Ultracold Neutral Plasmas at the Plasma Physics Frontier

Jacob Roberts, Colorado State University, on behalf of many others

Frontiers of Plasma Physics Workshops

Town Hall Meeting

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Goals for this talk

I. Provide a basic overview of ultracold neutral plasmas

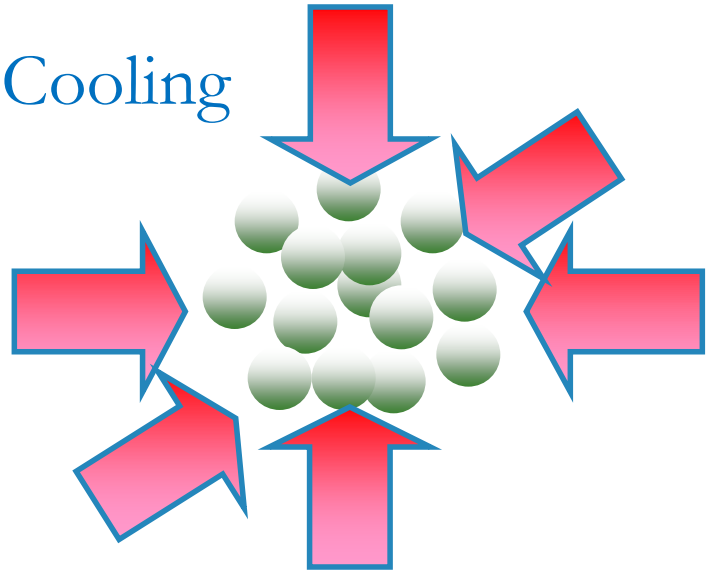
II. Describe efforts at the frontier of ultracold neutral plasma research

III. Relate these efforts to broader challenges in plasma physics

Creating an Ultracold Neutral Plasma Properties– Step 1

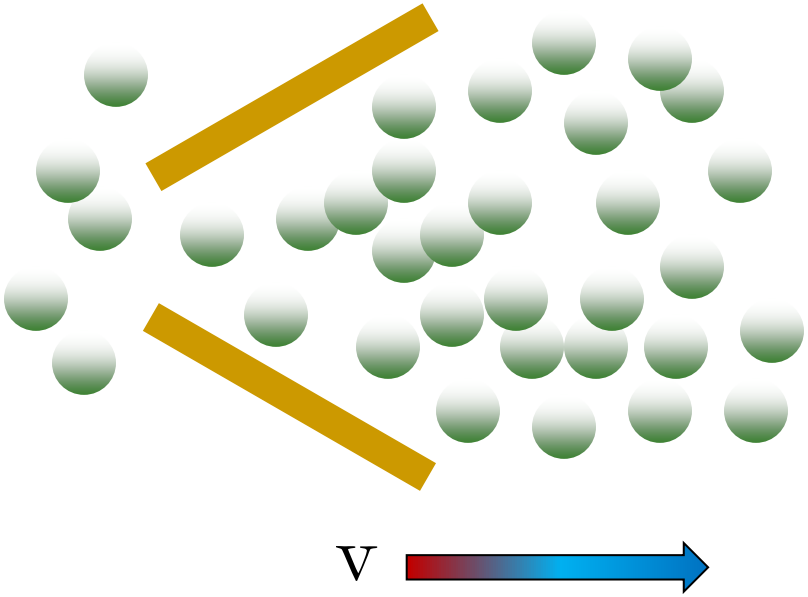
Start with cold atoms or molecules

Laser Cooling



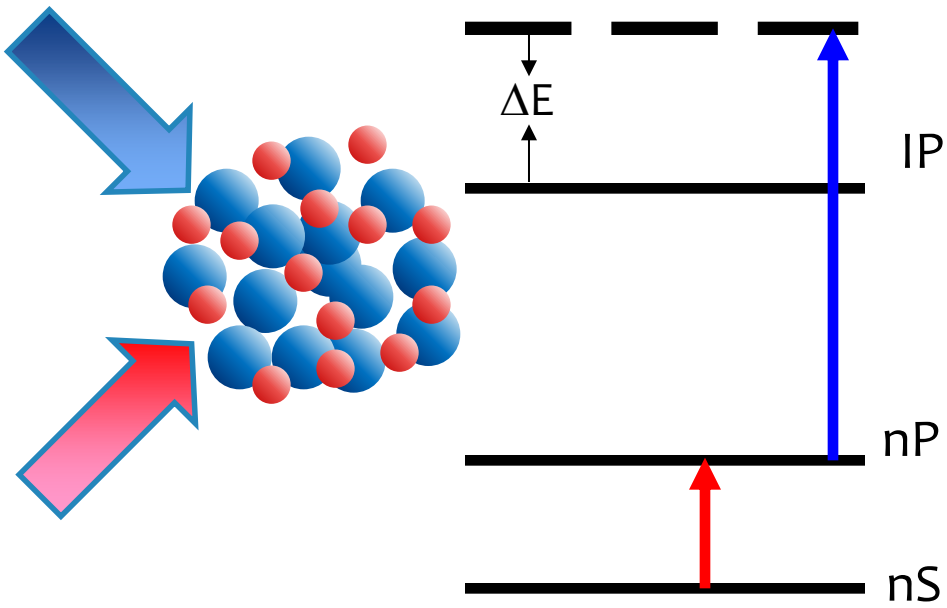
Atom Temperature is cooled down to ~100 μK

Supersonic Beam



Creating an Ultracold Neutral Plasma Properties– Step 2

Photoionize

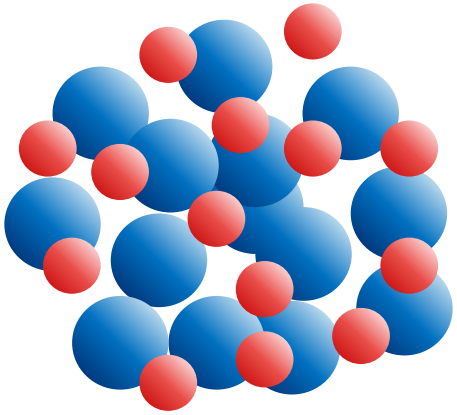


ΔE tunable from
~k_B·(0-1000K) with
~k_B ·0.1K precision

Experimental Control

After Ultracold Neutral Plasma Creation

- A few electrons escape, creating a confining potential for the rest
- Electrons and ions separately equilibrate in about 1μs
- Ions slowly expand (~100 μs)
- T_e as low as 2K and T_{ion} as low as a ~1 K

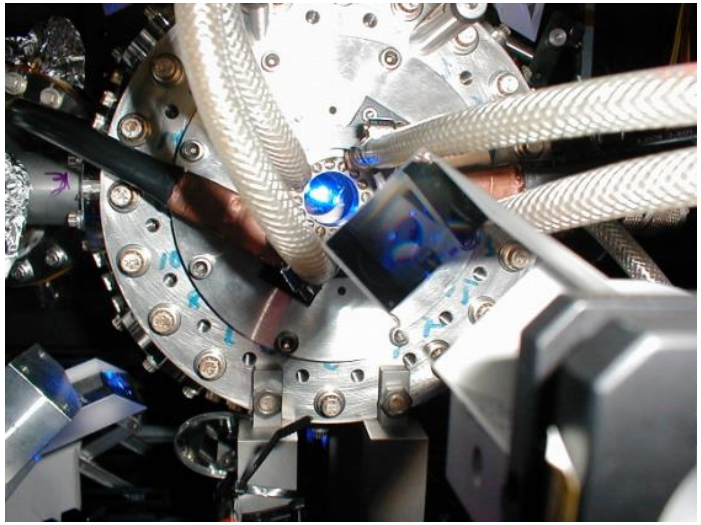


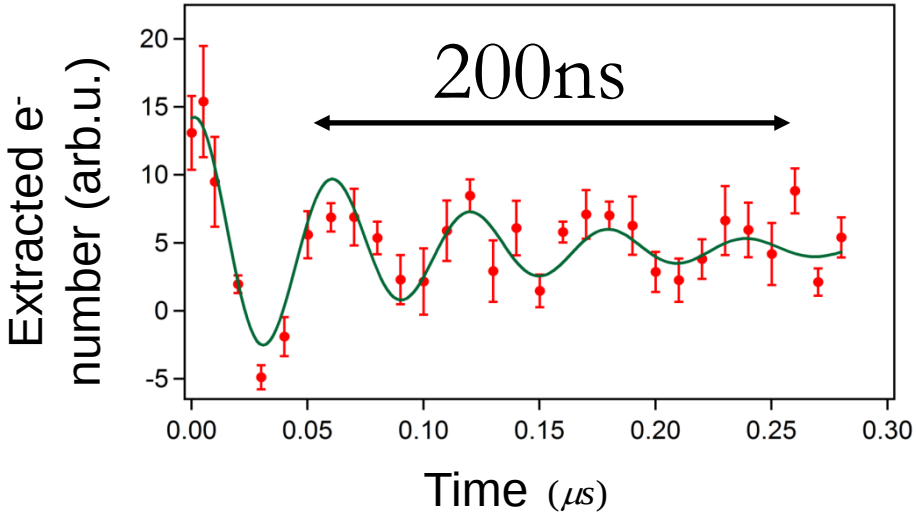
Ultracold Neutral Plasma Properties

Tabletop experiments
~Dozen experimental groups
~Same for theoretical groups

Exquisite control
- Density
- Initial Electron Temperature
- Ionization State
- No interaction with neutrals
- Millimeter scale spatial extent
- Applied **E** and **B** fields
- Effective diagnostics (space and velocity of ions from LIF)

Dilute – slow dynamics
ns-μs timescales





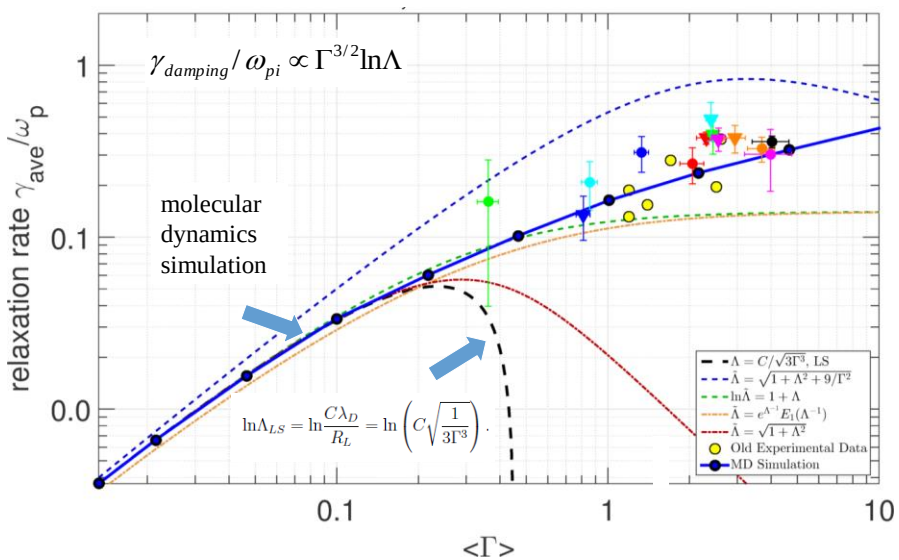
Ultracold Neutral Plasma Properties

$$\Gamma = \frac{\text{Nearest-neighbor Coulomb Energy}}{\text{Average thermal energy } (k_B T)}$$

Tunable Weak to Strong Coupling

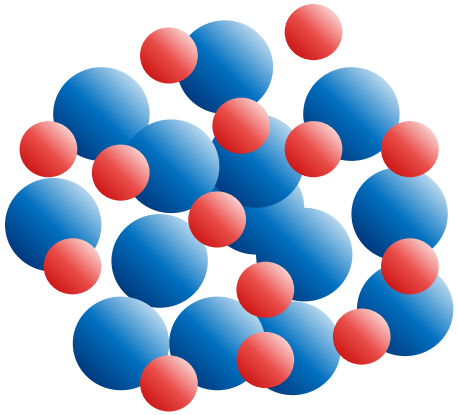
Γ_{ion}~0.5 to 5

Γ_e~0.001 to ≳0.2



After Ultracold Neutral Plasma Creation

Pretty good physical realization of something that looks like a "textbook" system –a one-component Yukawa system for the ions, for instance– with unique and tunable properties.

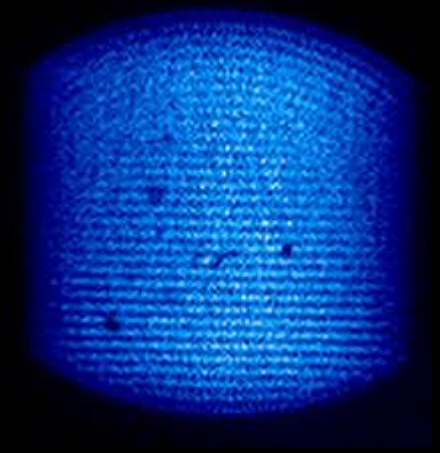


These are useful systems both experimentally and theoretically

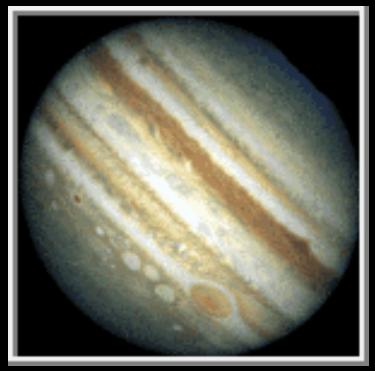
Use controllability to isolate desired physics, measure experimentally, compare to theory, and then use dimensionless scaling to relate to other plasma systems

Strong Coupling in Plasmas – Examples

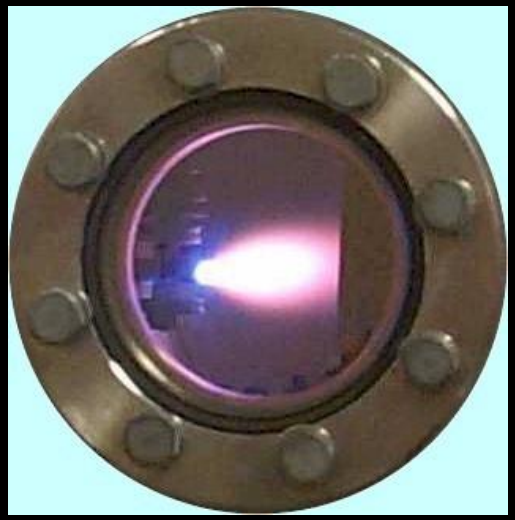
inertial confinement fusion experiments



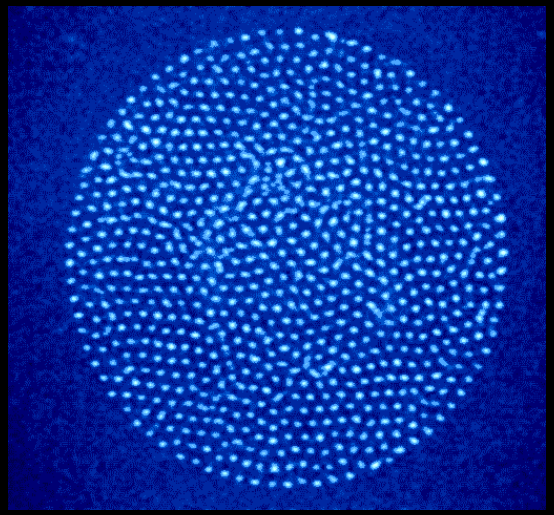
Laser Cooled Non-neutral Plasma



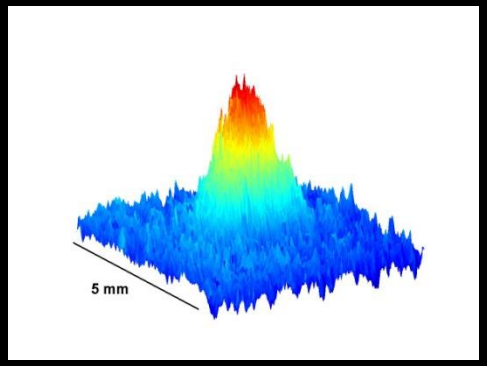
Jupiter interior



short pulse irradiation of solid targets



Dusty plasmas



Ions in an Ultracold Neutral Plasmas

Ultracold Neutral Plasmas Past Work

(theory and experiment)

~170 Publications since the start of the field (1999):

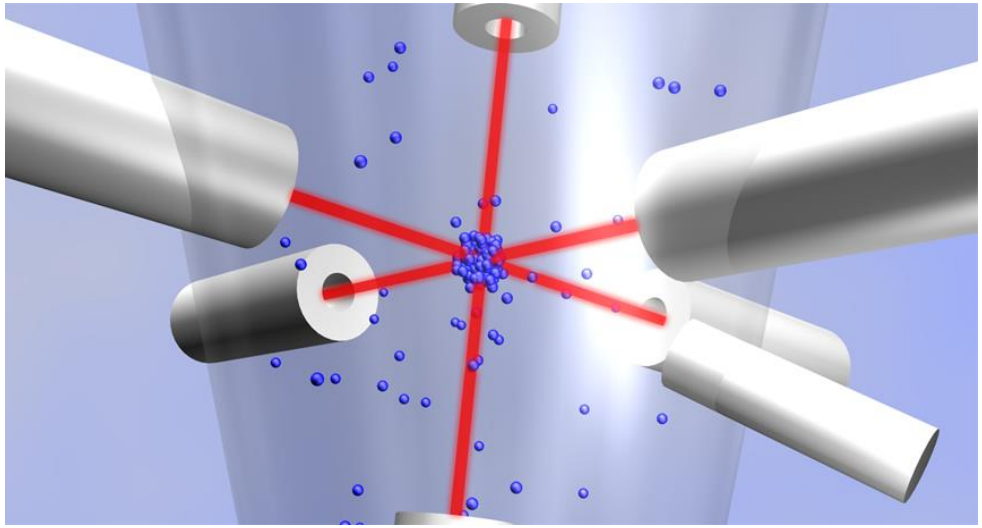
- Creation and Expansion Dynamics
- Collisions, Diffusion, Transport
- Statistical Mechanics, including initial equilibration, continuum lowering
- Ion Acoustic Waves and Electron Oscillations and instabilities
- Rydberg atom formation and interaction
- Theory concerning describing or extending strong coupling
- …

Examples from the Ultracold Neutral Plasma Frontier …

Ultracold Neutral Plasma Frontiers I – increase degree of strong coupling

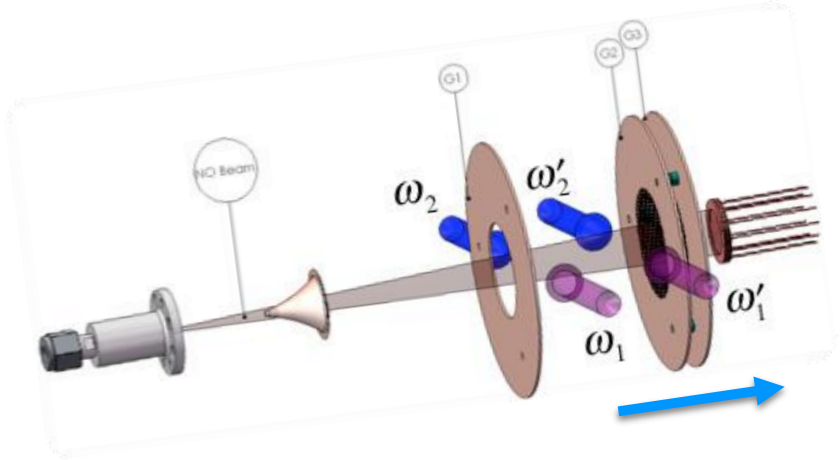
- Laser cooling of ions
- Other neutral atom manipulation techniques

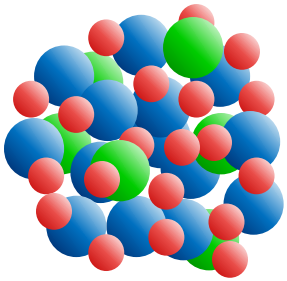
Extend Γ_{ion} past 5 to >100, especially to get to ~40 range

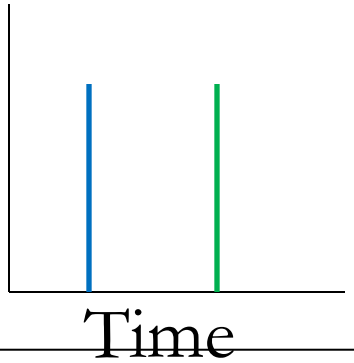


Ultracold Neutral Plasma Frontiers II
– multiple ionizations/multiple ion species

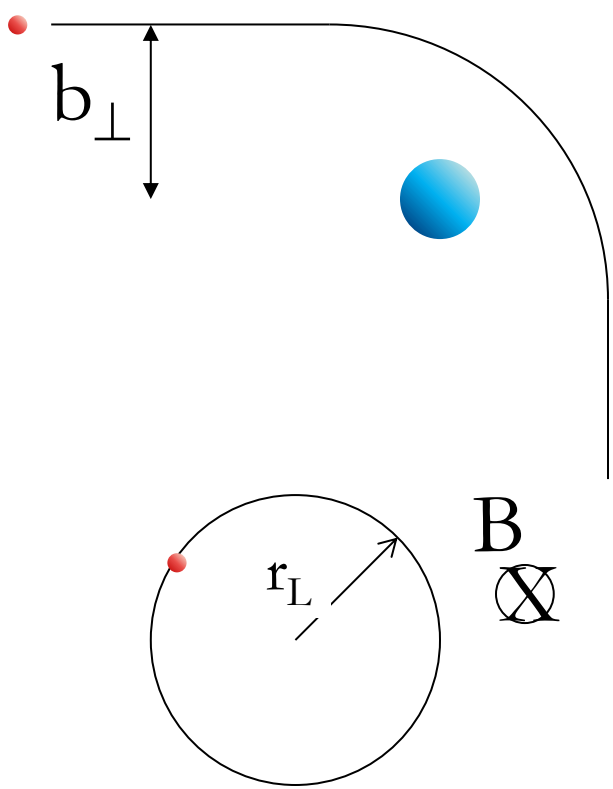
- Use one plasma to alter and/or probe another
- New avenues in collision, statistical mechanics, and equilibration studies







Ultracold Neutral Plasma Frontiers III
–magnetization of Ultracold Neutral Plasmas



B=0.1T @ 1K

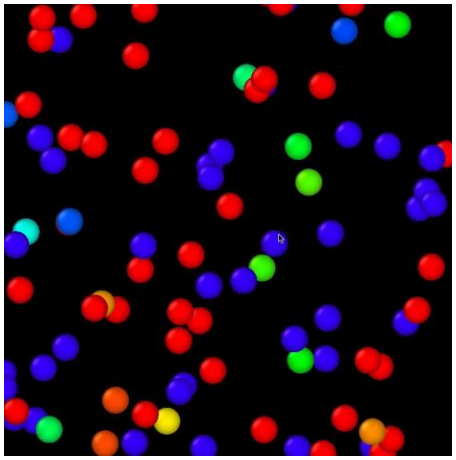
r_L ~0.01 $b_\perp$ (electrons)

r_L ~ $b_\perp$ (ions)

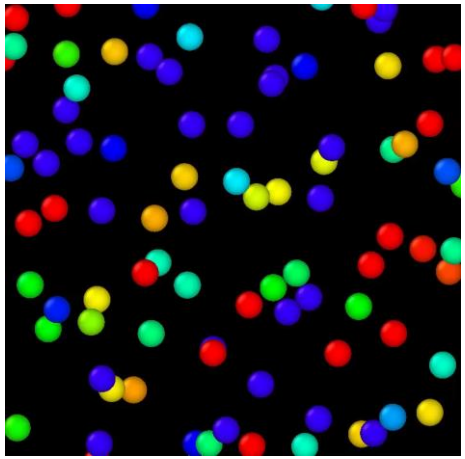
Equivalent to

B=100 kT @ 10,000K

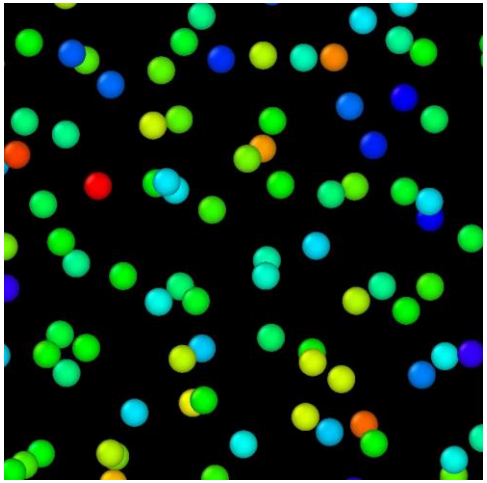
Ultracold Neutral Plasma Frontiers IV – plasma kinetic theory



Γ=1, κ=1



Γ=10, κ=1



Γ=100, κ=1

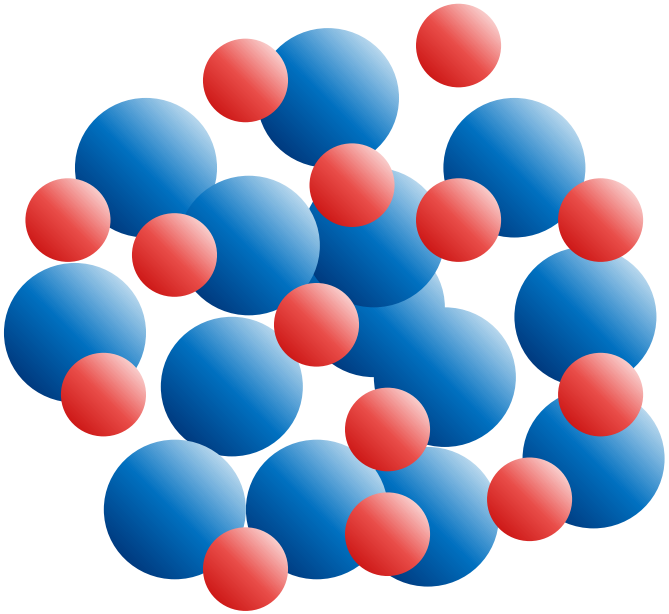
Michael Murillo, LANL

Because collective and collision dynamics of ultracold plasma are often inseparable, models need to go beyond typical plasma kinetic theory treatments

Ultracold Neutral Plasma Frontiers V – computational plasma modeling

- Experiments at LCLS/SLAC, NIF, Omega, and other intense laser sources produce matter in highly non-equilibrium states not modeled by usual plasma theory.
- New computational models are needed, and by scaling ultracold neutral plasmas can access similar regimes and perform precise measurements
- Coordinated efforts will develop computational tools broadly needed in plasma physics

Ultracold Neutral Plasmas



Set the parameters to the desired range that isolates the physics of interest, measure, compare to theory, extend to other plasma systems

Beyond Ultracold Neutral Plasma – Statistical Mechanics of Plasmas (Panel 4)

- Can we create new plasma kinetic theory models:
  - developed in response to and validated by experiment
  - over wide range of strong coupling and magnetization
  - in parameter ranges that can be difficult to access as directly in other systems?

- Can we understand, both theoretically and experimentally, the kinetics (e. g. velocity distributions and correlations as a function of time) of near-ideal Yukawa system plasmas
  - over a range of strong coupling parameters
  - well out of equilibrium
  - as they relax back toward equilibrium?

- Can continuum lowering in multispecies experiments be measured?

Beyond Ultracold Neutral Plasma – Turbulence and Transport (Panel 2)

Can we experimentally test to high precision (<10%) predicted ion/ion, ion/electron, electron/electron, and multispecies ion collision rates over a range of

- strong coupling parameters
- collisional/collisionless regimes with respect to collective excitations
- magnetization
- mass ratios?

Can we characterize ion diffusion rates in a similar way?

Beyond Ultracold Neutral Plasma –

Interactions of Plasmas and Waves (Panel 3)

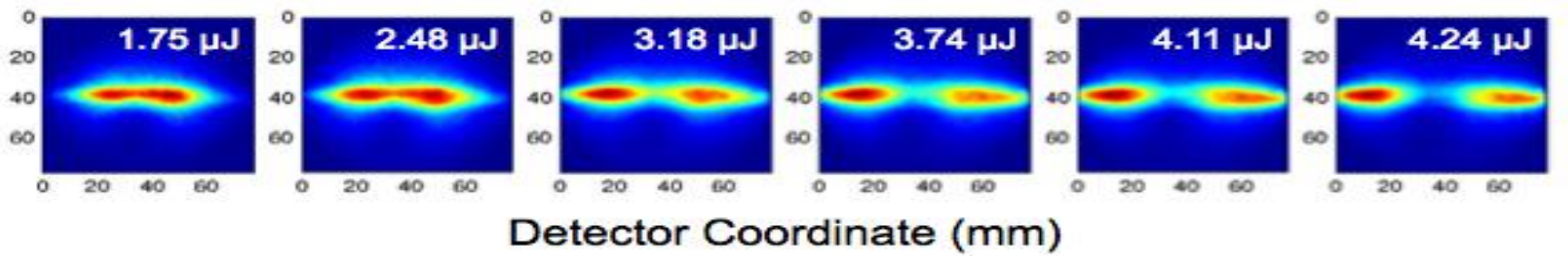
- Can we use multistep and multispecies ionization to create
  - novel shock structures
  - for studies of energy transport and relaxation
  - including under strong coupling conditions?

- Can new bright sources of charged particle beams be obtained?

Beyond Ultracold Neutral Plasma – Plasma atomic physics and the interface with chemistry and biology (Panel 1)

Three-body recombination under the influence of strong coupling

Rydberg atom influence on ultracold neutral plasma transport



Beyond Ultracold Neutral Plasma – Plasma Self-Organization (Panel 5)

Ultracold neutral plasmas in confining electrostatic/magnetostatic potentials (i.e. Penning-Malmberg traps)

Ultracold Neutral Plasmas at the Plasma Physics Frontier – white paper author list

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Funding Agencies Supporting Our Work

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