Plasma Science Frontiers Workshop

- Fusion Energy Sciences seeks to engage the community of scientific experts working in the field of plasma science in a series of community-led workshops to identify:
- Compelling scientific challenges at the frontiers of plasma physics, and
- Research tools and capabilities that exist presently, as well as the general requirements necessary to address these challenges in the next decade.

F. Skiff and Jonathan Wurtele, co-chairs
Sean Finnegan, DOE contact

Process

- Recruiting of the sub-panels.
- Organization of town hall meetings and solicitation of white paper input.
- Town hall in Bethesda followed by on-line town hall meetings.
- Initial synthesis of input (>200 white papers evenly distributed across the five sub-panels and ~100 town hall presentations.
- First workshop - in light of the input, where is the frontier?
- Second workshop - given the definition of the frontier - what will progress require?

Panel 1: Plasma atomic physics and the interface with chemistry and biology

Panel Leads: Dr. Mark Kushner (University of Michigan) & Greg Hebner (Sandia),
Panel Members: Alla Safronova (Nevada), Jorge Rocca (Colorado State), Randall Smith (Harvard-Smithsonian), David Graves (Berkeley), Michael Keidar (GWU), Jeff Hopwood (Tufts), Igor Adamovich (Ohio State)

Research areas represented in this area include but are not limited to:

Multiphase plasmas

Low-temperature plasma physics phenomena related to plasma processing, interactions of plasmas with materials and liquids

Atomic physics processes in plasmas across the full range of plasma parameters (low temperature, fusion, astrophysical)

Panel 2: Turbulence and transport

Panel Leads: Dr. Bruce Remington (Lawrence Livermore National Laboratory) & Dr. Michael Mauel (Columbia University)

Panel Members: Greg Howes (Iowa), Forrest Doss (LANL), S. Peter Gary (LANL), Jim Stone (Princeton), Gianluca Gregori (Oxford), George Tynan (UCSD), Dmitri Ryutov (LLNL), Stewart Zweben (PPPL), Anne White (MIT)

Research areas represented in this area include but are not limited to:

Plasma turbulence and associated transport phenomena in all contexts
(astrophysical, fusion, and high-energy-density)
Connection to many-body problems in condensed matter

Panel 3: Interactions of plasmas and waves

Panel Leads: Dr. Troy Carter (University of California, Los Angeles) & Dr. Gennady Shvets (University of Texas, Austin)

Panel Members: Alain Brizard (Saint Michael's), Martin Laming (NRL), Stuart Bale (Berkeley), John Cary (Boulder), Ellen Zweibel (Wisconsin), Julia Mikhailova (Princeton), Karl Krushelnik (Michigan), Nat Fisch (Princeton)

Research areas represented in this area include but are not limited to:

Linear and nonlinear Wave-wave, wave-particle interactions
Particle acceleration and radiation (laboratory and astrophysical)
Shock waves
Plasma field theory

Panel 4: Statistical mechanics of plasmas

Panel Leads: Dr. John Goree (University of Iowa) & Phil Morrison (University of Texas, Austin)

Panel Members: Jerome Daligault (LANL), Siegfried Glenzer (SLAC), Thomas Schenkel (LBNL), Scott Baalrud (Iowa), Tom Killian (Rice), Rob Rudd (LLNL), Michael Bonitz (Kiel)

Research areas represented in this area include but are not limited to:

Fundamental plasma kinetic theory including, but not limited to, collision operators, closures, strongly-coupled plasmas, order reduction and questions of the number of electro-mechanical degrees of freedom

Phase transitions, non-equilibrium processes, and warm dense matter

Connection to quantum mechanical descriptions

Panel 5: Plasma self-organization

Panel Leads: Dr. Igor Kaganovich (Princeton Plasma Physics Laboratory) & Dr. Cary Forest (University of Wisconsin, Madison)

Panel Members: John S. Sarff (Wisconsin), James F. Drake (Maryland), Don Lamb (Chicago), Matthew Kunz (Princeton), Uri Shumlak (Washington), James R. Danielson (UCSD), Andre Anders (LBNL), Edward Thomas (Auburn), Daniel Brian Sinars (Sandia), R. Paul Drake (Michigan)

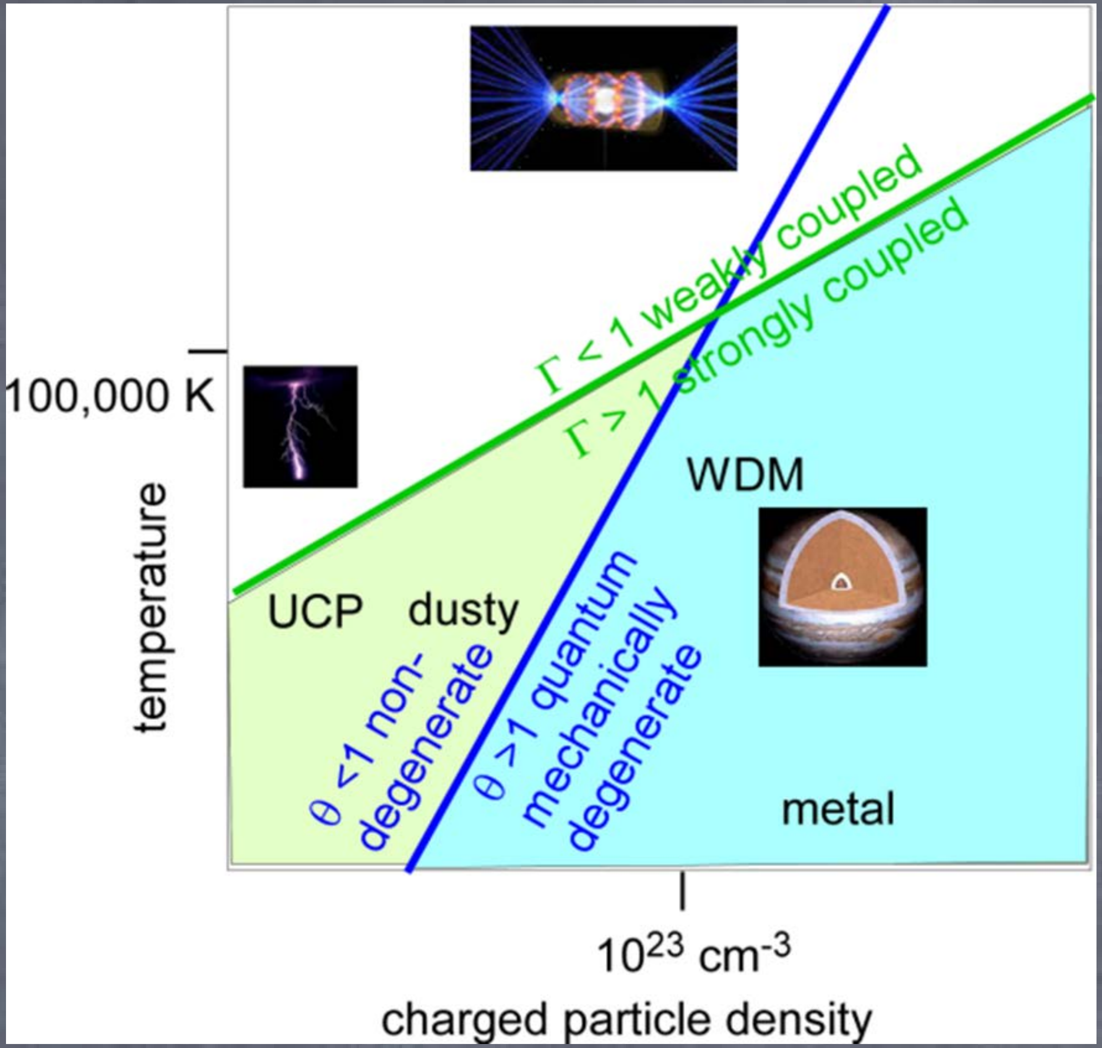
Research areas represented in this area include but are not limited to:

Magnetic self-organized states such as found in exploratory magnetic confinement and in astrophysics

Energy transformation between plasma flow, magnetic fields and particles, including dynamos and magnetic reconnection

Plasma electrical self-organization including, but not limited to, virtual cathodes and nonlinear phase space structures and waves, vortex dynamics and non-neutral plasmas

I. Extreme states of matter and plasmas



Plasma statistical mechanics

How do plasmas behave under extreme conditions
where our current descriptions fail?

I.1 Warm Dense Matter

How can we probe the warm dense matter regime?

What are the material properties of WDM and how can we predict them?

How does WDM transport energy and particles?

Can we gain an understanding of the physics of dense bodies in the cosmos through what we learn in the laboratory experiments and theoretical tools developed to answer the previous questions?

I.2 Ultra-high energy density laboratory plasmas

Courtesy of Colorado State University.

What are the atomic and plasma physics properties of highly stripped atoms?
What are the properties of plasmas with the same density as solids?

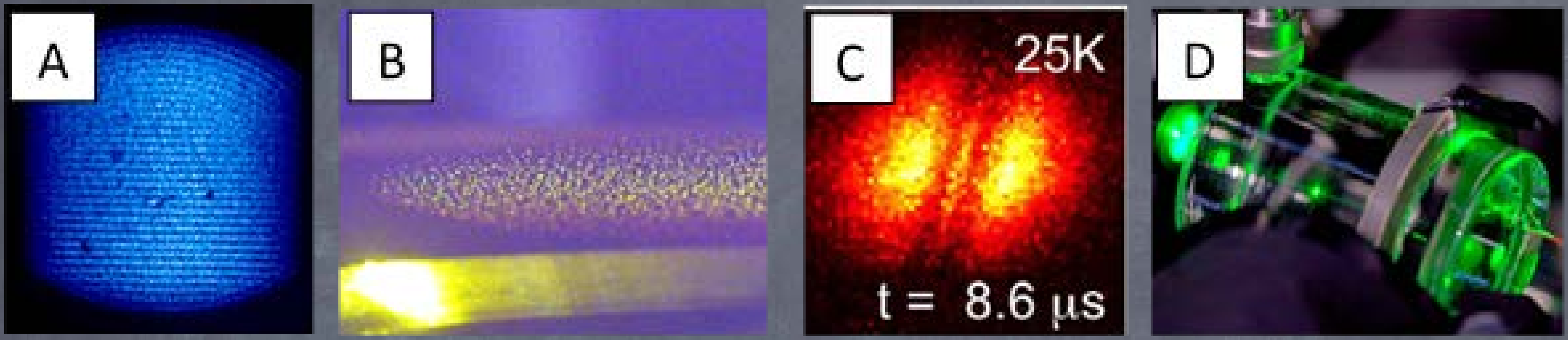
I.3 Antimatter and matter-antimatter plasmas

Can antimatter plasmas enable tests of fundamental physics theories such as CPT?

Can trapped antimatter plasmas provide revolutionary tools for medical and materials research?

Can the theoretically unique properties of pair-plasmas be experimentally demonstrated in electron-positron plasmas?

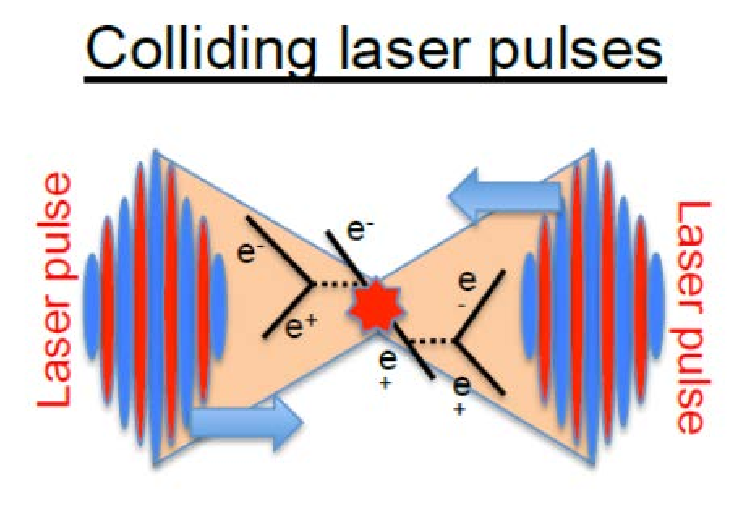
I.4 Strongly-coupled plasmas



A.Laser-cooled trapped ions. B. Complex plasmas with charged dust grains.
C. Ultra-cold neutral plasma. D. Sonoluminescent plasma.

How can we we gain fundamental knowledge about the structure and dynamics of strongly coupled plasmas by isolating classical effects using plasmas that allow more detailed observation?

I.5 Boiling vacuum to generate pair plasma, QED plasma

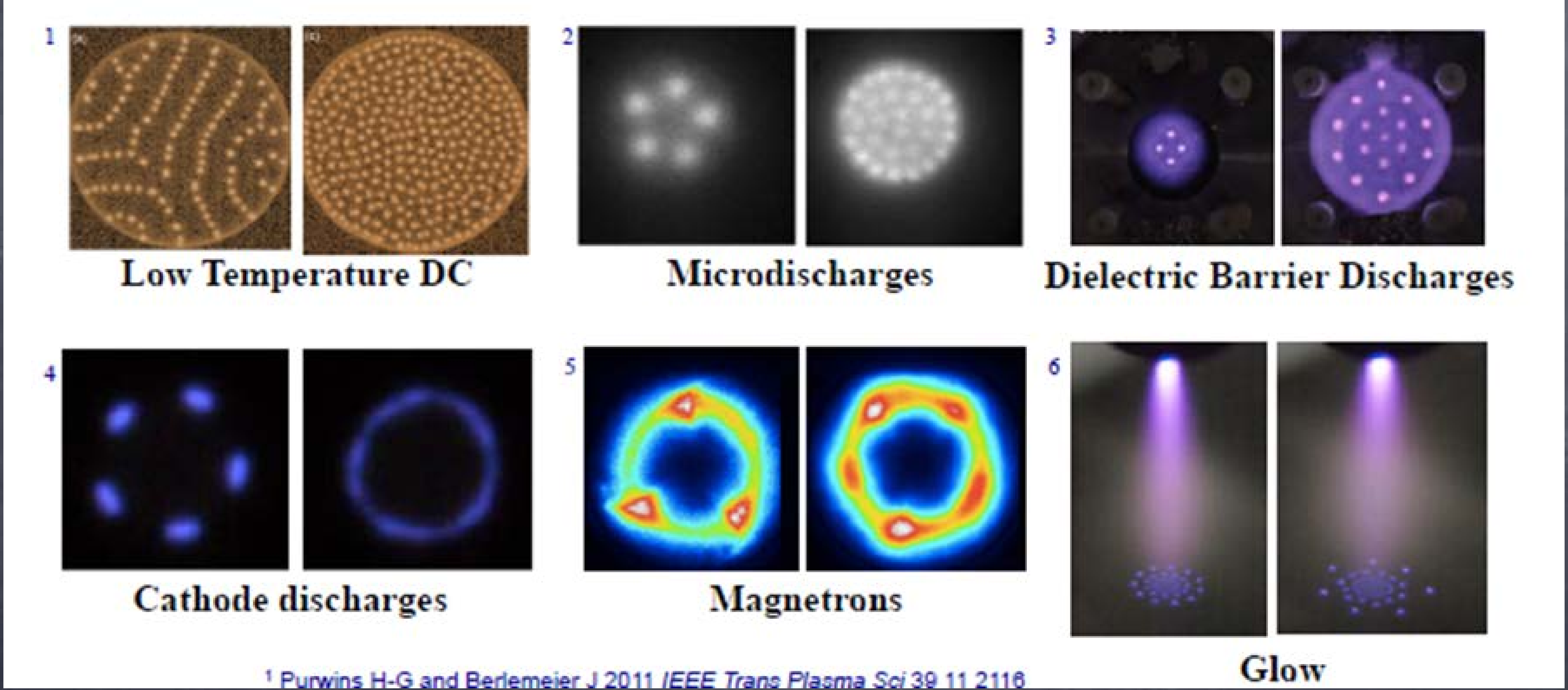


What is the intensity limit for electromagnetic waves?

What new phenomena are possible in the high-field limit?

II. Coherent Plasma Structures

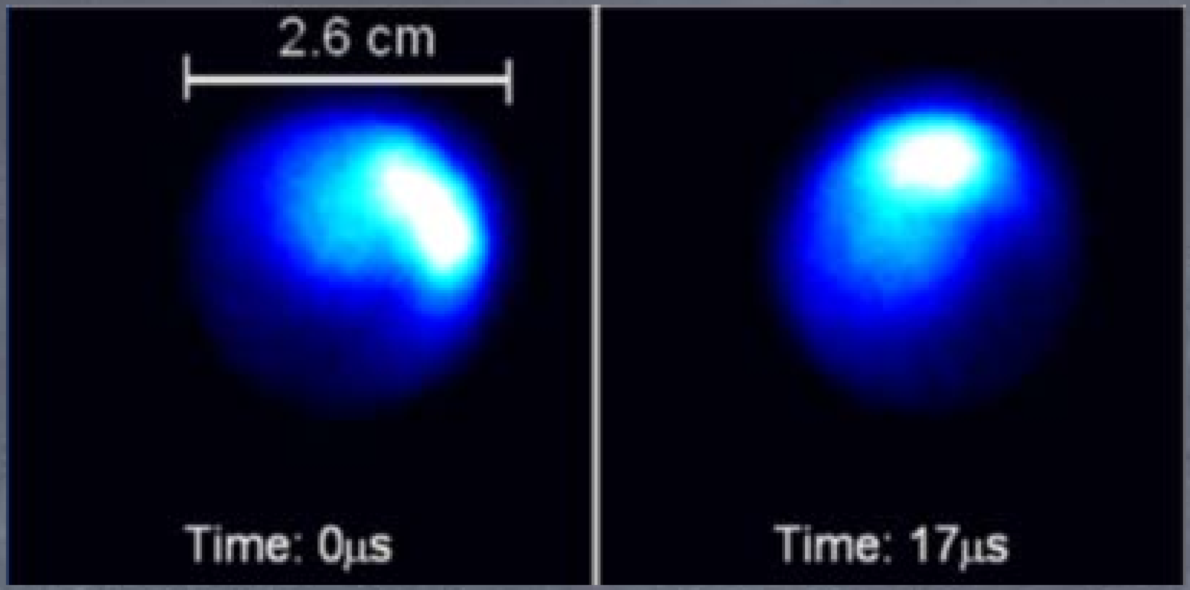
Plasma electrical nonlinearity and self-organization



[1] Purwins H-G and Berlemeier J 2011 *IEEE Trans Plasma Sci* 39 11 2116

How does pattern formation work both in physical space and in phase-space?

II.1 Spoke Phenomena

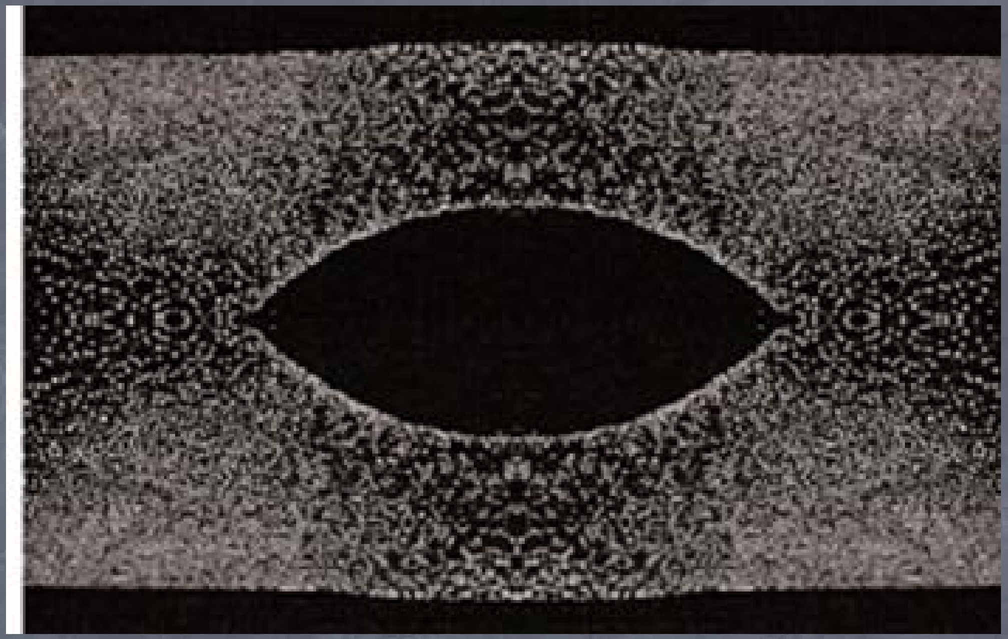


Images: E.V. Barnat, Sandia Labs

How can spoke phenomena be described, adequately diagnosed, and modeled?

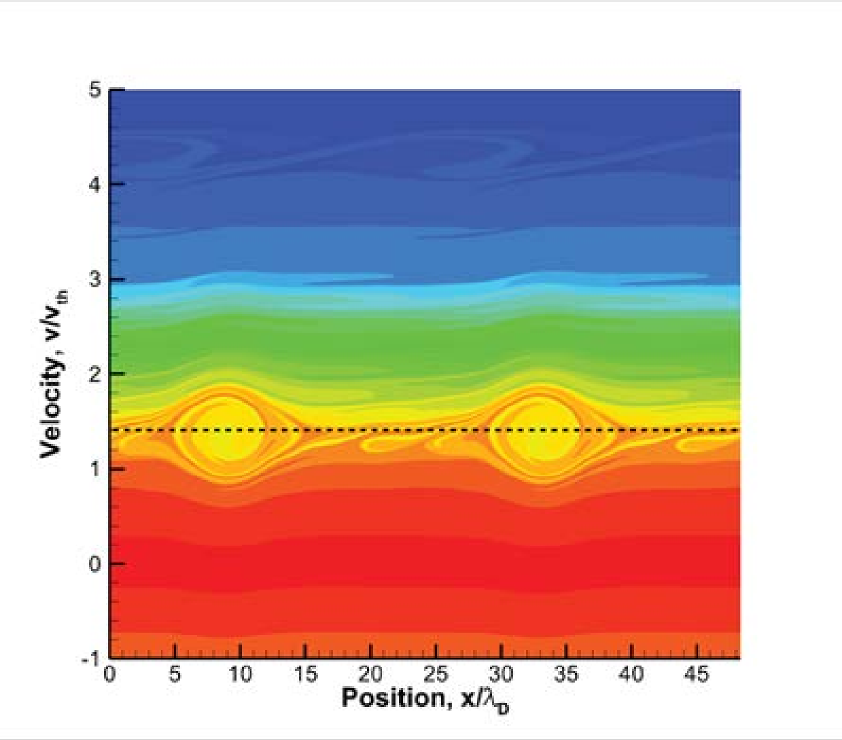
What basic principles are involved, and how universal are they for other kinds of structures?

II.2 Pattern formation in complex (dusty) plasma



How plasma and materials processes are self-organized?
What are the effects of interactions of nanoparticles with plasma (charging, radiation emission and absorption, heating)?
What are suitable diagnostic tools for measurements in plasmas with nanoparticles?

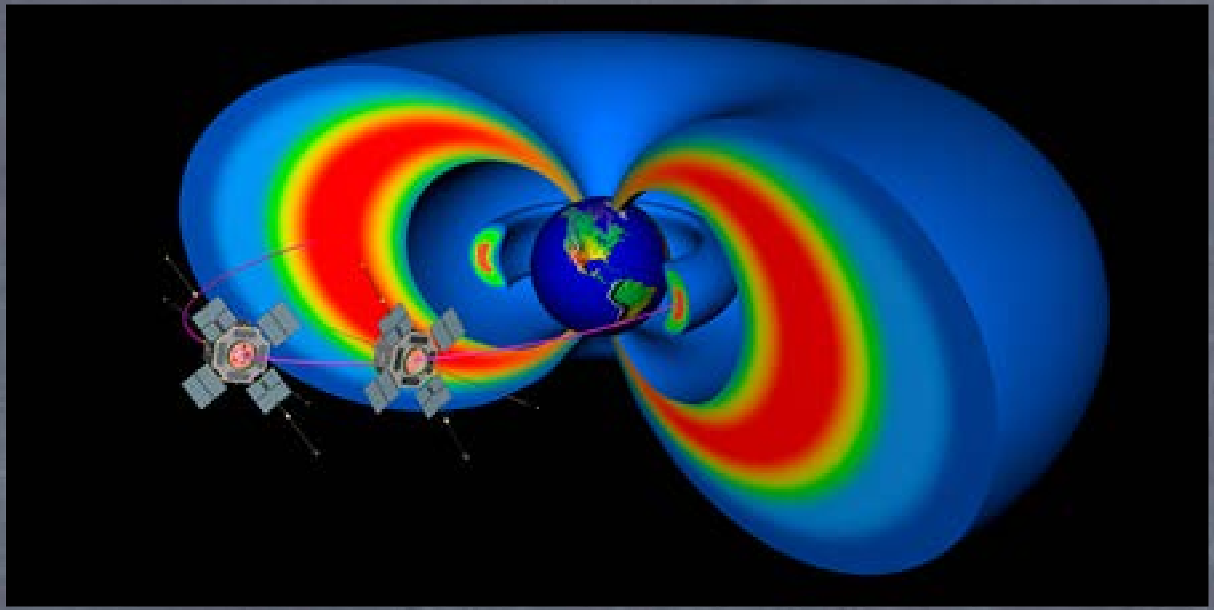
II.3 Phase-space structures



How do small changes in particle distribution functions produce long-lived structures?

Can plasma currents and gradients lead to the production of structures in uniform plasma?

II.4 Radiation belts in geospace plasma

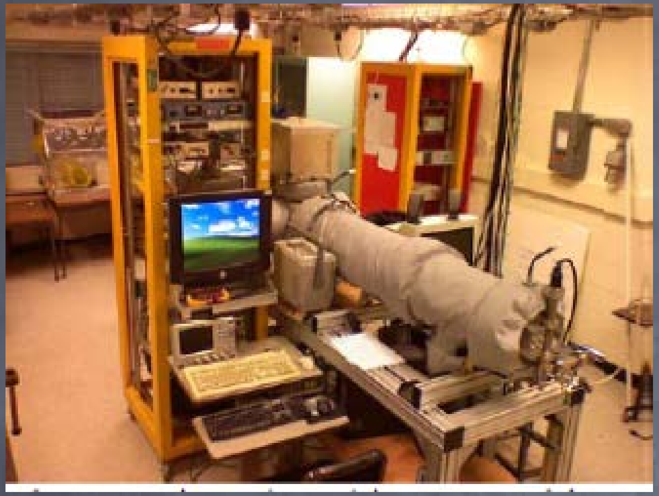


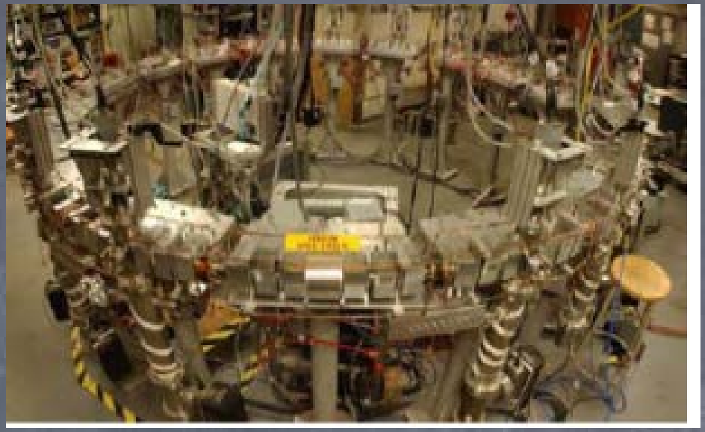
What processes control the internal structures of radiation belts and can they be controlled?

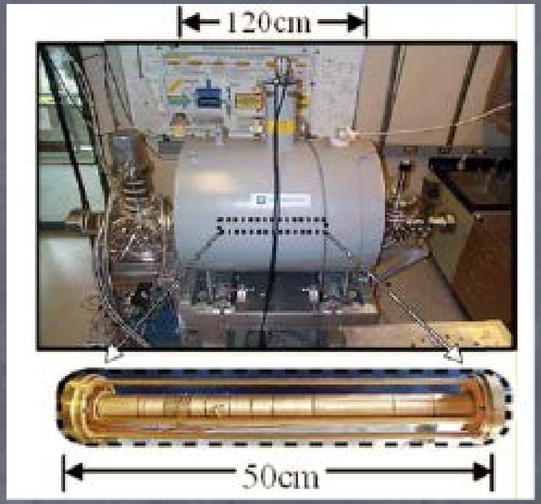
What is the role of reconnection vs mixing for transport?

What is the effect of the shocks produced by the observed vortex structures at the magnetopause boundary layer?

II.5 Non-neutral plasmas and beams





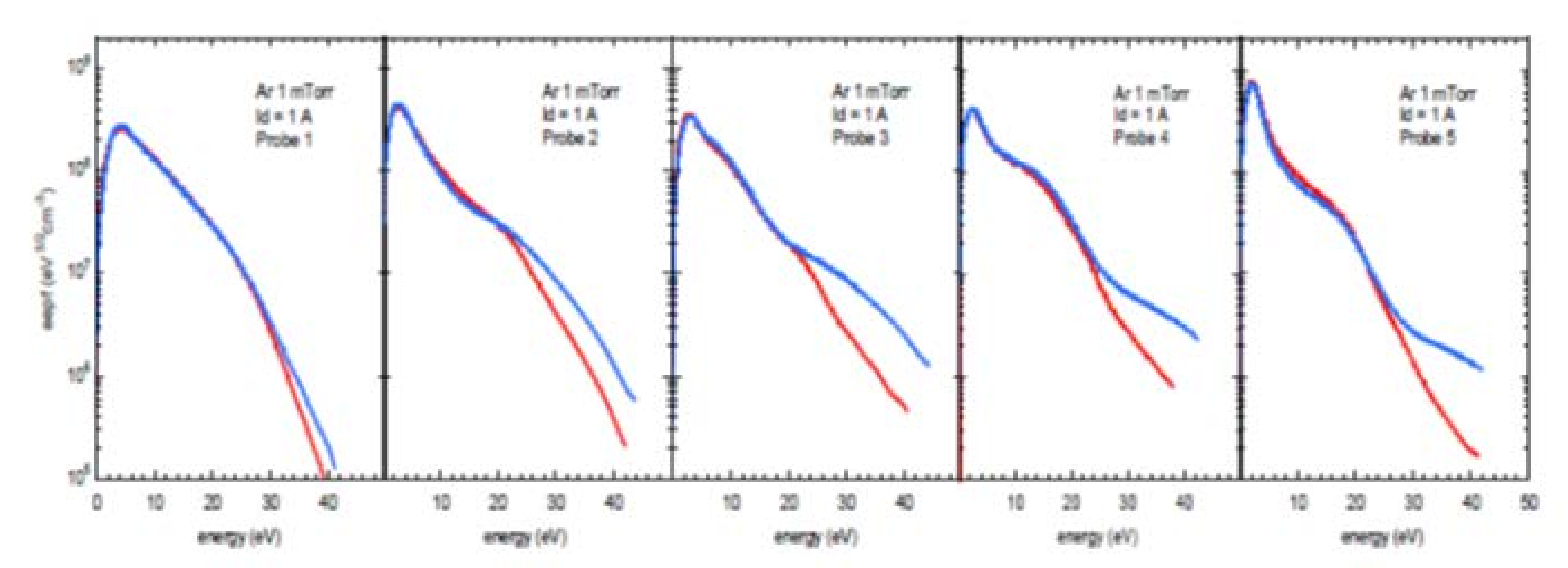


How can intense charged-particle beams be transported over long distances?

What produces emittance growth and halos?

Can systems be developed to control the phase space of charged particle beams?

II.6 Structure at boundaries



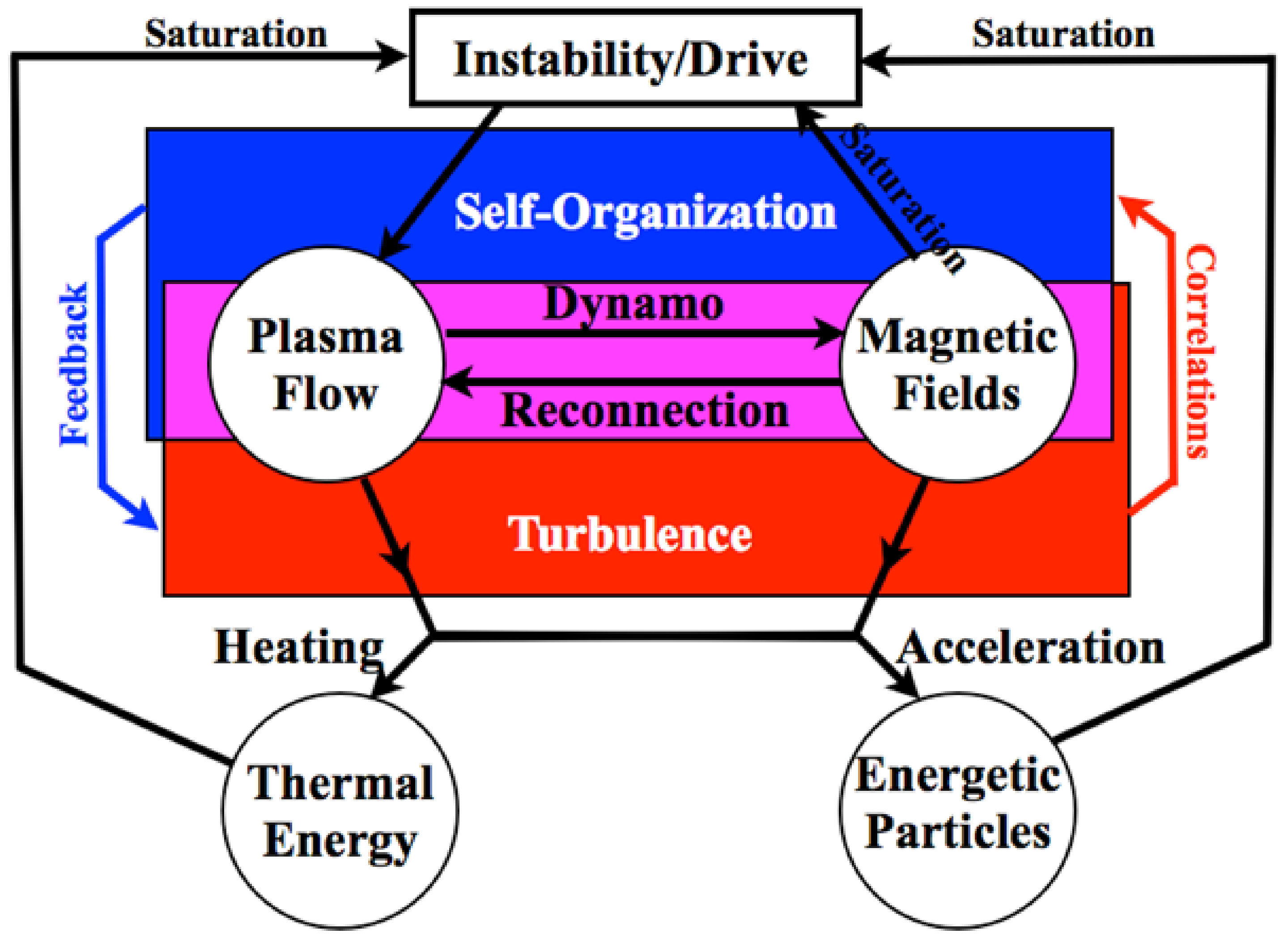
What is the nature of the electron and ion presheath and sheath under general conditions of collisionality and magnetization?

How do streaming instabilities affect double-layers?

To what degree can one control the exit-velocity of ions from the edge of a plasma?

III. Understanding the Energetics of the Plasma Universe

Plasma turbulence and magnetic self-organizaton



III.1 Energy Transformation: flow to magnetic field (dynamos)

How are magnetic fields created and amplified in the Universe?

How can we construct realistic multi-scale, multi-physics modeling and kinetic modeling of plasma dynamos?

III.2 Energy Transformation: magnetic field to flow (reconnection)

How do magnetic field lines break?
What controls the onset and rate of reconnection?
How does magnetic energy energize particles?
Why are energetic-particle spectra typically power laws?
What is the relation between two- and three-dimensional reconnection?
How do relativistic effects, radiation or pair-production impact the dynamics?

III.3 Acceleration of High-Energy Particles (cosmic rays)

How does nature extract extreme nonthermal tails from plasmas, in apparent defiance of thermodynamics?

How do energetic particles modify, and even regulate, their environments?

III.4 The turbulence cascade and dissipation

Can we understand the physical processes governing the nonlinear turbulent cascade and the dissipation of the turbulent fluctuations and resulting plasma heating?

Can we develop the capability to predict the evolution of turbulent plasma systems?

III.5 Magnetic self-organization: generation of coherent structures from a turbulent flow

How can we explain the formation of current sheets, plasmoids, astrophysical jets, zonal flows, and other coherent structures?

Can this process be modeled effectively?

III.6 Transport of plasma particles, momentum and energy through space

How can our understanding of turbulence be used to understand the large scale structure and properties of non-equilibrium plasmas?

IV. Disruptive Plasma Applications

Plasma field theory and wave-particle interactions.

How can efficient interactions between electromagnetic fields and particle motion be described, established and controlled?

IV.1 Compression of ultra-intense laser beams

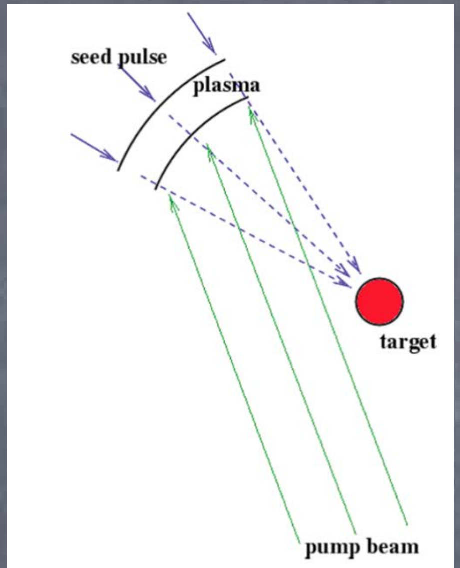
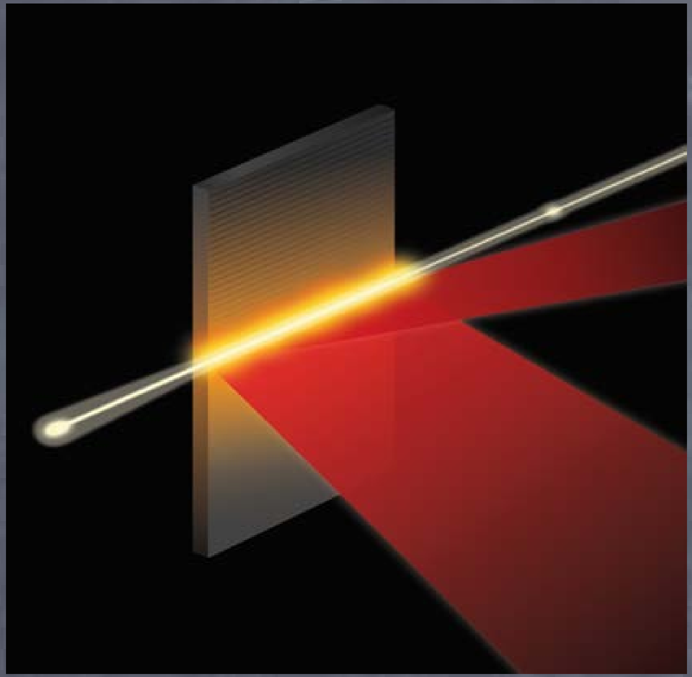


Fig.1 Schematic of Laser Compression in Plasma

Parametric amplification by stimulating plasma waves through the interaction of multiple laser beams has the potential to transfer significant energy from an energetic long-pulse laser to a low energy short-pulse seed over millimeter-scale interactions.

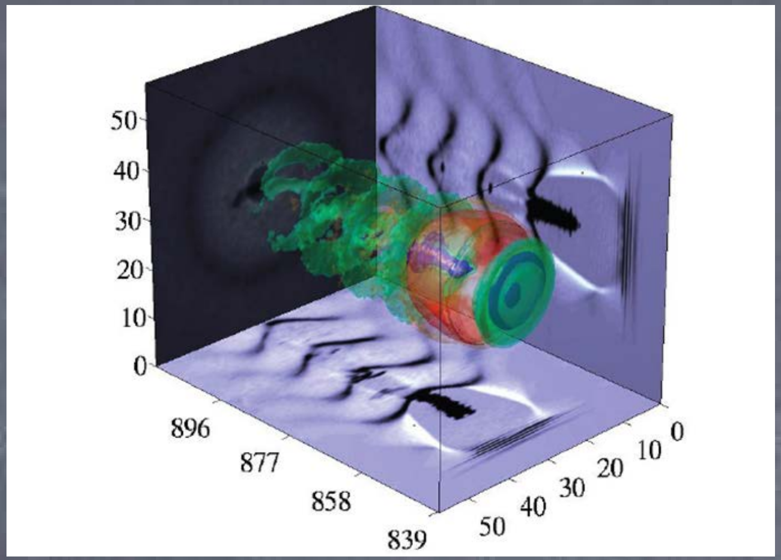
IV.2 Generation of high-flux high-intensity X-rays



Schematic diagram of the generation of fully coherent soft x-ray laser beam by amplification in an inverted atomic transition in i a dense plasma columnlse . Courtesy of Colorado State University.

New plasma-based EUV, x-ray, and gamma-ray sources have the potential to outperform existing light sources through their spectral and temporal properties including spatial and temporal coherence, power efficiency, compactness, and accessibility.

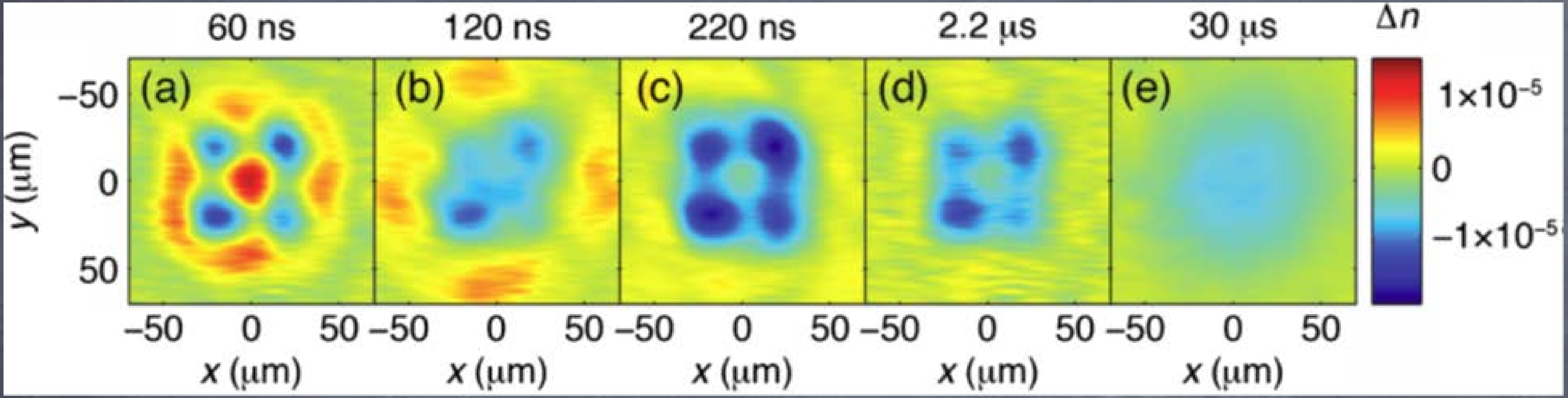
IV.3 Plasma-based accelerators



Plasma-based laser-driven electron and ion accelerators and particle beam wake-field accelerators have the potential to enable new compact, high performance, versatile, and low cost accelerators for many applications.

Target plasmas can also become a source for sub-atomic particles.

IV.4 Plasma Photonics



Courtesy University of Maryland

Plasma filaments and plasma waveguides produced by high power femtosecond laser propagation in has the potential to enable programmable microwave mirrors in air as well ans unique fundamental study of high field non-perturbative interactions with atoms, molecules, and plasma

V. The Interface of Plasma Science with Societal Needs Through Enabling Technology: Health, Food, Water

Low temperature plasmas:
The interface of plasma science with atomic physics, chemistry and biology.

Precision control of free electrons f(v): Making electrons do our bidding to benefit food, water, health, and economic security. In a future where renewable electricity is our primary and abundant energy source, plasmas become the ubiquitous tool to enable a better life.

V.1 Interfacial plasmas

How can we describe the interaction of plasmas with solids, liquids, and gasses?

- How are electrons generated and transported in liquids?
- What is the effect of the liquid properties (such as polarizability, dielectric constant, conductivity, secondary emission coefficient) on development of plasma and radical generation at a plasma-liquid interface?
- What is the method of transport of electrons, ions and neutral through the plasma-liquid interface, over a wide range of time scales (~ sub-ns to at least ~ s)?
- What is the effect of charge solvation and transport through the liquid on ion-molecule reactions in the liquid phase?
- What are the conditions when the plasma may be generated directly in the liquid phase (rather than in pre-existing micro-bubbles), e.g. using extremely high peak electric field, sub-ns duration pulses?

V.2 Plasmas for Human Healthcare

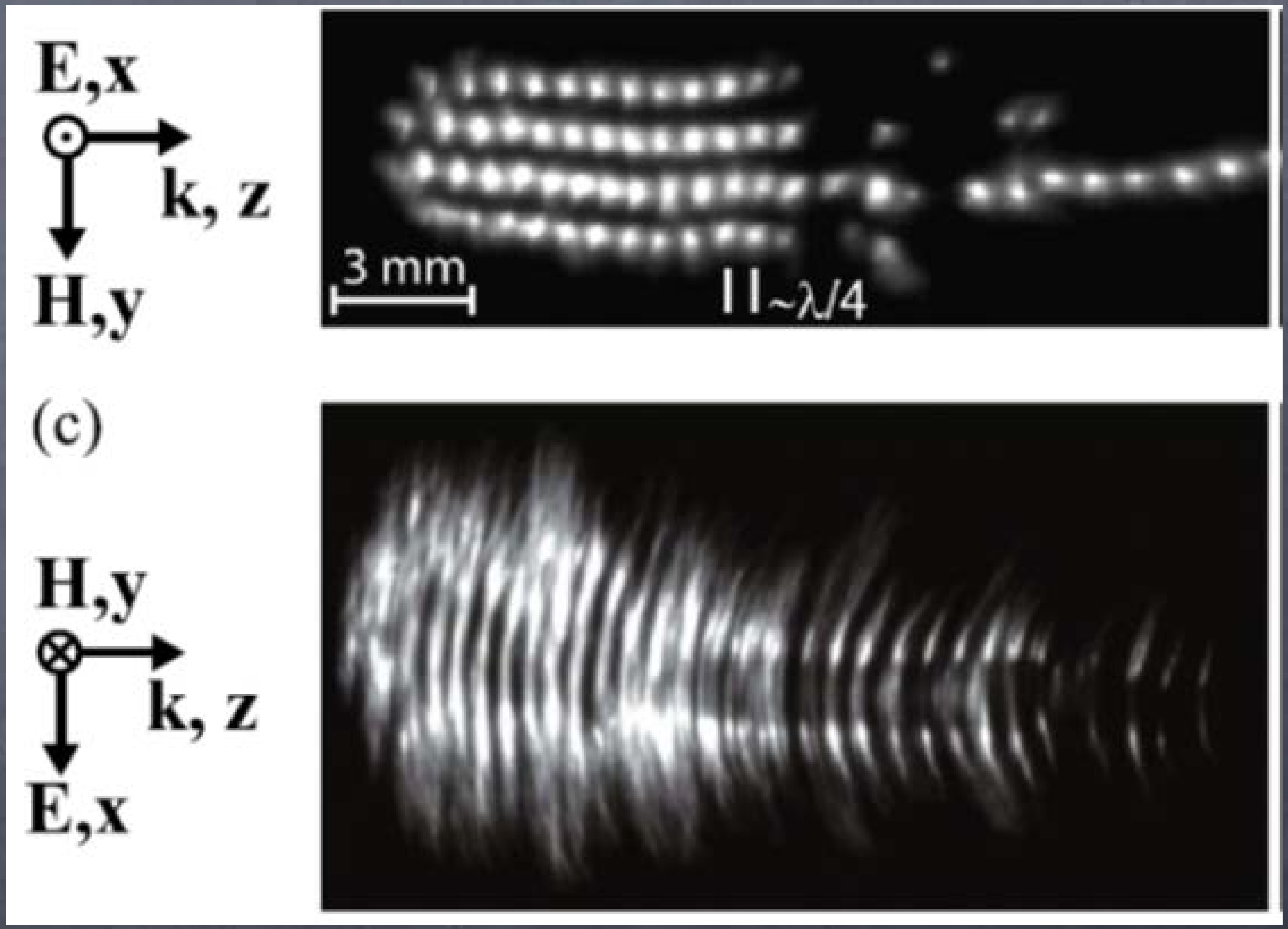
- Building on the observations that plasmas can induce beneficial effects in biological systems – healing wounds and reducing cancer tumors – can we understand the complicated interaction pathways that provide such biological benefits?
- Interactions of plasmas at permeable, reactive, dynamic, charged interfaces exemplified by liquids (e.g., biological fluids), soft matter (e.g. cells and tissues) and polymers (e.g., biocompatible materials and scaffolding)
- How do electrons and moderate energy ions (e.g., 10s of eV) cascade, deposit energy and modify chemistry within high density, amorphous materials such as water, polymer or bodily fluids?
- Symbiotic self-organization at the plasma-liquid interface induced by non-linear coupling between plasma fields and surface impedance.

V.3 Control of Plasma - Electromagnetic Interactions

- What are the fundamental properties of THz radiation interactions with plasmas?

- Can interactions of THz radiation with microplasma arrays or structured plasmas (“photonic crystal”) addresses the challenge of the control of THz radiation?

- How does THz radiation initially produce plasma and ultimately result in self-organized structures?



. Millimeter wave scattering and diffraction in 110 GHz air break down plasma, Alan M. Cook, Jason S. Hummelt, Michael A. Shapiro, and Richard J. Temkin, Physics of Plasmas 20, 043507

V.4 Plasmas for the Environment: Plasma Catalysis

- How can the energy distribution and radical chemical production in low temperature plasmas be optimized to drive advances in surface and water catalysis?

V.5 Plasma Aided Combustion for improved energy utilization

- Why does the application of plasmas to flames improve the fuel efficiency and flame stability?

V.6 The Interface between Plasma and Solid-State Physics

- How can we describe “extreme plasma processing” where the electron density and Debye lengths in the plasma and the solid are comparable and plasma-solid interactions may not be treated as isolated binary collisions?

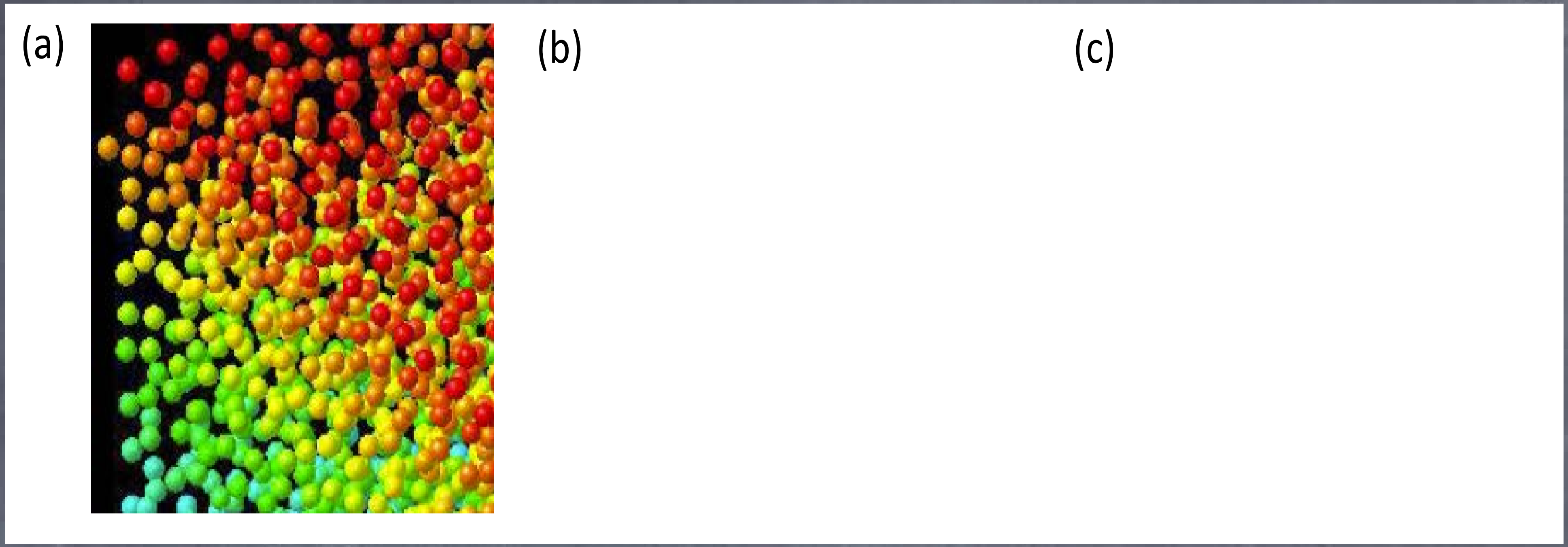
V.7 Atomic, Molecular and Optical Physics Fundamental Data Needs.

The current state of the art of plasma modeling and simulation, and of interpreting experimental measurements, is constrained the lack of a comprehensive, robust, validated and dynamic database of fundamental cross sections, rate coefficients, opacity and emission coefficients. That is, progress in improving our fundamental understanding of nearly all fields of plasma physics is rate limited by the lack of fundamental data.

VIII. Theory and Simulation

How can we meet the challenge of predicting the key properties of plasmas with dynamics over a wide range of temporal and spatial scales?

Can we significantly reduce the risk of underperformance of expensive experimental facilities and explore numerically wide ranges of parameter regimes?



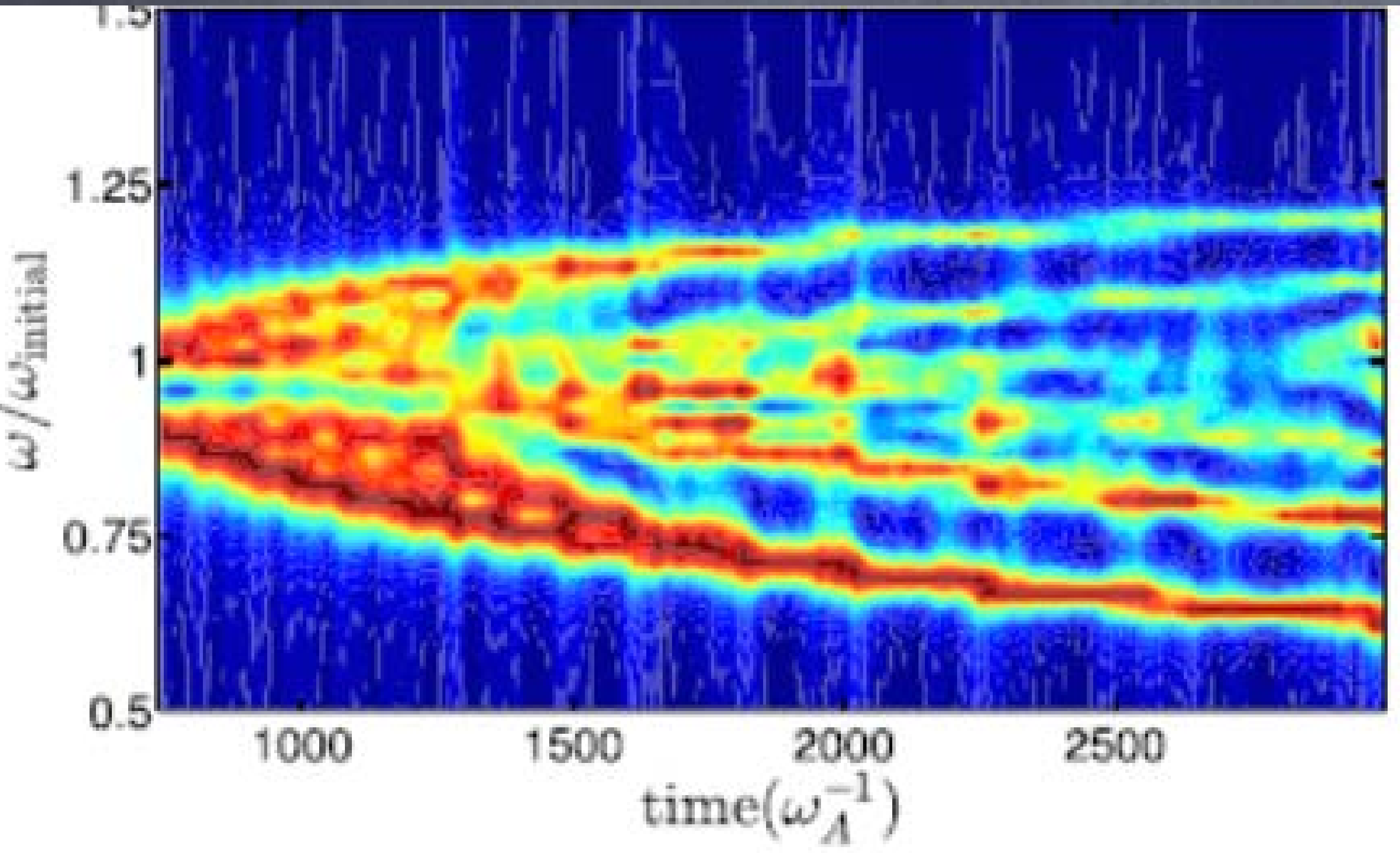
Extreme conditions are defined by where our theories break-down.

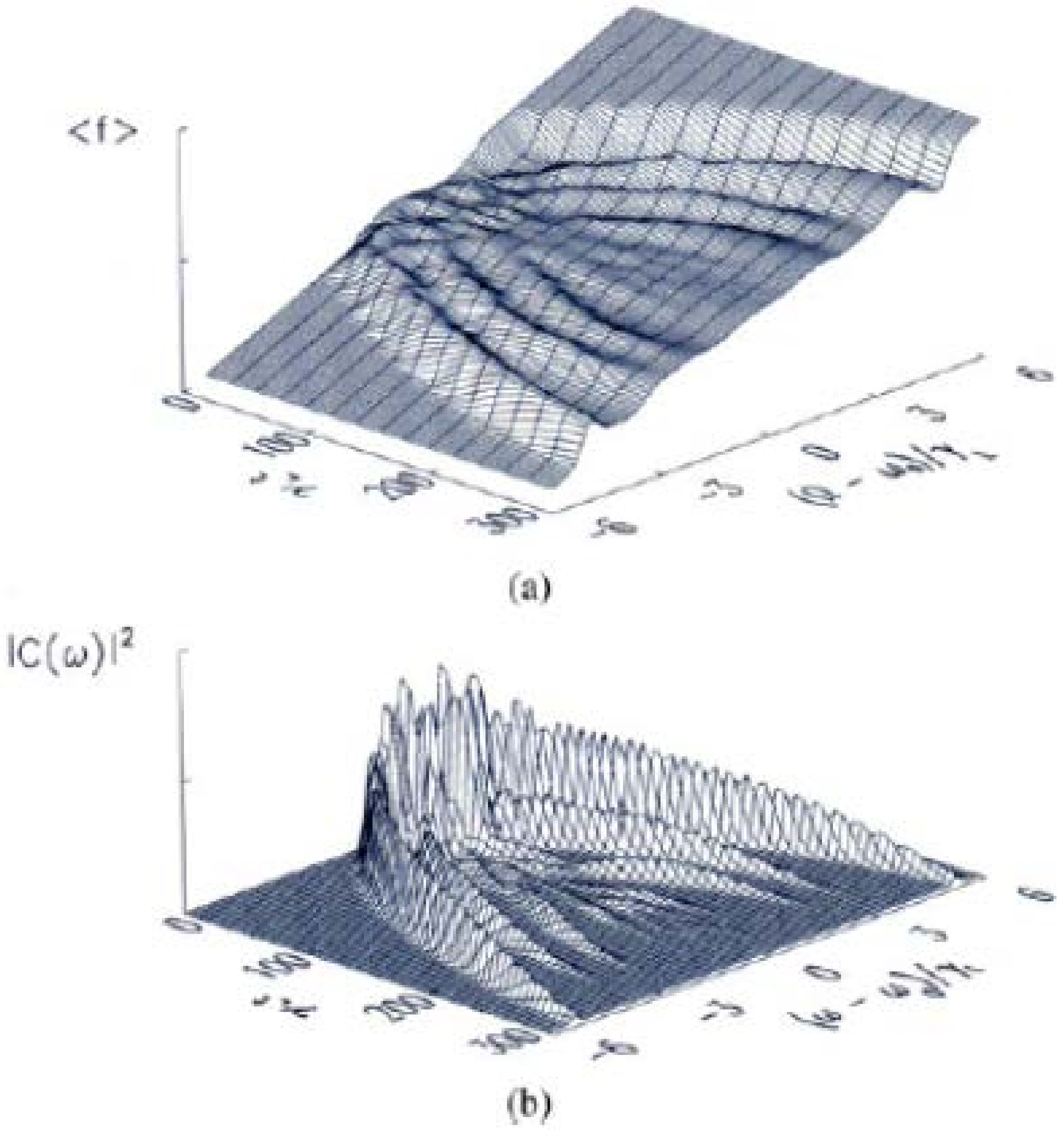
What are the correct descriptions of strongly coupled plasmas in the WDM and HEDP regimes?

Can we efficiently compute the dynamics and equilibria of stongly-coupled systems?

II

Can the connection between phase-space dynamics and macroscopic spatial patterns be included in a global simulation?



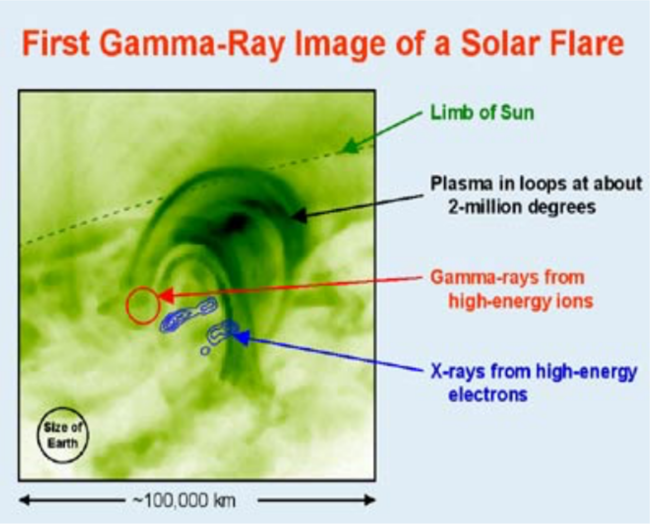


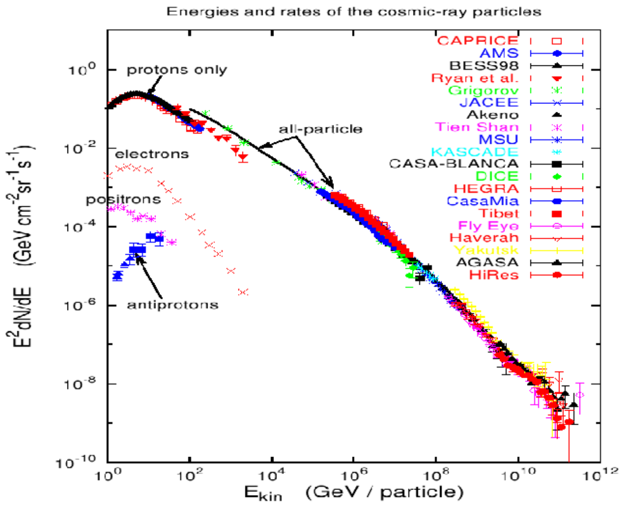
(a)

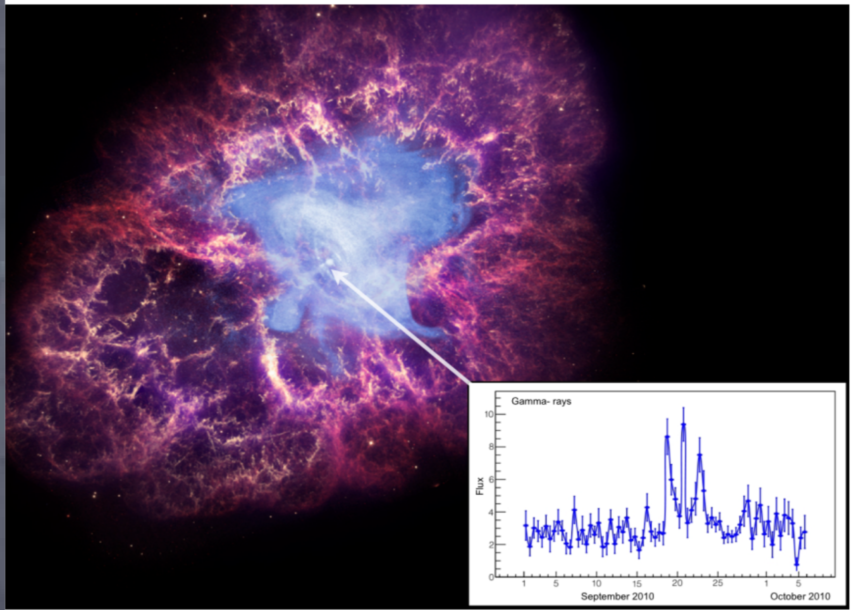
(b)

Fig. 5. Evolution of the wave spectrum and particle distribution function after explosive formation of holes and clumps in the hard nonlinear regime of near-threshold instability.

III



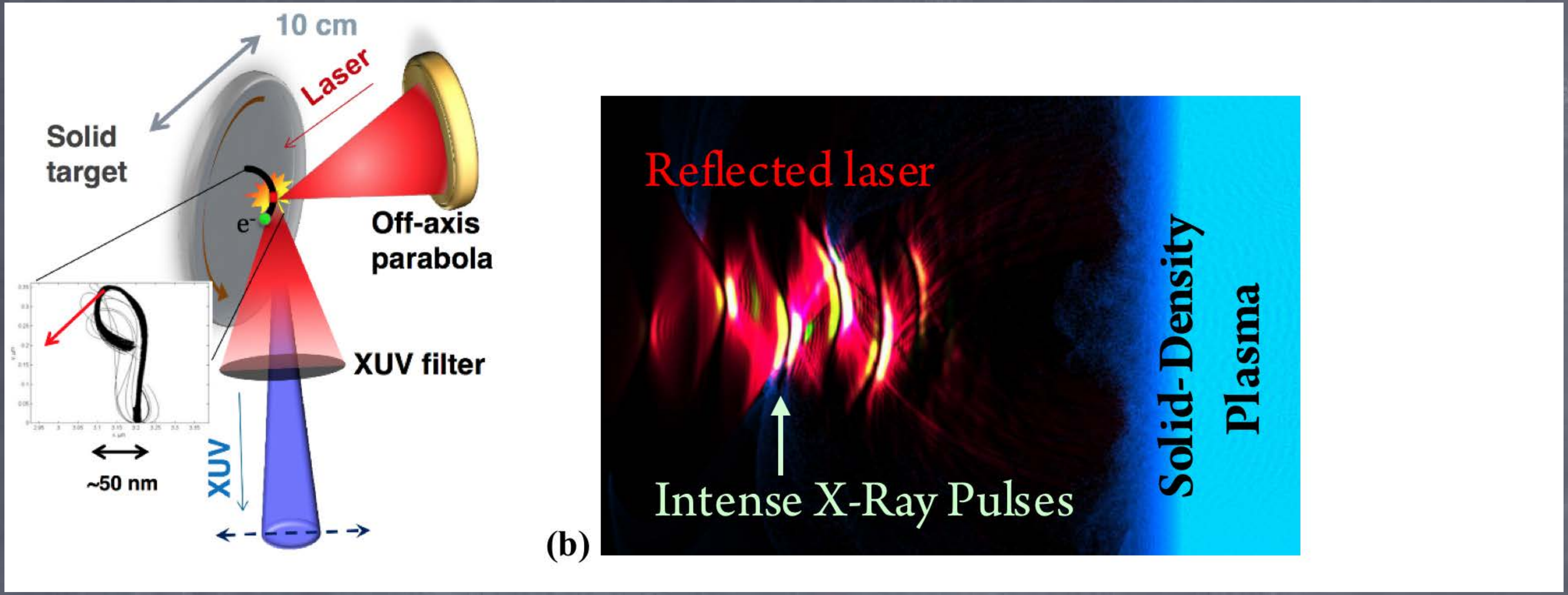




Top left: gamma-ray and microwave Emission from a solar flare. Top right: The cosmic ray spectrum detected at Earth. Bottom left: Gamma ray flare from the Crab Nebula.

Can comprehensive theoretical/modeling span from fluid to particle scales to capture the growth and saturation of plasma instabilities and the acceleration of particles from thermal to ultra-relativistic energies - cosmic rays?

IV



Plasma systems, from interface plasmas to compact X-ray sources, typically involve multi-scale and multi-phase physics and cannot be modeled with the same level of granularity in time and space.

Can new algorithms implementing advances in theory coupled with state-of-the-art computational technologies open new areas of plasma research and lead plasma experiments?

V

Can plasma descriptions be developed that enable the efficient modeling of plasmas in interaction with liquids and solids.