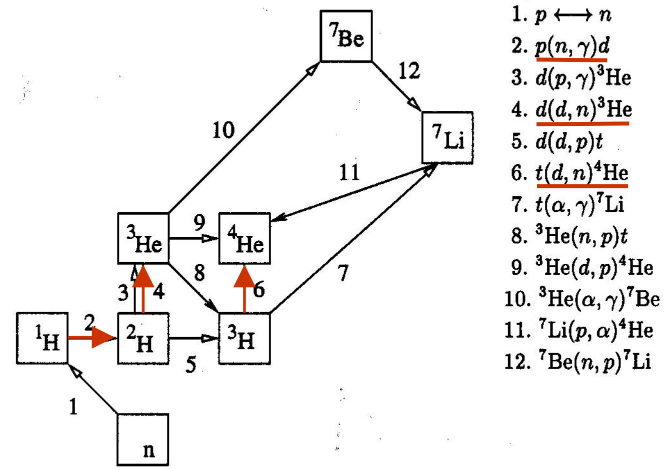
Particle acceleration to Relativistic Energies

- At least 3 components
  - Galactic (and solar) cosmic rays (CR)
  - Extragalactic cosmic rays
  - Ultra-high energy cosmic rays
- E < 10^{15} eV: shock acceleration
  - Shocks in supernova remnants
  - Parent particle population from stars
- E > "Knee" and beyond
  - Thought to result from new mechanism
  - Smooth "join" at knee suggests common source
    - Reacceleration of galactic CR?
- UHECR detected since ~1994
  - AGASA, Fly's Eye, Haverah Park
  - Isotropic distribution on sky
  - No Greisen-Zatsepin-Kuzmin cutoff
    - Local sources? ⟹ Comets impacting neutron stars
    - Mechanism? ⟹ Motional electric fields

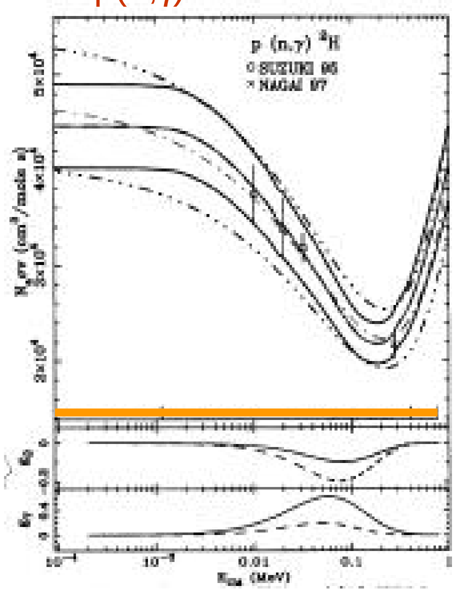


Precision Cosmology: Big-bang Nucleosynthesis

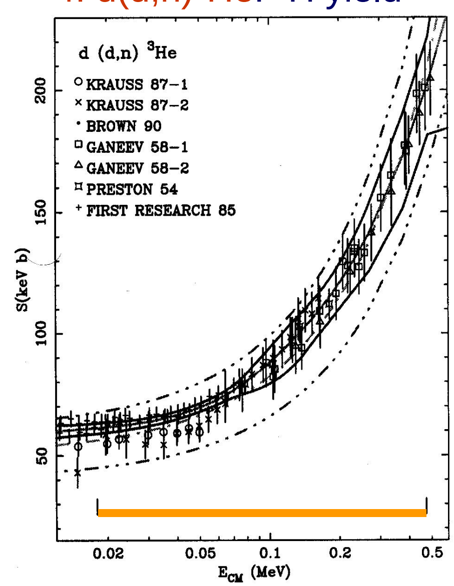
- Light elements production bounds baryon density
  - $\rho_{Deuterium} \sim \rho_B^{-1.6}$
  - Target precision is 1%; present precision is ~ 10%
- Cross sections uncertain at the 5-25% level
  - Errors up to factor of 2 for calculated ^{7}Li abundance
  - Cross-sections needed at relatively high energies
  - Nollett & Burles (2000): astro-ph/0001440



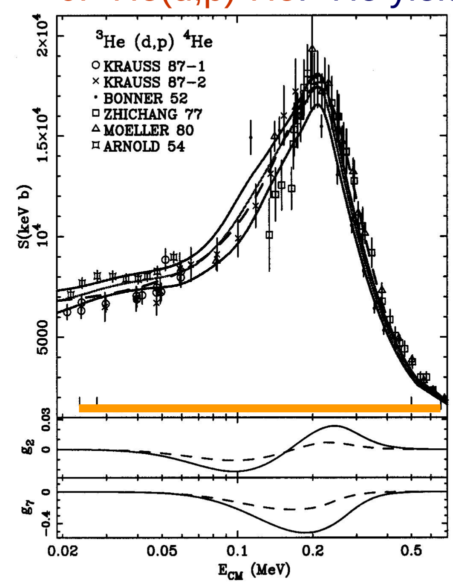
2: p(n,γ)d



4: d(d,n)^{3}He: ^{2}H yield



6: ^{3}He(d,p)^{4}He: ^{3}He yield

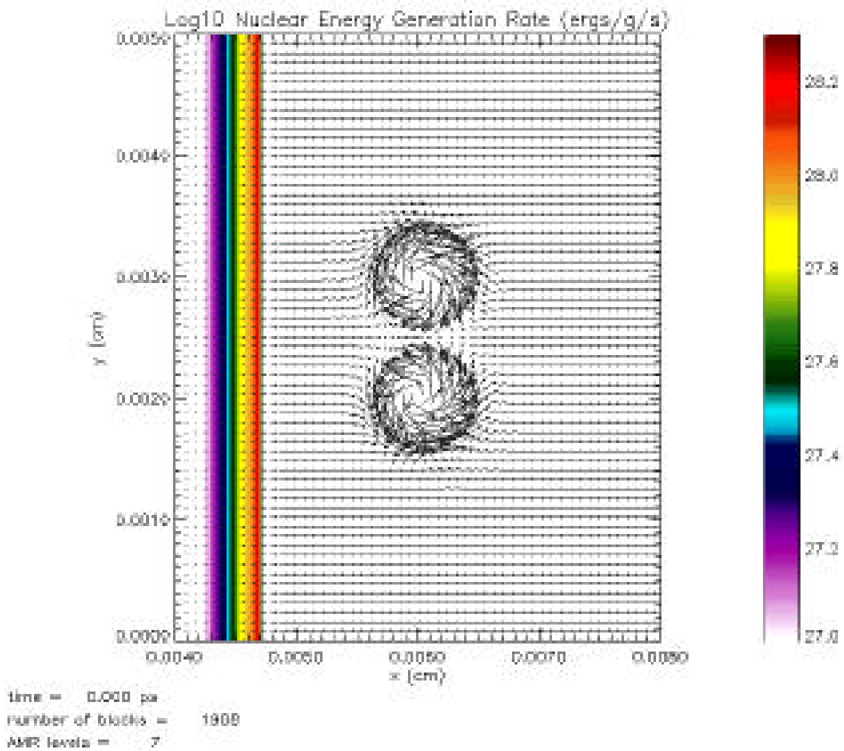


(Nuclear) Burning Plasmas

- Some of the key unanswered questions
  - Ignition: given a turbulent plasma state (and its mean properties), can we identify the state at which a self-sustained “flame” will propagate?
  - What is the scaling of mean flame speed with the properties of the underlying (turbulent) flow?
  - Under what conditions will (nuclear) flames quench?
  - Under what conditions will a (nuclear) deflagration transition to a detonation?
- Astrophysics problems in which these questions matter
  - Type Ia supernovae (burning of an entire white dwarf star)
  - Novae (burning of H/He on surface of white dwarf star)
  - X-ray bursts (burning of H/He on surface of neutron star)

Examples of nuclear flame calculations

Credits: DOE ASCI/Alliances Flash Center



Zingale et al. (2000)

Vladimirova et al. (2000)

Vladimirova et al. (2000)

Where does laboratory plasma physics enter?

- Exploration of physical mechanisms
  - Particle acceleration
  - Magnetospheric accretion: neutral beam injection
  - Plasma heating processes
  - Reconnection
  - Magnetic dynamos
  - …
- Measurement of fundamental physical properties
  - Nuclear cross-sections
  - Atomic oscillator strengths
  - …
- Validation of astrophysics simulations
  - Laboratory MHD experiments can have Lundquist and Reynolds numbers comparable to those of simulations
  - Laboratory experiments are relatively well-diagnosed

… and that leads us to

QUESTIONS AND DISCUSSION